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Applications of Strong Gravitational Lensing by Galaxy Clusters to Star Formation and
Cosmology

by

Massimo Pascale

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Astrophysics

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Liang Dai, Co-chair

Professor Wenbin Lu, Co-chair

Professor Daniel Weisz

Professor Christopher McKee

Summer 2025

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Abstract

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Professor Liang Dai, Co-chair

Professor Wenbin Lu, Co-chair

Strong gravitational lensing of distant background galaxies into magnified multiple-images by foreground galaxy clusters presents a number of exciting opportunities for observational astrophysics. This thesis concerns two primary applications of this observed consequence of Einstein's general relativity.

Using multiply-imaged galaxies as constraints, this thesis models the mass distributions of two galaxy clusters. Combining these mass models with ground- and space-based data we determine these clusters are likely recent mergers, and may be useful for detecting transient lensed stars.

Leveraging the achromatic magnification provided by strong lensing, this thesis also studies the $z=2.37$ Sunburst galaxy, focusing on two young massive star clusters which are bright and resolved from other star-forming regions in the galaxy due to lensing. Photoionization modeling with joint photo-spectroscopic data of these clusters reveal they host nebulae with unusual abundance patterns; both showcasing heavy gas-phase nitrogen enrichment. We investigate the physical origin of these nebulae, and connect these unusual abundances to the puzzle of multiple stellar populations in globular clusters.

This thesis also analyzes the $z=1.78$ SN H0pe, which is triply-imaged due to strong gravitational lensing. JWST observations of all three SN images confirmed the Ia typing, and enabled photometric and rare spectroscopic measurements of the two relative time delays. Synthesizing these measured delays with strong-lensing mass models yields a value for the Hubble-Lemaitre constant (H_0). Crucially, the lensing magnification obtained from the standard candle augments this inference, breaking strong-lensing degeneracies. Following strict double-blinded protocols, these two measured time delays and three measured magnifications

were compared to the predictions of seven independently constructed cluster strong-lensing models to measure H_0 to $< 10\%$ uncertainty.

Finally, this thesis revisits the enigmatic, Earendel, a lensed star candidate in the $z=6$ Sunrise galaxy. Using JWST spectroscopy, we evaluate Earendel's likelihood as a star cluster rather than an individual star or binary. We find the spectrum to be highly consistent with a star cluster, and moreover find that Earendel, as well as another star cluster within the Sunrise, are consistent with the formation age-metallicity expectations for intermediate age star clusters in the first billion years of the universe.

To my father for making me feel like I could do anything.

To my mother for being there for me when I couldn't.

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Chapter 1

Introduction

1.1 Strong Lensing by Galaxy Clusters: A Brief History

The deflection of light by massive objects has long been posited even prior to the development of general relativity. Newton in his 1704 treatise on Opticks had already speculated 'Do not Bodies act upon Light at a distance, and by their action bend its Rays, and is not this action strongest at the least distance?'. However, it was not until 1802 that the German physicist Johann Georg von Soldner put this into practice, estimating the deflection of light rays which pass along the outer edge of the Sun. Einstein reproduced this calculation over a century later via his equivalence principle (Einstein, 1911), before recognizing the need for a general relativistic correction of a factor of 2 (Einstein, 1916) that Arthur Eddington and Frederick Hoyle Dyson would observationally confirm in the Eclipse of 1919 (Dyson, Eddington, and Davidson, 1920).

It would not be until 20 years later that Einstein would extend this concept to describe the lens-like action created by gravitational deflectors. At the repeated request of Rudy Mandl, an amateur Czech engineer who had intuited an early concept of an Einstein Ring ¹, Einstein would eventually begrudgingly develop the early formalism for gravitational lensing (Einstein, 1936), not seeing the point in publishing a result that he believed wholly impractical observationally ². Of course not even a year later, Fritz Zwicky would point out that individual galaxies (still referred to as nebulae at the time) were likely massive enough to induce the 'rings' Einstein had predicted. At the time, Zwicky was simultaneously producing some of the earliest estimates of galaxy masses within the Coma cluster, and recognized observing lensing via either individual galaxies or galaxy clusters was 'practically a certainty'.

This 'certainty' would not be realized until more than forty years later with the detec-

¹Mandl also thought that lensing of high energy radiation may be accelerating the development of the human genome through mutations!

²While largely unrecognized, F. Link actually published an even more extensive theory of lensing which included the formation of multiply imaged systems more than nine months prior (Link, 1936)

tion of the $z = 1.405$ doubly-imaged quasar 0957+561 (Walsh, Carswell, and Weymann, 1979). First thought to be a coincidence, spectroscopic follow-up confirmed the two quasars separated by $5.7''$ to be identical images of one another, making them the first instance of strong gravitational lensing to be observed. Still, this was a far cry from the more dramatic ring-like structures suggested by Mandl and predicted by Einstein. These would take yet another decade to be found by Soucail et al. in 1987 who speculated the $z=0.724$ structure later known as ‘the Dragon’ in the Abell 370 cluster field was a giant partial Einstein ring (Soucail et al., 1987) before confirming it spectroscopically the next year (Soucail et al., 1988). The lensed galaxy identified by Soucail et al., later known as the ‘Dragon’ galaxy, remains to this day one of the most fantastic cases of strong-lensing observed (Fig. 1.1).

This discovery would kick off decades of efforts to exploit these lensing clusters for astrophysical science. Lensing evidence in these clusters would be used as input to construct mass models which probed the cluster dark matter (e.g., Kneib et al., 1993). At the advent of the *Hubble Space Telescope* (HST), lensed galaxies would be resolved in such detail that the effects of dark matter substructure within the galaxy cluster halo would become discernible (e.g., Natarajan and Kneib, 1996). Furthermore, this enabled systematic studies of large cluster samples to inform our understanding of the hierarchical build up of dark matter halos (e.g., Meneghetti et al., 2014).

The sensitivity of HST combined with lensing magnification would reveal some of the earliest detections of reionization era galaxies (e.g., Kneib et al., 2004a), and eventually out to cosmic dawn galaxies (Coe et al., 2013a). This would culminate in the Hubble Frontier Fields program (Lotz et al., 2017a), which would achieve depths of nearly 30 mags on six promising galaxy cluster fields. This enabled mapping of the UV luminosity function out to limiting depths impossible by blank fields (Mason, Trenti, and Treu, 2015), provided some of the earliest detections of individually microlensed stars (Kelly et al., 2018b), and stringently tested of our understanding of cluster dark matter (Meneghetti et al., 2017).

The launch of *JWST* dramatically amplified the cluster lensing science achievable with HST. Even the best studied clusters saw significant yields of new lensing evidence which refined precision lensing mass models (e.g., Bergamini et al., 2023; Diego et al., 2023a). Highly magnified cosmic dawn galaxies went from marginally detectable to being analyzed in detail (e.g., Hsiao et al., 2022; Adamo et al., 2024). Extreme starburst have been placed under the microscope, revealing new spectroscopic signatures which have informed our understanding of star formation (e.g., Topping et al., 2024). Coming full circle, the ‘Dragon’ of Abell 370 discovered by Soucail et al. has yielded dozens of individually lensed stars over 6 billion light years away (Fudamoto et al., 2024) which are informing dark matter models (Broadhurst et al., 2025). It is clear that in the current JWST era, the versatile applications of strong-lensing clusters are more effective than they have ever been, and the hold great potential to make strides on astrophysical problems from cosmology to star-formation.

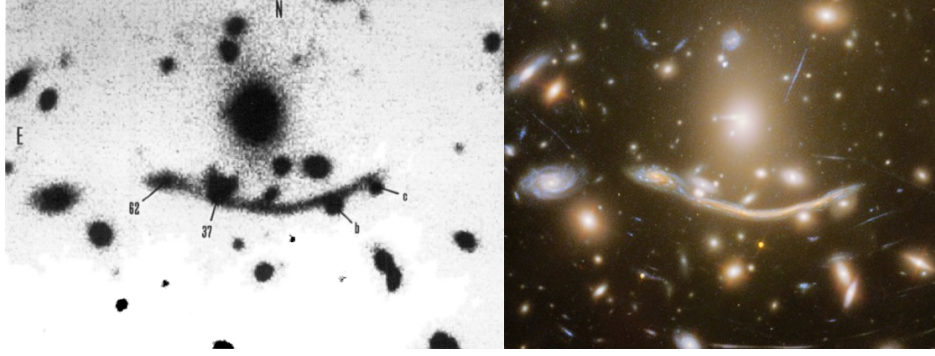


Figure 1.1 The original images of the ‘Dragon’ in Abell 370 from the Canada-France-Hawaii Telescope used to first detect it (Left; Soucail et al., 1987) versus to those taken three-decades later with HST through the Hubble Frontier Fields program (Right; Lotz et al., 2017a).

1.2 Gravitational Lensing Formalism

The Lens Equation and Lensing Jacobian

Here we give a brief overview of the underlying theory of gravitational lensing in the strong regime relevant for the lensing of distant galaxies by galaxy clusters (e.g., cosmological scales). We note that the following section is synthesized from Saha et al., 2024, Natarajan et al., 2024, and Narayan and Bartelmann, 1996, and we refer the reader to these texts for further information. The ‘lens-like’ action of light by gravitational deflectors can be evaluated in two regimes: ‘geometric’ and the ‘wave’ optics. The latter is only relevant when diffraction of interference effects become observable, requiring incredibly compact sources whose Einstein radii (detailed below) are comparable to the wavelength of light observed. Outside this regime, the light is considered incoherent, and the formalism of geometric optics is almost entirely adaptable. We can begin simplistically by imagining the deflection of light by a point mass lens, not unlike Einstein’s original 1919 prediction. Leaning on the theory of geometric optics, we imagine light passing through a lens of index of refraction n from vacuum. This index of refraction is described as the ratio of the speed of light in a vacuum to the speed of light in the lens medium. The deflection of light due to this lens over some path length dl is then:

$$\hat{\alpha} = - \int \nabla_{\perp} n \, dl \quad (1.1)$$

This equation can be straightforwardly appropriated for the deflection of light due to gravity. Whereas n provides the ratio of the speed of light in the medium and vacuum, we can instead understand it via the delay provided by the gravitational time dilation. we consider the Minkowski metric for a photon along a path length dl :

$$ds^2 = 0 = c^2 dt^2 (1 + 2\Phi/c^2) - (1 + 2\Phi/c^2)^{-1} dl^2 \quad (1.2)$$

where Φ is the Newtonian gravitational potential. The effective speed of light is by definition $c' = dl/dt$, and we assume the gravitational field to be weak, that is $\Phi \ll c^2$. Hence:

$$n = c/c' \approx (1 - 2\Phi/c^2) \quad (1.3)$$

Following this, we update the deflection for gravitation rather than tabletop optics:

$$\hat{\alpha} = - \int \nabla_{\perp} n \, dl = \frac{2}{c^2} \int \nabla_{\perp} \Phi \, dl. \quad (1.4)$$

We now consider the Newtonian potential Φ and thereby the deflection of a light ray with impact parameter b relative to an individual point mass deflector. As the unperturbed light ray approaches the plane of the deflector at some distance z , the Newtonian potential of the lens is:

$$\Phi(b, z) = -\frac{GM}{(b^2 + z^2)^{1/2}} \quad (1.5)$$

Our deflection therefore becomes:

$$\hat{\alpha} = \frac{2}{c^2} \int \nabla_{\perp} \Phi \, dz = \frac{4GM}{c^2 b}. \quad (1.6)$$

Note that the path length dl has now been replaced with dz , which is allowable under assumption that the gravitational field is weak, such that the deflection angle is very small.

Galaxy clusters of course are not point masses, and instead may take on complex, extended mass distributions. One potential issue with this is already solved by our assumption that the gravitational field is weak, and that the contributions of an extended mass distribution can be integrated over (or that it may be decomposed into the sum of many point masses). However our clusters depart from a point mass both in the plane of the sky and along the light of sight. To tackle this we invoke a new simplifying assumption known as the ‘thin sheet’ or ‘thin lens’ approximation: the distances between the observer, deflector (lens), and source are much larger than the region that the deflection occurs over. We can treat the light rays as deflecting instantaneously and solely at the lens rather than over some finite region, and ignore finite thickness in both the deflector and the lensed source. This establishes the notion of a ‘source’ plane and ‘lens’ plane.

Consequently, we collapse our complex mass distribution to a 2D surface density $\Sigma(\boldsymbol{\xi})$, where $\boldsymbol{\xi}$ is the 2D vector in the plane of our now 2D deflector. Synthesizing the assumptions made thus far, the deflection angle at $\boldsymbol{\xi}$ is then:

$$\hat{\alpha}(\boldsymbol{\xi}) = \frac{4G}{c^2} \int \frac{(\boldsymbol{\xi} - \boldsymbol{\xi}') \Sigma(\boldsymbol{\xi}')}{|\boldsymbol{\xi} - \boldsymbol{\xi}'|^2} d^2 \xi'. \quad (1.7)$$

Now that we can describe the deflection, we can straightforwardly express the mapping from the observed position to the true source position $\boldsymbol{\theta}$ and β by some gravitational deflection $\alpha(\boldsymbol{\theta})$, self-consistently accounting for the expansion of the universe by multiplying by angular diameter distances:

$$D_s \boldsymbol{\beta} = D_s \boldsymbol{\theta} - D_{ds} \hat{\alpha}(\boldsymbol{\theta}). \quad (1.8)$$

We can now define the ‘scaled’, ‘apparent’, or ‘reduced’ deflection as:

$$\boldsymbol{\alpha} = \frac{D_{ds}}{D_s} \hat{\boldsymbol{\alpha}}. \quad (1.9)$$

To yield the ‘lens equation’ as it is typically given in the literature:

$$\boldsymbol{\beta} = \boldsymbol{\theta} - \boldsymbol{\alpha}(\boldsymbol{\theta}). \quad (1.10)$$

This ‘lens equation’ (see Fig. 1.2) mirrors the tabletop analog when including this ‘apparent’ deflection. The multiple imaging that defines strong lensing is immediately apparent from this function as the mapping $\boldsymbol{\beta}$ and $\boldsymbol{\theta}$ is not injective, and multiple $\boldsymbol{\theta}$ may map to a single $\boldsymbol{\beta}$. Now let us revisit the scaled deflection but expand out the deflection for the mass sheet and convert from ξ to $\boldsymbol{\theta}$ ($\xi = D_d \boldsymbol{\theta}$):

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{D_{ds}}{D_d D_s} \frac{4G}{c^2} \int \frac{(\boldsymbol{\theta} - \boldsymbol{\theta}') \Sigma(\boldsymbol{\theta}')}{|\boldsymbol{\theta} - \boldsymbol{\theta}'|^2} d^2 \theta'. \quad (1.11)$$

We may rewrite this equation by defining what is typically referred to as the lensing convergence κ , which is defined as the ratio of the surface mass density to some scalar quantity defined as the critical density

$$\kappa(\boldsymbol{\theta}) = \Sigma(\boldsymbol{\theta}) / \Sigma_{cr} \quad (1.12)$$

$$\Sigma_{cr} = \frac{c^2 D_s}{4\pi G D_{ds} D_d}. \quad (1.13)$$

This defined scaling Σ_{cr} is not simply clean notation, and has an intuitive meaning. As is apparent in the scaled deflection, a lens with constant surface mass density Σ_{cr} will have deflection equal to the apparent source position $\boldsymbol{\alpha}(\boldsymbol{\theta}) = \boldsymbol{\theta}$, and thus $\boldsymbol{\beta} = 0$. That is, this is approximately the threshold for which multiple imaging may appear. Rewriting the deflection with the convergence:

$$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{1}{\pi} \int \frac{(\boldsymbol{\theta} - \boldsymbol{\theta}') \kappa(\boldsymbol{\theta}')}{|\boldsymbol{\theta} - \boldsymbol{\theta}'|^2} d^2 \theta'. \quad (1.14)$$

We can now also define deflection potential (or so-called lens potential):

$$\psi(\boldsymbol{\theta}) = \frac{1}{\pi} \int d^2 \theta' \kappa(\boldsymbol{\theta}') \ln |\boldsymbol{\theta} - \boldsymbol{\theta}'|. \quad (1.15)$$

This is indeed a projection of the Newtonian potential. This lens potential is defined such that the gradient yields the apparent deflection, and satisfies Poisson’s equation similar to the Newtonian potential:

$$\boldsymbol{\alpha} = \nabla \psi(\boldsymbol{\theta}) \quad (1.16)$$

$$2\kappa = \nabla^2 \psi(\boldsymbol{\theta}). \quad (1.17)$$

For a given observed image position, the properties of the image can be yielded from the lensing Jacobian:

$$\mathcal{A} = \frac{\partial \boldsymbol{\beta}}{\partial \boldsymbol{\theta}} = (\delta_{ij} - \frac{\partial \alpha_i(\boldsymbol{\theta})}{\partial \theta_j}) = (\delta_{ij} - \psi_{ij}). \quad (1.18)$$

where we define $\psi_{ij} = \frac{\partial^2 \psi(\boldsymbol{\theta})}{\partial \theta_i \partial \theta_j}$. Importantly, we can compare the differential area element of the true source to the apparent source, effectively yielding the magnification, μ of this area element:

$$\mu = \partial \beta^2 / \partial \theta^2 = 1 / \det \mathcal{A} = \det \mathcal{M}. \quad (1.19)$$

where $\mathcal{M}$ is the magnification tensor. Considering how the convergence relates to the deflection potential, we see:

$$\kappa = \frac{1}{2}(\psi_{11} + \psi_{22}) \quad (1.20)$$

We can now define the lensing shear via the Hessian of the lens potential, that being

$$\gamma_1(\boldsymbol{\theta}) = \frac{1}{2}(\psi_{11} - \psi_{22})\gamma_2(\boldsymbol{\theta}) = \psi_{12} = \psi_{21}\gamma = \sqrt{\gamma_1^2 + \gamma_2^2}. \quad (1.21)$$

Now we can more easily represent the lensing Jacobian:

$$\mathcal{A} = \begin{bmatrix} 1 - \kappa - \gamma_1 & \gamma_2 \\ \gamma_2 & 1 - \kappa + \gamma_1 \end{bmatrix}. \quad (1.22)$$

We redefine the magnification by taking the determinant:

$$\mu = \det \mathcal{M} = \frac{1}{(1 - \kappa)^2 - \gamma^2}. \quad (1.23)$$

Intuitively understanding the analogies to a tabletop optical lens: κ is a function of ‘focus’ and γ is a function of astigmatism.

The Fermat Formalism to Lensing and the Lensing Time Delays

Lensing can also be reimagined in terms of Fermat’s principle of least action. We can imagine a ‘wavefront’ known as the Fermat surface corresponding to light rays emitted from the source object at a given time. As the source-lens distance is great compared to the size of the source and lens, we can imagine this wavefront approaches the lens plane as itself a plane in the absence of gravity. In the presence of a deflector, light rays are deflected and their arrival time to the observer delayed, distorting the wavefront. Images in this wavefront appear at extrema where those images graze the wavefront of the observer. The delay in

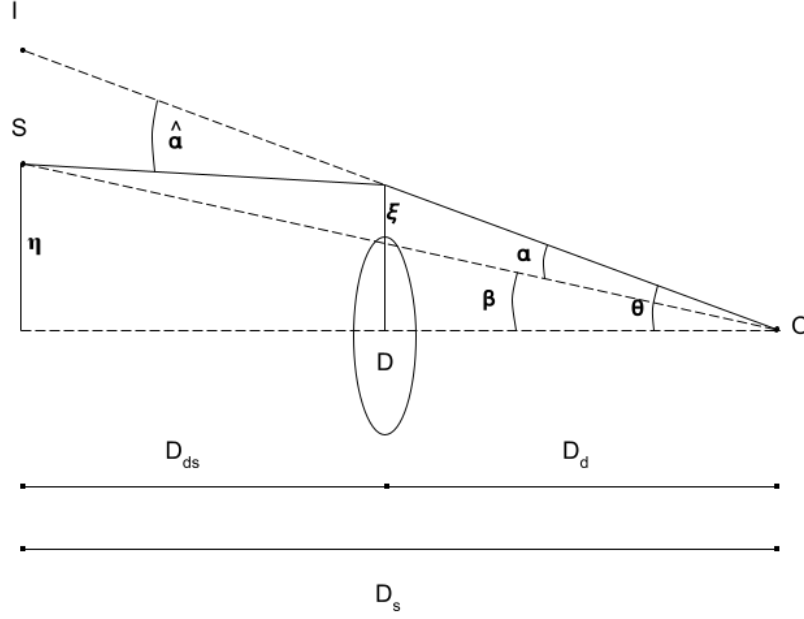


Figure 1.2 Visualization of the lens equation for a single source (S), lensed image (I), deflector/lens (D), and observer (O). The typical quantities for gravitational lensing formalism are labeled. Recreated from Narayan and Bartelmann, 1996.

arrival time of the surface can be decomposed into the geometric delay and the gravitational (or Shapiro) delay.

$$t_{\text{geo}}(\boldsymbol{\theta})/(1+z_d) = \frac{D_d D_s}{2c D_{ds}} |\boldsymbol{\theta} - \boldsymbol{\beta}|^2 \quad (1.24)$$

$$t_{\text{grav}}(\boldsymbol{\theta})/(1+z_d) = \frac{D_d D_s}{c D_{ds}} \psi(\boldsymbol{\theta}). \quad (1.25)$$

This is yielded by the lens equation, including an extra factor of $(1+z_d)$ to account for redshifting of the delay time, and thereby satisfies $\nabla_{\boldsymbol{\theta}} t = 0$ by definition. It is convenient to

introduce a new angular distance scale:

$$D_{\Delta t} = \frac{1 + z_d}{c} \frac{D_d D_s}{D_{ds}}. \quad (1.26)$$

Note that as there remains an extra angular diameter distance in the numerator, it is proportional to the expansion rate of the universe at the present day, H_0 , or the Hubble constant. The implication is such that if you know the relative delay in arrival time between any two extrema, i and j , of the time-delay surface, you can yield the Hubble parameter:

$$\Delta t_{ij}(\boldsymbol{\theta}_i, \boldsymbol{\theta}_j) = D_{\Delta t} \Delta_{ij} \left[\frac{1}{2} (\boldsymbol{\theta} - \boldsymbol{\beta})^2 - \psi(\boldsymbol{\theta}) \right]. \quad (1.27)$$

1.3 Time-Delay Cosmography

This notion that ascertaining the relative time delay between lensed images can measure the Hubble constant was first well-described by Sjur Refsdal in 1964 (Refsdal, 1964), and may well be the first suggestion that such a calculation was possible. In Refsdal’s picture, transient events with the lensed source (in his example, a supernova) could allow for the determination of the time delay, which would otherwise be impossible with static, incoherent lensed images. With a measurement of the time delay and an understanding of the deflection potential, this in turn yields the Hubble constant.

Hubble Tension

At the time of Refsdal’s derivation, constraints on the Hubble constant had progressed significantly from Edwin Hubble’s original suggestion of $\sim 500 \text{ km/s/Mpc}$ (Hubble, 1929), but was still only constrained at $\sim 50\%$ level precision (e.g., (Sandage, 1962)). Throughout the later half of the 1900s, two camps would emerge both using local distance indicators pushing for either $\sim 50 \text{ km/s/Mpc}$ (Sandage, 1962) or $\sim 100 \text{ km/s/Mpc}$ (de Vaucouleurs, 1973). This tension would finally be broken with the advent of the *HST*, where the HST Key project would build the local distance ladder (parallax to Cepheids to Tully-Fisher to SN Ia) would find an intermediate value $H_0 = 72 \pm 6 \text{ km/s/Mpc}$ (Freedman et al., 2001). This appeared to be confirmed by the Wilkinson Microwave Anisotropy Probe (WMAP) data of the cosmic microwave background (CMB) in 2007, which yielded $H_0 = 73 \pm 3 \text{ km/s/Mpc}$ (Spergel et al., 2007) assuming a power-law flat Λ CDM cosmological model and in turn bolstering the efficacy of the Λ CDM model.

This apparent agreement would unfortunately be short-lived. In the 2010’s cosmology reached a precision era which seeded a new tension. The newest microwave instrument *Planck* would measure H_0 first at the 1.5% and later breaking the 1% level, finding $H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc}$ (Planck Collaboration et al., 2020a). Meanwhile improvements on from the local distance ladder would reduce the measurement error to $< 3\%$ in 2016 and later $< 2\%$ in the 2020s through the the ‘Supernova H_0 for the Equation of State’ (SH0ES)

collaboration, yielding $73 \pm 1 \text{ km/s/Mpc}$ (Riess et al., 2022). At the same time, distance ladder measurements using alternative rungs, such as swapping Cepheids for RGB or AGB stars would determine $H_0 = 70 \pm 1.5$ (Freedman et al., 2025). This confusion in measuring the Hubble constant over a century after Hubble’s initial measurement continues to be a lingering problem in astrophysics. And more so it is a problem with high stakes: the Hubble constant crucially measures the age of the universe, and specifically the potential 5σ disagreement between distance ladder and CMB measurements threatens the Λ CDM model itself.

It has become apparent that viewing this problem as one approach versus another may come to a standstill, thwarted by systematics and so-called ‘unknown unknowns’. However if multiple independent methodologies manage to recover or reject this tension, then this can guide whether to place the burden of resolution on either the experimental or theoretical side. This has motivated the application of a wide range of methods for local or ‘late time’ measurements, from leveraging surface brightness fluctuations (Blakeslee et al., 2021), to utilizing standard sirens (Wang et al., 2023), to megamasers (Pesce et al., 2020). Still, this tensions persists, as these approaches have yet to become truly competitive with the CMB or SH0ES estimates.

H_0 from Strong-Lensing Time Delays

Time-delay cosmography has played a part in this effort, albeit not as Refsdal initially anticipated. Rather than lensed SNe, it has primarily been performed using multiply-imaged quasars, taking advantage of the intrinsic variability of AGN (Suyu and Halkola, 2010). In particular, it has been performed primarily for single foreground galaxies lenses, which introduces systematics distinct from galaxy cluster lenses. While these applications are vast and continue to improve (Wong et al., 2020; Millon et al., 2020; Birrer, Dhawan, and Shajib, 2022), this thesis instead turns its attention to galaxy clusters, a scale with a much sparser heritage. The sparse number of applications at this scale are likely due to the much smaller number of cluster lenses compared to galaxy-galaxy (e.g., Meneghetti et al., 2023), however clusters are worthwhile to pursue. While single-galaxy (or galaxy-galaxy) lenses are more simple to model, typically achievable with a single power-law surface density profile with a free slope, this simplicity comes with a trade off of scale. Galaxy-galaxy lenses (by definition) show only one system of multiple images, and the relative time-delay between these images is small (order days). The larger caustic area of clusters means they often show a number of distinct multiply-imaged galaxies at various redshifts, which crucially helps to break the well-known mass-sheet degeneracy, where in which adding constant sheets of mass to the lens affects the time-delay yet not the multiple-image apparent positions for any lone image system (Falco, Gorenstein, and Shapiro, 1985; Kochanek, 2002). The longer time-delay also means higher precision on the time-delay measurement, indeed time-delays at the $< 1\%$ level are attainable in many lenses (e.g., Kelly et al., 2023b; Rodney et al., 2021).

Time-delay cosmography in galaxy clusters was, similar to galaxy-galaxy lenses, primarily relegated to lensed quasars for much of the last 20 years. To date three galaxy cluster-lensed quasars suitable for time-delay cosmography are known, with long-term monitoring programs

enabling $< 1\%$ level uncertainties on the time-delays (Muñoz et al., 2022; Fohlmeister et al., 2013). Previous efforts have successfully measured H_0 at the $\sim 10\%$ level using these quasars (Napier et al., 2023; Liu, Oguri, and Cao, 2023) by combining them with lensing mass models of the foreground cluster. Similarly, the first lensed supernova to be discovered, the Type II SN Refsdal (Kelly et al., 2015), was also found on the cluster scale, yielding $< 1\%$ errors on the time delay while closer to $\sim 8\%$ level constraints on H_0 .

What thwarts these measurements from making full use of their precision time-delays (which in the absence of uncertainty in the deflection potential should propagate directly to H_0) is the understanding of the deflection potential. Galaxy cluster scale lenses are highly complex and typically not fully virialized. Indeed, it was not until the last 20 years that modeling the mass distribution of these lenses was even computationally tractable (e.g., (Frye and Broadhurst, 1998)). This ‘lens modeling’ is forced to make a handful of assumptions which limit the possible parameter space, both for practicality (e.g., computation) and physicality (e.g., the dark matter profile). For this reason, most modeling techniques take a ‘parametric’ approach, where the galaxy cluster is represented as a superposition of analytic density profiles which are widely-accepted to be appropriate for galactic scale (or greater) dark matter halos (e.g., Navarro, Frenk, and White, 1997). As the lens potential of such profiles is also analytic, these methods are both fast and physically motivated. Still, the number of galaxies within a cluster are great, involving sometimes a hundred of such profiles (e.g., Zitrin et al., 2009a). Rather, it is typically also assumed that the majority of galaxies follow scaling relations based on their luminosity, such as the Faber-Jackson relation (Faber and Jackson, 1976), with a select few given individual treatment and hence free parameters.

The lens potential uncertainties (as relevant to the H_0 measurement) scale straightforwardly with the number of constraints, yielding improvements for even the most constraint-rich lensing clusters (Liu and Oguri, 2024). These constraints include at minimum the angular positions and redshifts of multiply-imaged galaxies, but may be extended to include: velocity dispersion measurements of the galaxy cluster members, image system flux (magnification) ratios, and even ratios of the time-delays. Even still, these are not sufficient to yield competitive uncertainties with the time-delays themselves, adding roughly in quadrature to produce the H_0 uncertainty.

A long-understood way forward is to include magnification constraints on the lensed images, specifically on the transient host whose time-delays are used for the H_0 measurement. As visible from the lensing theory above, the magnification and time-delay are both products of the lens potential. Without information on either the magnification or time-delay, the lens potential is actually underconstrained: the constraints listed above (particularly ratios of any of these quantities) depend on the shape of the surface mass density distribution but not the absolute value of the mass density itself. Rather, an absolute magnification can anchor this quantity, breaking the degeneracy and directly tightening the constraints on the time-delay. As early as 1985, it has been posited that a lensed Type Ia SN could provide this solution, yielding simultaneously time-delay and magnification information (Falco, Gorenstein, and Shapiro, 1985) due to the standard candle. While tantalizingly close to such a scenario in two galaxy-galaxy supernovae (Goobar et al., 2017; Pierel et al., 2023) and a missed cluster-

lensed supernova (Rodney et al., 2021), this had yet to come to fruition as we entered the mid-2020s. If such an opportunity were to present itself, it would be a fantastic case-study to evaluate what may be the best path forward to reduce lensing uncertainties and ultimately reach H_0 uncertainties adequate for precision cosmology.

1.4 Strong Lensing of Star Clusters

Strong-lensing is also useful in tackling problems related to near-field cosmology, specifically the formation, evolution, and chemical buildup of modern-day globular clusters (GCs). Globular clusters are among the oldest stellar structures in the universe, serving as relics from a once-prominent site of star formation in the early cosmos. Despite extensive study, their formation and evolution are not well-understood (Adamo et al., 2020). GCs are exceptionally massive ($\sim 10^4\text{--}6 M_\odot$), compact (< 10 pc), and feature remarkably high stellar densities (Hopkins et al., 2010).

Curiously, virtually all observed GCs older than 2 Gyr host sub-populations with distinct chemical abundances (Bastian and Lardo, 2018). While initially thought to be a standard ‘simple stellar population’, the HST era revealed ‘splitting’ of the main-sequence diagrams which indicated otherwise (e.g., (Carretta et al., 2005)). Follow-up spectroscopy revealed that indeed there are typically star-to-star abundance variations in light elements such as C, N, O, Na, and Al. These subpopulations are classically divided into a ‘1P’ group with standard abundances and a ‘2P’ group enriched in certain light elements relative to others. The abundances of the 2P group, specifically the ubiquitous N-C, Na-O and Mg-Al anti-correlations, are not explained by standard stellar evolution models for a single stellar generation and imply the presence of material that has been processed through high-temperature hydrogen burning (CNO cycle and higher).

The mechanism for enriching stars with this CNO-processed material remains unconfirmed. Proposed scenarios generally involve an early generation of stars polluting the cluster’s interstellar medium with processed material, from which a second generation of stars then forms. Candidate polluters include asymptotic giant branch (AGB) stars, fast-rotating massive stars, and massive binaries, but all models face challenges in explaining the observed abundance patterns. The apparent universality of multiple populations in old, massive GCs, as well as clusters as young as 2 Gyr (Bastian et al., 2019), suggests that the multiple populations phenomenon may be more general and connected to star formation in dense environments. Nonetheless, a self-consistent theory that accounts for the full range of observational constraints across clusters of different ages, masses, and metallicities is still lacking.

A potential solution is to study the progenitors of these GCs, so-called Super Star Clusters (SSCs), and catch the formation of multiple populations in action. However the SSCs in the local universe rarely reach these densities or masses, with the best candidates either showing much higher metallicity than GCs (Whitmore et al., 2022), being obscured by dust (Kobulnicky et al., 1997), or lacking UV spectroscopy. While the investigation of local

analogs indeed yield insights, they may not be the direct precursors to GCs and hence offer limited insight into GC formation.

Strong gravitational lensing provides a way forward: high magnification resolves individual star clusters in high-redshift galaxies, revealing SSCs that are denser and more massive than those observed locally (e.g., Vanzella et al., 2017b; Vanzella et al., 2023; Adamo et al., 2024). Rather than looking for local analogs, these high redshift SSCs may indeed be the progenitors of modern-day GCs, the lookback time serving as a time machine when aided by lensing magnification. This was first enabled in the era of the HST Frontier Fields (Lotz et al., 2017a), which sought to capture deep HST multi-band imaging of prime lensing clusters. The resolution of HST in combination with models of the lensing clusters allowed for robust size measurements impossible from the ground at the time. HST sensitivity provided precise measurements of the stellar continuum which could provide constraints on stellar age and mass, while spectroscopy from the ground revealed nebular emission useful for metallicity and nebular parameters (e.g., Vanzella et al., 2017b).

In the JWST era, this effort has been amplified. Detailed studies of star cluster sizes and stellar densities have bridged the gap toward dense local GCs (Claeyssens et al., 2024; Messa et al., 2024). Similarly, metallicity and age measurements have further informed the picture of GC formation and evolution, filling out the GC formation age-metallicity relation in a high- z space (Adamo et al., 2023; Mowla et al., 2022). The multiple populations problem remains somewhat independent of these discoveries, but an emerging picture is growing. With quality spectra, detailed gas-phase chemical abundances can be measured for these young clusters (Fosbury et al., 2003), and even reveal the presence of massive, CNO-burning stars which may be the enrichment mechanism for the 2P population (Mestric et al., 2023). Comprehensive studies of the best globular cluster progenitor candidates may very well provide the path forward needed to connect these high- z clusters to the long-standing problems of their local elders.

Chapter 2

Discovery of a Possible Ongoing Merger in the PLCK G165.7+67.0 Galaxy Cluster

The content of this chapter is drawn from Pascale et al., 2022a, with permission from the co-authors.

2.1 Introduction

Ever since the discovery that a giant arc in a cluster field is the strongly-lensed image of a background galaxy (Soucail et al., 1987), astronomers have come to equate galaxy clusters with being powerful gravitational lenses. Strong lensing distorts the images of the background galaxies into shapes which trace out the gravitational potential of the cluster, in some cases rendering the image of a single galaxy into multiple locations. The image positions and redshifts of these image multiplicities place strong constraints on the distribution of the lensing mass. Starting at first by incorporating the constraints from one image multiplicity to anchor the lens model (Franx et al., 1997; Frye and Broadhurst, 1998), to increasing that number up to dozens of image multiplicities (Kneib et al., 2004b; Broadhurst et al., 2005b), the modeling schemes grew over time into a precision science (*e. g.*, Jullo et al., 2007a; Zitrin et al., 2009a; Zitrin et al., 2015a; Kneib and Natarajan, 2011). Lens models can flag the high magnification sightlines, offering windows into the distant universe at $z \approx 10$ (*e. g.*, Coe et al., 2013b), as well as rare studies of the interstellar medium within lensed sources at $z \approx 1$ (*e. g.*, Frye et al., 2012; Sharma et al., 2018; Fujimoto et al., 2021; Nagy et al., 2021). Knowing the exact placement of the critical curve enables searches at close angular separations ($\lesssim 2''$), resulting in detections of compact sources with ultra-high magnification factors of several thousands (Miralda-Escude, 1991; Venumadhav, Dai, and Miralda-Escudé, 2017a; Diego et al., 2018a; Oguri et al., 2018a; Windhorst et al., 2018b; Dai et al., 2018a; Dai and Miralda-Escudé, 2020a; Dai and Miralda-Escudé, 2020b; Vanzella et al., 2020b),

and yielding the discovery of individual stars at cosmological distances known as caustic transients (Kelly et al., 2018b; Kaurov et al., 2019a; Chen et al., 2019a; Welch et al., 2022a).

Obtaining the full entourage of image constraints is a challenge owing to limitations of high-quality and high-resolution observations. It is natural to ask how image constraints affect the construction of a reliable lens model, by which it is meant that the source plane positions, redshifts, and/or magnification factors are accurately recovered.

In one study, Ghosh, Williams, and Liesenborgs, 2020 analyzed simulations of clusters and found that introducing additional image constraints generally increased the accuracy of the mass map. To quantify the systematics of image constraints, Johnson and Sharon (2016) analyzed the strong lensing model of a single simulation of a single cluster hundreds of times, differing only the amounts and types of lensing evidence. They found that a reliable lens model is obtained for lensing constraints consisting of ≥ 10 image multiplicities, of which ≥ 5 had measured spectroscopic redshifts. Failing to input any spectroscopic redshift information was found to provide a poor fit relative to the fiducial lens model. They further noted that supplying photometric redshifts improved lens model reliability, a result that is especially impactful when photometric estimation is the only practicable option. These considerations have motivated this study of multi-band imaging and of spectroscopy in the field of the massive lensing cluster PLCK G165.7+67.0 (G165).

G165 was discovered using data from the *Planck* survey (Planck Collaboration et al., 2020b) and *Herschel Space Observatory* (Pilbratt et al., 2010) in a census of cluster-scale structures by its rest-frame far-infrared colors and *not* by the Sunyaev-Z’eldovich (SZ) effect (Planck Collaboration et al., 2015; Cañameras et al., 2015). Interestingly, G165 yields only an upper limit on the mass from the *Planck* Compton-Y map, and is a low-luminosity X-ray source despite its bimodal configuration Frye et al., 2019, hereafter F19. By contrast, Hubble Space Telescope (*HST*) imaging uncovers rich lensing evidence. Eleven image multiplicities consisting of 30 images are identified,

many of which are ‘caustic-crossing’ arcs that constrain the position of the critical curve. The positions and redshift information of these images are used to construct the lens model, and to estimate its mass ($10^{14}M_{\odot}$). The high measured mass and low X-ray luminosity mean that G165 may be participating in a major cluster-cluster merger in its initial infall, or in a relatively common but more distant cluster-cluster interaction. The current lens model, however, lacks the precision necessary to carry out this further work. This is not so surprising given that there are no published photometric redshifts, and a spectroscopic redshift has been measured for only one member of one image system, Arc 1a (initially in Cañameras et al. (2015), with uncertainties in Harrington et al. (2016), and later with multiple CO/[CI] emission lines in Cañameras et al. (2018) and Harrington et al. (2021)). Moreover, the cluster member catalog is estimated from a red-sequence fit guided by only a few spectroscopically confirmed cluster members. Redshift information on both the cluster galaxies and the image systems will significantly improve the precision of the lens model.

Here we present new imaging and spectroscopy in the G165 field. These data are combined with archival imaging so that the optical through near-infrared spectral energy distributions (SEDs) and photometric redshifts can be fit. Robust techniques are applied to

assemble the multi-band photometric catalog from these somewhat disparate imaging data sets by applying the template-fitting approach of T-PHOT (Merlin et al., 2015; Merlin et al., 2016a). The analysis yields new photometric redshifts for multiple members of three image systems and numerous cluster galaxies. These redshifts provide constraints on the lens model and hence the lensing mass distribution. We also acquired new spectroscopy and new radio maps which enables us to better understand the cluster kinematics and dynamics.

The paper is organized as follows: in §6.3 we present the new imaging and spectroscopy. The algorithms used to prepare the detection image for photometry are given in §2.3, and the detailed methods regarding object detection and incorporation of the new and archival imaging data sets are described in §6.4. The photometric imaging results such as the SED fits and the estimation of photometric redshifts are presented in §2.5. The spectroscopic results, such as the identification of new cluster members are given §2.6. The revised lens model based on the newly-obtained lensing constraints is presented in §2.7, with an analysis of the high-redshift population and Arc 1. Clues as to the cluster’s evolutionary state drawn from the multi-wavelength data including new VLA and LOFAR imaging are discussed in §2.8. The summary and conclusions appear in §2.9. We use the AB magnitude system throughout this paper and we assume a Λ CDM cosmology with $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{m,0} = 0.32$, and $\Omega_{\Lambda,0} = 0.68$ (Planck Collaboration et al., 2020b).

2.2 Observations and Reductions

Optical/Infrared Imaging

Large Binocular Telescope

Observations were obtained with the Large Binocular Telescope (LBT) Large Binocular Camera (LBC) in 2018 January 20 (2018A, PI: Frye). The imaging includes g - (68 minutes total exposure), and in i -bands (43 minutes) in 2018 January 20 (2018A, PI: Frye) at a native plate scale of $0.2255'' \text{ pixel}^{-1}$. We refer to Table 2.1 for the observing details. The image reductions were carried out using Theli (version 2.10.5), which is a general astronomical image reduction pipeline operated through a web-based interface (Erben et al., 2005; Schirmer, 2013). Details regarding the Theli application in this work have been documented separately and made publicly available.

Briefly, we performed initial calibrations of the bias-subtraction and flatfield corrections in the usual way. To correct for fringing, a superflat was generated by masking out the bad pixels and bright sources over subsets of contiguous science frames, median-combining them, and then dividing the superflat into the data. To compute the astrometric solution, the SCAMP software (Bertin et al., 2002; Bertin, 2006) was run through the Theli wrapper, selecting the Initial GAIA Source Catalog (IGSC) as the astrometric reference (Gaia Collaboration et al., 2016). Visuals and intermediate data products were produced as sanity checks to ensure that the dither pattern was recognized, the distortion pattern was measured, and the positional residuals were low and evenly distributed about zero. Following the ini-

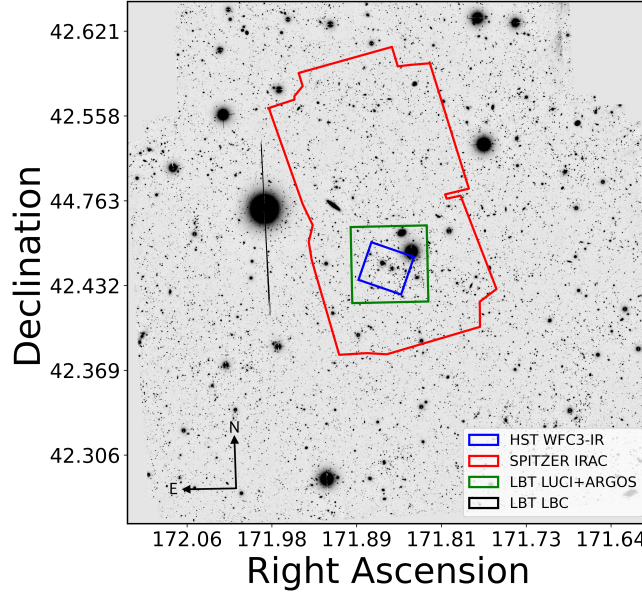


Figure 2.1 Footprint of the four instrument mosaics which make up the 7 filters contained in this study. The LBT/LBC field-of-view is depicted by the x- and y-axes, equating to $25' \times 27'$ (black frame). The fields-of-view covered by *Spitzer*/IRAC (red), LBT LUCI+ARGOS (green), and *HST* WFC3-IR (blue) are also depicted. The *HST* WFC3-IR filters limit the FOV for which photometric redshifts can be estimated to the central ~ 2 arcminutes of the cluster, which equates to ~ 600 kpc at the mean cluster redshift of 0.35.

tial frame calibration and registration, the background was modeled using Theli's internal pipeline. Finally, the individual frames were co-added using SWarp (Bertin, 2010) run from within the Theli GUI. Figure 2.1 depicts the *i*-band image of the full $25' \times 27'$ field-of-view (FOV) of LBT/LBC (outermost black frame), which reaches $3\text{-}\sigma$ limiting magnitudes of $g_{AB} = 25.42$ mag, and $i_{AB} = 24.67$ mag.

To test the absolute *gi* LBT/LBC photometry, the positions of the sources in the central 5×5 arcmin FOV were matched with their counterparts in the Sloan Digital Sky Survey (SDSS) DR16 catalog (Ahumada et al., 2020). On computing the magnitude differences of $g_{SDSS} - g_{LBC}$ and $i_{SDSS} - i_{LBC}$, and making a $3\text{-}\sigma$ clip to remove outliers, we measure mean offsets of 0.37 and 0.29 mag for *g* and *i*, respectively. This means that our LBT/LBC photometry was systematically brighter by those amounts. Figure 2.2 shows the magnitude difference histograms following the zeropoint offset correction that minimizes the mean difference to zero. The adopted photometric zeropoints are recorded in Table 2.1, and are used to extract the photometry. In sum, these images are deep, making them valuable for this study, and giving them leverage as veto bands for the planned high-redshift galaxy searches using Prime Extragalactic Areas for Reionization and Lensing Science (PEARLS; program

Table 2.1. The Sample: Observing Details

Filter ^a	Exp. (s)	m_{lim}^b	FWHM (") ^c	m_{zp}^d
<i>g</i>	4090	25.42	1.37	$27.57 + 0.25$
<i>i</i>	2600	24.67	1.07	$28.31 + 0.32$
<i>F110W</i>	2664	28.94	0.13	$26.82 + 0.05$
<i>F160W</i>	2556	27.97	0.15	$25.95 + 0.00$
<i>K</i>	120	24.07	0.29	$25.74 + 0.18$
Ch1[3.6]	1200	23.31	1.95	$21.59 + 0.21$
Ch2[4.5]	1200	23.33	2.02	$21.58 + 0.14$

^aThe filter images were acquired as follows: *gi*-bands using LBT/LBC, *F110W* and *F160W* bands using *HST* WFC3-IR, *K*-band using LBT/LUCI+ARGOS, and Channel 1 at $3.6\mu\text{m}$ and Channel 2 at $4.5\mu\text{m}$ using *Spitzer*/IRAC.

^bThe 3σ limiting magnitude is estimated by placing apertures of twice the FWHM of the PSF in empty regions of sky.

^cThe FWHM of the PSF is reported for each filter. We measure PSF FWHM by fitting a Gaussian to the PSFs measured in §4.3.

^d Zeropoint magnitudes are given as the quoted instrumental magnitude plus the observed zeropoint corrected in §4.6.1.

#1176).

The LBT Advanced Rayleigh Ground layer adaptive Optics System (ARGOS; Rabien et al., 2019) operates through the existing LUCI instrumentation. LUCI+ARGOS corrects the atmosphere for ground-layer distortions via multiple artificial stars which are projected by laser beams mounted on each of the two 8.4 m apertures. Observations of the G165 field were obtained in the *K*-band in 2016 December 16 (2016B; PI: Frye). We acquired the LUCI+ARGOS imaging in monocular mode with native plate scale of $0.12''\text{pixel}^{-1}$. The observing details are recorded in Table 2.1, and the image reduction are presented in F19 and in Rabien et al. (2019). In the reduced images, we measure a value for the point source FWHM $\approx 0.29''$. This angular resolution is comparable to *HST* within a factor of two, effectively extending the red wavelength reach of *HST*. We performed our own photometry on these data, using the instrumental zeropoint AB magnitude drawn from Table 9 of the LBT LUCI users manual¹.

¹https://lsw.uni-heidelberg.de/users/jheidt/LBT_links/LUCI_UserMan.pdf

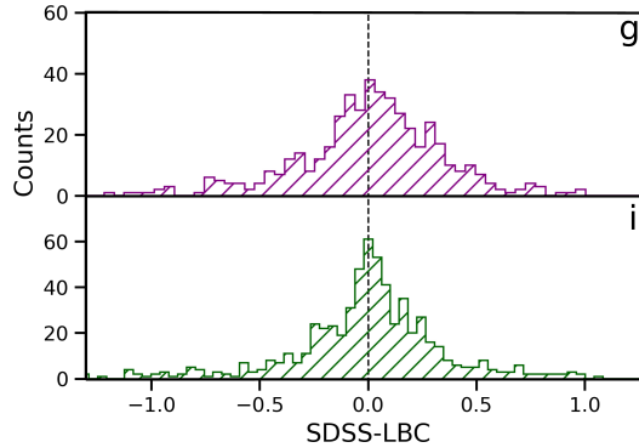


Figure 2.2 Histogram of the SDSS photometry relative to our LBT/LBC photometry. We measure mean systematic offsets within the central $5' \times 5'$ FOV of 0.37 and 0.29 mag in g - and i -bands, respectively. The magnitude difference histograms reflect the distributions after the correction has already been made. The corrected photometric zeropoints are recorded in Table 2.1. We refer also to §4.6.1 for details regarding an independent test of the zeropoints.

Hubble Space Telescope

Observations were obtained between 2015 December and 2016 July as a part of an *HST* WFC3-IR program (Cy23, GO-14223, PI: Frye). Exposures were taken in the $F110W$ and $F160W$ passbands ($0.13'' \text{ pixel}^{-1}$), reaching $3\text{-}\sigma$ point source limiting magnitudes of 28.94 and 27.97 AB mag, respectively. Details of the observations are summarized in Table 2.1, and a description of the calibration and image reductions can be found in F19. WFC3-IR $F160W$ is used as the detection image or High Resolution Image (HRI) for the matched aperture photometry performed in this study.

Spitzer

Spitzer Infrared Camera (IRAC) 3.6 and $4.5 \mu\text{m}$ imaging was taken in 2016 as a part of a larger program (Cy13, GO-13024, PI: Yan). The observing details can be found in Table 2.1, and the image reduction is described elsewhere (Griffiths et al., 2018). Images of the central region, and of the multiple images of the Dusty Star Forming Galaxy (DSFG) Arc 1 that is singularly detected using the *Planck* telescope, appear in F19. The *Spitzer* data have a native plate scale of $1.22'' \text{ pixel}^{-1}$ that is larger than the other filters used in this study. Yet these data are important for their role in settling photometric redshift ambiguities, particularly for distinguishing between natural continuum breaks such as the $4000 \text{ \AA}$ and Balmer breaks and lower redshift sources that are intrinsically dusty. We extract the photometry for the O/IR imaging by the T-PHOT method, as is described in §4.5.

VLA and LOFAR

Karl G. Jansky Very Large Array (VLA) 6 GHz imaging was acquired as part of a larger program (18A-399, PI: P. Kamieneski). Details of the image reductions will appear in an upcoming paper (Kamieneski et al. 2022, in preparation). Briefly, the G165 field was observed with C-band (4 – 8 GHz) with full polarization in a 3-hour track to improve uv -coverage, amounting to a total of 1.5 hours of on-source integration time. Baselines for this A-configuration observation ranged from 0.68 km to 36.4 km, resulting in a natural-weighted synthesized beam size of $0.65'' \times 0.37''$ at a position angle of 72° and a maximum recoverable scale of $8.9''$. The sensitivity is measured to be $2.7 \mu\text{Jy beam}^{-1}$ across the approximately 4 GHz of effective bandwidth. Data calibration and reduction were performed with the Common Astronomy Software Applications (CASA) package (McMullin et al., 2007), and the VLA Calibration pipeline. The radio maps uncover two head-tail radio galaxies which are discussed in §8.2.

Low Frequency Array (LOFAR) radio observations were acquired on 2016 March 22 through a single object request (PIs: Lehnert, Dole & Frye), as part of the Two-meter Sky Survey (LoTSS; Shimwell et al., 2017; Shimwell et al., 2019). The FITS image was delivered on 2019 February 19, following on-site calibration by the Default Preprocessing Pipeline (DPPP; van Diepen, Dijkema, and Offringa, 2018). These low-frequency (120–168 MHz) data have a typical angular resolution of $\sim 6''$ and a sensitivity of $\sim 100 \mu\text{Jy beam}^{-1}$. Large-scale radio emission is detected over a ~ 500 kpc scale that potentially arises from radio jets and/or electrons which are re-energized as a consequence of large-scale turbulence.

Spectroscopy

New multi-slit spectroscopy was obtained on 2019 February 8 using MMT/Binospec (PI: Frye, 2019A). To maximize the redshift search space, we selected the 270 lines mm^{-1} grating, which covers a wavelength range of $5500 \text{ \AA}$ about the central wavelength of each slitlet at a dispersion of $1.3 \text{ \AA pix}^{-1}$. We observed the central region of the G165 cluster in a single pointing consisting of two $8' \times 15'$ fields at a separation of 3.2 arcminutes. A total of 88 bright ($i_{AB} < 22$) galaxies populated the slitmasks. The observations were composed of 6×1200 s exposures, and were acquired under relatively-stable seeing conditions of $\sim 1''$ as measured off of isolated sky lines. This result sufficed for our science goal to measure spectroscopic redshifts given the $1''$ slitwidth and the relatively-bright magnitudes of our targets. The data were reduced using the observatory pipeline, which performed the bias correction, flat-fielding, wavelength calibration, relative flux correction, co-addition, and extraction to 1D spectra². Although redshift-fitting software was available, we opted to measure the spectroscopic redshifts of the coadded 1D spectroscopy in IDL³ by way of our own software. The SPEC task has a library of spectroscopic features and a reference sky spectrum extracted from the pre-sky-subtracted data, and is described elsewhere (Frye et

²https://bitbucket.org/chil_sai/binospec

³Interactive Data Language; <https://www.13harrisgeospatial.com/Software-Technology/IDL>

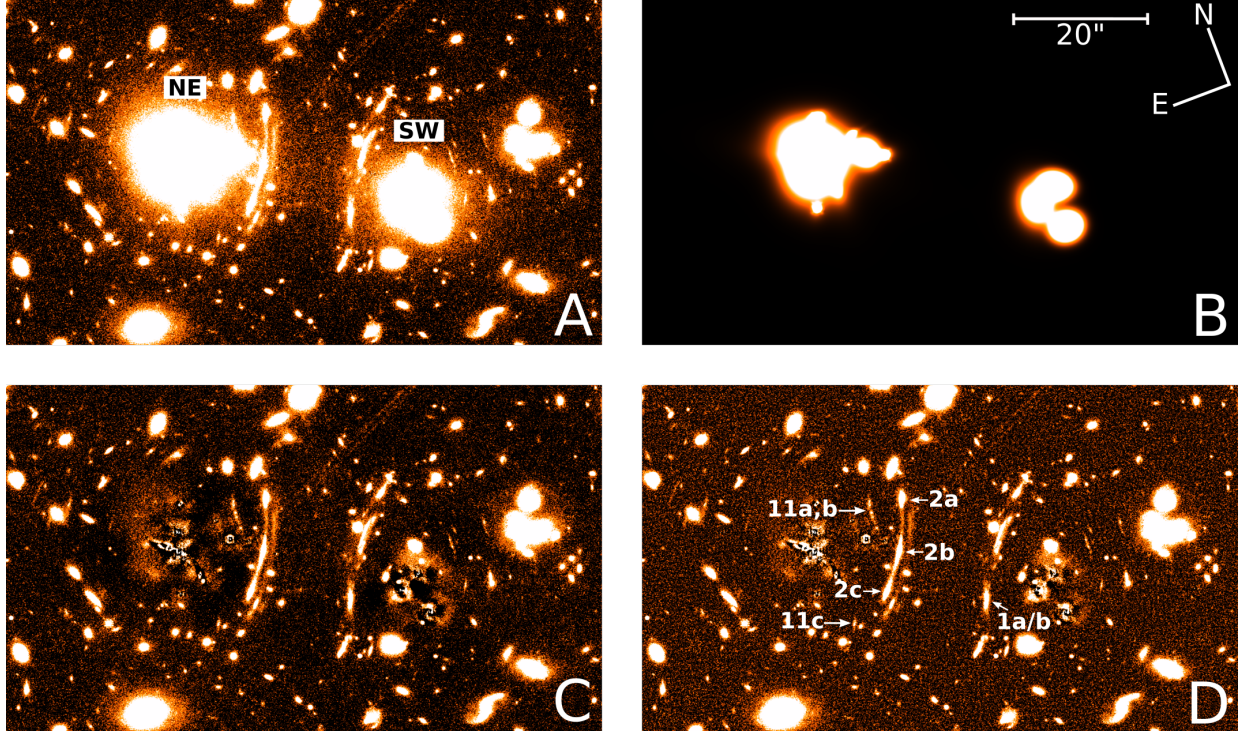


Figure 2.3 Preparation of the HRI $F160W$, as described in §3. The panels represent each stage in order of operation: (Panel A) the original reduced $F160W$ image; (Panel B) the best fit *Galfit* models for the 13 central galaxies and ICL discussed in §3.1 and §3.2; (Panel C) the model subtracted $F160W$ image; (Panel D) the median corrected image, which significantly flattens the residual over-subtractions discussed in §3.3. The two sides of the cluster are referred to as the northeast (NE) and southwest (SW) components, as labelled. The image sets for which we report new photometric redshift estimates are also labeled and discussed separately in §4.6.2.

al., 2012, and references therein). Our catalog contains the secure spectroscopic redshifts for 86 of 88 sources. Of these, we find eight new galaxies which meet our criteria for cluster membership as defined in §6.2.

2.3 Image Preparation for Photometry of the HRI

Motivation

Limited to a 7-band filter suite, the photometry in each band is impactful for making satisfactory SED fits. We perform the multiband photometry using the prior-based software package *T-PHOT*, which is designed to do photometry across images drawn from different observing facilities and/or instrument modes, and to different field depths. A single HRI is

designated with which to extract the master object catalog. To retain its information, priors on object morphology are derived from the HRI which are then enforced onto the images in the six other filters or Low Resolution Images (LRIs).

T-PHOT enlists two types of priors to generate a model of the LRI. The ‘real’ prior consists of cutouts from the HRI which are informed by the photometry, and is especially sensitive to background sources of light. To approximate this background, we carefully model both the ICL and the bright galaxy light components, where the latter component becomes the ‘analytic’ prior. Our approach follows closely the methods of the ASTRODEEP catalogs of the Frontier clusters (Merlin et al., 2016a; Castellano et al., 2016), and we refer also to the companion flowchart in Merlin et al., 2016a, their Figure 1. Once obtained, the background model is refined by an iterative process, and then subtracted off of the HRI. The background-subtracted HRI is further corrected for any residual light, as is described below.

Galfit Setup

The background modeling algorithms used in this study make extensive use of the **Galfit** tool (version 3; Peng et al., 2010). **Galfit** operates on an input science image in units of counts, and a sigma image, which is a map of the standard deviation of the science image. The sigma image can be generated externally, by using the weight files outputted from the *HST* MultiDrizzle task following Casertano et al., 2000, and also internally by inputting the values from the image headers into **Galfit**. To test the relative merits, we ran **Galfit** on a “sky” object consisting of a rectangular isolated region of sky. We found the reduced χ^2 to favor the internal approach, as the weight images underestimated the actual noise in the complex cluster scene, and adopt this method for generating the input sigma image for all of our **Galfit** modeling.

Initial Background Model Fits

The background consists of two components: (1) the intracluster light (ICL), and (2) the light from individual galaxies. We constructed an initial model for the ICL component by masking out all pixels in the HRI greater than $8\sigma_{sky}$, where σ_{sky} is estimated by sampling the sky in three small and statistically significant patches of the image separated from known sources. We then select the modified Ferrer profile included in **Galfit**, which is prescribed in Merlin et al., 2016a and Giallongo et al., 2014 due to its relatively flat core and freedom to change the sharpness of its truncation when compared to similar Sérsic profiles. As expected, a combination of two modified Ferrer profiles provided the best fit to the two light peaks visible in the data (Panel A of Figure 2.3). We note that while parameters like bending modes, diskiness/boxiness, and other profiles (*e. g.*, Sérsic) were tried, they did not improve the results and hence were discarded. The best-fit ICL model was then subtracted from the original image.

Our model for the cluster galaxy light contains the brightest cluster member in the field, the Brightest Cluster Galaxy (BCG), and five other dominant central cluster members or

Large Red Galaxies (LRGs) and their nearest satellites, to constitute a set of 13 galaxies. The inclusion of the satellite galaxies enables a better fit to the galaxy light by our `Galfit` approach. These bright galaxies typically require more than one `Galfit` profile to best model their overall brightness profile. Simultaneously fitting many `Galfit` profiles, however, can give rise to degenerate solutions, ultimately preventing `Galfit` from converging to a best-fit solution. We instead adopt an iterative approach, beginning with only a single Sérsic profile. For this initial fit, we make use of the software package `Galapagos`, which contains the desired functionality by performing separate `Galfit` fits for all objects at the positions given in SExtractor (Barden et al., 2012). We found that using a single profile per galaxy in this initial fitting stage helps to prevent degeneracies in the subsequent two-profile refinement fitting stage, as is described below.

We iterate on the initial galaxy light model by introducing an additional Sérsic profile, such that each galaxy model is made up of two Sérsic profiles. Following the prescription of Merlin et al. (2016a), we use the best fit parameters of the initial models to place constraints on the parameters of the refinement model. Some individual galaxies required even further refinement, with errors in the position angle and/or axis ratios evident by a visual comparison between the model and image. We tighten up the fitting constraints on an object by object basis, iterating as needed until a solution is reached that, upon visual inspection, produces reasonably flat residuals.

We then return to the ICL model and iterate on it by applying the results of the revised galaxy light model as a fixed component in `Galfit`, while both ICL Ferrer components from the ICL initial fit are left free. This step allows the ICL fit to be readjusted relative to the new bright galaxy model fits, thereby superseding the simple 8σ mask that was initially enforced in §3.1. The only other constraint placed on the ICL components is a position center good to ± 1 pix from the initial value in each coordinate. The results did not vary much from the initial ICL fit, providing a check on the quality of our overall fit. The resulting image depicting the combined background light appears in Panel B of Figure 2.3.

Residual Corrections

Subtracting the background image from the data leaves regions of negative flux. To alleviate the impact of these image residuals, we follow the prescription in Merlin et al., 2016a. The procedure is to run SExtractor on the sky surrounding each bright galaxy to estimate the sky RMS, σ_{SE} . Next, the image is median-filtered using the PyRAF task `median`, imposing a $1'' \times 1''$ window and excluding all pixels $> 1\sigma_{SE}$ and neighboring pixels. Finally, the median-filtered image is subtracted from the residual of the original image. The resulting image has the expected flatter background adequate for doing photometry (panel D of Figure 2.3). Since the photon noise is retained in the residual image, and the `Galfit` models themselves contain no noise, we do not find it necessary to adjust the $F160W$ RMS map in the subtracted image.

2.4 Photometry

Overview

We describe below our measurement of the photometry in the *HST* filters using SExtractor, and in the other LRIs using T-PHOT. To achieve a more realistic model for each LRI, T-PHOT is informed by the two different priors described in §3.1. In what follows, the real prior is obtained from the SExtractor catalog (§4.2), and the analytical prior is taken from the bright galaxy models (§3.2). The two priors are stitched together into a single 2D image which is referred to as a collage. This collage is subsequently degraded to match the PSF, and then scaled to match the flux of each LRI. This final step in the process yields the photometry for each LRI.

Object Detection

The *HST* WFC3-IR *F160W* image is our object detection reference, or HRI. We perform the photometry using SExtractor (Bertin and Arnouts, 1996) by implementing a two-step HOT+COLD method according to the prescription in Galametz et al., 2013. In this prescription, the COLD parameter set is tuned to the detection of bright, extended galaxies, while the HOT parameter set is optimized to detect the fainter galaxies not included in the preceding COLD mode run. We choose to match the parameters of Galametz et al., 2013 rather than Merlin et al., 2016a given the limited depth of our HRI, as the HOT mode run in Merlin et al., 2016a is significantly more aggressive than Galametz et al., 2013, producing many more spurious sources without additional true sources in our case.

The two catalogs and their SExtractor segmentation maps are combined non-redundantly following the methods of Galapagos. The COLD mode sources are all catalogued, and only HOT mode sources outside the Kron ellipses of the COLD run are accepted. The combined catalog contained 1228 sources. We clean this list by hand to remove artifacts such as edge effects, diffraction spikes, and residuals from the BCG subtraction. The final detection catalog contains 964+13 sources, with an average aperture Kron ellipse radius of 0.2". The '+13' here refers to the initial 13 bright sources in the image which are separately modeled by Galfit, and are subtracted prior to detection with the HOT+COLD method. We find the bright galaxy light and ICL subtraction described in §3 yields larger numbers of faint objects in the central region of the cluster

as is demonstrated in Figure 2.4. The photometry of faint objects is also more accurately recovered,

as depicted in Figure 2.5. This HRI photometric catalog and its accompanying segmentation map serve as the inputs for the multi-band photometry in T-PHOT. However, the default SExtractor segmentation map can cause inaccuracies in T-PHOT photometry for smaller sources (Galametz et al., 2013). To complete its setup, we had to modify the segmentation map of the HRI slightly by scaling the source area in the map with the dilate software (De Santis et al., 2007).

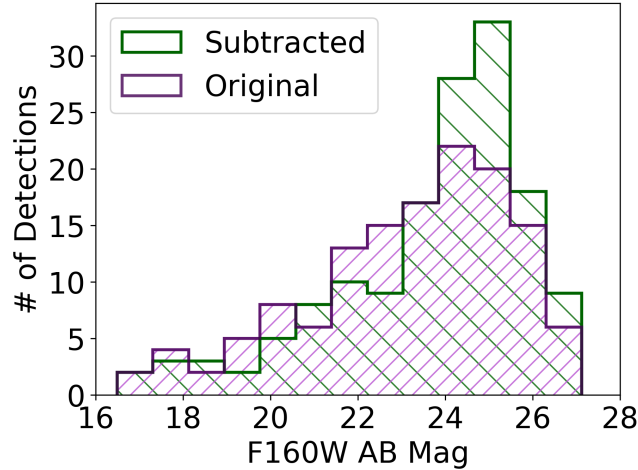


Figure 2.4 Object counts in the central cluster region as a function of $F160W$ AB mag (purple) relative to object counts extracted from the background-subtracted image (green). We delineate the central region by a $72'' \times 24''$ rectangle that runs along the long-axis of the cluster, covering the central LRGs on both the NE and SW sides of the cluster (Panel A of Figure 2.3). We detect 147 objects in the processed image, equating to a 10% increase from the 135 objects detected in the original image using the same SExtractor parameters. We measure more accurate photometry of central objects by their reduced contamination from the background light, and detect fainter objects, thereby pushing detections to fainter limiting magnitudes. We refer to Figure 2.5 for specific examples.

Image Alignment and PSF Constructions

PSFs need to be constructed for each LRI to prepare the images for simultaneous photometry. We start by aligning the images in each filter to the HRI in a two step process using the astropy package `reproject` and `astroalign` tasks. We find `astroalign` outperforms `reproject` in producing astrometrically precise image alignment, but fails when images are significantly misaligned. Hence, we first apply `reproject`, which transforms images to the same orientation and pixel scale based on the WCS header information. We then follow up on this step by applying the `astroalign` task in order to triangulate the source centroid positions and to calculate a revised value for the reprojection according to Beroiz, Cabral, and Sanchez (2020). We describe below the process of obtaining a good sampling of the PSF for each of the seven bands.

For the LBT/LBC gi filters, we extract an initial catalog of stars using the `DA0StarFinder` subroutine according to Stetson (1987). We then visually inspect the output star list and cull out by hand a set of 100 suitable (well isolated and unsaturated) stars. Cutouts centered on each star are extracted and are subsequently median-subtracted and normalized to lessen the impact from image contamination. Finally, the stellar cutouts are stacked into a single oversampled PSF using the `EPSFBuilder` function from the `photutils` python package.

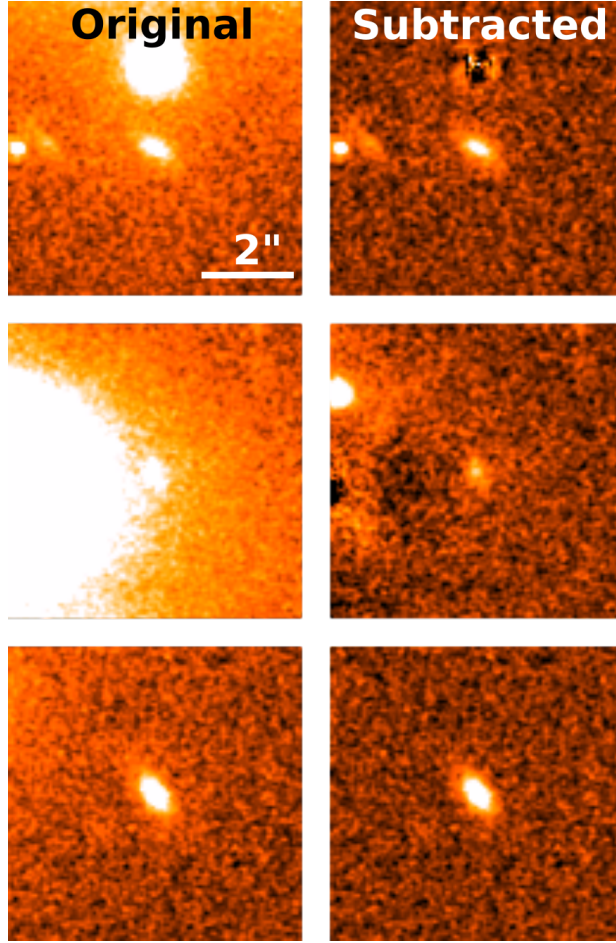


Figure 2.5 Images centered on three of the 964 galaxies detected in the HRI (*HST* WFC3-IR *F160W*) in the initial image (left-hand side, drawn from Panel A in Figure 2.3), and upon subtraction of the background (right-hand side, drawn from Panel D in Figure 2.3). In each example, the photometry of the background-subtracted image is fainter by at least 0.5 AB mag as a result of removing the contaminating light. A second effect of the background-subtraction is to enable detection of fainter sources because the noise level decreases. Both effects operate in the direction of increasing number counts in the fainter magnitude bins (Figure 2.4).

For *HST* WFC3-IR *F110W* and *F160W*, we adopt the PSFs provided by STScI⁴. These nine PSFs sample the profiles in different locations across the detector. We average all nine of them together to produce a single representative PSF. One averaged PSF is taken for each exposure that makes up the coadded image, and the PSF is rotated as needed, based on the WCS image header information. The individual exposure PSFs are subsequently averaged

⁴Empirical Models for the WFC3/IR PSF J. Anderson 08 Aug 2016

together and weighted by the exposure time to yield the PSF for the coadded image.

For the LUCI+ARGOS *K*-band image, the $4' \times 4'$ FOV lacked well-isolated, unsaturated stars, and only contained a handful of stars in total. While we found the `astropy` stacking method to produce a reasonable-looking PSF by-eye, we obtained a PSF that produced flatter residuals in the T-PHOT stage by fitting a 2D Gaussian to crowded but unsaturated stars in the field. The resulting Gaussian has a FWHM of $0.29''$, consistent with previous results (F19).

For the *Spitzer* IRAC image PSFs, we took two different approaches to build the PSF. First, we stacked the PSFs of isolated stars similar to the approach outlined above for the LBT/LBC *gi* images. Second, we tried using a set of 25 analytic PSFs supplied by the Spitzer Science Team⁵, which are each rendered onto a 5×5 pixel grid across the detector. For each individual exposure that makes up the IRAC coadded image, we interpolated over this PSF suite to generate the one that most closely corresponds to the location of each object in our catalog. Each PSF is then rotated according the orientation of its exposure relative to the coadded image. All of the rotated PSFs are then averaged together, and weighted by the exposure time. The product is an individual analytical PSF for each object in the catalog. We ultimately adopt the stacking method approach for obtaining the PSFs, as it produced noticeably flatter residuals in the T-PHOT stage. At the same time we acknowledge that the analytical model method has been demonstrated as preferable in other studies (Merlin et al., 2016a; Merlin et al., 2021; Pagul et al., 2021).

Photometry starting with the *F160W* and *F110W* filters

The *F110W* image was prepared by the same process as described in §3 for the HRI. We start by applying the final `Galfit` models for *F160W* as the initial models for *F110W* and fit for all objects simultaneously, including the ICL. The resulting models are subtracted from the *F110W* image and then undergo the same median subtraction process applied to the *F160W* band. *F110W* is then convolved with a matching kernel to the PSF of *F160W*. The matching kernel, K , is created by taking the ratio of the PSF of each image as per the convolution theorem, which states that the integral of two quantities is equivalent to their multiplication in Fourier space. Hence, we can write

$$\text{PSF}_2 = K \otimes \text{PSF}_1$$

where PSF_1 is the *F110W* PSF and PSF_2 is the *F160W* PSF. By the convolution theorem

$$\mathcal{F}(\text{PSF}_2) = \mathcal{F}(K) * \mathcal{F}(\text{PSF}_1)$$

$$K = \mathcal{F}^{-1} \left(\frac{\mathcal{F}(\text{PSF}_2)}{\mathcal{F}(\text{PSF}_1)} \right)$$

⁵irsa.ipac.caltech.edu/data/SPITZER/docs/irac/calibrationfiles/psfprf/

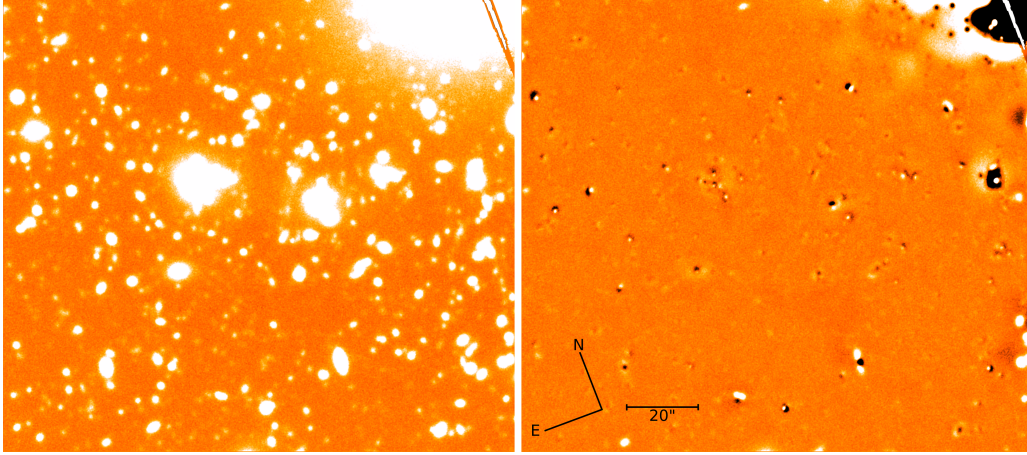


Figure 2.6 Quality check on the T-PHOT photometry for the LBT/LBC g -band LRI (left panel). T-PHOT creates a photometric collage from the HRI ($F160W$) and scales it to minimize the residual between the collage and the LRI. The residual is flat (right panel), indicating a good fit of the image priors to the data across the field (§4.5).

as desired. We apply a simple Cosine window function prior to convolution to eliminate any spurious modes picked up by noise. Generating a new RMS map for $F110W$ following the convolution is not straightforward, and we choose to approximate the new map with the original RMS map due to the similarity in PSF FWHM between $F110W$ and $F160W$. We then enforce the same apertures as used on the HRI via SExtractor’s dual image mode, selecting the $F160W$ image and its associated weight map for detection but the $F110W$ image and its weight map for measurements. This forced object catalog makes image registration more straightforward and alleviates some of the issues relating to image blending, yielding more accurate measured fluxes across both images. We cite the $F160W$ magnitude as the AUTO magnitude, which is measured selecting the Kron-like elliptical aperture, and we calculate $F110W$ magnitude by computing the difference in isophotal aperture magnitudes between the $F160W$ and $F110W$ bands added to the $F160W$ AUTO magnitude. We justify the isophotal selection aperture in this case because it is better at measuring colors, while the AUTO aperture better measures the total fluxes (Coe et al., 2006). Magnitude errors are derived using SExtractor, with the slightly larger $F110W$ errors resulting from the propagation of errors of each quantity used.

Photometry incorporating the other LRIs

The LBT/LBC gi , LBT/LUCI K , and *Spitzer* IRAC $Ch1$ and $Ch2$ bands all have larger PSF sizes relative to the *HST* images, making image blending more of a problem. We perform the multi-band photometry using T-PHOT in a similar way across all five of these LRIs. The HRI ($F160W$) catalog supplies the positions and fluxes of cutouts for the real prior, while the HRI *Galfit* models are applied as the analytical prior. Both sets of priors are held fixed

in all T-PHOT runs across all LRIs. The only difference between these T-PHOT runs is the required matching kernel for degrading the HRI cutouts to the LRI PSF, which we already derived in §4.3. For *giK*, the matching kernel is constructed using the filter’s data-derived PSF and the analytical *F160W* PSF through the Fourier methods explained in §4.4. For the *Spitzer*/IRAC channels, the PSF itself is applied as the matching kernel owing to its large profile compared to *F160W* (Galametz et al., 2013).

We initiated a series of two T-PHOT runs on the 5-filter image stack. T-PHOT photometry is especially sensitive to the LRI background, hence the purpose of the first T-PHOT run is to estimate the background of the LRI using the built-in option for local background estimation. Flat background object counterparts are assigned to each object in the input catalog. All objects are fit simultaneously, returning the 2D image collage as outlined in §4.1. We modify this collage to only retain the fitted flat background objects, yielding the background model. This model is subsequently smoothed using a 2D Gaussian kernel to produce a relatively smooth approximation of the image background. This background model is subtracted from the image to yield the final background-subtracted image.

To produce the multi-band photometry, we perform a second T-PHOT run on the background-subtracted images of the 5-filter suite. As a gauge of the quality of this run, the original LRI is compared to the LRI with the T-PHOT collage subtracted from it. A flat residual image, such as the one shown in Figure 2.6 for the *g*-band, indicates a good fit of the image priors to the data across the field. This procedure allows for iterative modifications to the image priors until a satisfactory residual is obtained.

Each T-PHOT run returns a covariance index that correlates with the quality of the fit. The covariance index is sensitive to the effects of crowding on the T-PHOT fit, such that covariance indices greater than unity suggest a high degree of degeneracy between the fit photometry of neighboring objects. We cite photometric errors according to the output from T-PHOT. We stress that these uncertainties are statistical relative to the input RMS map, and do not include systematic errors, such as artifacts introduced by the PSF estimation, or any remaining non-uniform background in the *F160W* image cutouts. Systematics are broadly accounted for in the photometric redshift estimation by enforcing a floor minimum uncertainty level for the input photometric measurements amounting to 0.05 mag for the *F110W*, *F160W*, and *K* filters, and 0.1 mag for the *gi* and IRAC filters as in Merlin et al., 2016a, Bradac et al., 2019 and Pagul et al., 2021.

Preparation for Photometric Redshift Estimation

We estimate photometric redshifts with the Bayesian Photometric Redshift (BPZ) software package (Benítez, 2000; Benítez et al., 2004; Coe et al., 2006). BPZ fits photometric measurements to SEDs of different galaxy types using Bayesian inference. Crucially, the Bayesian approach utilizes assumed priors on *i*-band brightness and galaxy type such that only the SEDs which best represent the input photometry are fit to the data. BPZ produces a best fit redshift and a galaxy type by interpolating over SED templates provided by Coleman, Wu, and Weedman, 1980, Kinney et al., 1996, and Bruzual and Charlot, 2003a. In preparation

to doing accurate photometric redshift estimation with BPZ, we also make adjustments to the photometric zeropoints and apertures.

Zeropoint Correction

We initially trained BPZ on a subset of 20 objects which also have spectroscopic redshifts. This involved fixing the object redshift to the spectroscopic redshift and then enforcing BPZ to fit the SEDs by only allowing the galaxy type to vary. In turn the BPZ code outputs suggestions of any zeropoint magnitude offsets. This is an iterative process in which an offset is computed, and then the code is rerun, until the suggested offset approaches zero.

We found the magnitude offsets to be small or zero in most bands. We did, however, notice non-negligible suggested offsets of ~ 0.35 and ~ 0.25 magnitudes in LBT g_{AB} and i_{AB} , respectively. To explore this difference, a second test was conducted comparing the photometry in the central 5×5 arcmin FOV with SDSS. We refer to §2.1.1 for details. Somewhat reassuringly, we obtain a similar zeropoint offset by both approaches. We opted to apply the offsets measured via the SDSS comparison for our photometry. The revised values for the zeropoint magnitudes are reported in Table 2.1.

Our BPZ calibration also motivated small zeropoint corrections in the IRAC images of 0.21 and 0.14 for Ch 1 and Ch 2, respectively. On further inspection, we confirmed that residuals from T-PHOT were generally more negative than the sky in those bands. We believe this is due to the unique structure and large width of the IRAC PSF. At the same time, systematic offsets in magnitude are not uncommon. For example, in one study of the HFF clusters, a minor IRAC offset was also reported of a similar degree but in the opposite direction, potentially owing to their analytical-style approach to estimate the PSF rather than our data-driven one as described in §4.3 (Pagul et al., 2021).

On applying all the zeropoint corrections to the data, the BPZ code is re-run with the full photometric catalog, freely and without any fixed redshifts, to create the photometric redshift catalog. In doing so, we impose a few criteria to ensure a valid measurement of the photometry. First, the photometry of objects whose ratios of flux to flux error are less than the measured image signal-to-noise ratio are classified as non-detections and are removed. We also throw out candidate detections for which the flux error is negative or unreasonably large, or the covariance index output by T-PHOT is larger than unity.

Custom Apertures on Arcs

The extraction apertures were tailored for the three sets of image multiplicities for which we achieve quality photometric redshift estimation: Arcs 1a/b, Arcs 11a,b, and Arcs 2a,c (Panel D of Figure 2.3). The infrared images of Arc 1a/b consist of two blue knots and a redder and more diffuse underlying component with a total angular extent of 5 arcseconds. Because the T-PHOT fitting method integrates across the image, the multi-component information gets subsequently lost. To recover the input redshift we found it necessary to place down one

aperture for each knot as well one for the overall arc-shape. We refer to §4.6.2 below for details.

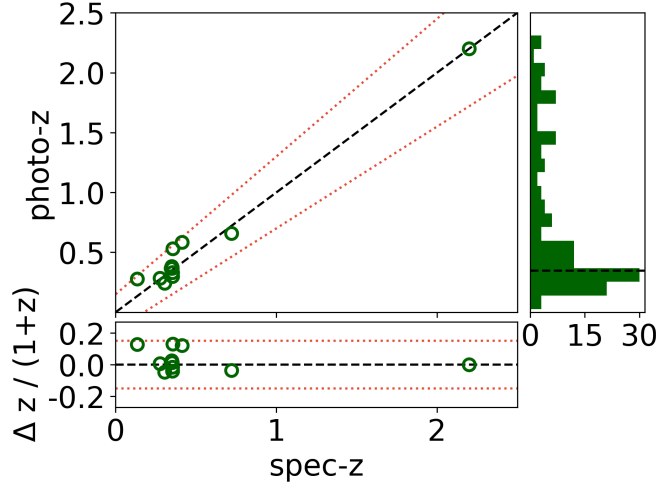


Figure 2.7 Comparison of the training set of galaxy redshifts with their photometric redshift estimates obtained in this study, up to $z = 2.5$. We define a metric for the goodness-of-fit as $|\delta z|/(1+z) < 0.15$ (dashed lines) to assess the overall performance of the photometry. The histogram on the right-hand-side depicts the distribution of photometric redshifts, which peaks at the cluster redshift $z = 0.348$ (black dashed line). We find the photometric redshift estimations to be contained within the goodness-of-fit metric for all sources.

On other image multiplicities, Arcs 11a,b consists of two bluer knots on top of a more extended, and somewhat redder, stellar continuum. For this case, we lay down four apertures, one for each of the knots. We choose not to put down an aperture over the larger arc structure because the surface brightness is low and in principle a photometric redshift can be obtained from any of the knots. This choice of a small aperture is also advantageous for minimizing background contamination. Arcs 2a and 2c are compact and bright, making them straightforward to detect using SExtractor. Given the compact morphology, further adjustments to the apertures or photometry were unnecessary.

2.5 Photometric Results

Photometric Catalogs

We estimate photometric redshifts for 143 galaxies, for which each galaxy is detected in at least five bands and has been confirmed to be a real source by our visual inspection.

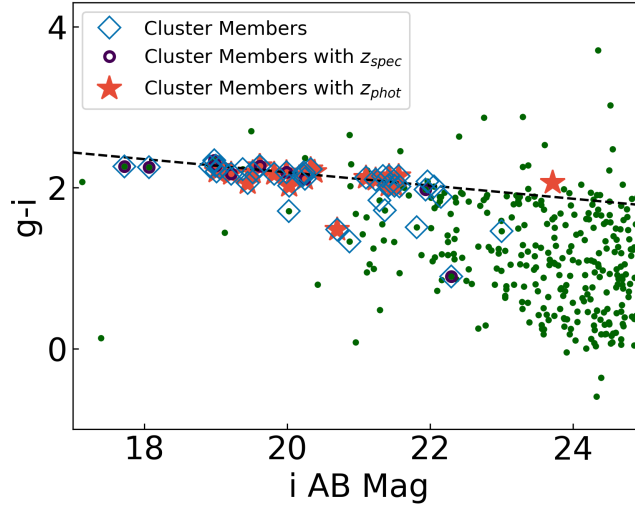


Figure 2.8 LBT/LBC $g-i$ colors for T-PHOT photometry performed on objects within the *HST* FOV (green filled circles). The spectroscopically confirmed cluster members are depicted by the purple open circles, while the photometrically confirmed cluster members are indicated by the red stars. The cluster red sequence is depicted for reference (black dashed line), which guides the selection of cluster members applied to our lens model (blue diamonds).

Furthermore, each SED fitting result must satisfy the condition that the modified $\chi^2 < 1$, a conservative cutoff to ensure high quality fits with BPZ introduced in Coe et al., 2006. The distribution of photometric redshifts peaks at the cluster redshift, and has a long tail extending to higher values (Figure 2.7). Of these, 22 objects are found to be in or near the cluster redshift, with 37 in the foreground and 84 in the background. On background objects, 42 objects are at $1 < z < 3$, with four high redshift sources at $z > 5$. The result of this study is that new optical-IR photometric redshifts are obtained for four lensed galaxy images from two image systems for which there was no previous photometric or spectroscopic values. These new values contribute tighter constraints to the lens model (§5.3, §7).

Selection of Cluster Members

The input catalog of cluster members for the lens model contains 40 galaxies, which results from a strict color cut following the red sequence (Figure 2.8). We use the 22 photometrically- and 10 spectroscopically-confirmed cluster members (some members have both redshift types) to guide the color cut. We find that the cluster member list does not change drastically from F19, yet still qualifies as an improvement because it includes 10 previously overlooked cluster members, and removes two $z \approx 0.48$ interlopers which share similar colors to the cluster members. Nearly all previously excluded cluster members were relatively faint, and also failed to meet the more stringent color criteria in F19. The $g-i$ colors of the spectroscopically confirmed cluster members as well as the photometrically confirmed cluster

members are depicted in Figure 2.8.

The Image Multiplicities

We set out to estimate photometric redshifts for all the images of all the image multiplicities, and succeeded in obtaining redshift values for Arc 1a/b, Arc 2a, Arc 2c, Arc 11a, and Arc 11b, which for reference are labeled on Figure 2.3 in Panel D, and are depicted as image stamps in Figure 5.5. Of these, Arc 1a/b is the only member of any image system with a spectroscopic redshift (Harrington et al., 2016; Harrington et al., 2021). Its magnification factor is estimated from our lens model to be $\mu \approx 25$. The morphology of Arc 1a/b consists of two bluer, star-forming knots opposite the critical line. As a sanity check on the photometry, we estimate a photometric redshift for Arc 1a/b of $z = 2.20 \pm 0.31$, which is consistent with its spectroscopic redshift. The counterimage, Arc 1c, is detected in K -band and $Ch1[3.6]$ and $Ch2[4.5]$ data, and has the similar colors and model-predicted location expected of a counterimage. However it is too faint and blended in the bluer bands to estimate its photometric redshift. The spectroscopic redshift is preferred for constraining lens model due to its much lower uncertainties.

Arcs 2a, 2b, and 2c belong to a single image system. They have a mean K_{AB} magnitude of ≈ 20.2 , and high magnification factors of $\mu \approx 10$. SED fits are made for Arcs 2a and 2c, for which we estimate photometric redshifts of $z = 2.30 \pm 0.32$ for both images (Figure 5.5). The similarity in redshift between Arcs 2a,c is expected under the interpretation that they are multiple images of the same background galaxy. According to the morphology, colors, and the lens model predictions, Arc 2b is also a member of this image system, but an SED fit was not made for this image family member owing to obscuration by a bright cluster galaxy.

Arcs 11a and 11b have a similar morphology consisting of a pair of compact knots that is doubly-imaged about the critical curve. These galaxy images are somewhat bluer and are more or less flat in $F110W - F160W$, suggesting that the source is a star forming galaxy that is relatively unobscured by dust. We measure high magnification factors of ≈ 50 and ≈ 60 for Arcs 11a, and 11b, respectively. Figure 5.5 shows the SED fits, which return estimates of $z_{phot} = 4.93 \pm 0.58$ for Arc 11a, and $z_{phot} = 4.82 \pm 0.57$ for Arc 11b. We choose to include K -band photometry for this arc, although it is at or slightly below the detection limit. 11c is also a member of this image system as predicted by the lens model, however a quality photometric redshift was not measured for this system, perhaps owing to its especially low surface brightness compared to its counterimages.

The High- z Arcs

We estimate photometric redshifts for 28 lensed sources with $z > 1.5$, including 6 lensed sources with $z > 4$. Table 2.2 gives the catalog, where the columns are: object name, coordinate, z_{phot} , and the AB magnitude in each of the seven bands. We identify many galaxies at similar redshifts, yet upon comparing the colors and the morphologies with the lens model, we do not confirm any new image multiplicities. The number count at $z > 4$ is consistent to

order of magnitude with the expected number for its redshift given by lensing the Mason, Trenti, and Treu, 2015 luminosity function with our lens model. We refer to §7.3 for a more complete discussion of the predicted galaxy number counts.

Comparison to Spectroscopic Members

We compare the redshifts of the spectroscopic sample with the photometric redshift catalog. This exercise provides an independent check on the overall quality of the photometric redshift fit. To make this comparison, we establish the goodness-of-fit metric $|\delta z|/(1+z) < 0.15$, which measures the fraction of outliers following Castellano et al., 2016 and Dahlen et al., 2013. We choose to only compare secure photometric redshifts, meaning that an object is clearly detected in 5 bands and provides a modified $\chi^2 < 1$. We find secure photometric redshifts for 12 of the 22 objects in the spectroscopic sample in the HST FOV, all of which pass our goodness-of-fit metric (Figure 2.7).

2.6 Spectroscopic Results

The MMT/Binospec Sample

We report secure redshift identifications of the Binospec spectroscopy, by which we mean that we require two or more spectroscopic features to be detected at the $>2\sigma$ level relative to the continuum. In the case of a single emission line source, we require also the detection of a second significant feature such as a continuum break. Typical absorption- and emission-line features detected in these spectra (depending on the redshift and object type) are: Fe II $\lambda\lambda$ 2587,2600, Mg II $\lambda\lambda$ 2796,2803, Mg I λ 2852, [O II] $\lambda\lambda$ 3727,3729, Ca H & K, G-band, [O III] $\lambda\lambda$ 4959,5007, Mg I $\lambda\lambda$ 5167,5173,5184, NaD, O I λ 6300, [N II] $\lambda\lambda$ 6548,6583, Balmer family (H α through H θ), and [S II] $\lambda\lambda$ 6716,6731.

The analysis yielded 86 redshifts. These redshifts separate out into 17 galaxies in the redshift range of the cluster of $0.330 < z < 0.366$ at any radius from the cluster center (clustercentric radius), and 51 sources with $0.366 < z < 1.13$. Nineteen objects have redshifts which place them in the foreground of the lens. The Dusty Star Forming Galaxy (DSFG) Arc 1a was targeted, but did not yield a redshift. No spectroscopic features are detected in its spectrum over the wide wavelength baseline of 3900–9200 Å. This result is not surprising given that the expected position of Ly α falls just blueward of the spectral bandpass, and the nebular [O II] line is redshifted out of the bandpass.

The Master Spectroscopic Sample

We combine the MMT/Binospec redshifts with other redshifts available in the literature (F19 and SDSS DR-16), which sum up to 273 spectroscopic redshifts. Cluster membership is met

for galaxies which have velocities within $\pm 4000 \text{ km s}^{-1}$ about the mean value of $z = 0.348$. This corresponds to range of $0.330 < z < 0.366$. We choose $\pm 4000 \text{ km s}^{-1}$ so as to include sources in the outskirts of this cluster with its somewhat elongated structure. Of the 273 redshifts, 39 galaxies make the redshift cut. We further downselect to the subset of galaxies whose clustercentric radii are within 1 Mpc. By these criteria, a total of 21 galaxies are admitted to the master cluster member catalog (Figure 2.10, inset). They are comprised of 8 galaxies from MMT/Binospec (this study), 6 galaxies from Gemini/GMOS (F19), 5 galaxies from MMT/Hectospec (F19), and 2 galaxies from the SDSS DR 16.

The vast majority of cluster members lie reasonably well on the cluster red sequence indicated in Figure 2.8. The one outlier, a faint elliptical galaxy with $i_{AB} = 22.4 \text{ mag}$, is situated in the outskirts of a luminous galaxy at $z = 0.033$ (SDSS, DR16) that skews its color. Thirteen cluster members are contained in the FOV of this study, which is the field of intersection of the 7-band filter suite roughly comparable to the *HST* WFC3-IR FOV. This number is a factor of three improvement relative to the number of cluster members reported in the same FOV in F19. Of the 18 cluster members in their study at any clustercentric radius, three are removed from consideration in our new member catalog. They are: “s7” from MMT/Hectospec, whose spectrum had an insecure redshift, “s57” from Gemini/GMOS catalog, and “s35” from the SDSS catalog which were both made redundant by our new MMT/Binospec catalog. There are a set of 22 galaxies which have spectroscopic redshifts behind the cluster of $0.398 < z < 0.426$. Of these, only one is situated within a clustercentric radius corresponding to the FOV of this study, and the vast majority (18 of 22) are situated at clustercentric radii greater than 1 Mpc. These galaxies are interesting because they may be part of a larger scale structure, but are not expected to make a significant contribution to the strong lensing model presented here.

The velocities of the cluster members in the common field of interest of 600 kpc are binned and plotted in Figure 2.11, where for reference 0 km s^{-1} marks the cluster’s systemic velocity and the solid vertical line marks the velocity of the brightest cluster galaxy. Although G165 is a visual double-cluster, it is a challenge to separate out the two halves based on their relative velocities. Within radii of 600 kpc and 1 Mpc we measure velocity dispersions of $1040 \pm 282 \text{ km s}^{-1}$ and $1010 \pm 209 \text{ km s}^{-1}$, respectively. We calculate the mass by applying the virial theorem via the Gapper method (Wainer and Thissen, 1976; Beers, Flynn, and Gebhardt, 1990). We obtain masses of $(4.9 \pm 2.6) \times 10^{14} M_{\odot}$ within 600 kpc, and $(4.6 \pm 1.9) \times 10^{14} M_{\odot}$ within a radius of $\sim 1 \text{ Mpc}$, where the uncertainty is computed by a jackknife sampling following the prescription in Beers, Flynn, and Gebhardt (1990). These values are consistent with each other and with the mass estimated from the lens model to within the stated uncertainties. If the hint of an increase in the mass with increasing radius turns out to be real, then we will have a velocity indicator that this system that is not virialized. We refer also to Ferragamo et al. (2020) for a discussion on the biases inherent to estimating masses based on velocity dispersions. We refer to §8 for a discussion of the cluster kinematics, and to Golovich et al., 2017 for a review of the pitfalls entailed with the approach to detect some mergers by the non-Gaussian shapes of their velocities alone.

2.7 Revised Lens Model

We use the well-tested light traces mass (LTM) approach to construct the 2D projected mass map as is used in F19 (Zitrin et al., 2009a; Zitrin et al., 2015a). This semi-parametric method assumes the galaxies are tracers of the dark matter, which for the case of G165 was shown to produce results consistent with non-parametric methods (F19). The inputs are the photometry and positions of the cluster members, and the redshifts of the lens and multiply-imaged sources. The cluster member observables inform the placement of power-law surface density profiles which are scaled based on the galaxy brightnesses. The superposition of these density profiles is smoothed with a Gaussian kernel to approximate the smooth dark matter distribution of the cluster. The cluster member density profiles are assigned a relative weight with respect to the dark matter. In turn, the total mass distribution is approximated as the sum of the smooth dark matter and the galaxy power law surface density profiles scaled by the galaxy relative weights. Additional parameters include values for external shear, shear orientation, individual galaxy weights, individual galaxy ellipticities and position angles, and arc family redshifts.

The free parameters are fit for via a MCMC minimization using thousands of steps to produce the final model. Errors are computed by bootstrapping the MCMC steps, sampling 100 random realizations in the MCMC and quoting the Gaussian errors. We stress that the MCMC errors are not robust to changes in the lensing constraints, and are purely statistical. Strong lens modeling is an intrinsically underconstrained problem, and the statistical errors will ultimately underestimate the true error which is dominated by the systematics (Johnson and Sharon, 2016; Meneghetti et al., 2017; Strait et al., 2018).

Image System Designations

We retain the same image system designations as in F19, with the exception that Arcs 1a,b are renamed as Arcs 1a/b,c. The Arc 1a/b nomenclature is preferred because it acknowledges that there are two contiguously-positioned images of this one lensed source. To remove ambiguity, it follows that the arc formerly named as Arc 1b is changed to Arc 1c. All image systems identified and used by the model are labeled in Figure 2.12.

The G165 Model

We introduce herein new photometric redshift information for Arcs 2a,c and Arcs 11a,b to refine the mass map in F19 that was anchored on a single spectroscopic redshift of a single image of a single system, Arc 1a/b. We also update the cluster member list as described in §5.2. We construct the model by fixing the Arc 1a/b redshift, and updating the constraints on Arcs 2 and 11, leaving their redshifts free to vary only within the 1σ uncertainty of its associated photometric redshift. The redshifts of all other arc systems (systems 3-10) are left to be optimized by the model without constraints. We fix the weights of all cluster members within the LTM algorithm on the basis of their brightnesses, with the exception

of the BCG, whose weight is left free to be optimized by the model. The new photometric and spectroscopic redshifts of the cluster members and arcs introduce additional constraints, which result in an improvement to the lens model.

The best model, which is the one for which χ^2 is minimized, is presented in Figure 2.12. Critical lines are overlaid for $z = 2.2$ (equating to the redshift of Arc 1a/b) and $z = 4.8$ (equating to the redshift of Arcs 11a,b) which delineate the elongated configuration and bimodal mass distribution. The revised model has a smaller measured area within the critical line when compared to the initial model in F19 by $\sim 20\%$. We estimate the lensing mass based on the MCMC to be $(2.36 \pm 0.23) \times 10^{14} M_{\odot}$ within 600 kpc. For this model we predict input image constraints to an RMS recovery angular position of $\sim 0.6''$. The model acquires improved functionality also for testing the positions of the image systems in F19. The image designations of Arc 5c and Arc 10c, which were plausible but unconfirmed in F19, remain as such in this study. At the same time, the updated model reduces the likelihood of the Arc 9 counterimages, 9d and 9e. We do not uncover any new image multiplicities. We discuss the high redshift population in §7.3.

Predicted Galaxy Number Counts

G165 remains a powerful lensing cluster, with a 2D projected mass estimate derived from our strong lensing model of $M_{600kpc} = (2.36 \pm 0.23) \times 10^{14} M_{\odot}$, and a $z = 9$ Einstein radius of $\theta_E \approx 15.3''$ that is comparable in strength to HFF cluster Abell 2744. We apply our revised model here in order to make predictions for the galaxy number counts extending to higher redshifts. This serves to place a check on the recovered photometric redshifts, as well as characterize the lensing strength implied by the model. Figure 2.13 shows the cumulative number counts of lensed galaxies observed within a 5 arcmin² FOV centered on G165 as a function of magnitude. We opt for the Mason, Trenti, and Treu, 2015 luminosity function to represent the blank field because it can accommodate a wide range of redshifts, as indicated. One result is that the lensed source counts do not win out over the field galaxy counts at all redshifts and limiting magnitudes. Even so, the number of lensed galaxies gains over the number of field galaxies with increasing mean redshift. This is because the faint end of the luminosity function flattens with increasing redshift, such that the loss of sources by field dilation is compensated for by the detection of sources which rise up above the apparent limiting magnitude.

Given the limiting AB magnitude of 27 of our *HST* data, the lensed luminosity function predicts order unity detections of $z \approx 6$ and $z \approx 8$ galaxies, and dozens of $z \approx 4$ galaxies. As shown in the results of Table 2.2, we detect only one $z \approx 6$ galaxy and a handful of $z \approx 4 - 5$ galaxies. While the predictions are only rough estimates, the lower numbers of observed detections are in part owing to incompleteness of the catalog, as Figure 2.13 represents an idealized survey. Moreover, although the detections made in the mixed bag of 7 bands of imaging with differing image characteristics and qualities presented here are the best available, they are not ideal for churning out large numbers of quality photometric redshifts. Increasing the number of filters to improve spectral coverage at high resolution, and

increasing the depth of the $3.6\ \mu\text{m}$ and $4.5\ \mu\text{m}$ filters beyond 23 AB mag will help to obtain a more complete photometric redshift catalog. Looking toward the planned observations of G165 using JWST/NIRCam, a limiting magnitude of 29 AB will be achieved in 8 bands, yielding ~ 100 sources at $z \approx 4$, and order unity sources at $z \approx 10$.

Arcs 1a/b, 1c

The DSFG Arc 1a/b ($z = 2.2$) is relatively-faint in the near-IR ($F160W_{ab} = 22.23$ mag) and red ($g - i = 0.9$ AB mag), as expected of a dust-obscured source. The high magnification factor derived from our revised lens model of $\mu \approx 25$ stretches this galaxy out to an angular extent of $\sim 5''$, enabling a privileged view at the kpc scale into the interstellar medium of a high-redshift star forming galaxy. Arc 1a/b is detected in the rest-frame ultraviolet, corresponding to observed g -band (23.4 ± 0.1 AB mag). From this we infer that there is at least some leakage of ultraviolet light from massive stars. DSFGs are highly dust-extincted, yet lensing may offer the advantage of stretching out the light into more pixels to achieve better sampling, which may allow the transmission of ultraviolet light. Although unresolved, the sources of this UV starlight appear to be the star forming knots (Figure 2.12). One counter image is detected, Arc 1c, but it is faint and drops out of detection in the three bluest filters, disallowing the estimation of a photometric redshift. Preliminary images acquired using the VLA detect Arc 1c, and separate out what appear to be the star forming regions of Arc 1a/b into four knots, two each on opposite sides of the critical curve. These results will appear in an upcoming paper (Kamieneski et al. 2022, *in preparation*).

2.8 Cluster Evolutionary State

The O/IR Picture

Our data gives clues as to the state of virialization of this cluster. We are given: (1) the photometric catalog of 22 member galaxies which cover the range $0.3 < z_{\text{phot}} < 0.4$ out to ~ 600 kpc, (2) the spectroscopic catalog of 21 cluster galaxies which covers the range $0.330 < z < 0.366$ within 1 Mpc, (3) the combined catalog of the four galaxies with both spectroscopic and photometric redshifts, and (4) the set of six central dominant galaxies. These six galaxies consist of three cluster members in the northeast (NE) component, and three cluster members in the southwest (SW) component (green stars in Figure 2.14). Although it is useful to further subdivide the cluster membership by galaxy activity levels and galaxy colors, such designations are limited given the small numbers of objects. Below we measure the quantities available to us which were demonstrated by Rumbaugh et al. (2018) to be correlated with cluster virialization: the offset of the luminosity mean center from the BCG and from the velocity center.

We identify the BCG as the cluster member with the highest luminosity as measured in i -band (“+” symbol in Figure 2.14. The i -band is selected because it is redder than the

4000 Å and Balmer breaks at the cluster redshift. The mean projected centroid of the cluster member luminosities is computed, from which we obtain the luminosity weighted mean center (LWMC; “x” symbol in Figure 2.14). The two centers are offset by 3.3 arcseconds, equating to 16.5 kpc. We note that although the *i*-band alone does not fairly represent the stellar mass, the FOV of the near-IR filters is too narrow to cover the full cluster member catalog (Figure 2.1). We do not undertake an analysis of the individual galaxy masses, nor compute a cluster mass centroid, because the set of 22 galaxies with fitted SEDs does not include certain crucial members such as the BCG and some of the LRGs.

The velocity histogram of the cluster members has a single broad peak. This suggests that the two sides are moving transverse to the line-of-sight. Three of the four central dominant members with spectroscopic redshifts have minimal pair-wise velocity offsets of $\lesssim 100 \text{ km s}^{-1}$ (red circles in Figure 2.14), providing further support that the major axis of the cluster is aligned preferentially in the plane of the sky. Intriguingly, the BCG is blueshifted by 2400 km s^{-1} relative to the velocity center (Figure 2.11). The BCG has all the spectroscopic features expected of a passively-evolving elliptical galaxy, from the prominent 4000 Å and Balmer breaks, to the G-band and Balmer lines in absorption. What is unexpected is the large velocity difference between the BCG and the cluster’s systemic velocity. It is interesting that, despite its designation as the BCG, there are no spectroscopically-confirmed neighbors at a similar velocity (to within 1000 km s^{-1}). Additional longslit spectroscopy centered on the BCG would be advantageous to search for its entourage.

The Radio Picture

Our radio maps corroborate the general picture of a cluster disturbance, and give clues as to the direction of motion of the NE and SW components. The LOFAR LoTSS map depicts emission with a physical extent of $\sim 500 \text{ kpc}$ that is elongated along the major-axis of the cluster. There are two dominant radio peaks, one roughly centered on each of the NE and the SW components. An elongated region of somewhat more diffuse radio emission extends to the southwest of the SW peak with a physical extent 300 kpc, and a shelf-like emission feature is detected protruding to the east. A distinctive comet-like morphology of the NE peak trails off into the southwesterly direction.

At the higher resolution of the VLA 6 GHz radio map, the NE peak separates out into two head-tail galaxies: one corresponding to the BCG and the other to an LRG (NE inset in Figure 2.14). The VLA map also detects two LRGs in the SW side as more compact radio sources in the same pointing, and all within the primary beam. The trails of each of the two head-tail galaxies are associated with an active galactic nucleus in the center of each galaxy that is ejecting a bipolar jet.

These Narrow Angle Tails (NATs)

(e. g., Müller et al., 2021) are relatively common in galaxy cluster fields (e. g., Malavasi et al., 2016; Garon et al., 2019). Interestingly, in the G165 field the trails of the two NATs are also more-or-less aligned with each other, a behavior that suggests a common ensemble jet motion. Given that a NAT will typically occupy the wake of its host,

we infer that the radio jets are being swept back from the northeast direction by ram pressure.

Curiously, G165 is not X-ray bright despite participating in an ongoing merger that should have shock-heated the intercluster gas to X-ray temperatures. In order to maintain the lower X-ray luminosity it is tempting to speculate that the two components may not have directly impacted each other, but instead achieved a longer distance cluster-cluster interaction.

The near-alignment of both pairs of radio trails suggests an ensemble motion that is not along the line-of-sight, making the transverse velocity nonzero (Gendron-Marsolais et al., 2020). There is not yet enough information to measure its value, but there are some clues. In a study incorporating the results of NATs in both poor and rich galaxy clusters, Venkatesan et al. (1994) find the appearance of NATs in all cases, and estimate typical NAT velocities of $\sim 600 \text{ km s}^{-1}$ to be able to form its distinctive morphology. In the large N-body dark-matter only numerical simulation, the JUropa Hubble volumE (Jubilee; Watson et al., 2014), they consider examples of merging halo pairs in the $z = 0.32$ redshift slice that is well-matched to that of G165. Although the velocity scatter is large, and the halo separations are less well sampled at $\lesssim 0.6 \text{ Mpc}$, an extrapolation to smaller halo separations indicates that typical pair-wise velocities of halo-halo mergers are $\approx 100 \text{ km s}^{-1}$ (Watson et al., 2014). In another recent study of three HFFs, space velocities at regular intervals in the range of $500 - 5000 \text{ km s}^{-1}$ are inserted to the measured velocities of the cluster members and its deviation from the line-of-sight velocity distribution recorded. By this kinematical analysis, an upper limit on the transverse velocity of 1700 km s^{-1} is allowed in order to still recover the observed line-of-sight velocity distribution (Windhorst et al., 2018b). These studies suggest that the transverse velocity of G165 may be in the $100 - 1700 \text{ km s}^{-1}$ range. X-ray observations will enable a study of the collision properties, and improved constraints regarding the viewing angle and transverse velocity.

2.9 Conclusions

G165 is a powerful lensing cluster with a bimodal mass distribution, rich lensing evidence, and low X-ray luminosity. Upon incorporating the new LBT/LBC and *Spitzer* imaging data, photometric redshifts are enabled for three image multiplicities. New MMT/Binospec spectroscopy contributed eight additional cluster members. These lensing constraints produced a lens model that refined the placement of the critical curve relative to the caustic-crossing arcs and but falls short of detecting the subhalo underlying the BCG velocity outlier.

The detection of the four radio trails in a roughly mutual alignment suggests an impact orientation in the plane of the sky and a direction of motion in the northeast-southwest direction. In this scenario, the NE and SW components have already traversed each other in an event that instigated the radio activity and supplied the pressure for the cluster gas to sweep past the radio jets. Here the low X-ray luminosity is explained by a more indirect cluster-cluster encounter of the NE and SW components.

High-resolution blue imaging is needed to constrain the age of the merger by its rest-frame ultraviolet-optical colors, and X-ray observations enable searches for shocks to establish the collision speed. The only way to uncover all halos participating in the cluster merger is by obtaining additional lensing evidence by deep high-resolution imaging in the planned *JWST*/NIRCam PEARLS-Clusters approved program.

Ultimately, such observations offer a viable route to constrain the evolutionary state of this binary cluster that in turn contributes to our understanding of mass assembly on cluster scales.

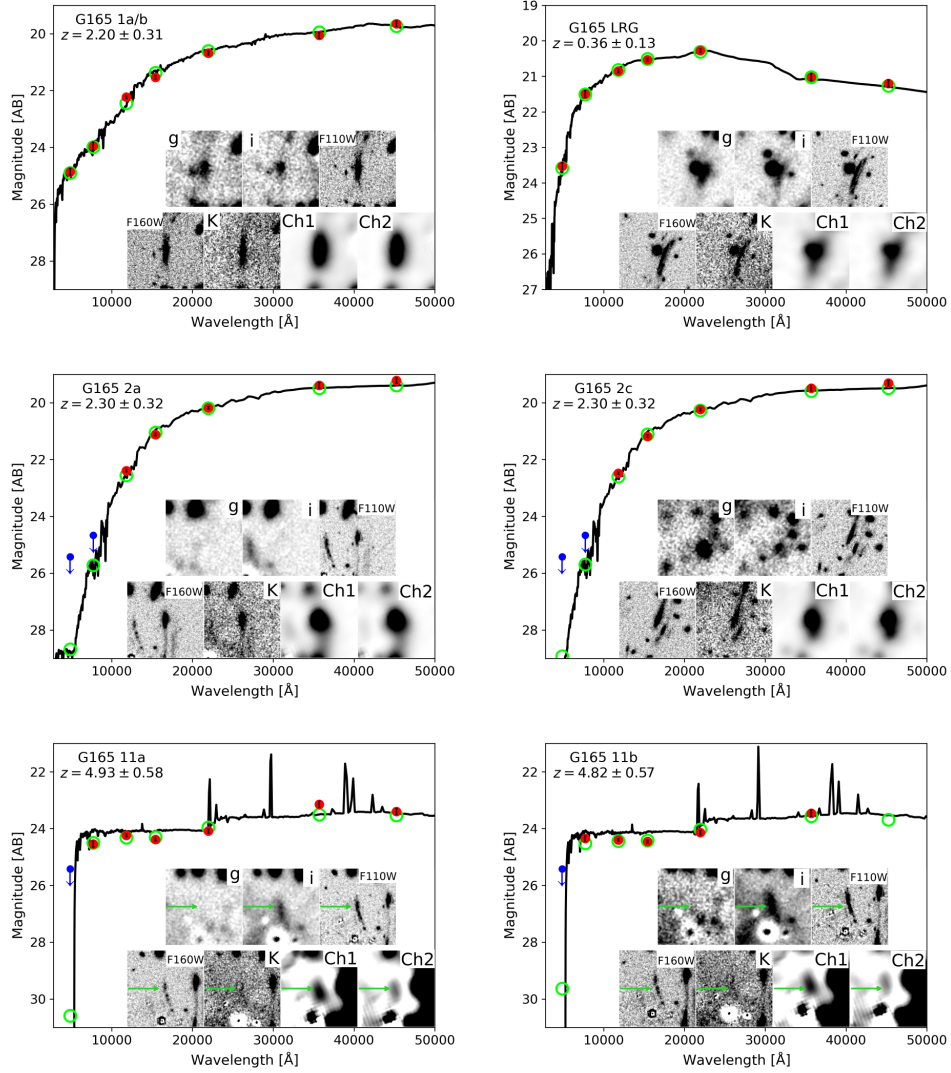


Figure 2.9 Best fit BPZ SEDs from SExtractor and T-PHOT photometry of Arcs 1a/b, 2a, 2c, 11a, and 11b and a typical example of a cluster LRG. The best fit SEDs (black line) interpolated from Kinney et al., 1996, Bruzual and Charlot, 2003a, and Coleman, Wu, and Weedman, 1980 templates satisfy our criterion for secure redshifts by returning a reduced $\chi^2 < 1$ while using a minimum of 5 bands. SED fit quality is determined by the offset between the photometry estimated for the SED in a given filter (green circles) and the photometry measured through SExtractor and T-PHOT (red dots), as well as by satisfying the BPZ prior on the i -band magnitude. Drop outs (blue arrows) are reported where the measured magnitude falls below the measured $3\text{-}\sigma$ detection limit. Image stamps of each object are shown in the insets with the filter as labeled. Photometric redshifts are obtained for these five members of three different image multiplicities, which contribute tighter constraints to the lens model.

Table 2.2 High- z Photometry From G165 Field

ID ^a	R.A.	Decl.	z_{phot}^b	g_{AB}^c	i_{AB}^c	$F110W_{AB}$	$F160W_{AB}$	K_{AB}	$Ch1_{AB}$	$Ch2_{AB}$
1 ^d	171.8113	42.47299	2.20 ^{+0.31} _{-0.31}	23.96 ± 0.11	24.86 ± 0.08	22.23 ± 0.02	21.54 ± 0.05	20.68 ± 0.05	20.06 ± 0.01	19.65 ± 0.01
2 ^e	171.81645	42.47473	2.30 ^{+0.32} _{-0.32}	> 26.1	> 26.8	22.39 ± 0.00	21.12 ± 0.00	20.18 ± 0.00	19.39 ± 0.00	19.22 ± 0.00
3 ^e	171.81384	42.47811	2.30 ^{+0.32} _{-0.32}	> 26.1	> 26.8	22.48 ± 0.00	21.18 ± 0.00	20.24 ± 0.00	19.49 ± 0.00	19.31 ± 0.00
4 ^f	171.81567	42.47835	4.93 ^{+0.58} _{-0.58}	24.55 ± 0.01	> 26.8	24.24 ± 0.01	24.38 ± 0.03	24.09 ± 0.06	23.15 ± 0.04	23.40 ± 0.03
5 ^f	171.81572	42.47802	4.82 ^{+0.57} _{-0.57}	24.35 ± 0.01	> 26.8	24.40 ± 0.01	24.46 ± 0.03	24.14 ± 0.07	23.46 ± 0.05	—
6	171.81575	42.47784	5.06 ^{+0.59} _{-0.59}	25.11 ± 0.02	> 26.8	24.94 ± 0.01	24.87 ± 0.04	24.61 ± 0.10	24.73 ± 0.10	—
7	171.8211	42.45727	1.86 ^{+0.29} _{-0.28}	25.67 ± 0.02	26.34 ± 0.02	25.28 ± 0.02	24.71 ± 0.03	24.69 ± 0.07	24.42 ± 0.04	24.21 ± 0.03
8	171.84108	42.46482	1.81 ^{+0.28} _{-0.55}	24.70 ± 0.01	24.98 ± 0.01	24.13 ± 0.01	23.76 ± 0.02	23.62 ± 0.03	23.46 ± 0.02	23.49 ± 0.01
9	171.8184	42.45991	1.99 ^{+0.48} _{-0.35}	27.54 ± 0.12	27.47 ± 0.05	26.88 ± 0.04	26.42 ± 0.10	—	25.98 ± 0.14	—
10	171.83697	42.46778	4.82 ^{+0.57} _{-0.57}	26.07 ± 0.03	> 26.8	25.94 ± 0.02	25.78 ± 0.06	25.67 ± 0.15	24.79 ± 0.07	24.83 ± 0.06
11	171.80296	42.4641	2.00 ^{+0.29} _{-0.29}	27.30 ± 0.11	> 26.8	24.04 ± 0.01	22.79 ± 0.01	22.12 ± 0.01	21.45 ± 0.00	21.34 ± 0.00
12	171.81299	42.471	2.05 ^{+0.30} _{-0.30}	23.91 ± 0.01	24.28 ± 0.00	23.40 ± 0.01	22.94 ± 0.01	22.66 ± 0.01	22.54 ± 0.01	22.52 ± 0.01
13	171.81502	42.47611	2.06 ^{+0.30} _{-0.30}	25.02 ± 0.02	26.60 ± 0.03	22.05 ± 0.00	20.82 ± 0.00	19.86 ± 0.00	19.13 ± 0.00	19.00 ± 0.00
14	171.79628	42.46708	1.94 ^{+0.29} _{-0.27}	23.90 ± 0.01	24.69 ± 0.00	23.67 ± 0.01	23.10 ± 0.01	23.01 ± 0.02	22.60 ± 0.01	22.57 ± 0.01
15	171.8178	42.47324	1.81 ^{+0.27} _{-0.27}	26.01 ± 0.03	28.87 ± 0.18	23.14 ± 0.01	22.26 ± 0.01	21.71 ± 0.01	21.26 ± 0.00	21.19 ± 0.00
16	171.83023	42.47862	1.80 ^{+0.27} _{-0.27}	23.56 ± 0.00	23.81 ± 0.00	23.27 ± 0.01	22.95 ± 0.01	22.89 ± 0.02	22.58 ± 0.01	22.61 ± 0.01
17	171.79925	42.47057	2.15 ^{+0.31} _{-0.31}	25.28 ± 0.02	26.19 ± 0.02	23.80 ± 0.01	22.59 ± 0.01	22.00 ± 0.01	21.29 ± 0.00	21.08 ± 0.00
18	171.81919	42.4768	3.12 ^{+0.40} _{-0.40}	24.97 ± 0.02	26.13 ± 0.03	25.21 ± 0.03	24.44 ± 0.05	23.54 ± 0.17	—	22.96 ± 0.01
19	171.82957	42.48002	1.82 ^{+0.28} _{-0.28}	26.20 ± 0.04	26.59 ± 0.03	24.57 ± 0.01	23.74 ± 0.02	23.22 ± 0.02	22.77 ± 0.02	22.53 ± 0.01
20	171.81498	42.47713	3.85 ^{+0.48} _{-3.36}	24.52 ± 0.01	26.09 ± 0.02	24.67 ± 0.01	24.64 ± 0.03	24.15 ± 0.06	—	—
21	171.82221	42.48107	1.95 ^{+0.29} _{-0.29}	24.43 ± 0.01	24.88 ± 0.01	23.53 ± 0.01	22.85 ± 0.01	22.52 ± 0.02	22.11 ± 0.01	22.16 ± 0.01
22	171.79848	42.48498	5.24 ^{+0.61} _{-0.61}	26.62 ± 0.07	—	25.90 ± 0.02	25.68 ± 0.09	25.68 ± 0.15	24.60 ± 0.10	24.24 ± 0.06
23	171.80525	42.48604	1.85 ^{+0.28} _{-0.28}	24.78 ± 0.01	26.14 ± 0.02	22.93 ± 0.01	22.03 ± 0.01	21.37 ± 0.01	20.53 ± 0.00	20.41 ± 0.00
24	171.82915	42.49285	3.34 ^{+0.42} _{-0.91}	25.82 ± 0.03	25.98 ± 0.01	25.75 ± 0.02	25.70 ± 0.10	—	25.46 ± 0.09	25.57 ± 0.08
25	171.83135	42.49005	3.37 ^{+0.43} _{-0.43}	25.89 ± 0.03	26.90 ± 0.03	25.59 ± 0.02	25.39 ± 0.06	—	24.49 ± 0.04	—
26	171.79051	42.47874	2.79 ^{+0.40} _{-0.37}	27.03 ± 0.12	28.91 ± 0.35	27.39 ± 0.07	26.01 ± 0.08	25.16 ± 0.11	—	—
27	171.80875	42.47923	1.81 ^{+0.28} _{-0.53}	24.29 ± 0.01	24.70 ± 0.01	23.87 ± 0.01	23.44 ± 0.02	23.54 ± 0.03	23.07 ± 0.02	23.12 ± 0.01
28	171.78579	42.47477	5.65 ^{+0.65} _{-4.25}	28.23 ± 0.22	—	26.61 ± 0.02	26.53 ± 0.15	26.13 ± 0.20	25.21 ± 0.07	—

^a Object ID number.

^b Photometric redshift estimates are presented for 26 objects with $z_{phot} > 1.8$ in at least five bands.

^c Lower limits are 3σ limiting magnitudes.

^d This is the DSFG Arc 1a/b, which has a $z_{spec} = 2.2357 \pm 0.0002$ (Harrington et al., 2016) and $z = 2.2362 \pm 0.0001$ (Nesvadba et al., 2019). The best fit SED can be found in Figure 5.5.

^e Arc 2a and 2b; the best fit SED can be found in Figure 5.5.

^f Arc 11a and 11b; the best fit SED can be found in Figure 5.5.

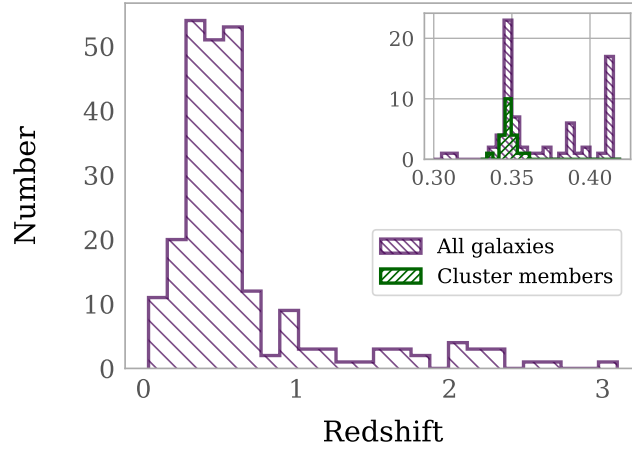


Figure 2.10 Spectroscopic redshift histogram for galaxies up to $z=3$ for the 273 redshifts drawn from all available sources. A peak appears at the cluster redshift of 0.348. A total of 39 galaxies meet the velocity criterion for cluster membership, of which only half meet also the radial cut (green-hashed histogram in the inset plot). We note that a smaller peak is identified at the slightly higher redshift of $z=0.41$. On further investigation, the vast majority of these galaxies are situated at large clustercentric radii of ≈ 1 Mpc. These galaxies may be part of a larger scale structure, but are not expected to contribute a significant strong lensing effect.

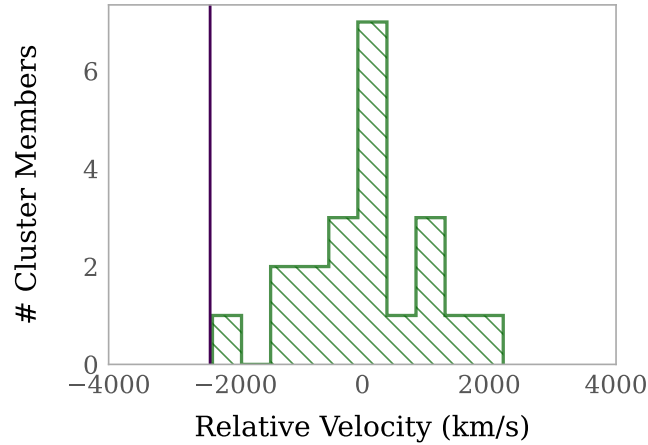


Figure 2.11 Histogram of the velocities of the confirmed cluster members in the common field that is covered by all of the data of 600 kpc (green-hatched histogram of the inset of Figure 2.10), plotted relative to the velocity center. The BCG is marked by the green vertical line at -2400 km s^{-1} . The velocities describe a roughly normal distribution, despite the cluster's visual bimodality. As such, the large velocity offset of the BCG suggests a cluster disturbance. Additional clues as to the cluster's dynamical state are discussed in §8.

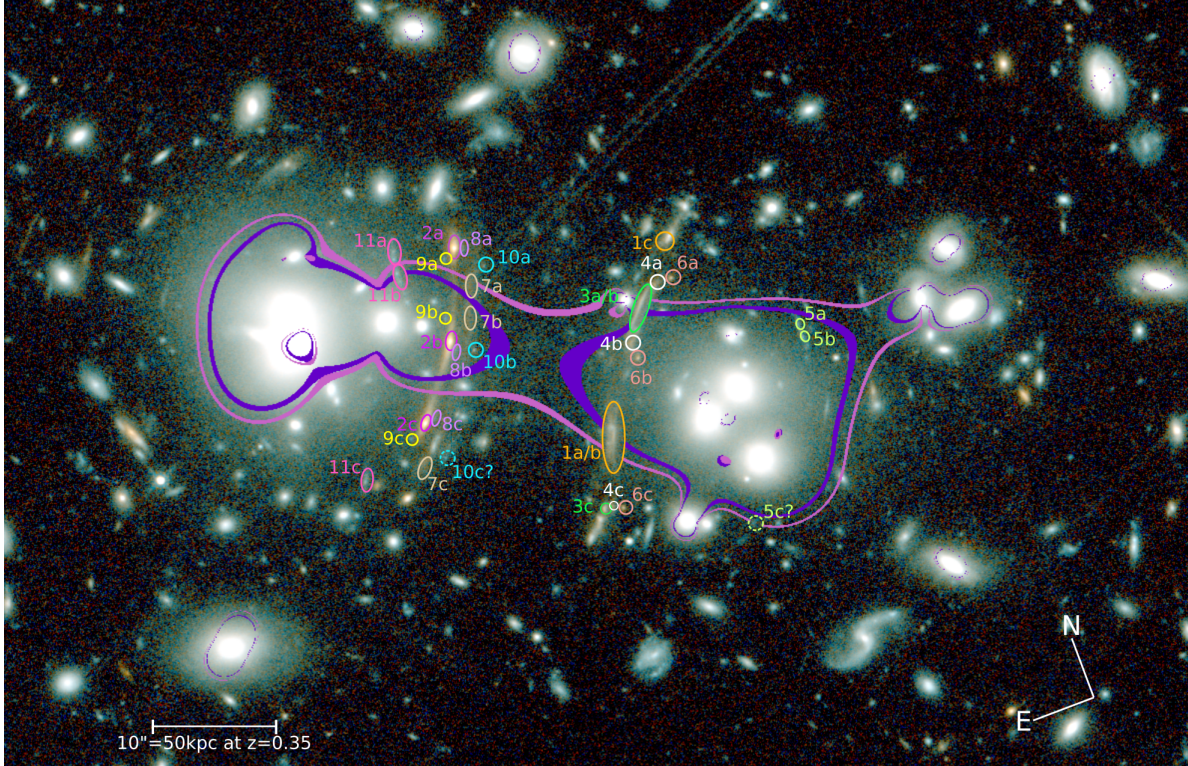


Figure 2.12 Composite two-color $F110W$ and $F160W$ image showing the $z=2.2$ (inner purple; equating to the redshift of Arc 1a/b) and the $z=4.8$ (outer pink; equating to the redshift of Arcs 11a,b) critical curves for the LTM lens model that incorporates the new photometric redshift estimates obtained in this study. The critical curves are determined as an absolute magnification cutoff in log space. All images of a single background galaxy are coded to the same color. Several arcs fold about the critical curve (*e.g.*, Arcs 1, 2, 3, 5, 7, 11), making this cluster potentially well-suited to the detection of caustic transients.

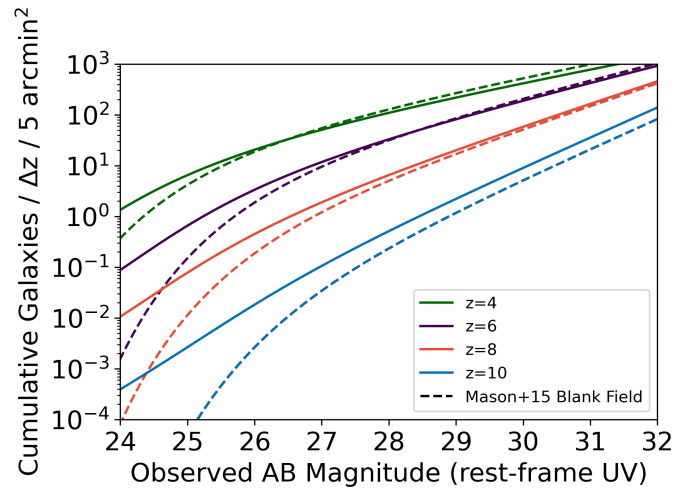


Figure 2.13 Cumulative number counts of lensed galaxies expected to be detected for different redshifts given a limiting AB magnitude and assuming a complete survey (continuous lines). We make a comparison with the blank field luminosity functions as measured by Mason, Trenti, and Treu, 2015, which we extrapolate beyond the $17.5 < M_{AB} < 22.5$ fitting range (dashed lines). In these models, the cumulative distribution is integrated down to the lower limit of the fitting range of 17.5 AB mag. G165 remains a powerful lensing cluster with a high predicted galaxy count at high redshifts in the planned JWST observations of limiting magnitude 29 AB mag.

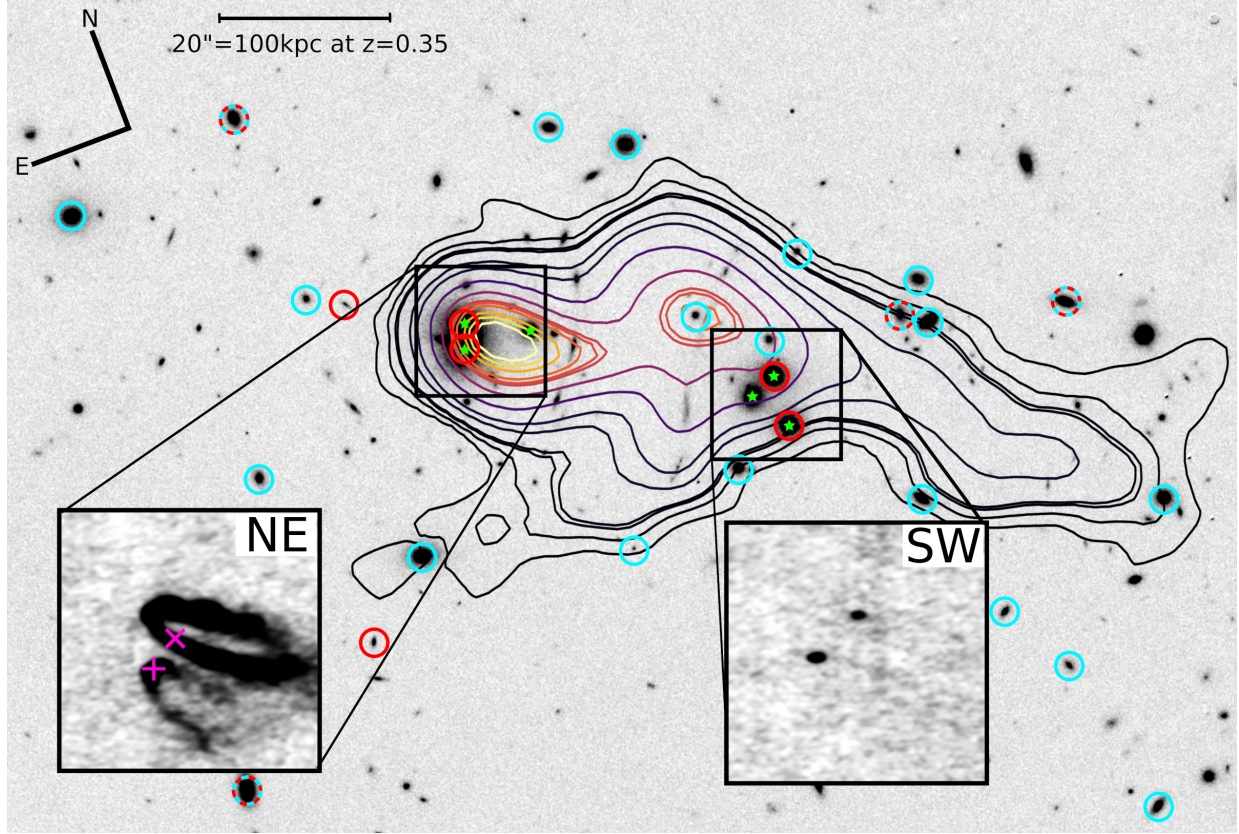


Figure 2.14 LUCI-Argos K band image depicting spectroscopically confirmed cluster members ($0.33 \leq z_{\text{spec}} \leq 0.36$, red circles), photometrically confirmed cluster members ($0.3 \leq z_{\text{phot}} \leq 0.4$, blue circles), and the set of six dominant galaxy members (green stars). The insets depict the VLA 6 GHz images in $15'' \times 15''$ patches centered on the SW and NE sides, as indicated. The BCG (magenta '+'), and luminosity weighted mean of the cluster (magenta 'x'), are offset from each other. The velocity of the BCG is also offset from the velocity mean, all of which suggest a dynamical disturbance. The LOFAR radio data (contours) recover the two central peaks, and show tails extending to the southwest and to the east with a physical extent of ~ 500 kpc. Two prominent head-tail galaxies are detected in the NE side of the VLA radio map. These galaxies are identified with the BCG and an LRG, whose jet orientations suggest a post-core passage. Based on the available information, this cluster appears to be undergoing a merger in a direction roughly transverse to the LOS.

Chapter 3

Unscrambling the Lensed Galaxies in SMACSJ0723

The content of this chapter is drawn from Pascale et al., 2022b, with permission from the co-authors.

3.1 Introduction

At long last, the first deep images from the *James Webb Space Telescope* (JWST) were delivered on July 11, 2022. The target is the central region of SMACS J0723.3-732 (SMACS0723 hereafter; $z_d = 0.39$), which is part of the southern extension of the MACS sample (Ebeling et al., 2010; Repp and Ebeling, 2018). SMACS0723 is a massive strong-lensing (SL) galaxy cluster which is rich in galaxy images distorted by the gravitational lensing effect, as was seen in recent *Hubble Space Telescope* (HST) imaging taken as part of the *Reionization Lensing Cluster Survey* (RELICS; Coe et al., 2019a). The *Planck*-derived mass is high $8.39 \times 10^{14} M_\odot$, and there were nine galaxies at $z > 5.5$ and two candidates at $z = 7$ based on their photometric redshift estimation (Salmon et al., 2020a; Strait et al., 2021). Three far-infrared sources have also been detected in the field using the *Herschel Space Observatory* (Sun et al., 2022).

A lens model for this cluster based on these previous HST images was published recently (Golubchik et al., 2022). This model uses the **Light-Traces-Mass** (LTM) method, which assumes that the galaxy light traces the underlying stellar and dark matter (DM) but does not assume a parametrized mass function for the DM (Broadhurst et al., 2005a; Zitrin et al., 2009b; Zitrin et al., 2015b). In Golubchik et al., 2022, the authors identify five strongly lensed galaxies and derive the spectroscopic redshifts for three of those systems using publicly-available ESO *Very Large Telescope* (VLT) *Multi Unit Spectroscopic Explorer* (MUSE; Bacon et al., 2010) data. Two additional models are also available, one based on **Lenstool** (Jullo et al., 2007b; Sharon et al., 2022a) and the other on **GlaGic** (Oguri et al., 2012). These models, however, do not use the spectroscopic information from MUSE.

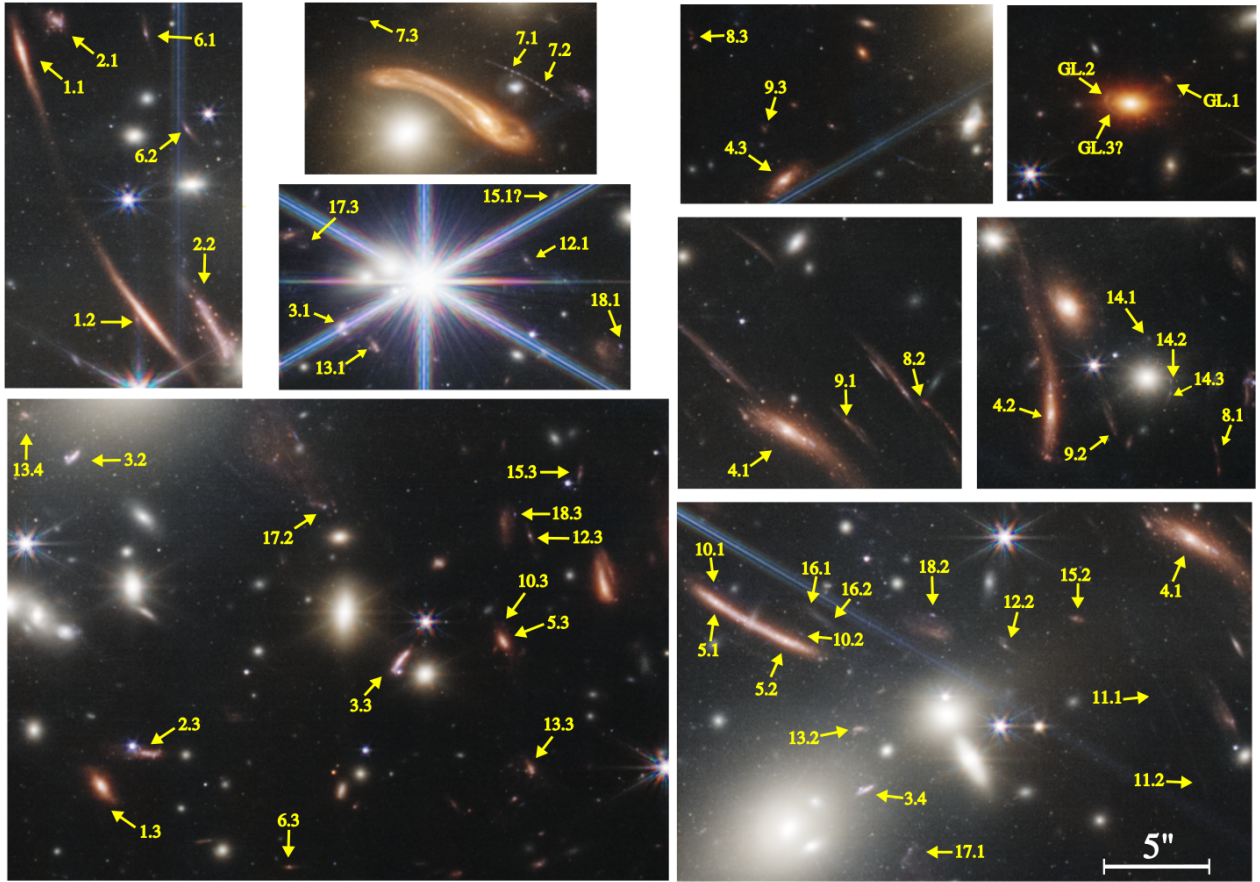


Figure 3.1 Image stamps depicting the 19 image multiplicities in the SMACS0723 field, as labeled. The publicly-available color image of SMACS0723 is depicted, which is valuable for the identification of image family members by their similar colors and morphological components. We also require that the model be able to reproduce the positions of the members of each image family. A $5''$ bar is shown for reference.

This first set of images of SMACS0723 from JWST represents a milestone for not only astronomy, but science in general. As with its predecessor, HST, this first image from JWST reveals the distant universe with incredible detail. Some of the most prominent arcs detected with the HST RELICS program now show multiple unresolved substructures in JWST previously unseen (see for instance system 4 in Figure 3.1). These substructures facilitate the identification of systems of strongly lensed images, where an image system consists of all the gravitationally-lensed counter-images from the same background galaxy. The greater sensitivity of JWST to small flux fluctuations and improved spatial resolution enable searches for the fainter caustic or micro-caustic crossing events of stars at $z < 2$ such as Icarus (Kelly et al., 2018a), or Warhol (Chen et al., 2019b; Kaurov et al., 2019b), stars between $2 < z < 5$

such as Godzilla (Diego et al., 2022a), stars at $z \approx 6$ such as Earendel (Welch et al., 2022b) or even further up to the first stars as proposed in Windhorst et al., 2018a.

JWST is already providing breakthrough results in the study of the most distant galaxies. Pointing JWST towards gravitational lenses results in a more powerful combined telescope with an effective diameter a factor $\sqrt{|\mu|}$ times larger, where $|\mu|$ is the absolute magnification of the lensed background object. For galaxies, typical magnifications can reach factors of a few tens, making the combination JWST+SL cluster similar to a space telescope analogue to JWST but with with 20-30 m diameter. In the context of high- z object detection, the lensed source counts are initially lower than a blank field due to the reduction in search volume from magnification. At the same time, the blank field luminosity function flattens with higher redshift, allowing the number of lensed galaxies to overtake the number of blank field galaxies (*e.g.*, Mahler et al., 2019; Salmon et al., 2020a; Pascale et al., 2022a).

For much smaller background objects like magnified stars near caustics or in general for sub-pc structures near caustics, the underlying magnification factor can be of order ~ 1000 . This translates into effective apertures for JWST of ≈ 200 meters! Even without the ultra-high magnification boosts near the critical lines, SL has allowed us to probe several magnitudes deeper than blank fields, *i.e.*, down to rest-frame UV luminosities $M_{\text{UV}} \lesssim -13$ magnitudes (Bouwens et al., 2017; Bouwens et al., 2022a; Bouwens et al., 2022b; Livermore, Finkelstein, and Lotz, 2017; Atek et al., 2018; Ishigaki et al., 2018; Vanzella et al., 2021) and stellar masses $M_\star \gtrsim 10^6 M_\odot$ (Bhatawdekar et al., 2019; Kikuchihara et al., 2020; Furtak et al., 2021; Strait et al., 2021). With the redder wavelength range, greater sensitivity, and resolving power of the JWST, we can expect many more galaxies at even higher redshifts to be detected in the coming months. In order to fully characterize them and study their physics, it is beneficial to have different models which are constructed in independent works. After this paper was submitted to the archive, we have become aware of two new lens models based on *Lenstool* which include both MUSE spectroscopic redshift constraints and JWST imaging (Mahler et al., 2022; Caminha et al., 2022).

In this paper we identify 14 new image families using the JWST data and present a new *parametric* SL model. The paper is organized as follows: In §3.2 we detail the NIRC*am* imaging and photometry needed to provide constraints for the lens model, which in turn is discussed in §3.3. In §3.4 we present and discuss the results. The conclusion appears in §3.5. Throughout this work we use a Λ CDM cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s $^{-1}$ Mpc $^{-1}$. Unless otherwise stated, we use AB magnitudes (Oke and Gunn, 1983), and errors correspond to 1σ .

3.2 Observations and Data

Observations with the *Near Infrared Camera* (NIRC*am*; *e.g.*, Rieke, Kelly, and Horner, 2005) aboard the JWST were executed as part of the Director’s Discretionary Time on 2022 June 06 (PI: Pontoppidan; Program ID 2736). Exposures were taken in F090W, F150W,

and F200W in the short-wavelength (SW), and F356W, F277W, and F444W in the long-wavelength (LW) channels, totalling 12.5 h of integration time. *Near Infrared Spectrograph* (NIRSpec; Jakobsen et al., 2022) observations were made in the same field as a part of the same program. Two exposures were taken in each of the F170LP and F290LP filters, totalling 11787 sec of integration time in each filter. SMACS0723 was also observed using the *Mid Infrared Instrument* (MIRI; Bouchet et al., 2015; Rieke et al., 2015) and the *Near Infrared Imager and Slitless Spectrograph* (NIRISS; Doyon et al., 2012). The JWST data analyzed in this work can be found on MAST.

The raw data from all four instruments were processed using the JWST science calibration pipeline which performed the background subtraction, flat-fielding, correction for cosmic ray hits, correction for image distortions, re-pixelization by the drizzle approach onto a common astrometric reference frame, co-addition to make the mosaic, and combination into a color image. For the NIRCам data, we reduce the raw data products independently from UNCAL files to i2D mosaics using a custom pipeline based on JWST pipeline version 1.6.2 alongside with the Calibration Reference Data System (CRDS) version 0942. The pipeline includes updates based on on-flight calibrations that account for zero point offsets between the filters and the NIRCам modules (Rigby et al., 2022), critical for accurate photometry and derived properties. Furthermore, this pipeline includes additional steps over the default JWST pipeline to improve on its astrometry and background subtraction. For a detailed description on the additional steps see Adams et al., 2022.

Using the NIRCам images based on our independent reduction with improved calibration, we extract photometry for our targets of interest using forced photometry of small, 0.32 arcsecond diameter circular apertures centered on the peak flux of the target in each band. The photometry is aperture corrected for a point spread function using the simulated point spread functions (PSFs) from WebbPSF (Perrin et al., 2014). This information is then fed into the photometric redshift code LePhare (Arnouts et al., 1999; Ilbert et al., 2006). LePhare operates by fitting a large grid of galaxy spectral energy distributions to the photometry provided. We run LePhare with a suite of galaxy templates from (Bruzual and Charlot, 2003b), allowing for E(B-V) values between 0 and 1.5 (Calzetti et al., 2000), redshifts between 0 and 12 and applying the (Madau, 1995) treatment for absorption from the IGM. The redshifts provided in Table 3.1 are the redshift of peak probability and errors generated from a χ^2 grid produced by LePhare based on the templates, redshifts and dust attenuation combinations available. Several entries are missing values as a result of various sources of contamination or by a lack of detection. We refer to the Appendix for more details. We note that these NIRCам data can be compared with bluer data using HST taken as a part of the RELICS program (PI: D. Coe), and the *Spitzer Space Telescope* (PI: M. Bradac).

We also made use of the available NIRSpec data set. In particular, we analyzed those spectra which were acquired at the positions of our image systems to confirm our image system designations. We refer to §3.1 for more details. We also consulted the MIRI images to test for achromaticity within each of our image systems, for those systems that were detected.

Overall, the arcs in this field make up a rich tapestry of distorted images typical of

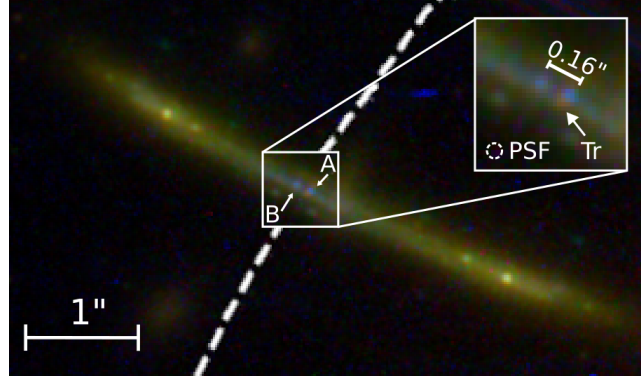


Figure 3.2 Close-up view of system 5 with the $z = 1.43$ critical curve marked in the dashed line on this F090W+F150W+F200W composite color image. Two compact sources in the inset, knots A and B, have a separation of $\sim 0.16''$, and have sizes that are consistent with the width of the PSF. The knots bracket the critical curve that must pass in between them at an angular separation of $\sim 0.08''$. We estimate high magnification factors as a result of this close proximity to the critical curve of $|\mu| \sim 750$ for each source. A red knot is also detected at a position slightly offset from knot A, Tr, which may be a microlensed transient. We refer to §3.4 for more information regarding this potential microlensed transient.

lensed sources and at a level of detail that has never been seen before. The increased spatial resolution reveals lensing constraints even down to the small substructures within the arcs, since many of these small scale sources are equally multiply-imaged, such as the double arc in system 5 (Figs. 3.1 and 3.2). Meanwhile on the scale of the cluster, thanks to the remarkably dark infrared sky background of JWST images, we can get a high signal-to-noise view of the intra-cluster light (ICL). This cluster has an ICL that is elongated and nonuniform. We refer to §4 for a discussion of how the ICL’s relatively unique features suggest that this cluster is not dynamically-relaxed.

3.3 SL modeling of SMACS0723

We generate a new SL model exploiting the JWST data in which we identify the new sets of multiple images, as is described in §3.3. Cluster member galaxies used in the modeling are described briefly in §3.3. The modeling method is described in §3.3.

New multiple images in SMACS0723

We identify new lensing constraints taking advantage of the superior quality of the JWST images. We start by adopting the first five multiple image systems published in Golubchik et al. (2022), following their numbering scheme. These systems serve also as a model-independent guide to search for new systems. For example, galaxies at close projected separations and at

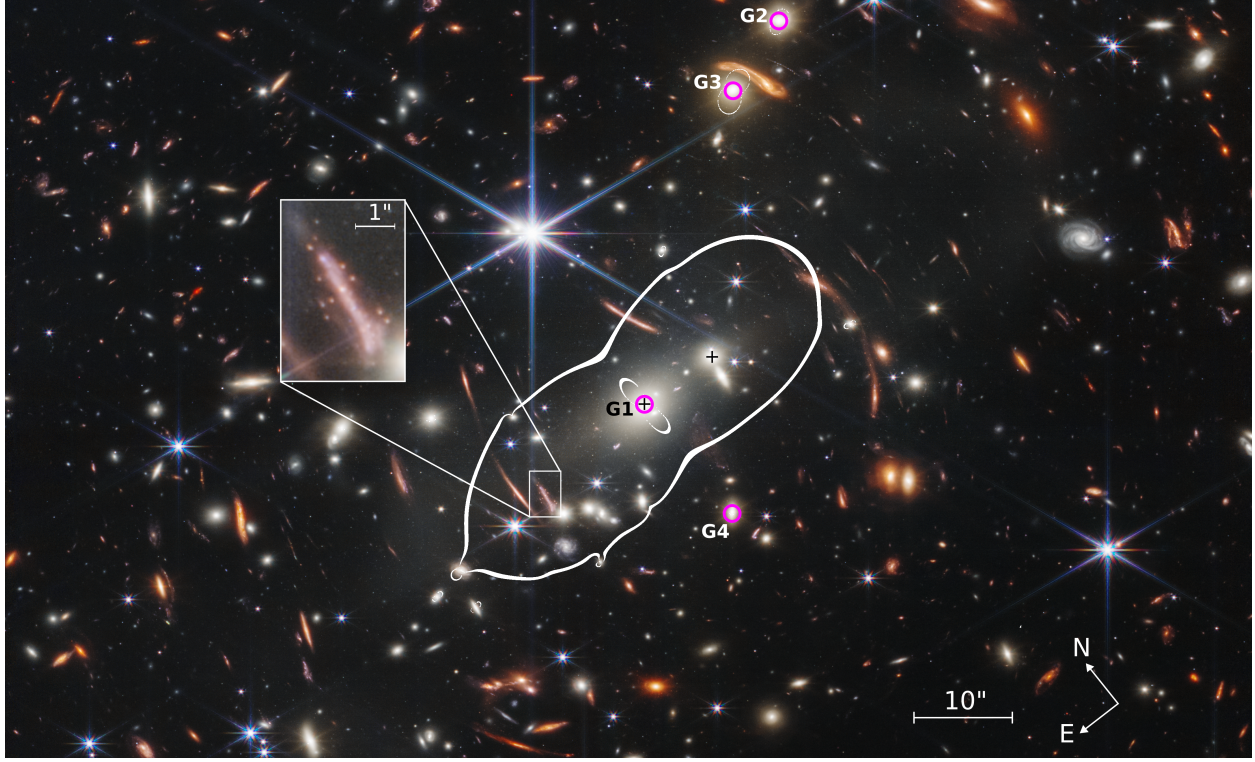


Figure 3.3 Critical curve at $z = 1.45$ from the SMACS 0723 lens model is overlaid as a color composite image generated from the six existing JWST NIRCcam filters depicting the central 1.5 by 1 arcminutes of the cluster. The model incorporates strong-lensing constraints from the 19 image families identified in total, 14 of which are discovered by this work using the JWST data). The two “+” symbols mark the positions of the two dark matter halos used in this model, and the 4 magenta rings mark the galaxies whose weight is left free in the model. Image 2.2 is rare for containing ≥ 10 bright knots located at large projected galactocentric radii (inset).

similar redshifts typically maintain similar spatial distributions when distorted by a gravitational lens. Moreover, amongst the galaxy images, counter images with negative and positive parities are in general symmetric to one another with respect to the critical curve. After visual inspection of the new JWST/NIRCcam image, and corroboration by available photometric and/or spectroscopy redshift constraints and model-predicted locations, we identify 14 new sets of multiply lensed galaxies which are reported in Table 1.

Fortunately, there are spectroscopic redshifts available for some of the image systems. The redshifts of image systems 1, 2, and 5 are $z = 1.450 \pm 0.001$, $z = 1.378 \pm 0.001$ and $z = 1.425 \pm 0.001$, respectively and were measured with MUSE (Golubchik et al., 2022). Note that while JWST/NIRSpec spectroscopic redshifts of 35 galaxies have been reported in this field with redshifts as high as 8.3 as reported by the JWST press release, an investigation of the NIRSpec spectroscopy uncovered spectra for only one of our 42 images from our 19

image families: image 4.1. However, an inspection of the spectrum in each of the spectral band-passes did not produce any significant features that were present in multiple visits and therefore did not yield a redshift. While valuable, further spectroscopic redshifts are however not crucially necessary for securing our image system identifications which relies on a large set of image multiplicities vetted in several ways. We note that NIRISS spectroscopy of SMACS0723 is also available but not used in this study. Its redshift constraints will inform future lens models.

Cluster member galaxies

For our model we use the same the cluster member galaxy selection as in Golubchik et al. (2022), which was based on the red sequence shown therein (their Fig. 4). In addition, we add here 3-4 galaxies not used in the initial model by Golubchik et al. (2022) which lie near the bright star 20'' north of the BCG (which hindered somewhat their previous detection), and are included as they may affect the reproduction of nearby counter images. A revision of this selection using spectroscopic data (such as *e.g.*, the NIRISS data), is deferred to future work.

SL modeling method

The LTM model presented in Golubchik et al. (2022) required a very strong external shear, indicating that the cluster's central mass distribution is highly elongated. Since the LTM approach is limited in the intrinsic matter ellipticity it can accommodate, and for comparison, we make use here of a new, fast parametric method that we recently constructed (A. Zitrin; in preparation; the method can also be referred to as analytic, *i. e.*, it is not limited to a grid's resolution). The method is similar in nature to other parametric lens modeling techniques such as **Lenstool** (Jullo et al., 2007b), **GlaGic** (Oguri et al., 2010) or **GLEE** (Halkola, Seitz, and Pannella, 2006; Grillo et al., 2015). In such parametric methods, dark matter halos can be elliptical which more easily accounts for the required elongation (which is also evident from the distribution of arcs).

The models in our new parametric method have two main components. First, the cluster members galaxies are modeled with double pseudo elliptical mass distributions (dPIE; Elíasdóttir et al. 2007) which are assumed spherically symmetric with the exception of the BCG, and are defined following the prescriptions of Jullo et al., 2007b and Zitrin et al., 2013:

$$\begin{cases} \sigma = \sigma^* (\frac{L}{L^*})^{1/4} \\ r_{cut} = r_{cut}^* (\frac{L}{L^*})^\alpha \\ r_{core} = r_{core}^* (\frac{L}{L^*})^{1/4} \end{cases} \quad (3.1)$$

Where the σ is the velocity dispersion, r_{cut} is the cut-off radius, r_{core} is the core radius, and L^* is the typical luminosity of a galaxy at the cluster redshift. We fix $r_{core}^* = 0.2$ kpc

for all dPIEs, use an L^* equivalent to a galaxy of $m_{F814W}^{ref} = 22.13$, and assume a constant mass-to-light ratio ($\alpha = 0.5$), while σ^* and r_{cut}^* are left free to be optimized by the model.

The second modeling component is the set of cluster DM halos. These can in principle be modeled either as elliptical Navarro-Frenk-White (NFW) profiles (Navarro, Frenk, and White, 1996), or as pseudo elliptical mass distributions (PIEMD; *e. g.*, Monna et al. 2015); or dPIEs. The third and last component which can be added if necessary is a two-component external shear.

The method is similar to our previous parametric implementation outlined in Zitrin et al. (2015b) which has been well vetted, but is not limited to the assigned grid resolution. The new improved version used here has been already applied to various clusters and has also been tested on simulated clusters, accommodating both image- and source-plane minimization. The minimization of the model is done via a Monte-Carlo Markov Chain (MCMC) with a Metropolis-Hastings algorithm (*e. g.*, Hastings, 1970). We include annealing in this procedure, and the chain typically runs for several dozen thousand steps after the burn-in stage. Errors are calculated from the same MCMC chain.

SMACS0723 SL model

For modeling SMACS0723 by this method, we constrain the model using 16 of the 19 identified image systems and a total of 48 images (2 sets of multiple images are used from system 5; see Table 3.1), including spectroscopic redshifts for 3 systems and leaving all other system redshifts to be fit by the model. We represent cluster members as dPIE profiles, as explained above, and the cluster DM halos as PIEMDs (*i. e.*, the main free parameters for each halo aside from the ellipticity and its position, are a core radius and a velocity dispersion). We use two DM halos, centered on the two central galaxies respectively (marked by “o” symbols in Fig. 3.3). We do not incorporate an external shear. Since galaxies can deviate from the assumed scaling relations, we leave the four brightest galaxies to be freely weighted (marked by rings in Fig 3.3), which means each of their velocity dispersions σ is scaled by a weighting parameter optimized by the model (see Table 3.6; G1-G4). The BCG’s ellipticity and position angle are also left free to be optimized by the model. In total, there are 29 free parameters in the model: the normalization for the galaxy velocity dispersion σ^* , the normalization for the galaxy cut-off radius r_{cut}^* , 4 free parameters for each of the 2 dark matter halo PIEMDs, 4 galaxy weights, the BCG ellipticity and position angle, and the 13 redshifts for systems without spectroscopic redshifts. For the lensed sources, each multiply-imaged system should converge to a single position in the source plane. To enforce this constraint, we minimize the differences between the image positions in the source plane following the prescription of Keeton (2010a), which usually converges to a solution relatively quickly and without loss of quality, as shown by Keeton (2010a) in their successful *Hubble Frontier Fields* (HFF; Lotz et al., 2017b) lens models. Given the 48 lensed images, this constraint amounts to 62 SL constraints on the model (two for each lensed image with the exception of one image per multiplicity), which gives a total of 33 degrees of freedom for the model.

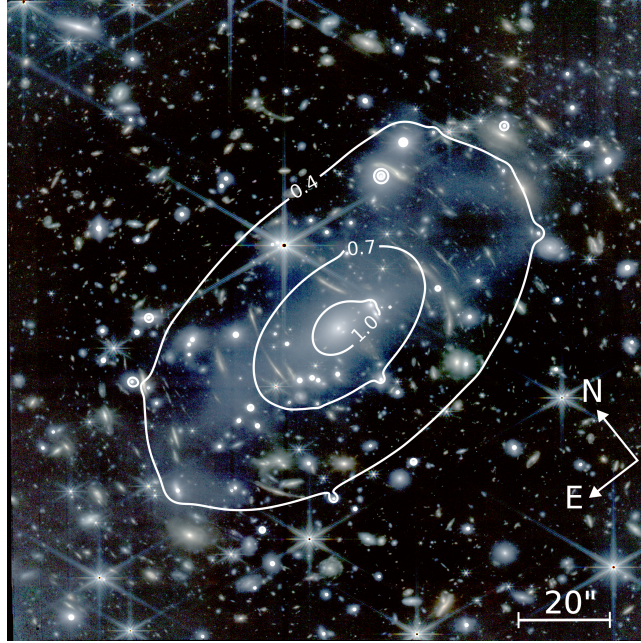


Figure 3.4 The intracluster light for SMACS 0723 in a F277W+F356W+F444W color composite image. The ICL structure is especially clear in F277W and F356W, and is much less prominent in the SW bands. The pronounced ICL extends along the long-axis of the cluster similar to the mass distribution from the lens model, as shown by the overlaid contours of projected mass density κ . Typically a smoothly-varying feature, in SMACS0723 the ICL has significant structures, including a large “loop” feature in the northwest component, and a large lobe-like feature in the southeast component.

3.4 Results and Discussion

The best-fit SL model, which is the one for which χ^2 is minimized, is presented in Fig. 3.3. Critical lines are overlaid for $z_s = 1.45$ (*i. e.*, the redshift of image system 1). The figure illustrates the elongated configuration of SMACS0723. The model was minimized using a positional uncertainty of $\sigma_{pos} = 0.5''$, resulting in a χ^2 of 159.4 ($\chi^2_\nu = 4.8$) in the image plane, and an *rms* of $0.48''$ in reproducing the positions of the multiple images; the optimized model parameters can be found in Table 3.6.

The effective Einstein radius at a given redshift is computed as $\theta_E = \sqrt{A/\pi}$, with A being the area enclosed within the critical curves. At $z = 2$, $\theta_E = 18.4'' \pm 1.8''$, and the mass contained inside the critical curve is $(5.91 \pm 0.83) \times 10^{13} M_\odot$, which is overall consistent with the values of $\theta_E = 16.9'' \pm 2''$, and $M = (4.15 \pm 0.58) \times 10^{13} M_\odot$ obtained in the HST LTM model (Golubchik et al., 2022). The uncertainties on the Einstein radius and mass are similar for each of the models and are limited by the systematics.

The JWST/NIRCam images uncover fine details of the faint substructures within the arcs. In particular, two compact sources in system 5, knots A and B (5.A and 5.B in

Table 3.1), are spatially-resolved on opposite sides of the critical curve, constraining the position of the critical curve in our lens model (Fig. 3.2). The image pair has a close angular separation to the critical curve of $0.08''$, implying extremely high magnifications for each image and making it an ideal system in the search for caustic crossing events. Near to the critical curve, magnification follows an inverse relationship with distance $\mu = \mu_0/D_{crit}$, where μ_0 is dependent on the slope of the lensing potential and can be measured from the lens model (Welch et al., 2022b; Diego, 2019a). Uncertainty in μ_0 is accounted for by sampling the model MCMC chain, while the uncertainty in D_{crit} is assumed to be the uncertainty in the centroid position of the images. Our parametric model implies a magnification of $\mu = 737^{+1553}_{-454}$ for each image, whose positions are reproduced to within $0.02''$ by the model.

Magnification near the critical curve is highly sensitive to systematics, and may vary significantly between modeling approaches (Meneghetti et al., 2017). Meneghetti et al., 2017 demonstrated that the uncertainty in magnification can reach greater than 30% at $\mu > 10$ across all modeling approaches. Hence statistical errors in magnification from the model are most likely underestimate the true error which is dominated by systematics. Assuming these images are unresolved, this magnification could imply parsec or even subparsec sizes for this object. Given the arc’s close proximity to the cluster center, however, microlensing from intracluster stars could work to smooth out the critical curve, placing an upper limit on the persistent magnification possible (Venumadhav, Dai, and Miralda-Escudé, 2017a; Dai, 2021a).

Consider again the image pair consisting of knots A and B in Fig. 3.2. There is a red knot offset from knot A that is detected only in some of the NIRCcam bands, called Tr (see appendix section 3.6). We present the argument that Tr is neither knot A nor knot B. Assuming knots A and B are counter images, the pair will always be detected together in any given band. Since the separation of these mirrored knots is about $0.16''$, which is larger than the FWHM of any JWST filter in this dataset (F444W, FWHM = $0.145''$, is the largest), JWST should be able to spatially resolve this pair. We detect knots A and B in all the SW filters, but detect only a single peak in each of the LW filters near to the position of knot A (see appendix, section 3.6 and Fig. 3.6). Since the image pair is not detected together through the LW filters, this single peak must refer to Tr. Hence, Tr is *distinct* from knots A and B. The lack of a counterimage, and its placement in close proximity to the critical curve, suggest Tr is a microlensing event. However we cannot rule out that it is a red foreground galaxy. Given the very red colors and small angular sizes involved, confirmation of Tr as a transient would require JWST follow-up observations. We note that there are no other similar dual-color detections in any other objects in system 5 that would suggest an image misalignment.

The giant arcs also present some rather unusual features, such as system 2 with a spectroscopic redshift of $z = 1.38$ first measured by Golubchik et al. (2022). Image 2.2 has >10 prominent clumps all of a similar red color and extending to high galactocentric radii (see Fig. 3, inset). While significant sub-kpc structure of star formation regions is not unusual for star-forming galaxies at $z = 1 - 3$ (or even sub-100pc, *e.g.*, Johnson et al. 2017), the very large separations cast some doubt that the extended knots are identical in nature to

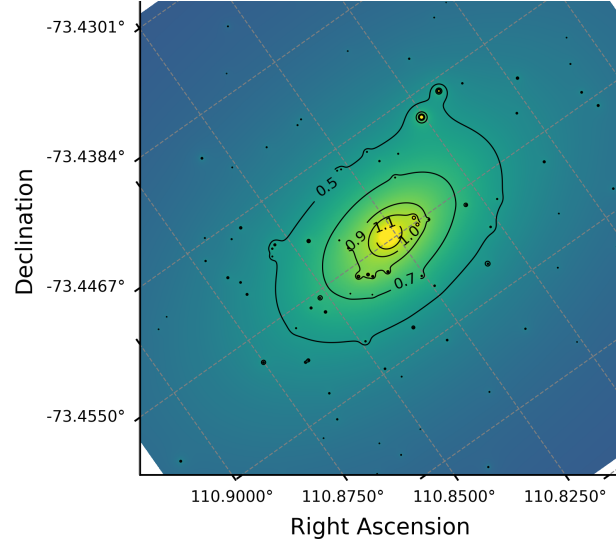


Figure 3.5 Projected mass density of SMACS0723. We show κ , the surface mass density distribution in units of the critical density for strong lensing, for the source redshift of system 1, at $z = 1.45$, plotted on a grid of constant RA and Dec (dashed lines). The resulting mass distribution exhibits a clear ellipticity along the same axis as the ICL as shown in Fig. 3.4

those in what might be the plane of a galactic disk. These clumps also appear to be different (redder) than those typically detected in clumpy galaxies (*e. g.*, Shibuya et al., 2016). The physical characteristics are more consistent with numerical predictions for globular clusters. For example, Sameie et al., 2022 found in hydrodynamic simulations that the longest lived globular clusters likely formed at high redshifts beyond the half-light radius (up to hundreds of parsecs away from their host galaxy). Pozzetti, Maraston, and Renzini, 2019 go on to predict the color evolution for high redshift globular clusters, but also point out that NIR-Cam colors are most likely insensitive to the formation redshift. Vanzella et al. (2017a) have reported detections of candidate young (< 10 Myr) globular clusters which are blue and at high redshifts of $z = 3-6$. Based on this information, it is tempting to speculate that the clumps seen in system 2 may be redder and older ($\sim$ Gyr) counterparts of those young candidate globular clusters detected at the much higher redshifts. Based on SED-fitting from $0.4 - 4.4 \mu\text{m}$, Mowla et al., 2022 found evidence that the clumps were consistent with evolved globular clusters with ages of 3.9–4.1 Gyr, implying formation a mere ~ 0.5 Gyr after the Big Bang. We note that another possible explanation, is that the red clumps fitting the description of those seen in system 2 may arise as a result of ram pressure stripping of dwarf galaxies in the dense environments near in projection to its disk (*e. g.*, Mayer et al., 2006; Boselli, Fossati, and Sun, 2022). Further follow-up, such as detailed source plane reconstruction and photometric SED modeling, is needed to uncover the nature of these sources.

A striking feature of this new JWST/NIRCam image is the morphology of the baryonic

component responsible for the intracluster light (ICL), which exhibits a loop-like feature in the northwest component and a large lobe in the southeast component. We perform our own reduction of the raw images to mitigate the variations in sky background across chips as described in §3.2, although some background noise can also be seen in each of the four corners of the image due to unoptimized sky subtraction in the JWST reduction pipeline (Fig. 3.4). The ICL is due to stars stripped away from their galaxies but still gravitationally bound to the cluster. Earlier work has suggested that the ICL is a good tracer of the DM distribution (or vice-versa) since both stars in the ICL and DM are expected to behave as collisionless particles and thus respond only to gravity (Montes and Trujillo, 2018). Our initial SL model exhibits a similar macro-structure to the ICL as seen in Fig. 3.4. The ICL also extends beyond the current set of SL constraints, but in combination with weak lensing derived from the JWST images it should be possible to produce a lens model that covers the entire range of the ICL in a way that gives insights as to the intriguing apparent correlation between the ICL and the DM distribution. In particular, the presence of these large-scale features in the ICL may motivate detailed simulations to examine the merging scenarios that constrain the time since the major merger and estimate the relative velocities involved.

We note that after this paper was submitted to the archive, and prior to submission to ApJ, we have become aware of two other papers on SL modeling in this field (Mahler et al., 2022; Caminha et al., 2022). There are some differences in the results presented in these other papers, but we have checked and found that including their results into our lens model does not alter the results of this study.

3.5 Summary

We presented a new JWST parametric model for the massive cluster SMACS0723, incorporating new multiple image family constraints identified in the JWST press-release color image and in the NIRCam data set. Our model builds upon the existing lens models (Golubchik et al., 2022) by increasing the SL constraints with 14 newly identified image families, which represents a factor of three improvement over the HST model. This parametric model has a large impact because it provides a starting point for modeling SL clusters in the era of JWST. The mass map reveals a somewhat complex and extended mass profile and, in the detection of the image pair knots A and B opposite the critical curve in system 5, also opens a route to the study of caustic transients in the discovery of an apparent microlensed transient adjacent to knot A. The ICL has a shape that is broadly-similar to that of the galaxies and the model, but with rare larger-scale features that appear to retain the memory of its dynamical history, a question which can be investigated further with numerical simulations. In the future, spectroscopic and photometric redshifts will bolster the reliability of our lens model, allowing also a more precise placement of the critical curve needed to engage in caustic transient studies.

3.6 Appendix

Arc systems in SMACS0723

We present the list of all multiply-imaged systems below. The image families are vetted in multiple ways: by their similar morphological components, similar colors, similar redshifts (photometric and/or spectroscopic), and/or consistency with the lens model. The IDs are given in the first column, where the “?” indicates an image member candidate, by which we mean that it fails one or more of the above criteria, or there is more than one candidate that fits these criteria. The photometric redshift estimates, z_{NIRCam} , are computed using the SED fitting code *LePhare*, as discussed in the main text, with matched-aperture photometry of the six bands of NIRCam imaging as described in Adams et al., 2022. An entry has no z_{NIRCam} value if the lensed source was significantly contaminated by a stellar diffraction spike, a bright cluster member galaxy or other projection effects, or if it was too faint to be detected in two or more of the NIRCam bands. The model-predicted redshifts, z_{model} and z_{NIRCam} are in relative agreement with the exception of five systems. The discrepancies in systems 3, 4, 12, and 15 can be attributed to a degeneracy in the SED fitting for $z=6-7$ and $z=1.5-2.5$, which comes as a result of the Lyman Break and Balmer Break both falling between F090W and F150W at these redshifts respectively. The inclusion of F115W could break this degeneracy in most cases, and may be necessary for any future surveys of the redshift distribution of background galaxies. The other outlier is image 16.1, for which $z_{NIRCam} - z_{model} > 3\sigma$. This system is faint and elongated, and is most likely not well represented by the $0.32''$ circular aperture imposed on these data, in addition to being contaminated by the ICL. We also note that the lens models are limited by the arc systematics. Lens predictions may change as image system constraints become improve, for example by the measurement of new spectroscopic redshifts.

Image Pair in System 5

Knots A and B of system 5 are counterimages which are situated opposite the critical curve and thus likely highly magnified. As shown in Fig. 3.6, the image pair appears in each of the SW filters and is spatially resolved, with an angular separation of $\sim 0.16''$. In SW filter F200W, the microlensed transient, Tr, is detected as well; it is bright and offset from the position of knot A, resulting in the red knot seen in Fig. 3.2. In the LW filters, the knots A and B drop out, leaving only the redder Tr visible as a single peak.

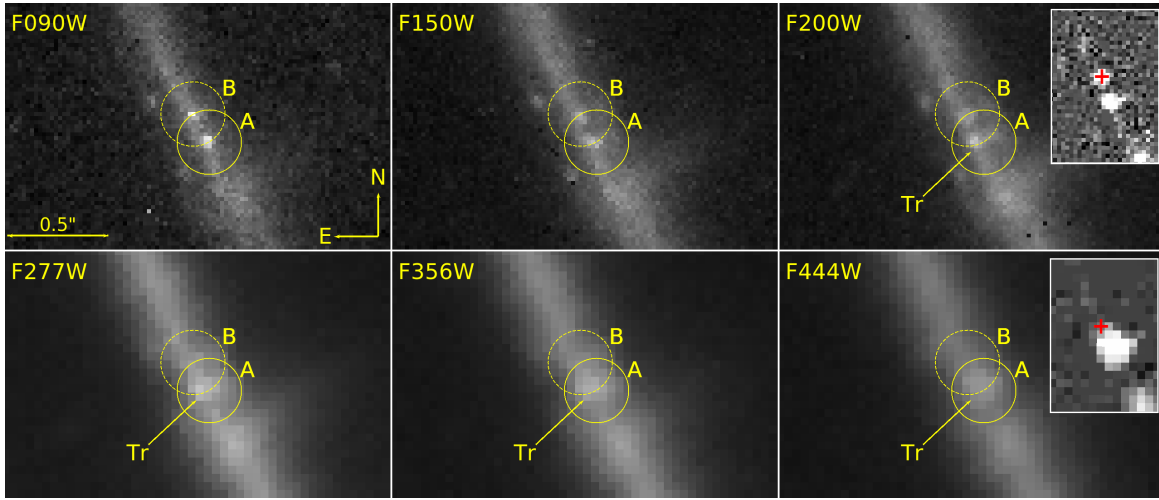


Figure 3.6 The image pair A and B of system 5 across all six available JWST filters. In each filter we center on the positions of A and B with rings of radius $0.16''$, which is roughly equal to their angular separation. The F090W, F150W, F200W filters exhibit two separate knots consistent with the marked positions of A and B. F200W, however, also shows the bright source Tr that is slightly offset from the position of knot A. Only a single peak is detected in each of the LW filters, which is also slightly offset from the position of knot A. The insets depict the F200W and F444W images with the diffuse arc background subtracted off and the position of knot B indicated by a “+” sign. Since knot A and knot B are counterimages of one another and must appear together, the Tr object seen in F200W and the LW filters is instead understood to be a candidate microlensing event.

Table 3.1 List of arc systems

ID ^a	R.A. J2000.0	Decl. J2000.0	z_{NIRCam}^b	z_{model}
1.1	07:23:21.8012	-73:27:03.467	1.45 ^c	
1.2	07:23:22.3430	-73:27:17.077	1.45 ^c	
1.3	07:23:21.4174	-73:27:31.329	1.45 ^c	
2.1	07:23:21.3288	-73:27:03.369	1.38 ^c	
2.2	07:23:21.8238	-73:27:18.337	1.38 ^c	
2.3	07:23:20.8184	-73:27:31.378	1.38 ^c	
3.1 ^e	07:23:19.3406	-73:26:54.554	—	1.81 [1.65 – 1.91]
3.2 ^e	07:23:19.6709	-73:27:18.562	—	”
3.3 ^e	07:23:18.0861	-73:27:34.507	6.65 ^{+0.05} _{-0.06}	”
3.4 ^e	07:23:17.6180	-73:27:17.238	—	”
4.1	07:23:13.3027	-73:27:16.373	6.64 ^{+0.03} _{-0.05}	2.02 [1.94 – 2.48]
4.2	07:23:13.7402	-73:27:30.116	2.16 ^{+4.54} _{-0.67}	”
4.3	07:23:15.2214	-73:26:55.308	2.20 ^{+4.46} _{-0.17}	”
5.1	07:23:17.7775	-73:27:06.454	1.43 ^c	
5.2	07:23:17.4012	-73:27:09.692	1.43 ^c	
5.3	07:23:17.0777	-73:27:36.422	1.43 ^c	
5.A	07:23:17.5937	-73:27:08.213	1.43 ^c	
5.B	07:23:17.6067	-73:27:08.073	1.43 ^c	
!6.1	07:23:20.6382	-73:27:06.170	2.66 ^{+0.04} _{-1.48}	1.44 [1.27 – 2.02]
!6.2	07:23:20.8642	-73:27:10.805	1.37 ^{+1.29} _{-0.23}	”
6.3	07:23:20.2857	-73:27:39.168	—	”
7.1	07:23:10.9765	-73:26:54.832	—	6.27 [2.95 – 8.38]
7.2	07:23:10.7520	-73:26:56.676	—	”
7.3	07:23:11.9016	-73:26:49.389	3.66 ^{+0.04} _{-0.91}	”
8.1	07:23:12.6279	-73:27:36.552	—	5.93 (> 4.67)
8.2	07:23:11.9399	-73:27:19.101	—	”
8.3	07:23:15.1738	-73:26:48.223	6.26 ^{+0.18} _{-0.1}	”
9.1	07:23:12.7404	-73:27:17.641	2.69 ^{+0.11} _{-0.03}	2.90 [2.57 – 3.14]
9.2	07:23:13.2719	-73:27:32.036	—	”
9.3	07:23:15.0263	-73:26:53.194	1.72 ^{+0.28} _{-0.04}	”
10.1 ^d	07:23:17.6727	-73:27:06.073	1.22 ^{+1.42} _{-0.05}	
10.2 ^d	07:23:17.2165	-73:27:09.979	1.26 ^{+1.41} _{-0.06}	
10.3 ^d	07:23:16.9616	-73:27:36.214	1.19 ^{+0.09} _{-0.10}	
11.1	07:23:14.4676	-73:27:21.001	—	1.66 [1.22 – 1.98]
11.2	07:23:14.6783	-73:27:25.882	—	”
12.1	07:23:17.3278	-73:26:56.724	—	1.56 [1.52 – 1.71]
12.2	07:23:15.5468	-73:27:15.540	6.75 ^{+0.05} _{-0.05}	”
12.3	07:23:16.2054	-73:27:33.241	6.79 ^{+0.03} _{-0.02}	”
13.1	07:23:19.1576	-73:26:56.027	1.73 ^{+1.03} _{-0.03}	2.34 [2.29 – 2.77]
13.2	07:23:17.3314	-73:27:14.825	—	”
13.3	07:23:17.6167	-73:27:41.842	2.69 ^{+0.05} _{-1.02}	”
13.4	07:23:19.8353	-73:27:15.697	—	”

Table 3.1. Cont.

ID ^a	R.A J2000.0	DEC. J2000.0	z_{NIRCam}	z_{model}
14.1 ^d	07:23:12.4242	-73:27:29.857	—	1.83 [1.68 – 2.03]
14.2 ^d	07:23:12.4965	-73:27:31.974	—	”
14.3 ^d	07:23:12.5821	-73:27:32.465	—	”
15.1 [?]	07:23:16.7116	-73:26:55.135	—	2.21 [1.67 – 2.29]
15.2	07:23:14.7745	-73:27:16.356	$6.59^{+0.05}_{-0.07}$	”
15.3	07:23:15.4182	-73:27:32.298	$2.30^{+0.06}_{-0.20}$	”
16.1	07:23:16.9967	-73:27:09.328	$0.29^{+0.06}_{-0.07}$	1.07 [0.82 – 1.04]
16.2	07:23:16.9296	-73:27:10.256	—	”
17.1	07:23:17.5975	-73:27:20.571	$2.34^{+0.31}_{-0.10}$	1.72 [1.68 – 1.92]
17.2	07:23:17.7931	-73:27:26.849	—	”
17.3	07:23:19.1779	-73:26:50.524	—	”
18.1	07:23:17.2313	-73:27:02.060	—	1.33 [1.24 – 1.37]
18.2	07:23:16.0440	-73:27:13.482	—	”
18.3	07:23:16.3551	-73:27:32.183	—	”
GL.1 ^d	07:23:21.8176	-73:27:41.814	—	1.31 [1.15 – 1.58]
GL.2 ^d	07:23:22.4453	-73:27:40.964	$1.49^{+0.88}_{-0.13}$	”
GL.3 [?] ^d	07:23:22.4781	-73:27:41.727	$1.49^{+0.88}_{-0.13}$	”
Einstein cross	07:23:02.7975	-73:27:08.814		

Note. — *Column 1*: ID; *Columns 2 & 3*: Right Ascension and Declination; *Column 4*: Redshift. For systems 1, 2 and 5 we quote the spectroscopic redshift from MUSE (Golubchik et al., 2022), and note that the NIRISS spectrum for system 1 confirms the stated redshift. *Column 5*: The redshift of the system as predicted from the SL model. Candidate images whose identification is not secure are marked with “?”. Note that these were therefore not used in the minimization.

^aThe first five image systems are drawn from Golubchik et al. (2022).

^bThese are the photometric redshift estimates using the six bands of NIRCam imaging.

^cThese redshifts are spectroscopic values from Golubchik et al. (2022).

^dThese systems were not used to constrain the parametric SL model, but were confirmed in the WSLAP+ model.

^eMahler et al., 2022 find a spectroscopic redshift of 1.99 for this system using MUSE, but this is not included in the model.

Table 3.2. SL Model Optimized Parameters

	e	$\theta[^\circ]$	$\sigma[kms^{-1}]$	$r_{cut}[kpc]$
Main DM Halo	$0.46^{+0.07}_{-0.05}$	$0.12^{+0.02}_{-0.02}$	$1276.50^{+60.28}_{-76.43}$	$84.43^{+7.32}_{-6.90}$
West DM Halo	$0.36^{+0.33}_{-0.25}$	$0.29^{+0.26}_{-0.16}$	$52.98^{+41.18}_{-41.04}$	$14.91^{+10.25}_{-10.55}$
BCG	$0.16^{+0.10}_{-0.09}$	$17.09^{+2.05}_{-2.41}$	—	—
Scalings ^a	$N_{gal} = 133$	$m_{F814W}^{ref} = 22.13$	$\sigma^* = 101.44^{+15.08}_{-16.10}$	$r_{cut}^* = 48.45^{+7.05}_{-6.37}$
Weights ^b _{gal}	$G1 = 1.87^{+0.10}_{-0.11}$	$G2 = 1.34^{+0.48}_{-0.31}$	$G3 = 1.64^{+0.27}_{-0.29}$	$G4 = 0.91^{+0.11}_{-0.15}$

Note. — *Column 1*: Object; *Column 2*: Ellipticity; *Column 3*: Position Angle; *Column 4*: Velocity Dispersion. *Column 4*: Cutoff Radius. All errors are given as the 68.3% Confidence Interval.

^aThe scaling relations for all galaxies.

^bWeights for the four galaxies allowed to deviate from the scaling relations, as labeled in Fig. 3.3.

Chapter 4

Dense, Nitrogen Enriched Clouds in a Cosmic Noon Super Star Cluster

The content of this chapter is drawn from Pascale et al., 2023, with permission from the co-authors.

4.1 Introduction

Massive star clusters represent the most prominent mode of star formation across cosmic history (Adamo and Bastian, 2018). In the hierarchical picture of star formation, massive clusters are considered to be the natural precursors of globular clusters (Kruijssen et al., 2019; Krumholz, McKee, and Bland-Hawthorn, 2019a). Understanding the internal dynamics of massive clusters during their formation and evolution episodes is crucial to properly answering many other important questions in astrophysics. Strong stellar feedback from young stars in massive clusters in the form of winds (Silich, Tenorio-Tagle, and Rodríguez-González, 2004a; Geen et al., 2021; Lancaster et al., 2021), radiation pressure (Murray, Quataert, and Thompson, 2010a; Kim, Kim, and Ostriker, 2018; Kim, Kim, and Ostriker, 2019; Menon, Federrath, and Krumholz, 2022a; Menon, Federrath, and Krumholz, 2022b), and supernova explosions (Walch and Naab, 2015) are known to regulate star formation and drive outflows on galactic scale. In addition, the extremely high stellar densities at the cores of massive clusters are conducive to stellar collisions and merging, a potential channel for seeding the formation of supermassive black holes (Portegies Zwart et al., 2004; Davies, Miller, and Bellovary, 2011) and making gravitational wave sources (Banerjee, 2017; Banerjee, 2018; Antonini, Gieles, and Gualandris, 2019; Rodriguez et al., 2019). During the epoch of reionization, very young massive star clusters are capable of releasing escaping Lyman continuum radiation to the intergalactic medium (IGM) and might make an important contribution to cosmic reionization (Vanzella et al., 2020a).

With high-density birth environments being rare in our cosmic backyard, well-resolved dense star clusters of a few million years old are uncommon in the Local Group. A short list

of examples include Westerlund 1 (Portegies Zwart, McMillan, and Gieles, 2010; Gennaro et al., 2017) and Westerlund 2 (Ascenso et al., 2007), the Arches (Espinoza, Selman, and Melnick, 2009; Harfst, Portegies Zwart, and Stolte, 2010), the Quintuplet (Figer, McLean, and Morris, 1999), and R136 in the Large Magellanic Cloud (Andersen et al., 2009; Cignoni et al., 2015; Crowther et al., 2016). These have relatively small stellar masses $M_\star \sim 10^4\text{--}10^5 M_\odot$. More massive systems $M_\star \sim 10^5\text{--}10^6 M_\odot$, either exposed or obscured by gas, are more frequently found in nearby dwarf or massive starburst galaxies, such as in NGC 5253 (Gorjian, Turner, and Beck, 2001; Turner et al., 2015), NGC 1569 (Ho and Filippenko, 1996), M82 (McCrady and Graham, 2007) and Henize 2-10 (Chandar et al., 2003). Recently, super star clusters with masses $M_\star = 10^6\text{--}10^7 M_\odot$ were also observed in the nuclear region of NGC 1365 with the James Webb Space Telescope (Whitmore et al., 2022). Remarkably, extragalactic observations aided with strong gravitational lensing have revealed that very massive $M_\star \gtrsim 10^6\text{--}10^7 M_\odot$ yet compact young systems appear commonplace in high-redshift star-forming galaxies (Vanzella et al., 2017b; Vanzella et al., 2022a). Strongly lensed systems hence offer a unique opportunity for studying clustered star formation at the highest densities.

In this work, we scrutinize a young massive star cluster found in the Sunburst Arc at $z_s = 2.369$. The lensed galaxy was first discovered by Dahle et al., 2016 behind the galaxy cluster PSZ1 G311.65-18.48 (Planck Collaboration et al., 2014). It is the brightest known gravitationally lensed starburst galaxy at Cosmic Noon. A lensed compact star-forming clump was found on the arc, which shows twelve different lensed avatars arising from an Einstein ring configuration disrupted by secondary lensing caustics cast by multiple cluster member galaxies (Rivera-Thorsen et al., 2019; Pignataro et al., 2021; Diego et al., 2022b; Sharon et al., 2022b).

The clump appears to be a super star cluster of about 3 Myr old (Chisholm et al., 2019). Remarkably, optically thin channels must have been carved out through the surrounding interstellar medium (ISM), as both triple-peaked $\text{Ly}\alpha$ line radiation (Rivera-Thorsen et al., 2017) and escaping Lyman continuum (LyC) radiation (Rivera-Thorsen et al., 2019) were detected from the super star cluster (hence we refer to it as the LyC cluster throughout this paper), with a high escape fraction $f_{\text{esc}} = 40\text{--}90\%$ along the line of sight (Rivera-Thorsen et al., 2019). High signal-to-noise ratio spectroscopy (Mainali et al., 2022) revealed evidences that the system drives outflowing nebular gas at $\sim 300 \text{ km s}^{-1}$, more dramatically so than in other Sunburst systems which do not allow LyC photons to escape. Mestric et al., 2023 suggest that a few dozen $> 100 M_\odot$ very massive stars aggregate at the cluster center from which escaping LyC photons appear to originate, and can account for the observed broad He II $\lambda 1640$ emission.

Since the LyC cluster is a fantastic example of clustered massive star formation and evolution at Cosmic Noon and probably resembles the exposed LyC sources that have reionized the intergalactic medium (IGM) at $z = 6\text{--}15$, much efforts have been made to understand its physical properties and the host galaxy. Rest-frame UV spectroscopy compared the LyC cluster of Sunburst to Starburst99 spectral models (Leitherer et al., 1999) and inferred a cluster age $\sim 3 \text{ Myr}$ from the broad He II $\lambda 1640$ emission, a moderately sub-solar stellar

metallicity $Z = 0.5\text{--}0.6 Z_{\odot}$ from the presence of C IV $\lambda 1550$ P Cygni stellar wind feature, and a moderate amount of dust reddening $E(B - V) = 0.15$ (Chisholm et al., 2019).

Vanzella et al., 2020a suggests that the LyC cluster spectrally resembles other known compact LyC leaking systems and should have an important contribution to cosmic reionization through holes created by stellar feedback. The cluster is shown to have strong emissions of (semi-)forbidden UV lines from O III, C III, Si III and Ne III (Vanzella et al., 2020c). Using multi-filter HST images to model the cluster SED and employing a detailed gravitational lensing model, Vanzella et al., 2022b concluded that the cluster is impressively massive $M_{\star} \approx 10^7 M_{\odot}$ yet compact $R_e \simeq (8 \pm 3)$ pc. From emission line widths they derived a line-of-sight velocity dispersion $\simeq 40 \text{ km s}^{-1}$, which suggests that the cluster is gravitationally bound. The authors also suggested that the host galaxy has a high specific star formation rate $\text{sSFR} \gtrsim 10 \text{ Gyr}^{-1}$.

In this work, we extract physical parameters describing the intriguing LyC cluster system and reliably estimate their uncertainties, by performing an independent spectral analysis using archival HST images and ground-based VLT/MUSE and VLT/X-shooter spectroscopy data. While the datasets we use (more details in Section 5.2) are not new to what were used in the aforementioned studies, we present independent multi-filter photometry and emission line flux measurements. We then construct a physical model for the star cluster and the surrounding photoionization nebula based on the BPASS synthetic spectra (Stanway, Eldridge, and Becker, 2016; Eldridge and Stanway, 2016) for young stellar populations, and perform photoionization calculations using Cloudy (Ferland et al., 2017).

Our spectral modeling improves upon previous efforts in the following ways. First, we self-consistently account for the density dependence of nebular observables by imposing the more realistic isobaric condition (Draine, 2011a; Kewley et al., 2019) in Cloudy calculations. This is crucial as we find a highly pressurized component ($n_e \sim 10^5 \text{ cm}^{-3}$) in the photoionized nebula as deduced from C III] $\lambda\lambda 1906, 1908$ and Si III] $\lambda\lambda 1883, 1892$ line ratios.

Moreover, we account for nebular continuum radiation powered by radiative recombination in the photoionized gas, which is substantial for systems younger than 5 Myr (Reines et al., 2010; Byler et al., 2017). On one hand, the superposition of nebular continuum on top of the direct star light changes the apparent UV spectral slope and is crucial for our conclusion that dust reddening from the host ISM is small $E(B - V) < 0.05$. On the other hand, the nebular continuum is proportional to the fraction of stellar ionizing radiation absorbed by the photoionized clouds; it enables us, when combined with nebular line strengths, to infer an isotropic LyC escape fraction $f_{\text{esc}} = (35 \pm 20)\%$ from the cluster vicinity. Furthermore, our inference of a higher line-of-sight escape fraction $(50 \pm 20)\%$ is a hint that we are seeing exposed cluster stars through an optically thin channel.

Since photoionized clouds may have an anisotropic distribution around the cluster, our model is flexible to account for the spectral difference between illuminated cloud faces and shaded faces. This can be important for hydrogen Balmer lines due to optical depth effect from a large H I column, and for extinction of UV-to-optical continuum and lines by dust in the cloud interior. This probes the geometric distribution of photoionized clouds located on the near side versus on the far side of the stars relative to our viewing angle.

We furthermore use emission lines to measure element abundances for C, N, Ne and Si. From the detection of unusually strong N III] $\lambda\lambda 1750, 1752$, we measure a remarkable N/O ratio enhanced by ~ 12 – 19 fold in the highly-pressurized clouds compared to what is expected for ISM at sub-solar metallicities. Knowledge of chemical anomalies informs us of the physical origin of the clouds, and provides clues to whether they might give birth to chemically self-enriched stellar population observed in evolved massive star clusters (i.e. globular clusters) (Bastian and Lardo, 2018). We also infer a depletion of gas-phase Si by ~ 4 – 5 fold, which indicates internal grain formation. Curiously but consistent with many other observations of high- z blue starburst systems, no strong dust reddening along the line of sight is seen from the host galaxy’s large-scale ISM.

Based on our analysis, we depict the following physical picture for the star cluster and its surroundings as illustrated by Figure 4.1. A young cluster of $t_{\text{age}} \lesssim 4$ Myr and sub-solar gas-phase metallicity $Z \approx 0.2$ – $0.3 Z_{\odot}$ consists of a compact central component and a subdominant extended component. Intense stellar radiation pressurizes nearby photoionized gas to $P = \text{a few} \times 10^9 \text{ K cm}^{-3}$ at several parsecs, while dust grains form inside these dense clouds. The clouds are significantly enriched with nitrogen and hence an order-unity mass fraction must have originated from massive star ejecta (Roy et al., 2022), perhaps through a mechanism of slow mass loss. Under irradiation by stars, these clouds glow in strong emission lines, processing $\sim 40\%$ of the cluster’s LyC output. These clouds might linger for a time much longer than the free-fall time in the cluster’s gravitational potential well, probably because they have large enough column densities $N_{\text{H}} > 10^{22.8} \text{ cm}^{-2}$ to counter ejection by radiation pressure. Some other $\sim 20\%$ of the cluster’s LyC output might be processed by lower-pressure photoionized clouds further from the cluster center, but those do not appear to have significant nitrogen enrichment. The remaining $\sim 40\%$ of the LyC radiation, together with the hot cluster gas, stream out of the system without obstruction through preferentially optically thin, low density channels.

The rest of the paper is organized as the following. In Section 5.2 we summarize the archival imaging and spectroscopy data used in our analysis. In Section 6.4 and Section 6.5, we provide details on how HST filter magnitudes and emission line fluxes are measured. In Section 4.5, we employ stellar population synthesis and photoionization calculations to construct a grid of spectral models for the composite emission from the star cluster and its surrounding nebula. We then fit our spectral models to data, and present Bayesian parameter inference results in Section 6.9. We give physical interpretation of the results in Section 7.4, and give concluding remarks in Section 7.5.

4.2 Data

In this section, we summarize the archival data used in this work: HST imaging data, VLT/MUSE IFU spectroscopy, and VLT/X-shooter slit spectroscopy.

HST Imaging

Observations for PSZ1 G311.65-18.48 were obtained across multiple programs between 2018 and 2020 (P.I. Dahle Program ID 15101, P.I. Gladders Program ID 15949, P.I. Bayliss Program ID 15377). In this work, we make use of observations publicly available on the MAST archive for 15 filters: WFC3/UVIS F390W, WFC3/UVIS F410M, WFC3/UVIS F555W, WFC3/UVIS F606W, ACS/WFC F814W, WFC3/UVIS F098M, WFC3/IR F105W, WFC3/IR F125W, WFC3/IR F126N, WFC3/IR F128N, WFC3/IR F140W, WFC3/IR F153M, WFC3/IR F160W, WFC3/IR F164N, WFC3/F167N. All UVIS+WFC images were aligned to a common pixel scale of 30 mas/pixel, while all IR images were aligned to a pixel scale of 60 mas/pixel using the astropy `reproject` package in combination with `astroalign` (Beroiz, Cabral, and Sanchez, 2020).

VLT/MUSE IFU Spectroscopy

We use archived and reduced MUSE IFU science datacubes directly accessed from the ESO archive¹. Two datacubes are used, which cover the observed wavelength range 475–935 nm at $R \approx 2600$ –3000 and were calibrated and reduced with the standard reduction pipeline: one from observations conducted on May 13 and Aug 24 in 2016 (Program 107.22SK; PI: E. Vanzella; total exposure 4449 s), and another from observation on Aug 10, 2021 (Program 297.A-5012; PI: N. Aghanim; total exposure 2808 s). All MUSE IFU observations were carried out in the Narrow Field Mode under a typical seeing condition $\text{FWHM} = 0.5$ – $0.6''$, achieving a sky resolution 1.4– $2''$.

VLT/X-shooter Slit Spectroscopy

We use ESO archived science data products of X-shooter slit spectroscopy reduced with the standard reduction pipeline. Data were collected from Program 0103.A-0688 (PI: E. Vanzella). Exposures were obtained under typical seeing conditions $\text{FWHM} \sim 0.5$ – $0.6''$. Slit spectra covering observed 994–2479 nm ($R \approx 8000$) are used for extracting fluxes for rest-frame NUV and optical emission lines, while additional spectra covering observed 534–1020 nm ($R \approx 11000$) are used for cross-checking strong FUV emission lines. For accessing spatially resolved spectral information, we carry out flux calibration of the 2D spectra using the flux-calibrated and flux-uncalibrated 1D spectra, and then extract fluxes at the location of the target objects.

4.3 Photometry

We measure the PSF of each HST image using the `photutils` package by stacking isolated, unsaturated stars across the image. An initial catalog of stars is generated using

¹<http://archive.eso.org/scienceportal/home>

`DAOStarFinder` following Stetson, 1987, and then each star is vetted by eye to be isolated and unsaturated, resulting in a final catalog of dozens of stars. The final star list is extracted into centered cutouts which are normalized and median-subtracted to mitigate sky background, and the cutouts are stacked into an oversampled PSF using the `EPSFBuilder` function. PSFs in the ACS filters were oversampled by a factor of 8, while WFC3 were only oversampled by a factor of 4 due to the lower native resolution. We found using stars throughout the entire image rather than those local to the LyC image produced more accurate PSFs, owing to the nearly a factor of 10 greater number of stars available.

Image 9

There are a total of 12 lensed images of the LyC cluster available for analysis (Rivera-Thorsen et al., 2019). Those have different magnification factors and are contaminated to various degrees by other sources on the arc. We perform PSF photometry on Image 9 (following designation of Rivera-Thorsen et al., 2019) using `Galfit` (Peng et al., 2002). We choose Image 9 due to its separation from other bright LyC images and neighboring galaxies, as well as its moderate brightness relative to other LyC images. The brightest lensed images, which are the most magnified, are generally poorly approximated by a PSF (Image 10 is an example), whereas the fainter images have lower SNRs - Image 9 offers a compromise between these two effects. For Image 9, we simultaneously model both the LyC cluster and the neighboring lensed knots as point-like objects in `Galfit`, and approximate the underlying diffuse arc background as having a flat surface brightness. To mitigate large-scale variations in the diffuse background, we first mask out fainter pixels with brightness $< N\sigma$ to fit only the lensed arc, where σ is the noise standard deviation of local sky background and N is a factor of order dozens chosen by eye on an image-to-image basis. We found that different choices for N caused small changes in the measured flux, and adjust the errors accordingly. We assign minimum errors of 0.05 and 0.1 magnitudes in the WFC3/UVIS+WFC/ACS and WFC3/IR bands respectively to broadly account for systematics. Our photometry results are reported in Table 5.3.

Image 10

Because of the higher magnification factor, an extended continuum component of the LyC cluster appears resolved in Image 10 (Vanzella et al., 2020a; Mainali et al., 2022), in addition to a bright central component. While the central component appears well-approximated by the PSF, the extended component extends $\sim 0.4''$ along the direction of the arc. The magnification in the radial direction, μ_r , is expected to be of order unity (see §7.1), such that the extended component is only resolved in the tangential direction. Hence we choose a 1D Gaussian convolved with the PSF to approximate the light profile of the extended component. Retaining the same masking approach for the arc background used for image 9, we spatially fit a 1D Gaussian for the extended component, an unresolved central component, and the arc background simultaneously using `PyMultinest` Feroz, Hobson, and Bridges, 2009; Buchner

Table 4.1 Photometry for lensed Image 9 and Image 10 of the LyC cluster.

Filter	Img. 9	Img. 10 central	Img. 10 extended	Comment
F275W	26.62 ± 0.05	25.27 ± 0.05	> 28.6	Rest-frame LyC; no extended component and not included in analysis
F390W	23.03 ± 0.05	22.09 ± 0.05	22.74 ± 0.05	Affected by Ly α and damping wings; not included in analysis
F410M	22.88 ± 0.05	22.04 ± 0.05	22.29 ± 0.05	Strongly affected by Ly α and damping wings; not included in analysis
F555W	22.95 ± 0.05	21.91 ± 0.05	22.56 ± 0.05	
F606W	22.91 ± 0.05	21.92 ± 0.05	22.46 ± 0.05	
F814W	23.10 ± 0.05	22.14 ± 0.05	22.57 ± 0.05	
F098M	23.10 ± 0.07	—	—	
F105W	23.01 ± 0.10	—	—	
F125W	23.05 ± 0.10	—	—	
F126N	22.50 ± 0.20	—	—	Strongly enhanced by [O II] $\lambda\lambda 3727, 3729$
F128N	23.01 ± 0.10	—	—	No strong lines
F140W	23.01 ± 0.10	—	—	Enhanced by multiple NUV lines.
F153M	23.57 ± 0.10	—	—	No strong lines
F160W	22.57 ± 0.10	—	—	Enhanced by mainly H β and [O III] $\lambda\lambda 4959, 5007$
F164N	22.55 ± 0.10	—	—	Strongly enhanced by H β , not included in analysis
F167N	21.61 ± 0.10	—	—	Strongly enhanced by [O III] $\lambda 4959$

et al., 2014. This allows for separate photometric measurements for both the central and extended components, which we perform only on the WFC3/UVIS and ACS/WFC bands due to their sharper PSF’s when compared to the IR bands. This is done for F555W, F606W and F814W, for which spatial resolution is good and continuum light is unaffected by Lyman alpha radiation transfer. Similar to the Image 9 photometry, we assign minimum errors of 0.05 and 0.1 magnitudes in the WFC3/UVIS+WFC/ACS and WFC3/IR bands respectively.

Magnification ratio between Images 10 and 9

Comparing the flux of Image 10 (sum of central and extended components) to that of the unresolved Image 9, we derive that the magnification ratio is $\mu_{10}/\mu_9 = 4.0 - 4.1$, consistent between F555W, F606W and F814W. However, we measure a magnification ratio $\mu_{10}/\mu_9 = 3.4 \pm 0.1$ in the F275W filter which probes escaping LyC radiation. Interestingly, the extended component is undetected in Image 10 for the F275W filter which is sensitive only to LyC photons (Mestric et al., 2023; Mainali et al., 2022). The discrepancy in the magnification ratio suggests that the extended component has a higher magnification than the central component. Such magnification variation across a small angular scale $\gtrsim 0.5''$ are not well-described by the large-scale cluster lens, and could be caused by a nearby invisible dark matter subhalo. While lens modeling predicts that Image 9 and Image 10 should have similar magnifications (Pignataro et al., 2021; Sharon et al., 2022b), photometric measurements from Vanzella et al., 2022b also confirmed a significant flux ratio of $\gtrsim 2$, albeit lower than those found in this work. This might be a hint for spatial fine structures in the lens model near Images 9 and 10. In this work, we do not delve into investigating the physical cause of this effect, but use separate magnification ratios as priors for subsequent analyses: $\mu_{10}/\mu_9 = 3.4 \pm 0.1$ for the central component, and $\mu_{10}/\mu_9 = 5.6 \pm 0.5$ for the extended component. We shall assume that the unresolved Image 9 has a single magnification factor μ_9 that applies to both components.

4.4 Spectroscopy

VLT/MUSE

In order to constrain physical properties of the LyC cluster and its surrounding nebula using line ratio information, we extract rest-frame UV emission line fluxes from VLT/MUSE IFU data. Limited by seeing, MUSE IFU imaging has poor spatial resolution compared to HST images, and it is difficult to separate the lensed images of the LyC cluster from nearby sources on the arc. Since Image 10 is the brightest among the 12 lensed images of the cluster (Rivera-Thorsen et al., 2019), we apply aperture photometry to it to robustly extract emission line fluxes. Using any of the other 11 fainter lensed images degrades the accuracy of line flux measurements due to reduced SNRs.

At a pixel scale $0.2''$, we extract fluxes from a 4×4 aperture placed on top of Image 10. The aperture size is suitably chosen so that line contamination from nearby (unresolved) sources on the arc is small while a significant fraction (but not entirety) of the LyC cluster’s flux is included. Sky background is then subtracted by extracting fluxes from an identical aperture placed at an empty location off the arc. Aperture correction is estimated by placing the same aperture at a nearby isolated star and comparing the extracted flux to that extracted from a sufficiently large aperture that includes all flux of the star. Within the MUSE wavelength coverage, the aperture correction factor varies from ~ 2.6 to ~ 2.3 with a mild wavelength dependence.

A number of rest-frame FUV lines are robustly detected (Vanzella et al., 2020c), all appearing to have the same systemic redshift. We fit each line to a Gaussian line profile on top of the local continuum, and flux uncertainty is estimated based on local flux fluctuations. Two MUSE IFU datacubes are used, one from combined exposures on May 13, 2016 and Aug 24, 2016, and another from observation on Aug 10, 2021. We found that all detected lines have fluxes consistent between the two datacubes (corresponding to an observed baseline of 5 years, or 1.5 years in the source frame) within the noise level, thus finding no evidence of spectral variability. We then combine measurements from both datacubes using inverse variance weighting. We report isotropic line luminosities multiplied by magnification in Table 5.1, which are aperture corrected but not dust reddening corrected.

VLT/X-shooter

Additional rest-frame NUV and optical lines have been detected from slit spectroscopy with VLT/X-shooter (Vanzella et al., 2020c). In the 2D spectra (for a $0.8'' \times 11''$ slit), we apply for a wavelength dependent flux calibration factor calculated as the ratio between the 1D spectrum and the reduced 1D spectrum. Flux is extracted from a $0.8'' \times 1.27''$ segment on the slit centered at Image 10. For each line, we fit a Gaussian line profile on top of the continuum. Since it is difficult to empirically determine the slit correction factor based on available data, we estimate a theoretical flux correction factor = 1.2 by modeling the effect of seeing as a Moffat PSF profile (Trujillo et al., 2001) calculated at the mean seeing

Table 4.2 Inferred isotropic luminosities of nebular emission lines detected from VLT/MUSE IFU data for Image 10 of the LyC cluster. The magnified isotropic line luminosity is calculated for a luminosity distance of $d = 19.566$ Gpc (corresponding to the source redshift $z_s = 2.369$), and is uncorrected for MW dust reddening.

Emission line	Luminosity $\mu L [10^{41} \text{ erg s}^{-1}]$
[O III] λ 1660	5.8 ± 2.2
[O III] λ 1666	17.0 ± 1.6
N III] λ 1750	13.7 ± 2.7
N III] λ 1752	6.8 ± 1.6
[Si III] λ 1883	4.8 ± 1.6
Si III] λ 1892	8.5 ± 1.0
[C III] λ 1906	22.9 ± 1.6
C III] λ 1908	45.7 ± 3.7
[O II] λ 2471	5.1 ± 1.0

Table 4.3 Inferred isotropic luminosities of nebular emission lines detected from VLT/X-shooter for Image 10 of the LyC cluster. Magnified line luminosities are reported, without correcting for dust reddening. We have applied a wavelength independent PSF correction factor = 1.2 using a theoretical Moffat PSF model with $\beta = 4.765$.

Emission line	Luminosity $\mu L [10^{41} \text{ erg s}^{-1}]$
[O II] λ 3726	36 ± 7
[O II] λ 3729	18 ± 11
[Ne III] λ 3869	47 ± 5
[Ne III] λ 3967	13 ± 4
H β	94 ± 32
[O III] λ 4959	295 ± 36
[O III] λ 5007	864 ± 86
[N II] λ 6548	2 ± 11
H α	335 ± 108
[N II] λ 6583	0 ± 11

FWHM=0.54'', and approximate it as wavelength independent. Inferred line luminosities multiplying magnification but without dust reddening correction are reported in Table 5.2.

4.5 Spectral Modeling

We jointly fit HST photometry as well as line fluxes and ratios from MUSE and X-shooter to spectral models that incorporate both direct stellar radiation and nebula reprocessed (continuum and line) radiation from photoionized clouds. In this way, we can infer physical

parameters that characterize the star cluster and the surrounding nebula. Below we discuss how we construct the spectral models.

Star Cluster SED

We use incident stellar spectra from the population synthesis model BPASS (v2.0) (Stanway, Eldridge, and Becker, 2016; Eldridge and Stanway, 2016) as the input for photoionization calculations. Our default choice is that the LyC cluster can be modeled as an instant burst of star formation, and we include output radiation from binaries. A stellar initial mass range $0.1 < m/M_{\odot} < 300$ is used with an IMF slope $\xi(m) \propto m^{-1.3}$ for $m < 0.5 M_{\odot}$ and a slope $\xi(m) \propto m^{-2.35}$ for $m > 0.5 M_{\odot}$. We later refer to this as the standard IMF. We choose a high mass cutoff $m < 300 M_{\odot}$ because the system is very massive $M \gtrsim 10^6 M_{\odot}$ (Vanzella et al., 2020a). The incident stellar spectrum is parameterized by cluster age t_{age} and metallicity Z . While BPASS uses a solar metallicity value $Z_{\odot} = 0.02$ to which early stellar atmosphere models were calibrated to, the solar nebular metal abundance we shall use later for photoionization calculation with `Cloudy` is $Z_{\odot} = 0.014$, which is the preferred value according to Asplund, Amarsi, and Grevesse, 2021.

Photoionization Calculations

Given the incident stellar radiation, we use the photoionization code `Cloudy` (v17) (Ferland et al., 2017) to compute nebular continuum and line emissions, as well as the attenuation of star light through the gas. For all except three elements, we set their nebular abundances to be a factor $Z/Z_{\odot}$ of `Cloudy`'s default solar abundance (Table 7.1 of `Cloudy` manual HAZY 1). For our purposes, those are consistent with the more recent compilation in Asplund, Amarsi, and Grevesse, 2021, and they correspond to $Z_{\odot} = 0.014$. We will use $Z_{\odot} = 0.014$ when reporting gas metallicity in units of solar metallicity.

Baseline abundances for helium, carbon and nitrogen are adjusted as a function of $Z/Z_{\odot}$ to account for nucleosynthesis (Dopita et al., 2006). For helium, we correct for primary nucleosynthesis in addition to primordial abundance (Russell and Dopita, 1992; Pagel et al., 1992), $\text{He}/\text{H} = 0.0737 + 0.024 (Z/Z_{\odot})$. For carbon and nitrogen, we adopt the enrichment model of Dopita et al., 2006, using $\text{C}/\text{H} = 6 \times 10^{-5} (Z/Z_{\odot}) + 2 \times 10^{-4} (Z/Z_{\odot})^2$, and $\text{N}/\text{H} = 1.1 \times 10^{-5} (Z/Z_{\odot}) + 4.9 \times 10^{-5} (Z/Z_{\odot})^2$, respectively. Through our analysis, we find significant depletion of gas phase silicon, which indicates grain formation. Hence, we reduce the baseline nebular silicon abundance by a fiducial factor of six in our models. Additionally, we find a strikingly elevated nitrogen abundance $\log(\text{N}/\text{O}) \simeq -0.21$ which is more dramatic than local nitrogen enrichment in H II regions around low metallicity young starbursts (Izotov et al., 2006). We therefore apply a fiducial nitrogen enhancement by a factor of four on top of the Dopita et al., 2006 baseline. Later when fitting emission lines, we will introduce abundance rescaling factors as free parameters relative to these baseline abundances, for C, N, Si and Ne; we set the baseline abundances to prevent big errors in gas cooling calculations in `Cloudy`.

We compute isobaric models, which are more realistic than constant density models (Kewley et al., 2019). To this end, we compute a grid for $6 < \log P [\text{K cm}^{-3}] < 12$, where P is the sum of gas pressure and radiation pressure, and is kept constant throughout the cloud.

In all runs, the cloud geometry is that of a plane parallel slab, calculated up to a fixed neutral column density $N_{\text{HI}} = 10^{22.5} \text{ cm}^{-2}$. This is very close to a sufficient value to prevent the (dusty) clouds from being ejected out of the cluster’s gravitational potential under radiation pressure (Krumholz, McKee, and Bland-Hawthorn, 2019a).

We compute for a grid of the standard ionization parameter U by varying an artificial cloud distance to the stars. While our results suggest that external ISM dust reddening is minimal toward the LyC cluster, gas-phase silicon depletion combined with the high inferred gas density indicates that dust grains should have efficiently formed in the cloud interior. We therefore set a dust-to-gas ratio that is rescaled by $Z/Z_{\odot}$ from the standard value 1% in the solar-metallicity ISM gas.

Furthermore, we set a fixed velocity dispersion 3 km s^{-1} for gas micro turbulence, which has unimportant effects on the nebular spectrum.

Viewing Geometry

Observed continuum and line radiation depends on the observer’s viewing angle. As illustrated in Figure 4.2, there are three generic types of viewing angle — the observer may see (1) light from exposed stellar photospheres and light emerged from the illuminated faces of the photoionized clouds; (2) light from exposed stellar photospheres and light emerged from the shaded faces of the clouds; (3) star light transmitted through the clouds and nebular light emerged from the shaded faces of the clouds.

Cloudy calculations conveniently provide four different spectral components, whose superposition can well approximate a viewing-angle-averaged observed spectrum: direct star light I_{ν} (from BPASS templates), star light transmitted through clouds T_{ν} , continuum and line nebular radiation emerging from illuminated cloud faces R_{ν} , and that emerging from shaded cloud faces D_{ν} . T_{ν} would exhibit spectral features due to absorption and scattering inside the clouds, while R_{ν} would include star light reflected backward by the clouds. Both R_{ν} and D_{ν} would include continuum radiation generated from the cloud interior (e.g. from radiative recombination). Optically thin emission lines would have equal fluxes in R_{ν} and D_{ν} . For simplicity, we distinguish between direct light and transmitted light from the stars, and between illuminated and shaded faces of the clouds, but do not explicitly model the spectral dependence on a continuously varying viewing angle.

In the simplest model, we may consider a homogeneous population of clouds with fixed $\log P$ and $\log U$. The observed spectrum F_{ν} is given by

$$F_{\nu} = (1 - z) I_{\nu} + z T_{\nu} + x (y R_{\nu} + (1 - y) D_{\nu}), \quad (4.1)$$

where $0 \leq x \leq 1$ is the geometric fraction of star light processed by the clouds and $0 \leq z \leq 1$ is the fraction of stellar photospheres obscured by clouds when viewed along the observer’s

line of sight. We have also introduced an asymmetry parameter, the fraction of illuminated cloud face observed $0 \leq y \leq 1$, to quantify the probability of clouds located on the near side versus on the far side of the star cluster. If y is closer to zero, clouds are preferentially located on the near side and we are more likely to see their shaded faces. If y is closer to 1, clouds are more likely located on the far side and we see their illuminated faces more.

Emission line data favors a picture in which two distinct population of nebular clouds with significantly different ionization degrees and densities are present. One population of high ionization degree $\log U > -2$ and high pressure $\log P \approx 9$ are needed to explain the observed $[\text{CIII}]\lambda 1906/\text{CIII}\lambda 1908$ and $[\text{SiIII}]\lambda 1883/\text{SiIII}\lambda 1892$ line ratios. However, these clouds are too dense ($\log n_e \approx 5$) and too highly ionized to emit strong $[\text{OII}]\lambda\lambda 3726, 3729$, hinting at an additional population of lower U and lower pressure.

HST continuum images in F555W, F606W and F814W show a two-component structure in Image 10 (see Figure 5.4 for an example). The extended component is $\sim 30 - 40\%$ as bright as the central component. Even in F390W and F410M, the extended component is similarly bright. The high relative brightness cannot be explained by recombination continuum. Reflected stellar UV light by dust grains only reaches $\sim 20\%$ even for a high dust albedo $a = 0.65$ and a low forward scattering parameter $g = 0.35$. Therefore, the extended continuum source must be predominantly stars on the outskirts of the cluster.

Sharon et al., 2022b derived a source-plane upper bound on the cluster size $r_{\text{eff}} \lesssim 20$ pc. Vanzella et al., 2020a and Vanzella et al., 2022b reported marginal evidence from Image 10 seen in the rest-frame FUV continuum that the cluster has an effective angular radius $r_{\text{eff}} = (0.06 \pm 0.02)''$. Their results likely reflect the superposition of the central and extended stellar components.

The above considerations motivate us to consider a cluster model of two spatial components, one at the center and another extended. Either component has stars and is associated with a population of photo-ionized clouds. It is unclear whether the two stellar components are coeval, so our model allows two separate ages. One population of clouds closely surrounding the central component have an ionization parameter U_1 and a high pressure P_1 and process a fraction x_1 of the total star light with asymmetry parameter y_1 . A second population of clouds, at larger distances from the cluster center, have a different ionization parameter U_2 and a lower pressure P_2 , and process another fraction x_2 of the total star light with asymmetry parameter y_2 . For this geometry, we assume that the low-pressure clouds are excited by ionizing radiation from both the central and the extended stellar components, while the high-pressure clouds are only excited by the central stellar component. Both populations are assumed to have the same metallicity, the same element abundance (except for nitrogen; see Section 4.5), and the same grain content.

The observed spectrum is given by the linear combination

$$\begin{aligned}
 F_\nu = & (1 - z_1 - z_2) I_\nu + z_1 T_{1,\nu} + z_2 T_{2,\nu} \\
 & + x_1 (y_1 R_{1,\nu} + (1 - y_1) D_{1,\nu}) \\
 & + x_2 (y_2 R_{2,\nu} + (1 - y_2) D_{2,\nu}) \\
 & + (1 - z_2) \hat{I}_\nu + z_2 \hat{T}_{2,\nu} \\
 & + x_2 \left(y_2 \hat{R}_{2,\nu} + (1 - y_2) \hat{D}_{2,\nu} \right).
 \end{aligned} \tag{4.2}$$

Contributions with and without a hat are powered by the central and extended stellar component, respectively. The subscript ₁ and ₂ indicates quantities that are associated with nebular reprocessing by the central and extended population of clouds, respectively.

The geometric parameters are subject to the physical constraints $0 \leq x_1 + x_2 \leq 1$ and $0 \leq z_1 + z_2 \leq 1$. In this picture, a fraction $(1 - z_1 - z_2)$ of the star light (including LyC radiation) reaches the observer along the line of sight without encountering any significant opacity, while the fraction $(1 - x_1 - x_2)$ represents the *isotropic* escape fraction that star light escapes the cluster vicinity without being processed by optically thick gas.

External Dust Reddening

Dust extinction due to Milky Way’s ISM from UV through NIR is applied through the `dust_extinction` package, using models from Fitzpatrick, 1999. The model is defined by the parameter $R(V) = A(V)/E(B - V)$, where we choose $R(V) = 3.1$, the mean value for MW extinction, and a normalization $E(B - V) = 0.08$ according to the galactic dust maps measured by Schlegel, Finkbeiner, and Davis, 1998.

To account for possible dust reddening due to ISM in the host galaxy, we adopt the phenomenological reddening law of Reddy et al., 2015a, which is empirically determined for $z \sim 1.4$ – 2.6 galaxies. This reddening law was used by Chisholm et al., 2019 to analyze the rest-frame UV stellar spectral features of the LyC cluster. We normalize host ISM reddening using $E(B - V)$, which we treat as a free parameter of the model.

Element Abundances

From observed emission line strengths, we can measure gas phase abundance for four elements: (1) C/O from C III] $\lambda\lambda 1906, 1908$; (2) N/O from N III] $\lambda\lambda 1750, 1752$ or constrained by upper limits on [N II] $\lambda\lambda 6548, 6583$; (3) Ne/O from [Ne III] $\lambda\lambda 3869, 3967$; (4) Si/O from Si III] $\lambda\lambda 1883, 1892$. As mentioned before, we set baseline abundance values for these elements in our `Cloudy` calculations (see Section 4.5). Since for a typical abundance pattern oxygen forbidden lines are the main coolants in the photoionized gas, we assume that rescaling the abundance of a specific element, at the leading order, leads to the same rescaling of all lines associated with that element, while changes to cloud ionization and temperature can be

neglected. In the fitting, we include one free rescaling factor for C, Ne and Si, respectively, which applies to both cloud populations.

For nitrogen, the low-pressure clouds are located further away from the cluster than the high-pressure ones, so they are not necessarily equally enriched. We therefore introduce separate N abundance rescaling factors for both cloud populations. From X-shooter data we derive upper limits for the optical forbidden lines [N II] $\lambda\lambda$ 6548,6583. These are suppressed if the photoionized gas has high density and high ionization degree. While low-density, low-ionization clouds contribute negligibly to N III] $\lambda\lambda$ 1750,1752, their N enrichment can be constrained by non-detection of [N II] $\lambda\lambda$ 6548,6583.

Spectral Fitting

Using model spectra, we compute observed fluxes for a list of HST filters (Table 5.3), and a selected list of emission line ratios (Table 4.4). Assuming uncorrelated errorbars, the log likelihood used for fitting is minus one-half of the total chi square combining all photometric and emission line observables.

We include a total of 12 available HST filters, but exclude F390W, F410M, and F164N. Fluxes in F390W and F410M are sensitive to Ly α emission and damping wing attenuation, for which robust predictions are challenging due to the possibility of significant intervening HI columns along the line of sight. Neutral gas content physically far from the cluster may contribute to this column, about which data provide inadequate information to constrain the details. Other filters should be insensitive to these effects. F164N, a narrow band filter expected to be enhanced by H β emission, may suffer from flux calibration issues, consistently underpredicting the flux expected from spectroscopic measurements. While our fitting does show a disagreement between the model predicted flux and data at the 2σ level, we found that inclusion of F164N resulted in only minor changes to the inferred physical parameters. Regardless, we choose to remove the filter from fitting to be conservative.

Fluxes in several filters (F126N, F160W and F167N) are expected to be significantly enhanced by one or several strong emission lines, such as [OII] $\lambda\lambda$ 3726, 3729, H β , and [OIII] $\lambda\lambda$ 4959, 5007. We find that through strong line contributions HST photometry significantly constrains nebular properties independently of the emission line data.

H II gas glows in continuum light due to radiative recombination of hydrogen. This nebular continuum is proportional to the amount of LyC radiation processed by the photoionized cloud. Young starburst systems with $t_{\text{age}} \lesssim 5$ Myr have strong enough LyC radiation relative to the non-ionizing FUV radiation, and therefore the nebular continuum is a sizable contribution to the observed continuum flux (Reines et al., 2010; Byler et al., 2017). Recombination continuum has spectral discontinuities at the wavelengths of Lyman limit, Balmer limit, Paschen limit, and so on. The Balmer discontinuity at rest-frame 3645 Å is particularly relevant at the redshift of Sunburst because several HST filters probe opposite sides of the redshifted break and hence are sensitive to the size of this discontinuity, which provides information about t_{age} , Z and the electron temperature T_e . The medium filter F153M, red-

Table 4.4 Nebular emission line ratios included in the spectral analysis.

Line ratio	Value & uncertainty	Comment
Si III] λ 1892 / [Si III] λ 1883	2.42 ± 0.97	Probe density of high-pressure H II clouds
C III] λ 1908 / [C III] λ 1906	2.32 ± 0.23	Probe density of high-pressure H II clouds
[O II] λ 2471 / [O III] $\lambda\lambda$ 1660,1666	0.23 ± 0.06	Probe ratio between the high-pressure and low-pressure clouds
[O II] λ 3729 / [O II] λ 3727	0.50 ± 0.32	Probe density of low-pressure clouds
[O II] $\lambda\lambda$ 3726,3729 / [O III] $\lambda\lambda$ 4959,5007	0.047 ± 0.012	Probe ratio between the high-pressure and low-pressure clouds
[O III] $\lambda\lambda$ 4959,5007 / H β	12.38 ± 4.40	Ionization and metallicity diagnostics

ward of the break, happens to be unaffected by strong lines. We indeed detect flux deficit in that filter relative to neighboring filters.

Table 4.4 lists 6 line ratios that we include in the analysis. To be conservative about element abundance uncertainties, we refrain from including line ratios that involve different metals except for measuring the abundance of certain metals. Compared to analyzing MUSE IFU data, we are relatively less confident about absolute flux calibration when analyzing X-shooter slit spectroscopy data. Hence, we refrain from using line ratios between MUSE detection and X-shooter detection. Line ratios based on X-shooter measurements always involve two lines with close wavelengths.

In particular, CIII] $\lambda\lambda$ 1906,1908 and SiIII] $\lambda\lambda$ 1883,1892 line ratios probe clouds of high ionization degree and are sensitive n_e diagnostics in the high density regime $3 \lesssim \log n_e \lesssim 6$ (Keenan, Feibelman, and Berrington, 1992; Jaskot and Ravindranath, 2016). The [OII] $\lambda\lambda$ 3726, 3729 line ratio probes n_e in clouds of low ionization degree, and is sensitive to a lower density range $1 \lesssim \log n_e \lesssim 4$ (Osterbrock, 1989). Ratios between the O II and O III lines, [OII] $\lambda\lambda$ 3726, 3729/[OIII] $\lambda\lambda$ 4959, 5007 (Kewley and Dopita, 2002; Kobulnicky and Kewley, 2004; Dors et al., 2011) in rest-frame optical and [OII] λ 2471/[OIII] $\lambda\lambda$ 1660, 1666 (Kewley, Nicholls, and Sutherland, 2019) in rest-frame UV, are sensitive to ionization degree and gas temperature, and simultaneously constrain the relative contributions to nebular radiation from the low-pressure and high-pressure clouds. The commonly used ratio [O III] $\lambda\lambda$ 4959,5007 / H β probes the gas metallicity and ionization parameter.

Since we combine observables of Image 9 and Image 10, uncertainty in the magnification ratio between the two must be taken into account. We treat the magnification ratio for both the central and the extended components as two free parameters with informative priors. This has been described in Section 4.3.

4.6 Parameter Inference Results

We fit our Cloudy models to the observed photometry (Figure 5.5), emission line fluxes and ratios (Figure 5.6) using PyMultinest (Feroz, Hobson, and Bridges, 2009; Buchner et al., 2014), with 1,000 live points running for 10,000 steps. The two-population model consists of 22 parameters in total: host dust reddening, metallicity, and the stellar age (for both stellar components); the pressure, ionization parameter and three geometric parameters for each population; the relative lensing magnification factor between the less magnified Image

9 (used for HST PSF photometry) and the more magnified Image 10 (used for emission line measurement) for both the central and extended components; the relative normalization of the two stellar components, overall normalization, and abundance rescalings for C, N (for both cloud populations), Ne and Si. The model is fit to 18 photometric measurements (Image 9 photometry for 12 HST filters, and Image 10 photometry for the central and extended components separately in 3 filters), 9 emission line fluxes, 6 emission line ratios, and 2 emission line non-detections; in sum 35 observables leading to 13 degrees of freedom overall. The best-fit model reproduces data with $\chi^2_\nu = 1.85$.

Star Cluster Properties

Properties of the star cluster are shown in Figure 5.7. Assuming a single burst, we derive a cluster age $t_{\text{age}} = 2.4^{+1.6}_{-1.0}$ Myr from the central component, which agrees with the independent UV spectroscopy analysis of Chisholm et al., 2019 when the BPASS SED model is used, and is broadly consistent with the age requirement for very massive stars powering broad He II λ 1640 wind emission as suggested by Mestric et al., 2023.

The age constraint on the extended component is less tight, but the posterior peaks at 4 Myr. Data disfavors the extended component being older than 7 Myr, and it is possible that the extended component is coeval with the central component. While our model suggests that the extended component may contribute as much as $\sim 25\%$ of the ionizing flux, no extended source of escaping LyC radiation is seen in Image 10 in F275W (Mainali et al., 2022; Mestric et al., 2023) (also see Figure 5.4). The low density channels that allow LyC photons to pass freely may be connecting only to the central part of the cluster.

We do not find any significant evidence for nonzero dust reddening caused by the host galaxy’s ISM, with $E(B - V) < 0.05$ at high confidence. The large-scale interstellar environment of the Sunburst galaxy toward the LyC cluster therefore does not appear dusty. This is in contrast to the result $E(B - V) = 0.15$ from Chisholm et al., 2019 even though the same empirical reddening curve has been used. We are unable to explain the data with dust reddening as large as $E(B - V) = 0.15$ even when model details are tweaked. While Chisholm et al., 2019 use an IMF of a similar shape, they use a lower $100M_\odot$ upper mass cutoff than our analysis, however we found that adopting this upper mass cutoff did not significantly change our inferred reddening. There is a degeneracy between the nebular continuum, which renders the total FUV spectral slope redder (c.f. Figure 5.5), and external dust reddening, but we find removal of the nebular continuum in our models results in only a modest increase in the inferred $E(B - V) \sim 0.04$. Mainali et al., 2022 measure reddening from stellar wind features in a similar approach to Chisholm et al., 2019, and find that the measured $E(B - V)$ varies greatly between the different multiple images; the $E(B - V)$ found for Image 9 and Image 10 are consistent with our results using those images. It is unclear which lensed images Chisholm et al., 2019 used for their measurements, which are consistent with Mainali et al., 2022’s measurement of Image 5. Mainali et al., 2022 also measure a dust reddening of $E(B - V) \sim 0.2$ via the balmer decrement, but use a different reddening law and fix the electron density and temperature to $n_e = 10^2 \text{ cm}^{-3}$ and $T_e = 10^4 \text{ K}$ respectively.

However at our inferred densities of $n_e \sim 10^5 \text{ cm}^{-3}$, the balmer decrement is sensitive to density and temperature (Osterbrock, 1989), and the unreddened balmer decrement predicted by our models is much higher than those assumed in Mainali et al., 2022, resulting in a lower $E(B - V)$.

We infer a gas-phase metallicity of $Z \sim 0.2 Z_\odot$, significantly lower than the stellar metallicities of $\sim 0.5 - 0.6 Z_\odot$ and $\sim 0.4 Z_\odot$ inferred by Chisholm et al., 2019 and by Mainali et al., 2022 respectively via the CIV λ 1550 and NV λ 1240 P Cygni stellar wind features. This is somewhat in contrast to other cosmic noon star forming galaxies, which usually have similar or slightly lower stellar metallicities when compared to the gas-phase (Sommariva et al., 2012). Mestric et al., 2023 infer a gas-phase metallicity of $Z \sim 0.4 Z_\odot$ via the N2 index (Marino et al., 2013), but the lack of a clear [NII] λ 6583 detection means this may instead be an upper limit.

For the IMF we choose (c.f. Section 4.5), we measure a stellar mass $\log(\mu_9 M_{\star,1}/M_\odot) = 8.8^{+0.2}_{-0.2}$ for the central component, and $\log(\mu_9 M_{\star,2}/M_\odot) = 8.3^{+0.2}_{-0.2}$ for the subdominant extended component. The precise mass is unknown due to the large uncertainty in the magnification factor of Image 9, μ_9 , as multiple independent lens modeling efforts (Vanzella et al., 2020a; Pignataro et al., 2021; Diego et al., 2022b; Sharon et al., 2022b) have obtained magnification factors of the various lensed images of the cluster that are different from each other and are discrepant with the observed flux ratios. A plausible range for the magnification of Image 9 might be $\mu_9 = 10 - 30$. Just the central component has $\sim 5 \times 10^6 M_\odot$ of stars even if Image 9 has $\mu_9 = 100$, which is one or two orders of magnitude more massive than any exposed young super star clusters seen in the local Universe. This is in agreement with the inference of (Vanzella et al., 2020a; Vanzella et al., 2022b) and supports the idea that such a system will likely evolve to a massive globular cluster.

We repeated our analysis with a top-heavy IMF with $\xi(m) \propto m^{-2}$ for $m > 0.5 M_\odot$. No significant changes to the model parameters were seen, except that the inferred cluster mass decreased by a factor of ~ 2 (see Table 5.4). This is because at $t_{\text{age}} \lesssim 4 \text{ Myr}$ the cluster ionizing output is completely dominated by the most massive stars. In particular, the central component of the young super star cluster has a huge output of LyC photons, $\log(\mu_9 Q(\text{H}^0)) = 55.5^{+0.3}_{-0.2}$. Barring the uncertainty in μ_9 , this result is insensitive to the IMF slope. We also decreased the upper mass cutoff to $100 M$, which resulted in a more sharply peaked age posterior at $1.5 - 2 \text{ Myr}$, but we did not find any significant differences in our inferred parameters.

Nebula Properties

Figure 5.8 shows inferred parameters describing the photoionized clouds: cloud pressure P , ionization parameter U , and the ionizing flux incident onto the cloud $\Phi(\text{H}^0)$. These intensive nebula parameters can be inferred independently of the uncertain lensing magnification factor.

The model has two cloud populations with well-constrained but distinct pressure values. The high-pressure clouds, which is the primary source for emission lines from high ionization

species, have $\log P_1 = 9.6^{+0.3}_{-0.2}$ (pressure in units of K cm^{-3}). Their ionizing parameter is high $\log U_1 = -1.25^{+0.4}_{-0.4}$. The H II gas pressure is constrained to be high because C III] $\lambda\lambda 1906, 1908$ line ratio indicates $\log n_e \approx 5$. The intensity of ionizing photons striking the cloud surface (in units of $\text{cm}^{-2} \text{s}^{-1}$) has a high value $\log \Phi_1(\text{H}^0) = 14.3^{+0.3}_{-0.3}$.

A second population of low-pressure clouds account for the strong [O II] $\lambda\lambda 3726, 3729$ doublet. They have a lower pressure $\log P_2 = 7.8^{+0.2}_{-0.3}$, a lower ionization parameter $\log U_2 = -2.5^{+0.2}_{-0.2}$, and are irradiated by a weaker ionizing flux $\log \Phi_2(\text{H}^0) = 11.5^{+0.3}_{-0.3}$.

Line profile analysis performed in Mainali et al., 2022 revealed that [O III] $\lambda 5007$ emission from the LyC cluster consists of two components with distinct kinematics: a narrow component with $\text{FWHM} = 100 \text{ km s}^{-1}$ and a broader component with $\text{FWHM} = 300 \text{ km s}^{-1}$. Since our model predicts that strong UV metal lines such as C III] $\lambda 1908$ are predominantly from the high-pressure nebula, and that those lines appear consistent with $\text{FWHM} = 100 \text{ km s}^{-1}$ rather than $\text{FWHM} = 300 \text{ km s}^{-1}$, we surmise that the narrow and broad line components correspond to the high- and low-pressure nebulae, respectively.

Geometric Parameters

Our analysis simultaneously constrain the spatial geometry of the surrounding photoionized clouds. Information about these mainly come from the relative fluxes between the observed lines and continuum, the spectral difference between the illuminated and shaded cloud faces, as well as the amount of reddening for stellar light transmitted through any obscuring clouds that intervene the light of sight compared to the incident stellar light.

The results for geometric parameters are shown in Figure 4.7. About $x_1 = (40^{+22}_{-17})\%$ of the cluster's ionizing output is processed by high-pressure clouds where high ionization emission lines are powered, and a remaining $x_2 = (20^{+17}_{-15})\%$ is processed by low-pressure clouds. While the geometry parameters have broad posterior distributions, our fitting results imply that a substantial fraction $(1 - x_1 - x_2) = (35^{+23}_{-21})\%$ of the ionizing output leaves the cluster vicinity in various directions without being processed by opaque clouds.

On the other hand, along the specific line of sight toward the observer, an even higher fraction $(1 - z_1 - z_2) = (52^{+20}_{-18})\%$ of the ionizing radiation from the stars escapes the system. This picture is fully consistent with previous study carried out by Rivera-Thorsen et al., 2019, who suggest a line-of-sight LyC escape fraction 40–90% if dust absorption within the host galaxy is negligible.

Since we assume that the photoionized clouds have a high H column density and have dust grains, illuminated cloud faces and shaded cloud faces are distinguishable because continuum and line radiation emerging from the shaded cloud faces is severely suppressed, especially at rest-frame UV wavelengths. In our results, both y_1 and y_2 have a broad posterior consistent with $y_1 = 1/2$ and $y_2 = 1/2$. This is compatible with the picture in which the photoionized clouds, of both populations, are isotropically distributed around the star cluster. In our opinion, this is a simple, natural scenario. If data preferred a situation where clouds were predominantly seen from the illuminated faces or from the shaded faces, we would have to either attribute that to chance, or would have to invoke additional physical explanations

Table 4.5 Inferred element abundances of carbon, nitrogen, neon and silicon. Also refer to the “Two-Comp” model in Table 5.4.

Abundance	Value	Solar	Important lines
$\log(\text{C}/\text{O})$	$-0.51^{+0.05}_{-0.05}$	-0.30	C III] $\lambda\lambda$ 1906,1908
$^2 \log(\text{N}/\text{O})$	$-0.21^{+0.10}_{-0.11}$	-0.76	N III] $\lambda\lambda$ 1750,1752
$^3 \log(\text{N}/\text{O})$	$\lesssim -1.31$	-0.76	[N II] $\lambda\lambda$ 6548,6583
$\log(\text{Ne}/\text{O})$	$-0.81^{+0.05}_{-0.05}$	-0.69	[Ne III] $\lambda\lambda$ 3869,3967
$\log(\text{Si}/\text{O})$	$-1.84^{+0.07}_{-0.07}$	-1.15	Si III] $\lambda\lambda$ 1883,1892

for such geometric asymmetry. There is insufficient information to determine whether the photoionized clouds are shattered into large quantities of cloudlets, in which case the line-of-sight escape fraction ($1 - z_1 - z_2$) may equal the isotropic escape fraction.

Element Abundances

Under the assumption that $[\text{O}/\text{H}] = \log(Z/Z_\odot)$ for a stellar metallicity Z and with our fiducial abundance pattern, we measure $Z/Z_\odot = 0.22 \pm 0.03$. This is lower than the results of Chisholm et al., 2019, $Z/Z_\odot = 0.5\text{--}0.6$, which was inferred from rest-frame UV spectral features of stellar winds. We consistently infer a gas metallicity $Z \approx (0.2 - 0.3) Z_\odot$ when modeling details are varied (c.f. Table 5.4).

The picture of dusty photoionized clouds is corroborated by the inferred gas-phase Si depletion by a factor $\sim 4\text{--}5$ (Figure 4.8). If seeds are present in the first place, grain growth should be efficient at high densities $\log n_e = 4\text{--}5$ and a cool gas temperature at a few thousand K, even under strong external UV irradiation. For example, dust grains are observed to rapidly form in colliding wind shells of the Wolf-Rayet binary system WR140 (Han et al., 2022; Lau et al., 2022).

Mg II $\lambda\lambda$ 2795,2803 doublet and [Fe IV] $\lambda\lambda$ 2829,2835 doublet are transitions from ionic ground levels. Photoionization calculation shows that strong emissions should emerge from the illuminated cloud face. Inspecting the the X-shooter data, we nevertheless detect only weak Mg II $\lambda\lambda$ 2795,2803 emission, and find no sign for [Fe IV] $\lambda\lambda$ 2829,2835 emission. The plausible explanation is that gas-phase Si, Mg and Fe are all depleted due to grain formation. This further supports the model of dusty photoionized clouds.

We have detected strikingly elevated nitrogen abundance $\log(\text{N}/\text{O}) = -0.21^{+0.10}_{-0.11}$ for the high-pressure clouds, a factor of $\sim 12\text{--}19$ higher than the typical ISM abundance $\log(\text{N}/\text{O}) \simeq -1.4$ at $Z/Z_\odot \simeq 0.2$ (Mollá et al., 2007). By contrast, no evidence of enrichment is seen for the low-pressure clouds, which have $\log(\text{N}/\text{O}) \lesssim -1.31$. This is evidence for localized self-enrichment by massive star ejecta (discussed in Section 4.7 with more details).

No dramatic abundance anomalies are noticeable for carbon $\log(\text{C}/\text{O}) = -0.51^{+0.05}_{-0.05}$ and for neon $\log(\text{Ne}/\text{O}) = -0.81^{+0.05}_{-0.05}$. The unremarkable Ne/O ratio disfavors significant gas-phase O depletion. Abundance results are summarized in Figure 4.8 and Table 4.5.

Altering Model Assumptions

We study how robust our parameter inference is by modifying some of the basic modeling assumptions. We study three alternate model assumptions. Parameter inference results for these modified models, together with our default model (“Two-Comp.”) already explained in previous sections, are tabulated in Table 5.4.

For the first alternative model (“Top-heavy”), we consider a top-heavy IMF for which high mass stars are up-weighted by having $\xi(m) \propto m^{-2}$ for $m > 0.5 M_{\odot}$, but retains the same IMF slope for lower mass stars, the same mass cutoff, and instant star formation. This model has a comparable reduced chi square. Compared to the default model, the inferred parameters are consistent within 1σ , with only exception being the magnified cluster stellar mass for both the central and extended components, which are a factor of two smaller. This is easily understandable because high mass stars dominate all light observables at $\lesssim 4$ Myr; the number of low mass stars, which dominate the stellar mass, is necessarily estimated by extrapolation following the assumed IMF. The same mass-IMF degeneracy is expected for other forms of top-heavy IMF.

Even though an instant starburst can be a good approximation for a localized starburst, we explore the alternative scenario of continuous star formation at a constant rate as the second alternative model (“Cont. SF”). This model has a reduced chi square comparable to that of the default model, and nearly all inferred parameters change by less than 1σ . The notable exception is the central cluster age, which favors 4.3 Myr but with larger uncertainties ($\pm 1-2$ Myr). Similarly, the extended cluster age favors 4.7 Myr with large uncertainties. This suggests observable features sensitive to t_{age} in the burst model are no longer constraining for continuous star formation. While our fitting does not show a significant preference for either an instant starburst or continuous star formation, Chisholm et al., 2019 found that constant star formation did not reproduce the observed C IV $\lambda 1550$ and N V $\lambda 1240$ P-Cygni features of massive star winds as well as instant starburst does.

Finally, we also test a simplified model without photometric constraints from Image 10, and without a second stellar population (“One-Comp.”). This model retains only a single free parameter for the magnification ratio between Images 9 and 10, which is applied uniformly across both the high-pressure and low-pressure cloud emission in order to fit to emission line fluxes measured from Image 10. With the removal of 6 observational constraints from Image 10 photometry and 3 free parameters corresponding to the extended stellar component, this model instead has only 11 degrees of freedom. We find this model provides a similarly good χ^2_{ν} to the two-stellar component model, and the inferred physical parameters are in agreement with the two-stellar component model. The inferred cluster age for the single stellar component, $t_{\text{age}} = 3.5^{+0.9}_{-0.9}$ Myr, is broadly in agreement with the central component from the two-stellar component model. This single stellar component has inferred magnified mass $\log(\mu_9 M_{\star}) = 8.8^{+0.2}_{-0.2}$, and magnified ionizing photon rate $\log(\mu_9 Q(\text{H}^0)) = 55.4^{+0.2}_{-0.2}$, also in agreement with the central component of the two-stellar component model. The high-pressure clouds see small variations in their ionization parameter and pressure, with $\log U_1 = -1.2^{+0.3}_{-0.4}$ and $\log P_1 = 9.8^{+0.7}_{-0.4}$, however these are well within 1σ of the two-stellar

component model. The uniform magnification ratio inferred is $\mu_{10}/\mu_9 = 3.40^{+0.34}_{-0.34}$, which is consistent at the 2σ level with the total magnification ratio measured photometrically in the F555W, F606W, and F814W filters as described in Section 4.3. The physical parameters for the low-pressure clouds, the geometric factors, and elemental abundances all see negligible changes between the two models.

We conclude that our most important qualitative findings about the cluster (e.g. age, metallicity, external dust reddening) and about the dense photoionized clouds (e.g. high pressure and high ionization, nitrogen enhancement, silicon depletion) are robust against tweaking of detailed model assumptions.

4.7 Discussion

In this section, we discuss the physical implications of our inferred model for the cluster and the surrounding nebula.

Nebula Size

The typical distance between the clouds from the cluster center can be computed from the ionizing flux striking the cloud surface Φ and the total ionizing output $Q(\text{H}^0)$. Up to a dependence on the uncertain lensing magnification factor μ_9 , we find that the high-pressure clouds form an inner nebula very close to the cluster at a distance $R_1 = (\mu_9/10)^{-1/2}$ (6–12) pc, while low-pressure clouds form an outer nebula at a much larger distance $R_2 = (\mu_9/10)^{-1/2}$ (130–320) pc. The angular diameter distance to $z_s = 2.369$ is $d_A = 1.7$ Gpc, corresponding to an apparent proper distance 8.4 kpc for one arcsecond. The high-pressure nebula has an angular half-width along the direction of arc elongation, for Image 9:

$$\theta_{1,9} = \frac{\mu_9 R_1}{\mu_r d_A} \approx 0.006'' \left(\frac{R_1 \sqrt{\mu_9}}{10^{20.0} \text{ cm}} \right) \left(\frac{\mu_9}{10} \right)^{1/2} \left(\frac{\mu_r}{2} \right)^{-1}, \quad (4.3)$$

where μ_r is the radial magnification. The angular half-width for the nebula comprised of the low-pressure clouds at larger distances is

$$\theta_{2,9} = \frac{\mu_9 R_2}{\mu_r d_A} \approx 0.15'' \left(\frac{R_2 \sqrt{\mu_9}}{10^{21.4} \text{ cm}} \right) \left(\frac{\mu_9}{10} \right)^{1/2} \left(\frac{\mu_r}{2} \right)^{-1}. \quad (4.4)$$

The fiducial values $\log(\sqrt{\mu_9} R_1) = 20.0$ and $\log(\sqrt{\mu_9} R_2) = 21.4$ we shall use are median values from the posterior distributions (c.f. Figure 4.10).

Absolute magnification factors of the various lensed images are uncertain, as existing lens models reproduce image locations well but not magnification ratios (Sharon et al., 2022b). There is also uncertainty for μ_r , whose value should vary moderately between lensed images. While Vanzella et al., 2022b predicted $\mu_r = 1.2$ – 1.3 , Diego et al., 2022b presented two models with $\mu_r = 1.4$ and $\mu_r = 2.1$, respectively. The source-plane reconstruction results of Sharon et al., 2022b imply $\mu_r = 1.6$ – 2 . We use a high fiducial value $\mu_r = 2$.

Table 4.6 Physical parameters derived for the two-stellar population (“Two-Comp.”), top-heavy IMF (“Top-heavy”), single-stellar population (“One-Comp.”), and continuous star-formation (“Cont. SF”) models. The “Two-Comp.” model is the default model of this work. Pressures are in units of K cm^{-3} , photon fluxes in units of $\text{cm}^{-2} \text{s}^{-1}$, and radii in units of cm. μ_9 is the magnification factor of Image 9.

Parameter	Meaning	Two-Comp.	Top-heavy	One-Comp. ^a	Cont. SF
χ^2_ν	Reduced chi square	1.85	1.82	1.89	1.96
χ^2	Chi square	24.08	23.68	18.92	25.51
$E(B - V)$	Host ISM dust reddening	$0.02^{+0.03}_{-0.01}$	$0.02^{+0.02}_{-0.01}$	$0.01^{+0.01}_{-0.01}$	$0.04^{+0.02}_{-0.02}$
$\log Z^b$	Absolute metallicity	$-2.33^{+0.05}_{-0.06}$	$-2.31^{+0.05}_{-0.06}$	$-2.20^{+0.06}_{-0.06}$	$-2.31^{+0.06}_{-0.07}$
$t_{\text{age},1}$	Cluster age of central stars [Myr]	$2.43^{+1.60}_{-0.99}$	$3.33^{+1.24}_{-1.77}$	$3.47^{+0.92}_{-0.97}$	$4.33^{+1.68}_{-1.85}$
$t_{\text{age},2}$	Cluster age of outskirt stars [Myr]	$4.18^{+1.62}_{-1.75}$	$4.18^{+1.70}_{-1.69}$	—	$4.73^{+1.48}_{-1.70}$
$\log U_1$	Ionization parameter of high-pressure clouds	$-1.25^{+0.44}_{-0.45}$	$-1.35^{+0.48}_{-0.46}$	$-1.19^{+0.47}_{-0.51}$	$-1.24^{+0.45}_{-0.53}$
$\log U_2$	Ionization parameter of low-pressure clouds	$-2.52^{+0.22}_{-0.21}$	$-2.50^{+0.22}_{-0.22}$	$-2.41^{+0.21}_{-0.28}$	$-2.51^{+0.23}_{-0.22}$
$\log P_1$	Total pressure of high-pressure clouds [K cm^{-3}]	$9.63^{+0.28}_{-0.24}$	$9.62^{+0.27}_{-0.25}$	$9.79^{+0.71}_{-0.40}$	$9.69^{+0.34}_{-0.29}$
$\log P_2$	Total pressure of low-pressure clouds [K cm^{-3}]	$7.81^{+0.22}_{-0.27}$	$7.78^{+0.25}_{-0.29}$	$7.86^{+0.23}_{-0.27}$	$7.84^{+0.23}_{-0.27}$
$\log(\mu_9 M_{*,1})$	(Magnified) stellar mass of central stars [$M_\odot$]	$8.77^{+0.21}_{-0.19}$	$8.41^{+0.25}_{-0.26}$	$8.85^{+0.20}_{-0.21}$	—
$\log(\mu_9 M_{*,2})$	(Magnified) stellar mass of extended stars [$M_\odot$]	$8.27^{+0.20}_{-0.19}$	$7.94^{+0.26}_{-0.34}$	—	—
$\log(\mu_9 \text{SFR}_1)$	(Magnified) SFR of central stars [$M_\odot/\text{yr}$]	—	—	—	$2.13^{+0.30}_{-0.19}$
$\log(\mu_9 \text{SFR}_2)$	(Magnified) SFR of extended stars [$M_\odot/\text{yr}$]	—	—	—	$1.49^{+0.19}_{-0.13}$
$\log(\mu_9 Q(\text{H}^0))$	(Magnified) ionizing output of central stars [s^{-1}]	$55.46^{+0.28}_{-0.23}$	$55.39^{+0.29}_{-0.21}$	$55.38^{+0.18}_{-0.15}$	$55.59^{+0.21}_{-0.16}$
$\log(\mu_9 Q(\text{H}^0_2))$	(Magnified) ionizing output of outskirt stars [s^{-1}]	$54.66^{+0.23}_{-0.23}$	$54.67^{+0.19}_{-0.21}$	—	$54.98^{+0.15}_{-0.13}$
$\log \Phi_1(\text{H}^0)$	Ionizing flux incident on high-pressure clouds [$\text{s}^{-1} \text{cm}^{-2}$]	$14.34^{+0.28}_{-0.26}$	$14.29^{+0.28}_{-0.28}$	$14.50^{+0.68}_{-0.39}$	$14.41^{+0.32}_{-0.30}$
$\log \Phi_2(\text{H}^0)$	Ionizing flux incident on low-pressure clouds [$\text{s}^{-1} \text{cm}^{-2}$]	$11.54^{+0.28}_{-0.30}$	$11.53^{+0.31}_{-0.31}$	$11.69^{+0.32}_{-0.39}$	$11.58^{+0.31}_{-0.30}$
$\log(R_1 \mu_9^{1/2})$	Distance of high-pressure nebula [cm] multiplying $\sqrt{\mu_9}$	$20.02^{+0.17}_{-0.17}$	$20.02^{+0.18}_{-0.17}$	$19.89^{+0.21}_{-0.35}$	$20.06^{+0.19}_{-0.19}$
$\log(R_2 \mu_9^{1/2})$	Distance of low-pressure nebula [cm] multiplying $\sqrt{\mu_9}$	$21.43^{+0.20}_{-0.20}$	$21.40^{+0.22}_{-0.20}$	$21.31^{+0.22}_{-0.19}$	$21.47^{+0.19}_{-0.20}$
x_1	Fraction of radiation processed by high-pressure clouds	$0.40^{+0.22}_{-0.17}$	$0.40^{+0.21}_{-0.16}$	$0.32^{+0.10}_{-0.14}$	$0.35^{+0.22}_{-0.15}$
y_1	Asymmetry of high-pressure cloud distribution	$0.52^{+0.28}_{-0.23}$	$0.53^{+0.26}_{-0.22}$	$0.56^{+0.26}_{-0.23}$	$0.49^{+0.28}_{-0.22}$
x_2	Fraction of radiation processed by low-pressure clouds	$0.20^{+0.17}_{-0.10}$	$0.19^{+0.16}_{-0.09}$	$0.33^{+0.21}_{-0.15}$	$0.16^{+0.15}_{-0.08}$
y_2	Asymmetry of low-pressure cloud distribution	$0.40^{+0.31}_{-0.20}$	$0.43^{+0.31}_{-0.21}$	$0.58^{+0.26}_{-0.25}$	$0.43^{+0.29}_{-0.21}$
z_1	Line-of-sight obscuration fraction by high-pressure clouds	$0.22^{+0.20}_{-0.15}$	$0.21^{+0.20}_{-0.14}$	$0.21^{+0.19}_{-0.15}$	$0.19^{+0.19}_{-0.14}$
z_2	Line-of-sight obscuration fraction by low-pressure clouds	$0.21^{+0.19}_{-0.14}$	$0.20^{+0.19}_{-0.14}$	$0.21^{+0.19}_{-0.15}$	$0.19^{+0.20}_{-0.13}$
$1 - x_1 - x_2$	Isotropic escape fraction of ionizing radiation	$0.35^{+0.23}_{-0.21}$	$0.35^{+0.22}_{-0.21}$	$0.30^{+0.20}_{-0.19}$	$0.43^{+0.21}_{-0.23}$
$1 - z_1 - z_2$	Line-of-sight escape fraction of ionizing radiation	$0.52^{+0.20}_{-0.18}$	$0.53^{+0.19}_{-0.18}$	$0.53^{+0.19}_{-0.17}$	$0.56^{+0.20}_{-0.20}$
$\log(\text{C}/\text{O})$	Carbon abundance	$-0.51^{+0.05}_{-0.05}$	$-0.51^{+0.05}_{-0.05}$	$-0.51^{+0.05}_{-0.05}$	$-0.51^{+0.05}_{-0.05}$
$\log(\text{N}/\text{O})_1$	Nitrogen abundance in high-pressure clouds	$-0.21^{+0.10}_{-0.11}$	$-0.25^{+0.09}_{-0.11}$	$-0.21^{+0.08}_{-0.11}$	$-0.23^{+0.08}_{-0.11}$
$\log(\text{N}/\text{O})_2$	Nitrogen abundance in low-pressure clouds	$\lesssim -1.31$	$\lesssim -1.26$	$\lesssim -1.20$	$\lesssim -1.31$
$\log(\text{Ne}/\text{O})$	Neon abundance	$-0.81^{+0.05}_{-0.05}$	$-0.81^{+0.05}_{-0.05}$	$-0.79^{+0.05}_{-0.06}$	$-0.83^{+0.05}_{-0.05}$
$\log(\text{Si}/\text{O})$	Silicon abundance	$-1.84^{+0.07}_{-0.07}$	$-1.84^{+0.07}_{-0.08}$	$-1.84^{+0.06}_{-0.06}$	$-1.83^{+0.07}_{-0.08}$
$\mu_{10,1}/\mu_{9,1}$	Magnification ratio for central component	$3.30^{+0.08}_{-0.08}$	$3.29^{+0.08}_{-0.08}$	$3.40^{+0.34}_{-0.34}$	$3.29^{+0.08}_{-0.08}$
$\mu_{10,2}/\mu_{9,2}$	Magnification ratio for extended component	$4.96^{+0.39}_{-0.38}$	$4.97^{+0.38}_{-0.37}$	—	$4.88^{+0.42}_{-0.39}$

^aImage 10 central and extended component photometry is excluded; a single magnification ratio μ_{10}/μ_9 is applied for both components.

^bWhere $\log Z_\odot = -1.85$

If the low-pressure nebula has a largely isotropic distribution around the cluster, the elongated image half-light full-width $\theta_{2,9} = 0.15''$ is smaller than the FWHM of the PSF we use $\approx 0.27''$ in the F126N filter from which we extract a flux enhanced by $[\text{O II}]\lambda\lambda 3726, 3729$. The angular half-light full-width for Image 10 is about a factor of ≈ 4 larger, reaching $\theta_{2,10} \approx 0.60''$, comparable to the seeing-limited FWHM $\sim 0.5\text{--}0.6''$ of X-shooter spectroscopy data.

Evidence for the spatially larger, low-pressure nebula is visible in Image 10 in a few filters enhanced by emission lines. The best example is the narrow filter F167N, whose flux is strongly boosted by $[\text{O III}]\lambda 4958$. The posterior distribution of this line flux shows significant contribution from both inner and outer populations of clouds. In F167N, a compact component appears superimposed on a more extended component slightly offset to one side along the arc direction. Given that our spectral model predicts much smaller stellar and nebular continuum compared to $[\text{O III}]\lambda 4958$ in F167N (c.f. Figure 5.6), they probably correspond to the $[\text{O III}]\lambda 4958$ emission from the high-pressure and the low-pressure nebulae, respectively.

If we focus on the central compact stellar component, and assumes that it is enclosed within R_1 , the mean stellar surface density is

$$\Sigma_\star = \frac{M_{\star,1}}{\pi R_1^2} = 1.9 \times 10^5 \frac{M_\odot}{\text{pc}^2} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_\odot} \right) \left(\frac{R_1 \sqrt{\mu_9}}{10^{20.0} \text{ cm}} \right)^{-2}, \quad (4.5)$$

independent of the uncertain magnification μ_9 . This is on the order of the maximum surface density $\Sigma_\star \simeq 10^5 M_\odot \text{ pc}^{-2}$ observed in local Universe stellar systems (Hopkins et al., 2010; Krumholz, McKee, and Bland-Hawthorn, 2019a), but a top-heavy IMF can lower this value.

The line-of-sight cloud velocity corresponding to a radius R_1 is

$$\begin{aligned} v(R_1) &= \left(\frac{G M_{\star,1}}{3 R_1} \right)^{\frac{1}{2}} \approx 90 \text{ km s}^{-1} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_\odot} \right)^{1/2} \\ &\times \left(\frac{R_1 \sqrt{\mu_9}}{10^{20.0} \text{ cm}} \right)^{-1} \left(\frac{\mu_9}{10} \right)^{-\frac{1}{4}}, \end{aligned} \quad (4.6)$$

where we exclude the extended stellar component as its size is significantly beyond R_1 . This is larger than the velocity dispersion of Milky Way globular clusters, but our inferred stellar mass $M_{\star,1}$, for a probably magnification factor $\mu_9 = 10$, is also more than an order of magnitude larger than that of the present-day Milky Way globular clusters. On the other hand, this is larger than the observed 40 km s^{-1} quoted by Vanzella et al., 2022b. Adopting a more top-heavy IMF will lead to a smaller $\mu_9 M_{\star,1}$, and hence a smaller $v(R_1)$, which may mitigate the discrepancy.

Nebula Mass and Column Density

Depending on the column density, the high-pressure clouds amount to mass

$$\begin{aligned} M_c &\simeq 1.4 \times 4\pi R_1^2 N_{\text{H}} m_p x_1 \\ &= 6 \times 10^5 M_{\odot} \left(\frac{N_{\text{H}}}{10^{23} \text{ cm}^{-2}} \right) \left(\frac{\sqrt{\mu_9} R_1}{10^{20.0} \text{ cm}} \right)^2 \\ &\quad \times \left(\frac{\mu_9}{10} \right)^{-1} \left(\frac{x_1}{0.4} \right), \end{aligned} \quad (4.7)$$

For a comparison, the cumulative stellar mass loss through massive star winds from the central stellar component, as predicted by the best-fit BPASS model up to $t_{\text{age}} = (3-4)$ Myr, is

$$\Delta M_{\star} = (1-2) \times 10^6 M_{\odot} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_{\odot}} \right) \left(\frac{\mu_9}{10} \right)^{-1}. \quad (4.8)$$

This is 2–4% of the initial stellar mass assuming the standard IMF.

We attempted to constrain the H I column N_{HI} from data by fixing cluster and nebula intensive parameters to the best-fit values but allowing extensive and geometric parameters to freely vary. Additionally, we varied $\log N_{\text{HI}} [\text{cm}^{-2}]$ from 21 to 24 in **Cloudy** calculations. We were however unable to obtain any significant constraint on N_{HI} , mainly because no emission lines that specifically probe the cool H I gas are available, and because dust attenuation through the H I column is strongly degenerate with extensive and geometric parameters. UV absorption lines are not useful either because the dusty clouds severely attenuate any UV light emerging from the shaded faces.

Nevertheless, dynamical consideration constrains N_{HI} for the high-pressure clouds. From the inferred ionizing photon flux striking the cloud surfaces $\Phi(\text{H}_0)$ for the high-pressure clouds, the H II gas has a thickness $\sim 0.02 \text{ pc}/(n_{\text{H}}/10^5 \text{ cm}^{-3})$ and a column $N_{\text{HII}} \sim 6 \times 10^{21} \text{ cm}^{-2}/(n_{\text{H}}/10^5 \text{ cm}^{-3})$. If the H II gas is density bounded, $n_{\text{H}} \sim 10^5 \text{ cm}^{-3}$ leads to a sufficient radiation pressure coupling with LyC photons that would rapidly eject the clouds out of the cluster potential compared to the free-fall timescale

$$\begin{aligned} t_{\text{ff}} &= \frac{\pi}{2} \left(\frac{R_1^3}{G M_{\star,1}} \right)^{\frac{1}{2}} \\ &\approx 10^5 \text{ yr} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_{\odot}} \right)^{-\frac{1}{2}} \left(\frac{R_1 \sqrt{\mu_9}}{10^{20.0} \text{ cm}} \right)^{\frac{3}{2}} \left(\frac{\mu_9}{10} \right)^{-\frac{1}{4}}. \end{aligned} \quad (4.9)$$

If instead the H II gas is ionization bounded, a minimum column $\log N_{\text{HI}} > 22.8$ is required for cluster gravity to counteract radiation pressure and retain the cloud (Fall, Krumholz, and Matzner, 2010; Murray, Quataert, and Thompson, 2010b; Krumholz, McKee, and Bland-Hawthorn, 2019a). For even larger N_{HI} , the bulk of the cloud would fall back to the cluster, but no faster than t_{ff} . For $23 < \log N_{\text{HI}} < 25$, dust reprocessed IR radiation trapped in the H

I gas may drive a slow outflow (Menon, Federrath, and Krumholz, 2022c), albeit the outflow velocity may be insignificant given the large escape velocity $v_{\text{esc}} \sim 100 \text{ km s}^{-1}$ involved here. Seeing short-lived clouds with a lifetime $< 10^5 \text{ yr}$ would appear unnatural given $t_{\text{age}} \lesssim 4 \text{ Myr}$, unless these clouds are continuously replenished.

The dusty cloud interior should cool down to a low temperature typical of molecular clouds, with an increased density $\sim 10^6\text{--}10^7 \text{ cm}^{-3}$ as a result of pressure equilibrium. The high-pressure clouds have a typical thickness

$$l = 0.03 \text{ pc} \left(\frac{N_{\text{H}}}{10^{23} \text{ cm}^{-2}} \right) \left(\frac{n_{\text{H}}}{10^6 \text{ cm}^{-3}} \right)^{-1}. \quad (4.10)$$

Since the dusty interior can cool down to very low temperatures, the pressure support in the cloud interior is likely dominated by turbulence (McKee and Tan, 2003). In this case, Eq. (4.10) holds whether or not the interior is atomic or molecular. Clouds are out of virial equilibrium and subject to collapse for pressures $P3\pi G \Sigma^2/20$ (Krumholz, McKee, and Bland-Hawthorn, 2019a). Correspondingly, if the high-pressure clouds have a column $N_{\text{H}} \gtrsim 0.9 \times 10^{24} \text{ cm}^{-2} (P_1/10^9 \text{ K cm}^{-3})^{1/2}$ and survive long enough near the star cluster, they can form stars internally. At this value of N_{H} , the total cloud mass may be too large to come entirely from cluster mass loss (c.f. Eq. (4.8)), and the clouds would have to be a mixture of stellar ejecta and leftover natal gas.

A delicate balance between outward radiation pressure and inward gravity may be unrealistic. If a cloud migrates to a different radius from the cluster center, the characteristic ambient pressure will change, which will in turn result in a pressure change in the cloud neutral interior. Assume that the ambient pressure scales with cluster-centric radius r as $P \propto r^{-\alpha}$ with $\alpha > 0$. If this pressure scale is set by radiation pressure, for instance, we may have $\alpha = 2$. If the dust-shielded, cold cloud interior is supported by either thermal pressure at a fixed temperature, or by turbulence at roughly a fixed velocity dispersion, the particle number density will scale as $n \propto r^{-\alpha}$, and the mass column density will scale as $\Sigma \propto r^{-2\alpha/3}$ under the assumption that the cloud geometry maintains an order-unity aspect ratio. This means that $P/\Sigma^2 \propto r^{\alpha/3}$. If gravity overcomes radiation pressure and pulls a cloud to a smaller r , it further pressurizes and the threshold for Jeans instability is easier to reach. Conversely, if radiation pressure overcomes gravity and pushes the cloud outward, the cloud will expand and will never form stars. If the observed high-pressure clouds can survive other possible mechanisms of shattering or destruction and sink toward the cluster center due to its weight, they may form stars internally.

When the star cluster is mass segregated, the most intensely radiating stars cluster in the core. In this situation, radiation pressure increases more steeply than gravity at distances smaller than the cluster's outer edge. We note that this may allow an intermediate range of distances where the balance between radiation pressure and gravity could be stable for clouds of suitable column density.

For a realistic cloud geometry radiation likely manages to expel peripheral parts of the clouds along low column density sight-lines even if the cloud bulk is retained by gravity (Yeh and Matzner, 2012; Thompson and Krumholz, 2016; Raskutti, Ostriker, and Skinner, 2017).

Without replenishment, the clouds are not expected to survive for many millions of years. It would be interesting to observationally determine N_{H} in order to better understand the dynamical origin and fate of the pressurized dusty clouds.

Nebula Pressure

For the high-pressure clouds, the ionizing flux $\log \Phi_1(\text{H}^0) \approx 14.3_{-0.2}^{+0.3}$ imparts a radiation pressure $\log P_{1,\text{rad}} = 9.0\text{--}9.5$. Further including dust absorption of UV light increases the total radiation pressure by about three fold to $\log P_{1,\text{rad}} = 9.5\text{--}10.0$. Compression by radiation appears to be a viable dynamical origin for the high-pressure clouds within our inference uncertainty. For our best-fit incident SED, external radiation pressure equals H II gas pressure if $\log U_1 = -1.4$. From C III] $\lambda\lambda 1908, 1906$ line ratio, the H II density $\log n_e \approx 5$ (Kewley et al., 2019) at $T_e = 15000$ K corresponds to a gas pressure $\log P_{1,\text{gas}} \approx 9.5$. The high-pressure clouds are in the regime where external radiation pressure is comparable or slightly higher than the H II gas pressure.

For the low-pressure clouds, on the other hand, the ionizing flux $\log \Phi_2(\text{H}^0) \approx 11.5_{-0.3}^{+0.3}$ converts into a radiation pressure $\log P_{2,\text{rad}} \approx 6.6\text{--}7.2$, which is subdominant than the inferred total pressure $\log P_2$. Radiation pressure therefore appears dynamically unimportant for the low-pressure clouds.

Another possible source of confining pressure is kinetic feedback from stellar winds and SN explosions (Koo and McKee, 1992a; Koo and McKee, 1992b; Rogers and Pittard, 2013; Calura et al., 2015; Wareing, Pittard, and Falle, 2017), and other means of cluster mass loss (de Mink et al., 2009). Taking $Z = 0.2 Z_{\odot}$ and at $t_{\text{age}} = 2\text{--}4$ Myr, the BPASS (v2.2) model predicts a total mass loss rate

$$\dot{M}_{\star,1} \approx 1 M_{\odot} \text{ yr}^{-1} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_{\odot}} \right) \left(\frac{\mu_9}{10} \right)^{-1}, \quad (4.11)$$

and a total mechanical luminosity dominated by the first SN explosions (onset at $t_{\text{age}} \approx 3$ Myr)

$$L_{\text{mech}} \approx 6 \times 10^{41} \text{ erg s}^{-1} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_{\odot}} \right) \left(\frac{\mu_9}{10} \right)^{-1}. \quad (4.12)$$

If the first SNe have not yet exploded, pure wind contributions to L_{mech} would be a factor of ~ 5 smaller. If these mass loss thoroughly thermalizes to drive a supersonic, non-radiative cluster wind (Chevalier and Clegg, 1985; Cantó, Raga, and Rodríguez, 2000; Wunsch et al., 2011; Silich et al., 2011), the wind reaches a velocity $v_w = (2 L_{\text{mech}} / \dot{M}_{\star,1})^{1/2} \approx 1400 \text{ km s}^{-1}$, with uncertainty on μ_9 and $M_{\star,1}$ canceling out. If the cluster wind is fully blown well within

radius R_1 , it should exert a ram pressure on the high-pressure clouds:

$$P_{\text{ram}} = \frac{\dot{M}_{\star,1} v_w}{4\pi R_1^2} = 3.8 \times 10^9 \text{ K cm}^{-3} \left(\frac{\mu_9 M_{\star,1}}{10^{8.8} M_{\odot}} \right) \times \left(\frac{R_1 \sqrt{\mu_9}}{10^{20.0} \text{ cm}} \right)^{-2} \left(\frac{v_w}{1400 \text{ km s}^{-1}} \right). \quad (4.13)$$

This is comparable to the inferred total pressure P_1 or the expected radiation pressure. Theoretical studies have suggested that for a very compact, massive star cluster the cluster wind may be subject to efficient or even catastrophic radiative cooling (Silich, Tenorio-Tagle, and Rodríguez-González, 2004b; Wünsch et al., 2011; Gray et al., 2019; Daneshkar, Oey, and Gray, 2021; Lochhaas and Thompson, 2017; Wünsch et al., 2017), which can further reduce kinetic feedback, which we investigate further in the next sub-section.

Nitrogen Enrichment

The N III] multiplet near 1750 Å (Feldman and Doschek, 1979) is not commonly reported as a strong UV line from H II nebulae as N is significantly less abundant than O and C in the ISM. Among a sample of 45 analogs of high- z starburst galaxies at $0.002 < z < 0.182$ from the CLASSY survey (Berg et al., 2022), there is only one strong detection of this multiplet from the blue compact dwarf galaxy Mrk 996, and a lower significance detection in $S/N \sim 3$ from another system (Mingozzi et al., 2022). The N III] detection in Mrk 996 is toward the nuclear region and indicates hugely enhanced N abundance $\log(N/O) = 0.0$ possibly related to ejecta from WN stars. However, a large velocity dispersion $\sim 450 \text{ km s}^{-1}$ is associated with the N III] emitter (Thuan, Izotov, and Lipovetsky, 1996), and it is unclear whether the example in Mrk 996 shares a similar origin from nebulae around a super star cluster as in Sunburst. On the other hand, a three-fold N enrichment $\log(N/O) = -0.85$ localized to a few super star clusters is reported in NGC 5253 (**Kobulnicky1997NGC5253**; López-Sánchez et al., 2007).

The detection of N III] $\lambda\lambda 1750, 1752$ in this paper, with $\log(N/O) = -0.21_{-0.11}^{+0.10}$, is localized to the LyC cluster vicinity but unseen in other parts of the arc. Mestric et al., 2023 mentioned the detection of N III] $\lambda 1750$ from the LyC cluster without giving further comments. The facts that (1) the $\lambda\lambda 1750, 1752$ lines show as the strongest among all five transitions of the N III] multiplet and (2) the observed line ratio $\lambda 1750/\lambda 1752 \approx 2$ are consistent with the inferred density of the high-pressure clouds. This indicates an N abundance that is increased by ~ 12 – 19 fold relative to the median interstellar N abundance $\log(N/O) \approx -1.4$ at $Z \approx 0.2 - 0.3 Z_{\odot}$ (Mollá et al., 2007; Berg et al., 2019) in the very vicinity of the star cluster, a scenario previously theorized by Izotov et al., 2006. This level of N enrichment is higher than what is found near several super star clusters in NGC 5253 (Kobulnicky and Kewley, 2004), and the N/O ratio is higher than what is observed from extragalactic H II regions in low metallicity emission (see Fig. 11 of Izotov et al., 2006). In contrast to the $z \approx 0$ HII regions, the nitrogen enhancement we find in the nebular gas is comparable to

that seen in post-turnoff dwarf stars of Milky-Way’s globular clusters such as NGC 6752 (Carretta et al., 2005).

Shortly after the completion of this work, four pre-prints have appeared and have examined remarkably strong nitrogen emission lines seen in GN-z11, a $z \approx 11$ galaxy confirmed through JADES NIRSpec IFU spectroscopy (Bunker et al., 2023; Cameron et al., 2023; Senchyna et al., 2023; Charbonnel et al., 2023). Using **Cloudy** photoionization calculations, Senchyna et al., 2023 showcase a similarly high density $n_e \gtrsim 10^5 \text{ cm}^{-3}$ for photoionized gas, and a high nebular N abundance $\log(\text{N/O}) \sim -0.25$ at a gas metallicity of $Z \approx 0.1Z_\odot$. This object may be a high-redshift, high-mass (stellar mass $\sim 10^8\text{--}10^9 M_\odot$ Bunker et al., 2023) version of the enrichment processes seen in Sunburst. Figure 4.11 shows the inferred LyC cluster nitrogen abundance compared to GN-z11, as well as to individual chemically anomalous stars in a local globular cluster, local star forming galaxies, and local HII regions.

We surmise that heavy N enrichment might be typical in the vicinity of very young super star clusters, and is indicative of either pollution of natal gas by WN stars or LBVs, or condensation solely from the wind material of those stars, or even ejecta from interacting binary massive stars (de Mink et al., 2009), which happens as early as $\sim 3\text{--}4$ Myr after the onset of star formation. The CNO cycle $^{14}\text{N}(p, \gamma)^{15}\text{O}$ bottleneck causes efficient conversion of C and O to N, such that ejecta mixed up with H-burning-processed material can be significantly N enhanced but is expected to have a conserved sum of C, N and O. Given the solar C:N:O ratio of 4:1:7, complete conversion of C and O into N can cause up to 12-fold increase in the absolute abundance of N in ejected material. Since the observed photoionized gas does not show extreme depletion of C and O abundances relative to elements like Ne, the CNO-processed material must mix with other chemically normal gas. The observed high N/O $\sim 0.5\text{--}0.8$ indicates that the CNO-processed material accounts for an order-unity mass fraction of the dense gas (also see Figure 1 of Charbonnel et al., 2023). Since we have estimated that the mass of the dense, N-enriched gas is substantial compared to the total massive star mass loss (Eq. (4.7)) based on the arguments of column density and efficient turbulence mixing (see the remainder of this sub-section), we suggest that high N abundance is evidence for radiation-hydrodynamic processes that have caused massive star ejecta to efficiently condense and be retained in the cluster potential.

High-pressure clouds condensed solely out of cooled SN ejecta is not favored since the high-pressure clouds do not appear rich in oxygen and carbon. The inferred cluster age constraint $t_{\text{age}} \lesssim 4 \text{ Myr}$ makes it unclear whether the first SNe have exploded (perhaps up to this age all massive stars have collapsed to black holes without ejecting significant amount of O, Mg, Si and Fe as SNe with lower-mass progenitors do), and if SNe do have exploded, whether the SN ejecta remains hot and quickly leaks out of the cluster vicinity via low density channels (Lopez et al., 2011; Rogers and Pittard, 2013; Rogers and Pittard, 2014). At radius R_1 , the escape velocity out of the cluster’s potential $v_{\text{esc}}(R_1) \sim 220 \text{ km s}^{-1}$ (a factor of $\sqrt{6}$ larger than Eq. (4.6)) is slow compared to that of the typical O-star/WR-star wind or a fully blown, hot cluster superwind. However, rapid radiative cooling may provide a route for retention of these ejecta. We follow the semi-analytic approach of Lochhaas and Thompson, 2017 to assess whether the cluster is in a regime where radiative cooling will

retain rejecta within the cluster radius R_1 . We assume the mass loss rates and mechanical luminosities given in Eq. (4.11) and Eq. (4.12) respectively, which we find are consistent with the linear scalings used by Lochhaas and Thompson, 2017. We use the same cooling function for $T > 10^5$ K from Draine, 2011a as used in Lochhaas and Thompson, 2017, but, following Mac Low and McCray, 1988, scale the cooling rate linearly with metallicity such that $\Lambda_0 \simeq 4.4 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^3$ for $Z \simeq 0.2Z_\odot$. Given these assumptions and assuming a thermalization efficiency $\alpha \simeq 0.1$ for merged stellar winds from individual stars and a conservative mass-loading factor of order unity (see discussion earlier in this subsection), we solve Eq.(14) in Lochhaas and Thompson, 2017 and find that it is possible for ejecta from hot massive star winds to cool and be retained within a radius R_1 for the LyC star cluster. However, given the likely small mass-loading factor of the nebula, it cannot be ruled out that a larger thermalization efficiency or a larger magnification factor could push the system out of the regime of catastrophic radiative cooling.

Slow outflows from massive rotating stars may also provide a suitable enrichment mechanism. This may be in the form of a single massive star rotating near its critical velocity, where rotational mixing causes dredge-up of heavy elements from the inner convective zone and allows for envelope material to be liberated in a slow wind (Roy et al., 2022).

Finally, ejecta from non-conservative binary mass transfer may also explain the observed Nitrogen enrichment (de Mink et al., 2009). A massive star may shed nearly half of the mass in interaction with a lower mass companion. The companion may then spin up to almost the critical rotation velocity as it accretes from the donor star and stops to accept transferred material. This then causes an outflow of H-burning processed material from the inner layers of the donor star, typically with a slow outflow velocity comparable to the binary orbital velocities.

In our best-fit model, the high-pressure clouds have a thickness given by Eq. (4.10), so that turbulent motion $\sigma \approx (P_1/n_H m_p)^{1/2} \approx 4 \text{ km s}^{-1} (n_H/10^6 \text{ cm}^{-3})^{-1/2}$ should quickly mix N throughout the cloud on a timescale

$$t_{\text{mix}} \approx \frac{l}{\sigma} = 8000 \text{ yr} \left(\frac{N_H}{10^{23} \text{ cm}^{-2}} \right) \left(\frac{n_H}{10^6 \text{ cm}^{-3}} \right)^{-\frac{1}{2}}. \quad (4.14)$$

Given the high $\log(\text{N/O})$ and the estimated total mass for the high-pressure clouds Eq. (4.7), if the clouds are gravitationally retained, we estimate a total nitrogen mass under the assumption of thorough mixing

$$\begin{aligned} M_N \approx & 500 M_\odot \left(\frac{N_H}{10^{23} \text{ cm}^{-2}} \right) \left(\frac{\mu_9^{1/2} R_1}{10^{20.0} \text{ cm}} \right)^2 \\ & \times \left(\frac{\mu_9}{10} \right)^{-1} \left(\frac{x_1}{0.4} \right) \left(\frac{\text{N/O}}{0.6} \right) \left(\frac{Z}{0.2 Z_\odot} \right). \end{aligned} \quad (4.15)$$

Until 3 Myr, about $8400 (\mu_9 M_{*,1}/10^{8.8} M_\odot) (\mu_9/10)^{-1}$ stars more massive than $140 M_\odot$ should have evolved to the end of their lives (Bressan et al., 2012). By 4 Myr, the minimum mass

becomes $60 M_{\odot}$ and the number becomes $3.6 \times 10^4 (\mu_9 M_{\star,1}/10^{8.8} M_{\odot}) (\mu_9/10)^{-1}$. For an average nitrogen yield $(0.01\text{--}0.1) M_{\odot}$ from each such star (Prantzos et al., 2018), the maximum nitrogen pollution should be about $\sim (84\text{--}3600) M_{\odot} (\mu_9 M_{\star}/10^{8.8} M_{\odot}) (\mu_9/10)^{-1}$, the estimate of which is insensitive to IMF assumptions. The high-pressure clouds therefore appear to have retained an order-unity fraction of the ejected nitrogen. As we have argued before, an order-unity fraction of the cloud gas must have originated from massive star ejecta to account for the observed enhancement. Given the expected nitrogen budget, Eq. (4.15) suggests that $\log N_{\text{H}} \gtrsim 24$ is unlikely unless the clouds are not well mixed and are only partially polluted with nitrogen on the illuminated side which includes the H II zone. The column density of the high-pressure clouds may barely reach the threshold of secondary star formation without violating the nitrogen budget constraint, unless they pressurize further.

4.8 Conclusion

High SNR archival data owing to large gravitational magnifications has enabled us to closely study a newborn, LyC-leaking super star cluster in the Sunburst galaxy at Cosmic Noon. We have used the BPASS stellar population SED templates that account for radiation from binary stars. Using these templates as the input, we have computed the observed spectrum from the system by performing self-consistent photoionization calculations using Cloudy, taking into account the dependence on nebula pressure, incident radiation strength, and nebula geometry. We have constructed a grid of spectral models from these calculations and have applied them to inferring physical parameters describing the super star cluster (summarized in Table 5.4).

We have demonstrated that a detailed, physically motivated photoionization model can be constructed for a super star cluster surrounded by photoionized clouds, and that a joint photometric and spectroscopic analysis enables comprehensive extraction of key physical parameters despite the tremendous cosmic distance to the source.

We have determined that the LyC cluster is very massive ($M_{\star} \sim \text{few} \times 10^7 M_{\odot}$), $\lesssim 4$ Myr old, and has a sub-solar metallicity $Z \approx 0.2 Z_{\odot}$. Little dust was detected from the large-scale ISM of the host galaxy (see §6.1 and Figure 5.7). Assuming the standard IMF, the cluster’s surface stellar mass density is on the order of the maximum observed in massive stellar systems in the local Universe, $\Sigma \sim 10^5 M_{\odot} \text{ pc}^{-2}$ (Hopkins et al., 2010).

We have shown that the cluster stars irradiate highly-pressurized ($P \sim 10^9 \text{ K cm}^{-3}$), probably density-bounded photoionized clouds located $\lesssim 10 \text{ pc}$ away from the cluster center (§6.2, Figure 5.8). The clouds show normal C/O and Ne/O abundance ratios but appear highly enriched with nitrogen, having $\log(\text{N/O}) \approx -0.21$ (§6.4, Figure 4.8). The clouds also exhibit depleted gas-phase Si and likely have self-shielded, dusty interior. To avoid rapid ejection from the system by radiation pressure, these clouds must have large enough column densities and hence amount to at least a few $\times 10^5 M_{\odot}$ of gas, and $\sim 500 M_{\odot}$ of nitrogen if chemically thoroughly mixed with a typical thickness of $\sim 0.03 \text{ pc}$. This requires efficiently retaining nitrogen from condensed massive star ejecta as up to 4 Myr stars heavier than

$60 M_{\odot}$ can yield up to $3600 M_{\odot}$ of nitrogen in optimistic estimates (see §7.4). Detection of optical [O II] doublet which requires a low ionization condition implies that a less dense nebula extends to tens of pc or beyond, and might have already been resolved in a few emission-line dominated HST filters. We have found that nitrogen is probably not as significantly enriched in this low-density component. While in our modeling we have introduced two cloud populations with disparate properties, it might as well be that there is a continuous distribution of photo-ionized clouds, with decreasing pressure, density and ionization parameter as the cluster-centric distance increases. Through modeling the nebula emission relative to direct star light, we have inferred that (10–50)% of the ionizing radiation escapes the cluster’s vicinity along unblocked sight lines, and that this fraction is as high as (30–70)% along our sight line (§6.3, Figure 4.7), consistent with previous works (Rivera-Thorsen et al., 2019).

The origin of the high-pressure clouds probably connects to radiation-hydrodynamic evolution of massive star winds, SNe, or binary ejecta from massive stars in the cluster potential. Mass loss mechanisms that predominantly produce slowly moving ejecta ($\lesssim 300 \text{ km s}^{-1}$) are favored. The inferred element abundance is more consistent with pollution by nitrogen-enriched H-burning-processed material than oxygen-rich He-burning-processed material. Since observational selection by strong lensing is likely independent of these source properties, we suggest that this phenomenon may be commonplace in the vicinity of newborn super star clusters. We have argued that these clouds likely have a large column density $N_{\text{H}} \gtrsim 10^{22.8} \text{ cm}^{-2}$. They might allow star formation in their interior if $N_{\text{H}} \gtrsim 10^{24} \text{ cm}^{-2}$, or if they sink further toward the cluster in the future. It is intriguing to ponder the question whether the nitrogen enriched gas connects to the puzzle of multiple stellar populations in GCs (Lochhaas and Thompson, 2017; Wünsch et al., 2017), as second-generation GC stars often exhibit elevated N abundance (Bastian and Lardo, 2018; Roy et al., 2022).

There are future observational prospects for the Sunburst galaxy to determine the physical origin of the dense photoionized clouds. Upcoming JWST imaging and spatially resolved spectroscopy (GO #2555; PI: T. E. Rivera-Thorsen) in near-IR will complement existing HST data and will put our nebula model to further test. It would be an interesting possibility to determine the column density of the dusty H I component or even detect a molecular component with JWST/MIRI or ALMA. Moreover, deep Chandra X-ray observations might constrain cluster wind/ejecta radiative cooling and determine whether radiation feedback is more important than kinetic feedback in the system.

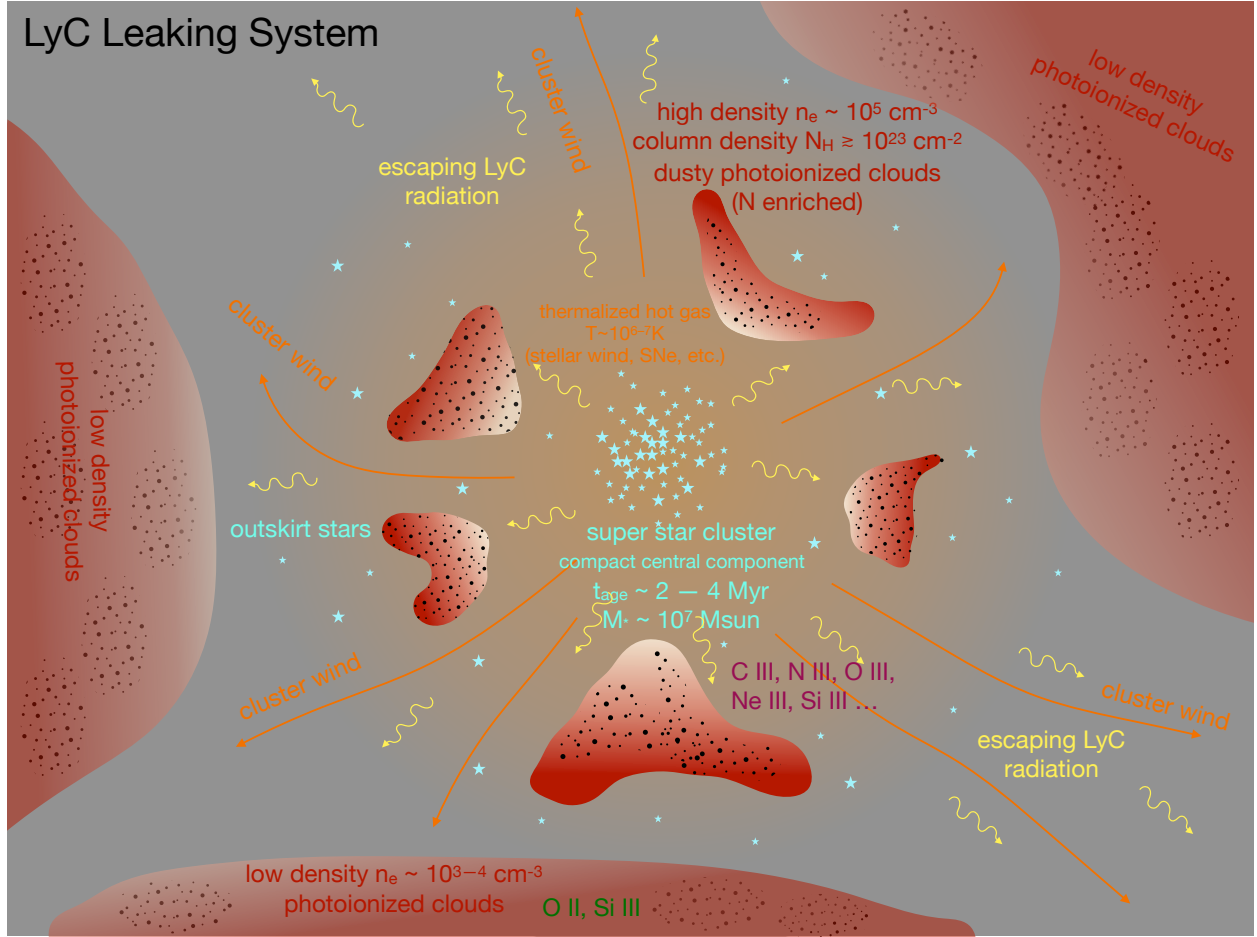


Figure 4.1 A cartoon illustrating a physical picture for the LyC leaking star cluster of Sunburst Arc derived from joint analysis of photometry and spectroscopy data. The central energy source, a super star cluster of $t_{\text{age}} \lesssim 4$ Myr old, consists of a compact central component and an extended component of outskirt stars. Mass and kinetic energy output from both massive star winds and probably the first SN explosions thermalize and create a hot ($T \sim 10^6\text{--}10^7$ K) cluster gas that blows out as a supersonic cluster wind. Pressed by stellar radiation (and possibly by the cluster wind), high-pressure ($n_e \sim 10^5 \text{ cm}^{-3}$ and $P \sim 10^9\text{--}10^{10} \text{ K cm}^{-3}$) clouds of large column density $N_{\text{H}} \gtrsim 10^{23} \text{ cm}^{-2}$ linger close to the cluster at $\sim 5\text{--}10$ pc, and are subject to a competition between outward pressure force and inward gravitational pull. Photoionized by the stars, these emit strong nebular lines from high-ionization ionic species, is chemically enriched by massive star ejecta, and is dense enough for dust formation. More clouds at lower densities ($n_e \sim 10^3\text{--}10^4 \text{ cm}^{-3}$ and $P \sim 10^{7\text{--}8} \text{ K cm}^{-3}$) exist at large distances, where nebular lines from low-ionization ionic species are excited. Photoionized clouds do not completely surround the star cluster, and a fraction of the LyC radiation escapes the system via low-density channels.

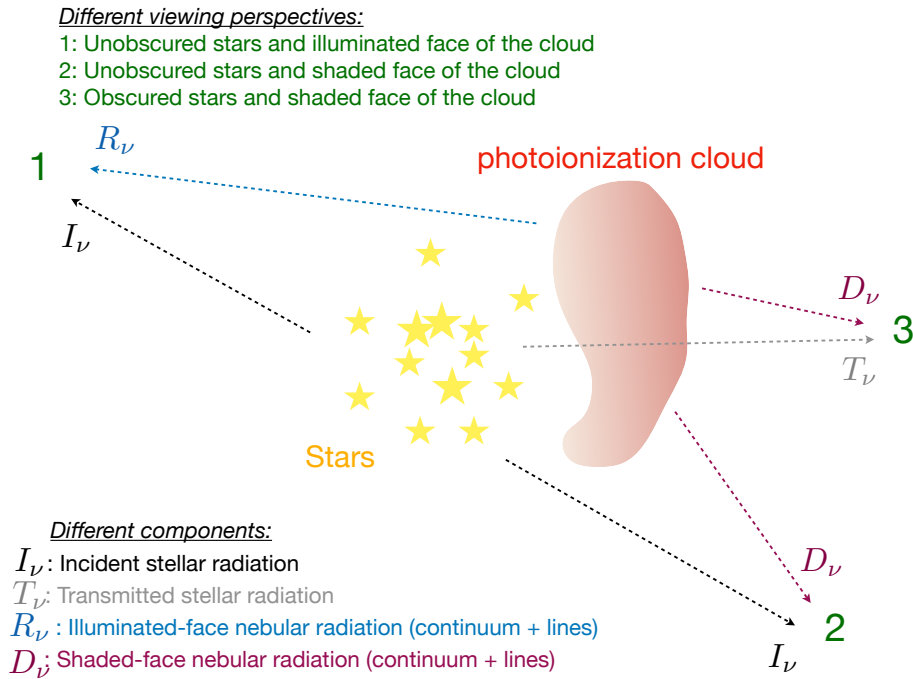


Figure 4.2 Effect of viewing angle on the observed spectrum. There are three generic viewing perspectives: (1) the observer sees unobscured stellar radiation I_ν , as well as radiation R_ν emerging from the illuminated faces of photoionized clouds; (2) the observer sees unobscured stellar radiation I_ν , as well as radiation D_ν emerging from the shaded faces of clouds; (3) the observer sees stellar radiation T_ν transmitted through the clouds, as well as radiation D_ν emerging from the shaded faces of the clouds.

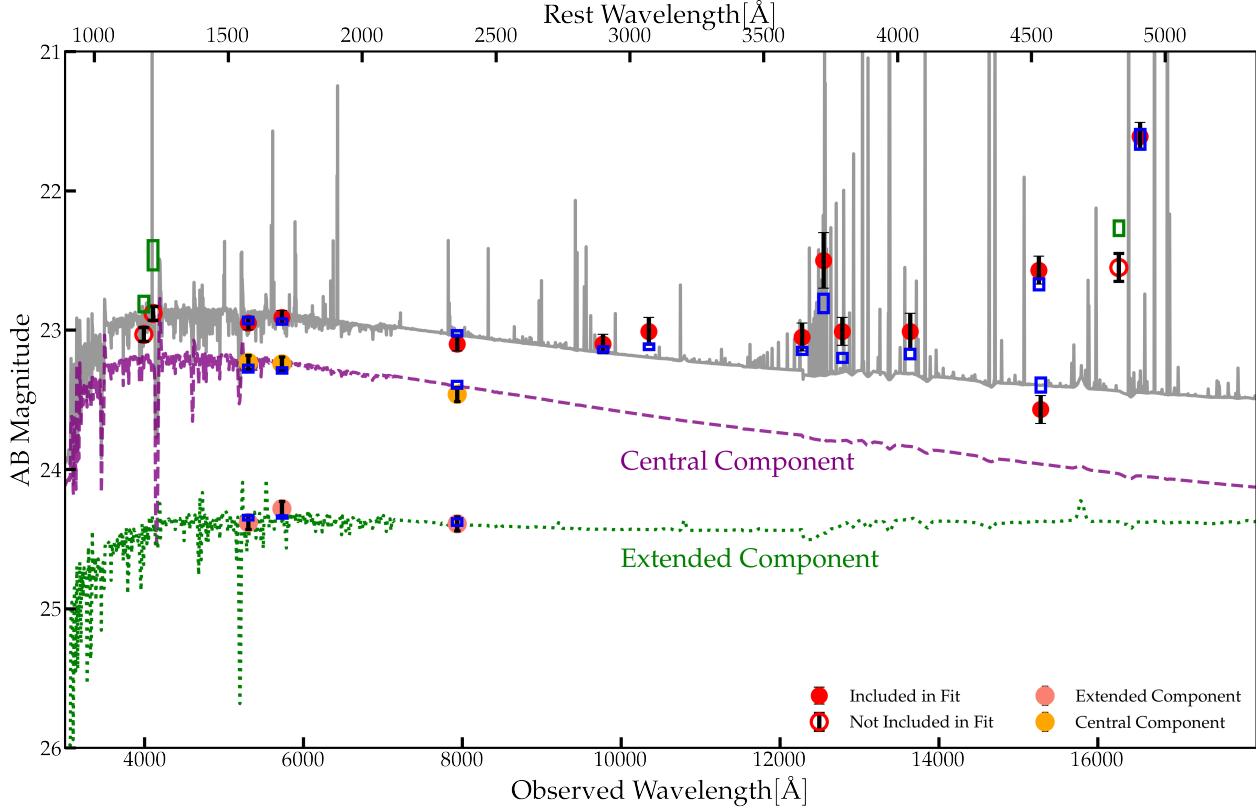


Figure 4.3 Best fit SED (grey) from `Cloudy` modeling. Co-plotted is the 68% C.I. range of the model predicted filter magnitude (open boxes) and the observed magnitude (circles with error bars). Two of the bluest filters F390W and F410M (open circles and green boxes) are not used in the fit since the flux might have been significantly affected by $\text{Ly}\alpha$ line formation and damping wing scattering by an intervening H I column. The fitted models predict fluxes higher than observed in these two filters. The narrow-band F164N filter is also not used due to potential flux calibration issues. The observed magnitudes of the extended and central component from image 10 are shown demagnified by the median predicted magnification ratio for each component applied (pink and orange circles with errors bars), as well as 68% C.I. range of the model predicted filter magnitudes demagnified in the same way (blue boxes). Best fit central (magenta) and extended (green) component continuum contributions are separately shown.

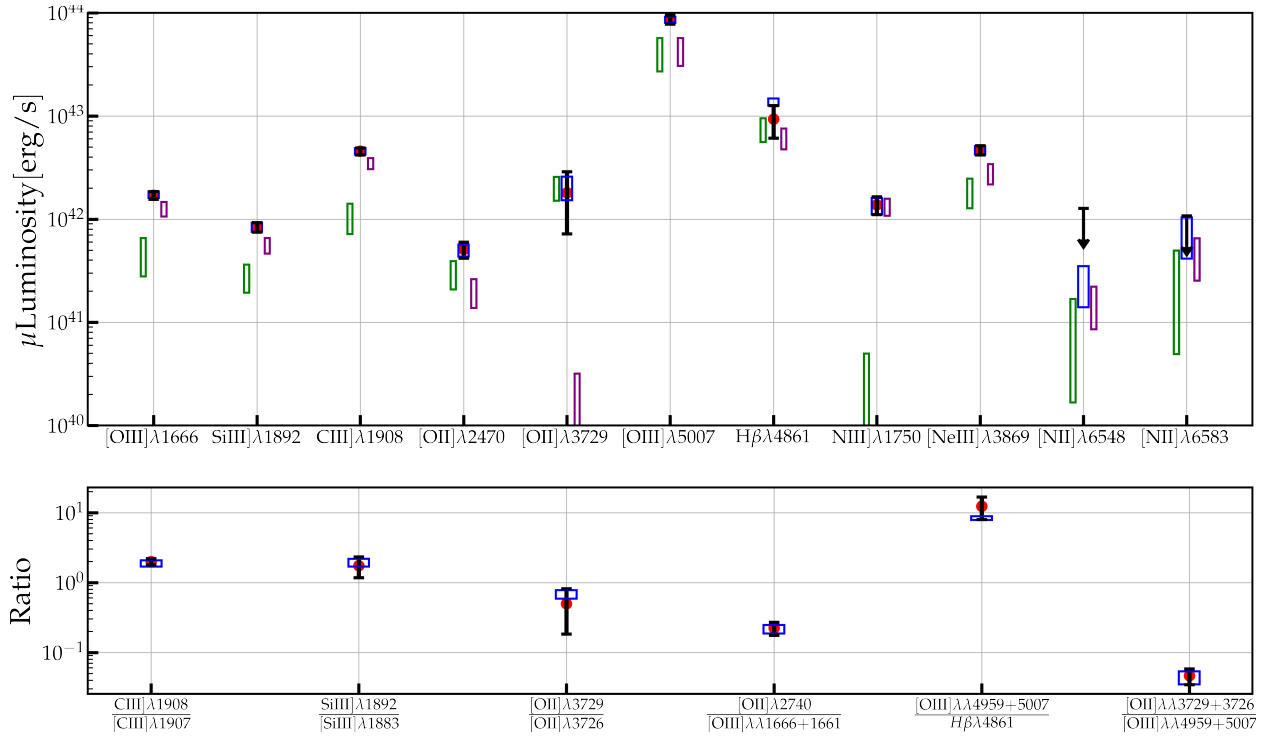


Figure 4.4 Top: 68% C.I. for model predicted line fluxes (blue boxes) and observed line flux measured from MUSE/X-Shooter (circles with errorbars). The 68% C.I. contributions from the high-pressure (purple boxes) and low-pressure (green boxes) clouds are shown separately. Bottom: 68% C.I. for model predicted line ratios (blue rectangles) and observed line ratios measured from MUSE/X-Shooter (red markers).

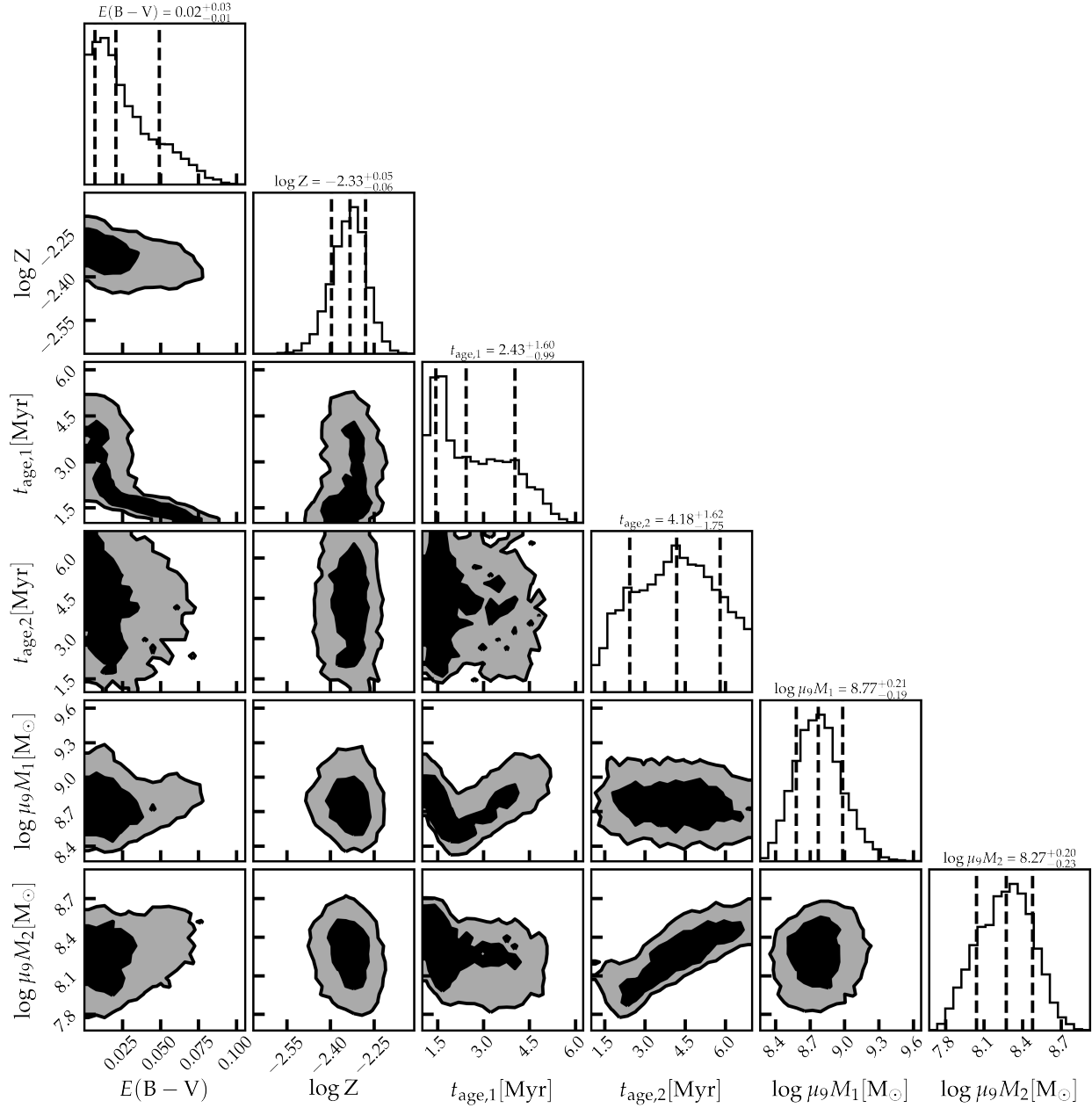


Figure 4.5 Posterior distributions for star cluster parameters. 1D histograms representing the posterior distributions are marked with the mean and 68% confidence intervals (C.I.'s, dashed lines). 2D contours show the 50% and 90% levels for the density of points from PyMultinest fitting. Refer to the “Two-Comp” model in 5.4 for the 68% C.I.'s of the parameters.

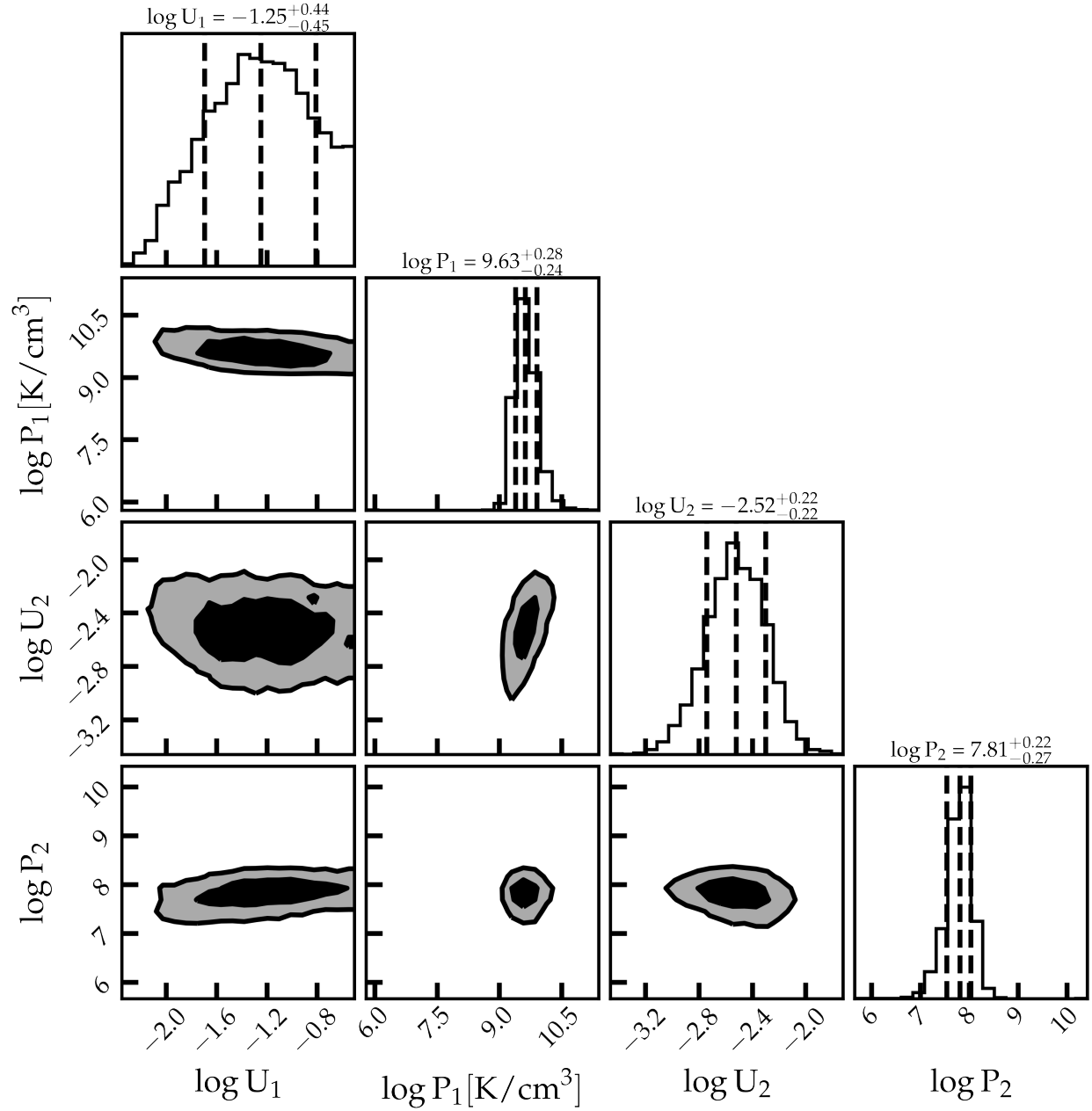


Figure 4.6 Posterior distributions for the measured physical parameters of the two cloud populations. Contours levels and histogram confidence intervals follow Fig. 5.7. Parameter 68% C.I.'s are tabulated in Table 5.4.

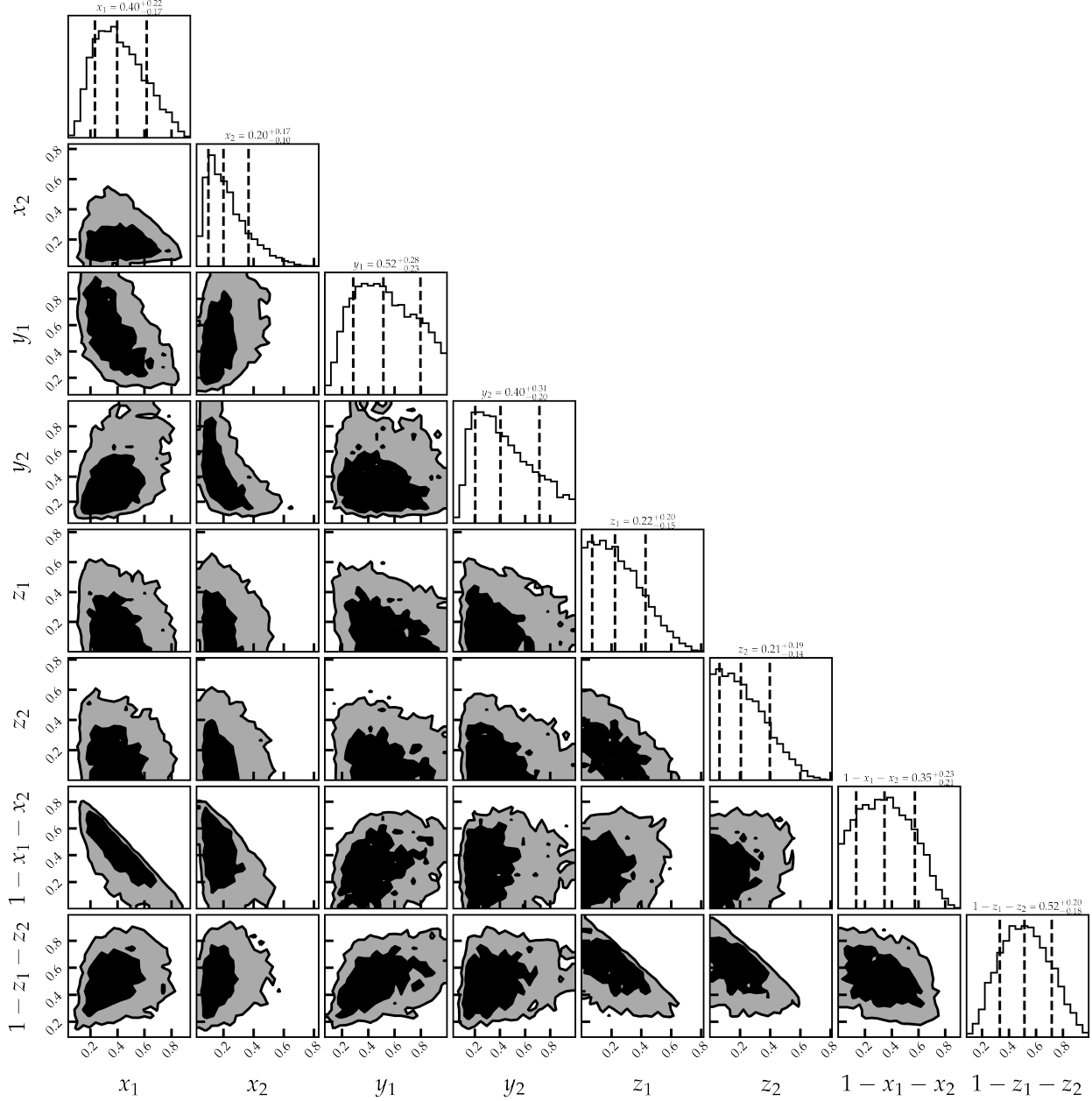


Figure 4.7 Posterior distributions for the measured geometric parameters of the two clouds, including covering factors, obscuring factors, and viewing angles. Contours levels and histogram confidence intervals follow Fig. 5.7. Refer to the “Two-Comp” model in Table 5.4 for the 68% C.I.’s of the parameters.

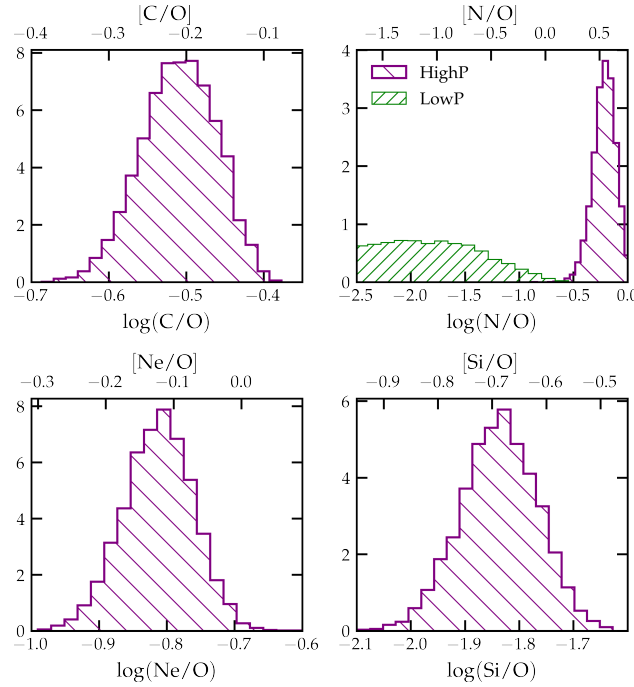


Figure 4.8 Posterior distributions for the gas-phase abundances of C, N, Ne and Si (arbitrary units for the vertical axis). We plot the absolute abundance on the bottom axis, and abundance relative to solar on the top axis. In the upper right panel, we observe high elevation of N abundance in the high-pressure clouds (purple) compared to the median ISM abundance at our inferred metallicity $Z \approx 0.2\text{--}0.3 Z_{\odot}$, which indicates enrichment by massive star ejecta. By contrast, the low-pressure, more distant clouds (green) cannot be as much enriched and are consistent with uncontaminated. We also observe significant Si depletion which is evidence for grain formation. C and Ne appear to have normal abundances. The results are also shown in Table 4.5.

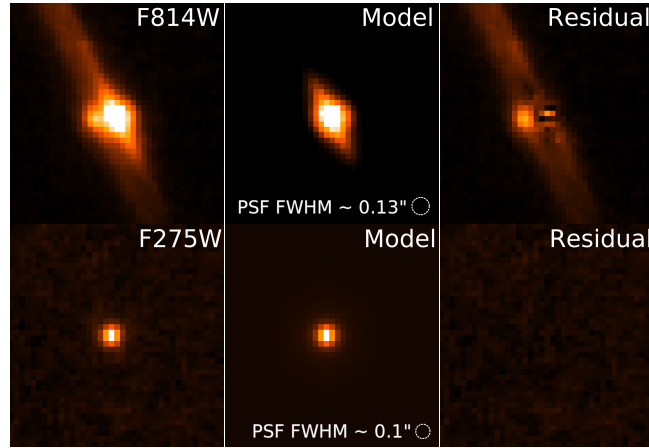


Figure 4.9 Spatially resolved modeling of Image 10. In the top panels, continuum image in F814W shows that stars in the LyC cluster can be modeled as the sum of a central unresolved component and an extended component modeled as a 1D Gaussian profile (due to lensing shear). The 1D Gaussian is centered at an angular separation $0.015'' \pm 0.001''$ away from the central component, with a Gaussian width $\sigma = 0.15'' \pm 0.01''$. However, in the F275W filter which probes escaping LyC radiation, the extended component is not visible. This implies that only LyC photons emitted from the central compact stellar component manage to escape.

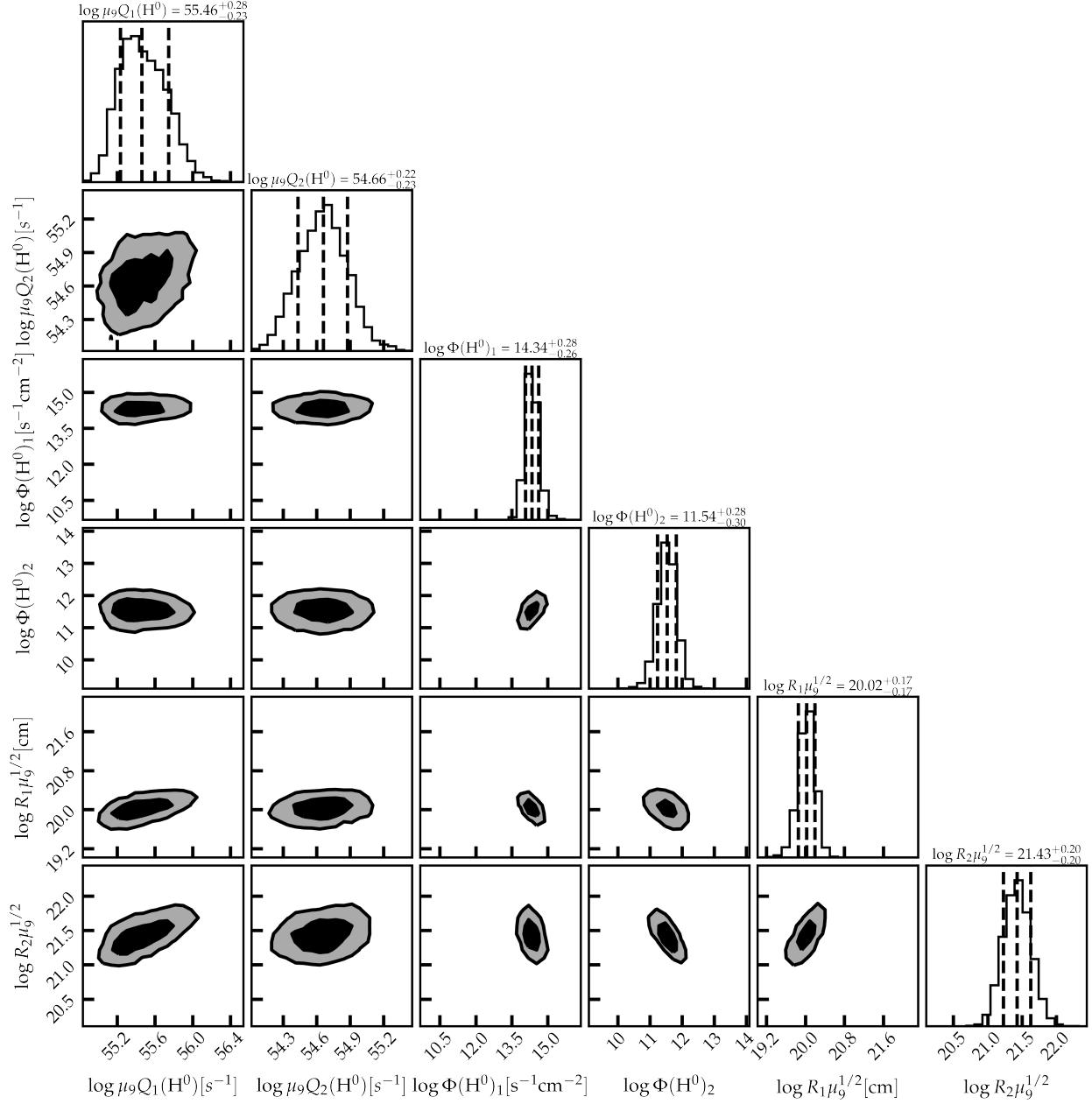


Figure 4.10 Posterior distributions for the measured ionizing photon rate, ionizing flux, and the typical distance from the cluster center for each cloud population. Contours levels and histogram confidence intervals follow Fig. 5.7. Refer to the “Two-Comp” model in Table 5.4 for the 68% C.I.’s of the parameters.

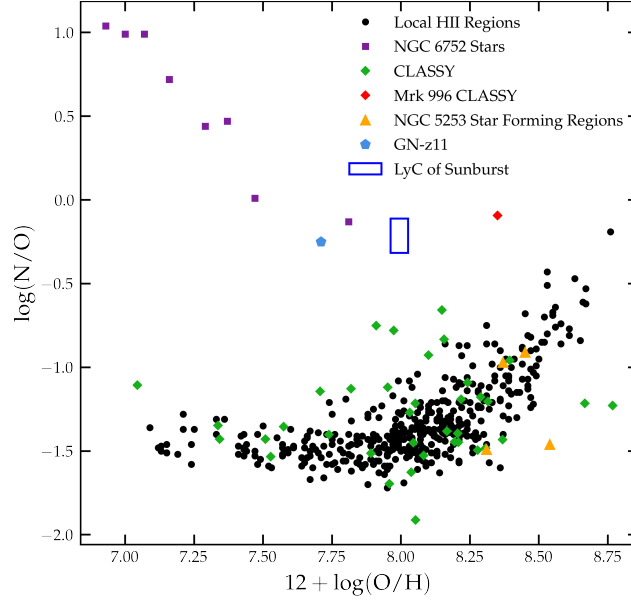


Figure 4.11 Nitrogen abundances of the LyC cluster compared to post-turnoff dwarf stars of local globular clusters NGC 6752 Carretta et al., 2005, star forming regions of NGC 5253 (López-Sánchez et al., 2007), local star forming galaxies Berg et al., 2022; Stephenson et al., 2023, CLASSY, and local HII regions in SDSS galaxies (Pilyugin, Grebel, and Mattsson, 2012). Our photoionization calculation infers a nitrogen abundance comparable to highest seen in local HII and star forming galaxies. Our measured abundance pattern falls on a diagonal line (which goes from upper left to lower right) that is traced by abundances measured from chemically anomalous dwarf stars in the Milky-Way globular cluster NGC 6752, which indicates the various degree of mixing between N-enriched gas and chemically normal gas. Finally, we also compare to GN-z11, a $z \sim 11$ galaxy hosting candidate globular cluster progenitors (Bunker et al., 2023; Cameron et al., 2023; Charbonnel et al., 2023; Senchyna et al., 2023).

Chapter 5

Retention of Massive Star Ejecta in Godzilla

The content of this chapter is drawn from Pascale and Dai, 2024, with permission from the co-authors.

5.1 Introduction

The Sunburst Arc, a Cosmic Noon Lyman- α emitter at $z_s = 2.37$ (Dahle et al., 2016) in the lensing field of the galaxy cluster PSZ1 G311.65-18.48 at $z_l = 0.443$ (Planck Collaboration et al., 2014), is a spectacular gravitationally magnified galaxy (Rivera-Thorsen et al., 2017; Rivera-Thorsen et al., 2019). With spectroscopic confirmation, the arc hosts an apparently unresolved source bright in rest-frame FUV ($m_{\text{F814W}} \approx 22$; Figure 5.1), which has been given the nickname “Godzilla” (Diego et al., 2022b).

Godzilla exhibits several enigmatic aspects. Much to the surprise of lens modellers, it has no confirmed counter lensed images elsewhere on the arc with comparable magnitudes, despite that multiple lens models predict so (Vanzella et al., 2020a; Pignataro et al., 2021; Diego et al., 2022b; Sharon et al., 2022b). This implies a compact source size, with a flux enhanced by invisible milli-lenses such as sub-galactic dark matter halos (Dai et al., 2020; Diego et al., 2022b; Diego et al., 2023b). Moreover, Godzilla shows a highly unusual nebular spectrum from rest-frame FUV to optical. Vanzella et al., 2020c first inferred extremely high electron density for the ionized gas $n_e \gtrsim 10^6 \text{ cm}^{-3}$ from CIII] $\lambda\lambda 1908, 1906$ and SiIII] $\lambda\lambda 1892, 1883$ line ratios, and commented on the striking weakness of hydrogen Balmer lines (Vanzella et al., 2020c). Vanzella et al., 2020c also detected rare Bowen fluorescence of Fe III lines pumped by Ly α radiation, implying an optically thick gaseous environment that efficiently traps but does not destroy Ly α photons.

Diego et al., 2022b considered multiple possibilities for the underlying nature of Godzilla, which include a bright stellar transient such as an ongoing luminous blue variable (LBV) magnified by $\sim 10^4$ fold, a hyper-luminous supermassive star, or a luminous accretion disk

around an intermediate mass black hole. Stringent limits on continuum photometric variability over the timescale of ~ 2 yr in the source frame constrain the transient scenario. Following the submission of this paper, a preprint by Choe et al., 2024 appeared, presenting new JWST NIRCам and NIRSpec IFU data. Choe et al., 2024 further explore the LBV scenario, detecting broad components to optical emission lines which were not detected from prior ground-based data. Choe et al., 2024 conclude that Godzilla may be a binary system consisting of a post-outburst LBV with an O4-O5 supergiant companion, mirroring the η Carinae system, however do not provide an investigation of the spectral energy distribution (SED) nor assessment of the necessary lensing magnification.

In this paper, we suggest that Godzilla is likely a compact young massive star cluster powering nebular emission, which we deem more probable as Sunburst is found to be vigorously forming stars in clusters (Vanzella et al., 2022b). Compared to the Lyman-continuum-leaking (LyC) star cluster in the same galaxy which has been extensively studied (Chisholm et al., 2019; Vanzella et al., 2022b; Mainali et al., 2022; Pascale et al., 2023; Kim et al., 2023; Mestric et al., 2023; Rivera-Thorsen et al., 2024), Godzilla shows a similar shape of the FUV continuum as well as prominent stellar wind features tracing O stars (e.g. C IV $\lambda 1550$ P Cygni profile; Figure 5.3), lending support to the star cluster interpretation. Narrow (FWHM $\lesssim 100$ km s $^{-1}$) emission lines of various metal ions (O II, O III, N III, C III, Ne III, Si III) are consistent with photoionization by O stars within a star-cluster-scale gravitational potential, but ions requiring more energetic ionizing sources such as an AGN are unseen. If our model is correct, detailed study of Godzilla will greatly deepen our understanding of feedback and self-enrichment from clustered star formation in dense environments at the culmination of cosmic star formation.

In this work, we perform a joint photometric and spectroscopic analysis using archival Hubble Space Telescope (HST) imaging and ground-based Very Large Telescope (VLT) MUSE and VLT/X-shooter spectroscopy. To infer the physical parameters of the system and the chemical abundances of the nebular gas, we follow a methodology which was successfully applied to the LyC cluster of the same galaxy in Pascale et al., 2023 (hereafter P23), fitting a spectral energy distribution (SED) to match broad-filter photometry and nebular emission line fluxes. Informed by this inference, we then construct a self-consistent physical model supported by the data.

Our modeling suggests that the cluster has an age ~ 4 –6 Myr and has a stellar metallicity similar to the Small Magellanic Cloud (SMC), consistent with the expectations from observed stellar wind features (Chisholm et al., 2019). Electron density diagnostics including the CIII] $\lambda\lambda 1908, 1906$ and SiIII] $\lambda\lambda 1892, 1883$ line ratios and the relative strengths between [O III] $\lambda\lambda 4959, 5007$ and [O III] $\lambda\lambda 1660, 1666$ confirm an unusually high density $n_e \sim 10^{(7-8)} \text{ cm}^{-3}$, corresponding to a pressure on the order $\log P [\text{K cm}^{-3}] \sim 11$ –12. Exciting such dense gas requires an enormous hydrogen ionizing photon flux $\log \Phi(\text{H}^0) [\text{s}^{-1} \text{ cm}^{-2}] \sim 15$ –16, which constrains the nebula to be smaller than ~ 1 pc and likely places it within the cluster. Remarkably, we find evidence of gas-phase abundance enhancement in N, C, O, and He, such that the nebula gas exhibits solar-like O/H, high N/O similar to high- z N-emitters (Marques-Chaves et al., 2024), yet sub-solar C/O, Si/O and Ne/O. We suggest this is due to self-enrichment

by massive star winds and core-collapse supernova (CCSN) ejecta, and corroborate this hypothesis through a comparison with synthetic light element yield models.

These remarkable properties may be a natural consequence of young star cluster evolution in the regime of high mass and high compactness. We develop a physical picture where the ejecta of winds and CCSNe stays inside the cluster through rapid radiative cooling (Wünsch et al., 2011; Wünsch et al., 2017), but is dynamically supported by supersonic turbulence driven by CCSNe. This physical picture, depicted in Figure 5.2, congruently interprets the unusual dataset; it can simultaneously explain the observed high electron density, high pressure, ionization parameter, and chemical abundances indicative of retention of stellar ejecta, and may provide the required gas geometry for Ly α -pumped Fe fluorescence.

The remainder of this paper will be organized as the following. In Section 5.2, we summarize the public imaging and spectroscopic datasets used in this work. In Section 6.4 and Section 7.3, we discuss how we will model broad-band photometry and emission lines for the star cluster and its nebula by applying BPASS stellar population synthesis models and Cloudy photoionization calculations. In particular, we will discuss how we extend our Cloudy calculations to allow for non-standard gas-phase element abundances. In Section 6.9, we present results for joint photometric and emission line fitting for two models and infer key physical and chemical properties of the star cluster and its ionized gas. In Section 5.6, we discuss the implications of our fitting results for the dynamics, chemical composition, and astrophysical origin of Godzilla’s nebula. In Section 5.7, we explore the possible magnification of Godzilla, setting upper limits on the basis of flux variability, and evaluating the probability of Godzilla being a single highly magnified, hyperluminous star. Concluding remarks will be provided in Section 7.5.

5.2 Data

In this section, we summarize the archival data used in this work: HST imaging data, VLT/MUSE IFU spectroscopy, and VLT/X-shooter slit spectroscopy.

HST Imaging

Observations for PSZ1 G311.65-18.48 were obtained across multiple programs between 2018 and 2020 (P.I. Dahle Program ID 15101, P.I. Gladders Program ID 15949, P.I. Bayliss Program ID 15377). In this work, we make use of observations publicly available on the MAST archive for 15 filters: WFC3/UVIS F390W, WFC3/UVIS F410M, WFC3/UVIS F555W, WFC3/UVIS F606W, ACS/WFC F814W, WFC3/UVIS F098M, WFC3/IR F105W, WFC3/IR F125W, WFC3/IR F126N, WFC3/IR F128N, WFC3/IR F140W, WFC3/IR F153M, WFC3/IR F160W, WFC3/IR F164N, WFC3/F167N. All UVIS+WFC images were aligned to a common pixel scale of 30 mas/pixel, while all IR images were aligned to a pixel scale of 60 mas/pixel using the astropy `reproject` package in combination with `astroalign` (Beroiz, Cabral, and Sanchez, 2020).

VLT/MUSE IFU Spectroscopy

We use reduced MUSE IFU science datacubes publicly accessible from the ESO archive¹. Two datacubes are used, which cover the observed wavelength range 475–935 nm at $R \approx 2600$ –3000 and were calibrated and reduced with the standard reduction pipeline: one obtained on May 13 and Aug 24 in 2016 (Program 107.22SK; PI: E. Vanzella; total exposure 4449 s), and another on Aug 10, 2021 (Program 297.A-5012; PI: N. Aghanim; total exposure 2808 s). The MUSE IFU observations were carried out in the Wide Field Mode under a typical seeing condition $\text{FWHM} = 0.5$ – $0.6''$, achieving a spatial resolution 1.4– $2''$ on the sky. Through a comparison between the two datacubes, we do not find any evidence for spectral variability, so we properly combine them to achieve the best signal-to-noise ratio for emission lines.

VLT/X-shooter Slit Spectroscopy

X-shooter slit spectroscopy data reduced with the standard reduction pipeline are accessed from the ESO archive. Data were collected from Program 0103.A-0688 (PI: E. Vanzella). Exposures were obtained under typical seeing conditions $\text{FWHM} \sim 0.5$ – $0.6''$. Slit spectra covering observed 994–2479 nm ($R \approx 8000$) are used for extracting fluxes for rest-frame NUV and optical emission lines, while additional spectra covering observed 534–1020 nm ($R \approx 11000$) are used for cross-checking strong FUV emission lines. For accessing spatially resolved spectral information, we carry out flux calibration of the 2D spectra by comparing the flux-calibrated and flux-uncalibrated 1D spectra, and then extract fluxes at the location of Godzilla.

For both MUSE and X-Shooter, the line flux uncertainty is calculated by line injection in the continuum neighboring each line followed by Gaussian fitting. For most optical lines in X-Shooter, candidate signal is visible at the location of Godzilla along the slit, but blending with strong line emissions from the neighboring Image 8 of the LyC cluster is too severe. Therefore, detection is conservatively quoted as an upper limit. Further details on extraction of the emission line fluxes, aperture correction and uncertainty estimation for the VLT/MUSE and VLT/X-Shooter spectra can be found in Section 2 of P23.

5.3 Photometry

Following the methods of P23, we measure the PSF of each HST image using the `photutils` package by stacking isolated, unsaturated stars in the field. An initial catalog of stars is generated using `DA0StarFinder` following Stetson, 1987, and then each star is vetted by eye to be isolated and unsaturated, resulting in a final catalog of dozens of stars. The final star list is extracted into centered cutouts which are normalized and median-subtracted to

¹<http://archive.eso.org/scienceportal/home>

Table 5.1 Inferred isotropic luminosities for nebular emission lines detected from VLT/MUSE IFU data for Godzilla. The isotropic luminosity is calculated for a luminosity distance of $d = 19.566$ Gpc (corresponding to the source redshift $z_s = 2.369$) and a fiducial achromatic magnification factor $\mu = 300$, and is uncorrected for dust reddening.

Emission line	Luminosity L [10^{38} erg s $^{-1}$]
O I λ 1641	26 ± 4
[O III] λ 1660	21 ± 7
[O III] λ 1666	55 ± 6
N III] λ 1750	73 ± 12
N III] λ 1752	29 ± 5
[Si III] λ 1883	$\lesssim 8$
Si III] λ 1892	54 ± 4
[C III] λ 1906	$\lesssim 10$
C III] λ 1908	123 ± 8
[O II] λ 2471	14 ± 4

Table 5.2 Inferred isotropic luminosities of nebular emission lines detected from VLT/X-shooter for Godzilla. The same luminosity distance and fiducial magnification factor $\mu = 300$ are used as in Table 5.1, while dust reddening is not corrected for. We have applied a wavelength independent PSF correction factor = 1.2 using a theoretical Moffat PSF model with $\beta = 4.765$.

Emission line	Luminosity L [10^{38} erg s $^{-1}$]
Ly α	$\lesssim 240$
[O II] λ 3726	$\lesssim 42$
[O II] λ 3729	$\lesssim 24$
[Ne III] λ 3869	37 ± 7
[Ne III] λ 3967	$\lesssim 12$
H β	$\lesssim 61$
[O III] λ 4959	$\lesssim 61$
[O III] λ 5007	$\lesssim 180$
H α	$\lesssim 185$
He I λ 5876	36 ± 18

mitigate sky background, and the cutouts are stacked into an oversampled PSF using the `EPSFBuilder` function.

To measure fluxes for Godzilla, we model the surface brightness profile as a Sérsic profile convolved with the PSF (Sersic, 1968). There are two primary sources of contamination which complicate fitting: neighboring star-formation knots on the arc and the diffuse arc background itself. Each of the neighboring knots are observed to be consistent with PSF profiles and are simultaneously fit in PSF photometry. The arc background is modeled as a thick line of smoothly-varying surface brightness, with free parameters for slope, intercept, and normalization. This simple parametrization is found to well approximate the arc background locally (within $\sim 1-2''$), and is fit simultaneously to Godzilla and neighboring knots. As an example, the best fit model and residual for the F814W filter is shown in Figure 5.4.

Across all HST images, the best-fit Sérsic profiles for Godzilla consistently have $r_{\text{eff}} \lesssim 1$ pixel, implying that Godzilla is unresolved and consistent with the PSF (we measure $\text{FWHM} \sim 0.13''$ in F814W, consistent with Vanzella et al., 2020a). This constrains the spatial extent $R_{\text{FUV}} \lesssim 1 \text{ pc} (500/\mu_t)$ of the OB star population, for a given tangential magnification μ_t . The tangential magnification is used in place of the total magnification as the source is preferentially stretched in the tangential direction. Indeed lens modeling studies find the radial magnification along the arc is likely modest $\mu_r \sim 2$, where $\mu = \mu_t \mu_r$ (Diego et al., 2022b). The statistical errors from fitting are likely subdominant to systematics involving parametrization of the various components – to account for this we set a conservative photometric error of 0.05 mag for the WFC3/UVIS and ACS/WFC filters and 0.1 mag for the WFC3/IR filters. These were assigned to be slightly larger than the systematics found from injection recovery tests of the PSF on blank (no bright point sources) regions of the arc, as these test were not robust to systematics involving the PSF itself.

5.4 Spectral Modeling

To unveil the nature of Godzilla and the origin of its nebular emission, we study several physical models describing a young mass star cluster associated with a photoionization nebula. We will adopt an iterative strategy. We shall first study simple models; if significant discrepancy with data is identified, we will be guided to consider models describing more unusual but physically motivated situations.

To that end, we will perform joint photometric-spectroscopic fitting using photometry from 12 HST filters (Table 5.3) and 18 emission line flux detections or upper limits from VLT/MUSE and VLT/X-shooter (Table 5.1 and Table 5.2). We shall include only 12 of the 15 available HST filters in fitting. Photometry in F390W and F410M are sensitive to $\text{Ly}\alpha$ line transfer and damping wing effects, which we do not attempt to carefully model. We also exclude F164N; while this filter constrains $\text{H}\beta$, we are aware of a flux calibration issue in this filter (Kim et al., 2023).

While several filters cover emission lines including $[\text{OII}]\lambda\lambda 3726, 3729$ (F126N), $\text{H}\beta$ (F160W, F164N), and $[\text{OIII}]\lambda\lambda 4959, 5007$ (F160W), they appear weak and only flux upper limits are

Table 5.3 HST photometry for Godzilla. Lensing magnification is uncorrected for.

Filter	AB magnitude	Spectral features
F275W ^a	$\gtrsim 28.6$	Rest-frame LyC;
F390W ^a	22.41 ± 0.10	Ly α & damping wing
F410M ^a	22.88 ± 0.10	Ly α & damping wing
F555W	22.00 ± 0.05	–
F606W	22.00 ± 0.05	–
F814W	22.00 ± 0.05	–
F098M	22.18 ± 0.10	–
F105W	22.16 ± 0.10	–
F125W	22.18 ± 0.10	–
F126N	22.16 ± 0.10	[O II] $\lambda\lambda 3727, 3729$
F128N	22.24 ± 0.15	–
F140W	22.18 ± 0.10	–
F153M	22.28 ± 0.10	–
F160W	22.17 ± 0.10	H β , [O III] $\lambda\lambda 4959, 5007$
F164N ^a	22.17 ± 0.10	H β
F167N	22.05 ± 0.10	[O III] $\lambda 4959$

^aExcluded from analysis.

reliable. We note that HST photometry is significantly more sensitive and hence may constrain these emission lines better than X-shooter data.

Emission line measurements prove highly valuable in probing the properties of Godzilla’s nebula gas. Even many upper limits are surprisingly informative. The C III] $\lambda\lambda 1908, 1906$ and Si III] $\lambda\lambda 1892, 1883$ line ratios probe the electron density in a high ionization environment. Non-detection of the forbidden component (Vanzella et al., 2020c) indicates that Godzilla has a nebula much denser than what are often considered dense high- z HII regions with $3 \lesssim \log n_e [\text{cm}^{-3}] \lesssim 6$ (Keenan, Feibelman, and Berrington, 1992; Jaskot and Ravindranath, 2016). Ratios between the O II and O III lines [OII] $\lambda 2471$ /[OIII] $\lambda\lambda 1660, 1666$ (Kewley, Nicholls, and Sutherland, 2019) are sensitive to ionization degree and electron temperature (Kewley and Dopita, 2002; Kobulnicky and Kewley, 2004; Dors et al., 2011). For Godzilla, the [OIII] $\lambda\lambda 1660, 1666$ /[OIII] $\lambda\lambda 4959, 5007$ line ratios also constrain the electron density, as these trace the same ion but the rest-frame optical doublet has a much lower critical density at $6.4 \times 10^5 \text{ cm}^{-3}$ (Draine, 2011b).

Base Model

We first study a model describing photoionized gas excited by the entire star cluster. This has been used to model the spectrum of the Lyman-continuum-leaking cluster of the Sunburst

Arc in P23. The model star cluster SED is taken from BPASS (v2.0) with binary stellar evolution accounted for (Stanway, Eldridge, and Becker, 2016). For a compact, massive star cluster, we consider an instantaneous burst of star formation with an initial mass function (IMF) $\xi(m) \propto m^{-1.3}$ for $m < 0.5 M_{\odot}$ and $\xi(m) \propto m^{-2.35}$ for $m > 0.5 M_{\odot}$ in the initial stellar mass range $0.1 < m/M_{\odot} < 300$. The cluster is characterized by the age t_{age} and stellar metallicity Z as free parameters.

Following the method of P23, nebular continuum, emission lines, and attenuation of incident star light are all modeled with the `Cloudy` code (v17 Ferland et al., 2017) assuming a plane-parallel, stratified structure locally. The nebula gas is assumed to be isobaric, such that it is characterized by the typical dimensionless ionization parameter U and the constant pressure P . In Bayesian inference, we shall use log-flat priors for these, in the range $-3 \leq \log U \leq -1$ and $6 \leq \log P [\text{K cm}^{-3}] \leq 13$.

When running `Cloudy` calculations for the Base Model, we identify the stellar metallicity Z with the gas-phase metallicity and use a rescaled solar abundance pattern (see Table 7.1 or the `Cloudy` manual HAZY 1), with non-rescaled-solar prescriptions for He (following Russell and Dopita, 1992), C, and N (following Dopita et al., 2006). The abundances of N, C, Ne, and Si are allowed to freely vary only when we fit the emission line data; we do this by rescaling the fluxes of emission lines corresponding to these elements. This is a computationally efficient and justifiable approximation provided that varying the abundance of these elements does not significantly change line cooling.

We also introduce two geometric parameters: the parameter x ($0 \leq x \leq 1$) is the fraction of ionizing radiation processed by the nebular gas. A second parameter, y , describes the fraction of nebular gas toward which our sight-line is intervened by HI gas ($y = 0$) versus the fraction toward which the sight-line is not ($y = 1$). We shall refer to the former case as “HI-obscured” (see Figure 2 of P23). For example, the latter case can correspond to directly seeing the irradiated side of the HII zone on the surface of a self-shielding cloud, without any intervening gas. The former case can correspond to viewing from the back side of the self-shielding cloud, so that photons reaching the observer must pass through a substantial HI column of the cloud. Without internal dust attenuation, the parameter y does not affect (semi-)forbidden lines, but has an impact on lines with a significant optical depth effect or with a large diffusive contribution in the HI layer.

P23 introduced a third geometric parameter, z , which measures the fraction of star light along the line-of-sight that is obscured by photoionized gas. Running `Cloudy` models without internal dust, we do not find it strongly constrained by data and hence set it to zero obscuration. Finally, we also incorporate external dust reddening, fixing Milky Way extinction following the galactic dust maps of Schlegel, Finkbeiner, and Davis, 1998, and fitting for host galaxy ISM dust reddening following the law of Reddy et al., 2015b, where the normalization $E(B-V)$ is left free. In total, the Base Model has 10 free parameters.

Chemically Anomalous Model

In Godzilla, some unusual emission line ratios hint at the possibility of non-standard gas-phase element abundances. Apart from a clear detection of N enhancement (like what we found for the LyC cluster in P23), we see evidence for He and O enhancement, as well as unusual C/O and Ne/O ratios. The surprising weakness of H Balmer lines relative to metal forbidden lines (Vanzella et al., 2020c) may also be related to an unusual abundance pattern.

Chemical self-enrichment is physically plausible for newborn massive star clusters if massive star ejecta can be retained in the cluster vicinity or interior (de Mink et al., 2009; Martell et al., 2013; Lochhaas and Thompson, 2017). Massive star winds or envelope stripping may cause self-enrichment of N and He, while CCSNe produce α -elements including O, Ne and Si. We are therefore motivated to consider more sophisticated non-rescaled-solar abundance patterns. In particular, the gas-phase oxygen abundance may be enhanced compared to the interior of stars. Unlike N, C, Si, and Ne, oxygen ions play a significant role in line cooling, and hence changes in oxygen abundance cannot be simply accounted for by rescaling O line fluxes in post-processing.

In the Chemically Anomalous Model, the stellar SED is the same as in the Base Model. We fix the stellar and gas-phase (before self-enrichment) metallicities to $0.25 Z_{\odot}$ following the best-fit Base Model. This gas-phase metallicity is consistent with what we found for the LyC cluster of Sunburst in P23, and within the inference uncertainty agrees with the gas metallicity determined by Rivera-Thorsen et al., 2024. We then compute a grid of `Cloudy` models for which O/H varies from one-fourth to twice the solar value (assuming $12 + \log(\text{O}/\text{H})_{\odot} = 8.69$) (Asplund, Amarsi, and Grevesse, 2021). Similarly, He abundance variation should be consistently treated with `Cloudy`. The detection of the recombination line He I λ 5876 probes He/H, which may be enhanced by evolved star winds. We create a He/H grid to allow enhancement up to five times greater than the prescription of Russell and Dopita, 1992 at one-fourth solar metallicity. In this model, the stellar metallicity is no longer a free parameter in fitting, while gas-phase O and He abundances are now left free to vary, increasing the total number of free parameters to 11.

5.5 Results

We fit the two models to data from 12 filters of HST photometry (Fig. 5.5) and 18 emission line fluxes and upper limits (Fig. 5.6). We use the sampler `PyMultinest` (Feroz, Hobson, and Bridges, 2009; Buchner et al., 2014) with 1,000 live points running for 10,000 steps to explore the model parameter space and derive posterior samples. Below we discuss the inferred physical parameters and the fitting performance for each model. We assign uncertainties in both filter photometry and emission line fluxes/upper limits conservatively, and hence the reduced chi-squared $\chi^2_{\nu} < 1$ obtained in our fitting is likely indicative of overestimated errorbars rather than overfitting.

Base Model

The Base Model well-reproduces all observables with a reduced chi-squared $\chi^2_\nu = 0.52$. However, constraints on the stellar properties are not extremely stringent. Using the BPASS instantaneous burst model, photometry of the stellar and nebular continuum indicates a high stellar mass $\log \mu M_\star/M_\odot = 9.29^{+0.11}_{-0.16}$, or $M_\star/M_\odot = 2 \times 10^6 (1000/\mu)$. The magnification of Godzilla is not known as multiple lens models make a range of predictions (Pignataro et al., 2021; Diego et al., 2022b; Sharon et al., 2022b). The surprising absence of bright counter images imply that Godzilla’s magnification factor may have been strongly boosted by milli-lensing (Diego et al., 2022b). Hereafter, we shall use a high fiducial value $\mu = 1000$ and denote $\mu_{1000} = \mu/1000$ (see Section 5.7 for more discussions of the magnification factor of Godzilla.).

The favored cluster age is in the range $t_{\text{age}} = 3\text{--}6$ Myr. Godzilla thus appears more evolved than the LyC cluster. As seen in Fig. 5.3, the emission component of the C IV $\lambda 1550$ P Cygni wind feature, whose strength is sensitive to age but not stellar metallicity (Leitherer et al., 2014; Chisholm et al., 2019), has a significantly lower equivalent width than for the LyC cluster in the same galaxy ($t_{\text{age}} \sim 3$ Myr; Chisholm et al., 2019; Pascale et al., 2023). The higher cluster age is further corroborated by the absence of broad He II $\lambda 1640$ emission, a unique signature of Very Massive Stars ($> 100 M_\odot$) seen in the LyC cluster that would likely have died by $t_{\text{age}} = 3 - 4$ Myr (Mestric et al., 2023).

The stellar and gas metallicity is constrained to be $\log Z = -2.29^{+0.16}_{-0.12}$, or 20%-40% of the solar value. The broad posterior distribution for Z is likely due to non-detections of H α , H β , and the [O III] $\lambda\lambda 4959, 5007$ doublet. Reassuringly, the median of the posterior matches the value inferred for the LyC cluster in P23 and Rivera-Thorsen et al., 2024, as the two objects reside in the same galaxy. For a further piece of evidence, we use the depth of the absorption component of the C IV $\lambda 1550$ P Cygni wind feature, which is primarily set by the stellar metallicity (Chisholm et al., 2019). The depths are observed to be consistent in both Godzilla and the LyC cluster (Fig. 5.3). Similar to Kim et al., 2023, we find a minimal amount of external dust reddening $E(B - V) = 0.02^{+0.02}_{-0.02}$ based on the continuum shape.

Remarkably, the ionized gas of Godzilla has an extremely high pressure $\log P = 11.56^{+0.14}_{-0.12}$ [K cm $^{-3}$] and a low ionization parameter $\log U = -2.61^{+0.13}_{-0.11}$, corresponding to a characteristic incident ionizing flux $\log \Phi(\text{H}^0) = 15.22^{+0.16}_{-0.15}$ [s $^{-1}$ cm $^{-2}$] and a high electron density $\log n_e = 7.12^{+0.30}_{-0.15}$ [cm $^{-3}$].

The Base Model allows the abundances of C, N, Ne and Si to vary freely in emission line fitting. We find all four to show unusual abundances relative to oxygen, with lower C/O, Ne/O and Si/O but significantly higher N/O compared to typical ISM values found in galaxies at sub-solar metallicity. The elevated N/O, $\log(\text{N/O}) = -0.30^{+0.07}_{-0.07}$, is reminiscent of the LyC cluster, a factor of ~ 13 greater than typical HII region abundances (Pilyugin, Grebel, and Mattsson, 2012). Thus, Godzilla appears to be another example of nitrogen emitters which have received heated discussion in the literature (Marques-Chaves et al., 2024).

While the measured $\log \text{C/O} = -0.79^{+0.05}_{-0.05}$ is low compared to the solar value of -0.30 (As-

plund, Amarsi, and Grevesse, 2021), we note that it is consistent with the ~ -0.7 ISM value observed in $z \sim 2-3$ galaxies at a similar metallicity (Berg et al., 2019) (see § 5.6). The gas-phase Si/O appears low, $\log(\text{Si/O}) = -1.84^{+0.06}_{-0.05}$, a factor of 4–5 lower than the solar value -1.15 (Asplund, Amarsi, and Grevesse, 2021). While grain depletion of Si may explain this, it may also point towards the intriguing possibility of self-enrichment of oxygen by CCSNe that go off in the star cluster. This, taken with the low C/O and the anomalously low measured $\log(\text{Ne/O}) = -1.20^{+0.11}_{-0.12}$ (factor of ~ 5 deficient relative to the solar value) motivates us to consider more sophisticated gas abundance models in which the gas-phase oxygen abundance differs from the stellar value.

The parameter y is tightly constrained to be very close to zero, $y < 0.03$, which implies that nearly all the nebular emission that we see is H I-obscured, mostly likely by the H I gas right behind the edge of the H II zone in an ionization-bounded geometry. The strong preference for this in data is driven by the need to significantly decrease the H Balmer lines. In Section 5.6, we discuss how H Balmer lines might be reduced by a dust-free H I zone.

Chemically Anomalous Model

To explore self-enrichment of gas-phase abundances, we fix the stellar metallicity to be $Z = 0.25 Z_{\odot}$ in the Chemically Anomalous Model, which corresponds approximately to the median of the posterior distribution of the Base Model as well as the Z value inferred for the LyC cluster in P23. In constructing Cloudy model grids, we scan a range of O/H and He/H values. The goodness of fit is notably improved over the Base Model, achieving a lower $\chi^2_{\nu} = 0.39$ despite only one more free parameter. For this reason, we think that the best-fit Chemically Anomalous Model reflects reality more than the best-fit Base Model.

For most parameters, we find posterior distributions consistent with what we derive for the Base Model (Table 5.4). There are three notable exceptions: (1) a lower value for the effective area covering factor $x \simeq 0.2$ is now preferred; (2) the gas pressure is ~ 0.3 dex higher at $\log P \sim 11.9$; (3) the posterior distribution of the ionization parameter keeps a peak at low values $\log U \simeq -2.6$ but develops a long tail toward higher values $\log U \simeq -(1-2)$.

Changes in the pressure and the effective covering factor result from a preference for enhanced O/H. The strong UV [O III] $\lambda\lambda 1660, 1666$ are detected, but there are interesting upper limits on the optical [O III] $\lambda\lambda 4959, 5007$ and H Balmer lines. [O III] $\lambda\lambda 4959, 5007$ are collisionally suppressed above $n_e = 6.4 \times 10^5 \text{ cm}^{-3}$ (Draine, 2011b), such that increased P will reduce the optical doublet relative to the UV doublet. By contrast, enhancing the O abundance dramatically enhances the optical [O III] doublet more than the UV [O III] doublet, likely owing to increased line cooling in a metal-rich gas preferentially suppressing the UV forbidden lines. These effects manifest as a positive correlation between P and O/H, and a negative correlation between x and O/H (Fig. 5.8). Since the oxygen lines increase with O/H, a solution with increased O/H is preferred to explain strong [O III] and [O II] without H Balmer detections. The covering factor must decrease to avoid overproducing oxygen lines. Because this enhances [O III] $\lambda\lambda 4959, 5007$ more than [O III] $\lambda\lambda 1660, 1666$, P and hence n_e must be increased to suppress the former.

The high $\log U$ tail appears in the posterior distribution due to a preference for enhanced He/H. At high $\log U$, emission lines from higher excitation ions (O III, N III, Ne III) are enhanced relative to lines of lower excitation ions (O II, Si III, Fe III). Increased He abundance, which consumes more He I ionizing photons ($h\nu > 24.6$ eV), has the opposite effect that a He I zone forms behind the He II zone where the low excitation ions can be abundant. Hence, there is a positive correlation between He/H and $\log U$ (Fig. 5.8), as the two approximately compensate for one another with the exception of He emission lines.

As we fix the stellar metallicity $Z = 0.25 Z_{\odot}$ in this model, fitting results indicate that the gas-phase oxygen is enhanced by ~ 2 –6 fold, producing an O/H at roughly the solar value. C, N, Si and Ne relative to O are found to be similarly abundant as in the Base Model, but have increased abundances relative to H. This implies that the inferred low C/O, Ne/O and Si/O values may be a symptom of O enrichment rather than a deficiency in C, Ne and Si. We find that He is enhanced relative to H by ~ 2 –4 fold compared to the prescription of Russell and Dopita, 1992.

This model again requires y to be closer to zero than to unity, but with a broader posterior distribution, $y < 0.2$, enabled by the enhanced O/H (see correlation in Figure 5.8). This implies that the nebular emission should be mostly HI-obscured, but up to $\sim 20\%$ of it may still come directly from unobscured irradiated cloud surfaces. As we shall discuss later, this preference in y has important implications for the probable nebula geometry (Section 5.6).

Since the Chemically Anomalous Model is consistent with a wide range of $\log U$ values, we further test a model involving two ionized gas components, one with low $\log U < -1.5$ as found in the Base Model, and another with high $\log U > -1.5$. The high ionization parameter $\log U > -1.5$ can be explained by photoionization nebulae in wind-blown bubbles surrounding individual main sequence O stars at ~ 4 Myr, if the cluster interior is filled with dense self-shielding gas which could have condensed from wind and CCSN ejecta (see Figure 5.2 and Section 5.6). Assuming that all other physical parameters are the same for the two components, we find that significant processing of the total cluster ionizing output ($\gtrsim 10\%$) by a second high $\log U$ nebula is neither favored nor ruled out by data, with the other inferred physical parameters unaltered.

5.6 Discussion

In this Section, we discuss the many implications of our fitting results for the dynamics, chemical composition, and astrophysical origin of Godzilla’s nebula. We will refer to our fitting results derived for the Chemically Anomalous Model as the favorable model.

Nebular Pressure and Ionization Parameter

The ionized gas excited in Godzilla appears extremely dense $n_e \sim 10^{7-8} \text{ cm}^{-3}$ and highly pressurized $P \sim 10^{11.5-12} \text{ K cm}^{-3}$. This result appears very robust to us. The tight lower limit on the C III] $\lambda 1908$ /[C III] $\lambda 1906$ alone implies $n_e > 10^6 \text{ cm}^{-3}$ (Vanzella et al., 2020c),

Table 5.4 Fitting results for the Base Model and the Chemically Anomalous Model. In the Base Model the gas-phase oxygen abundance is identified with the stellar metallicity, while in the Chemically Anomalous Model we fix the stellar metallicity to $0.25 Z_{\odot}$ but allows gas-phase O and He abundances to vary in **CLOUDY** calculations. Pressures are in units of K cm^{-3} , photon fluxes ($\Phi(\text{H}^0)$) in units of $\text{cm}^{-2} \text{s}^{-1}$, and the characteristic nebula radii (R) in units of cm. The magnification factor of Godzilla, μ , is likely large $\mu \sim 600\text{--}2000$ but uncertain (see Section 5.7).

Parameter	Base Model	Chem. Model
χ^2_{ν}	0.52	0.39
χ^2	9.36	6.63
$E(\text{B} - \text{V})$	$0.02^{+0.02}_{-0.02}$	$0.05^{+0.02}_{-0.02}$
$\log Z_{\star}^a$	$-2.29^{+0.16}_{-0.12}$	-2.3
$t_{\text{age}} [\text{Myr}]$	$4.03^{+1.78}_{-1.22}$	$5.01^{+1.55}_{-1.78}$
$\log U$	$-2.61^{+0.13}_{-0.011}$	$-2.29^{+0.62}_{-0.41}$
$\log P$	$11.56^{+0.14}_{-0.12}$	$11.91^{+0.25}_{-0.18}$
$\log(\mu M_{\star})$	$9.29^{+0.11}_{-0.16}$	$9.36^{+0.09}_{-0.18}$
$\log(\mu Q(\text{H}_1^0))$	$55.54^{+0.17}_{-0.25}$	$55.54^{+0.23}_{-0.27}$
$\log \Phi(\text{H}^0)$	$15.22^{+0.16}_{-0.15}$	$15.89^{+0.38}_{-0.34}$
$\log(R \mu^{1/2})$	$19.60^{+0.12}_{-0.13}$	$19.25^{+0.20}_{-0.17}$
x	$0.40^{+0.15}_{-0.09}$	$0.16^{+0.12}_{-0.07}$
y	$0.01^{+0.02}_{-0.01}$	$0.06^{+0.08}_{-0.04}$
$\log(\text{C}/\text{O})$	$-0.79^{+0.05}_{-0.05}$	$-0.84^{+0.06}_{-0.06}$
$\log(\text{N}/\text{O})$	$-0.30^{+0.07}_{-0.07}$	$-0.31^{+0.08}_{-0.08}$
$\log(\text{Ne}/\text{O})$	$-1.20^{+0.11}_{-0.12}$	$-1.13^{+0.16}_{-0.13}$
$\log(\text{Si}/\text{O})$	$-1.84^{+0.06}_{-0.05}$	$-1.90^{+0.15}_{-0.11}$
$12 + \log(\text{O}/\text{H})$	$^b 8.09^{+0.17}_{-0.11}$	$8.75^{+0.19}_{-0.25}$
He/H	$^c 0.08^{+0.00}_{-0.00}$	$0.27^{+0.09}_{-0.10}$

^aWhere $\log Z_{\odot} = -1.85$

^bDerived from $Z_{\star}$, where $12 + \log(\text{O}/\text{H})_{\odot} = 8.69$.

^cDerived from $Z_{\star}$ following Russell and Dopita, 1992.

but upper limits on $[\text{O III}]\lambda\lambda 4959, 5007$ in the presence of strong $[\text{O III}]\lambda\lambda 1650, 1666$ further requires $n_e > 10^7 \text{ cm}^{-3}$ to sufficiently suppress the former by electron collision. Interestingly, the high n_e reduces cooling via some collisionally excited metal lines such that dramatically increased O/H only causes a mild decrease in the electron temperature, a $\sim (10 - 15)\%$ drop in T_e for a five-fold increase in O/H. This leads to a unique situation where, despite a solar O/H, high excitation FUV lines like $[\text{O III}]\lambda\lambda 1660, 1666$ and $[\text{C III}]\lambda\lambda 1906, 1909$ remain strong, while at typical ISM densities these lines are not observed in star-forming regions with $Z \gtrsim 0.4 Z_\odot$ (Mingozi et al., 2024).

Enrichment by Massive Star Winds: N and He

The localized, elevated N/O seen in Godzilla is significantly higher than in typical ISM environments (Fig. 5.10), including local HII regions (Pilyugin, Grebel, and Mattsson, 2012) and low- Z dwarf starbursts such as in the CLASSY survey (Berg et al., 2022). However, it is consistent with the N/O found in the LyC cluster in the same galaxy (Pascale et al., 2023), and bears similarity to a growing list of high- z N emitters, such as GN-z11 (Cameron et al., 2023; Senchyna et al., 2023) and CEERS-1019 (Marques-Chaves et al., 2024). P23 propose that the N enhancement seen in the LyC cluster likely arises from CNO-processed material ejected through massive star winds. We find this to be the most plausible explanation for Godzilla as well. Apart from the winds of classical WN stars, N-rich ejecta could also be provided through slow mass loss from non-conservative mass transfer between binary massive stars (de Mink et al., 2009), dense equatorial winds from fast rotating massive stars (Roy et al., 2022), continuum-driven dense winds from Very Massive Stars (Vink, 2023), or even from supermassive stars that may form at the center of a dense super star cluster (Gieles et al., 2018; Charbonnel et al., 2023). All these could have happened in the cluster by 4 Myr.

Inside a sufficiently dense cluster, even fast line-driven winds from massive stars may be retained in the cluster potential from rapid loss of kinetic energy to radiative cooling (Wünsch et al., 2011; Wünsch et al., 2017). Following the criteria of the semi-analytic analysis of Lochhaas and Thompson, 2017, Godzilla appears compact enough ($M_*/R > 10^5 M_\odot \text{ pc}^{-1}$) that winds as fast as $v_w \sim 1000 \text{ km s}^{-1}$ are expected to condense in the cluster.

Enhancement in He/H by a factor of $\sim 2-4$ than the ISM He abundance in Russell and Dopita, 1992 is another piece of evidence for retained stellar wind material. Simultaneous N and He enrichment is not surprising given the inferred cluster age $> 3 \text{ Myr}$. For a smaller t_{age} , winds from the Very Massive Stars would cause N enrichment without major He enrichment (e.g., Roy et al., 2022; Vink, 2023), while moderate He enhancement is expected to accompany N enhancement in the winds of evolved He stars (e.g., Meynet, Ekström, and Maeder, 2006; Decressin et al., 2007).

Enrichment by CCSNe: C/O, Si/O, and Ne/O

Another marked event is the onset of CCSNe when the star cluster evolves beyond 3 Myr. Godzilla shows a low gas-phase $\log(\text{C/O}) = -0.8$ compared to the solar value and to HII

regions at the similar O/H (approximately solar). However, this C/O value is more consistent with star-forming regions of gas-phase $Z \lesssim 0.25 Z_{\odot}$ at Cosmic Noon (Fig. 5.10; Garnett et al., 1995; Berg et al., 2016; Nicholls et al., 2017; Berg et al., 2019). Berg et al., 2016 and Berg et al., 2019 observe a trend in C/O versus O/H in local and intermediate- z star-forming galaxies, which appears mostly flat at SMC-like metallicities or lower, but shows a strong upturn at higher metallicities (Figure 7 of Berg et al. 2016 and Figure 10 of Berg et al. 2019). Berg et al., 2019 posit that this trend can be explained by a model of bursty star formation, where prompt CCSNe first enhance the gas-phase oxygen to produce a mostly flat C/O trend with metallicity. Then, pseudo-secondary production of carbon from low-mass asymptotic giant branch (AGB) stars, together with Z -dependent winds of evolved stars relevant only for metallicities greater than the SMC value, is responsible for an upward trend of C/O versus O/H. This provides a plausible explanation for Godzilla, in which at an age of $\sim 4\text{--}6$ Myr the first CCSNe significantly enrich the cluster gas with oxygen, leading to a low gas-phase C/O. Godzilla, however, shows enhanced O/H and hence C/H, relative to the galaxies of the Berg et al., 2019 sample. This can be explained by the different length scales of enrichment. On the galactic scale, the CCSNe ejecta are likely diluted in the ISM, leading to sub-solar O/H values. The localized nebula gas of Godzilla may consist of, either entirely or significantly, the stellar ejecta, thus exhibiting a solar-like gas-phase O/H. Because the location of the upturn observed in the C/O versus O/H trend is set by the stellar metallicity, the gas-phase C/O of Godzilla would be consistent with the values for galaxies at sub-solar metallicities despite the inferred solar value for gas-phase O/H.

To further investigate whether the nebula of Godzilla is heavily enriched by massive star winds and CCSNe ejecta, we draw comparison to the models of Mollá and Terlevich 2012 (hereafter MT12), who calculated the element abundances for the cumulative wind and CCSN ejecta of a fiducial $M_{\star} = 10^6 M_{\odot}$ star cluster across the stage of early evolution up to an age of 20 Myr, assuming *complete* ejecta retention without mixing with the ISM.

This is intended to be a qualitative comparison, as there are numerous differences between our cluster model for Godzilla and the models assumed in MT12, in addition to other underlying theoretical uncertainties. First, MT12 used a Kroupa IMF (Kroupa, 2001) with lower and upper mass cutoffs at $m_{\min} = 0.15 M_{\odot}$ and $m_{\max} = 100 M_{\odot}$ respectively, and used stellar evolution tracks that do not account for the effects of stellar rotation or binary evolution. Additionally, our Godzilla model has $Z = 0.25 Z_{\odot}$ for the stars, while the set provided in MT12 with the closest stellar metallicity has $Z = 0.2 Z_{\odot}$. While $Z = 0.2 Z_{\odot}$ or $0.25 Z_{\odot}$ are well within our inference uncertainties and does not significantly change the incident stellar radiation, this is in a range of transition where the abundance of classical WR stars appears to depend sensitively on Z . Finally, we shall assume that the Ne and Si abundances of the wind shown in Figures 5.11 and 5.12 follow from one-fifth the solar value, as MT12 only provide Ne and Si yields from CCSNe. Hence in the wind ejecta the Ne and Si masses are set by the H mass, assuming that hydrogen in the wind material has not been significantly depleted into He through nuclear burning.

We compare our inferred abundances for Godzilla to those derived by MT12 in Fig. 5.11 and Fig. 5.12, which are shown relative to hydrogen and to oxygen, respectively. When

compared to hydrogen, we find the abundances of He, C, N, O, Si and Ne are all consistent with the MT12 predictions for complete retention of both wind and CCSN ejecta over the inferred cluster age. This supports the hypothesis that an order-unity fraction of Godzilla’s nebula gas is stellar ejecta. Given the sharp upturn in oxygen abundance after the onset of CCSNe at ~ 3.7 Myr in the MT12 models, many of the abundances are only consistent within a short age window of $\sim 4 - 6$ Myr. However, this is consistent with the cluster age we infer from broad-band photometry and nebular emission lines.

Plotting the abundances relative to oxygen (Fig. 5.12), all abundances remain in good agreement with the MT12 predictions, with the exception of Ne/O. In a broader context, ISM Ne/O measurements in star forming regions nearly ubiquitously show the solar value or are only mildly lower (Henry and Worthey, 1999; Willner and Nelson-Patel, 2002). While $\log(\text{Ne/O}) < -1$ was reported for a number of low ionization regions measured in the CHAOS sample of M33 (see Fig. 5.10; Rogers et al., 2022), those exhibited large measurement uncertainties and are qualitatively different environments than a young massive star cluster.

Rather, we suggest that a sub-solar Ne/O may be typical in the early evolution of super star clusters as a consequence of CCSNe yields for progenitors of high ZAMS masses. At an inferred age ~ 5 Myr, Godzilla uniquely probes CCSNe yields within only 1–2 Myr of CCSN onset when only stars $m_{\text{ZAMS}} \gtrsim 30\text{--}40 M_{\odot}$ have ended their lives (Bressan et al., 2012). While tables provided by MT12 show solar or even super-solar Ne/O values at these young ages (drawing from yield models of Woosley, Langer, and Weaver 1993 and Woosley, Langer, and Weaver 1995), Ne/O of massive stars is subject to significant theoretical uncertainty. For example, Limongi and Chieffi, 2018 predict solar and sub-solar Ne/O from massive stars at low metallicity, and the $\log(\text{Ne/O})$ values are significantly lowered below -1 in rotating star models, a feature not accounted for in the yield models used by MT12. More exotic sources, such as metal-free massive star hypernovae (Grimmett et al., 2018) or high mass pair-instability SNe (Heger and Woosley, 2002) have also been predicted to produce subsolar Ne/O (Ji et al., 2024).

To investigate possible reasons for the reduced Ne/O, we take the MT12 ejecta models but exclude Ne and Si yields from CCSNe. We find that this resolves the tension in Ne/O and may also improve the agreement for Si/O. This may be evidence that CCSNe of high m_{ZAMS} progenitors have deficient Ne/O compared to their lower m_{ZAMS} counterparts. While Ne and O are both abundant in the Ne-Mg-O shell of the pre-SN star, Ne may be depleted via photo-disintegration, converting to O pre-SN or during explosive nucleosynthesis (Boccioli and Roberti, 2024). This may also be related to a scenario in which the Ne-Mg-O and Si-S shells interior to the pre-SN star do not successfully get ejected while the more exterior C-O shell is ejected, although this may not provide enough O enhancement relative to C to match the observed sub-solar C/O value (Woosley, Heger, and Weaver, 2002).

Overall, and despite the various measurement and theoretical uncertainties, we find that the unusual gas-phase abundances we infer for Godzilla using the Chemically Anomalous Model can be remarkably well-explained by a model in which the nebula is a full mixture of winds and CCSN ejecta from stars with $m_{\text{ZAMS}} \gtrsim 30\text{--}40 M_{\odot}$. This interpretation is consistent with the inferred cluster age $\sim 4\text{--}6$ Myr.

Nebula Geometry and Dynamics

In this Section, we discuss the nebula geometry of Godzilla and the possible underlying dynamical reasons.

Spherical Shell Enclosing Stars

The simplest geometry would be a spherical shell of nebular clouds surrounding the entirety of the ionizing sources at some distance R_{sh} , with an area covering factor $x \simeq 0.1\text{--}0.2$. In P23, we found that this simple geometry can explain the spectra of the LyC cluster. For $\log P = 11.9$, $\log U = -1.5$ and $\text{He}/\text{H}=0.35$ (Figure 5.8), we require $n_e \sim 10^7 \text{ cm}^{-3}$, and the characteristic ionizing flux is $\log \Phi(\text{H}^0) = 15.9$. Comparing this to the BPASS prediction of ionizing photon production rate, we obtain $\log(R \mu^{1/2}) = 19.3 [\text{cm}]$ or $R_{\text{sh}} \simeq 0.2 \text{ pc } \mu_{1000}^{-1/2}$. While such a compact size would be implausible for the entirety of a star cluster that is more massive than $10^6 M_{\odot}$, the shell would only have to enclose the majority of the ionizing stars which may aggregate toward the cluster center (Sung and Bessell, 2004; Stolte et al., 2002; Crowther et al., 2010; Pang et al., 2013), but not necessarily all cluster stars. While it would help to place the major ionizing sources all within $\simeq 0.2 \text{ pc}$ by invoking primordial mass segregation, given the large cluster mass and its age $\sim 4\text{--}6 \text{ Myr}$ (so that the most massive stars have died), this compactness is still quite extreme.

Alternatively, the shell may have a 100% area covering but only encloses $x = (10\text{--}20)\%$ of the cluster's ionizing output. This, however, would require an even smaller shell radius $R_{\text{sh}} = 0.1 \text{ pc } \mu_{1000}^{-1/2} (x/0.2)^{1/2}$. A compact gas shell enclosing a hollow cavity in the cluster center seems geometrically unnatural. We note, however, that in case the shell is thick this geometry would resemble our most favored geometry to be discussed in Section 5.6, and the large hollow cavity could have been driven by a recent CCSN.

Shattered Clouds

A second possibility is that the nebula emission comes from a population of shattered, self-shielding clouds, which are hovering within a spherical volume of radius $R_c \simeq 0.2 \text{ pc } \mu_{1000}^{-1/2}$ that encloses nearly all of the cluster's ionizing output, but have an area covering factor $x \simeq 0.1\text{--}0.2$. The compactness of this volume may be explained again by mass segregation.

Similar to the geometry discussed in Section 5.6, we have to explain the high pressure $\log P \simeq 11.9$ of the nebula gas. Since we inferred $\log U < -1$, direct ionizing radiation pressure is insufficient (Yeh and Matzner, 2012),

$$P_{\text{rad}} = 6 \times 10^{10} \text{ K cm}^{-3} \left(\frac{\Phi(\text{H}^0)}{10^{15.9} \text{ s}^{-1} \text{ cm}^{-2}} \right) \left(\frac{\langle h\nu \rangle_{\text{ion}}}{20 \text{ eV}} \right), \quad (5.1)$$

where $\langle h\nu \rangle_{\text{ion}}$ is the average energy of the ionizing photons. Thus, thermal pressure from an intracloud hot gas component with $\log P_{\text{hot}} \simeq 11.9$ needs to confine the clouds.

Can a global hot cluster wind provide the sufficient pressure? In a simple picture, mass and kinetic energy output from individual stellar winds and CCSNe merge to drive a hot

cluster wind (Chevalier and Clegg, 1985; Cantó, Raga, and Rodríguez, 2000; Wünsch et al., 2011; Silich et al., 2011). Estimating from BPASS (v2.2), the total stellar mass loss rate is $\dot{M}_\star \approx 0.01 M_\odot \text{ yr}^{-1}$ per $10^6 M_\odot$ of stars, including wind and SN mass ejection. Taking a specific CCSN rate at $t_{\text{age}} \sim 5 \text{ Myr}$ of $\Gamma_{\text{SN}} \approx 5 \times 10^{-10} \text{ yr}^{-1} M_\odot^{-1}$ and an explosion energy $E_{\text{SN}} = 10^{51} \text{ erg}$ per CCSN, the mechanical luminosity due to CCSNe is $L_{\text{mech,SN}} \approx 1.6 \times 10^{40} \text{ erg s}^{-1}$ per $10^6 M_\odot$ of stellar mass. Including wind mass loss at $v_w \approx 2000 \text{ km s}^{-1}$ causes at most a factor of two increase in the total mechanical luminosity, reaching $L_{\text{mech,tot}} \approx 3 \times 10^{40} \text{ erg s}^{-1}$ per $10^6 M_\odot$ of stellar mass.

Assuming no radiative loss, we find a pressure for the cluster hot gas:

$$P_{\text{hot}} \approx 5 \times 10^{11} \text{ K cm}^{-3} \left(\frac{M_{\star,6}}{2} \right) \left(\frac{R_c}{0.2 \text{ pc}} \right)^{-2} \times \left(\frac{L_{\text{mech,tot}}}{3 \times 10^{40} \text{ erg s}^{-1}} \right)^{\frac{1}{2}} \left(\frac{\dot{M}_\star}{0.01 M_\odot \text{ yr}^{-1}} \right), \quad (5.2)$$

where $M_{\star,6} = M_\star / (10^6 M_\odot)$ and R_c is the radius of the cluster core region where the hot gas is fully thermalized. We obtain a sufficiently high value because we have used a compact radius $R_c = 0.2 \text{ pc}$ for thermalization, which we deem quite extreme.

However, we emphasize that the above analysis is very optimistic because it assumes maximal thermalization without radiative loss. Any radiative loss lowers the hot gas temperature and the pressure. Taking $\log P_{\text{hot}} = 11.9$, the hot gas needs to have a high density $n_{\text{hot}} = 8 \times 10^4 \text{ cm}^{-3}$ ($10^7 \text{ K} / T_{\text{hot}}$) and hence a short cooling time $t_{\text{cool}} \simeq 60 \text{ yr}$ ($T_{\text{hot}} / 10^7 \text{ K}$)^{1.7} ($n_{\text{hot}} / 10^5 \text{ cm}^{-3}$) (Draine, 2011b). This is not longer than the timescale of streaming across the core region $t_{\text{cr}} = R_c / v_{\text{hot}} = 200 \text{ yr}$ ($R_c / 0.2 \text{ pc}$) / ($v_{\text{hot}} / 1000 \text{ km s}^{-1}$), and is shorter than the typical time separation between successive CCSNe $\sim 1 / (\Gamma_{\text{SN}} M) \simeq 900 \text{ yr}$ ($\Gamma_{\text{SN}} / 5 \times 10^{-10} \text{ yr}^{-1} M_\odot^{-1}$)⁻¹ ($M / 2 \times 10^6 M_\odot$)⁻¹, even if all CCSNe occur at the cluster center. Therefore, such a compact hot cluster gas component seems unstable to radiative cooling.

Importantly, we expect $y \simeq 1/2$ for the shattered-cloud geometry, since the dense clouds would naturally have a more or less isotropic distribution about the cluster center. A y value that strongly hints at the HI-obscured geometry, $y < 0.2$, does not favor this geometry.

HII Bubbles within Condensed Gas

Following previous discussions, dense cluster hot gas inevitably enters the regime of catastrophic radiative cooling (Silich, Tenorio-Tagle, and Rodríguez-González, 2004b; Wünsch et al., 2011; Gray et al., 2019; Danekkar, Oey, and Gray, 2021; Lochhaas and Thompson, 2017; Wünsch et al., 2017), so that it would fail to blow out at all. It is found in hydrodynamic simulations that in this regime, gas undergoes rapid radiative cooling and accumulates at the cluster center (Wünsch et al., 2017).

Motivated by this insight, we propose a different nebula geometry (Figure 5.2): catastrophically cooled cluster gas expelled from the massive stars has accumulated in the cluster core since the beginning of the cluster evolution. This gas is dense enough that it self-shields

against ionizing photons even though it is interspersed between the O stars. If the gas is not dusty (no significant dust reddening is seen toward Godzilla), its neutral interior can still be heated due to photoionization of metals by the intense UV light and hence stay warm at a few thousand Kelvin. The nebular emission may then come from ionization-bounded HII bubbles surrounding individual O stars which are embedded in self-shielding cluster gas that fills the cluster core.

This scenario is motivated by several hints. First, special chemical abundances are indicative of a nebula gas origin from retained wind and CCSN ejecta; catastrophic cooling may first cause the wind material to accumulate in the cluster core, while the later CCSN ejecta may be trapped within. Second, individual ionization-bounded HII bubbles can be very compact, which allows for high $\Phi(\text{H}^0)$ values, as we will show. Finally, fitting preference for a small y value helps explain the weakness of H Balmer lines and indicates a high fraction of nebula emission that is affected by significant HI columns along the line of sight.

Each individual O star with wind mass loss rate $\dot{M}_w$, wind velocity v_w and ionizing photon rate S_0 blows a bubble around it within the dense cluster gas. The bubble feels a “headwind” of the ambient cluster gas due to the relative velocity between the star and the ambient gas flow. With efficient radiative cooling, shell gas can form from this interaction (Scherer et al., 2016; Titova, Korolkov, and Izmodenov, 2021). Accounting for wind and radiation pressures, the bubble radius R_b along the stagnation line can be estimated from $P = (4 \dot{M}_w v_w + \Phi_0 \langle h\nu \rangle_{\text{ion}})/(4\pi R_b^2)$, where $\langle h\nu \rangle_{\text{ion}} \approx 20 \text{ eV}$ is the typical energy of the ionizing photons and a factor of 4 in front of $\dot{M}_w v_w$ accounts for the thickness of the shocked wind. The bubble has a compact size:

$$R_b = 170 \text{ AU} \left(\frac{1 + \zeta}{2.5} \right)^{\frac{1}{2}} \left(\frac{S_0}{10^{48.5} \text{ s}^{-1}} \right)^{\frac{1}{2}} \left(\frac{\langle h\nu \rangle_{\text{ion}}}{20 \text{ eV}} \right)^{\frac{1}{2}} \times \left(\frac{P}{10^{11.9} \text{ K cm}^{-3}} \right)^{-\frac{1}{2}}, \quad (5.3)$$

where we define $\zeta = (4\dot{M}_w v_w)/(S_0 \langle h\nu \rangle_{\text{ion}})$. The fiducial values, $S_0 = 10^{48.5} \text{ s}^{-1}$, $\dot{M}_w = 10^{-7} M_\odot \text{ yr}^{-1}$, $v_w = 2000 \text{ km s}^{-1}$ and hence $\zeta = 1.5$, are chosen for median O stars that contribute to the ionizing output at $t_{\text{age}} = 5 \text{ Myr}$ ($m_{\text{ZAMS}} \simeq 25 M_\odot$) (Bressan et al., 2012). If instead $t_{\text{age}} = 4 \text{ Myr}$, we have $S_0 = 10^{49} \text{ s}^{-1}$, $\dot{M}_w = 10^{-6.5} M_\odot \text{ yr}^{-1}$ but again with $\zeta = 1.5$, for median O stars with $m_{\text{ZAMS}} \simeq 40 M_\odot$, which corresponds to $R_b = 300 \text{ AU}$. Since the HII bubbles are much smaller than the typical separation between O stars within the cluster, their total volume filling fraction is tiny.

In the ionized gas where nebular emission lines form, we have $P \approx 2 n_e k_B T_e$. For the ionizing photon rate S_0 from one O star, the ionization parameter is $U = S_0/(4\pi R_b^2 n_e c)$. This gives $U \approx (2 k_B T_e)/(\langle h\nu \rangle_{\text{ion}} (1 + \zeta))$, or numerically

$$U = 10^{-1.5} \left(\frac{1 + \zeta}{2.5} \right)^{-1} \left(\frac{T_e}{10^4 \text{ K}} \right) \left(\frac{\langle h\nu \rangle_{\text{ion}}}{20 \text{ eV}} \right)^{-1}, \quad (5.4)$$

which is insensitive to the exact value of the ambient pressure. This $\log U$ value is higher than what is inferred from the Base Model, but aligns more with solutions of elevated He/H found with the Chemical Anomalous Model (Figure 5.8). There is uncertainty in this estimation due to the anisotropic structure of the HII bubble given the motion of the O star relative to the cluster gas (e.g., Mackey 2023). We also caution about the uncertainty that the hot ionized bubbles could be larger with a lower $\log U$ value. It may be that some of these large bubbles are driven by ongoing SNRs from recent CCSNe (invoked to drive supersonic turbulence), a high-density, scaled-down analog of what happens to the multi-phase ISM in the Galaxy (McKee and Ostriker, 1977).

We suggest that the stellar ejecta accumulated in the cluster core is in a state of supersonic turbulence, analogous to giant molecular clouds. Maintained by UV heating, the gas is only at a few thousand K, and its sound speed c_s , at several km s^{-1} , is smaller than the virial velocity in the cluster potential, which easily reaches tens of km s^{-1} for $M_\star \sim 10^6 M_\odot$ and $R \sim 1 \text{ pc}$. Supersonic turbulence is therefore required to support this gas, at least for one or several Myr, against gravitational collapse which would quickly turn it into stars. The turbulence velocity should be on the order of the virial velocity in the cluster core.

Most of the volume is filled with the turbulent HI gas. For a large turbulence Mach number $\mathcal{M} = u/c_s$ (where u is the turbulence velocity on the largest scale), the gas is highly inhomogeneous (Hennebelle and Chabrier, 2008; Hopkins, 2012). The individual HII bubbles around O stars mostly probe the volume-weighted median density n_V , which should be high enough to provide the ram pressure in the “headwind”:

$$n_V \simeq \frac{P}{m_p u^2} = 3 \times 10^6 \text{ cm}^{-3} \times \left(\frac{P}{10^{11.9} \text{ K cm}^{-3}} \right) \left(\frac{u}{50 \text{ km s}^{-1}} \right)^{-2}. \quad (5.5)$$

The typical HI column density in front of the nebular source is $N_{\text{HI}} \simeq n_V R_g = 2 \times 10^{24} \text{ cm}^{-2} (n_V/10^{6.5} \text{ cm}^{-3}) (R_g/0.2 \text{ pc})$. Viewing from the outside, the FUV sources inside the HI gas is analogous of an extremely damped $\text{Ly}\alpha$ system. In fact, for $N_{\text{HI}} = 2 \times 10^{24} \text{ cm}^{-2}$, the $\text{Ly}\alpha$ damping wing absorption equivalent width is huge $\sim 1000 \text{ \AA}$, which means FUV flux in the wavelength range of H Lyman series should be completely attenuated. However, this does not necessarily contradict data, as in our model FUV sources embedded within the retained HI gas make up a small fraction (e.g. $\lesssim 10\%$) of the cluster’s total FUV flux. A lot more FUV sources are expected to be exterior to the HI gas; ionizing radiation are expected to be more concentrated than FUV radiation in dense young star clusters (Kim et al., 2023).

A more important, fundamental difference between damped $\text{Ly}\alpha$ systems and the geometry we consider is that for the former photons are scattered out of line of sight, while for Godzilla photons do have to eventually emerge from the HI gas cloud somewhere. Accounting for photons scattered back into the line of sight therefore reduces the trough width. Indeed, F390W and F410M fluxes appear to be moderately deficient but far from being completely attenuated (Figure 5.5).

According to the theory of supersonic turbulence, the mean density $\bar{n}$ should be larger than n_V by a factor $e^{\sigma_\delta^2/2}$ (Hennebelle and Chabrier, 2008; Padoan et al., 2014), where $\sigma_\delta^2 \simeq 4\text{--}5$ for $\mathcal{M} \simeq 10$ (Federrath et al., 2021). Thus, $\bar{n}$ should be a factor of 10 larger than Eq. (5.5).

The retained gas core radius R_g may be a fraction of the cluster size since we infer a small covering factor $x \simeq 0.2$. The gas mass required is

$$M_g \approx 3 \times 10^4 M_\odot \left(1 + \frac{4 \text{ He}}{\text{H}}\right) \left(\frac{\bar{n}}{10^{7.5} \text{ cm}^{-3}}\right) \left(\frac{R_g}{0.2 \text{ pc}}\right)^3. \quad (5.6)$$

For a cluster mass $M_\star = 2 \times 10^6 M_\odot / \mu_{1000}$ and if R_g is a small fraction of a parsec, there is sufficient wind mass loss and CCSN ejecta to account for $M_g \lesssim 3 \times 10^4 M_\odot$.

If we identify the turbulence outer scale with the radial extent of the accumulated gas cloud R_g , the sonic scale (Padoan, 1995),

$$l_s = \left(\frac{c_s}{u}\right)^2 R_c = 270 \text{ AU} \left(\frac{R_g}{0.2 \text{ pc}}\right)^2 \left(\frac{\mathcal{M}}{10}\right)^{-2}, \quad (5.7)$$

is larger or comparable to the typical HII bubble size R_b (see Eq. (5.3)). Hence the “head-wind” does not behave clumpy before colliding with the O star wind.

The SNR expands into the cluster gas at the volume-weighted median density n_V . For $n_V \gtrsim 10^6 \text{ cm}^{-3}$, the SNR can fail to break out of the condensed cluster gas before it dissipates, even for R_g as small as a fraction of a parsec. This allows the condensed gas to stay in the cluster potential, and injects a small fraction of the explosion energy into the gas to maintain turbulence. We will discuss this in Section 5.6.

We note that the geometry of individual HII bubbles embedded within turbulent HI gas can explain the preference for a small y value. There should still be ionizing sources beyond the radius R_g , which illuminate the cluster gas cloud from the outside. A y value close but not equal to zero may account for such non-HI-obscured contributions. This is an advantage of this model compared to the scenario of shattered dense clouds with a low area covering factor. We believe this unusual geometry best describes Godzilla in reality.

SN Driving of Turbulence

The state of supersonic turbulence is highly dissipative, radiating away the bulk of the flow energy on the order of the turnover time of the largest eddy, which should be on the order of the dynamic time (which is much shorter than $\sim \text{Myr}$). The energy dissipation rate is

estimated to be

$$\begin{aligned}
\left(\frac{dE}{dt}\right)_{\text{turb}} &\sim \frac{u^2}{2} \left(1 + \frac{4 \text{ He}}{\text{H}}\right) m_p \bar{n} \frac{4\pi}{3} R_g^3 \left(\frac{R_g}{u}\right)^{-1} \\
&\simeq 4 \times 10^{39} \text{ erg s}^{-1} \left(1 + \frac{4 \text{ He}}{\text{H}}\right) \left(\frac{\bar{n}}{10^{7.5} \text{ cm}^{-3}}\right) \\
&\times \left(\frac{R_g}{0.2 \text{ pc}}\right)^2 \left(\frac{u}{50 \text{ km s}^{-1}}\right)^3.
\end{aligned} \tag{5.8}$$

We surmise that supersonic turbulence can be sustained by CCSNe after $t_{\text{age}} \simeq 3 \text{ Myr}$, at least when all CCSNe occur well within the retained gas. The bulk of the CCSN explosion energy will be radiated away, but a subdominant fraction of it can maintain gas turbulence.

Let us crudely estimate CCSN driving using the semi-analytic theory of a spherical symmetric SN remnant expanding into an ambient gas of uniform density n_V . The initial adiabatic expansion (Sedov, 1959; Taylor, 1950) creates a growing hot bubble of size as a function of time t

$$R_{\text{SNR}} \simeq 0.04 \text{ pc} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}}\right)^{\frac{1}{5}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}}\right)^{-\frac{1}{5}} \left(\frac{t}{10 \text{ yr}}\right)^{\frac{2}{5}}. \tag{5.9}$$

A homologous Sedov-Taylor bubble has a temperature

$$T \simeq 6 \times 10^6 \text{ K} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}}\right)^{\frac{2}{5}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}}\right)^{-\frac{2}{5}} \left(\frac{t}{10^2 \text{ yr}}\right)^{-\frac{6}{5}}. \tag{5.10}$$

Shortly after the hot bubble cools radiatively, a mass shell forms at the edge of the bubble. The evolution transitions to a pressure driven phase (Cox, 1972; Chevalier, 1974). To analytically estimate this transition point, we use a simple cooling function for $\Lambda(T) = 1.6 \times 10^{-19} \xi_m (T/\text{K})^{-1/2} \text{ erg cm}^3 \text{ s}^{-1}$, valid for the hot gas in the temperature range $10^5 < T/\text{K} < 10^{7.5}$. Here ξ_m is an order-unity parameter depending on the gas metallicity and $\xi_m \simeq 1$ at solar metallicity. For high n_V , the pressure driven phase is quickly reached at a time

$$t_{\text{PDS}} \simeq 3 \text{ yr} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}}\right)^{\frac{3}{14}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}}\right)^{-\frac{4}{7}} \xi_m^{-\frac{5}{14}}, \tag{5.11}$$

with a shell radius

$$R_{\text{PDS}} \simeq 0.02 \text{ pc} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}}\right)^{\frac{2}{7}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}}\right)^{-\frac{3}{7}} \xi_m^{-\frac{1}{7}}. \tag{5.12}$$

The shell has swept up ambient gas of mass $M_{\text{PDS}} \simeq (4\pi/3) m_p n_V R_{\text{PDS}}^3$, which is

$$M_{\text{PDS}} \simeq 6 M_{\odot} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}}\right)^{\frac{6}{7}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}}\right)^{-\frac{2}{7}} \xi_m^{-\frac{3}{7}}. \tag{5.13}$$

The shell expands at a velocity

$$\begin{aligned} v_{\text{PDS}} &= \frac{2 R_{\text{PDS}}}{5 t_{\text{PDS}}} \\ &\simeq 3500 \text{ km s}^{-1} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{\frac{1}{14}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}} \right)^{\frac{1}{7}} \xi_m^{\frac{3}{14}}. \end{aligned} \quad (5.14)$$

At this point, the shell carries radial momentum (Ostriker and McKee, 1988)

$$\begin{aligned} p_{\text{PDS}} &= M_{\text{PDS}} \frac{9}{14} v_{\text{PDS}} \simeq 1.4 \times 10^4 M_{\odot} \text{ km s}^{-1} \\ &\times \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{\frac{13}{14}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}} \right)^{-\frac{1}{7}} \xi_m^{-\frac{3}{14}}. \end{aligned} \quad (5.15)$$

From this point onward, the SN remnant will expand substantially until the velocity of the wrinkled gas shell decreases to be comparable to the ambient turbulence velocity u . This process is close to but not perfectly momentum conserving. The final momentum injected into the ambient gas, p_{SN} , is estimated to be only a few times larger than p_{PDS} , $\epsilon_p = p_{\text{SN}}/p_{\text{PDS}} = 2\text{--}3$, the remnant radius will have expanded by several fold $\epsilon_R = R_{\text{SN}}/R_{\text{PDS}} = 2\text{--}5$, and will have swept up a total mass $M_{\text{SN}} = \epsilon_R^3 M_{\text{PDS}}$ (Cioffi, McKee, and Bertschinger, 1988). The ratios ϵ_p and ϵ_R are expected to depend rather weakly on n_V (Cioffi, McKee, and Bertschinger, 1988).

The final kinetic energy injected into the ambient gas can be estimated as

$$\begin{aligned} K_{\text{SN}} &= \frac{p_{\text{SN}}^2}{2 M_{\text{SN}}} = \frac{p_{\text{PDS}}^2}{2 M_{\text{PDS}}} \frac{\epsilon_p^2}{\epsilon_R^3} \\ &\simeq 1 \times 10^{50} \text{ erg} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \left(\frac{\epsilon_p}{3} \right)^2 \left(\frac{\epsilon_R}{3} \right)^{-3}. \end{aligned} \quad (5.16)$$

Assuming all CCSNe occur near the cluster center within the retained cluster gas around $t_{\text{age}} = 4\text{--}6 \text{ Myr}$, the total CCSN driving energy rate is

$$\begin{aligned} \left(\frac{dE}{dt} \right)_{\text{SN}} &= \Gamma_{\text{SN}} K_{\text{SN}} M_{\star} \\ &\simeq 3 \times 10^{39} \text{ erg s}^{-1} \left(\frac{\Gamma_{\text{SN}}}{5 \times 10^{-10} \text{ yr}^{-1} M_{\odot}^{-1}} \right) \left(\frac{K_{\text{SN}}}{10^{50} \text{ erg}} \right) \\ &\times \left(\frac{M_{\star}}{2 \times 10^6 M_{\odot}} \right). \end{aligned} \quad (5.17)$$

Despite much complexity in estimating CCSNe kinetic feedback in the radiative regime and with possibly inhomogeneous surrounding medium (Cowie, McKee, and Ostriker, 1981), the order-of-magnitude agreement between Eq. (5.17) and Eq. (5.8) following simple estimations

suggests that turbulence driving by CCSNe is at least plausible, provided that the cloud size R_g is not much larger than a fraction of pc and the turbulence velocity does not exceed $u = 100 \text{ km s}^{-1}$.

We note that having $\epsilon_R = 2\text{--}5$ puts $R_{\text{SN}} = 0.04\text{--}0.1 \text{ pc}$ for the fiducial values of E_{SN} and n_V , well within the size of the retained cluster gas $R_{\text{SN}} < R_g$. This is compatible with our physical picture here that CCSNe fail to remove the retained cluster gas, hence the efficient retention of their metal yield. SN remnant completely dissipates in the surrounding turbulent gas at the time $t_{\text{SN}} = \epsilon_t t_{\text{PDS}}$, where ϵ_t can be estimated

$$\begin{aligned} \epsilon_t &\simeq 300 \left(\frac{u}{50 \text{ km s}^{-1}} \right)^{-\frac{10}{7}} \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)^{\frac{5}{49}} \\ &\times \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}} \right)^{\frac{10}{49}} \xi_m^{-\frac{15}{49}}. \end{aligned} \quad (5.18)$$

For our fiducial model parameters, the lifetime of each SN remnant is on the order of $t_{\text{SN}} \sim 10^3 \text{ yr}$ and is comparable to the inverse frequency of CCSN occurrence $1/(\Gamma_{\text{SN}} M_\star)$. If CCSNe occur too frequently compared to the remnant lifetime, complication can arise due to clustered feedback from multiple SNe, which should enhance SN momentum feedback (Gentry et al., 2019).

Effect of HI Column

Our picture of HII bubbles embedded in condensed, self-shielding cluster gas requires that emission lines traverse a large HI column before they leave the cluster gas. Intriguing, our emission line fitting favors a y value close to zero, which means we are mostly seeing emission line photons propagating through the self-shielded HI column rather than directly from the irradiated faces. According to **Cloudy**, we find this optical depth effect significantly decrease H Balmer lines for $y = 0$ but does not impact the metal (semi-)forbidden lines.

Ferland and Netzer, 1979 studied line trapping of H Lyman and Balmer photons in an ionization-bounded HII region. In particular, trapped Ly α photons excite an $n = 2$ population which can provide a substantial resonant scattering optical depth to H Balmer photons, particularly in the absence of internal dust. As Grandi, 1980 explains (also see Hamann, 2012), the trapped H α photons can convert to Ly β photons, which can pump the abundant O I ions in the neutral zone. H α can thus be lost when there is a substantial line optical depth to H Balmer photons.

Interestingly, we see a significant detection of O I λ 1641 (the line center is inconsistent with He II λ 1640), which is a fluorescent signature of Ly β pumping of O I. We refrain from quantitatively comparing the O I λ 1641 detection to **Cloudy** predictions, as the line trapping effect is sensitive to the column density, kinematics of the neutral gas behind the ionization front, and internal grain abundance.

This provides a promising explanation, which is perhaps more important than merely the elevated O and He abundances, for the surprising weakness of H Balmer lines as first

pointed out by Vanzella et al., 2020c. We take this strong preference in data for an optical depth effect from a H I column as one more supporting evidence for our physical model for Godzilla’s nebular emission.

We also note that this optical depth effect results in a model-predicted unreddened $H\alpha/H\beta$ ratio much larger (~ 10) than the standard assumption for Case B recombination (~ 2.81 for $n_e \sim 10^6 \text{ cm}^{-3}$; Osterbrock, 1989). Scarlata et al., 2024 argue that in this regime of a large excited $n = 2$ population, a spherically symmetric cloud geometry may result in high intrinsic $H\alpha/H\beta$ ratio due to Balmer self-absorption, while highly non-symmetric geometries could preferentially scatter $H\alpha$ photons out of the line of sight, leading to lower intrinsic Balmer decrements. This implies that using Case B assumptions for the measurement of external dust reddening may be inappropriate in this regime. In the case of our model-predictions, it would mimic a substantial extinction ($E(B - V) \sim 1$) which would be inconsistent with the detection of a bright FUV stellar continuum with a blue SED slope and strong UV nebular emission lines.

Expectations for Emission Line Profile

The physical picture presented here may give some insight into understanding the emission line profile. Choe et al., 2024 show from high resolution JWST NIRSpec/IFU spectroscopy the superposition of narrow ($\text{FWHM} \lesssim 100 \text{ km/s}$), broad ($\text{FWHM} \sim 200\text{-}300 \text{ km/s}$), and very broad (in the case of $H\alpha$; $\text{FWHM} \sim 500 \text{ km/s}$) components to optical emission lines. While a quantitative prediction of the emission line profile and relative component strengths from our model requires extensive theoretical exploration that is beyond the scope of this work, the existence of a broad component can be qualitatively compatible with our physical picture.

In the picture of catastrophic cooling of a global cluster wind, the entire volume of the cluster is not expected to cool, except in the regime of high mass loading of the wind material with ambient cluster gas (Lochhaas and Thompson, 2017). Rather, there exists a cooling radius, outside of which massive stars may still inject mass and kinetic energy to drive a low-density hot cluster wind. At intermediate radii, there is likely a multi-phased transition regime between the fully condensed, self-shielding phase at the cluster center and the fast, radiatively inefficient hot wind outside (Wünsch et al., 2017). There, warm gas cloudlets, optically thick to ionizing photons but with a low total area covering fraction, may be accelerated to hundreds of km/s by gas pressure or radiation, outflowing out of the cluster potential. Nebular emissions from these outflowing cloudlets, powered by stars outside the central condensed gas component, would naturally result in broader nebular emission lines compared to emission from the central region.

In principle, accurate modeling would require including nebular emission from outflowing gas cloudlets. Choe et al., 2024 found that the broad component dominates the line flux in $H\alpha$, $H\beta$ and $[\text{O III}]\lambda\lambda 4959, 5007$, but in our model these are also the lines that are predicted to be unusually weak from dense gas settled at the cluster center (radiation transfer suppression for H Balmer lines and collisional suppression for $[\text{O III}]\lambda\lambda 4959, 5007$). In other major

optical lines, the broad component appears subdominant compared to the narrow component. The broad component appears weaker than the narrow component in aurora lines [O III] λ 4363 and [N II] λ 5755, which have critical densities around $3 \times 10^7 \text{ cm}^{-3}$. This supports the interpretation that the broad component appears dominant in [O III] $\lambda\lambda$ 4959,5007 and H α , H β because the narrow component, which as we hypothesize comes primarily from the condensed gas settled down at the cluster center, is weak in these lines.

This is compatible with the picture that the outflowing ionized gas sourcing the broad nebular emission have more ordinary conditions; most likely n_e is lower there, and the effect of H Balmer optical depth is insignificant due to an open geometry. It is unclear whether a broad component is important for the major UV emission lines such as C III] $\lambda\lambda$ 1906,1908, N III] λ 1750 and [O III] $\lambda\lambda$ 1660,1666. The SNRs in the MUSE data are not as high as in Choe et al., 2024, but it does appear that $\text{FWHM} < 200 \text{ km/s}$ for these lines. It is likely the broad component is sub-dominant in the UV lines just like in many optical lines such as the auroral lines. Such a component may also be dusty and not subject to removal by UV radiation pressure (see Section 5.6), and should this component also have a fairly low overall covering, the geometry may allow for dust reddening of the broad lines while retaining a strong stellar UV continuum and nebular UV emission lines.

As described in Section 5.6, the H Balmer lines experience significant optical depth. The subsequent resonant scattering of the Balmer lines and Balmer self-absorption are expected to broaden the H Balmer lines to 100's km/s, and may provide an explanation for the very broad component of the emission. Moreover, Balmer emission in the neutral gas resulting from fluorescence by the stellar continuum near higher-order H Lyman lines (e.g., Luridiana et al., 2009) may also result in broad H Balmer lines, and this fluorescence is seen in our CLOUDY models. However, it is unclear if CLOUDY's implementation of these effects is accurate and how broad these lines are expected to be. Furthermore, unknowns such as the column density or kinematics of the neutral region which could strongly affect this. Further detailed work is required to ascertain whether the presence of very broad $\sim 500 \text{ km/s}$ line emission is quantitatively consistent with our physical picture.

In this work, we choose to neglect a possible nebula component coming from outflowing photo-ionization clouds that may be responsible for the broad emission line components reported in Choe et al., 2024, with the justification that we have used in our analysis only the upper limits for the optical lines expect for [Ne III] λ 3869 and He I λ 5879. We leave a multi-nebular-component spectroscopic modeling covering from rest-frame UV to optical wavelengths, which is necessarily more sophisticated in terms of both data analysis and theoretical modeling, to future work when the JWST NIRSpec IFU data is incorporated into the analysis.

Ly α -pumped Fe III Fluorescence

Vanzella et al., 2020c discovered remarkably bright fluorescent emission lines of Fe III from Godzilla, which are shown to result from Ly α excitation of a nearby Fe III λ 1214 transition (Johansson et al., 2000). To our knowledge, the only detailed report of this exact Fe

III fluorescence process came from the Weigelt Blobs in η Car’s inner ejecta (Zethson et al., 2012), which are known to be heavily-CNO-processed material expelled by η Car. Similar to what we have found for Godzilla’s nebula, the fluorescent Weigelt Blobs host dense ionized gas $n_e \sim 10^{(7-8)} \text{ cm}^{-3}$ (Hamann, 2012) and exhibit large enhancement in N and He abundances (Verner, Bruhweiler, and Gull, 2005), and shows fluorescent O I lines by $\text{Ly}\beta$ pumping (Hamann, 2012). Godzilla’s nebula gas appears to physically and chemically resemble the Weigelt Blobs, but is excited by a much brighter radiation source. This similarity perhaps explains why both are conducive to $\text{Ly}\alpha$ -pumped Bowen fluorescence.

Given the large $\sim 270 \text{ km s}^{-1}$ frequency de-tuning between H $\text{Ly}\alpha$ and the excited Fe III $\lambda 1214$ line, a strong and broad $\text{Ly}\alpha$ line has to form within the nebula. This requires a geometry in which $\text{Ly}\alpha$ photons are spatially trapped by repeated resonant scattering after they are produced from recombination. This also requires a dust-free condition so that the $\text{Ly}\alpha$ photons are not internally destroyed. In the case of Godzilla, ionization-bounded hot bubbles embedded in the cluster gas, which we postulate as the formation sites of the nebular emission lines, may provide the right geometry as the surrounding self-shielded component of the cluster gas is optically thick to $\text{Ly}\alpha$ photons. The cluster gas is also required to be dust-free, which appears consistent with non-detection of significant reddening of Godzilla’s FUV continuum. We therefore suggest, at least qualitatively, that our physical picture for Godzilla’s nebula may explain the observed $\text{Ly}\alpha$ -pumped Fe III fluorescence. We plan to investigate this in more details in a future publication.

Removal of Dust Grains

Our inferred relatively low $E(B - V) < 0.08$ implies that the overall nebula environment of Godzilla is not extremely dusty and is largely transparent to FUV. A grain-free condition is also required in the active zones to allow for H Lyman-series pumping and fluorescence.

As our photoionization modeling implies, direct stellar irradiation, dominated by FUV in energy, may be intense enough to vaporize dust grains. For the high radiation intensity, we neglect the effects of time-dependent temperature spikes for small grains, and only consider an equilibrium-state grain temperature T_d , which can be found by balancing the rate of FUV heating and the rate of cooling by thermal re-radiation at infrared wavelengths (Draine, 2011b):

$$4\pi a^2 \langle Q \rangle_{T_d} \sigma_{\text{SB}} T_d^4 = \pi a^2 \langle Q \rangle_{\text{UV}} F_{\text{UV}}. \quad (5.19)$$

Here $\langle Q \rangle_{T_d}$ the absorption efficiency averaged over a Planck spectrum of temperature T_d , and $\langle Q \rangle_{\text{UV}}$ is the absorption efficiency averaged over the incident radiation, whose flux is dominated by UV photons, and σ_{SB} is the Stefan-Boltzmann constant.

The precise values of $\langle Q \rangle_{T_d}$ and $\langle Q \rangle_{\text{UV}}$ depend on grain size, grain composition, and the spectral shape of the incident star light, and are not always monotonic. For FUV photons

$\langle Q \rangle_{\text{UV}} \simeq 1$. According to Figure 24.3 of Draine, 2011b, we conservatively estimate:

$$\langle Q \rangle_{T_d} < 0.5 \left(\frac{a}{\mu\text{m}} \right), \quad (5.20)$$

in the temperature range $100 < T_d/\text{K} < 1000$, for sufficiently large grains $a > 0.01 \mu\text{m}$, and for both silicate and carbonaceous grains. These conservative limit leads to

$$\begin{aligned} T_d &> \left(\frac{(\mu\text{m}/a)}{0.5} \frac{\chi \Phi(\text{H}^0) \langle h\nu \rangle_{\text{ion}}}{4 \sigma_{\text{SB}}} \right)^{\frac{1}{4}} \\ &= 1200 \text{ K} \left(\frac{a}{0.01 \mu\text{m}} \right)^{-\frac{1}{4}} \\ &\times \left(\frac{\chi}{10} \right)^{\frac{1}{4}} \left(\frac{\Phi(\text{H}^0)}{10^{15.9} \text{ s}^{-1} \text{ cm}^{-3}} \right)^{\frac{1}{4}} \left(\frac{\langle h\nu \rangle_{\text{ion}}}{20 \text{ eV}} \right)^{\frac{1}{4}}. \end{aligned} \quad (5.21)$$

Here we have introduced the dimensionless χ , the ratio between the FUV flux and the ionizing flux. The lower bound is $T_d > 680 \text{ K}$ for $a = 0.1 \mu\text{m}$ and $T_d > 380 \text{ K}$ for $a = 1 \mu\text{m}$. Given the sublimation temperature $\sim 1200 \text{ K}$ for silicates and $\sim 1800 \text{ K}$ for carbonaceous grains, small silicates grains with $a \lesssim 0.01 \mu\text{m}$ could have been all evaporated by radiation, but large silicate grains or carbonaceous grains can likely survive.

For the geometry of embedded HII bubbles (Section 5.6), small silicate grains $a \lesssim 0.01 \mu\text{m}$ should be vaporized by individual O stars in the HII bubble vicinity, but it is unclear if the global FUV background throughout the retained gas cloud is intense enough to vaporize the other grains. Assuming that a fraction x_{FUV} of the FUV sources are enclosed within radius R_g , the mean FUV irradiation is a fraction $\simeq 0.11 (x_{\text{FUV}}/0.1) (R_g/0.2 \text{ pc})$ of the FUV irradiation in individual HII bubbles.

It may be that over time radiation pressure pushes all surviving grains out of the gas cloud. For grain collision with hydrogen atoms in an HI gas, Draine and Salpeter, 1979 introduced the function

$$G(s) = \frac{8s}{3\sqrt{\pi}} \left(1 + \frac{9\pi}{64} s^2 \right)^{1/2}. \quad (5.22)$$

Here $s = v_d / \sqrt{2 k_B T / m_p}$, where v_d is the grain drift velocity relative to the gas and T is the gas temperature. When the drift velocity is supersonic $s \gg 1$, $G(s) = s^2$. Following Draine, 2011a, we find a drift velocity

$$\begin{aligned} v_d &= 22 \text{ km s}^{-1} \left(\frac{\chi}{10} \right)^{\frac{1}{2}} \left(\frac{\Phi(\text{H}^0)}{10^{14.9} \text{ s}^{-1} \text{ cm}^{-2}} \right)^{\frac{1}{2}} \left(\frac{\langle h\nu \rangle_{\text{ion}}}{20 \text{ eV}} \right)^{\frac{1}{2}} \\ &\times \left(\frac{\langle Q_{\text{pr}} \rangle}{1.5} \right)^{\frac{1}{2}} \left(\frac{n_V}{10^{6.5} \text{ cm}^{-3}} \right)^{-\frac{1}{2}}, \end{aligned} \quad (5.23)$$

where $\langle Q_{\text{pr}} \rangle$ is the wavelength-averaged absorption efficiency. This is not small compared to the turbulence velocity u , so let us assume that turbulence motion does not significantly prohibit grain ejection. After a short time $R_g/v_d \approx 10^4 \text{ yr } (R_g/0.2 \text{ pc})/(v_d/20 \text{ km s}^{-1})$, FUV radiation should eject all grains out of the retained dense gas if they have survived sublimation.

In this process, dust grains drift relative to the gas at terminal speeds and exert an outward force on the gas as well. However, gravity of the cluster gas and the stars it encloses is strong enough to prevent gas from being ejected together with the dust grains. Indeed, the characteristic inward pressure due to gravity can be crudely estimated as

$$\begin{aligned} P_{\text{grav}} &\gtrsim \frac{G M_g^2}{R_g^4} \\ &\simeq 1.5 \times 10^{14} \text{ K cm}^{-3} \left(\frac{M_g}{10^5 M_\odot} \right)^2 \left(\frac{R_g}{0.2 \text{ pc}} \right)^{-4}. \end{aligned} \quad (5.24)$$

In comparison, the typical outward pressure from UV radiation transferred through the grain-gas coupling is significantly smaller

$$P_{\text{UV}} \simeq 10^{11} \text{ K cm}^{-3} \left(\frac{\Phi(\text{H}^0)}{10^{15.1} \text{ s}^{-1} \text{ cm}^{-2}} \right) \left(\frac{\langle h\nu \rangle_{\text{ion}}}{20 \text{ eV}} \right) \left(\frac{\chi}{10} \right). \quad (5.25)$$

Godzilla and Multiple Stellar Populations

The high mass and compactness of Godzilla make it a likely candidate for an analog progenitor of globular clusters (Kruijssen, 2014), which ubiquitously host multiple stellar populations of distinct light element abundances (see Bastian and Lardo, 2018 for a review). The dense nebula gas of Godzilla likely has accumulated inside the cluster, even at an age $t_{\text{age}} = 4\text{--}6 \text{ Myr}$ when the most massive stars have already started CCSNe. While the standard expectation is that CCSNe will quickly clear out any cluster gas (e.g., Calura et al., 2015; D’Ercole et al., 2010), the successful retention of stellar ejecta in Godzilla, if confirmed, will corroborate theoretical predictions that in dense star clusters feedback sometimes fails in doing this job (e.g., Krause et al., 2013; Tenorio-Tagle et al., 2016), leaving behind a gas reservoir conducive to forming new generation of stars.

However, it does not seem likely to us that this particular dense nebula gas we are witnessing in Godzilla will birth the typical second generation (2P) stars. Assuming that CCSNe fail to expel the cluster gas, as appears to be the case in Godzilla, the strong turbulence driven by CCSNe feedback is expected to prohibit gravitational collapse (Hayward and Hopkins, 2017), disfavoring formation of 2P stars after CCSNe onset. While some propose that this problem can be circumvented in the first 5–10 Myr of the cluster evolution by delaying the onset of CCSNe (e.g., Renzini, Marino, and Milone, 2022), our inferred cluster age suggests that the delay of CCSNe onset may either be at most 1–2 Myr or does not happen at SMC-like stellar metallicities. Even if star formation still proves possible

after CCSN onset, the observed simultaneous N and O enrichment is not compatible with the abundance pattern of the typical 2P stars, as they typically show N enhancement but no enhancement in α -elements. Should Godzilla be a true globular cluster progenitor, 2P star formation must have already occurred prior to the onset of CCSNe.

The observed enhancements in N/O and He/H should be primarily driven by wind ejecta (via comparison to MT12, see Figure 5.11). While our inferred N/O is broadly consistent with the 2P stars in globulars (Fig. 5.10), the inferred He/H value is likely too high. The He abundance in globulars typically has a small spread $\Delta Y \lesssim 0.1$, implying less than unity enhancement in the He/H ratio. By contrast, we infer a factor of ~ 2 –4 enhancement of He/H in Godzilla. Intriguingly, in some of the more special globular clusters such as ω Centauri, He/H differs by as much as a factor of two between multiple populations (Dupree and Avrett, 2013), although it is unclear whether Godzilla could be a progenitor of such unique GCs. It is possible that the observed dense nebular gas is unrelated to 2P star formation, and the typical 2P star formation occurs even earlier, prior to the onset of He-rich winds from evolved massive stars. The models of MT12 find this onset at ~ 2.5 Myr, at which point CNO-processed material is ejected and enriches the surrounding with N and He. However, we note that there are likely earlier sources unaccounted for in the MT12 models that produce ejecta rich in N but not in He, such as Very Massive Stars (Vink, 2023) or supermassive stars (Charbonnel et al., 2023). These sources would allow for similar N/O while significantly reduced (but still mildly enhanced) He/H to match what is observed in the majority of the GCs.

5.7 What Is the Magnification of Godzilla?

The magnification factor of Godzilla is a highly contested topic. Precise knowledge of or empirical constraints on its value will have strong implications for the physical nature of this object. Even though this work focuses on the spectroscopic interpretation of Godzilla, we feel compelled to discuss below how the magnification factor may be empirically constrained.

Constraints From Flux Ratios

Due to the anomalous lensing configuration required, general cluster-scale lensing models such as those in Pignataro et al., 2021 and Sharon et al., 2022b do not give trustworthy predictions of the magnification factor for Godzilla. However, these models can leverage candidate counter-images of Godzilla to infer a magnification on the basis of the observed flux ratio between Godzilla and a possible counter-image, as performed in Diego et al., 2022b. Simply put, assuming the macro lens model for a counter-image is reliable (because the counter-image typically is less magnified and further from critical curves), the flux ratio between Godzilla and its counter-image can be used to infer the magnification of Godzilla. Following this approach, Diego et al., 2022b find a minimum magnification of Godzilla $\mu \sim 600$ pulling from the lens model of Pignataro et al., 2021, and an even higher $\mu \sim 1400$ or

$\mu \sim 8000$ using the WSLAP+ lens modeling approach depending on the sets of constraints used. We note that this work effectively measured the magnification from the counterimage with the lowest fractional flux errors, and that the median across the counterimages typically skewed lower (see their Figure 4). We also repeat exactly the approach of Diego et al., 2022b with the lens model predictions of Sharon et al., 2022b, which uses the same modeling software as Pignataro et al., 2021, to infer a lower minimum magnification $\mu \sim 300$.

As is apparent, magnification predictions of these published Sunburst lens models vary by greater than an order of magnitude. This may result from families of degeneracies stemming from the mass-sheet degeneracy (Falco, Gorenstein, and Shapiro, 1985; Oguri and Kawano, 2003), which hinder absolute magnification estimates for lens systems without a high number of multiply-imaged sources at a number of redshifts, such as PSZ1 G311.65-18.48 which lenses the Sunburst galaxy. It may also be subject to other lensing systematics, such as milli-lensing by optically invisible dark matter subhalos (Dai et al., 2020) or line of sight structure (Dalal, Hennawi, and Bode, 2005) which are generally unaccounted for in strong lens models. With the above caveats in mind, we caution the reader for the following flux ratio estimates.

The candidate counter-images of Godzilla are not yet confirmed, however it is suggested that in the counter-images the source object of Godzilla may be blended with two neighboring knots, dubbed the “P knots” in Diego et al., 2022b, which themselves are likely a lensed image pair straddling a critical curve. Diego et al., 2022b propose 5 likely counter-images (see their Fig. 3) labeled t1-t5, while Sharon et al., 2022b propose a different set of 9 counterimages (their image system 4, see their Figure 2) named 4.1-4.10, where 4.8 corresponds to Godzilla. The two sets share only one candidate counter-image, which corresponds to t5 in Diego et al., 2022b and 4.7 in Sharon et al., 2022b. We opt to adopt the counter-image choice and nomenclature of Sharon et al., 2022b, which are shown in Figure 5.13, as this seems more consistent with the HST and JWST colors (see Choe et al., 2024).

Adopting these images, we follow the magnification ratio argument of Diego et al., 2022b, and restrict ourselves to 4.7, 4.9, and 4.10 for simplicity. There are three lens models from which the magnification of these sources can be inferred, however Diego et al., 2022b only makes a prediction for 4.7 (corresponding to t5). Using the PSF photometry approach described in Sec. 6.4, we measure the flux ratio of Godzilla, the P knots, 4.7, 4.9, and 4.10 in the F814W filter, which are shown in Table 5.7. We use these flux ratios to compute the Godzilla’s magnification, via 4.7, 4.9 and 4.10 separately, as the use of each candidate counter-image may be affected by systematics differently. The flux ratio of 4.7 to Godzilla is $\sim 2\%$ (which was similarly found by Diego et al., 2022b), and the magnification of 4.7 ranges from $\mu_{4.7} = 5.2^{+1.0}_{-0.4}$ from Sharon et al., 2022b to $\mu_{4.7} \sim 105$ from Diego et al., 2022b. This would in turn imply a lower limit on Godzilla’s magnification $\mu \gtrsim 250\text{--}5000$ as Godzilla may not account for the totality of the flux of 4.7. Similarly for 4.9, which has $\sim 8\%$ the flux of Godzilla, magnification predictions are $\mu_{4.9} = 31^{+9}_{-3}$ from Sharon et al., 2022b and $\mu_{4.9} = 71.1^{+7.6}_{-6.4}$ from Pignataro et al., 2021, while Diego et al., 2022b do not make a prediction for this image. Here, we require $\mu \gtrsim 390\text{--}890$. Finally we evaluate 4.10, which has 18% the flux of Godzilla (more than twice the flux of 4.9), despite the magnification predictions of Pignataro et al., 2021 and Sharon et al., 2022b being similar to those for 4.9. This yields

$\mu_{4.10} = 34^{+10}_{-3}$ and $\mu_{4.10} = 86.6^{+7.6}_{-6.1}$ respectively. This then implies a magnification for Godzilla $\mu \gtrsim 190 - 480$. These results are summarized in Table 5.7.

Lens model uncertainties vastly dominate this approach as apparent from the comparison between different lens models. While it is highly probable that Godzilla is magnified by factor of hundreds or greater, it is far from obvious to us that Godzilla must be magnified by thousands or even upwards of ten thousand. A more intermediate magnification of $\mu = 1000$ is not only consistent with the measured flux ratios as we have discussed, but would also be high enough to cause the source of the P knots to dominate the color of the counter-image. Indeed, the source of P knots is likely a more massive star cluster than Godzilla. This is corroborated by the ratio of the 4.9 and 4.10 fluxes to the neighboring two lensed images of the LyC star cluster, which we will refer to as LyC 9 and LyC 10 respectively. Given that 4.9 and 4.10 lie radially to LyC 9 and LyC 10, it is expected that each pair likely have similar magnification factors. This statement is independent of the lens model uncertainties cautioned above, and indeed, both Pignataro et al., 2021 and Sharon et al., 2022b predict this to be the case (despite disagreeing significantly on the magnification value itself). Pascale et al., 2023 and Vanzella et al., 2022b both find that the LyC cluster is likely extremely massive $\gtrsim 10^7 M_\odot$. We find that 4.9 and 4.10 are each $\sim 20\%$ the flux of their neighboring lensed image of the LyC star cluster, implying that 4.9 and 4.10 must host $\gtrsim 10^6 M_\odot$ in stellar mass. We find it plausible that, due to the complex caustic structure, the P knots are much less magnified than Godzilla (indeed they are similar in brightness to within a factor of 2 to 4.9 and 4.10, which are not unusually magnified), yet their underlying source is a more massive star cluster which outshines Godzilla in the candidate counter-image 4.7.

Constraints From Flux Variability

In the high magnification regime, the exact value of Godzilla’s magnification and its age has strong implications for the expected flux variability on the order of days to weeks due to microlensing by intracluster stars (Venumadhav, Dai, and Miralda-Escudé, 2017b; Diego et al., 2018b; Oguri et al., 2018b). These intracluster stars cast a fine network of micro caustics which cause a spatial pattern of magnification on the source plane that is highly non-uniform. As the entire star cluster moves across this pattern, each cluster member star will acquire a time-varying magnification factor, and such magnification factors behave uncorrelated between different member stars (Dai et al., 2020). Then, what can be measured is the superposition of variable fluxes from all stars in the star cluster. Dai, 2021b develops a quantitative framework to describe the statistics of this collective variability, and concludes that when observed at many random times the total flux has a standard deviation that is proportional to the standard deviation of the relative magnification factor fluctuation $\delta = \mu/\bar{\mu} - 1$ and is inversely proportional to the square root of the number of stars. At fixed observed magnitude, a more magnified star cluster must have less stars, which then implies larger fractional fluctuations in the flux. On the other hand, a higher macro magnification factors cause the micro caustics to crowd together, which increases the standard deviation of δ .

Table 5.5. Magnifications and Flux Ratios of Godzilla Counterimages

ID	μ_{Sharon}^a	$\mu_{\text{Pignataro}}^b$	μ_{Diego}^c	f^d/f_{Godzilla}	μ_{Godzilla}
4.7/t5	$5.2^{+0.2}_{-0.9}$	$[11, 19]^e$	$19, 105^f$	0.02	[250, 5000]
4.9	$31.1^{+9.9}_{-13.1}$	$71.1^{+7.6}_{-6.4}$	—	0.08	[390, 890]
4.10	$33.9^{+10.1}_{-12.9}$	$86.6^{+7.6}_{-6.1}$	—	0.18	[190, 480]

Note. — The ID’s (following Sharon et al. 2022b), lens model predicted magnifications, and measured flux ratios with respect to Godzilla for the candidate Godzilla counterimages. We also list the range of magnification lower limits for Godzilla implied by the lens model magnifications and measured flux ratios (see Section 5.7). If Godzilla’s counter image is blended with the counter image of the P knots and contributes to less than a fraction f of the flux, then the implied value for μ_{Godzilla} should be increased by a factor $1/f$.

^{a,b,c} Sharon et al., 2022b, Pignataro et al., 2021, and Diego et al., 2022b respectively.

^dMeasured in HST ACS/WFC F814W. Photometric uncertainties are generally $\lesssim 10\%$ and lens model uncertainty dominates the magnification estimate.

^eMagnification not given for 4.7, we instead cite their 5.1g and 5.2g which bracket 4.7 as the lower and upper limits respectively.

^fMagnifications given for the two different lens models M1 and M2 in Diego et al., 2022b.

Sharon et al., 2022b pointed out that Godzilla shows no signs of significant variability in multiple HST visits over a 2-year period. While it is clear from that work that Godzilla does not drastically brighten or fade, the next question is whether it exhibits subtle flux variability in the continuum. We seek to quantify this by making use of 8 imaging visits in the HST WFC3/IR F140W filter, which sample ~ 4 distinct time frames (i.e., separated by at least a day) across a time window of 1.5 yr. The 8 visit dates are as follows: 06/24/2019, 08/29/2020, 08/30/2020, 8/30/2020, 8/31/2020, 11/11/2020, 11/15/2020, and 12/30/2020. We align the image of each visit following the methodology outlined in Sec.5.2, but to the native WFC3/IR pixel scale of $0.13''$. We measure photometry for Godzilla within a fixed aperture of radius $0.4''$, and estimate the sky background in each visit placing the same aperture on a dozen locations off the arc in the blank sky. To estimate the fractional flux change from visit to visit, the mean flux across the visits is then set to the measured F140W flux from PSF photometry, as the aperture fluxes contain arc background which may otherwise dilute the fractional change. As a control sample, we repeat this procedure on the nearby image 8 of the LyC star cluster (LyC 8 hereafter) for an estimate of photometric systematics (e.g. PSF variation, subpixel misalignments) which certainly dominate over statistical errors. This is justified because the lower magnification of LyC 8 but higher number of stars of the LyC star cluster together imply microlensing-induced flux variations at the percent level or less (see discussion in Dai, 2021b). The fractional flux variations are shown in Figure 5.14. We

infer systematics at 2% from LyC 8. Intriguingly, Godzilla exhibits fluctuations marginally greater than this systematic uncertainty with a standard deviation of $\sim 3\%$ and a maximum range $\sim 13\%$. Figure 5.14 shows that the majority of the fluctuations between Godzilla and LyC 8 are correlated, this may be due to a flux calibration systematic or incomplete background estimation, but indicates the true flux variations may very well be closer to the 1% level.

To constrain Godzilla’s magnification by assuming that microlensing must induce flux variations with a standard deviation $< 3\%$, we need to estimate the surface density of intracluster stars by measuring the surface brightness of the intracluster light (ICL) (e.g., Kelly et al., 2018c; Meena et al., 2023a). Dai, 2021b estimated the ICL stellar population from MUSE IFU spectroscopy near the brightest cluster galaxy (BCG) and found a stellar age ~ 5 Gyr and metallicity $Z \sim 0.4 Z_{\odot}$. However, at the distance of the Sunburst arc ($\sim 30''$), Dai, 2021b judged that the ICL may fall below the diffuse sky background ($\sim 25\text{mag/arcsec}^2$ in F160W), resulting in an upper limit on the averaged convergence $\kappa_{\star} < 0.002$ from intracluster stars.

To improve, we fit elliptical isophotes to the ICL in F160W imaging following the methods of Montes et al., 2021. Briefly, we run **Source Extractor** (Bertin and Arnouts, 1996) following a HOT+COLD approach (e.g., Merlin et al., 2016b; Pascale et al., 2022a) to mask bright sources which may contaminate the fit. Stars are identified using the results of **DAOSTarFinder** from Sec. 6.4 and their masks are vetted by eye to be sufficiently large; features such as the PSF wings and diffraction spikes are typically not well masked by **Source Extractor** and are further masked by hand. Elliptical isophotes are then fit to the masked image using the **photutils.isophote** package, which implements the algorithm of Jedrzejewski, 1987. As seen in Figure 5.15, we find that the ICL at a distance of $\sim 25''$ from the BCG the ICL profile begins to flatten. It is not unusual for the ICL to be composed of both a steep and shallow components, as shown in Montes et al., 2021, however this may instead indicate it is approaching the diffuse sky background. To be conservative, we fit a Sérsic profile (Sersic, 1968) to the measured surface brightness from isophotes only up to $\sim 25''$. From this, we extrapolate to the location of Godzilla and infer an underlying ICL surface brightness 25.5 mag/arcsec^2 , implying $\kappa_{\star} \gtrsim 0.001$. For the following tests, we assign $\kappa_{\star} = 0.001$ as a conservative lower limit, emphasizing that a larger $\kappa_{\star}$ would induce larger variability and hence imply a decreased upper limit on Godzilla’s magnification.

The timescale of variability is set by the effective source velocity (see Eq.(12) of Venu-madhav, Dai, and Miralda-Escudé, 2017b, which however does not account for the observer’s motion)

$$v_t = \left| \left(\frac{\mathbf{v}_s}{1+z_s} - \frac{D_s}{D_l} \frac{\mathbf{v}_l}{1+z_l} + \frac{D_{ls}}{D_l} \frac{\mathbf{v}_o}{1+z_l} \right) \cdot \hat{\mathbf{s}} \right|. \quad (5.26)$$

Here D_l , D_s and D_{ls} are angular diameter distances to the lens, to the source, and from the lens to the source, respectively. $\mathbf{v}_s$, $\mathbf{v}_l$ and $\mathbf{v}_o$ are peculiar velocities of the source, the lensing galaxy cluster, and the Solar System, respectively. The unit vector $\hat{\mathbf{s}}$ is the direction perpendicular to the majority of the highly stretched micro caustics on the source

plane. While the value of v_t for Godzilla is not known, the probability distributions for $\mathbf{v}_s$ and $\mathbf{v}_1$ can be predicted from the theory of large-scale structure formation assuming Planck 2015 cosmology (Planck Collaboration et al., 2016). Furthermore, we infer $\mathbf{v}_o$ from the measurement of the CMB temperature dipole (Saha et al., 2021). We find that v_t is drawn from a normal distribution with a standard deviation $\sigma_{v_t} \approx 600$ km/s, but the sign of v_t is irrelevant.

We run microlensing simulations following the methods of Dai, 2021b to assess the probability of observing $\leq 3\%$ flux variations given the cadence of the F140W imaging visits. As an example, Figure 5.16 shows the statistics of the random magnification factor induced by intracluster microlensing for any individual cluster member star, where Godzilla is an unresolved pair of images of a lensed star cluster with a total magnification factor $\mu = 2000$. In this case, $\sqrt{\langle\delta^2\rangle} = 1.97$ (0.85) for the macro image of negative (positive) parity. Combining both images, we have a reduced effective $\sqrt{\langle\delta^2\rangle} = 1.5$. Our spectroscopic analysis suggests that Godzilla is a star cluster with $\log(\mu M_\star/M_\odot) = 9.3$, for which we estimate from Figure 1 of Dai, 2021b $\epsilon_2 \approx 0.03 (\mu/2000)^{1/2}$ (using the notation therein), a factor depending on the luminosity function of stars. The standard deviation of the fractional flux variability is $\epsilon_2 \sqrt{\langle\delta^2\rangle} = 4.5\%$ for $\mu = 2000$, which is a little larger compared to the measured standard deviation $< 3\%$ we derive from data. If the total magnification of the image pair is $\mu = 1000$, we find $\sqrt{\langle\delta^2\rangle} = 1.1$ and $\epsilon_2 \sqrt{\langle\delta^2\rangle} = 2.3\%$. The time intervals between imaging epochs are sufficiently long because in the lensed star cluster scenario the variability is rapid due to the large number of member stars, and hence the knowledge of v_t is not required here. We therefore conclude that if Godzilla is a young star cluster its magnification factor is unlikely to be higher than $\mu = 2000$.

We also consider the scenario that Godzilla is a single hyperluminous star very close to a caustic and the lensed image pair add up to a very high total magnification $\mu = 7000$, following the suggestion of Diego et al., 2022b. In Figure 5.17, we simulate the 4 distinct epochs corresponding to the HST F140W imaging data. For $v_t > 200$ km/s there is $< 1\%$ chance of not seeing any flux change $> 13\%$ among the F140W imaging visits. The chance increases to $> 40\%$ for $v_t < 50$ km/s; however, we emphasize that this velocity range is quite unlikely, with only a 7% occurrence chance a priori.

Figure 5.17 also shows that having one more imaging visit in late 2024 or later will provide a long time baseline and will tightly constrain the scenario of a single lensed star even for very low v_t . Low values of v_t are unlikely but certainly possible, so we suggest that the search for microlensing-induced flux variability is a robust way to test whether Godzilla could be a single star or a system of a few stars (Choe et al., 2024).

Taking into account both flux ratios and flux variability limits, we conclude that the scenario of a young star cluster magnified by somewhere around one thousand fold is viable and is compatible with the observed lensing properties of Godzilla. If Godzilla is a young star cluster, its magnification should be less than about $\mu = 2000$ and its stellar mass higher than $1 \times 10^6 M_\odot$.

5.8 Conclusions

High lensing magnifications have offered a unique view of the impressive star formation activities on parsec scales in the Cosmic Noon galaxy Sunburst. Apart from the 12-imaged Lyman-continuum-leaking super star cluster that has been previously studied, in this work we study Godzilla, which is seemingly a more perplexing source. We suggest that Godzilla is a young super star cluster with its core enshrouded with dense massive star ejecta photo-excited by stellar ionizing radiation. We have combined HST filter photometry and nebular emission line measurements from VLT/MUSE and X-shooter spectroscopy to model the star cluster and the associated nebula.

We find a cluster age 4–6 Myr and a likely stellar metallicity $Z = 0.25 Z_{\odot}$ for Godzilla. For a standard stellar IMF and depending on the total and tangential magnification factors μ and μ_t , we find a large cluster stellar mass $M_{\star} = 2 \times 10^6 M_{\odot} (1000/\mu)$, and a PSF-based size constraint for its FUV-bright component, $R_{\text{FUV}} \lesssim 1 \text{ pc} (500/\mu_t)$. The high compactness should place Godzilla in a regime where rapid radiative cooling renders stellar wind and CCSNe material trapped in the cluster potential regardless of the initial ejecta speed. Indeed, despite the inferred SMC-like stellar metallicity, we found evidence for gas-phase He ($\text{He}/\text{H} = 0.27^{+0.09}_{-0.10}$) and N ($\log \text{N}/\text{O} = -0.31^{+0.08}_{-0.08}$) enrichment indicative of massive star winds, as well as gas-phase O enhancement ($12 + \log \text{O}/\text{H} = 8.75^{+0.19}_{-0.25}$) indicative of CCSNe not long after onset. We also find sub-solar C/O, Ne/O and Si/O values in the nebula, which may have implications for CCSN light element yields for progenitor ZAMS masses greater than $40 M_{\odot}$.

Through a comparison to models of star cluster ejecta from MT12, we confirm that the inferred gas-phase abundances are consistent with complete retention of stellar winds and CCSN ejecta up to a cluster age around 4–6 Myr (Figure 5.11 and Figure 5.12), which also implies that stars more massive than $m_{\text{ZAMS}} = 40 M_{\odot}$ have successfully exploded and enriched the intracluster medium. We note that our inferred $\log \text{Ne}/\text{O} = -1.13^{+0.16}_{-0.13}$ is lower than the model prediction of MT12 and is interestingly lower than the solar value. While a large sample of less extreme star-forming regions show a solar Ne/O value independent of metallicity, Godzilla appears young enough that only stars more massive than about $40 M_{\odot}$ have reached the end of their lives. We therefore posit that the low Ne/O may be related to the CCSN yields of such massive progenitors, with speculations on photodisintegration of Ne to O through explosive nucleosynthesis and collapse of Ne-Mg-O shell into the remnant.

The nebula of Godzilla is remarkably dense $n_e \sim 10^{7-8} \text{ cm}^{-3}$, which indicates an extremely high intracluster pressure $P \sim 10^{11-12} \text{ K cm}^{-3}$. We suggest that the high pressure is provided by supersonic turbulence in stellar ejecta that is accumulated in the cluster’s gravitational potential due to runaway radiative cooling, which is perhaps only a fraction of a parsec across (Section 5.6). The retained stellar ejecta is dense enough to self-shield against ionizing photons, is likely dust-free, and stays warm by UV heating. Through simple analytic analysis of CCSN kinetic feedback within a dense medium, we find that CCSNe after an age $\sim 3 \text{ Myr}$, is possibly capable of maintaining this turbulence, but probably have failed to evacuate this enshrouding dense gas out of the cluster (Section 5.6). We theorize that nebular emission lines originate from many ionization-bounded hot bubbles that are blown either by massive

star winds or by past CCSNe (see Figure 5.2). We have argued that such unusual geometry with a significant HI column along the line of sight may explain the weakness of H Balmer lines (Section 5.6) and the observed Ly α -pumped Fe fluorescent emission (Section 5.6).

Recent JWST NIRCам and NIRSspec data (PID: 2555, PI: Rivera-Thorsen) revealed optical emission lines with both narrow and broad components, many of which had only conservative upper limits in this work. The UV emission lines show no evidence of such a broad component, and we speculate a lower density, outflowing gas component which dominates the [O III] $\lambda\lambda$ 4959,5007 and H Balmer lines may be a natural explanation for this emission in the context of our physical model. Further analysis of these data will test this scenario (Pascale et al., in preparation), and upcoming JWST MIRI imaging (PID: 6353, PI: Pascale) will allow for the best panchromatic view of this exciting object to date.

We have reminded the readers of the difficulty in accurately determining the magnification factor μ for Godzilla through galaxy-cluster scale lens modeling, in which it is challenging to include optically undetectable substructure lenses. We have discussed the possible value of μ from two considerations. For one, a lower limit on the magnification ratio between Godzilla and a possibly blended counter lensed image leads us to conclude that $\mu \gtrsim 500$ for Godzilla. Another consideration is based on flux variability expected from intracluster microlensing effects acting on member stars. We have derived stringent limits on the flux variability using archival HST imaging data over 18 observed months, which implies $\mu < 2000$ if Godzilla is a young star cluster. We have made the μ dependence explicit in those of our quantitative results that are sensitive to the value of μ , and have presented numerical results corresponding to a fiducial $\mu = 1000$. Our physical picture of condensed gas in a young star cluster is qualitatively robust for a wide range of magnification values $300 < \mu < 2000$. We further note that the stringent limits on flux variability are in tension with the alternative scenario that Godzilla is a magnified single star with $\mu > 7000$, unless the source's effective velocity relative to the caustic is one order of magnitude smaller than the most probable value.

Godzilla may be an analog of globular cluster progenitor at SMC-like metallicity. It is interesting to ponder whether the observed retained cluster gas would birth a 2P stellar population. However, the enhanced gas-phase O/H is not consistent with the typical abundance pattern of 2P stars. The gas-phase He/H elevation is consistent with pollution by evolved star winds, but is likely excessive compared to the typical He abundance variations seen in GCs. Altogether this implies that, should Godzilla be a true GC progenitor and host multiple stellar populations, the 2P stars probably have already formed, prior to the onset of evolved star winds and CCSNe which would dump excessive He and O respectively. This appears to align with very massive main sequence stars or supermassive stars as the polluters for multiple stellar population formation. Finding more objects similar to Godzilla will further shed light on these intriguing questions.

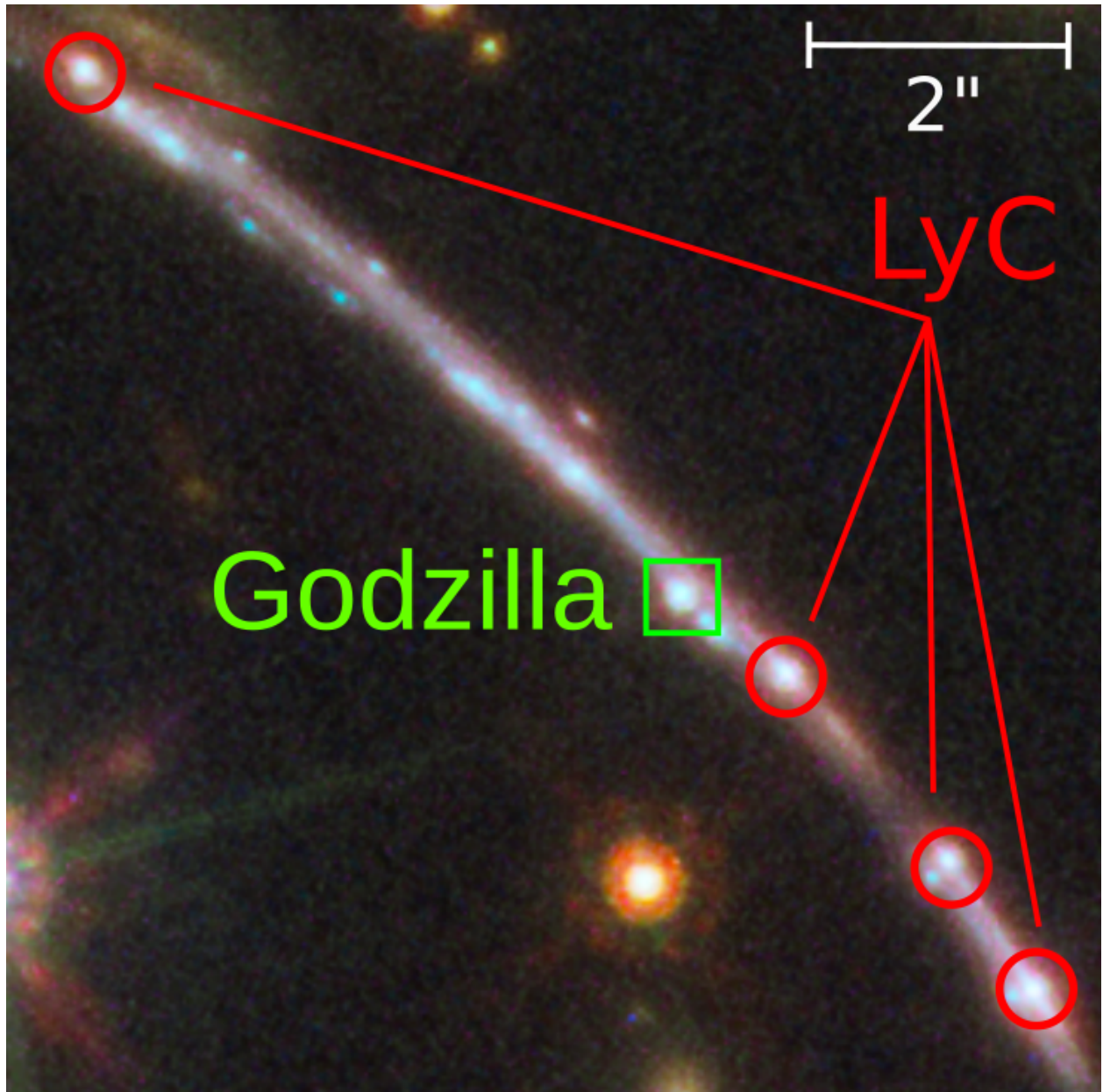


Figure 5.1 *HST* false color image of the Sunburst Arc with the lone image of Godzilla and four images of the Lyman-continuum-leaking (LyC) cluster marked. Godzilla appears similarly bright to the multiple images of the LyC cluster, so naively multiple counter-images of Godzilla would be detectable in a typical strong-lensing configuration. However, the non-detection of counter-images and time variability favors the hypothesis that Godzilla is milli-lensed and highly magnified.

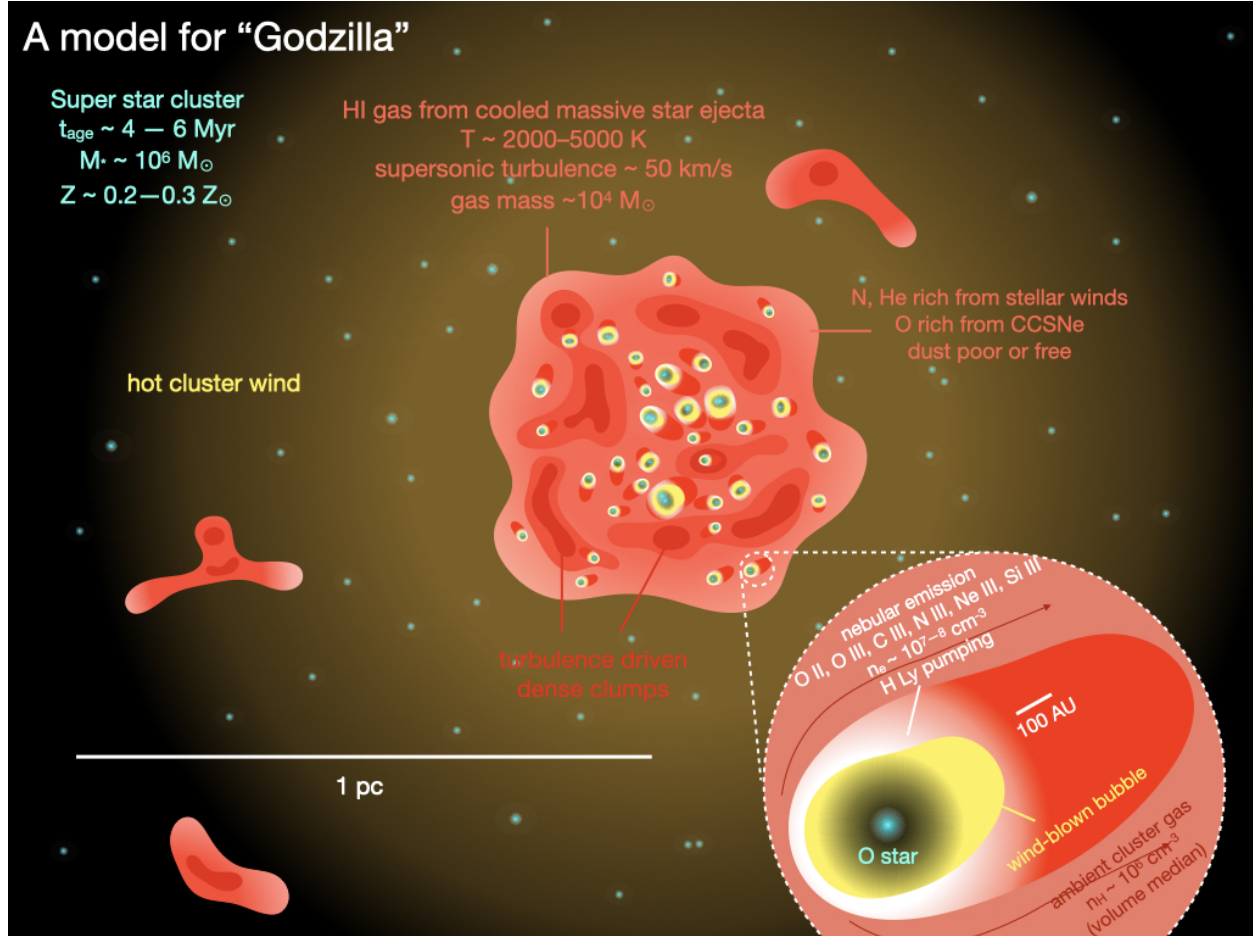


Figure 5.2 Illustration of our favored physical model for Godzilla and its nebula. Due to highly efficient radiative cooling, massive star ejecta from winds and CCSNe has accumulated at the center of a massive, compact young star cluster, forming self-shielded neutral warm gas in a state of supersonic turbulence driven by energy injection from CCSNe. Situated in an extreme radiation environment, this gravitationally retained gas likely has little to no dust. As a result, it is optically thick to ionizing photons but is transparent to UV and optical photons. O stars embedded inside it drive individual wind-blown hot bubbles in which the observed nebula emission lines are excited. In the outskirts of the cluster, stars likely drive a hot, low density cluster wind which may accelerate warm cloudlets resulting in a secondary broad nebular emission component.

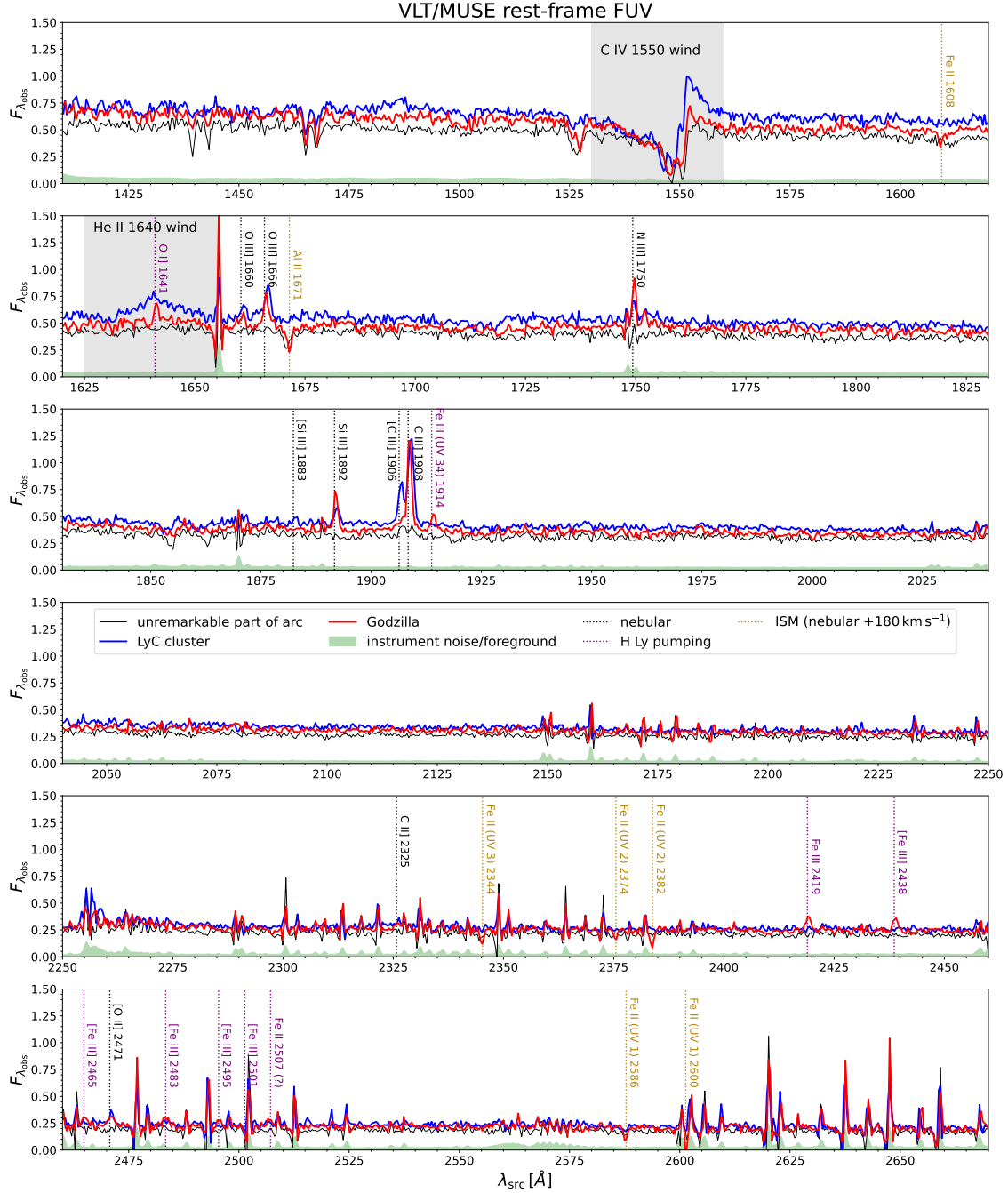


Figure 5.3 MUSE IFU spectrum in the rest-frame wavelength range 1410–2670 Å (observed flux density $F_{\lambda_{\text{obs}}}$ in units of $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}$). We compare specific fluxes extracted from three circular apertures of radius $0.5''$, centered on *Godzilla* (red), the LyC leaking star cluster (Vanzella et al., 2020a) (blue), as well as another unremarkable region on the Sunburst Arc (black), respectively. We mark narrow nebular emission lines (black dotted), ISM absorption lines (dotted yellow), and additional unusual emission lines related to H Lyman pumping (dotted magenta).

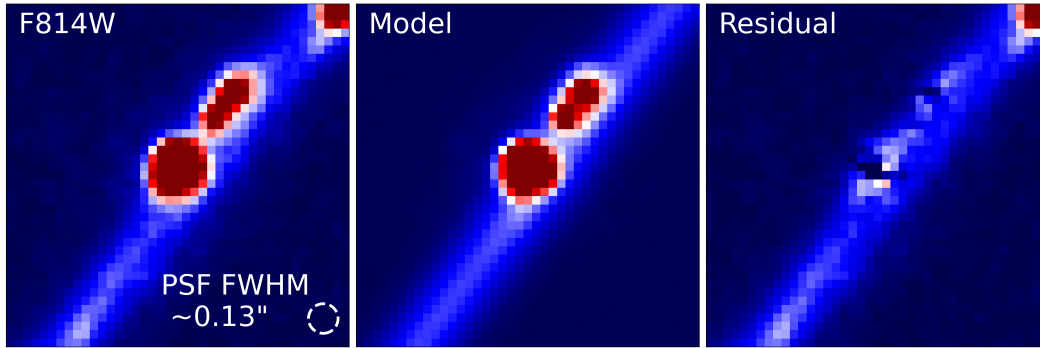


Figure 5.4 Example of surface brightness modeling of Godzilla and the host arc in F814W. Godzilla is modeled as a Sérsic profile convolved with the PSF, and its neighboring knots are modeled as simple PSFs. The underlying arc background is approximated as a line convolved with a 2D-Gaussian, for which the line slope and intercept, as well as the Gaussian width are free parameters. We find that, even in the highest resolution filters, the best fit Sérsic for Godzilla has effective radius $r_{\text{eff}} < 1$ pixel, consistent with an unresolved FUV source. For a fiducial tangential magnification value $\mu_t = 500$, this implies a physical size for the OB star component $R_{\text{FUV}} < 1$ pc given the measured F814W PSF FWHM of $0.13''$.

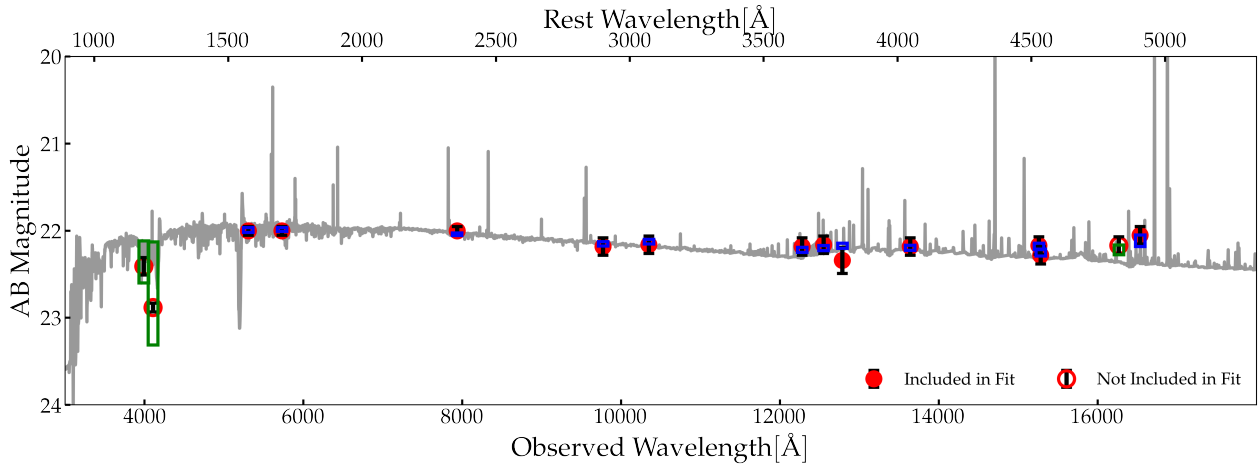


Figure 5.5 Best-fit SED (grey) from `Cloudy` modeling with the Chemically Anomalous Model (Section 5.4). Co-plotted is the 68% C.I. range of the model predicted filter magnitude (open boxes) and the observed magnitude (circles with error bars). Two of the bluest filters F390W and F410M (open circles and green boxes) are excluded from the fit since the fluxes might have been significantly affected by $\text{Ly}\alpha$ line transfer and damping wing effects. The narrow-band F164N filter, significantly enhanced by $\text{H}\beta$, is not used due to potential flux calibration issues; however, its measured flux is consistent with model prediction.

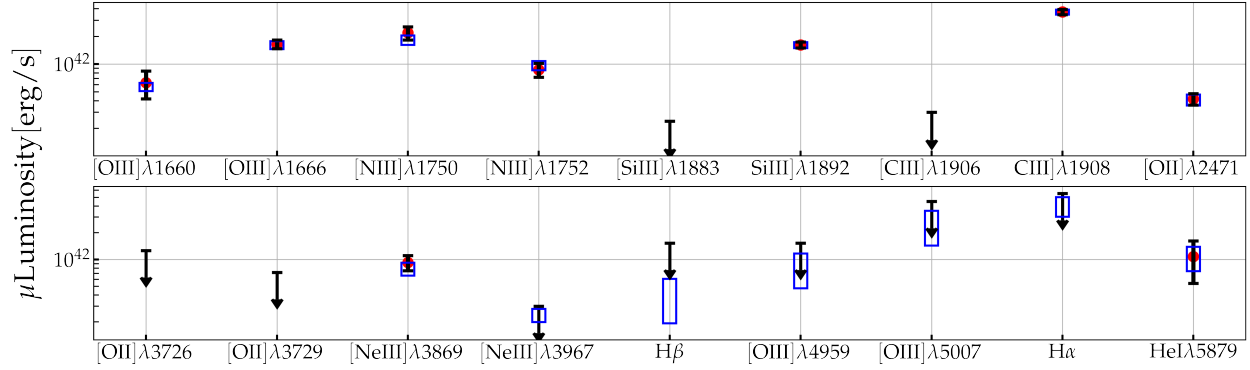


Figure 5.6 68% C.I. for model predicted line fluxes (blue boxes) in the Chemically Anomalous Model (Section 5.4) and observed line fluxes from the MUSE and X-Shooter data (circles with errorbars). For non-detections, upper limits are plotted as downward arrows, which are implemented in fitting as strict upper limits.

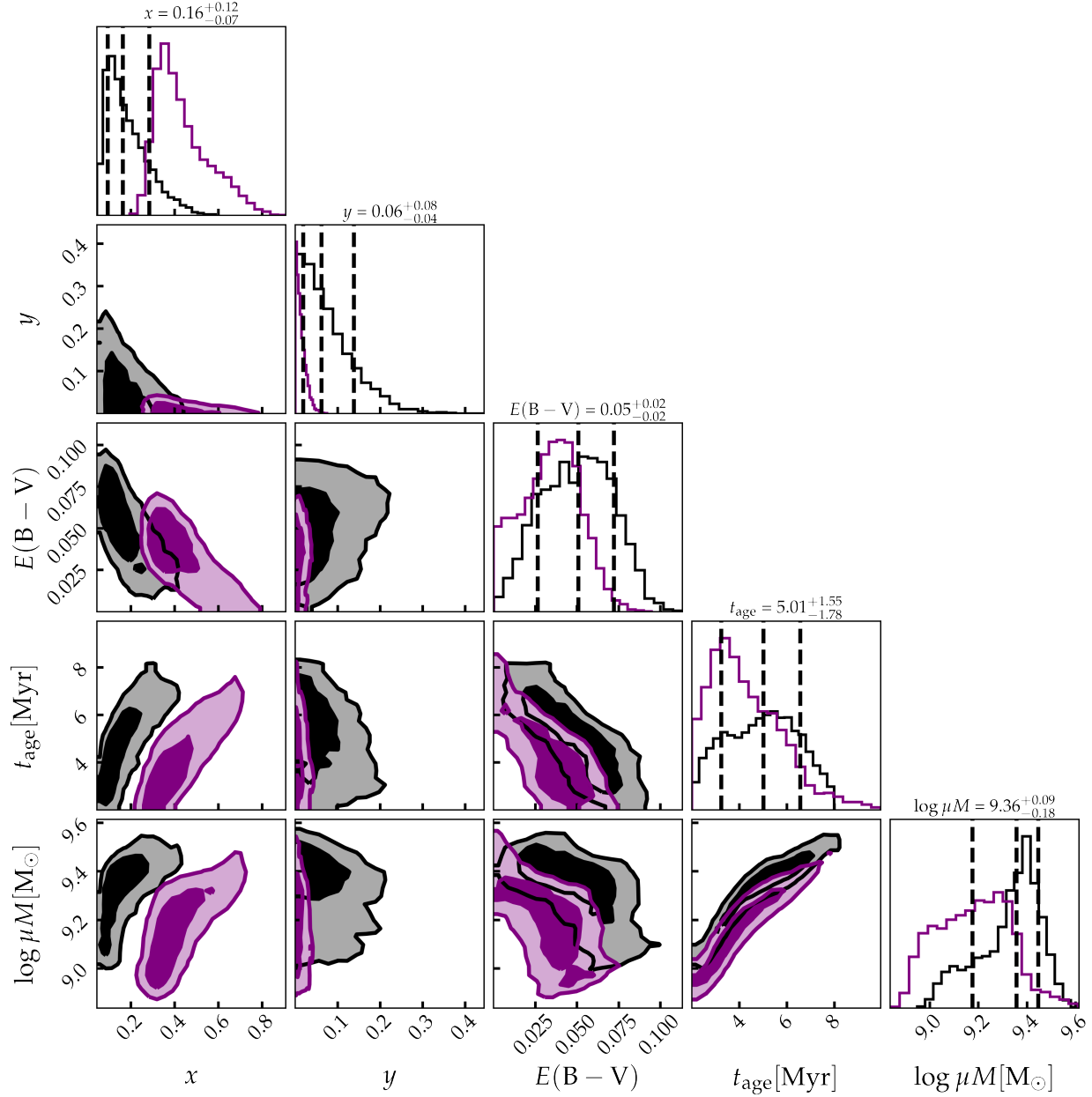


Figure 5.7 Posterior distributions for the star cluster parameters in the Chemically Anomalous Model (black) and the Base Model (purple). 1D histograms representing the posterior distributions are marked with the mean and 68% confidence intervals for the Chemically Anomalous Model (C.I.'s, dashed lines). 2D contours enclose 50% and 90% of the posterior samples. Refer to Table 5.4 for the 68% C.I.'s of the parameters.

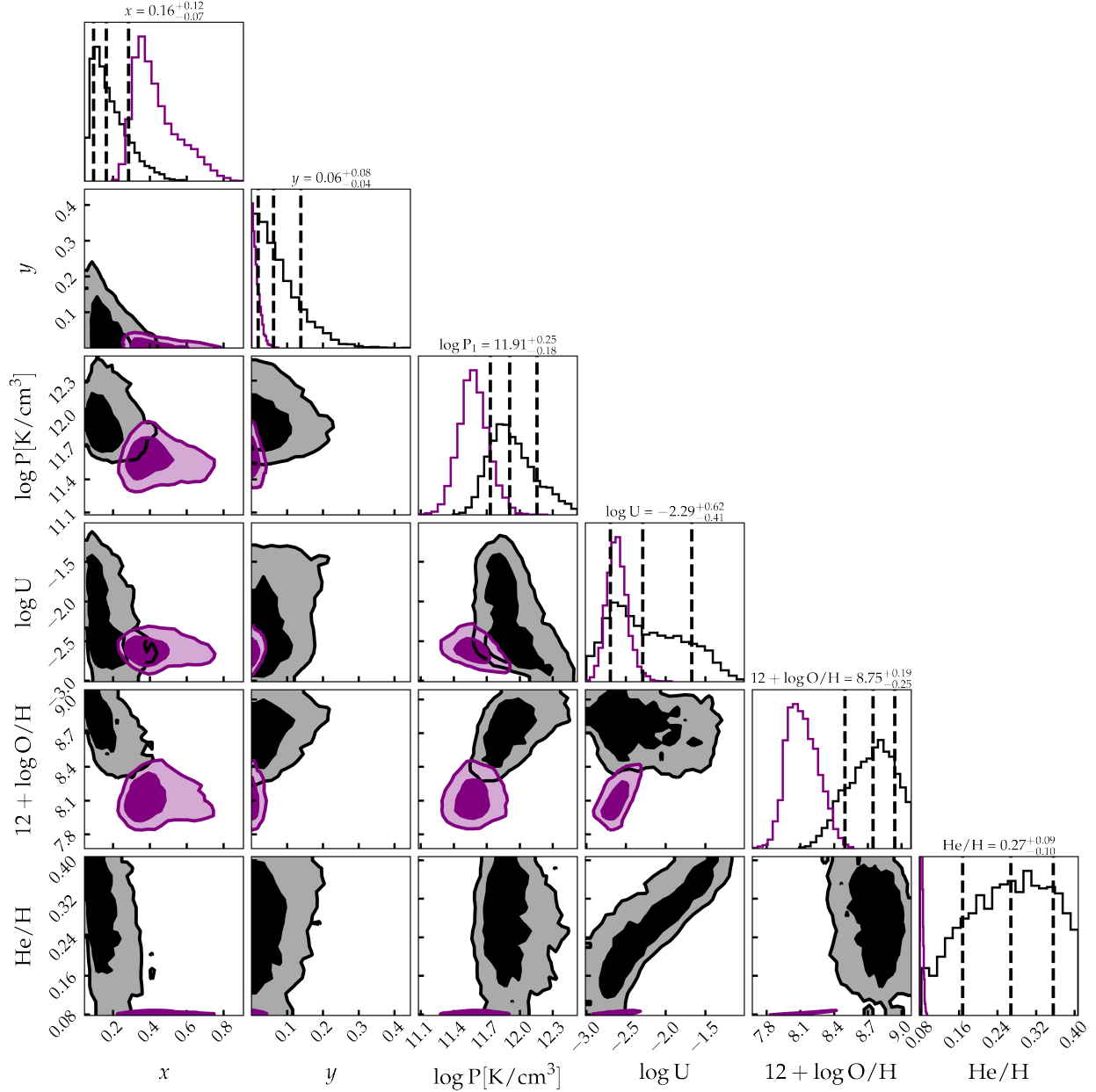


Figure 5.8 Posterior distributions for the physical parameters describing the nebula for the Chemically Anomalous Model (black) and for the Base Model (purple). Contours levels and histogram confidence intervals follow Fig. 5.7. The 68% C.I.'s of the parameters are tabulated in Table 5.4.

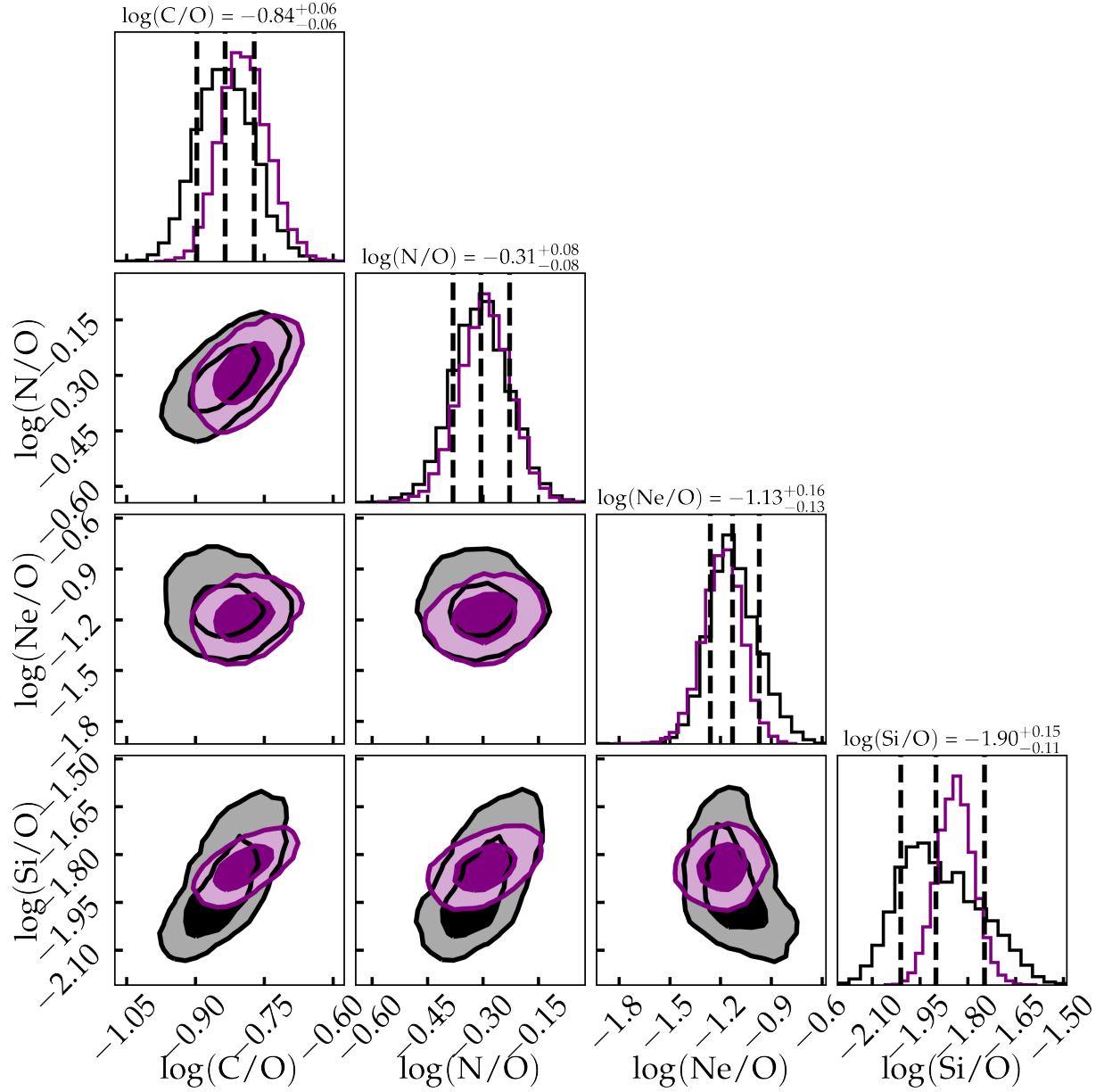


Figure 5.9 Posterior distributions for the gas-phase abundances of C, N, Ne and Si relative to O for the Chemically Anomalous Model (black) and the Base Model (purple). The 68% C.I.'s of the parameters are tabulated in Table 5.4.

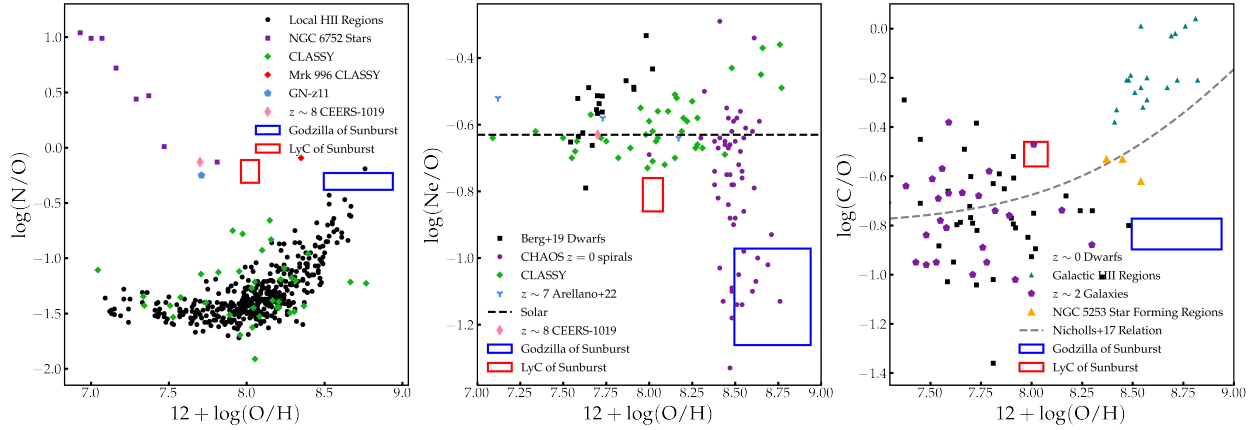


Figure 5.10 **Left:** Nitrogen abundances for Godzilla, the LyC cluster of Sunburst (Pascale et al., 2023), GN-z11 (Senchyna et al., 2023), the $z \sim 8$ galaxy CEERS-1019 (Marques-Chaves et al., 2024), stars of local globular clusters NGC 6752 Carretta et al., 2005, local star forming galaxies Berg et al., 2022; Stephenson et al., 2023, CLASSY, and local HII regions in SDSS galaxies (Pilyugin, Grebel, and Mattsson, 2012). **Middle:** Neon abundance of Godzilla compared to local star-forming galaxies from CLASSY and Berg et al., 2019, star-forming regions of M33 from Rogers et al., 2022, CHAOS, the $z \sim 7$ galaxies of Arellano-Córdova et al., 2022, and the solar value $\log(\text{Ne}/\text{O}) = 0.63 \pm 0.05$ (Asplund, Amarsi, and Grevesse, 2021). **Right:** Carbon abundance of Godzilla compared to local star-forming galaxies (Berg et al., 2016; Berg et al., 2019; Senchyna et al., 2017; López-Sánchez et al., 2007), galactic HII regions (Arellano-Córdova et al., 2020), a sample of $z \sim 2$ galaxies from the literature (Pettini et al., 2000; Fosbury et al., 2003; Erb et al., 2010; Christensen et al., 2012; Bayliss et al., 2014; James et al., 2014; Stark et al., 2014; Steidel et al., 2016; Vanzella et al., 2016; Amorín et al., 2017; Berg et al., 2018; Rigby et al., 2018) and the empirical relation derived by Nicholls et al., 2017. Figures are recreated following Senchyna et al., 2023, Berg et al., 2019, and Arellano-Córdova et al., 2022, and error bars are omitted for visual clarity.

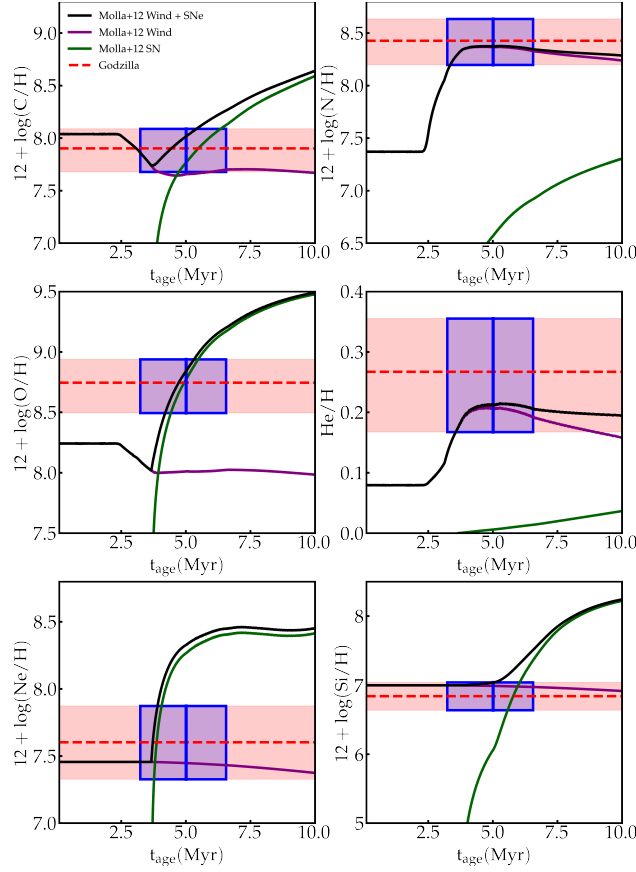


Figure 5.11 Evolution of the abundances of accumulated wind and CCSN ejecta. Model predictions from MT12 (black solid lines) are compared to abundances inferred for Godzilla with the Chemically Anomalous Model (dashed red lines and red swaths represent the median and 68% confidence interval respectively). The relative contributions of winds and SN to the total ejecta are plotted in purple and green respectively. We note that these represent the contribution to the abundance of the cumulative ejecta and not the abundances of the wind or SN themselves. For reference, we also plot for cumulative ejecta with CCSN yields of Ne and Si excluded (black dashed lines). We find the cluster age $\sim 4\text{--}6$ Myr (blue box) inferred from the Chemical Anomalous Model, is in good agreement with the MT12 predictions, such that Godzilla’s nebula may be an order-unity condensation of wind and CCSN ejecta.

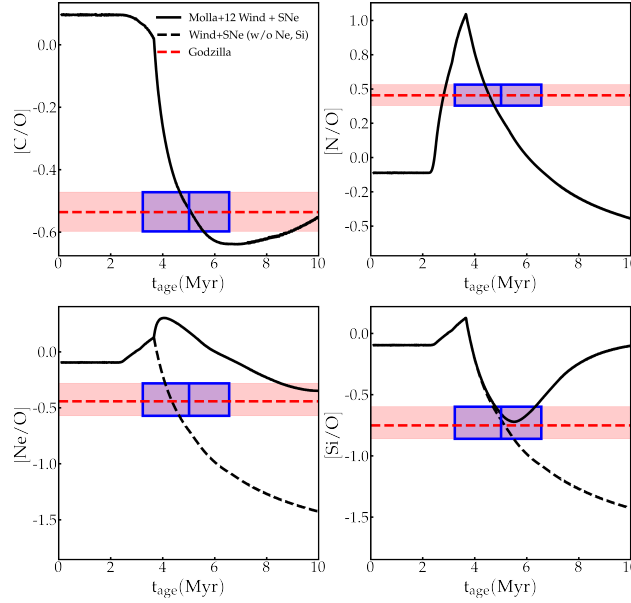


Figure 5.12 Same as Figure 5.11 but with abundances plotted relative to oxygen and normalized to the solar value. We find that the MT12 predictions agree with the inferred abundances of Godzilla at $\sim 4\text{--}6$ Myr, with the exception of Ne/O, which only shows agreement if the CCSN Ne yield is significantly reduced (dashed line).

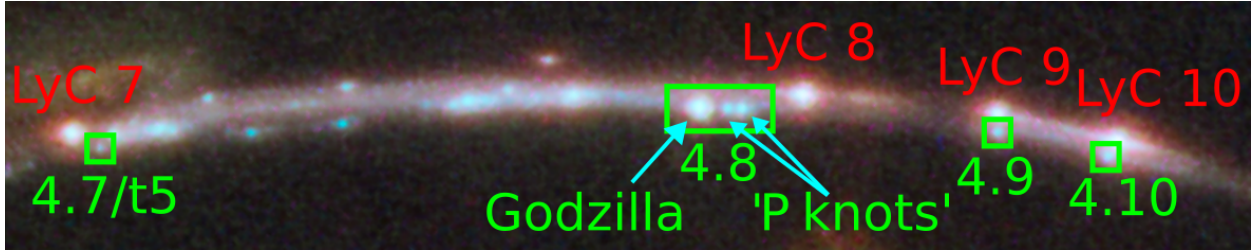


Figure 5.13 HST false color image of Godzilla, the ‘P knots’, and candidate counterimages identified by Sharon et al., 2022b and Diego et al., 2022b; the labeling reflects the the naming scheme of both papers. Godzilla is significantly brighter than its counterimages, implying it is highly magnified by comparison. The color of the counterimages may more closely match the color of the P knots, which may indicate that Godzilla is intrinsically fainter than the P knots and is blended with and dominated by them in the counterimages. This figure is modeled after Sharon et al., 2022b’s Figure 2 and Choe et al., 2024’s Figure 1, which both show color images using different HST or JWST filters, and provide useful further reference for the relative colors of Godzilla, the P knots, and the candidate counterimages.

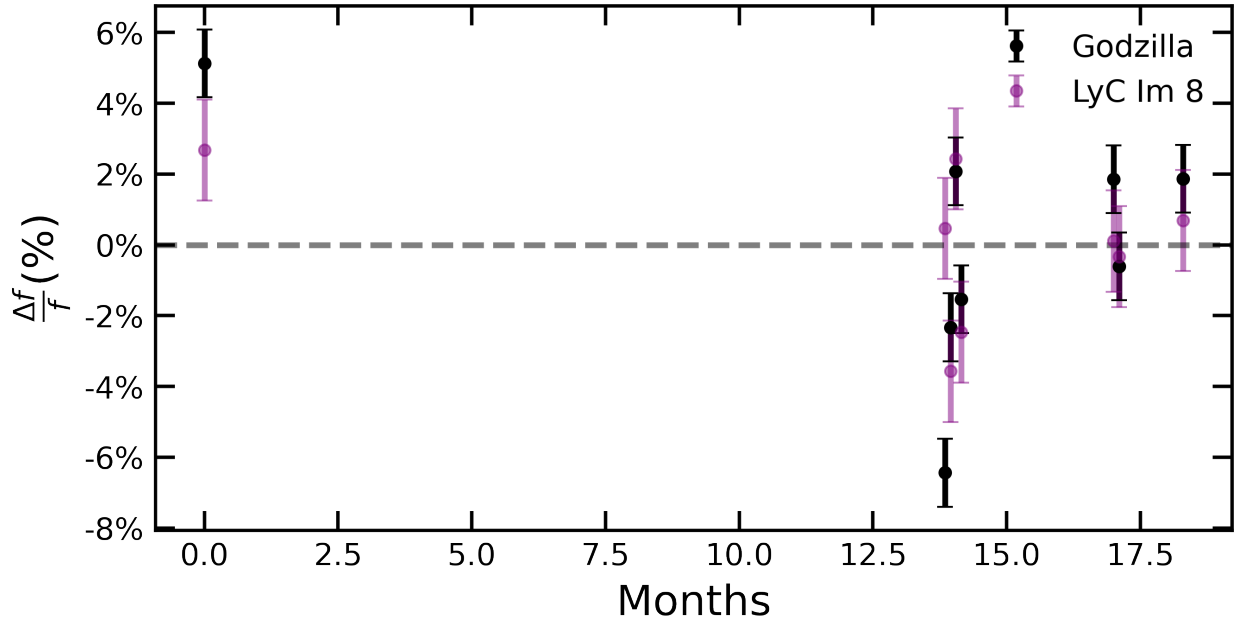


Figure 5.14 Fractional flux changes with respect to the mean for Godzilla (black) and image 8 of the LyC cluster (purple) sampled across 8 visits of HST WFC3/IR F140W. These 8 visits make up 4 distinct epochs relative to the timescales for microlensing fluctuations ($\gtrsim$ few days), with the first visit occurring on June 24, 2019. We observe that image 8 of LyC, which is not expected to showcase significant microlensing-induced variability, fluctuates at the $\sim 2\%$ level, while Godzilla fluctuates marginally greater at the $\sim 3\%$ level and shows the largest fractional change between any two visits of $\sim 13\%$. We note that the visit with the greatest fractional change of $\sim 8\%$ at 14 months is accompanied by 3 other visits with comparatively smaller fractional changes. These 4 visits take place over the span of 2 days, a timescale which is likely too short for microlensing to induce significant variability.

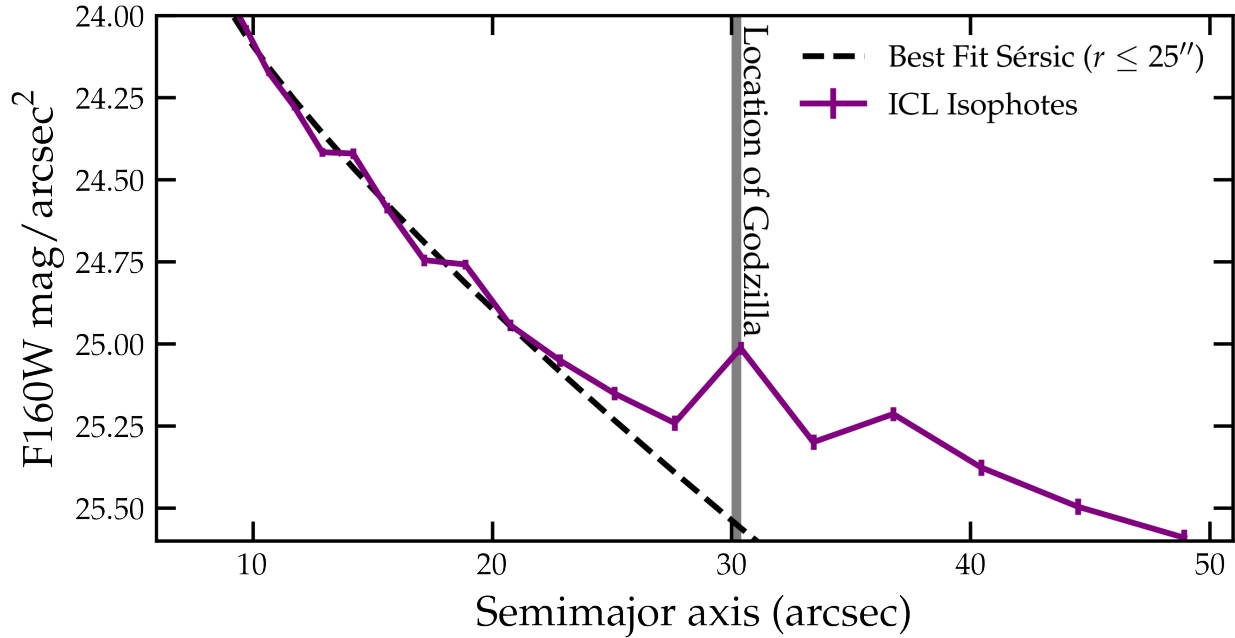


Figure 5.15 Intracuster light (ICL) surface brightness profile in HST WFC3/IR F160W measured via elliptical isophotes (purple) centered at the brightest cluster galaxy (BCG). The surface brightness profile begins to flatten at a semimajor axis $\sim 25''$, which may indicate the ICL is approaching the diffuse sky background. To conservatively estimate the ICL contribution at the location of Godzilla ($\sim 30''$), we fit a Sérsic profile to isophotes with semimajor axis $a \leq 25''$ and extrapolate to the location of Godzilla. We find an ICL surface brightness $\sim 25.5 \text{ mag/arcsec}^2$, corresponding to an average convergence $\kappa_\star \gtrsim 0.001$ from intracuster stars. We note the surface brightness profile shows a peak at the location of the Sunburst arc due to the diffuse arc background not well masked by SExtractor, where the arc generally makes up a large fraction of the isophote at that semimajor axis.

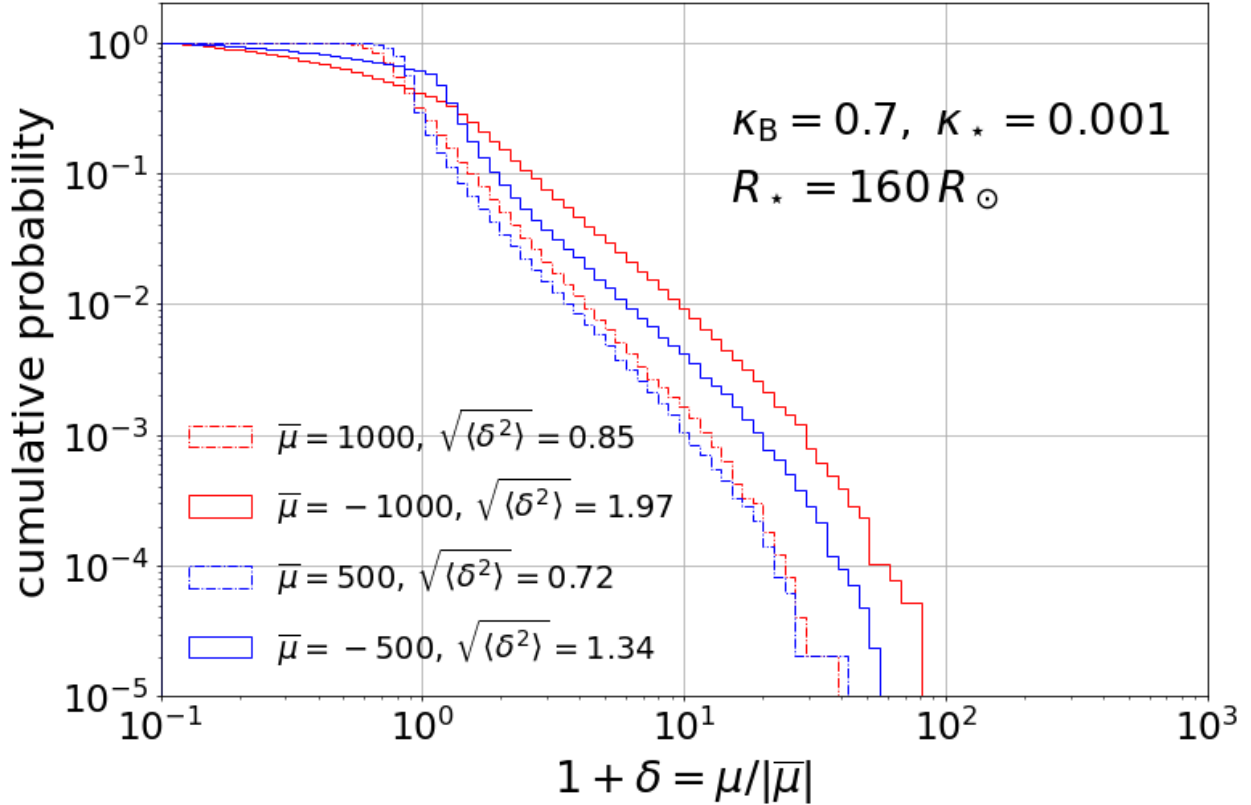


Figure 5.16 Probability distributions of $1 + \delta = \mu/\bar{\mu}$ for any individual source star, derived separately for a pair of macro images with macro magnification factors $\bar{\mu} = \pm 500$ (red) and $\bar{\mu} = \pm 1000$ (blue). The value of $\sqrt{\langle \delta^2 \rangle}$ for each macro image is quoted in the legend text. We set a local macro convergence $\kappa_B = 0.7$, $\kappa_* = 0.001$, and use a relatively large average value for the stellar photosphere radius $R_* = 160 R_\odot$ in order to be conservative in estimating $\sqrt{\langle \delta^2 \rangle}$.

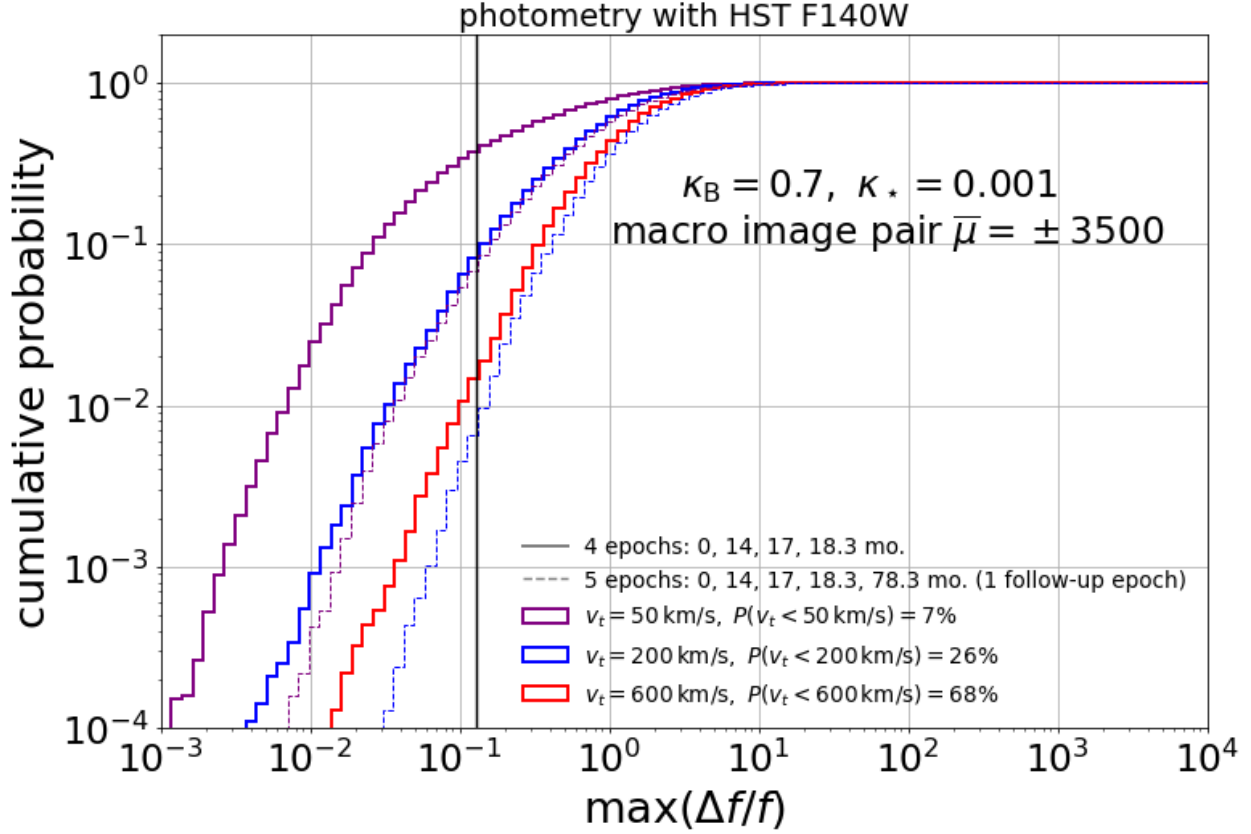


Figure 5.17 Probability distribution for the maximal observed flux variation expected for a single lensed star, derived from simulating the cadence pattern of the actual 4 distinct imaging epochs in F140W (solid curves). We set a local macro convergence $\kappa_B = 0.7$, $\kappa_* = 0.001$, and assume an unresolved macro image pair of $\mu_B = \pm 3500$. The black vertical line marks the maximal fractional flux change 13% between two epochs measured through aperture photometry. The results depend on the unknown effective velocity of the source v_t , which, in Planck 2015 cosmology, has a standard deviation 600 km s^{-1} for the Sunburst system. The single lensed star scenario is compatible with data only if the effective velocity is unusually small e.g. $v_t = 50 \text{ km s}^{-1}$, and would be tightly constrained with another measurement in 2024 or later (dashed curves).

Chapter 6

The Measurement of H_0 from the Type Ia SN H0pe

The content of this chapter is drawn from Pascale et al., 2025b, with permission from the co-authors.

6.1 Introduction

Determination of the current expansion rate of the Universe (the Hubble Constant, H_0) across a wide range of redshifts provides a fundamental test of the standard cosmological model, Λ CDM. While this model succeeds in reproducing an abundance of observed cosmological phenomena, disagreement between independent measurements of H_0 at early and late times in the Universe raises doubts about the model’s reliability. This tension primarily results from two independent precision methods for measuring H_0 : Type Ia supernovae (SNe Ia) using the local-distance-ladder approach and cosmic microwave background (CMB) observation in conjunction with the Λ cold dark matter (Λ CDM) model. Confirming or resolving the H_0 discrepancy is crucial for fundamental physics including the effects of neutrinos, the nature of dark energy, and the spatial curvature of the Universe.

For the local distance-ladder, the ‘Supernova H_0 for the Equation of State’ (SH0ES) team’s (Riess et al., 2022) calibration of distances to nearby Cepheid variable stars in multiple ways, followed by calibration of SNe Ia which share host galaxies with Cepheids, yields $H_0 = 73.29 \pm 0.090 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Murakami et al., 2023). In contrast, CMB measurements (Planck Collaboration et al., 2020a) from the *Planck* satellite favor $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$ assuming a flat Λ CDM cosmology. This apparent $>5\sigma$ disagreement between two premier methods is the basis of what is known as the ‘Hubble tension’. Examining other independent H_0 measurements can delineate the underlying discrepancy. Local-distance-ladder measurements using Hubble Space Telescope (HST) imaging of the ‘tip of the red-giant branch’ (TRGB) stars to calibrate SNe Ia from the Carnegie-Chicago Hubble Program (CCHP, Freedman et al., 2019), the Extragalactic Distance Database (EDD,

Anand et al., 2022), and Comparative Analysis of TRGBs (CATs, Scolnic et al., 2023) yield a range in H_0 of $70\text{--}73 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Through comparison of measured colors to measured surface-brightness fluctuations (SBF) calibrated on TRGB and Cepheids, Blakeslee et al., 2021 found $H_0 = 73.3 \pm 0.7 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, while Garnavich et al., 2023 found $74.6 \pm 0.9 \pm 2.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ by adding SNe Ia as the top rung. In a ‘single-rung’ distance ladder, the Maser Cosmology Project (MCP, Pesce et al., 2020) combined six maser distances and peculiar velocities to find $H_0 = 73.9 \pm 3.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Another single-rung method uses time variability between the multiple images of strongly gravitationally lensed quasars. The Time Delay COSMOgraphy (TDCOSMO) collaboration leveraged a joint measurement across seven lensed quasars to find $H_0 = 74.2_{-1.6}^{+1.6} \text{ km s}^{-1} \text{ Mpc}^{-1}$ assuming power-law mass profiles for the lens and a flat Λ CDM cosmology, and $H_0 = 73.3_{-5.8}^{+5.8} \text{ km s}^{-1} \text{ Mpc}^{-1}$ using free-form mass profiles (Shajib et al. 2023; see also Millon et al. 2020, Wong et al. 2020, and Birrer et al. 2020). This growing catalog of independent measurements has already provided insights into the Hubble tension (Verde, Schöneberg, and Gil-Marín, 2023), and new measurements at intermediate redshifts $1 < z < 10$ are imperative in elucidating when in cosmic history this discrepancy occurs.

Refsdal, 1964 first recognized that strong gravitational lensing of SNe enables another independent method for measuring H_0 . The ‘strong’ regime of gravitational lensing refers to the deflection of the light of a distant background object (star, galaxy, or QSO) by a foreground galaxy or cluster of galaxies such that the image of a single object is observed at multiple positions on the sky. For each observed image of an “image system,” the background object’s light traverses a different path length, resulting in different travel times for photons to each image. Transient events within the lensed object (e.g., a supernova or quasar variability) enable measurement of the time delay between multiple images. The time delay, together with a model of the lensing mass distribution, yields the timed delay distance to the source object, a quantity inversely proportional to H_0 .

Although initially envisioned for SNe, inference of H_0 through strong-lensing time delays was first applied to multiply-imaged quasars lensed by single foreground galaxies (Suyu and Halkola, 2010). The technique, known as time-delay cosmography, was not realized for SNe until the discovery of ‘SN Refsdal’, a multiply-imaged Type II SN found in the Massive Cluster Survey (MACS) J1149.6+2223 cluster field (Kelly et al., 2015). Crucially, strongly-lensed SNe in galaxy-cluster lenses provide an independent route for measuring H_0 whose systematics are distinct from the distance-ladder, quasar-time-delay cosmography, and CMB approaches (Suyu et al., 2023). SN Refsdal was observed as four multiple images in an Einstein cross around a single elliptical-galaxy lens (a ‘galaxy–galaxy’ lens). A fifth image with an ~ 1 year relative time delay was predicted (Sharon and Johnson, 2015; Diego et al., 2016; Oguri, 2015; Treu et al., 2016; Grillo et al., 2016) and later observed (Kelly et al., 2016). The relatively long time delay enabled SN Refsdal to be the first lensed SN for which meaningful constraints of H_0 could be inferred, and the nature of the galaxy-cluster-scale lens gave these constraints distinct systematics from previous galaxy–galaxy lens methods (Grillo et al., 2018; Vega-Ferrero et al., 2018). The constraints and their systematics were later quantified by Grillo et al., 2020. The most robust constraints to date from SN

Refsdal were provided by Kelly et al., 2023a, who inferred $H_0 = 64.8^{+4.4}_{-4.3} \text{ km s}^{-1} \text{ Mpc}^{-1}$ or $H_0 = 66.6^{+4.1}_{-3.3} \text{ km s}^{-1} \text{ Mpc}^{-1}$ depending on the set of lens models used. Liu and Oguri, 2024 and Grillo et al., 2024 further explored the systematics, employing lens modeling approaches designed explicitly for time-delay cosmography.

On the heels of the discovery of SN Refsdal, several other lensed supernova have been observed. These include other Type II SN, such as the $z \sim 3$ SN in the Abell 370 cluster field which allowed detailed studied of shock cooling in a red supergiant SN (Chen et al., 2022), as well as the SN Ia ‘iPTF16geu’ at $z = 0.409$ (Goobar et al., 2017) was the first SN Ia to have multiple images observed. It was followed by ‘SN Requiem’ at $z = 1.95$ (Rodney et al., 2021), and ‘SN Zwicky’ at $z = 0.3554$ (Goobar et al., 2023; Pierel et al., 2023). Both iPTF16geu and Zwicky were galaxy-scale lenses, whose $\sim$ day-long time delays limited inference of H_0 to $\gtrsim 40\%$ precision (Dhawan et al., 2020; Pierel et al., 2023). By contrast, the galaxy-cluster-scale lens of SN Requiem has a nearly decade-long time delay, which will yield a precision measurement of H_0 in 2037 when the SN counterimage is predicted to appear (Rodney et al., 2021). In the same host galaxy as SN Requiem, a second SN, SN ‘Encore’, was discovered, marking the first occurrence of a lensed galaxy producing multiple observed SNe (Pierel et al., 2024b). Across all of these SNe, SN Refsdal is the only one to provide precision H_0 constraints to date.

SN H0pe is a triply-imaged SN Ia discovered in the galaxy-cluster field PLCK G165.7+67 (‘G165’, $z = 0.348$). It is a massive lensing galaxy cluster ($M_{\text{tot}} = (2.6 \pm 0.3) \times 10^{14} M_{\odot}$, Frye et al., 2019; Pascale et al., 2022a), that induces a relatively long ~ 100 day time delay between the first and third image, offering only the second-ever opportunity for precision SN time-delay cosmography and the first with a SN Ia. The three supernova multiple images were discovered in *JWST*/NIRCam imaging in the lensed, NIR-bright host galaxy ‘Arc 2’, which itself is triply imaged (Frye et al., 2023). Polletta et al., 2023 first measured the Arc 2 redshift as $z = 1.783 \pm 0.002$. The SN H0pe discovery paper (Frye et al., 2024a) used followup *JWST*/NIRSpec spectroscopy to identify SN H0pe as a SN Ia, to confirm the SN host galaxy redshift to higher precision ($z = 1.7834 \pm 0.0005$), and to spectroscopically-confirm a coincident galaxy overdensity at the redshift of SN H0pe. The known spectroscopic evolution of SNe Ia allowed Chen et al., 2024 to determine the SN phases in the three multiple images of SN H0pe and thereby measure relative time delays of $-122.3^{+43.7}_{-43.8}$ days and $-49.3^{+12.2}_{-14.7}$ days between images a–b and c–b respectively. Image b is the last to arrive and consequently shows the earliest phase of the SN, which was near peak brightness at the time of discovery. This is the first time spectroscopy has provided useful time delay constraints. Chen et al., 2024 also classified SN H0pe as a normal SN Ia. Pierel et al., 2024a used three epochs of *JWST* NIRCam six-band imaging to photometrically measure relative image time delays of $-116^{+10.8}_{-9.3}$ days and $-48.3^{+3.6}_{-4.0}$ days for images a–b and c–b respectively.

Independently through the photometric and spectroscopic datasets respectively, Pierel et al., 2024a and Chen et al., 2024 use the standard-candle nature of the SN to constrain the absolute magnifications induced by strong lensing. Absolute magnification measurements have long been thought to break degeneracies among mass models inherent in H_0 measurements from strong-lens time delays (Falco, Gorenstein, and Shapiro, 1985; Kolatt and

Bartelmann, 1998; Oguri and Kawano, 2003; Schneider and Sluse, 2013), yet have previously been unavailable for time-delay cosmography. For example in the case of the cluster-lensed SN Refsdal, the inferred H_0 was found to vary across twenty-three different lens mass models despite all satisfying the same lensing constraints. However, since H_0 was found to strongly correlate with the predicted magnifications, magnification measurements could have broken this degeneracy (Liu and Oguri, 2024). SN H0pe provides the first opportunity to harness the standard candle for time-delay cosmography.

This paper presents the first precision measurement of H_0 from time-delay cosmography of a strongly-lensed SN Ia. The outline is as follows. Section 6.2 summarizes the underlying theory of time-delay cosmography. Section 6.3 describes the *HST* and *JWST* observations that led to SN H0pe’s discovery and subsequent analysis. Sections 6.4 and 6.5 briefly summarize the photometric light-curve fitting and spectroscopic age-dating analyses. Section 6.6 details the construction of the seven contributing lens models. Section 6.7 outlines the process through which H_0 was derived from measured observables. Section 6.8 outlines the guidelines for the blinded inference. Section 6.9 presents the results of the H_0 inference. Section 7.4 discusses the unique advantages provided by the SN Ia, the robustness of the various inference approaches, and the overall error budget. Finally, section 7.5 discusses future work and how SN H0pe fits into the broader picture of time-delay cosmography.

Throughout this analysis, we enforced a blinding between the seven independent lens models, the photometrically-derived time delays, and the spectroscopically-derived time delays from each other. Changes made after the unblinding and the impacts of each change are explicitly discussed in Section 6.8.

6.2 Time-Delay Cosmography

Here we briefly outline how the time delay, $\Delta t_{i,j}$, between any two lensed images i and j of a multiply-imaged source depends on the positions of the observed multiple images with respect to the source, the local lensing potential, and the assumed cosmological model. For an individual source at angular position β with a corresponding lensed image observed at angular position θ , the time delay can be expressed as:

$$t(\theta, \beta) = \frac{1+z_1}{c} \frac{D_1 D_s}{D_{ls}} \left[\frac{1}{2} (\theta - \beta)^2 - \psi(\theta) \right] \quad , \quad (6.1)$$

where z_1 is the redshift of the lensing cluster, $\psi(\theta)$ is the lensing potential at the observed image position θ , and D_1 , D_s , and D_{ls} are the angular diameter distances to the lens, the source, and between the lens and source respectively. If instead we measure the time delay between any two images of a set of multiple images:

$$\Delta t_{i,j}(\theta_i, \theta_j) = D_{\Delta t} \Delta \tau_{i,j}(\theta_i, \theta_j, \beta) \quad , \quad (6.2)$$

where τ is the Fermat potential, $\tau(\theta, \beta) = \frac{1}{2} (\theta - \beta)^2 - \psi(\theta)$ (Schneider, 1985; Blandford and Narayan, 1986). $D_{\Delta t}$ is the so-called ‘time delay distance’, $D_{\Delta t} = \frac{1+z_1}{c} \frac{D_1 D_s}{D_{ls}}$, and is dependent

on the angular diameter distances and hence the cosmological model (Refsdal, 1964; Schneider, Ehlers, and Falco, 1992; Suyu and Halkola, 2010). $D_{\Delta t}$ is inversely proportional to H_0 , while being only weakly dependent on other cosmological parameters (Bonvin et al., 2017). Hence, if the time delay between any two multiple images is known, as well as the redshifts of the lens and source, then a model of the lensing potential is necessary to constrain H_0 .

In practice a lens model can be constructed from lensing observables, such as the observed positions of multiply-imaged galaxies or information of the foreground lensing galaxies, and assumes a fiducial value of H_0 , $H_0^{\text{fid}} = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, to predict a fiducial time delay $\Delta t_{i,j}^{\text{fid}}$. Following equation 6.1, the true measured time delay for any image pair can be related to this lens model fiducial time delay by rescaling H_0 while holding all other cosmological parameters fixed, in turn inferring H_0 :

$$\Delta t_{i,j}^{\text{pred}}(H_0) = \Delta t_{i,j}^{\text{fid}} \times \frac{70 \text{ km s}^{-1} \text{ Mpc}^{-1}}{H_0} . \quad (6.3)$$

An alternative approach can be accomplished by using measured time delays as input lens model constraints and freely optimizing for all cosmological parameters (e.g., Grillo et al., 2020; Grillo et al., 2024), which has the advantage of probing degeneracies between H_0 and other cosmological parameters under different cosmologies. However functionality for this was not available to all lens models in this work, and the use of the time delays as input constraints for the lens models would have conflicted with the blinding goals of this work, as multiple lens model teams had constructed G165 lens models prior to the discovery of SN H0pe. Additionally, this would have added time delay ratio constraints to these models, which we instead reserved as a blinded prediction to be incorporated into the final weighting scheme (see Section 6.7). Finally, we point out that when imposing a standard flat Λ CDM cosmology, the lens model time delay is expected to vary $\lesssim 1\%$ with respect to Ω_m across a typical range $\Omega_m \in [0.2, 0.4]$ for the redshift of SN H0pe. While it is possible to explore parameter degeneracies under other cosmologies through such an approach (e.g., open Λ CDM), this is outside the intended scope of this work.

6.3 Observations

The discovery paper for SN H0pe (Frye et al., 2024a) supplied details regarding the *JWST* imaging and spectroscopic data sets. In brief, SN H0pe was initially discovered in NIRCcam images from the PEARLS GTO program (PI: Windhorst, PID: 1176; Windhorst et al., 2023). The discovery images were taken on 31 March 2023 in eight filters. The SN was recognized by comparing the F150W PEARLS NIRCcam imaging to WFC3/IR F160W HST images taken on 30 May 2016 (Figure 6.1). The discovery prompted a *JWST* disruptive Director’s Discretionary Time (DDT) program which acquired two additional epochs of NIRCcam imaging in six filters (PI: Frye, PID: 4446) on 22 April 2023 and 9 May 2023. Photometric analysis of the galaxy cluster field was presented by Frye et al., 2024a, and photometric light-curve fitting of the SN was presented by Pierel et al., 2024a.

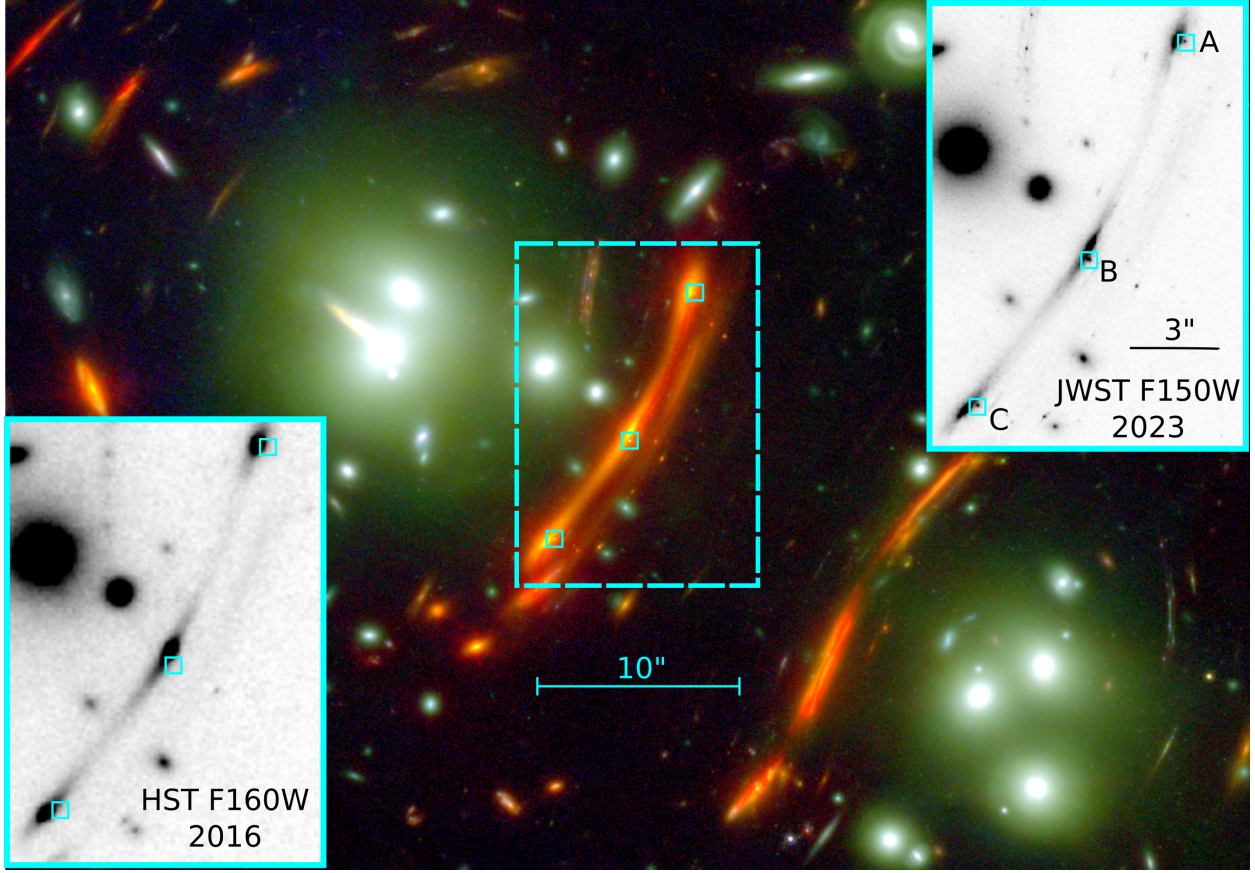


Figure 6.1 *JWST*/NIRCam color image in the central region of G165. Insets show closeup of the boxed region depicting the three multipole images of the host galaxy Arc 2 prior to SN H0pe in *HST* WFC3/IR F160W imaging from 2016 (lower left) and during its appearances in *JWST*/NIRCam F150W imaging from 2023 (upper right). The three images of the Type Ia SN H0pe appear only in the 2023 images, and their positions are marked by the blue boxes, where the ‘A’, ‘B’, and ‘C’ refer to images *a*, *b*, and *c*. North is up and east is to the left.

The DDT program also acquired *JWST*/NIRSpec Micro-shutter assembly (MSA) spectra (Frye et al., 2024a; Chen et al., 2024) in the PRISM, G140M, and G235M gratings targeting the SN host galaxy and the two brightest SN multiple images. The spectra, taken on 22 April, confirmed the Ia type from the identification of the requisite blueshifted [Si II] $\lambda 6355$ feature, Ca H&K, and other absorption-line features commonly found in Type Ia SNe (Figure 6.2).

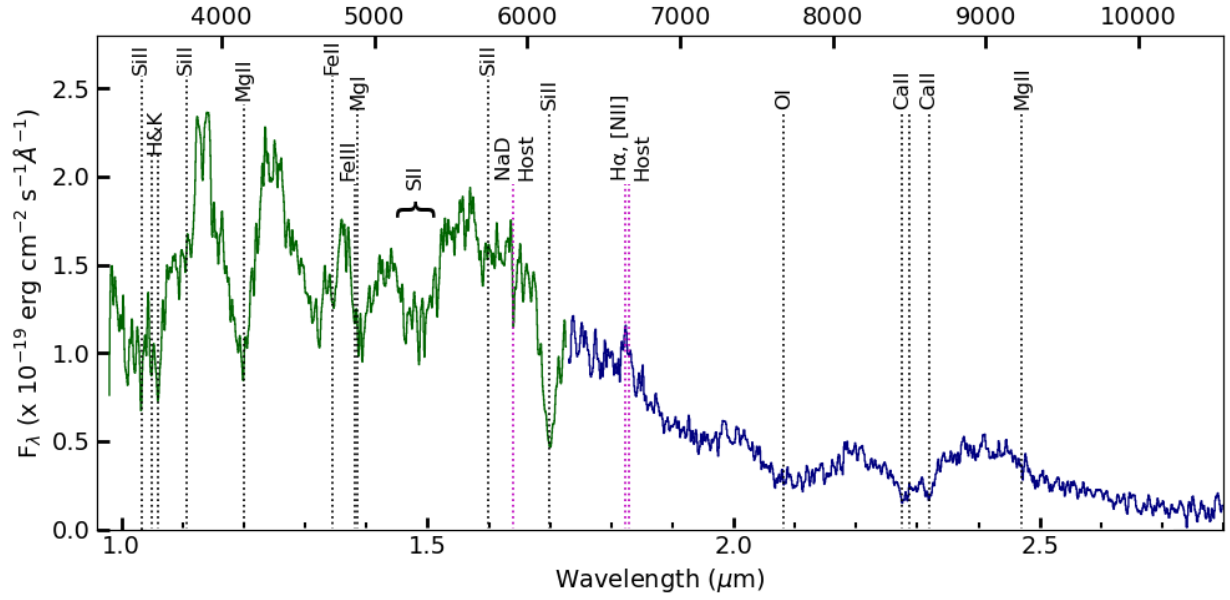


Figure 6.2 High signal-to-noise NIRSpec spectrum of SN H0pe. The G140M (green) and G235M (blue) grating spectra are shown. Some prominent line features are identified, such as the [Si II] line blueshifted to rest-frame ~ 6150 Å that is a requisite line feature of a Type Ia supernova. A few features are also traced to the SN host galaxy, such as NaD, H α , [N II] $\lambda\lambda 6548, 6584$ (magenta dotted-line). The observed wavelength is given on the lower abscissa and the rest wavelength in the frame of the host galaxy is provided on the upper abscissa.

6.4 Photometric Time Delays and Magnifications

The light-curve evolution of SNe Ia is well-studied (e.g., Hsiao et al., 2007; Pierel et al., 2021), such that precision measurements of the time delay can be made by fitting measured SN colors across multi-epoch imaging. Given that there are three epochs of NIRCImaging, and each epoch contains three SN multiple images, the SN evolution is photometrically sampled at nine points in time. Here we briefly summarize the light-curve fitting analysis of Pierel et al., 2024a. The halo of the bright galaxy host, a significant source of noise, is reconstructed and subtracted through simultaneous fitting of its surface brightness profile and cluster lens model with the GLEE software package (Halkola, Seitz, and Pannella, 2006; Suyu and Halkola, 2010, details in Caminha et al., in prep.). The photometry of the SN multiple images is then fit simultaneously to BayeSN SN Ia models (Mandel et al., 2022; Grayling et al., 2024). Time delays are inferred by fitting a common set of light curve parameters to each of the SN multiple images. The magnification ratios are estimated by normalizing the light curve to image b , and then computing the ratios of images a and c relative to b . Finally, the absolute magnifications are estimated by comparing the peak

F277W flux ($\sim$ rest-frame Y band) predicted by the BayeSN models, to the population of field SNe Ia.

Statistical uncertainties of the inferred time delays and magnifications are estimated by bootstrapping the photometric uncertainties assuming Gaussian errors. Systematic uncertainties resulting from the BayeSN model itself are produced in a similar manner. Systematic uncertainties from chromatic microlensing are estimated by examining the range of fits to a set of 1000 simulated SN H0pe light curves with variable realizations of the foreground microlensing. Systematics from millilensing by dark matter subhalos in the foreground cluster lens are achromatic, and applied directly as a correction to the distribution of inferred magnifications. Finally, the ~ 0.1 mag intrinsic scatter of SN Ia absolute magnitudes (Scolnic et al., 2018) is applied to the magnification distribution.

6.5 Spectroscopic time delays and Magnifications

Spectra from multiple images of a strongly-lensed SN obtained during a single observing epoch enable the measurement of time delays via spectroscopic-based phase analysis. Previously, the lack of quality simultaneously-obtained spectra have precluded such an analysis. Since SN H0pe was discovered from the PEARLS NIRCам Epoch 1 observation when its multiple images were near peak brightnesses, the rapid acquisition of spectra in a “disruptive” *JWST* DDT program using the *JWST* NIRSpec’s MSA enabled the identification of the SN as Type Ia through the detection of the requisite blueshifted [Si II] λ 6155 absorption-line feature.

The identification of SN H0pe as a SN Ia allowed for more straightforward template fitting to determine the phases between multiple images using spectroscopic methods. Below, we describe the process of measuring time delays through spectroscopic age-dating from NIRSpec data. We refer to Chen et al. (2024) for details.

Extraction of the SN spectrum from the NIRSpec data is performed using custom software designed to cope with background subtraction, host galaxy contamination, and bad pixels (e.g., cosmic rays). The error contribution from these potential systematics is included in the overall uncertainties, along with other sources of error such as slit loss and flux calibration. The relative delays between the multiple images’ emitting times are estimated by determining their SN phases (days post-B-band peak brightness) through a joint Markov Chain Monte Carlo (MCMC) fit of the SN spectra against various spectroscopic templates (e.g. Hsiao et al., 2007). The magnification is estimated by comparing the rest-frame Y -band magnitude of the best fit spectral models with that of an unmagnified SN Ia at $z = 1.783$. Systematics from microlensing, millilensing, and the ~ 0.1 mag intrinsic scatter in SN Ia absolute magnitudes are addressed precisely as described in the photometric light-curve fitting section outlined previously.

6.6 Lens Modeling

To obtain the cluster lens model-predicted time delays and magnifications, seven different teams agreed to construct independent lens models for this analysis. All lens modelers were supplied with the same input constraints. These consist of 21 multiple image systems (comprising 109 multiple images, 15 of which pertain to the SN and features within its host galaxy). Five multiple image systems have spectroscopically-confirmed redshifts, which corresponded to 8 multiple images with spectroscopic data (1a, 1b, 1c, 2a, 2c, 5a, 8c, and 9c). The image-system and cluster-member catalogs are public (Frye et al., 2024a).

The multiple image systems were selected predominantly by eye based on similar colors and morphology and informed by spectroscopic, photometric, and lens model-predicted redshift constraints. All lens modeling teams participated in the development and vetting of the image system catalog, which was unanimously agreed upon.

Cluster members were determined via the $1.6\ \mu\text{m}$ bump in color-color space from NIRCam photometry (Sawicki, 2002). Candidates were additionally vetted through spectroscopic redshifts (where available) and a standard red-sequence cut (Gladders and Yee, 2000). This cut removed two small galaxies situated near the SN host arc (R.A., Decl. = 11:27:15.84, +42:28:32.41 and 11:27:15.62, +42:28:30.462). Photometric redshifts also indicate that these are in the background at $0.5 < z < 1$. Additionally a bright, early-type galaxy (R.A., Decl. = 11:27:06.70, +42:27:50.46) in the NIRCam parallel field >2 from the apparent position of the SN host is in the foreground at $z \sim 0.28$. These galaxies were included in the catalog to the lens modelers to allow them to be optimized separately from the cluster members (e.g., Raney, Keeton, and Brennan, 2020; Acebron et al., 2022). NIRCam imaging with $m_{\text{lim}} = 28\text{--}29$ (depending on filter) reveals no other galaxies that may contribute significant line-of-sight structure to the lens, but low-surface-brightness perturbers below the detection limit of the NIRCam images cannot be ruled out. The final catalog consisted of 161 cluster members, of which 21 were spectroscopically confirmed (following the criterion of Pascale et al. 2022a).

We emphasize that each lens model was created without knowledge of the photometric or spectroscopic time delay and magnification measurements, and the results of any given model were also blinded from the other modeling teams. All lens models assume a fiducial flat cosmology $\Omega_m = 0.3$, $\Omega_\lambda = 0.7$, and $H_0^{\text{fid}} = 70\ \text{km s}^{-1}\ \text{Mpc}^{-1}$. The time delays and magnification predictions from the lens models are measured at the lens model-predicted positions of the multiple images rather than the observed positions.

We briefly summarize the general methods of lens models included in this analysis, the assumptions made by each, and the expected systematics. A full discussion of each lens model can be found in Appendix 6.12. The seven lens models in this analysis are broadly split into two categories. Parametric models (models 1, 2, 3) assume the mass distribution is entirely characterized as the superposition of analytic mass density profiles. These models typically impose large-scale profiles to describe the cluster-scale dark matter halo, and smaller halos to describe each galaxy, which include priors based on the galaxy brightness or morphology (Zitrin et al., 2015a; Oguri, 2010; Jullo et al., 2007a). Non-parametric models (models 4

and 6), on the other hand, make fewer assumptions on the profile of the cluster-scale dark matter, and allow a flexible grid to describe the mass distribution (Diego et al., 2005; Sendra et al., 2014). Some models (models 5 and 7) are so-called ‘semi-parametric’, and may make use of both analytic profiles and more flexible non-parametric distributions. Parametric models benefit from a small number of free parameters and mass distributions which more closely mirror the galaxy configuration of the cluster, while non-parametric methods are given greater freedom in the shape of the underlying mass distribution and include a number of regularization parameters and stopping criteria to avoid overfitting and unphysical solutions (Diego et al., 2005; Ponente and Diego, 2011; Cha and Jee, 2022).

One of the contributing models, model 4, leverages weak gravitational lensing to construct their lens model (Cha et al., 2023). This applies shape distortions of background galaxies in the galaxy cluster field as constraints on the cluster mass distribution, and extends far outside the locus of strong-lensing observables in the cluster center (e.g., Kaiser and Squires, 1993; Hoekstra, Franx, and Kuijken, 2000; Jee et al., 2006; Bradač et al., 2005). By incorporating weak-lensing into strong-lensing models, it is possible to further constrain the steepness of the mass profile which directly impacts the predicted time delay (Bradač et al., 2005; Jee et al., 2006; Zitrin et al., 2015a).

Lens models may also differ in how they optimize to estimate their posteriors, that is whether they minimize the separation of lensed multiple images traced back to the source plane or the separation of predicted and observed lensed multiple images in the image plane. The two approaches should in principle perform similarly (Keeton, 2010b), but source-plane optimization is generally much faster computationally. While there are concerns that source-plane optimization may be less accurate than image-plane optimization in practice (e.g., Keeton, 2001), strong lens modeling in the Frontier-Fields era has shown that both produce quality lens models (e.g., Meneghetti et al., 2017). In the case of SN Refsdal, Kelly et al., 2023a successfully applied a sample consisting of both image- and source-plane optimization models infer H_0 . This work similarly includes lens models which follow both approaches. We find the plane of optimization may in one modeling approach have a non-negligible impact on the resulting time delay and magnification posteriors, which is detailed in Appendix 6.12. For the case of this model, the image-plane version was chosen over the source-plane, as it was inherently more robust (see Section 6.8).

Lens model diversity broadly accounts for systematics regarding how the lensing mass and hence potential is parametrized. However, a number of systematics are expected to affect each lens model similarly. These include the thin-sheet mass assumption (Falco, Gorenstein, and Shapiro, 1985; Birrer, Amara, and Refregier, 2016), line-of-sight structure (Dalal, Hennawi, and Bode, 2005; Acebron et al., 2022; Raney, Keeton, and Brennan, 2020), multiplane lensing (McCully et al., 2014), millilensing from dark matter subhalos (Dai and Miralda-Escudé, 2020a; Gilman, Birrer, and Treu, 2020), and the effects of large-scale structure not captured within the field of view (Wong et al., 2011).

Beyond providing a uniform set of lensing inputs, a number of decisions were left up to the expertise of each individual team (e.g., the plane of optimization, uncertainty of the lensed image positions, priors on fitted parameters describing analytic mass profiles). This

reflects the realistic diversity of lens models in published works (e.g., Meneghetti et al., 2017; Kelly et al., 2023a). While SN H0pe presents a valuable opportunity to explore lens modeling systematics, as is done in Appendix 6.12, an exhaustive investigation of the full suite of lens modeling decisions is beyond the scope of this work.

6.7 Inferring H_0 Through Bayesian Analysis

We followed a Bayesian approach to constrain H_0 similar to the case of SN Refsdal in Kelly et al., 2023a. For any individual lens model, H_0 can be inferred by rescaling the lens model-predicted time delays to match the photometrically and/or spectroscopically measured time delays. There are two measured time delays, $\Delta t_{a,b}$ and $\Delta t_{c,b}$ for the image a–b and image c–b, respectively. We can infer H_0 from both time delays simultaneously, which is advantageous compared to doing so separately because the time delays may be covariant with one another.

From Time Delays Alone

We begin with a minimal set of observables made up of only the two time delays $\mathcal{O} : \{\Delta t_{a,b}, \Delta t_{c,b}\}$, however this may be expanded to include other observables covariant with the time delays. For simplicity, we first consider only the photometric results. The goal is to determine the probability of H_0 given the observed light curve (LC) $P(H_0|LC)$, and marginalize over each lens model M_l . The light curve yields measurements of each observable in $\mathcal{O}$, while each lens model M_l makes predictions for the same observables assuming the fiducial H_0 . For each model, the fiducial H_0 is rescaled such that the model predictions best match the measurements from the light curve. Using Bayes' theorem, we can write the probability for the value of H_0 from a single lens model as:

$$p_m(H_0|LC) \propto P(H_0)P(M_l) \int P(\mathcal{O}|M_l; H_0) \times P(\mathcal{O}|LC) d\mathcal{O}_1 \dots d\mathcal{O}_n \quad , \quad (6.4)$$

where n is the number of observables. Assuming the systematics of the lens models are not fully independent from one another, the overall likelihood is a weighted sum of the individual model likelihoods:

$$P(H_0|LC) = P(H_0) \sum_1^N \int P(\mathcal{O}|M_l; H_0) \times P(\mathcal{O}|LC) d\mathcal{O}_1 \dots d\mathcal{O}_n \quad , \quad (6.5)$$

where N is the number of lens models. This formalism can be understood as enforcing two priors: 1) following Eq. 6.4 each individual lens model will prefer values of H_0 that allow the lens model to best reproduce $\mathcal{O}$, and 2) following Eq. 6.5 the lens models which best reproduce the observables will have the greatest weight in the sum and hence hold the most influence over the H_0 inferred across all lens models. For a set of observables containing only the two time delays, this implies that 1) each lens model will favor values of H_0 for which

the model-predicted time delays (rescaled following Eq. 6.3) best match the two measured time delays and 2) the lens models which best match the ratio of the two time delays are the models which effectively determine the inferred H_0 .

Including Absolute Magnifications

Constraints on any observables which are correlated with the time delays effectively translate into constraints on the time delays themselves. The SN absolute magnifications are found to correlate with the time delays in the lens models, and, by including them into $\mathcal{O}$, it is possible to infer H_0 to greater accuracy and precision than time delays alone. The addition of the image a, b, and c absolute magnifications (μ) increases the total number of observables to five:

$$\mathcal{O} : \{\Delta t_{a,b}, \Delta t_{c,b}, \mu_a, \mu_b, \mu_c\} \quad . \quad (6.6)$$

The measurements for these observables are shown in Fig. 6.3 and Table 6.1. Once again following the formalism of Eq. 6.4 and Eq. 6.5, the lens model time delay–magnification covariance implies that inducting magnification into $\mathcal{O}$ affects the H_0 inferred by each individual lens model, as well as the H_0 inferred across all lens models. Because the absolute magnification was unavailable for the Type II SN Refsdal, this marks the first case where it can be meaningfully leveraged for time-delay cosmography. We refer to Sections 6.10 and 6.10 for further discussion.

Including Spectroscopic Constraints

The spectroscopic data set yields measurements of all five observables independently from the photometric data set. Though the spectroscopic measurements are somewhat less precise, it is possible to constrain the observables to even greater precision through a joint-fitting approach. Assuming the spectroscopic and photometric constraints are fully independent, the likelihood of Eq. 6.5 can be modified to include the spectroscopic measurements, such that we determine the probability of H_0 given both the observed light curve (LC), and the observed spectroscopic evolution (SP):

$$P(H_0|\text{LC}, \text{SP}) = P(H_0) \sum_1^N \int P(\mathcal{O}|M_l; H_0) P(\mathcal{O}|\text{LC}) \times P(\mathcal{O}|\text{Sp}) d\mathcal{O}_1 \dots d\mathcal{O}_n \quad (6.7)$$

Here $P(\mathcal{O}|\text{LC})$ and $P(\mathcal{O}|\text{Sp})$ refer to the posteriors for the photometric and spectroscopic constraints respectively.

Altogether, we employ three approaches to the inference of H_0 following this formalism. First, we infer $H_{0,\text{TD-only}}$, which uses only the photometric constraints following Eq. 6.5, and uses only the two time delays in the set of observables, $\mathcal{O} : \{\Delta t_{a,b}, \Delta t_{c,b}\}$. For the second approach, we similarly follow Eq. 6.5 with only photometric constraints, but include absolute

magnifications, following the full set of observables given in Eq. 6.6 to infer $H_{0,\text{phot-only}}$. Finally in the third approach, we follow Eq. 6.7 to infer $H_{0,\text{phot+spec}}$, which includes all available constraints from photometry and spectroscopy. We note that $H_{0,\text{TD-only}}$ inference provided identical results when spectroscopic constraints are added, and hence we do not include it as a separate approach. Across all approaches, we assign a top-hat prior for the Hubble constant: $H_0 \in (30, 130) \text{ km s}^{-1} \text{ Mpc}^{-1}$. The parametrization of $P(\mathcal{O}|M_i; H_0)$, $P(\mathcal{O}|\text{LC})$, and $P(\mathcal{O}|\text{SP})$ from the lens model, light-curve fitting, and spectroscopic age-dating posteriors respectively, as well as the integration of the likelihood, are described in Appendix 6.12.

Table 6.1 Magnifications and time delays from cluster lens models, photometry, and spectroscopy

#	Lens Model	$\Delta t_{a,b}$	$\Delta t_{c,b}$	$ \mu_a $	$ \mu_b $	$ \mu_c $
1	GLAFIC (Oguri, 2010; Oguri, 2021)	$-105.18^{+5.16}_{-7.89}$	$-50.71^{+3.37}_{-5.09}$	$8.02^{+0.64}_{-0.57}$	$12.23^{+1.30}_{-1.51}$	$9.32^{+0.80}_{-0.87}$
2	Zittrin-analytic ^b (Zittrin et al., 2015a)	$-105.52^{+5.09}_{-6.32}$	$-41.06^{+14.27}_{-13.19}$	$11.25^{+1.05}_{-0.90}$	$16.03^{+1.77}_{-1.81}$	$14.48^{+1.91}_{-1.65}$
3 ^c	LENSTOOL (Kneib et al., 2011)	$-102.68^{+6.47}_{-6.80}$	$-54.09^{+3.18}_{-3.76}$	$8.75^{+1.01}_{-0.60}$	$11.32^{+1.29}_{-1.14}$	$10.47^{+1.14}_{-0.74}$
4	MARS (Cha and Jee, 2022)	$-136.27^{+20.23}_{-20.32}$	$-63.72^{+29.24}_{-28.46}$	$6.82^{+0.50}_{-0.44}$	$9.17^{+0.80}_{-0.72}$	$7.55^{+0.86}_{-0.70}$
5	Chen, Kelly, and Williams, 2020	$-112.25^{+6.43}_{-6.57}$	$-53.35^{+2.71}_{-2.99}$	$6.52^{+0.24}_{-0.22}$	$10.35^{+0.46}_{-0.41}$	$6.68^{+0.24}_{-0.22}$
6	WSLAP+ (Diego et al., 2005)	$-273.35^{+95.30}_{-95.30}$	$342.75^{+92.54}_{-92.54}$	$16.38^{+0.71}_{-0.71}$	$47.54^{+3.23}_{-3.23}$	$33.35^{+0.74}_{-0.74}$
7	Zittrin-LTM (Zittrin et al., 2009a)	$-96.45^{+5.41}_{-5.85}$	$-27.64^{+6.52}_{-4.80}$	$5.66^{+0.15}_{-0.14}$	$9.77^{+0.47}_{-0.51}$	$8.80^{+0.67}_{-0.46}$
Photometry	Pierel et al., 2024a ^a	$-116.60^{+10.83}_{-9.29}$	$-48.30^{+3.58}_{-3.97}$	$4.43^{+1.52}_{-1.60}$	$8.00^{+3.42}_{-2.34}$	$6.43^{+1.25}_{-1.13}$
Spectroscopy	Chen et al., 2024 ^a	$-122^{+43.7}_{-43.8}$	$-49.3^{+12.2}_{-14.7}$	$10.93^{+8.63}_{-5.16}$	$13.22^{+7.49}_{-2.33}$	$7.14^{+1.53}_{-1.66}$

Note. — **Top:** The seven contributing cluster lens models, their primary references, and predicted time delays (in days) and magnifications given as the 68% confidence interval. **Bottom:** Measurements of the corresponding quantities from photometry and spectroscopy.

^aValues cited in this table assume Gaussian process regression interpolation for inference of the unlensed SN apparent magnitude.

^bTime delay values for this model were corrected for an error following unblinding. The error was in the TD measurement and did not require a modification of the underlying blind model. The initial blinded values were $\Delta t_{a,b} = -120.89^{+8.61}_{-11.31}$ days and $\Delta t_{c,b} = -27.94^{+5.56}_{-6.60}$ days. Details on the error and its correction are given in §6.8.

^cThis model was updated following unblinding. The blinded model values were $\Delta t_{a,b} = -105.68^{+1.51}_{-1.48}$ days, $\Delta t_{c,b} = -52.27^{+2.06}_{-2.44}$ days, $|\mu_a| = 6.67^{+0.11}_{-0.14}$, $|\mu_b| = 9.82^{+0.23}_{-0.31}$, and $|\mu_c| = 8.94^{+0.21}_{-0.29}$. Details on the blinded model and its correction are given in §6.8 and the model 3 section of Appendix 6.12.

6.8 Blinded Analysis

Blinding Protocols

Blinding protocols were installed to reduce the impact of human bias. They established the information that could be shared between subgroups of our team, the live unblinding process, and the rules for which changes were allowable post-unblinding. The values of the time delays

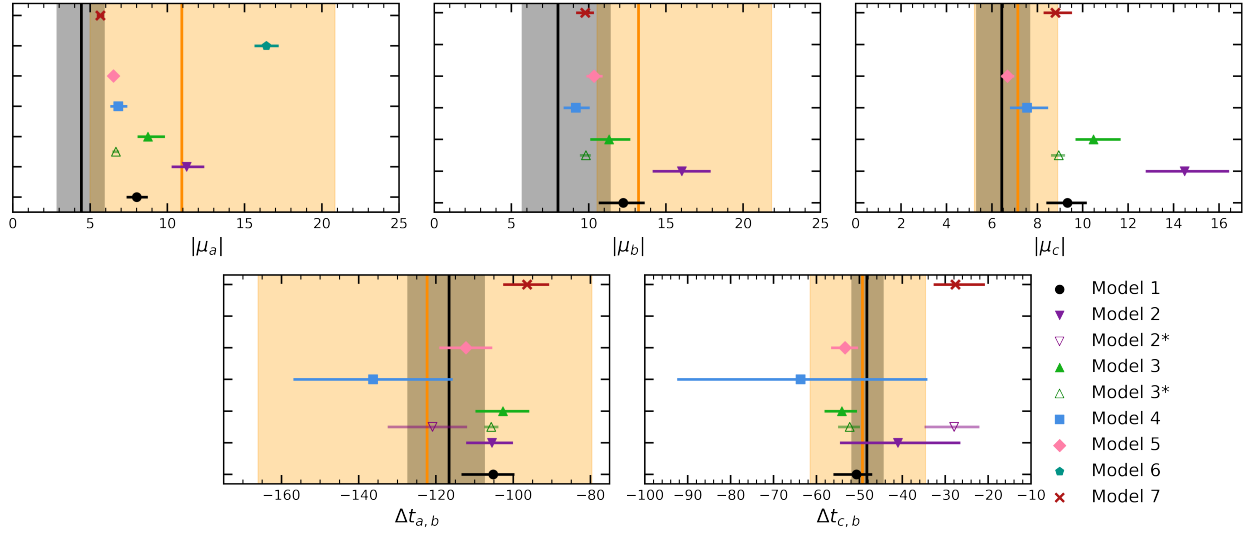


Figure 6.3 The absolute magnifications and relative time delays predicted by each of the seven contributing lens models (markers) and the measured quantities from photometric light-curve fitting (vertical black lines and gray swaths represent the median and 68% confidence interval respectively) and spectroscopic age-dating (orange lines and swaths). The x-axis limits are set for clarity, which omits model 6 for some quantities due to its inconsistency with both the other lens models and observations. The empty purple and green markers of ‘Model 2*’ and ‘Model 3*’ respectively represent the blinded results from Models 2 and 3 which contained an errors which were amended after unblinding (see § 6.8). The lens model-predicted time delays assume a fiducial $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Following Eq. 6.3, the time delays are inversely proportional to H_0 , and rescaled for a range of values of H_0 to infer the total probability distribution.

and the implied magnifications from both light curve analysis and spectroscopic analysis were not revealed to one another, nor to any of the lens modeling teams. The modelers assembled regularly to agree upon the set lensing constraints, such as the catalogs of lensed image positions, spectroscopic redshifts, and photometry of the cluster galaxies as stated explicitly in Frye et al. (2024a), and then constructed the individual lens models independently. All lens models submitted prior to unblinding were required to be included in the inference. More specifically, for the blinded inference of H_0 , the relative time delays and absolute magnifications from photometry and spectroscopy were blinded via a median subtraction of the probability distribution function (PDF) of each measurement.

One exception is that the spectroscopic time delay and magnification measurements were unblinded to the lens model 5 predictions. This is because the spectroscopic measurements and the lens model construction were performed by the same team, however the lens model was completed and locked prior to obtaining the spectroscopic results, and hence was blinded from the spectroscopic time delays and the magnifications.

The photometric and spectroscopic analysis timelines were different. To accommodate the staggered timelines, the initial live unblinding was performed only for $H_{0,\text{phot-only}}$, which the spectroscopic analysis remained blinded to until the $H_{0,\text{phot+spec}}$ value was unblinded at a later date. Post-unblinding changes were only allowed to address errors. We defined an error to be a genuine mistake for which there is an objectively correct solution rather than a subjective choice. Following the $H_{0,\text{phot-only}}$ unblinding, six errors were identified by this definition and corrected. Amending these errors ultimately resulted in a $\sim 1\sigma$ decrease in $H_{0,\text{phot-only}}$. While the resolution of these errors impacts the inference of H_0 , the methodology was unchanged, and the details of each error and its impact on both the observables and the inferred H_0 are listed below.

Errors Corrected Post-Unblinding

Here we discuss the initial unblinded value of H_0 , the seven errors found subsequent to the unblinding, and how amending the errors affected the inference. These errors result from genuine mistakes which had objective fixes. The following events are stated in chronological order beginning with the unblinding event. The initial unblinding was conducted using only photometric constraints, and all errors were found while blinded to the spectroscopic results. Hence, all values given pertain to $H_{0,\text{phot-only}}$.

The inference of $H_{0,\text{phot-only}}$ was unblinded live by revealing the median values of the distribution of measured magnifications and time delays from light-curve fitting, which yielded $H_{0,\text{phot-only}} = 81.3^{+15.9}_{-8.5} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Post-unblinding, the first error was a miscommunication between the light-curve fitting team and the team performing the H_0 inference that resulted in the exclusion of both the ~ 0.1 mag intrinsic scatter of SN Ia magnitudes and the scatter due to millilensing from the inference. Applying these effects broadened the measured magnification uncertainties by $\sim 25\%$, which resulted in an updated value of $H_{0,\text{phot-only}} = 79.6^{+15.0}_{-8.7} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Second, the light-curve fitting team found an error in the simulations which estimate the systematic uncertainty due to microlensing. The uncertainties were based on the bias and standard deviation for distributions of measured magnifications relative to the simulated magnifications. However, the measured magnifications were recorded as simply the ratio of measured amplitudes, which ignores the additional uncertainty from other light curve parameters. This was updated to match the final method used to measure the true magnifications (see Pierel et al., 2024a, for details), which takes the full uncertainty into account. This further increased magnification uncertainties on images a and b by $\sim 10\text{--}20\%$ while image c remained mostly unaffected because of its phase at the second infrared maximum. The same simulations were found to be using a different version of the BayeSN model (Mandel et al., 2022) for simulations and fitting, which led to an artificial bias in fitted parameters. Fixing this error decreased the uncertainty of both time delays by $\sim 20\%$, altogether resulting in an updated value of $H_{0,\text{phot-only}} = 76.9^{+14.2}_{-8.2} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Third, the light-curve fitting team discovered a numerical error in the removal of bias induced by systematics on the magnification and time delays. The median of each retrieved

magnification and time delay distribution, created from the simulations discussed above (and see Pierel et al., 2024a, for more details) was removed from the measured values to account for biases identified by fitting the simulations (following Kelly et al., 2023a). After unblinding, it was discovered that this bias was being removed with a sign error. This shifted the median magnifications by $\lesssim 5\%$, the median $\Delta t_{c,b}$ by $\sim 4\%$, and $\Delta t_{a,b}$ by $\lesssim 1\%$. These resulted in an updated value of $H_{0,\text{phot-only}} = 75.9^{+15}_{-8.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Fourth, the lens modeling team for model 3 corrected an error in the sampling of the lens model results which had been used for estimation of the posterior distribution in the inference. This was caught serendipitously when the lens modeling team was requested to generate samples for other lens model parameters to gauge the dominant source of lens model uncertainty. The improper sampling resulted in a loss of covariance information between the magnification and time delays and significantly overestimated the time delay uncertainties by a factor of ~ 5 . Re-generating the samples correctly did not require any changes in the lens model itself and did not change the median predictions of the magnifications or time delays. The lens model was given similar weight in the $H_{0,\text{phot-only}}$ inference both before and after making this adjustment, resulting in an updated value of $H_{0,\text{phot-only}} = 76.7^{+15.5}_{-6.7} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Fifth, the lens modeling team for model 2 found an error in the calculation of the time delay from the lens model, where the source position sampled was offset by 1 pixel (003) in the source plane. This did not require any modification of the underlying lens model, only a change in how time delays were measured from it. As this significantly changed the time delay distribution for this model, both the blinded values and the error-corrected values are shown Table 6.1 and Figure 6.3. Both $H_{0,\text{phot-only}}$ and $H_{0,\text{phot+spec}}$ were unaffected by this change as a result of negligible weighting both before and after the correction. For $H_{0,\text{TD-only}}$, however, the model weighting rose from ~ 0 to $\sim 16\%$, changing the inference from $H_{0,\text{TD-only}} = 73.2^{+10.5}_{-6.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$ to $H_{0,\text{TD-only}} = 71.8^{+9.2}_{-8.1} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Sixth, during the review process it was determined that lens model 3 included two choices of model parameters which were not sufficiently justified, and ultimately the lens modeling teams mutually agreed these decisions were inappropriate. This specifically referred to the choice of positional uncertainty ($0.03''$), which was found to be too small compared to prescriptions in the literature (e.g., Johnson et al., 2014; Grillo et al., 2016), and the choice to fix the cluster member reference cutoff radii and velocity dispersions, which were found to bias the results. Updating the model with a more appropriate positional uncertainty of ($0.3''$) and allowing the cluster member parameters to be freely optimized was found to increase the time delay and magnification fractional uncertainties as much as a factor of 5, and also increased the median magnifications by $\sim 25\%$. The model updates are given in greater detail in Appendix 6.12. We note that the model was also changed from source-plane to image-plane optimization, as the source-plane model had produced unphysical results at the larger positional uncertainty. Both $H_{0,\text{TD-only}}$ and $H_{0,\text{phot+spec}}$ were negligibly affected by this change, however in the $H_{0,\text{phot-only}}$ inference the model weighting decreased from 28% to 6%, resulting in a change from $H_{0,\text{phot-only}} = 74.4^{+13.0}_{-6.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$ to $H_{0,\text{phot-only}} = 76.7^{+15.5}_{-6.7} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Seventh, it was found during the review process that the Model 6 magnifications and time delays were measured at the observed SN positions rather than the model-predicted positions, which was inconsistent with the guidelines determined for lens model submission. To ensure a consistent approach across all models, the model 6 results were updated to instead use measurements made at the model-predicted positions. This did not involve any modification of the model itself, nor did this meaningfully affect the H_0 inference.

6.9 Results

Following the most straightforward approach, we inferred H_0 using only the photometric time delays, yielding $H_{0,\text{TD-only}} = 71.8^{+9.2}_{-8.1} \text{ km s}^{-1} \text{ Mpc}^{-1}$. In this approach, the lens models are weighted based on their ability to reproduce the ratio between the two photometrically measured time delays. This inference is dominated by five models: model 5 (30%), model 1 (23%), model 2 (17%), model 4 (16%), and model 3 (9%). We found that including the spectroscopic time delays did not change the result due to their agreement with the photometric time delays while carrying uncertainties that were larger by a factor of ~ 4 . Model 6 in particular is truncated by the $130 \text{ km s}^{-1} \text{ Mpc}^{-1}$ upper bound of the top-hat H_0 prior, resulting in only 3% of the weighting. Removal of this prior results in a dominant weighting of $\sim 20\%$ for $H_{0,\text{TD-only}}$, while the magnification-weighted approaches remain unaffected.

We next included magnification into the suite of observables, which yields $H_{0,\text{phot-only}} = 76.7^{+15.5}_{-6.7} \text{ km s}^{-1} \text{ Mpc}^{-1}$ from photometric constraints. Because the lens model-predicted time delays and magnifications are correlated, the magnifications influence both the H_0 inferred by an individual lens model, as well as the relative weighting each model receives in the H_0 inferred across lens models. The weighting is such that the models which best reproduce the two measured time delays and three measured absolute magnifications simultaneously are given greater contribution to the PDF of $H_{0,\text{phot-only}}$. The result is primarily influenced by three lens models: model 5 is given 43% of the weighting, model 4 is given 29%, and model 1 is given 21%. No single model dominates the inference, instead the three subdominant contributions individually predict different H_0 's which ultimately broaden the resulting PDF.

Finally, we obtained the highest precision estimate by making use of all available constraints, inferring $H_{0,\text{phot+spec}} = 75.7^{+8.1}_{-5.5} \text{ km s}^{-1} \text{ Mpc}^{-1}$ from joint photometric-spectroscopic constraints. This inference is dominated by model 5 (65% of the weighting), with subdominant contributions by model 1 (19%), and model 4 (14%). While the individual lens model predictions are similar to those in $H_{0,\text{phot-only}}$ (that is, joint time delay constraints are effectively the same as those from photometry alone), the joint magnification constraints favor a single model, resulting in a significantly reduced uncertainty. For each approach, the H_0 predictions of each individual model as well as their assigned weights are shown in Table 6.9. These results are also illustrated in Figure 6.4, which shows the PDF of each lens model as well as the total PDF of H_0 .

Table 6.2. H_0 Inferences

Model	$H_{0,\text{phot+spec}}$	$H_{0,\text{phot-only}}$	$H_{0,\text{TD-only}}$	$\mathbf{W}_{\text{phot+spec}}$	$\mathbf{W}_{\text{phot-only}}$	$\mathbf{W}_{\text{TD-only}}$
1	$76.05^{+6.41}_{-6.01}$	$75.55^{+6.71}_{-6.31}$	$69.74^{+7.11}_{-5.71}$	0.19	0.21	0.23
2	$83.55^{+6.61}_{-5.91}$	$82.05^{+7.01}_{-6.11}$	$64.73^{+7.31}_{-6.31}$	0.00	0.00	0.17
3	$76.05^{+5.51}_{-5.11}$	$75.85^{+5.91}_{-5.31}$	$72.24^{+6.21}_{-5.51}$	0.00	0.06	0.09
4	$93.96^{+15.02}_{-14.31}$	$93.66^{+14.91}_{-14.21}$	$85.96^{+16.02}_{-14.21}$	0.15	0.29	0.16
5	$74.54^{+5.11}_{-4.70}$	$73.84^{+5.31}_{-4.80}$	$73.84^{+5.51}_{-5.01}$	0.65	0.43	0.30
6	> 130	> 130	> 130	0.00	0.00	0.00
7	$53.92^{+4.90}_{-4.40}$	$57.03^{+5.01}_{-4.50}$	$54.82^{+5.31}_{-4.80}$	0.00	0.01	0.03
Total	$75.7^{+8.1}_{-5.5}$	$76.7^{+15.5}_{-6.7}$	$71.8^{+9.2}_{-8.1}$	1.00	1.00	1.00

Note. — The seven contributing cluster lens models with their individual predictions for the three H_0 ($\text{km s}^{-1} \text{ Mpc}^{-1}$) inferences. Also listed are the relative weightings ($\mathbf{W}$) for each model in the likelihood across the three inferences. We also present the results for the total inference resulting from Eq. 6.5 and Eq. 6.7.

Figure 6.5 compares H_0 inferred from SN H0pe to other H_0 measurements, including that from SN Refsdal. The combined photometric-spectroscopic inference, $H_{0,\text{phot+spec}}$, provides the strongest constraints and agrees with most other late-time measurements, showing less than $<1\sigma$ tension with measurements from SH0ES, CCHP, and TDCOSMO (Murakami et al., 2023; Freedman et al., 2019; Wong et al., 2020). By contrast, SN H0pe’s $P(H_0 < 67.5 \text{ km s}^{-1} \text{ Mpc}^{-1}) < 7\%$ shows $1.4\text{--}1.5\sigma$ tension with early-time measurements. SN H0pe’s H_0 is also in $1.3\text{--}1.5\sigma$ tension with the SN Refsdal result of Kelly et al., 2023a. However, further exploration of SN Refsdal’s systematics (Liu and Oguri, 2024; Grillo et al., 2024) measured $H_0 = 70.0^{+4.7}_{-4.9} \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $H_0 = 65.1^{+3.5}_{-3.4} \text{ km s}^{-1} \text{ Mpc}^{-1}$. The Grillo et al., 2024 result did not include priors from other cosmological experiments, while this work, Kelly et al., 2023a, and Liu and Oguri, 2024 all assumed a flat Λ CDM cosmology.

6.10 Discussion

Time-Delay Cosmography With a SN Ia

SNe Ia as standard candles offer unique advantages for time-delay cosmography compared to SNe II such as ranking the lens models via absolute magnification, constraining the impact of mass-sheet degeneracy, and providing an alternative and independent method to measure the time delays and magnifications via spectroscopy. As a start, we assess the impacts of SN type by repeating the inference of H_0 , this time by modifying the set of observables to include only constraints available to SNe II: the photometric measurements of the time

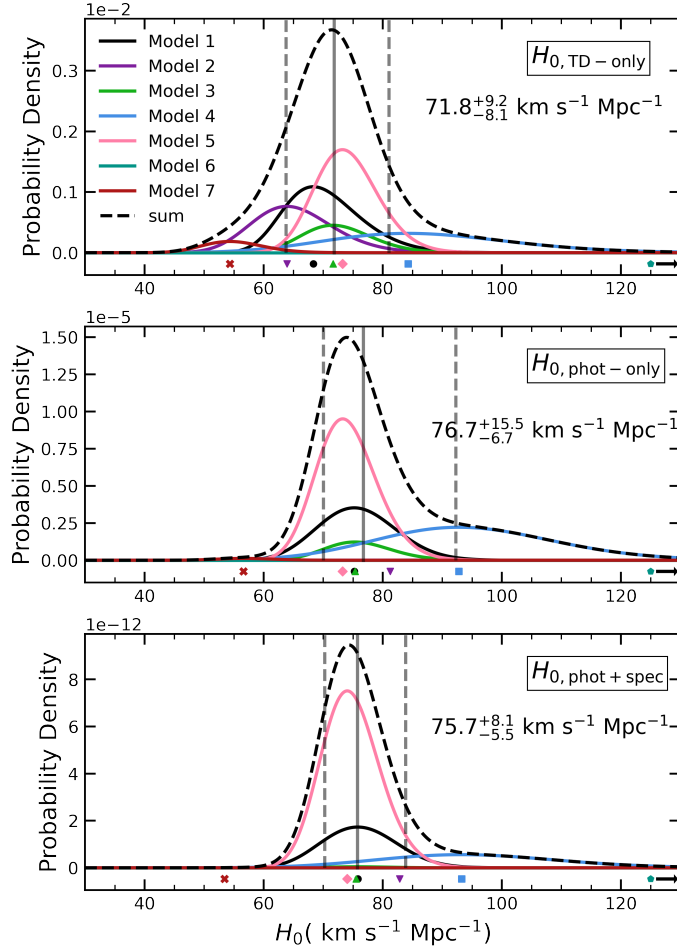


Figure 6.4 Inferred H_0 from comparing lens model-predicted time delays and absolute magnifications to those measured from (in order of increasing constraints) only time delays (top), only photometry (middle), and combined photometry and spectroscopy (bottom). The summed PDF (dashed curves) represents the total PDF of the H_0 inferred. Individual lens model inferences (solid curves) are shown with normalization equal to their weighting, and the median prediction of each model is plotted as markers below the curves.

delays and the magnification ratios. This exercise, which makes use of magnification ratios, returns $H_{0,\text{Type II}} = 73.0^{+11.3}_{-7.8} \text{ km s}^{-1} \text{Mpc}^{-1}$, providing no meaningful improvement over the inference from time delays alone, $H_{0,\text{TD-only}}$. This test demonstrates that all the lens models which satisfy the time delay ratios also satisfy the measured magnification ratios to within 1σ . While magnification ratios do not give additional footholds to break the degeneracy between the lens models and H_0 , absolute magnifications do provide the necessary leverage to rank the lens models. It can be seen that the photometric magnification measurements alone already tighten the overall constraints, downweighting two models which initially satisfied the

magnification ratios. On combining the photometric measurements with the spectroscopic measurements, the best constraints of all are obtained, thereby favoring a single lens model (Figure 6.4). This clearly demonstrates how the magnification helps break this degeneracy and improves the precision of the H_0 inference.

Lens Model Covariance

The contributing lens models exhibit varying degrees of covariance between the predicted absolute magnifications and the time delays. The likelihoods of Eq. 6.5 and Eq. 6.7 depend on both the time delays and magnifications, implying this covariance affects both the H_0 inference made by each individual lens model as well as their relative weightings. The lens model-predicted absolute magnifications and time delays are inversely correlated, meaning lower magnifications are associated with larger time delays (2D posteriors in Fig. 6.6) and therefore larger values of H_0 . Among parametric models (1, 2, and 3), this correlation extends between the models, manifesting as an inverse correlation between $H_{0,\text{TD-only}}$ and the predicted magnification of each model. Liu and Oguri, 2024 found the same correlation for SN Refsdal. The semi- and non-parametric models (4, 5, 6, 7), however, do not follow this correlation across models, affirming they likely probe a different parameter space than parametric models and one that cannot easily be re-created through variations in the parameterization (e.g., the slope of the radial density profile).

Across the full set of models, the parametric models tended to exhibit a stronger correlation between magnifications and time delays than the non-parametric models, perhaps owing to the inflexibility of fully-parametrized mass distributions enforcing a stricter allowable parameter space. We also found that using magnification as a constraint in the lens modeling produces results consistent with the expectations of the covariance (see purple contours of Fig. 6.6). The specifics of these ‘unblinded’ models are detailed in Appendix 6.12.

The Mass-Sheet and Related Degeneracies

Time-delay cosmography can be limited by model-independent degeneracies, such as the mass-sheet and by extension in mass-slope degeneracies, the latter of which is present in simply-parameterized mass models. This implies that the time delays and magnifications are sensitive to the addition of constant sheets of surface mass density or variations in the slope of the radial surface-density profile, both of which may still satisfy the lensing constraints (Kochanek, 2002; Schneider and Sluse, 2013). While these degeneracies tend to plague galaxy–galaxy lenses, in galaxy-cluster lenses they can be broken by the availability of two or more multiple-image systems at different spectroscopically confirmed redshifts (Falco, Gorenstein, and Shapiro, 1985; Kawano and Oguri, 2006; Schneider and Sluse, 2014). For example, Grillo et al., 2020 and Grillo et al., 2024 examined the case of SN Refsdal in the MACS J1149 cluster field and concluded that the availability of 89 multiple images from 27 distinct multiple-image systems (8 with unique spectroscopic redshifts) diminished these degeneracies to insignificant levels. However, Liu and Oguri, 2024 found for a similar set of

lensing constraints (but different lens modeling approach) that the mass-slope degeneracy, while diminished, could be still further decreased by the incorporation of new multiple-image systems.

G165 presents five systems at three unique spectroscopically confirmed redshifts and an additional sixteen multiple image systems with photometric constraints. These constraints already break these degeneracies, however it is unlikely that they are completely eliminated, as is illustrated by the scatter in our seven model-predicted time delays. Furthermore, as pointed out in Section 6.10, many of the lens models satisfy the measured magnification ratios yet do not agree with the measured magnification, an indication of the mass-sheet degeneracy at play. This further emphasizes the importance of obtaining a magnification constraint, which has been widely-advocated for resolving this degeneracy in galaxy–galaxy and galaxy-cluster lenses alike (e.g., Oguri and Kawano, 2003; Foxley-Marrable et al., 2018; Birrer, Dhawan, and Shajib, 2022; Liu and Oguri, 2024).

As discussed in §6.10, a magnification constraint is effective at breaking the degeneracy among lens models, reflecting its leverage over the mass-sheet degeneracy. It is interesting to ask to what degree the measured magnification precision can constrain such a mass-sheet. The mass-sheet degeneracy, or more generally the mass-sheet transformation allows for a mapping of the surface mass density $\kappa' = \lambda\kappa + (1 - \lambda)$ which induces a change in the true source position $\beta' = \lambda\beta$ while leaving the apparent source position invariant. The second term in the convergence transformation, $(1 - \lambda)$, makes up a constant sheet of surface mass density which gives the MST its name; we refer to this term as κ_λ . This directly scales the magnifications $\mu' = \mu/\lambda^2$ and time delays $\Delta t' = \lambda\Delta t$, however it is clear the ratios remain invariant. From photometry and spectroscopy, the magnifications are generally measured to an average fractional precision $\sim 25\%$. This implies that a single magnification measurement can rule out $|\Delta\lambda| \gtrsim 0.1$ or directly $|\kappa_\lambda| \gtrsim 0.1$. When combining all three multiple images, this holds the potential to be much stronger. For example we evaluate lens model 5, which gives the best agreement with measured magnifications, and in post-processing apply a range of $\lambda \in [0.8, 1.2]$ to its predicted magnifications. We find that only a very small $\Delta\lambda \sim 0.05$, is required to reduce the model weighting by a factor of two, implying only a very small allowance of $|\kappa_\lambda| \lesssim 0.05$.

We emphasize this test is not comprehensive: an external convergence need not present itself as a constant sheet of mass (Khadka et al., 2024), and it alone does not quantify the extent to which the availability of many multiple image systems breaks this degeneracy. In the case of an individual lens model, the degeneracy could be quantified explicitly by incorporating free parameters for the addition (or subtraction) of sheets of constant surface mass density or for varying the slope of the surface mass density profile during optimization (e.g., Grillo et al., 2020; Grillo et al., 2024). This could capture degeneracies between an external convergence and the lens model parameters, which are not addressed in our test. For example, such an external convergence could result in a fundamentally different lens model with a distinct κ distribution (e.g., the isodensity contours are not preserved). Similarly, testing a wide variety of mass profile parametrizations, such as in Liu and Oguri, 2024, could illustrate the degree of any persisting mass-slope degeneracy. Incorporating magnification

constraints into these tests gives additional opportunities to explore lensing degeneracies at the cluster lensing scale, but is outside the scope of this work.

Kawano and Oguri, 2006 found time delay ratios can provide an alternate route to breaking the mass-slope degeneracy. This constraint is rarely highlighted in the literature, but its power is apparent in the inference of $H_{0,\text{TD-only}}$ in this study, where the time delay ratio alone determines the model weighting. This weighting provides a $\sim 12\%$ fractional uncertainty in the $H_{0,\text{TD-only}}$ measurement, but removal of this weighting scheme (i.e., the PDFs of the models are rescaled to the same normalization) results in uncertainties which are larger by more than a factor of two. This demonstrates the utility of multiple image systems for which multiple precision time delays are available, as these hold an under-recognized ability to break lensing degeneracies.

SN Ia Apparent Magnitude Interpolation

To ensure the magnifications for SN H0pe are measured independently of cosmology, both the spectroscopic and photometric methods compared the peak apparent magnitude of each SN image to the distribution of field SNe Ia. Due to the relatively small number of spectroscopically confirmed SNe Ia at $z > 1$ (Scolnic et al., 2018), the field SN Ia peak magnitudes had to be fit with a smooth model to enable an interpolated inference at $z = 1.783$. Before the un-blinding step in this analysis a choice was made to perform this fit with a Gaussian process, but after the un-blinding we explored two additional options for the fitting to understand the impact for our measurement. We fit the field SN Ia peak magnitudes with a second-order polynomial in $\log(z)$ -space (allowing all coefficients to vary), as well as with a second-order cosmology-independent kinematic expansion (see Riess et al., 2022, Equation 4).

We find that the range predicted by these three methods is fairly large, $\sim 0.3\text{mag}$, but that the Gaussian process result is situated directly in the center of the polynomial and kinematic expansion fits (see Figure 6 of Pierel et al., 2024a). We cannot change this method after un-blinding, as there is no evidence to suggest any of the three approaches are in error. Nevertheless we evaluate the impact of the interpolation method on the H_0 inference, as this value directly translates to the magnification measurements and therefore affects the H_0 prediction. The inferences across the three interpolation methods are shown in Figure 6.7; the median H_0 varies at most 3% in both the photometric and the joint photometric-spectroscopic inferences. As more SNe Ia at $z > 1.5$ are spectroscopically confirmed, the three methods are expected to converge while still remaining independent of cosmology.

Error Budget

The lens model predictions and the photometric plus spectroscopic measurements both contribute significantly to the error budget, resulting in the $\sim 9\%$ uncertainty in the joint photometric-spectroscopic H_0 inference (Table 6.9 column 2). Lens model 5 dominates the

weighting in this inference and by itself gives $\sim 6.5\%$ uncertainties for the H_0 (see the model 5 row of Table 6.9). The difference between these uncertainties confirms that disagreements among lens models drive up the uncertainty. This represents the systematic uncertainty of the lens models, which could be mitigated by stricter magnification constraints from photometry and spectroscopy or by including new lensing constraints (e.g., Liu and Oguri, 2024). We found the removal of image systems which did not have spectroscopic redshifts worsened the agreement between the lens-model predicted magnifications and observations, demonstrating that even photometrically-selected image systems can provide impactful constraints on the lens models. Thus the addition of new photometric systems, or spectroscopic confirmation of existing systems may both serve to increase lens model precision.

The photometric time delays each carry $\sim 8\%$ uncertainty, but the inclusion of two time delays is more constraining than a single one of similar precision. To estimate the error budget, the two time delays can be approximated as a single effective time delay with uncertainty $\sim 8\%/\sqrt{2} = 5.6\%$ (following error propagation through Eq. 6.3). Indeed, an H_0 inference assuming zero uncertainty from the lens models (i.e., taking the time delays of lens model 5 with zero error bars) gives an uncertainty on H_0 of 5–6%, consistent with the expectation from the single effective time delay. Taking this approximation, we can straightforwardly decompose the $\sim 9\%$ H_0 uncertainty into two-fifths contribution from photometry and spectroscopy and three-fifths contribution from lens modeling. Furthermore, the lens model uncertainty can be decomposed into one-fourth ‘measurement’ uncertainty (originating from a single model) and three-fourths ‘systematic’ uncertainty (the spread between contributing models).

As shown above, ignoring the lens model uncertainty altogether still results in a modest H_0 uncertainty, and therefore improvements in photometry or spectroscopy still matter. Approved follow-up *JWST* Cycle 3 imaging (PID: 4744) after SN H0pe has faded will provide a template image for precision difference-image photometry, which is expected to improve magnification constraints and nearly halve photometric time delay uncertainties. This could result in as small as a 2.8% effective time delay uncertainty. Given an effective lens model time delay uncertainty 7% (which approximately accounts for the model 5 uncertainties and smaller contributions of other lens models), this would translate to $\sim 7.5\%$ uncertainty on H_0 . Should the improved magnification constraints from photometry prove to entirely favor a single lens model, this could push the uncertainty to $\lesssim 5\%$.

6.11 Conclusions

SN H0pe is only the second opportunity for precision SN time-delay cosmography. We measured the probability distribution of H_0 by comparing the photometrically and spectroscopically measured time delays and magnifications to those predicted by seven independently created lens models, inferring $H_0 = 75.7^{+8.1}_{-5.5} \text{ km s}^{-1} \text{ Mpc}^{-1}$. We found the lens model-predicted time delays and magnifications were correlated, such that including magnifications could break degeneracies between the lens models and H_0 , influencing both the H_0 predic-

tion of each individual lens model as well as weighing its contribution to the total inference. We demonstrated this constraint is a powerful tool to select for lens model accuracy, disfavoring lens model predictions that otherwise would have been admitted had the SN been a Type II. The lens model predictions and combined photometric-spectroscopic measurements both contribute significantly to the error budget, resulting in the $\sim 9\%$ uncertainty in the joint photometric-spectroscopic inference. Follow-up epochs of *JWST* NIRCcam imaging after SN H0pe has faded are approved, and will improve the precision of the SN photometry, and hence also both the time delay and magnification estimates. This combined with the additional constraining power provided by two precision time delays may allow for constraints at the $\lesssim 5\%$ level, comparable to or exceeding that of SN Refsdal.

SN H0pe is the first cluster-lensed SN where the methodology for the H_0 inference could be developed in advance of the lens model construction and photometric and spectroscopic measurements. All lens modelers received identical lensing constraints, providing a novel opportunity to ensure consistency between lens models and test lens systematics. We found it was crucial to establish rules for blinding due to the number of independent teams contributing to the analysis, which included a formalized process to address errors. We distinguished objective errors from subjective choices, and only admitted changes to the former following unblinding. These protocols were successfully implemented for SN H0pe and provide a timely point of reference for growing the catalog of H_0 measurements from cluster-lensed SNe. Upcoming surveys from the Vera C. Rubin and Nancy Grace Roman observatories as well as continuing *JWST* programs will increase the sample of cluster-lensed SNe, which promises to ultimately drive H_0 constraints down to percent-level precision.

6.12 Appendix

The Seven Cluster Lens Models

All models were constructed using the same set of lensing constraints and were blinded from one another as well as from the photometrically and spectroscopically measured time delays and magnifications. The exception is model 5, for which the modelers knew the spectroscopic results but did not include them in the lens model constraints. Model 7 was constructed prior to the unblinding, but was not present at the unblinding owing to logistical difficulties. The model was later added to the analysis. Table 6.3 gives goodness-of-fit statistics and modeling parameters. The lens models all showcase relatively good quality fits as evidenced by the small root-mean-squared (RMS) offsets between modeled and observed multiple images and the general agreement among the lens models' predictions.

Model 1 implements the GLAFIC software (Oguri, 2010; Oguri, 2021), which utilizes a parametric approach to solve for the analytic lens profiles. GLAFIC adopts an adaptive-mesh grid to increase computation efficiency, essentially increasing resolution in regions with larger magnification gradients (e.g., near critical curves). The model used five Navarro–Frenk–White (NFW) profiles to model the dark-matter halos of the cluster. These were chosen

to correspond to the 5 bright galaxies which make up the centers of the two merging mass components. The cluster galaxies were modeled with pseudo-Jaffe ellipsoid profiles scaled according to each galaxy’s observed F200W flux density. An external shear component was included to improve fitting flexibility. Higher-order multipole perturbations $m = 3$ and 4 (where $m = 2$ represents the external shear) were also included. Free parameters were also included for the redshifts of the 16 photometrically-constrained multiple image systems. The optimization was performed using an image plane χ^2 approximately estimated in the source plane (See Oguri 2010 appendix) using an MCMC with $\sim 10^4$ steps. This approximate χ^2 has been found to well-correlate with the true image plane χ^2 (Fig. 5 of Oguri 2010).

Model 2 was created using a revised version of the parametric approach detailed by Zitrin et al., 2015a. The new version (sometimes referred to as **Zitrin-Analytic**; see also Furtak et al. 2023) is no longer limited to a grid resolution. This approach operates similarly to other parametric lens modeling techniques and has been successfully applied to *JWST* imaging of other clusters (e.g., Pascale et al., 2022b; Meena et al., 2023b). The model employs two primary components, each described by an analytic profile. The cluster galaxies were parametrized as double pseudo-isothermal elliptical mass-density distributions (dPIE, Elíasdóttir et al., 2007) scaled by their luminosities following common relations. The cluster-scale dark matter halo was parametrized with a pseudo-isothermal elliptical mass-density distribution (PIEMD; Kassiola and Kovner, 1993). Constituting a minor component, the masses of four central galaxies were scaled independently to allow further flexibility ($(\alpha, \delta) = (11:27:06.6969, +42:27:50.363)$, $(11:27:20.0475, +42:29:08.292)$, $(11:27:14.4389, +42:28:14.066)$, $(11:27:14.5094, +42:28:07.004)$). While the model can incorporate galaxy ellipticities, for the current model all cluster galaxy profiles were assumed to be circular. In a suite of self-simulated mass distributions, both image- and source-plane optimizations accurately recovered the input parameters, fulfilling the expectation that these should perform similarly (Keeton, 2010b). For G165, the model optimization was performed in the source plane via a Markov Chain Monte Carlo, which was sampled to derive the uncertainties. The MCMC consisted of ~ 100 initial chains of $\sim 10^3$ steps, which is then refined by a final chain run for $\sim 10^4$ steps. For more details on the methodology, including scaling relations and minimization, we refer to Furtak et al. (2023).

Model 3 was constructed using LENSTOOL¹, which applies parametric mass profiles constrained straightforwardly by the observed positions of the multiply-imaged systems. In this case, the only mass profiles employed were the $z \approx 0.35$ cluster members identified by Frye et al. (2024a) plus two cluster-scale halo profiles for the dominant components of the merging cluster, all having a PIEMD profile. Positions and shape parameters (ellipticity and orientation) of the cluster members were held fixed to their F200W values. The mass of each cluster member was scaled in proportion to its F200W flux, following Limousin, Kneib, and Natarajan, 2005. A characteristic L_* galaxy at the cluster redshift ($m_{\text{F200W}} = 17.0$ AB mag) was set to a velocity dispersion σ_0^* , a core radius r_{core}^* , and a cutoff radius r_{cut}^* . The core radius was fixed to $r_{\text{core}}^* = 0.15$ kpc similar to other strong-lensing works (e.g., Johnson et al.,

¹<https://projets.lam.fr/projects/lenstool/wiki>

2014), while the velocity dispersion and cutoff radii were left to be freely optimized by the model. The masses were fixed according to their scaling relative to $L_\star$ with the exception of the BCG and a perturber cluster galaxy near Arc 3 $((\alpha, \delta) = (11:27:14.304, +42:28:32.32))$, whose scalings were optimized independently. For the two cluster halos, their positions, ellipticities, orientations, velocity dispersions (mass), and core radii were left free to vary. The halos' cut radii are poorly constrained and therefore were held fixed at 1 Mpc. The redshifts of the 16 photometrically-constrained multiple image systems were left to be freely optimized by the model. This model was optimized in the image plane with a positional uncertainty $\sigma_{\text{pos}} = 0.3''$, which was chosen to match the RMS of earlier model iterations. This model was optimized using MCMC, and was run with 10 chains of 1000 steps each, which was found to be much longer than the burn-in time of $\lesssim 100$ steps. For further model information, we refer to Kamieneski et al., 2024.

The model detailed above was constructed following unblinding, correcting a number of issues in the initial blinded model. The blinded iteration fixed the reference values for the cluster member scaling relations to a velocity dispersion $\sigma_0^\star = 120 \text{ km s}^{-1}$ and a cutoff radius $r_{\text{cut}}^\star = 30 \text{ kpc}$. While these values were commensurate with findings from other works (e.g., Limousin et al., 2008; Mahler et al., 2022; Furtak et al., 2023), it was found to bias the model toward lower magnifications. Leaving these to be freely optimized instead found a much different, but reasonable solution $\sigma_0^\star = 210 \text{ km s}^{-1}$ and $r_{\text{cut}}^\star = 8 \text{ kpc}$.

The blinded iteration of the model was run via source plane optimization with a small positional uncertainty $\sigma_{\text{pos}} = 0.03''$. While this was chosen to match the astrometric uncertainty of the observed lensed-image centroids (which were independently assigned to the same image pixel by multiple team members), previous works using parametric models indicated that this likely underestimated the uncertainties of the model (Zitrin et al., 2015a; Grillo et al., 2016). The source plane approach, which approximated an image plane chi-squared (see Eq. 12 of Jullo and Kneib 2009), was found to also underperform the image plane optimization, producing an RMS nearly a factor of two larger, and suffered from unphysical solutions at the larger positional uncertainty. The source-plane model also showed evidence for being generally less robust: for example, the posterior median was found to change with positional uncertainty (which was not seen in the image-plane variant). For these reasons, the corrected model was run in the image plane, which may have implications for the model posteriors (see Appendix 6.12). The results of the blinded model are noted in Table 6.1, and the impact of its correction on the H_0 inference is detailed in Section 6.8.

Model 4 was constructed by the **MARS** algorithm (Cha and Jee, 2022), which is a free-form, grid-based approach. **MARS** consists of two terms, one a chi-square minimization of strongly-lensed (SL) multiple images in the source plane and the other a regularization term. The **MARS** algorithm adopts maximum cross-entropy for the regularization. This approach can suppress fluctuations and generate a quasi-unique solution for a given SL multiple images. For lens modeling, **MARS** can consider not only SL multiple images but also weakly-lensed (WL) galaxies (Cha et al., 2023). To account for WL galaxies, **MARS** utilizes an additional term that minimizes differences between observed and predicted reduced shear. For this study, **MARS** provided lens models from both SL-galaxies-only and SL+WL datasets to predict

magnifications and time delays. The SL-galaxies-only model consists of a 100×100 pixel grid covering $90'' \times 90''$ around the two BCGs. The SL+WL model consists of a 400×400 pixel grid encompassing the entire $360'' \times 360''$ FoV. One of the interesting differences between the SL-only and the SL+WL reconstructed mass distributions is that the SL-only model shows an offset of the mass peak from the northeastern core because of the deficiency of SL multiple images, but the SL+WL mass map exhibits good agreement with the luminosity distributions of the galaxy-cluster members.

Model 5 uses the lens modeling software originally developed for a blind prediction of the SN Refsdal reappearance and time delays (Chen, Kelly, and Williams, 2020). This approach makes minimal assumptions about the mass distribution at the galaxy-cluster scale, similar to non-parametric methods, but uses a parametric approach at the individual-galaxy scale. This semi-parametric method parameterizes the dark-matter halos of the cluster galaxies as symmetric analytic Navarro–Frenk–White profiles (Navarro, Frenk, and White, 1997) with the same scale radius and assumes the halo mass scales in proportion to stellar flux. The scale radius is set to 3.84 kpc, and the mass-luminosity ratio for $r < 30$ kpc, M/L ($r < 30$ kpc) = $9.4 M_\odot/L_\odot$. The luminosity is measured from *JWST* F090W photometry (approximately V/R band rest-frame). The goal of the cluster member halos is to serve as an initial condition of a concentrated mass distribution around the core of each cluster member, as this cannot be well-constrained by observed multiple images due to the cluster-scale lensing. These profiles do not hold after many iterations of the global perturbation function described below, such that the final solution of the cluster-scale mass distribution is only weakly dependent on the choice of scale radius and halo mass. For the cluster-scale dark-matter distribution, the model makes no assumptions about symmetry. Instead, the global lensing potential is deformed by a set of curving functions that apply numerical perturbations to the potential. These curving functions are inherently smooth on the cluster scale and are applied to determine a source plane position that minimizes the separation between source-plane positions of lensed multiple images of image families. The model aims to find the best source-plane position for each set of multiple images that can minimize the image-plane offset. Thus, although the perturbations are driven by the source-plane positions, the model is still optimized using image-plane statistics. While the only previous application of this model was to the MACS J1149.5+2223 cluster, its predictions of the reappearance position of SN Refsdal’s image SX as well as Refsdal’s four relative time delays and magnification ratios are consistent with other well-tested parametric models (Kelly et al., 2023a). This model does not optimize for the redshifts of photometrically constrained multiple image systems, but instead these systems are assigned to their photometric redshifts and are given a factor of 2.5 lower weighting in the model optimization compared to systems with spectroscopic redshifts.

Model 6 is a hybrid model, implementing the WSLAP+ (Diego et al., 2005) software, where the large-scale component of the lens model is described by a grid of Gaussians, and the small-scale component traces the light distribution of member galaxies. The model is optimized by solving a system of two linear equations per lensing constraint (one for the x coordinate and one for the y coordinate) of the form $\theta = \beta - \alpha(\theta, M)$ with θ the observed position of the lensed galaxy, β the unknown position of the galaxy in the source plane, and

$\alpha(\theta, M)$ the deflection angle at the position θ produced by the unknown mass distribution M .

For G165, the distribution of grid points for the smooth component was built recursively with a first solution obtained from a uniform grid that was then used to derive an adaptive grid that increased the spatial resolution in regions with higher mass concentrations. Using the adaptive grid, WSLAP+ derived 20 solutions varying the initial guess from the optimization and the redshifts of the systems with photometric redshifts. These models were used to derive predicted magnifications and time delays at the three model-predicted positions of SN H0pe. The lack of lensing constraints in the east portion of the cluster and between the two groups resulted in large variations in the predicted magnifications and time delays. In particular, the critical curve at $z = 1.78$ exhibits a dual behavior with some models predicting a single critical curve that connects both groups and other models predicting two disjoint critical curves, one around each group. Model 6 is the only lens model which predicts image C of the SN to arrive last, which is inconsistent with measurements from both photometric light curve fitting and spectroscopic age-dating. This results in the model receiving zero weighting across all three H_0 inferences, as each make use of time-delay ratio constraints. Across the suite of solutions used to derive the model uncertainties, some solutions do correctly predict the image arrival order, indicating that new lensing constraints may improve the accuracy of the model.

Model 7 uses an updated version of the Zitrin-LTM software (Zitrin et al. 2009a, Zitrin et al. 2015a; see also Broadhurst et al. 2005b), which was modified to accommodate time-delay cosmography of galaxy cluster lenses following SN Refsdal (see Zitrin, 2020). In this semi-parametric approach, it is assumed that the light traces the mass (LTM), such that observed cluster-member light is assumed to trace the underlying dark matter. The stellar mass of each cluster galaxy is represented analytically as power-law mass surface-density profile with relative weights determined by the galaxy F200W brightness. The profiles are then simultaneously smoothed with a Gaussian kernel to approximate the projected cluster-scale dark matter distribution, which receives a free weighting relative to the parametric galaxy component. An external shear component with free amplitude and position angle is also applied to broadly account for systematics like large scale structure. Finally, additional flexibility is included for individual galaxies of interest, which included two nearby perturber galaxies specified in Sec. 6.6, and the three brightest central galaxies. For the bright galaxies, the position angle, ellipticity, and mass-to-light ratio can be fit freely. Five of the image systems were set to their spectroscopic redshifts, and for all other systems the redshifts were left free in the model, using the photometric redshift estimate of Frye et al., 2024a as an initial guess. The minimization of the model is done in the image plane, using a MCMC with a final chain of 2000 steps from which the posteriors are sampled.

Lens Model Positional Uncertainties

The positional uncertainties of the lens models play a determining role in the time delay and magnification errors of the parametric lens models of this sample, namely models 1, 2, 3,

and 7. The choice of positional uncertainty is not straightforward. It is suggested that, in order to correctly capture lensing systematics (e.g., line of sight structure, complex structure within the cluster), it should be chosen to be large enough that the RMS of each model is comparable to the positional uncertainties assigned to the multiple image systems, and the resulting χ_ν^2 values are near unity (e.g., Zitrin et al., 2015a; Grillo et al., 2016). We stress that this metric is not always a useful guideline (for example, it is not a relevant metric for non-parametric models), and that the choice of positional uncertainty is not agreed upon across lens models in the literature (e.g., Meneghetti et al., 2017; Kelly et al., 2023a). There is also not a consensus whether this guideline is best suited for the case of a single cluster (e.g., Acebron et al., 2022), whether it should be chosen based off the results of many clusters (e.g., Zitrin et al., 2015a), or drawn from results on simulated clusters (D’Aloisio and Natarajan, 2011; Jullo et al., 2010). As seen in Table 6.3, all but one lens model (for which chi-squared statistics are applicable) satisfy or exceed these guidelines, implying these models adequately capture or even overestimate their uncertainties. One exception, lens model 3, did show large discrepancies between its RMS and positional uncertainty (e.g., model 3) and by extension a large χ_ν^2 , which warranted further investigation and updating of the choice of positional uncertainty as detailed in Appendix 6.12. We note that the posteriors of models 2 and 7 are sampled with an effective positional uncertainty of $\sigma_{\text{pos}} \sim 1.4''$, such that their reduced chi-squared’s become much lower than one, however this positional uncertainty was found to best account for systematics across a range of clusters (Zitrin et al., 2015a).

We emphasize that the choice of positional uncertainty was left to the expertise of each individual lens modeling team. In a landscape where the choice of positional uncertainty is not agreed upon, we favor this approach, and a discussion of appropriate positional uncertainties is outside the scope of this work. However it is interesting to ask how standardizing the models by their positional uncertainty or chi-squared statistics would affect the H_0 inference. For this exercise, we approximate the posterior of each lens model as a single multivariate Gaussian (this results in only minor information loss since the posteriors are fairly well-behaved), and, assuming a Gaussian likelihood, can approximate the effect of increasing or decreasing the positional uncertainty on the lens model time delay and magnification PDFs as scaling the PDF width linearly with the positional uncertainty (i.e., scaling with $\sqrt{\chi_\nu^2}$).

This was not straightforward for each model; here we detail the modifications made to each model posterior to achieve this standard. For model 1, the posterior width is re-scaled by a factor of $\sqrt{0.44}$ to achieve an effective chi-squared of unity, narrowing the uncertainties by $\sim 33\%$. For lens models 2 and 7, the effective positional uncertainty used to generate the posteriors ($\sigma_{\text{pos}} = 1.4''$) was already chosen to have $\chi_\nu^2 \sim 1$ across a large sample of lensing clusters, and as such these are left unchanged. We note that the reduced chi-squared is already far below unity assuming $\sigma_{\text{pos}} = 1.4''$, and re-scaling the posterior width would result in much smaller uncertainties on the time delays and magnifications. For model 3, which had $\chi_\nu^2 = 0.30$, the uncertainties are rescaled by a factor $\sqrt{0.30}$. In the case of model 5, positional uncertainties and chi-squared statistics are not applicable; instead an effective positional uncertainty is estimated as $\sigma = 0.18''$ and the posterior widths are rescaled by $0.1/0.18 = 0.56$ to match the positional uncertainty to the RMS of $0.1''$ (this is similar to

achieving a reduce chi-squared of 1 when assuming a Gaussian likelihood, as seen in model 1). Models 4 and 6 are left unchanged: model 4 does not make use of positional uncertainty (a term for the mean source scatter is used in uncertainty estimation, however it is not functionally equivalent the positional uncertainty term of typical parametric lens models; see Cha and Jee, 2022; Cha et al., 2023), and model 6’s uncertainties are determined via modification of the lensing assumptions, not the positional uncertainty.

Performing this test and recomputing the H_0 inference results in only very minor changes: $H_{0,\text{TD-only}} = 72.9^{+9.9}_{-8.0}$, $H_{0,\text{phot-only}} = 75.3^{+16.6}_{-5.3}$, $H_{0,\text{phot+spec}} = 74.9^{+6.5}_{-4.7}$. As is apparent, none of the inferences are affected in a statistically significant fashion, despite most of the lens models having a substantial reduction in their uncertainties. This follows the expectation of Section 6.10, where the uncertainty of the individual lens model is subdominant to the uncertainty induced by the spread between lens models.

While the results of this exercise are to be taken with caution, as there is no straightforward way to standardize the diverse set of lens models on the basis of positional uncertainty or chi-squared statistics, it further emphasizes the findings of Section 6.10. The precision of the magnification and time delay ratio measurements from photometry and spectroscopy are such that they can find agreement with multiple lens models, however these lens models can exhibit $\gtrsim 1\sigma$ tensions between one another. In this regime, the disagreement between lens models is the dominant barrier in reducing uncertainty on H_0 , highlighting the importance of using a range of models to capture lensing systematics. This in turn implies that the uncertainty estimation for any individual lens model is likely sufficient for this inference, but as time delay and magnification measurements improve (thereby improving the weighting scheme) or as the agreement between lens models improve (e.g., refining multiple image systems, using magnifications or time delay ratios as model constraints), the uncertainty of individual lens models will ultimately have the greatest impact on the H_0 uncertainty.

The Plane of Optimization

This analysis includes lens models which optimize both in the image plane and in the source plane (see Table 6.3). Both approaches have been shown to perform similarly in previous analyses on galaxy cluster lenses (e.g., Meneghetti et al., 2017), however this has not been thoroughly evaluated for time delays in the literature. More generally, for this precision measurement, it is useful to evaluate the effects of the plane of optimization. Across the seven lens models in the sample, no clear trend emerges upon comparison of the source plane and image plane models, however the approaches of these models are in some cases substantially different. To better quantify this effect, we investigate models 1, 2, and 3, which had the functionality to optimize in the image plane and the source plane (however we note that this functionality is not typically used in the literature for models 1 and 2). Model 4 cannot be optimized in the image plane, however this effect is likely subdominant to the regularization term used in its minimization (see Cha and Jee, 2022).

Each image plane model was run using the same constraints as its source plane counterpart, and the resultant magnifications and time delays were compared. For Models 1 and 2,

the source- and image-plane models were found to agree at the $< 1\sigma$ level; this corroborates findings from previous testing of these softwares on simulated lenses (Furtak et al., 2023; Oguri, 2010). By contrast the model 3 source plane model was found to produce larger magnifications by $\sim 10\%$ while inferring similar time delays. In principle, the use of the magnification tensor in the source plane chi-squared should prevent such an effect, preventing models from arbitrarily scaling the magnification to minimize the scatter of images in the source plane (e.g., Oguri, 2010). One caveat is that source plane models may find unphysical solutions, predicting counterimages which are not observed, however upon inspection this does not occur in model 3. We speculate that the software model 3 uses, **LENSTOOL**, may struggle with posterior estimation with the source-plane χ^2 . Jullo et al., 2007a caution this software may be less robust with this approach. Indeed in testing we found the source-plane optimization to behave in unreliable ways (e.g., the choice of positional uncertainty affected the posterior medians) whereas the image-plane optimization did not. Furthermore providing the image-plane model solution to the source-plane χ^2 yielded a better solution than what was found in the source-plane optimization.

Across the three models, this may tentatively suggest that overall source-plane optimization is a sufficient approximation for the current lens model precision. However we caution that for this cannot be taken for granted, and some models show significant deviations in their solutions between the source- and image- plane. As lensing constraints grow tighter (e.g., more spectroscopic redshifts, more image systems), image-plane modeling may be preferred, and further detailed comparison between these approaches is needed in future work.

Probability Distribution Function Parametrization and Likelihood Integration

The probability distribution functions (PDFs) from the photometric light-curve fitting, spectroscopic fitting, and the lens model fitting are parametrized as Gaussian-mixture models (GMMs). Each fit (photometry, spectroscopy, or lens model), F , generated a few hundred to thousands of samples from the posterior distribution, $P(\mathcal{O}|F)$, which was then fit by a linear combination of N multivariate Gaussians such that:

$$P(\mathcal{O}|F) \approx \sum_{i=1}^N w_i \mathcal{N}_F(\mathcal{O}|\mu_i, \mathcal{C}_i) \quad , \quad (6.8)$$

where w_i is the weight assigned to each normalized multivariate Gaussian, μ_i and $\mathcal{C}_i$ are the associated mean vectors and covariance matrices respectively, and N was chosen for each model based on the Bayesian information criterion (BIC) to avoid overfitting to artifacts which may result from undersampling. Thus, the integrand in Eq. 6.5 becomes the product

of two GMMs or equivalently the sum of products of multivariate Gaussians:

$$\int P(\mathcal{O}|M_l; H_0)P(\mathcal{O}|LC)d\mathcal{O}_1\dots d\mathcal{O}_n = \int \sum_{i=1}^N \sum_{j=1}^N w_i w_j \mathcal{N}_{M_l}(\mathcal{O}|\mu_i, \mathcal{C}_i) \mathcal{N}_{LC}(\mathcal{O}|\mu_j, \mathcal{C}_j) d\mathcal{O}_1\dots d\mathcal{O}_n \quad (6.9)$$

where i indices refer to the Gaussians which make up the GMM representing the lens model posterior, and the j indices refer to the Gaussians which make up the GMM representing the light-curve fitting posterior. This formalism is advantageous in that this integral can be solved analytically as the multiplication of two multivariate Gaussians is itself a multivariate Gaussian with a known renormalization.

The combined photometric–spectroscopic likelihood of Eq. 6.7 follows the same formalism, where the posterior from spectroscopic fitting is also parametrized as a GMM, and the integrand is the distributive product of three GMMs. Because the product of any two multivariate Gaussians is itself a Gaussian, the product of 3 multivariate Gaussians is also a Gaussian.

Unblinded Lens Models

After the submission of the blinded model results, the contributing lens model teams also had the option to construct unblinded lens models, where absolute magnifications measured from light-curve fitting were used as constraints. Only the teams for models 2 and 4 did so, but these two models represent both parametric and non-parametric types. Figure 6.6 illustrates parameter changes and their covariance for model 2. Reassuringly, the unblinded model 2 posterior follows the expectations from the correlations seen in the blinded model posterior, where the median predicted time delay increases due to the now-lower magnifications. The non-parametric model 4, however, saw very little change in its time delay predictions. The blinded version of model 4 predicts fairly accurate magnifications with the exception of μ_a , but μ_a is the only magnification which lacks significant covariance between the time delays, resulting in only minor changes to the time delays in the unblinded model.

For both unblinded models, we infer only $H_{0,\text{TD-only}}$ because magnifications became constraints in the lens models rather than predicted observables. While model 4 gives similar results in both the blinded and unblinded cases, the unblinded model 2 gives a much larger H_0 than the blinded model. Interestingly, both unblinded models predict the time delay ratio more accurately than their blinded counterparts, implying they would receive generally higher weighting in the $H_{0,\text{TD-only}}$ inference. While it is difficult to make strong conclusions based on a sample of only two models, it is interesting to ask whether unblinding the magnifications may better address systematics between lens models, allowing for more modeling approaches to accurately reproduce the observables and hence contribute to the H_0 inference. As the sample of cluster-lensed SNe Ia grows, functionality for magnification constraints will likely become more ubiquitous in lens modeling techniques, creating an opportunity for a more comprehensive view of lens model systematics.

Testing Lens Model Systematics

All seven lens models were fully blinded from the time delays, magnification ratios, and absolute magnifications inferred from the photometric light-curve fitting of Pierel et al., 2024a. While these measurements provide strong constraining power for weighting model contributions to H_0 , they also introduced an opportunity to test lens model systematics using the absolute magnification at the galaxy cluster scale with a multiply-imaged source. Note that this is a more stringent test than lower magnification singly-imaged cases such as SN HFF14Tom in the Abell 2744 cluster field (Rodney et al., 2016). Here we broadly follow Rodney et al., 2016 to provide an in-depth discussion of the performance of the contributing models, which in turn determines the weighted contributions to the H_0 measurement.

Parametric versus Non-Parametric: While the contributing models are broadly divided into two categories, parametric and non-parametric, each model is distinct from one another. Here we compare the most free-form models, models 4 and 6, to the three classically parametric models, models 1, 2, and 3.

We find the non-parametric models have longer relative time delays (assuming the fiducial H_0 value), and hence higher H_0 inferences than the parametric models. The inferred H_0 's also have higher uncertainties. This may be owing to the greater flexibility of non-parametric models, which can explore solutions for the lens potential inaccessible to rigid fully-parametric profiles. Owing to the lack of sufficient lensing constraints about the north-eastern core of the cluster, parametric methods do effectively reduce the parameter space by assuming the analytic profiles are centered at the locations of the bright cluster galaxies. As shown in Table 6.9, both parametric and non-parametric models receive significant weighting under all three inferences, where the weighting reflects the agreement between model predictions of observables and their corresponding measurements from photometry and spectroscopy. As the non-parametric models tended to predict longer time delays, this emphasizes the need for a wide variety of lens model approaches to fully capture the range of possible solutions.

Strong versus Strong+Weak: Model 4 makes use of both weak lensing and strong lensing constraints. While only this model was used for the H_0 inference, an additional version of the model using only strong lensing was also constructed for testing purposes only. This comparison offers a rare opportunity to evaluate the benefits weak lensing. The addition of weak lensing constraints are found to generally increase the time delay uncertainties without greatly impacting their median, while decreasing uncertainties on the magnifications and generally shifting their median lower. This significantly improves the agreement of both the lens model-predicted time delay ratios and the predicted magnifications with those measured by photometry and spectroscopy. As a result, the model receives a much greater weighting in the $H_{0,\text{phot+spec}}$ inference, increasing the weighting to 14% for strong+weak constraints rather than $< 1\%$ for strong-lensing alone. This suggests that weak lensing constraints are crucial for non-parametric modeling methods, especially when the available number of strong-lensing constraints is low.

Table 6.3 Lens model Information

#	Model and Reference	RMS (")	$\sigma_{\text{pos,SN}}$ (")	$\sigma_{\text{pos,global}}$ (")	DoF	χ_ν	Optimization
1	GLAFIC (Oguri, 2010; Oguri, 2021)	0.07	0.1	0.1	119	0.44	Source
2	Zitrin-analytic (Zitrin et al., 2015a)	0.21	0.1	0.3 ^a	86	0.61	Source
3 ^b	LENSTOOL (Kneib et al., 2011)	0.16	0.3	0.3	109	0.3	Image
4	MARS (Cha and Jee, 2022)	0.07	N/A	N/A	N/A	N/A	Source
5	Chen, Kelly, and Williams, 2020	0.1	0.18 ^c	0.18 ^c	N/A	N/A	Image
6	WSLAP+ (Diego et al., 2005)	1.1	0.03	0.03	N/A	N/A	Image
7	Zitrin-LTM (Zitrin et al., 2009a)	0.7	0.1	0.5 ^a	95	1.23	Image

Note. — Columns are the RMS separation between model and observed positions lensed images (RMS), the positional uncertainty for multiple image systems used for the χ^2 minimization ($\sigma_{\text{pos,global}}$), the positional uncertainty used for the SN images ($\sigma_{\text{pos,SN}}$), the number of degrees of freedom (DoF) in the model, the χ^2 per DoF (χ_ν^2), and which plane the minimization was performed in (Optimization). All quantities are given for the best-fit model. RMS and σ_{pos} refer to the image plane unless otherwise specified. ‘N/A’ indicates quantities that are not applicable to non-parametric models, for which chi-squared statistics are not relevant for parameter estimation.

^aUncertainties are extracted using an effective positional uncertainty $\sigma_{\text{pos,global}} \sim 1.4''$ following the prescription of Zitrin et al., 2015a.

^bThis model was updated following unblinding, the blinded version of the model was run with source plane optimization using a positional uncertainty $0.03''$, resulting in an RMS $0.26''$ and $\chi_\nu^2 = 72$. This blinded model is detailed in 6.12.

^cEffective positional uncertainty approximated for reference; model is not optimized using chi-squared statistics.

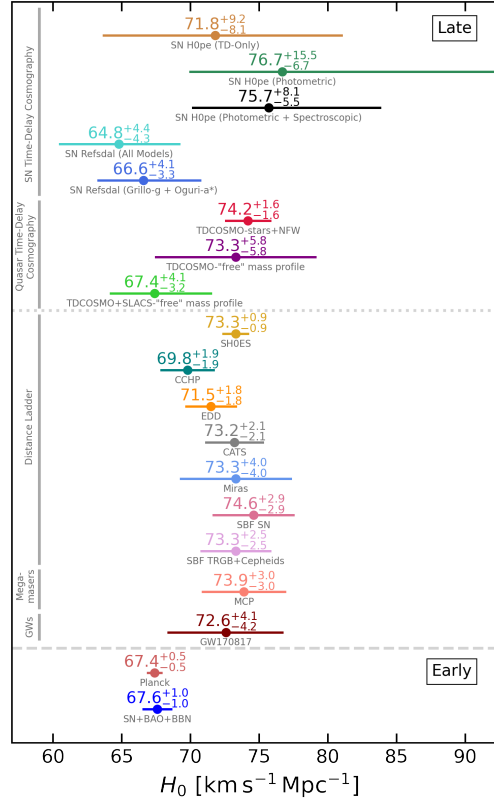


Figure 6.5 H_0 measurements from SN H0pe compared to other independent methods, including those from SN Refsdal (Kelly et al., 2023a) using all contributing lens models and using a subset of two models (Grillo-g and Oguri-a*). Quasar time-delay cosmography measurements include those using fully analytic mass profiles (stars+NFW; Millon et al., 2020) and free-form mass profiles (“free” mass profile; Birrer et al., 2020) from the TDCOSMO collaboration and SLACS (Bolton et al., 2006). Distance-ladder measurements include those from SH0ES (Murakami et al., 2023), the CCHP (Freedman et al., 2019), the EDD (Anand et al., 2022), CATs (Scolnic et al., 2023), Miras (Huang et al., 2020), SBF from SNe (Garnavich et al., 2023) and TRGBs+Cepheids (Blakeslee et al., 2021). Measurements using megamasers from the MCP (Pesce et al., 2020) and using GW170817 as a standard siren (Wang et al., 2023) are also included. Early-time measurements include those from CMB anisotropies from Planck (Planck Collaboration et al., 2020a) and from large-scale-structure clustering using SNe, baryon acoustic oscillation (BAO), and big-bang nucleosynthesis (BBN) data (Schöneberg et al., 2022). This figure is adapted from Bonvin and Millon, 2020.

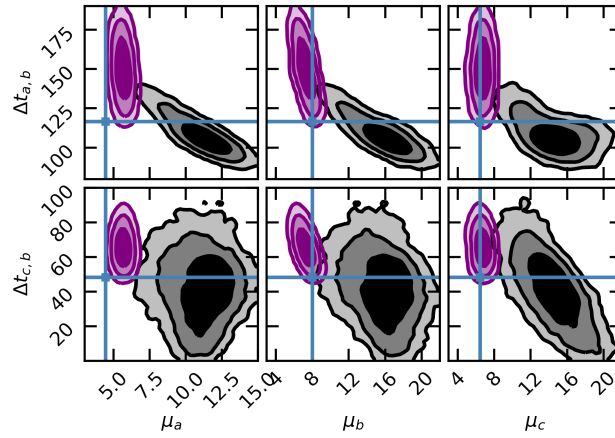


Figure 6.6 2D posterior distributions relating time delays and absolute magnifications predicted by the blinded lens model 2 used in this study (black). The contours represent the 68, 95, and 99% confidence intervals, and the measured values from light-curve fitting are overplotted (blue lines). As seen in the black contours, the blinded lens model-predicted magnifications and time delays are inversely correlated. We also plot posteriors for a lens model constructed after unblinding which uses an identical approach to model 2, with the exception that the magnifications measured from light-curve fitting are now applied as constraints in modeling (referred to as an ‘unblinded’ version of the model; purple contours). Including magnification constraints causes the predicted time delays to become larger, following the expectation from the covariance of the blinded model.

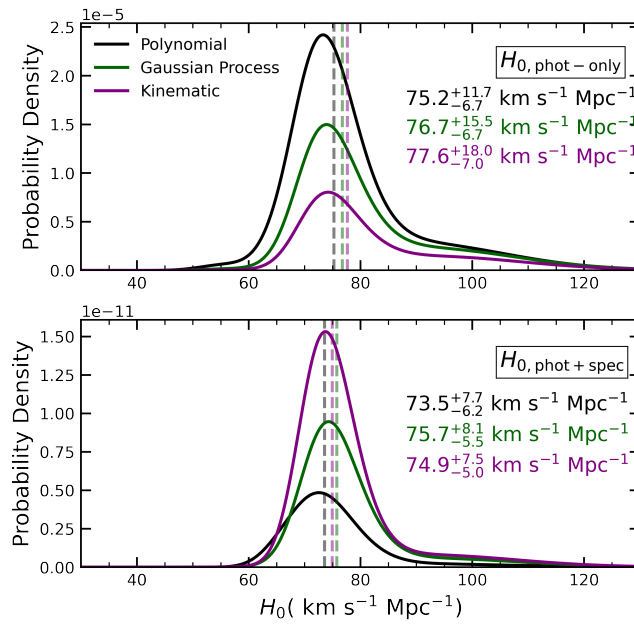


Figure 6.7 The effect of different interpolation methods for estimating the unlensed SNe Ia apparent magnitude at $z = 1.783$ on H_0 . We compare the inferred H_0 under three interpolation approaches: polynomial, Gaussian process, and kinematic expansion. The interpolation method affects the inferred magnification of each SN image, which in turn influences the H_0 inference. The impact is $\sim 3\%$ for both photometric-only constraints and joint photometric-spectroscopic constraints, well within the 1σ uncertainties.

Chapter 7

Is Earendel a Star Cluster?: Globular Cluster Progenitors at $z \sim 6$

The content of this chapter is drawn from Pascale et al., 2025a, with permission from the co-authors.

7.1 Introduction

Strong gravitational lensing has enabled the study of distant galaxies at unprecedented spatial scales (e.g., Vanzella et al., 2017b; Mowla et al., 2022). High magnification from foreground galaxy clusters stretches background galaxies, resolving individual stellar associations such as parsec-scale star clusters at a high signal-to-noise ratio (Pascale et al., 2023; Vanzella et al., 2023). While strong-lensing magnification is typically on the order of dozens or fewer, compact stellar sources serendipitously situated near the lensing caustic can be magnified by factors of hundreds to thousands (e.g., Welch et al., 2022d; Pascale and Dai, 2024). In extreme cases, even individual stars may be detectable in sensitive space-based imaging (Miralda-Escudé, 1991; Windhorst et al., 2018b; Dai et al., 2018b; Diego, 2019b). These have been observed in low to intermediate ($z \lesssim 1$) galaxies strongly-lensed by a foreground galaxy cluster (e.g., Kelly et al., 2018c; Rodney et al., 2018; Chen et al., 2019a; Kaurov et al., 2019a; Pascale et al., 2022a; Fudamoto et al., 2024), assisted by temporary flux boosts induced by microlensing from intracluster stars (Venumadhav, Dai, and Miralda-Escudé, 2017b; Diego et al., 2018b; Oguri et al., 2018b; Weisenbach et al., 2024).

In other cases, it is thought the source-caustic alignment can be so fortuitous that strong-lensing alone delivers sufficiently large magnification factors ($\sim 10^4$) to reveal individual stars in high redshift galaxies ($z \gtrsim 5$) in deep Hubble Space Telescope (*HST*) or James Webb Space Telescope (*JWST*) imaging (e.g., Meena et al., 2023b; Furtak et al., 2024; Diego et al., 2023b). The first such example reported is Earendel (Welch et al., 2022d; Welch et al., 2022c) at $z \sim 6$, which remains the highest redshift lensed star candidate identified to date. Earendel, or WHL 0137-LS, was discovered in the WHL J013719.8-82841 galaxy cluster field

in *HST* imaging acquired through the RELICS program (Coe et al., 2019b; Salmon et al., 2020b). The *HST* discovery was first presented in Welch et al., 2022d, and later with *JWST* NIRCcam imaging in Welch et al., 2022c. Earendel is thought to be persistently magnified by factors of $10^3 - 10^4$ due to a close proximity to the lensing critical curve, and that the image flux appears stable across a two-year baseline in the observer frame, indicating that its brightness is not primarily a result of microlensing.

Synthesizing the predictions of four strong-lensing models of the foreground galaxy cluster ($z_{\text{cluster}}=0.566$), Welch et al., 2022c constrain the intrinsic size of Earendel to be $r \lesssim 0.02$ pc, or ~ 4000 AU, placing it at the scale of an individual stellar system rather than a star cluster. Welch et al., 2022c found *JWST* NIRCcam photometry is not well fit by a single star, but rather that a binary system of two $\sim 20 M_{\odot}$ stars of effective temperatures ~ 34000 K and 9000 K is more consistent with the data. Given the tight size constraint provided by strong-lensing models, a simple stellar population (SSP) fit has not been explored in that work or other prior works on Earendel.

Ji and Dai, 2024 recently identified that in cases such as Earendel, deriving size constraints solely from macro strong-lensing models can be prone to bias, as such models only include dark matter subhalos which have galaxies visible in *HST* or *JWST* imaging. In the hierarchical picture of structure formation in Λ CDM cosmology, the dark matter subhalo population likely extends below the typical galactic mass scale ($\sim 10^{10} M_{\odot}$) down to $10^6 M_{\odot}$ or even smaller. Such small subhalos are optically invisible, but can have a pronounced effect on the lensing caustic strength while only modestly affecting the deflection and hence astrometric position of the lensed object (Dai et al., 2018b; Dai et al., 2020; Williams et al., 2024). Indeed, Ji and Dai, 2024 find through a combination of semi-analytic modeling and numerical ray-tracing that accounting for this population of subhalos relaxes the constraint on the source size on the visible side of the caustic derived in Welch et al., 2022c to as large as ~ 3 pc without contradicting observations. This light-weighted size is compatible with many of the massive star clusters seen both in the local universe for a review see Krumholz, McKee, and Bland-Hawthorn, 2019b and at high redshift (e.g., Adamo et al., 2024), and has re-opened the discussion on the nature of Earendel and other similar highly magnified high-redshift sources.

Recently, Scofield et al., 2025 have also shown from a macroscopic analysis (i.e., not including the subhalos treatment of Ji and Dai, 2024) that Earendel’s magnification may be as low as $\mu \sim 50$. While Ji and Dai, 2024 assume the strong-lensing models of Welch et al., 2022d which predict magnifications in excess of 1000 and then subsequently evaluate how this changes in the presences of dark matter subhalos, Scofield et al., 2025 construct a new joint strong- and weak-lensing model which itself finds Earendel may only be modestly magnified. The approach of Scofield et al., 2025 was found to accurately predict magnifications for SN H0pe, the only multiply-imaged source in the galaxy cluster lensing regime with a known magnification in the literature (Frye et al., 2024b; Pascale et al., 2025b), and further draws the nature of Earendel into question.

Motivated by the conclusions of Ji and Dai, 2024 and Scofield et al., 2025, in this letter we consider whether Earendel could instead be a compact star cluster rather than an individual

star or star system, and simultaneously evaluate other stellar knots within the Sunrise galaxy. Sunrise is known to host multiple compact star clusters with exceptional stellar surface densities ($> 10^4 M_\odot/\text{pc}^2$) at both young (< 10 Myr) and evolved ages (Vanzella et al., 2023). More generally, strongly-lensed galaxies have revealed an abundance of high density star clusters which are rare in our cosmic backyard (e.g., Adamo et al., 2024; Whitaker et al., 2025; Messa et al., 2024; Fujimoto et al., 2024). These clusters can probe vigorous star formation which may be more commonplace in the high redshift universe, and furthermore may be the progenitors of locally observed globular clusters whose origin and evolution are not yet fully understood (e.g., Vanzella et al., 2017b). Deep UV-Optical spectroscopic studies of these clusters are sparse, particularly for evolved cluster ages > 10 Myr. At the redshift of Sunrise, deep publicly available NIRSpec spectroscopy covers the rest-UV through Optical of Earendel as well as multiple other stellar clumps within the galaxy which are more widely-accepted as star clusters. Hence Earendel and the Sunrise galaxy may be valuable assets for furthering our understanding of high redshift star clusters.

In section 7.2, we describe the datasets used for this analysis, including archival *JWST* NIRSpec spectroscopy which has not been evaluated in prior literature on the Sunrise galaxy. Section 7.3 details the methods involved, including derivation of the spectroscopic redshift and the SED fitting to derive the physical properties. We discuss the results and the nature of Earendel as well as other stellar clumps in the Sunrise galaxy in section 7.4. We evaluate whether the spectrum is consistent with the expectation of a star cluster, and assess how this system relates to the picture of star cluster formation and evolution. In section 7.5, we provide concluding remarks on this analysis.

7.2 Observations

This work makes use *JWST* datasets which are available on the MAST archive. *JWST* NIRCам imaging is not directly used in this analysis, however photometry results from Welch et al., 2022c and Vanzella et al., 2023 which make use of images from Cycle 1 Go program 2282 (PI: Coe) are used. *JWST* NIRSpec PRISM spectra were queried from version 3 of the DAWN *JWST* Archive (DJA, Heintz et al., 2024), which make use of *msaexp* (Brammer, 2022) for the reduction pipeline; further details can be found in Heintz et al., 2024 and de Graaff et al., 2025. We highlight that the background subtraction is performed using a ‘master sky background’ approach which fits to empty portions of the source slitlets and optimizes for signal to noise as described in Appendix A of de Graaff et al., 2025. We make use of four spectra in the Sunrise for Earendel, image 1b, image 1a, and one of the star-forming regions along the Sunrise arc, which correspond to 2282_10000, 2282_10002, 2282_10001, and 2282_12001 respectively. The Sunrise galaxy and clumps of interest are shown in Fig. 7.1. The Earendel and 1b spectra are shown in Fig. 7.2. We note that the singular emission-line spectrum, 2282_1200, may contain a combination of images 4, 5, and 6 which are denoted in Vanzella et al., 2023 as making up a so-called ‘star-forming complex’ (SFC). This spectrum is only used for the spectroscopic redshift measurement, and as such the multi-component

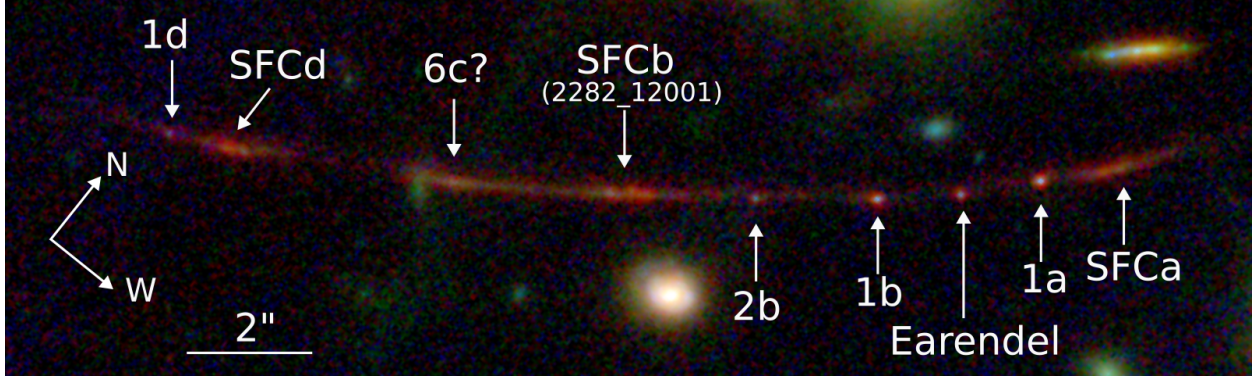


Figure 7.1 *JWST* NIRCам F090W+F200W+F444W false color image of the Sunrise galaxy at $z \approx 5.93$. The multiple images shown sweep out an angular extent of ~ 16 arcsec. At the redshift of Sunrise, the compass $2''$ corresponds to ~ 11.8 kpc. Labeled are multiply-imaged clumps of interest within the galaxy: Earendel, image 1, image 6, and the so-called ‘star-forming complex’, or SFC, consisting of images 3, 4, 5, and 6. We note the *JWST* NIRSpec MSA slit ID which covers image b of the SFC, 2282_12001, which is used for the spectroscopic redshift measurement.

aspect of this spectrum is not accounted for in this work.

We adopt the nomenclature of Vanzella et al., 2023 for image system designations in this work (see our Fig. 7.1 or their Fig. 2). However we note that the system of d images of the SFC is somewhat misleading, as these images have an opposite parity to the system of b images, indicating there must be an odd number of critical curve crossings through the Sunrise arc between the b and d systems. Scofield et al., 2025 similarly point out that the image system designations may be inaccurate. For simplicity, we retain the nomenclature used in previous works, however we caution that the image system designations are subject to change in future works.

7.3 Methods

Redshift Determination

We determine the spectroscopic redshift of the Sunrise arc via nebular line emission detected in slit 12282_12001, which contains SFCb on the arc (see Fig. 7.1) consisting of $4b$, $5b$, and $6b$ (see nomenclature in Vanzella et al., 2023). The spectrum shows clear detections of $[\text{O II}]\lambda\lambda 3727, 3729$, $[\text{Ne III}]\lambda 3869$, $\text{H}\beta$, $[\text{O III}]\lambda\lambda 4959, 5007$, and $\text{H}\alpha$ at $\text{SNR} \gtrsim 5$. The redshift is determined via simultaneous fitting of Gaussian line profiles to the H-Balmer and $[\text{O III}]$ features, yielding $z = 5.926^{+0.013}_{-0.012}$. This is consistent with the Lyman-series break spectroscopically observed in the stellar continuum of other knots within the Sunrise (e.g., Earendel, 1a/b). Our spectroscopic measurement is lower than the photometric redshift

$z_{\text{phot}} = 6.2 \pm 0.1$ inferred by Welch et al., 2022c, but consistent with the $z_{\text{phot}} = 5.9^{+0.3}_{-0.2}$ determined by Vanzella et al., 2023.

SED Fitting

We perform Spectral Energy Distribution (SED) fitting to the continuum of Earendel and the lensed knot *1b* to infer their physical parameters. We also perform fitting to the counterimage of *1b*, *1a*, whose spectrum is lower SNR but useful for testing the robustness of the fitting procedure as *1b* and *1a* should ideally yield comparable results. We choose to fit only to the NIRSpec spectrum rather than performing a joint photometric-spectroscopic fit. Welch et al., 2022c performed detailed photometry of Earendel synthesizing 14 different measurements conducted by 10 separate people (a so-called “wisdom of crowds” approach), however we find the Welch et al., 2022c measurements to disagree with the spectroscopic continuum at the $\gtrsim 20\%$ level in Earendel, and features an enhancement in the F115W filter flux which is not seen in the spectrum (see Fig. 6 of Welch et al., 2022c). Given the thoroughness of the Welch et al., 2022c approach, we speculate that systematics may dominate the photometric error, or that the F115W filter may suffer from an artifact at the location of Earendel.

This photometric-spectroscopic tension is not seen in the neighboring knot, *1b*, however as a caution we opt to fit only to the NIRSpec spectrum in all cases. While systematics from the spectroscopic calibration may affect the results, we find that the goodness-of-fit is reasonable in all spectroscopic fits, and furthermore that including photometry with the F115W filter removed generally agrees to within 1σ . Stellar masses are measured by scaling to the F200W filter photometry from Welch et al., 2022c and Vanzella et al., 2023, with the exception of *1a* which does not have existing photometry in the literature, and is only used to probe systematics in the SED fitting.

SED fitting is conducted by fitting a simple stellar population (SSP) to the observed NIRSpec spectra. The approach is modeled after the well-tested **Bagpipes** software (Carnall et al., 2018; Carnall et al., 2019), however our methodology is optimized for use of instantaneous burst star formation histories (SFH), which is likely appropriate for an individual star cluster (Wofford et al., 2016). We briefly describe the approach below, noting that the methodology follows **Bagpipes** unless specified otherwise. We also test an exponentially decaying SFH in Appendix 7.6.

The stellar SED is constructed using three separate well-known SSP libraries to account for systematics involving the SSP used: 1) **BPASS** (Stanway, Eldridge, and Becker, 2016) including binary evolution and using an initial mass function (IMF) $\xi(m) \propto m^{-1.3}$ for $m < 0.5 M_{\odot}$ and $\xi(m) \propto m^{-2.35}$ for $m > 0.5 M_{\odot}$ in the initial stellar mass range $0.1 < m/M_{\odot} < 100$. 2) The 2016 version of the BC03 (Bruzual and Charlot, 2003a; Chevallard and Charlot, 2016) models using a Kroupa, 2001 IMF and an upper-mass cutoff $M_{\text{cut}} = 100 M_{\odot}$. And 3) **FSPS** (Conroy and Gunn, 2010) using the MIST (Choi et al., 2016) isochrones with the MILES empirical stellar library and a Kroupa, 2001 IMF with an upper-mass cutoff $M_{\text{cut}} = 120 M_{\odot}$.

For each SSP library, we construct a grid of ages and metallicities using values natively available from the library which we linearly interpolate across in $\log(t_{\text{age}})$ and metallicity to

yield the stellar SED. This is the primary difference between our approach and **Bagpipes**, which resamples the SSP age grid using a weighted summation approach (Carnall et al., 2018). In fitting, the population age is allowed to vary freely from 1 Myr to 1 Gyr (roughly the age of the universe at this redshift), and the metallicity is optimized in the range $Z/Z_{\odot} \in (0.0005, 1)$ for **BPASS** and $Z/Z_{\odot} \in (0.005, 1)$ for **BC03** and **FSPS** (where $Z_{\odot} = 0.0142$; Asplund, Amarsi, and Grevesse, 2021).

We also include a nebular component with free ionization parameter $\log U \in (-4, -1)$ and free covering factor $x \in (0, 1)$ which directly scales the nebular component flux. The nebular component is constructed using **CLOUDY** (Ferland et al., 2017) with input incident radiation from the stellar SEDs which make up our grid. For each nebular realization, we fix the gas-phase metallicity to the metallicity of the input stellar population, assume rescaled solar chemical abundances (with the exception He and N which follow Dopita et al., 2000), and use a fixed electron density $n_e = 100 \text{ cm}^{-2}$. Unlike **BAGPIPES**, we extend the nebular grid to include stellar populations out to 1 Gyr, as stripped stars may provide a non-negligible ionizing budget through the first ~ 100 Myr of the cluster lifetime (Götberg et al., 2019).

We note that we identify candidate marginal detections of $[\text{O III}]\lambda 5007$ and $\text{H}\alpha$ in the Earendel spectrum which are measured to 2.5σ and 1.6σ significance respectively. Investigation of the 2D spectrum shows these features appear only marginally more extended than the underlying continuum, and we cannot rule out that they result from contamination from the arc background. As a caution we masked these features, but note that their inclusion was not found to impact the posterior of the fits.

We apply an ISM dust reddening law following Salim, Boquien, and Lee, 2018, which includes a free reddening power law slope on which we force a prior $\delta \in [-2.0, 0.75]$. This has the freedom to reproduce both the Calzetti, 2001 ($\delta = 0$) and SMC ($\delta \sim -0.45$) reddening curves, as well as significantly steeper curves $\delta < -1$ which may be better representative of low mass high redshift galaxies (Salim, Boquien, and Lee, 2018). We also include a free $2175\text{\AA}$ bump strength $B \in [0, 3]$ where $B = 3$ matches the Milky Way bump strength of Cardelli, Clayton, and Mathis, 1989. IGM attenuation and dust emission follow exactly the prescription of **Bagpipes** and we refer the reader to Carnall et al., 2018 for further details.

The system redshift was allowed to vary following a Gaussian prior with median and width $(\mu, \sigma) = (5.926, 0.013)$ following the redshift determined in Sec. 7.3. The spectral resolution was set by the NIRSpec PRISM resolution curves provided by the *JWST* User documentation (JDox) - as Earendel and image 1 are point-like sources, their position in the slit may affect the wavelength-dependent spectral resolution (de Graaff et al., 2024), however the resolution curve provided by JDox is likely a sufficient approximation for this analysis. We additionally allow for a velocity dispersion $\sigma \in (1, 100) \text{ km/s}$, encompassing the range of dispersions seen in even the most compact star clusters. Finally, we include an additional white noise scaling term $\alpha \in (1, 10)$, which directly scales the NIRSpec spectrum uncertainties, and can help mitigate both underestimation of uncertainties and SED model systematics.

The resulting model consists of 10 free parameters for 407 observables with 397 degrees of freedom. Parameter inference is computed using **Nautilus** (Lange, 2023) using 3000 live

points. Robustness of the posterior is ensured following recommendations from Lange, 2023, specifically that: 1) increasing the number of live points does not change the result, 2) points from the exploration phase are discarded, and 3) the shell-bound occupation fraction is unity beyond the earliest iterations.

We perform two primary tests to address underestimation of uncertainties beyond the inclusion of the white noise scaling term. We first test if outlier features, such as those at $\sim 10500\text{\AA}$ observer frame in the Earendel spectrum (see Fig. 7.2), skew the fit by masking them, which we did not find to meaningfully impact the posteriors. We also test in the limiting case where the intrinsic spectrum is mostly smooth, by applying a boxcar smoothing function from the spectrum redward of the Lyman-series limit. We subtract the smoothed spectrum from the original, which was found to approximately center at zero, and then calculate a running standard deviation across the spectrum. We find this running standard deviation to be consistent with the uncertainties applied in fitting after accounting for the best fit white noise scaling. Furthermore, recomputing the fit assigning the running standard deviation as the error was found to produce similar results to the assigned errors.

7.4 Results and Discussion

Metal Poor Globular Cluster Progenitors

We find the Earendel spectrum to be highly consistent with that of a simple stellar population across all three SSP libraries. Each library produces a comparable best-fit, in each case requiring a white noise scaling ~ 1.3 to reach a reduced chi-squared of unity, translating to a typical $\chi^2_\nu \sim 1.7$ without the noise scaling term. We similarly find a nearly equivalent goodness-of-fit for image *1b*, which is commonly accepted to be a star cluster. We reassuringly find that repeating the same fitting procedure for the *1a* spectrum yields comparable results to *1b*, as seen in Fig. 7.3 and Table 7.4. The results of BPASS and BC03 strongly agree to within 1σ , while the FSPS fits show a weaker $\sim 2\sigma$ level agreement but remain qualitatively similar.

The best fit spectrum from the BPASS templates is shown in Fig. 7.2. All three SSP libraries produce qualitatively similar posteriors for both Earendel and *1b*, however some physical parameters disagree to $\gtrsim 2\sigma$; the inferred parameters are given in Table 7.4 and the BPASS posteriors are plotted in Fig. 7.3. For both Earendel and *1b*, we infer an evolved (> 30 Myr), metal-poor ($Z/Z_\odot < 10\%$) star cluster with a magnified mass $\mu M \sim 10^9 M_\odot$ and a minimal ISM dust reddening $A_V < 0.1$ mag. We do not find the velocity dispersion to be well-constrained, nor does it significantly impact the posteriors, reflecting both the low spectral resolution of PRISM and the lack of significant absorption features.

Stellar Surface Density

The Sunrise galaxy is well-known to host some of the highest stellar surface density clusters observed, and indeed Vanzella et al., 2023 determine from photometrically derived stellar masses and astrometrically derived sizes the stellar surface density of *1b* to be $\Sigma_\star \approx 3 \times$

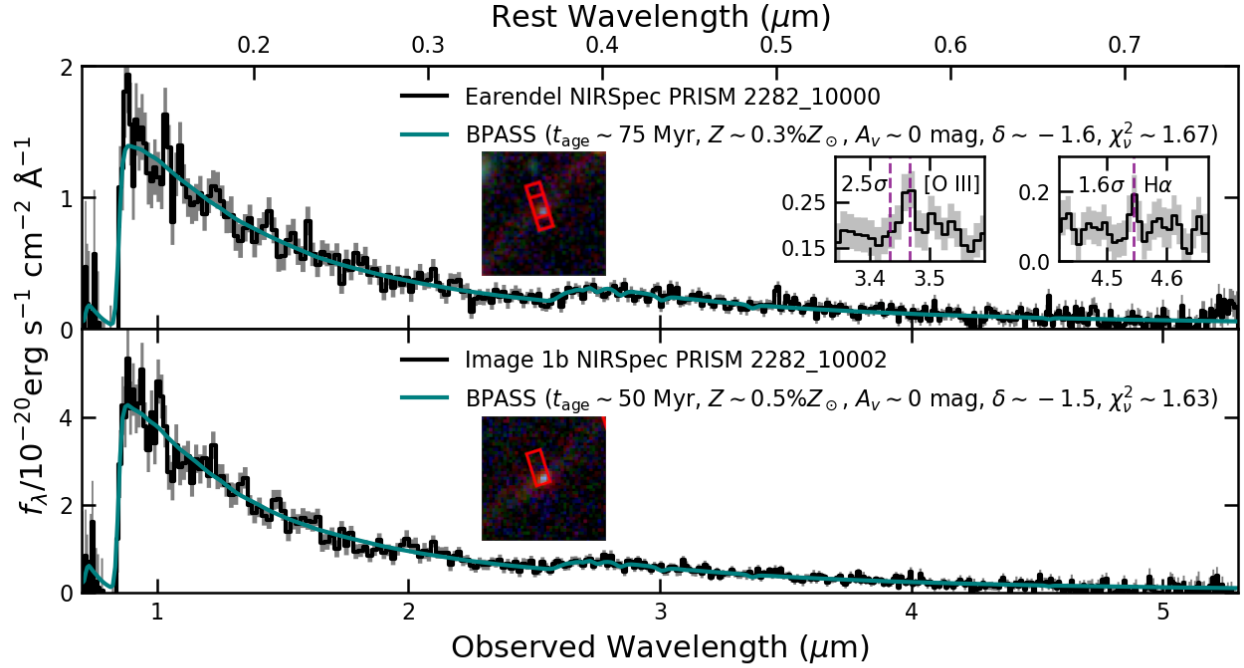


Figure 7.2 NIRSpect PRISM spectra of Earendel and 1b with the best fit BPASS model from SED fitting overplotted. We omit the BC03 and FSPS best fit SEDs for clarity, as they appear similar to the result from BPASS. Spectra are taken from version 3 of the DJA (Heintz et al., 2024). Both Earendel and 1b have similar spectra indicative of stellar continuum from an evolved simple stellar population. The fit is influenced by the shape of the continuum, the lack of significant absorption features, as well as the clear Balmer break seen in both spectra. SED fitting measures similar parameters for these two objects, which are labeled approximately. Left insets show stamps from a *JWST* false color image with the NIRSpect MSA slits overplotted. Right insets show smoothed zoom-ins of the Earendel spectrum where we identify marginal detections of nebular line emission $[\text{O III}]\lambda 5007$ ($[\text{O III}]\lambda 4959$ non-detection also marked) and $\text{H}\alpha$ which are measured at 2.5σ and 1.6σ significance respectively.

$10^5(\frac{\mu}{70})M_{\odot} \text{ pc}^{-2}$. We find our updated spectroscopically derived stellar masses are higher than those determined by Vanzella et al., 2023, a consequence of generally older derived ages. Assuming the magnification and size estimates of Vanzella et al., 2023 and our BPASS results (the intermediate of the three SSP mass estimates) of $M_{\star}/M_{\odot} \approx 2.5 \times 10^7(\frac{\mu}{70})$, we estimate the *1b* stellar surface density to be $\Sigma_{\star,1b} \approx 1.3 \times 10^6(\frac{\mu}{70})M_{\odot} \text{ pc}^{-2}$.

The stellar surface density measurement for Earendel is less straightforward, as the magnification and size measurements are not well-understood. Welch et al., 2022c find the apparent surface brightness of Earendel to be approximately consistent with the PSF in *JWST* NIRCcam F090W imaging, placing the apparent source size below that of a native *JWST* pixel ($0.031'' \sim 200 \text{ pc}$ at $z=5.926$).

In the simulations of Ji and Dai, 2024, the light of Earendel is dominated by a single lensed image, and the intrinsic source size may be as large as 1-3 pc while still appearing below this $0.031''$ limit. Additionally, new strong lensing models by Scofield et al., 2025 find macroscopically (e.g., without subhalos) that Earendel’s magnification may be as low as $\mu \sim 40 - 70$, further complicating the choice of magnification.

We consider a range of fiducial tangential magnifications $\mu_t \sim 50 - 500$ with an assumed radial magnification $\mu_r \sim 2$, producing FUV size upper limits $r_{\text{FUV}} \approx 0.4 - 4 \text{ pc}$ and star cluster of masses $M_{\star}/M_{\odot} \approx 10^{6-7}$ assuming the BPASS posterior median. The resulting stellar surface density upper limit is hence $\Sigma_{\star,e} \approx 3 \times 10^{5-6}M_{\odot} \text{ pc}^{-2}$.

Both Earendel and *1b* produce incredible stellar surface densities, which for some magnifications exceed the observed $\Sigma_{\star,\text{max}} \approx 3 \times 10^5 M_{\odot} \text{ pc}^{-2}$ ceiling seen in local universe clusters (Hopkins et al., 2010; Grudić et al., 2019). Such densities may indicate the star-formation in these clusters is feedback free, allowing for higher star formation efficiency and hence higher stellar densities (Dekel et al., 2023). However Williams et al., 2025 determine that in such a scenario, clusters of stellar surface density $\log(\Sigma_{\star}) > 10^5$ and $M_{\star} > 10^6 M_{\odot}$ are typically bound yet non-virialized; such high densities may not be maintained across the cluster evolution to the present day. Highly efficient star-formation may also be conducive for the formation of populations with top-heavy IMFs (e.g., Menon et al., 2024; Lake et al., 2025), however we did not find that implementing SSPs with a top-heavy IMF ($\xi(m) \propto m^{-2.00}$ for $m > 0.5M_{\odot}$) meaningfully changed the stellar mass estimates. Finally, we note that we derive these stellar surface densities using rest-FUV sizes, which due to mass segregation (e.g., Hosek et al., 2015; Mestric et al., 2023) may be smaller than the optical sizes typically quoted for local universe clusters or those quoted from simulations.

Age and Metallicity

All three SSPs show general agreement at the $\sim 1\sigma$ level in their metallicity predictions for both Earendel and *1b*, and consistently predict the metallicity to be in the metal-poor regime. Choosing whichever SSP posterior predicts allows the highest metallicities (generally BPASS), the inferred posteriors rule out $Z/Z_{\odot} > 10\%$ to $\sim 95\%$ confidence in Earendel and $\sim 99\%$ confidence for *1b*. Similarly $Z/Z_{\odot} > 5\%$ is ruled out to $\sim 80\%$ and $\sim 99\%$ confidence

for Earendel and *1b* respectively. We point out that the uncertainties quoted for the BPASS fit of Earendel are somewhat misleading. Fig. 7.3 reveals the age-metallicity posterior is closer to double-peaked rather than classically broad, and metal-poor solutions are strongly favored.

We found these metallicity measurements were influenced primarily from the shape of the spectroscopic continuum (e.g, the UV and optical slopes, the observed Balmer break), as the depth of absorption features was not found to approach the flux uncertainties until $Z \sim 0.5 Z_{\odot}$. While we are cautious to assign an exact metallicity to either Earendel or *1b* given the potential systematics, the synthesis of the three SSP fits confidently places these clusters in the metal-poor regime ($\lesssim 10\% Z_{\odot}$). Further tests assessing systematics in the metallicity measurement are detailed in Appendix 7.6.

The ages are in weaker agreement with one another compared to the metallicity. For Earendel the SSPs predict a wide range of ages 30 – 110 Myr, and the uncertainties are of order 10’s of Myr. In the case of *1b*, the statistical precision is much higher (noting that uncertainties are scaled up $\sim 30\%$ via a white noise term), with BC03, BPASS, and FSPS predicting $t_{\text{age}} \sim 30, 45$ and 160 Myr respectively to within a $\sim$ few Myr precision. This may be reflective of the overall slow evolution of the stellar continuum beyond 10 Myr, and perhaps somewhat poorly understood ingredients in the SSP such as the treatment of binaries (though we note that repeating fitting with the BPASS single star models was not found to impact the solution) or the evolutionary tracks of red supergiants (e.g., Vázquez and Leitherer, 2005). Indeed visual inspection shows that crucial spectral features for this work, such as the Balmer break strength, are not in always in strong agreement across the 10-100 Myr age range in these SSPs.

Observations out to redder wavelengths may help narrow both the age and metallicity estimates. Specifically, observations of the broad photospheric $1.6\mu\text{m}$ H^- opacity feature could be leveraged to age-date star clusters in the > 10 Myr range due to red supergiants at early times (Eldridge, Beasor, and Britavskiy, 2020) and later red giants and AGB stars (e.g., Sawicki, 2002). This feature is most apparent at low metallicities (Yang et al., 2021), and is broad enough to be identifiable photometrically with *JWST* MIRI imaging.

The cosmic formation epoch and metallicities of Earendel and *1b* are consistent with the age-metallicity sequence observed from globular clusters in local galaxies (e.g., Cezario et al., 2013; Usher et al., 2019, also see Fig. 7.4). Furthermore, these findings appear consistent with the ongoing picture of star cluster evolution indicated by high redshift proto-GCs. Earendel and *1b* may be evolved cousins of the clusters seen in the $z \sim 10$ Cosmic Gems (Adamo et al., 2024) and the $z \sim 8.3$ Firefly Sparkle (Mowla et al., 2024), while perhaps being the precursors to older proto-GCs seen at more intermediate redshifts such as the $z \sim 1.4$ Sparkler (Mowla et al., 2022; Adamo et al., 2023) or the $z \sim 2.5$ Relic (Whitaker et al., 2025).

In Fig. 7.4, we compare the cosmic formation ages and metallicities of various high redshift clusters to predictions of the cluster age-metallicity relation (AMR) for MW, LMC, and SMC-like galaxies presented by Horta et al., 2021 from the E-MOSAICS simulation (Pfeffer et al., 2018; Kruijssen et al., 2019), where the MW relation is derived from zoom-in

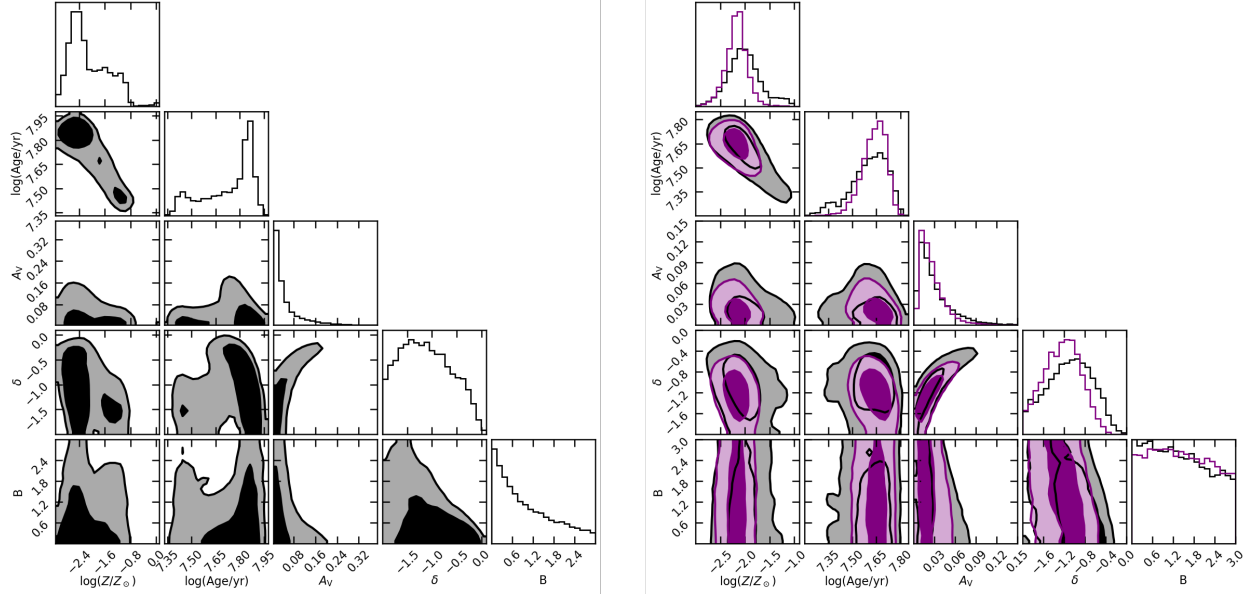


Figure 7.3 Posterior distributions for the Earendel (left), 1b (right purple), and 1a (right black) physical parameters from fitting with the **BPASS** SSP library, which generally yielded the largest age and metallicity uncertainties. We omit the ionization parameter, covering factor and velocity dispersion as they go unconstrained. We also omit the white noise scaling, which is $\lesssim 1.3$ in all cases. 2D contours enclose 50% and 90% of the posterior samples. Refer to Table 7.4 for the 68% C.I.’s of the parameters.

simulations in Kruijssen et al., 2019 and the LMC/SMC relations are from Horta et al., 2021. While Earendel and 1b show best agreement with SMC/LMC-like halos, the Sunrise galaxy may actually be closer to a MW-like halo mass. Vanzella et al., 2023 derive a magnification-corrected total stellar mass $M_\star \sim 10^{8-9} M_\odot$, which is as much as an order of magnitude higher than the LMC had at this cosmic age (Weisz et al., 2013). Given the low metallicities inferred for these clusters, it is not immediately clear if they more closely resemble the in-situ or ex-situ branch of GCs seen in the Milky Way (Forbes and Bridges, 2010). Should Earendel’s true metallicity correspond to the lower age, higher metallicity solution seen in Fig. 7.3, this would place it more squarely in the in-situ branch, reflecting the rapid build up of up metals achievable in a Milky Way mass halo (e.g., Kobayashi, Karakas, and Lugaro, 2020)

Dust Reddening and Nebular Parameters

Across the three SSP inferences of Earendel and 1b, we find minimal dust reddening $A_V \lesssim 0.1$ mag. The reddening law slope δ is not well-constrained; the **BPASS** and **BC03** fits loosely preferring slopes steeper than SMC-like (corresponding to $\delta = 0.45$) however **FSPS** generally prefers slopes Calzetti-like ($\delta = 0$) and shallower. The former results may be more consistent

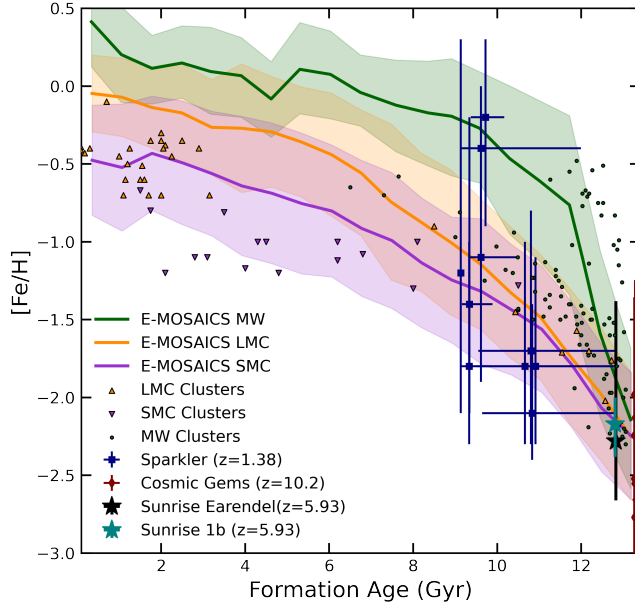


Figure 7.4 Massive star cluster age-metallicity relation predicted for MW, LMC, and SMC mass host galaxies predicted by the E-MOSAICS cosmological simulation (Kruijssen et al., 2019; Horta et al., 2021) compared to measurements from LMC and SMC clusters (see Table A1 of Horta et al., 2021, and references therein), MW clusters (see Table A1 of Kruijssen et al., 2019, and references therein), from the Sparkler ($z = 1.38$; Adamo et al., 2023), the Cosmic Gems ($z \approx 10.2$; Adamo et al., 2024), and Earendel and 1b (BPASS results which have the largest uncertainties) from this work. We note that the younger ages of some clusters within both the Sparkler and the Cosmic Gems implies the best-fit metallicity is dictated in part by enhancement from nebular emission, however we still approximate $\log(Z/Z_{\odot}) \approx [\text{Fe}/\text{H}]$. All three sets of clusters appear broadly consistent with the predictions of SMC/LMC mass host galaxies, with the Sunrise also showing consistency with a MW mass host. This figure is adapted from Fig. 4 of both Adamo et al., 2023 and Horta et al., 2021.

with the expectation that high redshift star-forming galaxies should have steeper reddening laws, for example the relations of Salim, Boquien, and Lee, 2018 find a slope of $\delta \sim -0.8$ for high redshift analogs of stellar mass $M_{\star}/M_{\odot} \sim 10^8$ similar to the Sunrise (Vanzella et al., 2023). By contrast, Sanders et al., 2024 found the nebular attenuation curve of high star-forming galaxy at $z = 4.41$ to have an FUV-Optical slope similar to Cardelli, Clayton, and Mathis, 1989, more closely matching the FSPS result. We also do not see a preference for a strong 2175 Å bump, but it is weakly disfavored for all fits to Earendel. Higher SNR is necessary to more confidently rule out the presence of a bump.

None of the fits provide any significant constraints on the ionization parameter nor the covering factor, reflecting the preference for evolved cluster ages which have lost the bulk of their ionizing budget. As noted in Sec. 7.3, we identify candidate detections of $[\text{O III}]\lambda 5007$

Table 7.1. SED Parameters

Image	SSP	$\log(t_{\text{age}}/\text{yr})$	$\log(\mu M/M_{\odot})$	$\log(Z/Z_{\odot})$	A_V (mag)	δ	B	χ^2_{ν}
Earendel	BC03	$7.50^{+0.04}_{-0.04}$	$8.87^{+0.03}_{-0.04}$	$-1.67^{+0.26}_{-0.21}$	$0.03^{+0.03}_{-0.01}$	$-1.44^{+0.44}_{-0.35}$	$0.98^{+1.10}_{-0.71}$	1.71
	BPASS	$7.79^{+0.08}_{-0.27}$	$9.06^{+0.07}_{-0.23}$	$-2.28^{+0.90}_{-0.38}$	$0.03^{+0.06}_{-0.02}$	$-1.15^{+0.61}_{-0.52}$	$0.77^{+1.17}_{-0.59}$	1.67
	FSPS	$8.05^{+0.14}_{-0.27}$	$9.24^{+0.18}_{-0.23}$	$-1.67^{+0.48}_{-0.40}$	$0.05^{+0.14}_{-0.04}$	$-0.09^{+0.49}_{-0.93}$	$0.73^{+1.19}_{-0.56}$	1.68
Im 1b	BC03	$7.47^{+0.01}_{-0.02}$	$9.21^{+0.02}_{-0.02}$	$-2.12^{+0.05}_{-0.03}$	$0.03^{+0.02}_{-0.01}$	$-1.25^{+0.29}_{-0.30}$	$1.57^{+0.94}_{-0.97}$	1.65
	BPASS	$7.64^{+0.06}_{-0.08}$	$9.33^{+0.04}_{-0.06}$	$-2.17^{+0.18}_{-0.21}$	$0.02^{+0.02}_{-0.01}$	$-1.22^{+0.34}_{-0.39}$	$1.40^{+1.02}_{-0.93}$	1.63
	FSPS	$8.21^{+0.03}_{-0.05}$	$9.73^{+0.05}_{-0.05}$	$-2.41^{+0.12}_{-0.06}$	$0.02^{+0.05}_{-0.02}$	$0.30^{+0.33}_{-0.61}$	$1.42^{+1.03}_{-0.97}$	1.65
Im 1a	BC03	$7.47^{+0.02}_{-0.02}$	$^a 9.07^{+0.02}_{-0.01}$	$-2.10^{+0.07}_{-0.04}$	$0.03^{+0.02}_{-0.01}$	$-1.29^{+0.33}_{-0.35}$	$1.49^{+0.97}_{-0.96}$	1.77
	BPASS	$7.62^{+0.10}_{-0.13}$	$^a 9.17^{+0.08}_{-0.11}$	$-2.03^{+0.33}_{-0.31}$	$0.02^{+0.03}_{-0.01}$	$-1.08^{+0.43}_{-0.48}$	$1.32^{+1.08}_{-0.92}$	1.72
	FSPS	$8.01^{+0.11}_{-0.13}$	$^a 9.42^{+0.14}_{-0.11}$	$-1.81^{+0.33}_{-0.40}$	$0.04^{+0.07}_{-0.03}$	$0.30^{+0.32}_{-0.51}$	$1.26^{+1.13}_{-0.90}$	1.77

Note. — Physical parameters for Earendel, image 1b, and image 1a of the Sunrise arc using three separate SSP libraries: the 2016 version of the Bruzual and Charlot, 2003a, BC03, models (Chevallard and Charlot, 2016), BPASS (Stanway, Eldridge, and Becker, 2016), and FSPS (Conroy and Gunn, 2010). We list the object, the SSP library, the burst age, the magnified stellar mass (μ is the flux magnification factor due to lensing), the stellar metallicity, visual band extinction, reddening law slope following Salim, Boquien, and Lee, 2018, reddening law 2175 Å bump strength following Salim, Boquien, and Lee, 2018, and the reduced chi-squared statistic for 397 degrees of freedom without the $\sim 30\%$ white noise scaling applied. While the nebular ionization parameter and covering factor are also optimized for in this analysis, they are omitted from the table for clarity as they go unconstrained within their uniform priors listed in Sec. 7.3.

^aThe 1a magnified mass is derived solely from the spectrum and not via rescaling to the measured F200W flux, as is the case for Earendel and 1b. The 1a spectrum suffers from slit loss, and the mass is likely underestimated by a factor of 2-3.

and H α in the nebular spectrum. Given their low statistical significance, we refrain from making any definitive statements about their nature - the 2D spectrum does not clearly confirm nor deny them to be associated with the underlying arc, and they indeed may merely be a statistical fluke altogether.

The lack of prominent dust reddening and nebular emission is perhaps consistent with the expectation evolved star clusters are nearly devoid of gas Lada and Lada, 2003, as feedback from massive stars is typically expected to expel nearly all of the cluster gas after the first ~ 10 -20 Myr of the cluster lifetime (Calura et al., 2015). While SNe and Wolf-Rayet stars are expected to provide the bulk of the cluster’s dust production within first ~ 10 Myr (Schneider and Maiolino, 2024), it is possible their dusty ejecta is not efficiently retained within the cluster, or that their overall covering is fairly low.

We note more generally that the use of the Salim, Boquien, and Lee, 2018 reddening law is impactful for capturing uncertainties on the dust and age constraints in this work. Prior work by Nakane et al., 2025 has pointed out that, for a fixed Calzetti, 2001 reddening law, the age, dust, and metallicity affect the continuum in distinct ways, reducing the presence

of a degeneracy between these three parameters. However the dust reddening law of high redshift galaxies is not necessarily Calzetti-like nor is it standardized (e.g., Fisher et al., 2025), and assuming a fixed slope could induce a bias in the inference or underestimate the uncertainties. Indeed, we find in our fits the flexible Salim, Boquien, and Lee, 2018 reddening law has a modest, but statistically relevant impact on the metallicity compared to implementing a fixed reddening law, even in the regime of $A_V < 0.1$. This is most apparent in the BPASS fit to Earendel shown in Fig. 7.3, where a secondary low age, high metallicity solution appears only for steep slopes $\delta < -1$. Given the broad posterior inferred on the reddening law slope δ in all of our fits, we find implementing the Calzetti, 2001 or SMC (Gordon et al., 2003) reddening laws generally still agree with our Salim, Boquien, and Lee, 2018 fits to within 1σ , however in a higher SNR regime this is likely to no longer be the case. As the dust reddening slope optimized for in this work, we acknowledge that it does not fully eliminate systematic bias related to the slope, however we find it is reduced compared to assuming the fixed slope apriori.

Is Earendel a Star or Star Cluster?

Prior work by Welch et al., 2022c found the *JWST* photometry of Earendel was inconsistent with single star models from the PoWR and TLUSTY models. Rather the photometric data is better fit by a binary system, consisting of two massive ($m_{\text{ZAMS}} \gtrsim 20 M_\odot$) stars: an evolved supergiant with $T_{\text{eff},1} \sim 9000$ K, and a main sequence O star of $T_{\text{eff},2} \sim 34000$ K. Assuming the largest magnification inferred across all existing lens models for the system, $\mu \sim 17000$, the total bolometric luminosity for Earendel must reach $L_{\text{bol}}/L_\odot \sim 10^6$. Welch et al., 2022c find the hotter star has a bolometric luminosity $L_{\text{bol}}/L_\odot \sim 10^{5.8}$, ~ 0.5 dex greater than the cooler star. Such a system may be somewhat unusual compared to binary systems typically observed in local galaxies, as the hotter, brighter O star would be expected to leave the main sequence prior to its lower mass companion. Furthermore, the stellar parameters of the cooler star are indicative of passing through the short-lived ($\lesssim 10^4$ yr) yellow supergiant phase (e.g., Drout et al., 2009), however the longer-lived ($\sim \text{Myr}$) phase of a cool blue supergiant may also match the parameters.

This does not definitively rule out the binary scenario (see Nabizadeh et al., 2024 for possible solutions). While it is possible a single or binary stellar SED fit to the NIRSpec spectrum may provide results more consistent with local observations, it more generally may be difficult to confirm a binary or single-star scenario based on the spectrum alone. The hotter star in the Welch et al., 2022c fit would likely present strong stellar wind features in emission such as the C IV $\lambda 1550$ or N IV $\lambda 1240$ P-Cygni features given an SMC-like metallicity (undetectable at the PRISM resolution), which would be highly inconsistent with an evolved star cluster. However if the system is instead metal poor, the wind mass loss rate and hence strength of these wind features would be too weak to be detectable in even deep high resolution spectra (e.g., Leitherer et al., 2014; Telford et al., 2024). By contrast, the cooler star would present stellar absorption features, such as the Balmer series or Ca II H&K, however these would also be consistent with an evolved star cluster which consists of many

cool stars without strong winds. Ultimately, detection of microlensing-induced photometric variability may be the most promising ‘smoking gun’ indicator (Welch et al., 2022d), however multi-epoch imaging has not yet confirmed such variability (Welch et al., 2022c).

A star cluster appears to be a natural conclusion from the spectroscopic data, and provides an exceptional fit across three different SSP libraries. The physical parameters estimated for the star cluster are consistent with the expectations of a globular cluster progenitor at $z \sim 6$, and are in agreement with the results of simulation work on star cluster formation and evolution. The cluster age is also in alignment with the non-detection of statistically significant variability across the 2 year observer-frame baseline (Welch et al., 2022c), as such an evolved cluster lacks the massive stars necessary for microlensing to induce large fluctuations (Dai et al., 2020).

A third, but less well-defined scenario could be that Earendel consists of a “small group” of dozens of stars, requiring a large ($\mu > 1000$) but not extreme ($< 10^4$) magnification. Such a group likely cannot be sampled from a standard IMF, and must instead be a young system consisting of luminous O and B supergiants in order to reach the necessary bolometric luminosity $L_{\text{bol}} \sim 10^7 L_{\odot}$ for $\mu \sim \mathcal{O}(10^3)$. Such a system in isolation is not seen in the local universe, and furthermore it is unclear whether it would match the observed spectrum without significantly fine-tuning the stellar members. However given the overall small number of stars, microlensing induced variability should be measurable through precision *JWST* photometry (Dai, 2021b), and stellar wind features may be detectable in medium resolution *JWST* spectroscopy given the system is not metal poor.

7.5 Conclusion

In this letter, we evaluated two stellar clumps within the $z \approx 5.93$ lensed Sunrise galaxy: Earendel, which we hypothesize is a star cluster, and another star cluster within the galaxy, 1b. The quality of rest-UV through optical *JWST* NIRSpec spectra of these objects enabled detailed physical parameter estimation of these star clusters. Through SED fitting with three well-tested simple stellar population libraries, BC03, BPASS, and FSPS, we inferred their ages, metallicities, masses, and dust extinctions. We found both have intermediate ages, $t_{\text{age}} \sim 30\text{--}150$ Myr, and inferred their stellar metallicities are $Z \lesssim 10\% Z_{\odot}$, as low as $Z \lesssim 1\% Z_{\odot}$ depending on the SSP model.

The formation ages and metallicities of these clusters are in relative agreement with the age-metallicity relation of globular clusters both measured in local galaxies and recovered in simulations. The results are in best agreement with the expectations of SMC/LMC halo mass host galaxies with more marginal consistency with a MW mass halo, which given the stellar mass of Sunrise ($M_{\star} \sim 10^{8-9} M_{\odot}$) is likely more appropriate. We have concluded that, when taken together with other high-redshift star cluster measurements, such as the Sparkler or the Cosmic Gems, these clusters appear to corroborate the picture of globular cluster formation and evolution illustrated by local GCs and simulations.

This study represents a first for spectroscopic fitting of evolved star clusters covering from rest-frame UV to optical wavelengths at these redshifts. Past studies have typically relied on nebular emission lines, which is only practical for very young ages, or solely photometry for ascertaining high redshift star cluster characteristics. While we do not find complete agreement between the three SSP libraries used, we find the low metallicity and intermediate ages inferred to be consistent results. Given that these clusters are extremely faint $m_{F200W} \sim 27$ AB mag, the quality of these measurements showcases the power of *JWST*, and indicates that spectroscopic analysis of evolved star clusters in other high redshift lensed galaxies are viable.

7.6 Appendix

Tests of Star-formation History

For the SED fitting in this work, we assume the star formation history of these star clusters is representative of an instantaneous burst, which is appropriate for such dense star clusters which likely form their stars over only a few free-fall times of the parent giant molecular cloud ($t_{\text{ff}} \sim 3$ Myr assuming $R_{\text{GMC}} \sim 100$ pc and $\Sigma_{\text{GMC}} \sim 1000 M_{\odot}/\text{pc}^2$; Grudić et al., 2023). However we also test an exponential decay SFH prescription in SED fitting on 1*b* to evaluate its impact. To conduct this, we use **Bagpipes** (Carnall et al., 2018), as the SED fitting approach used in this work only includes the instant burst SFH. Indeed the age and metallicity binning approach of **Bagpipes** is likely more suitable for extended SFHs (e.g., not a delta function). We choose our parameter priors to match those described in section Sec. 7.3, noting that the covering factor is not available in **Bagpipes** which effectively assumes a covering factor unity. We allow τ to freely vary from 1 Myr to 1 Gyr which lends much greater flexibility to the SED compared to a pure SSP, however we note that this can permit star formation timescales which may not necessarily reflect observations and simulations.

We find across all three SSPs that the ‘free τ ’ inference agrees well with the instantaneous SFH prescriptions, detailed in Table 7.6. In each, τ converges to $< \text{few Myr}$, effectively becoming a ‘short burst’ which closely matches a true SSP. We also explore cases where nebular emission is removed, which returns nearly identical results for **BPASS** and **FSPS**, however the BC03 fit returns a young (~ 6 Myr) solution with much higher metallicities $\sim 20\%$ solar. We ultimately disfavor this solution given the lack of detectable nebular emission, whereas nebular emission is readily detected in other young massive clusters within the Sunrise (Vanzella et al., 2023). If such a solution is true and this young cluster is somehow void of gas, *JWST* medium resolution spectra could reveal stellar wind features, namely the C IV λ 1550 P-Cygni feature, which would be strong at that age and metallicity.

Table 7.2. Image 1*b* Free τ SFH SED Parameters

SSP	$\log(t_{\text{age}}/\text{yr})$	$\log(\mu M/M_{\odot})$	$\log(Z/Z_{\odot})$	$\log(\tau/\text{Gyr})$	A_V (mag)	δ	B
BC03	$7.50^{+0.04}_{-0.01}$	$9.19^{+0.02}_{-0.01}$	$-2.10^{+0.06}_{-0.04}$	$-2.56^{+0.18}_{-0.24}$	$0.06^{+0.03}_{-0.02}$	$-1.28^{+0.25}_{-0.24}$	$2.05^{+1.56}_{-0.24}$
BPASS	$7.69^{+0.05}_{-0.08}$	$9.30^{+0.03}_{-0.04}$	$-2.10^{+0.17}_{-0.12}$	$-2.52^{+0.32}_{-0.29}$	$0.05^{+0.04}_{-0.02}$	$-1.13^{+0.29}_{-0.27}$	$1.77^{+1.60}_{-1.23}$
FSPS	$8.20^{+0.03}_{-0.05}$	$9.67^{+0.02}_{-0.04}$	$-2.27^{+0.10}_{-0.02}$	$-2.23^{+0.42}_{-0.54}$	$0.03^{+0.05}_{-0.02}$	$0.29^{+0.35}_{-0.58}$	$2.21^{+1.74}_{-1.37}$

Note. — Physical parameters for Image 1*b* using BAGPIPES with the BC03, BPASS, and FSPS SSP libraries and an exponential decay SFH. We list the object, the SSP library, the population age, the magnified stellar mass (μ is the flux magnification factor due to lensing), the stellar metallicity, the characteristic timescale (τ), visual band extinction, reddening law slope following Salim, Boquien, and Lee, 2018, and reddening law 2175 Å bump strength following Salim, Boquien, and Lee, 2018.

Testing Metallicity Systematics

The precision achieved on the metallicity in each SSP is impressive, at the < 0.2 dex level for the higher SNR 1*a*, *b*. SSP fitting of the rest-UV through Optical integrated cluster continuum at this spectral resolution for these intermediate ages is somewhat unexplored, with the majority of works in both the local universe and at high redshift relying solely on photometry (e.g., Wofford et al., 2016) or lacking the rest-FUV. Without the availability of metal-line absorption features, our fitting implies that the continuum alone provides non-negligible leverage to break well-known age-dust-metallicity degeneracies. We develop three tests to further probe the effectiveness of the continuum for constraining the physical parameters of the stellar population in this intermediate age, metal-poor regime.

We first use the spectrum of 1*b* and iteratively mask out portions of the spectrum from the FUV to the optical, at each step performing fitting with the BPASS SSP to infer the metallicity (Fig. 7.6; top). Surprisingly, removal of both the FUV and NUV ($< 3800\text{\AA}$ rest frame) is only modestly impactful, softening the metallicity constraints to ~ 0.5 dex. It is only after further masking beyond the Balmer break to $< 4800\text{\AA}$ (roughly SDSS *g*-band) which finally eliminates the metallicity constraints, producing an approximately uniform posterior across a range of metallicities $0.005 \leq Z/Z_{\odot} \lesssim 1$.

We identify that this is due in part to the formation of younger age solutions $\lesssim 10$ Myr with low covering factors $x < 10\%$ which favor all metallicities roughly uniformly. In practice this could arguably be disfavored apriori by the small covering which would be surprising for such a young cluster, however we retain these solutions for the sake of thoroughness. This exercise confirms that the clear Balmer break detected in Earendel and 1*b* is a defining feature in our inference, helping to break age-dust-metallicity degeneracies at these intermediate ages.

We construct a second test to ascertain how the constraints are affected by the noise

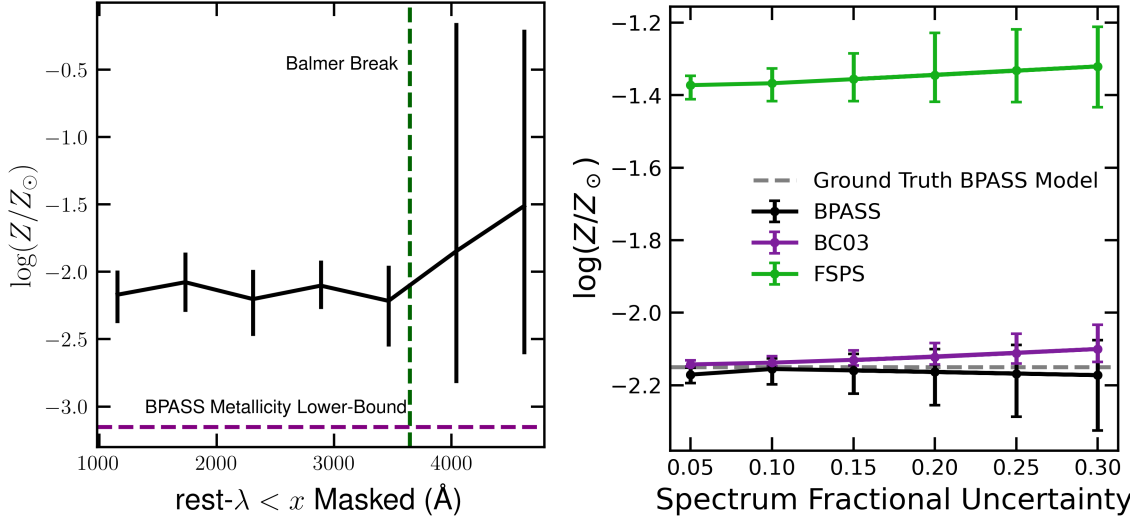


Figure 7.5 **Left:** Metallicities inferred from the *1b* NIRSpec PRISM spectrum using the BPASS SSPs (black error bars) with an iterative masking of wavelengths from the rest-FUV to the rest-Optical. Masking the FUV through NUV does not appear to significantly affect the inferred metallicity, however masking beyond the Balmer break (green dashed line) which is clearly detected in the NIRSpec spectrum (Fig. 7.2) results in the metallicity becoming effectively unconstrained. **Right:** Metallicities inferred via the BPASS (black), BC03 (purple) and FSPS (green) SSPs from a mock BPASS model of $\log(Z/Z_{\odot}) = -2.15$, $\log(t_{\text{age}}/\text{yr}) = 7.7$ and $A_V = 0$ with increasing uniform fractional Gaussian noise applied. While BPASS and BC03 recover the ground truth (grey dashed line), FSPS exhibits an offset of ~ 0.8 dex towards higher metallicities.

level. We create a mock BPASS spectrum of age 50 Myr, metallicity $\log(Z/Z_{\odot}) = -2.15$, and $A_V = 0$ (approximately the *1b* best fit) without any nebular emission (e.g., $x = 0$). We convolve to the PRISM resolution and iteratively implement increasing fractional uniform Gaussian noise scalings from $\sigma_{\text{noise}} = 5 - 30\%$ of the model flux. For each noise scaling, we perform fitting using each of the three SSPs and evaluate the inferred metallicity, shown in Fig. 7.6 (bottom). Each model shows general agreement with itself across the different noise levels, and the BC03 and BPASS fits generally agree with the ground truth BPASS model metallicity. FSPS, however, shows a ~ 0.8 dex offset toward higher metallicities. This disagreement is not seen in the fits to Earendel or *1b*, and is perhaps somewhat surprising given that both BPASS and FSPS rely on the C3K spectral library in this metallicity regime. Inspection of the posteriors reveals that the FSPS fits converge to a slightly lower ~ 30 Myr age solution; extrapolating age-metallicity degeneracy out to older ages could indeed yield lower metallicities, however these solutions are highly disfavored even in the noisiest models.

Finally, we conduct a third test to evaluate whether the results are a product of a random noise realization. To do so we once again construct a mock BPASS model as described above.

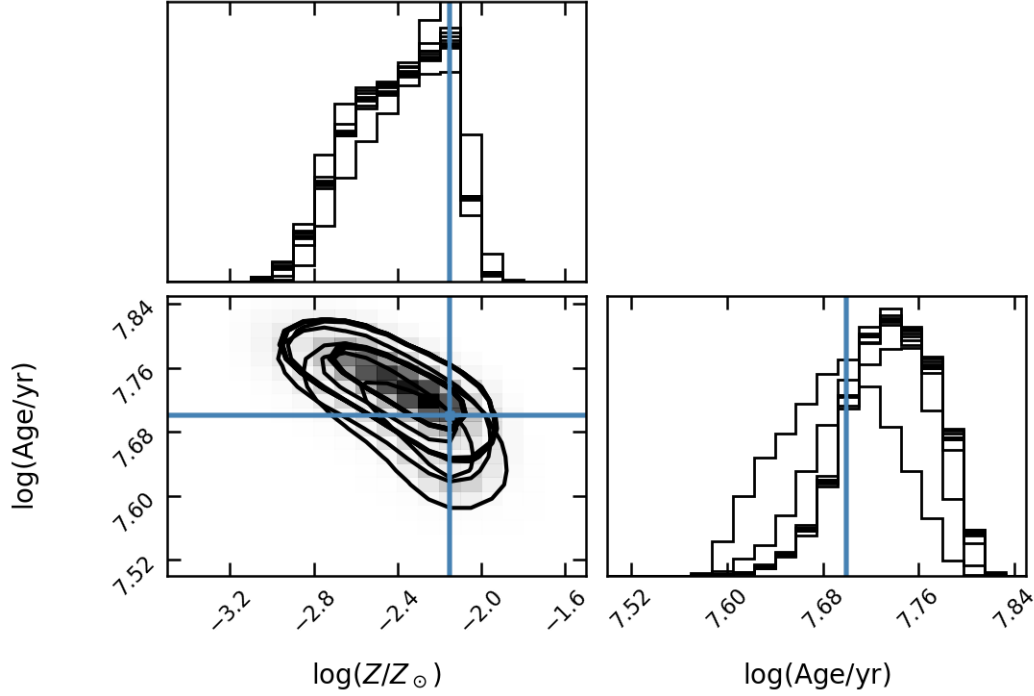


Figure 7.6 Metallicities and ages posteriors from fitting the BPASS SSPs to 10 mock spectra constructed using a BPASS model of $\log(Z/Z_{\odot}) = -2.15$, $\log(t_{\text{age}}/\text{yr}) = 7.7$ and $A_V = 0$ with noise realizations applied which approximate the wavelength-dependent noise of the 1*b* NIRSpect PRISM spectrum. 2D contours enclose 50% and 90% of the posterior sample. The ground truth (blue lines) is generally recovered to within 1σ , however the metallicity exhibits a noticeable bias towards lower metallicities.

To apply noise, we take the fractional uncertainties of the 1*b* spectrum, smooth it with a median filter to yield the approximate 1σ noise level, and apply random realizations of Gaussian noise to the mock spectrum following these uncertainties to create 10 mock spectra. We then fit each of these spectra following our SED fitting procedure with the BPASS models to check if the metallicity is generally well-recovered.

As seen in Fig. 7.6, we find the inferences on these models both generally agree with one another, as well as the ground truth to within 1σ . Somewhat concerningly, we do observe a systematic bias towards lower metallicities across all of these fits of $\sim 0.1 - 0.2$ dex. As these do not appear in the prior test which uses uniform fraction noise, this could indicate that this is actually a result of the wavelength dependent noise in our 1*b* spectrum. It is possible that correlated or wavelength-dependent noise could be biasing the fit, which may also be present in Earendel and 1*a* (in fact they must, as 1*a* and 1*b* yield similar results in our analysis). However we find that changing the size of the median filter can change both the strength and direction of the bias, cluing that this may instead be a systematic introduced by our noise implementation. Taking this in combination with the magnitude of the biases

being comparable to the uncertainties of our inferred metallicities, we conclude that this bias, if real, would have only a modest impact on this work given the current precision of our constraints.

Chapter 8

Conclusion & Future Outlook

In this thesis we have covered a wide range of observational applications of strong-lensing galaxy cluster fields. Chapters 2 and 3 focused on how lensing evidence could be leveraged to map the surface mass density distributions of these clusters. Combining the positions and redshifts of lensed images with information of the cluster galaxies resulted in mass distributions which revealed potential disturbances within the clusters. Synthesizing these strong-lensing results with auxiliary observations of the cluster, such as the intracluster light in Optical-NIR imaging, or the detection of head-tail radio emission from the brightest cluster galaxies, the picture became clearer: the G165 cluster is likely an ongoing cluster merger, and the SMACSJ0723 cluster similarly has yet to virialize. Follow-up radio observations of these clusters have already detected diffuse radio halos, and future multi-wavelength follow-up could allow for measurement of the spectral index and hence the primary mechanism of the emission. In turn, these clusters may make a valuable contribution to the overall understanding of galaxy cluster build-up and evolution.

These works also used photometric information to probe the lensed background, identifying intermediate to high-redshift ‘caustic crossing’ galaxies with large lensing magnifications, making them suitable for the detection of lensed transients. Indeed, a microlensed star within a $z \sim 2$ arc in SMACSJ0723 was identified and later confirmed (G. Brammer, private communication). Similarly, microlensed transients in a cosmic noon galaxy in G165 have recently been detected in JWST imaging, and will be the focus of a future work. These lensed stars have the potential to simultaneously probe the stellar population of the underlying galaxy, as well as test dark matter models which may influence the microlensing occurrence rate.

Chapters 4 and 5 tightened the focus on the lensed background galaxies, honing in on individual super star clusters highly magnified within the $z=2.37$ Sunburst galaxy. Through joint photometric-spectroscopic fitting which used both spaced-based HST imaging and ground-based VLT spectroscopy, the stellar and nebular populations of these star clusters were characterized.

Chapter 4 examined the so-called Lyman-continuum-leaking cluster, which had been identified in prior works by its detectable Lyman-continuum radiation. Our work built on prior efforts by determining robust measurements of the star clusters age, stellar density, and

metallicity, concluding that it had the necessary qualities to be the early progenitor of even the most massive globular clusters seen in the local universe. Assessment of its nebula found the cluster hosted dense ionized gas which was significantly enhanced in Nitrogen relative to Oxygen. We concluded that, based on the young age and high stellar density of the cluster, that this Nitrogen enrichment must be CNO-processed ejecta from massive stars that reside within the cluster. This spurred a novel connection to the multiple populations of globular clusters, whose ‘2P’ subgroups have stars with unusual N/O enhancement not seen in field stars. Synthesizing the circumstantial evidence, we posited that we may be witnessing the formation of these ‘2P’ stars in action. If confirmed, this would shed light on the enrichment channel for these ‘2P’ stars, as it would guarantee it must occur in the few million years of the cluster lifetime.

Chapter 5 studied another super star cluster in the Sunburst galaxy, Godzilla, whose nature was hotly debated in prior literature. Due to its anomalous lensing configuration, it had been argued that it may be a transient supernova or perhaps an individual highly magnified star. Our work showed from spectral energy distribution fitting that a star cluster provided a natural solution, and that furthermore microlensing statistics favored magnifications that only a star cluster could satisfy. This star cluster is only marginally older than the Lyman-continuum leaking cluster (that is to say quite young), and is incredibly compact. The cluster’s gas is exceptionally dense and enriched in Nitrogen, Oxygen, and Helium. We hypothesized that this cluster is not only enhanced by the CNO-processed material of massive stars, but may also be enriched by massive star supernovae, allowing for greater O yields. Such a scenario has consequential implications for star-formation, as it would imply that gas in sufficiently dense star clusters is robust to wind and supernova feedback from the cluster stars. Furthermore, it also held implications for the multiple populations problem, as the O and He yields were unlike 2P stars and instead meant any 2P stars in the cluster had already formed.

Since these works were conducted, JWST NIRSpec IFU spectroscopy has yielded the most detailed rest-Optical spectra of these objects to date. Future work will leverage these spectra to achieve even tighter constraints on the physical parameters of these star clusters and the nebulae they host. Additionally, it will open up new constraints, such as He measurements for the Lyman-continuum leaking cluster, which will further narrow down the massive star polluters (e.g., wolf-rayet contributions must be He rich). Furthermore, recent JWST MIRI imaging will push the panchromatic dataset of these clusters out to the rest mid-infrared, probing emission from red supergiants and crucially hot ($> 100\text{ K}$) dust thermal emission. The latter is particularly exciting, as the huge ionizing flux of these clusters implies that any dusty nebulae should shine brightly in the MIR. Confirmation of such dust emission will strengthen the scenario of secondary star formation, as dust is a pivotal catalyst for the formation of molecular hydrogen, a necessary precursor to star formation.

Chapter 6 entailed the measuring of the Hubble constant from the triply-imaged Sn Ia H0pe. The G165 galaxy cluster strongly lensed a massive post-starburst galaxy into images at three distinct angular positions on the sky. A Type Ia SN was observed by JWST in this galaxy, and follow-up photometry and spectroscopy allowed for measurements of both

the relative time-delay between lensed images, as well as the absolute lensing magnification of each image. Comparing these measured quantities to predictions by seven independently constructed lensing mass models, we inferred the Hubble constant. This expanded on prior work on lensed supernovae as it 1) included absolute magnification constraints and 2) included spectroscopic time-delay constraints.

Importantly, we found that these magnification constraints were effective at breaking degeneracies among lens models, for the first time confirming decades-old predictions. This in turn allowed for the measurement of H_0 to $< 10\%$ precision, with roughly equal contributions to the error budget from the time-delay measurements and the lens model predictions.

Time-delay cosmography on the cluster scale is still a budding field, and it is crucial to make the most of each of these rare events. SN H0pe still has more to offer. New JWST imaging of the cluster field after the SN has faded will allow for tighter measurements on both the time delays and the magnifications. There also remains room to improve the lens model predictions - the set of lensing constraints is still sparse compared to the best-studied clusters in the literature. More broadly, this field is quickly running up against the systematics of the lensing models. For an individual modeling technique, systematics are only fully understood after running as many as dozens of iterations with changes in the hyperparameter selection. Lensing models built with cosmological precision in mind, which adequately capture their systematics on a cluster-by-cluster basis and make full use of all available lensing constraints (e.g., the magnifications or the surface brightness distributions of the lensed galaxies) are required to catch up to the precision of the time-delay measurements.

In chapter 7, we turned to the highly contested Earendel object in the $z=5.93$ strongly-lensed Sunrise galaxy. While previous work had suggested that Earendel was an individual star based on lensing size constraints, follow-up analyses showed that star cluster-like sizes were indeed allowable. Through application of three premier simple stellar population (SSP) libraries, we found that deep JWST spectra of Earendel are highly consistent with an individual SSP, equivalently so compared to other knots in the Sunrise which are more widely-accepted to be star clusters. Furthermore, we found that the rest-UV through optical spectroscopic continuum was surprisingly effective at producing metallicity and age measurements of these (candidate) star clusters, implying they are metal poor and at an intermediate age. While this work revealed significant systematics due to differences between SSPs, it is perhaps promising that naked stellar populations can be characterized even without high resolution spectroscopy. Other existing high redshift star clusters, such as those at $z=7-10$ for which quality absorption features are likely unattainable, could potentially be better understood through this approach, motivating spectroscopic programs which could otherwise seem fruitless. Earendel and other lensed star clusters in the Sunrise, however, are bright enough to be viable in a high resolution regime with ambitious ultra-deep spectroscopy. Such data could narrow the metallicity measurement, and firmly connect these clusters as the metal-poor progenitors of modern day globular clusters.

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