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Charting the Chemical Compositions of Massive Galaxies Across Cosmic Time

by

Aliza Gray Beverage

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 Mariska Kriek, Co-Chair

Professor Daniel Weisz, Co-Chair

Professor Jessica Lu

Professor Chung-Pei Ma

Summer 2025

Charting the Chemical Compositions of Massive Galaxies Across Cosmic Time

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Abstract

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Doctor of Philosophy in Astrophysics

University of California, Berkeley

Professor Mariska Kriek, Co-Chair

Professor Daniel Weisz, Co-Chair

Massive galaxies are fundamental to our understanding of cosmic history, yet the physical processes that governed their rapid assembly and quenching remain incompletely understood. This thesis presents a comprehensive, multi-epoch investigation of the chemical compositions of massive quiescent galaxies across cosmic time, combining full-spectrum fitting of large spectroscopic surveys—including SDSS and LEGA-C—with new observations with the Keck Telescopes and *JWST*.

At intermediate redshift ($z \sim 0.7$), we measure Mg and Fe abundances for a representative sample of quiescent galaxies, demonstrating robust correlations between stellar compactness as traced by M_*/R_e , age, and metallicity, and showing that younger, more compact galaxies exhibit higher [Mg/H] and [Fe/H]. Extending these measurements to a broader suite of elements, we find that multi-element abundance patterns are most strongly governed by stellar velocity dispersion. At higher redshift ($z \gtrsim 1$), with the Keck Heavy Metal Survey, we identify galaxies with depleted iron and elevated [Mg/Fe], signatures of short, intense star-formation histories not seen in the local universe. These trends are inconsistent with pure minor-merger-driven evolution, suggesting a key role for major mergers or centrally rejuvenated star formation in shaping the massive quiescent population.

JWST observations enable abundance measurements for an expanded range of elements at $z = 1\text{--}3$, revealing that the earliest quiescent galaxies are markedly Fe-poor and carbon-deficient. This result is consistent with extremely rapid star formation and quenching, preceding significant enrichment from Type Ia supernovae and asymptotic giant branch (AGB) stars. Chemically inferred star-formation timescales are found to be up to six times shorter than those derived from traditional spectral fitting, emphasizing the diagnostic power of detailed abundance analysis.

To interpret these data, we introduce a new chemical evolution framework that applies empirically calibrated, IMF-averaged, metallicity-dependent yields from Milky Way disk stars. This model successfully reproduces observed multi-element abundance patterns from $z \sim 0$ to $z \sim 2$ with typical offsets of just 0.06 dex. Furthermore, we show that the abundances of most elements can be accurately predicted using only Mg and Fe, revealing highly regular chemical enrichment pathways in massive galaxies. This finding provides a straightforward and efficient framework for incorporating detailed abundance predictions into stellar population models, and paves the way for using chemical abundances to probe the high-mass end of the stellar initial mass function in massive galaxies.

Together, this thesis charts the evolution of massive quiescent galaxies across cosmic time, establishing detailed chemical abundances as essential tracers of their rapid formation and quenching, and introducing a new framework that provides deeper insight into the physical mechanisms that shape them.

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Chapter 1

Introduction

Massive galaxies play a crucial role in advancing our understanding of the universe. Found in some of the densest reaches of the cosmos, these galaxies provide the ideal laboratories for studying extreme physics. Massive galaxies are also home to the most massive black holes, offering a unique opportunity to explore the interplay between galaxy evolution and black hole activity (see, e.g., Man et al., 2021). Additionally, because these galaxies live in large dark matter halos, they act as markers for mapping the universe’s large-scale structure. However, despite their significance in various areas of astrophysics, the processes governing their formation remain poorly understood.

JWST is revolutionizing our knowledge of massive galaxies by allowing us to look deeper into space—and thus further back in time—than ever before. One of *JWST*’s most remarkable discoveries is that massive galaxies in the early universe grew astonishingly fast, reaching the mass of the Milky Way in only 3% of the time (e.g., Wang et al., 2024; Shapley et al., 2024). Such rapid galaxy formation challenges our understanding of the physics of the early universe, as it is difficult to reconcile how these galaxies accumulated such vast amounts of gas and efficiently converted it into stars. Another surprising discovery is that many of these massive galaxies have already stopped forming stars, even though they live in a universe full of fresh gas—the essential fuel for star formation (e.g., Carnall et al., 2024; Weibel et al., 2024). Several theories have been proposed to explain these “quiescent” galaxies, such as gas being heated or expelled by supermassive black holes, but which mechanism dominates remains unclear. These discoveries raise critical questions: How did massive galaxies form so rapidly, and what caused them to stop forming stars so early?

One way to address these questions is by studying the star-forming progenitors of massive quiescent galaxies, observing them as they transition through the quenching phase (e.g., Toft et al., 2014). However, this approach presents several challenges. These progenitors of massive quiescent galaxies, especially the most extreme star-forming ones, are rare and therefore difficult to identify. Additionally, the quenching phase is brief, making it hard to capture galaxies in this fleeting state. And finally, it is challenging to properly connect these high-redshift star-forming galaxies to their quiescent descendants due to limitations in our understanding of galaxy evolution. As a result, an alternative approach is required.

quiescent galaxies are dominated by cooler, lower-mass stars with prominent absorption lines, but these stars do not emit the ionizing photons needed to generate strong emission lines.

This Thesis

At the outset of this thesis, the chemical compositions of quiescent galaxies beyond the local universe remained largely uncharted, whereas measurements for star-forming galaxies extended out to $z \gtrsim 3$. The reason is because the absorption lines required for these measurements are much fainter than the emission lines in star-forming systems (as illustrated by the significantly lower flux for the quiescent galaxy in Figure 1.1). The arc of this thesis begins by extending chemical abundance measurements of quiescent galaxies to higher redshifts, and then broadening these measurements to encompass a wider range of elements. Finally, I focus on improving the frameworks used to interpret these chemical abundances, connecting them more directly to the underlying chemical and stellar evolution.

In the first chapter of this thesis, using ultra-deep spectroscopy from the LEGA-C survey, we measure Mg and Fe abundances of the largest sample of quiescent galaxies beyond the low-redshift universe (Beverage et al., 2021). Surprisingly, the oldest galaxies at these redshifts ($z \sim 0.7$) exhibit lower metallicities than their younger and local counterparts, which presented a puzzle: Given that these galaxies are no longer forming stars, how could they have such different metal contents? To investigate, we turn to chemical evolution models and find that a major outflow event, triggered by an accreting supermassive black hole, could expel much of the gas from these galaxies, halting star formation and cutting off enrichment. In contrast, typical quiescent galaxies at lower redshift likely quenched more gradually (see also Trussler et al., 2020).

While the initial work with Mg and Fe provided valuable insights, these two elements only began to scratch the surface. In the local universe, a broader range of elements has been well-studied to constrain star formation histories and nucleosynthetic yields, but these elements have never been directly measured in distant quiescent galaxies. Unfortunately, measuring the abundances of other elements poses a significant challenge, as their faint absorption features are often buried in spectra. Traditional methods, such as stacking to improve S/N, can inadvertently obscure these features. To address this challenge, in 3, we utilize a hierarchical Bayesian approach, revealing the abundances of *eleven* elements at $z \sim 0.7$ (Beverage et al., 2023). We find that the elemental abundance ratios $[X/Fe]$ in the most massive galaxies are strikingly similar to those at $z \sim 0$, while lower mass galaxies exhibit enhanced $[X/Fe]$. This result suggests significant growth in the low-mass quiescent galaxy population over the past 6 Gyr.

To fully harness the power of chemical compositions for studying massive galaxy evolution, we need to push these studies to even higher redshift, where we can observe the most extreme galaxies during the peak epoch of star-formation quenching. At the start of my PhD, *only one* Mg and Fe measurement existed at $z \gtrsim 2$ (Kriek et al., 2016). In Chapter 4,

with the Heavy Metal Survey, an ambitious Keck program, we aim to address this gap by measuring the chemical compositions of 19 massive quiescent galaxies between $1.3 < z < 2.3$ (Kriek et al., 2024). With these ultra-deep spectra, we present the first sample of stellar metallicity measurements at $z > 1$ (Beverage et al., 2024). We discover that the abundance ratios $[\text{Mg}/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ at $z \sim 2$ are unlike any seen in nearby massive galaxy population, underscoring the crucial role of major mergers and/or late-time star formation in shaping their chemical compositions over cosmic time.

Building on this work, we sought to constrain the abundances of more elements at $z \gtrsim 1$. In Chapter 5, using *JWST*/NIRSpec, we obtain continuum spectroscopy of 20 massive quiescent galaxies at $z = 1\text{--}3$. These unprecedented *JWST* spectra enable the first measurements of seven elements in quiescent galaxies beyond $z > 1$. We discover that quiescent galaxies at $z \gtrsim 1$ are strikingly deficient in carbon and iron. Using C as a tracer of enrichment from AGB stars and Fe as a tracer of Type Ia supernovae (Ia SNe), these deficiencies imply that these galaxies formed and quenched star formation over extremely short timescales—before substantial AGB and Ia SNe enrichment.

The growing trove of chemical abundance data from ultra-deep spectroscopic surveys using the VLT, Keck, and now *JWST* is transforming our understanding of how massive galaxies form and evolve. However, we currently lack a quantitative framework to fully exploit this wealth of data. To begin bridging this gap, in Chapter 6, I lay the groundwork for using chemical evolution models to interpret multiple elements simultaneously. I apply a two-process model and empirical nucleosynthetic yields, originally developed for the MW (Weinberg et al., 2022; Gountanis et al., 2024), to predict the chemical compositions of nearby massive quiescent galaxies in SDSS, LEGA-C, and SUSPENSE. These predictions closely match the observed abundances, demonstrating that both the framework and the nucleosynthetic yields in the MW can be effectively applied to chemical compositions of massive quiescent galaxies.

Chapter 2

Elemental Abundances and Ages of $z \sim 0.7$ Quiescent Galaxies on the Mass-Size Plane: Implication for Chemical Enrichment and Star-Formation Quenching

The content of this chapter is drawn from Beverage et al. 2021, with permission from the co-authors.

2.1 Abstract

We present elemental abundances and stellar population ages for 65 massive quiescent galaxies at $0.59 \leq z \leq 0.75$ from the LEGA-C survey. The abundance patterns and ages, derived from full-spectrum modeling, are examined as a function of stellar mass (M_*) and size (i.e., half-light radius; R_e). We find that both $[\text{Mg}/\text{H}]$ and $[\text{Fe}/\text{H}]$ do not vary with stellar mass but are correlated with M_*/R_e for quiescent galaxies with $M_* > 10^{10.5} \text{ M}_\odot$. Thus, at fixed mass, compact quiescent galaxies are on average more metal rich. This result reinforces the picture that supernova feedback and gravitational potential regulate chemical enrichment. $[\text{Mg}/\text{Fe}]$ does not vary with M_* or M_*/R_e , but there is a marginal positive relation between age and mass. Our results support low-redshift findings that more massive galaxies form their stars at earlier times. However, in contrast to low-redshift studies, star formation timescale does not appear to depend on mass or size. We also compare the mass- $[\text{Fe}/\text{H}]$ and mass- $[\text{Mg}/\text{H}]$ relations to stacks of quiescent galaxies at $z \sim 0$ and find that both relations increase by ~ 0.2 dex over the past 7 Gyr. Furthermore, at $z \sim 0.7$ we find a clear trend with age, such that older quiescent galaxies have lower metallicities. Both results can be explained by a chemical evolution model in which galaxies quench via gas removal. Future work, in

particular with JWST/NIRSpec, will extend this analysis to higher redshifts, allowing us to fully exploit abundance patterns to study the formation histories of quiescent galaxies.

2.2 Background

The metallicity of a galaxy is a fundamental property sensitive to many complex evolutionary processes such as metal production and enrichment, removal of enriched gas via galactic winds, and the accretion of circum/intergalactic gas. It is well established that metallicity is correlated with galaxy mass, wherein galaxies with larger stellar mass are more metal rich (e.g., Lequeux et al., 1979; Tremonti et al., 2004). This so-called mass-metallicity relation (MZR) has been confirmed to extend over five decades in stellar mass, flattening at the highest masses (e.g., Tremonti et al., 2004; Gallazzi et al., 2005; Kirby et al., 2013). The MZR holds for both the gas-phase metallicity, as well as the stellar metallicity, and has been observed in both star-forming and quiescent populations. The origin of this relation is still debated, but has historically been attributed to the strength of a galaxy’s potential well; galaxies with larger stellar masses, and thus larger escape velocities, are better at retaining metal-enriched gas (e.g., Larson, 1974; Dekel & Silk, 1986; Tremonti et al., 2004).

Interestingly, studies of low-redshift galaxies have found that metallicity has a secondary dependence on galaxy size, such that at a fixed mass, smaller galaxies have higher metallicities. This size dependence, which has been found in both star-forming (e.g., Ellison et al., 2008; Scott et al., 2017; Li et al., 2018; D’Eugenio et al., 2018) and quiescent (McDermid et al., 2015; Barone et al., 2018; Li et al., 2018) populations, reinforces the importance of the gravitational potential in regulating metallicity; at a given mass, smaller galaxies have steeper potential wells.

Whereas the star-forming MZR has been extensively studied out to $z \sim 3.5$ (e.g., Erb et al., 2006; Onodera et al., 2016; Sanders et al., 2020), the quiescent MZR has only been measured out to $z \sim 0.7$ (Gallazzi et al., 2014). Measuring robust metallicities of distant quiescent galaxies is extremely difficult and requires ultra-deep continuum spectroscopy, as it relies on faint absorption lines shifted to near-IR (NIR) wavelengths. Consequently, the few existing studies beyond low-redshift have large uncertainties and/or are based on stacked spectra (Gallazzi et al., 2014; Choi et al., 2014; Leethochawalit et al., 2019).

In this Letter, we utilize the public Large Early Galaxy Astrophysics Census (LEGA-C; van der Wel et al., 2016; Straatman et al., 2018), which has obtained ultra-deep continuum spectra (~ 20 hrs) for 1988 galaxies at $0.6 < z < 1$ in the COSMOS field using VIMOS on the Very Large Telescope with an average signal-to-noise ratio (S/N) of $S/N \sim 20 \text{ \AA}^{-1}$. We analyze the spectra using a full-spectrum modeling code. We then assess how the metal content of quiescent galaxies at $z = 0.59 - 0.75$ relate to their stellar masses and sizes, and study how these relations evolve between $z \sim 0.7$ and $z \sim 0$. Throughout this work we assume a flat Λ CDM cosmology with $\Omega_m = 0.29$ and $H_0 = 69.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

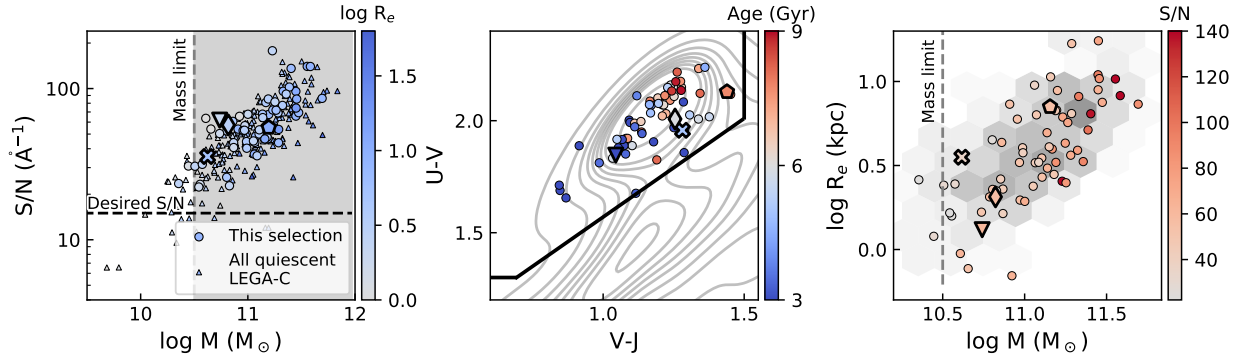


Figure 2.1: *Left*: the distribution of stellar mass and S/N at rest-frame $5000 \text{\AA}$ of all available quiescent LEGA-C galaxies in the redshift range $0.59 < z < 0.75$ colored by their half-light radius. Galaxies included in the final selection are identified. The 95% mass-limit ($\log M_{*}/M_{\odot} = 10.5$) and required rest-frame S/N ($= 15 \text{\AA}^{-1}$) are marked. Not all galaxies with $S/N > 15$ are included in the final sample, as we require that the spectra cover $\lambda = 4800 - 5430 \text{\AA}$. *Middle*: the selected sample in UVJ space colored by stellar age, as derived from `alf`. The contours represent the full LEGA-C sample. *Right*: the selected sample in mass-size space colored by S/N at rest-frame $5000 \text{\AA}$. The density map underneath shows the quiescent LEGA-C sample from the left panel. In all panels we highlight four galaxies using different symbols that correspond to the galaxies in Fig. 2.2.

2.3 Sample and Methods

We use deep continuum spectroscopy from the public Large Early Galaxy Astrophysics Census (LEGA-C), a survey of 3600 galaxies at $0.6 < z < 1$ selected from the UltraVISTA K-band catalog by Muzzin et al. (2013a). The deep, high-resolution spectra were collected using the VIMOS multiobject spectrograph at the ESO Very Large Telescope and have an average $S/N \sim 20 \text{\AA}^{-1}$. For more information on the survey design see van der Wel et al. (2016). For details on the observation and data reduction see Straatman et al. (2018).

We select quiescent galaxies from the second LEGA-C data release (1922 targets), based on the rest-frame $U - V$ and $V - J$ colors, as prescribed in Muzzin et al. (2013a). From the 751 quiescent galaxies, we make a selection based on the quality and wavelength range of the spectra. First, to ensure reliable abundance pattern measurements, we require each spectrum to contain at least two FeI features and one Balmer line ($H\beta$), translating to a required rest-frame wavelength coverage of $4800 \text{\AA} < \lambda < 5430 \text{\AA}$. This wavelength selection effectively sets an upper limit on the redshift ($z = 0.75$). We set the minimum redshift to $z = 0.59$, thereby removing spurious $z \sim 0.3$ galaxies. Second, we select galaxies with rest-frame $S/N > 15 \text{\AA}^{-1}$ as measured at $5000 \text{\AA}$. Finally, we visually inspect the 87 remaining spectra and remove five galaxies with obvious emission lines (which are likely active galactic nuclei (AGN) or chance alignments with a star-forming galaxy). The initial selection includes

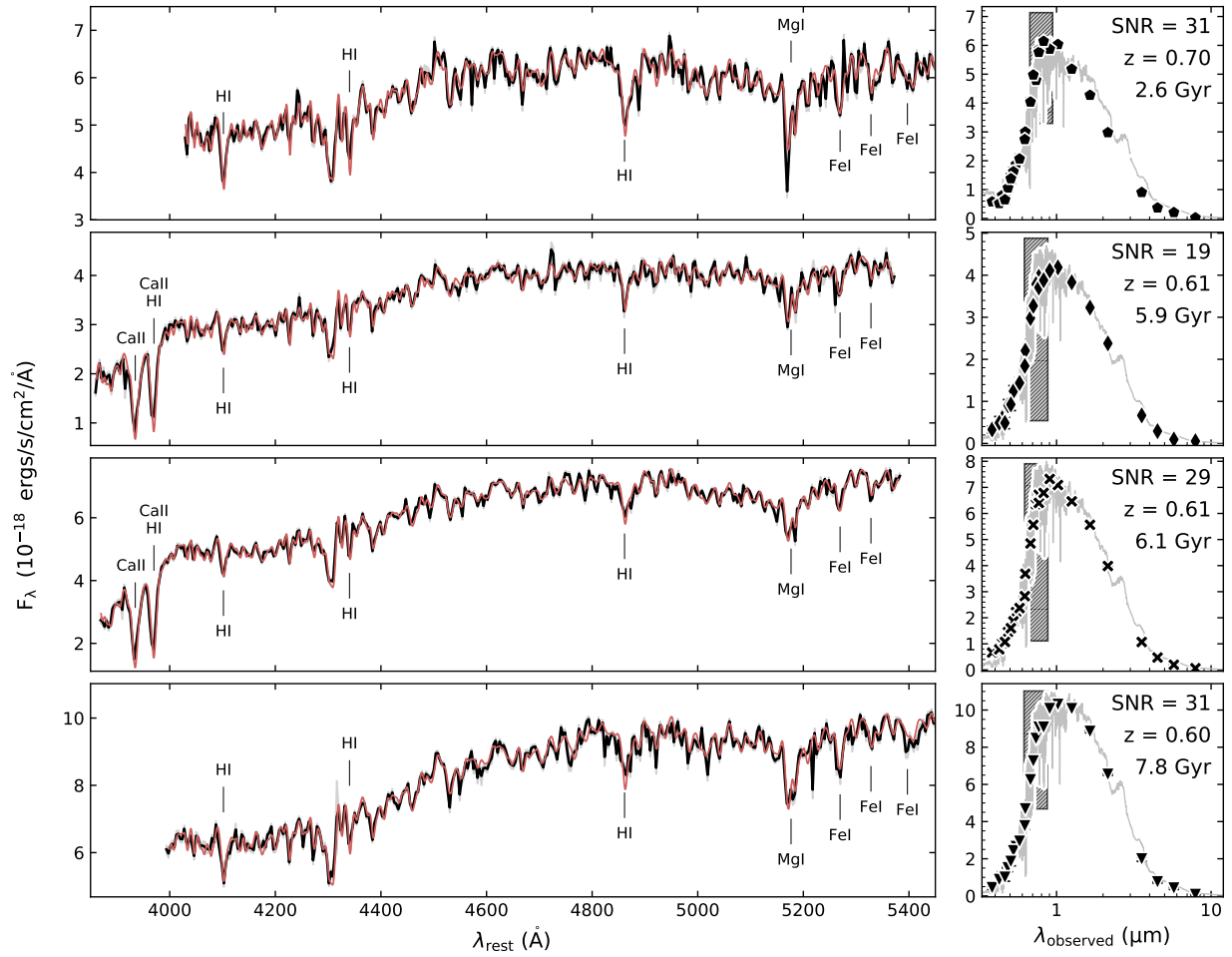


Figure 2.2: *Left*: LEGA-C spectra for four representative galaxies (black) with 1σ uncertainties in gray. For displaying purposes the spectra are binned by 10 pixels, corresponding to ~ 3.5 rest-frame $\text{\AA}$ per bin. The best-fit *alf* model is shown in red. *Right*: the corresponding photometry along with the best-fit FSPS model. The gray boxes represents the extent of the left panels. The S/Ns of the spectra are reported at rest-frame $5000 \text{ \AA}$ per rest-frame $\text{\AA}$. The symbols used for the photometry match those in Fig. 2.1.

82 quiescent galaxies for which we derive stellar masses and sizes.

Galaxy Sizes and Stellar Masses

We derive galaxy sizes from the *HST* ACS COSMOS F814W images (Scoville et al., 2007) by fitting a single-component Sérsic model with GALFIT (Peng et al., 2010). For each galaxy we make $25''$ cutouts and mask out nearby sources. Similar to the procedure in van der Wel

et al. (2014), the Sérsic index is constrained to the values $0.7 \leq n \leq 8$. We define galaxy size (R_e) as the semi-major axis of the ellipse containing half of the total flux of the best-fit model.

We visually inspect the resulting best-fit Sérsic models and residuals and remove one galaxy in a close pair and one with a disturbed morphology (likely due to a recent merger). Additionally, we remove three galaxies with GALFIT-derived Sérsic indices that hit the $n = 8$ constraint.

Next, we derive stellar masses by fitting UltraVISTA photometry with Flexible Stellar Population Synthesis (FSPS Conroy et al., 2009) templates using the FAST fitting code (Kriek et al., 2009). We assume a delayed exponentially declining star formation history, the Chabrier (2003) initial mass function (IMF), and the Kriek & Conroy (2013) dust attenuation law. We also assume solar metallicity to facilitate comparison to other studies. To test this last assumption, we take six metal-poor galaxies and refit their masses by fixing the template metallicities to the values derived from their spectra. The resulting masses do not change by more than 0.1 dex. Next, we correct the stellar masses such that they are consistent with the GALFIT profiles by multiplying them by the ratio of the GALFIT-derived F814W flux and the interpolated F814W flux from the photometric catalog. On average, this procedure increases the stellar mass by 4%. Furthermore, we increase the masses by 0.1 dex to correct for a systematic offset between the space-based 3D-*HST* and ground-based UltraVISTA photometry (see Mowla et al., 2019).

We determine a lower mass-limit using an iterative method. We first derive the relation between S/N and $\log M/M_\odot$ by fitting to all available quiescent galaxies at $0.59 < z < 0.75$ (272; see the left panel of Fig. 2.1). Using this fit, we take all galaxies above a given cutoff mass and calculate what their S/N would be if they had a mass equal to the cutoff mass. We then determine the S/N below which 5% of these scaled-down galaxies would not be included in the sample. We repeat this method, starting with a high cutoff mass and iterating down to lower masses. We find that at $M = 10^{10.5} M_\odot$ the sample is 95% complete for a S/N criterion of $15 \text{ \AA}^{-1}$. We note that at this redshift LEGA-C is representative of the full galaxy population down to $\log M/M_\odot = 10.4$.

Elemental Abundances

We derive the elemental abundances for the remaining 77 galaxies using the full-spectrum absorption line fitter (**alf**) code (Conroy et al., 2018). This method is preferred over the use of specific features (i.e., Lick indices) because it can leverage the entire spectrum and is better at dealing with (non-Gaussian) noise due to OH lines or instrumental artifacts. **alf** fits optical–NIR spectra of quiescent populations older than $\gtrsim 1$ Gyr and uses libraries of isochrones and empirical stellar spectra (Sanchez-Blazquez et al., 2006; Choi et al., 2016; Villaume et al., 2017), along with synthetic spectra covering a wide range of elemental abundances. In the analysis presented here, we use **alf** in *simple* mode, which fits for 13 parameters; a single stellar age, velocity dispersion, velocity offset, metallicity scaling, and the abundances of 9 elements (Fe, O, C, N, Na, Mg, Si, Ca, and Ti). We assume the Kroupa

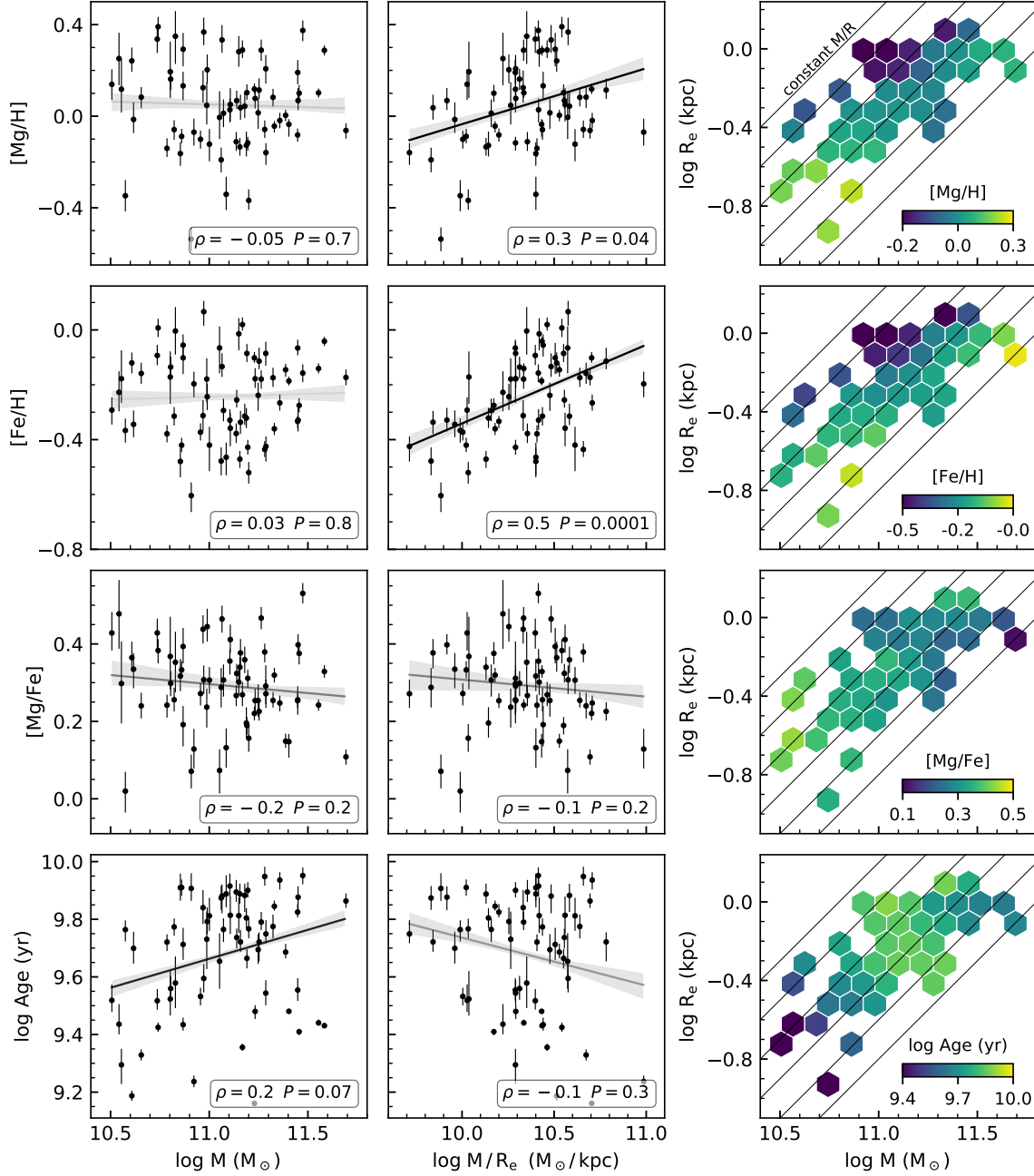


Figure 2.3: Correlation between [Mg/H], [Fe/H], [Mg/Fe], and stellar age with stellar mass (left) and M_*/R_e (middle). The right column shows the parameters on the mass-size plane, averaged using the LOESS algorithm. In the bottom right corner of these panels we show the P -value from a Spearman correlation test. Correlations with P -values less than $P < 0.05$ are considered significant. The best-fit linear relations are shown in each panel, with the shaded regions showing the 1σ confidence intervals. The transparency of the best-fit lines are a reflection of the P -value. [Mg/H] and [Fe/H] show no trend with M_* but are significantly correlated with M_*/R_e .

(2001) IMF, fit using a single burst star formation history, and use metallicity-independent response functions. We also set a maximum age of 10 Gyr, which is the age of the universe at $z = 0.75 +1$ Gyr.

Given the flexibility of `alf`, we run many tests to ensure the robustness of our measurements. These tests include: fitting without the age-sensitive CaII HK lines, allowing for two bursts of star formation, and with and without emission. The results of these tests are all within error of the analysis presented here.

After fitting, we visually inspect the best-fit `alf` models and the corresponding corner plots. Galaxies with unconstrained ages or metallicities, or those that run up against the upper-limit age prior are removed from the sample. Many of these galaxies have obvious skyline contamination near key absorption features. After removing these ten galaxies, along with the two galaxies that fall below the mass limit (see the left and right panels of Fig. 2.1), we are left with the final sample of 65 galaxies. The mean redshift of the sample is $z = 0.66$. Fig. 2.1 shows the distribution of the final sample in mass-S/N (left), UVJ (middle), and mass-size (right) space. Fig. 2.2 shows LEGA-C spectra along with their corresponding best-fit `alf` models for four representative galaxies.

2.4 Chemical abundances of $z \sim 0.7$ quiescent galaxies

In this section, we investigate the dependence of elemental abundances and stellar population ages on galaxy mass and size for quiescent galaxies at $z \sim 0.7$. In the left and middle columns of Fig. 2.3 we show $[\text{Mg}/\text{H}]$, $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, and age versus stellar mass and mass-to-radius ratio (M_*/R_e). We use M_*/R_e instead of velocity dispersion σ ($\propto M/R$), as the quiescent LEGA-C galaxies have been found to be partially rotationally supported (Bezanson et al., 2018). For each panel, we fit to all galaxies with a linear regression and measure their Spearman rank coefficient, where the confidence intervals are determined by perturbing each data point in the y-direction according to their uncertainties. Including the x -direction uncertainties (~ 0.1 dex) in the fits does not significantly change the results (see Kriek et al., 2016, for motivation of mass uncertainties). In the right column we show the mean trends of the stellar population parameters on the mass-size plane, where the properties have been smoothed using the Locally Weighted Regression (LOESS; Cleveland & Devlin, 1988) python package (Cappellari et al., 2013).

We first consider $[\text{Mg}/\text{H}]$ and $[\text{Fe}/\text{H}]$. Mg, an α -element, is almost exclusively produced in the cores of massive stars and released via core-collapse supernovae. Given the short lifetime of massive stars, Mg is almost instantaneously released and recycled and is thus a good tracer of the overall enrichment. Fe-peak elements are also produced in the cores of massive stars, but are predominantly forged during Type Ia supernovae. The latter descend from remnants of long-lived, low-mass stars, and as such, Type Ia supernovae products are only recycled if star formation is still ongoing. Thus, $[\text{Fe}/\text{H}]$ depends both on the overall metal enrichment *and* the duration of star formation. Interestingly, as seen in the first two rows of Fig. 2.3, both $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$ correlate with M_*/R_e , but not with M_* , despite

their different enrichment mechanisms. These trends are especially apparent in the mass-size panels.

Our results are consistent with studies at low- z that find a flattening of the quiescent MZR at the highest masses (Gallazzi et al., 2005; Peng et al., 2015), but show a strong increasing trend with M_*/R_e (Barone et al., 2018). Studies of high-mass quiescent galaxies at $z \sim 0.5$ find similarly shallow mass-[Fe/H] and mass-[Mg/H] relations for stacks of galaxies (Choi et al., 2014) and cluster galaxies (Leethochawalit et al., 2019). Gallazzi et al. (2014) also find a slope for the MZR consistent with zero at $z \sim 0.7$ using Lick indices; this is the only study of the quiescent MZR at a comparable redshift to this study.

Our results show, for the first time, that size plays an important role in regulating the elemental abundances of massive quiescent galaxies beyond $z \sim 0.1$; while the trends with M_* are mostly flat, we find strong correlations with M_*/R_e . This result implies that chemical enrichment is regulated by the strength of the potential well, as M_*/R_e is a better tracer of the gravitational potential than just M_* ($\Phi \propto M/R$). The flattening of the abundances with M_* is thought to be due to minor mergers, as more massive galaxies accrete more metal-poor satellites. This flattening is not as prominent in the M_*/R_e relations, possibly because compact metal-rich satellites sink to the center of progenitors, whereas diffuse metal-poor satellites distribute around the outskirts (Boylan-Kolchin & Ma, 2007; Amorisco, 2017). Thus, minor mergers may reinforce the M_*/R_e relations (see discussion in Barone et al., 2018).

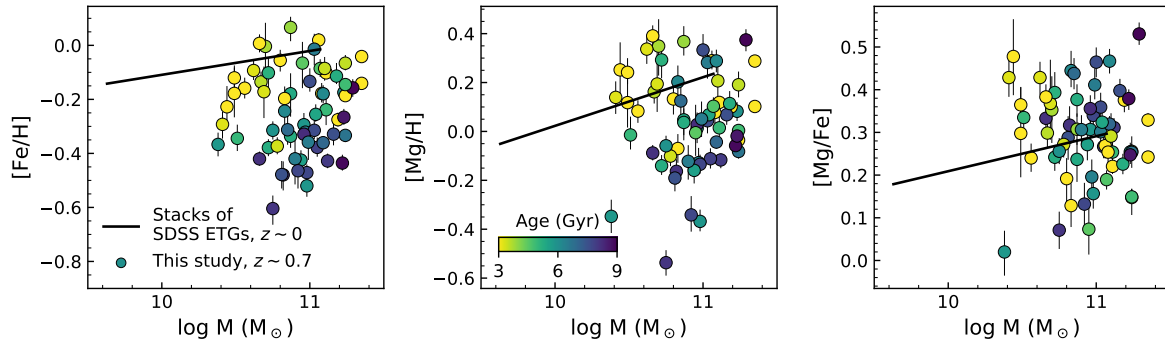


Figure 2.4: The mass-[Fe/H] (left), mass-[Mg/H] (center), and mass-[Mg/Fe] (right) relations colored by stellar age. The black lines show the results from stacks of local quiescent SDSS galaxies from Conroy et al. (2014). We find ~ 0.2 dex evolution in the mass-[Mg/H] and mass-[Fe/H] relations, and a clear trend between metallicity and stellar age at $z \sim 0.7$, such that younger galaxies are more metal rich. We find no such trend or evolution in the mass-[Mg/Fe] relation.

Next, we look at [Mg/Fe] and stellar population age. Since [Mg/H] and [Fe/H] enrich on different timescales, [Mg/Fe] is a direct tracer of how quickly a galaxy formed its stars. [Mg/Fe] is often discussed in tandem with age, as the combination of the two quantities

provides a strong constraint on when and how quickly galaxies formed their stellar mass. As shown in the bottom two rows of Fig. 2.3, $[\text{Mg}/\text{Fe}]$ does not correlate with M_* or M_*/R_e , while age marginally correlates with M_* .

Our $[\text{Mg}/\text{Fe}]$ and age results are similar to findings at low redshifts. At $z \sim 0$, the $M_*/R_e - [\text{Mg}/\text{Fe}]$ and $M_*/R_e - \text{age}$ trends are shallow and the mass- $[\text{Mg}/\text{Fe}]$ and mass-age relations flatten above $\log M_*/M_\odot \gtrsim 10.5$ (McDermid et al., 2015; Scott et al., 2017; Barone et al., 2018). Our results also agree with studies at $z \sim 0.5$ that find little to no correlation between mass and $[\text{Mg}/\text{Fe}]$, but a positive correlation between mass and age (Leethochawalit et al., 2019; Choi et al., 2014; Gallazzi et al., 2014), and no correlation between galaxy age and size (e.g., Zanella et al., 2016; Fagioli et al., 2016). Drawing from the same LEGA-C parent sample, Wu et al. (2018) find that at a fixed mass, smaller quiescent galaxies actually tend to be older using $D_n(4000)$, but they ignore the $D_n(4000)$ metallicity dependence. In this study, we find a strong correlation between metallicity and galaxy size, thus explaining larger $D_n(4000)$ for smaller galaxies.

Our age results imply that the integrated SFHs of all the stars currently in a galaxy (both in situ and accreted) only slightly depend on mass, with more massive galaxies forming at higher redshift. Our $[\text{Mg}/\text{Fe}]$ results indicate no clear trend between the star formation timescale and stellar mass. However, the interpretation is not straightforward, as both minor mergers and star formation timescales affect $[\text{Mg}/\text{Fe}]$. To break this degeneracy, studies need to push to higher redshifts, where the effect of mergers is less significant. Indeed, recent single-object studies have found that massive quiescent galaxies at $z \sim 2$ are extremely α -enhanced, a result that is in favor of evolution via minor mergers (Kriek et al., 2016; Jafariyazani et al., 2020).

2.5 Evolution in the Mass-Metallicity Relation

Next, we investigate the evolution of the quiescent MZR between $z \sim 0.7$ and $z \sim 0$. In Fig. 2.4 we show $[\text{Mg}/\text{H}]$, $[\text{Fe}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ as a function of stellar mass, colored by stellar population age. We compare these results with stacks of $z \sim 0$ Sloan Digital Sky Survey (SDSS) galaxies from Conroy et al. (2014) that have been fit using the procedure in Section 4.3. We find that, at a given mass, there is ~ 0.2 dex of evolution in both the mass- $[\text{Mg}/\text{H}]$ and mass- $[\text{Fe}/\text{H}]$ relations between $z \sim 0$ and $z \sim 0.7$, and that younger galaxies have higher $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$. Interestingly, at $z \sim 0.7$ Gallazzi et al. (2014) find no evolution using Lick indices. However, the uncertainties on their metallicities are significantly larger than in this work. At $z \sim 0.5$, Choi et al. (2014) and Leethochawalit et al. (2019) find that metal abundances are ~ 0.1 dex lower using full spectral modeling, in broad agreement with our results.

Since quiescent galaxies are, by definition, no longer forming stars, they are unable to change their stellar metallicities by star formation. Instead, metallicities can change by either minor mergers or population growth (i.e., progenitor bias). The observed MZR evolution cannot be explained by minor mergers, as the accretion of low-mass metal-poor satellites would

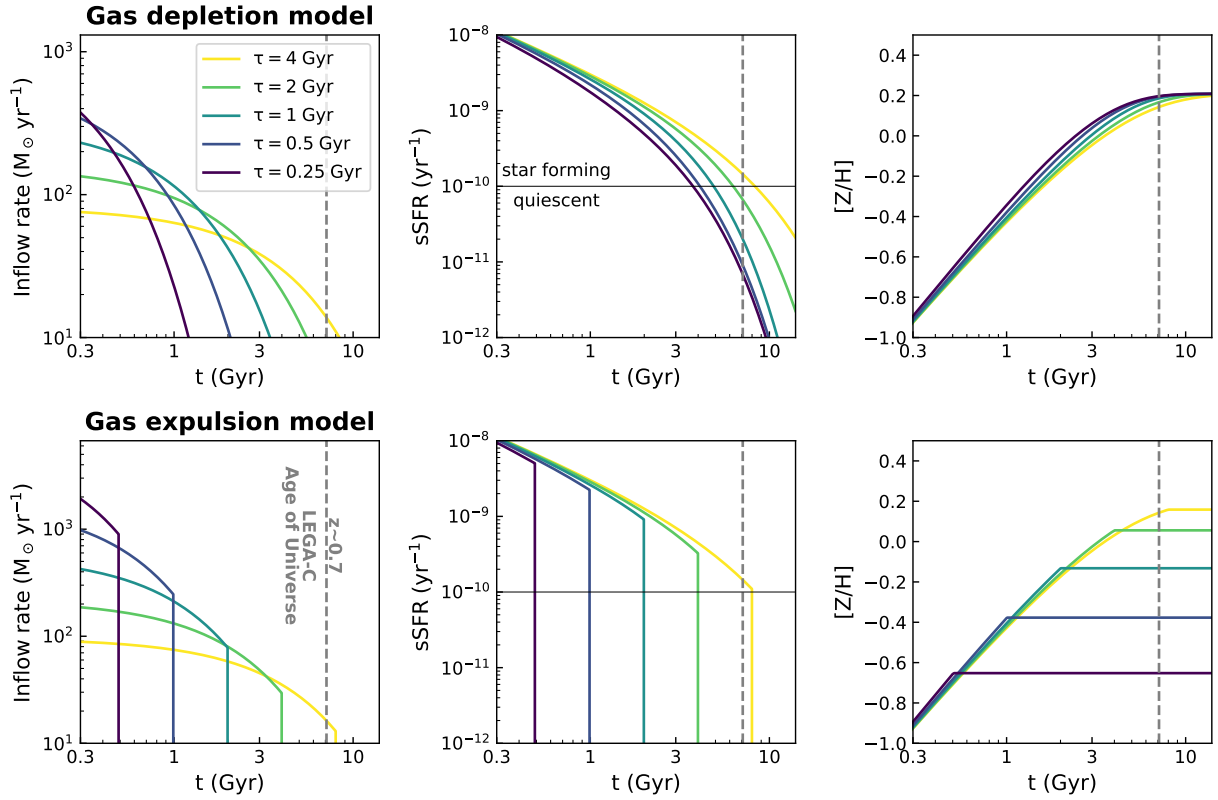


Figure 2.5: Results from a chemical evolution model with an exponentially declining inflow rate for five different inflow timescales, τ . The left, middle, and right panels show the inflow rate, specific SFR, and mass-weighted stellar metallicity $[Z/H]$, respectively. The top row is the “gas depletion” model with solutions directly from Spitoni et al. (2017). The bottom row is the “gas expulsion” model where inflows from the Spitoni et al. (2017) model are terminated and the remaining star-forming material is removed after two e -folding times. Both models assume a star formation efficiency $\epsilon = 0.5 \text{ Gyr}^{-1}$, a Chabrier (2003) IMF, and supernovae feedback with a mass-loading factor $\lambda = 1$. The gas expulsion model successfully reproduces both the observed age-metallicity trend and the MZR evolution.

decrease the metallicity of the progenitor galaxy. Progenitor bias, in contrast, can explain the observed evolution only if galaxies that quench at later times also have higher metallicities. Indeed in Fig. 2.4 we observe that younger galaxies have higher $[\text{Mg}/\text{H}]$ and $[\text{Fe}/\text{H}]$.

To understand why galaxies that quench at later times have higher metallicities, we turn to chemical evolution models. We utilize solutions from Spitoni et al. (2017), which assume an exponentially decreasing inflow rate with timescale τ , a linear Schmidt (1959) law, and an outflow rate proportional to the star formation rate (SFR) with a mass-loading factor λ . In the first row of Fig. 2.5 we show solutions for the inflow rate, SFR, and mass-weighted metallicity for model galaxies with five different inflow timescales and a constant mass-loading factor of $\lambda = 1$. In the second row of Fig. 2.5 we show the same five model galaxies, except the star formation and gas inflows are instantaneously terminated after two e -folding times (e.g., AGN feedback). Thus, the first model represents quenching via smooth gas depletion, while in the second model the quenching happens much more abruptly via gas expulsion¹, in particular for early quenchers. In both models, the four galaxies with the shortest star-formation timescales would be identified as quiescent at the LEGA-C redshift, whereas the fifth and youngest model with the highest metallicity would only be added to the quiescent population at later times (thus identified as quiescent by $z = 0$).

In the smooth gas depletion model, all quiescent galaxies end up with the same high metallicity by $z = 0$ no matter their star formation timescale. Thus, this model fails to reproduce the observed evolution. One way to prevent the galaxies from converging to the same metallicity is to vary the mass-loading factor such that at a constant mass galaxies with the shortest inflow timescales have $10x$ more efficient outflows than galaxies with the longest inflow timescale. Given that the mass-loading factor is thought to be primarily driven by galaxy mass (e.g., Dekel & Silk, 1986), and that here we are considering models at the same mass, this large difference in outflow efficiency is unlikely.

In the gas expulsion model we find that the younger galaxies – those that quench at later times – are more metal enriched. Galaxies that quench at earlier times shut off their star formation when the inflow rate is still high and thus the gas-phase metallicity is still low. The galaxies that quench at later times, however, have a lower inflow rate and thus higher gas-phase metallicity when they quench, leading to a higher stellar metallicity. The $[\text{Z}/\text{H}]$ panel shows that the gas expulsion model is successful at reproducing the observed age-metallicity trend found in Fig. 2.4. The same model can also explain the observed MZR evolution; galaxies that quench before $z \sim 0.7$ have lower metallicities than those that quench at later times. Thus, in this model, the average metallicity of the quiescent population increases over cosmic time.

Finally, we turn to $[\text{Mg}/\text{Fe}]$. In the right panel of Fig. 2.4 we find no $[\text{Mg}/\text{Fe}]$ evolution between $z \sim 0.7$ and $z \sim 0$, and no clear trend with age. This result is consistent with the work by Leethochawalit et al. (2019) and Choi et al. (2014) who find little to no $[\text{Mg}/\text{Fe}]$ evolution out to $z \sim 0.54$. The lack of $[\text{Mg}/\text{Fe}]$ evolution is hard to interpret because it can

¹The star formation quenching does not need to be instantaneous, and can instead be modeled as a leaky box with a large mass-loading factor.

be affected by both the star formation history and minor mergers. Both processes should decrease the mass-[Mg/Fe] relation over time; however, in reality, these effects are subtle due to the shallowness of the mass-[Mg/Fe] relation and the weakened sensitivity of [Mg/Fe] at longer star formation timescales. In order to disentangle both effects, we need to push current studies to higher redshifts, where the effects of mergers are less significant and the difference in star formation histories are easier to measure.

2.6 Summary and Conclusion

In this Letter we derive chemical abundances and stellar population ages for 65 massive quiescent galaxies from the LEGA-C survey at $z \sim 0.7$ and examine them as a function of mass and size. We find that [Mg/H] and [Fe/H] do not vary with M_* but are correlated with M_*/R_e , reinforcing the picture that the strength of the gravitational potential was instrumental in regulating their chemical enrichment. We also find that age and M_* are marginally correlated, but that [Mg/Fe] does not vary with M_* . These results suggest that star formation timescales are independent of mass and size but that more massive galaxies formed their stars earlier.

Through comparison with stacks of $z \sim 0$ quiescent galaxies from SDSS, we find that the mass-[Mg/H] and mass-[Fe/H] relations increased by ~ 0.2 dex since $z \sim 0.7$. Furthermore, we find that older galaxies at $z \sim 0.7$ have lower metallicities. The observed evolution and age trend can be explained in a chemical evolution model where galaxies quench via a major outflow event (e.g., AGN feedback).

This study was enabled by the ultra-deep LEGA-C spectra, which, in combination with full-spectrum modeling techniques, has provided the most robust measurements of chemical abundances at $z \sim 0.7$. Our results highlight how ultra-deep spectra can be harnessed to uncover the star-formation and chemical-enrichment histories of quiescent galaxies, and further demonstrate that metallicities can be used to constrain star-formation quenching models (see also Peng et al., 2015; Spitoni et al., 2017; Trussler et al., 2020). In the future, ultra-deep ground-based surveys and JWST/NIRSpec will enable the extension of this analysis to higher redshift, allowing for better constraints on the quiescent MZR, its evolution, and its dependence on galaxy size.

Chapter 3

From Carbon to Cobalt: Chemical Compositions and Ages of $z \sim 0.7$ Quiescent Galaxies

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

3.1 Abstract

We present elemental abundance patterns (C, N, Mg, Si, Ca, Ti, V, Cr, Fe, Co, and Ni) for a population of 135 massive quiescent galaxies at $z \sim 0.7$ with ultra-deep rest-frame optical spectroscopy drawn from the LEGA-C survey. We derive average ages and elemental abundances in four bins of stellar velocity dispersion (σ_v) ranging from 150 km s^{-1} to 250 km s^{-1} using a full-spectrum hierarchical Bayesian model. The resulting elemental abundance measurements are precise to 0.05 dex. The majority of elements, as well as the total metallicity and stellar age, show a positive correlation with σ_v . Thus, the highest dispersion galaxies formed the earliest and are the most metal-rich. We find only mild or non-significant trends between $[X/\text{Fe}]$ and σ_v , suggesting that the average star-formation timescale does not strongly depend on velocity dispersion. To first order, the abundance patterns of the $z \sim 0.7$ quiescent galaxies are strikingly similar to those at $z \sim 0$. However, at the lowest velocity dispersions the $z \sim 0.7$ galaxies have slightly enhanced N, Mg, Ti, and Ni abundance ratios and earlier formation redshifts than their $z \sim 0$ counterparts. Thus, while the higher-mass quiescent galaxy population shows little evolution, the low-mass quiescent galaxies population has grown significantly over the past six billion years. Finally, the abundance patterns of both $z \sim 0$ and $z \sim 0.7$ quiescent galaxies differ considerably from theoretical prediction based on a chemical evolution model, indicating that our understanding of the enrichment histories of these galaxies is still very limited.

3.2 Background

The chemical composition of a galaxy reflects the complex interplay of many factors such as inflow rate of gas, outflow rate of metal-rich gas, star formation efficiency, and merger history. Whereas the composition of interstellar *gas* in a galaxy provides an instantaneous snapshot of its metal-content, the composition of its *stars* encodes the integrated enrichment of the gas over its entire star-formation and assembly history. Thus, the chemical makeup of the stars in a galaxy is a powerful probe of their star-forming and assembly histories (e.g. Maiolino & Mannucci, 2019, and references therein). Stellar chemical abundances are a particularly effective probe in quiescent galaxies, which have prominent stellar absorption features.

Stellar population modeling and elemental abundances at $z \sim 0$ have yielded crucial insights into the formation and evolution of the massive quiescent galaxy population. One important finding is that the most massive quiescent galaxies in the local universe are also the most metal-rich (e.g. Trager et al., 2000; Gallazzi et al., 2005; Thomas et al., 2005). This finding is thought to reflect the strength of the gravitational potential of the galaxy; supernovae explosions and stellar winds in galaxies with deeper potential wells are less effective at removing metal-rich gas (e.g. Larson, 1974; Dekel & Silk, 1986; Tremonti et al., 2004). Massive quiescent galaxies are also found to be the oldest and most enriched in α -elements as traced by the ratio $[\alpha/\text{Fe}]$ (e.g. Thomas et al., 2005; Conroy et al., 2014; McDermid et al., 2015). $[\alpha/\text{Fe}]$ reflects the relative enrichment by prompt core-collapse and delayed Type Ia supernovae and thus directly probes the star-formation timescale of a galaxy (Matteucci, 1994; Trager et al., 2000). These results imply that the most massive galaxies in the local universe formed the bulk of their stars earliest and over the shortest timescales. Finally, detailed elemental abundance patterns have helped reveal the nucleosynthetic origins of various elements in massive galaxies. For example, there are indications that Fe-peak element Co may have significant contribution from core-collapse (Conroy et al., 2014), while the α -elements Ca and Ti may have significant contribution from Type Ia supernovae (e.g. Saglia et al., 2002; Thomas et al., 2003; Graves et al., 2007; Johansson et al., 2012).

Whereas unresolved archaeological studies of $z \sim 0$ galaxies have revealed a lot about the formation of quiescent galaxies, they also have their drawbacks. First, the abundances of stars in nearby galaxies only tell us about the star-formation histories of *all* the stars currently in the galaxy, including younger and metal-poor stars accreted during late-time mergers. And second, inferring ages and star-formation histories becomes increasingly more difficult for old stellar populations. To overcome these challenges we must study the chemical compositions of galaxies at earlier epochs. Unfortunately, detailed stellar population modeling requires ultra-deep spectroscopy of the stellar continuum emission. As we push to higher redshift, the required signal-to-noise ratio (S/N) becomes increasingly expensive to reach. For this reason, the few existing studies of chemical abundances and stellar population properties of massive galaxies beyond $z \sim 0$ have small sample sizes and only focus on a total metallicity, age, and sometimes an α -abundance (e.g. Gallazzi et al., 2014; Kriek et al., 2016; Leethochawalit et al., 2019; Kriek et al., 2019; Jafariyazani et al., 2020; Beverage et al., 2021; Carnall et al.,

2022). Only Choi et al. (2014) measured additional abundances (C, N, and Ca) by stacking quiescent SDSS galaxies out to $z \sim 0.7$.

The Large Early Galaxy Astrophysics Census (LEGA-C) survey is a major step forward in characterizing the $z \sim 0.7$ massive galaxy population (van der Wel et al., 2016; Straatman et al., 2018; van der Wel et al., 2021). With ultra-deep continuum spectra for thousands of massive galaxies at $0.6 < z < 1.0$ it is now finally possible to measure detailed elemental abundances and stellar population properties from absorption line spectroscopy. Here we apply full-spectrum stellar population modeling to the LEGA-C sample, and present detailed abundance patterns of quiescent galaxies at $z \sim 0.7$. We employ a hierarchical Bayesian method to measure the average abundances for galaxies in bins of velocity dispersion. Additionally, we revisit the $z \sim 0$ SDSS stacks from Conroy et al. (2014) and re-fit them updated stellar population synthesis (SPS) models. We compare the updated $z \sim 0$ abundance patterns with what we find at $z \sim 0.7$ to probe the evolution of massive quiescent galaxies over the last six billion years.

The paper is organized as follows. In Section 6.3 we discuss the data and sample selection, in Section 3.4 we describe the fitting methods, and in Section 5.4 we present the abundance results. A discussion of our results and a comparison to SDSS are presented in Section 3.6, along with a summary in Section 3.8. Throughout this work we assume a flat Λ CDM cosmology with $\Omega_m = 0.29$ and $H_0 = 69.3 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and Solar abundances of Asplund (2009), such that $Z_\odot = 0.0142$.

3.3 Data

LEGA-C

We select our sample from the third data release of the Large Early Galaxy Census (LEGA-C) Public Spectroscopic Survey (van der Wel et al., 2016; Straatman et al., 2018; van der Wel et al., 2021). LEGA-C is a deep spectroscopic survey targeting 3528 galaxies at intermediate redshifts ($0.6 \lesssim z \lesssim 1.0$) in the COSMOS footprint (Scoville et al., 2007). The galaxies were selected from the public UltraVISTA catalog (Muzzin et al., 2013a) using a redshift-dependent K_s magnitude limit, which range from $K_s = 21.0 - 20.4$. The 20-hr spectra were collected using VIMOS on the VLT, and have an average continuum S/N of $20 \text{ \AA}^{-1}$. For further details on survey design, we refer to Straatman et al. (2018), and for details regarding the specifics of DR3 we refer to van der Wel et al. (2021).

Stellar masses and rest-frame colors

We measure stellar masses and rest-frame colors using the multi-wavelength UltraVISTA photometric catalog (Muzzin et al., 2013a). We determine rest-frame UVJ colors using EAZY (Brammer et al., 2008) and measure stellar masses with the **FAST** fitting code (Kriek et al., 2009), fixing the input redshifts to the spectroscopic redshifts provided in the LEGA-C catalog. In the **FAST** fitting we use Flexible Stellar Population Synthesis (Conroy et al.,

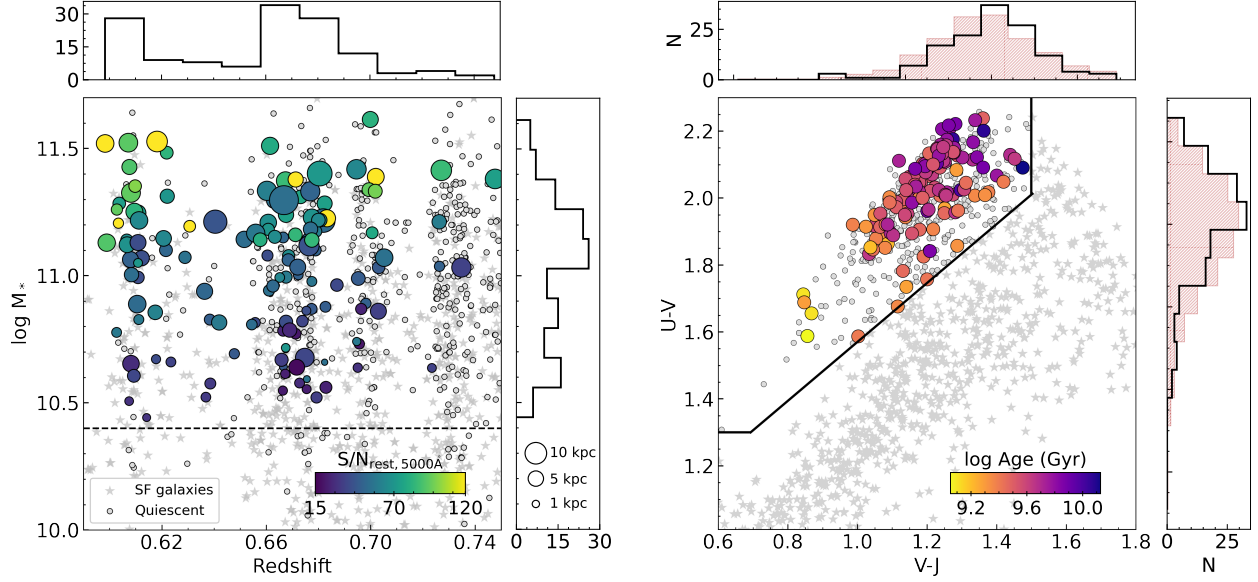


Figure 3.1: *Left:* The selected sample in redshift vs stellar mass space, colored by S/N at rest-frame $5000\text{\AA}$. The sizes of each point correspond to the physical half-light radius of the object, with the smallest and largest circles representing 1 kpc and 10 kpc, respectively. At higher redshift, fewer quiescent galaxies are included in the sample, as they do not reach the required wavelength range of $5350\text{\AA}$. The dashed line shows the 90% mass-completeness limit ($\log M/M_\odot = 10.4$). *Right:* The selected sample in UVJ space, colored by best-fit stellar ages from `alf`. For comparison, both panels show the full LEGA-C dataset for the selected redshift range ($0.6 < z < 0.75$). The small stars represent star-forming galaxies, and small circles are quiescent, according to their position on the UVJ diagram (Muzzin et al., 2013b). The black histograms show the distribution of the selected sample along each axis. For the UVJ panel we also include distributions of the quiescent LEGA-C dataset in red, normalized to the area of the black histograms.

2009, FSPS) templates, assuming a delayed exponentially declining star formation history, the Chabrier (2003) initial mass function (IMF), the Kriek & Conroy (2013) dust attenuation law, and solar metallicity. The impact of using solar metallicity and solar-scaled abundance pattern templates on stellar mass estimates is further explored in Beverage et al. (*in prep*). Finally, we correct the stellar masses such that they are consistent with the best-fit Sérsic profiles by multiplying the stellar masses by the ratio of the Sérsic model flux in F814W and the interpolated F814W flux from the photometric catalog (e.g. Taylor et al., 2010). On average, this procedure increases the stellar mass by 4%. We compare our corrected FAST stellar masses to those derived using MAGPHYS (da Cunha et al., 2008; de Graaff et al., 2021) and find no systematic offset and a scatter that is consistent with the uncertainties on individual stellar mass measurement (~ 0.1 dex). We refer to de Graaff et al. (2021) for a detailed comparison of the two methods.

Sample selection

We use the stellar masses and rest-frame colors to select a mass-complete quiescent galaxy sample from the LEGA-C catalog. We begin by requiring each galaxy spectrum to cover $H\beta$, Mgb , and at least two FeI features (rest-frame $4300 \text{ \AA} < \lambda < 5340 \text{ \AA}$), which translates to a redshift limit of $z < 0.75$. This wavelength regime is crucial for accurately modeling the Mg and Fe abundances. Next, we classify galaxies as quiescent and star-forming using the rest-frame $U-V$ and $V-J$ colors and the selection criteria from Muzzin et al. (2013b). After removing the star-forming galaxies, we enforce a 95% completeness limit of $\log M/M_{\odot} = 10.4$ corresponding to a S/N limit of $15 \text{ \AA}^{-1}$ following the procedure outlined in Beverage et al. (2021). The completeness limit matches what is found in van der Wel et al. (2021) at $z \sim 0.65$.

The above selection criteria produce a mass-complete sample of 135 quiescent galaxies. The right panel of Figure 3.1 shows the selected sample in UVJ space, along with the full LEGA-C dataset at $0.6 < z < 0.75$. The left panel of Figure 3.1 shows the sample in redshift vs stellar mass space, colored by the S/N at rest-frame $5000 \text{ \AA}$. The size of each point represents the physical half-light radius in kpc as measured in *HST* ACS F814W (rest-frame $\sim 5000 \text{ \AA}$) from the public LEGA-C catalog. Briefly, sizes were measured from $10''$ cutouts by fitting a single-component Sérsic profile to the public COSMOS imaging (Scoville et al., 2007) using *galfit* (Peng et al., 2010) (for details refer to van der Wel et al., 2012, 2016). The bias of our selection towards galaxies at lower redshifts is due to the imposed spectral range criterion.

To illustrate the quality of the LEGA-C spectra, we split the galaxies into four bins of velocity dispersion and stack their spectra. The velocity dispersions are taken from the LEGA-C DR3 catalog. In order to combine spectra with different continuum shapes and normalizations, we first divide each spectrum by an $n = 7$ polynomial. We find that polynomials with degree $4 < n < 9$ successfully remove the broad continuum shape of the spectra while preserving their absorption features. Next, we smooth each spectrum to a common velocity broadening by convolving each spectrum with a Gaussian kernel to achieve an effective dispersion of 300 km s^{-1} . The continuum-normalized and smoothed spectra are coadded by taking the median flux at each wavelength.

The stacked spectra are shown in the top panel of Figure 3.2. In the bottom panel we show the flux of each stack divided by the flux of the lowest velocity dispersion bin. While the differences between the stacked spectra are small, the combined S/N of the LEGA-C spectra reveal subtle trends; the Balmer lines become shallower with increasing velocity dispersion, while the MgI and CH features become deeper. By eye it is impossible to untangle whether these trends with velocity dispersion are due to underlying trends with age, metallicity, or both; we turn to full-spectrum hierarchical Bayesian modeling to quantify the age, metallicity, and individual abundances separately.

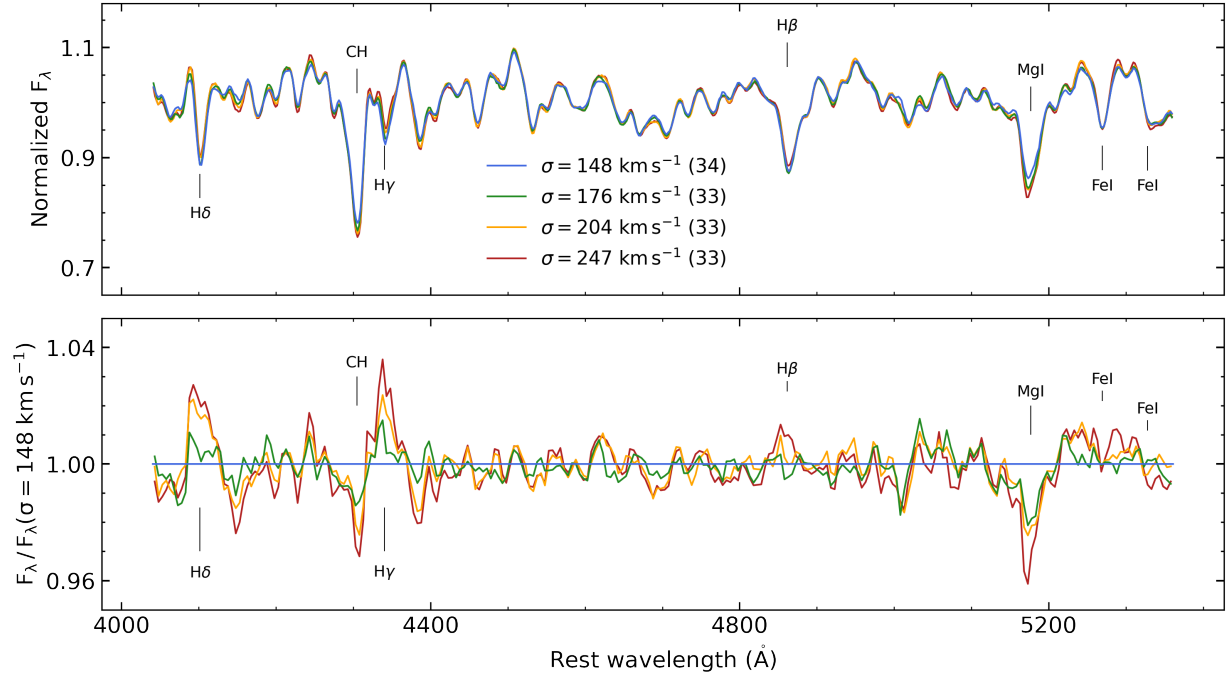


Figure 3.2: Continuum-normalized stacked LEGA-C spectra in bins of increasing velocity dispersion. Before stacking, each spectrum is smoothed to the same velocity dispersion (300 km s^{-1}). The lower panel shows the ratio of the flux in each stack divided by the flux of the lowest velocity dispersion bin. The listed velocity dispersions in the legend are the median observed values of the individual galaxies in each bin. In parenthesis we list the number of individual spectra that went into each stack. These stacked spectra are not fit directly (see Section 3.4), but demonstrate the high quality of the LEGA-C spectra. It is clear from both panels that galaxies with larger velocity dispersions have deeper metal features and shallower Balmer lines.

SDSS comparison sample

We use the early-type galaxies from SDSS of Conroy et al. (2014, C14) as a low-redshift comparison sample. Conroy et al. (2014) stacked thousands of massive early-type galaxies in bins of velocity dispersion and measured their abundance patterns. In this paper we use the same stacks but re-fit the spectra with updated stellar population models (see next section). We refer to Conroy et al. (2014) for details on their sample selection and stacking method. Briefly, the galaxies were selected from the SDSS Main Galaxy Survey Data Release 7 (Abazajian et al., 2009) within the redshift interval $0.025 < z < 0.06$. Passive galaxies were identified by requiring no emission in H α or [OII] $\lambda 3727$, and the sample was further restricted to galaxies that lie on the Fundamental Plane (FP) as defined by the central FP slice in Graves & Faber (2010). The LEGA-C quiescent galaxies in the current study

were instead selected based on their UVJ colors only and not emission line fluxes, mainly because most of the LEGA-C spectra do not cover the $H\alpha$ and $[\text{OII}]\lambda 3727$ lines. However, Maseda et al. (2021) show that most quiescent galaxies in LEGA-C with $[\text{OII}]\lambda 3727$ coverage indeed have detected nebular low-ionization emission most likely originating from evolved stars (i.e., post-AGB and blue horizontal branch stars) and not low-level star-formation. Furthermore, at low-redshift it has been shown that this emission is unlikely to originate from low-luminosity AGN (Yan & Blanton, 2012).

The SDSS spectra were continuum-normalized and convolved to an effective velocity dispersion of 350 km s^{-1} before stacking. At this redshift, the SDSS fiber samples the inner $\sim 0.5 R_e$, whereas the LEGA-C slit on average samples slightly larger than $1 R_e$ in the wavelength direction. The slit still captures a fraction of light at large radii in the spatial direction, however due to optimal extraction weighing, the spectra are still dominated by the centers. We discuss the implications of this aperture difference in Section 3.6.

3.4 Model Fitting

Full-spectrum modeling with `alf`

We derive stellar population parameters using the full-spectrum absorption line fitter code `alf` (Conroy & van Dokkum, 2012; Conroy et al., 2018). `alf` generates models by combining the metallicity-dependent MIST isochrones (Choi et al., 2016) with the MILES and Extended-IRTF empirical stellar libraries (Sanchez-Blazquez et al., 2006; Villaume et al., 2017). To adjust the stellar libraries for abundance variations in individual elements, `alf` uses metallicity- and age-dependent synthetic response functions to determine the fractional change in spectra due to the variation of each individual element. To match the continuum shape of the input spectrum to the `alf` models, a high-order polynomial with degree n , where $n \equiv (\lambda_{\text{max}} - \lambda_{\text{min}})/100 \text{ \AA}$, is fit to the ratio of data/model (see Conroy & van Dokkum, 2012, for details). This polynomial is then divided by the input spectrum. The posteriors are computed on the continuum-matched input spectrum using Markov-Chain Monte Carlo (MCMC) as implemented by the `emcee` package (Foreman-Mackey et al., 2013).

In this study, we configure `alf` with a Kroupa (2001) IMF and a single stellar population age. In total, we fit for 33 parameters with `alf`: recessional velocity, line-of-sight velocity dispersion (LOSVD) and corresponding hermite parameters h_3 and h_4 , a single stellar population age, a scaling metallicity, 19 individual elemental abundances (Fe, C, N, O, Na, Mg, Si, Ca, Ti, K, V, Cr, Mn, Ni, Co, Sr, Ba, Eu), six emission line fluxes (Balmer lines, $[\text{OII}]$, $[\text{OIII}]$, $[\text{SII}]$, $[\text{NI}]$, and $[\text{NII}]$), and two nuisance parameters (a temperature shift applied to the fiducial isochrones and a “jitter” term that accounts for over- or under-estimated uncertainties on the data). fix the IMF to Kroupa (2001). For the MCMC fits we use 1024 walkers with a 20,000-step burn-in and assume uniform priors on all model parameters. In Figure 3.4 we show the results from the individual fits for $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$ and stellar age. These results are used in the next section to derive the average abundances and stellar ages

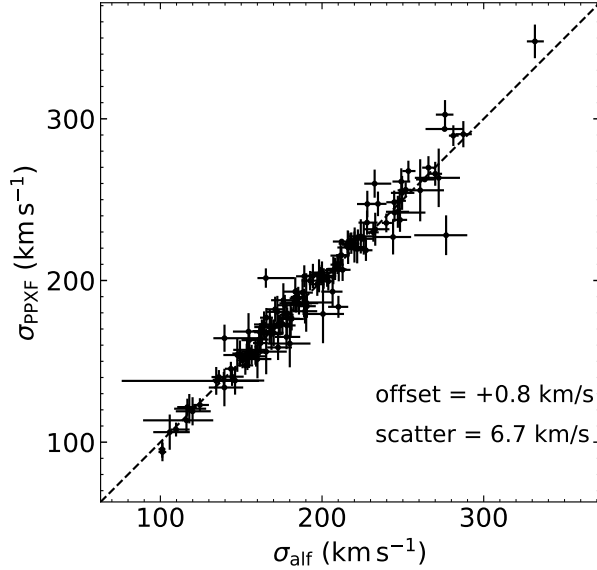


Figure 3.3: Comparison between velocity dispersions from `alf` (this study) and from PPXF (reported by the LEGA-C team). Both methods use full-spectrum modeling, but with different underlying stellar libraries. The two methods are in good agreement.

in bins of velocity dispersion. Example LEGA-C spectra with corresponding best-fit models can be found in Beverage et al. (2021).

In Section 3.7 we test the robustness of our fitting by simulating LEGA-C spectra and attempting to retrieve the true values with `alf`. This test is used to determine which element can be confidently constrained. We only include parameters with reduced $\chi^2 < 2$ and uncertainties < 0.15 dex. For the LEGA-C spectra, that includes 11 out of the 19 elements (C, N, Mg, Si, Ca, Ti, V, Cr, Fe, Co, and Ni).

In Figure 3.3 we compare the velocity dispersions derived using `alf` with the publicly-available LEGA-C values measured using PPXF (Cappellari & Emsellem, 2004; Cappellari, 2017; Bezanson et al., 2018; Cappellari, 2022). Both methods use full-spectrum fitting, but differ in their underlying model assumptions and stellar libraries. Nonetheless, the velocity dispersions are in very good agreement, with the offset nearly zero, and the scatter of the data consistent with the errors on the individual measurements.

As an independent check of our stellar age measurements we show the selected sample in UVJ space colored by the best-fit stellar ages from `alf`. It is clear that the oldest `alf` ages correspond to the redder UVJ colors and thus older ages (see Belli et al., 2019). This result is reassuring given that the UVJ ages – measured using the continuum shape – are independent from the `alf` ages, which rely solely on absorption features.

Conroy et al. (2014) also use `alf` to measure the stellar population parameters and

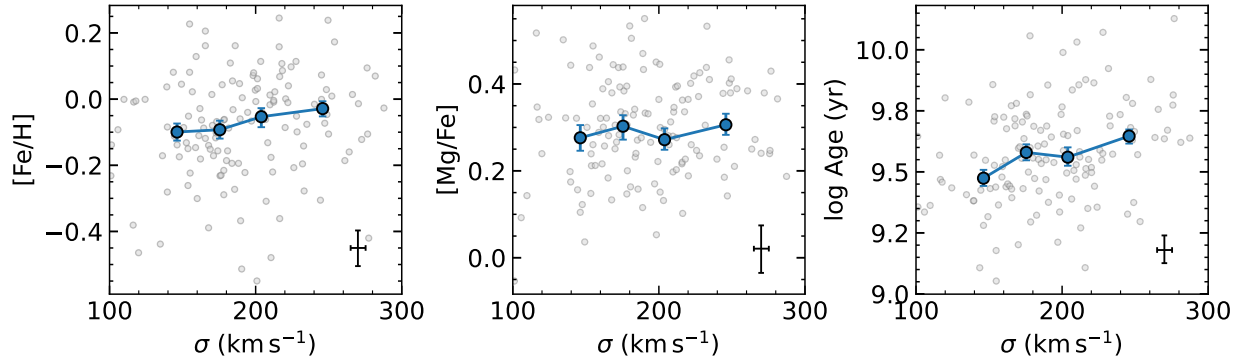


Figure 3.4: The $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, and stellar age results for the individual galaxies in our sample (gray). Typical errorbars are shown in bottom right corner of each panel. As described in Section 3.4, the PDFs from the individual fits are used in the hierarchical Bayesian model to derive average abundances and ages in bins of σ_v . The blue points show the results of this modeling.

elemental abundances of the stacks of massive early-type galaxies. However, since the publication of Conroy et al. (2014) several ingredients in the **alf** models have seen improvements, such as metallicity- and age-dependent response functions, along with updated isochrones and empirical spectral libraries (Villaume et al., 2017; Conroy et al., 2018). Thus, we re-fit the stacked SDSS spectra with the improved **alf** models using identical settings to the LEGA-C spectra. We test various **alf** settings to ensure the SDSS results are not affected by fitting decisions. Our tests include fitting with a hot star component, setting the IMF as a free parameter, and adding a young stellar population component. The abundance results are affected by only < 0.05 dex, however the addition of the hot star component results in unrealistic ages. Thus, we turn off the hot star component for both LEGA-C and SDSS fitting.

SDSS covers a much redder wavelength range than LEGA-C and thus we also investigate the impact of different spectral fitting regions on the **alf** results. When we limit the SDSS spectral range ($0.38\mu\text{m} - 0.64\mu\text{m}$ and $0.80\mu\text{m} - 0.88\mu\text{m}$) to match LEGA-C ($0.38\mu\text{m} - 0.54\mu\text{m}$) we find that the results are consistent but the uncertainties on the individual measurements increase as expected.

We also compare our LEGA-C abundance results to those from the previous data release (DR2 van der Wel et al., 2016) presented in Beverage et al. (2021). Beverage et al. (2021) measured individual Mg- and Fe-abundances and stellar population ages using the same **alf** setup as described here. However, since DR2, the LEGA-C catalog has nearly doubled in size and the spectrum reduction pipelines have since been updated (van der Wel et al., 2021). We compare the 65 overlapping galaxies in the Beverage et al. (2021) sample and the sample presented in this paper. Interestingly, we find ~ 0.2 dex difference in the absolute abundance measurements $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$, while the $[\text{Mg}/\text{Fe}]$ and age measurements are

consistent. Upon closer inspection, the DR3 spectra indeed have deeper absorption features, as measured by their equivalent widths. This difference is likely due to improvements in the background subtraction and object extraction algorithms between DR2 and DR3. Further testing of systematic uncertainties on absolute abundances is required, and thus here we restrict the discussion between the $z \sim 0.7$ and $z \sim 0$ samples solely to the abundances ratios $[X/Fe]$. Nonetheless, we caution that this type of work can be extremely sensitive to background subtraction.

Average ages and abundances of $z \sim 0.7$ galaxies from hierarchical Bayesian modeling

In the previous section we derived stellar population properties and elemental abundances for individual LEGA-C galaxies. To assess the abundances of many more elements than possible for an individual galaxy, we derive averages using hierarchical Bayesian modeling. This approach has several advantages compared to fitting a stacked spectrum as shown in Section 3.7. First, we do not have to smooth the spectra to a common velocity dispersion; smoothing introduces correlated noise and smooths out the absorption features. And second, we do not have to interpolate the spectra or remove the continuum by fitting polynomials, both of which introduce more correlated noise and may result in signal that is not real.

To overcome these concerns, we turn to hierarchical Bayesian modeling. In a hierarchical framework, models can be defined to have multiple “levels,” wherein the first level describes individual observations and the second level describes how the individual observations are distributed as a group. The individual- and population- level parameters can be evaluated simultaneously using Bayes’ Theorem,

$$P(\theta|X) = \frac{P(X|\theta) \cdot P(\theta)}{P(X)} \quad (3.1)$$

where θ are the set of parameters describing the model and X is the data. The left-hand side is the probability of the model given the data, also known as the posterior. The first term on the right-hand side is the likelihood, while the second term is the prior on the model parameters. The denominator is a normalizing constant, known as the “evidence,” which is often ignored. For hierarchical models, Bayes’ Theorem can be re-written,

$$\begin{aligned} P(\theta, \alpha|X) &= \frac{P(X|\theta, \alpha) \cdot P(\theta) \cdot P(\alpha)}{P(X)} \\ &= \frac{P(X|\theta) \cdot P(\theta|\alpha) \cdot P(\theta) \cdot P(\alpha)}{P(X)}. \end{aligned} \quad (3.2)$$

where θ is the set of parameters in the first (individual) level, and α describes how these parameters are distributed globally (population-level). The posteriors on both θ and α can be evaluated by integrating Equation 3.2. In what follows, we describe our hierarchical model and how it is implemented.

The Hierarchical Model

We use a two-level model that directly mimics the results we would expect from stacking the LEGA-C spectra in bins of velocity dispersion. The first level of our hierarchical model is the full-spectrum population synthesis models in `alf`, described by various stellar population parameters. The second level describes how these parameters are distributed in the *population* of galaxies (α). We assume that they are distributed normally $\mathcal{N}(\mu_{\theta_i}, \sigma_{\theta_i}^2)$, with a mean of μ_{θ_i} and an intrinsic spread of σ_{θ_i} . In this study we are primarily interested in μ_{θ_i} , and as such the population-level model choice has little impact on our conclusions. However, with a larger sample, it may be interesting to investigate trends in σ_{θ_i} . Furthermore, future studies with larger samples can use a model selection criteria (e.g., Bayesian Information Criterion) to select the optimal population-level model and provide insight into the true distribution of stellar population parameters.

While the scope of this paper is limited to a normal distribution population model, we emphasize that this method can easily handle something more complicated. For example, an interesting extension would be to use a population-level model that asserts all galaxies follow a linear mass-metallicity relation.

Implementation

In hierarchical Bayesian modeling, typically the individual- and population-level parameters are evaluated simultaneously. However, in the case presented here, we use the posteriors from individual full-spectrum fits (Section 4.3) to evaluate the population model. The MCMC posterior chains from the individual full-spectrum fits $P(\theta|X)$ can be expressed by Eq. 3.1. Substituting this expression into Eq. 3.2, we arrive at an expression for $P(\theta, \alpha|X)$, or the posterior on the population-level model,

$$P(\theta, \alpha|X) = P(\theta|X) \cdot P(\theta|\alpha) \cdot P(\alpha) \quad (3.3)$$

where the first term on the left-hand side is the set of posteriors from the individual fits, the second term describes the population-level model, which in our case is $P(\theta|\alpha) \sim \mathcal{N}(\mu_{\theta_i}, \sigma_{\theta_i}^2)$, and the final term is the prior on the population-level parameters $\alpha = (\mu_{\theta_i}, \sigma_{\theta_i})$, which we assume to be uniform, i.e. $P(\alpha) \sim \mathcal{U}$. The above equation can be re-written in integral form,

$$P(\theta, \alpha|X) = \prod_{n=1}^N \int P(\theta_n|X_n) \cdot P(\theta_n|\alpha) d\theta. \quad (3.4)$$

These integrals can be numerically integrated with MCMC sampling.

In Figure 3.5 we illustrate the implementation of our hierarchical model. Take for example $\theta = [\text{Fe}/\text{H}]$. As described in Section 4.3 the $[\text{Fe}/\text{H}]$ posteriors for each individual galaxy have already been derived. We use these posteriors to determine the mean (μ) and intrinsic scatter (σ) of Fe-abundances for each velocity dispersion bin. In the left three rows of Figure 3.5 we

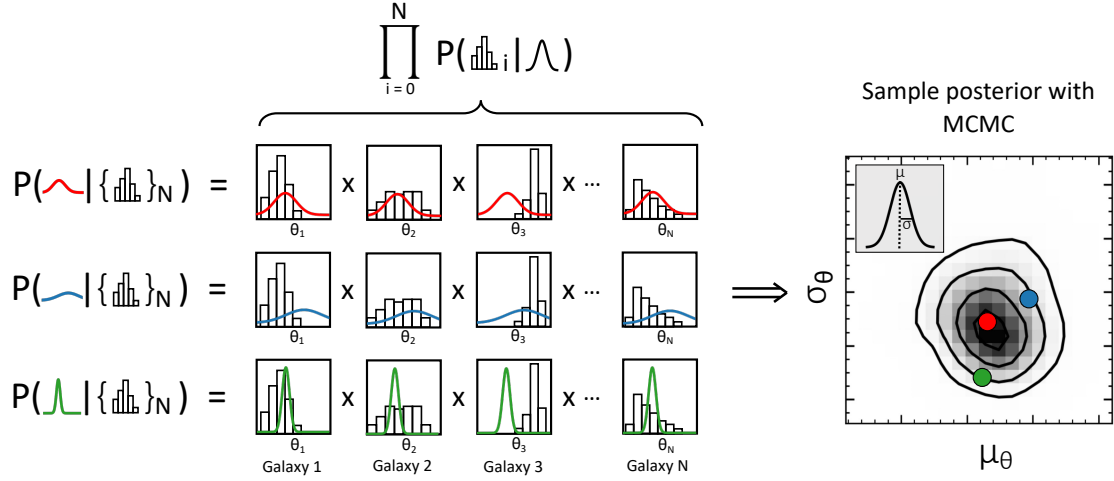


Figure 3.5: Illustration of our hierarchical Bayesian modeling implementation. An example posterior for the population-level mean μ_θ and spread σ_θ for parameter θ is shown in the right panel. On the left we show how to evaluate the likelihood for three different population distributions (one for each row). Instead of modeling the individual- and population-level parameters simultaneously, we evaluate the population-level distribution using the results from individual full-spectrum fits. The likelihood function for the population model is defined by calculating the probability of each individual posterior (histograms in each column) given the model (normal distributions in each row) and taking the product of these probabilities over all N galaxies. The posteriors of μ_θ and σ_θ are computed by sampling this likelihood function using MCMC.

show how to calculate the likelihood of three example population-level models. Essentially, we take the $[\text{Fe}/\text{H}]$ posteriors for each galaxy in the bin (histograms in the middle columns) and calculate the probability of those posteriors given the particular model. Then to get the likelihood, we take the product of these probabilities over all N galaxies in that bin. With enough MCMC samples it is eventually possible to populate a posterior for μ and σ such as the one in the right panel.

We use the hierarchical Bayesian model to derive average stellar population properties and elemental abundances of the LEGA-C galaxies in four bins of velocity dispersion. For consistency with our abundance results, the binning is done using velocity dispersions from the individual `alf` fits instead of the `PPXF` measurements in the LEGA-C public catalog, although the two measurements are in good agreement (see Figure 3.3). This method is prohibitively expensive at the scale of thousands of spectra included in the Conroy et al. (2014) comparison sample. Thus, we use results from the stacked SDSS spectra instead of hierarchical Bayes. The problems introduced by stacking are often worse with low numbers of contributing spectra (e.g. LEGA-C), and therefore the SDSS stacks, each with thousands of spectra, are more robust to stacking. Following the discussion in Section 3.4, hierarchical

Bayesian analysis is preferred over stacking in almost all cases unless the cost of fitting becomes prohibitively expensive. Additionally, for extremely noisy data where fits to individual galaxies are impossible or untrustworthy, stacking may be preferred.

In Figure 3.4 we show the results of the hierarchical Bayesian modeling (blue) in comparison to the results from the individual fits (gray). This figure serves as an illustration and shows that our method successfully captures the average abundances and ages in each σ_v bin. The actual trends and their significance (for these and other elements) are discussed in the next section. In Section 3.7 we compare hierarchical Bayesian modeling to the stacking method used in Conroy et al. (2014) and find mostly consistent results, although the Bayesian method is more accurate and the uncertainties are better estimated. The results of these tests are summarized in Figure 3.12. In Section 3.7 we provide a more complete derivation of the hierarchical Bayesian method and its implementation.

3.5 Abundance Patterns of $z \sim 0.7$ Galaxies

The elemental abundance results as a function of observed velocity dispersion based on the hierarchical Bayesian modeling are summarized in Figure 3.6. The ten elements are split into three categories: CNO products (C, N; left column), α elements (Mg, Ca, Si, Ti; middle column), and Fe-peak elements (V, Cr, Co, Fe, Ni; right column). In the top row we show the absolute abundances $[X/H]$ as a function of observed velocity dispersion, while in the bottom row we show the abundance ratios $[X/Fe]$. We evaluate the correlation with least-squares minimization and show the best-fit line for each element. The dashed black line in each panel of the top row reflects the best-fit line to the “total” metallicity $[Z/H]$ which is defined as the sum of all ten absolute abundances.

The absolute abundances of each element, as well as the total metallicity $[Z/H]$, scale positively with velocity dispersion. All elements, except Ca, V, and Ni, have positive slopes that are significant at the 3σ -level. The trend between velocity dispersion and absolute abundance has been studied extensively at low- z (e.g., Gallazzi et al., 2005; Thomas et al., 2010; Conroy et al., 2014), this is the first time we show this trend at intermediate redshift for as many elements.

The positive trend between the absolute abundances and velocity dispersion is in broad agreement with what is found at $z \sim 0$ (e.g. Gallazzi et al., 2005; Thomas et al., 2010; Conroy et al., 2014; McDermid et al., 2015). It is also consistent with initial work at $z \sim 0.5$ that show results for $[Z/H]$, $[Fe/H]$, $[Mg/H]$, $[C/H]$, $[N/H]$, and $[Ca/H]$ (Gallazzi et al., 2014; Choi et al., 2014; Leethochawalit et al., 2019). These trends have historically been interpreted as galaxies with larger velocity dispersions having steeper gravitational potential wells, thus allowing them to hold onto metal-rich gas during feedback events like supernovae and high-speed stellar winds (Larson, 1974; Dekel & Silk, 1986; Tremonti et al., 2004). In Section 3.6 we discuss whether observed velocity dispersion is indeed a good tracer of the gravitational potential.

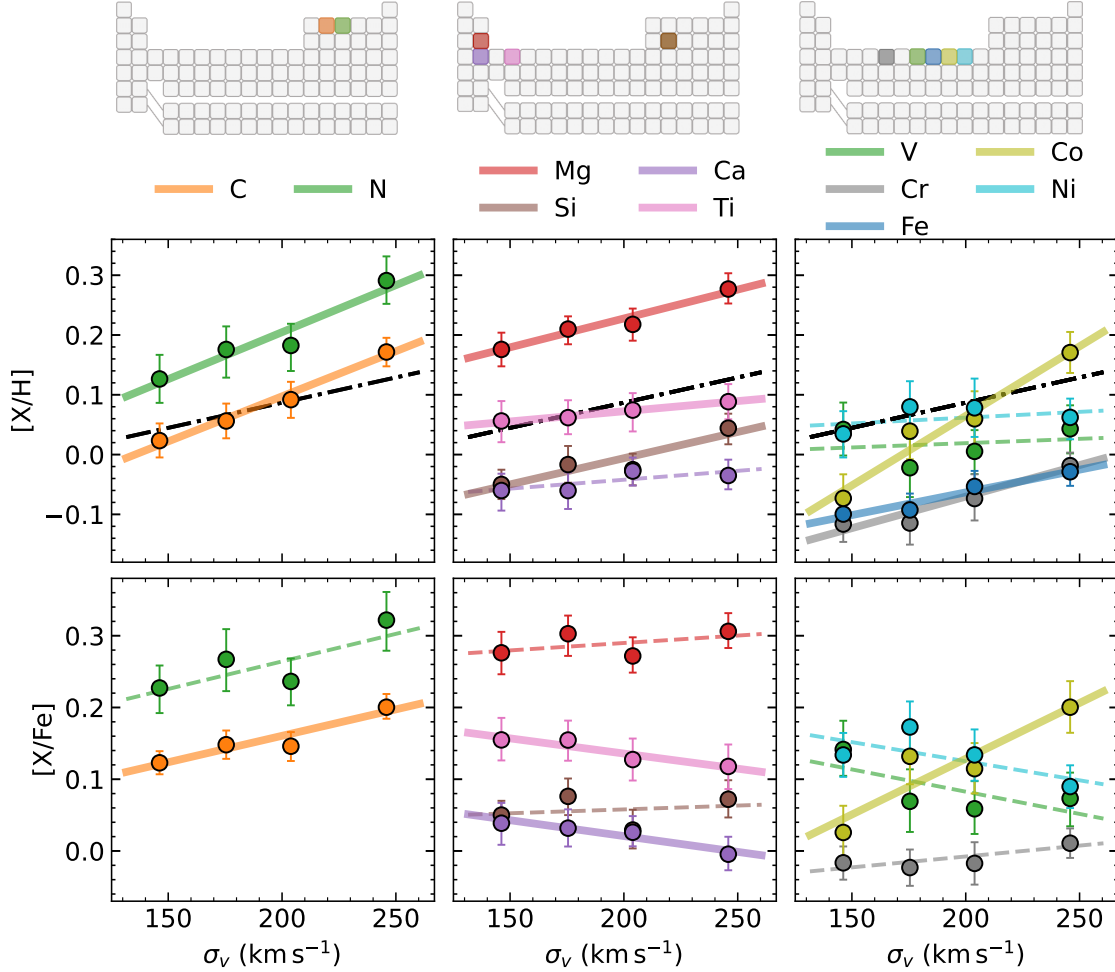


Figure 3.6: Absolute abundances $[X/H]$ (top row) and abundance ratios $[X/Fe]$ (bottom row) of C, N (left column), α elements (middle column), and iron peak elements (right column) as a function of observed velocity dispersion. The galaxy sample was split into four velocity dispersion bins before fitting. The individual points represent the mean abundance of the population of galaxies in each bin (μ_{θ_i}), as defined in Section 3.4. The error bars reflect the 1σ 16th and 84th percentiles of the (μ_{θ_i}) PDFs. For each element, we include the best-fit linear relation to the bins. Solid lines indicate elements with slopes that deviate significantly from zero (at the 3σ level), whereas elements with dashed lines do not. The dash-dotted black lines in the $[X/H]$ panels reflect the “total” metallicity $[Z/H]$, which we define as the sum of all ten absolute abundances included in the fits.

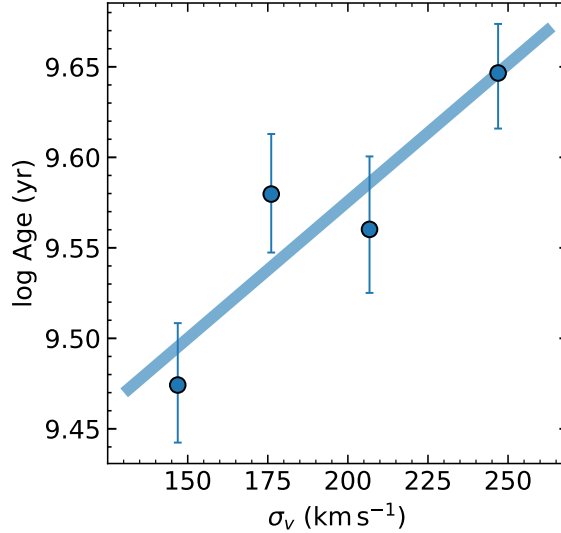


Figure 3.7: Stellar population ages as a function of observed velocity dispersion. The best-fit line from least-squares fitting is shown. It is clear that galaxies with higher velocity dispersions formed earlier.

We now turn to the Fe-scaled abundance ratios $[X/Fe]$ as a function of velocity dispersion. The abundance ratio $[\alpha/Fe]$ is often used as a tracer of the star-formation timescale, as α elements are produced on shorter timescales than Fe due to the relative difference in timescales between core-collapse and Type Ia SNe (e.g. Matteucci, 1994; Trager et al., 2000; Thomas et al., 2005; Conroy et al., 2014). A similar argument can be used for $[C/Fe]$ and $[N/Fe]$, with C and N probing a slightly longer timescale than α -elements due to the contributions from AGB winds. In the second row of Figure 3.6 we find that only $[Co/Fe]$ and $[C/Fe]$ have significant (3σ -level) positive correlations with σ_v , while the α elements Ti and Ca have significant mild negative correlations. All of the other elements have abundance ratios consistent with no correlation. To first order, the mostly flat $[X/Fe]$ results imply that the average star-formation timescales are similar and we see no significant trend with velocity dispersions over the studied range. In other words, the gravitational potential of a galaxy appears to regulate absolute abundances but *not* the star-formation timescale.

The above abundance ratio results are mostly consistent with Choi et al. (2014) – the only other study of abundance patterns at $z > 0$. They presented the elemental abundances C, N, Mg, Fe, and Ca for stacks of massive quiescent galaxies in six different redshift bins out to $z \sim 0.7$, though their $0.55 < z < 0.7$ stack has S/N much less than what is presented here ($25 - 150 \text{ \AA}$ for Choi et al. (2014) compared to $\approx 60 \text{ \AA}$ for each individual LEGA-C spectrum). They find mostly flat elemental abundance ratios with stellar mass, especially in the higher redshift bins. The flat $[X/Fe]$ results presented here and in Choi et al. (2014) are somewhat surprising, as at $z \sim 0$, massive quiescent galaxies appear to have a positive

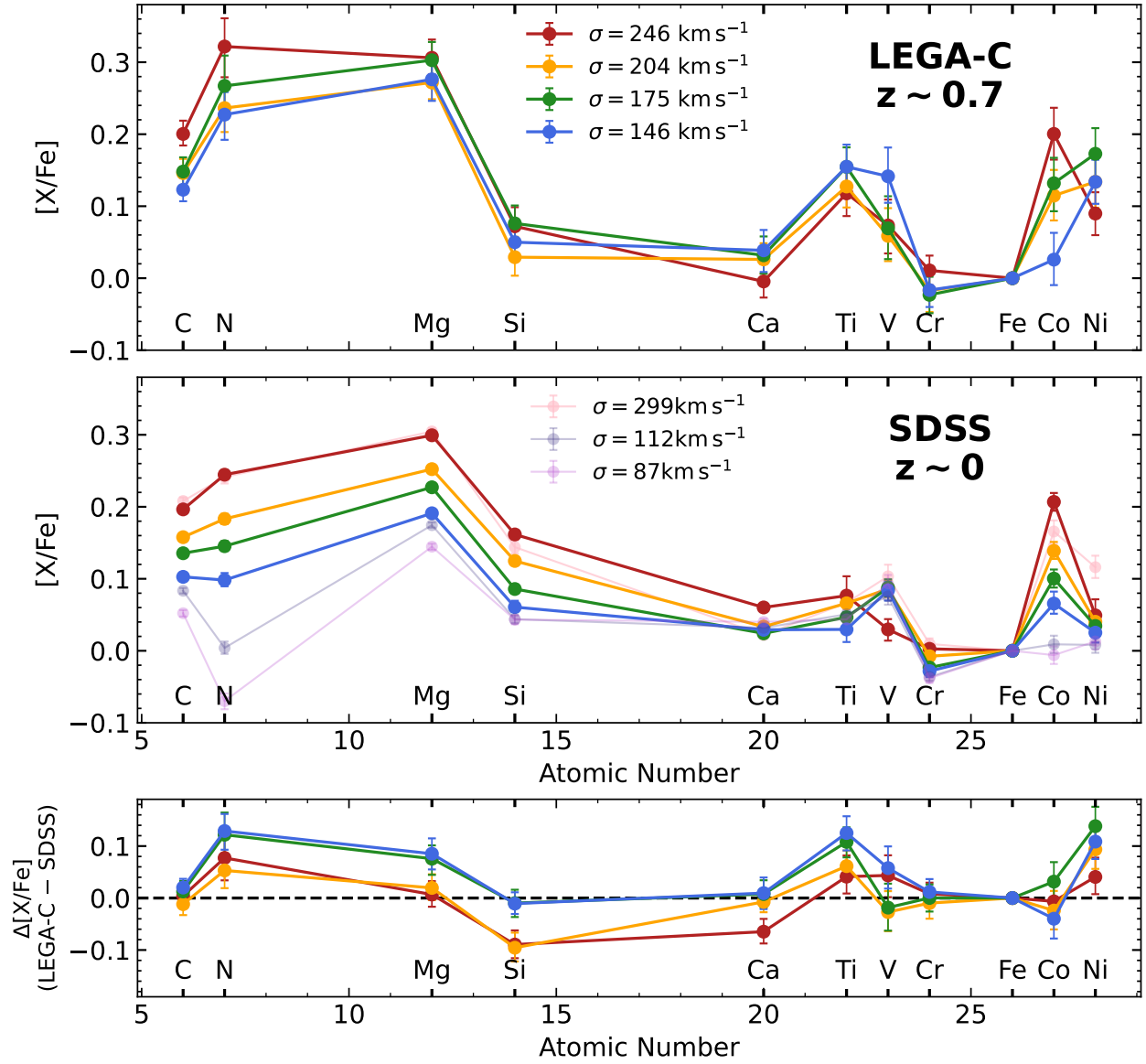


Figure 3.8: The elemental abundance patterns derived from the LEGA-C $z \sim 0.7$ sample (top panel) and the SDSS $z \sim 0$ sample from Conroy et al. (2014) (middle panel). The SDSS sample covers velocity dispersions ranging from $\sigma = 90 \text{ km s}^{-1}$ (light purple) to $\sigma = 300 \text{ km s}^{-1}$ (pink). We highlight the best matching dispersion bins in LEGA-C and SDSS using lines of the same color. The abundance patterns are remarkably similar. In the bottom panel we show the difference in abundance ratios between LEGA-C and SDSS. It is apparent that the N, Mg, Ti, and Ni abundance ratios are enhanced in LEGA-C compared to SDSS, especially at low dispersions.

correlation between abundance ratios and stellar mass or velocity dispersion (e.g. Worthey et al., 2014; Conroy et al., 2014; McDermid et al., 2015). However, the limited dynamic range in velocity dispersion and relatively small sample size make it difficult to say for certain whether the above abundance trends with velocity dispersion exist at this redshift. Thus a larger statistical sample that reaches to lower stellar masses and velocity dispersions would be necessary to directly test this correlation past $z \sim 0$.

The bottom row of Figure 3.6 also gives some insights into the nucleosynthetic origins of the elements. While N does not have a significantly positive slope due to the large uncertainties on the binned measurements, it still appears to trace $[\text{C}/\text{Fe}]$ as a function of velocity dispersion. The similarity in slope may indicate that they are forged from the same processes and on similar timescales. This is in qualitative agreement with results at $z \sim 0$ (Graves et al., 2007; Schiavon, 2007; Smith et al., 2009; Johansson et al., 2012). The slightly negative slopes found for $[\text{Ti}/\text{Fe}]$ and $[\text{Ca}/\text{Fe}]$ may indicate Ti and Ca are not pure core-collapse products and could have significant contributions from both core-collapse and Type Ia supernovae. In the local universe, this is also found to be the case (Saglia et al., 2002; Cenarro et al., 2003; Thomas et al., 2003; Graves et al., 2007; Schiavon, 2007; Smith et al., 2009; Johansson et al., 2012). Finally, the Fe-peak element Co exhibits a steep positive correlation with velocity dispersion. This result is surprising, as no other element has such an extreme trend with velocity dispersion. Interestingly, the strong trend with Co is also found in massive early-type galaxies in the nearby universe (Conroy et al., 2014). As explained by Conroy et al. (2014), this result could indicate that a significant portion of Co may originate from core-collapse supernovae, and not Type Ia. Indeed, this is seen in Type Ia SNe yields of Nomoto et al. (1984), who show a deficit of Co compared to other Fe-peak elements.

It is not obvious why only $[\text{C}/\text{Fe}]$ and $[\text{Co}/\text{Fe}]$ show significant positive relations with σ , while none of the α elements do. If the star-formation timescale is the primary driving factor setting the slopes of the abundance trends, then core-collapse products have the steepest trend with velocity dispersion, followed by CNO and Type Ia products. The fact that we do not observe these trends, and instead find Co (an Fe-peak element) to have the steepest slope, followed by C (AGB and core-collapse product) may indicate there are other factors at play. One such explanation could be that the IMF varies with velocity dispersion (as found by e.g. van Dokkum & Conroy, 2010; Conroy & Dokkum, 2012; Conroy et al., 2013a). Metallicity- and mass-dependent supernova yields combined with a more top-heavy IMF can alter the relative abundances of the elements. Further chemical evolution modeling is required to confirm whether a variable IMF could explain the observed abundance trends. We caution that the observed trends are measured to varying degrees of significance and larger samples are required to confirm all trends.

Next we turn to the SSP-equivalent ages as a function of velocity dispersion. In Figure 3.7 we find a significant positive trend between age and velocity dispersion. This result implies that galaxies with larger gravitational potentials form the bulk of their stars at earlier epochs. The trend between stellar age and velocity dispersion is in agreement with other studies at similar redshift that look at age as a function of stellar mass (e.g. Gallazzi et al., 2014; Choi et al., 2014; Leethochawalit et al., 2019; Beverage et al., 2021) and with studies of massive

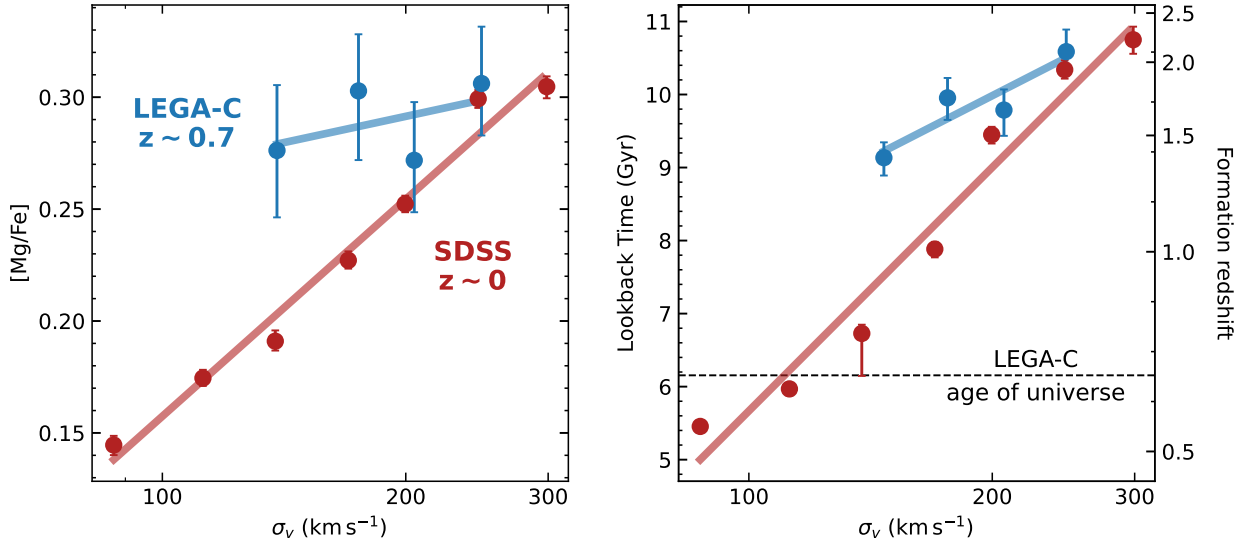


Figure 3.9: Comparison of the $[Mg/Fe]$ (*left*) and formation redshift (*right*) for stacks of massive quiescent galaxies in SDSS at $z \sim 0$ (red; Conroy et al., 2014) and LEGA-C at $z \sim 0.7$ (blue), along with the best-fit power laws. The formation redshift is calculated by taking into account the age of the universe at each redshift. In both samples, galaxies with higher velocity dispersions have higher $[Mg/Fe]$ and formed earlier. The $z \sim 0.7$ and $z \sim 0$ populations differ most significantly in the lowest velocity dispersion bin, with the $z \sim 0.7$ galaxies having ≈ 0.1 dex higher $[Mg/Fe]$ and ≈ 2 Gyr earlier formation times compared to the corresponding $z \sim 0$ bin. This difference can be explained by newly quenched galaxies with young ages and lower $[Mg/Fe]$ being added to the low- σ_v bins over the last six billion years.

quiescent galaxies at $z \sim 0$ (Thomas et al., 2010; McDermid et al., 2015; Barone et al., 2018).

3.6 Discussion

Comparison with local early-type galaxies

There are a few key advantages to studying the chemical compositions of galaxies at higher redshift. First, their in-situ stellar populations experience less pollution by late-time mergers. Second, observations at higher redshift reach closer to the epoch of formation, making the ages and star-formation histories easier to determine. And third, by comparing these results to $z \sim 0$ we can further characterize the evolution of the quiescent galaxy population over cosmic time.

In this section we first compare our $z \sim 0.7$ abundance results to stacks of massive local early-type galaxies from SDSS and to test whether the massive quiescent galaxy population

has evolved over the past six billion years. Figure 3.8 shows the abundance patterns for both the LEGA-C (top panel) and SDSS (middle panel) stacks as a function of velocity dispersion, along with the residuals between the two populations (bottom panel). As a reminder, the SDSS stacks were taken directly from Conroy et al. (2014) but re-fit here using the same SSP models and `alf` setup as the individual LEGA-C spectra (see section 4.3). The SDSS stacks cover a larger range in velocity dispersion (90 km s^{-1} to 300 km s^{-1}) compared to the LEGA-C sample (150 km s^{-1} to 250 km s^{-1}) and thus we highlight the best matching dispersion bins in LEGA-C and SDSS using lines of the same color.

One concern in comparing the SDSS and LEGA-C results is that the SDSS spectra have an aperture that covers the inner $\sim 0.5 R_e$, while the LEGA-C aperture covers $\sim 1 R_e$. Thus, the presence of stellar population gradients in these galaxies can significantly bias the resulting measurements integrated over the aperture. Spatially resolved studies of massive early-type galaxies in the local universe reveal steep $[X/H]$ gradients but flat stellar age and abundance ratio $[X/Fe]$ gradients (e.g. Spolaor et al., 2010; Greene et al., 2019; Feldmeier-Krause et al., 2021; Parikh et al., 2021). Choi et al. (2014) model the effects of metallicity gradients on integrated $[Fe/H]$ measurements and find only a modest effect (a difference of only 0.05 dex between fibers covering $0.5 R_e$ and $1 R_e$). Nonetheless, we refrain from comparing absolute abundances $[X/H]$, and instead focus on abundance ratios $[X/Fe]$ and ages, which are less impacted by aperture bias.

Figure 3.8 shows that the SDSS and LEGA-C abundance patterns closely trace one another. In both cases CNO products (C, N) and α -element Mg all have enhanced abundances followed by a steep drop to approximately solar abundances for the heavier α (Si, Ca, Ti) and Fe-peak (V, Cr, Fe, Co, Ni) elements. These similarities imply that on average, massive quiescent galaxy at $z \sim 0.7$ have similar chemical enrichment histories to those at $z \sim 0$. One difference in the $z \sim 0$ and $z \sim 0.7$ abundance patterns is that Si is slightly depressed in LEGA-C compared to SDSS, while Ti is slightly enhanced. The small uncertainties ($\lesssim 0.05$ dex for both SDSS and LEGA-C) on these measurements suggest that these abundance differences, albeit subtle, are real. Chemical evolution modeling is required to shed light on the origin of these differences.

Another difference between the SDSS and LEGA-C abundance patterns is that the lowest velocity dispersion bins in SDSS have depressed abundance ratios compared to LEGA-C, in particular for N, Mg, Ti, and Ni (see bottom panel of Figure 3.8). As such, the trends between $[X/Fe]$ and velocity dispersion for these elements become stronger over the past six billion years. In the left panel of Figure 3.9 we show this directly by comparing $[Mg/Fe]$ for the $z \sim 0$ and $z \sim 0.7$ populations. It is clear that the $z \sim 0.7$ population is Mg-enhanced compared to the quiescent galaxies at $z \sim 0$, especially at the lowest velocity dispersions. We discuss possible implications of this result in the next section.

Finally, in the right panel of Figure 3.9, we compare the formation redshift of the $z \sim 0$ and $z \sim 0.7$ quiescent galaxy populations. We calculate the formation redshift by correcting the stellar ages for the age of the universe at each redshift. Thus, the right panel Figure 3.9 allows us to directly compare the stellar ages of the galaxies in the two redshift bins. In both cases we find that galaxies with the largest velocity dispersions on average formed the earliest.

We also find that the $z \sim 0.7$ quiescent galaxy population on average formed earlier than $z \sim 0$ quiescent galaxies, especially at lower dispersions (by ≈ 2 Gyr for $\sigma = 150 \text{ km s}^{-1}$). Thus, both the stellar ages *and* the abundance ratios differ the most in the lowest velocity dispersion bins. This difference in the lowest dispersion bin could be explained by mergers or newly quenched galaxies being added to the quiescent population at later times. Alternatively, some star formation between $z \sim 0.7$ and $z \sim 0$ may explain the formation time differences. In particular, because SSP-equivalent ages are basically luminosity-weighted ages, and thus they are more sensitive to the younger stellar populations.

There are several additional caveats that must be considered before interpreting the abundance and age results in the context of galaxy evolution. First, we assume that the observed velocity dispersion traces the strength of the potential well. However, Bezanson et al. (2018) find many of the quiescent galaxies in LEGA-C are in fact supported by rotation. As a result, the measured velocity dispersions may underestimate the strength of the potential well if the disks have significant rotational components ($V/\sigma \sim 1$) and are also observed face-on. Therefore, the observed trends with velocity dispersion could be artificially flattened compared to SDSS, where rotation appears to be less prevalent. We investigate the significance of this effect using the inclination- and aperture-corrected velocity dispersions provided by van der Wel et al. (2021, Eq. 2). The abundance ratio trends remain qualitatively the same and thus we conclude that inclined rotating disks have minimal impact on our results.

A second caveat is that the SDSS selection is different than our LEGA-C selection; Conroy et al. (2014) remove galaxies that fall outside of the central slice of the fundamental plane. Effectively, this selection removes inclined rotation-supported disks. We test the impact of this effect by selecting a sub-sample of LEGA-C galaxies with axis ratios $b/a > 0.6$, which removes the inclined disks from the sample. We find that the trends with abundance ratio remain qualitatively the same. Therefore, this selection criterion appears to have little impact on our results. Finally, SDSS galaxies are selected to be quiescent based on $H\alpha$ and $[\text{OII}]\lambda 3727$, whereas LEGA-C quiescent galaxies are selected by their UVJ colors. As mentioned earlier (Section 3.3), most LEGA-C galaxies still have some $[\text{OII}]$ emission, which most likely originates from blue evolved stars, and thus may decline as the stellar population ages to present day. Hence, we do not expect that the difference in selection criteria has any significant affect on the comparison.

Our results are also broadly consistent with other large spatially resolved studies of nearby early-type galaxies. For example, Martín-Navarro et al. (2018) used extended MILES models to investigate abundance ratios over a wide mass range, finding enhanced $[\alpha/\text{Fe}]$ at high velocity dispersions. Using MaNGA IFU data, Parikh et al. (2019) measured spatial gradients and showed that abundance ratios correlate strongly with velocity dispersion, again in broad agreement with our findings. They also reported that $[\text{C}/\text{Fe}]$ and $[\text{Mg}/\text{Fe}]$ track one another, whereas $[\text{Ca}/\text{Fe}]$ is offset to lower values, consistent with the trends we observe. Differences in modeling methods, abundance scale calibrations, and sample selection preclude the kind of detailed quantitative comparison we make with Conroy et al. (2014). Nevertheless, the qualitative agreement across these diverse datasets supports our main conclusions.

Implications for galaxy evolution since $z \sim 0.7$

In the previous section we found that massive quiescent galaxies at $z \sim 0.7$ stellar have ages and abundance ratios broadly consistent with observations at $z \sim 0$. However, galaxies in the lowest velocity dispersion bin are found to have formed earlier and have more enhanced abundance ratios compared with galaxies at $z \sim 0$. This result agrees with the findings of Choi et al. (2014) who find abundance ratios and stellar ages that are consistent with passive evolution since $z \sim 0.7$ for the *most* massive ($\log M > 11 M_\odot$ or $\sigma_v \approx 200 \text{ km s}^{-1}$) quiescent galaxy population. In this section we discuss possible evolutionary scenarios that could explain the results at low velocity dispersion.

Quiescent galaxy populations (that by definition no longer form stars) can still evolve via minor mergers (e.g. Bezanson et al., 2009; Naab et al., 2009; Hopkins et al., 2009; van de Sande et al., 2013), the addition of newly quenched galaxies to the quiescent population (e.g., van Dokkum & Franx, 2001; Carollo et al., 2013; Poggianti et al., 2013; Belli et al., 2019), and late-time star formation (e.g. Donas et al., 2007; Schawinski et al., 2007; Thomas et al., 2010). In the minor merger scenario, the abundance ratios and ages of massive quiescent galaxies are diluted by the accretion of lower mass galaxies (with mass ratios of around 1:10). Due to the younger ages and near-solar abundances of lower mass galaxies, minor mergers typically lower the abundance ratios of massive quiescent galaxies over time. Furthermore, they result in radial stellar population gradients, as have been found in massive elliptical galaxies in the local universe (e.g., Greene et al., 2015, 2019; Oyarzún et al., 2019; Feldmeier-Krause et al., 2021; Parikh et al., 2021), and perhaps even at earlier times (Suess et al., 2020). However, due to prevalence of galactic conformity, or the idea that old galaxies merge with other old galaxies (e.g., Weinmann et al., 2006; Kauffmann et al., 2013), merging would not significantly impact stellar ages.

The addition of newly quenched galaxies can also reduce the average ages and abundance ratios of quiescent galaxies over time, as is found in Figure 3.9. In this scenario, star-forming galaxies continue to quench after $z \sim 0.7$, especially at lower stellar masses. Thus, the newly added young and Fe-enhanced galaxies lower the *average* ages and abundance ratios. We do indeed know that the quiescent galaxy population has grown significantly since $z \sim 1$ (e.g., Bell et al., 2004; Faber et al., 2007; Taylor et al., 2010; Muzzin et al., 2013b; Tomczak et al., 2014; McLeod et al., 2021). Finally, late-time star-formation, also known as “rejuvenation,” can alter the abundances and ages of the quiescent galaxy population by giving more weight to the newly formed bright, young, and more chemically evolved stellar population.

All of the above evolutionary scenarios produce the observed decrease in formation redshift and abundance ratios over time found in Figure 3.9. However, in order to explain this decrease, the evolution must be the strongest in the lowest velocity dispersion bin. Both progenitor bias and late-time star-formation – but not minor mergers – preferentially affect the evolution of galaxies in the lower velocity dispersion bins. For progenitor bias, this is because the most massive galaxies are already quiescent by $z \sim 0.7$ (McLeod et al., 2021; Taylor et al., 2022). Thus, evolution of the quiescent galaxy population via quenching of star-forming galaxies between $z \sim 0.7$ and $z \sim 0$ is strongest for galaxies with lower velocity

dispersions. Alternatively, evolution through late-time star-formation could explain the results if this scenario preferentially affects galaxies with lower velocity dispersions. Indeed, in the local universe, Thomas et al. (2010) find that star formation “rejuvenation” is more commonly observed in galaxies with lower stellar masses. However, studies of the star-formation histories of LEGA-C galaxies at $z \sim 0.7$ find that rejuvenation is not necessarily an important evolutionary channel for the growth of the quiescent population since $z \sim 0.7$ (Chauke et al., 2019).

One way to differentiate between the progenitor bias and rejuvenation scenarios would be to trace the scatter of individual abundances and ages over time; progenitor bias adds young galaxies to the existing old population and thus increases the scatter in individual galaxies over time, whereas late-time star formation does not. With deeper spectra that trace to lower velocity dispersions, as well as careful treatment of S/N-related scatter, such analysis will be possible.

Comparison with theoretical predictions

The elemental abundance patterns provide unique constraints on chemical enrichment histories of galaxies. In this section we compare our results with theoretical predictions from Nomoto et al. (2013). They report theoretical predictions for 16 elements in $[X/Fe]$ - $[Fe/H]$ for two elliptical galaxy models – one low-mass galaxy with $\sigma = 50 \text{ km s}^{-1}$, and one high-mass galaxy with $\sigma = 400 \text{ km s}^{-1}$ – from a one-zone chemical evolution model. This model assumes infall of primordial gas, supernova winds, a Salpeter (1955) IMF, and star formation histories that reflect the observed ages and formation timescales of elliptical galaxies in the local universe. In Figure 3.10 we show the results of these models at a fixed Fe-abundance ($[Fe/H] \sim 0$) (gray lines), and shade the regions between the two abundances. For comparison, in blue we show the average abundance pattern for *all* galaxies in the $z \sim 0.7$ quiescent galaxy, along with the SDSS abundance pattern at $\sigma \sim 200 \text{ km s}^{-1}$ (to match the average velocity dispersion of the $z \sim 0.7$ sample) in red. $[V/Fe]$ is excluded from this figure, as this element is not included in the analysis presented by Nomoto et al. (2013).

This figure shows that the observed abundance patterns are very different from those predicted by chemical evolution models. In particular, the models cannot recover C, N, and Ti. C and N are both elements with large contribution from evolved intermediate-mass stars and thus the models may require longer star-formation histories to incorporate more CNO products, or alternatively require different supernovae and AGB yields. Interestingly, chemical evolution studies in the Local Universe find that AGB production of N has a shorter time-delay than previously thought, and could explain some of the observed discrepancy (Johnson et al., 2023). Furthermore, the under-abundance of Ti predicted by models has been noted in the Solar Neighborhood (Nomoto et al., 2006), the Milky Way halo (François et al., 2004), and dwarf galaxies (Kirby et al., 2011), and is likely due to uncertain core-collapse yields. The deviation of our observations from the theoretical predictions by this model imply that there may be components of the chemical enrichment of massive quiescent galaxies that are still poorly understood. However, here we make the comparison with only

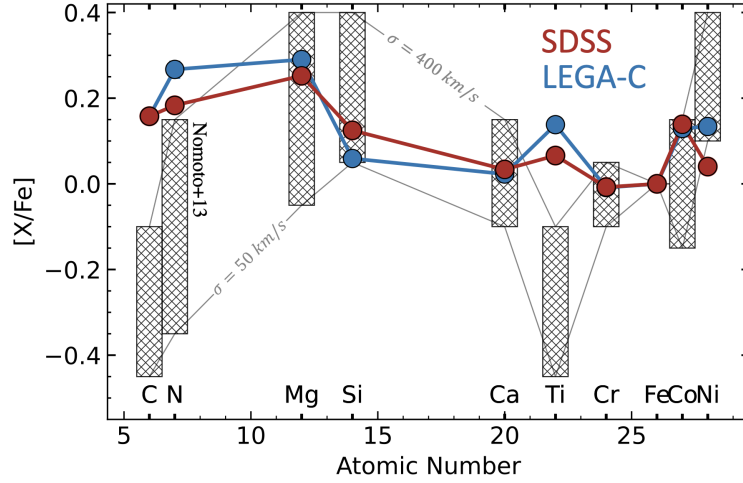


Figure 3.10: Comparison between the observed abundance patterns and theoretical predictions from one-zone chemical evolution models for elliptical galaxies from Nomoto et al. (2013). The blue line represents the average abundance pattern of the entire LEGA-C sample (with an average velocity dispersion of $\sigma = 200 \text{ km s}^{-1}$) and the red line represents the SDSS abundance pattern for a bin centered around $\sigma = 200 \text{ km s}^{-1}$. The gray lines show the predicted abundance patterns for elliptical galaxies with $\sigma = 50 \text{ km s}^{-1}$ and $\sigma = 400 \text{ km s}^{-1}$ from chemical evolution modeling. We shade the region between these lines for each element to show the predicted range of abundance ratios. Nomoto et al. (2013) assume an infall+wind model with a Salpeter IMF, and a star formation history that reflects the “red and dead” properties of local elliptical galaxies. There are major differences between the observations and the theoretical predictions, especially for elements C, N, and Ti.

one chemical evolution model. In the future with a wider set of models and higher-S/N data, this sort of comparison may be able to provide more concrete constraints on the IMF and yields of massive quiescent galaxies beyond the low-redshift universe.

3.7 Additional details and tests of stacking methods

Parameter Retrieval From Simulated Spectra

The abundance results in this paper are evaluated using a hierarchical Bayesian model. The first level of this model relies on the individual fits to the LEGA-C spectra. The posteriors of these fits are then combined in a Bayesian framework as described in Section 3.4. Thus, for reliable combined results we require the individual parameters to be accurate and constrained to at least within the imposed priors. In this Section we describe the simulation and recovery test used to quantitatively evaluate which parameters can be constrained.

For our recovery tests, we simulate 30 mock LEGA-C spectra, each with randomly drawn

velocity dispersions, stellar ages, and elemental abundances. These values are drawn from a normal distributions with mean and spread that reflect the individual LEGA-C results. Next, we generate the 30 **alf** models. We then match each model with a LEGA-C spectrum that has the closest stellar age and metallicity. In order to add the appropriate noise to each model, we identify the LEGA-C spectrum that has the closest continuum shape to the **alf** model. We then regrid the model onto the same wavelength grid and use a high-order polynomial to match the model continuum shape to the LEGA-C spectrum. Finally, we take the S/N of the LEGA-C spectrum (typically $\approx 60 \text{ \AA}^{-1}$), inflate the noise using the **alf** jitter term, and add in this random Gaussian noise to the **alf** model. The simulated error spectrum is computed by scaling down the simulated spectrum according to the S/N of the model.

Second, we fit the simulated spectra with **alf** using the identical setup to what is de-

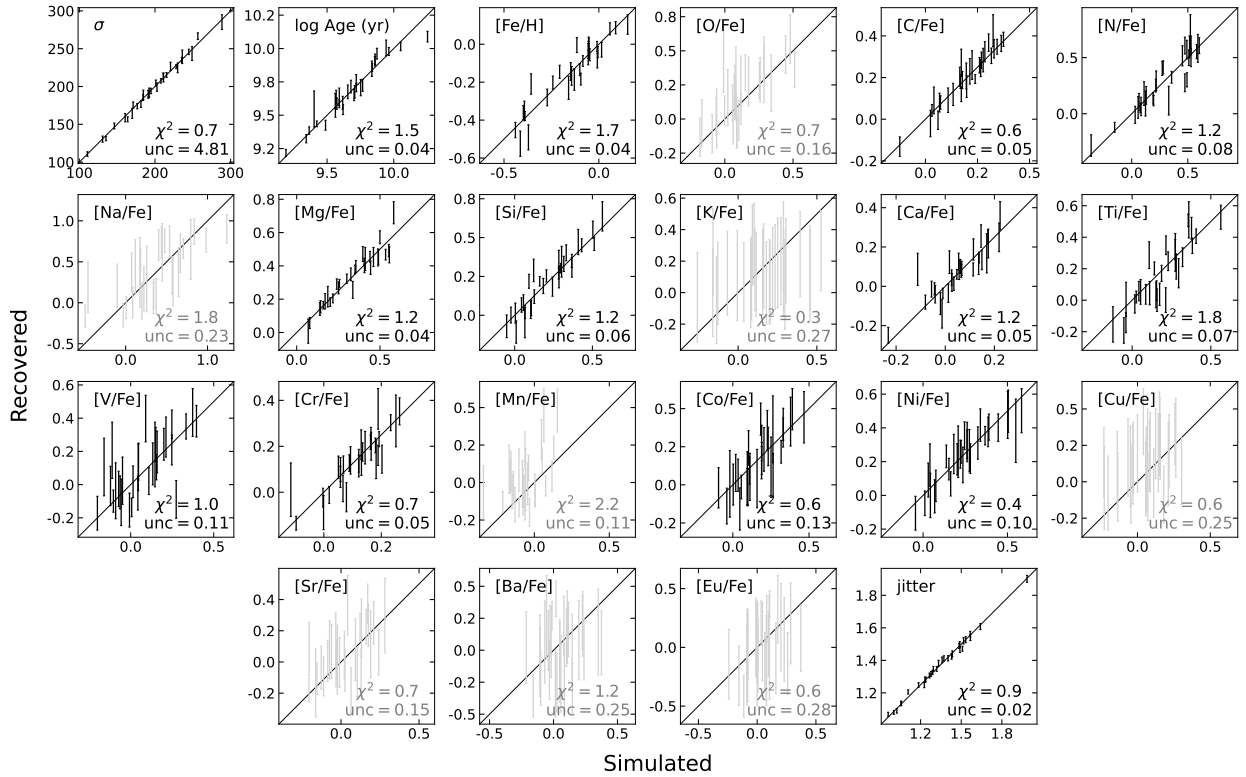


Figure 3.11: Recovery results from simulating 30 LEGA-C spectra. The true values (x-axis) are shown against the recovered values with 1σ uncertainties (y-axis). One-to-one lines are included in each panel. The reduced χ^2 and average 1σ uncertainties are provided in the lower right corner for each of the parameters. Overall, the recovery is accurate. However, panels with light-gray data points are deemed unreliable and were thus omitted from discussion in the main text.

scribed in Section 4.3. The results are shown in Figure 3.11 where we compare the fits to the true simulated values. The reduced χ^2 and average 1σ uncertainties for the 30 spectra are listed in each panel, and we also include one-to-one lines. For the most part, the fits are in good agreement with the simulated values.

Finally, we select which parameters can be constrained. The primary selection criterion is that the uncertainties on the fitted parameters must be < 0.15 dex. We make this selection to ensure that the PDFs for the elemental abundances do not hit the upper or lower prior limits. Alternatively we could extend the prior limits. However, the large uncertainties on some of the abundance measurements would require very large prior limits, and include regions that the models do not cover. Thus, the results would be based off extrapolated models. The second selection criterion is that the reduced $\chi^2 < 2.0$. This selection ensures the parameters are well-constrained to within error.

The constrained parameters (velocity dispersion, stellar ages, jitter term, and 11 abundances) based on the average uncertainties and reduced χ^2 are highlighted in Figure 3.11 in black. The parameters that do not meet our criteria (O, Na, K, Mn, Cu, Sr, Ba, and Eu) are shown in light gray. It is unsurprising that these parameters do not meet our criteria, as their absorption features are either weak or at redder wavelengths than targeted by the LEGA-C spectra.

Stacking Versus Hierarchical Bayes

In this section we use the simulated spectra described in Section 3.7 to test different spectral stacking methods. The results of these methods are compared with the results from hierarchical Bayesian modeling.

cccccc[b]	Method	Continuum	Smoothed	Weighing	Combination	Error
Normalization (Y/N)	Propagation	Stacking	Methods	stack1	Median	N None Median
MAD						
stack2	Polynomial	N	None	Median	MAD	
stack3	Polynomial	Y	None	Mean	bootstrap	

The three stacking methods tested in Appendix 3.7 with results shown in Figure 3.12.

Historically, when spectra have insufficient S/N, it is commonplace to take the spectra of many similar galaxies and stack them together. The act of stacking boosts the S/N and therefore enables us to derive average measurements. As described in the main text, the primary shortcoming of stacking is that it introduces systematic uncertainties and potential bias. For example, in order to stack the spectra, it is common to continuum normalized by fitting a high-order polynomial, smooth each spectrum to a constant velocity dispersion, interpolate them onto a global wavelength grid, and finally combine all the spectra via a weighted sum. Each of these steps introduces a different type of systematic uncertainty; fitting a polynomial runs the risk of removing part of the absorption features by over-fitting, smoothing introduces correlated noise and reduces the information content of the spectrum, linear interpolation does a poor job at conserving the noise level, and the way you combine the spectra (e.g. mean, light-weighted mean, median) affects the relative weighing of the

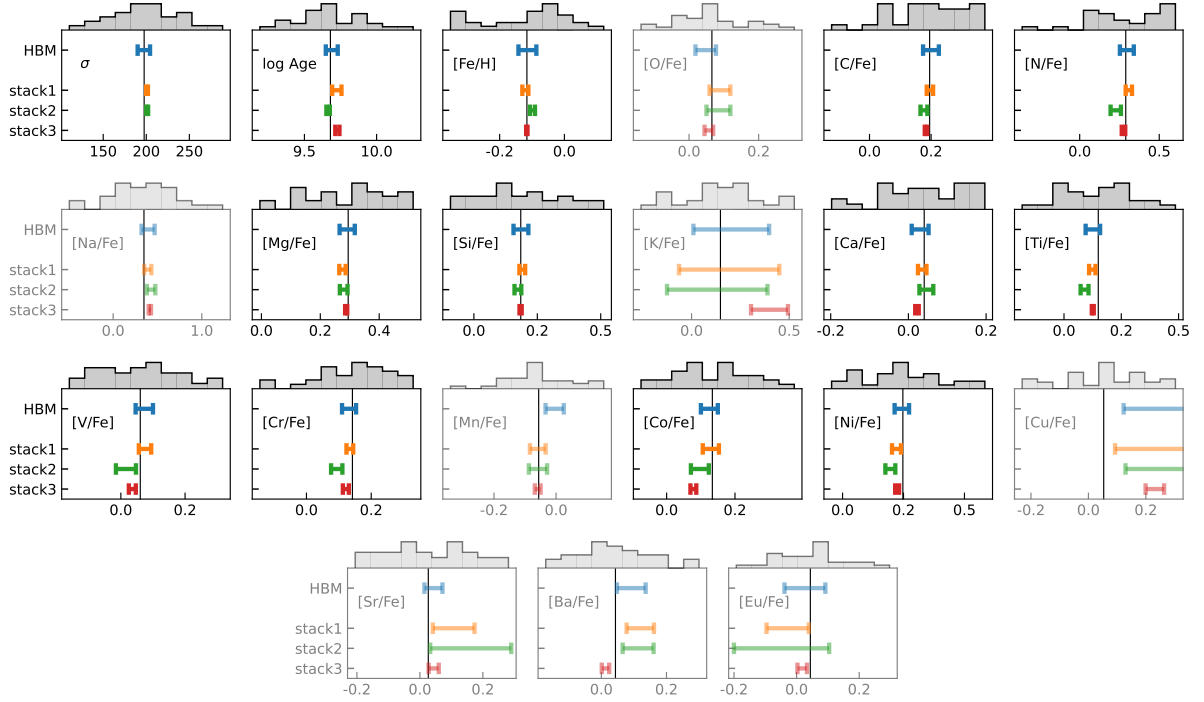


Figure 3.12: The 30 simulated spectra from Section 3.7 are combined using hierarchical Bayes and three different stacking methods to test how well the mean value of each parameter can be recovered. On top of each panel we show the distribution of simulated values. The vertical line is the value we try to recover (the mean of the distribution of parameters). The labeling of the different stacking methods correspond to Table 1. The error bars represent the 16th and 84th percentiles on the PDF for each parameter. Parameters with low-transparency panels were deemed unreliable in Section 3.7, and are thus omitted from discussion in the main text. All four methods produce accurate results, however HBM is the most consistent, with 1σ uncertainties always encompassing the true value.

individual spectra. For these reasons we turn to hierarchical Bayesian modeling (see Section 3.4). Here, we use simulated spectra from Section 3.7, for which we know the ground truth stellar population parameters, and we test whether the hierarchical Bayesian modeling method quantitatively outperforms various stacking methods.

The simulated spectra are stacked according to the three methods summarized in Table 3.7 and then fitted using `alf`. Some of the differences between the stacking methods include: whether and how to remove the continuum before fitting, whether or not to smooth the spectra to the same velocity dispersion, whether and how to weigh each spectrum when combining, how to combine (e.g., mean vs median), and finally, how to propagate the errors through to an stacked error spectrum.

The results from the stacked spectra are compared to the hierarchical Bayesian modeling method in Figure 3.12 for various stellar population parameters and elemental abundance ratios. On the top of each panel we include a histogram showing the distribution of the 30 simulated spectra from Section 3.7. The mean of the distribution is marked in each panel. This is the value we wish to recover. On the y-axis we label each method, where the stack number corresponds to Table 3.7. The 1σ uncertainties for each parameter are shown. All four methods reproduce the desired results quite closely (typically within 0.1 dex). This result is reassuring given the various stacking methods found in the literature. The hierarchical Bayesian modeling method, however, produces the most consistent results to within error. Furthermore, the PDF more accurately represents which parameters we can actually constrain. For example, there are no strong Na features in the blue LEGA-C spectra, and thus the uncertainties on [Na/Fe] reflect this. Stacking methods often underestimate the error spectrum and therefore underestimate the uncertainties on individual elemental abundances.

Hierarchical Bayesian Modeling

In this section we derive the hierarchical Bayesian modeling method and its application to combining spectra. In the specific case of this paper, we first fit all of the individual spectra and then combine the resulting PDFs using the hierarchical Bayesian framework. Following the hierarchical Bayesian prescription, we demonstrate how to combine the spectra in “post-processing.”

In the hierarchical framework, where we use α to describe the population parameters θ , Bayes’ theorem can be written,

$$P(\theta, \alpha | X) = \frac{P(X | \alpha, \theta) \cdot P(\alpha) \cdot P(\theta)}{P(X)} \quad (3.5)$$

Or, expanded using the chain rule,

$$P(\theta, \alpha | X) = \frac{P(X | \theta) \cdot P(\theta | \alpha) \cdot P(\alpha) \cdot P(\theta)}{P(X)} \quad (3.6)$$

Next, we re-write Hierarchical Bayes’ Theorem using problem-specific variables,

$$\begin{aligned}
 P(\{X_n\}, \theta | \{S_n\}) &= \frac{P(\{S_n\} | \theta, \{X_n\}) \cdot P(\theta) \cdot P(\{X_n\})}{P(\{S_n\})} \\
 &= \frac{P(\{S_n\} | \{X_n\}) \cdot P(\{X_n\} | \theta) \cdot P(\theta) \cdot P(\{X_n\})}{P(\{S_n\})},
 \end{aligned} \tag{3.7}$$

where X_n is the set of individual parameters describing the n^{th} galaxy, and $\{X_n\}$ is the set of these parameters for all N galaxies. θ is the population parameters that describe the distribution of $\{X_n\}$, and $\{S_n\}$ is the set of spectra for all N galaxies. For readability, the brackets will be dropped for the remainder of this section. Next, we put this equation in integral form,

$$P(X_n, \theta | S_n) = \prod_{n=1}^N \int \frac{P(S_n | X_n) P(X_n | \theta) P(\theta) P(X_n)}{P(S_n)} dX_n. \tag{3.8}$$

Taking a uniform prior on θ and X_n , we can remove $\frac{P(\theta)}{P(S_n)}$ from the integral and set $P(X_n) = 1$,

$$P(X_n, \theta | S_n) = \frac{P(\theta)}{P(S_n)} \prod_{n=1}^N \int P(S_n | X_n) P(X_n | \theta) dX_n. \tag{3.9}$$

Hierarchical Bayes in post-processing

In this paper, each of the individual spectra are first fit with `alf`. As a result, we already have MCMC chains for each spectrum. Instead of fitting for the individual parameters (X_n) and population parameters (θ) simultaneously, the above definitions can be re-written to include the pre-computed X_n PDFs. The set of MCMC chains that describe the X_n PDFs for all N galaxies can be defined mathematically as,

$$X_n^{(k)} = P(X_n | S_n) = \frac{P(S_n | X_n) P(X_n)}{P(S_n)}, \tag{3.10}$$

Note that $P(S_n | X_n)$ is actually $P(S_n | X_n, \theta)$ but we assert that the spectra do not care about the population parameters θ (e.g. galaxies don't talk to each other) and therefore we remove the dependence on θ . Solving for $P(S_n | X_n)$, setting the prior on the individual parameters $P(X_n) = 1$, and substituting into Eq. 3.9,

$$P(X_n, \theta | S_n) = \frac{P(S_n) P(\theta)}{P(S_n)} \prod_{n=1}^N \int P(X_n | S_n) P(X_n | \theta) dX_n. \tag{3.11}$$

The first term in the integral, $P(X_n | S_n)$, describes the MCMC chains from the individual fits (Eq. 3.10) and the second term, $P(X_n | \theta)$, is the population model. This integral is

too complicated to evaluate analytically, and thus we rely on finite sampling via MCMC. Eq. 3.11 can be approximated as a sum over the chains, k , following the prescription in Hogg & Foreman-Mackey (2018),

$$\int f(x) p(x) \approx \frac{1}{K} \sum_{k=1}^K f(x) \approx \frac{1}{K} \sum_{k=1}^K e^{\log f(x)}, \quad (3.12)$$

with the right-hand-side of this equation being a simple way to avoid numerical errors. Comparing Eqs. 3.11 and 3.12, we can define $f(x) \equiv P(X_n|\theta)$ (i.e. the population model). Taking the log of Eq. 3.12 and substituting Eq. 3.11, we arrive at

$$\log P(X_n, \theta | S_n) = \log P(S_n) - P(S_n) + \log P(\theta) - \log K + \sum_{n=1}^N \log \left[\sum_{k=1}^K e^{\log P(X_n|\theta)} \right]. \quad (3.13)$$

The first and second terms are the “evidence” because we do not care about the relative probability scaling, they can be ignored. The third term, $\log P(\theta)$, is the prior on the population parameters, which in our case is uniform and thus a constant that can also be ignored. Therefore, to calculate the posteriors on the global parameters given the MCMC chains of individual fits, we must evaluate the following:

$$\log P(X_n, \theta | S_n) \propto \sum_{n=1}^N \log \left[\sum_{k=1}^K e^{\log P(X_n|\theta)} \right]. \quad (3.14)$$

In this study, we set the population model to $P(X_n|\theta) \sim \mathcal{N}(\mu_{\text{pop}}, \sigma_{\text{pop}}^2)$, such that each of the elemental abundances and stellar population parameters in a given bin are distributed normally, with a mean μ_{pop} and spread σ_{pop} . Finally, we use MCMC to sample the μ_{pop} and σ_{pop} PDFs, where the likelihood is given by Eq. 3.14. In words, the likelihood function is given by the following: for each galaxy, evaluate $\mathcal{N}(\mu_{\text{pop}}, \sigma_{\text{pop}}^2)$ at the location of the pre-computed MCMC chains. Sum this over all K chains and then over all N galaxies.

3.8 Conclusion

In this paper we presented detailed elemental abundance patterns and stellar population ages for 135 massive quiescent galaxies at $z \sim 0.7$ drawn from the LEGA-C survey. We modeled the ultra-deep rest-frame optical spectra using a full-spectrum fitting code with varying elemental abundances. We then placed the galaxies in four bins of velocity dispersion and calculated the average abundance results in each bin using a hierarchical Bayesian modeling technique. Finally, we compared the binned results to stacks of massive early-type galaxies at $z \sim 0$. The main conclusions are summarized as follows:

1. The absolute abundances $[X/H]$ are correlated with the observed velocity dispersion, such that galaxies with larger σ_v are more metal-rich. This result reinforces that

galaxies with larger gravitational potentials are better at retaining their enriched gas reservoir.

2. The abundance ratios $[X/Fe]$ show only mild or non-significant trend with velocity dispersions for nearly all elements. To first order this result implies that, on average, massive quiescent galaxies form on similar timescales over the studied range of velocity dispersions. Briefly, we note the small range in velocity dispersions probed by this study. A larger sample probing lower-dispersion galaxies may reveal a possible trend.
3. The stellar population age increase as a function of velocity dispersion such that galaxies with deeper gravitational potentials formed earlier.
4. To first order, massive quiescent galaxies at $z \sim 0.7$ and $z \sim 0$ have remarkably similar abundance patterns, with enhanced CNO products (C, N) and α -element Mg followed by a steep drop to approximately solar abundances for the heavier α (Si, Ca, Ti) and Fe-peak (V, Cr, Fe, Co, Ni) elements. However, in the lower velocity dispersion bins, galaxies at $z \sim 0.7$ are found to have formed earlier and are more enhanced in $[X/Fe]$ for elements N, Mg, Ti, and Ni compared to $z \sim 0$. These findings may indicate that the low-dispersion quiescent galaxy population is still evolving either by late-time star formation or the late additions of newly quenched galaxies between $z \sim 0.7$ and $z \sim 0$.
5. The measured abundance patterns show major differences with theoretical predictions based on one-zone chemical evolution models for elliptical galaxies from Nomoto et al. (2013), indicating that our current understanding of the detailed chemical enrichment histories of massive quiescent galaxies is still limited.

The LEGA-C survey has enabled us to measure the detailed and robust elemental abundance patterns of quiescent galaxies beyond $z \sim 0.5$. These abundance patterns may serve as powerful probes of the chemical enrichment and formation histories of these galaxies. However, the interpretation is currently still limited by low S/N measurements, our reliance on “stacking” spectra, and our incomplete theoretical understanding of the nucleosynthetic origins of many elements. Using more detailed and updated chemical evolution modeling, along with abundance pattern measurements for larger samples extending to higher redshift enabled by JWST, this field is expected to make major leaps forward over the coming decade.

Chapter 4

The Heavy Metal Survey: The Evolution of Stellar Metallicities, Abundance Ratios, and Ages of Massive Quiescent Galaxies Since $z \sim 2$

The content of this chapter is drawn from Beverage et al. 2024, with permission from the co-authors.

4.1 Abstract

We present the elemental abundances and ages of 19 massive quiescent galaxies at $z \sim 1.4$ and $z \sim 2.1$ from the Keck Heavy Metal Survey. The ultra-deep LRIS and MOSFIRE spectra were modeled using a full-spectrum stellar population fitting code with variable abundance patterns. The galaxies have iron abundances between $[\text{Fe}/\text{H}] = -0.5$ and -0.1 dex, with typical values of -0.2 $[-0.3]$ at $z \sim 1.4$ [$z \sim 2.1$]. We also find a tentative $\log \sigma_v$ - $[\text{Fe}/\text{H}]$ relation at $z \sim 1.4$. The magnesium-to-iron ratios span $[\text{Mg}/\text{Fe}] = 0.1 - 0.6$ dex, with typical values of 0.3 $[0.5]$ dex at $z \sim 1.4$ [$z \sim 2.1$]. The ages imply formation redshifts of $z_{\text{form}} = 2 - 8$. Compared to quiescent galaxies at lower redshifts, we find $[\text{Fe}/\text{H}]$ was ~ 0.2 dex lower at $z = 1.4 - 2.1$. We find no evolution in $[\text{Mg}/\text{Fe}]$ out to $z \sim 1.4$, though the $z \sim 2.1$ galaxies are 0.2 dex enhanced compared to $z = 0 - 0.7$. A comparison of these results to a chemical evolution model indicates that galaxies at higher redshift form at progressively earlier epochs and over shorter star-formation timescales, with the $z \sim 2.1$ galaxies forming the bulk of their stars over 150 Myr at $z_{\text{form}} \sim 4$. This evolution cannot be solely attributed to an increased number of quiescent galaxies at later times; several Heavy Metal galaxies have extreme chemical properties not found in massive galaxies at $z \sim 0.0 - 0.7$. Thus, the

chemical properties of individual galaxies must evolve over time. Minor mergers also cannot fully account for this evolution as they cannot increase $[\text{Fe}/\text{H}]$, particularly in galaxy centers. Consequently, the build-up of massive quiescent galaxies since $z \sim 2.1$ may require further mechanisms such as major mergers and/or central star formation.

4.2 Background

In the present-day universe, nearly all massive galaxies have quiescent stellar populations. Archaeological studies have revealed that they formed the bulk of their stars rapidly at $z > 2$ (e.g., Gallazzi et al., 2005; Thomas et al., 2005; McDermid et al., 2015). Thus, these studies imply that quiescent galaxies should already exist when the universe was only a fraction of its current age.

Quiescent galaxies have indeed been identified and studied out to $z \sim 5$ (e.g., Franx et al., 2003; Daddi et al., 2005; Cimatti et al., 2004; Kriek et al., 2006; Cimatti et al., 2008; Kriek et al., 2009; van de Sande et al., 2013; Belli et al., 2014; Glazebrook et al., 2017; Schreiber et al., 2018; Valentino et al., 2020; Nanayakkara et al., 2023; Carnall et al., 2023; Antwi-Danso et al., 2023) and are thought to dominate the massive galaxy population out to $z = 2.5$ (e.g. Muzzin et al., 2013b; Tomczak et al., 2014; McLeod et al., 2021). Interestingly, quiescent galaxies at higher redshifts are significantly more compact than the population at $z \sim 0$, with their half-mass radii growing by a factor of three since $z \sim 2$ (Daddi et al., 2005; Dokkum et al., 2008; Damjanov et al., 2009; van der Wel et al., 2014; Mowla et al., 2019; Suess et al., 2019a,b; Miller et al., 2023). Distant quiescent galaxies, however, have central mass densities similar to their nearby analogs, and the size difference is primarily attributed to the larger envelopes of the lower-redshift galaxies (e.g., Bezanson et al., 2009; Hopkins et al., 2009; van Dokkum et al., 2010; Barro et al., 2017; van de Sande et al., 2013; Ji & Gialalisco, 2022). Furthermore, the color gradients of quiescent galaxies become stronger with time, with galaxy outskirts becoming progressively bluer than the centers (Suess et al., 2019a,b, 2020; Miller et al., 2023).

One way to understand the structural evolution of massive quiescent galaxies is through the “inside-out” growth scenario, in which compact galaxies still grow via gas-poor minor mergers after they have become quiescent (e.g., Bezanson et al., 2009; Naab et al., 2009; van Dokkum et al., 2010; Oser et al., 2012). An alternative explanation is suggested by the fact that the stellar mass function shows a tenfold increase in the number of massive quiescent galaxies since $z \sim 2$ (McLeod et al., 2021). If galaxies that quench at lower redshift have larger sizes and stronger color gradients, the observed evolution of *average* properties could instead be explained by population growth (i.e., progenitor bias; e.g., Khochfar & Silk, 2009; van Dokkum et al., 2010; Carollo et al., 2013; Poggianti et al., 2013). The relative importance of minor mergers vs progenitor bias remains a central question in massive galaxy evolution.

The evolution in elemental abundances and stellar population properties over cosmic time provides a unique insight into the assembly and star-formation histories of massive quiescent galaxies (e.g., Matteucci, 1994; Trager et al., 2000; Conroy et al., 2014; Choi et al.,

2014; Maiolino & Mannucci, 2019; Beverage et al., 2021; Peng et al., 2015; Spitoni et al., 2017; Trussler et al., 2020). Unfortunately, measuring elemental abundances beyond the low-redshift universe poses a considerable challenge. At higher redshifts, key absorption features are faint and shifted to near infrared (NIR) wavelengths. Recently, ultra-deep spectroscopic surveys have started pushing these measurements beyond the low-redshift universe and find that the chemical properties of massive quiescent galaxies at $z \sim 0.7$ closely resemble today’s massive early-type galaxies (Choi et al., 2014; Leethochawalit et al., 2018; Beverage et al., 2023; Bevacqua et al., 2023). These studies show that the most massive galaxies were already in place six billion years ago, while the low-mass quiescent population have continued to grow since $z \sim 0.7$ (see Leethochawalit et al., 2019; Beverage et al., 2023).

While minimal evolution is found out to $z \sim 0.7$, the picture at higher redshift is less clear. The few existing stellar metallicity measurements of massive quiescent galaxies at $z \gtrsim 1.4$ show systematically lower $[\text{Fe}/\text{H}]$ compared to $z \sim 0$, but there is large scatter depending on the methods used to derive the metallicities (Lonoce et al., 2015; Onodera et al., 2015; Kriek et al., 2016, 2019; Carnall et al., 2022; Saracco et al., 2023; Zhuang et al., 2023). At $z > 2$, the only *two* existing measurements show strong α -enhancement, with $[\text{Mg}/\text{Fe}] \sim 0.5 - 0.6$ dex, indicative of extremely short star-formation timescales of < 100 Myr (Kriek et al., 2016; Jafariyazani et al., 2020). To further clarify the picture at $z > 1$, and assess the assembly of the quiescent galaxy population over the past 11 billion years, larger galaxy samples are needed.

To that end, we have executed the Keck Heavy Metal survey, an ultra-deep spectroscopic survey with LRIS (Oke et al., 1995; Rockosi et al., 2010) and MOSFIRE (McLean et al., 2010, 2012) on the Keck I Telescope (see Kriek et al., 2023). This survey collected high-S/N spectra of 21 massive quiescent galaxies at $1.4 \lesssim z \lesssim 2.2$, covering multiple Balmer and metal absorption lines.

The Heavy Metal survey has more than tripled the number of individual galaxies at $z \gtrsim 1.4$ with measurements of stellar metallicities, ages, and elemental abundance ratios. Preliminary results of five Heavy Metal galaxies were presented in Kriek et al. (2019) and are updated in the current work. The survey design is presented in the companion survey paper (Kriek et al., 2023). In section 2 we describe our full-spectrum modeling technique. In section 3 we present the stellar population results. In section 4 we assess how the metal content of quiescent galaxies evolves between $z \sim 2.2$ and $z \sim 0$ by comparing our results with the LEGA-C ($z \sim 0.7$) and SDSS ($z \sim 0$) surveys. In section 5 we consider the implications of our results in the build-up of the massive quiescent galaxy population. In section 6 we summarize our results. Throughout this work we assume a flat Λ CDM cosmology with $\Omega_m = 0.3$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

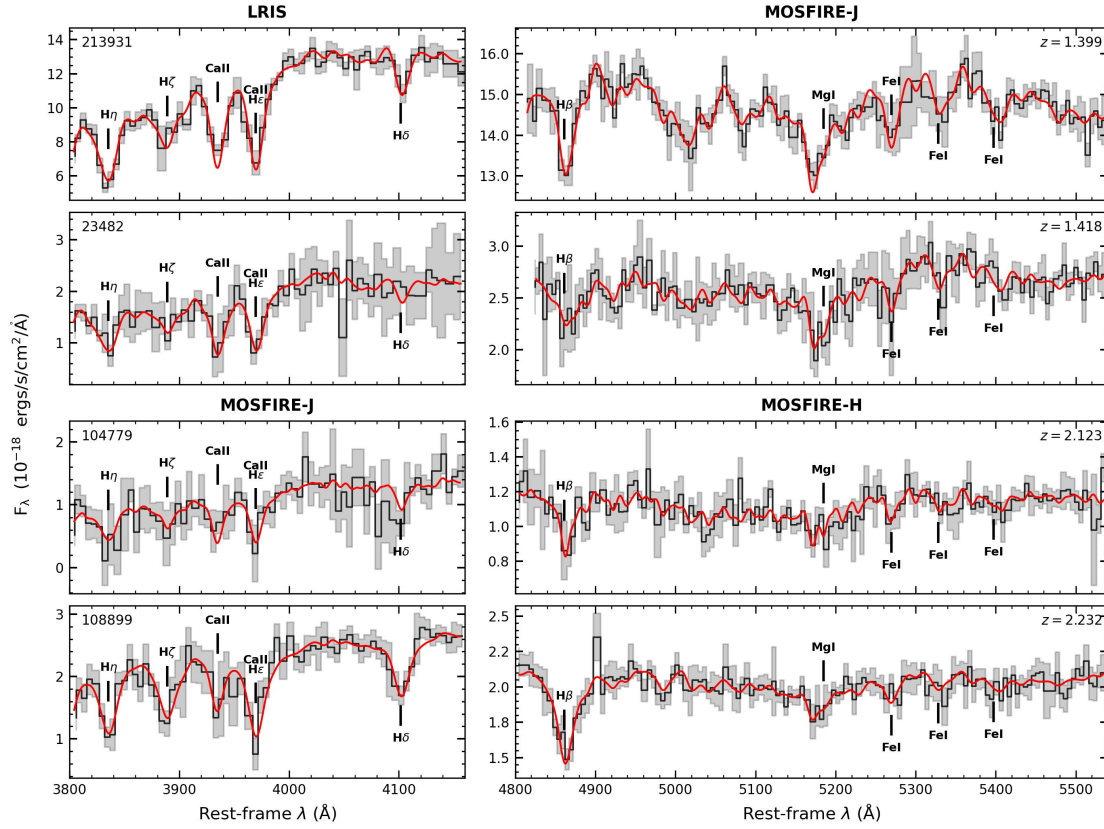


Figure 4.1: Spectra (black) and corresponding 1σ uncertainties on the flux (gray), along with the best-fitting `alf` models used to derive the ages and elemental abundances (red) of primary Heavy Metal Survey targets, sorted by redshift. Spectra are binned such that one pixel is $\simeq 5 \text{ \AA}$. The spectra were fit prior to binning.

4.3 Sample and Methods

The Heavy Metal Survey

The targets in this study are selected from the Keck Heavy Metal Survey; an ultra-deep rest-frame optical spectroscopic survey of massive quiescent galaxies at $z = 1.3 - 2.2$. The 21 quiescent targets were identified using the UltraVISTA K -band selected catalog (v4.1) by Muzzin et al. (2013b) and were selected to be quiescent using UVJ colors (Wuyts et al., 2016; Williams et al., 2009). The redshift intervals $1.30 < z < 1.50$ and $1.92 < z < 2.28$ were chosen such that key rest-frame NIR metal absorption features, namely Balmer lines, $H\beta$, and MgI , fall within the wavelength windows of the Keck/LRIS and Keck/MOSFIRE spectrometers. Primary targets were further required to have $J < 21.5$ and $H < 21.7$ at $z \sim 1.4$ and $z \sim 2.1$, respectively

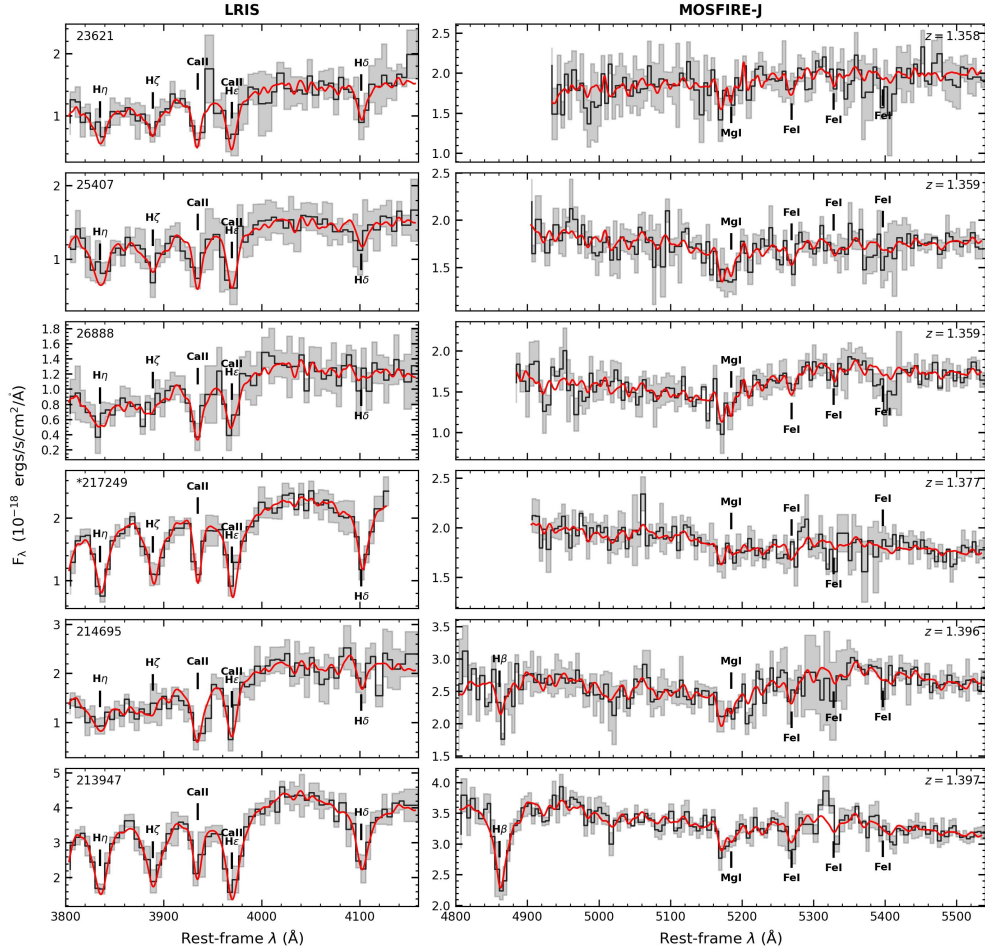


Figure 4.1: Continued

The $z \sim 1.4$ targets were observed for a total of ~ 17 hrs on Keck (~ 5 hrs with LRIS using the 600/10000 red grating and ~ 12 hrs with MOSFIRE-*J*), while the $z \sim 2.1$ targets were observed for ~ 30 hrs (~ 13 hrs with MOSFIRE-*J* and ~ 16 hrs with MOSFIRE-*H*). These integration times provide sufficient S/N for modeling the faint stellar absorption features of individual massive quiescent galaxies. The typical S/N for the $z \sim 1.4$ sample is $8 \text{ \AA}^{-1}$ and $15 \text{ \AA}^{-1}$ in the rest-frame for LRIS and MOSFIRE-*J*, respectively, while the S/N for the $z \sim 2.1$ sample is $4 \text{ \AA}^{-1}$ and $12 \text{ \AA}^{-1}$ for MOSFIRE-*J* and MOSFIRE-*H*. For further details on the target selection, observing strategy, data reduction, galaxy sample characteristics, and stellar population properties (i.e., stellar masses) we refer to Kriek et al. (2023).

One of the 21 primary targets (ID:55878) is removed from this study before fitting due to strong line emission, likely originating from AGN (see Ma et al. 2023, in prep). Another galaxy is also removed (ID:59449) because there are no clear absorption lines in the spectra.

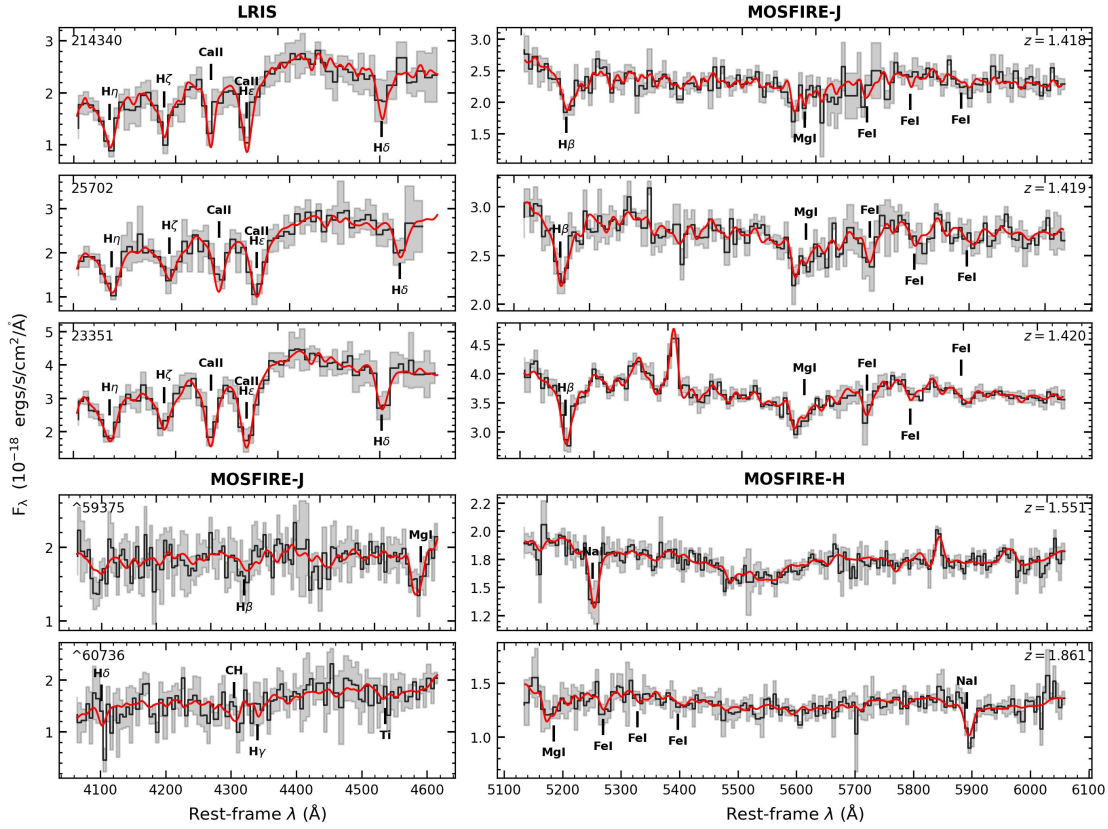


Figure 4.1: Continued

Stellar ages and elemental abundances

We derive chemical compositions and stellar ages of the 19 Heavy Metal targets using the full-spectrum absorption line fitter (**alf**) code (Conroy & van Dokkum, 2012; Conroy et al., 2018). **alf** is designed to fit the individual elemental abundances and stellar ages from optical-NIR stellar continuum of > 1 Gyr stellar populations. **alf** combines metallicity-dependent MIST isochrones (Choi et al., 2016), empirical MILES and IRTF spectral libraries (Sanchez-Blazquez et al., 2006; Villaume et al., 2017), and synthetic metallicity- and age-dependent elemental response spectra for 19 elements.

4.4 Results

In the fitting presented here, we assume a model with a single burst of star formation (approximated as an SSP) and a fixed Kroupa (2001) IMF. We note that **alf** also allows for a young second SSP component to account for late-time star formation. In the end, the full-spectrum model has 26 free parameters: velocity offset, velocity dispersion, SSP age,

Table 4.1: Heavy Metal Quiescent Galaxy Parameters

ID ^a	z	σ (km/s)	Age (Gyr)	[Fe/H]	[Mg/Fe]
23621	1.358	199^{+38}_{-41}	$2.1^{+1.0}_{-0.7}$	$-0.41^{+0.36}_{-0.41}$	$0.31^{+0.34}_{-0.37}$
25407	1.359	201^{+27}_{-28}	$2.5^{+0.9}_{-0.6}$	$-0.47^{+0.26}_{-0.24}$	$0.64^{+0.24}_{-0.26}$
26888	1.359	166^{+33}_{-27}	$3.7^{+2.3}_{-1.1}$	$-0.10^{+0.20}_{-0.26}$	$0.27^{+0.22}_{-0.23}$
217249 ^{b,c}	1.377	185^{+21}_{-24}	$0.8^{+0.2}_{-0.1}$	$-0.38^{+0.21}_{-0.26}$	$0.34^{+0.25}_{-0.25}$
214695 ^b	1.396	210^{+24}_{-25}	$3.4^{+2.2}_{-0.9}$	$-0.29^{+0.24}_{-0.27}$	$0.34^{+0.18}_{-0.19}$
213947 ^b	1.397	216^{+16}_{-13}	$0.9^{+0.1}_{-0.1}$	$-0.17^{+0.17}_{-0.18}$	$0.38^{+0.20}_{-0.21}$
213931 ^b	1.399	371^{+13}_{-13}	$2.6^{+0.6}_{-0.4}$	$-0.12^{+0.13}_{-0.12}$	$0.27^{+0.07}_{-0.07}$
214340 ^b	1.418	149^{+19}_{-23}	$1.4^{+0.4}_{-0.3}$	$-0.34^{+0.20}_{-0.20}$	$0.24^{+0.23}_{-0.23}$
23482	1.419	289^{+38}_{-35}	$2.6^{+1.3}_{-0.7}$	$-0.09^{+0.24}_{-0.26}$	$0.29^{+0.23}_{-0.22}$
25702	1.419	243^{+21}_{-20}	$1.8^{+0.7}_{-0.4}$	$-0.24^{+0.18}_{-0.17}$	$0.32^{+0.15}_{-0.16}$
23351	1.420	257^{+14}_{-13}	$1.3^{+0.3}_{-0.2}$	$-0.07^{+0.15}_{-0.17}$	$0.12^{+0.14}_{-0.13}$
59375 ^c	1.550	333^{+42}_{-43}	$9.5^{+3.4}_{-4.9}$	$0.21^{+0.30}_{-0.30}$	$0.36^{+0.28}_{-0.29}$
60736 ^c	1.861	270^{+30}_{-27}	$2.1^{+1.7}_{-0.6}$	$-0.49^{+0.23}_{-0.25}$	$0.60^{+0.26}_{-0.30}$
104779	2.123	186^{+30}_{-31}	$1.5^{+0.9}_{-0.4}$	$-0.15^{+0.24}_{-0.28}$	$0.55^{+0.23}_{-0.23}$
56163 ^c	2.160	213^{+34}_{-48}	$2.9^{+1.1}_{-1.1}$	$-0.43^{+0.32}_{-0.32}$	$0.29^{+0.32}_{-0.31}$
106812	2.230	187^{+41}_{-45}	$1.5^{+1.1}_{-0.4}$	$-0.44^{+0.28}_{-0.28}$	$0.41^{+0.36}_{-0.32}$
108899	2.233	306^{+24}_{-23}	$1.2^{+0.2}_{-0.1}$	$-0.38^{+0.22}_{-0.30}$	$0.48^{+0.25}_{-0.29}$
107590 ^c	2.234	173^{+25}_{-23}	$0.8^{+0.1}_{-0.1}$	$-0.42^{+0.18}_{-0.22}$	$0.44^{+0.26}_{-0.30}$
103236	2.243	197^{+37}_{-35}	$1.5^{+1.0}_{-0.4}$	$-0.23^{+0.22}_{-0.23}$	$0.50^{+0.25}_{-0.23}$

^a See Kriek et al. (2023) for coordinates, magnitudes, and stellar population and structural properties

^b Appears in Kriek et al. (2019)

^c Poorly constrained, removed from analysis

isochrone metallicity, the abundances of 19 individual elements (Fe, O, C, N, Na, Mg, Si, K, Ca, Ti, V, Cr, Mn, Co, Ni, Cu, Sr, Ba, and Eu), and the emission line strengths of H, [OIII], and [NII].

The fitting is done in the rest-frame and the instrumental resolution of the data is accounted for by convolving the grid of models to match the resolution of the spectrum. We measure this instrumental resolution for each spectrum by finding the average full width at half maximum (FWHM) of 20-25 skylines in the variance spectrum. The average instrumental dispersions are $\sigma_{\text{inst}} = 62, 36, \text{ and } 33$ km/s for the LRIS-Red, MOSFIRE-J, and MOSFIRE-H spectra, respectively. We note that the instrumental dispersion is lower than the template resolution in **alf**. This template resolution can be an issue if the intrinsic velocity dispersion is lower than 100 km/s. However, as we will find, the intrinsic velocity dispersions of the Heavy Metal galaxies are significantly higher than 100 km/s. The spectral continuum is also removed from the observations by fitting a high-order polynomial to the ratio of the data to the model (where $n \equiv (\lambda_{\text{max}} - \lambda_{\text{min}})/100 \text{ \AA}$). We test the impact of the polynomial on the results by assuming different orders than the default ($n = 8$ and $n = 6$). We find that the polynomial order does not make a meaningful impact on the results, to well within the 1σ uncertainties. Furthermore, Conroy et al. (2018) test the impact of the

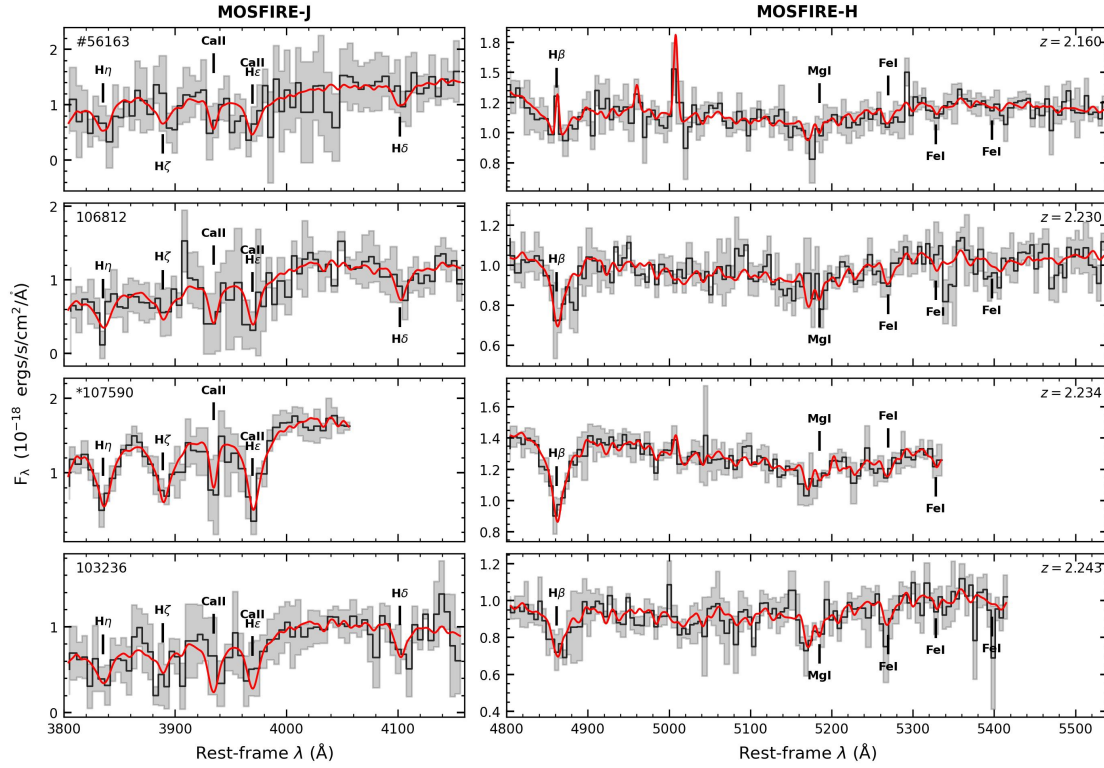


Figure 4.1: Continued

normalizing polynomial on the fitting results and find that if fluxing issues are approximately linear on $< 50 \text{ \AA}$ scales, the default polynomial assumption is sufficient. Once normalized, the spectrum is fit using Markov-Chain Monte Carlo (Foreman-Mackey et al., 2013) with 1,024 walkers and a burn-in of 20,000 steps. The priors of the MCMC fit are uniform and the walkers are initialized around the solar abundance pattern.

After fitting all 19 galaxies, we visually inspect the best-fit models and the corresponding posterior distribution functions (PDFs) and remove any galaxy with poorly constrained parameters. We removed three galaxies because their PDFs do not follow normal distributions and/or they have ill-defined peaks. Two of these galaxies lack spectral coverage of key absorption features (D4000 break), leading to unreliable abundance measurements, and the third galaxy has strong [O II] and Hydrogen emission. We also remove two galaxies with best-fit stellar ages $< 1 \text{ Gyr}$, as the stellar population models are not optimized for these young ages. As a sanity check, we also inspect correlations between all fitted parameters to ensure the relevant parameters are not being driven by other poorly constrained parameters. After removing these five galaxies, we are left with elemental abundances and stellar age measurements for ten galaxies at $z \sim 1.4$ and four galaxies at $z \sim 2.1$.

Five of the original 19 galaxies in this study were originally presented in Kriek et al.

(2019). In this study, we have since re-extracted the 1D spectra using an improved optimal weighing procedure. We also assume a single SSP when fitting, whereas Kriek et al. (2019) assume a two-burst model. Nonetheless, the results presented here are consistent to within 1σ of what is found in Kriek et al. (2019).

Example spectra with corresponding best-fit models are shown in Figure 4.1, while the remaining spectra and fits can be found in Section ???. Corner plots corresponding to the galaxies in Figure 4.1 are included in Section 4.7. The best-fit parameters are listed in Table 5.1 for all 19 galaxies. Objects with poorly constrained abundances are noted and are removed from the following analysis. In Section 4.7, we conduct a mock recovery test to check for systematic uncertainties in the `alf` fitting as a function of SNR. Systematic uncertainties remain <0.1 dex even at the lowest S/N ($8\text{\AA}^{-1}$). We refer to Kriek et al. (2023) for tabulated details of the observations and SED fitting results.

In addition to elemental abundances and stellar ages, the full-spectrum fitting provides measurements of the stellar velocity dispersions. We find that the velocity dispersions of the Heavy Metal galaxies agree with previous measurements of the dynamical mass-stellar mass relation at similar redshifts (e.g., Belli et al., 2016) and we explore the implications of the Heavy Metal dynamical masses in the companion survey paper (Kriek et al., 2023).

Figure 4.2 shows the variation in $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, and formation time (t_{form}) as a function of velocity dispersion σ_v for the Heavy Metal galaxies at $z \sim 1.4$ (blue triangles) and $z \sim 2.1$ (purple stars). For comparison, we also show trends of quiescent galaxies at $z \sim 0$ and $z \sim 0.7$ from Beverage et al. (2023) in Figure 4.2. The $z \sim 0$ trends are derived by re-fitting the stacked spectra of a sample of 5,234 quiescent galaxies in SDSS from Conroy et al. (2014), while the $z \sim 0.7$ trends are based on 135 quiescent galaxies in the LEGA-C survey. Initially, Beverage et al. (2021) reported a -0.2 dex offset in $[\text{Fe}/\text{H}]$ between LEGA-C and SDSS galaxies based on the spectra from the second LEGA-C data release (DR2). However, with the subsequent release, DR3, which doubled the sample size and improved data reduction (see van der Wel et al., 2021), Beverage et al. (2023) no longer found an offset in $[\text{Fe}/\text{H}]$ between $z \sim 0.7$ and $z \sim 0$. Figure 4.2 also includes results from other studies of quiescent galaxies at $z \sim 1.5$ (Carnall et al., 2022; Zhuang et al., 2023) and $z \sim 2.1$ (Kriek et al., 2016; Jafariyazani et al., 2020).¹ We note that several other works have derived stellar metallicities of distant quiescent galaxies by fitting low-resolution grism spectra (e.g., Morishita et al., 2018; Estrada-Carpenter et al., 2019). However, such studies rely on the shape of the stellar continuum to constrain the metallicities, leading to high degeneracies with stellar age, and therefore we do not include these results in our comparison. To ensure unbiased comparisons, we restrict the analysis to studies that utilize `alf`.

In the left panel of Figure 4.2 we show that the Heavy Metal galaxies have lower $[\text{Fe}/\text{H}]$ compared to the $z \sim 0$ and $z \sim 0.7$ galaxies with similar velocity dispersions. Both the $z \sim 1.4$ and $z \sim 2.1$ galaxy populations have Fe-abundances between -0.5 and -0.1 dex, with typical uncertainties of 0.2 dex. There is a hint that the $z \sim 2.1$ are slightly offset to

¹Carnall et al. (2022) do not measure a velocity dispersion. We infer one using the average stellar mass of galaxies in the stacked spectrum and an empirically calibrated σ_v - M_* relation from Zahid et al. (2016).

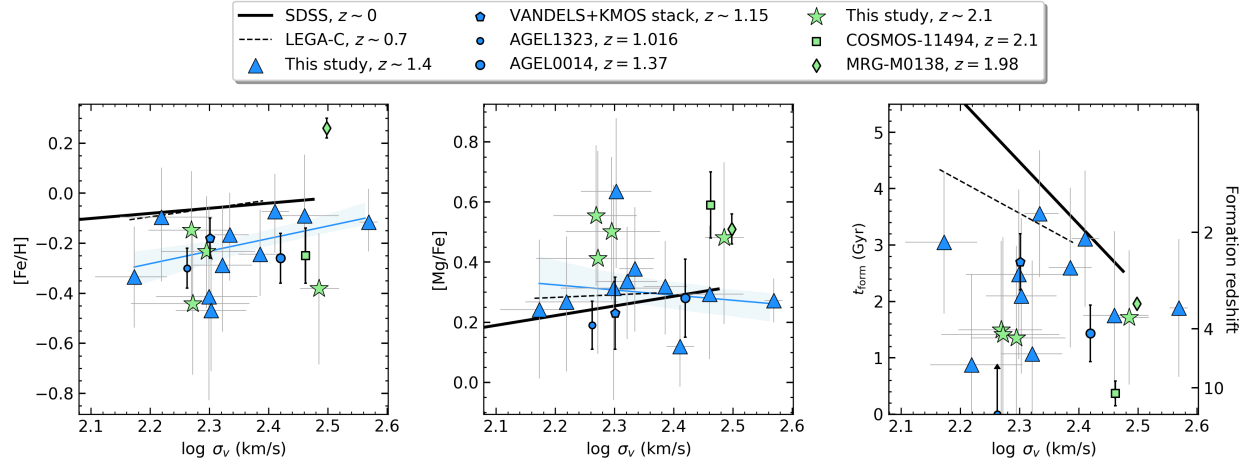


Figure 4.2: $[\text{Fe}/\text{H}]$ (left), $[\text{Mg}/\text{Fe}]$ (middle), and formation redshift (right) results for the $z \sim 1.4$ (blue triangles) and $z \sim 2.1$ (green stars) Heavy Metal targets as a function of stellar velocity dispersion. The black solid line shows the σ_v -abundance relations of massive quiescent galaxies at $z \sim 0$ (Conroy et al., 2014; Beverage et al., 2021), while the black dashed lines denote relations at $z \sim 0.7$ (Beverage et al., 2023). We include a quiescent galaxy at $z = 2.1$ (green square; Kriek et al., 2016), a lensed quiescent galaxy at $z = 1.98$ (green diamond; Jafariyazani et al., 2020), a stack of quiescent galaxies at $1.0 < z < 1.3$ (blue pentagon; Carnall et al., 2022), and two lensed quiescent galaxies at $z = 1.016$ and $z = 1.37$ (blue circles; Zhuang et al., 2023). The solid blue line in the left panel represents the best-fit σ_v - $[\text{Fe}/\text{H}]$ with the 16th and 84th percentile uncertainties on the fit shown in light blue. The results from all studies were derived using `alf`. Quiescent galaxies at $z > 0.7$ have lower $[\text{Fe}/\text{H}]$, enhanced $[\text{Mg}/\text{Fe}]$, and earlier formation times than galaxies at lower redshifts.

lower $[\text{Fe}/\text{H}]$ compared to $z \sim 1.4$. We fit a σ_v - $[\text{Fe}/\text{H}]$ relation to the $z \sim 1.4$ population using a simple linear regression, with confidence intervals determined by perturbing the $[\text{Fe}/\text{H}]$ of each data point according to their uncertainties and re-fitting 1000 times. The resulting relation is shown in the left panel of Figure 4.2 (blue line, with shaded confidence intervals). We find a positive slope of $0.52^{+0.38}_{-0.23}$, which is consistent with the $z \sim 0$ and $z \sim 0.7$ relations. However, there is a clear offset to lower $[\text{Fe}/\text{H}]$. We do not fit a relation to the $z \sim 2.1$ population because of the small sample size.

The observed evolution in $[\text{Fe}/\text{H}]$ between $z = 1.4 - 2.1$ and $z < 1$ is corroborated by studies of other quiescent galaxies at similar redshifts. At $z \sim 1.4$, galaxies in the VANDELS+KMOS survey (Carnall et al., 2022) and two lensed galaxies in the AGEL survey (Zhuang et al., 2023) have $[\text{Fe}/\text{H}] \sim -0.25$, in agreement with the $z \sim 1.4$ Heavy Metal galaxies (see Figure 4.2). At $z = 2.1$, Kriek et al. (2016) measure $[\text{Fe}/\text{H}] = -0.25$ for a massive quiescent galaxy (COSMOS-11494), consistent with the values of the $z \sim 2.1$ Heavy

Metal galaxies (refer to Figure 4.2). Interestingly, the only other study at $z \sim 2.1$ finds super-solar $[\text{Fe}/\text{H}]$ for a lensed galaxy (MRG-M0138) at $z = 1.98$ (Jafariyazani et al., 2020). It was previously unclear whether this large variation in $[\text{Fe}/\text{H}]$ is typical of the $z \sim 2.1$ quiescent galaxy population. Now, with four Heavy Metal galaxies at $z \sim 2.1$ with sub-solar $[\text{Fe}/\text{H}]$, there is additional evidence suggesting that typical massive galaxies at $z \sim 2.1$ are indeed Fe-deficient and that the Fe-abundance of MRG-M0138 may be anomalous. Nevertheless, the sample size is small and the large uncertainties on the Fe-abundances prevent any definitive statement about the $z \sim 2.1$ population.

In the middle panel of Figure 4.2 we see that the Heavy Metal galaxies at $z \sim 1.4$ have similar $[\text{Mg}/\text{Fe}]$ to what is found in the SDSS ($z \sim 0$) and LEGA-C ($z \sim 0.7$) samples. Meanwhile, the $z \sim 2.1$ Heavy Metal galaxies have $[\text{Mg}/\text{Fe}]$ that are ≈ 0.2 dex higher than what is found at lower redshifts, though typical uncertainties are large (0.2 dex) and the sample size is small. We derive a σ - $[\text{Mg}/\text{Fe}]$ relation for the $z \sim 1.4$ Heavy Metal galaxies using the same method as with $[\text{Fe}/\text{H}]$, resulting in a negative slope of $-0.15^{+0.17}_{-0.29}$ (blue line with shaded confidence intervals). This slope is consistent with zero to within 1σ and there is no significant offset compared to the $z < 1$ relations. These results are supported by the other studies of quiescent galaxies at $z > 1$. The two studies at $z \sim 1.4$ find $[\text{Mg}/\text{Fe}]$ consistent with the LEGA-C and SDSS, while the two at $z \sim 2$ find enhanced $[\text{Mg}/\text{Fe}]$ consistent with the $z \sim 2.1$ Heavy Metal galaxies.

Finally, in the right panel of Figure 4.2 we show galaxy σ_v vs. galaxy formation time. This age is determined using the best-fit stellar population age. We find that the formation time of the Heavy Metal galaxies range from 1 Gyr ($z_{\text{form}} = 9$) and 4 Gyr ($z_{\text{form}} = 2$) after the Big Bang, with an average formation time of 2.5 Gyr ($z_{\text{form}} = 3$) and 1.5 Gyr ($z_{\text{form}} = 4$) for the $z \sim 1.4$ and $z \sim 2.1$ samples, respectively. We note that the galaxy formation times are calculated using an SSP-equivalent age, and more complex SFHs would have likely resulted in slightly earlier formation times. The assumption of an SSP, however, does not bias the stellar metallicities or elemental abundance measurements (Serra & Trager, 2007). In the next section we consider the results in Figure 4.2 in the context of galaxy evolution.

4.5 The evolution of massive quiescent galaxy population since $z = 2.1$

In this section, we investigate the changes of *average* stellar metallicities, abundance ratios, and ages of massive quiescent galaxies as a function of redshift and discuss implications for their evolution over the past 11 billion years. In Figure 4.3 we show the average $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, t_{form} , and $[\text{Mg}/\text{Fe}]$ for quiescent galaxies in the SDSS, LEGA-C, and Heavy Metal surveys as a function of redshift. To allow for a fair comparison between surveys, we only consider the SDSS and LEGA-C galaxies that fall in bins with similar σ_v as the Heavy Metal galaxies. Specifically, we remove three SDSS bins and one LEGA-C bin with $\sigma < 170$ km/s. Thus, the average velocity dispersions of the SDSS and LEGA-C galaxies used in Figure 4.3

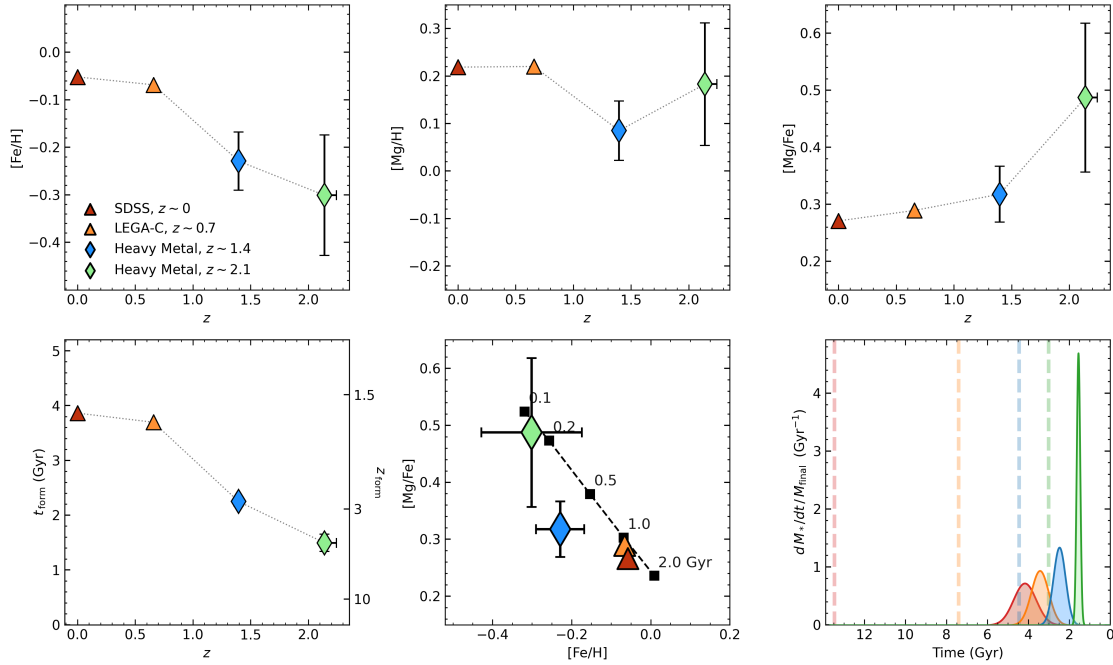


Figure 4.3: Average elemental abundance and stellar age results for the Heavy Metal galaxies at $z \sim 1.4$ and $z \sim 2.1$, and for stacks of massive quiescent galaxies at $z \sim 0$ and $z \sim 0.7$ across various axes. The error bars on the SDSS and LEGA-C data points are smaller than the symbol size. *Top row:* the $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ abundances as a function of redshift. *Bottom row:* the left panel shows the formation time as a function of redshift. In the middle panel, we compare the average abundances on the $[\text{Fe}/\text{H}]$ - $[\text{Mg}/\text{Fe}]$ plane to a simple closed-box chemical evolution model (black dashed line). Black squares represent predicted elemental abundances for various star-formation timescales, denoted in Gyr. The right panel shows the inferred star-formation history at each redshift interval. The age of the universe for each sample is marked with a dashed line. Typical quiescent galaxies at higher redshift formed earlier and over shorter timescales than massive quiescent galaxies today.

are $\sigma_v = 240 \text{ km s}^{-1}$, with the number of galaxies in each respective sample now being 2,990 (SDSS) and 101 (LEGA-C).

Examining the top left panel of Figure 4.3, we observe an increase in the average $[\text{Fe}/\text{H}]$ from $z = 2.1$ to $z = 0$, with distinct offsets of -0.2 and -0.3 dex at $z \sim 1.4$ and $z \sim 2.1$, respectively, between the Heavy Metal galaxies and the lower redshift samples. Moving to the middle upper panel, we find less evolution in $[\text{Mg}/\text{H}]$ compared to $[\text{Fe}/\text{H}]$; the $z = 1.4$ sample is 0.1 dex lower compared to the $z = 0.7$ and $z = 0$ galaxies. The $z = 2.1$ galaxies have no $[\text{Mg}/\text{H}]$ offset compared to lower redshift galaxies, although uncertainties remain substantial. Primarily due to the increase in $[\text{Fe}/\text{H}]$, the average $[\text{Mg}/\text{Fe}]$ decreases towards lower redshift, as revealed in the upper right panel. The $z = 2.1$ sample exhibits $[\text{Mg}/\text{Fe}]$ elevated by 0.25 dex, while the $z = 1.4$ sample is only elevated by 0.08 dex. In the bottom left panel we show that the average t_{form} changes from $t_{\text{form}} = 1.5$ to $t_{\text{form}} = 4 \text{ Gyr}$ from $z = 2.1$ to $z = 0$.

In the bottom middle panel of Figure 4.3 we compare the average $[\text{Mg}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ with a simple closed-box chemical evolution model from Kriek et al. (2016, represented by a black dashed line). The model provides mass-weighted abundances for various different star-formation timescales (indicated in Gyr next to the black boxes). The behavior of the model is driven by the differential enrichment timescales of Fe and Mg. While Mg is predominantly synthesized in massive stars and promptly returned to the interstellar medium (ISM) through core-collapse supernovae (SNe), Fe is produced through the explosions of intermediate-mass stars (Type Ia SNe; SNIa) and is released on delayed timescales. Therefore, galaxies with shorter star-formation timescales experience less Fe-enrichment from SNIa prior to quenching, resulting in stellar populations with lower $[\text{Fe}/\text{H}]$ and higher $[\text{Mg}/\text{Fe}]$.

The simple chemical evolution model used in this paper is illustrative, and is by no means meant to capture the complex feedback processes and star-formation histories likely present in the galaxies at hand. More detailed chemical evolution models, including inflows and outflows, along with varied star-formation histories, will help decipher the various factors shaping the elemental abundances and stellar metallicities of integrated stellar populations, especially as we move to higher redshifts (e.g., see N. Gountanis in prep.).

A visual comparison between the observations and the simple chemical evolution model highlights that the inferred star-formation timescales of the $z \sim 0$ and $z \sim 0.7$ samples are longer than the extreme timescales observed for the Heavy Metal galaxies, which are approximately 0.15 Gyr and 0.7 Gyr for the $z \sim 2.1$ and $z \sim 1.4$ samples, respectively. These inferred star-formation timescales derived from $[\text{Mg}/\text{Fe}]$, along with the results for t_{form} , paint a picture of galaxy formation in which typical massive quiescent galaxies at higher redshift formed earlier and underwent more rapid star formation compared to their counterparts at $z \sim 0$. To visually depict this scenario, we present the implied average star-formation histories in the lower right panel of Figure 4.3. We adopt a Gaussian parameterization for the star-formation histories, with the mean centered at t_{form} and the FWHM corresponding to the star-formation timescale, which is determined by comparing the abundances to the chemical evolution model. It is important to note that this panel serves as an illustrative tool,

and the choice of a Gaussian star-formation history is driven by its simplicity rather than a specific physical motivation. Nevertheless, it is evident that the star-formation histories of the Heavy Metal galaxies, particularly at $z \sim 2.1$, are extremely short compared to the lower redshift samples. We also note that this panel does not take into account the evolution of the stellar mass function, nor the spread in formation redshifts and star-formation timescales within the sample. Instead, it shows the *typical* SFH at each redshift interval.

Before considering how one should interpret the observed evolution, it is important to understand how selection biases influence the results. Unlike the Heavy Metal survey, the $z \sim 0$ and $z \sim 0.7$ samples are mass-complete, and therefore, the average stellar population properties should reflect the general galaxy population at each redshift. The Heavy Metal sample, however, has a complex selection function (see Kriek et al., 2023). The selection favors quiescent galaxies with lower mass-to-light ratios (M/L), indicative of younger ages. As a result, the ages of the Heavy Metal galaxies are likely biased young compared to the true population of quiescent galaxies at $z > 1$. Accounting for this bias, however, would strengthen the observed evolution in Figure 4.3; galaxies at $z > 1$ could have even earlier formation redshifts, and therefore more extreme chemical properties, than what is found in this sample.

One possible explanation for the observed evolution is the growth of the quiescent galaxy population due to the continuous quenching of star-forming galaxies between $z = 2.1$ and $z = 0$ (i.e., progenitor bias; van Dokkum & Franx, 2001; Carollo et al., 2013; Lilly et al., 2013). Galaxies that quench at later epochs presumably form their stars over longer timescales, resulting in later t_{form} and more Fe-enrichment from SNIa (lower [Mg/Fe]) before quenching. Hence, the addition of these galaxies to the quiescent population steadily increases the *average* t_{form} and [Fe/H], as observed. In fact, the number of quiescent galaxies with $M_* > 10^{10.5} M_\odot$ has increased tenfold since $z = 2$, as evident from the evolution of the stellar mass function (e.g., Conselice et al., 2022; McLeod et al., 2021). Furthermore, most of this evolution occurs at $z > 0.5$ (McLeod et al., 2021), which could explain the pronounced jump in [Fe/H] and t_{form} from $z \sim 1.4$ to $z \sim 0.7$.

An alternate explanation is mergers and late-time star formation, which impact the elemental abundances of *individual* galaxies; when galaxies accrete satellites or form new stars, their integrated elemental abundances are altered by the newly added stars. Indeed, the importance of (dry) minor mergers in the evolution of quiescent galaxies has been posited by observations that they were more compact and had flatter color gradients at earlier times (e.g., van Dokkum et al., 2008, 2010; Naab et al., 2009; Trujillo et al., 2009; Taylor et al., 2010; Suess et al., 2019b, 2020; Miller et al., 2023) as well as by direct pair fraction measurements (Newman et al., 2012). Furthermore, Suess et al. (2023) show that tiny companions with stellar mass ratios 1:900 compromise some 30% of their total stellar mass budget.

The extent to which mergers, late-time star formation, and progenitor bias contribute to the evolution of the massive quiescent galaxy population remains a topic of ongoing debate (e.g., Bezanson et al., 2009; Hopkins et al., 2009; Carollo et al., 2013; Poggianti et al., 2013; van de Sande et al., 2013; Williams et al., 2017; Damjanov et al., 2019). In the following section we examine the elemental abundances and stellar ages of individual galaxies to help

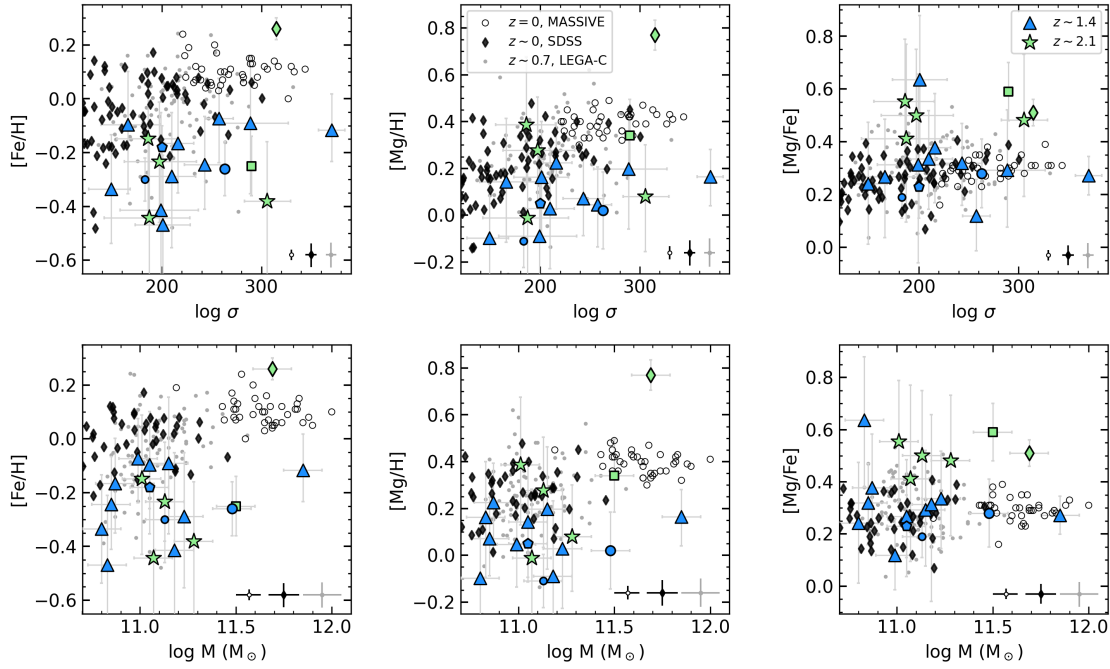


Figure 4.4: Individual measurements of $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ as a function of σ_v (top row) and M_* (bottom row). The Heavy Metal galaxies are split into $z \sim 1.4$ (blue triangles) and $z \sim 2.1$ (green stars) samples. We include results from other studies of massive quiescent galaxies at similar redshifts (see legend in Figure 4.2). We compare these results to individual abundance measurements from the MASSIVE ($z = 0$; Gu et al., 2022, open circles), SDSS ($z \sim 0$; Zhuang et al., 2023, black diamonds), and LEGA-C ($z \sim 0.7$; Beverage et al., 2023, gray dots) surveys, with their typical uncertainties provided at the bottom of each panel. At constant M_* and σ_v , galaxies at $z > 1$ have different chemical properties than those at lower redshifts.

differentiate between the various evolutionary scenarios; if mergers and/or late-time star formation play only a small role in the evolution of massive quiescent galaxies, then the extreme galaxies observed at $z \sim 2$ should persist as rare remnants in the $z \sim 0$ population.

4.6 Implications for the build-up of massive quiescent galaxies

In the previous section, we observed significant evolution in the average elemental abundances of massive quiescent galaxies from $z \sim 2.1$ to $z \sim 0$, suggesting that galaxies at higher redshift are typically metal-poor, have shorter star-formation timescales, and formed earlier. In this section, we examine the abundance ratios of individual galaxies over cosmic time to help

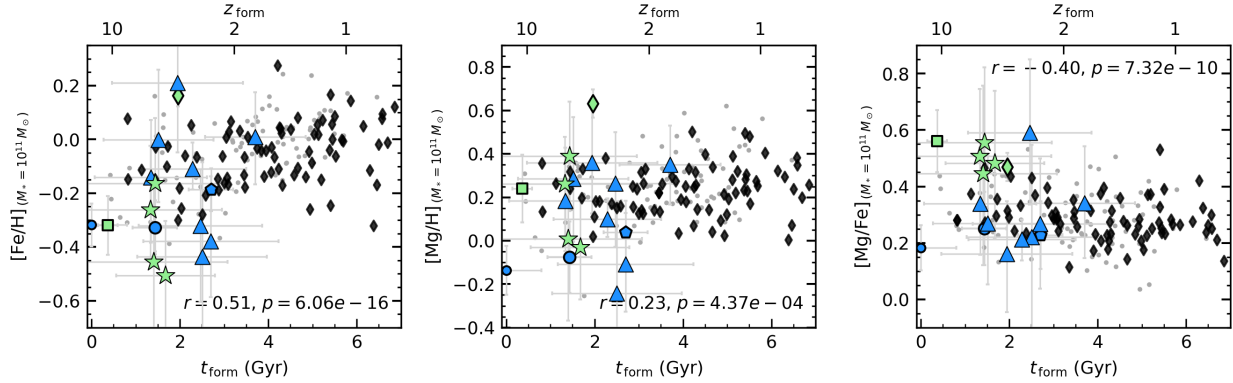


Figure 4.5: $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ at a fixed stellar mass ($M_* = 10^{11} M_\odot$) as a function of formation time for the LEGA-C (gray circles), Heavy Metal (blue triangles and green stars), SDSS (red shading) and various other $z > 1$ studies (refer to the legend in Figure 4.2). Abundances at *fixed* stellar mass are calculated from the M_* -abundance relations at $z \sim 0$ shown in Figure 4.4. We assess the strength of the correlation between the elemental abundances and formation time using the Pearson correlation test (results listed in each panel). Galaxies that form at later cosmic epochs have higher $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$, and slightly lower $[\text{Mg}/\text{Fe}]$. At a fixed t_{form} , the Heavy Metal galaxies exhibit similar abundances to the SDSS and LEGA-C populations.

differentiate between various evolutionary channels.

Figure 4.4 shows $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ as a function of σ_v (top row) and M_* (bottom row). The stellar masses of the Heavy Metal galaxies are derived in (Kriek et al., 2023). We compare the Heavy Metal galaxies to the abundances of individual LEGA-C galaxies (Beverage et al., 2023, gray circles), and to galaxies in SDSS (black diamonds) presented by Zhuang et al. (2023). Additionally, we compare to `alf`-derived abundances of 41 galaxies from the MASSIVE survey, a volume-limited survey of the most massive galaxies in the local universe (black diamonds, Ma et al., 2014; Gu et al., 2022). We also include abundance results from other studies of quiescent galaxies at $z \sim 1.4$ and $z \sim 2.1$, with the same markers as Figure 4.2. We note that the SDSS fiber, and the LEGA-C and Heavy Metal slits cover similar physical extents within the galaxies (3-4 kpc). However, as galaxies were smaller at earlier times, the Heavy Metal and LEGA-C slits cover 1-1.2 R_e , while SDSS only covers 0.4-0.8 R_e . The MASSIVE spectra were extracted from the inner $R_e/8$ and therefore represent only the cores of nearby massive early-type galaxies.

In the previous section, we proposed two theories to explain the observed abundance differences between the Heavy Metal survey and $z \sim 0$. In the first scenario, the quiescent galaxy population is continuously growing by the addition of newly quenched galaxies, driving the evolution of the observed average abundances (“progenitor bias,” e.g., van Dokkum & Franx, 2001; Carollo et al., 2013; Poggianti et al., 2013). In this scenario, we expect to find

galaxies with properties similar to the Heavy Metal galaxies in the lower redshift universe, and thus the populations at higher and lower redshift should overlap. In other words, the Heavy Metal galaxies should constitute the lower metallicity and high-[Mg/Fe] tail of the $z \sim 0$ samples. Indeed, the top panels of Figure 4.4 show that this is mostly the case for the Heavy Metal galaxies, though there are a few exceptions; most of the Heavy Metal galaxies with high σ_v have significantly lower [Fe/H] and [Mg/H] than any galaxy found at $z \sim 0$ and $z \sim 0.7$. Furthermore, in the rightmost panel, we find that galaxies at $z \sim 2.1$ are *all* [Mg/Fe]-enhanced compared to the galaxies at lower redshifts.

When considered as a function of stellar mass, the metallicity differences between the lower and higher redshift populations become more apparent. At all stellar masses, and particularly at the highest stellar masses, the Heavy Metal galaxies have [Fe/H] and [Mg/H] ≈ 0.2 dex lower than any individual galaxy in SDSS or LEGA-C. This result poses a problem for the progenitor bias scenario; if these Heavy Metal galaxies passively evolve to $z \sim 0$, we would expect to find Fe- and Mg-deficient remnants in the SDSS and MASSIVE populations. Specifically, in this scenario, 10% of the SDSS and MASSIVE galaxies should be direct descendants of $z > 2$ quiescent galaxies given the rapid evolution of the stellar mass function (McLeod et al., 2021). Thus, the $z \sim 0$ galaxies are likely not the direct descendants of the $z \sim 2$ Heavy Metal galaxies. It is important to acknowledge, however, that uncertainties are substantial and sample sizes are limited. Thus, the possibility remains that we may have simply missed the rare metal-poor remnants in the $z \sim 0$ samples. We also note that the Heavy Metal galaxies were selected to maximize the number of bright quiescent galaxies in one field of view. As such, the environments of these galaxies may not be representative of the broader massive quiescent galaxy population at higher redshift.

As previously mentioned, minor mergers provide an alternate way to explain the observed evolution. In this picture, the $z \sim 1.4 - 2.1$ quiescent galaxies may grow into the cores of today’s massive early-type galaxies by accreting low-mass galaxies (e.g., Bezanson et al., 2009; Hopkins et al., 2009; van de Sande et al., 2013). This scenario can successfully explain the observed increase in stellar metallicity and decrease in [Mg/Fe], but only if the accreted galaxies form over long timescales (i.e. lower [Mg/Fe]) and are more metal-rich. There are, however, two problems with this scenario. Firstly, our observations show there is evolution within the inner $1 R_e$, while minor mergers are typically accreted onto galaxy outskirts (Naab et al., 2009; Oser et al., 2010). Secondly, given the mass-metallicity relation, the accreted low-mass galaxies will likely be metal-poor, and therefore cannot explain the increase in metallicity (Kirby et al., 2013). Major mergers with galaxies that have longer star-formation timescales (and thus lower [Mg/Fe]) solve both of these problems, as more massive galaxies tend to be more metal-rich *and* can more easily disrupt galaxy cores. However, the observed major merger rate is likely too low to fully account for the observed evolution (Oser et al., 2012; Nipoti et al., 2012; Newman et al., 2012) and major mergers alone cannot explain the size evolution (e.g., Hopkins et al., 2009; van Dokkum et al., 2010; Hilz et al., 2013; Belli et al., 2014). Therefore, a combination of major and minor mergers may be necessary to explain the observed evolution.

Finally, late-time star formation, likely in combination with or triggered by mergers,

can increase the metallicities of individual galaxies while decreasing $[\text{Mg}/\text{Fe}]$; if the star-formation material is enriched in SNIa products by previous epochs of star formation, then the newly formed stars will be younger, more metal-rich, and more α -enhanced. It should be noted that a burst of central star-formation is expected in a wet merger scenario (e.g., Hopkins et al., 2006) and thus the two scenarios together are effective at explaining the absence of metal-poor and $[\text{Mg}/\text{Fe}]$ -enriched galaxies by $z \sim 0$ as observed in Figure 4.4.

Crucially, all of the above scenarios rely on the assumption that at the same stellar masses, younger galaxies have higher metallicity and lower $[\text{Mg}/\text{Fe}]$. For example, the progenitor bias scenario only works if the galaxies that quench at later times are more metal-rich and form over longer timescales. In Figure 4.5 we search for such trends in $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ as a function of t_{form} for the SDSS, LEGA-C, and Heavy Metal quiescent galaxies. In each panel, we remove the first-order mass dependence by subtracting the SDSS M_* -abundance relations from all galaxies and then scaling them to the value of the M_* -abundance relations at $M_* = 10^{11} M_\odot$ (e.g., Leethochawalit et al., 2019; Zhuang et al., 2023). To assess the level of correlation between quenching time (as traced by t_{form}) and stellar metallicities, we use the Pearson correlation coefficient. A correlation is deemed “marginal” if the Pearson correlation coefficient is $0.2 \leq r < 0.4$, “moderate” if $0.4 \leq r < 0.6$, and “strong” if $r \geq 0.6$. We list the correlation coefficients along with the associated p-value in Figure 4.5. At fixed stellar mass, we do in fact find that younger SDSS and LEGA-C galaxies exhibit higher $[\text{Fe}/\text{H}]$ ($r = 0.53$), marginally higher $[\text{Mg}/\text{H}]$ ($r = 0.26$), and moderately lower $[\text{Mg}/\text{Fe}]$ ($r = -0.40$), as previously found by Beverage et al. (2023) and Zhuang et al. (2023), respectively (see also Leethochawalit et al., 2018).

The trends with $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{Fe}]$ can be naturally explained by galaxies joining the quiescent galaxy population at later times (higher t_{form}) having more time to form stars from gas that is rich in SNIa products (namely, Fe). However, the marginal trend with $[\text{Mg}/\text{H}]$ is more challenging to explain, as Mg-enrichment is independent of the star-formation timescale and instead primarily depends on the size of the gas reservoir at the time of star-formation quenching. Beverage et al. (2021) propose a model to explain the marginal trend with t_{form} by invoking rapid gas removal during the quenching process. In summary, if galaxies at earlier epochs, that form earlier and over shorter timescales, quench more abruptly and have larger gas fractions at the time of quenching (e.g. effective AGN outflows), then $[\text{Mg}/\text{H}]$ is truncated to lower values. Thus, the marginal trend with $[\text{Mg}/\text{H}]$ may suggest that galaxies at earlier times experience more effective outflows (see also the outflow model proposed by Leethochawalit et al., 2019).

Furthermore, Figure 4.5 shows that high- z galaxies have a slight systematic offset to lower metallicities compared to local galaxies even when the dependence on M_* and stellar age is removed. This same result was also found by Zhuang et al. (2023), but for a smaller galaxy sample. Thus, this result confirms the finding by Zhuang et al. (2023) and reinforces the need for mergers or late-time star formation to alter the chemical compositions and stellar ages of these extreme individual galaxies by $z \sim 0$. Again, we note that comparisons at “fixed formation times” between galaxies at different redshift regimes should be approached with caution; the SSP-equivalent ages can be biased young. As a result, a more complicated

star-formation history may shift the Heavy Metal galaxies in Figure 4.5 towards even earlier formation times. As a result, the ages of the Heavy Metal galaxies are likely biased young compared to the true population of quiescent galaxies at $z > 1$. Nonetheless, correcting for such a bias would not change our interpretation.

Figures 4.4 and 4.5 together demonstrate that progenitor bias, minor and major mergers, and late-time star formation are likely all responsible, to some extent, for the observed evolution in the elemental abundances of massive quiescent galaxies over cosmic time. This analysis further shows that the existing story of massive quiescent galaxy assembly – namely, that the $z > 1$ quiescent galaxies are the progenitor cores of today’s massive early-type galaxies – is more complicated than initially anticipated. We arrive at a similar conclusion based on the dynamical masses of the Heavy Metal galaxies in Kriek et al. (2023).

4.7 Assessing the quality of our stellar population modeling

Example Corner Plots

In Figure 4.6, we present corner plots from the full-spectrum `alf` fitting. The four corner plots correspond to the same four spectra showcased in the first four panels from Figure 4.1. Next to each corner plot we provide information about the object: ID, redshift, and SNR ($\text{\AA}^{-1}$). We present the four essential parameters, $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, $[\text{Mg}/\text{Fe}]$, and the age of the stellar population. The dashed lines in the plots represent the 1σ uncertainties. Though the uncertainties are large, the results follow a normal distribution. We find there to be a degeneracy between stellar age and metallicity. Target 213931 shows the strongest degeneracy, likely because the observations are a blend of two nearby systems, resulting in the superposition of stellar populations with different ages and metallicities. For the other galaxies, the age- Z degeneracy is considerably less pronounced.

Comparison with Lick Indices

In this Section we compute absorption line indices for the Heavy Metal galaxies. The Lick/IDS system, first introduced by Faber et al. (1985) and updated by Worthey et al. (1994), is the most common method for measuring elemental abundances and stellar ages of nearby quiescent galaxies. However, as we continue to push observations to higher redshifts, absorption features become fainter and more contaminated by NIR skylines. As a result, Lick indices and their derived stellar population parameters become highly uncertain. Full-spectrum modeling was, in part, developed to account for these issues. By fitting the entire stellar continuum, noise peaks can be easily down-weighted, and all absorption features for a single element can be evaluated simultaneously.

In this Section, we check that the absorption line indices of the Heavy Metal galaxies agree with our main results from full-spectrum modeling. Specifically, we compute the $\langle \text{Fe} \rangle$

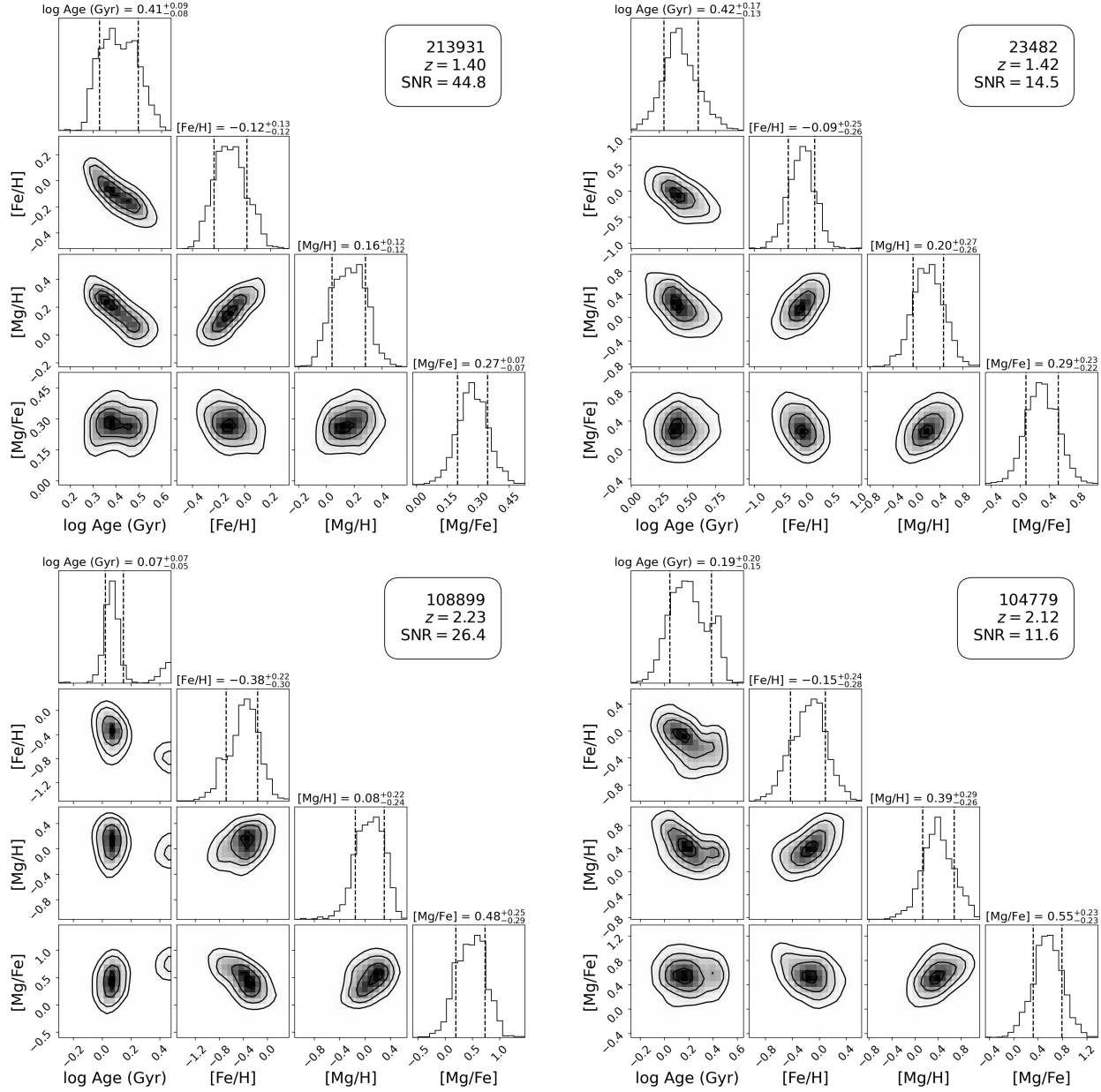


Figure 4.6: Four example corner plots from the full-spectrum `alf` modeling. In each panel, we show the probability distributions for four different physical parameters. The dashed lines in the 1D distributions show the 1σ levels. For each corner plot we report the galaxy ID, redshift, and SNR ($\text{\AA}^{-1}$) of the observations.

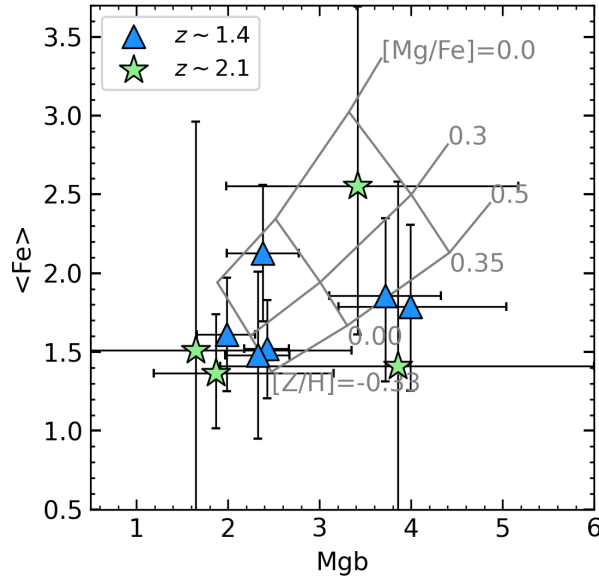


Figure 4.7: Lick/IDS indices Mgb and $\langle Fe \rangle$ for ten primary $z \sim 1.4$ (blue triangles) and $z \sim 2.1$ (green stars) Heavy Metal targets. A grid of models from Thomas et al. (2003) stellar population model ($t_{\text{age}} = 2$ Gyr) is superimposed in gray. The Heavy Metal galaxies tend towards low metallicities and high $[Mg/Fe]$, in general agreement with what is found from the full-spectrum fitting. Uncertainties are large, motivating the need for full-spectrum modeling.

and Mgb indices, where $\langle Fe \rangle = 0.5 \times (Fe5270 + Fe5335)$. We then compare these indices to simple spectrum models from Thomas et al. (2003).

Given the prevalence of skylines in the Heavy Metal spectra, we must account for the prominent noise peaks. However, by default, the Lick/IDS system does not use the variance spectrum because it biases the equivalent widths. Thus, to overcome skyline contamination, we follow the approach of van der Wel et al. (2021). For each spectrum, we take the best-fitting `alf` model and compute its χ^2 . We then scale the noise to a $\chi^2 = 1$. Any pixel that is more than 2σ or 20% offset from the model flux is masked. If more than 30% of the pixels in the index wavelength interval (including the pseudo-continuum intervals) are masked, the index is deemed unreliable. Four Heavy Metal galaxies are removed at this step. For the other ten galaxies, the masked pixels are replaced by a linear interpolation using the good pixels. We note that the `alf` models are *only* used to help identify which pixels should be masked.

Next, we correct the absorption line indices to a constant velocity dispersion. This step is important if we want to compare indices between objects and to stellar population models. In the Lick/IDS system, indices are corrected to have zero intrinsic velocity dispersion and to have a standard wavelength-dependent resolution, ranging from $8.4\text{\AA}$ to $11.5\text{\AA}$ (Worthey

& Ottaviani, 1997). We compute correction factors using **alf** models at a variety of velocity dispersions (e.g., see Davies et al., 1993; Kuntschner, 2004). This correction factor is applied after measuring the equivalent widths. For the Heavy Metal galaxies, the correction ranges from $C(\sigma_v) = 1.0 - 1.5$. With the corrected Lick indices in hand, we finally estimate uncertainties by bootstrapping the spectrum and re-computing equivalent widths 10,000 times, taking the 16th and 84th percentile as the index uncertainty.

In Figure 4.7, we present $\langle \text{Fe} \rangle$ as a function of Mgb for 10 Heavy Metal galaxies. We compare these indices with a set of 2 Gyr models from Thomas et al. (2003). Drawing conclusions from this figure is challenging, as numerous Heavy Metal galaxies display index measurements with substantial uncertainties that span the entire model grid. This issue is particularly pronounced for galaxies at a redshift $z \sim 2.1$. The increased uncertainties at higher redshifts can be attributed to the younger ages of these galaxies, resulting in less pronounced metal lines. Additionally, significant contamination from skylines in the near-infrared underscores the necessity for full-spectrum modeling, as opposed to index fitting, at higher redshifts.

Parameter recovery with mock heavy metal spectra

In this Section, we test the robustness of our results as a function of SNR. The primary goal of this test is to check for any systematic uncertainties in full-spectrum modeling, especially as we push the limits of this fitting to lower SNRs. We begin by generating mock Heavy Metal spectra at various SNRs, fitting them using **alf**, and finally by comparing the best-fit values and their uncertainties to the true values. It is worth noting that Choi et al. (2014) conducted a similar test in their Appendix A. However, there are a few notable differences in our approach. Firstly, **alf** has undergone significant updates since the work of Choi et al. (2014). Secondly, while Choi et al. (2014) used a flat noise spectrum for their simulated spectra, we use actual LRIS+MOSFIRE noise spectra. And finally, the Heavy Metal galaxies have much younger stellar ages, and therefore less pronounced absorption features, than what was tested in Choi et al. (2014).

All mock spectra are generated from a single **alf** model with stellar population parameters reflecting average values from Table 5.1. We degrade the model spectrum to the desired SNR at rest-frame 5000Å using the Heavy Metal noise spectrum. In this way, we can replicate the observations, accounting for wavelength-dependent sensitivities. The model spectrum is also resampled to the LRIS+MOSFIRE resolution using **spectres** (Carnall, 2017). We generate 45 realizations at SNRs = 8, 12, 20, 40 and fit them using the same method described in Section 4.3. For all realizations we compute the difference between the best-fit parameter and the known model parameters.

We present the results in Figure 4.8. The black rectangles show the average parameter offset for the 45 realizations, with the blue errorbars representing the 1σ scatter of these offsets. We also show the typical uncertainties on a single realization in red. The gray tick marks at the bottom of each panel represent the SNR of the individual Heavy Metal spectra. All but one Heavy Metal spectrum has $\text{SNR} \gtrsim 10\text{\AA}^{-1}$. σ_v is recovered extremely well with

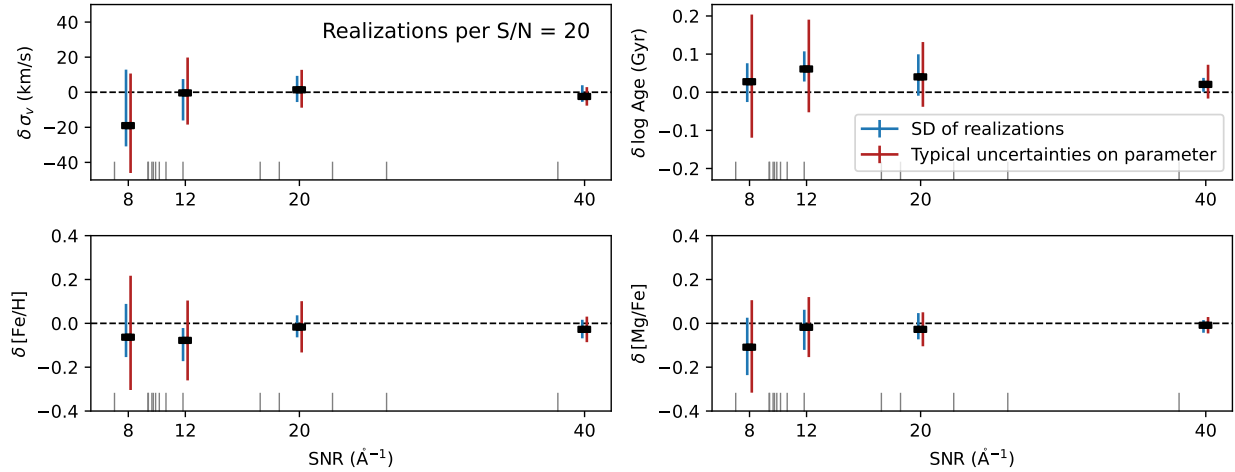


Figure 4.8: Results from the parameter recovery of mock Heavy Metal spectra. We show systematic offsets in the stellar population fitting code as a function of SNR for four key parameters. At each SNR, we generate 20 mock spectra and fit their elemental abundances and ages following the procedure in Section 4.3. The black rectangles represent the median offset between the simulated and best-fit values for the 20 realizations. The blue errorbars represent the 16th and 84th percentiles of the best-fit values for the 20 realizations. The red errorbars show the typical uncertainties on a single realization. The gray tick marks at the bottom of each panel show the true SNR of the individual Heavy Metal spectra. For the typical Heavy Metal galaxy, the systematic offsets are ≈ -0.05 dex for $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{Fe}]$ and ≈ 0.05 dex for $\log \text{Age}$.

no systematic uncertainties at $\text{SNR} \gtrsim 12$. The stellar ages are also recovered well, with only a slight (~ 0.05 dex) systematic offset towards older ages at $\text{SNR} \lesssim 20$. The elemental abundance recovery also shows very little systematic uncertainty. There is a -0.1 dex offset in $[\text{Fe}/\text{H}]$ at $\text{SNR} = 8$, but at the typical SNR of the Heavy Metal galaxies ($\text{SNR} > 12$) there is no appreciable systematic offset to within 0.05 dex. Similarly, $[\text{Mg}/\text{Fe}]$ shows a slight systematic offset of 0.05 dex at $\text{SNR} = 8$ and $\text{SNR} = 12$, though at larger SNR there is no appreciable systematic effect.

This parameter recovery test confirms that the abundance results corresponding to the Heavy Metal spectra ($\text{SNR} \gtrsim 12 \text{ \AA}^{-1}$) have systematic uncertainties of $\lesssim 0.05$ dex and can be constrained to within at least 0.15 dex. Furthermore, the results are mostly consistent with Choi et al. (2014), despite major updates to `alf` and mock spectra generated using real LRIS+MOSFIRE noise spectra.

4.8 Summary and Conclusion

In this paper, we present the stellar metallicities, elemental abundance ratios, and stellar ages of 19 massive quiescent galaxies from the Keck Heavy Metal survey. The galaxies are divided over two redshift intervals around $z \sim 1.4$ and $z \sim 2.1$. We fit the ultra-deep LRIS+MOSFIRE spectra using a full-spectrum modeling code with variable elemental abundance ratios. Combined, these measurements represent the largest sample of individual quiescent galaxies at $z \gtrsim 1.4$ with stellar metallicity and elemental abundance measurements.

We find that massive quiescent galaxies at $1.4 \lesssim z \lesssim 2.2$ have subsolar Fe-abundances, ranging from $[\text{Fe}/\text{H}] = -0.5$ to -0.1 dex, with typical values of -0.2 and -0.3 dex at $z \sim 1.4$ and $z \sim 2.1$, respectively. We also find a trend between σ_v and $[\text{Fe}/\text{H}]$, with a best-fit slope consistent with what is found at lower redshifts. We find high $[\text{Mg}/\text{Fe}]$ of ≈ 0.5 for the $z \sim 2.1$ galaxies, while those at $z \sim 1.4$ are lower with $[\text{Mg}/\text{Fe}] \sim 0.3$. The ages range from 0.9–3.7 Gyr, implying formation redshifts $z_{\text{form}} = 2 - 8$.

We examine the evolution of the massive quiescent galaxy population over cosmic time by comparing the average Heavy Metal elemental abundances and ages to those in the LEGA-C ($z \sim 0.7$) and SDSS ($z \sim 0$) surveys. The $z \sim 1.4$ and $z \sim 2.1$ galaxies have $[\text{Fe}/\text{H}]$ that are 0.15 and 0.23 dex lower than what is observed at $z \lesssim 0.7$. Interestingly, we find no evolution in $[\text{Mg}/\text{Fe}]$ at $z \lesssim 1.4$, though the $z \sim 2.1$ galaxies have 0.2 dex higher $[\text{Mg}/\text{Fe}]$. By comparing these results with a simple chemical evolution model, we find that galaxies at higher redshifts formed at progressively earlier epochs and shorter timescales, with the $z \sim 2.1$ galaxies forming in only ≈ 150 Myr at $z = 4$.

The observed evolution of stellar population properties provides a unique insight into the assembly histories of massive quiescent galaxies. One possible explanation is the growth of the quiescent galaxy population. If the galaxies that join the population at later times are younger, more metal-rich, and less alpha-enhanced, then the average properties will evolve. However, this scenario cannot fully explain the observations because we do not find the direct descendants of the chemically extreme Heavy Metal galaxies at $z \lesssim 0.7$. Minor mergers also fail to account for the observed evolution; due to the mass-metallicity relation, they cannot increase $[\text{Fe}/\text{H}]$, in particular in the galaxy centers. Thus, major mergers and/or late-time star formation are required to explain the evolution of chemical properties across cosmic time. These results imply a more complicated assembly history than the minor-merger driven inside-out growth scenario previously inferred from the evolution in the sizes, color gradients, and central densities of quiescent galaxies. In our accompanying paper, Kriek et al. (2023), arrive at a similar conclusion based on the dynamical masses of the Heavy Metal galaxies.

This study was enabled by ultra-deep spectroscopic observations conducted with the most efficient ground-based spectrographs. With up to 16 hr of integration per galaxy per band, these spectra represent some of the deepest spectroscopic observations of individual galaxies at $z \gtrsim 1.4$ with coverage of key absorption features. As a result, the Heavy Metal survey has tripled the number of individual stellar metallicity measurements at $z \gtrsim 1.4$. Nonetheless, sample sizes at these redshifts remain small, and the uncertainties on each measurement

remain substantial.

In the future, JWST will provide even deeper spectroscopy of massive quiescent galaxies at $z \gtrsim 1.4$, extending the existing sample sizes, reaching to lower stellar masses, and enabling the measurements of more elements. Thus, JWST will revolutionize our understanding of the assembly of massive quiescent galaxies over cosmic time.

Chapter 5

Carbon and Iron Deficiencies in Quiescent Galaxies at $z = 1 - 3$ from *JWST*-SUSPENSE: Implications for the Formation Histories of Massive Galaxies

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

5.1 Abstract

We present the stellar metallicities and multi-element abundances (C, Mg, Si, Ca, Ti, Cr, and Fe) of 15 massive ($\log M/M_\odot = 10.2 - 11.2$) quiescent galaxies at $z = 1 - 3$, derived from ultra-deep *JWST*-SUSPENSE spectra. Compared to quiescent galaxies at $z \sim 0$, these galaxies exhibit a deficiency of 0.26 ± 0.04 dex in [C/H], 0.16 ± 0.03 dex in [Fe/H], and 0.07 ± 0.04 dex in [Mg/H], implying rapid formation and quenching before significant enrichment from asymptotic giant branch stars and Type Ia supernovae. Additionally, we find that galaxies forming at higher redshift consistently show higher [Mg/Fe] and lower [Fe/H] and [Mg/H], regardless of their observed redshift. The evolution in [Fe/H] and [C/H] is therefore primarily driven by lower-redshift samples naturally including galaxies with longer star-formation timescales. In contrast, the lower [Mg/H] likely reflects earlier-forming galaxies expelling larger gas reservoirs during their quenching phase. Consequently, the mass-metallicity relation, primarily reflecting [Mg/H], is somewhat lower at $z = 1 - 3$ compared to the lower redshift relation. Finally, we compare our results to standard stellar population modeling approaches employing solar abundance patterns and non-parametric star-formation histories (using PROSPECTOR). Our SSP-equivalent ages agree with the mass-weighted ages from

PROSPECTOR, while the metallicities disagree significantly. Nonetheless, the metallicities better reflect $[\text{Fe}/\text{H}]$ than total $[\text{Z}/\text{H}]$. We also find that star-formation timescales inferred from elemental abundances are significantly shorter than those from PROSPECTOR, and we discuss the resulting implications for the early formation of massive galaxies.

5.2 Background

The chemical makeup of a galaxy is intimately linked to its past star formation, the amount of gas and stars it accretes, and the gas that is expelled through outflows. Consequently, the metal content of galaxies reflects fundamental physical processes that influence their evolution, such as star formation efficiency, feedback from massive stars and active galactic nuclei (AGN), and previous merger events. By characterizing how the metallicities of galaxies evolve across redshifts, we can obtain direct insights into the processes shaping galaxy growth throughout cosmic time.

In the nearby universe, galaxies display a tight correlation between their stellar mass and metallicity, known as the mass-metallicity relation (MZR; e.g., Lequeux et al., 1979; Tremonti et al., 2004; Gallazzi et al., 2005; Kirby et al., 2013). For star-forming galaxies, the gas-phase MZR has been routinely studied out to $z \sim 3$ mostly using strong-line indicators (e.g., Maiolino et al., 2008; Zahid et al., 2013; Sanders et al., 2020, 2021; Papovich et al., 2022; Shapley et al., 2023) and has recently been confirmed up to $z \sim 8$ with the advent of *JWST* (Langeroodi et al., 2023; Nakajima et al., 2023; Curti et al., 2024). Quiescent galaxies, however, lack the strong emission lines needed for gas-phase measurements, so we instead rely on faint absorption lines originating from stellar atmospheres. At higher redshifts, measuring stellar metallicity becomes increasingly challenging as key absorption features shift to near-infrared (NIR) wavelengths, where ground-based spectroscopic observations are severely hindered by skylines. As a result, the MZR of quiescent galaxies has only been systematically studied up to $z \sim 0.7$, showing little evolution since $z \sim 0$ (Choi et al., 2014; Gallazzi et al., 2014; Barone et al., 2022; Beverage et al., 2023).

Beyond $z \sim 1$, the picture is much less clear. Currently, there are only a handful of stellar metallicity measurements of quiescent galaxies at $z = 1 - 2.2$ based on absorption lines, mostly relying on methods such as spectral stacking (Onodera et al., 2015; Carnall et al., 2022), observations of rare lensed massive galaxies (Jafariyazani et al., 2020; Man et al., 2021; Zhuang et al., 2023; Akhshik et al., 2023; Jafariyazani et al., 2024), low-resolution spectroscopy (Morishita et al., 2018; Estrada-Carpenter et al., 2019; Akhshik et al., 2023), or utilizing extreme integration times on the most efficient ground-based telescopes (Kriek et al., 2016, 2019, 2024; Beverage et al., 2024). Despite the small samples at these redshifts, there is a growing consensus that massive quiescent galaxies at $z \gtrsim 1$ exhibit significantly lower $[\text{Fe}/\text{H}]$ compared to their present-day counterparts (e.g., Kriek et al., 2019; Zhuang et al., 2023; Beverage et al., 2024). There are, however, a couple of conflicting findings, with two studies reporting exceptionally high metallicities comparable to the most metal-rich galaxies at $z \sim 0$ (Lonoce et al., 2015; Jafariyazani et al., 2020). These contrasting results

may not be surprising, given that the uncertainties in individual measurements remain high, and the methods vary significantly between studies (e.g., Lonoce et al., 2015; Onodera et al., 2015; Kriek et al., 2016; Estrada-Carpenter et al., 2019; Saracco et al., 2023).

Understanding the metallicities of distant quiescent galaxies is crucial, as it holds significant implications for the enrichment, star-formation timescales, quenching, and assembly of galaxies across cosmic time. Specifically, the multi-element abundance patterns provide direct insight into the star-formation histories (SFHs) of galaxies. Such insight is largely owed to the diverse enrichment timescales of the elements. α elements (e.g., O and Mg) are instantaneously released by core-collapse supernovae (CC SNe). C and N are released approximately equally by CC SNe and by the winds of low-mass asymptotic giant branch (AGB) stars which only contribute after a characteristic delay-time of ~ 250 Myr (e.g. Cristallo et al., 2011, 2015; Maiolino & Mannucci, 2019; Johnson et al., 2023). Fe-peak elements are enriched by both CC and the explosions of intermediate-mass stars (Type Ia SNe; Ia SNe), which occur only after a longer delay (of ~ 1 Gyr Maoz et al., 2010).

To fully exploit chemical compositions for understanding the formation histories of massive galaxies, we need a larger sample of massive quiescent galaxies at $z \gtrsim 1$ with deep spectra covering multiple absorption features. Such observations are now finally possible with *JWST*. To that end, we have conducted the *JWST*-SUSPENSE program, an ultradeep rest-frame optical spectroscopic NIRSpec/MSA survey of 20 massive quiescent galaxies at $z = 1 - 3$ (Slob et al., 2024).

In this paper, we present the metallicities and multi-element abundances of distant quiescent galaxies at $z = 1 - 3$ from the *JWST*-SUSPENSE survey. In Section 5.3 we describe the observations and elemental abundance analysis, in Section 5.4 we present the abundance results, in Section 5.5 we present the MZR at $z = 1 - 3$, and in Section 6.6 we discuss the implications of the results on star-formation timescales, the assembly of massive galaxies, and star-formation quenching. In Section 6.6 we also compare the full-spectrum modeling results to those from PROSPECTOR and discuss the implications of this comparison on the early formation of massive galaxies. In Section 6.7, we present a summary. Throughout this Paper, we assume a Kroupa (2001) IMF, solar abundances from Asplund (2009), and a flat Λ CDM cosmology with $\Omega_m = 0.3$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

5.3 Observations & Analysis

All galaxies in this study are drawn from the *JWST*-SUSPENSE Program (ID:2110) which obtained ultra-deep (16.4 hr) NIRSpec-MSA/G140M-F100LP observations of a sample of 20 massive quiescent galaxies at $z = 1 - 3$ (Slob et al., 2024). The spectroscopic observations were reduced using a modified version of the *JWST* Science Calibration Pipeline (Bushouse et al., 2023) v1.12.5, and version 1183 of the Calibration Reference Data System (CRDS) (see Slob et al., 2024, for details). Primary targets were initially identified using the UltraVISTA K-band selected DR3 catalog (Muzzin et al., 2013a) and selected to be quiescent using the *UVJ* criterion from Muzzin et al. (2013b). The targets represent the general population of

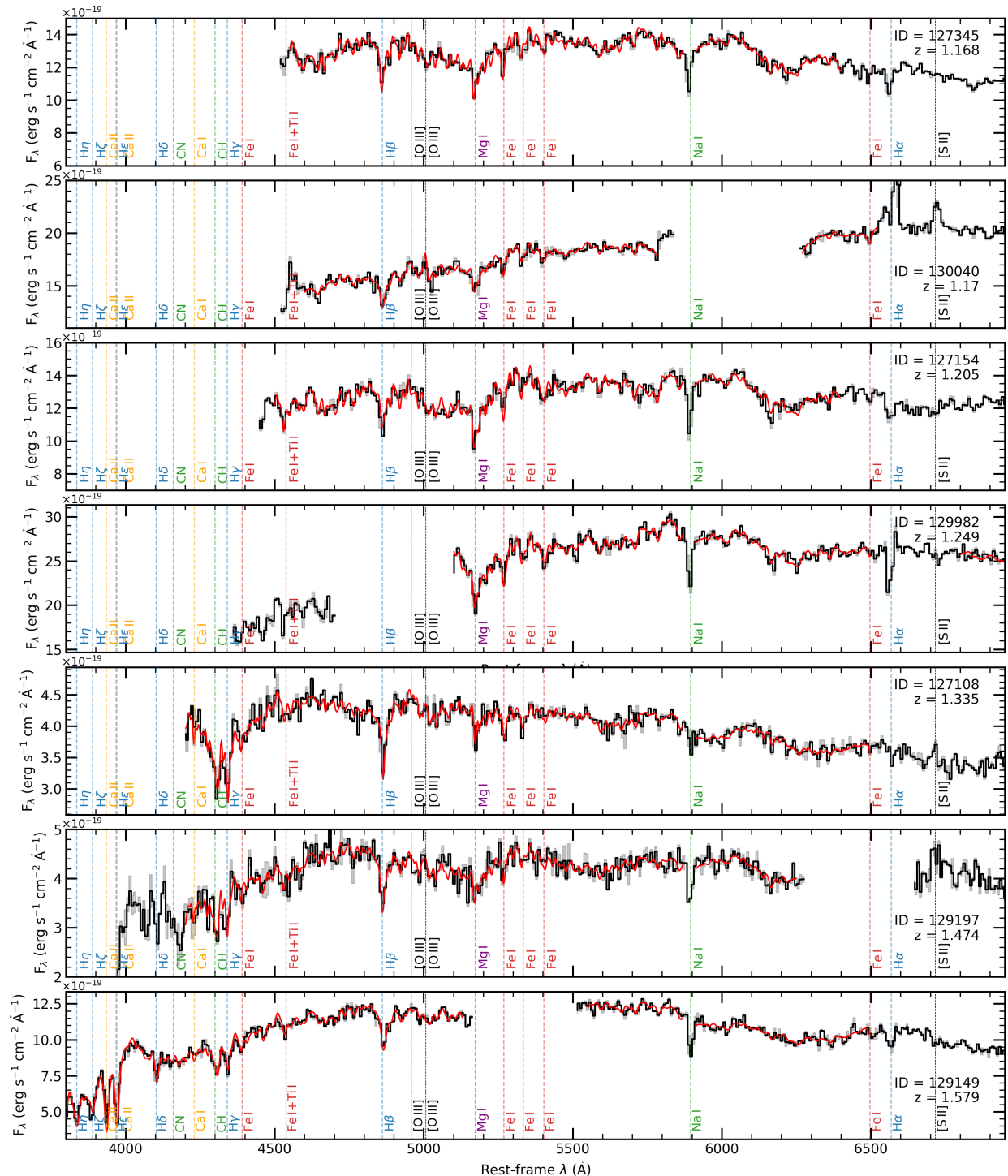


Figure 5.1: *JWST*-SUSPENSE spectra of quiescent galaxies at $z = 1 - 3$ (black) and corresponding 1σ uncertainties (gray). The best-fit stellar population models are shown in red. The wavelength array has been corrected for redshift and is shown in the rest frame. The spectra have been median binned by 3 pixels ($8 \text{ \AA}$ in the rest frame).

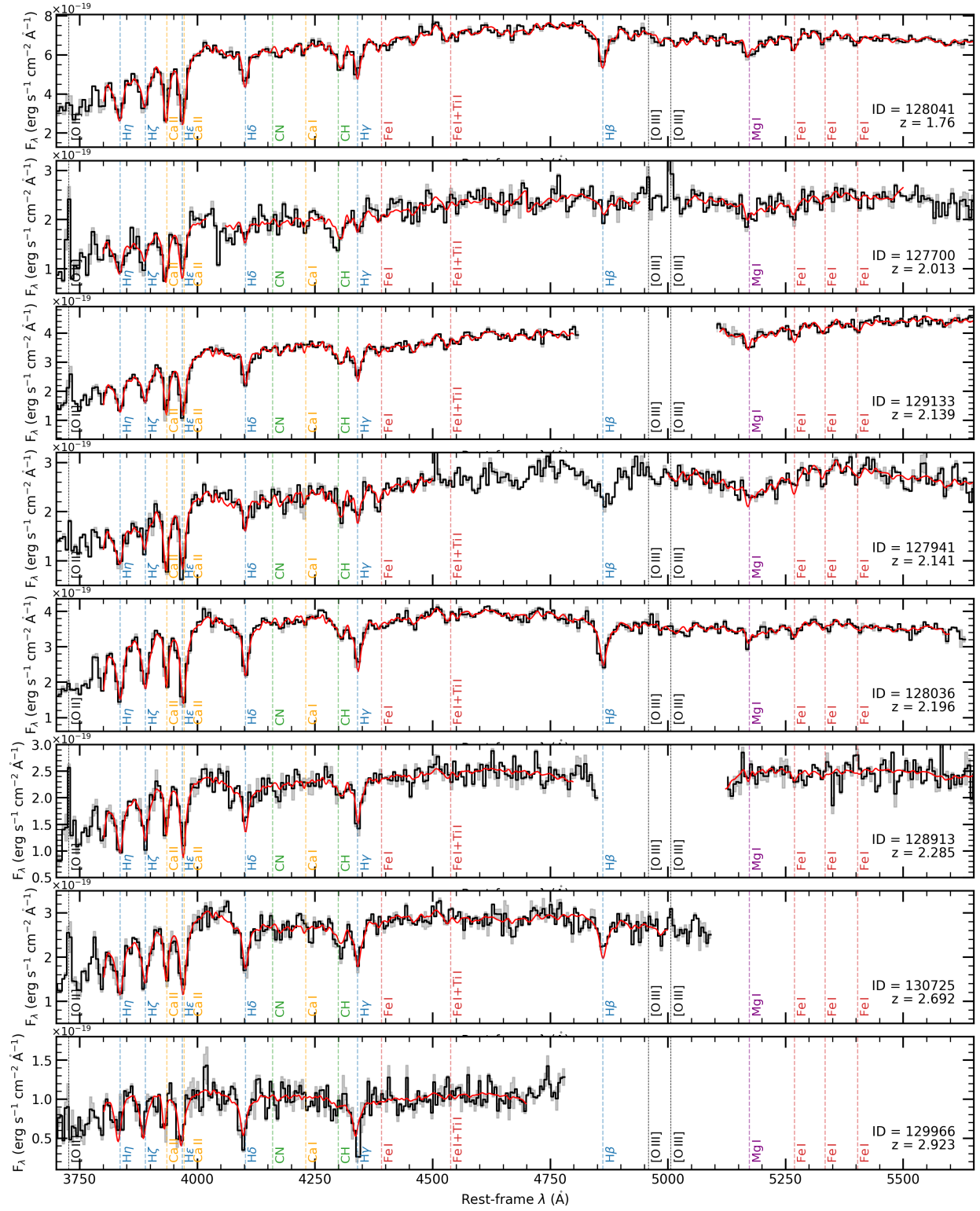


Figure 5.1: Continued

quiescent galaxies at $z = 1 - 3$, encompassing the full quiescent range in UVJ space at these redshifts, and are all confirmed to have quiescent stellar populations (see Slob et al., 2024).

The observations cover wavelengths from 0.97 to 1.84 μm , corresponding to a typical rest-frame range of approximately 3700 to 7000 Å. Most objects have coverage of the Mg b line, several prominent Fe features, and multiple Balmer lines. The stellar masses and star-formation rates were derived by Slob et al. (2024) by fitting the spectra and photometry simultaneously with PROSPECTOR (Leja et al., 2019a; Johnson et al., 2021) assuming a Chabrier (2003) IMF. They consider two non-parametric SFH models; a fixed-bin model (Leja et al., 2019a) and a post-starburst model (Suess et al., 2022a). For more details on target selection, observing strategy, data reduction, redshift determination, and stellar population properties we refer to Slob et al. (2024).

We measure the individual elemental abundances and stellar population ages using a custom full-spectrum fitting code `alf $\alpha$` (Beverage, 2024)¹ based on the `alf` fitting code presented in Conroy et al. (2018). The Conroy et al. (2018) models were developed to measure the elemental abundance patterns of old ($\gtrsim 1$ Gyr) stellar populations. They combine metallicity-dependent MIST isochrones (Choi et al., 2016), empirical MILES and IRTF spectral libraries (Sanchez-Blazquez et al., 2006; Villaume et al., 2017), and synthetic metallicity- and age-dependent elemental response spectra for 19 elements.

The models assume a single burst of star formation and a Kroupa (2001) IMF. We fit for a total of 20 free parameters; velocity offset, velocity dispersion, single SSP-equivalent stellar population age, isochrone metallicity, 10 individual elemental abundances (Fe, C, N, Mg, Na, Si, Ca, Ti, Cr), Balmer emission line flux, the emission line velocity and broadening, a shift in the effective temperature of the fiducial isochrones (T_{eff}), and an instrumental jitter term to account for under/overestimation of the uncertainties. The abundance ratios of the other nine elements are fixed to solar ($[X/\text{Fe}] = 0$) following results of the mock-recovery test presented in Beverage et al. (2023). We use the `dynesty` dynamic nested sampling package (Speagle, 2020) to sample the posterior distributions of the 20 parameters.

Before fitting, we smooth the models to the instrumental resolution of the observations. We derive the instrumental resolution as a function of wavelength in the raw spectral frames using `msafit` (De Graaff et al., 2024). We provide `msafit` with the morphology of each galaxy, its position and angle with respect to the MSA slit, and a spectrum filled with equally spaced delta functions that simulate idealized emission lines. The software then simulates a 2D spectrum for each object. We process these 2D spectra using the JWST NIRSpec reduction pipeline in the same manner as the actual data. Finally, we measure the spectral resolution by analyzing the broadening of the simulated emission lines. We find that the wavelength dependence of the instrumental resolution is consistent with the online pre-launch estimates from JDox, but typically a factor of 1.3 better, corresponding to a resolution of $R \sim 1300$. For each galaxy, we derive this factor and assume the corrected JDox curve when fitting. See Slob et al. (2024) for more details on this procedure.

During the fitting procedure, the spectral continuum is removed from the observations by

¹<https://github.com/alizabeverage/alfalpha>

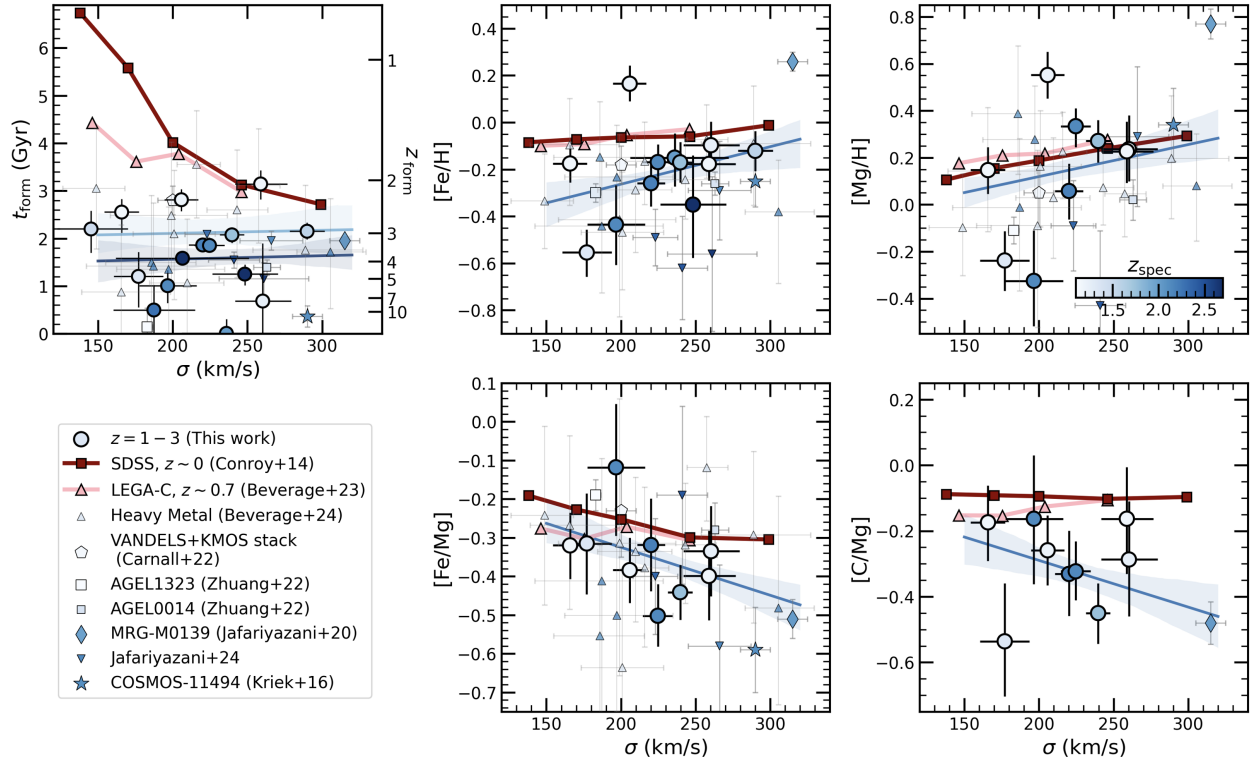


Figure 5.2: The formation time (t_{form}), $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, $[\text{Fe}/\text{Mg}]$, and $[\text{C}/\text{Mg}]$ as a function of velocity dispersion for the $z = 1 - 3$ *JWST*-SUSPENSE quiescent galaxy sample (circles) and for other various measurements at similar redshifts from the literature. Each point is colored by its spectroscopic redshifts. To guide the eye, we include the best-fit relations and corresponding confidence intervals in each panel, fit to the $z = 1 - 3$ data point. In the t_{form} panel, we instead present two relations, one for $z < 1.5$ and the other for $z > 1.5$. For comparison, we also include the abundances of stacks of quiescent galaxies at $z \sim 0$ from SDSS (Conroy et al., 2014; Beverage et al., 2023) and at $z \sim 0.7$ from LEGA-C (Beverage et al., 2023). At constant σ , the SUSPENSE galaxies form earlier and are more deficient in Fe and C than the $z < 0.7$ galaxies.

fitting an $n = 7$ Chebyshev polynomial to the ratio of the data to the model. We note that the results are robust to decisions regarding the order of the polynomial. Where available, we fit the wavelength regions $3800 - 4800 \text{ \AA}$, $4800 - 5800 \text{ \AA}$, $5800 - 6400 \text{ \AA}$, and $8000 - 8600 \text{ \AA}$ (each with their own normalized continuum). We mask the NaD absorption feature, the [OIII] lines where present, and the $H\alpha + [\text{NII}]$ complex. We also exclude wavelengths $6400 - 8000 \text{ \AA}$ due to the dominant TiO absorption in the spectrum, as these broad features are typically over-fitted by the continuum polynomial.

After fitting all 20 galaxies, we visually inspect the best-fit model, the normalizing polynomial, and the corresponding corner plots. We remove five galaxies; two because they have low S/N (< 15 per rest-frame $\text{\AA}$; 130183, 130934), one because it is lacking wavelength coverage of key absorption features (130208), and two because of strong emission lines likely associated with AGN (130647, 128452). We also re-fit 127941, masking the $H\beta$ region, which was poorly fit due to spectral contamination. Object 127108 is also re-fit, masking the region $> 5500 \text{ \AA}$ due to the lack of clear features. Finally, for each object, we inspect the posteriors of all 10 fitted elements and determine which elements can be constrained by requiring their posterior to be Gaussian and not run against the prior limits (-0.5 and 0.5 dex). Figure 5.1 shows the quiescent SUSPENSE spectra at $z = 1 - 3$ and corresponding best-fit $\text{alf}\alpha$ models. We present the stellar population properties and elemental abundances $[\text{X}/\text{H}]$ in Table 5.1. The elements flagged as “poorly constrained” during the visual inspection are omitted from Table 5.1. We also omit the abundances of 129966 because the best-fit age is below the lowest age in the stellar population models (1 Gyr). Tables of the elemental abundance ratios $[\text{X}/\text{Fe}]$ and $[\text{X}/\text{Mg}]$ are provided in Appendix 5.8.

5.4 The multi-elemental abundances of distant quiescent galaxies

In this section, we present the multi-element abundances of the massive quiescent galaxies at $z = 1 - 3$ from the JWST-SUSPENSE program. For each SUSPENSE galaxy, we only consider the elements that have well-behaved normal posterior distributions. Among the ten fitted elements, C, Mg, and Fe have the most galaxies with well-constrained measurements, likely due to their prominent absorption features, such as CH (G4300), Mgb, Fe5270, Fe5335, and Fe5406.

In Figure 6.4, we present the formation time (t_{form}), $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, $[\text{Fe}/\text{Mg}]$, and $[\text{C}/\text{Mg}]$ as a function of line-of-sight velocity dispersion (circles). Here, we adopt Mg as the reference element instead of Fe (i.e., $[\text{X}/\text{Mg}]$) because it is mostly produced by CC SNe and thus a simpler tracer of chemical enrichment (see e.g., Weinberg et al., 2019). The formation time is calculated using the stellar ages from Table 5.1, corrected for the age of the universe at the observed redshift. The points are colored by their spectroscopic redshifts. We also include the results of stacked quiescent galaxies at $z \sim 0$ from SDSS (red squares) and $z \sim 0.7$ from LEGA-C (pink triangles Beverage et al., 2023). The stacked SDSS spectra and corresponding

elemental abundance results were first presented in Conroy et al. (2014) and later re-fit by Beverage et al. (2023) to reflect updates in the stellar population models (see Conroy et al., 2018). We note that the SDSS fiber and the LEGA-C and SUSPENSE slits all cover similar physical radii (3 – 4 kpc). However, since galaxies were smaller in the past, the SUSPENSE and LEGA-C slits cover $1 - 1.2 R_e$, while SDSS covers only $0.4 - 0.8 R_e$.

In Figure 6.4, we also include all available elemental abundance measurements in the literature at $z = 1 - 3$. We only include measurements that use the same full-spectrum fitting method, and thus are comparable to the SUSPENSE results. We do not include grism or prism results because they rely heavily on the shape of the continuum and are therefore highly susceptible to fitting degeneracies. We also exclude abundances derived from Lick indices because, at these redshifts, the individual absorption features are faint and easily contaminated by NIR skylines. We color all points by their spectroscopic redshifts.

In each panel of Figure 6.4, we present the results from a linear structural regression fit applied to *all* available points within the redshift range $z = 1 - 3$. The linear model assumes intrinsic scatter around the best-fit line, which is described by a third parameter alongside the slope and intercept. Using a Bayesian approach, we determine the best-fit line and its associated shaded confidence intervals by sampling the posterior distributions with MCMC. We fit two relations to the formation times, one at $z < 1.7$ (light blue) and another at $z > 1.7$ (dark blue). During the fitting process, we set a lower limit of 0.1 dex on the uncertainties of the elemental abundance, to prevent single high S/N measurements from dominating the fit and to account for possible systematic uncertainties.

In the top left panel of Figure 6.4, we find that the formation redshifts of the SUSPENSE galaxies range from $z_{\text{form}} = 1.5$ to 9. No clear trends are observed between σ and formation time at $z \gtrsim 1$. However, there is a clear trend with observed redshift, where typical galaxies at $z \gtrsim 1$ formed earlier than those at lower redshifts, as expected. This redshift trend is also evident within the $z \gtrsim 1$ sample, with the best-fit relation for $z > 1.7$ being lower than that for $z < 1.7$. A similar trend has been shown by Beverage et al. (2023) and will be discussed in detail in Section 5.6

In the next panel, we show that quiescent galaxies at $z = 1 - 3$ have $[\text{Fe}/\text{H}]$ ranging from -0.6 to 0.3 , with typical values of -0.22 . We find a trend between σ and $[\text{Fe}/\text{H}]$, with a statistically significant slope (2σ certainty). The normalization of these measurements are 0.16 ± 0.03 dex lower than what is found at $z \sim 0$ and $z \sim 0.7$. A 1D Kolmogorov-Smirnov (KS) test comparing the Fe abundances of galaxies at $z \sim 0$ and $z \sim 2$ yields significant p-values (< 0.01), allowing us to reject the null hypothesis and conclude that the Fe abundances of these two populations are drawn from different distributions. Thus, we confirm earlier results that quiescent galaxies at $z \sim 2$ are Fe-deficient (Kriek et al., 2016, 2019; Morishita et al., 2018; Zhuang et al., 2023; Beverage et al., 2024; Jafariyazani et al., 2024). In the next panel, we find that $[\text{Mg}/\text{H}]$ varies from -0.3 to 0.6 , with a typical value of $[\text{Mg}/\text{H}] = 0.15$. The slope of the $\sigma - [\text{Mg}/\text{H}]$ relation agrees with the results at $z \sim 0$ and $z \sim 0.7$ and the normalization is only slightly lower (0.07 ± 0.04 dex).

In the bottom left panel of Figure 6.4 we find $[\text{Fe}/\text{Mg}]$ ranging from -0.50 to -0.10 , with a typical value of -0.35 . The best-fit $\sigma - [\text{Fe}/\text{Mg}]$ relation has a negative slope, in agreement

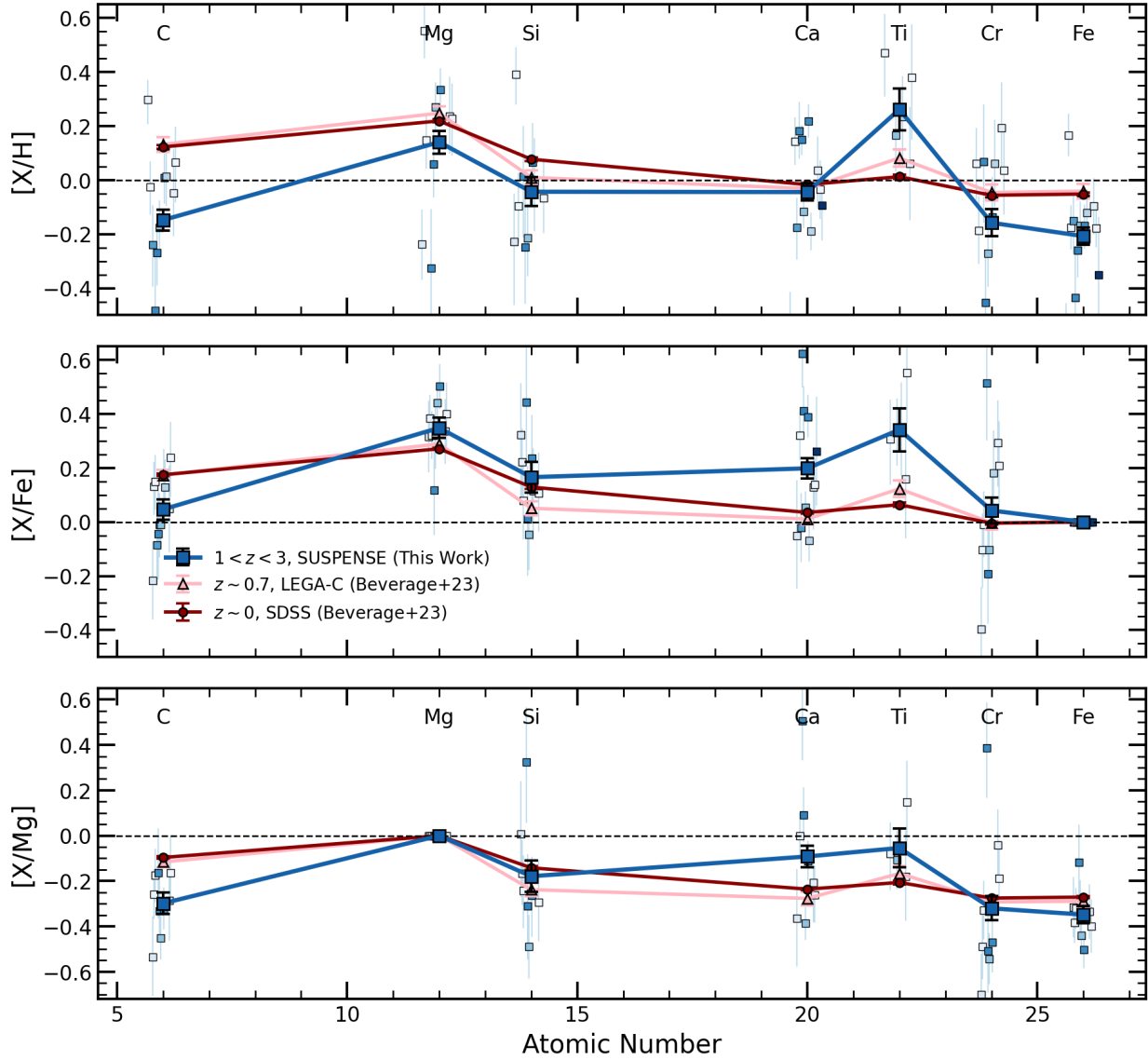


Figure 5.3: The abundance patterns of the $z = 1 - 3$ quiescent galaxies (blue squares). We show the absolute abundances, $[X/H]$, in the top panel, followed by the abundance ratios $[X/Fe]$ (middle) and $[X/Mg]$ (bottom), with the solar values marked with a dashed black line. The thick solid blue line with square markers shows the median abundance pattern of the $z = 1 - 3$ quiescent galaxies. For comparison, we include the average abundance patterns of $z \sim 0$ (red solid line with circle markers) and $z \sim 0.7$ (pink solid line with triangle markers) galaxies with the *same* velocity dispersions ($175 - 275 \text{ km s}^{-1}$). The $z = 1 - 3$ galaxies are significantly deficient in $[C/H]$ and $[Fe/H]$ compared to lower redshift samples.

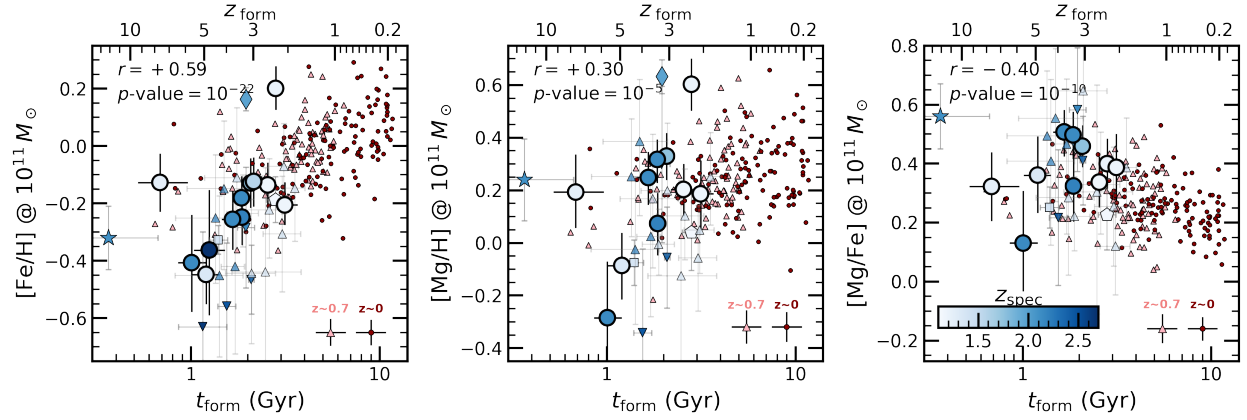


Figure 5.4: $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ as a function of galaxy formation time for massive quiescent galaxies at $z = 0 - 3$. Data points for the redshift range $z = 1 - 3$ are color-coded based on their spectroscopic redshift, and their shapes follow the same legend as Figure 6.4. The red circles [pink triangles] represent individual quiescent galaxies from SDSS [LEGA-C] (Zhuang et al., 2023; Beverage et al., 2023). Typical uncertainties for the SDSS and LEGA-C points are shown in the bottom right of each panel. We remove the first-order dependence on stellar mass by adjusting all measurements to reflect the abundances at $M_* = 10^{11} M_\odot$ (refer to the text for details). We calculate the Pearson correlation coefficients, including all galaxies at all redshifts, and list the corresponding correlations (r) and p -values in the top left corner of each panel. Regardless of observed redshift, galaxies that form earlier have lower $[\text{Fe}/\text{H}]$, slightly lower $[\text{Mg}/\text{H}]$, and higher $[\text{Mg}/\text{Fe}]$, consistent with more rapid formation and efficient quenching at earlier times.

with lower redshift results, however, the relation is offset to lower $[\text{Fe}/\text{Mg}]$ by 0.10 ± 0.04 dex. A 1D KS test of $[\text{Fe}/\text{Mg}]$ show that the $z \sim 0$ and $z \sim 2$ abundances are drawn from different distributions, with a mildly significant p -value (< 0.05). This low $[\text{Fe}/\text{Mg}]$ is consistent with the other results at similar redshifts in this figure (Kriek et al., 2016; Beverage et al., 2024; Jafariyazani et al., 2020, 2024).

In the bottom right panel, we show $[\text{C}/\text{Mg}]$. We highlight that these are the first measurements of C abundances for a sample of distant quiescent galaxies and that only one other $[\text{C}/\text{Mg}]$ measurement at these redshifts is available in the literature (Jafariyazani et al., 2020). We find $[\text{C}/\text{Mg}]$ ranges from -0.55 to -0.05 , with a typical value of -0.3 , in good agreement with Jafariyazani et al. (2020). The best-fit trend with σ is still highly uncertain given that there are only 10 C measurements at this redshift but it is clear that the SUSPENSE galaxies have ~ 0.2 dex lower $[\text{C}/\text{Mg}]$ than the $z \sim 0$ and $z \sim 0.7$ samples (3σ certainty). Given that the average $[\text{Mg}/\text{H}]$ is similar (to within 0.07 dex) across the redshift samples, the low $[\text{C}/\text{Mg}]$ and $[\text{Fe}/\text{Mg}]$ are caused by deficiencies in C and Fe.

Next, we present the elemental abundance patterns of the SUSPENSE galaxies in Fig-

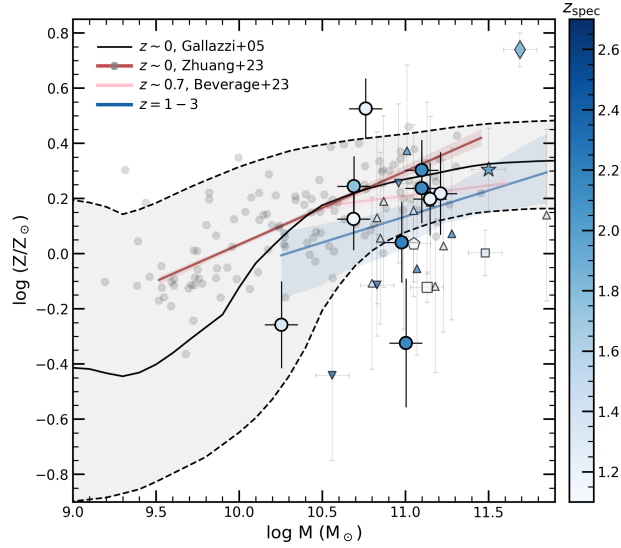


Figure 5.5: Stellar metallicity as a function of stellar mass for quiescent galaxies at $z = 1 - 3$ in the *JWST*-SUSPENSE program (circles) and from various other studies (following the same legend as Figure 6.4). All points are colored by their spectroscopic redshifts. The blue line shows the best-fit stellar mass-metallicity relation at $z = 1 - 3$, measured from all available measurements at $z = 1 - 3$. We include the stellar MZR at $z \sim 0.7$ from Beverage et al. (2023, black dashed line) and $z \sim 0$ from Gallazzi et al. (2005, black line and gray shaded region). We also show individual values from the SDSS sample presented in Zhuang et al. (2023, gray hexagons). Galaxies $z = 1 - 3$ on average have -0.17 ± 0.09 dex lower metallicities than those at $z \sim 0$ and $z \sim 0.7$.

Figure 5.3. We show the average absolute abundances $[X/H]$ (top panel) the abundance ratios with respect to Fe $[X/Fe]$, (middle panel), and the abundance ratios with respect to Mg $[X/Mg]$ (bottom panel). We only include elements for which we have at least five constrained individual measurements; namely C, Mg, Si, Ca, Ti, and Cr, and Fe. The small blue squares represent the individual abundances from SUSPENSE, while the large squares depict the mean of these measurements. The black error bars are calculated by perturbing the abundances of each data point based on their uncertainties and then determining the standard deviation of the resulting mean abundance values. Figure 5.3 also includes the abundance patterns of $z \sim 0$ (red circles) and $z \sim 0.7$ quiescent galaxies (pink triangles) from Beverage et al. (2023). These $z \sim 0$ [$z \sim 0.7$] results represent the average of thousands [hundreds] of quiescent galaxies from the *same* velocity dispersion range as the SUSPENSE galaxies ($200 - 300 \text{ km}^{-1}$).

Consistent with the findings of Figure 6.4, massive quiescent galaxies at all three redshift intervals have non-solar abundance patterns, being deficient with respect to Mg. These trends are further evident when examining the individual elements in greater detail. In

the top panel of Figure 5.3, we find that distant quiescent galaxies in SUSPENSE have significantly lower $[\text{C}/\text{H}]$ and $[\text{Fe}/\text{H}]$ ($> 3\sigma$ certainty) and slightly lower $[\text{Mg}/\text{H}]$ (1.5σ) than the $z < 1$ galaxies. Specifically, $[\text{C}/\text{H}]$, $[\text{Fe}/\text{H}]$, and $[\text{Mg}/\text{H}]$ are lower by 0.25, 0.16, and 0.07 dex, respectively, than at $z \sim 0$. Therefore, the $[\text{Mg}/\text{Fe}]$ enhancement observed in the central panel is primarily driven by a deficiency in Fe. Moving on to the other elements, we find that Ca has a similar behavior as Mg, with a mostly constant $[\text{Ca}/\text{H}]$ across the three redshift regimes, but with enhanced $[\text{Ca}/\text{Fe}]$ and $[\text{Ca}/\text{Mg}]$ at higher redshift. Ti is unique because the absolute abundance $[\text{Ti}/\text{H}]$ and abundance ratios $[\text{Ti}/\text{Fe}]$ and $[\text{Ti}/\text{Mg}]$ increase with increasing redshift. We highlight that high Ti abundances present a long-standing problem in chemical evolution modeling (e.g., Kobayashi et al., 2020). $[\text{Cr}/\text{H}]$ on the other hand behaves more like Fe and C, with $[\text{Cr}/\text{H}]$ being lower at $z = 1 - 3$. This result is unsurprising given that Cr is typically considered an Fe-peak element. Si shows no significant evolution in $[\text{X}/\text{H}]$, $[\text{X}/\text{Fe}]$, or $[\text{X}/\text{Mg}]$. Thus, Si behaves more similarly to Mg and Ca. However, the abundance uncertainties on Ti, Si, and Cr are quite large. We note that these abundance results are roughly consistent with the only other existing abundance pattern at $z \gtrsim 0.7$, observed in a lensed quiescent galaxy by Jafariyazani et al. (2020). In Section 5.6, we explore the implications of these abundance patterns in the context of chemical enrichment histories.

Finally, in Figure 5.4, we show $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ as a function of formation time, as in Zhuang et al. (2023). In addition to the SUSPENSE sample (blue circles, colored by spectroscopic redshift), we include individual results from massive quiescent galaxies in the SDSS survey from Zhuang et al. (2023, red circles) and LEGA-C from Beverage et al. (2023, pink triangles). In each panel of Figure 5.4, we remove the first-order dependence on stellar mass by subtracting the SDSS M_* –abundance relations from Zhuang et al. (2023) from all galaxies and then scaling them to the value of the M_* –abundance relations at $M_* = 10^{11} M_\odot$. We utilize the Pearson correlation coefficient to assess the degree of correlation between the parameters in Figure 5.4. We include all points in Figure 5.4 (at all redshifts) when computing the degree of correlation. The resulting Pearson coefficients and corresponding p -values are listed in the top left of each panel. Correlations with p -values $p < 0.01$ are considered significant.

At fixed stellar mass, the formation time and $[\text{Fe}/\text{H}]$ have a significant positive correlation ($r = 0.59$), with galaxies forming at earlier times having lower Fe enrichment. $[\text{Mg}/\text{H}]$ shows a moderate positive correlation ($r = 0.30$), with galaxies forming earlier having slightly lower Mg enrichment. Finally, there is a negative correlation ($r = -0.40$) between $[\text{Mg}/\text{Fe}]$ and formation time, indicating galaxies that form earlier have slightly higher $[\text{Mg}/\text{Fe}]$. These correlations are primarily driven by the large quantity and dynamic range in t_{form} of $z \sim 0$ abundance measurements and thus agree with the results presented in Zhuang et al. (2023). Therefore, it is striking that the correlations found at lower redshifts are mostly consistent with the $z \sim 2$ data, in the sense that the oldest galaxies at $z \sim 0$ have similar abundance patterns as those at $z \sim 2$. In Section 5.6, we discuss the implications of these results on the assembly of massive galaxies.

5.5 The Stellar Mass-Metallicity Relation at $z \sim 2$

In this section, we present the stellar mass-metallicity relation of quiescent galaxies at $z = 1 - 3$. In Figure 5.5, we show the stellar metallicities $\log(Z/Z_\odot)$ of the *JWST*-SUSPENSE quiescent galaxies as a function of their stellar mass (circles). We compute these metallicities following the calibration $\log(Z/Z_\odot) = [\text{Fe}/\text{H}] + 0.94[\text{Mg}/\text{Fe}]$ from Thomas et al. (2003). As in Figure 6.4, we include all existing measurements of stellar metallicities derived from full-spectrum fitting at $z = 1 - 3$ derived using the same full-spectrum fitting method and underlying models. For comparison, we also include the $z \sim 0$ MZR and corresponding 1σ scatter from Gallazzi et al. (2005, black line and gray shaded region). Additionally, we show individual measurements for a subsample of these SDSS galaxies from Zhuang et al. (2023, gray hexagons). The Gallazzi et al. (2005) relation was measured using a different method than Zhuang et al. (2023), with different stellar population models, and assuming a different solar abundance pattern. Therefore, we calibrate the Gallazzi et al. (2005) MZR to match the normalization of the Zhuang et al. (2023) measurements by applying a shift of $+0.16$ dex.

We fit a mass-metallicity relation to all available $z = 1 - 3$ measurements using the same structural linear regression applied to the abundances in Figure 6.4, where we assume that the points have an intrinsic scatter around the best-fit line. Again, we set the lower limit on the error of the metallicity to 0.1 dex so that high S/N measurements do not dominate the fit. Uncertainties on all stellar mass estimates are assumed to be 0.1 dex, to properly account for systematic uncertainties involved in the stellar population modeling (see Kriek et al., 2016, for motivation of mass uncertainties). The best-fit parameters and corresponding uncertainties are estimated using MCMC. We use the same fitting method to re-determine the MZR at $z \sim 0$ (red line) and $z \sim 0.7$ (pink line) for the Zhuang et al. (2023) and Beverage et al. (2023) samples, respectively. We emphasize again that the individual metallicity measurements at $z \sim 0$ and $z \sim 0.7$ were made using the same full-spectrum modeling method as the $z = 1 - 3$ sample.

The best-fit stellar MZRs at each redshift interval correspond to the following relations:

$z = 1 - 3$:

$$\log(Z/Z_\odot) = 0.19^{+0.17}_{-0.12} \log\left(\frac{M_*}{10^{11} M_\odot}\right) + 0.13^{+0.05}_{-0.11}$$

$z \sim 0.7$:

$$\log(Z/Z_\odot) = 0.08^{+0.04}_{-0.04} \log\left(\frac{M_*}{10^{11} M_\odot}\right) + 0.21^{+0.02}_{-0.02}$$

$z \sim 0$:

$$\log(Z/Z_\odot) = 0.27^{+0.02}_{-0.02} \log\left(\frac{M_*}{10^{11} M_\odot}\right) + 0.30^{+0.02}_{-0.02}$$

The slope of the MZR at $z = 1 - 3$ is consistent with that at $z \sim 0$, within the uncertainties. The normalization, though, appears to have increased by 0.17 ± 0.09 since $z \sim 2$. We

note that the sample at $z = 1 - 3$ is still small, and the metallicity measurements have significant statistical uncertainties. Consequently, the evidence for evolution remains below the 2σ level. Thus, larger samples and deeper observations are needed to confirm this potential evolution with more certainty.

An evolving MZR, if confirmed, is not surprising given that the total metal content of a galaxy is primarily in α elements (70 percent² by mass) and that we find slightly lower Mg in Figure 5.3. Even though distant quiescent galaxies are Fe deficient, Fe-peak elements only contribute 10 percent by mass to the total metallicity. Therefore, the observed offset in the MZR to lower $Z/Z_{\odot}$ could be explained by these galaxies having lower Mg abundances.

Other studies based on Lick indices instead point to a redshift-invariant MZR, with galaxies at $z \sim 2$ having super-solar Z_* (Lonoce et al., 2015; Onodera et al., 2015). However, these conclusions are based on individual measurements or a single stacked spectrum, and therefore they carry large uncertainties. Similarly, Estrada-Carpenter et al. (2019) report a redshift-invariant MZR, with stellar metallicities derived from low-resolution spectroscopy. In section 5.6, we compare these methods and demonstrate that metallicities derived from spectrophotometric fitting primarily reflect $[\text{Fe}/\text{H}]$. Given the Fe deficiencies found in this work, it is notable that Estrada-Carpenter et al. (2019) find no evolution in the MZR.

5.6 Discussion & Implications

Star-formation timescales

In this work, we present the first abundance pattern study (including Fe, C, Mg, Si, Ca, Ti) based on a sample of $z > 1$ quiescent galaxies. Jafariyazani et al. (2020) had previously measured an abundance pattern at $z \sim 2$, but only for a single lensed system, whereas Beverage et al. (2024) measured only the Mg and Fe abundances of a larger sample of quiescent galaxies at $z \sim 1.4$ and $z \sim 2.1$. In this section, we discuss the implication of multi-element abundance results on the star-formation histories of distant quiescent galaxies.

A key observation from Figure 5.3 was that massive quiescent galaxies at $z = 1 - 3$ are deficient in Fe and C, whereas Mg, Si, Ca, and Ti have higher abundances. When considering the full ISM enrichment over a stellar population’s lifetime, Fe is forged approximately equally in CC and SNe Ia, whereas C is enriched approximately equally by CC SNe and low-mass AGB stars. The other elements, Mg, Si, Ca, and Ti, are all primarily α elements, produced in CC SNe. These processes enrich over a diverse set of timescales; exploding massive stars (CC SNe) eject α elements almost instantaneously after the commencement of star formation, swiftly incorporating them into subsequent stellar generations. Alternatively, low- to intermediate-mass stars enrich the ISM on a delayed timescale due to their longer lifespans. One mechanism is via SNe Ia, which typically eject Fe-peak elements (e.g., Cr and Fe) only after a time delay of $\sim 0.5 - 1$ Gyr. The other mechanism is via AGB stars, which

²Calculated using the Asplund (2009) solar abundances and taking α elements to include N, O, Mg, Na, Ne, S, Si, Ti, and Ca.

have even shorter delay times than SNe Ia, enriching primarily C (and N) as early as 50 Myr but with a typical delay of ~ 250 Myr (e.g., Cristallo et al., 2011, 2015; Maiolino & Mannucci, 2019; Johnson et al., 2023). Thus, galaxies that stop forming stars before significant AGB and SNe Ia contributions have very low Fe-peak and C+N stellar abundances, but still high α abundances.

Considering the different enrichment timescales, our low C and Fe abundance results imply that the SUSPENSE galaxies formed most of their stellar mass before significant AGB and Ia SNe enrichment, corresponding to a timescale of $\lesssim 0.2$ Gyr. Such an extreme star-formation timescale would translate to an SFR of $\geq 500 M_{\odot} \text{ yr}^{-1}$, putting these galaxies among the most vigorous star-forming galaxies in the Universe (e.g., Riechers et al., 2013; Decarli et al., 2017; Gullberg et al., 2019; Liao et al., 2024).

This interpretation assumes that the observed deficiencies in C and Fe are solely driven by shorter star-formation timescales in higher-redshift galaxies. However, variations in the IMF may also play a significant role in shaping the relative elemental abundances. For instance, a top-heavy IMF would increase the relative number of CC to Ia supernovae, increasing the Mg producers over the Fe producers. This would elevate $[\text{Mg}/\text{Fe}]$ without requiring extremely short star-formation timescales (e.g., Matteucci, 1994; ?). Furthermore, a top-heavy IMF could alter the IMF-averaged CC SNe yields, introducing even more variation. A top-heavy IMF is indeed plausible in these extreme galaxies, potentially due to unique environmental conditions or the effect of an integrated galaxy-wide IMF (e.g., ?). However, the extent of this impact—particularly on elements that are produced by multiple enrichment pathways—remains unclear. Detailed chemical evolution modeling is necessary to disentangle the respective roles of the IMF and star-formation timescales in producing these unusual abundance patterns.

Such detailed chemical evolution models would also provide more precise estimates of star-formation timescales, a task we leave for a future work. However, we note that the inferred extreme star-formation timescales conflict with the results from spectrophotometric fitting using the non-parametric star-formation histories of the SUSPENSE galaxies Slob et al. (2024). In Sections 5.6 and 5.6 we discuss the implications of these differences.

The assembly of massive galaxies over cosmic time

Our elemental abundance patterns imply that galaxies at $z \sim 2$ on average formed earlier (Section 5.4) and over shorter timescales (Section 5.6) compared to galaxies with similar velocity dispersions at $z \sim 0$ and $z \sim 0.7$. The most straightforward explanation for this observed increase is that galaxies in the quiescent sample at $z = 1 - 3$ are among the earliest quenchers in the $z \sim 0$ population; galaxies that form over longer timescales quench and join the quiescent galaxy population at later times. Thus, by $z = 0$, the SUSPENSE sample represents only the extreme tail of the t_{form} distribution. This explanation is akin to the “progenitor bias” scenario (i.e., van Dokkum & Franx, 2001) used, for example, to explain the size growth of quiescent galaxies over time (e.g., Khochfar & Silk, 2006; van Dokkum et al., 2010; Carollo et al., 2013; Poggianti et al., 2013).

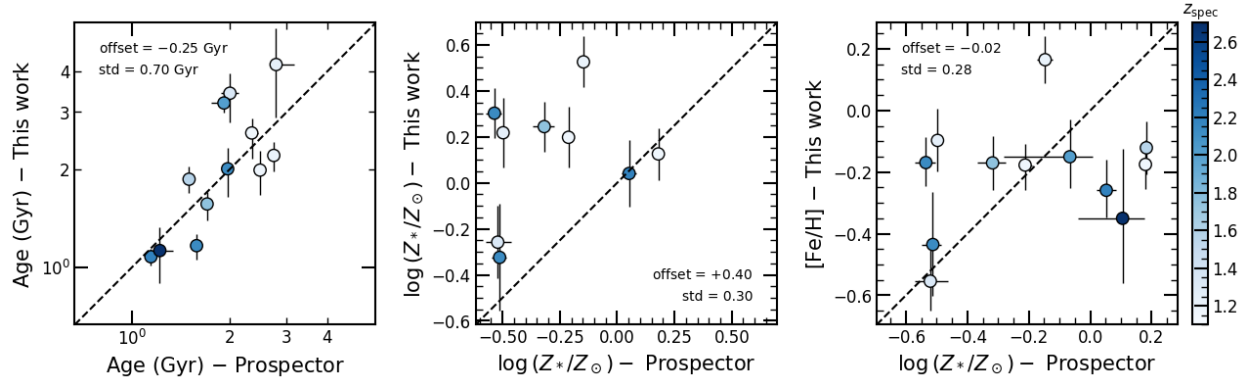


Figure 5.6: Comparison between PROSPECTOR and *alf* measurements of the ages (left), metallicities (middle), and $[\text{Fe}/\text{H}]$ (right) of the massive quiescent galaxies at $z = 1 - 3$ from JWST-SUSPENSE. The dashed black line shows a one-to-one relation. The data points are colored by their spectroscopic redshifts. The metallicities from this work are calculated using the (Thomas et al., 2003) conversion to $[Z/\text{H}]$ from $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{Fe}]$. The standard deviation of the points and mean offset are listed in each panel.

This progenitor bias scenario is reinforced by Figure 5.4, where we find a negative correlation between formation time and $[\text{Mg}/\text{Fe}]$, irrespective of the observed redshift of the galaxies. Thus, the evolution in C and Fe is mostly due to the lower redshift samples naturally including galaxies with earlier formation times and shorter star-formation timescales.

A closer look at Figure 5.4, however, reveals that progenitor bias alone may not be able to explain the observations. If the $z \sim 2$ galaxies passively evolve over the past 10 billion years, without merging or experiencing late-time star formation, then the trends with formation time at $z \sim 0$ and $z \sim 2$ should exactly overlap at the earliest epochs. Instead, we find very few SDSS galaxies at these early formation times and we find that the $z \sim 2$ samples exhibit slightly lower $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$, and higher $[\text{Mg}/\text{Fe}]$ than the lower redshift samples. This offset was first identified by Zhuang et al. (2023) using a small sample of objects at $z = 1 - 3$, and later confirmed by Beverage et al. (2024) with a larger sample.

One way to explain the lack of chemically extreme galaxies at $z \sim 0$ is late-time star formation episodes. If the star-formation material is pre-enriched with SN Ia products by previous epochs of star formation, then the newly formed stars would be younger, more metal-rich, and more α/Fe enhanced, pushing them along the abundance trends of Figure 5.4 towards younger ages (later formation times). Major mergers between galaxies with different star-formation histories would also shift galaxies upward along the formation time sequence. In contrast, minor mergers tend to decrease not only $[\text{Fe}/\text{H}]$ but also $[\text{Mg}/\text{H}]$ levels. However, due to aperture effects, interpreting the impact of minor mergers is more complicated because they are preferentially accreted to the outskirts of galaxies. Therefore, minor mergers likely have minimal influence on the observed abundance patterns. Larger sample sizes at $z \gtrsim 1$

and $z \sim 0$ with careful consideration of stellar mass completeness is required to clarify the relative importance of progenitor bias, mergers, and late-time star formation.

Galaxy quenching

A key finding from Figure 5.4 is galaxies that form at earlier epochs have lower $[\text{Mg}/\text{H}]$. Unlike the correlation with $[\text{Fe}/\text{H}]$, this result cannot be explained using star-formation timescales, because $[\text{Mg}/\text{H}]$ instead reflects instantaneous enrichment by CC SNe.

One possible explanation for galaxies with earlier formation times having slightly lower $[\text{Mg}/\text{H}]$ is that they expel larger gas reservoirs during the quenching phase. Beverage et al. (2021) proposed this model to explain a similar trend in the LEGA-C sample. They used a leaky box model with exponentially declining inflow rates and SNe-driven outflows, with analytical solutions from Spitoni et al. (2017). In their models, galaxies with smooth star-formation histories that quench via slow gas depletion end up with high stellar $[\text{Mg}/\text{H}]$ by $z = 0$, regardless of their star-formation history.

The implementation of rapid gas expulsion after two e -folding times (akin to AGN-driven feedback), successfully keeps the stellar $[\text{Mg}/\text{H}]$ low. In these models, galaxies that quenched at higher SFR and thus expel larger gas reservoirs, have lower $[\text{Mg}/\text{H}]$ and earlier formation times. Thus, the observed correlation between $[\text{Mg}/\text{H}]$ and t_{form} may indicate more efficient gas expulsion at higher redshift. These more efficient outflows in combination with progenitor bias, in turn, can explain the increase in $[\text{Mg}/\text{H}]$ and the MZR over cosmic time.

This result, in combination with the extreme SFRs inferred from the C and Fe deficiencies, is consistent with quasar-driven quenching resulting from rapid gas inflows. Indeed, evidence of ejective AGN outflows has been found in galaxies that rapidly quenched after $z \sim 2$, indicated by pronounced blueshifted Na I D and other ISM absorption lines (e.g., Maltby et al., 2019; Kubo et al., 2022; Belli et al., 2023; D'Eugenio et al., 2023; Davies et al., 2024; Park et al., 2024). Future chemical evolution modeling will help determine the mass-loading factors and star-formation timescales required to reproduce the trends with t_{form} .

SPS fitting

In this section, we compare measurements derived in this work with those obtained using a more standard stellar population modeling approach, which employs solar abundance patterns and non-parametric star-formation histories. Slob et al. (2024) present stellar population parameters for the SUSPENSE galaxies using the PROSPECTOR code (Leja et al., 2019a; Johnson et al., 2021). PROSPECTOR utilizes the Flexible Stellar Population Synthesis (FSPS; Conroy et al., 2009; Conroy & Gunn, 2010) library, the MILES spectral library, and the MIST isochrones, assuming a Chabrier (2003) IMF. The fitting process incorporates both *JWST* spectroscopy and UltraVISTA DR3 photometry. For more details, see Slob et al. (2024).

There are a few key differences between this standard modeling approach and the method used in this work. Firstly, in PROSPECTOR and similar codes, such as BAGPIPES (Carnall

et al., 2018), CIGALE (Burgarella et al., 2005), and MAGPHYS (da Cunha et al., 2008), the star-formation history (SFH) is a free parameter. Secondly, they assume a solar-scaled abundance pattern (and sometimes $Z = Z_{\odot}$). Another key difference is that PROSPECTOR, when fitting both the photometry and spectra, heavily relies on the galaxy continuum shape and consequently does not put emphasis on reproducing the individual absorption features. In contrast, our full-spectrum modeling assumes a variable abundance pattern, a single burst of star formation, and relies solely on the stellar absorption features.

Before comparing the results from these codes, it is important to highlight that differences in the SFH assumptions lead to the derived quantities being either light-weighted values in PROSPECTOR or SSP-equivalent values in ALFA. Thus, it is crucial to assess how these assumptions may impact the inferred properties. Recent work by Gountanis et al. (2024) tested the SSP-assumption by generating composite spectra using a superposition of SSPs with evolving ages, metallicities, and abundance ratios $[\text{Mg}/\text{Fe}]$, informed by a delayed-tau star-formation history and chemical evolution models. They then fit these composite spectra using **alf** α , assuming a single SSP. The results showed excellent agreement between the SSP-equivalent parameters and the true light-weighted averages, with discrepancies within 0.05 dex for ages, metallicities, and $[\text{Mg}/\text{Fe}]$ (see their Figure 13). This test indicates that using an SSP-equivalent approach in **alf** α does not introduce significant biases, allowing for a valid comparison between the codes.

In Figure 5.6, we compare our best-fit ages and metallicities to those from PROSPECTOR. The points are colored by their spectroscopic redshift, and the dashed black lines represent the one-to-one line. The left panel shows stellar ages, where PROSPECTOR provides mass-weighted estimates and our full-spectrum fitting gives SSP-equivalent ages. Despite different assumptions in star-formation history (extended non-parametric vs. single age), the two sets of stellar ages agree remarkably well. This result may not be surprising, as all of the galaxies in our sample have been quiescent for at least $\gtrsim 1$ Gyr. At these older ages, these stellar populations are less susceptible to the outshining problem, wherein the youngest stars with low M/L dominate the continuum.

Next, we examine stellar metallicities in the middle panel of Figure 5.6, comparing $\log(Z/Z_{\odot})$. As a reminder, the total metallicities from this work were computed using a combination of the best-fit $[\text{Mg}/\text{Fe}]$ and $[\text{Fe}/\text{H}]$. We find poor agreement between our total metallicities and those from PROSPECTOR, with significant scatter ($\text{std} = 0.32$ dex) and a systematic offset of 0.41 dex towards lower values in the PROSPECTOR measurements. When we compare the PROSPECTOR metallicities instead to $[\text{Fe}/\text{H}]$, the systematic offset disappears. However, the large scatter around the one-to-one line remains. Additionally, the uncertainties on the PROSPECTOR measurements are significantly underestimated.

The reason the PROSPECTOR $\log(Z/Z_{\odot})$ aligns better with $[\text{Fe}/\text{H}]$ rather than the total stellar metallicity is that Mg has less impact on the spectral shape compared to Fe (e.g., Choi et al., 2019; Leja et al., 2019c). As discussed in Section 5.5, despite Fe’s significant contribution to the absorption features in galaxies, it contributes only a small fraction to the total metal content. This effect is even more pronounced in light of the Fe-deficiencies found for the $z = 1 - 3$ sample.

The significant disagreement between the metallicities derived from PROSPECTOR and those presented here is surprising, especially given that both methods use nearly identical stellar population models (MIST isochrones and MILES stellar libraries). However, three key differences remain: PROSPECTOR incorporates photometry (capturing continuum shape), allows for an extended SFH, and uses a solar-scaled abundance pattern. To investigate the source of the discrepancy, we conducted the following tests. First, running PROSPECTOR on the continuum-normalized spectrum (excluding photometry) still showed a significant discrepancy with the results presented here, indicating the continuum shape is not the main cause. Second, constraining PROSPECTOR to an SSP to match ALFA’s SFH did not resolve the disagreement either. Finally, additionally forcing ALFA to adopt a solar-scaled abundance pattern improved the metallicity agreement, though significant scatter remained. This final test was the only case where the metallicities from PROSPECTOR and ALFA showed significant correlation according to the Pearson correlation test (p-value= 0.08). These results suggest that while multiple factors contribute, fitting non-solar populations with solar-scaled abundance patterns significantly impacts the metallicity estimates.

This impact of assuming a solar-scaled abundance pattern when fitting α -enhanced galaxies is further demonstrated by the performance of PROSPECTOR’s best-fit models, as shown in Slob et al. (2024). PROSPECTOR often struggles to reproduce key spectral features, particularly those associated with Mg, Si, and C, underscoring that solar-scaled models fail to capture the non-solar abundances present in these galaxies. This finding is corroborated by the reduced χ^2 values from fitting the spectra with solar-scaled abundance patterns with ALFA: solar-scaled fits result in a typical reduced χ^2 of 1.3, while allowing for non-solar abundances improves the fit to 1.1.

Therefore, caution is needed when interpreting or assuming metallicities derived from codes using a solar abundance pattern. Such measurements often carry underestimated uncertainty, fail to trace the true metallicity, and, on average, are more likely to reflect the Fe abundance, which is a biased indicator of total metallicity.

Finally, we compare the best-fit SFHs from PROSPECTOR to those inferred from the elemental abundances. The typical star-formation timescales from PROSPECTOR, which we define as $(t_{84} - t_{16})^3$, is 1.2 Gyr, a factor of $6\times$ longer than that predicted by the C and Fe deficiencies and chemical evolution arguments (~ 200 Myr). It is perhaps not surprising that the SFHs derived from Prospector tend to be longer. At these stellar ages (1-4 Gyr), the time resolution of the SPS models is only ~ 1 Gyr (?), since the spectra of older stellar populations are less sensitive to changes in age. In contrast, the spectra of young quiescent galaxies are significantly more sensitive to age, and age resolution can be as low as ~ 20 Myr (Suess et al., 2022b). This lower resolution in older stellar populations motivates future work that integrates stellar population modeling with priors informed by chemical evolution, which could help reveal the shorter star-formation timescales we infer from chemical evolution arguments. These shorter timescales provide crucial insights into the build-up of massive galaxies, as discussed in the next section.

³where t_x corresponds to the age of the universe at which x percent of the stellar mass has been formed

The early formation of massive galaxies

The short star-formation timescales inferred from the abundance patterns may have broader implications for the formation of massive galaxies in the early universe. Recently, *JWST* identified a population of quiescent and extremely massive galaxies at $z \gtrsim 3$ (Antwi-Danso et al., 2023; de Graaff et al., 2024; Glazebrook et al., 2024; Stawinski et al., 2024; Carnall et al., 2024). The SFHs of these galaxies, derived using PROSPECTOR and similar fitting codes, indicate that they begin to accumulate their stellar mass at very early epochs ($z \gtrsim 10$). It has been suggested that this early stellar mass growth may be in conflict with the predictions of Λ CDM, even when assuming a maximum (100%) baryon-to-star conversion efficiency, highlighting the “impossibly early galaxy problem” (e.g., Steinhardt et al., 2016).

One way to explain this tension is that the SFHs derived from standard modeling techniques are biased towards more extended SFHs. Most of the non-parametric SFHs were intentionally designed to include an early build-up of stellar mass, to solve inconsistencies with lower redshift galaxy evolution studies (Leja et al., 2019a,b; Carnall et al., 2019, 2024). Therefore, these models may not apply to the $z \gtrsim 2$ galaxy population. Carnall et al. (2024) fitted an instantaneous burst of star formation to three massive quiescent galaxies at $z \gtrsim 3$. In this test, the best-fit stellar ages were consistent with the original fits; however, the initial buildup of stellar mass was delayed. These results show that these early massive galaxies could be explained within the Λ CDM framework by simply shortening the assumed SFHs.

Our elemental abundance results indeed show that standard stellar population modeling codes overestimate the duration of the star-forming phase. Thus, assuming that quiescent galaxies at $z > 3$ will have similarly short star formation timescales, the early mass buildup in these massive galaxies may be less problematic than found by earlier studies. As elemental abundance studies will be prohibitively difficult at $z > 3$, our elemental abundance pattern may help set more informative priors on the SFHs in stellar population modeling codes.

5.7 Summary

In this Paper, we present the stellar metallicities and multi-element abundances (C, Mg, Si, Ca, Ti, Cr, and Fe) of 15 massive quiescent galaxies at $z = 1 - 3$ from the *JWST*-SUSPENSE program. The ultra-deep (16 hour) NIRSpec/MSA spectra were modeled using the custom full-spectrum fitting code `alf $\alpha$` , a Python implementation of `alf` (Conroy et al., 2018), which has been made publicly available.

Compared to the $z \sim 0$ and $z \sim 0.7$ population of massive quiescent galaxies, those at $z = 1 - 3$ have -0.26 ± 0.04 dex lower [C/H], -0.16 ± 0.03 dex lower [Fe/H], and -0.07 ± 0.04 dex lower [Mg/H]. There is also evidence that the quiescent MZR at $z = 1 - 3$ is lower by 0.17 ± 0.09 dex, but the uncertainties are large and the sample size is small. The C and Fe deficiencies indicate that distant quiescent galaxies form over shorter star-formation timescales than today’s quiescent galaxy population, quenching before significant enrichment by AGB stars and SNe Ia. Such rapid star-formation timescales (~ 0.2 Gyr) correspond

to extreme star-formation rates of $\sim 500 M_{\odot} \text{yr}^{-1}$ at $z \sim 2 - 10$, putting these galaxies among the most vigorous star-forming galaxies in the Universe. In the future, chemical evolution modeling will offer more precise constraints on the star-formation timescale, while also providing insights into the role of a top-heavy IMF in shaping this timescale.

We also find correlations between galaxy formation time and $[\text{Fe}/\text{H}]$, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$, such that galaxies that form at earlier times have abundances consistent with shorter star-formation timescales (i.e., higher $[\text{Mg}/\text{Fe}]$ and lower $[\text{Fe}/\text{H}]$). These trends had previously been found within the $z \sim 0$ and $z \sim 0.7$ populations (Zhuang et al., 2023; Beverage et al., 2023), however, using the $z = 1 - 3$ results, we show that the same trends extend to higher redshift and earlier formation times. This result suggests that the observed evolution in $[\text{C}/\text{H}]$ and $[\text{Fe}/\text{H}]$ over cosmic time is driven by lower redshift samples naturally including galaxies that formed over longer timescales. In other words, the $z = 1 - 3$ quiescent galaxies represent the extreme tail of today’s massive quiescent galaxy population. Interestingly, the $z \sim 0$ sample lacks the chemically extreme galaxies at $z = 1 - 3$, indicating mergers and/or late-time star formation likely contribute to the evolution in the elemental abundances. Larger sample sizes and careful consideration of completeness are required to clarify this picture.

Additionally, we confirm the marginal correlation between $[\text{Mg}/\text{H}]$ and formation time, suggested by previous results with smaller sample sizes and larger measurement uncertainties (Zhuang et al., 2023; Beverage et al., 2024). Given that Mg is a tracer of instantaneous metal enrichment and not the star-formation timescale, this marginal trend may imply that galaxies that form at earlier times expel larger gas reservoirs during the quenching phase, as suggested previously by Beverage et al. (2021). Combined with the extreme SFRs inferred from the C and Fe deficiencies, this interpretation is consistent with quenching by AGN-driven outflows. In the future, we will use chemical evolution modeling to measure the mass-loading factors and star-formation timescales required to reproduce the trends with t_{form} .

Next, we compare our stellar ages and metallicities to results from the spectrophotometric modeling code PROSPECTOR, which assumes a solar-scaled elemental abundance pattern and a non-parametric SFH. The stellar ages agree remarkably well, but the stellar metallicities disagree significantly. Furthermore, the PROSPECTOR metallicities carry vastly underestimated uncertainties. However, despite the large scatter, the PROSPECTOR metallicities are in better agreement with $[\text{Fe}/\text{H}]$, *not* the total metal content $[\text{Z}/\text{H}]$. We attribute this result to solar-scaled models being more sensitive to $[\text{Fe}/\text{H}]$ because of the strong impact of Fe on the stellar spectrum. Thus, although Fe only contributes approximately 10 percent by mass to the total metal content of quiescent galaxies, its abundance significantly impacts the optical stellar spectrum. In light of the observed Fe deficiencies and underestimated measurement uncertainties, we therefore emphasize caution when interpreting or assuming metallicities from modeling codes that adopt solar abundance patterns.

Finally, we find that the star-formation timescales indicated by the extreme elemental abundance patterns of distant quiescent galaxies are significantly shorter than those predicted by standard spectrophotometric modeling codes. This discrepancy confirms that the SFHs from these codes may be overly biased towards extended and early stellar mass buildup

when applied to distant quiescent galaxies (e.g., Carnall et al., 2019; Leja et al., 2019a,b). Addressing this bias could help mitigate the possible tension with Λ CDM for quiescent galaxies at $z > 3$ (see also Carnall et al., 2024). As elemental abundance measurements become prohibitively challenging at $z > 3$, these findings demonstrate how our elemental abundance patterns can provide more informative priors on the SFHs in stellar population modeling codes.

In this Paper, we demonstrate the power of *JWST* for studying the multi-element abundances of distant quiescent galaxies. In the future, we will combine this expanding multi-element dataset at $z \gtrsim 1$ with chemical evolution modeling, to uncover a more detailed picture of the star-formation histories, quenching, and assembly of massive quiescent galaxies over cosmic time.

5.8 Appendix

Tables of elemental abundance ratios

In this Appendix, we present tables of the abundance ratios $[X/Mg]$ (Table 5.2) and $[X/Fe]$ (Table 5.3) of the SUSPENSE galaxies. The uncertainties are derived from the MCMC chains, which account for potential non-Gaussianity in the posterior distributions of the absolute abundances, $[X/H]$.

Table 5.1: JWST-SUSPENSE stellar population parameters

ID	z_{spec}	$\log M^a (M_\odot)$	σ (km s $^{-1}$)	Age (Gyr)	[Fe/H]	[Mg/H]	[C/H]	[Ca/H]	[Ti/H]	[Cr/H]	[Si/H]
127345	1.168	10.7	166^{+11}_{-12}	$2.6^{+0.4}_{-0.3}$	$-0.17^{+0.08}_{-0.08}$	$0.15^{+0.10}_{-0.10}$	$-0.03^{+0.09}_{-0.10}$	$0.14^{+0.09}_{-0.08}$	—	$-0.19^{+0.12}_{-0.12}$	$-0.10^{+0.12}_{-0.13}$
130040	1.170	11.1	259^{+17}_{-17}	$2.0^{+0.3}_{-0.3}$	$-0.18^{+0.07}_{-0.07}$	$0.23^{+0.13}_{-0.13}$	$0.07^{+0.13}_{-0.13}$	$-0.04^{+0.11}_{-0.11}$	$0.38^{+0.19}_{-0.19}$	$0.04^{+0.16}_{-0.16}$	$-0.07^{+0.13}_{-0.13}$
127154	1.205	10.8	206^{+11}_{-11}	$2.2^{+0.2}_{-0.2}$	$0.17^{+0.08}_{-0.08}$	$0.55^{+0.10}_{-0.10}$	$0.30^{+0.09}_{-0.09}$	—	$0.47^{+0.16}_{-0.16}$	$0.06^{+0.13}_{-0.13}$	$0.39^{+0.10}_{-0.11}$
129982	1.249	11.2	260^{+19}_{-18}	$4.2^{+1.3}_{-1.2}$	$-0.10^{+0.10}_{-0.10}$	$0.24^{+0.14}_{-0.14}$	$-0.05^{+0.16}_{-0.16}$	$0.04^{+0.12}_{-0.12}$	$0.06^{+0.21}_{-0.21}$	$0.19^{+0.16}_{-0.16}$	—
127108	1.335	10.3	177^{+17}_{-16}	$3.4^{+0.6}_{-0.5}$	$-0.55^{+0.10}_{-0.10}$	$-0.24^{+0.12}_{-0.13}$	$-0.77^{+0.14}_{-0.14}$	$-0.61^{+0.19}_{-0.18}$	—	$-0.95^{+0.14}_{-0.13}$	$-0.23^{+0.18}_{-0.23}$
129197	1.474	10.6	145^{+25}_{-23}	$2.1^{+0.5}_{-0.4}$	—	—	—	—	—	—	—
129149	1.579	11.0	290^{+12}_{-12}	$1.9^{+0.2}_{-0.2}$	$-0.12^{+0.08}_{-0.08}$	—	$0.01^{+0.10}_{-0.10}$	$-0.19^{+0.07}_{-0.07}$	$0.23^{+0.15}_{-0.15}$	$0.06^{+0.16}_{-0.16}$	$-0.01^{+0.16}_{-0.16}$
128041	1.760	10.7	240^{+18}_{-18}	$1.6^{+0.2}_{-0.1}$	$-0.17^{+0.09}_{-0.09}$	$0.27^{+0.09}_{-0.09}$	$-0.18^{+0.10}_{-0.10}$	$-0.12^{+0.06}_{-0.06}$	$0.17^{+0.13}_{-0.13}$	$-0.27^{+0.12}_{-0.12}$	$-0.21^{+0.12}_{-0.14}$
127700	2.013	10.8	236^{+36}_{-30}	$3.2^{+0.2}_{-0.3}$	$-0.15^{+0.12}_{-0.12}$	—	$-0.24^{+0.14}_{-0.15}$	$-0.18^{+0.11}_{-0.11}$	—	—	—
129133	2.139	11.1	225^{+10}_{-10}	$1.2^{+0.1}_{-0.1}$	$-0.17^{+0.08}_{-0.08}$	$0.33^{+0.08}_{-0.09}$	$0.01^{+0.09}_{-0.09}$	$0.22^{+0.06}_{-0.06}$	—	$-0.14^{+0.15}_{-0.14}$	$0.07^{+0.14}_{-0.15}$
127941	2.141	11.0	197^{+20}_{-19}	$2.0^{+0.4}_{-0.3}$	$-0.43^{+0.17}_{-0.17}$	$-0.33^{+0.22}_{-0.19}$	$-0.48^{+0.21}_{-0.21}$	$0.18^{+0.10}_{-0.10}$	—	$0.07^{+0.21}_{-0.22}$	$0.01^{+0.18}_{-0.22}$
128036	2.196	11.0	220^{+9}_{-9}	$1.1^{+0.1}_{-0.1}$	$-0.26^{+0.09}_{-0.10}$	$0.06^{+0.12}_{-0.12}$	$-0.27^{+0.11}_{-0.12}$	$0.15^{+0.05}_{-0.05}$	—	$-0.45^{+0.18}_{-0.18}$	$-0.25^{+0.18}_{-0.21}$
128913	2.285	10.8	187^{+28}_{-27}	$2.3^{+0.5}_{-0.5}$	—	—	—	—	—	—	—
130725	2.692	11.2	248^{+22}_{-22}	$1.1^{+0.2}_{-0.2}$	$-0.35^{+0.21}_{-0.23}$	—	—	$-0.09^{+0.12}_{-0.13}$	—	—	—
129966*	2.923	10.9	207^{+44}_{-45}	$0.6^{+0.1}_{-0.1}$	—	—	—	—	—	—	—

^a Presented in Slob et al. (2024)

^{*} Removed from analysis because younger than the stellar population model grid (< 1 Gyr)

Table 5.2: Elemental abundance ratios with Mg as the reference element

ID	[Fe/Mg]	[C/Mg]	[Ca/Mg]	[Ti/Mg]	[Cr/Mg]	[Si/Mg]
127345	$-0.32^{+0.09}_{-0.09}$	$-0.17^{+0.11}_{-0.12}$	$-0.00^{+0.10}_{-0.10}$	—	$-0.33^{+0.13}_{-0.12}$	$-0.24^{+0.15}_{-0.16}$
130040	$-0.40^{+0.12}_{-0.11}$	$-0.16^{+0.16}_{-0.17}$	$-0.26^{+0.12}_{-0.12}$	$0.15^{+0.18}_{-0.20}$	$-0.19^{+0.16}_{-0.16}$	$-0.29^{+0.18}_{-0.17}$
127154	$-0.38^{+0.08}_{-0.08}$	$-0.26^{+0.11}_{-0.11}$	—	$-0.08^{+0.14}_{-0.16}$	$-0.49^{+0.14}_{-0.14}$	$-0.17^{+0.14}_{-0.14}$
129982	$-0.34^{+0.12}_{-0.12}$	$-0.29^{+0.18}_{-0.17}$	$-0.21^{+0.16}_{-0.17}$	$-0.18^{+0.20}_{-0.19}$	$-0.04^{+0.16}_{-0.16}$	—
127108	$-0.32^{+0.13}_{-0.13}$	$-0.54^{+0.18}_{-0.17}$	$-0.36^{+0.21}_{-0.21}$	—	$-0.70^{+0.18}_{-0.18}$	$0.01^{+0.23}_{-0.28}$
129197	—	—	—	—	—	—
129149	—	—	—	—	—	—
128041	$-0.44^{+0.07}_{-0.07}$	$-0.45^{+0.09}_{-0.09}$	$-0.39^{+0.07}_{-0.07}$	$-0.11^{+0.12}_{-0.13}$	$-0.54^{+0.11}_{-0.11}$	$-0.49^{+0.14}_{-0.14}$
127700	—	—	—	—	—	—
129133	$-0.50^{+0.08}_{-0.08}$	$-0.32^{+0.09}_{-0.09}$	$-0.11^{+0.09}_{-0.08}$	—	$-0.47^{+0.14}_{-0.13}$	$-0.26^{+0.17}_{-0.18}$
127941	$-0.12^{+0.16}_{-0.18}$	$-0.16^{+0.19}_{-0.20}$	$0.51^{+0.16}_{-0.17}$	—	$0.39^{+0.20}_{-0.22}$	$0.32^{+0.24}_{-0.27}$
128036	$-0.32^{+0.12}_{-0.12}$	$-0.33^{+0.13}_{-0.13}$	$0.09^{+0.12}_{-0.12}$	—	$-0.51^{+0.19}_{-0.18}$	$-0.31^{+0.22}_{-0.23}$
128913	—	—	—	—	—	—
130725	—	—	—	—	—	—
129966	—	—	—	—	—	—

Table 5.3: Elemental abundance ratios with Fe as the reference element

ID	[Mg/Fe]	[C/Fe]	[Ca/Fe]	[Ti/Fe]	[Cr/Fe]	[Si/Fe]
127345	$0.32^{+0.09}_{-0.09}$	$0.15^{+0.10}_{-0.10}$	$0.32^{+0.09}_{-0.09}$	—	$-0.01^{+0.12}_{-0.12}$	$0.08^{+0.13}_{-0.14}$
130040	$0.40^{+0.11}_{-0.12}$	$0.24^{+0.13}_{-0.14}$	$0.14^{+0.10}_{-0.10}$	$0.55^{+0.20}_{-0.23}$	$0.21^{+0.16}_{-0.16}$	$0.11^{+0.15}_{-0.14}$
127154	$0.38^{+0.08}_{-0.08}$	$0.13^{+0.09}_{-0.10}$	—	$0.31^{+0.14}_{-0.17}$	$-0.10^{+0.13}_{-0.14}$	$0.22^{+0.12}_{-0.13}$
129982	$0.34^{+0.12}_{-0.12}$	$0.05^{+0.16}_{-0.16}$	$0.13^{+0.15}_{-0.15}$	$0.16^{+0.21}_{-0.22}$	$0.29^{+0.16}_{-0.16}$	—
127108	$0.32^{+0.13}_{-0.13}$	$-0.22^{+0.14}_{-0.14}$	$-0.05^{+0.20}_{-0.19}$	—	$-0.40^{+0.15}_{-0.14}$	$0.32^{+0.19}_{-0.24}$
129197	—	—	—	—	—	—
129149	—	$0.13^{+0.10}_{-0.09}$	$-0.07^{+0.08}_{-0.08}$	$0.35^{+0.16}_{-0.18}$	$0.18^{+0.16}_{-0.15}$	$0.12^{+0.16}_{-0.18}$
128041	$0.44^{+0.07}_{-0.07}$	$-0.01^{+0.08}_{-0.08}$	$0.05^{+0.06}_{-0.06}$	$0.34^{+0.12}_{-0.13}$	$-0.10^{+0.11}_{-0.11}$	$-0.05^{+0.12}_{-0.13}$
127700	—	$-0.08^{+0.15}_{-0.15}$	$-0.02^{+0.13}_{-0.12}$	—	—	—
129133	$0.50^{+0.08}_{-0.08}$	$0.18^{+0.09}_{-0.09}$	$0.39^{+0.08}_{-0.07}$	—	$0.03^{+0.14}_{-0.13}$	$0.24^{+0.16}_{-0.17}$
127941	$0.12^{+0.18}_{-0.16}$	$-0.04^{+0.17}_{-0.17}$	$0.62^{+0.12}_{-0.12}$	—	$0.51^{+0.18}_{-0.21}$	$0.44^{+0.21}_{-0.24}$
128036	$0.32^{+0.12}_{-0.12}$	$-0.01^{+0.11}_{-0.12}$	$0.41^{+0.09}_{-0.09}$	—	$-0.19^{+0.19}_{-0.18}$	$0.01^{+0.19}_{-0.21}$
128913	—	—	—	—	—	—
130725	—	—	$0.26^{+0.20}_{-0.20}$	—	—	—
129966	—	—	—	—	—	—

Chapter 6

Are Nucleosynthetic Yields Universal? Interpreting the Multi-Elemental Abundances of Quiescent Galaxies over Cosmic Time Using Milky Way Stars

6.1 Abstract

The chemical abundance patterns of massive quiescent galaxies encode valuable information about their star formation histories, initial mass functions (IMFs), and enrichment processes. However, interpreting these abundance patterns is difficult, particularly due to uncertainties in theoretical yields. In this paper, we test whether empirically calibrated, IMF-averaged yields from Milky Way (MW) stars can reproduce the abundance patterns of massive quiescent galaxies. We combine these yields with analytical galactic chemical evolution predictions, with prompt enrichment from core-collapse supernovae and delayed enrichment from Type Ia supernovae. Applying this framework to observed abundances of quiescent galaxies at $0 < z < 3$, we find agreement to within 0.05 dex for nearly all elements, with nitrogen as a notable exception. We show that the observed nitrogen excess is fully explained by enrichment from a third source, asymptotic giant branch stars. Finally, we assess the impact of IMF variation. Once normalized by $[\text{Mg}/\text{Fe}]$, changes to the high-mass IMF affect most elements by only ~ 0.05 dex. Thus, Milky Way-based yields provide a reasonable approximation for interpreting the abundances of massive quiescent galaxies, with extensions to SPS models.

6.2 Background

Chemical abundances provide unique insights into a galaxy’s evolutionary history, encoding detailed records of star formation, quenching mechanisms, and hierarchical assembly (e.g., Tinsley, 1979; Matteucci, 1994; Thomas et al., 2005; Choi et al., 2014; Kriek et al., 2016; Beverage et al., 2021). Since each element arises from distinct nucleosynthetic processes associated with stars of different masses and lifetimes, elemental abundances carry additional crucial information about the initial mass function (IMF) and the origins of chemical elements (Conroy et al., 2014; den Brok et al., 2024).

However, extracting this wealth of information is challenging. Observationally, chemical abundances rely on faint stellar absorption features that become increasingly difficult to detect at higher redshifts. Fortunately, recent improvements in ground-based instrumentation and the advent of *JWST* have enabled measurements of abundance patterns at unprecedented distances, from $z \sim 0.7$ with LEGA-C (van der Wel et al., 2016, 2021; Beverage et al., 2023) to $z \sim 3$ using Keck and *JWST* (Beverage et al., 2024; Slob et al., 2024; Beverage et al., 2025). Complementing these observational advances, full-spectrum modeling techniques (e.g., Conroy & van Dokkum, 2012; Villaume et al., 2017; Conroy et al., 2018) now enable precise measurements of multi-element abundances for thousands of galaxies in the local universe.

Despite these observational breakthroughs, modeling the underlying chemical enrichment remains difficult. Galactic chemical evolution (GCE) models, which can independently constrain chemical enrichment and star-formation histories beyond traditional stellar population modeling methods, rely heavily on uncertain theoretical inputs. Key uncertainties include the stellar initial mass function (IMF) and nucleosynthetic yields—the latter quantifying how much of each element stars produce. These yields are notoriously difficult to measure directly from supernova explosions, and theoretically difficult to predict, due to complex processes such as stellar mass loss, rotation, and variations in supernova explosion mechanisms (e.g., Nomoto et al., 2013).

Consequently, most chemical evolution studies focus predominantly on just two elements: Mg and Fe. Magnesium typically traces rapid enrichment from core-collapse supernovae (CCSN), whereas Fe primarily traces delayed enrichment from Type Ia supernovae (SNIa). Thus, the [Mg/Fe] ratio serves as a convenient proxy for star-formation timescales¹, circumventing explicit modeling of the full enrichment history. Interpreting [Mg/Fe] in this simplified manner has nonetheless produced critical insights: massive low-redshift galaxies formed rapidly and early, indicated by their elevated [Mg/Fe] ratios and old stellar populations (e.g., Trager et al., 2000; Thomas et al., 2005; McDermid et al., 2015). At higher redshifts, massive quiescent galaxies exhibit even higher [Mg/Fe] ratios, posing fundamental questions about their evolutionary paths over cosmic time (Zhuang et al., 2023; Beverage et al., 2024; Beverage et al., 2025).

Relying exclusively on Mg and Fe, however, neglects significant chemical information

¹To a lesser extent, [Mg/Fe] also traces variations in the IMF

encoded in other elements. While multi-element measurements are now feasible, few studies have exploited these broader abundance patterns. Notable exceptions include Conroy et al. (2013b), who utilized *s*-process elements (e.g., Sr, Ba) from asymptotic giant branch (AGB) stars to enhance chronometric constraints on star-formation histories, and Conroy et al. (2014), who demonstrated that calcium enrichment closely tracks Fe, deviating from typical α -element behavior.

A robust interpretation of multi-element abundances thus requires improved constraints on nucleosynthetic yields. Recently, Weinberg et al. (2019) introduced an alternative empirical method, circumventing theoretical yield uncertainties by calibrating nucleosynthetic yields directly against observed abundance patterns of Milky Way stars. This approach demonstrates remarkable success in the local universe: given measurements of Mg and Fe abundances in any MW star, this method can accurately predict the abundances of the other elements to within 0.01 dex. If these empirically derived IMF-integrated yields are indeed universal, they present a powerful and broadly applicable framework for decoding the chemical evolution histories of distant galaxies.

In this paper, we directly test whether empirically derived, IMF-integrated nucleosynthetic yields calibrated from MW data can reproduce the abundance patterns observed in massive quiescent galaxies. Section 2 describes the observational data used in this analysis. In Section 3, we describe our chemical evolution model and its integration with MW nucleosynthetic yields. Section 4 details our comparison of our model predictions to the observed galaxy abundance ratios. Section 5 discusses the implications of our results for galaxy evolution. Finally, Section 6 summarizes our findings and concludes the paper.

6.3 Data

In this work, we utilize multi-element abundance measurements of massive quiescent galaxies from three spectroscopic surveys spanning different cosmic epochs: SDSS ($z \sim 0$; Conroy et al., 2014; Beverage et al., 2023), LEGA-C ($z \sim 0.7$; Beverage et al., 2023), and *JWST*-SUSPENSE ($z \sim 2$; Beverage et al., 2025). These samples probe comparable ranges of velocity dispersion, though the SDSS data extend to significantly lower values. Below, we summarize the galaxy selection criteria and abundance measurement techniques for each sample.

The selection and abundance measurements for the SDSS sample were first presented in Conroy et al. (2014). Galaxies were chosen to be quiescent, requiring no detectable H α or [OII] λ 3727 emission, and to have early-type morphologies, defined by their location on the fundamental plane (Graves & Faber, 2010). The corresponding SDSS spectra were binned by velocity dispersion into seven stacks, each containing about 1000 galaxies on average. Spectra were continuum-normalized and smoothed to a velocity dispersion of 350, km, s⁻¹ before fitting. In this study, we use the updated abundance measurements from Beverage et al. (2023).

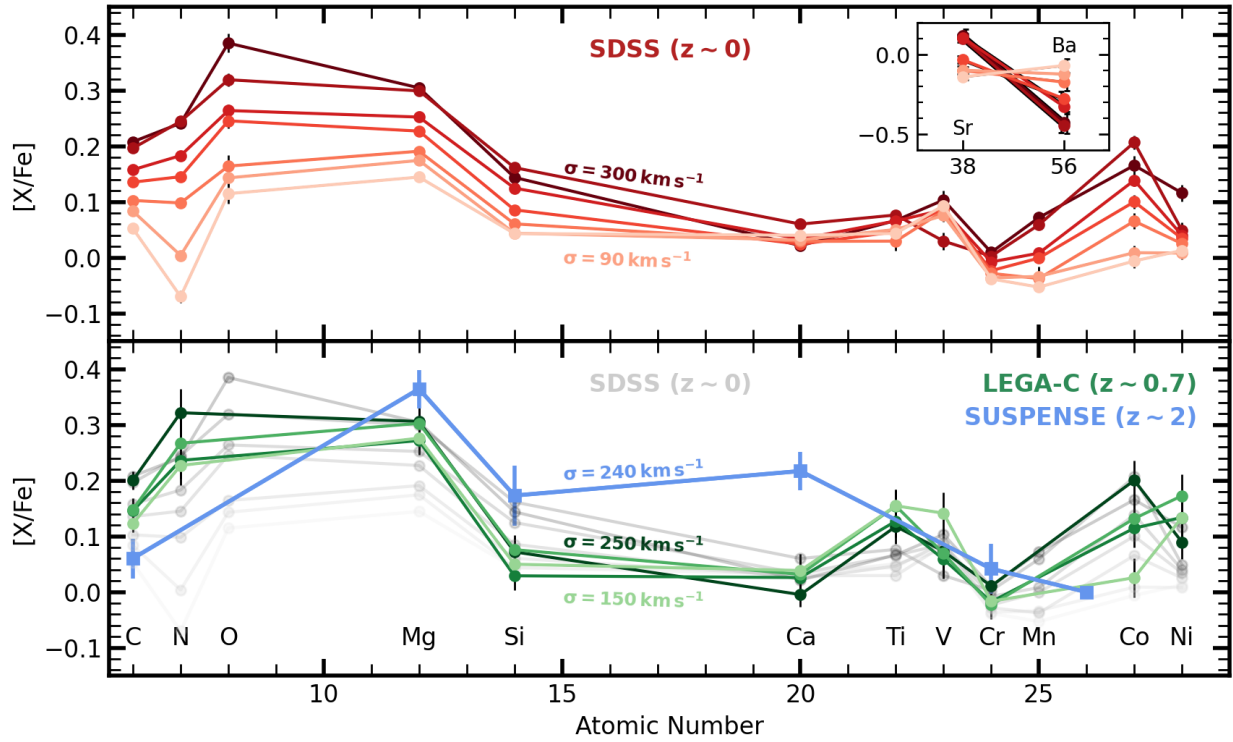


Figure 6.1: Multi-element abundance patterns used in this study. In the top row, we show the abundance ratios $[X/Fe]$ for the low-redshift (SDSS, $z \sim 0$) galaxy sample selected by Conroy et al. (2014), with abundance measurements from Beverage et al. (2023). Darker line colors indicate galaxies in higher velocity dispersion (σ) bins. The small right-hand panel displays measurements for heavier elements (Sr, Ba). In the bottom panel, we present abundance ratios for intermediate-redshift (LEGA-C, $z \sim 0.7$; green lines) and high-redshift (SUSPENSE, $z \sim 2$; blue lines) galaxies, with gray lines repeating the SDSS sample for comparison. Error bars indicate typical measurement uncertainties for each element.

The $z \sim 0.7$ sample is presented in Beverage et al. (2023). It is drawn from the third data release of LEGA-C (van der Wel et al., 2016; Straatman et al., 2018; van der Wel et al., 2021). LEGA-C is a deep spectroscopic survey of nearly 4000 massive galaxies at $0.6 \lesssim z \lesssim 1.0$ in the COSMOS footprint conducted with VIMOS on the VLT. The Beverage et al. (2023) quiescent galaxy sample was selected by requiring them to have UVJ colors corresponding to the quiescent box defined by Muzzin et al. (2013a). Galaxies were also selected to have a signal-to-noise ratio (S/N) $\gtrsim 15$ per $\text{\AA}$ in their rest-frame optical spectra and to cover key Balmer, Mg and Fe absorption features. This sample of 135 galaxies was split into four velocity dispersion bins, with about 40 galaxies per bin on average. Each spectrum was fit individually to avoid complications from continuum normalization and stacking. After fitting, posterior distribution functions within each bin were combined to emulate stacked

results.

The $z \sim 2$ sample is from the Cycle I *JWST*-SUSPENSE survey (ID:2110), which obtained ultradeep (16.4 hr) NIRSpec-MSA/G140M-F100LP observations of 20 massive quiescent galaxies at $z = 1 - 3$ in the COSMOS footprint (Slob et al., 2024). Quiescent galaxies were selected using the same UVJ criteria as for LEGA-C. Similar to LEGA-C, the posterior distributions of all galaxies were combined after fitting, resulting in one stacked abundance pattern, reflecting the median properties of all galaxies in the sample. For more information on the abundance fitting and parameter stacking, we direct readers to Beverage et al. (2025).

We modeled the elemental abundance patterns of the galaxies in all three samples with a full-spectrum approach, using the **absorption line fitter (alf)**. (Conroy & van Dokkum, 2012; Conroy et al., 2018). These models rely on metallicity-dependent MIST isochrones (Choi et al., 2016) and the MILES and IRTF empirical stellar libraries (Sanchez-Blazquez et al., 2006; Villaume et al., 2017), along with synthetic metallicity- and age-dependent elemental response spectra for 19 elements (Conroy et al., 2018). All three redshift samples were fit using the same settings, however, the $z \sim 2$ sample was fit using a python implementation, **alf α** (Beverage et al., 2025). The primary difference between these fitting codes is the posterior sampling; the original code uses MCMC, whereas the updated python version uses a dynamic nested sampler (**dynesty** Speagle, 2020). We note that these two fitting approaches, nonetheless, yield similar results.

While the code fits all 19 elements, constraints are only available for a subset in each sample, depending on the wavelength coverage and S/N of the spectra. For the $z \sim 0.7$ and $z \sim 2$ samples, elements were considered constrained if their posterior distributions were distinguishable from the input (uniform) prior (see Beverage et al., 2023; Beverage et al., 2025). Additionally, for the $z \sim 0.7$ sample, model-recovery tests were performed to further validate the constraints. In the end, SDSS has reliable abundances of 15 elements (C, N, O, Mg, Si, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Sr, and Ba), LEGA-C has 10 elements (C, N, Mg, Si, Ca, V, Cr, Fe, Co, and Ni), and the $z \sim 2$ SUSPENSE sample has 6 (C, Mg, Si, Ca, Cr, Fe).

In Figure 6.1, we summarize the multi-element abundance patterns for each sample, illustrating which elements are well-constrained at each redshift. The top panel shows abundance measurements for SDSS galaxies, stacked by velocity dispersion. The bottom panel shows the LEGA-C abundance patterns in green for 4 velocity dispersions bins (150, 180, 210, 250 km s^{-1}) and SUSPENSE abundance pattern in blue for a single velocity dispersions bin (240 km s^{-1}), with the SDSS measurements shown in gray for comparison.

6.4 Modeling the multi-element abundance patterns of Quiescent Galaxies

Understanding the detailed abundance patterns of quiescent galaxies requires models that connect star-formation histories, nucleosynthetic yields, and the time-dependent enrichment

of multiple elements. In this section we describe our model, which is rooted in the analytical one-zone fully mixed chemical evolution solutions developed by Weinberg et al. (2017). These models include a realistic delay time distribution for SNe Ia, thus tracking the separate evolution of α -elements produced by CCSN and iron peak elements synthesized in both CCSNe and SNe Ia. Building on this foundation, we incorporate additional elements using empirically calibrated, IMF-averaged, metallicity-dependent yields, anchored to observed abundances in MW stars. Below, we first summarize the assumptions and implementation of the Weinberg et al. (2017) framework, then describe how we extend the model to track a broader set of elements.

The Weinberg et al. (2017) model

The Weinberg et al. (2017) model provides a flexible, analytical description of the chemical evolution of α and Fe-peak elements. A defining feature of this model is its explicit treatment of the time delay between CCSN, which enrich the ISM with α and Fe instantaneously, and SNIa, which contribute Fe in equal amounts but over a longer timescale. This time delay is essential for interpreting abundance ratios such as $[\text{Mg}/\text{Fe}]$, which encode information about the star-formation timescales and enrichment history of a galaxy.

Key assumptions of the model include:

- *Two enrichment pathways:* Chemical enrichment proceeds through two distinct channels. The *prompt* channel, corresponding to CCSNe, instantaneously mixes newly synthesized elements into the ISM. The *delayed* channel represents SNe Ia-like enrichment, injecting Fe into the ISM following a characteristic time delay.
- *Delay-time distribution for SNe Ia:* The time delay for SNe Ia enrichment is modeled as the sum of two exponential functions, closely approximating a $t^{-1.1}$ power law, with a minimum delay time of 0.15 Gyr, as advocated by Maoz et al. (2010).
- *Flexible star-formation history:* The star-formation history (SFH) is parameterized using the “rise-fall” prescription of Johnson et al. (2021), allowing for a wide range of formation scenarios:

$$\text{SFH} \equiv \dot{M}_\star(t) \propto (1 - e^{-t/\tau_1}) \cdot e^{-t/\tau_2}, \quad (6.1)$$

where τ_1 and τ_2 set the characteristic rise and fall timescales, respectively.

- *Stellar mass recycling:* The model assumes a recycling fraction of $r = 0.4$, such that 40% of stellar mass is instantaneously returned to the ISM. This is consistent with a Kroupa (2001) IMF.
- *Star formation efficiency (linear Schmidt law):* The model assumes that the SFR is directly proportional to the gas mass, following a linear Schmidt law (e.g., Recchi et al., 2008). The star formation efficiency (SFE), defined as $\tau_\star \equiv M_g/\dot{M}_\star$, is treated as a free parameter, but is assumed to be constant over time.

- *Metallicity-independent Mg and Fe yields:* The Weinberg et al. (2017) model tracks α and Fe-peak elements separately, and assumes that the nucleosynthetic yields for each channel are independent of metallicity. This is a good approximation for elements such as O and Mg produced in CCSNe, and for Fe synthesized in SNe Ia. In this work, we adopt Mg as our representative α element and Fe as our iron-peak element.

Additional free parameters include the outflow mass-loading factor $\eta \equiv \dot{M}_{\text{out}}/\dot{M}_{\star}$, the onset of star formation (t_{start}), and a quenching time (t_{quench}), which allows for rapid truncation of star formation.

We implement the Weinberg et al. (2017) framework using the Python package `fanCE`² (Gountanis et al., 2024) (Gountanis et al., 2024), which enables efficient exploration of model parameters.

Mg and Fe yield normalization

While Weinberg et al. (2017) adopt theoretical IMF-averaged yields from Chieffi & Limongi (2004), here we take an empirical approach, following recent work by Gountanis et al. (2024) and Weinberg et al. (2024). We assume that Mg is produced exclusively through the prompt enrichment channel (i.e., CCSNe), whereas Fe receives equal contributions from both prompt (CCSN) and delayed (SNIa) processes.

We anchor our CCSN yields using empirical observations from the MW. For Fe, these yields come from observations by Rodríguez et al. (2023). With the Fe yield in hand, we can determine the Mg CCSN yield using the observed $[\text{Mg}/\text{Fe}]$ ratio in very metal-poor MW halo stars from the H3 Survey (Conroy et al., 2022). In these stars, the Fe contributed by Type Ia supernovae is still negligible so their $[\text{Mg}/\text{Fe}]$ ($[\text{Mg}/\text{Fe}]_{\text{cc}} = 0.55$) directly reflects the ratio of Mg to Fe produced by massive stars alone. Thus, using the Fe CCSN yield, we can empirically calibrate the Mg yield. This approach ensures that our yields are consistent with real stellar populations, rather than relying solely on theoretical supernova models.

Thus,

$$\frac{y_{\text{Mg}}^{\text{cc}}}{Z_{\text{Mg},\odot}} = 1.22 \quad (6.2)$$

$$\frac{y_{\text{Fe}}^{\text{cc}}}{Z_{\text{Fe},\odot}} = 0.345 \quad (6.3)$$

The integrated SNIa Fe yield is calibrated by matching the observed decline in $[\text{Mg}/\text{Fe}]$ from the CCSN plateau to its value in the solar neighborhood today ($[\text{Mg}/\text{Fe}] = 0$), assuming a smooth, extended MW SFH, resulting in:

$$\frac{y_{\text{Fe}}^{\text{Ia}}}{Z_{\text{Fe},\odot}} = 0.967 \quad (6.4)$$

Further details on these empirical calibrations can be found in Weinberg et al. (2024).

²<https://github.com/nmgountanis/fanCE>

Extension to Additional Elements using Empirical Yields

A central goal of this paper is to test whether empirically calibrated, IMF-averaged nucleosynthetic yields from the MW can accurately reproduce the abundance patterns observed in massive quiescent galaxies over cosmic time. While the Weinberg et al. (2017) framework describes the evolution of Mg and Fe, we now extend this analysis to all available elements measured in these galaxies, as illustrated in Figure 6.4.

The chemical evolution model introduced in Section 6.4 assumes that each element is enriched through two processes: prompt enrichment (i.e. CCSNe) and delayed enrichment (i.e. SNe Ia). In reality, some elements (e.g., Ba, Sr, C, N) also receive contributions from intermediate-timescale sources like asymptotic giant branch (AGB) stars. Thus, if we were to simply use theoretical CCSN and SNe Ia yields, we would systematically underestimate the abundances of these elements. To overcome this limitation, we adopt empirically calibrated nucleosynthetic yields derived under the same two-process assumption, as developed in the APOGEE survey analysis (Weinberg et al., 2022). In this framework, the observed abundance patterns of MW stars are interpreted as the sum of two main enrichment processes. By comparing median abundance ratios (e.g., $[X/\text{Mg}]$) in MW stellar populations that are dominated by either prompt or delayed enrichment, the analysis empirically separates and calibrates the relative yields of each process. This means that, for elements with more complex production channels (such as those with significant AGB contributions), the two-process yields still account for their contribution even if not explicitly modeled. As a result, these “effective yields” are well-suited for use in our two-process chemical evolution framework.

For most elements, we adopt the IMF-averaged two-process yields $q_{\text{cc}}^X(Z)$ and $q_{\text{Ia}}^X(Z)$ derived from the APOGEE survey analysis (Weinberg et al., 2022). However, because Sr and Ba are not included in the original APOGEE element set, we instead use Ba yields from Griffith et al. (2019) based on GALAH data, and adopt the GALAH Y yields as a proxy for Sr. For C and N, we rely on the results of Roberts et al. (2024), who measure abundances in subgiant stars (unaffected by dredge-up), providing a snapshot of their natal chemical composition.

With nucleosynthetic yields in hand, we can now predict the abundance evolution of any element X . The first step is to estimate the relative contributions of CCSNe and SNe Ia to the ISM at each timestep, parameterized as A_{cc} (prompt) and A_{Ia} (delayed). We then combine these contributions with the corresponding yields for each process, such that the total enrichment of element X at each time is given by the sum of CCSN and SNe Ia yields weighted by A_{cc} and A_{Ia} . This yields the chemical abundance of X in the gas as it evolves over time.

- *CCSN enrichment (A_{cc}):* We use Mg as a tracer, since it is produced exclusively by CCSNe. Thus, A_{cc} is defined as:

$$A_{\text{cc}} = 10^{[\text{Mg}/\text{H}]}, \quad (6.5)$$

where $A_{\text{cc}} = 1$ corresponds to solar $[\text{Mg}/\text{H}]$.

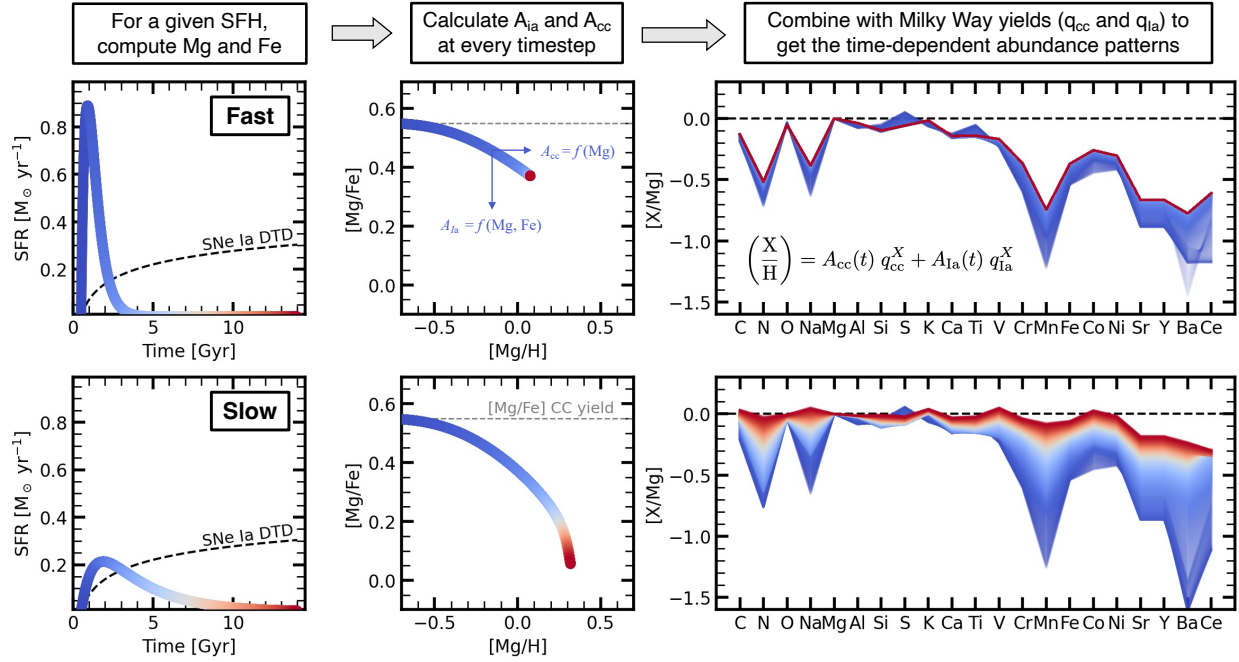


Figure 6.2: Illustration of our chemical evolution modeling framework for two representative SFHs: a rapid, short-lived burst (top row) and a more extended episode (bottom row). Left panels: Input SFHs and the SNe Ia delay time distribution. Middle panels: Predicted, light-weighted $[\text{Mg}/\text{Fe}]$ versus $[\text{Mg}/\text{H}]$ tracks from the Weinberg et al. (2017) analytical solutions, color-coded by time. The rapid SFH results in less Fe from SNe Ia, maintaining high $[\text{Mg}/\text{Fe}]$, while the extended SFH allows more SNe Ia enrichment, driving $[\text{Mg}/\text{Fe}]$ lower over time. Right panels: Evolution of the full multi-element abundance patterns, also color-coded by time, as inferred from the evolving mix of CCSN and SNe Ia enrichment. All abundances are computed in a light-weighted sense to match observational inference from stellar spectra.

- *SNe Ia enrichment* (A_{Ia}): Fe is produced by both CCSNe and SNe Ia. The relative importance of delayed enrichment is traced by $[\text{Mg}/\text{Fe}]$. At early times, before SNe Ia begin to contribute, $[\text{Mg}/\text{Fe}]$ reflects only CCSN yields, corresponding to the plateau value $[\text{Mg}/\text{Fe}]_{\text{cc}}$. As time progresses and SNIa enrichment becomes significant, $[\text{Mg}/\text{Fe}]$ decreases below this plateau. Thus, the SNe Ia contribution is:

$$A_{\text{Ia}} = A_{\text{cc}} \frac{10^{[\text{Fe}/\text{Mg}]} - 10^{-[\text{Mg}/\text{Fe}]_{\text{cc}}}}{1 - 10^{-[\text{Mg}/\text{Fe}]_{\text{cc}}}}, \quad (6.6)$$

where $A_{\text{Ia}} = 1$ at solar $[\text{Fe}/\text{H}]$ and $[\text{Mg}/\text{H}]$.

This formalism allows us to decompose the ISM at any time into its prompt and delayed enrichment components. The abundance of element X relative to solar is then:

$$\frac{(X/\text{H})}{(X/\text{H})_{\odot}} = A_{\text{cc}} q_{\text{cc}}^X + A_{\text{Ia}} q_{\text{Ia}}^X, \quad (6.7)$$

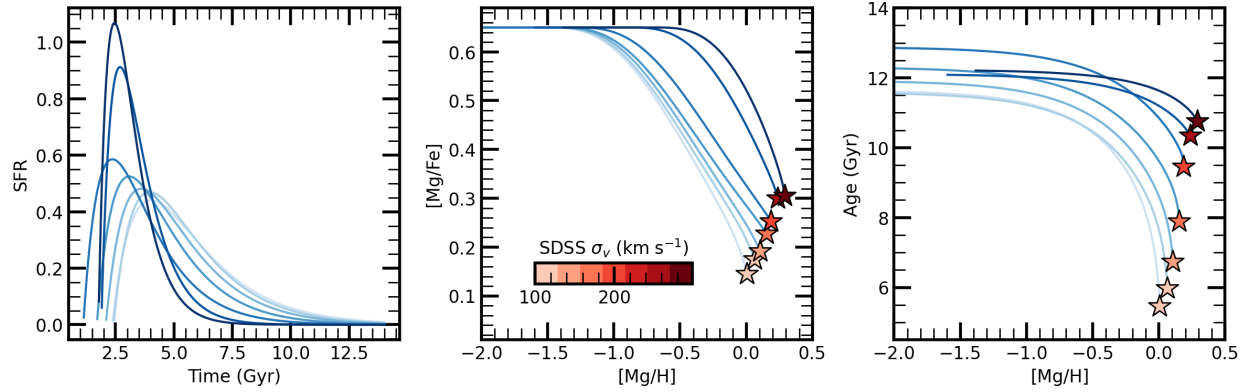


Figure 6.3: Tracks that fit the SDSS observations. The tracks are in blue and the observations are shown as red stars, colored by velocity dispersion. Left: Best-fit star-formation histories for each galaxy. Middle: Corresponding $[\text{Mg}/\text{Fe}]$ versus $[\text{Mg}/\text{H}]$ evolutionary tracks, with observed values indicated. Right: Best-fit age versus $[\text{Mg}/\text{H}]$ tracks, also showing the observed values. The models were simultaneously fit to age, $[\text{Mg}/\text{H}]$, and $[\text{Mg}/\text{Fe}]$ for each galaxy.

where q_{cc}^X and q_{Ia}^X are the empirically calibrated, metallicity-dependent IMF-averaged yields for each element.

Finally, in order to compare with observed stellar spectra, we must compute light-weighted *stellar* abundances, not just the instantaneous ISM composition. We do this by integrating the modeled gas-phase abundances over the galaxy’s star-formation history, weighting by the star formation rate and the evolving mass-to-light ratio (M/L), as in Eq. 1 of Gountanis et al. (2024).

Model Illustration

Figure 6.2 illustrates our chemical evolution modeling approach using two representative SFHs: a rapid, short-lived burst (top row) and a more extended episode (bottom row). The left panel shows the assumed SFH for each scenario, along with the SNe Ia delay time distribution.

Using the SFH as input, we first apply the Weinberg et al. (2017) analytical solutions to predict the evolution of Mg and Fe abundances. The middle panel displays the predicted, light-weighted $[\text{Mg}/\text{Fe}]$ versus $[\text{Mg}/\text{H}]$ tracks, with color indicating the passage of time. In the fast SFH scenario, less Fe is produced overall because SNe Ia have less time to enrich the ISM before star formation ceases.

Next, we use the evolving gas-phase Mg and Fe abundances to calculate the relative contributions of CCSNe and SNe Ia at each timestep (A_{cc} and A_{Ia}). These, combined with the empirically calibrated nucleosynthetic yields, allow us to predict the evolution of any

element X .

The right panel shows the resulting evolution of the full multi-element abundance pattern, again color-coded by time. These model predictions are calculated in a light-weighted sense, matching how abundances are inferred from stellar spectra, and can be directly compared to observations.

In the fast SFH, SNe Ia begin to contribute just as the star formation is tapering off. Therefore, the stars don't include many of these products. This means that the stellar mg/fe remains high. The chemical abundance pattern evolves accordingly, aka not much away from pure CC yields. In the slow SFH scenario, many more stars include SNe Ia products and thus, the full abundance pattern deviates significantly from the CC yields and towards the Ia yields over time.

Applying GCE Models to the Observed Abundance Patterns

Having established this empirical foundation, we now apply our full chemical evolution modeling framework to observed galaxy data to test its predictive power. Figure 6.3 demonstrates how this modeling framework is applied to real galaxy data to assess the validity of yields, using SDSS as an example. Following Gountanis et al. (2024), we first identify GCE models that reproduce the observed $[\text{Mg/Fe}]$, $[\text{Mg/H}]$, and stellar age of each SDSS bin. While Gountanis et al. (2024) found it challenging to simultaneously match the high $[\text{Mg/Fe}]$ and relatively young ages of galaxies, our objective differs slightly: we primarily aim to identify plausible GCE models that are consistent with the observed Mg and Fe abundances. To do this, we relax their assumption of early star-formation onset ($t_{\text{start}} \lesssim 1$ Gyr), allowing for delayed bursts of star formation that can elevate $[\text{Mg/Fe}]$ while matching observed stellar ages.

The best-fit model parameters (τ_1 , τ_2 , t_{start} , t_{quench} , τ_* , and η) are determined by minimizing the χ^2 difference between the modeled and observed values of $[\text{Mg/Fe}]$, $[\text{Mg/H}]$, and stellar age. The left panel of Figure 6.3 displays the resulting best-fit SFH. The middle and right panels show the corresponding chemical evolution model predictions for $[\text{Mg/Fe}]$ versus $[\text{Mg/H}]$, and stellar age versus $[\text{Mg/H}]$, respectively.

While these GCE models primarily serve as a tool for multi-element abundance predictions, they also offer insight into galaxy chemical evolution. For example, we find that galaxies with higher velocity dispersion exhibit elevated $[\text{Mg/Fe}]$ and $[\text{Mg/H}]$, reflecting shorter star-formation intervals ($t_{\text{quench}} - t_{\text{start}}$). In addition, we find that the outflow parameter η decreases with increasing velocity dispersion, consistent with the expectation that deeper gravitational potentials more efficiently retain metals (e.g., Dekel & Silk, 1986).

To predict the full set of elemental abundances, we treat each best-fit GCE model as a set of pseudo-resolved stellar populations, assigning A_{Ia} and A_{cc} at each timestep. Using Eq. 6.7, we compute the multi-element abundances for each population, then calculate their luminosity-weighted averages. The resulting abundance patterns from the GCE model are shown in Figure ?? as filled circles connected by solid lines in the bottom panel of Figure 6.3.

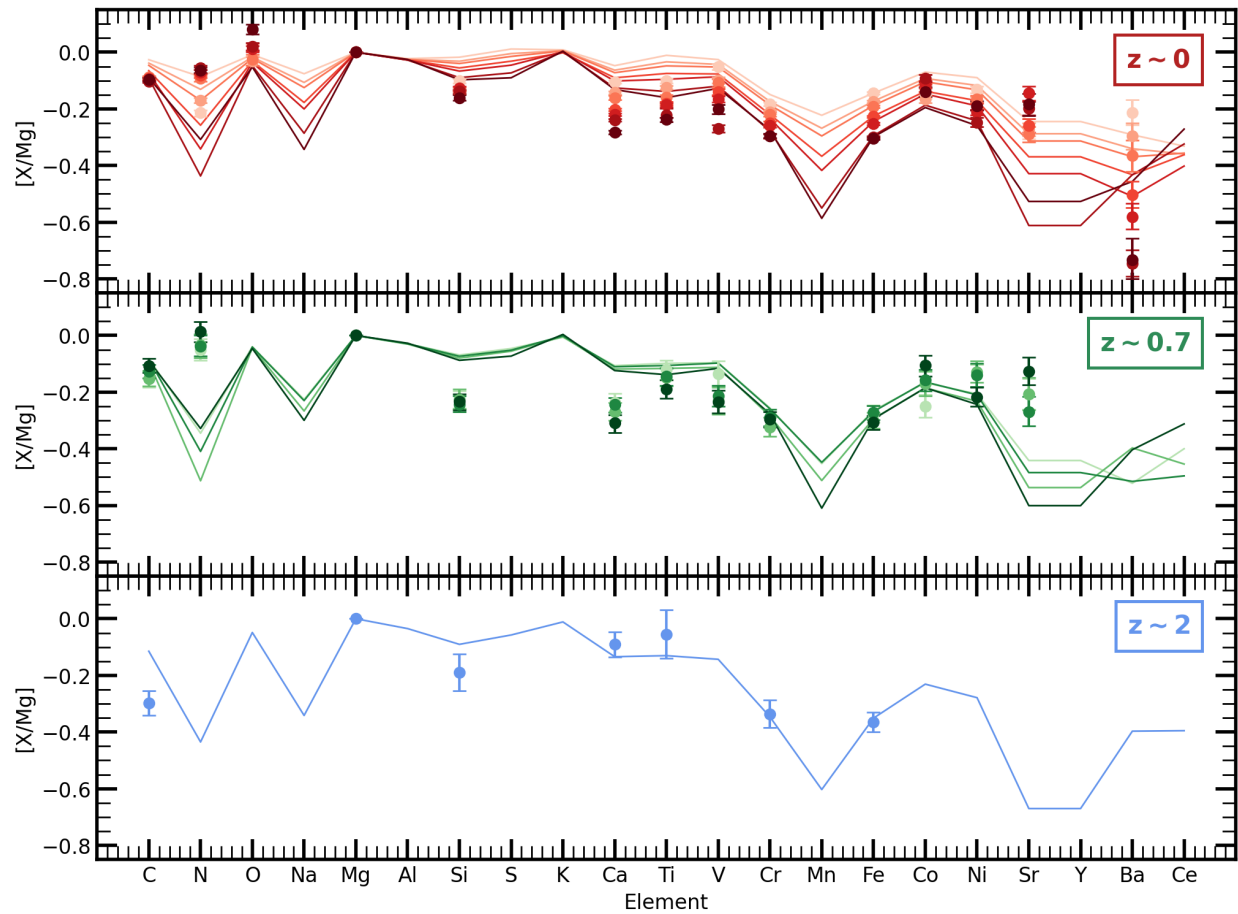


Figure 6.4: Comparison of observed elemental abundance patterns (points with error bars) to empirical predictions (solid lines) at three cosmic epochs. Line color and darkness indicate velocity dispersion, as in Figure 6.1: red ($z \sim 0$, SDSS), green ($z \sim 0.7$, LEGA-C), and blue ($z \sim 2$, *JWST*). The predictions reproduce most observed elements well, with notable discrepancies for N, Si, Ca, and Sr (see Section 3.6).

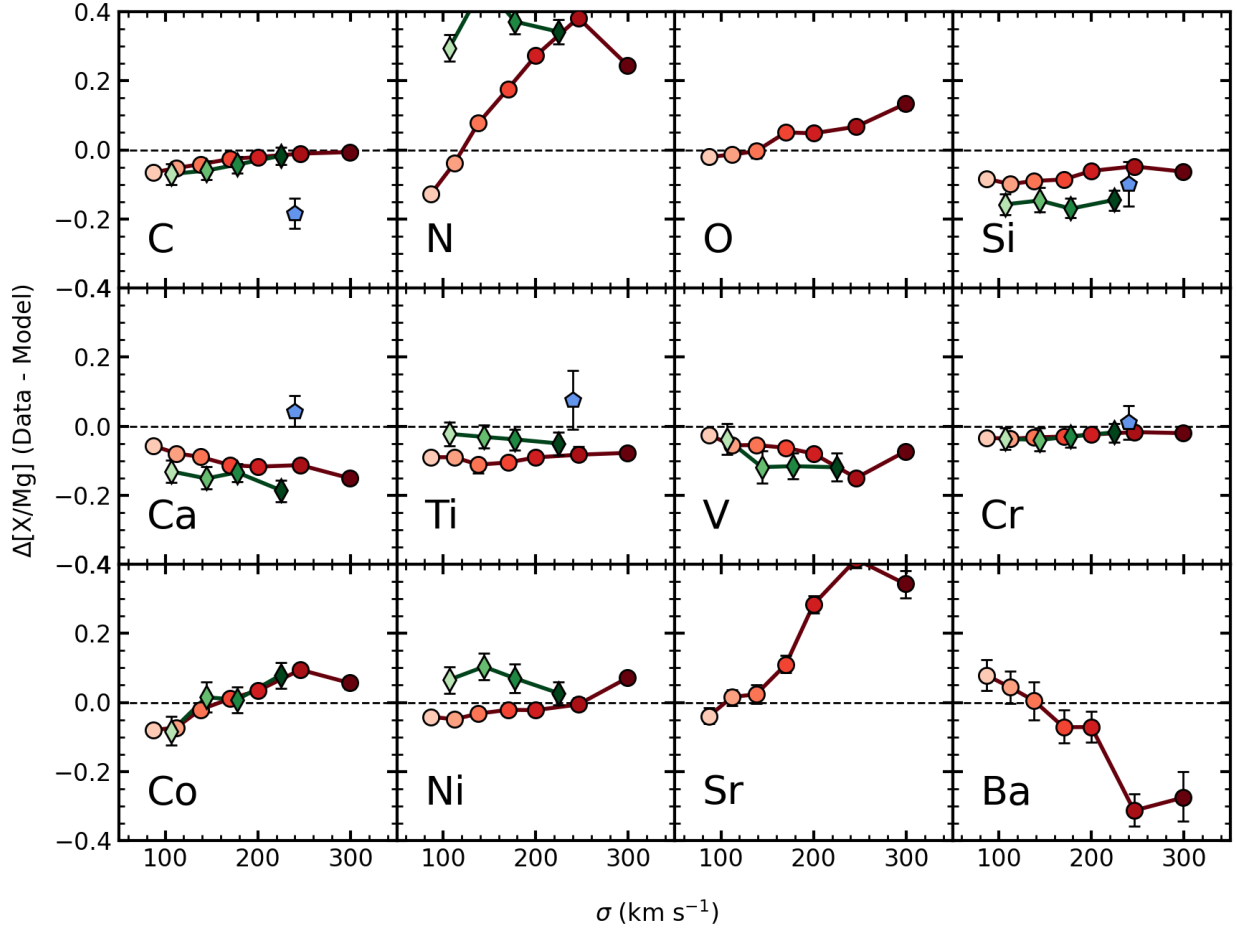


Figure 6.5: Residuals between observed and predicted chemical abundances as a function of velocity dispersion for SDSS (red circles, $z \sim 0$), LEGA-C (green diamonds, $z \sim 0.7$), and SUSPENSE (blue pentagons, $z \sim 2$) galaxy samples. The mean offset between observed and predicted abundances across all elements is only 0.06 dex

6.5 Results

In the previous section, we introduced our method for predicting the chemical abundances of massive quiescent galaxies, rooted in empirical observations of Milky Way stars. In this section, we test whether this approach can successfully explain the observed chemical abundances.

Figure 6.4 compares the observed abundance patterns (points with error bars) to our empirical predictions (solid lines) at different cosmic epochs. The top panel (red) shows galaxies at $z \sim 0$ from SDSS, demonstrating close agreement between observations and predictions across most elements, with the largest discrepancies found for O, Ca, Co, and Sr—particularly in the highest velocity dispersion bin. The middle panel (green) displays galaxies at intermediate redshift ($z \sim 0.7$) from LEGA-C, again showing strong overall consistency with model predictions and reinforcing the applicability of Milky Way-based yields at earlier epochs. The bottom panel (blue) presents $z \sim 2$ results from *JWST* observations. While measurements at this redshift are fewer and more uncertain, the available data still broadly align with model expectations.

Figure 6.5 shows the residuals between observed and predicted abundances for each element. In this figure it is easier to diagnose that the largest positive offset is for nitrogen, with Sr also showing a substantial excess and Ba exhibiting a negative residual. Si, Ti, Ca, and V are all underpredicted by about 0.1 dex, while the other elements are closely matched. Notably, there are clear trends with velocity dispersion. The origins of these residuals are discussed further in Section 3.6. Overall, the empirical model performs remarkably well, successfully capturing the abundance patterns of massive quiescent galaxies across cosmic time.

6.6 Discussion

The Importance of a Third Enrichment Channel

The element with the most significant deviation from our predicted abundance patterns is nitrogen. In SDSS galaxies, the nitrogen deviation rises steadily to ~ 0.4 dex, while in the LEGA-C sample, it remains elevated at ~ 0.4 dex across all measurements. This persistent excess is not unexpected, as our baseline model assumes only two enrichment sources: CCSN and SNIa. In reality, a substantial fraction of nitrogen originates from AGB stars, which enrich the ISM on timescales intermediate between CCSN and SNIa. In quiescent galaxies, where SNIa enrichment is minimal but AGB stars have had time to contribute, it could be that our two-process model underestimates the nitrogen abundance.

To test whether the faster enrichment timescale of AGB stars could explain the high nitrogen, we modified the Weinberg et al. (2017) analytic models (assuming metallicity-independent yields) to include nitrogen from AGB stars with a characteristic delay of ~ 0.3 Gyr. In this scenario, nitrogen enrichment is more prompt, resembling that of α -

elements, while iron from SNeIa rises more slowly. This timescale difference naturally boosts the N/Fe ratio relative to the original two-process model.

However, this effect is not sufficient to explain the full observed nitrogen excess. Because the Milky Way itself contains both fast- and slow-forming populations, MW-calibrated yields already capture some of these timescale effects. Thus, the persistent nitrogen excess in quiescent galaxies must have an additional explanation.

A crucial assumption in our analytic models is that AGB yields are metallicity-independent. However, it is well established that AGB yields are highly sensitive to metallicity (e.g., Johnson et al., 2023). To test whether metallicity-dependent yields can account for the remaining discrepancy, we turn to more sophisticated modeling. Using VICE (Johnson et al., 2021), we input our best-fit chemical evolution models and adopt CCSN nitrogen yields from Johnson et al. (2023) and metallicity-dependent AGB yields from Cristallo et al. (2011) and Cristallo et al. (2011). The resulting N/Mg predictions for SDSS and LEGA-C are shown in Figure 6.6. With metallicity-dependent yields, the excess nitrogen is fully accounted for, and the strong velocity dispersion dependence is resolved.

In summary, only by including metallicity-dependent AGB yields can we fully reproduce the nitrogen abundances observed in quiescent galaxies.

Multi-element constraints on the IMF

Although our default yield calculations assume a Kroupa (2001) IMF, numerous spectroscopic and dynamical studies indicate that massive quiescent galaxies typically have bottom-heavy IMFs, particularly at high velocity dispersion (σ) (e.g., van Dokkum & Conroy, 2012; La Barbera et al., 2013; Martín-Navarro et al., 2015). More recently, van Dokkum & Conroy (2024a) presented evidence for an even more complex IMF shape in these galaxies—the so-called “ski-slope” IMF—which can be both bottom-heavy and top-heavy. They find that galaxies with higher velocity dispersion tend to display the most extreme IMFs.

Such IMF variations can significantly impact chemical evolution predictions, particularly when interpreting abundance patterns as a function of σ . To explore this effect, Figure 6.7 shows how the CCSN yields of various elements change with velocity dispersion for the “ski-slope” IMF defined in van Dokkum & Conroy (2024a), normalized to the Kroupa IMF. These offsets are calculated using theoretical yields from Sukhbold et al. (2016) (N20 explodability landscape).

Interestingly, the elements that are most under-produced for extreme IMFs tend to be the same elements that our model under-predicts, and vice versa. While this does not conclusively demonstrate that IMF variations are the cause, it suggests a potential connection. A more detailed investigation of this possibility is beyond the scope of this work, but these findings underscore the importance of incorporating realistic, σ -dependent IMFs into chemical evolution models. Doing so is essential for accurately interpreting the abundance patterns of massive quiescent galaxies and for understanding the physical origin of their IMF variations.

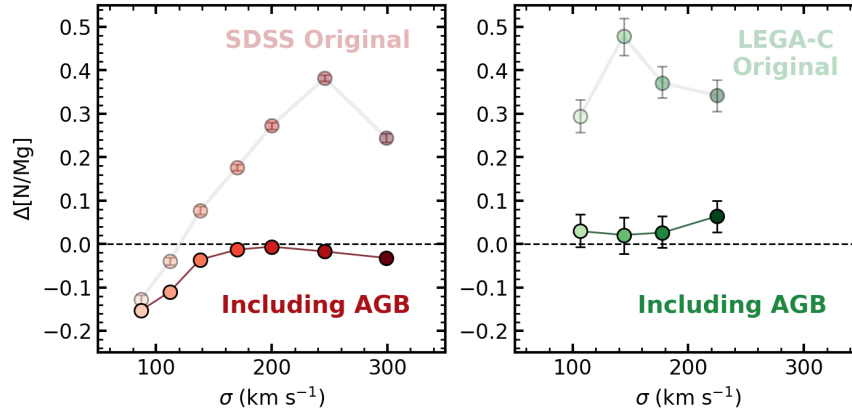


Figure 6.6: Residuals in $[N/Mg]$ for SDSS (left, red) and LEGA-C (right, green) galaxies as a function of velocity dispersion. The lightly shaded lines show the predictions of the chemical evolution model (CCSN + SNe Ia) described in Section 6.4 and Figure 6.5, which systematically underpredict nitrogen. The darker lines show results from a full chemical evolution model that includes AGB star enrichment, both with shorter enrichment timescales and metallicity-dependent yields. Incorporating this third enrichment channel removes the observed nitrogen excess, demonstrating that proper modeling of AGB stars—especially their metallicity-dependent yields—is essential to accurately reproduce nitrogen abundances in quiescent galaxies.

A Shortcut to Predicting Elemental Abundances?

The empirical nucleosynthetic yields adopted in our analysis were made possible by a crucial feature revealed by large spectroscopic datasets: for any star in the MW disk, measuring just Mg and Fe allows you to accurately predict the abundances of roughly ten other elements, often to within 0.01 dex (Ting & Weinberg, 2022; Weinberg et al., 2019; Weinberg et al., 2022; Griffith et al., 2019). While this finding may seem surprising at first, the underlying reason is straightforward: the chemical composition of a star-forming gas cloud is determined by the cumulative yields from CCSN and SNe Ia. Mg and Fe abundances act as effective “scorekeepers” of these two processes. Once these are specified, the expected abundances of other elements are set by the abundance pattern of CCSNe and SNe Ia yields, adjusted for the overall metallicity.

This principle extends to galaxy-scale chemical evolution models as well. At any given time, the chemical composition of a galaxy’s ISM is governed by the total number of CCSNe and SNe Ia that have enriched the gas. Thus, the relative abundances of most elements can be directly inferred from the measured Mg and Fe abundances of the galaxy, following the same logic as for single stars. The mean stellar abundances in galaxies, which are averaged over populations with a range of metallicities, do not always adhere to this simple relationship as tightly, since the yields themselves are metallicity-dependent and it’s possible to have stellar

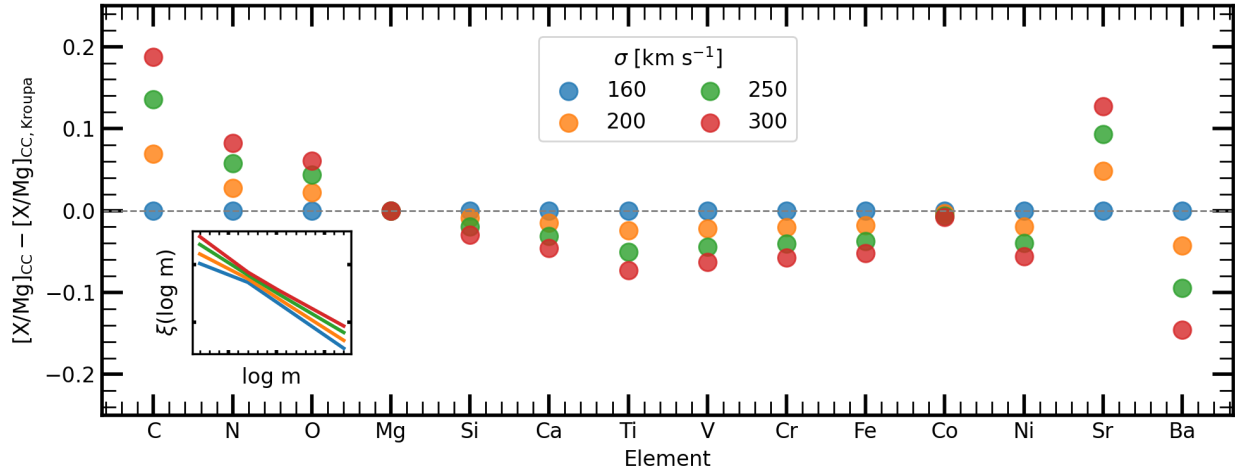


Figure 6.7: The ratio of CCSN yields relative to magnesium, normalized by the corresponding yields from a Kroupa (2001) IMF, assuming the N20 explodability prescription from Sukhbold et al. (2016) based on progenitor models from Shigeyama & Nomoto (1990); Nomoto & Hashimoto (1988); Saio et al. (1988). The dashed line marks the Kroupa (2001) IMF reference. Colored points correspond to different stellar velocity dispersions, where increasing σ implies increasingly top-heavy IMFs as suggested by van Dokkum & Conroy (2024b). While magnesium yields rise with σ (see Figure ??), this panel isolates how the yields of other elements shift relative to Mg. Elements lighter than Mg show enhanced relative yields at higher σ , while heavier elements exhibit suppressed ratios.

populations with disparate metallicities contributing to the stellar light.

The success of this extremely simplified approach for modeling galaxy abundance patterns leads to two key points for stellar population modeling. First, *elemental abundances are not independent*. The abundances of many elements are tightly correlated, and their values are largely determined by the relative mix of CCSN and SNe Ia enrichment. This means that, in composite stellar populations, once Mg and Fe are measured, the abundance of most other elements can be robustly estimated.

Second, this insight offers an opportunity to build better models. With the discovery of chemically peculiar galaxies at high redshift, there is growing interest in developing “alpha-enhanced” stellar population models. However, these models often assume that all α -elements (e.g., O, Mg, Si, Ca, Ti) are enhanced by the same factor, which is not supported by observations (see Fig. 1; also Zhuang et al. 2024). A more realistic approach is to model abundance patterns as a function of Mg and Fe, tracing the relative contributions of CCSNe and SNe Ia at the galaxy’s metallicity—a mapping directly motivated by empirical findings.

6.7 Summary

The detailed chemical abundance patterns of massive quiescent galaxies offer a powerful window into their star-formation histories, initial mass functions (IMFs), and enrichment processes. However, interpreting these patterns—especially beyond $[\text{Mg}/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ —remains challenging due to uncertainties in theoretical nucleosynthetic yields and the complexity of modeling chemical evolution in integrated stellar populations. In this first paper of a two-part series, we test whether empirically calibrated, IMF-averaged yields from Milky Way disk stars can reproduce the observed abundances of 14 elements in quiescent galaxies across cosmic time.

We adopt a simplified two-process model in which chemical enrichment is driven by core-collapse and Type Ia supernovae. When applied to quiescent galaxies at $z \sim 0\text{--}3$, the predicted abundance patterns agree remarkably well with our observations, typically within 0.05 dex—despite the vastly different environments and independent systematics between Milky Way stars and distant galaxies. Exceptions include N, Co, Sr, and Ba, which deviate from the two-process predictions in ways consistent with an additional source of enrichment from AGB stars.

To understand what drives this agreement, we test the sensitivity of the abundance patterns to IMF shape and find they are remarkably insensitive once $[\text{Mg}/\text{Fe}]$ is matched—suggesting that the yields themselves are effectively universal. Despite their extreme formation histories, massive quiescent galaxies appear to share the same fundamental enrichment channels as the Milky Way. These results emphasize that future modeling efforts should prioritize accurate yield prescriptions over simplistic assumptions of uniform α -enhancement.

Chapter 7

Conclusions and Future Directions

In this thesis, we have charted the chemical compositions of massive quiescent galaxies across cosmic time. The second chapter focused on measuring Mg and Fe for a sample of quiescent galaxies at $z \sim 0.7$ from the LEGA-C survey. We find that both Mg and Fe scale with galaxy compactness (as traced by M_*/R_e). We find a strong correlation also between galaxy age and its metal content, such that younger galaxies have higher Mg and Fe abundances. We also find that, when compared to galaxies at $z \sim 0$, the LEGA-C galaxies are Fe and Mg deficient. Both of these results can be explained using a chemical evolution argument, wherein galaxies quench via gas removal.

The third chapter focused on measuring, for the first time, the chemical abundances of elements beyond Mg and Fe, in distant galaxies from the same LEGA-C sample. We find that these elements correlate most strongly with velocity dispersion, and to first order, the abundance patterns are similar to galaxies at $z \sim 0$ from SDSS, with the strongest evolution observed for galaxies with the lowest velocity dispersions, indicating significant evolution over the past six billion years.

In the fourth chapter, we made the first measurements of Mg and Fe for a sample of quiescent galaxies beyond $z \gtrsim 1$. We find these galaxies have lower Fe and higher Mg/Fe ratios compared to local galaxies, signaling intense, short bursts of star formation. These extreme chemical abundances, not seen in the modern universe, indicate evolution in the massive galaxy population over cosmic time. Our results suggest that minor mergers alone cannot explain this evolution—other mechanisms, like major mergers or renewed central star formation, likely contributed.

In the fifth chapter, we used *JWST* to extend our chemical abundance measurements to even earlier times ($z = 1\text{--}3$) and to a wider range of elements. We find that these galaxies are even more metal-poor than those at lower redshift, showing pronounced deficiencies in iron, magnesium, and especially carbon compared to similar galaxies today. These patterns point to rapid star formation and quenching, occurring before slower enrichment from Type Ia supernovae and AGB stars could significantly contribute. Notably, galaxies that formed earliest in cosmic history consistently exhibit the most extreme chemical signatures. This trend likely reflects the inclusion of galaxies with longer star-formation timescales at lower red-

shifts. We also compare these chemically inferred star-formation histories to those estimated from traditional stellar population models, finding that the latter overestimate formation timescales by a factor of six. These results underscore the value of detailed abundance measurements for revealing how quickly massive galaxies assembled in the early universe.

Finally, in the sixth chapter, we develop a new framework for interpreting the multi-element abundance patterns of distant galaxies. By leveraging empirically calibrated yields from Milky Way disk stars, we generate chemical evolution predictions and compare them to observed abundance patterns in galaxies spanning a wide range of redshifts, from SDSS ($z \sim 0$) to LEGA-C ($z \sim 0.7$) and SUSPENSE ($z \sim 2$). We find that these models reproduce the observed abundances to within a typical offset of just 0.06 dex, demonstrating the robustness of the chemical evolution framework and the applicability of these empirically derived yields. Subtle residual differences between the models and observations may point to trends in the high-mass IMF, as explored in this chapter. In addition, we find that the abundance of any individual element can be accurately predicted using only Mg and Fe. This result suggests that much of the information in the full multi-element abundance pattern is already captured by these two elements, providing an opportunity to develop more efficient and physically motivated stellar population modeling approaches where the evolution of α -elements and other key species can be tracked in a self-consistent and predictive way.

Future Directions

The advent of *JWST*, along with some of the groundwork in this thesis, has opened the door to using chemical compositions to address long-standing questions in galaxy formation. Yet, we still lack the modeling tools needed to connect these observations to the underlying physics. Current stellar population models, such as FSPS (Conroy et al., 2009), overlook the inextricable link between chemical enrichment and star-formation history (SFH), limiting our ability to fully exploit the abundance of information now accessible.

Looking ahead, it is essential to develop models that integrate chemical evolution predictions into stellar population synthesis frameworks. These tools will allow us to interpret the chemical fingerprints of massive quiescent galaxies across cosmic time and unlock new insight into their formation and evolution.

This endeavor will require a multi-tiered observational approach, like a wedding cake. At the top: spatially resolved spectroscopy of a small number of objects across redshift, offering the most detailed view of galaxy formation. These include nearby relics and gravitationally lensed galaxies at cosmic noon, where we can resolve the inside-out or outside-in assembly histories. In the middle tier: ultra-deep, unresolved spectroscopy with *JWST* of individual galaxies, allowing precise multi-element abundance measurements for on order of 100 galaxies. At the base: upcoming large surveys such as the Prime Focus Spectrograph (PFS), which will provide the necessary statistical foundation. By targeting nearly 14,000 galaxies at $0.7 < z < 2$, PFS will overcome a major limitation of current *JWST* programs, which focus on only a few objects. Although individual PFS spectra will not be deep enough

to measure detailed abundances, they will allow reliable measurements of $[\alpha/\text{Fe}]$ and total metallicities, enabling population-level insight into the processes that shape massive galaxies at the peak of cosmic star formation.

This thesis highlights the power of chemical abundances for understanding galaxy formation and evolution. Building on these insights, new tools and upcoming observations, from detailed spectroscopy to large-scale surveys, will enable significant progress. With this multi-pronged approach, we will be better equipped to answer key outstanding questions in galaxy formation: When did the most massive galaxies form? What are the origins of their chemical elements? What mechanisms quenched their star formation? And how does the stellar initial mass function vary across time and environment?

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