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UNIVERSITY OF CALIFORNIA
RIVERSIDE

The Dark, Gaseous, and Stellar Halos of Galaxies in LCDM as Tracers of Evolution

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

Lydia McLennan Elias

September 2020

Dissertation Committee:

Dr. Laura Sales, Chairperson
Dr. Brian Siana
Dr. George Becker

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The Dissertation of Lydia McLennan Elias is approved:

Committee Chairperson

University of California, Riverside

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To my family, friends, and cat who buoyed me throughout the calmest waters and
roughest seas of my PhD.

ABSTRACT OF THE DISSERTATION

The Dark, Gaseous, and Stellar Halos of Galaxies in LCDM as Tracers of Evolution

by

Lydia McLennan Elias

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, September 2020
Dr. Laura Sales, Chairperson

Within Λ CDM, galaxies are regulated by both large-scale processes such as mergers, tidal torques and smooth accretion via filaments, as well as by small-scale processes such as star formation and feedback. These mechanisms leave characteristic signatures imprinted in the stellar, gaseous, and dark matter halos of the galaxy. We use numerical simulations to study these halos and focus on establishing the link between halo observables today and the past evolution of galaxies. We find that stellar halos in Milky Way (MW)-like objects have a wide variety of masses and shapes that strongly correlate with their assembly histories. In particular, the low stellar halo fraction of our own Galaxy indicates an overall early and quiet assembly history. The recent detection of a major merger event ~ 10 Gyr ago leading to a massive and radial stellar halo component seems plausible, although its compactness is difficult to reproduce within Λ CDM. We predict that a significant fraction of the mass associated with this merger may lie undiscovered in the outskirts of the MW's stellar halo. Further clues on galaxy assembly histories may lurk in their gaseous halos, whose observational study has only recently become possible for large galaxies. Using intermediate-volume

simulations, we investigate the potential of MUSE to detect the gaseous filaments feeding galaxy halos and tracing the cosmic web. We find that including feedback effects and degrading pixel resolution may increase the detectability of these flows in realistic mock images. Furthermore, filaments are affected by feedback, providing powerful observational constraints to theoretical models. The phenomenon of feedback remains, however, too simplistically modeled within cosmological simulations and is expected to have its maximum impact on low-mass galaxies. We use idealized numerical simulations of a dwarf halo to understand the interplay between two possible feedback sources: stars and black holes. We find that although black holes negligibly affect the star formation history of the dwarf, they may leave strong signatures on outflow properties. The future observational detection of these outflows promises novel constraints on black hole growth as well as stellar and black hole feedback models in cosmological numerical simulations.

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Chapter 1

Introduction

A galaxy is not only composed of the luminous disk or bulge we commonly picture in our minds. Typically, the main body of the galaxy is embedded within three main halos: the dark matter halo, the gaseous halo, and the stellar halo which, as their names imply, are composed of dark matter particles, gas particles, and stars, respectively. These halos extend much further out than the classical disk and bulge components, and they harbor important clues to the formation and evolution of galaxies in the Universe.

According to the standard cosmological model, Λ CDM, galaxies and their halos are built hierarchically by aggregating smaller galaxies (White and Rees, 1978; White, 1996). Testing this theory poses a challenge as it requires studying merger events that occurred several billion years ago. However, present day dark matter, gaseous, and stellar halos all contain traces of ancient mergers which may be used to probe and constrain the cosmological model. Studying galactic halos can elucidate questions that are still open in the field: what is the connection between a galaxy and its halos, how exactly does gas cool

and condense to form stars, which feedback processes are most effective, and how can we best relate observations to physical interpretations?

Simulations may be the best answer to the last question. Large, cosmological simulations are typically composed of millions of simulated particles being acted upon by gravitational and hydrodynamical forces to produce a small copy of the universe. They allow us to test Λ CDM on a statistically large set of galaxies, study their long-term evolution, and predict how past accretion events can influence present day observable properties of galaxies.

In addition to large-scale external events, simulations allow realistic modeling of the physical processes driving the formation of stars within galaxies. Smaller, isolated simulations are useful for studying physical processes (e.g feedback) at higher resolution levels which may also affect the observables (star formation, black hole accretion, morphologies, among others) that we use to compare to the cosmological predictions of Λ CDM.

The combination of both types of simulations is a powerful tool to understand how the universe works. In this thesis we investigate aspects related to stellar, dark matter and gaseous halos, which we describe in more detail in what follows.

1.1 Stellar halos

The stellar halo refers to stars residing in the outskirts of the galaxy that were either formed in the disk and ejected (in situ) or were brought in by a merger with a satellite galaxy (ex situ). The exact fraction of stars deposited in the stellar halo by either of these mechanisms is currently unknown, but may be an important constraint on the cosmological

and galaxy formation models.

Interestingly, past merger events that occurred billions of years ago may still be reconstructed from properties of the present-day stellar halo such as morphology, metallicity, mass fraction, etc., making stellar halos powerful “time-machines” to decipher the accretion histories of galaxies. Due to our location within the Milky Way, our own Galaxy offers the best opportunity to study the stellar halo component. Using position and velocity measurements from recent extensive surveys of the Milky Way such as Gaia DR2 (Gaia Collaboration et al., 2018), even more detailed properties of past mergers can be recreated, including their original trajectories and infall times (Helmi, 2008). This allows for a proper exploration of how our Galaxy came together and how it compares with the bulk of other thousands of millions of galaxies in the Universe.

In **Chapters 2 and 3** we use the large volume cosmological simulation Illustris to connect observed stellar halo properties to past merger histories of galaxies comparable to the Milky Way. We then apply our findings to describe a likely merger history for the Milky Way itself, and place one of its most significant ancient merger events – the so-called Gaia-Enceladus/Gaia-Sausage – within the cosmological context.

1.2 Dark matter halos

Dark matter halos are the backbones of structure and galaxy formation, providing the gravitational potential where baryons can accrete and condense to form the galaxies that we see today. Despite being the most massive galactic component, the dark matter halo can only be detected indirectly through its gravitational effects, making simulations integral to

its study. For example, simulations have long predicted the existence of the cosmic web, a distribution of matter into sheets and filaments connecting massive halos (Peebles and Groth, 1975; Klypin and Shandarin, 1983; Haider et al., 2016; Mandelker et al., 2019).

As galaxies and dark matter halos grow through simultaneous merger events, the positions of stars and gas should trace the distribution of dark matter throughout the universe. By searching for these observable markers of dark matter presence, a new generation of deep, wide-area surveys, have the potential to map the cosmic web for the first time.

In **Chapter 4** of this work we use a cosmological volume simulation to explore the potential for MUSE, a deep, wide-field instrument (Bacon et al., 2017), to detect the cosmic web via Lyman α emission from co-spatial, gaseous filaments at $z=3$. Determining the large-scale distribution of dark matter has the potential to constrain models of dark matter and inflationary potential (Wechsler and Tinker, 2018) and is a powerful test of Λ CDM.

1.3 Gaseous halos

Gas within filaments will eventually flow into a gaseous halo surrounding a galaxy, becoming its main source of fuel for star formation. The gaseous halo also traces inflows and outflows, enrichment, and quenching due to both stellar and active galactic nuclei (AGN) feedback. As such, gaseous halos are an essential element in understanding galaxy evolution (Putman et al., 2012).

Increasingly, simulations are able to resolve these processes as well as the multiphase nature of the gas occupying the interstellar medium (ISM) in the galaxies sitting

at the innermost regions of their dark matter halos. However, several unknowns and free parameters still plague cosmological hydrodynamical simulations which resort to “sub-grid” models to describe the physics that occurs on scales that are not currently resolved. The physics of gas halos offers a promising avenue to place further constraints on the remaining unknowns in theoretical modeling of galaxies, in particular through observations of inflows, outflows and their metal content.

In **Chapter 5** of this thesis we study the interplay of stellar and black hole feedback for a simulation of an isolated dwarf galaxy. Although AGN feedback is known to play an important role in massive galaxies, their effect on the scale of galaxies less massive than our own are still poorly known. As more dwarf galaxies with signatures of AGNs are uncovered in observations, a new opportunity appears to further our understanding of feedback in the universe and its different sources.

Chapter 2

Stellar halos in Illustris: probing the histories of Milky Way-mass galaxies

2.1 Abstract

The existence of stellar halos around galaxies is a natural prediction of the hierarchical nature of the Λ CDM model. Recent observations of Milky Way-like galaxies have revealed a wide range in stellar halo mass, including cases with no statistically significant detection of a stellar halo, as in the case of M101, NGC3351 and NGC1042. We use the Illustris simulation to investigate the scatter in stellar halo content and, in particular, to study the formation of galaxies with the smallest fraction of this diffuse component. Stellar halos are far from spherical, which diminishes the surface brightness of the stellar halo for

face-on disks. Once accounting for projection effects, we find that the stellar halo fraction f_{SH} correlates strongly with galaxy morphology and star formation rate, but not with environment, in agreement with observations. Galaxies with the lowest stellar halo fractions are disk-dominated, star-forming and assemble their dark matter halos on average earlier than galaxies with similar stellar masses. Accreted satellites are also lower in stellar mass and have earlier infall times than centrals with high f_{SH} . In situ rather than accreted stars dominate the stellar halos of galaxies with the lowest stellar halo fractions, with a transition radius from in situ to accretion-dominated $r \sim 45$ kpc. Our results extrapolated to real galaxies such as M101 may indicate that these galaxies inhabit old halos which endured mergers only at higher redshifts and evolved relatively unperturbed in the last ~ 10 Gyrs.

2.2 Introduction

Stars can be found out to very large distances away from the center of galaxies and certainly well beyond their optical radii. This extended and diffuse stellar component—the stellar halo—is typically composed of metal poor stars that are often distributed inhomogeneously and present substructures in both configuration as well as in velocity space. This phase-space coherence was predicted early by cosmological models of galaxy assembly (Johnston et al., 1996; Johnston, 1998; Helmi and White, 1999; Bullock et al., 2001) and also found in observations of stellar moving groups in the Milky Way (Ibata et al., 2014, 1994; Shapley, 1938; Willman et al., 2005) as well as in several tidal streams (Lynden-Bell and Lynden-Bell, 1995; Belokurov et al., 2006; Grillmair, 2009). In fact, within the leading cosmological framework Lambda Cold Dark Matter (Λ CDM), stellar halos are the natural

outcome of the galaxy formation process where galaxies form hierarchically by aggregating smaller ones (White and Rees, 1978; White, 1996). The disruption of these satellite galaxies deposits stellar debris in the outskirts of the galactic domain of the host galaxy, building up and shaping the stellar halo component. Stellar halos carry information on the properties of satellite galaxies that no longer exist and on the assembly history of the host galaxy. Because they are extended (they can reach 100 kpc and beyond for L_* galaxies), dynamical times are long, and tidal features such as streams and shells –records of past disruptions– can survive for very long timescales (Helmi and White, 1999; Bullock and Johnston, 2005), making stellar halos invaluable proof of the cosmological model.

The stellar halos of our own Milky Way and closest neighboring galaxy M31 have been studied most extensively. In particular, our own Galaxy offers an advantageous view from where to select halo stars with precise photometry and kinematics either within the solar neighborhood (by specific cuts in metallicity and or kinematics, e.g. Eggen et al., 1962; Chiba and Beers, 2000; Helmi et al., 2017) or by looking to stars that are beyond the confines of the disk (Morrison et al., 2000; Fernández-Trincado et al., 2015). Photometric campaigns such as that of SDSS/SEGUE have played a fundamental role in building our current understanding of the Galactic stellar halo by revealing a rich level of substructure where streams and overdensities abound (Belokurov et al., 2006; Bell et al., 2008; Jurić et al., 2008; Odenkirchen et al., 2001; Grillmair and Johnson, 2006). Deep observations of our closest neighbour M31 by the PAndAS survey (McConnachie et al., 2009) also reveal a complex stellar halo structure with a massive stream dominating most of the light, but with several other substructures easily identifiable (Ibata et al., 2014; Ferguson et al., 2002;

Tanaka et al., 2010). An unexpected conclusion of these studies is that the stellar halo of M31 is significantly more massive than that of our own Galaxy: 4% compared to $\sim 1\%$, with possible interpretations pointing to a more active merging history for M31 than for the Milky Way. Stellar halos may therefore also provide an avenue to reconstruct the past merger history of galaxies once the link between the galaxy build-up and its stellar halo structure, mass and shape is fully understood.

The large number of substructures seen in the Milky Way and Andromeda serves as confirmation that accretion events are responsible to a large extent for the build up of our stellar halo. However, kinematics and metallicity analysis of stars suggest a more complex structure for the stellar halo where more than one component is needed (Carollo et al., 2007; Deason et al., 2013; Carollo et al., 2010; Tissera et al., 2014), including some hints that the inner stellar halos may have a significant contribution from in situ stars (Gilbert et al., 2014; Reitzel and Guhathakurta, 2002; Bonaca et al., 2017), as opposed to the common view of an accreted origin for stellar halos. The mechanisms able to propel in situ born stars onto more external orbits are not yet well understood, nor has a convincing way been demonstrated to observationally distinguish between these two possible origins for halo stars in external galaxies.

Clearly, a complete understanding of stellar halos will come from surveying more galaxies beyond the Local Group. Such observations are challenging due to the associated low surface brightness in these halos. For instance, if one were to place a Milky Way-like stellar halo uniformly in a sphere of radius 100 kpc it would have a stellar surface density of $1.6 \times 10^4 M_{\odot}/\text{kpc}^2$ in projection, which means that we would need to reach levels of

~ 30.9 mag/arcsec² to detect it. Although this calculation is only approximate (in the sense that stars will distribute in some power law and not homogeneously and also in that it ignores substructures), it provides a good intuition about the high sensitivity needed in observations of extragalactic stellar halos.

A clever way to circumvent this limitation is by means of stacking images of thousands galaxies and their halos (e.g., Zibetti et al., 2004; Tal and van Dokkum, 2011; D’Souza et al., 2014). Another possibility is detailed observations of a handful of galaxies with HST, such as the approach taken by the GHOSTS survey (Radburn-Smith et al., 2011b; Monachesi et al., 2016), for which random fields across the halo are selected providing information on localized regions with resolved stellar populations. More recently, the availability of telescopes with full time dedication have allowed the mapping of several stellar halos by very long exposures. Such is the case of the Dragonfly telescope (Abraham and van Dokkum, 2014; van Dokkum et al., 2014; Merritt et al., 2016) or the HERON survey (Rich et al., 2017) reaching an unprecedented depth up to 29-32 mag/arcsec², in an extension of a technique used previously to uncover several extragalactic streams (Martínez-Delgado et al., 2010; Tal et al., 2009a).

The emergent picture from all these recent studies, in agreement with the already detected differences between the Milky Way and M31 halos, is a wide diversity in the amount, shape and gradients of stellar halos among different galaxies (Monachesi et al., 2016; Harmsen et al., 2017; Merritt et al., 2016). Even within the limited sample of deep observations that is currently available, some intriguing cases have already arisen. In particular, the apparent non-detection of M101’s stellar halo by van Dokkum et al. (2014) is

at odds with the predictions from Λ CDM. *How can a galaxy avoid merging and disrupting satellites throughout its entire history?* Furthermore, Merritt et al. (2016) present two additional cases, NGC1042 and NGC3351 together with M101, among their eight galaxies with comparable stellar mass to the Milky Way which are also consistent with no stellar halo component down to 32 mag/arcsec². This apparent lack of stellar halo, if proven not to be an observational artifact, seems not uncommon in the galaxy population and is therefore an interesting puzzle to be explored within the current models of galaxy formation.

Numerical simulations have shown remarkable successes at reproducing several of the properties of stellar halos as well as at providing insights into stellar halo formation (e.g., Abadi et al., 2006, 2003a,b; Helmi, 2008; Cooper et al., 2013; Tissera et al., 2014; Pillepich et al., 2015, 2014; Amorisco, 2017). Recent simulations have shown that theoretical models also predict that the stellar halo consists not only of a component accreted through mergers but also of an in situ component made of stars that were formed locally in the host galaxy. The exact origin and fractions of in situ stars in the stellar halo is not completely agreed upon. In situ stars have been shown to dominate the inner regions of the stellar halo and be displaced early in a galaxy’s history by dynamical processes such as mergers (Pillepich et al., 2015; Zolotov et al., 2009; Tissera et al., 2014; McCarthy et al., 2012). By contrast Cooper et al. (2015) find that the majority are formed as a result of the gas stripped from infalling satellites. In situ stars have also been claimed to be born in the stellar halo directly in localized condensations of gas (Tissera et al., 2013). As different mechanisms are responsible for the accreted and in situ components, one needs to address both in order to understand: (i) how diversity in stellar halos arises and (ii) specifically

inspired by recent observations, how a galaxy continues to assemble without growing its stellar halo. A promising avenue to make progress on this question is to study the emergent stellar halos in a large statistical ensemble of galaxy assembly paths and merger histories predicted by Λ CDM.

In this paper we take such an approach by using the large-volume cosmological hydrodynamical simulation Illustris ([Vogelsberger et al. 2014a](#), [Vogelsberger et al. 2014b](#), [Genel et al. 2014](#)). Illustris is an ideal tool to tackle this problem since it provides a sample of 1115 central galaxies of mass comparable to the Milky Way with predictions for both their dark matter as well as baryonic assembly. This sample thus provides an unbiased view of stellar halo formation, allowing further inspection of dependencies on accretion history, environment and morphology of the central galaxy among others. Although we sacrifice spatial resolution compared to a zoom-in approach (Illustris' gravitational softening length for stars is 0.7 kpc), the nature of the main quest in this paper calls for large statistical samples and not for a detailed view of a few individual galaxies, making the analysis of a large cosmological box, such as Illustris, the most attractive strategy.

This paper is organized as follows: In Sec. 2.3 we briefly describe the simulations and define our samples. We explore the properties of stellar halos and their centrals in Sec. 2.5, with specific emphasis in the populations with the smallest and highest stellar halo fractions. We turn our attention to the in situ and accreted origin of stellar halos in Sec. 2.6 and summarize our findings in Sec. 2.7.

2.3 Numerical Simulations

Illustris is a cosmological hydrodynamical simulation of a representative volume of the Universe, comprising a box of size 106 Mpc on a side that was run with the moving grid code AREPO (Springel, 2010). In its high resolution version, Illustris-1, the mass per particle is 1.6 and $6.3 \times 10^6 M_\odot$ for baryons and dark matter, respectively, and a typical gravitational softening length smaller than 0.7 kpc (Vogelsberger et al., 2014a). The simulation is consistent with WMAP-9 standard cosmology, with $\Omega_m=0.2726$, $\Omega_b=0.0456$, $\Omega_\Lambda=0.7274$, and $H_0=70.4\text{km/s/Mpc}$ (Hinshaw et al., 2013). It follows gravity by means of an octree algorithm and the hydrodynamics of the gas including star formation and feedback processes that are believed to be fundamental to the reproduction of the properties of galaxies.

Gas cells can cool and heat self-consistently with a minimum temperature floor of $T = 10^4\text{K}$ (Vogelsberger et al., 2013). Above a density threshold of $n_H = 0.2\text{cm}^{-3}$, gas follows an equation of state that is used to implicitly treat the multi-phase structure of the unresolved ISM (Springel and Hernquist, 2003). Cold and dense gas above this threshold also becomes eligible for star formation with a timescale proportional to the local density. After stars form following a Chabrier initial mass function they are evolved using Starburst99 (Leitherer et al., 1999) stellar evolution tracks. Stellar feedback is modeled kinematically, by adding 100% of the available energy due to supernovae as momentum to surrounding gas cells. The mass loading of the wind scales inversely with the local velocity dispersion of the dark matter (Vogelsberger et al., 2013). Illustris also includes a treatment for black hole growth and feedback, including a dual quasar/radio mode (see details in Di Matteo et al., 2005; Springel et al., 2005; Sijacki et al., 2015), but given the mass range

and properties studied in this paper, our conclusions are only minimally impacted by the physics of black holes. The free parameters in the model were tuned to reproduce the global star formation history of the universe and approximately follow the observed stellar mass function at $z = 0$. With those choices, Illustris has been proven to successfully reproduce a series of *global* properties of the galaxy population, such as scaling relations, morphology bimodality, color distribution, merger rates, environmental trends, among others (Genel, 2016; Rodriguez-Gomez et al., 2015; Sales et al., 2015; Sijacki et al., 2015; Snyder et al., 2015).

Halos and galaxies are identified using the SUBFIND algorithm (Springel et al., 2001; Dolag et al., 2009). In short, groups are first identified based on a spatial-only information using the Friends of Friends (FoF) algorithm and gravitationally self-bound structures are later identified within groups by using SUBFIND. The object sitting at the center of the gravitational potential of each halo is called the central or host galaxy and all other substructures associated with the group will be referred to as satellites or subhalos. We trace the history of each galaxy by means of the SUBLINK merger tree algorithm introduced in Rodriguez-Gomez et al. (2015); Nelson et al. (2015) which allow the user to trace the assembly history of any subhalo for up to 13.76 Gyr.

2.3.1 Sample Selection

Our galaxies are selected to be comparable to the Milky Way by imposing a virial mass ¹ cut $M_{200} = 8 \times 10^{11} - 2 \times 10^{12} \text{ M}_{\odot}$ and selecting central galaxies only (i.e. no

¹We define the virial mass, M_{200} , as that enclosed by a sphere of mean density 200 times the critical density of the Universe, $\rho_{\text{crit}} = 3H^2/8\pi G$. Virial quantities are defined at that radius, and are identified by a “200” subscript.

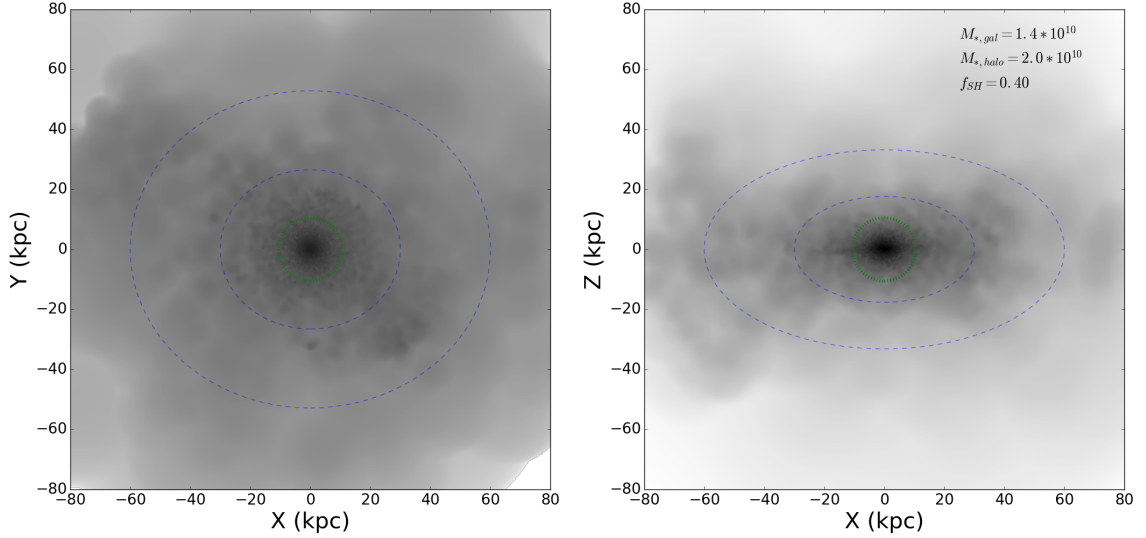


Figure 2.1: Face-on (left) and edge-on (right) stellar projections of a randomly selected object in our sample. The inner green circle shows the separation between galaxy and stellar halo, defined here as all stars with distance smaller or larger than twice the half mass radius of the stars, $2r_h^*$, respectively. Dashed blue lines show the projected ellipsoids corresponding to the inertia tensor of stars in the stellar halo (i.e. $r > 2r_h^*$) at two arbitrary radii 30 and 60 kpc. For comparison, the virial radius is 196 kpc. The extended stellar halo in this object is preferentially oblated and aligned with the orientation of the inner galaxy, which is a common signature in our sample.

satellites). A total of 1115 central galaxies lie in this range. We define as a “galaxy” all stars or gas elements that are within a galactic radius defined as $r_{\text{gal}} = 2r_h^*$, where r_h^* is the half-mass radius of the stars as computed by SUBFIND. Each central galaxy has stellar particles associated to it (and gravitationally bound) all the way out to the virial radius. Stars that are located beyond r_{gal} that do not belong to any satellite and that are within r_{200} will be assigned to the stellar halo component.

We define stellar halo fraction as:

$$f_{SH} = \frac{M_{*,\text{tot}} - M_*}{M_*} \quad (2.1)$$

where $M_{*,\text{tot}}$ is the total stellar mass of the halo and M_* is the stellar mass of the halo

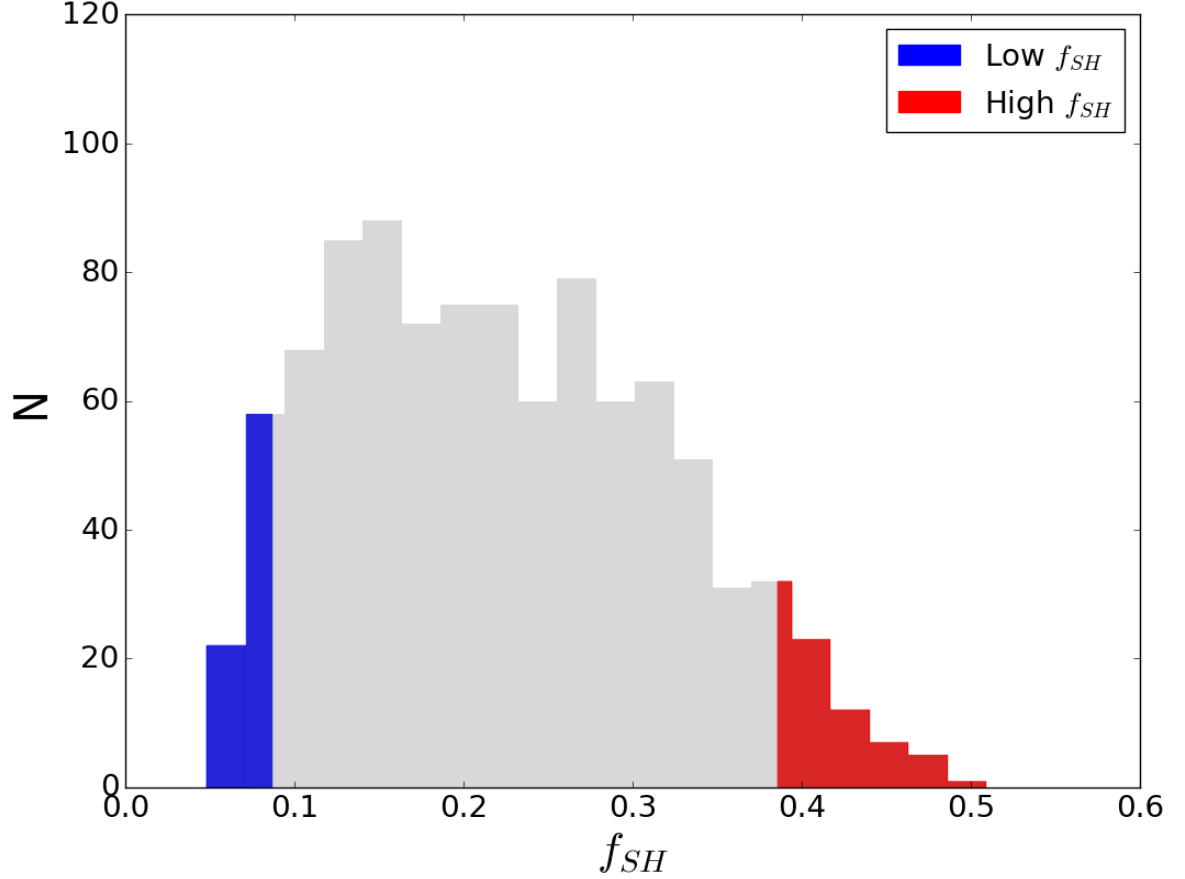


Figure 2.2: Distribution of the stellar halo fraction, $f_{SH} = M_*(r > 2r_h^*)/M_*^{\text{tot}}$, of all central galaxies in Illustris within virial mass range $8.0 \times 10^{11} \text{ M}_\odot \leq M_{200} \leq 2.0 \times 10^{12} \text{ M}_\odot$. There is a large variation in f_{SH} , with 5% tails having low ($f < 0.07$) and high ($f > 0.45$) stellar halo fractions, highlighted by blue and red respectively. Each of these subsamples contains 60 galaxies.

within r_{gal} . Although there is no consistent definition of stellar halo across the field, similar definitions have been adopted in previous studies (e.g. Pillepich et al., 2015; Merritt et al., 2016).

Fig. 2.1 shows an example of one of our simulated galaxies and its halo. Using the angular momentum vector of the central galaxy (i.e. stars within r_{gal}) we define face-on (left) vs. edge-on (right) projections. Stars distribute well beyond the galaxy radius r_{gal}

shown by the green dotted circle, forming a diffuse and extended stellar halo reaching out beyond 100 kpc. Stellar halos are often inhomogeneous with the presence of substructure indicating the occurrence of relatively recent merger events in the past. Note that these halos are far from spherical, as indicated by the blue ellipsoids showing the inertia tensor axis-ratios for stars at two different radii (calculated with all stars outside r_{gal} but within the radius of interest), a subject we return to in Sec. 2.4.

We exclude centrals that have massive satellites ($M_* \geq 10^9 \text{ M}_\odot$) within 50 kpc from the center as well as centrals with a satellite of stellar mass $M_{*,\text{sat}} \geq \frac{1}{4} M_{*,\text{cen}}$ anywhere within the virial radius (r_{200}). These two conditions ensure that the stellar halo mass estimates will not be enhanced artificially by stars in the outskirts of satellites that are mistakenly assigned to the central by limitations of our subhalo finder. With these definitions, our sample comprises of 967 centrals and spans a wide range in stellar halo fraction, $0.05 \leq f_{SH} \leq 0.51$, shown in Fig. 2.2. Understanding the origin of such diversity is one of the main objectives of this paper. To that end, we will compare the properties and evolution of both tails of this distribution, which we will refer to as the “low/high stellar halo fraction” samples and use blue and red respectively to denote them. The low and high f_{SH} samples are selected to be the 5% tails, with a total of 60 galaxies each.

2.4 Shape and surface brightness profiles of stellar halos

We start by quantifying the shapes of the simulated stellar halos. Fig. 2.3 shows the b/a and c/a axis ratios, where a , b and c are the square roots of the eigenvalues corresponding to the major, intermediate and minor axes of the inertia tensor of the stars in each stellar

halo of our sample. We adopt the definition from Vera-Ciro et al. (2011), for which the normalized inertia tensor is:

$$I_{ij} = \sum_{x_k \in V} \frac{x_k^{(i)} x_k^{(j)}}{d_k^2} \quad (2.2)$$

where d_k is a distance measure to the k th star and V is the set of stars in the stellar halo. We use all stars in the stellar halo to assign a single b/a and c/a to each of our centrals. Fig. 2.3 shows that the majority of stellar halos are not spherical and, in fact, they occupy almost all available space in the axis ratios map with a slight tendency for oblated distributions (large c/a). This trend is stronger for galaxies with low stellar halo component than with large f_{SH} and is in good agreement with observational estimates of halo shapes in disk galaxies (Harmsen et al., 2017). Color coding follows from Fig. 2.2, with gray for the whole sample of MW-like objects and blue or red highlighting our low and high f_{SH} subsamples respectively. We have checked that for the cases where the central galaxy has a well-defined disk, the shapes of the stellar halos tend to align with the inner disk, as is the case in the example shown in Fig. 2.1.

This asphericity can introduce observational biases in stellar halo studies, in particular for those which targets are selected based on inclination of the disk. Consider, for instance, an oblated distribution, $a \sim b \gg c$. If we “observe” the object face-on, the projection will be done along the short axis rendering a considerably lower stellar density than if the object was observed edge-on where the projection is done along the more extended axes a or b . With the typical axis ratios found in our simulations, the effect can be sizable, as shown in Fig. 2.4. Thick dotted and dashed lines show the median projected mass surface

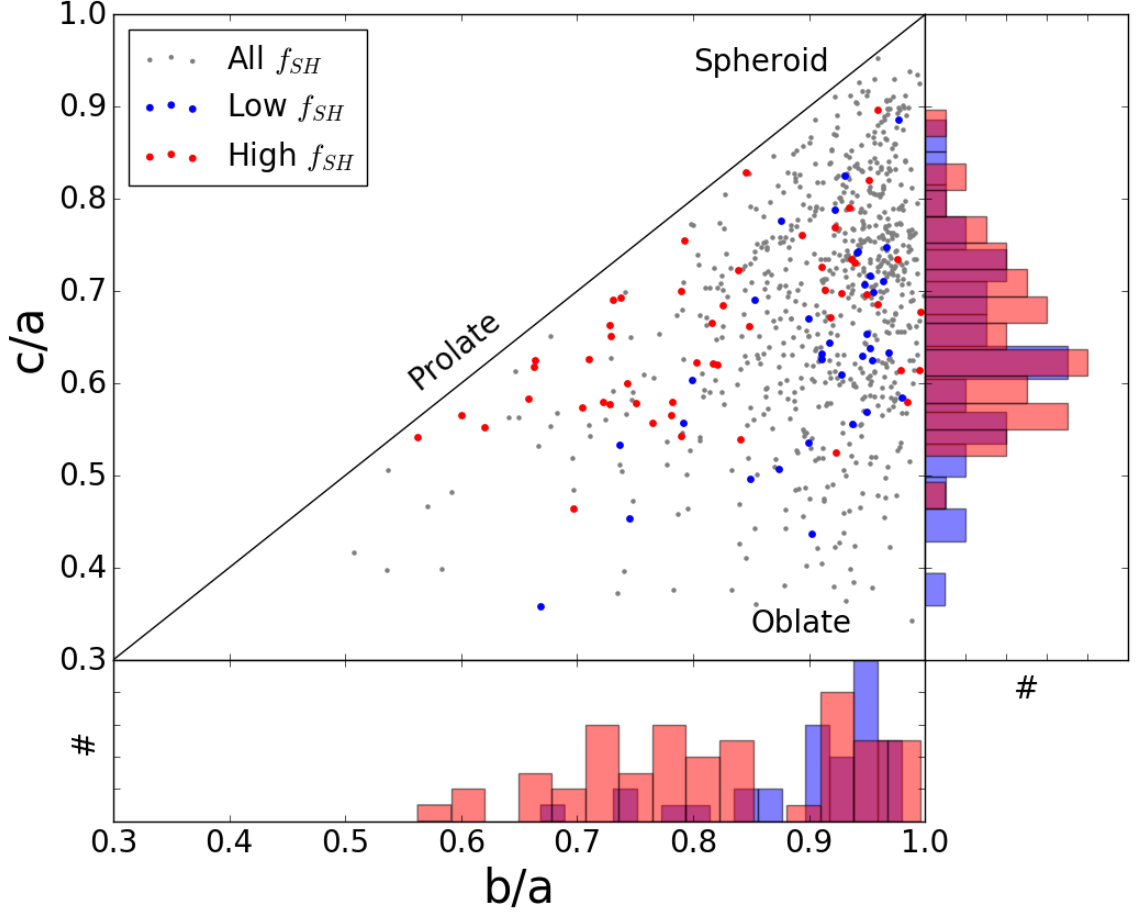


Figure 2.3: Stellar halo shapes in the Illustris simulation for galaxies in the virial mass range $8 \times 10^{11} < M_{200}/M_{\odot} < 2 \times 10^{12}$. a , b and c correspond to the major, intermediate and minor axis lengths of the ellipsoid with inertia tensor defined by stars in the stellar halos. Grey shows the whole sample and highlighted in blue and red are the low and high stellar halo fraction samples, respectively, as defined in Fig. 2.2. The distribution favors oblate halos overall, with no particular dependence on the fraction of stellar halo.

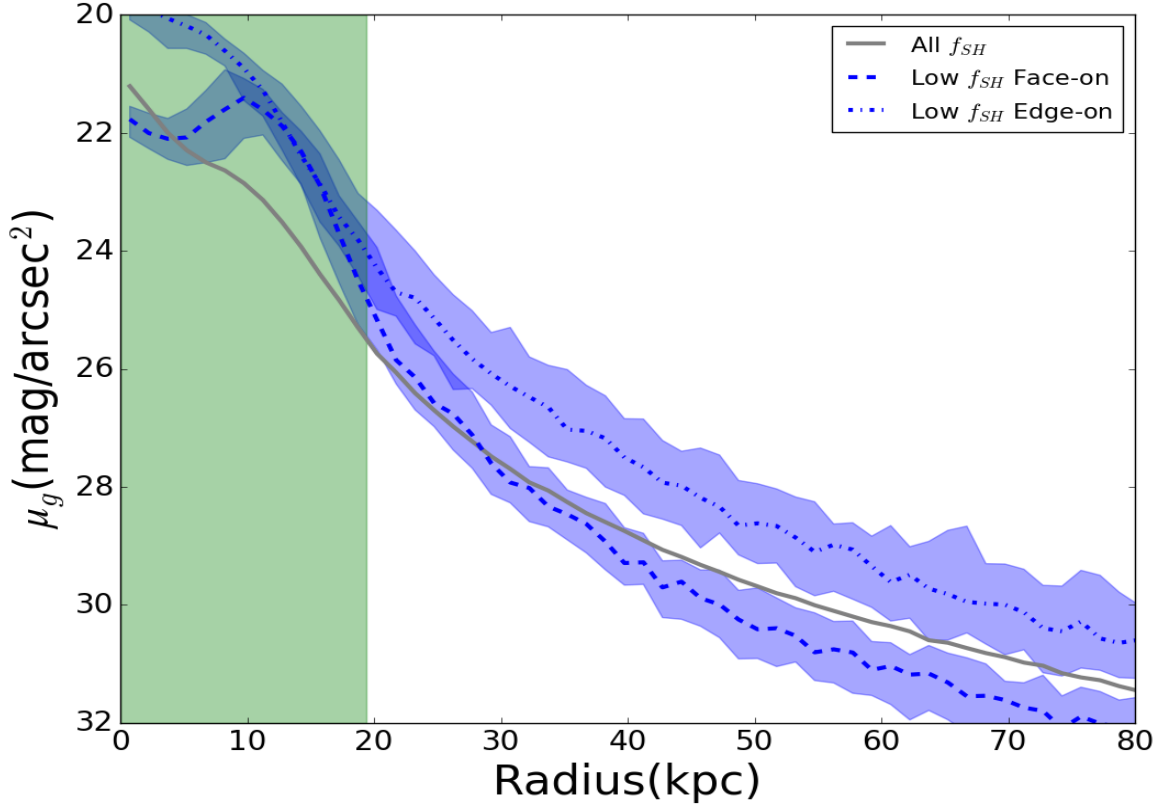


Figure 2.4: Projection effects on the surface brightness profiles of stellar halos. There is a sizable effect according to the orientation of galaxies, with face-on projections (dashed line) giving a fainter stellar halos outskirts than when the galaxy is edge-on (dotted line). The effect can be as large as 2 magnitudes fainter in the outskirts of the halos.

density profile of our sample with low f_{SH} when the galaxies are all oriented face-on or edge-on, respectively, based on the angular momentum of the stars within r_{gal} . The profiles are computed in integrated ellipsoidal shells, with the horizontal axis showing the ellipsoidal radius as computed from the inertia tensor axis ratios (b/a or c/a depending on the projection). This procedure is equivalent to the common practice in observations of measuring the axis ratios of the isodensity contours on light profiles and scaling the ellipsoidal radius accordingly.

Our tests indicate that solely changing the orientation of the projection for the *same* simulated objects can result in a difference of up to 2 g -band magnitudes. This effect will artificially introduce variations among observed stellar halo profiles and should be taken into account when analyzing stellar halo diversity in real galaxies. *One prediction from our study is that surface brightness profiles of face-on oriented disks will be biased low with respect to a more inclined sample.* Interestingly M101, a galaxy put forward by several authors as having little to no stellar halo, has an almost perfect face-on projection (inclination angle $i = 16.0$, from the HyperLEDA database (Makarov et al., 2014)). The other two cases with no stellar halos drawn from the Dragonfly study in Merritt et al. (2016), NGC1042 and NGC3351, are less clear. With inferred inclinations of $i = 58.1$ and 54.6 , they would show a milder effect due to projections compared to M101. A more conclusive analysis will come once more observations of galaxies and their faint stellar halos become available. For now, we just highlight the need for addressing projection effects due to stellar halo shapes and, in particular, the derived conclusions on stellar halo mass and structure.

With these caveats in mind, we compare our simulated samples to available observations in Fig. 2.5. On the left panel we show the stellar halo fraction as a function of stellar mass of the central galaxy. To more closely match the definition introduced in Merritt et al. (2016), we consider the fraction of the stellar mass that is beyond $5r_h^*$ instead of the $2r_h^*$ adopted for the rest of our paper. For simplicity, this quantity in simulations is computed in 3D instead of in projection as is done in observations. The gray solid line shows the median for a representative number of central galaxies on a wide mass range in Illustris, with the shaded area corresponding to the 25th to 75th percentiles. Red and blue

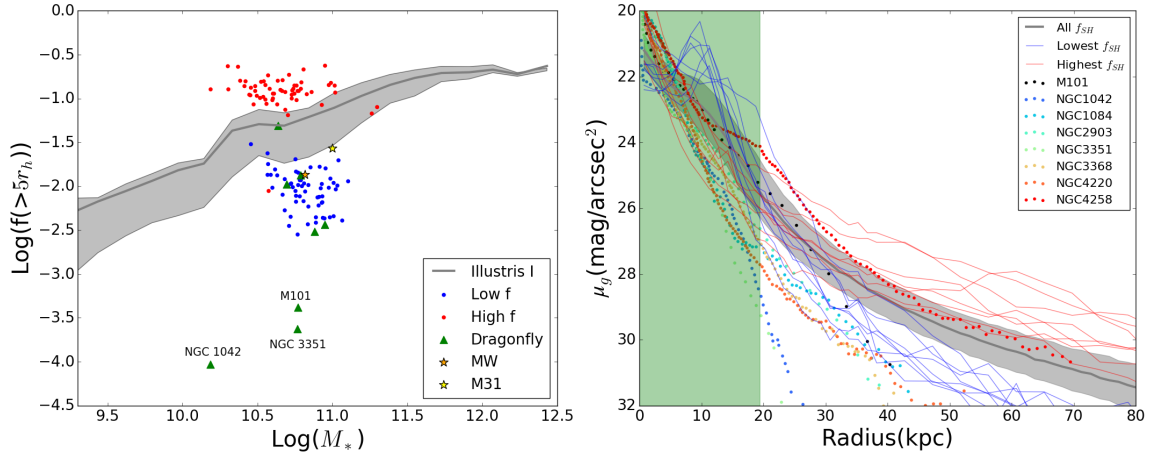


Figure 2.5: *Left*: Stellar halo fraction calculated as the mass beyond $5 * r_h^*$ for easy comparison to observations. Color coding as before shows in gray the simulated sample and highlighted red and blue points correspond to the high and low f_{SH} galaxies, respectively. The sample overlaps well with data from the Dragonfly Telephoto Array, shown in green triangles (Merritt et al., 2016). M31 (yellow) and the MW (orange) are also indicated with a starred symbol (Carollo et al., 2010; Courteau et al., 2011). A few objects stand out from the observational sample having a very low and almost undetected stellar halo, such as M101, NGC3351 or NGC1042. *Right*: Median (face-on) surface brightness profile for the simulated stellar halos is shown in gray solid line with shading indicating the 25%-75% percentiles in our sample. A green vertical region is used to indicate twice the average half-mass stellar radius of the stars, and therefore the division between the average “galaxy” regime, and the stellar halo extending beyond that. For comparison, data from disk galaxies in Merritt et al. (2016) is shown with colored dots. Thin blue/red lines indicate individual profiles of the 8 most extreme objects in Illustris with low and high f_{SH} respectively.

dots indicate the values for our low and high stellar halo fraction galaxies that according to our selection criteria cluster around MW-like objects, $M_* \sim 6 \times 10^{10} M_\odot$.

As expected, the blue and red subsamples represent the tails of the normal population, even though the selection was made using $2r_h^*$ instead of 5. We note that there is one central from the high f_{SH} sample with a particularly low value of f_{5rh} . This galaxy is undergoing a merger that is too minor to qualify for our conditions, but is affecting the subhalo finder. Results for real observed galaxies are shown in green triangles (Dragonfly) and yellow/orange starred symbols for the Milky Way and M31, respectively. Although no extreme outliers such as M101, NGC3351 and NGC1042 seem to appear in Illustris, the simulated sample occupies roughly the same region as the observed stellar halos in literature. The good agreement is particularly encouraging if one takes into account the difference in definitions (3D vs. 2D) and procedures (i.e. background subtraction) that go into computing such fractions. Simulations with low f_{SH} (blue) seem to better represent the observations in the mass range of overlap. As we will see in Sec. 2.5.1, this can be easily explained as a morphological bias in observed samples as we are considering all simulated galaxies in the mass range with no morphological cuts.

The right panel of Fig. 2.5 confirms that the median surface brightness profiles of simulated galaxies (shown in gray) is also in reasonable agreement with individual observations from Dragonfly (colored symbols), although there is a trend in Illustris to have slightly more massive stellar halos overall. In particular, we are unable to find good analogs to the lowest stellar halo mass objects such as M101 in Illustris. The averaged more massive stellar halos in the simulations is already hinted on the left panel of Fig. 2.5 and is mainly

driven by the fact that observations typically target disk-dominated galaxies whereas we are including all galaxies in a halo mass range, regardless of their morphology. In addition to this, one cannot disregard the possibility that stellar halos in Illustris are overpredicted due to the over abundance of low mass galaxies in the simulation (see top right panel in Fig.2 of Genel et al. 2014), which presumably can also be tidally disrupted, contributing more stars than they should to the stellar halos. This, however, does not represent a major limitation of our analysis as the main objective is to understand the *variations* on the stellar halo fractions in a narrow range of halo mass, and not to exactly match individual galaxies from observations. Indeed, as highlighted in Fig. 2.2 and 2.5, the diversity shown in f_{SH} for our simulations is significant and comparable to observations, making Illustris and its large statistical sample a powerful tool to study the emergence of diversity in stellar halos within ΛCDM .

2.5 Building the Stellar Halos' diversity

2.5.1 Properties of the host galaxy

Our low/high f_{SH} samples are selected purely on the fraction of mass in their stellar halos compared to that of the stars in the host galaxy which is essentially blind to the properties of the central galaxy. It is therefore interesting to explore how the central galaxies in each f_{SH} subsample compare to each other. We start by looking at the environment of galaxies with the lowest and highest stellar halo fractions in the top panel of Fig. 2.6. Environment has been quantified by means of the mean stellar density Σ_5 , defined as the

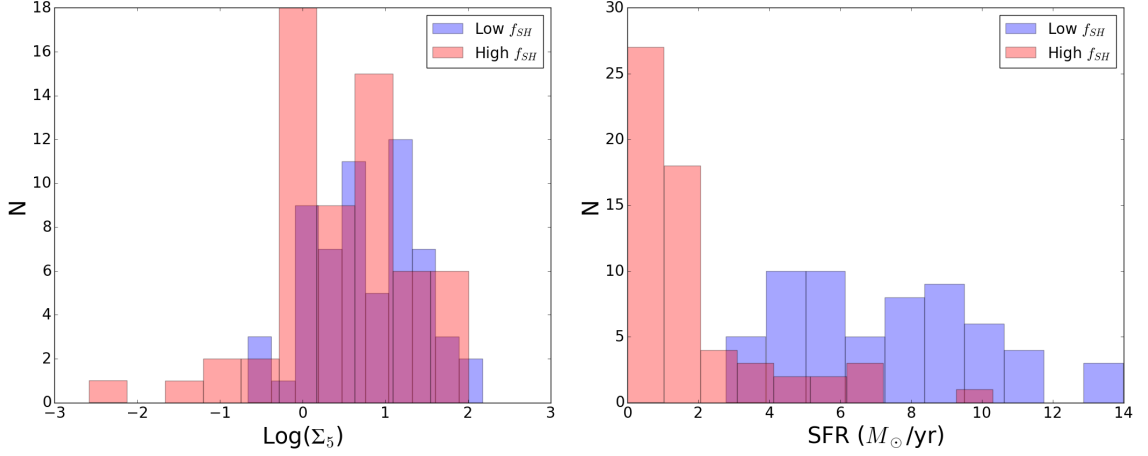


Figure 2.6: Distribution of environment (as defined by the distance to the fifth neighbor Σ_5) in the left and the star formation rate (SFR) in the right panels for the low and high stellar halo fraction samples. Whereas there is no obvious trend with environment, there is a clear difference in the SFR between both samples, with low f_{SH} galaxies being more actively star forming than the galaxies with the highest stellar halo content.

stellar mass density enclosed within the distance to the 5th nearest neighbor with stellar mass above $M_* = 10^{10}$. In our sample, the average distance to the 5th neighbor is $r_5 = 4.8$ Mpc. We find no significant difference between the low and high f_{SH} which suggests that the medium-scale vicinity of a halo at present day encodes little information on the formation of stellar halos. This lack of correlation with environment is in agreement with trends found in observations (see e.g. Merritt et al., 2016). On the other hand, there is a clear difference in the star formation activity of centrals according to their stellar halo fraction (see right panel Fig. 2.6), with high stellar halo content centrals being preferentially non-star forming in contrast with galaxies with low f_{SH} which are actively forming stars. *This correlation is also present in the morphology of the galaxies, with disk-dominated galaxies having on average a significantly lower fraction of stars in the stellar halo compared to the central galaxy than early-types.* This can be seen in Fig. 2.7, where morphology κ is estimated

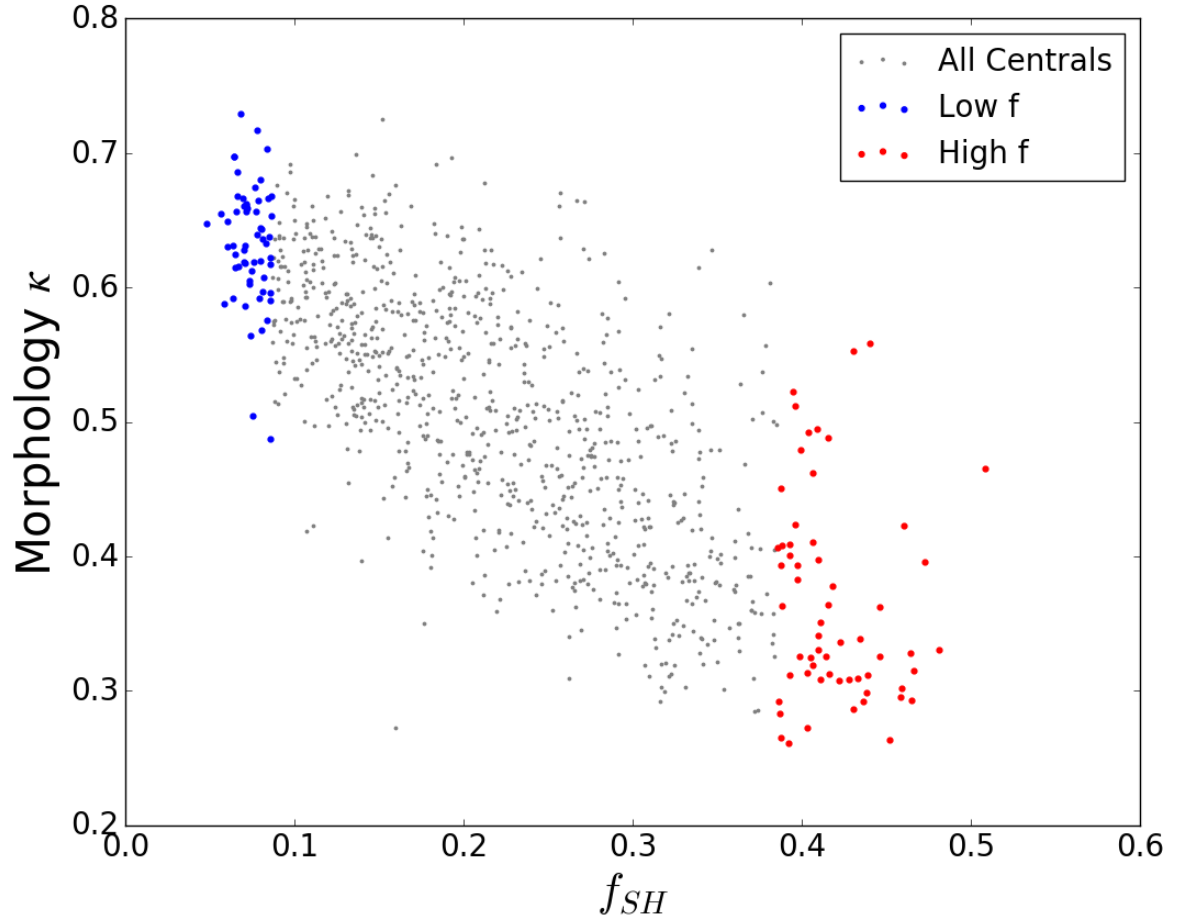


Figure 2.7: There is a well-defined correlation between the fraction of stellar halo f_{SH} and galaxy morphology as quantified kinematically through κ . Disk-dominated galaxies (large κ values) show the least amount of stellar halo fractions with average $f_{SH} \sim 0.15$. The trend of f_{SH} with morphology is much stronger than the relevance of accreted stars or mergers *within* the galaxy radius (see e.g., Sales et al., 2012; Rodriguez-Gomez et al., 2016).

following the methodology of Sales et al. (2012), as the ratio between the kinetic energy of stars in ordered motion around the z -axis and the total kinetic energy of the system. Large κ values correspond to disk-dominated morphology, whereas a low κ index is indicative of spheroidal morphologies with no dominant rotation. Although the scatter is significant, the correlation between f_{SH} and κ is well defined in our sample and agrees well with the observational trends reported in stacked SDSS observations of stellar halos for galaxies of different morphological types (D’Souza et al., 2014).

The link between stellar halo content and morphology, although not completely unexpected, is still nontrivial. For MW-mass objects as analyzed here, mergers have been shown to correlate very poorly with the central morphology of the galaxy (Sales et al., 2012; Rodriguez-Gomez et al., 2017), yet they are believed to build the majority of the stellar halo. How does this correlation then get established? From Fig. 2.7 it is clear that the processes responsible for shaping the morphology of galaxies also have a large impact on the formation of the stellar halo. We turn our attention to the general assembly of the galaxies and their dark matter halos for further clues.

2.5.2 Assembly histories for dark and stellar halos

Fig. 2.8 shows the virial mass M_{200} assembly histories for our objects in low (blue) and high (red) f_{SH} subsamples. To ease the comparison, the vertical axis shows the virial mass at a given time normalized to the final mass at $z = 0$ such that most curves stay within the 0-to-1 range. Thin lines indicate tracks for each individual object and the thick curve shows the median of each subsample. Although the object-to-object scatter is large, the

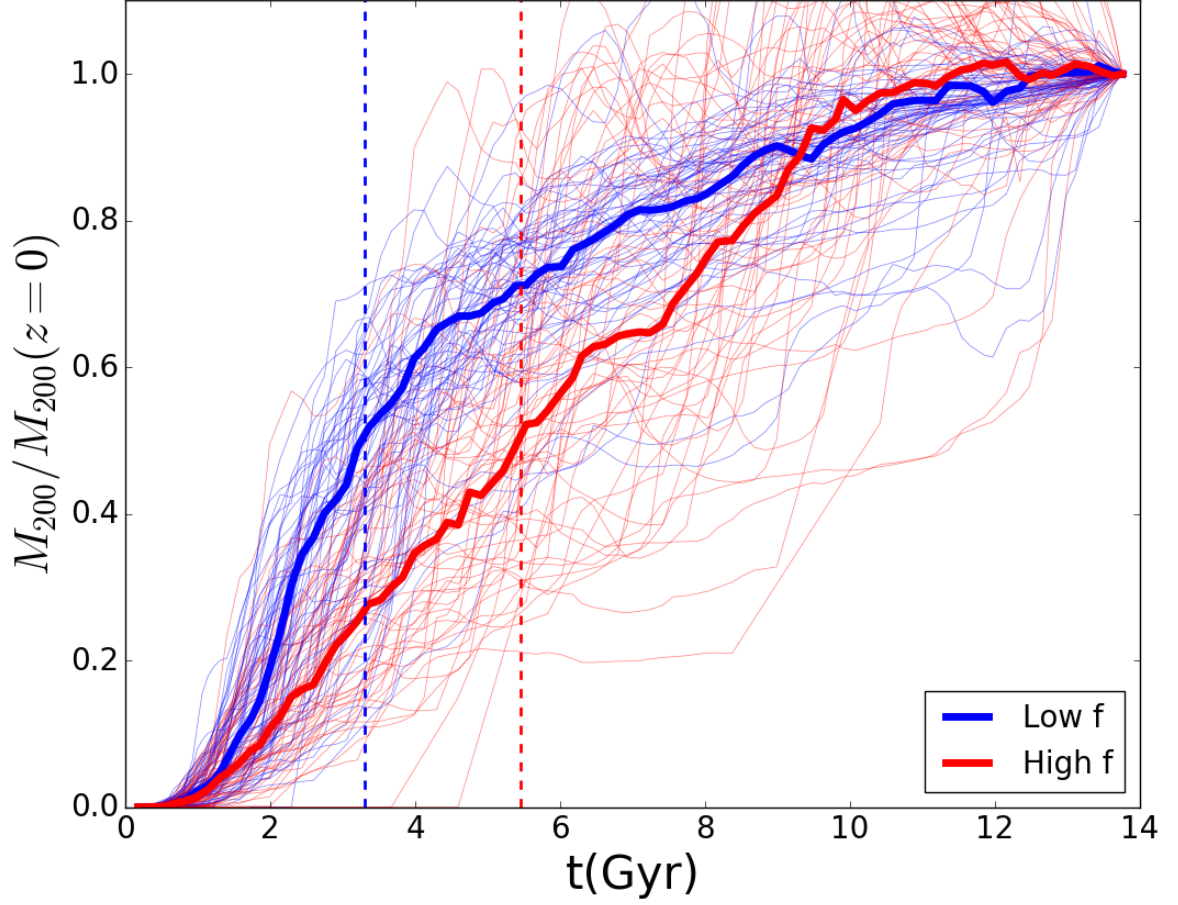


Figure 2.8: Virial mass accretion history as a function of time for galaxies with low (blue) and high (red) stellar halo fraction. Thick lines indicate the median and thin lines show individual tracks for each halo. Galaxies with low f_{SH} show an earlier total mass assembly, reaching half their present-day mass by $t \sim 3$ Gyr compared to $t \sim 5.5$ Gyr for the objects in the high stellar halo fraction subsample. The late-time evolution in the last 3 Gyr is similar for both groups.

median trend suggests a different mass assembly history characteristic for each subsample. Galaxies with low stellar halo fractions assemble their halo mass earlier compared to objects with larger f_{SH} , as shown by the blue and red thick lines. For instance, galaxies with low f_{SH} have acquired on average half of their mass by $t_{50} = 3 \text{ Gyr}$ ($z_{50} = 2.2$) whereas the counterparts with large stellar halo fraction take double the time to reach that value, or $t_{50} \sim 6 \text{ Gyr}$.

Moreover, the overall shapes of the assembly histories are different. High f_{SH} objects show a steady growth throughout most of their history, slowing down slightly after $t \sim 10 \text{ Gyr}$. Instead, in galaxies with low f_{SH} the growth is much more rapid in the initial phase ($t \leq 4 \text{ Gyr}$), gradually slowing down afterwards. Interestingly, the late time evolution of M_{200} for both subsamples is comparable after $t \sim 9 \text{ Gyr}$, or equivalently, $z = 0.45$. It is worth highlighting that the median virial masses of the low and high f_{SH} subpopulations are 1.1 and $1.4 \times 10^{12} \text{ M}_{\odot}$ respectively, which partially explains the earlier collapse of galaxies with low stellar halo fractions (as lower mass halos collapse earlier). However, the bias in halo mass is not large enough to fully explain the difference in median formation history found in Fig. 2.8.

If the dark matter halos of galaxies with low stellar halo assemble earlier, one is left to wonder whether the same applies to the stellar assembly. We explore this in Fig. 2.9, where solid lines correspond to the median assembly of the stellar halo component and dashed curves indicate the stellar assembly of the central galaxy. To guide the eye, we have included the median assembly of M_{200} from the previous figure in thin dotted lines. To calculate these curves, we trace the progenitors of our galaxies backwards in time and at

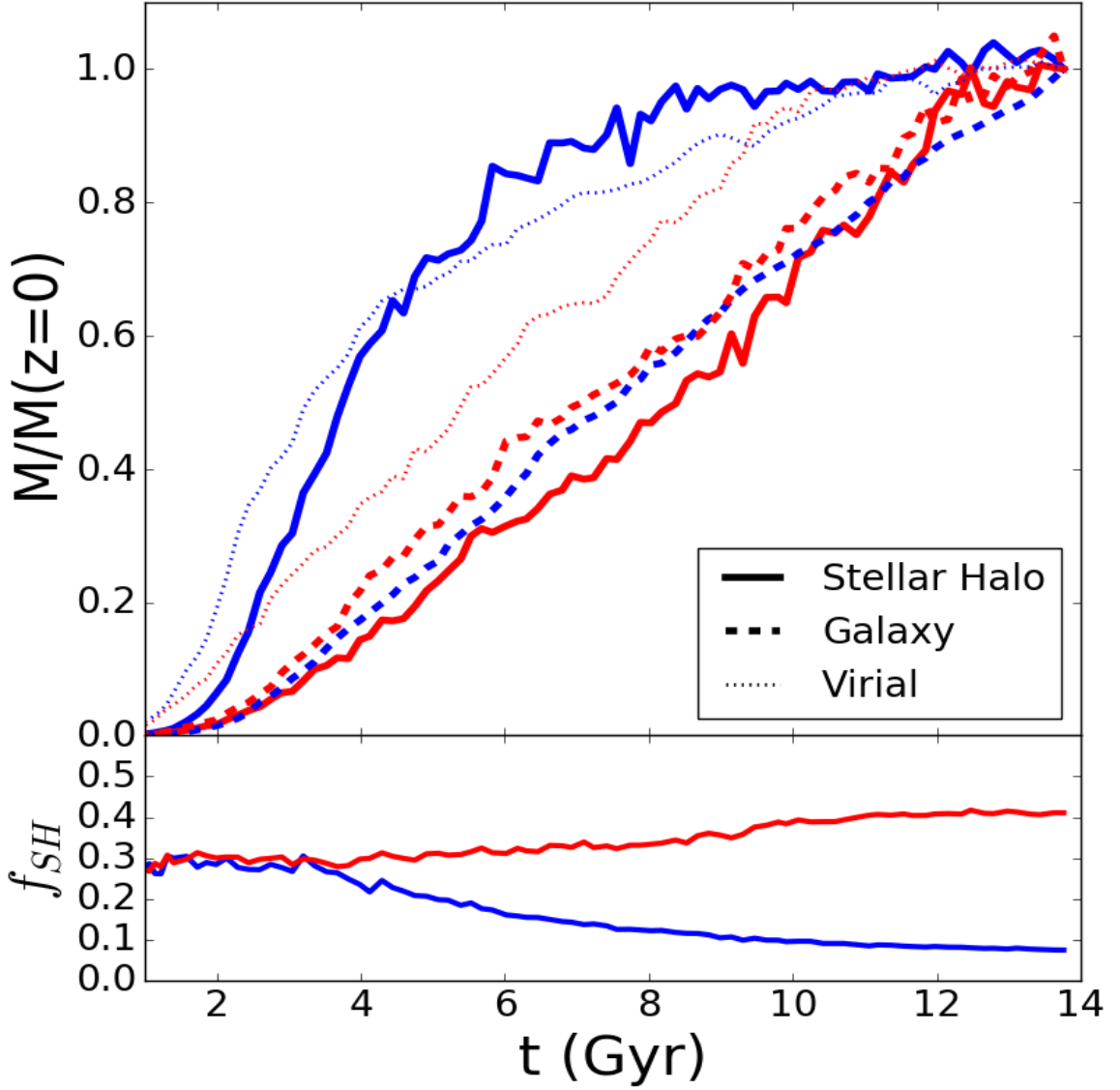


Figure 2.9: *Top*: Similar to Fig. 2.8, but for the assembly history of the *stellar halo* mass. Thick solid lines show the median for the low and high f_{SH} sample and confirms that the stellar halos of galaxies with low f_{SH} also assemble earlier on average compared to those stellar halos in the high f_{SH} sample, in agreement with the trend found for virial mass (shown in thin dotted curves). In contrast, the mass assembly of the central galaxies (long-dashed curves) show no statistical difference between both samples. This then means that the evolution of the stellar halo fraction f_{SH} with time (bottom panel) is similar in both samples at the beginning ($t \leq 3$ Gyr), but as the low f_{SH} stops growing their halos but continue to grow their central galaxy, their overall stellar halo fraction declines with time afterwards. On the other hand, the red curve grows their stellar halo faster than their central mass, causing them to populate the largest f_{SH} of the population at $z = 0$.

each snapshot count the amount of mass within (for M_*) and beyond (for the stellar halo mass M_{SH}) the instantaneous galaxy radius r_{gal} defined as before, $r_{\text{gal}} = 2r_{h,*}$, with $r_{h,*}$ the half mass radius of the stars in the galaxy at each time. We then take the median mass at a given time from each subsample. We highlight that these curves measure the mass assembly onto each object and not the formation time of the stars.

The trends in Fig. 2.9 are intriguing and suggest that the assembly of the mass in the stellar halo component itself is different between both samples. Galaxies with low f_{SH} build their stellar halo early on in a similar fashion as the virial halo build up: a rapid early growth followed by a slow down of the evolution at later times. For instance, 80% of the stars in the stellar halos are already in place at $t = 6$ Gyr while later evolution during half a Hubble time only adds the remaining 20%. Note that this behavior is different from the stellar mass growth proceeding in the central galaxy, which is almost constant with time (see blue dashed curve), with a median time of 12 Gyr to build 80% of the stars in the center. On the other hand, galaxies with large stellar halo content assemble both the mass in their stellar halos *and* in the central galaxy at a steady rate which is only loosely connected to the M_{200} growth.

The combined effect of stellar halo and central stellar growth is shown in the bottom panel of Fig. 2.9. By construction, both our subsamples have very different f_{SH} today. However, this seems not to have been always the case. The early progenitors of both samples had similar fractions of mass in the stellar halo compared to the central until $t \sim 4$ Gyr, after which both subsamples start to deviate, an effect governed mainly by the fact that the low f_{SH} sample has significantly slowed down the building of its stellar halo

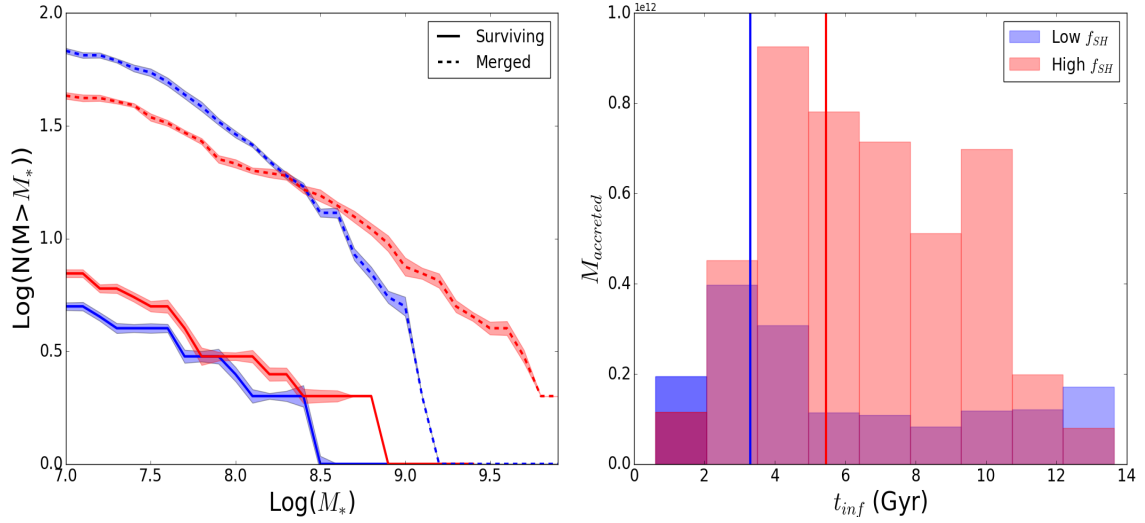


Figure 2.10: *Left:* Stellar mass functions for merged (dashed) and surviving (solid) satellites. Red and blue lines are medians of the high and low f_{SH} populations, respectively. High f_{SH} galaxies have, on average, both more merged and more surviving satellites than low f_{SH} population, but the effect is small ($\sim 30\%$) and independent of satellite mass. *Right:* Histogram of infall times weighted by stellar mass for merged satellites. The infall time, t_{inf} , is defined as the time at which a satellite reaches its peak total (dark matter, gas and stars) mass. The accreted stellar mass for the low f_{SH} population infalls earlier compared to that of the high stellar mass fraction. For comparison, the time for the virial mass t_{50} is shown and roughly reproduces the peak time of infall for disrupted satellites.

but continues to actively grow the stellar mass in the central object bringing the f_{SH} ratio down with time. *Galaxies with low stellar halo content might be the most ancient stellar halos ever assembled.*

An important ingredient in the evolution of stellar halos is the population of satellite galaxies, in particular, those satellites that get partially or totally tidally disrupted contributing their stars to the extended halo². Surviving satellites do also donate some of their stars to the stellar halo, and their contribution to the stellar halo can vary from negligible to significant (e.g. Sales et al., 2007; Cooper et al., 2010) according to the halo

²The reader should bear in mind that disrupted satellites can contribute stars to the stellar halo or central galaxy, depending on the position where they distribute their stars

assembly history. We investigate in Fig. 2.10 the median satellite mass function of surviving (solid) and merged (dashed) satellites for each of our subsamples. Error bars correspond to dispersion obtained after 100 bootstrap resampling of the data.

The surviving population in low and high f_{SH} is roughly similar in shape, with a small excess of satellites for galaxies with large stellar halo. *This weak but yet significant correlation between stellar halo content and observed number of satellites is an interesting prediction of our model that may become available to observations soon as a larger number of galaxies are observed to low surface brightness limits.* On the other hand, the spectrum of merged satellites shows instead a strong and significant difference in the shape of the mass distribution of merged satellites (see dashed curves in Fig. 2.10. *We find a large preference for centrals with low stellar halo fraction to have accreted an excess of low mass satellites and a deficit of high mass satellites compared to centrals with high stellar halo content.*

Counterintuitively perhaps, centrals with low stellar halo content have had on average a *larger* number of mergers compared to the high f_{SH} sample, albeit such mergers have been dominated by satellites of smaller mass than in the high f_{SH} sample. Centrals with low stellar halo content have mostly avoided mergers with satellites with stellar mass $M_{*,\text{sat}} \sim 10^9 M_{\odot}$ and above, whereas such events are not rare for galaxies with similar virial mass but larger stellar halo fractions. We conclude that the mass of the merged satellite and not the number of mergers, is a dominant factor in determining the stellar halo content of the central.

As the population of merged satellites largely determines the amount of stellar halo content, we investigate their times of infall t_{inf} , and find they differ significantly. Infall

time is defined as the time at which a satellite reaches its peak total mass, a definition that roughly coincides with the last time an object was considered a central before it accreted onto a larger system. The right panel of Fig. 2.10 shows an average weighted histogram with the infall times of merged satellites, where each satellite is weighted by their stellar mass (results do not change significantly if we plot the unweighted histogram). As expected, low f_{SH} centrals have on average less stellar mass brought in by satellites, but these satellites also infall at earlier times than the high f_{SH} population. The earlier infall times partially explains the excess of low mass satellites that merged to centrals of low f_{SH} , as galaxies that infall at earlier times will have, at fixed total mass, a larger fraction of their baryons in the form of gas compared to a satellite that infalls later and have had the time to turn more of their gas into stars.

Moreover, the earlier infall times for merged satellites in centrals with low stellar halo content are also consistent with the time of rapid build up of the M_{200} and stellar halos in these objects according to Fig. 2.9. To guide the eye, the blue and red vertical lines denote the t_{50} of the low and high f_{SH} populations, respectively. This suggests that for the centrals with low f_{SH} no significant satellite infall has occurred since $z \sim 1$, consistent with the hypothesis of early assembled halos and implying that not many phase-space features such as stellar streams or substructures are expected in these hosts today. For high f_{SH} the incidence of young tidal features such as streams could be more common.

2.6 The in situ vs. accreted halos

It is commonly assumed that the majority of the stars in stellar halos were contributed by a single most massive event (D’Souza and Bell, 2017; Deason et al., 2016). We explore this for our sample in Fig. 2.11 where for each central in our low and high f_{SH} subsample we select the most massive (in stars) merged satellite over their entire history. For such an event, we record the infall time and its maximum stellar mass, $M_{*,\text{sat}}$. By comparing $M_{*,\text{sat}}$ to the mass of the stellar halo at $z = 0$ we compute the fraction of the stellar halo mass that could have been brought in by the most massive merger event (y -axis). Note that this is an upper limit since some of the stars could have been deposited onto the central galaxy and not in the stellar halo itself (that is why some of the points scatter above the 1 line). We find that most of the objects sit near a ratio of 1, especially for the centrals with high f_{SH} . However, there are a large number of systems where the fraction of stars in the most massive merger is only a minor contributor, meaning that the stellar halo mass was either built by more than one event or it has a completely different origin not associated to accretion from satellites.

Further exploration of the systems with $M_{*,\text{sat}}/M_{\text{SH}} < 0.1$ demonstrated that a large fraction of the stars were born in situ and not accreted from satellites. This seems to occur more frequently in our centrals with low fraction of stellar halos (blue dots in Fig. 2.11) and earlier assembly (low t_{inf}). In practice, we followed Rodriguez-Gomez et al. (2016) to determine the origin of stellar particles, where a star is labeled “in situ” if it belonged to the main branch of the progenitor tree at the time when it was born, or “accreted” if it was formed in a different substructure. The contribution of in situ stars to stellar halos have

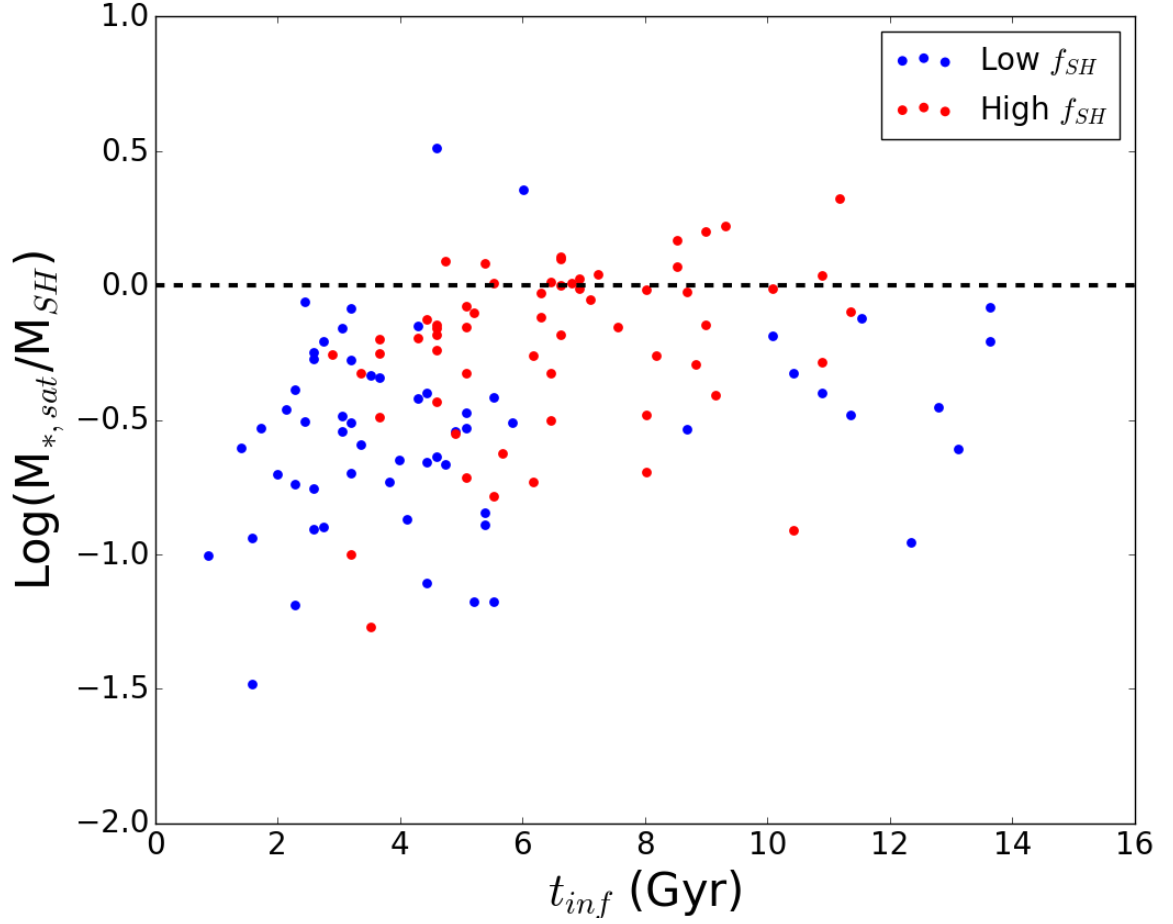


Figure 2.11: Fraction of the total mass of the stellar halo that is contributed by the most massive accretion event as a function of the infall time of such an accreted satellite. In galaxies with high stellar halo fractions (red dots), the stellar halo mass is dominated by that single accretion event, as seen by the proximity to the horizontal line. For galaxies with low stellar halo fraction (blue dots) instead, the distribution is much wider, with cases where the most massive accretion event contributed less than 10% of the total halo mass, suggesting a fundamental difference in the build up of the stellar halos of these two samples.

been suggested before, both in simulations (e.g., Zolotov et al., 2010; Purcell et al., 2010; Font et al., 2011; Tissera et al., 2013) and also in observations of the Milky Way, based for example on metallicity and kinematics difference between the inner halo –presumed to be formed in situ– and the external stellar halo –mostly accreted– (e.g., Nissen and Schuster, 2010; Carollo et al., 2007, 2010). In Illustris, the in situ component of stellar halos seems significant for a large number of objects, especially those with a relatively low fraction of stellar halo.

This is shown more clearly in the left panel of Fig. 2.12, where we show the median surface brightness profile for low and high f_{SH} subsamples (solid line) separated into the in situ contribution (dotted line) and accreted (dashed line). Here, we rotate each galaxy to be face-on (although our results do not depend strongly on this) and add the g -band luminosity of all stars contributing in each radial annulus. The luminosity is then normalized by the area of each annulus and the galaxies are assumed to be at a distance 7 Mpc to convert to apparent magnitude. Vertical shaded areas indicate the regions within twice the average half mass radius of the stars in each subsample. By definition, the stellar halo considered in this work extends outside the indicated shaded rectangles.

In the case of centrals with low stellar halo content (blue curves), the in situ population dominates the profile in the inner galaxy region, as expected, but beyond the optical radius as well, closely following the solid (all stars) line out to very large distances. For instance, one can consider the radius where the in situ and the accreted population contribute equally to the total profile, indicated by a blue vertical arrow, which reads $r \sim 45$ kpc in the case of the low f_{SH} sample. Instead, for the galaxies with a massive

stellar halo (red curves), the transition radius occurs almost at the edge of the galaxies, or $r \sim 18$ kpc, being accretion-dominated throughout most of the stellar halo component.

For comparison, we include in the left panel of Fig. 2.12 the observed density profile of M101 from Merritt et al. (2016), which seems to agree well with the average in situ component in the low f_{SH} in Illustris. Although our simulations do not have an analog with such a low stellar halo component as measured for M101 (see Fig. 2.5), it is interesting to see that the in situ distribution of stars predicts such a similar overall shape for this diffuse component. If Illustris indeed overestimates the accreted contribution due to the larger number of dwarf galaxies predicted with respect to observations, *there is some room to suggest that the halo of M101 and galaxies alike might be the ideal place to study this elusive in situ component in stellar halos.*

The different origins predicted for the stellar halos of galaxies with low and high fraction of stars on their halos are also evident in the metallicity profile shapes. Right panel of Fig. 2.12 shows the metallicity profile predicted for all stars (solid) and the in situ (dotted) and accreted (dashed) components. As expected, the in situ stars have a larger metallicity compared to the accreted component since they were born in a more massive progenitor. However, for galaxies in the low f_{SH} sample there is an intrinsic steep negative slope in the change of metallicity with radius and since it dominates out to large radii, the overall metallicity profile changes rapidly as we move outwards. By contrast, in the high f_{SH} sample, the accreted component dominates and has a more shallow slope as a product of the mixing of material of stripped satellites at different radii. This agrees with and extends previous results on stellar halos of early types galaxies presented in Cook et al. (2016). *Our*

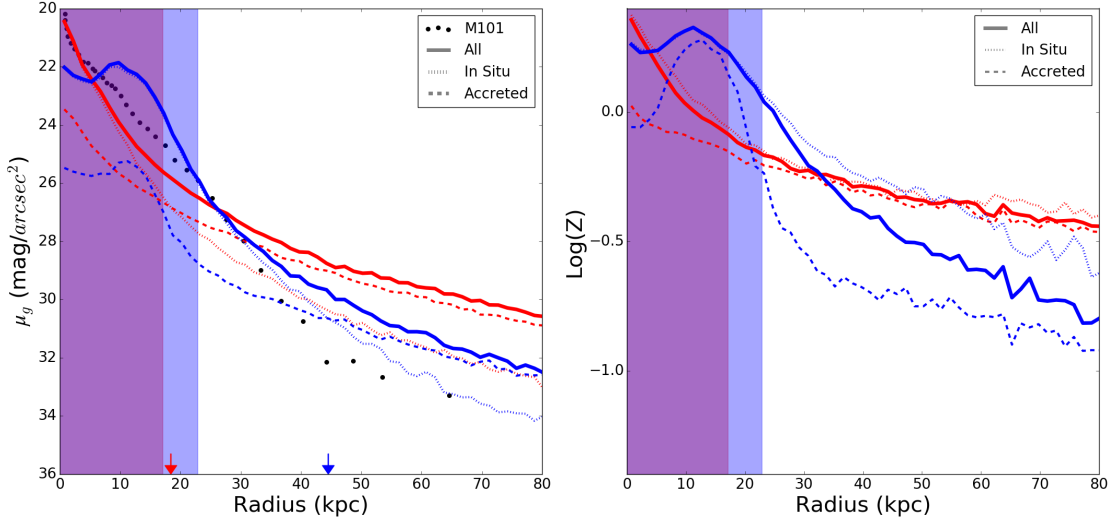


Figure 2.12: *Left*: Contributions from the in situ (dotted) and accreted (dashed) populations to the total surface brightness profile in the g-band (solid). The transition from in situ dominated to accreted dominated regime for galaxies with high f_{SH} (red curves) occurs roughly at the optical edge of the galaxy (green vertical region shows twice the average half-mass radius of the stars in the sample). In galaxies with low stellar halo fractions (blue lines) that transition takes place much further out, $r \sim 45$ kpc, indicating that in situ formed stellar halo strongly dominate the inner halos in these galaxies. *Right*: Median metallicity profiles expected for the stellar halos in our low and high f_{SH} sample. A much steeper radial gradient in the inner halo might be the smoking gun of a preferentially in situ-formed halo.

results indicate that a steep metallicity gradient may be the smoking gun of a mostly in situ formed stellar halo. Such profiles are expected to be more common around galaxies with low fraction of mass on their stellar halos, but the signature is expected to be independent of mass content.

2.7 Summary and Discussion

We use the Illustris cosmological hydrodynamical simulations to study the assembly of stellar halos in galaxies of mass comparable to the MW within the Λ CDM scenario. In particular, for a narrow range of virial halo mass $M_{200} = 8 \times 10^{11} - 2 \times 10^{12} M_{\odot}$ we focus on the relative amount of stellar mass in the extended halos normalized to the stars in the central galaxy, $f_{\text{SH}} = M_{*,\text{SH}}/M_{*,\text{gal}}$. Stellar halo mass is calculated as all stellar mass within the virial radius that is beyond twice the half mass radius of the stars (considered the galaxy) and is not associated to satellites. Our results can be summarized as follows:

- Simulated stellar halos span a large range in $f_{\text{SH}} \sim 5\text{-}50\%$ with a median value $\langle f_{\text{SH}} \rangle \sim 21\%$. Stellar halo masses for this virial mass range can therefore be as low as $M_{*,\text{SH}} = 2 \times 10^9 M_{\odot}$ or as massive as $6 \times 10^{10} M_{\odot}$. Simulated halos can be fairly oblate, with median $\langle b/a \rangle \sim 0.87$ and $\langle c/a \rangle \sim 0.49$, where a, b, c are the major to minor principal axes of the inertia tensor for the stars. This departure from sphericity can generate significant differences in the derived surface brightness profiles of the halos, with face-on objects being up to two magnitudes fainter than the same objects when viewed edge-on. Caution should therefore be exercised when analyzing observed profiles of galaxies at different inclination angles.
- Simulations present a large variety of stellar halo profiles and masses which can accommodate the diversity of observed stellar halos to a certain degree. However, when considering the specific shape of the profiles, simulated galaxies in Illustris are in tension with the most steeply declining surface brightness profiles such as those observed in NGC1042 and NGC3351. The excess of stars at large distances in the simulations

can partially be attributed to the overly massive low mass end of the mass function, meaning that merging satellites contribute more stars than they should to the stellar halos. Yet it is encouraging that galaxy formation models are able to predict a set of distinct behaviors for the surface brightness profiles of extended halos, some with relatively shallow profiles whereas other galaxies in the same mass range might show a rather rapidly declining stellar light in their outskirts (see also Pillepich et al., 2014).

- We study the origin of this diversity of stellar halos by selecting the 5% tails of low and high stellar halo fractions, f_{SH} . We find fundamental differences in the properties of the central galaxies in each subsample, with objects with low stellar halo content (low f_{SH}) being in general more disk-dominated and star-forming whereas high f_{SH} centrals are spheroidals and not forming stars. On the other hand, environment seems not to play a major role in the assembly of the stellar halo, as the present-day density of galaxies around centrals, as characterized by Σ_5 , of low and high f_{SH} galaxies are remarkably similar. These findings are in good agreement with observations.
- Galaxies with low stellar halo content form in halos that assemble more rapidly, reaching half their present day mass on average by $z_{50} = 1.5$. In contrast, galaxies with a massive stellar halo are more typical in late-forming halos, with a median redshift for the assembly of half their mass $z_{50} = 0.73$. The scatter from object to object is, however, large. Similarly, satellites that get tidally disrupted building the stellar halos infall earlier and are less massive in galaxies with low mass stellar halos. Average infall times for low and high stellar halo centrals are $\langle t_{\text{inf}} \rangle = 2.6$ and 5.2 Gyr, respectively.

- In Illustris, stellar halos can have a significant fraction of in situ formed stars. Those stars form over time within ~ 30 kpc of the center, but are located today out to ~ 100 kpc, favoring a dynamical scenario for their launch into their more extended orbits. In situ formed halos decline steeply with radius and can dominate the contribution in low f_{SH} objects. We argue therefore that extreme objects such as M101 and the lowest stellar halo galaxies are the prime candidates to observationally study the in situ formed stellar halos. Furthermore, we predict that stellar halos formed mainly by contribution of in situ stars should have a markedly steep metallicity profile that can be used as a 'smoking gun' for identification in observations.

The diversity of stellar halo shapes is an interesting new avenue to recover information on the past merger history of galaxies through their present day properties. Numerical simulations seem to naturally reproduce a large variety of shapes and mass for stellar halos in the Milky Way mass regime. Whether the simulated diversity matches observations or not is not yet settled. To first order, galaxies with little or no stellar halo are difficult to find in cosmological simulations within Λ CDM where mergers are a prevalent feature. Biases and sky subtractions in observations that push the boundary of observability are challenging and difficult to quantify, which, in addition to the scarcity of objects observed to very faint surface brightness, hinders a correct interpretation of the comparison between observations and simulations. Current efforts such as GHOSTS (Radburn-Smith et al., 2011b) and Dragonfly observations (Merritt et al., 2016) have been transformative. But more complete samples of galaxies at a fixed mass and varied morphology will lay the ground for a more fair comparison with models. From this perspective, projects targeting the faint outskirts

of galaxies in large numbers are a necessity. The HERON Survey (Halos and Environments of Nearby Galaxies, Rich et al., 2017) and future missions such as WFIRST might help define the expected global properties of stellar halos and whether theoretical predictions are (or not) a good match to the observed Universe.

Chapter 3

Cosmological insights into the assembly of the radial and compact stellar halo of the Milky Way

3.1 Abstract

Recent studies using Gaia DR2 have identified a massive merger in the early history of the Milky Way (MW) whose debris is dominated by radial and counterrotating orbits. This event, dubbed the Gaia-Enceladus/Gaia-Sausage (GE/GS), is also hypothesized to have built the majority of the inner stellar halo. We use the cosmological hydrodynamic simulation Illustris to place this merger in the context of galaxy assembly within Λ CDM. From ~ 150 MW analogs, $\sim 80\%$ have experienced at least one merger of similar mass and infall time as the GE/GS. Within this sample, 37 have debris as radial as the GE/GS,

which we dub the Ancient Radial Mergers (ARMs). Counterrotation is not rare among ARMs, with 43% having $> 40\%$ of their debris in counterrotating orbits. However, the compactness inferred for the GE/GS debris given its large radial orbital anisotropy, β , and its substantial contribution to the stellar halo are difficult to reproduce. The median radius of ARM debris is $r_{*,deb} \simeq 45\text{kpc}$, while GE/GS is thought to be mostly contained within $r \sim 30\text{ kpc}$. For most MW analogs, few mergers are required to build the inner stellar halo, and ARM debris only accounts for (median) $\sim 12\%$ of inner accreted stars. Encouragingly, we find one ARM that is both compact and dominates the inner halo of its central, making it our best GE/GS analog. Interestingly, this merger deposits a significant number of stars ($M_* \simeq 1.5 \times 10^9 M_\odot$) in the outer halo, suggesting that an undiscovered section of GE/GS may await detection.

3.2 Introduction

Traces of past accretion events in our Galaxy are imprinted as tidal stellar streams in the outer halo of the MW (Belokurov et al., 2006), where long dynamical times allow substructure to remain recognizable for several Gyr. The inner regions of our halo, on the other hand, are characterized by shorter dynamical times, $\leq 100\text{ Myr}$, requiring full phase-space information to identify the debris of once-coherent structures (Helmi and White, 1999; Helmi et al., 1999; Bullock and Johnston, 2005). The availability of data from Gaia DR2 (Gaia Collaboration et al., 2018), including positions and velocities for millions of stars, unveiled the remnant of one of the largest accretion events in the history of our Galaxy, the Gaia Enceladus (Helmi et al., 2018) or Gaia Sausage (Belokurov et al., 2018) event.

Since GE and GS were discovered independently in different studies and it is difficult to establish precise membership criteria, the relation between the two has not always been clearly discussed in the literature (although see Helmi, 2020). It is nonetheless evident that there is a large degree of overlap in the stars belonging to GS and GE (Myeong et al., 2019; Matsuno et al., 2019; Koppelman et al., 2019). The motion of GE/GS stars is largely eccentric, with radial anisotropy $0.8 < \beta < 0.9$ (Belokurov et al., 2018), as well as counterrotating (Helmi et al., 2018), both characteristics enhancing the profile of GE/GS as the result of a past accretion event.

Beyond its kinematics, the GE/GS structure also sticks out because of its high stellar metallicity compared to other halo stars. Cross-correlated data with other surveys such as SDSS, APOGEE or H3, among others, measure a metallicity range $-1.7 < [Fe/H] < -1$ for GE/GS stars (Helmi et al., 2018; Belokurov et al., 2018; Conroy et al., 2019). This, together with the trend measured for $[\alpha/Fe]$ vs. $[Fe/H]$, advocates for a somewhat massive progenitor, with stellar mass estimates placing GE/GS at infall comparable to the SMC, $5 \times 10^8 \leq M_*/M_\odot \leq 5 \times 10^9$ (Helmi et al., 2018; Vincenzo et al., 2019; Myeong et al., 2019; Mackereth et al., 2019). Although GE/GS debris is often referred to “high-metallicity”, we hasten to add that this is only relative to other stellar halo stars, which are typically more metal poor. A comparison to external galaxies stellar halo metallicities still places the MW’s stellar halo as relatively metal poor (e.g., see Table 1 in (Bell et al., 2017) or (D’Souza and Bell, 2018b) Fig. 3), in agreement with a somewhat quiet merger history expected in more recent times (Elias et al., 2018).

The stars in GE/GS are old and can be used to constrain the time of the merger to occur on average $\sim 8\text{-}10$ Gyr ago (age of the Universe $t \sim 4\text{-}6$ Gyr). This is assuming that the progenitor stopped forming stars at the time of the merger with the MW, a hypothesis that we briefly explore further in this paper.

If these estimates are correct, the GE/GS event should have had important consequences for the present-day structure of the MW. For instance, the merger with a massive GE/GS would stir up the proto-disk of the MW, perhaps triggering dynamical heating and the posterior build up of the old thick disk in our Galaxy (Helmi et al., 2018; Belokurov et al., 2019; Haywood et al., 2018); a hypothesis confirmed by cosmological simulations identifying GE/GS analogs (Bignone et al., 2019; Grand et al., 2020). These studies also suggest that the gas-rich nature of high-redshift mergers would simultaneously imply an enhancement of the MW’s star formation rate as the GE/GS coalesces into the central regions, a prediction for which there is already observational evidence (Kruijssen et al., 2019). Somewhat more surprising is the fact that such a catastrophic encounter occurred at all in the MW, whose dominant and dynamically cold stellar disk would not necessarily convey the idea of a major merger happening at all during the past assembly history of our Galaxy.

Arguably, the most important contribution of GE/GS is to the stellar halo of the MW. While locally – within a few kpc of the solar neighborhood – stars belonging to GE/GS completely dominate the stellar halo, its general contribution is less well constrained. There is some consensus that GE/GS is an important contributor to the nearby stellar halo, with estimates in the range 30%-50% within the inner ~ 25 kpc of the Galaxy (Lancaster et al., 2019; Mackereth and Bovy, 2019). Moreover, the pile-up of stars in the apocenter of GE/GS

may solely be responsible for the “break” radius in the 3D density of the MW’s stellar halo around $r \sim 25$ kpc. However, only a small fraction of the inferred mass for GE/GS has been positively identified. Where are the rest of the stars brought in by GE/GS today in our Galaxy?

Numerical simulations indicate that mergers similar in mass, infall time, and radiality to GE/GS are rare (Mackereth et al., 2019; Bignone et al., 2019), especially when requiring that they contribute such a large fraction of the inner halo (Fattahi et al., 2019). Typically, the accreted stellar halos of MW-like galaxies are built (in mass) from more than one progenitor (Cooper et al., 2010; Pillepich et al., 2014; Elias et al., 2018; Tissera et al., 2018; Monachesi et al., 2019), with important contributions from at least a few. The metallicity, however, seems a better indication of the most massive merger event (D’Souza and Bell, 2018a,b). Given the suggested rarity of the event, large statistical samples of simulated galaxies are required to shed light on the nature and fate of GE/GS-like events within the Λ CDM model.

In this paper we take advantage of the large population of MW analogs in the Illustris simulations (Vogelsberger et al., 2014b,a) to study the frequency of events comparable to GE/GS in the simulations (Sec. 3.4); the typical morphology and properties of their remnants (Sec. 3.5); and their contribution to the stellar halo, including inner and outer regions (Sec. 3.6). We conclude with results on the unidentified segment of the GE/GS debris and summarize our results in Sec. 3.7.

3.3 Numerical Simulations

Illustris is a cosmological hydrodynamical simulation run with the AREPO code (Springel, 2010) and covering a cubic volume with 106 Mpc on a side (Vogelsberger et al., 2014b,a; Genel et al., 2014). Illustris cosmological parameters are consistent with the Λ CDM model as determined by WMAP-9: $\Omega_m=0.2726$, $\Omega_b=0.0456$, $\Omega_\Lambda=0.7274$, and $H_0=70.4$ km/s/Mpc (Hinshaw et al., 2013). The project¹ includes a suite of simulations run with different numerical resolutions and with/without the inclusion of baryons. In this work, we use data from the largest resolution baryonic run, Illustris-1, featuring a mass per particle of 1.6 and $6.3 \times 10^6 M_\odot$ for baryons and dark matter, respectively and a gravitational softening length 0.7 kpc or better.

Gravitational forces in AREPO are calculated via an oct-tree approach while the hydrodynamic equations are solved by means of a finite-volume moving mesh technique (Springel, 2010; Weinberger et al., 2019). Besides cooling and heating of the gas, a variety of baryonic physical processes are added to the code to track the formation and evolution of galaxies. The main features of the model, including the treatment for heating and cooling, star formation and stellar feedback are described in detail in Vogelsberger et al. (2013, 2014a). In what follows we briefly summarize the main aspects of the baryonic treatment in Illustris, referring the interested reader to the aforementioned work for more specific information.

The impact of radiation and reionization is followed via a time-dependent spatially-uniform ultraviolet background according to Nelson et al. (2015). Gas is allowed to cool

¹<https://www.illustris-project.org>

to $T \sim 10^4$ K including H, He and metal cooling lines. Gas above a density threshold $n_H=0.13 \text{ cm}^{-3}$ is put into an effective equation of state modeling a two-phase fluid and is allowed to transform into stars stochastically with 1% efficiency per local dynamical time (Springel and Hernquist, 2003). The model adopts a Chabrier initial mass function for stars (Chabrier, 2003) and follows the subsequent stellar evolution according to STARBURST99 (Leitherer et al., 1999), keeping track of stellar lifetimes, mass loss and metal production.

Two main sources of stellar feedback are included: stellar winds and supernova explosions. Supernovae play a major role in shaping the baryonic content of galaxies and are implemented in Illustris in kinetic form, adding 100% of the available energy due to supernovae as a velocity-scaled wind (that depends on the local dark matter velocity dispersion) and a mass-loading inferred from the available supernova energy. Additionally, all halos with virial mass above $M_{200} = 7 \times 10^{10} M_\odot$ are seeded with a supermassive black hole which is allowed to grow and exert feedback on the surrounding interstellar and intergalactic gas according to two feedback modes: quasar (high accretion rate) and radio-mode (low accretion rate) following Sijacki et al. (2015). We use virial quantity definitions corresponding to 200 times the critical density of the Universe.

The *subfind* halo finder is used to identify halos and galaxies on the fly in Illustris (Springel et al., 2001; Dolag et al., 2009). First, groups are identified using space information via the Friends-of-Friends (FoF) algorithm (Davis et al., 1985). Subsequently, self-gravitating subhalos are identified within these groups, giving rise to a catalog of substructure with assigned dark matter and baryonic content. The object at the center of the gravitational potential of each group is defined as the “central” galaxy, while all other sub-

structure are considered “satellites”. Following previous work in Illustris, we use a fiducial radius of $r \leq 2 * r_h$ to assign particles to galaxies and compute all “galaxy” properties (stellar and gas mass, angular momentum, etc.); with r_h defined as the half mass radius of the stars for each object. Particles beyond this radius that are not associated to satellites and are within the virial radius of each central are considered part of the stellar/gaseous halos. We use the SUBLINK trees to trace the evolution of each subhalo through the 135 snapshots of the simulation.

Illustris has been shown to reliably reproduce global properties of the galaxy population such as stellar mass functions, stellar mass-halo mass relations, specific star formation rates, distribution of satellite galaxies, HI column density distribution, color distribution, morphology bimodality, the metallicity-environment relation etc. back to $z=7$ (Genel et al., 2014; Sales et al., 2015; Rodriguez-Gomez et al., 2015; Snyder et al., 2015; Genel, 2016; Kauffmann et al., 2016), and unusual objects such as shell galaxies (Pop et al., 2017, 2018).

3.3.1 Milky Way analogs

We select an initial sample of (central galaxies) MW-analogs in Illustris based on virial mass, $8 \times 10^{11} \leq M_{200} \leq 2 \times 10^{12} M_{\odot}$. A statistical analysis of the stellar halos of this sample has already been presented in Elias et al. (2018). We use the κ_{rot} parameter to quantify the stellar morphology of our galaxies. After rotating each galaxy with their total angular momentum pointing along the z -direction, κ_{rot} compares the total kinetic energy of stars to the energy in co-rotation around the z -axis (see Sales et al., 2010, 2012, for details). By construction, large κ_{rot} values indicate that a large fraction of the stellar mass is in a

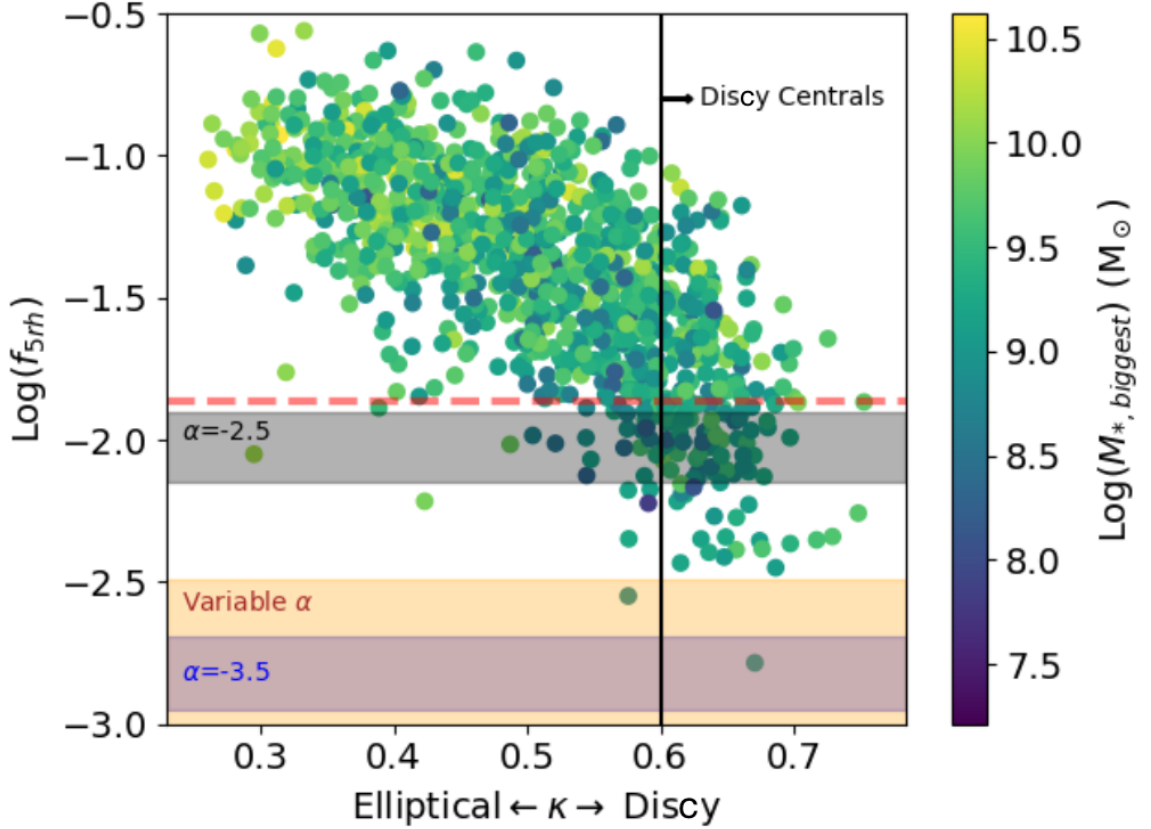


Figure 3.1: Stellar halo fraction measured for $r > 5r_h$ (f_{5rh}) vs. morphology index κ_{rot} for MW-like centrals, colored by the stellar mass of their most massive merger. All galaxies in the sample have experienced at least one merger with a satellite of mass $M_* \geq 10^8 M_{\odot}$. Disk-dominated centrals (large κ_{rot} values) have a lower fraction of mass in their stellar halo component, albeit with significant dispersion. We define a sample of disk-dominated centrals (154 objects) selecting those with $\kappa_{\text{rot}} > 0.6$, indicated with the vertical line. The red horizontal line and the shaded regions represent different estimates of f_{5rh} for the MW (see text for more details). The MW’s stellar halo seems consistent with the lowest end of stellar halo fractions in Illustris.

disk component supported by rotation. Furthermore, κ_{rot} has been shown to correlate well with other techniques to quantify morphology such as dynamical decomposition of galaxies (Abadi et al., 2003b; Scannapieco et al., 2009). A total of $N=1115$ galaxies fall in our virial mass range.

In Fig. 3.1 we begin to characterize the stellar halos of this sample of MW-analogs via f_{5r_h} , defined as the fraction of stellar mass beyond $5r_h$ compared to the central galaxy following Merritt et al. (2016). As discussed in Elias et al. (2018), the fraction of stellar halo correlates with morphology such that spheroid-dominated galaxies have larger fractions of their mass in their extended halos compared to their more disk-like counterparts. The color-coding in Fig. 3.1 further indicates that at fixed stellar mass, galaxies with more massive stellar mergers also show a more prominent stellar halo, in agreement with previous results (Monachesi et al., 2019; D’Souza and Bell, 2018b).

To select closer analogs to the MW we impose a more stringent cut in disk-like morphology: $\kappa_{\text{rot}} > 0.60$. This is indicated in Fig. 3.1 as all points to the right of the vertical black line. With this criterion, our sample of disk-dominated MW analogs consists of 154 central galaxies. The stellar halo fraction of this sample is lower than considering all galaxies in the virial mass cutoff, which is in agreement with the MW having only a modest stellar halo. The total mass of the MW stellar halo is not well constrained. Different measurement methods as well as definitions of the stellar halo have resulted in significantly varying stellar halo values in the $4.0 \times 10^8 - 1.4 \times 10^9 M_\odot$ range (see e.g. Deason et al. (2019); Carollo et al. (2010); Bell et al. (2008) for measurements and Helmi (2008); Belokurov (2013) for reviews of the literature).

Given these uncertainties, shaded regions in Fig. 3.1 indicate several estimates for the fraction of light in the MW stellar halo beyond $5r_h$ using different assumptions. The dashed red horizontal line corresponds to the quoted estimate for the MW in (Merritt et al., 2016). Assuming the mass of the stellar halo, $M_{SH} = 1.4 \pm 0.4 \times 10^{10} M_\odot$ (Deason et al., 2019) and for the disk $M_{disk} = 6.43 \pm 0.63 \times 10^9 M_\odot$ (McMillan, 2011), the orange shaded region is calculated using a triple power law profile for the stellar halo mass density with slopes measured in previous studies in the literature: $\alpha = [-2.7, -2.9]$ for $0 < r \leq 25$ (Xue et al., 2015), $\alpha = [-4.6, -3.8]$ for $25 < r \leq 50$ (Pillepich et al., 2014) and $\alpha = [-6.5, -5.5]$ for $50 < r \leq 100$ (Deason et al., 2014). For simplicity, we also include in black and purple regions the stellar halo fractions assuming a single power law with slopes $\alpha=-2.5$ and $\alpha=-3.5$, respectively. The different f_{5rh} estimates tend to populate the lower end of our simulated centrals with disk-like morphology, and hint at an overly-efficient formation of stellar halos in Illustris, as suggested by previous work (D’Souza and Bell, 2018b). In what follows, we will include only accreted stars (as opposed to in-situ) in our definition of stellar halos to partially mitigate this issue.

3.4 GE/GS like mergers for Milky Way analogs

As discussed in Sec. 3.2, the stellar mass estimates for the GE/GS event are in the range $5 \times 10^8 \leq M_* \leq 5 \times 10^9 M_\odot$. We find that in our sample of disk MW analogs, 80% have experienced at least one merger with a satellite of average stellar mass in this range ($M_* \geq 5 \times 10^8 M_\odot$). The median stellar mass of the most massive merger experienced by a central in our sample is $M_* \simeq 1.25 \times 10^9 M_\odot$, suggesting that merger events of mass similar

to GE/GS are, in fact, common for Milky Way-like galaxies within Λ CDM, in agreement with previous simulation findings (Bose et al., 2019) and observational results (Harmsen et al., 2017; D’Souza and Bell, 2018a).

The selected merged satellites with mass comparable to GE/GS display a wide range of infall times t_{inf} and orbital anisotropies β as shown in Fig. 3.2. Here β is computed as

$$\beta = 1 - \frac{v_T^2}{2v_R^2} \quad (3.1)$$

where v_T is the mean velocity in the tangential direction and v_R is the mean velocity in the radial direction of the satellite debris at $z = 0$. This quantifies the degree of radial anisotropy in the stellar orbits, with $\beta \sim 1$ for fully radially-biased systems while tangential motions correspond to $\beta = -\infty$ (Binney and Tremaine, 2008). Infall times are defined as the snapshot at which the galaxy reaches maximum total mass.

Fig. 3.2 also shows the corresponding histograms for both axes, indicating that early infall times ($t_{\text{inf}} < 5$ Gyr) and rather radial motions ($\beta > 0$) are the norm for this subsample of GE/GS mass-objects. Note that the early infall times obtained for these relatively massive merger events can be considered almost a selection effect in our sample. By selecting disk-dominated morphology for the central host galaxy, we drive a correlation with a low fraction of mass in the stellar halo and bias the infall redshift high for merger events, as shown in Elias et al. (2018) and expected for our Galaxy. Massive mergers that occur at late times, shown as light points on the right side of Fig. 3.2, are not as significant as they may first appear since the disk is more massive at those times. Thus, the mass ratio of the satellite to the central is still small enough to result in a disk morphology.

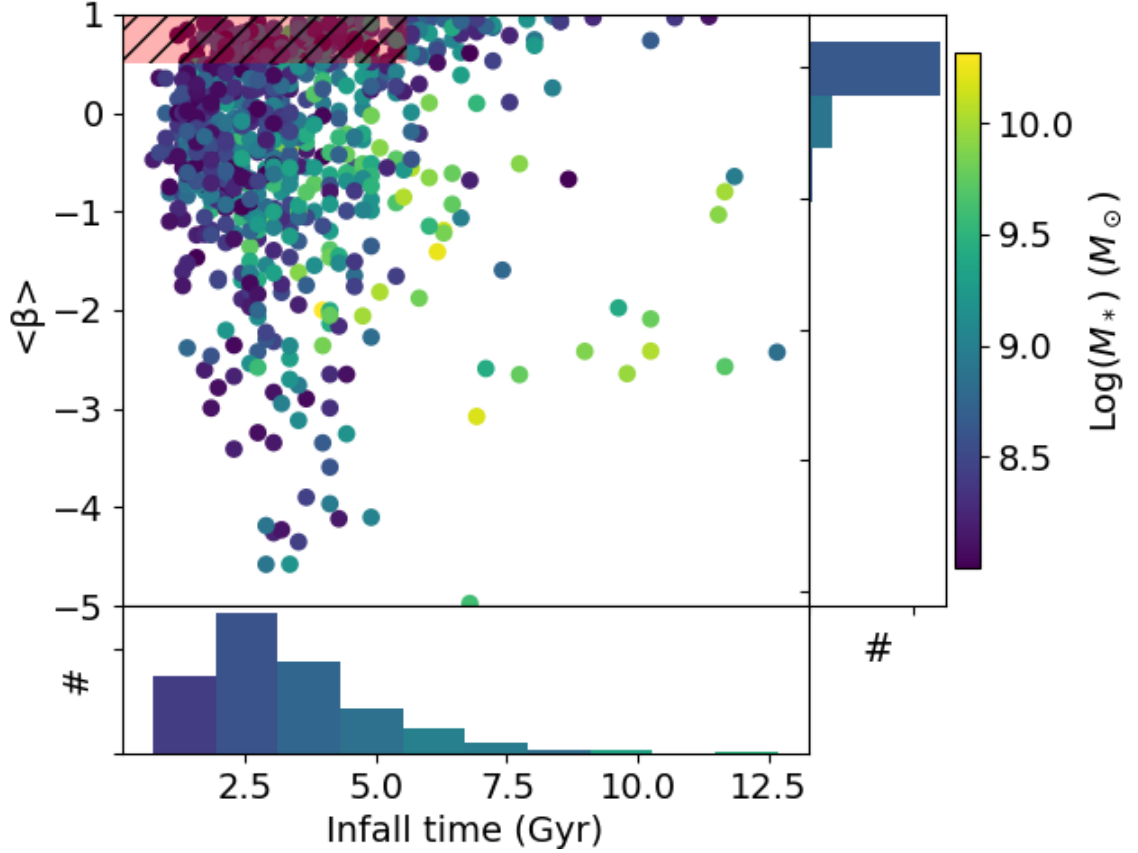


Figure 3.2: Average orbital anisotropy $\langle \beta \rangle$ vs. infall time t_{inf} (defined as the time of maximum total mass) for the stellar debris of all merged satellites in our disk-dominated centrals. Symbols are colored by maximum stellar mass of each satellite. Histograms along both axes show the individual distributions of t_{inf} and $\langle \beta \rangle$, color-coded by average satellite mass contributing to each bin. Earlier infall times and radially-biased debris are preferred in our sample of disky MW-analogs, although the distributions are wide. Inspired by the GE/GS debris, we study in detail a sample of massive ($M_* > 10^{8.5} M_\odot$), early ($t_{\text{inf}} < 6$ Gyr) and radial ($\beta > 0.5$) mergers, indicated by the shaded red box. We call them “Ancient Radial Mergers”, or ARMs for short.

Encouragingly, early infall times are also suggested from observations of GE/GS, with estimates of the event placing it at least 8 Gyr ago (Gallart et al., 2019; Helmi et al., 2018; Mackereth et al., 2019) based on a variety of arguments including the age of the youngest stars in the debris. Inspired by this, we refine our sample by defining GE/GS events to have $t_{\text{inf}} \leq 5.6$ Gyr (i.e., lookback time ≥ 8 Gyr).

Furthermore, Gaia measurements of identified stars belonging to GE/GS also indicate a largely radial orbit, with $0.8 < \beta < 0.9$ (Belokurov et al., 2018). We find that such extreme radial orbits are less common in our sample, with only 46 objects (or $\sim 6\%$) consistent with such measurement. However, the constraints on β may be softened by considering spatial variations along the orbit (as Gaia estimates are rather local to the solar neighborhood while simulated values pertain to the entire debris) and observational errors. Taking this into account, in what follows, we use $\beta > 0.5$ to select the most radial mergers in our disk MW-like galaxies. Satellites in this sample deposited a varying fraction of stars with $0.8 < \beta < 0.9$, varying from 8% to 26%.

Our final selection criterion, including cuts in mass ($5 \times 10^8 < M_* < 5 \times 10^9$), infall times ($t_{\text{inf}} < 5.6$ Gyr) and $\beta > 0.5$ is highlighted by a red dashed rectangle in Fig. 3.2, resulting in 37 MW analogs that have experienced a GE/GS-like merger. We refer to this sample of merged satellites as Ancient Radial Mergers (ARMs). Note that this definition is quite restrictive, and represents a very selective subsample of mergers compared to wider studies of stellar halo assembly in previous Illustris works (e.g., D’Souza and Bell, 2018b; Elias et al., 2018).

3.5 Diverse morphology and kinematics for the ancient merger debris

Our highly specialized sample of 37 ARMs demonstrates a considerable degree of diversity in their distribution and kinematics. To ease visualization, we choose four satellite galaxies that represent the variety of the entire sample. Fig.3.3 shows face-on and edge-on projections of these four galaxies, named Satellite 1,2,3, and 4 for simplicity and hereafter (or S1-S4 for short). White points represent both gas and star particles in the central galaxy, while red points represent the stellar debris of each satellite at $z = 0$. For instance, satellites S1 and S3 have extremely extended debris, with their once-bound stellar particles found today out to several hundred kiloparsecs. By contrast, S2 and S4 have relatively concentrated remnants. Given that the progenitors of these debris have a restricted range of masses, infall times, and orbits, the extreme degree of diversity found on their present-day distribution is somewhat surprising.

We can use these examples to shed light on the link between the GS and the GE events. As mentioned in Sec. 3.2, they are often referred to interchangeably in the literature but given their different identification criteria it is currently unclear if they are the same object. Our sample of satellites has been selected to have extremely radial remnants, which a priori suggests a similarity to the GS. However, in order to keep the analysis general, for now we place no constraints on the velocity with respect to the disk or whether this debris dominates the solar neighborhood, which both the GS and GE debris do.

Fig. 3.4 makes a direct comparison of the debris of our four selected ARMs in

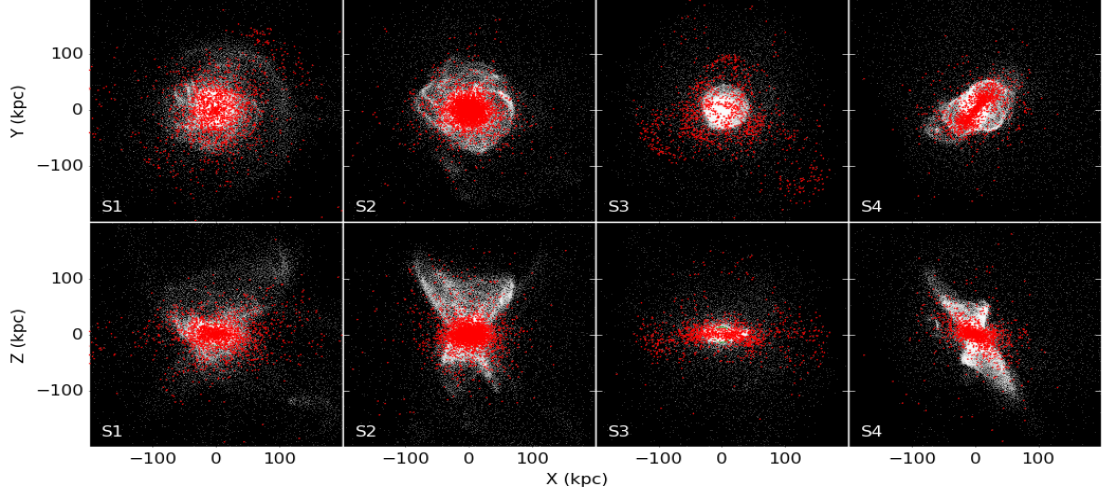


Figure 3.3: Face-on (top row) and edge-on (bottom row) projections of four representative disk-dominated galaxies with an ancient radial merger (ARM). ARM stellar debris is colored in red. Gas and stellar particles of the central are colored in white. Debris from ARMs can extend out to hundreds of kpc as in columns 1 and 3 (S1 and S3), or be very concentrated, as in columns 2 and 4 (S2 and S4).

Fig. 3.3, using the same identification space of the GE (top, Helmi et al., 2018) and the GS (bottom, Belokurov et al., 2018). All stars brought in by satellites S1-S4 are colored by their galactocentric distance today. The black points correspond to disk stars associated with our simulated centrals, selected by satisfying our disk criteria: $r_{xy} < 2r_h$, $|z| < 3\text{kpc}$, and $\text{circ} > 0.5$. Here $r_{xy} = \sqrt{x^2 + y^2}$, r_h is the half light radius, and circularity is defined as:

$$\text{circ} = \frac{j_z}{r \cdot v_{\text{circ}}} \quad (3.2)$$

where j_z is the angular momentum in the z-direction (oriented by the disk), r is the 3D radius and v_{circ} is the circular velocity of the particle.

Satellites S2 and S4 in Fig. 3.4 are good analogs to both GS and GE, demonstrating that it is possible within the ΛCDM framework to explain this remnant as a result of a single

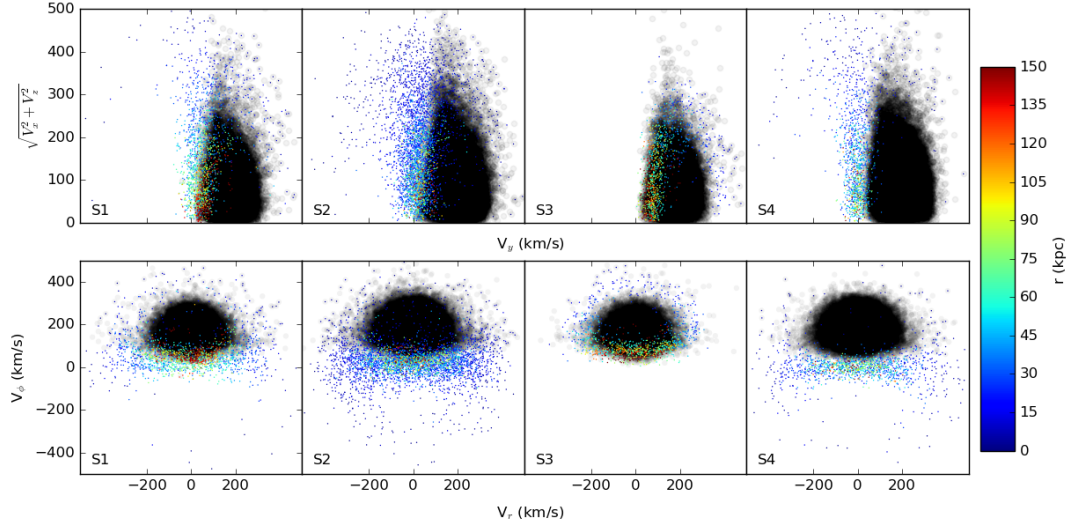


Figure 3.4: Decomposition of Satellites 1-4 in velocity space. Black points represent stars belonging to the disk, while colored points are stellar debris from S1-S4, colored by galactocentric distance as indicated on the right. Note that all stellar particles in the debris are included in the plot, even beyond 50 kpc, which is different from observational samples that are dominated by stars within $r < 50$ kpc. Our sample of massive, early and radial mergers (ARMs) frequently resemble both the Gaia Sausage (GS) *and* the Gaia Enceladus (GE), like the case of S2 and S4, suggesting a common origin for these structures. Lack of counter-rotating stars make examples S1 and S3 unlikely matches to GE/GS.

common event. On the other hand, S1 would not be a good candidate to GE but shows certain similarities to GS while S3 results in a debris with no resemblance to either GE or GS. The color gradient in the bottom row of Fig. 3.4 indicates that the accreted stars have larger velocities at smaller galactocentric radii (bluer colors).

3.5.1 Present-day radial extent of the debris

There is a growing body of evidence suggesting that the GE/GS is almost completely contained within a galactocentric radius of ~ 25 -30kpc, which coincides with the ‘break’ radius of the stellar halo in the MW (Deason et al., 2018; Lancaster et al., 2019). A

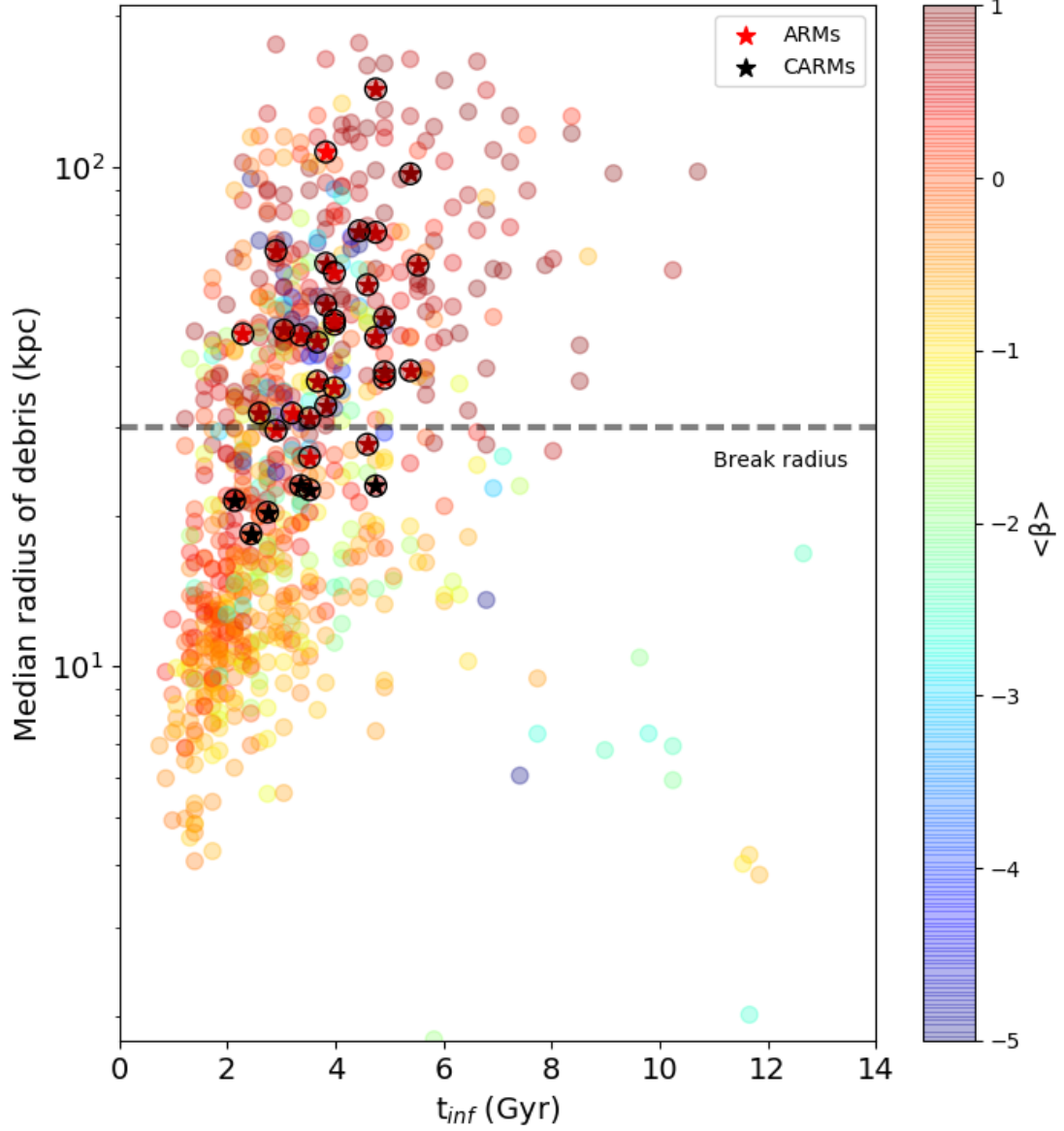


Figure 3.5: Radius encompassing 50% of stars in merged satellite debris, $r_{*,\text{deb}}$, vs. infall time for our disk MW-like galaxies. Symbols are color-coded according to the median anisotropy of the stars, $\langle \beta \rangle$, with all mergers shown in semi-transparent circles and ARMs highlighted in solid starred symbols. Naturally, more radial orbits (larger $\langle \beta \rangle$) corresponds to more extended debris. This is at odds with the compact distribution of stars inferred observationally for GE/GS. The horizontal dashed line indicates the ‘break’ radius in the MW stellar halo, presumably associated with the outer edge of GE/GS. We define a set of Compact ARMs (or CARMs), by requiring additionally $r_{*,\text{deb}} < 25$ kpc.

quick inspection of Fig. 3.3 suggests a wide range in the morphology and radial extension of the remnants for the S1-S4 satellite examples. In Fig. 3.5, we quantify the radial extent of the debris in our full sample of ancient radial mergers (ARMs, solid red points). For reference, we also show all satellites that have merged with our sample of 154 disk MW-like centrals (semi-transparent symbols). The radial extent is characterized by $r_{*,\text{deb}}$, the radius containing 50% of the stars in each mergers' debris and symbols are color-coded by their median orbital anisotropy $\langle \beta \rangle$.

There is a clear trend between the radial extent of the debris and its radial anisotropy: the more radial the orbit the more extended the debris. This trend can be understood in terms of orbital dynamics, where at a fixed angular momentum (which is given by the orbit of the satellite), a circular orbit will minimize the radii (see for instance Eq. 3.25b in Binney and Tremaine, 2008). Large anisotropy values ($\beta > 0$) correspond to radially-biased orbits with large eccentricities, explaining the more extended distribution of stars in such orbits.

In this context, the rather compact distribution inferred for GE/GS ($r < 30$ kpc) combined with its very large measured orbital anisotropy ($\beta \sim 0.95$) makes it a rather rare event. More than 80% of the simulated objects with infall times and orbital anisotropies similar to the GE/GS (labelled ARMs) have $r_{*,\text{deb}} \geq 45$ kpc, too large to be considered analogs of the observed GE/GS. We note that the average stellar mass radius of the disk-dominated MW analogs is $r_h \sim 10$ kpc, indicating that, typically, the debris of early radial mergers is expected to be quite extended, similar to those illustrated for S1 and S3 in Fig. 3.3.

Instead, GE/GS in the MW presents a compact morphology, perhaps more reminiscent of that of S2 in our sample. Therefore, in what follows we define a further subsample of our ARMs set by additionally requiring that their debris at $z = 0$ fulfills the criterion $r_{*,\text{deb}} < 25$ kpc. The resulting 6 satellites have on average 80% of their stellar debris within ~ 36 kpc, in better agreement with estimates for GE/GS. We hereafter refer to this subsample as compact ancient radial mergers (CARMs), highlighted with black stars in Fig. 3.5.

Besides the debris' radial extension, our numerical simulations give predictions of other dynamical and stellar properties for our sample of ARMs. Fig. 3.6 further explores the orbits (top), metallicity-stellar age (middle) and circularity (bottom) at $z = 0$ of the stars belonging to satellites S1-S4 (left to right). We use $[\alpha/\text{Fe}] = 0.2$ to compute the simulations total metallicity Z into the iron abundance $[\text{Fe}/\text{H}]$ following Salaris and Cassisi (2005). Stars are color coded according to their present-day distance, using the same scale than in Fig. 3.4.

3.5.2 Age and metallicity of the debris

The middle row in Fig. 3.6 shows a wide range of metallicities associated to stars in a single satellite. This range overlaps well with the estimated metallicity of GE/GS, $\log([\text{Fe}/\text{H}]) \sim -1.5$ (Helmi et al., 2018), although we find that ARMs stars tend to be slightly more metal rich than the constraints for GE/GS. For instance, the median metallicity of all stars belonging to our identified ARMs is $\log([\text{Fe}/\text{H}]) \sim -0.72$. Likely, this upwards shift

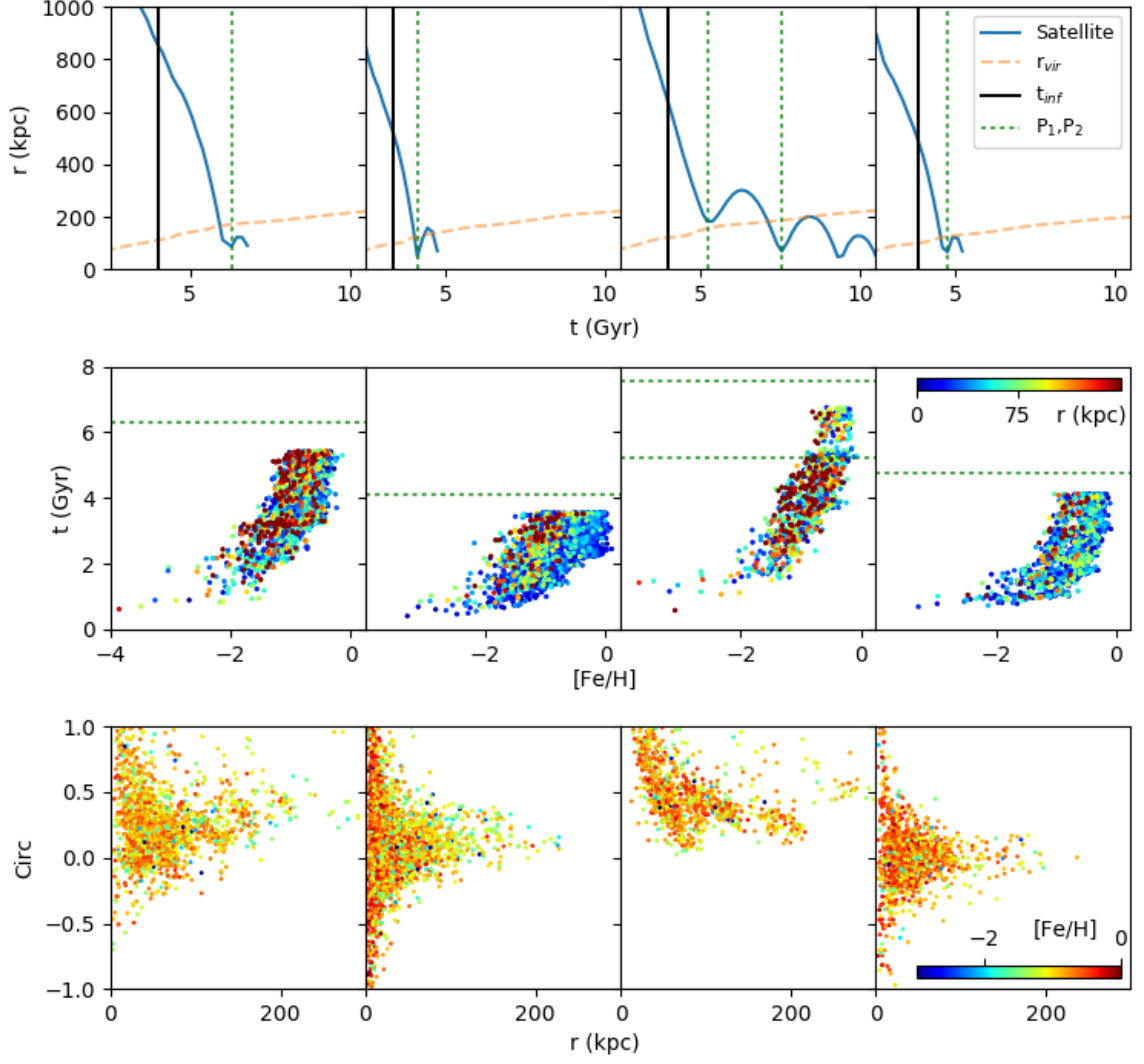


Figure 3.6: Orbits (top), metallicity (middle) and circularity (bottom) of stars deposited by ARMs examples S1-S4. *Top row*: infall time is highlighted by black vertical lines while dashed orange lines indicate the virial radius evolution of their disk-dominated MW-like central. We also indicate the times of pericenter passages with dotted green lines. *Middle row*: Time vs. metallicity of their stars, colored by galactocentric radius (same colorbar as Fig. 3.4). Note that stars stop forming roughly at the time of their pericenters (green dotted lines). *Bottom row*: Circularity of stellar debris as a function of galactocentric radius, colored by stellar metallicity as indicated by the color bar. S2 and S4 show a large fraction of radial, counterrotating orbits in agreement with GE/GS. Notice that the circularity does not appreciably change with radius and that no significant metallicity gradient with radius is found.

in metallicity is related to the imperfect match of Illustris to the metallicity evolution of galaxies with redshift, as discussed in (D’Souza and Bell, 2018b).

We find no significant segregation with present-day distance of the stars (see color coding as in Fig. 3.4), meaning that the remnants of GE/GS may be spotted outside of the solar neighborhood by looking at stars with similar ages and metallicities of the already-identified debris. However, we caution that the numerical resolution of Illustris and in particular the gravitational softening, $\epsilon_* = \epsilon_{\text{DM}} \sim 0.7$ kpc, is comparable to the sizes of these satellites, which may be preventing us from resolving any population gradients within the satellites and driving the lack of correlation with present-day distance in this simulations.

Encouragingly, we detect a clear cut-off of the star formation associated to the infall of these objects. The age of the youngest stars is a very good indicator of the time of the first pericenter passage, as indicated by the green dotted lines in the top and middle rows. This provides partial validation to the observational interpretation of stellar age of the debris as the time of the merger. Previous works have placed the merger of GE/GS at $t \sim 6 - 10$ Gyr ago (see Sec. 3.2). In general, our ARMs coalesce shortly after infall, although some exceptions showing several apocenters and pericenters may also be found (see for instance S3, which coalesces after the second pericenter). The time when the subhalo merges (the end of the orbits in the top row) is always later than the cut off in ages of the stars seen in the plots, confirming that the satellites are indeed quenched before being disrupted.

3.5.3 Orbit and rotation of the debris

An interesting feature of the GE/GS event is the large fraction of counterrotating stars with respect to the rotation of the MW’s disk. In our simulations we find that counterrotating orbits are not difficult to obtain, although are perhaps not the most likely. Examples of this can be seen in the bottom row of Fig. 3.6 which shows, from left to right, the present-day circularity vs. galactocentric radius of the stars in S1-S4 debris.

Stars from S1 and S3 have almost completely positive circularities (i.e. are prograde), while those from S2 and S4 have a significant retrograde component ($f_{\text{ctr}} = 32\%$ and 49% respectively). In fact, out of our whole ARMs sample of 37 objects, the median fraction of stars in the debris that are retrograde is 39% , indicating that the large fraction of counterrotating stars in GE/GS is not difficult to accommodate within the Λ CDM assembly of MW-like galaxies.

In the classical view where disk galaxies inhabit halos with enough angular momentum (White and Frenk, 1991; Mo et al., 1998) and where angular momentum has been preserved and coherently added over time (Sales et al., 2012; Garrison-Kimmel et al., 2018), the presence of counterrotating debris in disk MW analogs is somewhat unexpected. However, this may be better understood when considering the early time of the GE/GS merger event. Fig.3.7 shows the infall time of satellites for our disk MW sample, compared to the median formation time of the disk in each central. The disk formation time is computed as the median age of stars kinematically associated to the disk, defined with the criteria: $r_{xy} < 2r_h$, $z < 3$ kpc, $\text{circ} > 0.5$.

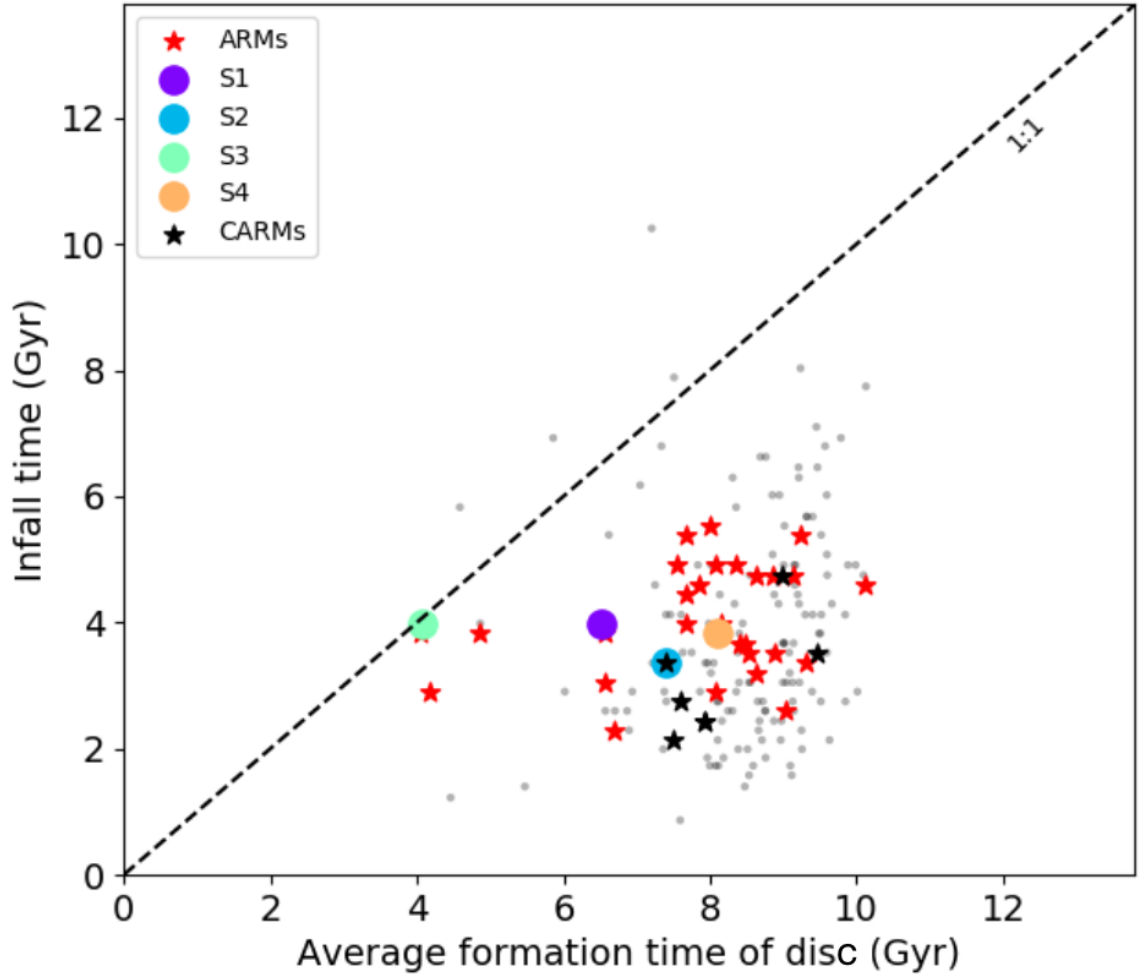


Figure 3.7: Infall time of satellites vs. (averaged) formation time of the disks for our disk-dominated centrals with at least 1 ARM. Gray, red-starred and black-starred symbols show all satellites, ARMs and CARMs, respectively. Large colored circles show S1-S4 as before. All centrals, with the exception of one, form their disks after the infall time of the ARM, explaining how the disk of the MW could have survived the merger with GE/GS.

The vast majority of cases lay to the right of the 1:1 line (blue dashed), indicating that the infall times of satellites occur well before the typical epoch of formation of the disk. In particular, our set of most compact radial merger events (or CARMs, black starred symbols) and closest GE/GS analogs, have infall times $t_{\text{inf}} \sim 4$ Gyr, about half the typical age of disk formation, $t \sim 8$ Gyr. It is therefore possible that the orientation of early merger events like GE/GS may be considered random with respect to the late-established direction of disk rotation, helping explain the large fraction of counterrotating stars found in these remnants.

3.6 The contribution of GE/GS to the stellar halo build up

Stars now associated to the GE/GS debris dominate the local sample of stellar halo stars in the solar neighborhood (Helmi et al., 2018; Belokurov et al., 2018). However, we have fewer constraints on the overall contribution of the GE/GS event to the build up of the total galaxy-wide stellar halo of the MW. Deason et al. (2018) have linked the $r \sim 30$ kpc break in the MW’s stellar halo to the pileup of stars at the apocenters of the GE/GS orbit, implying that the majority of the inner halo in the MW was built by the single merger with the GE/GS. It is important to bear in mind that multiple shells possibly associated to previous apocenter passages may also be expected from the debris.

More quantitatively, orbital modeling of the stars in the GS debris estimate that up to 50% of the stellar halo stars within $r \leq 25$ kpc were brought in by the GS event alone (see e.g., Lancaster et al., 2019; Iorio and Belokurov, 2019). We can use our simulations to shed light on the expected contribution of GE/GS events to the stellar halo and aid the

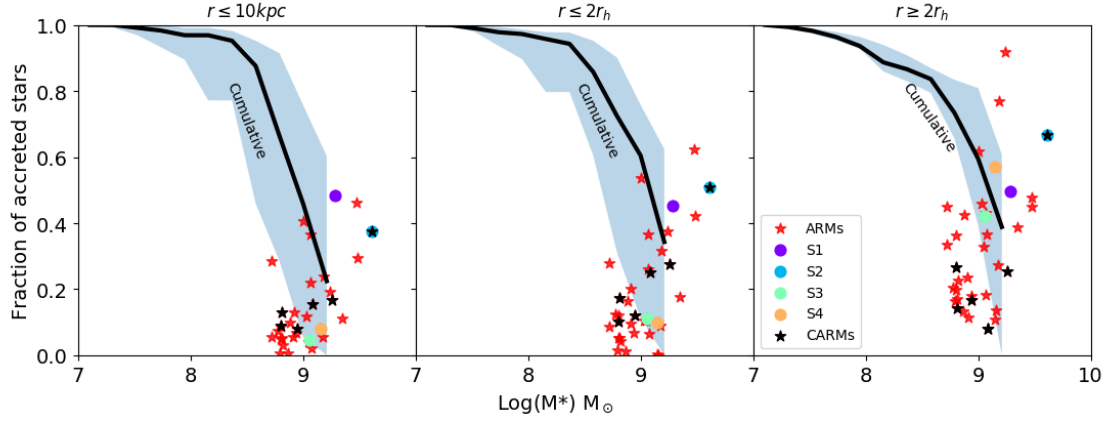


Figure 3.8: Stellar halo fraction contributed by our identified ARMs (red starred), CARMs (black starred) and S1-S4 (color circles). From left to right, we differentiate the very inner halo ($r < 10$ kpc), inner halo ($r < 2r_{h,*}$) and outer halo ($r > 2r_{h,*}$), respectively. Although some of these individually comprise up to 50% of the inner and outer components by themselves, in general GE/GS-like events contribute a much smaller fraction of the accreted halo. For instance, ARMs and CARMs individually contribute a median of 12% and 21%, respectively, suggesting that a larger number of relatively massive events is the norm for these MW-like analogs. This is confirmed by the median cumulative stellar halo fraction deposited by satellites above a given M_* (solid black curve), with shaded blue regions indicating the 25%-75% quartiles in our simulated sample. Note that S2 is the only CARM that contributes significantly to the inner halo, as is inferred for GE/GS. Interestingly, S2 also shows a large contribution to the outer halo, inviting further exploration of the outer halo in MW data.

interpretation of solar neighborhood-based results in a galaxy-wide context. Moreover, we can also find clues as to the contribution of the GE/GS event to the outer halo and guide future identification of this debris in the outer MW regions.

We restrict our study to the 37 disk-dominated MW galaxies that have experienced at least one ARM-like merger and identify their accreted stellar component within the stellar halo. We further divide the stellar halos in 3 regions: very inner accreted halo ($r < 10$ kpc), inner halo $r < 2r_h$ with r_h the half mass radius of the stars in each host, and outer halo, $r > 2r_h$. The solid black curves in Fig. 3.8 show, for these three regions, the median cumulative fraction of the stars in the accreted halo that were contributed by any satellite of a given (maximum) stellar mass or above (x-axis). The 25%-75% quartiles are also highlighted in blue shading. We find that the largest contributors to the build up of their stellar halos are satellites in the mass range $M_* \sim 5 \times 10^8 - 5 \times 10^9 M_\odot$. Furthermore, our simulations predict no significant differences between the inner vs. outer regions, except for a slightly enhanced contribution of low mass mergers to the outer $r > 2r_h$ stellar halos compared to the inner regions.

To evaluate the individual contribution of our identified GE/GS events, we overplot in Fig. 3.8 the (non-cumulative) fraction of stars deposited by each identified old and radial merger (ARMs, red stars). Surprisingly, we find a rather modest contribution, typically accounting for 10% of the accreted inner halo and up to 20% for the outer regions. Even selecting those that are the most compact events (CARMs, black stars) as closest analogs to GE/GS suggests an average contribution of less than 20% for $r < 10$ kpc and as much as 25% of the outer accreted halo. We conclude that, for this sample of MW-like analogs,

GE/GS-like mergers seem to provide a more minor contribution to the stellar halo than that inferred for the case of the MW. Our theoretical results are therefore better aligned with other estimates that place the GS as a non-dominant contributor (perhaps lower end of the modeling in Helmi et al., 2018; Mackereth and Bovy, 2019).

Interestingly, some exceptions occur, for instance, such as our selected S2 satellite, whose stars alone account for $\sim 50\%$ of the inner stellar halo in this central. Encouragingly, S2 also satisfies the compactness CARMs criteria (cyan/black symbol) and seems to be our best match to the observed GE/GS in the MW.

If the GE/GS analogs identified in Illustris are mostly minor contributors to the stellar halo of their hosts, one might wonder what else helps build the stellar halos in such centrals. We explore this in Fig. 3.9. Each circle is a merger experienced by a central galaxy that has experienced a CARM (shown in red). The sizes of the circles are proportional to the number of stars deposited in the inner stellar halo and the black line shows the stellar mass of the central. The top left panel presents the CARM with the largest contribution to the inner accreted stellar halo, which is satellite S2. For this central, the CARM is the latest merger and also the largest contributor, in good agreement with estimates of GE/GS in the MW. However, both Fig. 3.8 and Fig. 3.9 show this merger is an anomaly rather than the norm. Yet, it is still plausible within the wide diversity of stellar halos predicted by Λ CDM.

We highlight here that the results presented in this section pertain to analogs to the GE/GS event which are defined by requiring significant orbital radiality in the debris. This information is not available in external galaxies. In general, simulations and observations

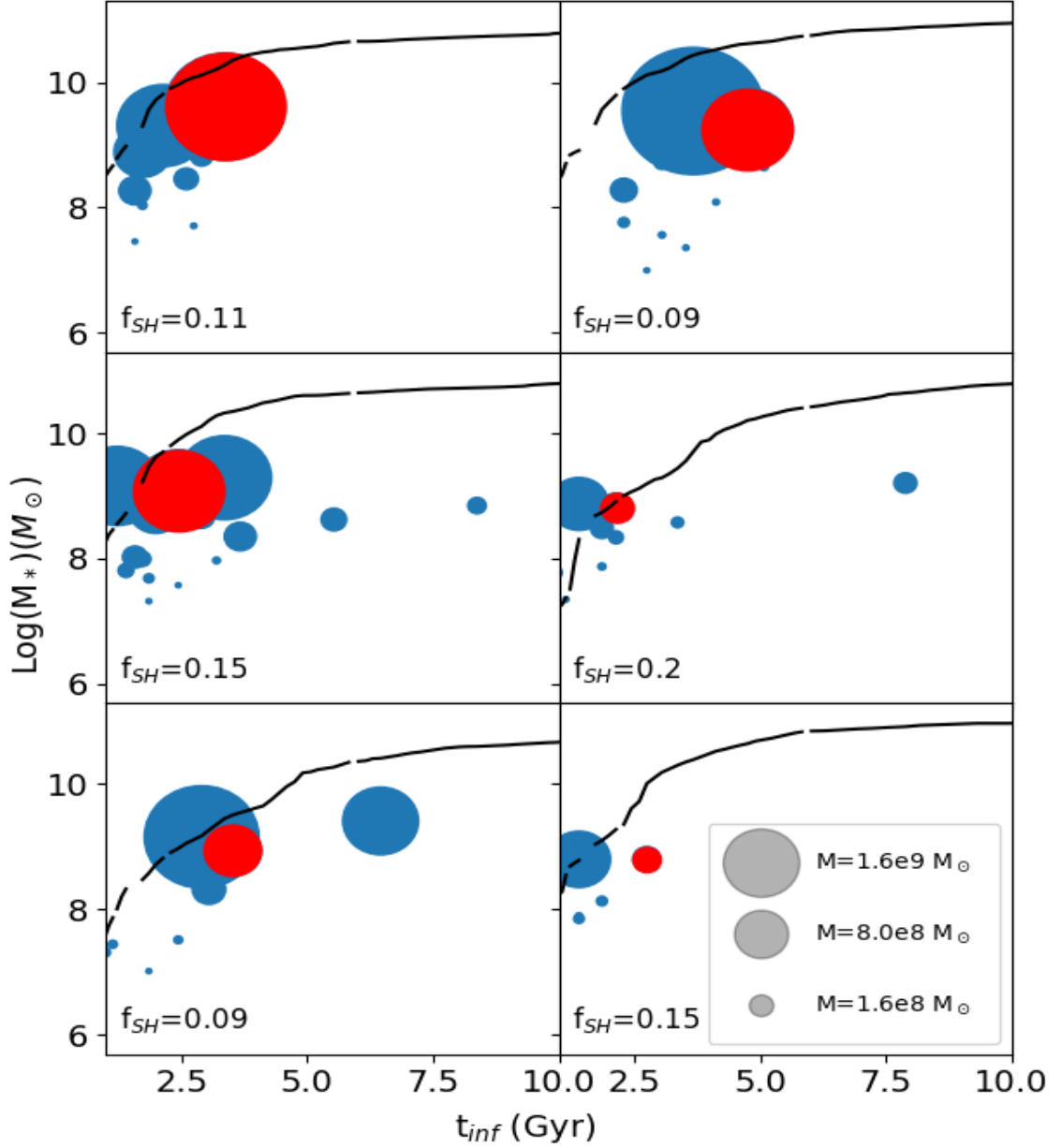


Figure 3.9: Building blocks of the accreted stellar halos in disk-dominated MW-analogs that have experienced a CARM. The figure shows the maximum stellar mass vs. infall time of the merged satellites in these centrals. The size of each point scales with the number of stars contributed to the inner stellar halo by each merger event. Red circles highlight the CARM contribution. Most of the accreted stars in the galaxy are acquired early on and, with the exception of S2 (top left panel) the debris of the CARM does not dominate the accreted material. Solid black line indicates for comparison the stellar mass of the central galaxy as a function of time and the stellar halo fraction is quoted for each central.

indicate that their inner halos are built from a few contributors, with some scatter (e.g., D’Souza and Bell, 2018b; Monachesi et al., 2019). Our results align well with those studies, but are more strict in the definition of what is building the stellar halos of MW analogs, and, in particular, we find that radial mergers similar to those of GE/GS analogs tend to contribute less to the inner halos amid their more extended distributions (see Fig. 3.5).

The right-most panel in Fig.3.9 may be used to guide future searches for the remaining GE/GS debris. Our simulations indicate that the most compact of our GE/GS analogs also build up to $\sim 20\%$ of the stars in the outer stellar halo. Moreover, our closest analog S2 provides 60% of the accreted outer halo in this central, suggesting the idea that a sizable fraction of the MW’s outer halo could be associated to the GE/GS event. Although the peculiarity of this event prevents us from having a statistical basis to make predictions about the singular case of the MW, our results support a scenario where more of the GE/GS remnant might be uncovered in the future by studying not only further into the inner regions of the MW’s stellar halo, but also perhaps outwards of the solar region, where long dynamical times may be more favorable to the identification of merger debris.

3.7 Summary and Discussion

We use a sample of MW analogs identified in the Illustris simulations to study the present-day remnants of mergers comparable to the Gaia Enceladus/Sausage (GE/GS) event. Observationally, the GE/GS object has been inferred to be old $t_{\text{inf}} \sim 10$ Gyr ago, in a radial orbit (orbital anisotropy $\beta = 0.8 - 0.9$) and massive ($M_* \sim 10^9 M_\odot$). It largely dominates the stellar halo stars in the solar neighborhood (Helmi et al., 2018) and is thought

to make up to $\sim 50\%$ of the inner stellar halo in our Galaxy (Lancaster et al., 2019). These conclusions, however, originate from a small and local fraction of its inferred mass, where the high quality of the data allows for the identification of substructure in position and velocity space. Much is unknown about the distribution, kinematics and stellar properties of the rest of the mass estimated for the progenitor of GE/GS. The large volume of Illustris allows for a statistical basis to place GE/GS-like events within the cosmological predictions of the Λ CDM model and to make statistical predictions about the remaining stream.

From a sample of 1115 isolated galaxies in the mass range $M_{200} = 0.8\text{-}2.0 \times 10^{12} \text{ M}_{\odot}$, we select 154 Milky Way analogs that show a disk-dominated morphology. In agreement with the early accretion inferred for the merger of GE/GS, our sample of disk-like hosts naturally shows an early assembly history, with 86% of the mergers with satellites of stellar mass $M_* > 5 \times 10^8 \text{ M}_{\odot}$ happening by $t < 6 \text{ Gyr}$ ($z \sim 0.9$). Moreover, almost all centrals in our sample (80%) show at least 1 merger with a satellite of such mass. The stellar content of GE/GS and its early accretion seem to be a natural prediction for our Galaxy within the cosmological model.

We focus our analysis on the study of early mergers ($t < 8 \text{ Gyr}$ ago) in these centrals that involved massive ($5 \times 10^8 \leq M_* \leq 5 \times 10^9 \text{ M}_{\odot}$) satellites with a stellar debris characterized (today) by radial orbits ($\beta > 0.5$). We find that 37 ($\sim 25\%$) of our centrals have had at least one such ancient radial merger (ARM). Despite the specific constraints on the identification of these ARMs, there is a wide range of morphologies and kinematics associated to the stellar streams and remnants of these events. Looking in the space of velocities and/or energies, as GE/GS was identified, we find that good GE candidates also

seem to be consistent with GS, providing support for a scenario where both structures could be, predominantly, the same.

Two remaining properties have been highlighted from observations of GE/GS. First, a significant counter-rotating component. Second, it appears likely to have deposited most of the stars within 25-30 kpc, as inferred by the break in the stellar halo density profile (Deason et al., 2018; Lancaster et al., 2019). We find that counterrotation is rather common in our sample of ARMs, with 43% of satellites depositing at least 40% of their stars in present-day counter-rotating motion. The early times of these mergers, coupled to a later build up of the disk in the simulations help explain the large number of stars in the debris that are counterrotating.

Compactness of GE/GS debris in our sample is significantly more rare given its radial orbit. Massive and early mergers in Illustris with $\beta > 0.5$ show median radius containing half of the mass $r_{*,\text{deb}} \sim 45$ kpc; with the most extreme objects extending to $r_{*,\text{deb}} \sim 143$ kpc, well into the dark matter halos of their host galaxies. In general, the more radial the orbit, the more extended the debris. Instead, studies of GE/GS place it mostly within 30 kpc despite its $\beta \sim 0.9$. Only 6 ($\sim 16\%$) of our radial mergers have a comparably compact radial extension today, with $r_{*,\text{deb}} < 25$ kpc. We refer to them as compact ARMs, or CARMs for short.

We can use our simulations to shed light on the contribution of GE/GS to the build up of the global (i.e. beyond the solar neighborhood) stellar halo in the MW. Considering our 37 disk-dominated MW-like centrals, we find that their accreted components are built generally by a few (but more than one) relatively massive accretion events. Individual

objects are unlikely to dominate the entire stellar halo. For instance, ARMs contribute only $\sim 9\%$ (median) of the inner stellar halo within 10 kpc and 12% within ~ 25 kpc (corresponding to twice the average half mass radius of the centrals). These numbers increase to 14%-21% when considering the more compact CARMs. In Illustris, for those MW-like analogs that have experienced a GE/GS like event (defined as ancient, massive, radial and compact), it is not a single event but the contribution of 2-3 $M_* > 5 \times 10^8 M_\odot$ satellites that make up to 90% of the stars in the inner halos.

There are, however, a few extreme cases where we find ARMs and CARM events contributing up to $\sim 60\%$ of the accreted inner halo on an individual basis. This is more in line with some results that place GE/GS as the dominant builder of the MW’s inner halo (Belokurov et al., 2018; Deason et al., 2018), although different estimates suggest a more modest contribution (Helmi et al., 2018; Mackereth and Bovy, 2019). In our sample, we find one good GE/GS analog (named S2 throughout the paper) that shows a compact enough distribution to be comparable to GE/GS and that simultaneously brought in 50% of the inner accreted halo.

Interestingly, for the same particular host galaxy, the merger event S2 also contributes significantly to the outer stellar halo, perhaps suggesting that hidden stars of GE/GS lie outside of $r > 30$ kpc, waiting to be discovered. The predictions for the amount and distribution of such outer halo stars vary among our 6 identified CARMs, with a median of $\sim 3.25 \times 10^8 M_\odot$ outside ~ 25 kpc, but as much as $1.5 \times 10^9 M_\odot$ for the most promising case of S2 in our sample. The median radius for these outer stars is ~ 40 kpc, but they can extend as far as ~ 230 kpc.

If GE/GS stars could be found beyond $r \sim 25$ kpc, our simulations predict that their age and metallicities should be comparable to the section already identified of GE/GS, a conclusion that needs confirmation from higher resolution experiments and a more detailed ISM treatment than in our simulations (along the lines of work proposed by Bignone et al. (2019)). Our sample has more predictive power for dynamical quantities instead. We find that in all our CARMs the stellar debris contributing to the outer stellar halo preserves a similar radial orbit distribution as the stars deposited in the inner regions of the disk. For the specific case of our best analog S2, we find a moderate evolution of the orbit orientation, such that the fraction of counterrotating stars in the outer halo is smaller ($\sim 26\%$) than in the inner halo ($\sim 42\%$).

It is unclear whether significant amounts of stars belonging to GE/GS could be hidden in the outer halo of the MW, but theoretical predictions strongly support such a case. The data shows a clear drop in the number density of stars kinematically associated to GE/GS beyond $r \sim 30$ kpc (Deason et al., 2018; Lancaster et al., 2019). However, our study of ~ 1000 MW-mass galaxies indicates that even the most compact, early and massive mergers with comparable radial orbits than GE/GS deposit roughly $0.13\text{--}1.7 \times 10^9 M_\odot$ in the outer stellar halo. It is then possible (and even likely) that a significant fraction of the GE/GS progenitor is in a more diffuse stream extending into the outer realms of the Milky Way. Future observational efforts targeting the oldest and most radially-biased stars may be able to recover the earliest stripped shells from the GE/GS progenitor.

Chapter 4

Detecting the cosmic web: $\text{Ly}\alpha$ emission from simulated filaments at $z=3$

4.1 Abstract

The standard cosmological model (Λ CDM) predicts the existence of the cosmic web: a distribution of matter into sheets and filaments connecting massive halos. However, observational evidence has been elusive due to the low surface brightness levels of the filaments. Recent deep MUSE/VLT data and upcoming observations offer a promising avenue for $\text{Ly}\alpha$ detection, motivating the development of modern theoretical predictions. We use hydrodynamical cosmological simulations run with the AREPO code to investigate the potential detectability of large-scale filaments, excluding contributions from the halos

embedded in them. We focus on filaments connecting massive ($M_{200c} \sim (1 - 3) \cdot 10^{12} M_{\odot}$) halos at $z = 3$, and compare different simulation resolutions, feedback levels, and mock image pixel sizes. We find increasing simulation resolution does not substantially improve detectability notwithstanding the intrinsic enhancement of internal filament structure. By contrast, for a MUSE integration of 31 hours, including feedback increases the detectable area by a factor of $\simeq 5.5$ on average compared with simulations without feedback, implying that even the non-bound components of the filaments have substantial sensitivity to feedback. Degrading the image resolution from the native MUSE scale of $(0.2'')^2$ per pixel to $(5.3'')^2$ apertures has the strongest effect, increasing the detectable area by a median factor of $\simeq 200$ and is most effective when the size of the pixel roughly matches the width of the filament. Finally, we find the majority of Ly α emission is due to electron impact collisional excitations, as opposed to radiative recombination.

4.2 Introduction

Cosmological simulations have long suggested the presence of diffuse filaments of both dark and baryonic matter between galaxies (Peebles and Groth, 1975; Klypin and Shandarin, 1983; Haider et al., 2016; Mandelker et al., 2019). However, it is only recently that the contribution of the cosmic web to galactic evolution has been fully appreciated. Specifically, at $z \geq 2$, the primary mode of gas accretion for massive galaxies may be through streams of cold ($\sim 10^4$ K) gas that feed the dark matter halo from cosmic web filaments (Furlanetto et al., 2003; Katz et al., 2003; Kereš et al., 2005; Dekel and Birnboim, 2006; Ocvirk et al., 2008; Dekel et al., 2009; van de Voort et al., 2011; Nelson et al., 2016).

The low density of the filaments prohibits star formation, making observation extremely challenging. However, Ly α emission originating from the diffuse gas in the filaments is theoretically predicted (Hogan and Weymann, 1987; Gould and Weinberg, 1996; Cantalupo et al., 2005; Laursen et al., 2009; Faucher-Giguère et al., 2010; Goerdt et al., 2012; Rosdahl and Blaizot, 2012). If the only source of ionizing radiation is the UV background, which Bolton et al. (2005) and Faucher-Giguère et al. (2008) find to have a hydrogen photoionization rate $\Gamma = 0.9(0.5) \times 10^{-12}$ at $z=3$ ($2 \leq z \leq 4$), respectively, the Ly α emission from filaments is expected to be faint, on the order of $SB \simeq 10^{-20} \text{ergs}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$ for optically thick clouds. This is well below most modern detection limits and accounts for the large number of non-detections reported (Lowenthal et al., 1990; Martinez-Gonzalez et al., 1995; Cantalupo et al., 2005; Rauch et al., 2008). The difficulty of detection towards lower redshifts is exacerbated by the expansion of the universe, which stretches the filaments, decreasing their density, and towards higher redshifts by the higher degree of homogeneity and less pronounced features of the cosmic web.

Even in a new era of deeper observations, a statistically robust sample of detections remains elusive. Gallego et al. (2018) stack 390 subcubes of the deepest MUSE/VLT data (~ 30 hrs of exposure, reaching a 2σ surface brightness levels of $0.44 \cdot 10^{-20} \text{ergs}^{-1} \text{cm}^{-2}$ in an aperture of $1'' \times 6.25 \text{ \AA}$) oriented according to the positions of Ly α emitters and their neighbors. They find no detectable Ly α emission in the intergalactic medium.

However, when gaseous filaments are illuminated by more energetic sources such as quasars, the Ly α signal is boosted and detection is made easier. Recently, Ly α blobs have been detected around several high-redshift quasars (Martin et al., 2014; Cantalupo et al.,

2014; Swinbank et al., 2015; Borisova et al., 2016; Kikuta et al., 2019). These blobs may extend out to several hundred physical kpc and well beyond the virial radius of the host halo, suggesting that they are tracing the filaments of the cosmic web. When the quasars illuminating the gas are clustered, even larger extended Ly α nebulae (ELANe) have been detected (Hennawi et al., 2015; Arrigoni Battaia et al., 2018). A recent observation of filamentary Ly α structures between two quasars has signaled that this technique is effective for detecting more extended gaseous filaments (Arrigoni Battaia et al., 2019). Feedback from other energy sources, such as star formation and supermassive black hole activity may also illuminate the gas surrounding these sources above the detection threshold (Umehata et al., 2019).

Simulations have also indicated that Ly α emission induced by the UV background is too faint to be currently detectable. For example, Kollmeier et al. (2010) predict that only Ly α emission from gas illuminated from energetic sources such as quasars, like the Ly α blobs mentioned above (see also Cantalupo et al. (2005)), should be detectable. Rosdahl and Blaizot (2012) investigate the detectability of extended Ly α emission using cosmological zoom simulations and find that the Ly α luminosity is concentrated in the central 20% of the halo, making detection even more difficult. However, others are more optimistic. Bertone and Schaye (2012); Corlies et al. (2018); Smith et al. (2019) model Ly α radiative transfer in large cosmological hydrodynamical simulations to predict features of the Ly α emission line arising from gas in the IGM and find that MUSE and future projects such as the Square Kilometer Array (SKA) (Kooistra et al., 2019), the James Webb Space Telescope and CETUS Probe Mission (Hull et al., 2018) should be able to detect the brightest filaments.

In preparation for this upcoming observational revolution, our paper aims to investigate detectability of Ly α emission from cold gas filaments using large volume cosmological hydrodynamical simulations. In Section 4.3.1 we detail the simulations used, in Section 4.3.2 we describe the Ly α emission processes, in Section 4.4 we focus on sources of Ly α emission, in Section 4.5 we present our main results by investigating the effects of resolution, feedback, and pixel size on the detectability of gaseous filaments, and in Section 4.6 we state the conclusions of the project.

4.3 Methods

4.3.1 Simulations and Halo Selection

Six main simulations were used for the analysis and are described in Table 4.1. The simulations vary in resolution, volume, and feedback implementation. They are run with the moving mesh code AREPO (Springel, 2010), and are consistent with WMAP-9 standard cosmology, with $\Omega_m=0.2726$, $\Omega_b=0.0456$, $\Omega_\Lambda=0.7274$, and $H_0=70.4\text{km/s/Mpc}$ (Hinshaw et al., 2013). Gas cooling and heating as well as star-formation follow the prescriptions given in Vogelsberger et al. (2012) and Pillepich et al. (2018), for simulations without and with feedback, respectively. In all simulations, gas above a density threshold of $n_H = 0.13 \text{ cm}^{-3}$ follows an equation of state that is used to implicitly treat the multiphase structure of the ISM (Springel and Hernquist, 2003). Cold and dense gas above this threshold becomes eligible for star formation with a timescale that depends on the local density. In the simulations used in this analysis that include stellar and supermassive black hole feedback, denoted by ‘TNG’ in the simulation name, it is implemented as in IllustrisTNG (Weinberger et al.,

Simulations						
Name	Volume	N	Feedback	m_{DM}	m_{gas}	Softening length
	$[(\text{cMpc}/h)^3]$			$[M_{\odot}]$	$[M_{\odot}]$	$[\text{ckpc}/h]$
L17n1024NF	17^3	1024^3	No	$4.1 \cdot 10^5$	$8.3 \cdot 10^4$	0.39
L17n512NF	17^3	512^3	No	$3.3 \cdot 10^6$	$6.6 \cdot 10^5$	0.78
L25n1024NF	25^3	1024^3	No	$1.3 \cdot 10^6$	$2.6 \cdot 10^5$	0.5
L25n512NF	25^3	512^3	No	$1.0 \cdot 10^7$	$2.1 \cdot 10^6$	1
L25n1024TNG	25^3	1024^3	Yes	$1.3 \cdot 10^6$	$2.6 \cdot 10^5$	0.5
L25n512TNG	25^3	512^3	Yes	$1.0 \cdot 10^7$	$2.1 \cdot 10^6$	1

Table 4.1: Description of the six simulations used. There are two volumes simulated without feedback, each at two resolution levels. For the two large volume simulations, additional simulations have been run with the IllustrisTNG feedback prescriptions.

2017; Pillepich et al., 2018). Groups are identified based only on particle positions using the Friends of Friends algorithm.

For our analysis, we choose to focus on the 12 most massive halos in the large-volume, high-resolution simulation (L25n1024NF) and the 4 most massive halos in the small-volume, high-resolution simulation (L17n1024NF) for a total of 16 halos. All halos are analyzed at redshift $z = 3$. We focus on these massive halos, which span a virial mass range of $M_{\text{vir}} = 7.8 \cdot 10^{11} - 2.9 \cdot 10^{12} M_{\odot}$, reasoning that larger halos may be more likely to reside in larger filaments.

4.3.2 Modeling $\text{Ly}\alpha$ Emission

$\text{Ly}\alpha$ emission can originate from two main processes: electron impact collisional excitation and radiative recombination. We assume the optically-thin limit as we are interested in detections from diffuse filaments outside of halos. In particular, we do not consider resonant scattering or dust absorption of the $\text{Ly}\alpha$ photons. One might expect this scattering to smear out bright spots in our simulated $\text{Ly}\alpha$ maps, reducing their intensity. We

have explored this possibility by performing radiative transfer on a test box of side length 1.25Mpc centered on the most massive $z = 3$ halo in the simulations. The results of this validation test are summarized in Appendix A. In the case of 5.3" pixels, we find the impact of scattering to be relatively modest. The brightest pixels are reduced in intensity by a factor of ~ 2 .

Collisional Excitation

Ly α photons are emitted following $1s - 2p$ electron impact excitation of neutral hydrogen atoms at a rate per unit volume ($\text{cm}^{-3} \text{ s}^{-1}$) given by

$$R_{\text{col}} = q_{\text{col}}(T) \cdot n_{\text{e}} \cdot n_{\text{H}} \quad (4.1)$$

where q_{col} is the collisional excitation rate coefficient, and n_{e} and n_{H} are the electron and neutral hydrogen volume number densities respectively. We adopt $q_{\text{col}}(T) = (8.63 \cdot 10^{-6} \text{cm}^3 \text{s}^{-1}) \cdot e^{-E_{\text{Ly}\alpha}/kT} / (2\sqrt{T})$ (Dijkstra, 2017) where T is the gas temperature in Kelvin, $E_{\text{Ly}\alpha} = 10.19 \text{ eV}$ is the energy of the Ly α transition, and k is the Boltzmann constant.

Recombination

For radiative recombination we assume the optically thin case A, for which the Ly α emission rate per unit volume is

$$R_{\text{rec}} = \alpha(T) \cdot n_{\text{e}} \cdot n_{\text{p}} \quad (4.2)$$

where $\alpha(T)$ is the effective Ly α case A recombination coefficient, n_{p} is the proton volume number density and n_{e} is the electron volume number density. For Ly α emission, $\alpha(T) = \alpha_{\text{tot}}(T) \cdot f_{\text{rec}}(T)$ where α_{tot} is the total case A recombination coefficient for HII and f_{rec} is the fraction of recombination that results in emission of a Ly α photon. We adopt from Hui

and Gnedin (1997),

$$\alpha_{\text{tot}}(T) = 1.269 \times 10^{-13} \cdot \frac{\lambda^{1.503}}{(1 + (\lambda/0.522)^{0.7})^{1.923}} \text{cm}^3 \text{s}^{-1}, \quad (4.3)$$

where $\lambda = 2 \cdot 157807/T$, and from Dijkstra (2017),

$$f_{\text{rec}}(T) = 0.41 - 0.165 \cdot \log_{10}(T/10^4) - 0.015 \cdot (T/10^4)^{-0.44}. \quad (4.4)$$

Eq. 4.4 is a fit to a non-analytic expression of f_{rec} for Case A that is valid out to $T=4 \times 10^5$ K (see Eq.15 in Dijkstra (2017)). Therefore, beyond this temperature we adopt a constant $f_{\text{rec}}(T > 4 \times 10^5 \text{K}) = f_{\text{rec}}(4 \times 10^5 \text{K}) = 0.14$.

The temperature dependence of collisional and recombination emissivity is shown in Fig. 4.1 assuming the hydrogen is in collisional ionization equilibrium and ignoring photoionization (e.g Gnat and Sternberg (2007)). At higher temperatures, the gas becomes completely ionized and recombinations dominate, while at low temperatures the neutral fraction increases and collisional excitation dominates. The total Ly α luminosity from every simulation gas cell (without photoionizations), in units of erg/s, equals $L_{\text{tot}} \equiv (R_{\text{col}} + R_{\text{rec}}) \cdot E_{\text{Ly}\alpha} \cdot V$, where V is the volume of the cell.

4.3.3 Image Generation

To create our final surface brightness images of filaments we first remove any particles identified by FoF to be within a halo, both to avoid regions that are expected to be optically-thick and because we do not resolve the multi-phase structure of the interstellar medium inside galaxies. Since we are focused on exploring the detection of the cosmic web outside of dark matter halos, this excision is not expected to affect our results.

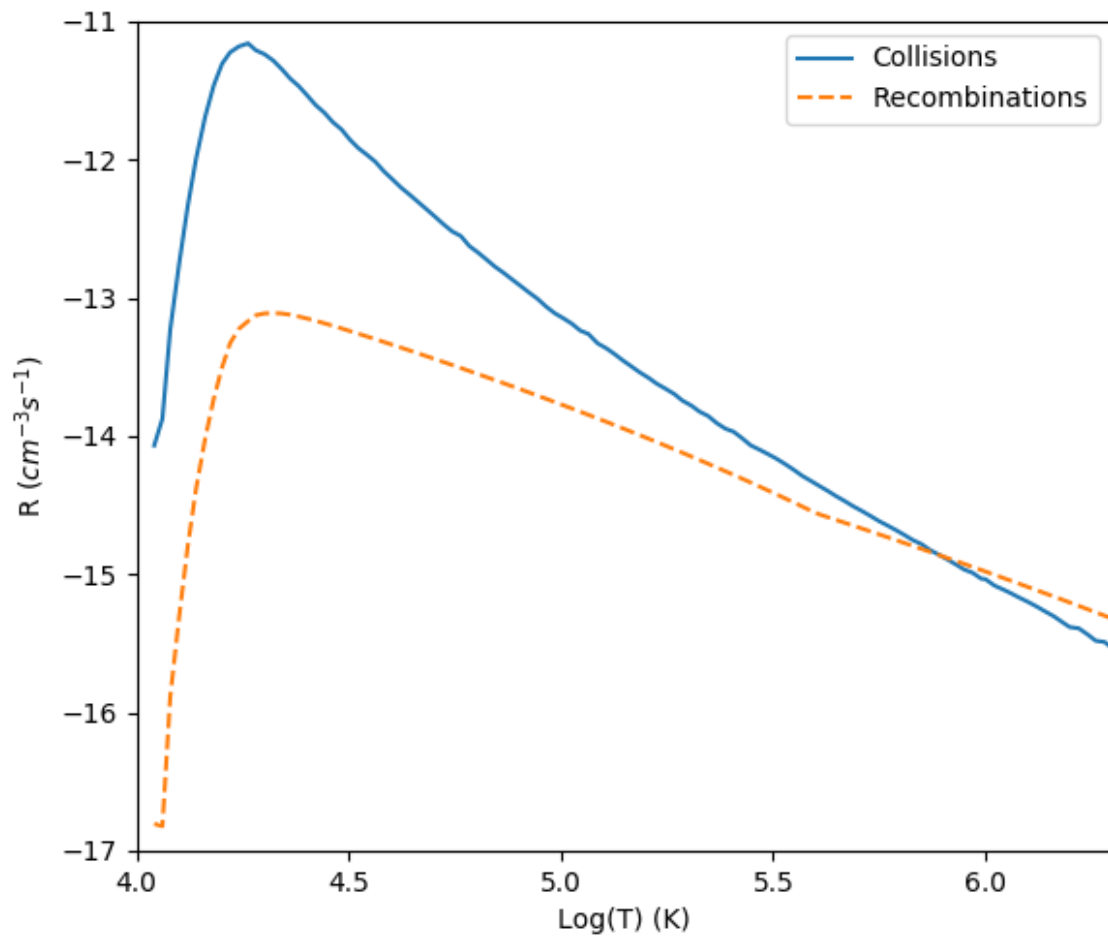


Figure 4.1: Temperature dependence of collisional excitation and recombination rates for hydrogen gas Ly α emission in collisional ionization equilibrium. Rate is per unit density squared.

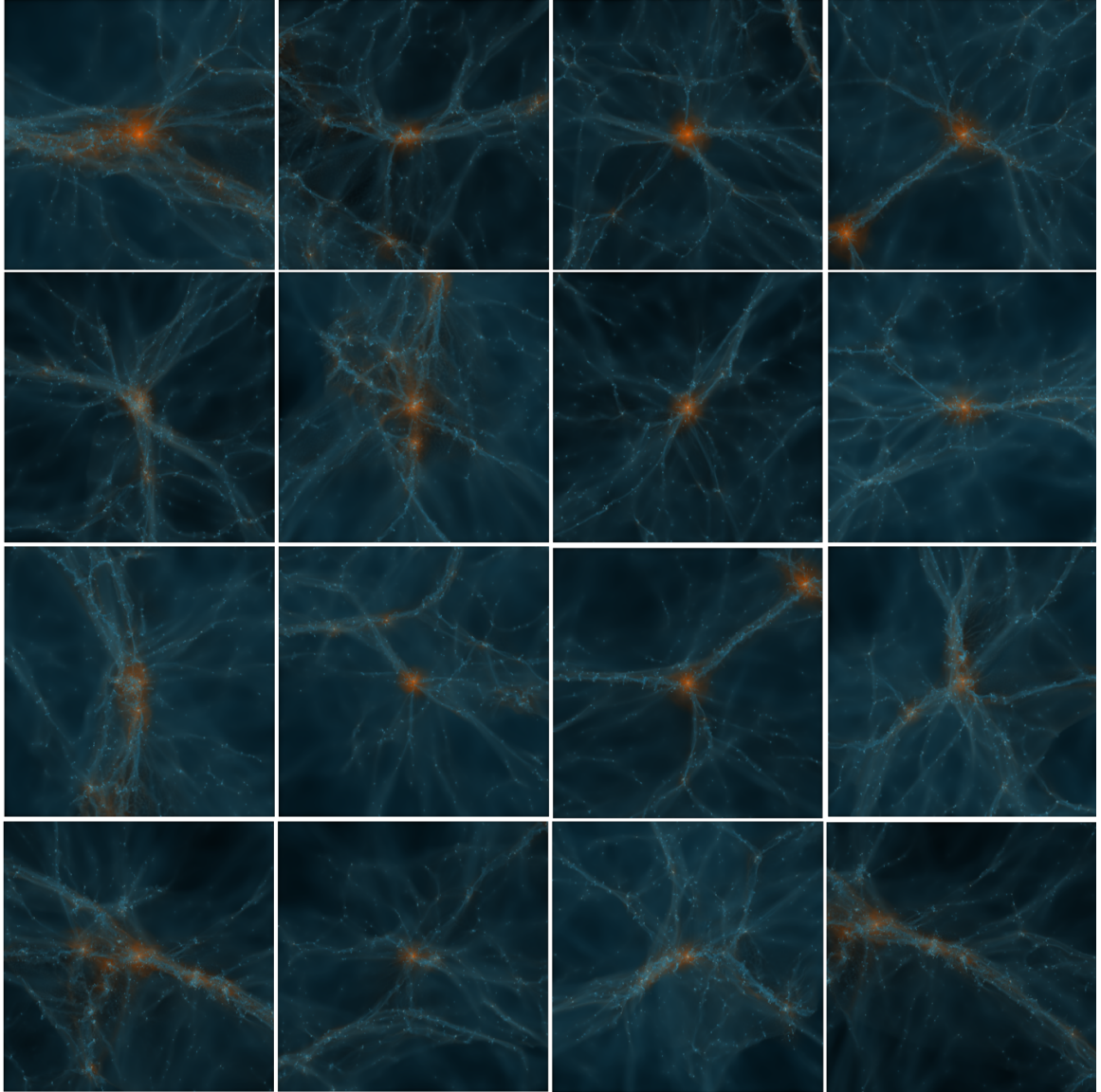


Figure 4.2: Temperature and density maps of $(5\text{cMpc})^2$ regions centered on each halo from simulations L25n1024NF and L17n1024NF. Density is shown in blue and temperature in orange. First three rows show the four most massive halos (ordered in mass from most massive at top left to least massive on the bottom right) in the high resolution, $(25\text{cMpc}/h)^3$ box. The bottom row shows most massive halos in the high resolution, $(17\text{cMpc}/h)^3$ box. Filaments are populated by high temperature and density subhalos, which we remove in the remaining analysis to focus on the cold, gaseous filaments.

We then cut out a $(5 \text{ cMpc})^2$ comoving region $((1250\text{kpc})^2$ in physical units) centered on each halo. In the ‘line of sight’ direction (which we arbitrarily choose to be the complete z axis of the simulation box) we make a velocity-based cut such that only gas cells with galactocentric velocities in a range of $\pm(\Delta v/2 = 193 \text{ kms}^{-1})$ are included. This velocity range is chosen to be consistent with the narrow band wavelength width of the images in Gallego et al. (2018), which are composed of 5 stacked voxels, each of width $1.25 \text{ \AA}$ to reach a total wavelength width of $\Delta\lambda = 6.25 \text{ \AA}$. We convert the wavelength width into a velocity range via Eq. 4.5:

$$\Delta v = c \cdot \frac{\Delta\lambda}{\lambda(1+z)} \quad (4.5)$$

where c is the speed of light, $\Delta\lambda$ is the wavelength width of the stacked image, and λ is the $\text{Ly}\alpha$ rest wavelength. This volume shows the extent of the filaments while not being so large so as to increase the likelihood of contamination from other massive centrals.

Since we have removed subhalos from our analysis, all surface brightnesses reported here are lower limits for detection. We create maps of $\text{Ly}\alpha$ surface brightness (Fig. 4.3) by summing the $\text{Ly}\alpha$ signal along the $6.25\text{\AA}$ width in the spectral or z direction and dividing by $6.25\text{\AA}$ so as to obtain an averaged flux density in units of $\text{erg s}^{-1}\text{cm}^{-2}\text{arcsec}^{-2}\text{\AA}^{-1}$.

Finally, in order to account for the numerical effects of particle resolution, we use the smoothing code `swiftsimio`¹ to smooth the gas particles with a 2D Wendland C2 kernel whose FWHM is equal to the distance to the 15th nearest neighboring gas particle. We choose 15 for the number of neighbors as it is the typical number of faces of a Voronoi cell given a pseudo-random distribution of mesh-generating points in 3D. To test the validity of

¹<https://pypi.org/project/swiftsimio/>

this choice, we also try smoothing with kernel FWHM values equal to the distance to the 30th and 60th neighbor. We find that the results are converged, and therefore adopt the distance to 15th nearest neighbor as the FWHM of the smoothing kernel for the remainder of the analysis.

4.3.4 Detection Limit

MUSE is a panoramic, integral-field spectrograph currently operating on the Very Large Telescope (VLT) of the European Southern Observatory (ESO). The MUSE Hubble Ultra Deep Field survey includes an ultra deep, 30.8 hour exposure of a 1.15 arcmin^2 field. The field has a propagated noise standard deviation of $0.33 \cdot 10^{-20} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ for a sampling voxel. In Wide Field Mode, MUSE has a spatial sampling of $0.2'' \times 0.2''$ and a spectral line resolution of $1.25 \text{ \AA}$. (Bacon et al., 2017)². Voxels in our analysis have the same area as the sampling voxels, but a spectral line width of $6.25 \text{ \AA}$ (consistent with Gallego et al. (2018)). To obtain the surface brightness limit for our voxels, we first convert the noise to units of $\text{ergs}^{-1} \text{ cm}^{-2}$: $0.33 \cdot 10^{-20} \text{ ergs}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1} \times 1.25 \text{ \AA} = 0.4125 \times 10^{-20} \text{ ergs}^{-1} \text{ cm}^{-2}$.

Our voxels have the equivalent depth of 5 Wide Field Mode sampling voxels. Since noise scales as the square root of the number of voxels, the noise for a single voxel of area $0.2'' \times 0.2''$ and depth $6.25 \text{ \AA}$ level is:

$$\begin{aligned} \sigma &= 0.4125 \cdot 10^{-20} \times \sqrt{5} \\ &= 9.2 \cdot 10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \end{aligned} \tag{4.6}$$

²Note the inconsistency between the values shown in Figures 18 and 19 of Bacon et al. (2017), which is a result of an incorrect conversion of the raw measurements shown in Figure 18 into the quantity shown in Figure 19 (Bacon R., private communication). In this work, we use only the width of the histogram shown in their Figure 18 to derive the appropriate surface brightness limit directly from the pixel noise.

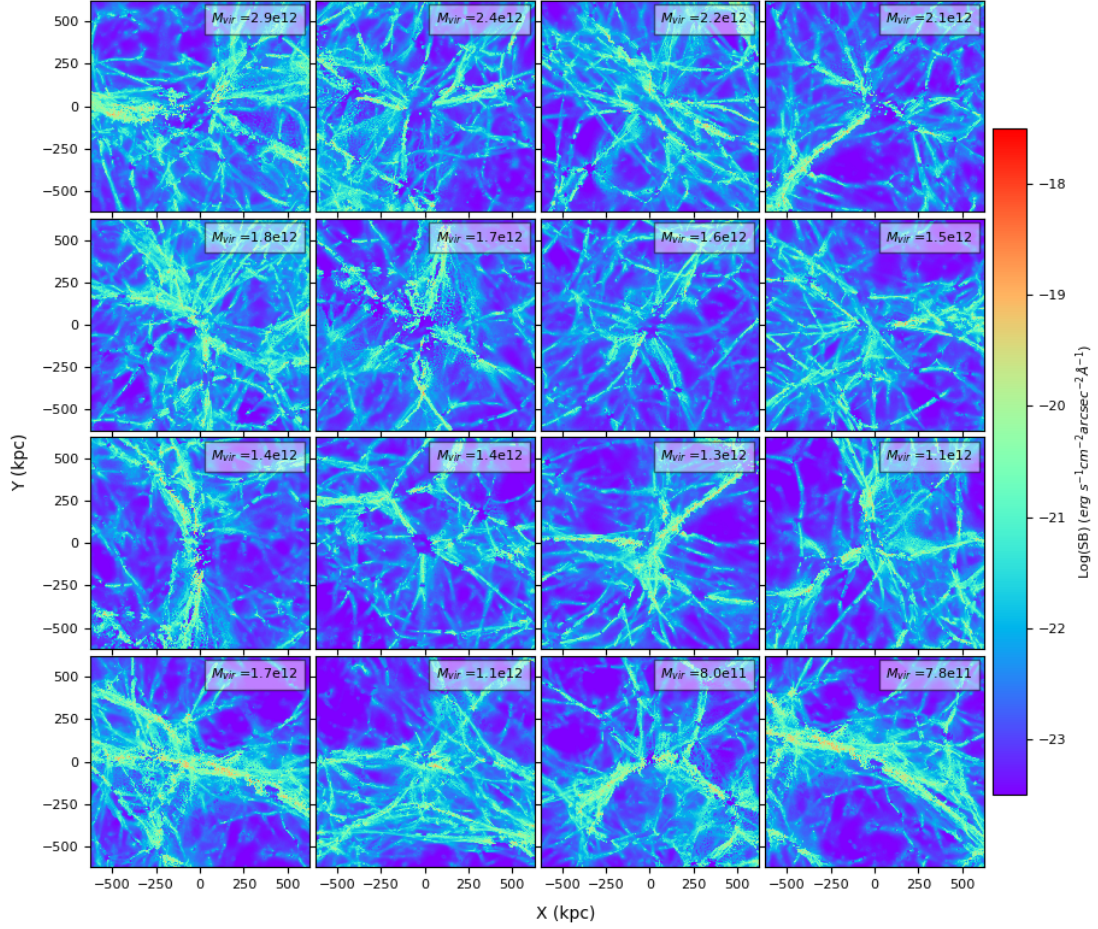


Figure 4.3: Pseudo narrow-band images of Ly α surface brightness of the regions shown in Fig. 4.2, which at $z = 3$ are 2.6 arcmin on a side, created using L25n1024NF and L17n1024NF. All subhalos are excised and the pixel size matches that of MUSE. Box in top left panel indicates MUSE Hubble Ultra Deep Field exposure area. In comparison with Fig. 4.2, the locations of brightest Ly α emission correspond to the locations of high temperature and density.

Finally we convert this value to units of surface brightness. Our surface brightness detection limit for a Wide Field Mode sampling voxel at the 5σ level is:

$$\begin{aligned} \text{SB}_{\text{lim}} &= 5 \times 9.2 \cdot 10^{-21} \text{erg s}^{-1} \text{cm}^{-2} / 6.25 \text{\AA} / 0.2^2 \text{arcsec}^2 \\ &= 1.84 \cdot 10^{-19} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2} \text{\AA}^{-1} \end{aligned} \tag{4.7}$$

4.4 Results: Sources of Ly α

Images of the halos in temperature and density are shown in Fig. 4.2, and in total Ly α surface brightness in Fig. 4.3. The areas of high density (shown in light blue) in Fig. 4.2 correspond to the highest Ly α emission in Fig. 4.3. Areas of high temperature (shown in orange) in Fig. 4.2 are mostly confined to halos which are excised in Fig. 4.3 and thereafter, as described in Section 4.3.2.

To explore the dependence of the total Ly α luminosity on the physical conditions of the gas and discern the contributions of collisional excitation vs. recombination, we investigate the phase diagram of the gas within the spatial and velocity bounds mentioned above. Since in this context the results are essentially invariant between different halos, we focus here on the most massive halo, the one that is shown in the top left panel of Fig. 4.2 and Fig. 4.3. We begin with Fig. 4.4, which presents the intrinsic dependence of the luminosity on density and temperature irrespective of the actual mass distribution of gas in the phase diagram. The left column was created including subhalos while for the right column the subhalos have been excised. The color in the first row indicates the total Ly α emission (from both processes) per unit mass as a function of gas density and

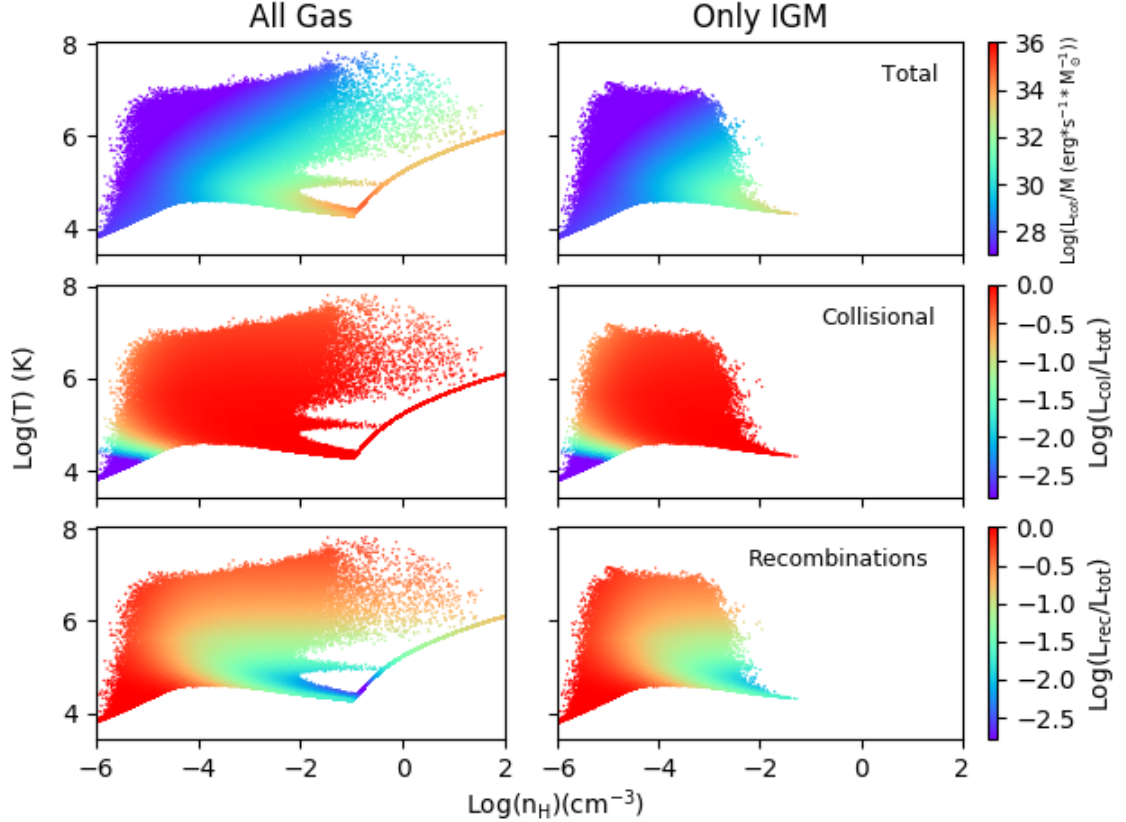


Figure 4.4: Temperature vs. density phase space diagrams for gas cells within a region of $(1250 \text{ kpc})^2$ and velocity depth of $v = \pm 193 \text{ km/s}$ for the most massive halo in the L25n1024NF simulation (top left panel of Fig. 4.3 and 4.2). The left column includes particles bound to subhalos, the right column does not. From top to bottom: phase space colored by total $\text{Ly}\alpha$ emission, fraction of emission due to collisions, and fraction of emission due to recombinations. In regions of high density and low temperature, collisional excitation dominates as expected from Fig. 4.1.

temperature. The second row is colored by the fraction of total emission due to collisional excitation, and the third by the fraction of total emission due to recombinations. Until this point we have assumed collisional ionization equilibrium, which only considers collision and recombination processes. The luminosity from both is only dependent on temperature. However, in the simulation, photoionizations are also possible, which creates an implicit dependence of ionization fraction on density. The ionization fraction of the gas decreases with density and increases with temperature, reducing n_{H} and increasing n_{e} and n_{p} . This relation is reflected in Fig. 4.4 which shows recombination dominating the total emission at low densities and high temperatures, while the contribution of collisional excitation is largest at low temperatures. Above $n_{\text{p}} + n_{\text{H}} \simeq 10^{-2.5} \text{cm}^{-3}$ almost all emission is due to collisional excitation .³

From Fig. 4.4 alone, it is impossible to tell which process is responsible for the majority of *total* emission that is potentially detectable, since it presents the luminosity per unit mass. Fig. 4.5 addresses this by showing the distributions in phase space of total, collisional excitation, and recombination emission (from top to bottom), averaged over all 16 halos in Fig. 4.2 and Fig. 4.3. The resulting areas of high and low emission are a reflection of both the luminosity per unit mass and the mass distribution on the phase diagram. Fig. 4.5 clearly shows the largest total amount of $\text{Ly}\alpha$ emission is due to gas with temperature below $T \simeq 10^5 \text{K}$ and density above $n \simeq 10^{-3} \text{cm}^{-3}$. At these temperatures and densities, collisional excitation dominates over recombination (see Fig. 4.4, second row).

Although detection of $\text{Ly}\alpha$ emission is dependent on the spatial distribution of the gas, our

³The ‘tail’ feature in the plots in the left column reflects the polytropic equation of state assumed in the simulations to prevent artificial fragmentation at high densities (Springel and Hernquist, 2003).

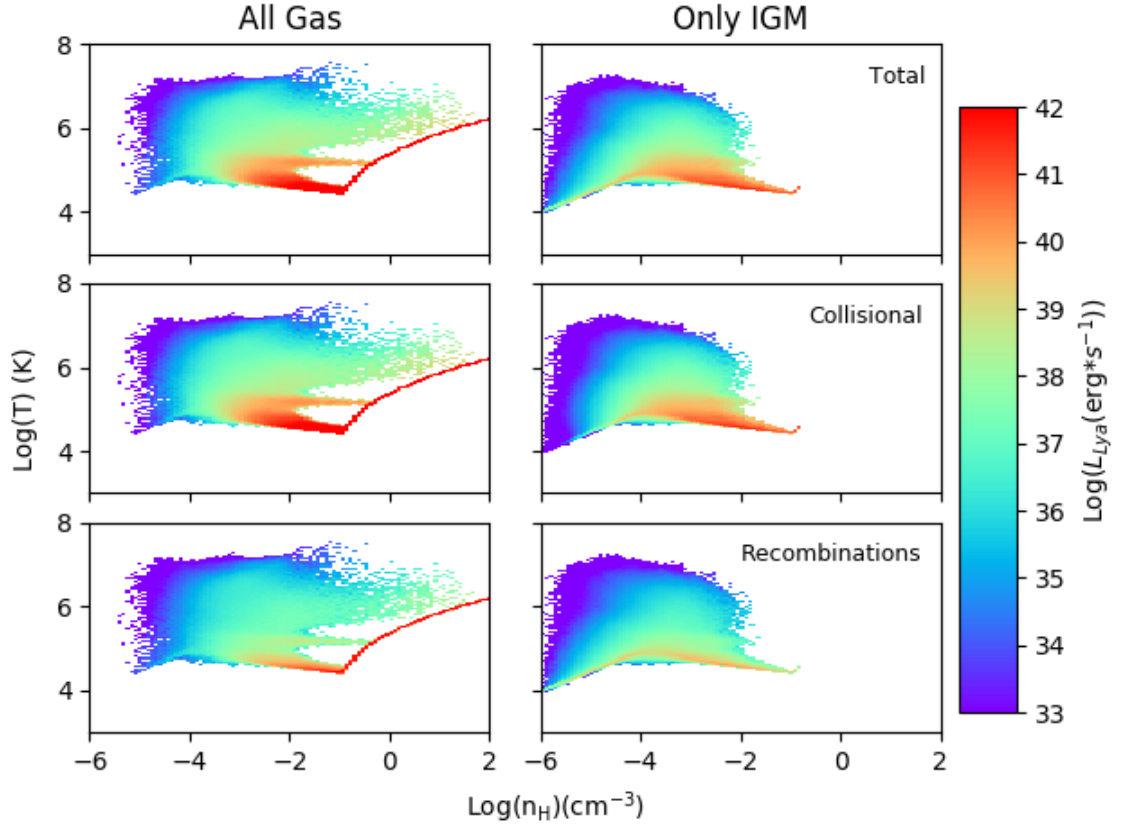


Figure 4.5: Density of phase space for gas cells within a region of $(1250 \text{ kpc})^2$ and velocity depth of $v = \pm 193 \text{ km/s}$. Median of all 16 halos. Left column includes particles bound to halos, right column does not. From top to bottom: 2d histograms weighted by total Ly α emission, emission due to collisions, and emission due to recombinations. 100x100 pixels in each panel. Emission from collisions dominates total emission.

results suggest that collisional excitation is a more likely source of detectable emission than recombination. In fact, it is responsible for 95% of the total emission, on average, assuming no additional sources of photoionization.⁴

4.5 Results: Improving Detectability

We now focus on the detectability of the gaseous filaments surrounding massive halos with the MUSE instrument. We describe the effect of varying simulation resolution (Section 4.5.1), pixel resolution (Section 4.5.2), and feedback models (Section 4.5.3) in order to optimize detection.

4.5.1 Simulation Resolution

A natural step towards boosting the signal is to increase the resolution of the simulation to reveal substructure within the filaments. Since the emissivity scales as density squared, small variations of the gas in phase space could be amplified in Ly α emission. Gas at higher densities will increase the total Ly α emission, making the filament more detectable.

To quantify the expected signal boost, the left panel of Fig. 4.6 compares the median distribution of total Ly α surface brightness per pixel for all 16 halos from the low (black) and high (blue) resolution simulations with no feedback (L25n512NF and L25n1024NF, respectively). The red vertical line represents the MUSE detection limit, while the number in the bottom left corners represent the median combined angular area of pixels above the MUSE detection limit.

⁴We note that this result is unchanged whether the analysis is performed with data from the low- or high-resolution simulation.

The size of the MUSE pixel is ~ 1.5 kpc on a side - small enough to probe fine substructure. It is therefore surprising that at most surface brightness levels, the images created with higher resolution simulations are consistent with their low resolution counterparts, suggesting that any overdensities that are resolved by increasing resolution are not significant enough to boost the Ly α surface brightness. Small differences occur between the two simulation resolutions at mid-range surface brightnesses ($\text{Log}(\text{SB}) \sim -21$) and at the high surface brightness tail. In this regime, which represents the detectable pixels, the images created with a low resolution simulation have a factor of $\simeq 1.5$ more detectable area than images from the high resolution simulation, on average. The differences between the two resolutions are a numerical artefact of the low resolution creating dense ‘clumps’ of particles that are spread more continuously over neighboring pixels at higher resolution. The numerical effect is dependent on both pixel resolution and feedback, which will be discussed in Sec. 4.5.2 and Sec. 4.5.3, respectively. Observations, of course, are free from numerical resolution effects. Overall our findings suggest, somewhat counterintuitively, that the degree of substructure within the filaments is not a strong indicator of their detectability.

4.5.2 Pixel Resolution

Observationally, detecting filaments has proven difficult and has often relied on stacking techniques (Steidel et al., 2000; Matsuda et al., 2004, 2011). Stacking images containing filaments is challenging to do observationally because it requires the images to be stacked in such a way that the filaments align, but their geometry is not known a priori (e.g. Steidel et al., 2010). Gallego et al. (2018) attempt to overcome this limitation by using

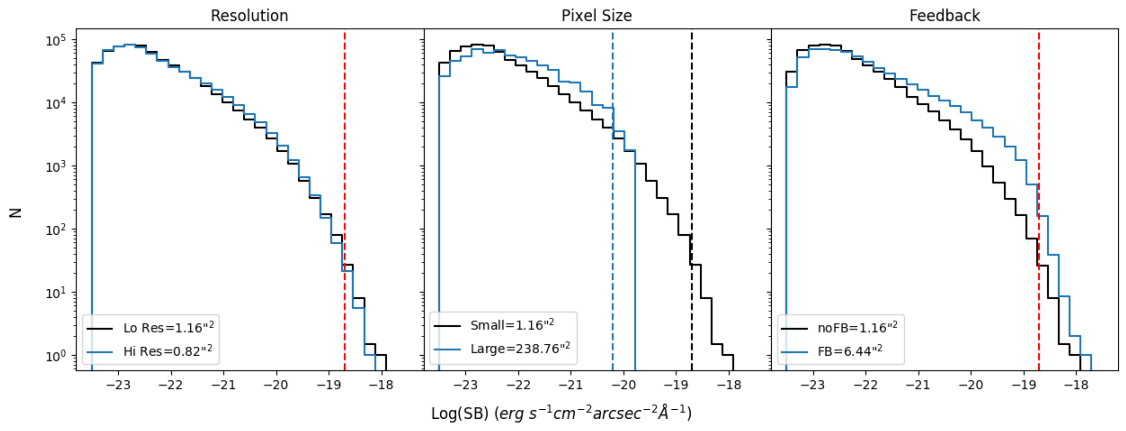


Figure 4.6: Effects of changing simulation resolution, pixel size, and feedback on surface brightness. Each histogram represents the median distribution of the total Ly α surface brightness of the 16 galaxies in Fig. 4.2. Black (blue) histogram corresponds to low (high) resolution in the left panel, small (large) pixel size in the middle panel and no feedback (feedback) in the right panel, respectively. The dashed red line shows the MUSE detection limit. In the middle panel, there are two detection limits shown since the detection limit varies with pixel size and the blue histogram is renormalized so that the area below the histogram matches the others. Numbers in bottom left corner denote detectable area on the various types of average images, each of which has a total area of $(2.64')^2 = 25000''^2$. Simulation resolution does not significantly affect the detectable area. However, larger pixel size and implementing feedback both significantly increase detectability.

positions of nearby Ly α galaxies and assuming they are connected by a filament to orient subcubes before stacking, but are not able to make a detection even with 390 ‘oriented’ stacks of MUSE data. They thus suggest that 2/3 of their cubes may not contain filaments.

We hence turn to a different image processing technique: pixel degradation. The effects of artificially resizing pixels on detectability have been addressed in similar contexts (see, e.g Bertone and Schaye, 2012; Hani et al., 2020). We note that Gallego et al. (2018) effectively use pixel degradation in their analysis by ‘resampling’ so that the area of their pixels increases by a factor of two in order to avoid empty ones. Here we suggest a more extreme resampling. By decreasing the number of pixels in an image (effectively combining them), the number of Ly α photons per pixel is increased, thus increasing the signal by a factor of n , where n is the factor by which the angular area of a pixel is increased, and the noise by a factor of $\sqrt{n}$, thereby increasing the signal-to-noise ratio by a factor of $\sqrt{n}$. The drawback to this technique is that the continuum of the sources needs to be removed to high accuracy, and of course the lost information on smaller substructures within the filaments. However, if our main aim is simply to detect a filament, degrading is sufficient for this purpose.

Fig. 4.7 shows an example for the results of the degrading technique. The area of each pixel in the right panel is $\simeq 700$ larger than the area of each MUSE-like pixel in the left panel. Changing the pixel size has also changed the detection limit, which scales as $1/\sqrt{n}$ where n is the ratio of the area of the pixel to the area of a pixel of MUSE sampling size. Several pixels are now above the threshold for detection by MUSE, and begin to delineate the filaments. For example, the filament that extends below the main horizontal one is

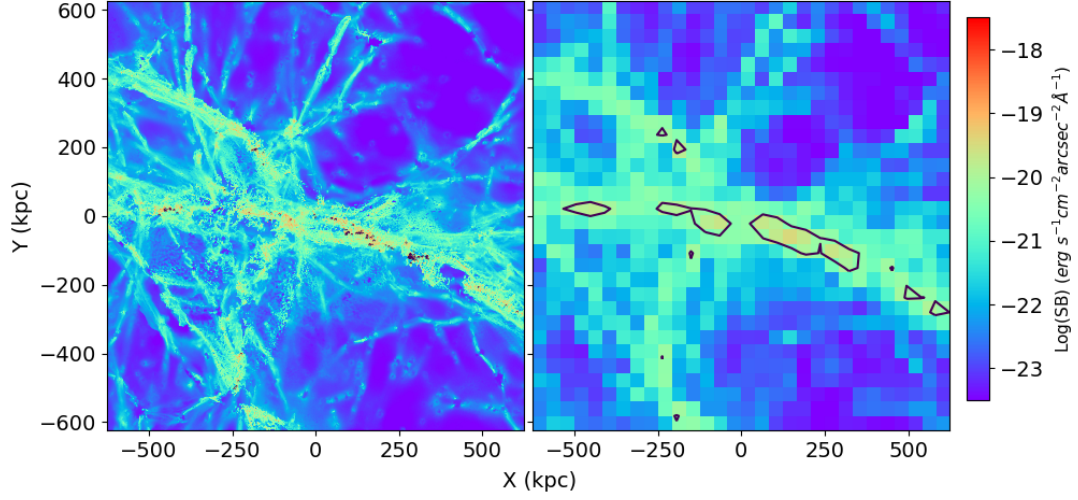


Figure 4.7: MUSE pixel size vs. degraded pixel size images of the galaxy in the bottom left of Fig. 4.2 and Fig. 4.3 from the L17n1024NF simulation. Black contours show MUSE detection limit. In the left (right) panel there are 791 (30) pixels on a side, resulting in a pixel area of $(0.2'')^2$ $((5.3'')^2)$. All filaments are more easily detected at the larger pixel size.

now detected, whereas with the MUSE pixel size an observer would never have known of its presence. In order to maximize the effectiveness of this technique, the area of the pixel should be chosen to minimize contamination from nearby pixels with low S/N values. We have therefore chosen the size of pixel to roughly match the width of a typical filament (not the largest filament).

The middle panel of Fig. 4.6 better quantifies the effect of pixel degradation by binning the $\text{Ly}\alpha$ luminosities in images of both pixel sizes. Blue and black histograms are derived from images of pixel area $(5.3'')^2$ and $(0.2'')^2$, respectively, and dashed lines illustrate corresponding detection limits. The total detected image area is clearly greater when using large pixels. On average, the detectable area is over two orders of magnitude larger for the degraded images. However, in most cases, *more* pixels are detectable with a small pixel size. For example, for the second-most massive galaxy (top row, second from left galaxy

in Fig. 4.3), only one large pixel is detected, compared to 4 small pixels. This suggests that either all of the small detected pixels are located in an area encompassed by the large detected pixel, or, far more likely, they are more spread out but the degree of degradation is too large, such that when they are combined with nearby pixels of lower luminosities, potentially located in a void, the signal is diluted. However, in most cases, such as for the halo in the bottom left of Fig. 4.3, combining pixels allows for a clear detection. In this case, instead of detecting many smaller pixels that may lie in several different filaments, pixel degradation facilitates detection of fewer, larger pixels that trace filaments more reliably. Our technique is not new, however, to our knowledge, this is the first time degrading to such an extent has been suggested for use on deep MUSE data.

4.5.3 Feedback

Until this point all results have been derived using simulations without feedback. We now investigate the effects of feedback on the detectability of filaments using the identical initial conditions but with supernovae and black hole feedback modeled in the same way as in IllustrisTNG. The right panel of Fig. 4.6 compares the average total $\text{Ly}\alpha$ surface brightness histograms for the 12 halos from the low resolution, $(25\text{cMpc/h})^3$ box simulation with (blue, L25n512TNG) and without (black, L25n512NF) feedback. The four halos from the high resolution, $(17\text{cMpc/h})^3$ box are not included as we do not have available an equivalent simulation with feedback.

The right panel of Fig. 4.6 clearly demonstrates the strong effect of feedback on detectability. We find that feedback increases the number of detected pixels by a factor of

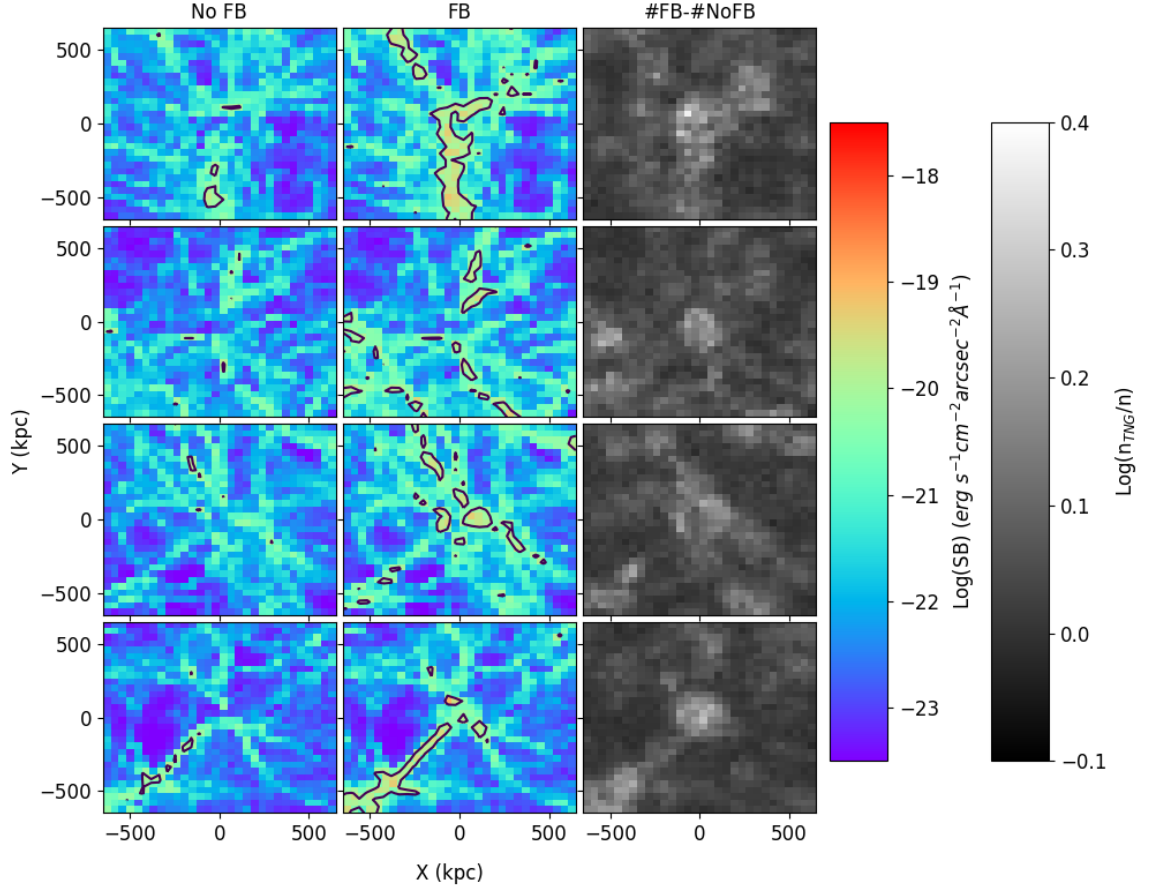


Figure 4.8: First column: Degraded images of the four most massive galaxies in the sample (shown in the top row of Fig. 4.2 and Fig. 4.3) created using the high resolution, large volume simulation without feedback (L25n1024NF). There are 30 pixels on a side, resulting in a pixel area of $(5.3'')^2$. Second column: Same as the first column but with feedback (L25n1024TNG). Black contours denote MUSE detection limit. Third column: Enhancement in number of gas cells per pixel when implementing feedback in the low resolution simulation. Enhanced pixels coincide spatially with filaments.

$\simeq 5.5$ on average. That such a substantial signal boost should occur is not obvious. Black hole-driven winds have been shown to destroy galactic disks and other structures (Beckmann et al., 2019; Grand et al., 2017). Gas filaments, which have low densities and are not bound, are especially susceptible to disruption through feedback processes. However, we find that the amount of gas that is blown out of the filaments due to feedback is negligible when compared with the amount of gas blown from the central halo into them.

Fig. 4.8 shows the increase in number of gas cells in each pixel between the feedback and no-feedback simulations, coupled with the effect of pixel degradation, for the four halos in the top row of Fig. 4.2 and Fig. 4.3. The third column illustrates the difference between the number of gas cells occupying each pixel in the images of the first and second columns. Boosts in number of gas cells (shown in white) are preferentially located along existing filaments, while voids experience almost no change. This is consistent with our understanding of the feedback model. Filaments are populated by small halos whose galactic winds travel at velocities that scale with local dark matter velocity dispersion (Pillepich et al., 2018). The wind velocities do not allow gas to easily escape their potential wells. Thus, most feedback is localized to the halo, while any gas that escapes the halo is not likely to have a high enough velocity to escape the filament. Therefore, although we excise the halos, traces of feedback are mostly confined to the filaments.

The TNG feedback model is so effective that filaments are detectable even at the MUSE pixel size. That we have not yet observed a filament with MUSE suggests that the model is ejecting too much gas from subhalos into filaments. One possible reason for this could be the speed of the galactic winds. The TNG feedback model relies on strong ejective

feedback instead of preventative feedback to regulate gas. For low mass galaxies, the TNG model predominantly consists of galactic winds that are faster, warmer, and more efficient than the previous Illustris model (Pillepich et al., 2018). The speeds of the TNG galactic winds are fast enough to escape the halo, but not the filament it resides in, resulting in an excess of gas within the filaments. While this results in a better match to observational constraints such as galaxy size and stellar content at the low mass end, it may not lead to a realistic gas distribution at larger radii.

4.6 Summary and Discussion

Our standard cosmological model, Λ CDM, predicts that gas in the intergalactic medium is distributed in filaments linking massive halos. Furthermore, cosmological simulations suggest that these filaments trace underlying dark matter filaments that make up the cosmic web. Recombinations and collisional excitation processes result in faint Ly α emission from the gaseous filaments, allowing for possible detection by deep imaging instruments such as MUSE. In this study we have used six simulations of differing resolutions and physics models to investigate the detectability of the filaments feeding 16 massive ($M_{\text{vir}} = 7.8 \cdot 10^{11} - 2.9 \cdot 10^{12} M_{\odot}$) halos at $z=3$ with the MUSE/VLT instrument. We summarize our findings below:

- Assuming an optically thin limit, we map total Ly α emission (collisional excitation and recombination) and find it correlates with the temperature and density of the filaments as expected. That is, collisional excitation (recombination) channels dominate at high (low) densities and low (high) temperatures.

- The vast majority of the $\text{Ly}\alpha$ emission from gas (excluding that in halos) is caused by collisional excitations which dominate in low temperature, high density regions. It is not entirely surprising that most emission arises from cool clumps instead of hot, ionized streams of gas. Furlanetto et al. (2005) find a similar domination of collisional processes in a similar redshift, temperature, and density regime. Witstok et al. (2019) analyze $\text{Ly}\alpha$ emission at $z=5.76$ using the Sherwood simulation suite and, assuming an optically thin limit, find that while collisional processes dominate in high density areas, recombinations dominate at lower densities common in filaments. Finally, Rosdahl and Blaizot (2012) compute $\text{Ly}\alpha$ emission from filaments surrounding a halo of the same virial mass as the most massive halo in this study ($2.9 \times 10^{12} M_{\odot}$) and find that 95% of the total $\text{Ly}\alpha$ emission is contributed through collisional channels. However, we note that their analysis focuses on the inner regions of the halo (r_{vir}), thus excluding the gas from the long, extended filaments. Furthermore, we have removed any particles associated to any halo via SUBFIND, while Rosdahl and Blaizot (2012) employ radiative transfer and self-shielding models to these regions. However, it is worth noting that for observations, additional sources of photoionization could enhance recombination emission, especially at large distances from dense subhalos.
- Changing the resolution of the simulation does not result in a significant signal boost. This suggests that filaments with a higher degree of substructure will not be significantly more detectable.
- By degrading the pixel resolution of the original mock image by a factor of $\simeq 700$ in pixel area, the area of the image above the detection limit is boosted by a factor of

$\simeq 200$ on average. Although we have lost information about small scale structure we are easily able to detect diffuse gaseous filaments at $z = 3$ to the 5σ level.

- Implementing feedback increases the detectable area by a factor of $\simeq 5.5$ on average in filaments. Furthermore, the effect is focused along the filaments: gas is blown out from the halos lying along the filaments, increasing filament densities and thus boosting $\text{Ly}\alpha$ emission. When combined with the effect of pixel degradation, filaments are clearly detected. Even using the MUSE pixel size, employing the TNG feedback model boosts a considerable number of pixels beyond the detection threshold, suggesting that filaments should be observable. The fact that we have not observed them yet indicates that the TNG model is most likely overpopulating the filaments with gas.

4.7 Appendix A

To compute the impact of $\text{Ly}\alpha$ scattering, we have used a parallelized 3D Monte Carlo $\text{Ly}\alpha$ radiative transfer code, which was originally developed for line-intensity mapping predictions (Visbal and McQuinn, 2018). This code is similar to the one described in Faucher-Giguère et al. (2010) (see also Zheng and Miralda-Escudé, 2002; Cantalupo et al., 2005; Dijkstra et al., 2006; Laursen and Sommer-Larsen, 2007). For a detailed description see Appendix C in Faucher-Giguère et al. (2010). To generate a distant-observer image, the code follows the paths of $\text{Ly}\alpha$ photons packets as they scatter throughout the simulated neutral gas field.

For the radiative transfer calculation, the neutral hydrogen density, temperature, $\text{Ly}\alpha$ emissivity, and gas velocity in a $(1250 \text{ kpc})^3$ volume centered on our most massive

galaxy (top left in Fig. 4.2 and Fig. 4.3) were smoothed over a 500^3 cubic grid using a gaussian kernel whose width depends on the local density such that it is smaller in denser regions. We then follow $\sim 10^6$ Ly α photons packets, distributed proportionally to the filaments' Ly α emission to estimate the distant-observer image cube (two spatial dimensions and one frequency dimensions). We also utilize the “accelerated scheme” described in Appendix C of Faucher-Giguère et al. (2010) with $x_{\text{crit}} = 2.5$, which greatly speeds up our calculation without significantly impacting the results.

We have checked convergence for the number of packets, x_{crit} , the grid resolution, and the integration of packets' paths through the simulation. Our results are summarized in Fig. 4.9 where we plot the histogram of observed Ly α intensities with and without performing radiative transfer. Here we have convolved our 500^3 resolution image cube with a top-hat window function with dimensions to $5.3'' \times 5.3'' \times 6.25$ Angstroms. This corresponds to the degraded resolution used in Section 4.5.2. We see that the smearing of the signal due to radiative transfer reduces the intensity of the brightest pixels by a factor of $\sim 2 - 3$ compared to ignoring this effect. Shifting the surface brightness distributions in Fig. 4.6 lower by a factor of $\sim 2 - 3$ would alter the detectable area, particularly for the large pixel size, which has a steep cutoff at the high surface brightness end. We have not checked how radiative transfer affects surface brightness at different pixel sizes, simulation resolutions, or feedback implementations. Given the above calculations, we expect the impact to be relatively modest (particularly in the large pixel size case).

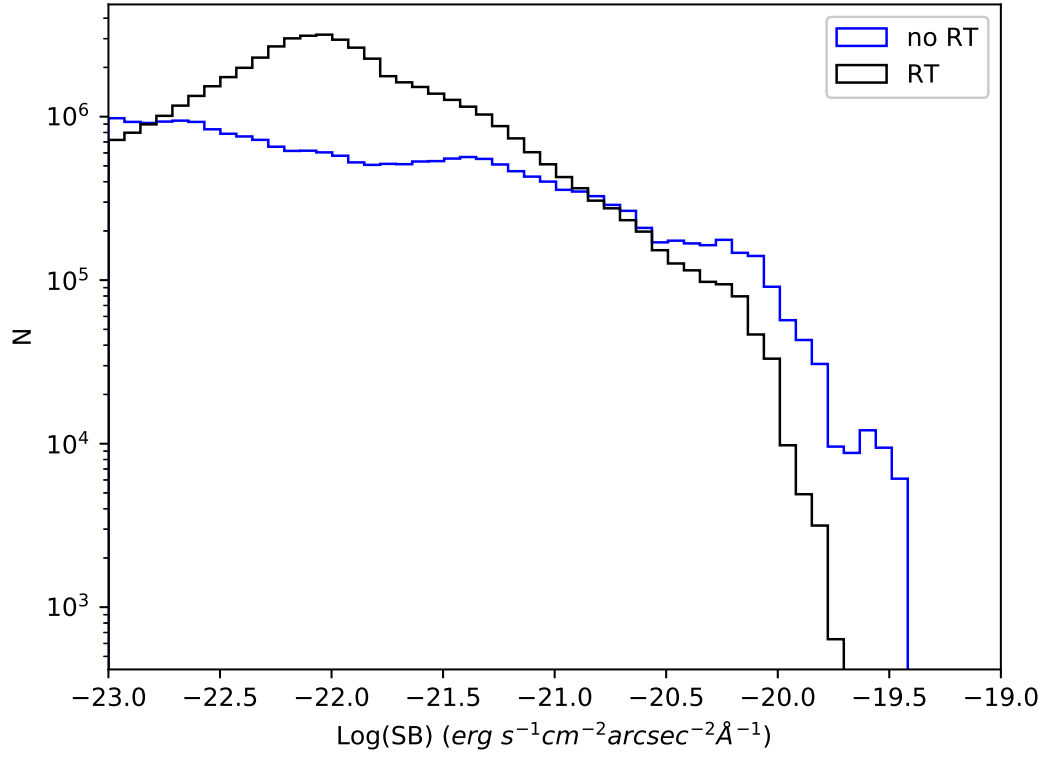


Figure 4.9: Impact of radiative transfer on surface brightness. Distributions of surface brightness in a box of sidelength 1250 kpc with and without radiative transfer included. Box is centered on the most massive halo in the L25n512NF simulation and has 500 pixels on a side. Radiative transfer can smear the signal so as to reduce the surface brightness in the brightest parts of the box by a factor of ~ 2 .

Chapter 5

Simulating AGN feedback in isolated dwarf galaxies

5.1 Abstract

A recent increase in observations of Active Galactic Nuclei (AGN) signatures in dwarf galaxies has emphasized the need for modeling black hole feedback and their effects on the evolution of low-mass galaxies. We use the *SMUGGLE* model in conjunction with the Illustris AGN feedback model to study the role of an intermediate mass black hole in the star formation and outflow rates of an isolated dwarf galaxy. For our particular implementation, we find that AGNs spend the majority of the time in the radio “maintenance” mode although accretion bursts onto the black hole may temporarily trigger the fast-accreting quasar mode effects. This conclusion may, however, depend on the particular feedback model and assembly history of each particular halo, conditions that should be

explored before more firm conclusions can be drawn. Including the effects of AGN does not substantially modify the star formation history of the simulated dwarf, although the overall stellar mass formed in runs including AGN effects decreases by $\sim 10\%$ after 1 Gyr of evolution compared with stellar-feedback only runs. The effect of AGN is, however, much more relevant on the outflow properties, generating extended gaseous halos well beyond the virial radius. In comparison with outflows due to stellar feedback alone, outflows from AGN have larger median mass content and lower median outflow velocities. We argue that this decreased velocity is a consequence of the now more substantial gas halo component against which outflows need to push through compared to free-streaming in the case of stellar-feedback only runs.

5.2 Introduction

In massive galaxies, active galactic nuclei (AGN) have a well-documented relationship with their host halos (see e.g., Kormendy and Ho, 2013), regulating galaxy properties through energetic feedback processes like winds and outflows (see Fabian (2012); King and Pounds (2015) for observational reviews). AGN activity is often invoked in simulations to recreate these observed relations. For example, AGN feedback is necessary in all hydrodynamical simulations and semi-analytic models to quench star formation in massive ellipticals and reconcile the luminosity function with observations (Puchwein and Springel, 2013; Vogelsberger et al., 2014c; Schaye et al., 2015; Beckmann et al., 2017; Henden et al., 2018; Terrazas et al., 2020). Previous observational studies and simulations have shown no need

for AGN feedback effects in order to explain star formation in the dwarf regime. Instead, stellar feedback processes such as winds from supernovae are responsible for most of the quenching in this regime, effectively depleting reservoirs of cold gas over time and regulating star formation (Martín-Navarro and Mezcua, 2018; Trebitsch et al., 2018; Koudmani et al., 2019).

In observations, previous studies have been biased towards massive AGN as their higher luminosities make them easier to detect (Greene and Ho, 2007b). Emission from AGN in dwarf galaxies, which typically host less massive black holes, can be obscured by stellar feedback processes (Moran et al., 2002, 2014; Trump et al., 2015) or by heavy X-ray absorption (Chen et al., 2017). However, several recent studies have successfully detected AGN corresponding to intermediate mass black holes (IMBHs) in a mass range ($M_{BH} = 10^3 - 10^6 M_{\odot}$) via optical and infrared signals (Greene and Ho, 2007a; Dong et al., 2012; Reines et al., 2013; Sartori et al., 2015; Latimer et al., 2019; Reines et al., 2020). Furthermore, interesting cases of off center black holes (Reines et al., 2020) and previously ‘hidden’ AGN (Mezcua and Domínguez Sánchez, 2020) have indicated that there is much we have yet to understand about the nearby population of IMBHs.

Of the many nearby AGN within dwarf galaxies that have been detected, some have shown evidence of significant outflows, including asymmetries in the ionized gas distribution (Penny et al., 2018), AGN-like line ratios in a sample of isolated non-star forming dwarfs (Janz et al., 2017; Bradford et al., 2018; Dickey et al., 2019) and direct detection of AGN-driven winds in dwarfs with active BHs (Manzano-King et al., 2019). While AGN are widely known to create outflows in more massive galaxies, their role in dwarf galaxies is not yet

well understood, with current evidence suggesting that it might have a significant impact in at least *some* dwarfs.

Analytical arguments indicate that feedback from IMBHs could potentially dominate the energetic budget over stellar sources, although how effectively it might couple that energy to the surrounding gas in the interstellar medium of dwarfs is largely an unknown (Silk, 2017). To date, a few numerical hydrodynamical simulations of AGNs in the dwarf regime have been carried out. For example, Koudmani et al. (2019) simulate several isolated dwarf galaxies with varying AGN feedback implementations and find that the presence of an AGN increases the amount of thermal energy expelled from the galaxy by up to five orders of magnitude. Similarly, Dashyan et al. (2018) model AGN outflows in a dwarf galaxy and find that under certain conditions, AGN may be more efficient than supernovae at regulating star formation. However, although some consensus seems to arise on AGNs impacting the outflows properties of dwarfs, its effect on the star formation history and possibilities of quenching the host dwarf remain still poorly understood.

Neither the simulations of Koudmani et al. (2019) nor Dashyan et al. (2018) resolve the multiphase structure of the interstellar medium (ISM). Taking the ISM into consideration has been shown to increase efficiency of stellar feedback by enhancing the coupling of the gas to the supernovae in the FIRE simulations (Hopkins et al., 2014) and in Kimm et al. (2015). Furthermore, there is evidence that it may reduce the efficiency of AGN feedback (Costa et al., 2014). Both of these effects combined may account for the aforementioned negligible effect of AGN on star formation rate. In this study, we model the multiphase structure of the ISM using the *SMUGGLE* model and we study the interplay between stellar

feedback and AGNs in dwarfs by extending *SMUGGLE* to include the AGN model in the Illustris simulations (Vogelsberger et al., 2014b,a; Sijacki et al., 2015).

Our paper is structured as follows: in Sec. 5.3 we discuss the simulation set up, feedback models used, and resulting black hole accretion rates; in Sec. 5.4.1 we explore the effects of AGN feedback on global star formation rates; in Sec. 5.4.2 we investigate the outflows created by AGN; finally, in Sec. 5.5 we summarize and discuss our results.

5.3 Numerical Simulations

We run idealized halo and galaxy simulations using the code AREPO (Springel, 2010). Gravitational forces are calculated via an oct-tree algorithm and hydrodynamics are implemented using a finite-volume moving mesh technique. The *SMUGGLE* model (Marinacci et al., 2019) is used to calculate stellar feedback, gas heating and cooling, and star formation. Stellar feedback includes photoionization and radiation pressure from young stars, gaseous outflows, and energy and momentum injection from stellar winds. Gas is allowed to cool to temperatures of $T \sim 10$ K via low-temperature metal line, fine-structure, and molecular cooling processes.

This new ISM model in AREPO differs substantially from its predecessors (e.g., those used in projects like Illustris, Auriga or IllustrisTNG). For instance, the star formation modeling in Illustris is characterized by a relatively low density threshold, $n_H = 0.2 \text{ cm}^{-3}$ above which gas follows an equation of state used to mimic the multi-phase structure of the ISM (Hernquist and Springel, 2003) (it models, in practice, a two-phase media composed of cold clouds embedded in a hot low-density bath). Star particles, which follow a Chabrier

initial mass function, are created stochastically above a specific density threshold. Gas cells are turned into collisionless star particles with a probability according to their local SFR.

By contrast, the *SMUGGLE* star formation treatment uses an H₂-based criteria for star formation (the fraction of molecular gas in a star-forming cell should be above 50%) on top of a higher density threshold ($n_H \sim 100 \text{ cm}^{-3}$) and also explicitly follows the multiphase nature of the dense gas without imposing an equation of state. We extend the *SMUGGLE* model to include the Illustris AGN treatment, as detailed in Sec. 5.3.2. We choose this particular model since it has been shown to reproduce BH-related observables and scaling relations statistically for a wide population of galaxies simulated in the large volume of Illustris.

5.3.1 Simulations Set Up

We simulate an isolated (non-cosmological) dwarf with $M_{halo} = 10^{11} M_\odot$ and disk scale length $r_{disk}=0.55 \text{ kpc}$. The mass and extent of the dwarf are inspired by the sample of dwarf galaxies with AGN signatures of Reines et al. (2013) consisting of 151 galaxies ranging in stellar mass from $M_* = 10^{8.5}-10^{9.5} M_\odot$ and $r_{50}=0.52-6.66 \text{ kpc}$.¹ The simulation box is 200 kpc on a side, with a resolution of $m_{drk} \simeq 3 \times 10^4 M_\odot$ and $m_{gas} \simeq 2 \times 10^4 M_\odot$, halo concentration $c=10$, and gravitational softening of 0.054 kpc. Fig. 5.1 shows a face-on and edge-on view of our run with AGN seed mass $5 \times 10^3 M_\odot$ for illustration.

To explore the effects of AGN feedback and its robustness to numerical choices, we run several simulations including different variations of our model as follows: No-

¹Stellar mass is related to halo mass via the stellar mass-halo mass relation in Girelli et al. (2020) and $r_{disk}=r_{50}/2.17$

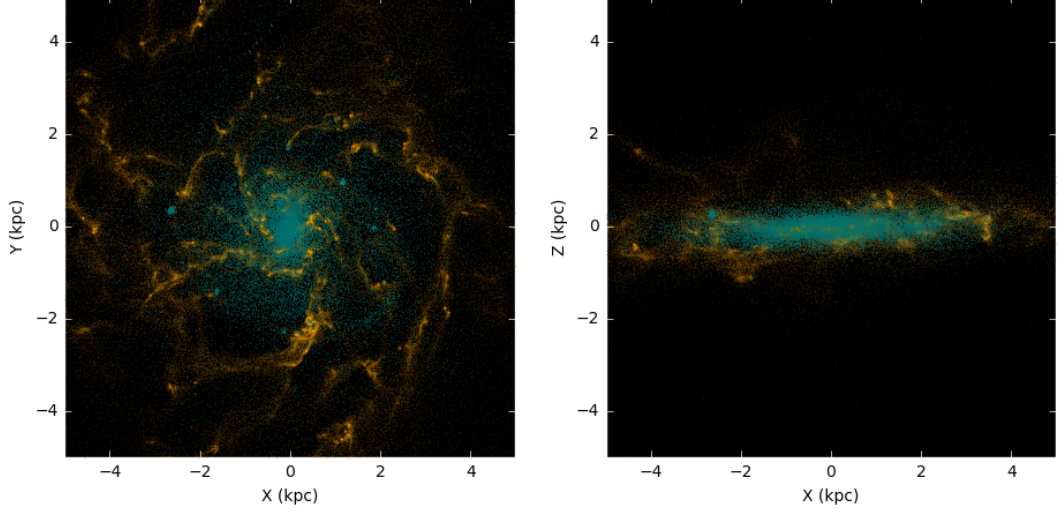


Figure 5.1: Face-on (left) and edge-on (right) projections of a sample dwarf galaxy with AGN seed mass $5 \times 10^3 M_\odot$ at $t=1\text{Gyr}$. Gas particles are plotted in orange and stellar particles are overplotted in cyan. Feedback from Illustris AGN and *SMUGGLE* models create complex distributions of gas in the ISM.

AGN (only *SMUGGLE*), 4 runs seeded with a different mass central black hole, $M_{BH} = [10^3, 5 \times 10^3, 10^4, 5 \times 10^4] M_\odot$ while all other AGN-related parameters follow exactly the Illustris implementation, and one where the distance and radius of the “radio-mode” injection bubbles (see details below) are half those used for the Illustris run.

5.3.2 Black Hole Accretion and AGN Feedback

Following Sijacki et al. (2007), black hole feedback is separated into two modes depending on accretion rate, a high accretion “quasar” mode and a low accretion “radio” mode. In quasar mode, energy is coupled thermally to the surrounding gas, and is directly dependent on the black hole accretion rate. Radio mode is characterized by mechanical feedback from hot bubbles in the gas surrounding the black hole. Bubbles are rescaled

according to their energy and surrounding gas density. See Sijacki et al. (2007) for more a more detailed description of the AGN feedback model.

The accretion rate of black holes within our simulations are determined via the Bondi-Hoyle-Lyttleton prescription:

$$\dot{M}_{BH} = \frac{4\pi\alpha G^2 M_{BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \quad (5.1)$$

where alpha is a dimensionless parameter set at $\alpha = 100$, G is the gravitational constant, M_{BH} is the mass of the black hole, ρ is the density, c_s is the speed of sound in the gas and v is the velocity of the black hole relative to the gas. To ensure prevention of runaway accretion, the model imposes an upper limit on accretion rate $\dot{M}_{BH,max} = \dot{M}_{Edd}$. The Eddington limit, $\dot{M}_{Edd}$, is defined as:

$$\dot{M}_{Edd} = \frac{4\pi M_{BH} m_p}{\epsilon_r \sigma_T c} \quad (5.2)$$

where m_p is the mass of the proton, ϵ_r is the radiative efficiency, and σ_T is the Thompson cross section. All constants and factors in our runs are set to the same values as used in the Illustris simulations (Sijacki et al., 2007, 2015).

Which AGN feedback mode is active at each time is determined by the ratio $\dot{M}_{BH}/\dot{M}_{Edd}$. Below the threshold $\dot{M}_{BH}/\dot{M}_{Edd} < 0.05$ ², the AGN is said to be in the radio mode, and feedback is modeled to resemble the effect of an AGN jet inflating hot bubbles in the gas surrounding the black hole. Above the threshold of $\dot{M}_{BH}/\dot{M}_{Edd} > 0.05$, the AGN is said to be in quasar mode, and feedback is modeled to resemble a quasar thermally heating nearby gas.

²The threshold value is inspired by observations of X-ray binaries in Gallo et al. (2003).

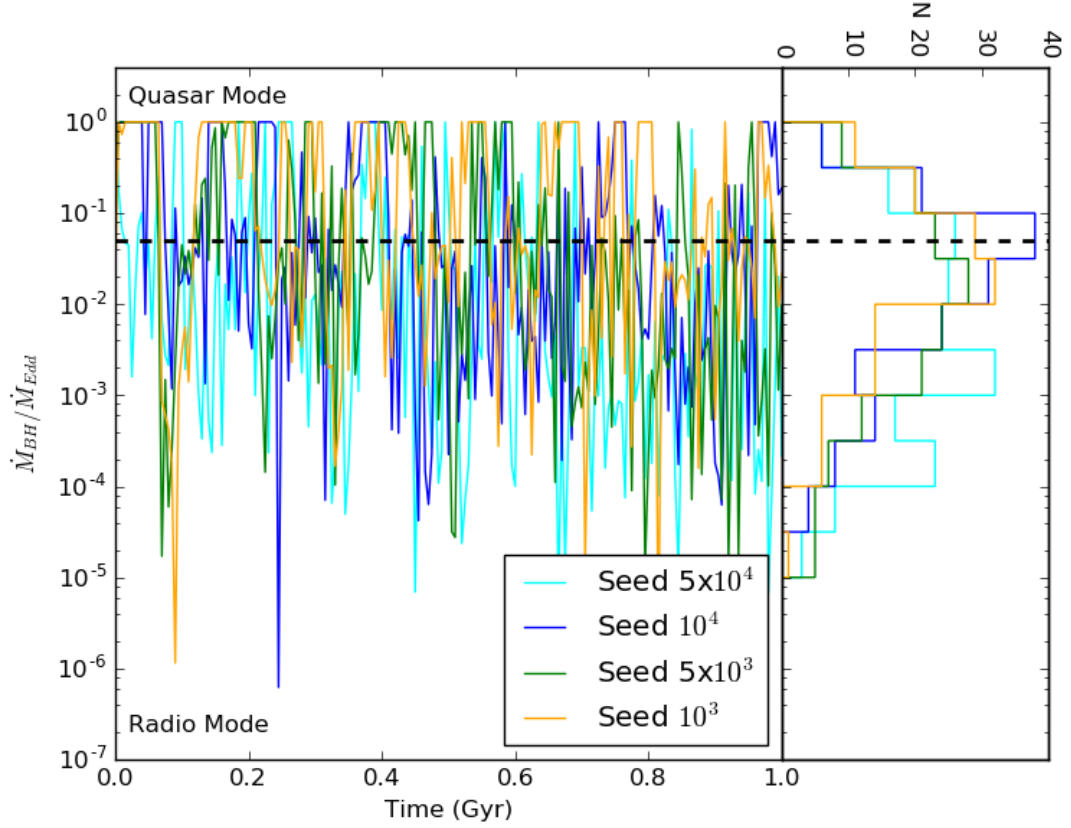


Figure 5.2: Black hole accretion rate in Eddington units (BHAR) as a function of time in each of our simulations with different black hole seed mass. The dashed horizontal line represents the threshold used in our AGN feedback model ($\dot{M}_{BH}/\dot{M}_{Edd}=0.05$) to switch between high- (quasar) and low-accretion (radio) modes. The right histograms show the cumulative over 1 Gyr. The majority of the time black hole feedback is in the form of hot bubbles (i.e radio mode), however smaller seed masses might have a slightly larger contribution from the quasar mode.

Numerically, the Illustris AGN model is implemented as follows. In radio mode, a bubble of radius $r_{\text{bub}}=10$ kpc is placed randomly within a sphere of radius $r_{\text{sph}}=20$ kpc centered on the black hole, and imparts energy by *mechanically* heating the surrounding gas particles. On the other hand, for the quasar mode, a small fraction of the bolometric luminosity, set by the factor ϵ_f , is coupled *thermally* to the surrounding gas particles.

In the regime of our dwarf simulations, we find that the radio feedback mode is dominant over the entire 1 Gyr timespan. Fig. 5.2 shows the feedback mode for all simulations seeded with a black hole. The dashed horizontal line denotes the threshold at which the transition between the two modes occurs. The AGN seed mass has a slight effect on the black hole accretion rate; a larger seed mass corresponds to more time spent in radio mode while a smaller seed mass corresponds to more time in quasar mode.

While early studies of AGN in dwarf galaxies were biased towards detection of black holes accreting at large fractions of their Eddington luminosity (Greene and Ho, 2007b), recent studies have supplied more evidence for black holes with significantly sub-Eddington accretion rates (Schulze and Wisotzki, 2010; Latimer et al., 2019; Mezcua and Domínguez Sánchez, 2020). Our results extend even further into the low accretion radio regime, suggesting that recent studies may also suffer from incompleteness at the low mass-accretion-rate end despite the relatively large mass of these AGNs.

Given the variability in accretion rate, it is interesting to explore the mass evolution of the central black holes in each of our runs. The top panel of Fig. 5.3 shows the black hole mass as a function of time, while the bottom panel of Fig. 5.3 shows the growth normalized by the initial BH mass in each run. All simulations finish, after 1 Gyr, with black hole

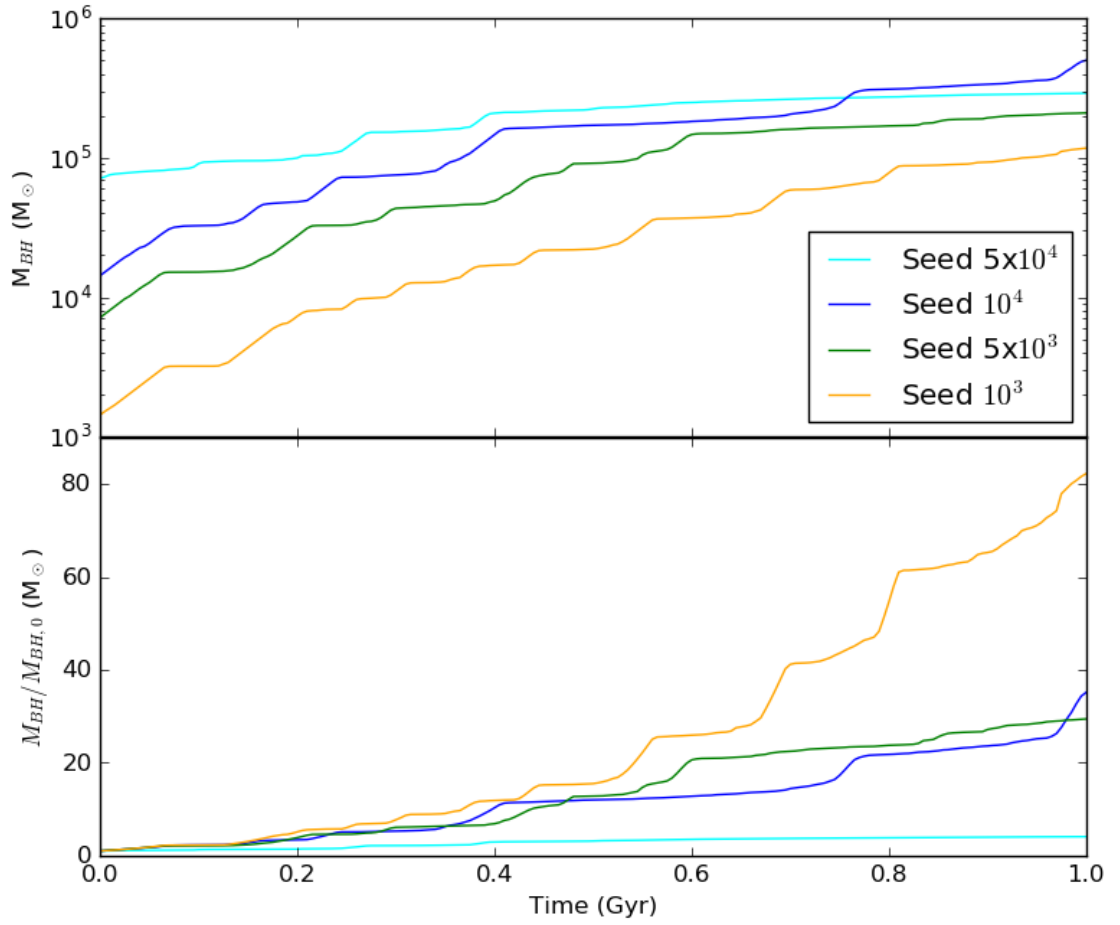


Figure 5.3: Growth of the black holes in our runs. Top panel: mass of black hole as a function of time. Bottom panel: mass of black hole normalized to its initial seed value. The smallest black hole increases its mass by a factor of ~ 80 while the largest black hole only increases its mass by a factor of 4. Final M_{BH} are in the range $1-5 \times 10^5 M_{\odot}$, a value consistent with estimates for AGN dwarfs in observations.

masses between $1\text{--}5 \times 10^5 \text{ M}_\odot$, regardless of their initial seed. For all of our runs, with the exception of $M_{\text{BH}} = 5 \times 10^4 \text{ M}_\odot$, this represents a significant growth and departure from the (arbitrary) initial condition, indicating that the evolution is not only a direct consequence of the starting point, but instead may carry physical meaning. In fact, we find that smaller initial seed mass results in a larger *relative* growth compared to the initial state (see bottom panel). This can be understood by considering that black holes maximize their growth when they are in phases of rapidly accreting quasar-mode while radio mode corresponds to a slow, steady mass accretion. Given our findings in Fig. 5.2, the fact that the smallest seed run shows the largest relative growth is not unexpected.

5.4 Results: Impact of AGN Feedback in Dwarf Galaxies

5.4.1 Star Formation

We test the effects of both stellar and AGN feedback mechanisms on the star formation of our set of simulated dwarfs in Fig. 5.4. We find that, in agreement with previous simulations results (e.g. Koudmani et al., 2019), including AGN feedback does not substantially change the instantaneous star formation rate of dwarf galaxies compared to the non-AGN run (black curve, upper panel). However, small differences accumulated during the full 1 Gyr of our experiments lead to the runs with AGN feedback to systematically have smaller M_* at the end of the simulation compared to the non-AGN run (see bottom panel in Fig. 5.4).

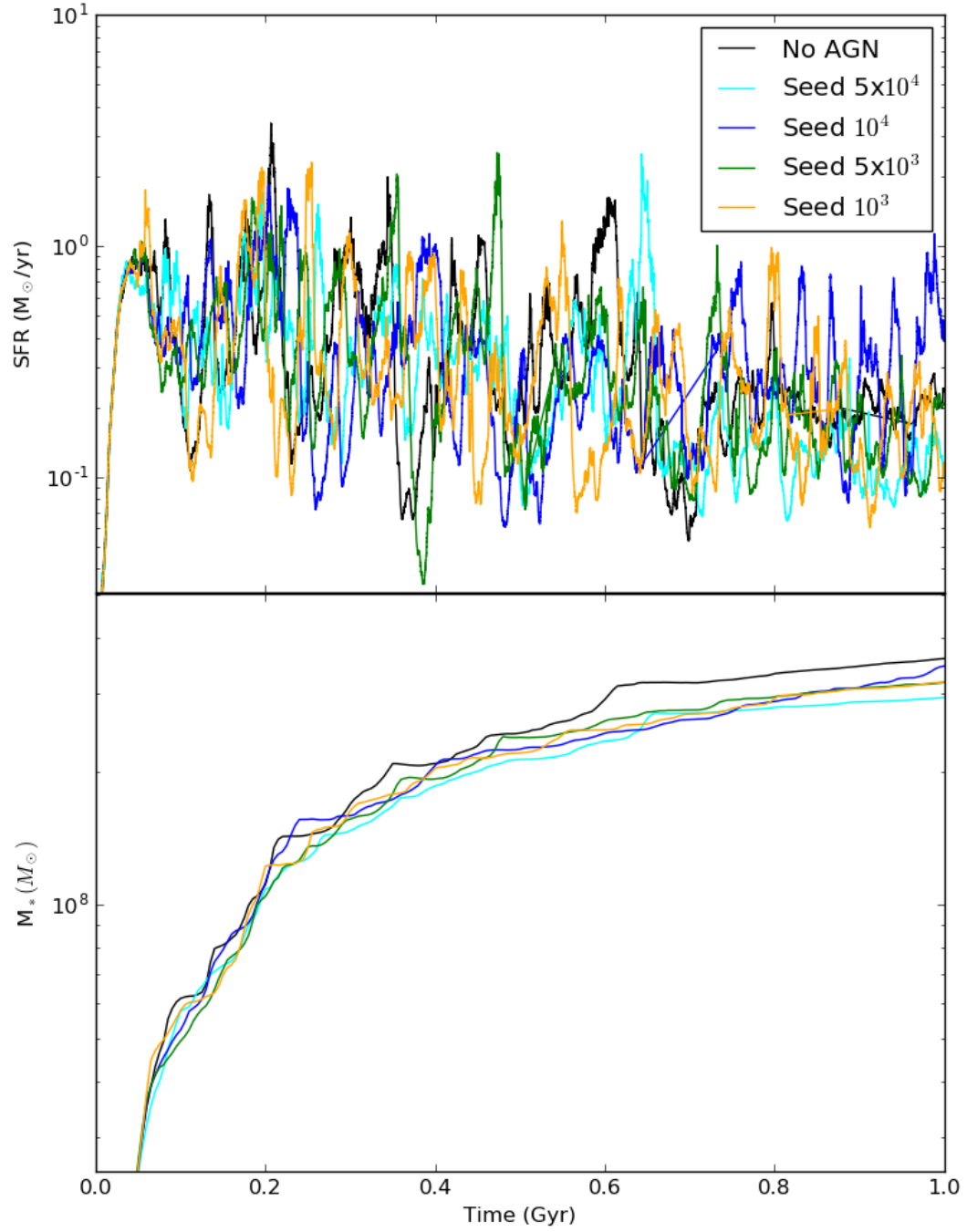


Figure 5.4: Global star formation rate (top panel) and stellar mass (bottom panel) as a function of time for all simulations. Star formation rates are roughly independent of the presence of an AGN or the mass of its seed. The stellar masses of the dwarf galaxies are also similar throughout their lifetimes, regardless of their central black hole masses.

These results suggest that AGN-feedback alone may not be sufficient to explain the full quenching of isolated dwarfs, contrary to what has been suggested in several observational studies (Penny et al., 2018; Dickey et al., 2019; Manzano-King et al., 2019). Alternatively, the coupling of AGN feedback to the surrounding gas needs to be made significantly more efficient in the low mass end than current theoretical models.

5.4.2 Outflows

Interestingly, although our results suggest that AGN feedback does not greatly affect SFR in dwarf galaxies, the outflows properties of our simulated dwarfs show more substantial effects. In Fig. 5.5 we investigate AGN outflows within (bottom) and outside (top) the disk. We define the disk to have radius $r_d=5\text{kpc}$ and height $z=\pm 1\text{kpc}$. The top row of Fig. 5.5 shows the phase diagrams (density vs. temperature) of gas cells outside of the disk. All dwarfs with AGN display an overdensity of high temperature, low density gas that we identify with AGN-driven outflows. While the dwarf without AGN also displays this feature, there are considerably fewer gas element belonging to its outflows. As expected from the previous section, the gas properties in the “disk zone” (bottom panel) do not change dramatically once AGN feedback is included.

We say a gas particle belongs to an outflow if it is low density ($\rho = 10^{-6.5} - 10^{-5.5} \text{ cm}^{-3}$) and high temperature ($T = 5.5 - 6.5 \text{ K}$). The average galactocentric distance of outflow particles is $r \simeq 100\text{kpc}$, approximately the virial radius of our dwarf halo, regardless of seed mass. For all seed masses, over half of the outflow particles lie outside the virial

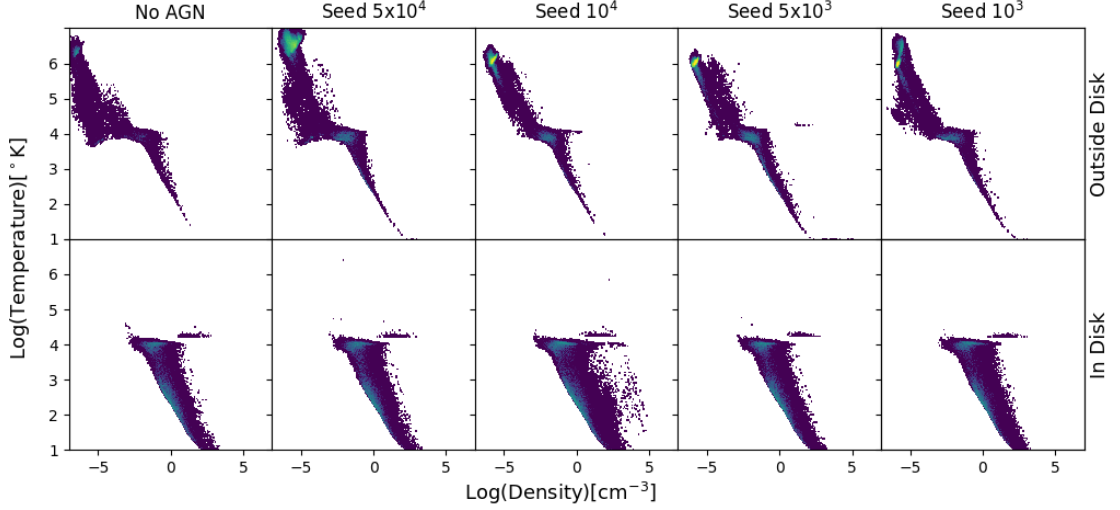


Figure 5.5: Temperature versus density of the gas for dwarf galaxies with and without AGN at $t=1\text{Gyr}$. Top row shows gas particles outside of a disk of radius $r=5\text{kpc}$ and height $z=\pm 1\text{kpc}$. Bottom row shows remaining gas particles within the disk. Colors correspond to the density of gas particles within each pixel. The presence of a black hole correlates with the presence of hot low density gas in the halo (top row). Dwarfs with AGNs do not differ significantly from those without when only taking into account gas within the disk.

radius, with interesting observational consequences once future studies reach the sensitivity needed for this low-density gas.

We further explore in more detail the properties of gaseous outflows in Fig. 5.6. Following Koudmani et al. (2019) we study outflows at distances of $z=2$, 20, and 75 kpc above and below the disk for a slice of thickness $dz=500$ kpc. The top row of Fig. 5.6 shows the mass outflow rate $\dot{M}_{gas}$ and the bottom row shows the median outflow velocity v_{out} . Only gas flowing away from the disc (i.e $\text{sgn}(v_z) = \text{sgn}(z)$) is included in the calculation of outflow rates and velocities.

At a height of $z=2$ kpc, any differences in outflows between simulations are dominated by noise since there are very few gas particles that truly belong to an outflow, i.e

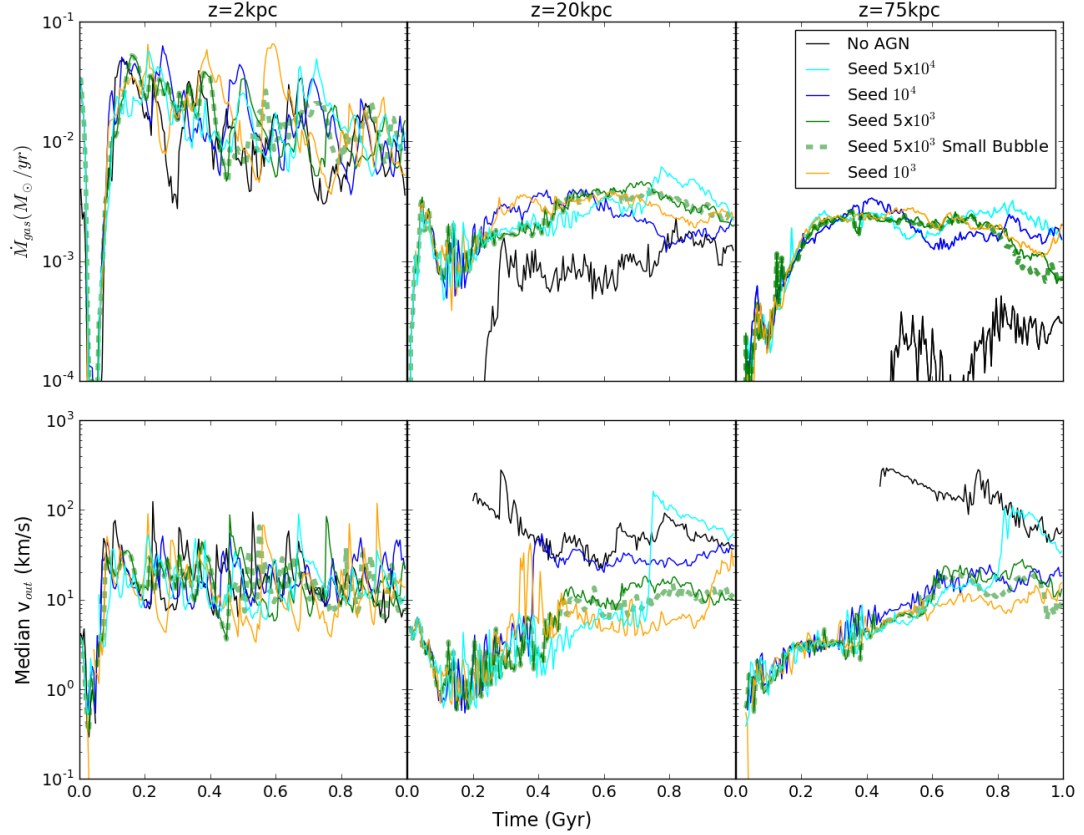


Figure 5.6: Outflow mass loading $\dot{M}_{gas}$ (top) and velocities (bottom) as a function of time for our simulations. Different columns correspond to distances of $z=2$, 20, and 75 kpc from the disk. Spikes in median outflow velocity correspond to stochastic bursts of hot gas due to AGN feedback. Reducing bubble radius and distance from the black hole does not significantly affect the outflow properties (green dashed curve). Dwarf galaxies with AGN should experience more massive outflows although they would be slower in comparison to dwarf galaxies without AGN.

particles that are underdense and hot. This result is in agreement with the absence of hot, underdense gas in the disk seen in Fig. 5.5.

However, at larger distances from the disk, strong trends become apparent. For $z=20$ kpc and $z=75$ kpc, the dwarf without an AGN has a consistently lower outflow rate than dwarfs with AGN, and a consistently higher median outflow velocity. In other words, the presence of an AGN increases the amount of gas being expelled from the galaxy, but decreases its velocity.

The larger mass loads are simply due to the AGN acting as a second source of energy to the gas, heating more gas to extreme temperatures than stellar feedback would achieve on its own. The slower velocities are likely due to gas heated by the AGN (and now forming a more substantial hot halo) disrupting the streaming out of gaseous outflows attributed to stellar feedback.

The AGN outflows push gas out of the disk, creating a hot halo which mixes with the stellar feedback outflows, reducing their velocity due to drag forces against the hot, low-density media. For instance, we find a time-averaged mass of gas in the halo during the simulations, defined as gas cells with $r_{xy} > 5$ kpc and $|z| > 1$ kpc, about 3 times more massive in the AGN runs compared to the non-AGN case ($7.5 \times 10^8 M_\odot$ vs. $2.5 \times 10^8 M_\odot$ for the AGN and non-AGN runs, respectively). These results may offer interesting observational constraints to current theoretical models once outflows can be observed far out into the halos of AGN and non-AGN dwarfs.

The stochasticity of the AGN outflows is noticeable in the bottom middle panel of Fig. 5.5, where the dwarf with the largest seed mass experiences an extremely fast blowout

at $t \simeq 0.7$ Gyr. Similarly, the dwarf with the smallest seed mass also shows considerable variation in median outflow velocity at $t \simeq 0.4$ Gyr. By contrast, the outflows due to stellar feedback only (black line) have much smaller relative changes in velocity. While we cannot make a strong claim without a larger sample, AGN could add 'burstiness' to the mounting observational evidence of bursty star formation in dwarf galaxies (Emami et al., 2019).

Finally, we have explicitly checked that reducing the size and location of the hot bubbles imparting momentum during radio mode does not noticeably affect outflows (dashed green line in Fig. 5.5 shows a model with bubble radius r_{bub} and maximum distance from the AGN r_{sph} reduced by a factor of 2).

5.5 Summary and Discussion

We have presented a study of the affects of AGN feedback on a set of isolated dwarf galaxies simulations. The runs were performed with the moving-mesh code AREPO and the new ISM model *SMUGGLE*. We updated the latter to include the effects of black hole feedback by using the same modeling of AGN as that presented in the Illustris simulations.

We run several simulations with different initial masses for the black hole seed ranging from $M_{BH} = 10^3 M_{\odot}$ to $5 \times 10^4 M_{\odot}$. In all cases, the final mass after 1 Gyr of evolution was $M_{BH} = 1\text{--}5 \times 10^5 M_{\odot}$, in good agreement with observations of AGNs in this mass range. The growth was predominantly dominated by the radio-mode (low accretion rates), although the smaller seeds showed some incidence of the quasar-mode (high accretion rates) as well. The effects measured on the hosts dwarf galaxy did not show

any appreciable dependence on these different black hole growth regimes, suggesting that our results are robust to the choice of initial seed mass.

We study the effects of AGN feedback on the star formation and outflows properties of the simulated dwarf. In agreement with previous findings in simulations, we find that AGN has at most only a weak effect on star formation, resulting on an overall average reduction of stellar mass by 4-19% after 1 Gyr. Although the star formation history might not be appreciably affected in the host dwarf, AGN can still have a substantial effect on the properties of outflows. We find that gaseous outflows caused by AGN have larger median mass outflow rates, but lower median outflow velocities compared with outflows attributed to stellar feedback. We posit that these outflows may be mixing with the stellar outflows, decreasing the median velocity. The AGN outflows dominate over stellar outflows, and can extend well beyond the virial radius.

Given the substantial effect of AGN on outflow properties, it is somewhat surprising that star formation is not altered by AGN presence. This is likely because cold, dense gas and hot outflows exist in different spatial locations. Fig. 5.5 shows that cold, dense gas destined to become stars almost exclusively belongs within the disk whereas hot outflows lie outside the disk. Even the innermost regions are seemingly unaffected by AGN outflows. This is at odds with recent observational detections of AGN outflows in dwarf, which are found within the central kiloparsecs (Manzano-King et al., 2019). Further studies on the coupling of these winds to the surrounding media are needed to solve this issue.

Future analysis could be expanded by implementing other AGN feedback models, for example from Illustris TNG series, and more detailed schemes for black hole growth that

take into account the multi-phase nature of the ISM now resolved by *SMUGGLE*. Next steps include expanding the study presented here to cosmological zoom-in simulations of dwarfs which will naturally incorporate the effects of gas infall and halo growth necessary to make firmer predictions for upcoming observational campaigns of dwarfs with AGN signatures.

Chapter 6

Conclusions

Observational traces of ancient evolutionary events that shaped galaxies can be detected in the stellar, gaseous, and dark matter halos that surround them. However, it is not clear how exactly a galaxy’s formation process connects to its observed evolutionary markers. In this thesis we have used a combination of different numerical simulations to shed light on these connections and infer what stellar halos, gaseous halos, and dark matter halos may convey about galactic evolution.

Traces of ancient mergers are preserved as substructures (e.g shells or streams) in galaxy stellar halos. Inspired by recent surveys of millions of stars within the stellar halo of the Milky Way, we have focused on galaxies of similar mass to our own within the Illustris simulation. We found a strong correlation between assembly history and star formation rate, morphology, and stellar halo fraction. In particular, Milky Way-like galaxies, that is star forming, disk galaxies with little stellar halo, typically experience a few early mergers followed by a long period of quiescence. Our results are in agreement with observations,

which also suggest that the Milky Way has not experienced a recent major merger. We then focus our study to a single ancient merger of the Milky Way: the recently-discovered Gaia-Enceladus/Gaia Sausage. Events of similar mass, infall time, and radial anisotropy are relatively common within Λ CDM. However, reproducing the hallmark compactness of the GE/GS stellar debris is more challenging. We therefore predict that there may be a significant portion of yet undetected stars belonging to the GE/GS in the outskirts of the Galaxy. External galaxies like M101, whose stellar halo is almost absent, may also exist within predictions of Λ CDM, although they should be extremely rare.

Besides merger events, galaxies accumulate most of their mass via smooth accretion from gaseous filaments into gaseous halos. Λ CDM predicts that these filaments should also trace the large-scale distribution of dark matter known as the cosmic web. One of the most promising instruments for mapping gaseous filaments via $\text{Ly}\alpha$ emission is MUSE, a panoramic, integral-field spectrograph. Using numerical simulations we have investigated the impact of feedback, simulation resolution, and pixel size on the detectability of gaseous filaments with MUSE. While simulation resolution (a proxy for substructure) has a negligible impact, feedback and pixel size both significantly affect detectability. We predict that if pixel size is increased to roughly match the width of a gaseous filament, the area above the MUSE detection limit should increase by a factor of ~ 200 , providing compelling hints at the existence and properties of the predicted cosmic web.

Gaseous filaments like those mentioned above feed gaseous halos, which trace inflows and outflows, metal enrichment, and feedback processes within galaxies. From the numerical perspective, these processes are best modeled and understood on small scales,

while their coupling to galaxy and halo-wide processes is only weakly constrained. Due to their shallower potential wells, low mass dark matter halos harboring dwarf galaxies offer the best laboratories to study non-linear baryonic processes. In particular, feedback processes are believed to regulate star formation rate (SFR) in dwarfs while keeping most of the gas from turning into stars. The main source of SFR regulation in numerical simulations of dwarfs has traditionally been stellar feedback. However, observational evidence of active black holes and their feedback effects (AGN) in low mass galaxies has recently emerged. We have used tailored idealized hydrodynamical simulations of a dwarf halo (virial mass $\sim 10^{10} \text{ M}_{\odot}$) to explore the interplay between the two different feedback sources: stellar vs. black holes. We have extended the *SMUGGLE* ISM model to include AGN feedback effects within the AREPO code. By resolving the multiphase structure of the ISM, we trace both star formation from cold, dense gas and the hot, diffuse outflows. We find that for this particular modeling, while AGN feedback does not impact star formation strongly, its effects on the properties of outflows are much more significant. Specifically, AGN feedback in *SMUGGLE* increases the mass loading in winds while decreasing their typical velocities compared to those due to stellar feedback alone.

Using both large cosmological simulations and small idealized simulations, we have explored correlations between the past evolutionary history of galaxies and the properties of their halos at present day. Observationally, the detection of low-surface brightness stellar halo components around a significant number of galaxies combined with studies of gaseous halos show promise for constraining not only our cosmological model, but also the physics

of feedback and its coupling to kiloparsec-scale processes. On the theoretical side, incorporating such constraints to guide more complex, realistic models of galaxies and their ISM may help us on our quest to determine how our Galaxy, and others, came to be in our Universe.

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