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TOWARD A COMPLETE PICTURE OF STAR FORMATION AND THE BARYON
CYCLE IN DWARF GALAXIES

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To my parents, who have always supported me in becoming the best version of myself.

“The stars are indifferent to astronomy

And all that we think we know”

— Nada Surf, “Clear Eye Clouded Mind”

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ABSTRACT

Dwarf galaxies are a major frontier in modern astrophysics, representing an extreme end of galaxy formation and evolution. Because of their shallow gravitational potentials, low-mass galaxies are sensitive laboratories in which to study the nature and impact of baryonic feedback processes. At the same time, their intrinsically low luminosities make systematic observational study a challenge, and only state-of-the-art simulations are able to resolve small enough scales to capture the properties and behavior of such galaxies. In this dissertation, I describe my recent efforts, using a combination of constraining observations and detailed numerical simulations, to shape our end-to-end understanding of the baryon cycle in low-mass galaxies with a particular eye toward elucidating the multi-scale processes that regulate star formation. In Chapters 2 and 3, I detail work using a suite of high-resolution hydrodynamics simulations of isolated galaxies at different metallicities to study how the cold, dense interstellar medium and star formation rate vary as a function of chemistry, ionizing radiation field strength, and smaller scale density fluctuations. We find that, although the molecular hydrogen fraction depends sensitively on the local metallicity and far UV flux, the star formation efficiency per free-fall time does not, indicating that the local universality of star formation efficiency arises due to the interplay between turbulent compression of gas and its subsequent dispersion due to feedback. In Chapter 4, I present a comprehensive study of a quiescent field dwarf galaxy, COSMOS-dw1. Given its isolation, it is likely to have quenched due to stellar feedback associated with its last episode of star formation. As COSMOS-dw1 was discovered serendipitously in the small and extremely well-studied COSMOS field, it is likely that the number density of quenched isolated dwarf galaxies is much higher than previously thought, a result that has been reinforced by the subsequent publication of many more candidates. In Chapter 5, I introduce the QUEST Dwarf program, which is aimed at systematic study of the gaseous environment in and around dwarf galaxies and is designed to gain a comprehensive understanding of the baryon cycle in low-mass halos. The project uti-

lizes far-ultraviolet QSO spectra to probe the circumgalactic medium, optical spectroscopy to measure the interstellar medium’s chemical and physical properties, and high-resolution imaging to characterize stellar populations. Together, these data offer a unique opportunity to identify the mechanisms that regulate the low-mass baryon cycle. Finally, in Chapter 6, I move to larger scales, describing how we can use existing instrumentation in novel ways to constrain the available reservoir of star-forming material in galaxy cluster environments at intermediate redshifts. Taken together, these results from both observations and simulations shape our detailed understanding of the complex processes that regulate star formation in dwarf galaxies on both large and small scales. Chapters included in this dissertation are organized roughly from the smallest to the largest scales, with the first chapters focusing on the physics of star formation and feedback in the interstellar medium and the later chapters addressing galaxies’ gaseous environments.

CHAPTER 1

INTRODUCTION

1.1 Dwarf galaxies as a critical observational frontier

Though dwarf galaxies ($M_{\star}/M_{\odot} \lesssim 10^9$; see Figure 1.1 for some examples) dominate the overall galaxy population by number density (e.g., Bell et al., 2003; Baldry et al., 2008, 2012; Tomczak et al., 2014; Wright et al., 2018; Weaver et al., 2023; Sbaioni et al., 2025), it has only been in the last ~ 30 years that we have been able to conduct population-level studies of low-mass ($M_{\star}/M_{\odot} \lesssim 10^8$) dwarf galaxies (e.g., Simon, 2019). By necessity, most of these efforts center on Local Group dwarfs, which are very nearby, but also, by their very nature, not representative of low-mass galaxies in general.

The discovery space for dwarf galaxies outside of the Local Group (and especially outside of the Local Volume) in integrated light is immense (Danieli et al., 2018). While the community has long been interested in finding and characterizing low surface brightness galaxies (e.g., Longmore et al., 1982; Sandage & Binggeli, 1984), there are now many surveys and instruments that are specifically sensitive to the low surface brightness universe, facilitating dwarf galaxy studies, including the Dark Energy Camera Legacy Survey (Dey et al., 2019; Drlica-Wagner et al., 2021), the Hyper Suprime-Cam Strategic Survey Program (Aihara et al., 2018), the Dragonfly Telephoto Array Wide Field (Danieli et al., 2020) and Ultrawide (Shen et al., 2024) surveys, and observations by the Condor Array Telescope (Lanzetta et al., 2023) and *Euclid* (Euclid Collaboration et al., 2025; Marleau et al., 2025; Euclid Collaboration et al., 2026) among others. Looking forward, the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (Ivezić et al., 2019), which just began at the end of June 2026, also promises low surface brightness coverage of the Southern Hemisphere, with projected detection limits of $\mu_{\text{eff}} \gtrsim 30$ mag arcsec $^{-2}$ on galaxy scales by the end of the 10-year survey. The detection of low surface brightness galaxies is now finely tuned and

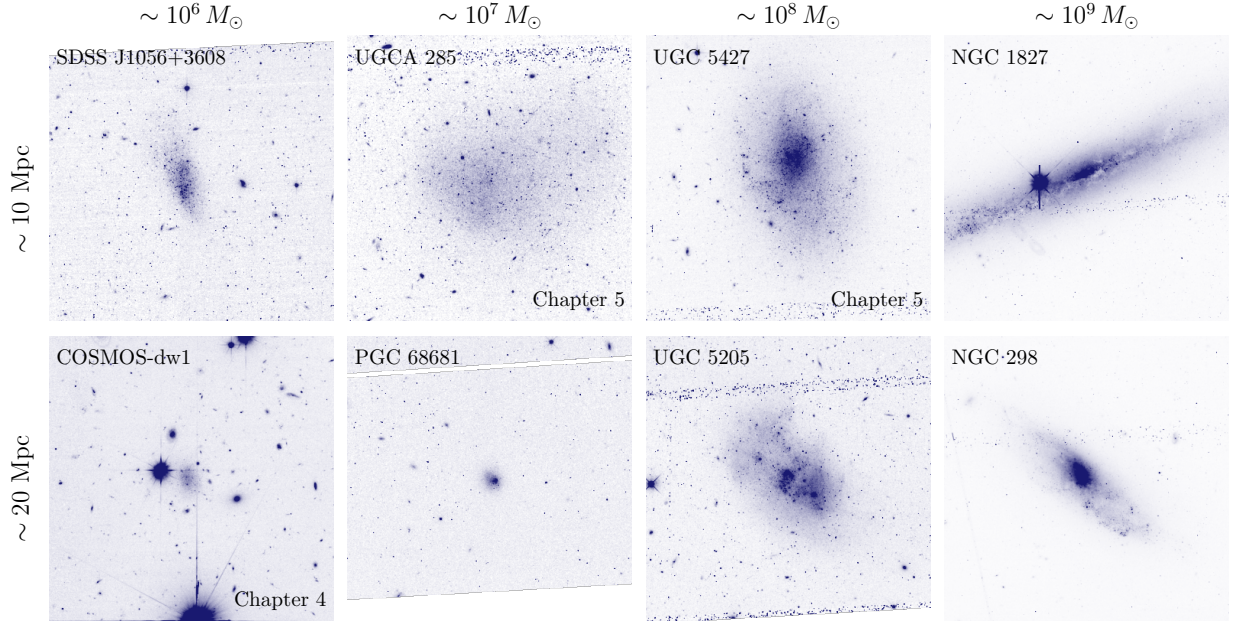


Figure 1.1: *Hubble Space Telescope* imaging of dwarf galaxies in F814W across a range of stellar masses ($\sim 10^6 - 10^9 M_\odot$). The top row shows dwarf galaxies at distances of approximately 10 Mpc (the outer edge of the Local Volume), and the bottom row shows dwarf galaxies at distances ~ 20 Mpc. All cutouts share a field of view of $100'' \times 100''$. Galaxy masses and distances not reported in this dissertation are taken from Kado-Fong et al. (2024), Ohlson et al. (2024), and Pace (2025). In addition to the observational challenges that come with dwarf galaxies generally being low-luminosity and/or low-surface brightness objects, the diversity of dwarf morphologies poses a problem for developing systematic detection methods that can build a complete census.

augmented/enhanced with techniques and tools to help identify low luminosity objects (e.g., SMUDGes, *mrf*, SEAMLESS; Zaritsky et al., 2019; van Dokkum et al., 2020; Jones et al., 2024), but no single method can yet return complete catalogs.

There have also been substantial efforts to characterize the intrinsic nature of the low-mass galaxies in these low surface brightness-sensitive surveys (e.g., Tanoglidis et al., 2021; Prole et al., 2021). The challenge remains that generally the most massive, largest angular scale galaxies are included in catalogs and analysis. Deep, high-resolution imaging offers another avenue to look at smaller (in scale and mass) galaxies, but presents other challenges, including that low-mass galaxies appear fainter with their light spread across more pixels and there is increased potential for confusion with higher redshift sources (Wolfe & Chen, 2006).

Recovering accurate distances to low-surface brightness galaxies outside of the Local Volume remains a consideration as it significantly determines the interpretation of physical systems (Carleton et al., 2024a,b). Some headway has been made toward photometric survey-scale distance estimators (Miller et al., 2025), but most dwarf galaxies still require individualized study. As we enter the era of deep, all-sky surveys, we will uncover a plethora of dwarf galaxies with a wide variety of characteristics in a wide variety of environments, gaining a truly comprehensive sense of the diversity of low-mass systems.

Chemically, dwarf galaxies are generally metal-poor (e.g, Berg et al., 2012; Kirby et al., 2013; Hidalgo, 2017) because feedback drives chemically enriched gas from the interstellar medium. As galaxies at high redshift are also metal-poor (e.g., Langeroodi et al., 2023), understanding the evolution of low-metallicity galaxies is rapidly becoming a key goal of both local dwarf and high redshift communities. Dwarf galaxies are then (possibly imperfect given density evolution with redshift) analogs for high-redshift galaxies and remain one of our best detailed observational windows into the evolution of low-mass, low-metallicity galaxies.

1.2 Dwarf galaxies as a frontier in simulations

While observations are crucial for placing constraints on the behavior of the *real* universe, simulations and models allow us to create carefully controlled numerical experiments to interpret the physics driving observed behavior. Using simulations to consistently test galaxy (and structure) formation and evolution is now a rather mature field (see, e.g., Vogelsberger et al., 2020; Crain & van de Voort, 2023, for reviews).

Low-mass galaxies, however, remain a particular challenge for cosmological simulations (see Somerville & Davé, 2015, for a review) as such galaxies are intrinsically small and the mass or spatial resolution rarely reaches the relevant scales. For instance, while, EAGLE (Schaye et al., 2015), Romulus25 (Tremmel et al., 2017), and TNG50 (Pillepich et al., 2019; Nelson et al., 2019a) contain massive dwarf galaxies, no one dwarf galaxy contains enough

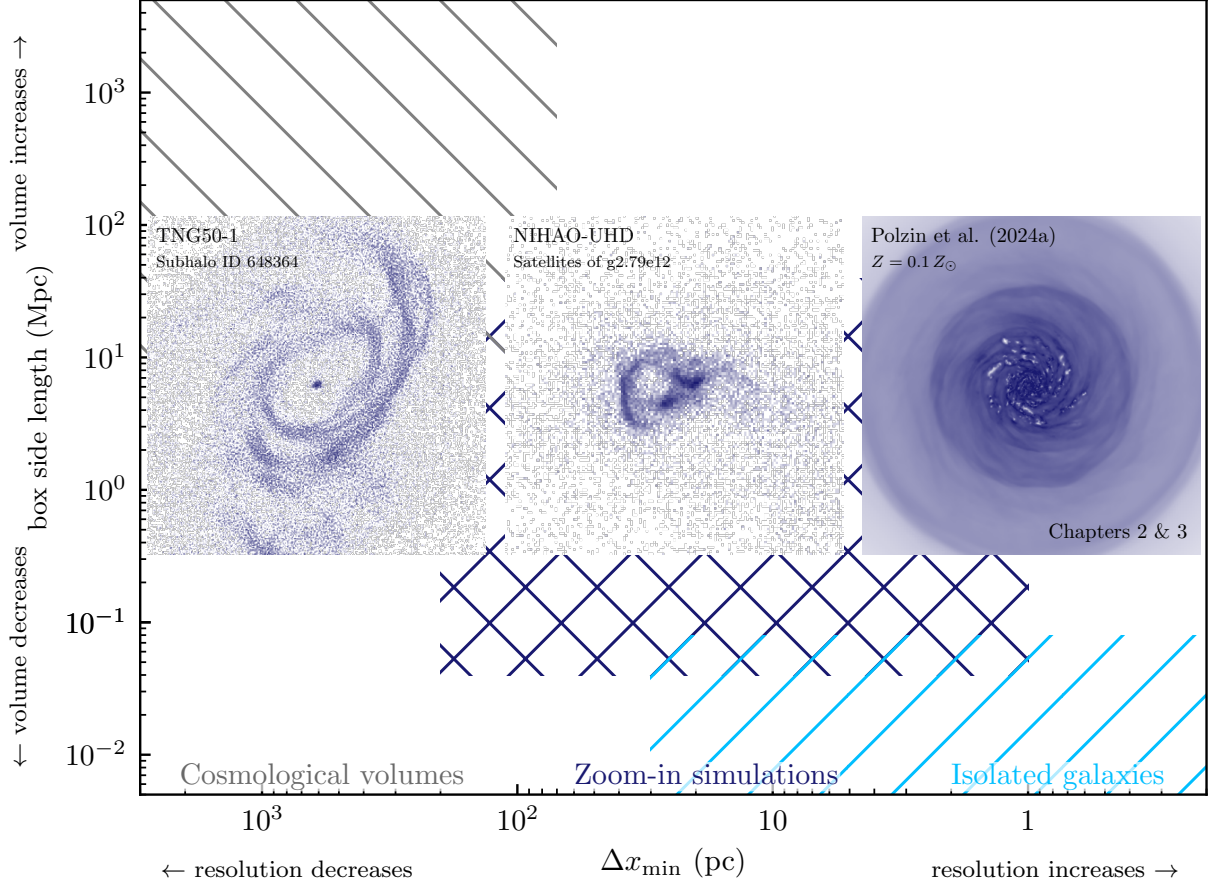


Figure 1.2: The approximate box side length vs. spatial resolution parameter space for hydrodynamics simulations that focus on or include dwarf galaxies. Note that this phase space is intended to be *representative* rather than *comprehensive*. Concrete visual examples of dwarf galaxies in each category of simulation (cosmological, zoom-in, and isolated disk) are overplotted: a TNG50 (Pillepich et al., 2019; Nelson et al., 2019a) dwarf galaxy, interacting satellites of a NIHAO-UHD (Buck et al., 2020) halo, and one of the low-metallicity galaxies used in the analysis of Chapters 2 and 3. Each inset example is roughly $20 \text{ kpc} \times 20 \text{ kpc}$.

resolution elements to conduct detailed study. Instead, studies of simulated dwarf galaxies have often come from semi-analytic models of galaxy formation (e.g., Sales et al., 2013; Ledinauskas & Zubovas, 2018; Cora et al., 2018; Kravtsov & Manwadkar, 2022; Ahvazi et al., 2024), cosmological zoom-ins (e.g., Wang et al., 2015; Wheeler et al., 2015; Mandelker et al., 2019, 2021; Applebaum et al., 2021; Wetzel et al., 2023, 2025) and other small box simulations, or from simulations of isolated galaxies (e.g., Emerick et al., 2019; Romano et al., 2019; Gutcke et al., 2021; Semenov et al., 2021). I illustrate the general phase space of numerical simulations including dwarf galaxies in Figure 1.2.

Relevant processes that govern galaxy evolution are inherently multi-scale, including the formation of individual stars (on $\lesssim 1$ pc scales); energy and momentum injection from stellar winds, supernovae, and active black holes (on scales ranging ~ 10 pc to > 1 kpc); and large scale in- and outflows through which galaxies interact with their surroundings (on kpc to Mpc scales). As such, in an ideal case, simulations would both be able to resolve the smallest scales on which stars form in large enough boxes to encompass the circumgalactic (and even intergalactic) medium. This presents a real challenge for self-consistently modeling these processes; even with adaptive refinement schemes, attempting to cover > 7 dex in scales means that much physics goes unresolved and is relegated to the “subgrid” regime. On larger scales, successfully reproducing the diversity of cosmic environments can be a similar challenge. Many zoom-in simulations focus on dwarf satellites of more massive galaxies by necessity, with a significant subset of satellite studies specifically examining Local Group analogs. This poses problems for constraining the role of environment in regulating the evolution of low-mass galaxies.

In addition to resolution challenges, despite their “predictive” (or at least diagnostic) power, simulations are best-constrained in parts of the parameter space where there are many observations against which to calibrate. Because dwarf galaxies have been less comprehensively observed than more massive galaxies, simulations and modeling rely more heavily

on inference in the low-mass regime. Simulations may struggle to match the properties of low-mass dwarf galaxies (Martin et al., 2025), though this part of the phase space can also offer critical constraints on feedback and star formation prescriptions.

1.3 Star formation and feedback in low-mass galaxies

In order to form stars, galaxies require a reservoir of cold, dense gas. Star formation uses up this reservoir, requiring replenishment either by accretion from the larger cosmic environment or by recycling, as the gas in stars is returned to the ISM (e.g., Leitner & Kravtsov, 2011). At the same time, this replenishment is counteracted by the galaxy’s environment (i.e., interactions with other nearby galaxies or large scale structure) and internal feedback mechanisms, which can remove gas from the system or prevent accretion. The existing reservoir of star-forming material can experience energy and momentum injection that disrupts, heats, and ionizes the gas, halting star formation.

Dwarf galaxies are a uniquely interesting population in which to study the (self-)regulation of star formation because their low masses (and so shallow gravitational potentials) make them especially sensitive to feedback. They also have a higher ratio of gas to stars than their more massive counterparts (Geha et al., 2006), but the global star formation efficiency is suppressed in low-mass galaxies as is evidenced by a decline in the stellar-to-halo mass ratio (Naab & Ostriker, 2017; Read et al., 2017; Wechsler & Tinker, 2018). The details of the mechanisms driving this mass-dependent, halo-scale inefficiency is an open question, though feedback-driven outflows are understood to play a significant part.

For galaxies of all masses – from dwarfs through Milky Way-like L^* galaxies – environmental mechanisms play a role in halting star formation (Omand et al., 2014), but environmental quenching is a very broad designation. Galaxies in crowded environments are subject to a range of processes that disrupt star formation. Ram pressure stripping (Gunn & Gott, 1972; Emerick et al., 2016; Simpson et al., 2018) and tidal stripping (e.g., Fang et al., 2016) are ef-

fective at removing gas from galaxies. Galaxy harassment (e.g., Bialas et al., 2015) can both remove gas from galaxies and dynamically heat the ISM. Galaxies that are undergoing environmental quenching generally stop forming stars due to starvation or strangulation, where they have depleted their gaseous reservoir – sometimes helped along by nearby galaxies – and are prevented from accreting new star-forming material.

On somewhat larger scales, cosmic reionization can process galaxies via photoevaporation, photoionization, and heating, both removing gas from galaxies and preventing accretion (e.g., Bullock et al., 2000; Okamoto et al., 2008; Katz et al., 2020). The star formation histories (SFHs) of ultrafaint dwarf galaxies (generally $M_{\star}/M_{\odot} \lesssim 10^5$) are consistent with those extremely low mass galaxies being “fossils” (Ricotti & Gnedin, 2005; Brown et al., 2014; Weisz et al., 2014). Because rejuvenation can occur with reaccretion, both a galaxy’s mass and the existence and nature of its neighbors plays a role in establishing the SFH, with M31 ultrafaints showing a more extended period of star formation than Milky Way ultrafaints (Savino et al., 2025).

Notably, Local Group dwarf galaxies, which, for their proximity, are the best-studied low-mass galaxies, are almost universally gas-poor (Tollerud & Peek, 2018; Putman et al., 2021). This has been attributed both to reionization and environmental effects from interactions with the Milky Way, M31, and the Milky Way-M31 system. In either case, Local Group satellites are not representative, in environment or state, for studying the broader regulation of star formation in dwarf galaxies.

Even among satellites, there is evidence low-mass dwarfs are more susceptible to environmental processes than higher mass satellites (Bluck et al., 2020). Geha et al. (2012) found that the quenched fraction for isolated dwarf galaxies is a function of stellar mass and decreases significantly for galaxies with masses between $10^9 M_{\odot}$ and $10^8 M_{\odot}$ (the completeness limit of their sample). This corresponds to the stellar mass regime where active galactic nucleus (AGN) feedback (Best et al., 2006; Cattaneo et al., 2006; Dashyan et al., 2019) and

virial shocks (Dekel & Birnboim, 2006) are thought to be less operative. There is, however, mounting statistical evidence that low-mass ($M_{\star}/M_{\odot} \lesssim 10^8$) do quench in the field (e.g., Kado-Fong et al., 2025; Carlsten et al., 2026a), away from neighboring galaxies that could easily account for environmental effects. The U-shaped quenched fraction of isolated galaxies suggests there are roughly three mass regimes in self-regulation (or the intrinsic processes that suppress star formation): (1) the halos of low-mass dwarfs ($M_{\star}/M_{\odot} \lesssim 10^8$) have sufficiently shallow potentials, allowing “weaker” feedback processes (supernovae, stellar winds, stellar radiation) alone to effectively quench the galaxy; (2) intermediate-to-high mass dwarfs ($10^8 \lesssim M_{\star}/M_{\odot} \lesssim 10^9$) are resistant to stellar feedback, but do not host powerful enough AGN to readily shut off star formation; and (3) more massive galaxies ($M_{\star}/M_{\odot} \gtrsim 10^9$) experience significant co-evolution with their supermassive black holes, with AGN feedback dominating quenching mechanisms. This is also nicely summarized in fig. 2 of Wechsler & Tinker (2018).

In the last years, even without systematic searches in deep all-sky survey data (as will be facilitated by, for instance, Rubin Observatory for the low surface brightness universe; Ivezić et al. 2019), there has been a steady increase in the number of candidate quenched, isolated, low-mass ($M_{\star}/M_{\odot} \lesssim 10^8$) galaxies, suggesting that stellar and supernova feedback play a vital role in regulating star formation in dwarf galaxies. There is now a growing (see Figure 1.3) list of isolated, low-mass galaxies which appear to have stopped forming stars (Whiting et al., 1999; Lavery, 1990; Makarov et al., 2012; Karachentsev et al., 2015; Polzin et al., 2021; Li et al., 2024; Sand et al., 2024; Fielder et al., 2025; Hai et al., 2026; Carlsten et al., 2026a,b).

While the candidate quiescent field dwarf galaxies enumerated here are unlikely to be backplash galaxies or otherwise experiencing long-range environmental feedback (e.g., Fillingham et al., 2018) given their isolation from any neighbors, some groups have posited that isolated dwarf galaxies may quench after interactions with cosmic filaments or cosmic sheets

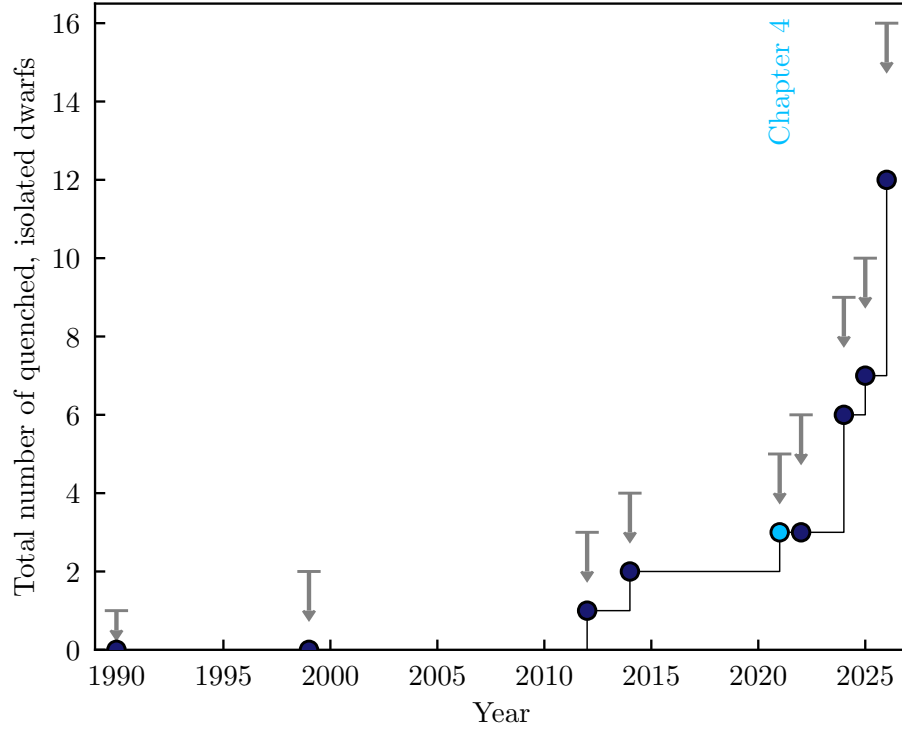


Figure 1.3: The cumulative number of quenched, isolated dwarf galaxies (with $M_{\star}/M_{\odot} \lesssim 10^8$) based on the year each dwarf was first reported in the literature (current through July 2026). Candidates that adhere to the most stringent definitions of isolation are included in the primary count and the upper limit, while galaxies with more complex environments or environmental histories are only counted in the upper limit. Galaxies that have large uncertainties on their primary characteristics or otherwise require significant follow-up are not included here. See a complete and up-to-date list of quenched isolated dwarf galaxy candidates at https://avapolzin.github.io/projects/quench_list.

(e.g., Pasha et al., 2023; Benavides et al., 2025). Like better understood environmental effects, such interactions could strip the galaxies of their gas or heat the gas and prevent accretion from the intergalactic medium. There is no single observable associated with this sort of proposed environmental quenching driven by overdensities in the universe associated with the structure of the cosmic web, and there are other mechanisms that can regulate star formation in isolated galaxies without invoking an unseen environmental process.

A common explanation for self-quenching in dwarfs is that, in low-mass ($M_{\star}/M_{\odot} \lesssim 10^8$) dwarf galaxies, supernova or stellar feedback (e.g., Larson, 1974; Dekel & Silk, 1986; Zhang, 2018; Collins & Read, 2022) alone are able to regulate star formation because such galaxies have shallow gravitational potentials that are easily overcome by energetic winds. As with other quenching mechanisms, supernova and stellar feedback operate by a combination of ionization, heating, and physical removal of gas from the ISM.

It is also possible, especially in somewhat more massive galaxies, that AGN feedback (e.g., Dashyan et al., 2018; Dickey et al., 2019; Kaviraj et al., 2019; Mezcua et al., 2019; Koudmani et al., 2021; Arjona-Gálvez et al., 2024) plays a role in regulating star formation, as well. In fact, dwarf AGN are increasingly found to be common (e.g., Reines et al., 2013; Messick et al., 2023; Wasleske & Baldassare, 2024; Kimbro et al., 2025; Kaviraj et al., 2026), as existing AGN diagnostics are inconsistent (unlikely to provide false positives, but also unlikely to catch all AGN candidates) for low-mass galaxies. AGN feedback comes in two flavors (see e.g., Combes, 2017, for a short review): radio mode feedback, in which energetic jets mechanically disrupt the gas in and around galaxies (gas compression from AGN jets can simultaneously spur star formation, with stars forming particularly at the boundary between the jet and the ISM; Gaibler et al. e.g., 2012; Zinn et al. e.g., 2013), and quasar mode feedback, in which radiation and winds from the supermassive black hole heats and ionizes the gas. Given their low luminosities, dwarf AGN are more likely to experience radio mode feedback, with the host galaxy quenching due to gas loss coupled with an inability to

re-accrete star-forming material.

Effectively modeling star formation is then complicated by the range of scales and complex processes involved (McKee & Ostriker, 2007; Gnedin et al., 2016; Teyssier & Commerçon, 2019). As was discussed in Section 1.2, dwarf galaxies in particular remain a challenge for simulations because of numerical effects that result from poorly resolving such small scales, a paucity of constraining observations, and the use of models and subgrid physics that have been calibrated in a very different regime. While many population-level properties are readily matched to observations via common relations (i.e., size-mass relation, mass-metallicity relation, stellar-to-halo mass relation, Kennicutt-Schmidt relation), detailed processes like star formation and feedback can deviate significantly from what has been observed. The so-called “overquenching” problem is one example, wherein a much greater proportion of galaxies in a simulation stop forming stars relative to observations (Dickey et al., 2021; Sharma et al., 2023). Overquenching can occur because of the way feedback is tuned and implemented (Sharma et al., 2023), which may mean that simulated dwarfs are experiencing *too much* feedback or are *too susceptible* to feedback, but it can also be driven by resolution effects (Hopkins et al., 2018; Rodríguez-Cardoso et al., 2025), in which case the smallest galaxies will be the most prone to numerical overquenching. Note that these two avenues are not mutually exclusive and both feedback modeling and resolution may play a role. Another potential concern is how star formation is implemented in simulations. Star formation is often coupled to a virial parameter (e.g., Bertoldi & McKee, 1992; Padoan et al., 2012; Sillero et al., 2021; Hopkins et al., 2023), a density threshold (e.g., Hopkins et al., 2018; Sillero et al., 2021), and/or the H_2 abundance (Kuhlen et al., 2012; Christensen et al., 2012; Hopkins et al., 2018; Sillero et al., 2021). These different modeling schemes can have very different outcomes, not all of which are equally consistent with observed galaxy properties in all regimes.

Observationally, studying star formation in dwarf galaxies is also a challenge. There are

various robust indicators (see e.g., Calzetti, 2013, for a review) used to ascertain the recent star formation histories of galaxies, but in some cases the size and chemistry of dwarf galaxies can muddy interpretation. $H\alpha$ emission, which, as a recombination line, traces gas ionized by young, massive stars, constraining the star formation history on ~ 10 Myr timescales, will only be present if O- and B-type stars form in the galaxy. For very low-mass galaxies that are sustaining commensurately low levels of star formation, it is not foregone that massive stars will form during every episode of star formation (Applebaum et al., 2020), given the stochasticity of sampling from the stellar initial mass function (Salpeter, 1955; Kroupa, 2001; Chabrier, 2003; Kroupa et al., 2026). The far ultraviolet (FUV), which traces star formation on ~ 100 Myr timescales (Kennicutt, 1998; Flores Velázquez et al., 2021) should be less attenuated by dust in dwarf galaxies given relatively low metallicities (Fisher et al., 2014); for the same reason low-mass galaxies are, on average, bluer and more UV-bright regardless of their star formation rate (Sanders et al., 2013). This tendency toward bluer integrated light measurements both makes using more global calibrations of FUV flux as a star formation rate indicator challenging¹ and poses additional problems for optical color-based SFH determinations. Similarly, the 4000Å break (Bruzual A., 1983; Hamilton, 1985), D_n4000 , which is used as a stellar population age indicator becomes less sensitive to galaxy age with decreasing metallicity (van den Bergh, 1963; Paulino-Afonso et al., 2020). In the resolved star regime, color-magnitude diagrams lose their discriminating power at larger distances, where only brightest O/B and post-main sequence stars are detectable. In ideal cases, studies of star formation in low-mass galaxies will use multiple indicators to better understand the star formation history on different timescales.

1. It is possible that best practice is to correct both $H\alpha$ and FUV star formation rates for metallicity effects (Kennicutt & Evans, 2012), with both revised downward (by 0.4 dex and 0.07 dex respectively for every factor of 10 decrease in $[Fe/H]$).

1.4 The circumgalactic medium of dwarf galaxies

Interaction between galaxies and their gaseous halos is critical for maintaining and regulating star formation, and galaxies’ halos often encode information about both galaxies’ star formation history and recent feedback processes. The circumgalactic medium (CGM; see Tumlinson et al., 2017; Faucher-Giguère & Oh, 2023; Chen & Zahedy, 2026, for recent reviews) is the halo of gas around a galaxy. It serves as a reservoir of cool, neutral gas that may be accreted by the galaxy, providing fuel for star formation (e.g., Putman et al., 2012; Weng et al., 2023; Decataldo et al., 2024) as inflows pass from the CGM into the ISM. It also retains metal-enriched gas ejected from the galaxy by feedback processes (e.g., Peebles et al., 2014; Muratov et al., 2017; Piacitelli et al., 2025). The temperature, chemistry, and kinematics offer insights into the nature of the feedback the galaxy is experiencing (e.g., Shen et al., 2013; Suresh et al., 2015; Fielding et al., 2017; Medlock et al., 2025; Baumschlager et al., 2025; Messere & Bryan, 2026).

However, because the gas content of the CGM is largely diffuse, measuring CGM properties is an immense challenge. Very energetic gas in the inner CGM (Augustin et al., 2019; Zhang & Zaritsky, 2024; Peng et al., 2025) and hot X-ray halos (Wijers & Schaye, 2022; Silich et al., 2025) may be observed in emission. Generally, our understanding of the circumgalactic medium comes from absorption measurements along one-dimensional “pencil-beam” sightlines. Using FUV-bright background sources (often quasars – or QSOs) to “backlight” the CGM (Rauch, 1998; Steidel et al., 2010; Chen, 2017), it is possible to access the hydrogen Lyman series and a suite of metal resonance lines that trace the conditions of the circumgalactic gas. Unfortunately, this method requires that a bright background source is serendipitously aligned in such a way that it illuminates a small part of a galaxy’s CGM, which can complicate interpretation as such observations carry limited spatial information and are not possible for every galaxy.

While there are many such absorption studies for more massive galaxies, there are rela-

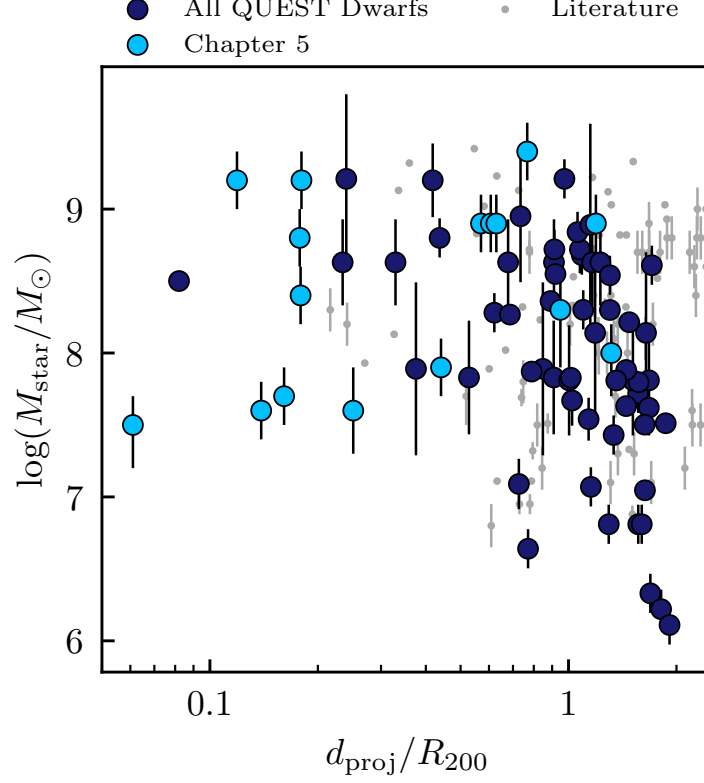


Figure 1.4: The stellar mass of galaxies beyond the Local Group with CGM constraints from absorption plotted against the projected distance to the bright background source. The dark blue points show the full extent of the QUEST Dwarfs program, noting that the mass and/or the projected distance used in the sample definition and shown here may be significantly revised during our more careful analysis, and the bright blue points show the already carefully constrained “first release” QUEST Dwarfs sample presented in this dissertation (Chapter 5). Existing sightlines in the literature are shown in gray and are from the Zheng et al. (2024) compilation (Bordoloi et al., 2014, 2018; Liang & Chen, 2014; Johnson et al., 2017), Mishra et al. (2024), and Johnson et al. (2026).

tively few observations of dwarf-QSO pairs, even with the most generous definition of “dwarf galaxy” (Prochaska et al., 2011; Bordoloi et al., 2014; Liang & Chen, 2014; Johnson et al., 2017, 2026; Zheng et al., 2020, 2024; Qu & Bregman, 2022; Mishra et al., 2024; Fox et al., 2026, see Figure 1.4 for a summary). Focusing only on *representative* dwarf galaxies beyond the Local Group, the list of observations gets shorter (Prochaska et al., 2011; Bordoloi et al., 2014; Liang & Chen, 2014; Johnson et al., 2017, 2026; Zheng et al., 2024; Mishra et al., 2024). This is due to dwarf galaxies’ low masses, in part because of the innate challenge of observing low-luminosity galaxies (Section 1.1) and in part because such low masses require that FUV-bright sightlines be projected within just 50 – 100 kpc in order to trace halo gas (from the low-mass SHMR, Read et al., 2017; Nadler et al., 2020; Manwadkar & Kravtsov, 2022). In fact, Liang & Chen (2014) found that most absorption is measured within $\lesssim 0.5 R_{\text{vir}}$ and traces the inner CGM, further restricting relevant impact parameters, with the caveat that H I absorption is often extended and O VI absorption, which traces highly ionized gas, has been seen out to $2 R_{\text{vir}}$ in dwarf galaxies (Mishra et al., 2024).

In an attempt to connect scales and better understand the complete baryon cycle, defined, in part, as the set of processes that govern the circulation of gas between galaxies and their environments, some groups have worked to understand the behavior of the gas moving between the ISM and CGM (e.g., Mello et al., 2019; Bish et al., 2019, 2026) and static in each of these reservoirs (e.g., Kacprzak et al., 2019). Because of the reliance of CGM measurements on absorption spectroscopy, these studies are often conducted on either side of the disk-halo interface² and the extent of the transition between these two spatial phases is not well understood. As a point of semantic clarification: The CGM-IGM boundary is similarly difficult to distinguish. The critical distinction between the circumgalactic and intergalactic medium is that the CGM is *bound* to the halo, while the IGM simply fills the space between galaxies. As such, gas can generally be attributed to the CGM if it is at

2. While this is the common term, as particularly low-mass galaxies lack defined disks, this language may be less instructive for studies of the dwarf CGM.

$$r \lesssim R_{\text{vir}} \text{ or } \Delta v \lesssim v_{\text{esc}}.$$

1.5 A holistic approach to studying the baryon cycle

The baryon cycle is comprised of multi-component, multi-scale processes that regulate the growth and evolution of galaxies. As gas coalesces to form stars, that gas gets locked up in the stellar phase, depleting the available reservoir of star-forming material. For galaxies to continue forming stars, additional gas must enter the system, either through recycling, when the end stages of stellar evolution return gas to the interstellar medium, or accretion from the circumgalactic and intergalactic medium. This replenishment is counteracted by feedback processes that can remove the gas from the system or make it unusable for star formation. Young stars, newly formed from cold, dense gas give off intense radiation and energetic winds, which can heat, dissociate, and mechanically disrupt their natal clouds, preventing further star formation on small scales. Tens of Myr after stars form, supernovae can blow gas out of the galaxy and into the CGM and IGM; supernova feedback can be an especially efficient quenching mechanism in the lowest mass galaxies for their extremely shallow gravitational potentials. In more massive galaxies, the radiation, winds, and jets from supermassive black holes play a similar role and are capable of shutting down star formation and preventing (re-)accretion of gas from the galaxy’s halo. On yet larger scales, the gravitational influence of nearby galaxies can both strip gas from a galaxy’s ISM and effectively regulate the presence and accretion of the gas reservoir around the galaxy. Together, all of these different processes make up the baryon cycle. Because it spans from the formation of individual stars on sub-pc scales to the circumgalactic and intergalactic media as reservoirs for both star-forming material and already processed gas that has been expelled from galaxies’ interstellar medium, studying the baryon cycle requires a range of approaches to understand each process individually and as part of a larger integrated system.

In this dissertation, I walk through each of the major stages of the baryon cycle (see

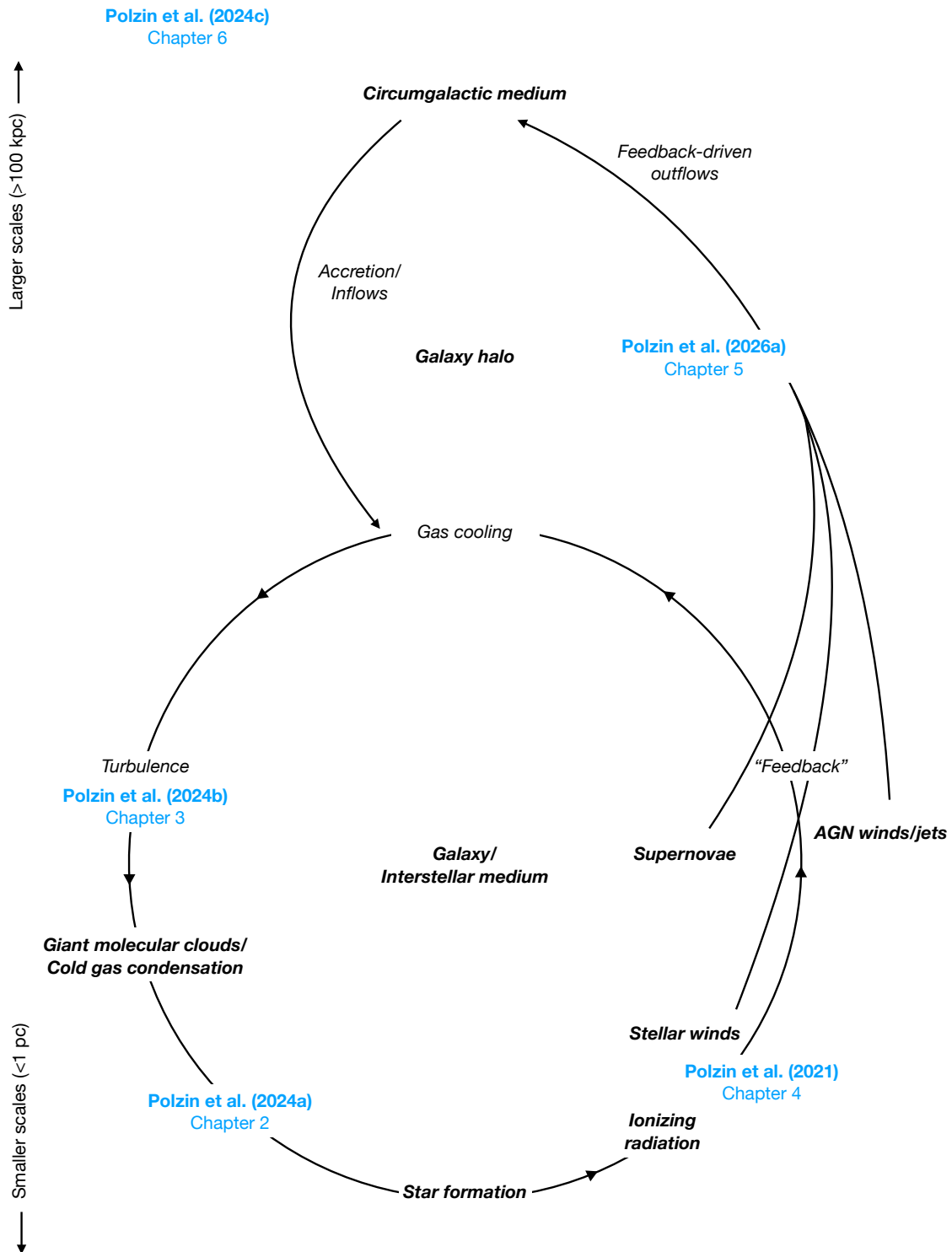


Figure 1.5: (Caption next page.)

Figure 1.5: (*Previous page.*) The baryon cycle is complex and multi-scale, encompassing star formation, feedback, and the interaction of the galaxy with its gaseous halo. Chapters of this dissertation are contextualized by the topics they cover and are highlighted in light blue.

Figure 1.5 for a summary). In Chapter 2, I describe efforts to model the H I-H₂ transition in metal-poor galaxies and address the predicted chemical nature of star-forming gas at low metallicities. In Chapter 3, I examine the impact of cloud-scale galaxy properties on the efficiency of star formation, finding that the interplay between feedback and turbulence is critical to the self-regulation of galaxies' star formation. In Chapter 4, I present a detailed study of a quenched, isolated dwarf galaxy that provides insight both into the mechanisms that halt star formation in low-mass halos and the expected number density of such self-regulated systems. In Chapter 5, I introduce our QUEST Dwarfs program and walk through some of our initial results using just $\sim 20\%$ of the total sample, integrating stellar population and ISM diagnostics with constraints on the CGM. In Chapter 6, I present a proof of concept for a novel approach to measuring the reservoir of H I in galaxy clusters at intermediate redshifts using existing 21 cm experiments, which can also constrain models of feedback on halo scales. Finally, in Chapter 7, I highlight the major takeaways from these works and describe some ongoing efforts to use cross-cutting techniques to holistically study the interconnected processes that comprise the baryon cycle.

CHAPTER 2

MODELING MOLECULAR HYDROGEN IN LOW METALLICITY GALAXIES

Polzin et al. (2024a) presented as part of a thesis to the Department of Astronomy and Astrophysics, The University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

A. Polzin, A. V. Kravtsov, V. A. Semenov, and N. Y. Gnedin, “Modeling molecular hydrogen in low-metallicity galaxies”, ApJ, vol. 966, no. 2, p. 172, May 2024, DOI: 10.3847/1538-4357/ad32cb.

2.1 Introduction

The cold, dense tail of the multiphase interstellar medium (ISM) is generally home to cold atomic gas (e.g., Wolfire et al., 2003) and molecules, such as CO, HCN, H₂, etc., which play an important role in the thermodynamics of gas in this phase (e.g., Omont, 2007; Draine, 2011; Galli & Palla, 2013). At the same time, molecular gas is one of the very few direct observational probes of this tail (see Carilli & Walter, 2013; Saintonge & Catinella, 2022, for reviews). Given that stars also form in high-density regions, empirical studies of molecular gas are intricately tied to studies of how star formation occurs in galaxies (e.g., Kennicutt & Evans, 2012).

Empirically, it is established that a fairly tight relation between surface densities of molecular gas and star formation exists both within individual galaxies and among different galaxies (the molecular Kennicutt-Schmidt relation; e.g., Kennicutt, 1989, 1998; Wong & Blitz, 2002; Bigiel et al., 2008; Baker et al., 2023); that relation is now well understood theoretically (e.g., Semenov et al., 2019). Observationally, that correlation is tied to CO, but the assumption is that CO traces H₂ reasonably well, with the possible exception of

extreme starbursts (Meier et al., 2001; Schruba et al., 2012; Carilli & Walter, 2013; Madden, 2022).

The existence of such a tight correlation was used as a basis for modeling star formation in galaxy formation simulations (e.g., Robertson & Kravtsov, 2008; Gnedin et al., 2009; Jaacks et al., 2013; Christensen et al., 2014) and semi-analytic models (e.g., Popping et al., 2014) and motivated development of theoretical models of molecular gas (e.g., Leroy et al., 2008; Krumholz et al., 2009a; Gnedin & Kravtsov, 2011; Gnedin & Draine, 2014; Sternberg et al., 2014, see Diemer et al. 2018 for a review). However, most existing models of molecular hydrogen gas fraction are calibrated in the relatively high mass, high metallicity regime. The HI-H₂ transition models that are formulated for lower Z gas are often more complex and have additional assumptions and tunable parameters (Krumholz et al., 2009b; Krumholz, 2013; Gnedin & Draine, 2014; Bialy & Sternberg, 2016). Furthermore, most models estimate the abundance of H₂ assuming chemical equilibrium whereby the process of molecular gas formation is not limited in time.

The low-metallicity regime is different. It is generally expected that the formation time of H₂ increases with decreasing metallicity. At the same time, the lifetime of dense regions of the ISM is finite due to a combination of shearing forces and effects of stellar feedback. If the lifetimes of dense ISM regions are shorter than the characteristic H₂ formation time, the molecular fraction in low-metallicity gas may never reach high values, which means that stars in such regions must form from the largely atomic gas (Krumholz, 2012; Glover & Clark, 2012a; Hu et al., 2016). Indeed, physically star formation can occur in purely atomic gas because cooling and other processes driving the formation of star-forming regions are only mildly affected by the presence of molecular gas (Glover & Clark, 2012b). This implies that chemical equilibrium models of f_{H_2} that assume no time limit to H₂ formation systematically overpredict f_{H_2} in low-metallicity gas (Krumholz, 2012). Conversely, as shown by Glover & Clark (2012a) models that use non-chemical equilibrium calculations of H₂ abundance to

estimate star formation rate will underpredict star formation rate, if star-forming regions have low molecular fractions but otherwise form stars with a regular efficiency.

Low metallicities are relevant for modeling the two regimes of galaxy evolution that are at the current frontiers of extragalactic research: the earliest stages of evolution of massive galaxies at $z \gtrsim 5$ and evolution of local dwarf galaxies. It is thus important to examine and calibrate the abundance of molecular gas and star formation efficiency in this low-metallicity regime. Likewise, theoretical models of the interstellar medium and star formation in galaxy formation simulations may potentially be tested by contrasting their results with observational estimates of the H_2 abundance and star formation in dwarf galaxies (e.g., Bolatto et al., 2011; Jameson et al., 2016) and galaxies at high redshifts.

In this paper, we examine the abundance of molecular hydrogen – the dominant mass component of molecular gas – using a suite of realistic simulations of a dwarf galaxy’s ISM across a wide range of metallicities. These simulations use a generalized star formation prescription that is not based on the local H_2 abundance (Semenov et al., 2021). Instead, the star formation prescription in the simulations is based on the results of high-resolution magneto-hydrodynamic simulations of star-forming regions (Padoan et al., 2012; Semenov et al., 2016). Most importantly, the model reproduces the abundance and spatial distribution of molecular and atomic gas in NGC 300, and the observed de-correlation between cold molecular gas and clusters of young stars as a function of scale in this galaxy (Semenov et al., 2021). This gives credence to the model as a benchmark that can be used to calibrate star formation and molecular gas abundance in the ISM as a function of its properties.

We present fitting formulae for both volumetric and projected molecular hydrogen fractions that depend on the gas density, gas metallicity, and local ionizing UV field. We show that the fits reproduce known trends in the location and shape of the HI-H_2 transition with metallicity and accurately reproduce both the form of the dependence of molecular fraction on the (volume or column) density and the total molecular gas mass in simulations. In

addition, we demonstrate that the structure and behavior of the ISM changes qualitatively when gas metallicity decreases to $\lesssim 0.1Z_{\odot}$.

The paper is organized as follows. In Section 2.2, we describe the simulation used to calibrate our f_{H_2} models. In Section 2.3, we lay out our simple models for f_{H_2} to be used in both a volumetric and projected case, and in Section 2.4, we present tests of the accuracy of the models. Finally, in Section 2.5, we discuss the implications for models of galaxy formation and compare them against existing f_{H_2} models, details of which are presented in the Appendix A.1.

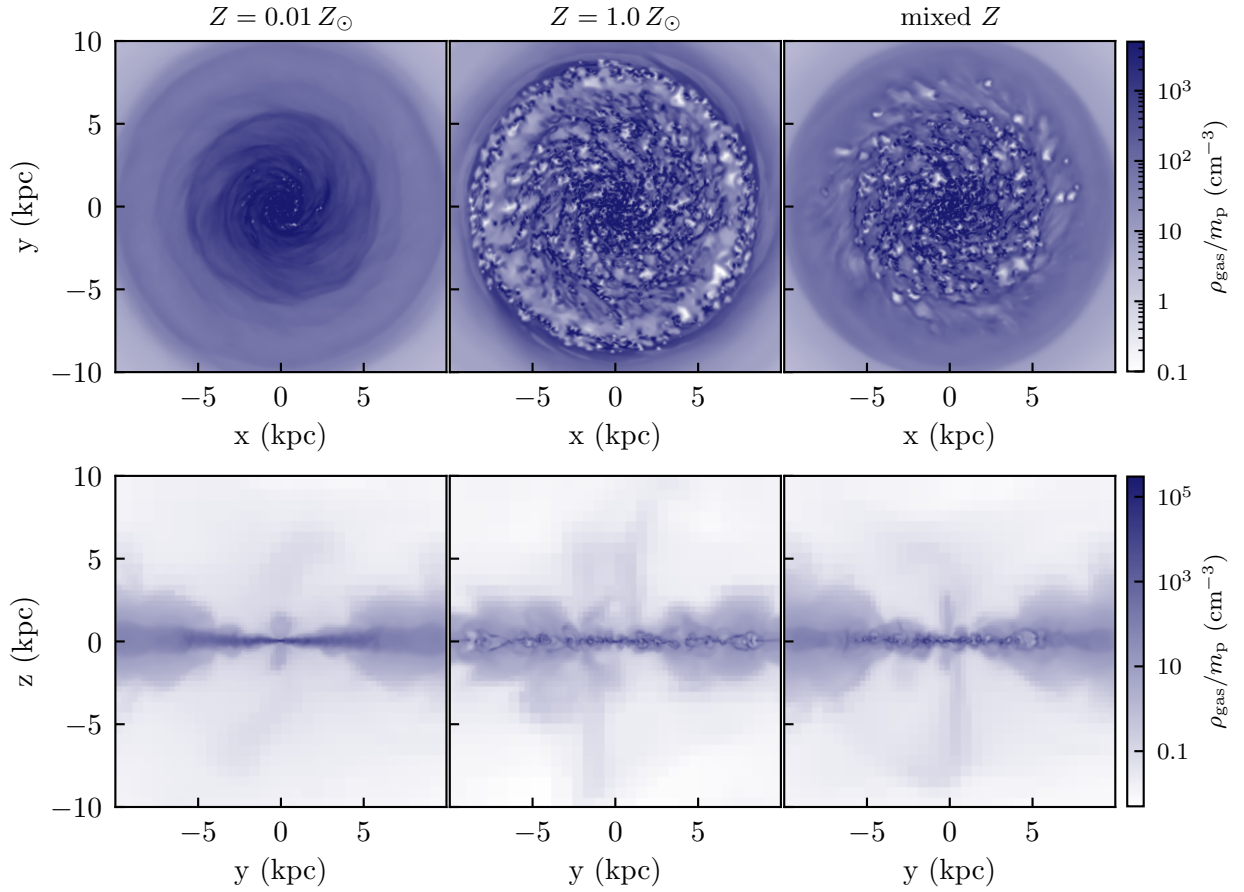


Figure 2.1: Face-on (*top*) and edge-on (*bottom*) gas density slices of our simulated NGC 300-like galaxy in our runs with the lowest and highest Z fixed metallicity as well as our fiducial simulation with variable metallicity.

2.2 Simulations

We conduct our analysis using a suite of simulations of an isolated disk galaxy that is initialized with structural properties similar to those observed in the dwarf galaxy NGC 300 (Semenov et al., 2021). We refer the reader to that paper for a detailed description of the simulation setup and implementations of various included physical processes. Below we summarize the key aspects of the simulations.

The fiducial simulation has been shown to reproduce details of the star formation and atomic and molecular gas distributions in NGC 300, including the observed spatial decorrelation of cold gas with recent star formation as a function of averaging scale (or the “tuning fork”; Kruijssen et al., 2019).

The simulations are carried out using the ART N -body+hydrodynamics code (Kravtsov, 1999; Kravtsov et al., 2002; Rudd et al., 2008; Gnedin & Kravtsov, 2011) with self-consistent modeling of radiative transfer (RT; Gnedin, 2014) and non-equilibrium abundance of molecular hydrogen coupled to the local UV radiation field (using the 6-species model described in the Appendix of Gnedin & Kravtsov, 2011). With the inclusion of RT and a realistic ISM structure shaped by star formation and feedback, as well as the simulation’s maximum resolution of ~ 10 pc (the average grid cell size is ~ 22 pc when $n_{\text{H}} \geq 0.1 \text{ cm}^{-3}$), the simulation offers a highly realistic model for the formation/destruction of molecular hydrogen gas.

Star formation in the simulation is not tied to f_{H_2} but follows the prescription introduced in Semenov et al. (2016). This implementation uses a dynamical model for unresolved turbulence to predict locally variable star formation efficiency instead of assuming a constant tunable value. As was shown in Semenov et al. (2017, 2019, 2021), modeling star formation efficiency based on local properties of turbulence is important for reproducing the linear molecular KS relation on kiloparsec scales and the spatial decorrelation between young stars (UV sources) and molecular gas regions on sub-kiloparsec scales. It was also shown that this model can reproduce star formation and molecular gas properties both in Milky Way-sized

Table 2.1: Basic properties of the snapshots (within 15 kpc of the simulation center), which were fit to construct our models. Each version of the simulation was run for sufficient time that M_{H_2} was not evolving significantly between snapshots.

Run	Time/Myr	$M_{\text{H}_2}/M_{\odot}$	$M_{\text{HI}}/M_{\odot}$	$M_{\text{gas}}/M_{\odot}$
$Z = 0.01 Z_{\odot}$	900	1.4×10^4	1.2×10^9	2.0×10^9
$Z = 0.03 Z_{\odot}$	921	4.8×10^4	1.2×10^9	2.0×10^9
$Z = 0.1 Z_{\odot}$	880	6.4×10^5	1.1×10^9	2.0×10^9
$Z = 0.2 Z_{\odot}$	890	3.5×10^6	1.1×10^9	2.0×10^9
$Z = 0.3 Z_{\odot}$	841	7.3×10^6	1.1×10^9	2.0×10^9
$Z = 0.6 Z_{\odot}$	801	2.2×10^7	1.1×10^9	1.9×10^9
$Z = 1.0 Z_{\odot}$	821	4.3×10^7	1.1×10^9	2.0×10^9
mixed Z^{a}	901	1.9×10^7	1.1×10^9	1.9×10^9

^a For our fiducial mixed metallicity run, the grid cells range in Z from 10^{-20} to $\sim 4 Z_{\odot}$, with a median metallicity of $\sim 0.4 Z_{\odot}$ in higher density ($n_{\text{H}} \geq 0.1 \text{ cm}^{-3}$) gas.

galaxies and in a dwarf galaxy like NGC 300. Results of the analyses presented in this paper should therefore be generally applicable to a wide range of regular galaxies with similar chemical and physical properties. We note, however, that the ISM in strongly starbursting galaxies can have a considerably different density distribution and both the abundance of molecular gas and star formation may behave differently in these environments compared to predictions of our model.

In our fiducial simulation, the metallicity of gas is initialized to have the radial profile similar to the metallicity profile observed in NGC300, after which metallicity is evolved self-consistently. The final snapshot that we use in our analysis contains cells with gas metallicity ranging from effectively 0 to $4.2 Z_{\odot}$ (the former corresponds to the halo gas, while the latter gas is in the regions newly enriched by supernova ejecta).

In order to examine the role of metallicity in determining the molecular gas fraction and star-forming gas fraction, we ran a suite of seven re-simulations of the same galaxy, in which gas metallicity is fixed to values approximately evenly distributed in $\log_{10} Z$: $Z = 0.01, 0.03, 0.1, 0.2, 0.3, 0.6, 1.0 Z_{\odot}$. We conservatively assume a dust-to-gas ratio that scales linearly with metallicity (Wolfire et al., 2008). The dust-to-gas ratio likely decreases faster

than linearly at low metallicity. However, this will only make the decrease of molecular fraction stronger at lower metallicities than what we find here, thereby strengthening our conclusion that it cannot be a linear tracer of star formation in the metal-poor regime. Note that, although gas metallicity is fixed in these runs, all other processes are modelled in the same way. In particular, radiative transfer is performed and UV field varies spatially, reflecting the distribution of sources and absorbing gas. We use the variation of the UV flux within a run to study the dependence of the molecular fraction on this flux at a given gas metallicity. Details of these runs are presented in Table 2.1.

Figure 2.1 presents face-on and edge-on views of the gas distribution in three of these runs. The gas density distribution varies substantially with metallicity, with a more homogeneous density distribution at low Z and a more flocculent density distribution at higher Z . This trend is also apparent in the fiducial run with a non-uniform metallicity distribution shown in the right column, in which inner high- Z regions are similar to the $Z = 1 Z_{\odot}$ run, while the outer lower- Z regions have a much smoother gas distribution.

We compare the projected molecular hydrogen fraction, $F_{\text{H}_2} \equiv N_{\text{H}_2}/(N_{\text{HI}} + 2N_{\text{H}_2})$, from the single Z runs of the simulation to observations of F_{H_2} in the Large and Small Magellanic Clouds (Tumlinson et al., 2002; Bolatto et al., 2011; Welty et al., 2012) in Figure 2.2. We select the single Z run closest to the gas metallicities of the LMC and SMC, adopting our $0.6 Z_{\odot}$ run as an analog for the LMC and our $0.2 Z_{\odot}$ run as an analog for the SMC. The location of the HI-H₂ transition is in good agreement between the observations and the simulation.

Although we do not exactly match the high F_{H_2} observations of the SMC from Bolatto et al. (2011) in our $0.2 Z_{\odot}$ run, there are two effects that likely contribute to this discrepancy. The novel method for measuring Σ_{H_2} used in Bolatto et al. (2011) does not fully distinguish between H₂ and cold HI, potentially yielding a slightly higher molecular fraction that is ultimately more reflective of the fraction of cold neutral gas. Additionally, even though the

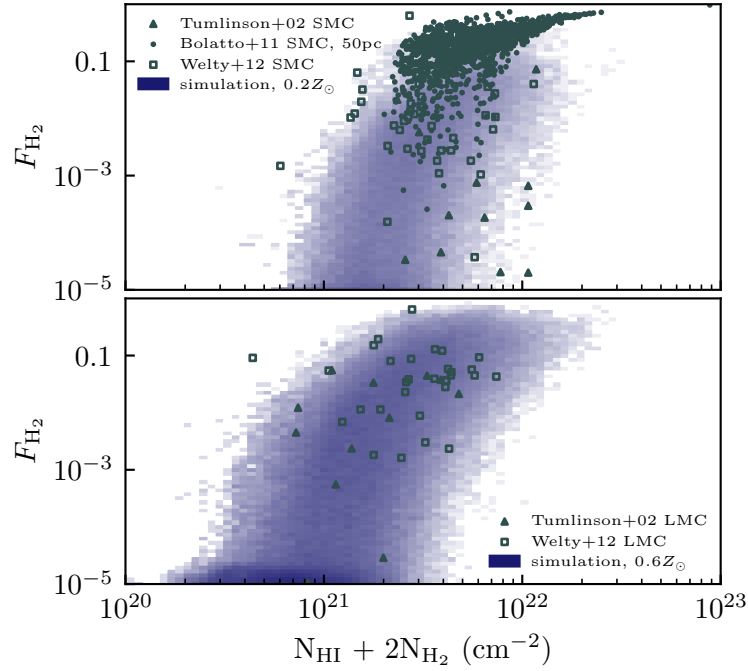


Figure 2.2: Molecular hydrogen gas fraction in projected patches with $S = 10$ pc as a function of gas column density. We compare the $Z = 0.2 Z_{\odot}$ and $Z = 0.6 Z_{\odot}$ simulation runs to observations of F_{H_2} in the Small Magellanic Cloud (SMC; *top*) and Large Magellanic Cloud (LMC; *bottom*) respectively.

highest resolution of our simulation grid cells is 10 pc, the effective resolution is several times this, which means that we are not sensitive to features below this effective resolution scale. It is then possible that the less prevalent high density, highest F_{H_2} regions are averaged to somewhat lower molecular fraction.

2.3 Modeling the molecular gas fraction

In this section, we present two versions of fitting formulae suitable for application in different regimes: fits to a volumetric f_{H_2} fitted to the cell-by-cell distribution of the molecular gas fraction in simulations, which can be used in high-resolution simulations (Section 2.3.1), and fits to projected molecular fraction F_{H_2} , fitted to projected 2D maps averaged on different spatial scales, which can be used in low-resolution simulations and semi-analytic models (Section 2.3.2).

2.3.1 Volumetric f_{H_2} model

We model the molecular hydrogen fraction as a function of hydrogen gas density, metallicity, and UV field strength in individual simulation grid cells. The functional form of f_{H_2} fit is motivated by the fact that we expect f_{H_2} to exhibit a fairly sharp transition at a certain density or column density and saturate at values close to some maximum value $f_{\text{H}_2, \text{max}}$. We thus choose a sigmoid-like function:

$$f_{\text{H}_2} = \frac{f_{\text{H}_2, \text{max}}}{1 + \exp(-x + \ln f_{\text{H}_2, \text{max}} + 7.42)}. \quad (2.1)$$

This form allows us to account for the fact that the maximum possible molecular hydrogen fraction $f_{\text{H}_2, \text{max}}$ varies as a function of metallicity. We parameterize this dependence as

$$f_{\text{H}_2, \text{max}} = [1 + 2(1 - f_{\text{m}})/f_{\text{m}}]^{-1} \quad (2.2)$$

where

$$f_{\text{m}} = 1 - \exp(-Q) \quad (2.3)$$

and

$$Q = 6R_0 \left(\frac{Z}{0.2} \right)^{1.3} n_{\text{H}} \text{ Myr}. \quad (2.4)$$

Here $R_0 = 3.5 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}$ is the rate of H_2 formation on dust grains (see Wolfire et al., 2008) and Z is the metallicity in solar units.

We define x as

$$x \equiv g(Z) \ln \frac{n_{\text{H}}}{n_{\text{tr}}} \quad (2.5)$$

where

$$g(Z) = 7.6 Z^{0.25}. \quad (2.6)$$

The functional form and parameter values in these equations were chosen so that the average trend of f_{H_2} with gas density in the simulation and the maximum values of f_{H_2} are reproduced. Equation 2.5 accounts for the dependence of the location and shape of the HI-H_2 transition on UV field strength and metallicity. The density at which this transition occurs is set by the value of n_{tr} , while the metallicity-dependent pre-factors are responsible for the changing slope of f_{H_2} vs. n_{H} . The value of n_{tr} can be measured from the simulation and fit directly.

Given the very low molecular gas fraction at low metallicities, the parameterization using $n_{1/2}$ – the density at which $f_{\text{H}_2} = 0.5$ in Gnedin & Kravtsov (2011) and Gnedin & Draine (2014) at higher metallicities does not work in our lowest- Z runs as f_{H_2} never reaches 0.5 (see Figure 2.3). Instead, we define n_{tr} as the hydrogen number density (cm^{-3}) at which the molecular hydrogen fraction is 5×10^{-4} , which characterizes the transition even in this low metallicity regime.

Figure 2.3 shows that the atomic-to-molecular transition occurs at lower n_{H} for higher metallicities, while Figure 2.4 shows that n_{tr} behaves like a power law with respect to both

U_{MW} and Z . This power law at each discrete metallicity for binned values of U_{MW} on a volumetric cell-by-cell basis can be approximated by

$$n_{\text{tr}}(D, U_{\text{MW}}) = b(U_{\text{MW}}) - a(D, U_{\text{MW}}) \log_{10} D + c(D) \quad (2.7)$$

Here U_{MW} is the free-space¹ UV flux relative to the MW value $U_{\text{MW}} = J_{1000}/J_{\text{MW}}$, where J_{1000} is the interstellar UV flux at 1000 Å, $J_{\text{MW}} = 10^6 \text{ photons cm}^{-2} \text{ s}^{-1} \text{ ster}^{-1} \text{ eV}^{-1}$ (Draine, 1978; Mathis et al., 1983), and D is the dust-to-gas ratio, which we assume to be equal to the unnormalized mass fraction of heavy elements in the gas.

We then determine fit parameters a and b as a function of U_{MW} using a simple least squares fit of simulation results:

$$a = 34.7 U_{\text{MW}}^{0.32} - 2.25 \left(\frac{D}{0.0199} \right)^{0.3}$$

$$b = -53.9 U_{\text{MW}}^{0.31}$$

The strength of the D -dependence of n_{tr} becomes weaker at higher metallicities for all U_{MW} . To reflect this saturation of the metallicity dependence at near-solar metallicities, we add a correction term assuming that solar metallicity corresponds to mass fraction of 0.0199:

$$c(D) = \frac{D}{0.2 \times 0.0199}. \quad (2.8)$$

To avoid non-physical, negative n_{tr} at high Z and very low U_{MW} , the floor of n_{tr} can be set explicitly. We choose a minimum value of $n_{\text{tr}} = 0.1 \text{ cm}^{-3}$ given that we anticipate very

1. Free-space UV flux is the flux at a given location not attenuated by *local* extinction. Krumholz et al. (2009a), for example, use free-space flux to mean the flux incident on molecular clouds. In our simulations, the radiative transfer calculations do not include absorption by H_2 lines and thus do not model radiation field self-consistently inside molecular-rich regions and have to rely on the subgrid model. In this case the free-space flux is the flux returned by the radiative transfer solver and has the physical meaning of the incident field on the molecular gas.

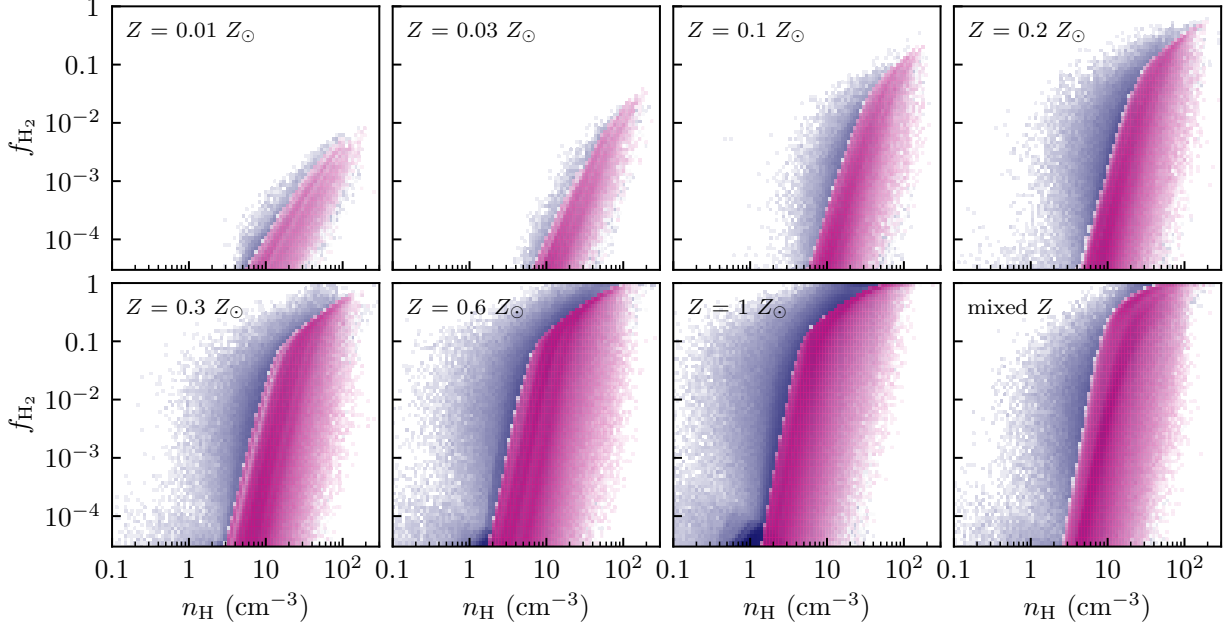


Figure 2.3: Molecular hydrogen gas fraction (f_{H_2}) in computational grid cells of different hydrogen gas density, n_{H} , for each run in our suite. The values in simulation cells are shown in blue, with the model described in Equation 2.1 overplotted in pink. The model explicitly captures the behavior of f_{H_2} at high n_{H} owing to the metallicity- and density-dependent cap value $f_{\text{H}_2,\text{max}}$ (see Equation 2.2). The model was not designed to reproduce the tail of high f_{H_2} at lower densities for the reasons discussed in Section 2.4.1.

little cold, dense molecular hydrogen gas at $n_{\text{H}} \lesssim 0.1 \text{ cm}^{-3}$, but this can be set even lower without affecting the accuracy of the overall model. The results of this fit to n_{tr} are shown in Figure 2.4 overplotted on the measured location of this transition.

Equations 2.1-2.8 can be used to estimate f_{H_2} in the high-density gas (see Figure 2.3), as this gas constitutes most of gas mass in galaxies. The molecular fraction in the low-density unshielded gas does not require a fitting formula and can be obtained by simply equating the H_2 formation and photo-dissociation rates (see, e.g., Section 3.2 in Wolfire et al., 2008):

$$f_{\text{H}_2} = \frac{2n_{\text{H}}R_0}{U_{\text{MW}}I}, \quad (2.9)$$

where $R_0 \approx 3.5 \times 10^{-17} (D/0.019) \text{ cm}^3 \text{ s}^{-1}$ is the rate of H_2 formation on dust grains assumed

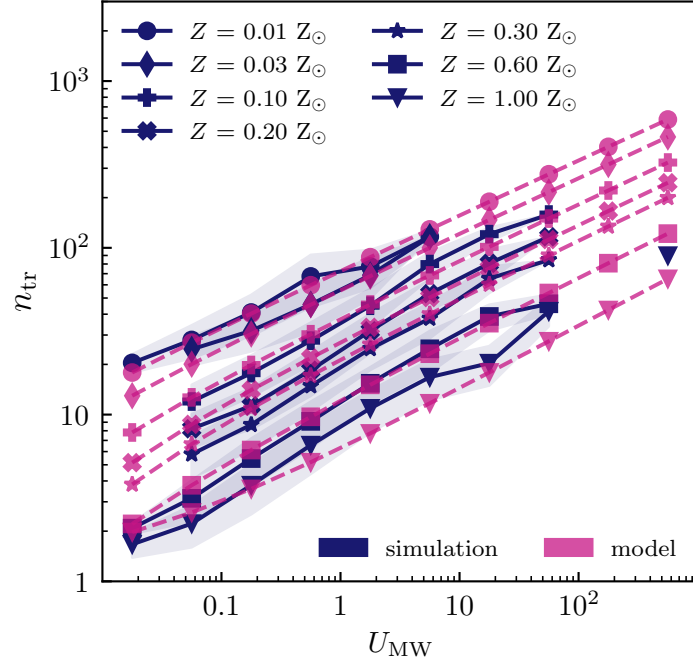


Figure 2.4: Values of n_{tr} estimated for each metallicity and U_{MW} bin as a function of U_{MW} are shown for each of the seven runs with fixed metallicities (blue symbols connected by solid lines). The shaded region corresponds to the 16th and 84th percentile of n_{tr} in each bin. The n_{tr} model results as a function of metallicity and U_{MW} (Equation 2.7) are shown by magenta symbols connected by the dashed lines.

here to scale linearly with D , n_{H} is the number density of hydrogen nuclei, and $I = 4.7 \times 10^{-11} \text{ s}^{-1}$ is the unshielded photodissociation rate in the local interstellar UV field.

We note that the volumetric f_{H_2} fit presented in this section is applicable at densities $n_{\text{H}} \lesssim 10^3 \text{ cm}^{-3}$ probed in our simulations. The upper limit on densities in the simulations is determined by the star formation and feedback model used in these simulations and not by resolution. The gas would have reached higher densities at the resolution of the simulations if not for the exponential increase in the star formation efficiency per free fall time assumed in our model and strong stellar feedback in the form of thermal and turbulent energies and momentum injection. Star formation and feedback disperse the gas before it can reach very high densities.

2.3.2 *Model for projected molecular fraction*

In observations, low-resolution simulations, and semi-analytic models one often needs to work with the projected mass densities and we thus present fitting formulae for projected molecular fraction below. To distinguish it from the volumetric one we will denote the projected fraction as

$$F_{\text{H}_2} = \frac{\Sigma_{\text{H}_2}}{\Sigma_{\text{H}_2} + \Sigma_{\text{HI}}}. \quad (2.10)$$

To obtain projected molecular fractions F_{H_2} on different spatial scales in the simulations, we use the face-on projection of the simulated galaxy with gas properties binned on grids with physical cell sizes 10 pc to 1 kpc. The gas surface (column) density is computed simply as the gas mass (atom number) in each bin divided by its area. The UV flux and metallicity in each bin are estimated as the gas-density weighted averages of U_{MW} and Z in the computational cells enclosed in a given bin.

Projected molecular fractions as a function of column density, $F_{\text{H}_2}(N_{\text{H}})$, are shown in Figure 2.5 for two representative averaging scales – 30 pc and 300 pc. Similarly to the

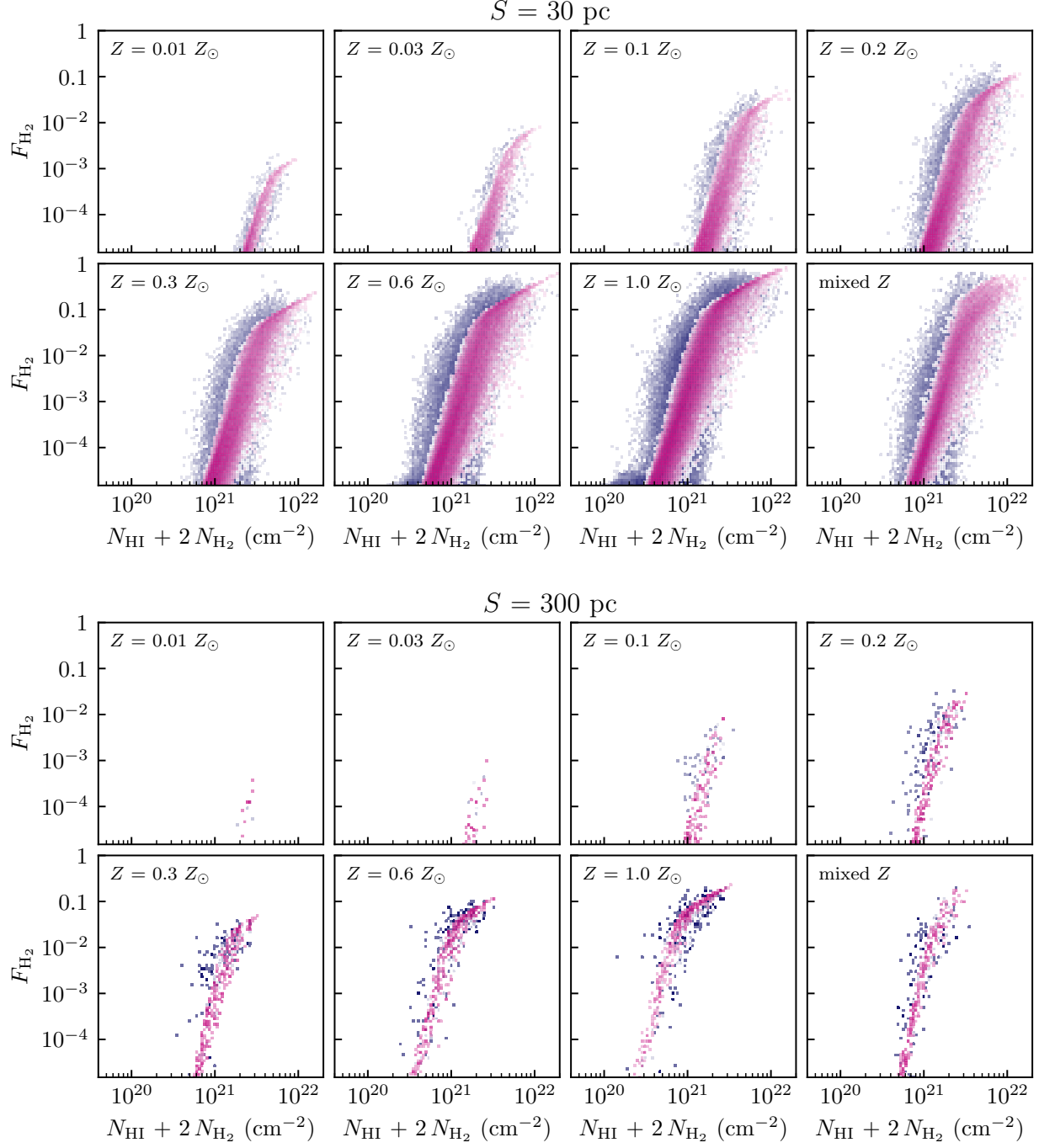


Figure 2.5: Molecular hydrogen gas fraction (F_{H_2}) in projected patches of size S of different hydrogen gas column density, $N_{\text{HI}} + 2 N_{\text{H}_2}$, for each run in our simulation suite at two representative scales, $S = 30$ pc and $S = 300$ pc. The simulation values are shown in blue, while the model described in Equation 2.1 is overplotted in pink.

volumetric molecular fractions, we use the sigmoid-like functional form of the model for F_{H_2} :

$$F_{\text{H}_2} \approx \frac{F_{\text{H}_2, \text{max}}}{1 + \exp(-x + \ln F_{\text{H}_2, \text{max}} + 8.71)}, \quad (2.11)$$

where

$$F_{\text{H}_2, \text{max}} = [1 + 2(1 - F_{\text{m}})/F_{\text{m}}]^{-1}, \quad (2.12)$$

and

$$F_{\text{m}} = 1 - \exp(-Q), \quad (2.13)$$

$$Q = 3R_0 \left(\frac{Z}{0.1} \right)^{1.3} \frac{N_{\text{H}}}{4.63 \times 10^{20} \text{ cm}} \text{ Myr}, \quad (2.14)$$

and where, as before, $R_0 = 3.5 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}$ (see Wolfire et al., 2008), and x in Equation 2.11 is

$$x = g(Z, S) \ln \frac{N_{\text{H}}}{N_{\text{tr}}}, \quad (2.15)$$

where

$$\begin{aligned} g(Z, S) = 1 &+ 1.35 \left(\frac{Z}{0.01} \right)^{-0.25} \left(\frac{S}{10 \text{ pc}} \right)^{0.6} \\ &+ 3.4 \left(\frac{Z}{0.6} \right)^{0.02}, \end{aligned} \quad (2.16)$$

and S is the resolution of the projected map from the simulation, i.e. the scale on which surface densities and fractions are averaged.

The transition column density, $N_{\text{tr}}(Z, U_{\text{MW}}, S)$, is defined as the median column density of all cells with molecular hydrogen fractions between 5×10^{-5} and 5×10^{-4} . This region in the $F_{\text{H}_2} - N_{\text{H}}$ parameter space was chosen because $F_{\text{H}_2}(N_{\text{H}})$ is increasing sharply with increasing column density and F_{H_2} range is sufficiently low to be used at very small metallicities. As in the volumetric model, the location of the transition is set by N_{tr} (Figure 2.6), while the slope of $F_{\text{H}_2}(N_{\text{H}})$ is set by the pre-factors, which have a weak dependence on the

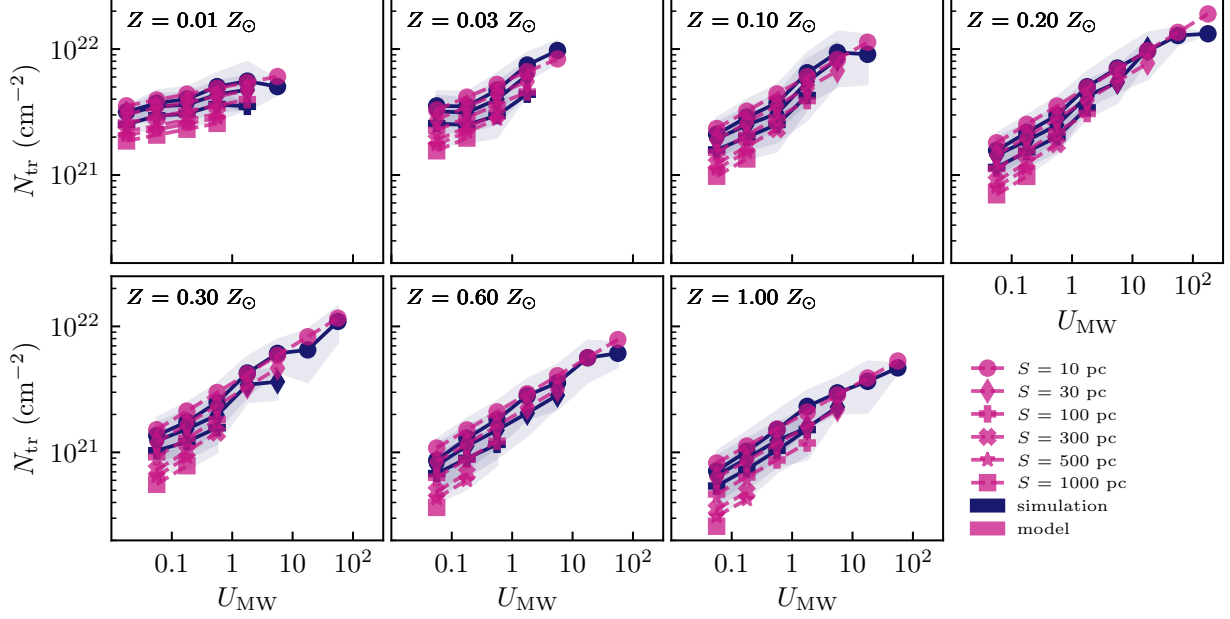


Figure 2.6: The median column density for which the molecular fraction is between 5×10^{-5} and 5×10^{-4} , which marks the location of the H I-H₂ transition, as a function of U_{MW} and S for each of our single metallicity runs. The measured values are shown by the dark blue symbols connected by lines. Given that we only fit explicitly for averaging scales S between 10 and 100 pc due to the number of available grid cells, we do not include the measured values for scales between 300 and 1000 pc. The model results as a function of U_{MW} , Z , and S (Equation 2.17) are shown by the magenta symbols connected by dashed lines.

scale S (in parsecs) and metallicity, $\zeta = \log_{10} Z$:

$$N_{\text{tr}} = U_{\text{MW}}^{w(\zeta)} 10^{y(\zeta, S)} N_{\text{corr}}(\zeta, S) \quad (2.17)$$

$$w = 0.27 - 0.01 \left[9.25 \zeta^2 + 9.64 \zeta \right],$$

$$y = y_{\text{norm}} \exp \left(-0.5 \left[\frac{\zeta + 1.5}{6.84} \right]^2 \right)$$

$$y_{\text{norm}} = 21.96 - 0.19 \log_{10} S.$$

As for the volumetric model, the functional forms and their parameter values are chosen so that equation 2.11 reproduces the mean trend of F_{H_2} as a function of N_{H} in the simulations

for each metallicity, UV flux and scale.

N_{corr} is the correction factor introduced to address two distinct limitations of our original fit to the measured median column density of the HI-H₂ transition. Due to a paucity of grid cells at larger scales ($S > 100$ pc), we only explicitly fit for N_{tr} in the $S = 10, 30$, and 100 pc cases, which means that our parameterization does not account for the behavior on larger spatial scales. In addition, given that F_{H_2} is defined assuming that the transition occurs at 1.65×10^{-4} as defined by N_{tr} , while the median molecular fraction between 5×10^{-5} and 5×10^{-4} varies subtly with scale and metallicity. We capture these effects using the following functional form:

$$N_{\text{corr}} = 1 - 0.13 \log_{10} \left(\frac{Z}{0.1} \right) \log_{10} \left(\frac{S}{10 \text{ pc}} \right). \quad (2.18)$$

2.4 Comparisons of fits to simulation

2.4.1 The volumetric f_{H_2} fit

The validity and accuracy of the volumetric f_{H_2} fitting formulae (Equations 2.1-2.8) can be gauged by comparing the f_{H_2} according to the fit to the simulation f_{H_2} for all grid cells in the simulation with molecular fractions larger than 10^{-5} . We do this for all fixed metallicity runs and for the fiducial run with non-uniform metallicity, which was not used in deriving the fit. Note also that the latter includes cells with metallicities outside of the range within which we calibrated the model.

Figure 2.3 shows a good qualitative agreement between the molecular fractions produced by the model fits and the simulation results for each run. Because we impose a strict $f_{\text{H}_2, \text{max}}$ condition, the model f_{H_2} distribution has a sharp boundary at the highest fraction values at each density. In principle, one can introduce scatter around the model relations to reproduce the tail of high f_{H_2} cells at small densities. However, we do not think it is worthwhile for two reasons. First, as we show next, the presented fit accurately recovers molecular mass,

M_{H_2} , for the galaxy at all metallicities. This means that the molecular mass in this tail is fairly small. Second, the bulk of the high f_{H_2} gas at low densities could be due to numerical diffusion of radiation and molecular gas around star-forming regions and thus may be a non-equilibrium artifact.

The accuracy of the fit in reproducing the molecular content of the ISM in the simulated galaxy can be assessed by comparing the total H_2 mass estimated by the model with the total simulation H_2 mass summed across each computational cell. The left panel of Figure 2.7 shows the ratio $M_{\text{H}_2,\text{sim}}/M_{\text{H}_2,\text{mod}}$ as a function of metallicity for the volumetric model as magenta open circles and indicates that the fit is accurate in predicting H_2 mass to $\lesssim 25\%$.

To test whether results depend on the time snapshot of the simulation we estimated the ratio of the actual-to-model-predicted molecular mass at a series of different simulation snapshots. These estimates are shown in Figure 2.8, which shows that generally, the fit accuracy is similar at most snapshots, except for a single snapshot where the ratio increased to ≈ 1.8 one where likely non-equilibrium processes related to a local starburst changed the ISM significantly.

The figure shows that variation of the mass ratio from snapshot to snapshot increases significantly in lower metallicity runs. This is likely related to the rapidly increasing H_2 formation time with decreasing metallicity. Indeed, using $t_{\text{chem}} = 105 (Z/Z_{\odot})^{-1} (n_{\text{H}}/\text{cm}^{-3})^{-1} (10/f_c)$ Myr from Krumholz (2012) and assuming a clumping factor $f_c = 10$ due to turbulence on the scale of molecular clouds (see Appendix A.7 of Gnedin & Kravtsov, 2011), the H_2 formation time for gas of $Z = 0.01 Z_{\odot}$ and number density $n_{\text{H}} = 50 \text{ cm}^{-3}$ should be 210 Myr, while it is only ≈ 2.1 Myr for $Z = Z_{\odot}$ gas of the same density. Given that the typical lifetime of a molecular cloud is significantly shorter, $\sim 5 - 15$ Myr (Semenov et al., 2017), it is not surprising that f_{H_2} is generally suppressed in low- Z gas ($Z \lesssim 0.1 Z_{\odot}$), where the time for the gas to reach chemical (HI-H_2) equilibrium is longer than the timescales on which molecular clouds persist without disruption. In low-metallicity runs, H_2 abundance is much more sus-

ceptible to disruption of individual star-forming regions (which are also fewer), which leads to larger variations of the H_2 abundance.

We note that the fit should not to be extrapolated to the *zero* metallicity case. In practice, however, a very small value of metallicity should return reasonable results. Though the model is accurate when applied to a run that includes negligible, but non-zero metallicity grid cells, we suggest that model can most confidently be used for $Z \gtrsim 10^{-3} Z_\odot$. These metallicities correspond to local dwarf galaxies and are roughly consistent with the gas out of which Population II stars form, making this low metallicity model relevant for high z galaxies, as well.

2.4.2 The projected F_{H_2} fit

Figure 2.5 shows good agreement between the projected molecular fraction, F_{H_2} , estimated using fit (equations 2.11-2.18) and simulation results across metallicities *and* across averaging scales. We show this explicitly for two representative scales of 300 pc and 30 pc, both of which are fairly well-populated by simulation grid cells with $f_{\text{H}_2} \geq 10^{-5}$ even at the lowest metallicities. As with the volumetric fit, the imposed maximum fraction $F_{\text{H}_2, \text{max}}$ results in a hard upper boundary on $F_{\text{H}_2}(N_{\text{H}})$ (see Section 2.4.1). Also, the scatter of F_{H_2} in the model at a given number density is somewhat smaller than in the simulations. As we argued in the discussion of the volumetric model comparisons above, the additional scatter can be added to the model, but the amount of molecular gas associated with the tails of the distribution is fairly small.

Indeed, Figure 2.7 shows that the total molecular gas mass estimated using the fit formulae is accurate to better than a factor of $\lesssim 1.5$ across the full probed range of metallicities and averaging scales.

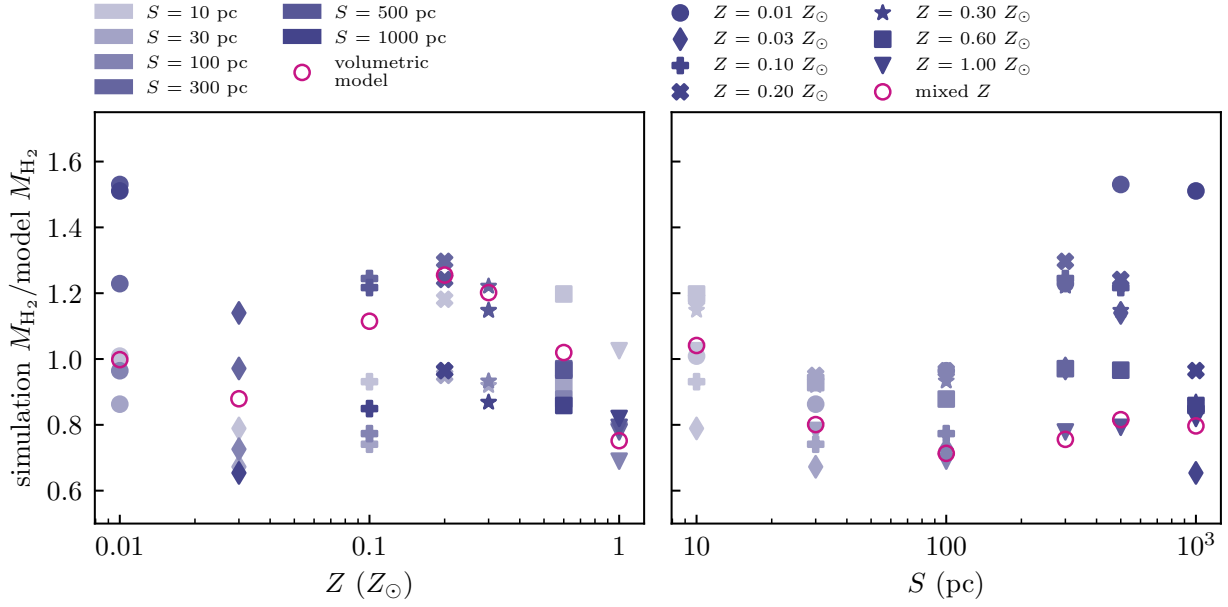


Figure 2.7: The ratio of H_2 mass measured in the simulations using the grid cells with $f_{\text{H}_2} \geq 10^{-5}$ to the H_2 mass predicted by the model using the densities, metallicities, and UV fluxes in the individual simulation cells as a function of metallicity for both the volumetric case (magenta, *left*) and the scale-dependent projected measurements. Notably, the model is accurate to better than a factor of ≈ 1.5 in most cases for both the fixed metallicity runs and the fiducial run with non-uniform metallicity (magenta, *right*) across a range of scales.

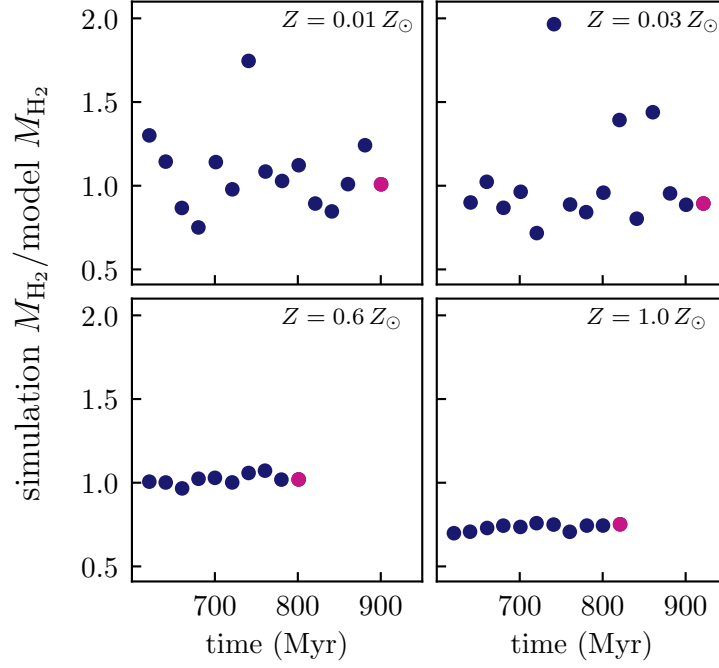


Figure 2.8: The ratio of the H_2 mass in the simulation and the H_2 mass inferred from the volumetric model (Equation 2.1) as a function of snapshot time. The most advanced snapshot used in calibrating our model is shown by the magenta point. We show the evolution of this ratio for the two lowest metallicity and two highest metallicity runs we use in this work. The figure indicates that results of the test shown in Figure 2.7 are not sensitive to the specific output used.

2.5 Discussion

2.5.1 Implications for galaxy formation modeling

In simulations and analytical models of galaxies, molecular gas is sometimes used as a proxy for star-forming gas, which is motivated by the observed constant depletion times of molecular gas in normal (non-starburst) galaxies of metallicities $\approx 0.1 - 1Z_{\odot}$ (see Introduction).

Figure 2.9, however, shows that the depletion time of molecular hydrogen gas is expected to change by nearly three orders of magnitude from $0.01Z_{\odot}$ to $Z_{\odot}$ in our simulations, while the SFR is changing only by a factor of ten over the same metallicity range. Thus, according to our simulations the star formation rate at low metallicities is a nonlinear function of the molecular mass, which implies that the fraction of stars forming in atomic gas increases with decreasing metallicity.

As discussed by Krumholz (2012), the use of chemical equilibrium models to estimate H_2 abundance for star formation rate calculations can partly compensate for this trend and will result in higher SFR at low metallicity. However, this is hardly justified because this effectively trades one error for another by artificially overestimating f_{H_2} in the environment where the fraction is actually low. A much better alternative is to switch to a star formation prescription that captures the metallicity dependence of the actual star formation.

2.5.2 Comparisons with other models

Motivated by the paucity of reliable HI- H_2 transition models for the $Z \lesssim 0.2Z_{\odot}$ regime (corresponding to metallicities typical of dwarf galaxies and galaxies at high redshift), we constructed fitting formulae for the molecular fraction as a function of gas density (or column density), local UV flux, and metallicity down to $Z = 0.01Z_{\odot}$. This metallicity range includes the smallest metallicities observed in galaxies in the ultra-faint regime (Hidalgo, 2017; Simon, 2019). Simultaneously, as we showed above these fitting formulae perform well at higher Z

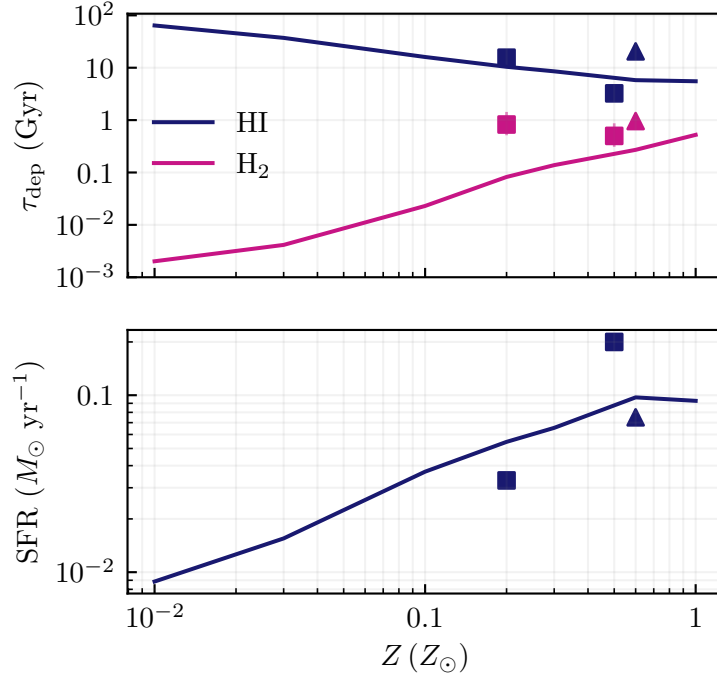


Figure 2.9: The depletion time ($\tau_{\text{dep}} = M_{\text{gas}}/\text{SFR}$) as a function of metallicity and gas species relative to the star formation rate (SFR) as a function of metallicity. We use M_{gas} within 5 kpc of the simulation center. While $\tau_{\text{dep,H}_2}$ varies by a factor of 260 between $Z = 0.01 Z_{\odot}$ and $1 Z_{\odot}$, the star formation rate (defined here by the mass of stars formed over the last 10 Myr) only varies by a factor of 11. This is indicative of the fact that the star formation in low metallicity galaxies is not directly tied to H_2 abundance. We also include the inferred SFR and H_2 and HI τ_{dep} in the Large and Small Magellanic Clouds from Jameson et al. (2016) as squares, which we correct by a factor of 1.35 for the presence of He, and the inferred SFR and τ_{dep} for NGC 300 digitized from Kruijssen et al. (2019) as triangles.

up to the solar metallicity.

Here we compare the fitting formulae presented in this paper and a number of models of molecular fraction in the literature (namely, Krumholz et al., 2009b; Gnedin & Kravtsov, 2011; Krumholz, 2013; Sternberg et al., 2014; Gnedin & Draine, 2014) with simulation results. The models parameterize average f_{H_2} and F_{H_2} as a function of gas density, metallicity, and UV field strength (the KMT09b model only accounts for the dependence on column density and metallicity; see Appendix A.1 for details of the model implementations).

Figure 2.10 shows comparisons of the average f_{H_2} and F_{H_2} to the molecular fraction as

a function of volumetric and projected densities in simulations. In order to have a more direct comparison between existing models and the fits presented in this study, we also show predictions of each model when applied to the individual computational grid cells in our simulation for our single metallicity runs with the lowest and highest Z in Figures 2.11 and 2.12. The very narrow distribution of f_{H_2} as a function of density in the KMT09b model is likely due to its neglect of dependence on U_{MW} , which drives the scatter in the simulation and in other models, including the model calibrated in this study.

Given that most existing models have been calibrated in the high-metallicity regime, it is not surprising that their accuracy improves with increasing metallicity (see Table 2.2). Interestingly, the accuracy of the K13 model is better at low metallicities for volumetric grid cells, but the match to the shape and behavior of the HI- H_2 transition is better at high Z . This seems to be driven by their very steep functional form of f_{H_2} , so that only a few grid cells with high f_{H_2} contribute to the inferred mass at lower Z , while at higher metallicity, the transition n_{H} is underestimated, leading to the model underprediction of M_{H_2} .

In the case of the projected models, KMT09b performs consistently well for $Z \gtrsim 0.1 Z_{\odot}$. The shape of $F_{\text{H}_2}(N_{\text{H}})$ is very close to what we observe in the simulation for these metallicities and the transition between atomic and molecular gas is consistent with the location of the transition in the simulation for $Z \gtrsim 0.4 Z_{\odot}$. GK11 is the next most accurate of the existing models. The lowest metallicity runs result in an inferred $M_{\text{H}_2} = 0 M_{\odot}$ with this model, but this is expected behavior for the projected GK11 model, which is known to not be accurate for $Z \lesssim 0.01 Z_{\odot}$ (Gnedin & Kravtsov, 2011).

With regard to the GD14 model, it is worth noting that this model includes a phenomenological account for the H_2 self-shielding due to line overlap. This results in near independence of f_{H_2} on dust abundance (and thus metallicity) for $D \lesssim 0.2 D_{\text{MW}}$. The simulations used here do not include any accounting for such line overlap and thus a part of the difference of GD14 model and simulation results at $Z \lesssim 0.2 Z_{\odot}$ may be due to this

difference. Otherwise, the GK11 and GD14 models are quite similar and thus the accuracy of the GK11 model should be comparable to predictions of the GD14 model without the line overlap effect. The similarity of these two models is the reason why their estimated molecular mass is similar at $Z \lesssim 0.2Z_{\odot}$ (see Table 2.2).

The fit presented in this paper reproduces the total molecular hydrogen mass in the simulations considerably better than previous models. Even restricting K13 to $Z \lesssim 0.1 Z_{\odot}$, where their model results in masses within a factor of $\sim$ two of those measured in simulation, it appears to be a coincidence given the steep relation and few high f_{H_2} cells.

2.6 Conclusions

In this work we presented fitting formulae for volumetric (equations 2.1-2.8) and projected (equations 2.11-2.18) molecular gas fractions. The fits consist of a set of simple scalings calibrated to reproduce mean trends measured in simulations of a realistic dwarf galaxy similar to NGC 300 (Semenov et al., 2021). Both volumetric and projected fits parameterize the molecular fraction as a function of gas density, gas metallicity, and the strength of the local free space ionizing UV field.

Our main results and conclusions are as follows:

- We show that the interstellar medium in the simulated galaxy changes qualitatively when gas metallicity is varied by two orders of magnitude. The density distribution becomes increasingly non-uniform as metallicity increases from $0.01Z_{\odot}$ to $Z_{\odot}$ (see Figure 2.1).
- In addition to the well-known trend of the HI-H₂ transition shifting to higher densities with decreasing metallicity, the maximum achieved molecular fraction in the interstellar medium drops drastically to values much less than 1 at $Z \lesssim 0.2 Z_{\odot}$ (see Figures 2.3 and 2.5), while the dependence of molecular fraction on density becomes less steep.

Table 2.2: The ratio of H_2 mass in the simulation to model predicted value, $M_{H_2, \text{sim}}/M_{H_2, \text{mod}}$, for different models (both volumetric and projected), where masses are obtained by summing the actual and predicted H_2 value for every grid cell. We assume the same model parameters as in Figures 2.11 and 2.12 respectively. For the projected models, we adopt show the accuracy for the representative $S = 100$ pc case. We denote model and metallicity combinations that produce no molecular hydrogen with a dash.

Model	$0.01 Z_{\odot}$	$0.03 Z_{\odot}$	$0.1 Z_{\odot}$	$0.2 Z_{\odot}$	$0.3 Z_{\odot}$	$0.6 Z_{\odot}$	$1 Z_{\odot}$	mixed Z
KMT09b	35.5	4.25×10^3	262	72.3	27.2	27.5	29.8	17.3
GK11	2.27×10^{-4}	2.38×10^{-4}	2.72×10^{-3}	0.0130	0.0227	0.0527	0.0883	0.0572
K13	1.18	0.51	1.76	4.55	7.56	15.8	20.7	13.12
S14	2.29×10^{-3}	6.20×10^{-3}	0.0339	0.10	0.18	0.39	0.60	0.45
GD14	5.41×10^{-5}	1.91×10^{-4}	2.31×10^{-3}	0.0109	0.0194	0.0450	0.0748	0.0506
This work	1.01	0.89	1.12	1.26	1.20	1.02	0.75	0.79
KMT09b	1.94×10^4	335	2.37	1.49	0.82	0.57	0.48	0.40
GK11	-	-	1.42	0.25	0.18	0.16	0.16	0.16
K13	0.0743	0.0188	0.0201	0.0382	0.0548	0.0970	0.13	0.10
S14	3.90×10^{-3}	0.0153	0.0417	0.0669	0.0800	0.11	0.14	0.12
GD14	1.35×10^{-4}	5.98×10^{-4}	8.06×10^{-3}	0.0346	0.0572	0.1	0.13	0.11
This work	0.94	0.68	0.76	0.96	0.93	0.88	0.69	0.71

volumetric
100 pc
projected, 100 pc

- We show that accurate fitting functions for volumetric and projected molecular fractions can be constructed if they account for the dependence on gas density, gas metallicity, the strength of the ionizing UV field (Figures 2.4 and 2.6). We demonstrate that the presented fits reproduce the dependence of the HI-H₂ transition on metallicity and the overall shape of the molecular fraction-density distribution than existing models (Figures 2.10–2.12)
- We also show that the volumetric (projected) molecular fraction fit is applied to individual cells (projected patches) reproduces the total molecular mass in the simulated galaxies to a factor $\lesssim 1.25$ ($\lesssim 1.5$) across the entire explored range of galaxy metallicities (Figures 2.7 and 2.8). This is considerably better than the estimates using existing models of the molecular hydrogen fraction and HI-H₂ transition (see Figures 2.10 and 2.11 and Table 2.2).

The presented model should be useful in modeling molecular gas abundance in simulations that do not include explicit modeling of H₂ and low-resolution simulations and semi-analytical models. However, we argue that star formation modeling in simulations should not be based on molecular gas fraction because our simulation results indicate that star formation rate becomes a non-linear function of molecular gas density at metallicities $< 0.1Z_{\odot}$ due to non-equilibrium effects (see Section 2.5 and Fig. 2.9). As an alternative, the star formation efficiency and depletion time can be calibrated using such simulations and we will present such calibrations in the follow-up work.

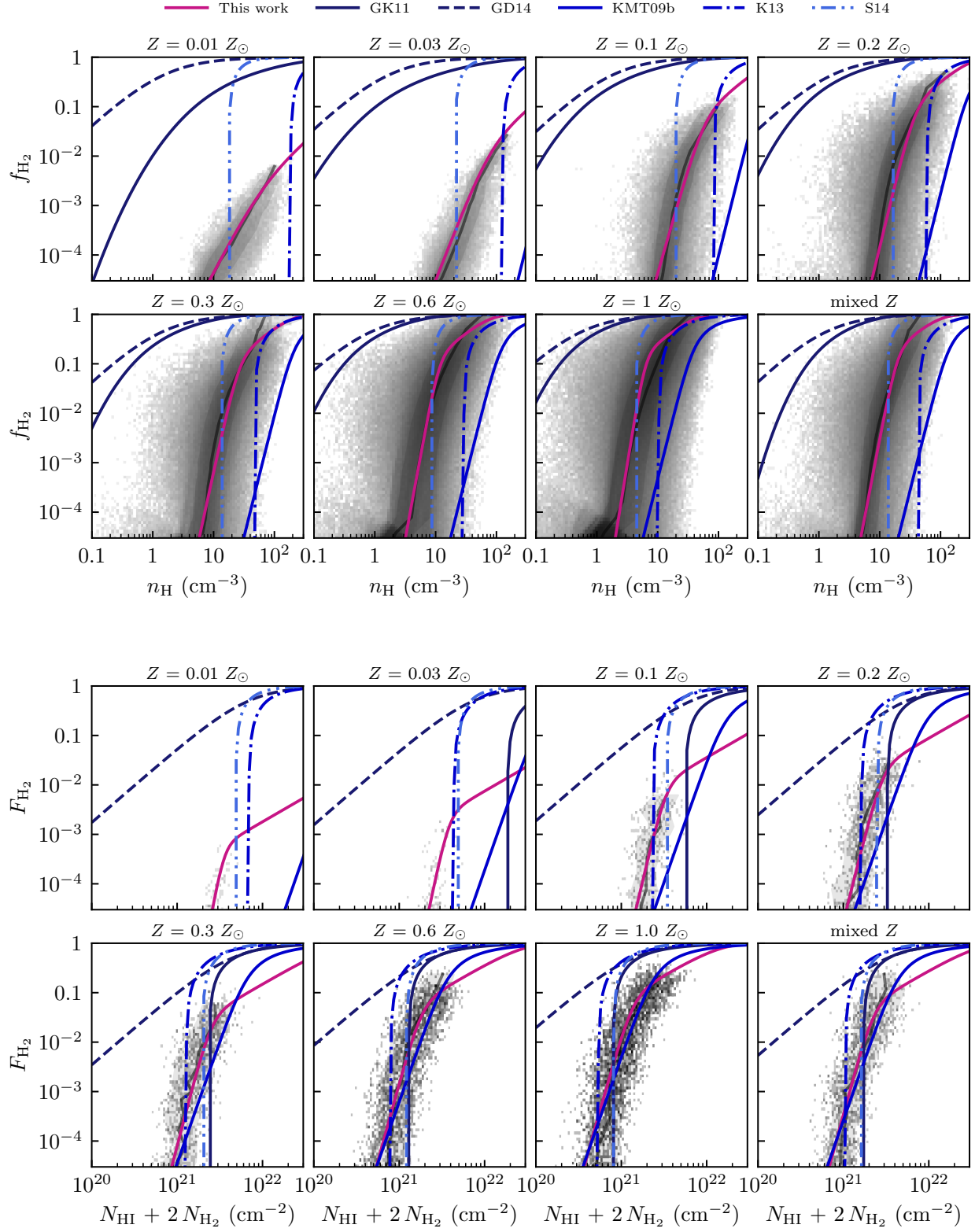


Figure 2.10: (Caption next page.)

Figure 2.10: (*Previous page.*) The molecular hydrogen fraction as a function of n_{H} (*top*) and N_{H} ($S = 100$ pc, *bottom*) for different models including our own overplotted on the underlying f_{H_2} vs. n_{H} distribution from the simulation. For each model, we use the median U_{MW} ($U_{\text{MW}} \sim 0.1$) and S ($S \sim 10$ pc, *top*; $S = 100$ pc, *bottom*) for the high molecular fraction ($f_{\text{H}_2} \geq 10^{-5}$) cells in the simulation. For our mixed metallicity run, we also use the median Z ($\sim 0.5 Z_{\odot}$). For K13 and S14, we assume a clumping factor of 1, and for K13 we also set ρ_{SD} (the density of stars and dark matter) to $\sim 0.1 M_{\odot} \text{ pc}^{-3}$, which is the median for the high molecular fraction cells in the simulation with a non-zero ρ_{SD} . We underplot the median density in bins of f_{H_2} in black for each run of the simulation.

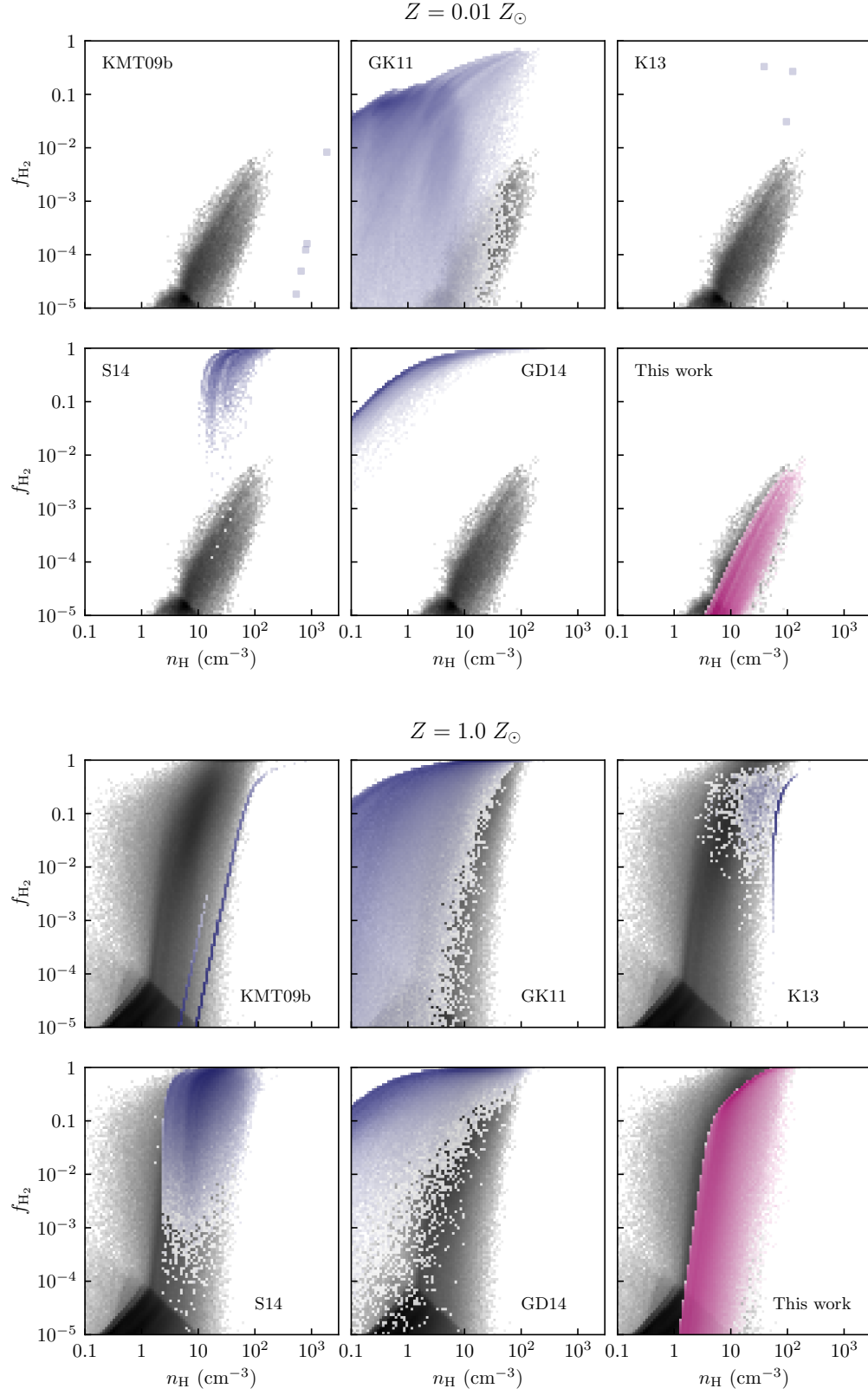


Figure 2.11: *(Caption next page.)*

Figure 2.11: (*Previous page.*) Comparison of existing models and the HI-H₂ model we present here on a volumetric cell-by-cell basis for $Z = 0.01 Z_{\odot}$ and $Z = 1.0 Z_{\odot}$. We use simulation values of density, metallicity, UV field strength, and grid cell size, and assume $f_c = 1$ for K13 and S14 as in Figure 2.10 and Table 2.2. Given how few KMT09b and K13 model cells have $f_{\text{H}_2} \geq 10^{-5}$ at densities consistent with those in the $Z = 0.01 Z_{\odot}$ simulation, we plot the phase space location of each cell individually for these two models.

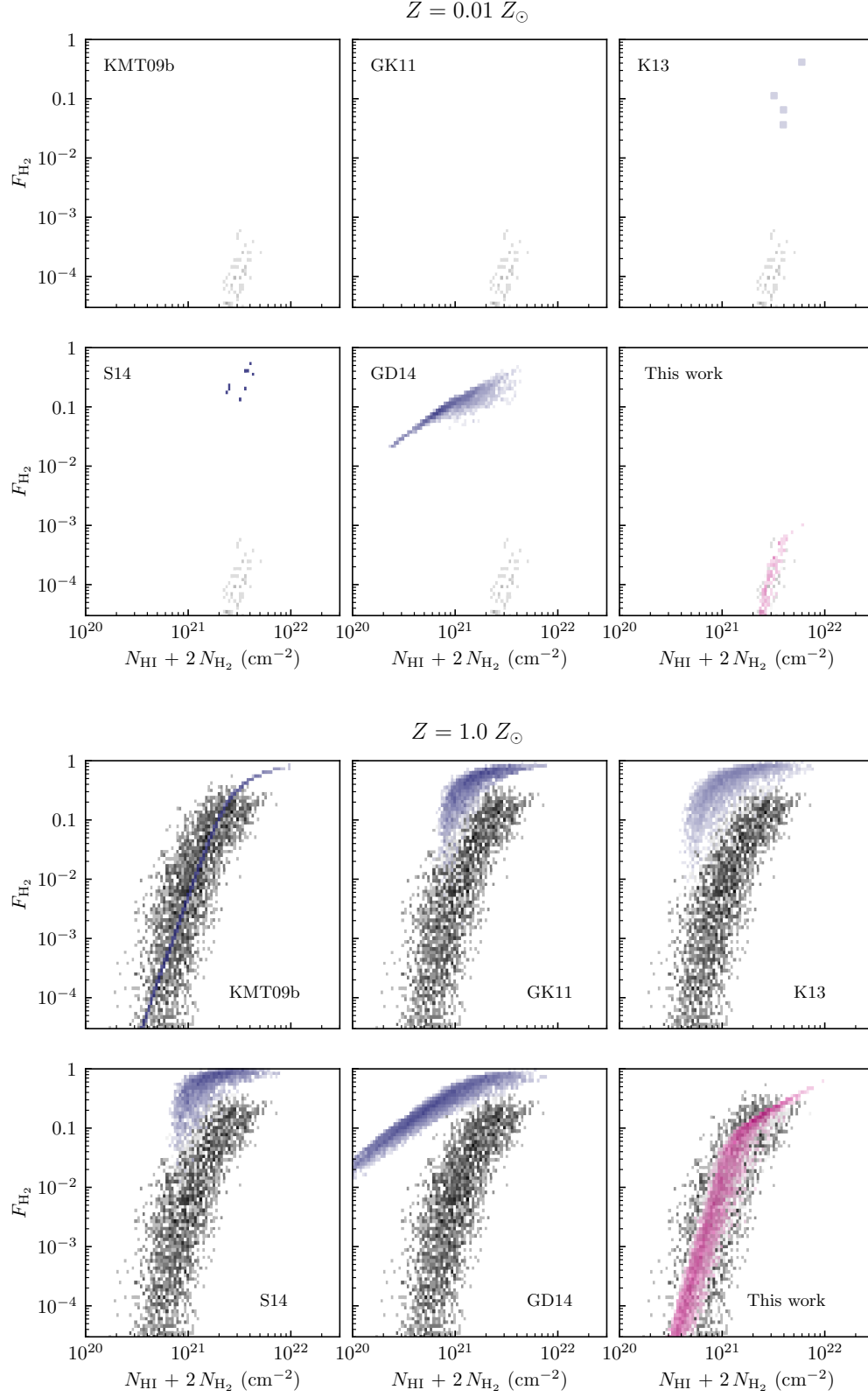


Figure 2.12: (Caption next page.)

Figure 2.12: (*Previous page.*) Comparison of existing models and the HI-H₂ model we present here on a projected cell-by-cell basis for $Z = 0.01 Z_{\odot}$ and $Z = 1.0 Z_{\odot}$. We use simulation values of density, metallicity, UV field strength, and scale, and assume $f_c = 1$ for K13 and S14 as in Figure 2.10 and Table 2.2. At low metallicities, neither KMT09b nor GK11 predict $f_{\text{H}_2}(N_{\text{H}})$ within the range shown here. As in Figure 2.11, given how few K13 model cells have $f_{\text{H}_2} \geq 10^{-5}$ at densities consistent with those in the $Z = 0.01 Z_{\odot}$ simulation, we plot the phase space location of each cell individually for that model. Unlike in Figure 2.11, where we compute ρ_{SD} on a per grid cell basis, we instead use a global value $\sim 0.1 M_{\odot} \text{pc}^{-3}$ based on the median for each run.

CHAPTER 3

ON THE UNIVERSALITY OF STAR FORMATION EFFICIENCY

Polzin et al. (2024b) presented as part of a thesis to the Department of Astronomy and Astrophysics, The University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

A. Polzin, A. V. Kravtsov, V. A. Semenov, and N. Y. Gnedin, “On the universality of star formation efficiency in galaxies”, OJAp, vol. 7, Dec. 2024, DOI: 10.33232/001c.127042.

3.1 Introduction

It has been known for about five decades that the efficiency with which gas is converted into stars in star-forming regions (the star formation efficiency) is small (e.g., Zuckerman & Evans, 1974). Over the past two decades, observations showed that star formation efficiency per free-fall time is only a few percent for a wide range of environments and scales (e.g., Krumholz & Tan, 2007; Krumholz et al., 2012; García-Burillo et al., 2012; Evans et al., 2014; Utomo et al., 2018; Pokhrel et al., 2021; Hu et al., 2022; Sun et al., 2023; Mattern et al., 2024, see Section 3.2 of Krumholz et al. 2019 for a review).

Theoretical models aiming to explain the low efficiency on the scales of star-forming regions (see McKee & Ostriker, 2007; Krumholz, 2014, for reviews) include magnetic pressure support against collapse of gas (e.g., Mouschovias, 1976a,b; Price & Bate, 2009; Krumholz & Federrath, 2019) and supersonic turbulence (e.g., Elmegreen, 2002; Krumholz & McKee, 2005), possibly mediated by magnetic fields (e.g., Padoan et al., 2012; Federrath & Klessen, 2013; Federrath, 2015; Girma & Teyssier, 2024).

On kiloparsec and larger scales galaxies also form stars inefficiently, which is partly related to the local efficiency per free-fall time (e.g., Krumholz et al., 2012; Semenov et al., 2018).

The connection between efficiency in star-forming regions and star formation rate measured on large scales arises because the local inefficiency of star-forming regions and their short lifetimes result in only a small fraction of gas being converted into stars in each star-forming region. Therefore, a given gas parcel has to go through a large number of star formation-dispersal cycles, each taking $\approx 50\text{--}100$ Myr as ISM atoms make their way into a star-forming region (Semenov et al., 2017).

In this paper, we examine the dependence of the star formation efficiency per free-fall time, ϵ_{ff} , on local properties (metallicity, UV radiation field, and density of gas and stars) in a suite of high-resolution simulations that recover observed star formation properties of nearby dwarf galaxies (Kruijssen et al., 2019; Semenov et al., 2021). We show that simulations naturally produce values of ϵ_{ff} in the range $\approx 0.01 - 0.1$ close to the values estimated for observed star-forming clouds in regions of very different metallicity, UV flux, and density. We show that turbulence and stellar feedback play a key role in producing universal ϵ_{ff} values as they regulate the virial parameter of star-forming regions to a fairly narrow range. This is consistent with a picture of self-regulation of star formation via rapid dispersal of star-forming gas in a turbulent ISM.

The paper is laid out as follows: in Section 3.2, we describe the simulation used in this analysis; in Section 3.3, we examine the relationship between star formation parameters and local galaxy properties; and in Appendix B.1, we investigate the role of turbulence in regulating star formation. We discuss and summarize our results in sections 3.4 and 3.5, respectively.

3.2 Simulations

We use a suite of simulations of an isolated disk galaxy adopting initial conditions similar to the properties of the NGC 300 galaxy (Semenov et al., 2021). These simulations are run using the ART N-body+hydrodynamics code (Kravtsov, 1999; Kravtsov et al., 2002; Rudd et al.,

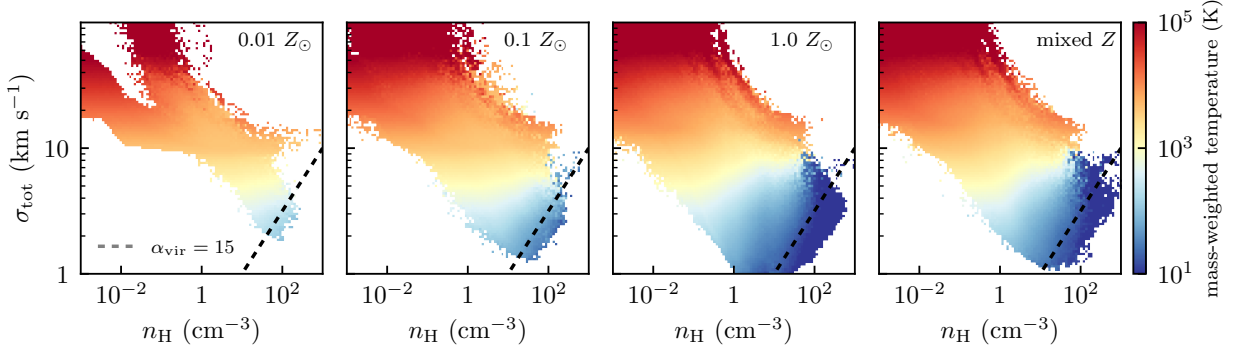


Figure 3.1: The gas mass-weighted $\sigma_{\text{tot}} - n$ phase space for four of our simulation runs. The color indicates gas temperature (see side color bar). The figure shows gas with the highest star formation rate (roughly $\alpha_{\text{vir}} \lesssim 15$) has temperatures (10-30 K) and densities ($10 - 1000 \text{ cm}^{-3}$), which is similar to the typical temperatures and densities of observed star-forming giant molecular clouds when averaged on similar scales. As discussed in Polzin et al. (2024a), the low metallicity runs have a lower star formation rate, not because ϵ_{ff} is intrinsically lower in low Z gas, but because the *amount* of cold, dense gas decreases.

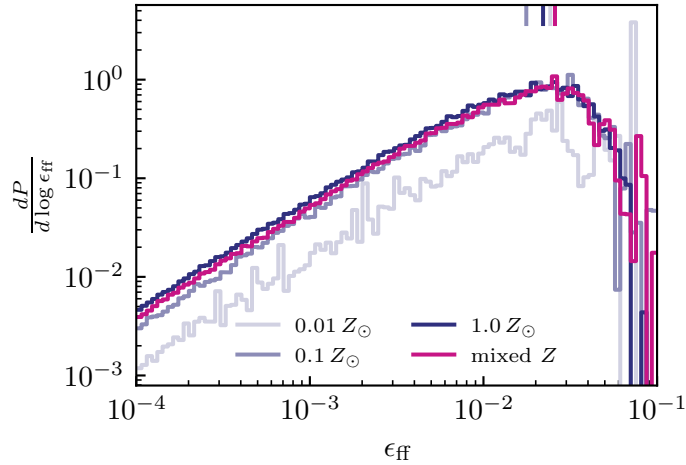


Figure 3.2: The probability density function of star formation-weighted star formation efficiency per free-fall time in four representative simulation runs. Median values are shown as vertical lines near the top of the figure and demonstrate that there is a $\sim$ universal characteristic ϵ_{ff} of a few percent in the simulations. The low ϵ_{ff} tail in $dP/d \log \epsilon_{\text{ff}}$ persists with the same slope even below the range shown here.

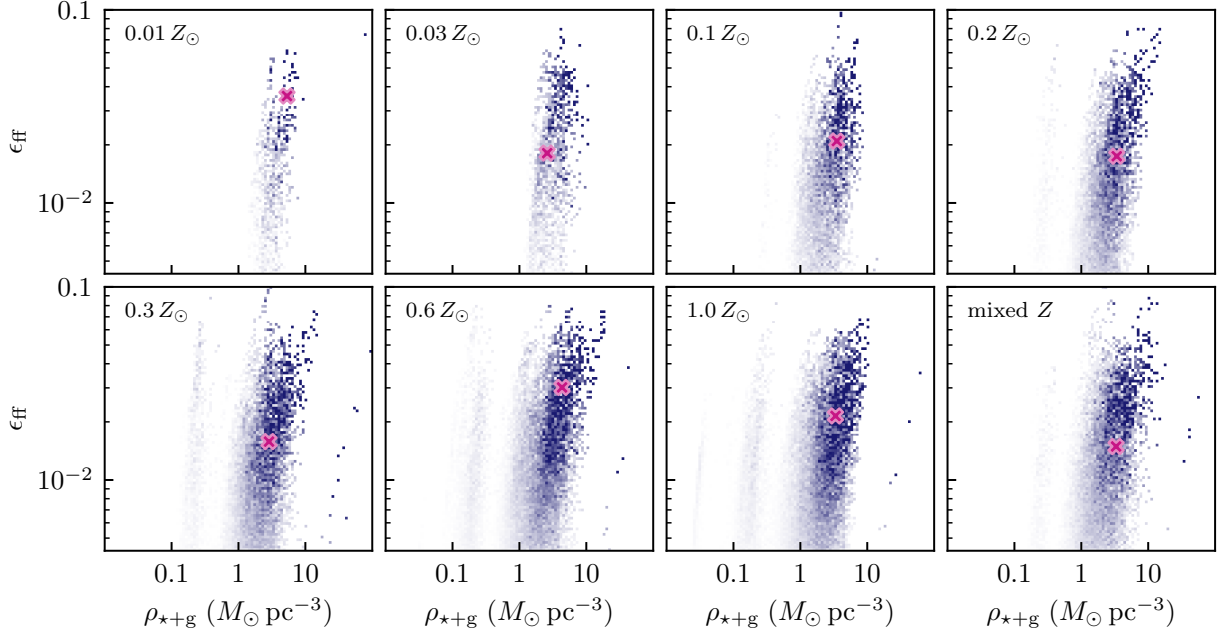


Figure 3.3: The star formation rate-weighted star formation efficiency per free-fall time, ϵ_{ff} , as a function of density of gas and stars in individual simulation cells for each of individual runs. The shading indicates the density of the simulation cells with given values of efficiency and density, linearly scaled between the 5th and 95th percentiles of the distribution for each run. Ridges at different densities are associated with different refinement levels in the simulation. Magenta crosses are placed at the star formation rate-weighted median ϵ_{ff} and $\rho_{\star+\text{g}}$ of the star-forming grid cells.

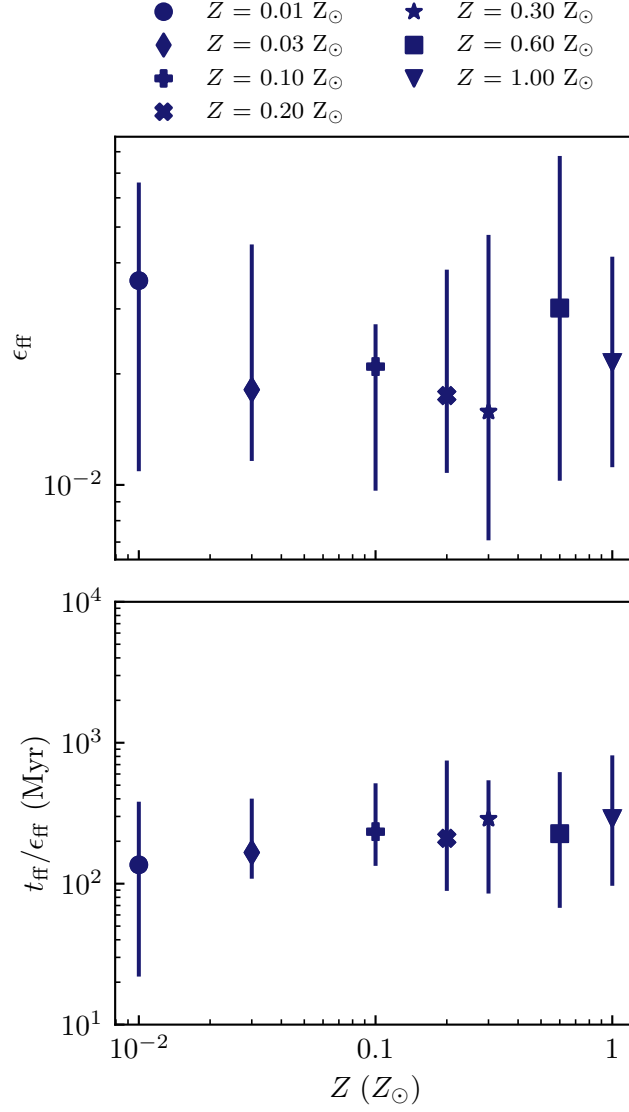


Figure 3.4: The star formation rate-weighted mean ϵ_{ff} (top) and depletion time (bottom) as a function of gas metallicity in the simulation grid cells (i.e. ~ 10 pc scale). Error bars correspond to the 16th and 84th percentiles of the distribution.

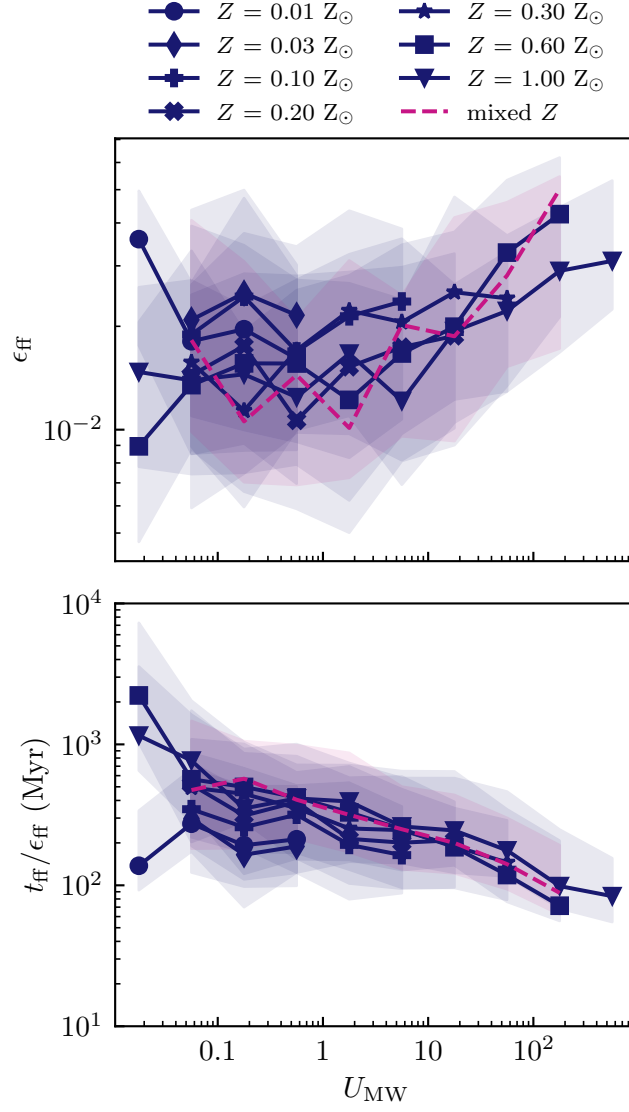


Figure 3.5: The same as Figure 3.4 for the dependence of each run of the simulation on the ionizing radiation field. Shaded regions correspond to the 16th and 84th percentiles of the distribution.

2008; Gnedin & Kravtsov, 2011) and include self-consistent modeling of radiative transfer (RT; Gnedin 2014), non-equilibrium chemistry of hydrogen, helium, and molecular hydrogen, as well as realistic prescriptions for star formation and feedback. The latter is sufficiently realistic to replicate detailed properties of star forming regions in NGC 300 (Semenov et al., 2021), and the resolution ($\Delta x = 10$ pc in the highest refinement level grid cells, where most star formation is occurring) is sufficient to model feedback-regulated density fluctuations in the simulated interstellar medium.

In these simulations, the star particles form stochastically using the rate $\dot{\rho}_\star = \epsilon_{\text{ff}} \rho_g / t_{\text{ff}}$, where ρ_g is gas density, t_{ff} is the free-fall time, and ϵ_{ff} is the star formation efficiency per free-fall time. The latter is assumed to be an exponential function of the local virial parameter α_{vir} (Padoan et al., 2012):

$$\epsilon_{\text{ff}} = \exp(-\sqrt{\alpha_{\text{vir}}/0.53}) \quad (3.1)$$

Here the virial parameter, α_{vir} , is defined following Bertoldi & McKee (1992) such that

$$\alpha_{\text{vir}} = \frac{9.35 (\sigma_{\text{tot}}/10 \text{ km s}^{-1})^2}{(n/100 \text{ cm}^{-3}) \times (\Delta x/40 \text{ pc})^2} \quad (3.2)$$

where the total sub-grid velocity dispersion, $\sigma_{\text{tot}} = \sqrt{\sigma_{\text{t}}^2 + c_{\text{s}}^2}$, includes contributions of both turbulence and the thermal energy of the gas. Note that the virial parameter depends on both the gas temperature through the sound speed and on the turbulent velocity dispersion. This, for example, prevents star formation in the warm gas ($T \gtrsim 10^3$ K). Note also that there is no explicit dependence of ϵ_{ff} on the Mach number because no significant dependence on the Mach number was found in simulations by Padoan et al. (2012) and more recent simulations by Brucy et al. (2024). Figure 3.1 shows the $\sigma_{\text{tot}} - n$ phase space in our simulations. The dashed line shows the constant value of $\alpha_{\text{vir}} = 15$, below which most of the star formation occurs. The figure shows that with the prescription we use in our simulations stars form in cold gas ($T \sim 10 - 30$ K) with densities of $n \sim 10 - 10^3 \text{ cm}^{-3}$ similar to the densities of

observed star-forming molecular clouds averaged on similar scales (tens of parsecs). It also shows that the star-forming gas is different than the gas selected above a constant density and or below a given temperature threshold.

The local value of ϵ_{ff} in simulation cells evolves with the evolution of the interstellar medium, based on its density and the level of turbulence on small scales. The latter is modeled using an explicit subgrid turbulence model (Semenov et al., 2016).

To isolate the dependence of the results on gas metallicity, we ran a series of simulations in which metallicity in all cells is fixed throughout the simulation. Specifically, we ran simulations in which metallicity of all cells was fixed to $0.01Z_{\odot}$, $0.03Z_{\odot}$, $0.1Z_{\odot}$, $0.2Z_{\odot}$, $0.3Z_{\odot}$, $0.6Z_{\odot}$, and $1Z_{\odot}$ at all times during the run (Polzin et al., 2024a). This is in addition to the original run initialized with the metallicity profile matching the observed radial metallicity profile of NGC 300 and with on-the-fly enrichment turned on (Semenov et al., 2021). For comparison, we also re-ran these simulations without the subgrid turbulence model, so that the contribution of turbulence to α_{vir} is ignored.

3.3 Results

3.3.1 *Star formation efficiency as a function of metallicity on ~ 10 pc scale*

The main result of our analyses is that the values of star formation efficiency per free-fall time in the star-forming regions of our simulations are confined to the range $\sim 0.01 - 0.1$ with no or little dependence on the local metallicity and UV flux. Figure 3.2 shows the probability density distribution of ϵ_{ff} values in the simulations of different gas phase metallicity. The distribution of ϵ_{ff} arises from the distribution of α_{vir} values in the simulations. The figure shows that the peak of the PDF and its medians occur in similar ranges at different metallicities.

Although the distribution extends to very low ϵ_{ff} values, the contribution of low- ϵ_{ff} regions

to the total star formation rate is small. Moreover, results of star-forming cloud simulations of Padoan et al. (2012) used to set local ϵ_{ff} in our simulations were calibrated only at $\alpha_{\text{vir}} \lesssim 15$. Thus, in the rest of our analysis we focus on the *star-forming* grid cells contributing the bulk of star formation in regions of $\alpha_{\text{vir}} \leq 15$ or $\epsilon_{\text{ff}} \gtrsim 4 \times 10^{-3}$.

Figure 3.3 shows the distribution of star formation efficiency per free-fall time as a function of the baryon density (defined here as the density of stars and gas) in our simulation in grid cells (with sizes of $\approx 10 - 30$ pc). These 2D histograms are weighted by the local SFR in each cell to show the parameter space that contributes most to the total star formation rate.

The figure shows that the star-formation weighted efficiency per free-fall time has typical values of $\epsilon_{\text{ff}} \sim 0.01 - 0.1$, which is similar to the range estimated in observations (e.g., Krumholz & Tan, 2007; García-Burillo et al., 2012; Evans et al., 2014; Agertz & Kravtsov, 2015), and that the range of efficiencies does not depend on the density.

We note these characteristic efficiency values are not a result of tuning but arise naturally in simulations (see Section 3.4 for discussion). Furthermore, the top panels in Figures 3.4 and Figure 3.5 show that the characteristic ϵ_{ff} range does not depend on gas metallicity and depends only very weakly on free-space¹ UV flux, U_{MW} , normalized by the Milky Way value at 1000 Å (Draine, 1978; Mathis et al., 1983).

Remarkably, while the amount of star-forming gas decreases with decreasing metallicity due to increasingly inefficient cooling (see Polzin et al., 2024a, for a detailed discussion), the range of ϵ_{ff} remains the same for all simulated metallicities. In what follows we show that ϵ_{ff} also has no, or very weak, dependence on the averaging scale and other properties of the local galactic environment.

1. Free-space UV flux is the flux at a given location not attenuated by *local* extinction. Krumholz et al. (2009a), for example, use free-space flux to mean the flux incident on molecular clouds. In our simulations, the radiative transfer calculations do not include absorption by H_2 lines and thus do not model the radiation field self-consistently inside molecular-rich regions and have to rely on the subgrid model. In this case, the free-space flux is the flux returned by the radiative transfer solver and has the physical meaning of the incident field on the molecular gas.

Figures 3.4 and Figure 3.5 also show the averages and characteristic range of the local depletion time of the gas in simulations cells, $t_{\text{ff}}/\epsilon_{\text{ff}}$ as a function gas metallicity and UV flux. Typical depletion time in star-forming cells in the simulation ($\approx 70 - 500$ Myr) is similar to that measured in the individual star-forming regions in the Milky Way (e.g., Heiderman et al., 2010; Lada et al., 2010, 2012; Evans et al., 2014). The figures show that characteristic depletion time does not depend on gas metallicity and exhibits only a weak trend with the UV flux.

We note that the width of the star-formation weighted rate distribution shown in Figures 3.4 and Figure 3.5 is comparable to the ≈ 0.3 dex scatter of ϵ_{ff} estimated by Hu et al. (2022) for observed star-forming clouds. However, previous studies indicated that the evolution of star-forming cloud properties can contribute significantly to the apparent scatter of ϵ_{ff} estimated in observations. For example, Grisdale et al. (2019) show that dramatic changes in the properties of star-forming clouds during their evolution contribute most of the scatter in ϵ_{ff} values estimated for star-forming molecular clouds the way it is done in observations. Notably, they show that the distribution of ϵ_{ff} estimated in observations by Lee et al. (2016) can be matched in a simulation in which intrinsic ϵ_{ff} in star-forming molecular gas is fixed to a constant value.

3.3.2 Star formation efficiency as a function of local environment properties on 500 pc scale

We examine the star formation efficiency per free-fall time (ϵ_{ff}), the free-fall time (t_{ff}), and the depletion time ($t_{\text{ff}}/\epsilon_{\text{ff}}$), averaged in patches of 500 pc size, as a function of metallicity, UV flux, and baryon (stars and gas) surface density. Namely, we compute the weighted medians² of these quantities using the normalized local star formation rate in each cell as

2. We define weighted quantiles by the value corresponding to the percentile of the cumulative distribution of weights ordered by the product of the values and the weights.

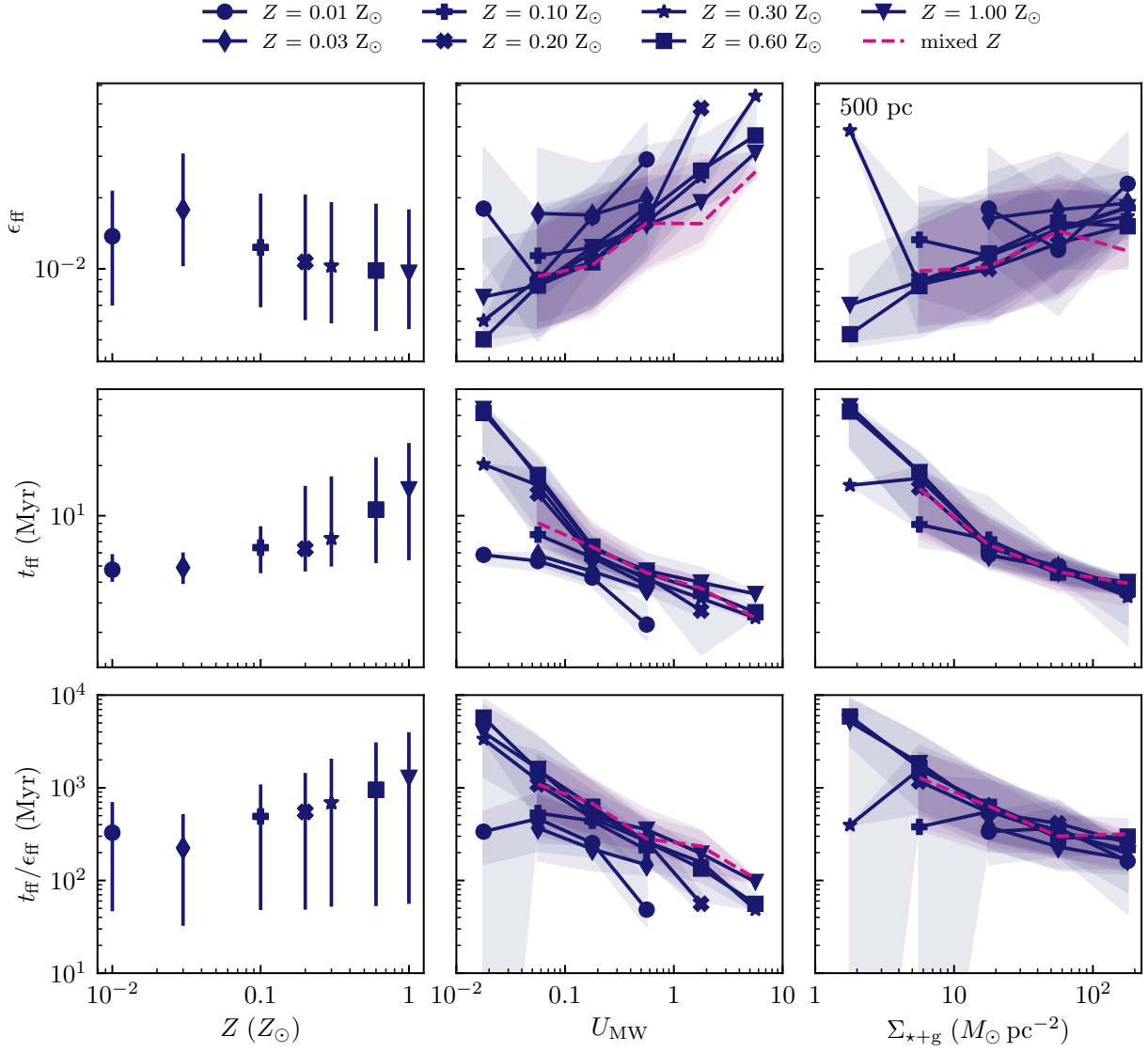


Figure 3.6: *Top*: The star formation rate-weighted median ϵ_{ff} as a function of gas metallicity (left), UV field strength (middle), and surface density of stars and gas (right) smoothed on 500 pc scales for each of our single Z simulation runs and the mixed Z run. *Middle*: The same as the top but for t_{ff} . *Bottom*: The same as the top but for $t_{\text{ff}}/\epsilon_{\text{ff}}$. The error bars and shaded regions correspond to the 16th and 84th percentiles of the distributions. It is notable that ϵ_{ff} , t_{ff} , and $t_{\text{ff}}/\epsilon_{\text{ff}}$ are not dependent on the gas phase metallicity and exhibit only weak trends with UV flux and gas surface density.

a weight. We also only use the cells with $\alpha_{\text{vir}} \leq 15$, which contribute the bulk of the total star formation in each simulated galaxy. Note that we actually compute the SFR-weighted averages of $1/t_{\text{ff}}$ and $\epsilon_{\text{ff}}/t_{\text{ff}}$ because the star formation rate is proportional to these quantities. However, we plot their inverses t_{ff} and $t_{\text{ff}}/\epsilon_{\text{ff}}$ since the free-fall time and the depletion time values are more easily interpretable.

The left column of Figure 3.6 shows the SFR-weighted median ϵ_{ff} , t_{ff} , and $t_{\text{ff}}/\epsilon_{\text{ff}}$ for all star-forming grid cells in 500 pc patches in the runs of different metallicity. Similar to the ϵ_{ff} on ≈ 10 pc scale, the figure shows that the median efficiency per free-fall time on 500 pc scale does not exhibit any trend with gas metallicity and ranges in $\epsilon_{\text{ff}} \approx 0.007 - 0.04$ – the values broadly consistent with efficiencies inferred from observations on similar scales (e.g., McKee & Ostriker, 2007; Schinnerer & Leroy, 2024, and references therein). The free-fall time and depletion time $t_{\text{ff}}/\epsilon_{\text{ff}}$ also do not exhibit strong trends with metallicity.

The middle column of Figure 3.6 shows the dependence of ϵ_{ff} , t_{ff} , and $t_{\text{ff}}/\epsilon_{\text{ff}}$ on the UV flux. The median ϵ_{ff} exhibits a trend with U_{MW} , but the trend is very weak with ϵ_{ff} increasing by a factor of $\sim$ three as UV flux increases by three orders of magnitude. This correlation does not reflect causation, but the fact that regions with higher ϵ_{ff} have higher star formation rate and thus higher FUV flux.

Also, over the entire range, the median values of the efficiency are in the range $\approx 0.005 - 0.05$. Note that this range of values is a bit different than the range of ϵ_{ff} in the $\epsilon_{\text{ff}} - Z$ panel quoted above because averaging in bins of U_{MW} is over somewhat different gas elements than averaging in bins of Z .

There is also a weak anti-correlation of t_{ff} and U_{MW} , which can arise because t_{ff} decreases with increasing density, while U_{MW} increases with increasing gas density due to the increase of star formation rate with density. Finally, there is a weak trend of increasing t_{ff} and $t_{\text{ff}}/\epsilon_{\text{ff}}$ with increasing metallicity at a given U_{MW} .

The right column of panels of Figure 3.6 shows the SFR-weighted medians of ϵ_{ff} , t_{ff} ,

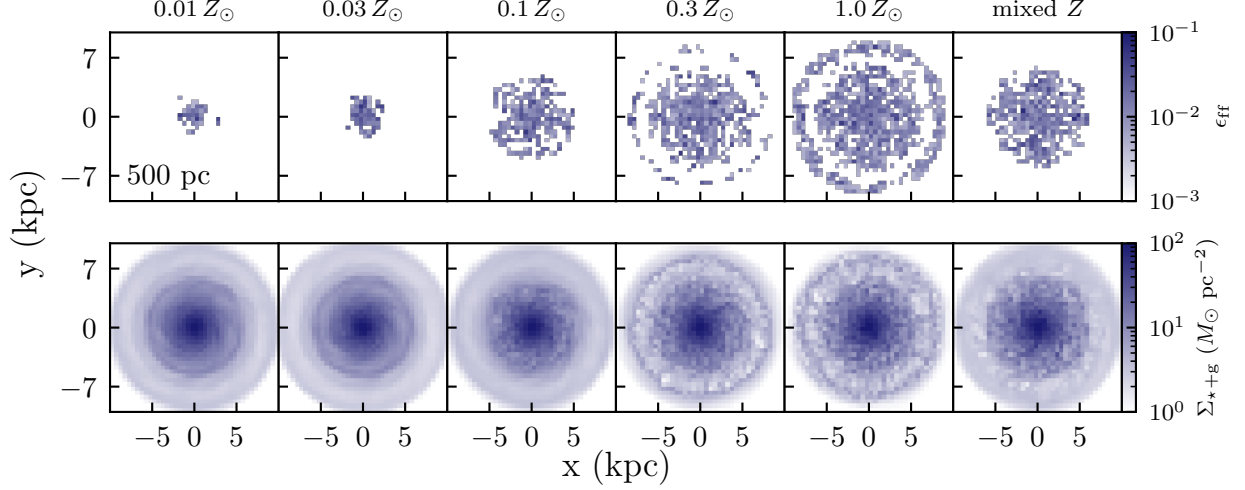


Figure 3.7: Projected face-on maps showing the mean ϵ_{ff} along the line of sight and the baryon surface density, $\Sigma_{\star+\text{g}}$, on 500 pc scales for some of the runs in the simulation suite we use here.

$t_{\text{ff}}/\epsilon_{\text{ff}}$ in the projected patches as a function of the baryon surface density of the patches. The density of gas and stars is directly integrated along the line-of-sight, while the statistics of ϵ_{ff} , t_{ff} , and $t_{\text{ff}}/\epsilon_{\text{ff}}$ are computed using grid cells with $\alpha_{\text{vir}} \leq 15$ and a refinement level with $\Delta x < 500$ pc.

The efficiency ϵ_{ff} shows only a weak trend with surface density. Our results thus indicate that in the simulations with the turbulence-based SFR model with realistic stellar feedback, the natural result is the universality of characteristic ϵ_{ff} values of star-forming gas in environments with a wide range of metallicities, UV fluxes, and densities and over a wide range of averaging scales. This is further illustrated in Figure 3.7, which shows the face-on projected maps of ϵ_{ff} along with the maps of baryon surface density. The figure visually shows that while surface density varies by more than an order of magnitude in the inner regions of the disk, the values of ϵ_{ff} stay in a narrow range around $\epsilon_{\text{ff}} \approx 0.01$.³

3. Note that the trend with surface density shown in Figures 3.6 and 3.7 is different from that derived by Sun et al. (2023) for observed galaxies. This is likely because efficiency and free-fall time are defined differently in that study. Namely, the free-fall time is defined as the median time of molecular gas averaged on 60 pc scale, while Σ_{sfr} in their study is estimated on the 1.5 kpc scale rather than 500 pc in our case. Moreover, we define both ϵ_{ff} and t_{ff} relative to the star-forming gas, which is not the same as molecular gas in our model (see

The median free-fall time of star-forming gas, on the other hand, shows tight, nearly metallicity-independent correlations with the UV flux and baryon surface density. This indicates that star-forming gas is denser in denser regions of the galaxy. This may be because gas in high surface density regions experiences a stronger gravitational pull by the disk compressing it to higher densities. The trend with UV flux may reflect the positive correlation between the UV flux and star formation rate, which, in turn, correlates with gas density. These trends of t_{ff} result in similar trends of the depletion time with U_{MW} and $\Sigma_{\star+\text{g}}$.

3.4 Discussion

As noted above, the characteristic values of ϵ_{ff} in our simulations arise naturally from the specific star-formation prescription based on the simulations of star formation in turbulent molecular clouds (see eq. 3.1 above; Padoan et al., 2012). The efficiency in this simulation-calibrated prescription is an exponential function of $\sqrt{\alpha_{\text{vir}}}$, where α_{vir} is the virial parameter given by eq. 3.2, which measures the relative importance of turbulent and thermal pressure relative to gravitational force.

The characteristic values of $\epsilon_{\text{ff}} \approx 0.01 - 0.1$ measured in the simulations thus correspond to the characteristic values of $\alpha_{\text{vir}} \approx 3 - 10$, which are set by the dynamics of the ISM gas and stellar feedback that affects the thermal and turbulent pressure of the gas.

Large-scale ISM flows lead to compression and expansion of the gas and fluctuations of α_{vir} (e.g., Semenov et al., 2017). As a local compression decreases α_{vir} locally, ϵ_{ff} grows as $\propto \exp(-\sqrt{\alpha_{\text{vir}}})$. This growth is accompanied by the growth of star formation rate and associated stellar feedback, which increases local thermal and, importantly, turbulent pressure.

Semenov et al., 2019, for detailed discussion). If our definition $\epsilon_{\text{ff}} \approx \Sigma_{\text{sfr}}/(\Sigma_{\text{sf}}/t_{\text{ff}})$, where Σ_{sf} is the surface density of star-forming gas, while Sun et al. (2023) define $\epsilon_{\text{ff,mol}} = \Sigma_{\text{sfr}}/(\Sigma_{\text{mol}}/t_{\text{ff,mol}})$, where Σ_{mol} is the surface density of molecular gas. The two definitions are thus related by $\epsilon_{\text{ff}} = (\Sigma_{\text{mol}}/\Sigma_{\text{sf}})(t_{\text{ff}}/t_{\text{ff,mol}})\epsilon_{\text{ff,mol}}$. The relation depends on the trend of $(\Sigma_{\text{mol}}/\Sigma_{\text{sf}})(t_{\text{ff}}/t_{\text{ff,mol}})$ with surface density.

This limits the decrease of α_{vir} and leads to self-regulation of its values to the characteristic range of $\alpha_{\text{vir}} \approx 3 - 10$. Part of the reason behind the narrow range of α_{vir} is the fact that during compression and expansion due to large-scale flows and feedback turbulence often evolves adiabatically, $\sigma \propto n^{1/3}$, and the virial parameter changes only mildly during such evolution, $\alpha_{\text{vir}} \propto \sigma^2/n \propto n^{-1/3}$. The characteristic values of $\epsilon_{\text{ff}} \approx 0.01 - 0.1$ in our simulations are thus the result of the star formation prescription and the stellar feedback model adopted in our simulations.

This also allows us to interpret the universality of ϵ_{ff} in environments of different metallicity, UV flux, and densities demonstrated above. The pressure and α_{vir} in star-forming regions in these simulations are dominated by turbulence. The turbulent energy is driven by gas compression by large-scale flows and the dissipation on the turbulent crossing time scale. Both processes do not depend on the metallicity, UV flux, or density. In contrast, the gas cooling and heating, and therefore thermal pressure, do depend on these properties and thus, when α_{vir} is dominated by the thermal pressure, the efficiency per free-fall time varies more strongly with the properties of the environment. This is illustrated explicitly in Appendix B.1, where we show ϵ_{ff} as a function of metallicity, UV flux, and surface density in simulations in which subgrid turbulence is not modeled and its contribution to α_{vir} is ignored. The turbulence thus plays an important role in making ϵ_{ff} value range universal.

The values of ϵ_{ff} and their universality exhibited in our simulations are consistent with the typical values of $\approx 0.01 - 0.1$ estimated for observed gas in diverse environments and averaging scales (e.g., García-Burillo et al., 2012; Utomo et al., 2018; Sun et al., 2023). As noted in the previous section, the definitions of star formation efficiency and scales on which it is measured vary among studies. The comparison here is therefore ballpark by necessity and the trends with scale or surface density for different ϵ_{ff} definitions may differ.

Estimates of ϵ_{ff} from the star-forming sub-pc cores to giant molecular clouds on tens of pc scales are $\approx 0.01 - 0.1$ (e.g., Krumholz & Tan, 2007; Evans et al., 2014; Pokhrel et al.,

2021; Hu et al., 2022). Similar values of ϵ_{ff} are estimated on the scales of hundreds of pc in other galaxies with a diverse range of metallicities and surface densities (e.g., Leroy et al., 2008; Utomo et al., 2018; Teng et al., 2024). Our results indicate that these characteristic values of ϵ_{ff} and their universality can be plausibly explained by the turbulence-driven and feedback-regulated properties of star-forming regions.

We note, however, that comparing detailed distributions of ϵ_{ff} estimated in observations and simulations is not straightforward. In simulations, instantaneous values of ϵ_{ff} are considered, while in observations, these values are estimated using instantaneous gas properties and star formation rate indicators that are sensitive to star formation over a certain time scale. The gas density is expected to evolve strongly as the star formation and feedback proceed in a given region (Feldmann & Gnedin, 2011). The large apparent scatter of observational estimates of ϵ_{ff} thus largely reflects diverse evolutionary stages of the regions in which these estimates are made (e.g., Feldmann & Gnedin, 2011; Lee et al., 2016; Grisdale et al., 2019). Nevertheless, the simulations shed light on why the characteristic average values of ϵ_{ff} do not vary with environment properties.

Finally, we note that recently Semenov et al. (2024) and Segovia Otero et al. (2024) presented results of cosmological galaxy formation simulations of Milky Way-sized galaxies with the same prescription for ϵ_{ff} given by equations 1 and 2 above. In both studies, the authors found that the average ϵ_{ff} of the simulated galaxies was $\sim 1\%$, although rapidly changing conditions during early stages of evolution result in significant efficiency fluctuations around this characteristic value. In particular, Semenov et al. (2024) showed that fluctuations of ϵ_{ff} are the dominant source of burstiness of star formation during the early stages of galaxy evolution.

3.5 Summary and conclusions

In this study, we analyze high-resolution simulations of gas dynamics and star formation in an isolated disk dwarf galaxy with an explicit model for unresolved turbulence and turbulence-based star formation prescription calibrated on MHD simulations of turbulent molecular clouds. As demonstrated by Semenov et al. (2021), the star formation and feedback model used in the simulations reproduces star formation and gas correlations in observed galaxy NGC 300 in fine detail. We use a suite of simulations at different metallicities to examine the characteristic values of the star formation efficiency per free-fall time, ϵ_{ff} , and its variations with local environment properties, such as metallicity, UV flux, and surface density. Our results and conclusions can be summarized as follows.

1. We show that the star formation efficiency per free-fall time in ≈ 10 pc star-forming regions of the simulated disks has characteristic values in the range $\epsilon_{\text{ff}} \approx 0.01 - 0.1$ (Figures 3.2 and 3.3). We show that the characteristic values of ϵ_{ff} do not vary with metallicity and exhibit only a very weak trend with UV flux (Figures 3.4 and 3.5).
2. Likewise, we show that ϵ_{ff} estimated on a 500 pc scale does not vary with metallicity and shows only weak trends with average UV flux and gas surface density estimated at this scale (Figures 3.6 and 3.7).
3. The characteristic values of $\epsilon_{\text{ff}} \approx 0.01 - 0.1$ arise naturally in the simulations as a result of the gas dynamics leading to gas compression and ensuing stellar feedback that injects thermal and turbulent energy into the gas. The compression and feedback regulate the virial parameter, α_{vir} , in star-forming regions, limiting it to the range $\alpha_{\text{vir}} \approx 3 - 10$ (see discussion in Section 3.4). Turbulence plays an important role in the universality of ϵ_{ff} because turbulent energy driven by gas dynamics and feedback and its dissipation are not sensitive to the standard metallicity and UV flux cooling and heating processes that affect thermal energy.

4. We show explicitly that ϵ_{ff} values do depend on the metallicity and UV flux in simulations where turbulent pressure contribution to the virial parameter is ignored (Figure B.1).

The efficiency per free-fall time and its universality are similar to the values of observed star-forming regions in different environments and galaxies. This indicates that the universality of observational estimates of ϵ_{ff} can be plausibly explained by the turbulence-driven and feedback-regulated properties of star-forming regions. In the future, it will be important to forward model observational measurements using simulations taking into account evolutionary effects on the estimates of ϵ_{ff} .

CHAPTER 4

A RECENTLY QUENCHED ISOLATED DWARF GALAXY OUTSIDE OF THE LOCAL GROUP ENVIRONMENT

Polzin et al. (2021) presented as part of a thesis to the Department of Astronomy and Astrophysics, The University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

*A. Polzin, P. van Dokkum, S. Danieli, J. P. Greco, and A. J. Romanowsky, “A recently quenched isolated dwarf galaxy outside of the Local Group environment”, *ApJL*, vol. 914, no. 1, p. L23, Jun. 2021, DOI: 10.3847/2041-8213/ac024f. © AAS. Reproduced with permission*

4.1 Introduction

Dwarf galaxies in the Local Group play a pivotal role in many areas of astrophysics, including star formation, galaxy formation, and cosmology (see, e.g., Mateo 1998; Simon 2019). Given their outsized importance and impact there is great interest in finding dwarf galaxies at larger distances, as they provide information on the environmental dependence of low mass galaxy formation and can be used to determine how typical Local Group galaxies are for the general population (Weisz et al., 2011a).

Most general galaxy catalogs are biased against the lowest mass dwarfs due to incompleteness (e.g., Tollerud et al. 2008; Walsh et al. 2009), which is caused by their low surface brightness (see Danieli et al., 2018). To overcome this barrier, various telescopes and surveys have been designed to be sensitive to low surface brightness emission, making use of specialized algorithms and instruments to detect/characterize low luminosity galaxies (e.g., Greco et al., 2018; van Dokkum et al., 2020). As a result, wide field surveys are now providing comprehensive catalogs of low luminosity galaxies.

Past studies of star formation in dwarf galaxies have been subject to these same limitations. For instance, while Geha et al. (2012) were able to study complete samples of galaxies with $M_* \gtrsim 10^8 M_\odot$ with SDSS spectroscopy, they probe only a very small volume at lower masses. Galaxies with masses $M_* \lesssim 10^7 M_\odot$ have not yet been exhaustively analyzed.

The interpretation of detected low surface brightness objects generally requires ancillary data, such as spectroscopy or high resolution imaging (see, e.g., Greco et al. 2021). Archival data offers a shortcut: if dwarf galaxies are sought and found in fields that already have a suite of ancillary data, the task of determining distances, structural parameters, and stellar population parameters is far more efficient. Here we present the serendipitous discovery of an isolated and seemingly quenched dwarf galaxy in the well-studied COSMOS-CANDELS field.

4.2 A faint, extended object in the COSMOS field

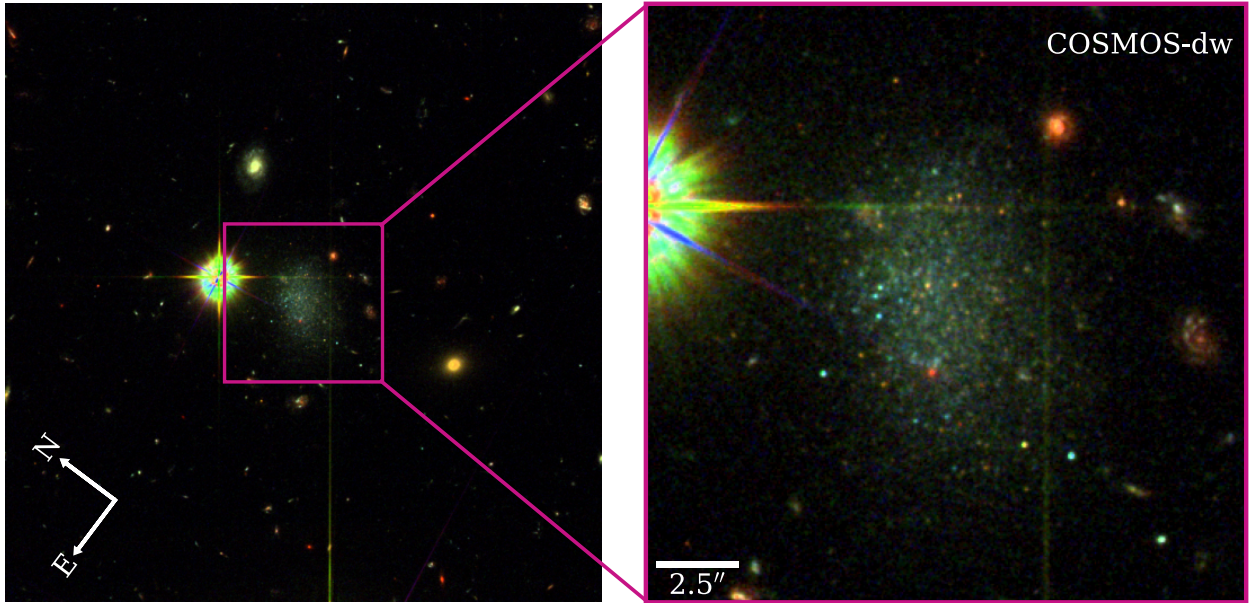


Figure 4.1: Both panels show color composite image of COSMOS-dw1 using F475W, F606W, and F814W. The left panel is $68'' \times 68''$; the right panel is $18'' \times 18''$.

4.2.1 *HST* observations

The COSMOS-CANDELS (Koekemoer et al., 2011; Grogin et al., 2011) field covers ~ 200 square arcmin and is one of the most observed regions in the sky, with data taken in all major wavelength regimes from X-ray to radio.

COSMOS-dw1 ($\alpha = 10^h00^m30.03^s$, $\delta = +02^\circ08'59.47''$) was identified in archival *Hubble Space Telescope* (*HST*) data of the COSMOS field as an object with a semi-resolved appearance, suggesting that it is nearby. The galaxy had been previously overlooked, probably because it is split in multiple very faint objects in standard catalogs (Lilly et al., 2007; Alam et al., 2015).

We obtained the CTE-corrected individual `flc` files in the ACS/WFC F475W, F606W, and F814W bands from the *HST* Archive. We use `DrizzlePac` (STSCI Development Team, 2012) to align the images in each filter via `TweakReg` and then combine them via `AstroDrizzle`.¹ Total exposure times are 2028 s in F475W, 3328 s in F606W, and 6864 s in F814W.

An RGB image combining the *HST* data is shown in Figure 4.1. Several notable features are apparent. COSMOS-dw1 is a low surface brightness, semi-resolved object. Its appearance is somewhat asymmetric, as it has a clump of blue stars off-center to the North. The rest of the galaxy appears to be dominated by red, likely post-main sequence, stars that are distributed more evenly.

4.2.2 *GALFIT*

We begin by measuring the global structural parameters of the galaxy, such as its apparent size, brightness, and color, using `GALFIT` (Peng et al. 2010). We first ran `GALFIT` on the combined F814W+F606W image, after smoothing it with a Gaussian kernel with $\sigma = 2$ pix ($0''.1$). The galaxy was modeled with a single Sérsic fit and the image was aggressively

1. We did not use existing data products from CANDELS or 3D-HST for consistency with our analysis of individual `flc` files in § 4.

masked, using a **SEP** (Bertin & Arnouts 1996; Barbary 2016) segmentation map and manually masking additional potential contaminants. The resulting Sérsic index is $n = 0.69$, and the effective radius is $4''.20$. Next, **GALFIT** was run in each band separately, holding the r_{eff} , Sérsic index, position angle, ellipticity, and x, y position fixed and letting only the brightness vary in the fit. The resultant parameters of our **GALFIT** runs are listed in Table 4.1. Errors are determined in the following way. Eleven copies of the best-fitting **GALFIT** model were injected into uncrowded areas in our images and then fitted in the same way as the actual data. The rms variation in the resulting parameters was taken as the uncertainty for each parameter. This method captures errors that are introduced by improper masking of background sources and noise. However, it assumes that the galaxy is smooth and has a perfect Sérsic profile, and it does not take deviations from those assumptions into account.

4.3 Velocity and Distance

4.3.1 Keck Spectroscopy

We observed COSMOS-dw1 with the Low Resolution Imaging Spectrograph (LRIS, Oke et al. 1995) on Keck I on 2018 November 5. The $1''.5$ long slit was used, with the 300 l mm^{-1} grism blazed at $5000 \text{ \AA}$. The total exposure time was 4600 s in excellent conditions. The data reduction followed standard procedures for long slit data. The spectrum is shown in Fig. 4.2. The most prominent features are strong Balmer absorption lines, indicating a dominant population of A stars and an age of $\sim 1 \text{ Gyr}$. There are no clearly detected emission lines.

We use a χ^2 minimization scheme over the spectral range $3875 - 5200 \text{ \AA}$ to determine the radial velocity, with **Flexible Stellar Population Synthesis** (FSPS; Conroy et al. 2009) template spectra smoothed to the instrumental resolution. We measure a heliocentric radial velocity of $1222 \pm 64 \text{ km s}^{-1}$; the uncertainty in this result includes fits for a range of ages ($0.5\text{--}8 \text{ Gyr}$) and metallicities ($-2 \leq [\text{Fe}/\text{H}] \leq -1$).

Table 4.1: COSMOS-dw1 – Observed properties

Parameter	Value
m_{F475W}	19.43 ± 0.07
m_{F606W}	19.31 ± 0.04
m_{F814W}	19.17 ± 0.03
$\text{F475W} - \text{F814W}$	0.26 ± 0.08
$\text{F606W} - \text{F814W}$	0.14 ± 0.05
$\mu_{0,g}$ (mag arcsec $^{-2}$)	23.03 ± 0.08
$\mu_{0,V}$ (mag arcsec $^{-2}$)	22.90 ± 0.06
$\mu_{0,I}$ (mag arcsec $^{-2}$)	22.77 ± 0.05
$\mu_{\text{eff},g}$ (mag arcsec $^{-2}$)	24.19 ± 0.08
$\mu_{\text{eff},V}$ (mag arcsec $^{-2}$)	24.07 ± 0.06
$\mu_{\text{eff},I}$ (mag arcsec $^{-2}$)	23.93 ± 0.05
Sérsic index	0.69 ± 0.01
b/a	0.721 ± 0.008
PA (deg)	-30.2 ± 0.6
r_{eff} (arcsec)	4.20 ± 0.07
R_{eff} (kpc)	0.45 ± 0.06
v_{rad} (km s $^{-1}$)	1222 ± 64
D_{SBF} (Mpc)	22 ± 3

Intrinsic parameters are calculated assuming a distance of 22 Mpc. All magnitudes are quoted in the AB system.

This velocity is consistent with COSMOS-dw1 being at a distance of $20.0^{+0.8}_{-0.7}$ Mpc via the `Cosmicflows-3` (Kourkchi et al. 2020; $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$) calculator. However, this uncertainty ignores the peculiar velocity of COSMOS-dw1; a peculiar velocity of 300 km s^{-1} would correspond to a distance uncertainty of 5 Mpc.

4.3.2 Surface brightness fluctuations

A distance can also be obtained from the *HST* imaging. The galaxy is only semi-resolved, and we cannot obtain a distance from the tip of the red giant branch (see Section 4.4.3). Instead we use surface brightness fluctuations (SBFs, e.g., Tonry & Schneider 1988; Greco et al. 2021) to constrain the distance to COSMOS-dw1. The SBF method relies on the decreasing pixel-to-pixel brightness variance of a stellar population with increasing distance.

Because this method is sensitive to the nature of the stellar population, we use the integrated galaxy colors shown in Table 4.1 and the $\bar{M}_{814}$ vs. $g_{475} - I_{814}$ relation from Carlsten et al. (2019). We find $\bar{M}_{814} = -2.8 \pm 0.3$ using the luminosity-weighted average $g_{475} - I_{814}$ color of the galaxy (see Table 4.1).

We then generate a variance map from our raw F814W image and the model returned from `GALFIT` ($[\text{image} - \text{model}]/\sqrt{\text{model}}$), which we mask, using the aggressive mask we applied to our `GALFIT` runs plus an elliptical aperture to make sure any measured surface brightness fluctuations are actually coming from the galaxy. In order to avoid biasing our results with selection of aperture size (or the range of assessed wave numbers), we run our SBF analysis repeatedly, randomly selecting our wave number range and ellipse dimensions from reasonable uniform distributions, storing the apparent SBF magnitude from each run.

As shown in § 4.3 the galaxy has a region that is dominated by blue stars. We therefore separately analyze the blue region and red region (in addition to the full galaxy). As is evident from the power spectra (see Figure 4.2), the full galaxy measurement is strongly affected by the bright, resolved blue stars. As SBF is a more robust method within the

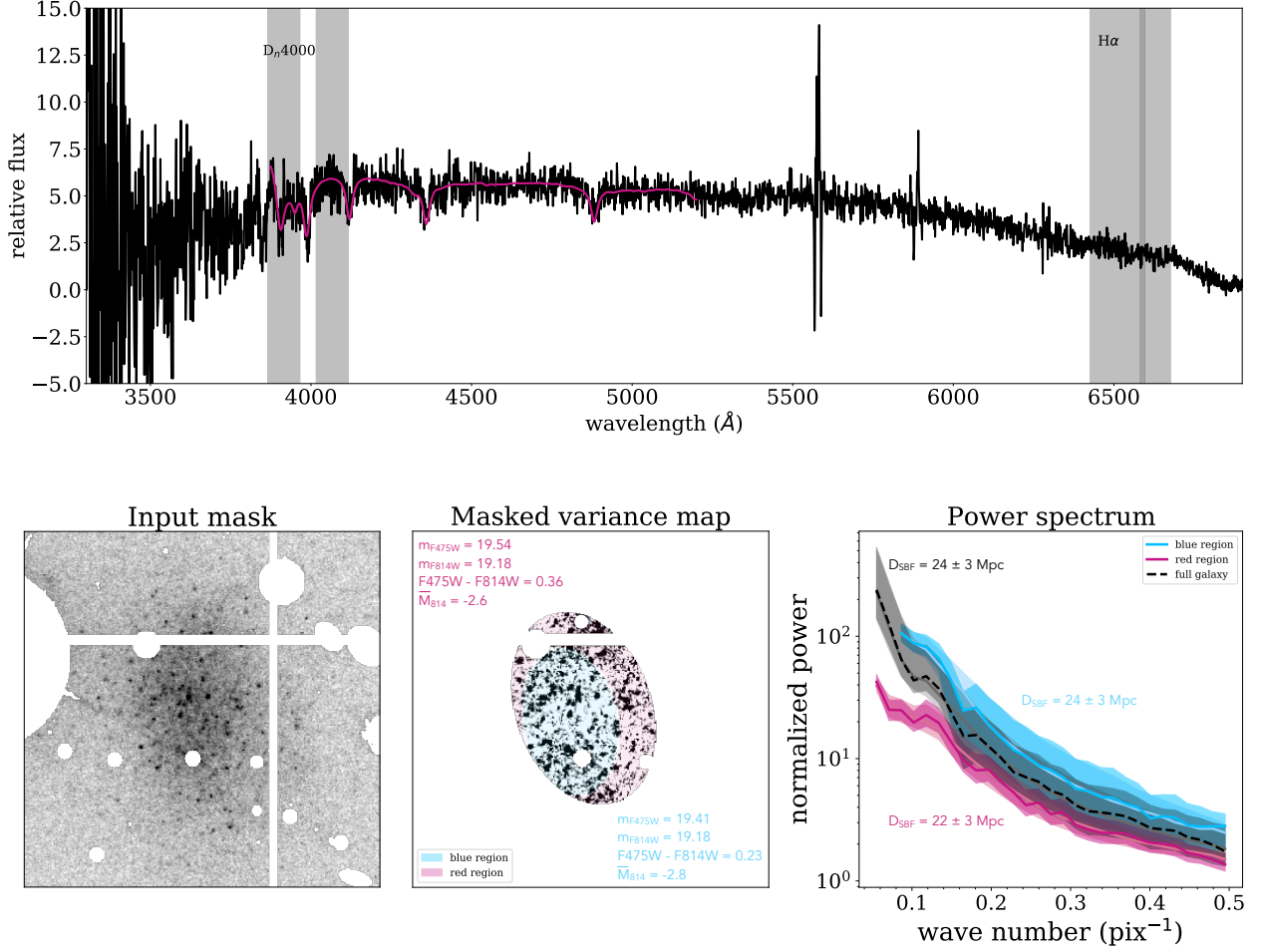


Figure 4.2: Top panel: The median model spectrum (a linear combination of weighted template spectra) $\pm 1\sigma$ output by `emcee` (Foreman-Mackey et al., 2013) is shown in pink, plotted over a subset of our LRIS data on the interval 3875 – 5200 Å. In black, we show the flux-calibrated spectrum (the instrument response curve was from a different night). Gray regions mark the continuum around the 4000 Å line break – used to calculate D_n4000 – and the $H\alpha$ line – used to determine the rms error on the equivalent width. Bottom panel: At left, we show the masked combined F814W image used for the full galaxy SBF analysis (also used when running `GALFIT`). The middle panel shows the variance map of the full galaxy (as well as the red and blue regions that were analyzed). The median of the fits to the power spectra are shown at the right, with the shaded area representing the 68th percentile of the distribution, plotted under the median measured power spectra and the 68th percentile of their distributions.

redder regime, we adopt the measurement from our red region, finding that the galaxy is located at 22 ± 3 Mpc ($\bar{M}_{814} = -2.6 \pm 0.3$ and $\bar{m}_{814} = 29.15 \pm 0.08$), consistent with the redshift distance, which suggests this galaxy has a small peculiar velocity. The results from

the full galaxy/blue region fall within these error bars (24 ± 3 Mpc), and the measurements for each subset of the galaxy are also consistent with the SBF distance using an extrapolation of the Blakeslee et al. (2010) relation.

We determine distance-dependent quantities with D_{SBF} (see Table 4.1). We find that the galaxy has a luminosity of $L_{\text{F606W}} = (7 \pm 2) \times 10^6 L_{\odot}$ and a physical size of $R_{\text{eff}} = 450 \pm 60$ pc.

4.4 Stellar population

4.4.1 Constraints from the integrated colors

We first use the *HST*-measured colors to constrain the stellar population properties. To break the age–metallicity degeneracy we assume that COSMOS-dw1 falls on the mass–metallicity relation. Running a grid of ages and metallicities through FSPS, COSMOS-dw1’s integrated F606W–F814W and F475W–F814W colors and absolute F606W magnitude imply a stellar population of age 0.9 Gyr, $[\text{Fe}/\text{H}] = -1.6$, and $M_* = 2.4 \times 10^6 M_{\odot}$. This age is qualitatively consistent with the prominent Balmer lines in the spectrum.

To illustrate that this SSP provides a reasonable description of the galaxy we use the **ArtPop** code (Greco & Danieli 2022; first described in Danieli et al. 2018), which creates full 2D models of galaxies by drawing stars from isochrones. We then inject the simulated galaxy into our drizzled *HST* images on a filter-by-filter basis (see the rightmost panel of Figure 4.3). The overall appearance is a good match, although the morphological structure of the model is clearly more regular than that of the data. Furthermore, there are blue stars that are not accounted for in the **ArtPop** model; we will return to those below.

4.4.2 Constraints from spectral indices

We measure $\text{EW}(\text{H}\alpha)$ and the strength of the 4000 Å line break (Balogh et al., 1999). We find an equivalent width consistent with no $\text{H}\alpha$ emission (-0.4 ± 0.5 Å) and $\text{D}_{\text{n}4000} \text{ index} =$

1.22 ± 0.02 , which is *just* inconsistent with a quenched galaxy per the relation and criterion from Geha et al. (2012). The $H\alpha$ equivalent width corresponds to a 3σ specific star formation rate (sSFR) upper limit of $1.5 \times 10^{-12} \text{ yr}^{-1}$ (Belfiore et al., 2018). We infer that the galaxy is young but is not forming stars at present.

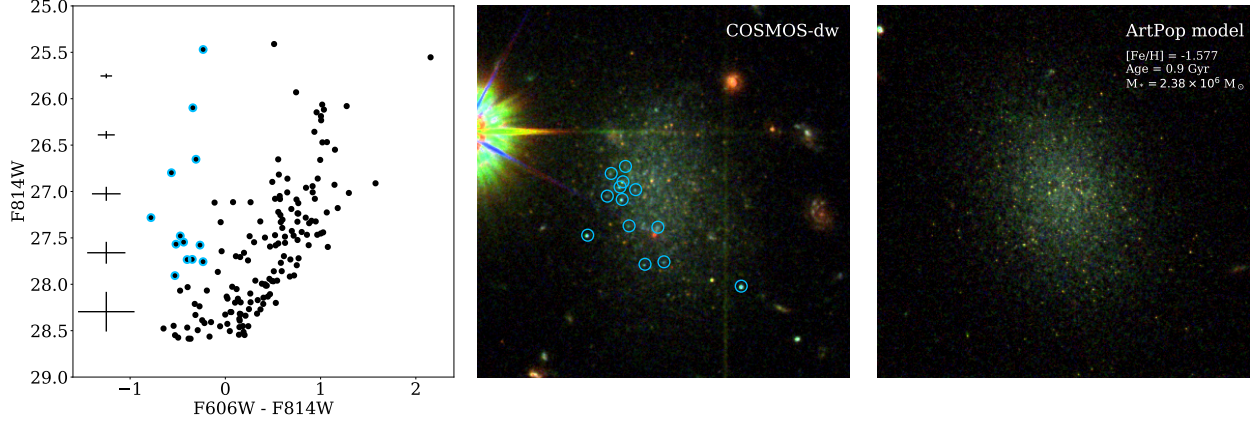


Figure 4.3: Left panel: COSMOS-dw1’s CMD is shown using stellar photometry from DOLPHOT. Average error bars for each m_{F814W} bin are shown at the far left. The points marked by a blue circle correspond to the brightest, bluest stars with $F606W - F814W \leq -0.2$ and $m_{F814W} \leq -28$. These same stars are marked in RGB image of COSMOS-dw1 in the middle panel. Right panel: An ArtPop model of a simple stellar population placed at 22 Mpc that has the same integrated properties as COSMOS-dw1 (see Table 4.1).

4.4.3 Evidence for a complex stellar population

We use the ACS module from DOLPHOT, an adapted version of HSTphot (Dolphin, 2000), to obtain photometry of individual stars in COSMOS-dw1. We follow the module’s pre-processing steps, including bad pixel rejection, sky estimation, and fine alignment of the input images. Using our drizzled F814W image as the reference, we run DOLPHOT twice, once for all F814W and F606W f1c files and once for F814W and F475W. For the photometry’s PSF fitting, we use TinyTim PSFs (Krist et al., 2011).

Our parameter files closely follow the recommendations from the DOLPHOT handbook, but we adopt the Dalcanton et al. (2009) values for the sky-fitting parameter ($FitSky = 3$),

aperture radius ($RAper = 10$ pix), and flag that forces all detected sources to be treated like stars for the purpose of fitting ($Force1 = 1$).

We make quality cuts on the detected/photometered sources in the DOLPHOT output to make sure we only include sources with high quality stellar photometry. Following Danieli et al. (2017), we include “good stars” ($object\ type = 1$) with high quality photometry ($photometry\ quality\ flag \leq 2$), high signal-to-noise ($signal\ to\ noise \geq 4$), and object sharpness within a star-like range ($-0.3 \leq sharpness_{F606W+F814W} \leq 0.75$). Spatially, we include all stars that reasonably belong to COSMOS-dw1. The resultant color–magnitude diagram (CMD) is shown in the leftmost panel of Figure 4.3.

As is notable in the color composite images of COSMOS-dw1, the CMD shows a population of bright, very blue stars. These stars ($F606W - F814W \leq -0.2$ and $m_{F814W} \leq -28$) are marked in both the CMD and the RGB image in Figure 4.3. Their location provides an upper limit to their age: the dynamical time at their distance from the center is only $\approx 10^8$ yr, and the stars would have dispersed throughout the galaxy if they formed earlier than that.

4.5 Environment

Dwarf galaxies are thought to be quenched predominantly by environmental effects, such as ram pressure stripping and tidal stripping (e.g., Boselli & Gavazzi 2006; Weisz et al. 2011b; Fillingham et al. 2018), so it is expected that seemingly quiescent galaxies with little-to-no evidence of $H\alpha$ emission are within one to two virial radii of a bright companion. Intriguingly, COSMOS-dw1 does not have an obvious luminous companion.

We search within 5° (~ 2 Mpc projected at 22 Mpc) and 300 km s^{-1} of COSMOS-dw1 in order to assess its immediate environment. There are 19 nearby galaxies within this projected distance in the radial velocity range $922\text{--}1522\text{ km s}^{-1}$. Assuming each of these nearby galaxies is also located at a distance of 22 Mpc and using an r -band mass-to-light

ratio of $\Upsilon_r = 3.05 M_\odot L_\odot^{-1}$ (Bell et al., 2003), we find that two of the 19 galaxies exceed the minimum mass to potentially be considered a “luminous neighbor” ($M_* > 2.5 \times 10^{10} M_\odot$) as in Geha et al. (2012). The closest of these, NGC 3166, is 1.4 Mpc away in projection, just inside the 1.5 Mpc limit used by Geha et al.².

We further explore an association with this galaxy, or other nearby galaxies, by estimating the virial radii of potential neighbors using the stellar mass– r_{80} and r_{80} –virial radius relations defined in Mowla et al. (2019), which take $\Delta_c = 200$. The results are shown in Figure 4.4. NGC 3044, the closest non-dwarf galaxy to COSMOS-dw1 with a calculated stellar mass below our luminous neighbor threshold ($M_* \sim 1.2 \times 10^{10} M_\odot$) and $v_{\text{rad}} - v_{\text{rad,dw}} = 66 \text{ km s}^{-1}$, is located $4.1 R_{\text{vir}}$ from our isolated dwarf in projection. NGC 3166, the closest luminous neighbor ($M_* \sim 6.1 \times 10^{10} M_\odot$, $\Delta v_{\text{rad}} = 106 \text{ km s}^{-1}$), is $3.9 R_{\text{vir}}$ away. It is worth noting that these values are strict lower limits, as we assume that the projected distances equal the physical distances.

There are also three dwarf galaxies near COSMOS-dw1: LEDA 1230703 ($M_* = 1.2 \times 10^8 M_\odot$, $\Delta v_{\text{rad}} = -109 \text{ km s}^{-1}$), 0.41 Mpc ($5.3 R_{\text{vir}}$) from COSMOS-dw1; 2dFGRS TGN353Z197 ($M_* = 8.3 \times 10^7 M_\odot$, $\Delta v_{\text{rad}} = 124 \text{ km s}^{-1}$) at a distance of 0.48 Mpc ($6.7 R_{\text{vir}}$); and SDSS J100517.67+013831.2 ($M_* = 8.3 \times 10^7 M_\odot$, $\Delta v_{\text{rad}} = 43 \text{ km s}^{-1}$), 0.50 Mpc ($6.9 R_{\text{vir}}$) from COSMOS-dw1.

We note that the nearest galaxies’ Δv_{rad} distribution is consistent with the distribution of the full sample returned in our search.

2. We note that the intriguing early-type galaxy Ark 227 (Arakelian, 1975) is at a projected distance of only 4 arcmin from COSMOS-dw1. However, its redshift ($cz = 1793 \text{ km s}^{-1}$; Falco et al. 1999) is 571 km s^{-1} removed from that of COSMOS-dw1, corresponding to a distance of approximately 30 Mpc and effectively ruling out an association.

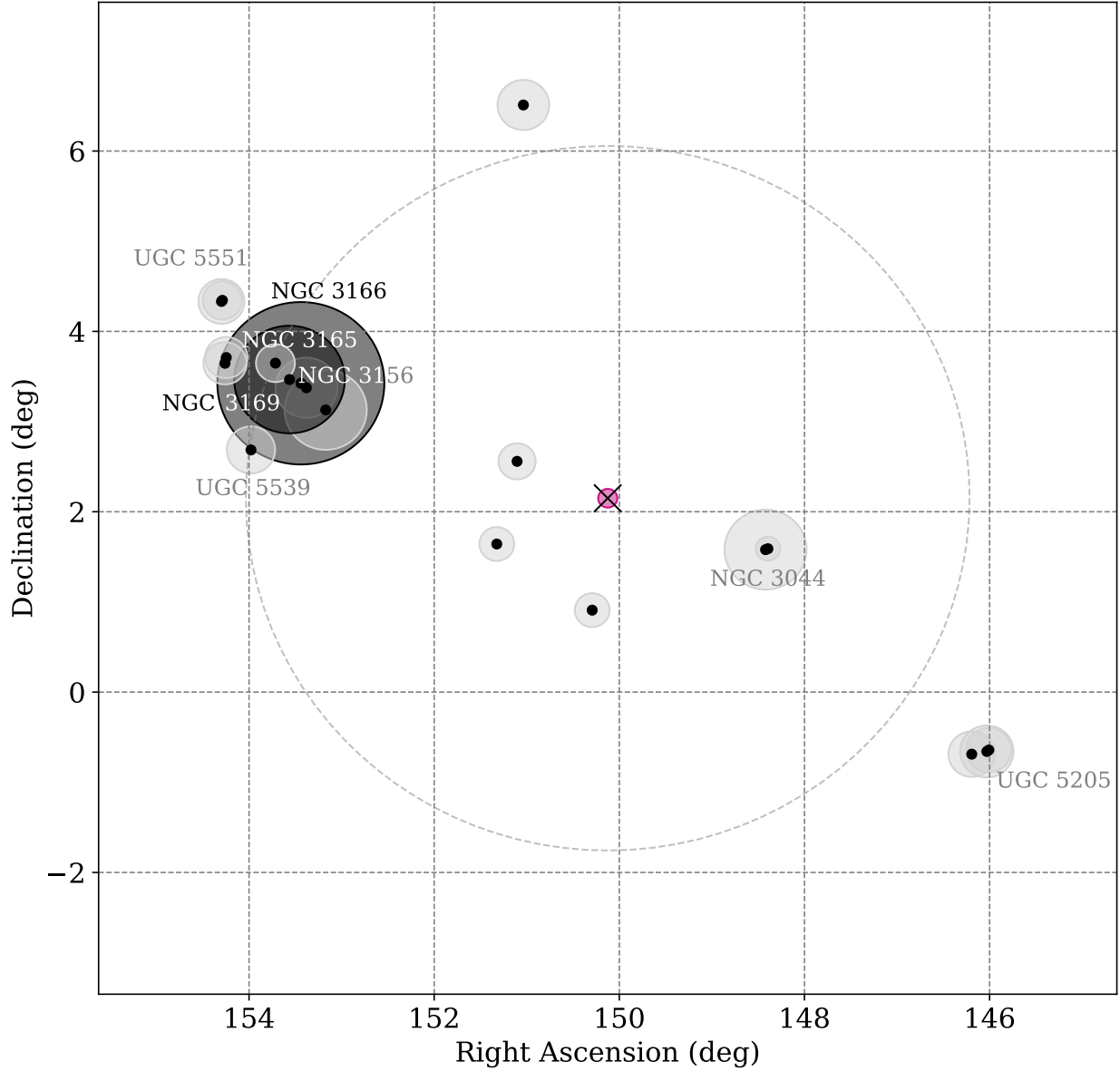


Figure 4.4: We assess the environment of COSMOS-dw1 by estimating the virial radii of nearby galaxies, assuming that they are all at the same distance as the dwarf. We show the 1.5 Mpc projected radius as the dashed gray circle, while all galaxies within 5° and 300 km s^{-1} of COSMOS-dw1 are shown as black points with their virial radii underplotted; galaxies with $M_* > 2.5 \times 10^{10} M_\odot$ are marked by darker underplotted virial radii. NGC and UGC objects are labeled. Each square of the grid is $0.77 \times 0.77 \text{ Mpc}^2$ at a projected distance of 22 Mpc. We find that COSMOS-dw1 is at least $\gtrsim 4$ virial radii away from any other galaxy.

4.6 Discussion and Conclusion

We report the serendipitous discovery of an isolated quenched low mass galaxy at a distance of ~ 22 Mpc. All other known and well-studied galaxies in this region of parameter space are in the immediate vicinity of the Local Group. The four isolated Local Group dwarfs are Cetus (Whiting et al., 1999), Tucana (Lavery, 1990), KKR 25 (Makarov et al., 2012), and KKs 3 (Karachentsev et al., 2015). There is evidence to suggest that Cetus and Tucana are backsplash galaxies (Teyssier et al., 2012) which were environmentally quenched during a previous passage through the Local Group. KKR 25 and KKs 3 are ≈ 2 Mpc away from the Local Group, further than the projected distance of COSMOS-dw1 to its nearest potential neighbor. However, NGC 3166 and NGC 3044 have a lower mass than the Milky Way and M31, and when expressed in virial radii, KKR 25 and KKS 3 are a factor of ≈ 2 *closer* to their nearest neighbor than COSMOS-dw1 is.

The quenching mechanism for COSMOS-dw1 is a puzzle. The isolation of the galaxy combined with the fact that quenching happened recently makes an environmental cause very unlikely. Interestingly, all three galaxies (COSMOS-dw1, KKR 25, and KKS 3) have complex stellar populations (Makarov et al., 2012; Karachentsev et al., 2015), suggesting that star formation stopped and started several times over their lifetimes.

We suggest that quenching was due to internal feedback. Simulations suggest that supernova feedback can shut down star formation in low mass galaxies, but only for a short time (Fitts et al., 2017; Fillingham et al., 2018). Whenever we catch a galaxy in this short-lived phase we observe it to be young. Of the three galaxies in this limited sample, COSMOS-dw1 appears to be the youngest, and the clump of blue stars in COSMOS-dw1 may represent the site of the feedback event that temporarily halted further star formation (see also Geha et al., 2012). The intriguing nearby spheroidal object APPLES 1 (Pasquali et al., 2005) may also fit in this category: its distance is uncertain, but its young age and likely isolation are consistent with recent quenching.

In the near future, various wide field surveys/instruments such as the Rubin Observatory’s Legacy Survey of Space and Time (Ivezić et al., 2019) and, later, the *Roman Space Telescope* (Spergel et al. 2015) should help us determine how common these quiescent isolated dwarfs are. The fact that COSMOS-dw1 was found in a very small and very well-studied field suggests that they may be quite common (as indicated by Klypin et al. 2015) and can easily be missed. Low surface brightness-optimized surveys, such as the HSC-SSP (Aihara et al., 2018) and the Dragonfly Wide Field Survey (Danieli et al., 2020), will provide an additional avenue to obtaining a census of isolated low mass quiescent galaxies.

CHAPTER 5

THE LOW-MASS BARYON CYCLE IN QUEST DWARF GALAXIES: SAMPLE DEFINITION AND FIRST RESULTS

Polzin et al. (2026) presented as part of a thesis to the Department of Astronomy and Astrophysics, The University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

A. Polzin, H.-W. Chen, Z. Qu, E. Boettcher, A. Strom, and T.K. Chan, “The Low-Mass Baryon Cycle in QUEST Dwarf Galaxies I: Sample definition and first results”, submitted.

5.1 Introduction

The circumgalactic medium (CGM; see, e.g., Tumlinson et al., 2017; Faucher-Giguère & Oh, 2023; Chen & Zahedy, 2026, for recent reviews) is a critical component of galaxies’ cosmic ecosystems. It serves as a reservoir of gas bound to a galaxy’s halo, including both cool, neutral gas that, once accreted, will act as fuel for star formation (e.g., Weng et al., 2023; Decataldo et al., 2024) and metal-enriched gas that was driven out of the galaxy by jets and wind (e.g., Peebles et al., 2014; Muratov et al., 2017).

Because the multiphase (in temperature, chemistry, and kinematics) CGM acts as a reservoir for recently expelled gas, it encodes critical information about feedback processes occurring within the galaxy (e.g., Shen et al., 2013; Suresh et al., 2015; Fielding et al., 2017; Medlock et al., 2025; Baumschlager et al., 2025). It can be challenging to quantify the extent or the nature of the circumgalactic gas because it is generally diffuse, and emission studies are often limited to highly ionized phases in the inner CGM (e.g., Augustin et al., 2019; Zhang & Zaritsky, 2024; Peng et al., 2025) or hot halos that are X-ray bright (e.g., Wijers & Schaye, 2022; Silich et al., 2025). Instead, the CGM can be traced in far ultraviolet (FUV) absorption (e.g., Rauch, 1998; Steidel et al., 2010; Chen, 2017), which provides access

to a suite of metal resonance lines sensitive to different ionization conditions (included in this analysis: Si II, Si III, Si IV, C II, C IV), as well as the hydrogen Lyman series. This method, however, relies on the chance alignment of UV-bright background sources with objects of interest. By necessity, galaxies’ gaseous halos are then often characterized along one-dimensional “pencil-beam” sightlines.

Studying the CGM in absorption along pencil-beam sightlines is relatively advanced field for massive galaxies, with many systems examined and characterized. However, few such observational studies include dwarf galaxies (Prochaska et al., 2011; Bordoloi et al., 2014; Liang & Chen, 2014; Johnson et al., 2017, 2026; Zheng et al., 2020, 2024; Qu & Bregman, 2022; Mishra et al., 2024; Fox et al., 2026) with yet fewer focused on dwarfs outside of the Local Group (e.g., McConnachie, 2012) at distances greater than 3 Mpc (Prochaska et al., 2011; Bordoloi et al., 2014; Liang & Chen, 2014; Johnson et al., 2017, 2026; Zheng et al., 2024; Mishra et al., 2024) due to the intrinsic challenges related to their faintness and small sizes, which also affect the fruitful extent of the impact parameter. To get the strongest absorption, it is critical to analyze sightlines that are at small impact parameters (ideally $\lesssim 0.5 R_{\text{vir}}$, e.g., Liang & Chen, 2014). Given typical dwarf galaxy halo masses (e.g., Read et al., 2017; Nadler et al., 2020; Manwadkar & Kravtsov, 2022), sightlines must generally be within 50-100 kpc to stay within R_{vir} , though H I absorption is often extended and O VI absorption has been seen out to $2R_{\text{vir}}$ (Mishra et al., 2024).

Additionally, there are indications that the CGM of dwarf galaxies is somewhat different than in more massive galaxies due to intrinsic differences in the baryon cycle for low-mass systems (Li et al., 2021; Zhu et al., 2024). It is more easily stripped, encodes different feedback processes, and has somewhat different chemistry. Understanding the CGM is critical to understanding feedback processes (Baumschlager et al., 2025) and the baryon cycle (Piacitelli et al., 2025) in this regime. The CGM is sensitive to feedback and formation/growth history, as, especially in dwarf galaxies, star formation itself can drive gas into the halo. In this vein,

Table 5.1: Summary of first release QUEST Dwarfs galaxies and their properties. New and interacting satellites of QUEST Dwarfs, which are also analyzed in this work, have their names italicized below.

Galaxy ^a (1)	RA (2)	Dec (3)	D (Mpc) ^b (4)	cz (km s ⁻¹) ^c (5)	$\log M_*/M_\odot$ ^d (6)	QSO (7)	d_{proj} (kpc) (8)	Environment ^e (9)
PGC 4143	01:09:41.5	-02:15:59.3	21 ± 2	1770 ⁺¹⁰⁹ ₋₁₂₉	8.9 ± 0.02	LBQS 0107-0232 LBQS 0107-0235 QSO J0110-0218 LBQS 1230-0015 QSO B1217+023 LEDA 169472	51 ± 5 54 ± 5 56 ± 5 3.0 ^{+0.3} _{-0.7} 81 ⁺² ₋₅ 13 ± 3	Isolated Group Group Interacting
UGCA 285	12:33:08.5	-00:31:55.0	9 ⁺¹ ₋₂	754 ⁺¹⁵ ₋₁₂	7.5 ^{+0.2} _{-0.3}			
UGC 7370	12:19:40.3	+02:04:46.5	35 ⁺¹ ₋₂	1949 ⁺⁹² ₋₁₁₉	9.4 ± 0.2			
PGC 41458	12:31:33.4	+12:03:49.6	9 ± 2	596 ⁺¹⁴⁷ ₋₁₅₀	7.6 ± 0.3			
<i>PGC 41458b</i>	12:31:34.0	+12:04:03.4	10 ⁺¹¹ ₋₆	688 ⁺³¹⁴ ₋₃₉₆	7.2 ^{+0.9} _{-0.5}			
LeG 26	10:51:21.1	+12:50:56.0	8.9 ^{+1.1} _{-0.9}	481 ⁺⁵² ₋₅₈	7.7 ± 0.2	2MASS J10512569+1247462	8.7 ^{+1.1} _{-0.9}	Group
UGC 75	00:08:46.2	+15:49:01.0	5 ± 2	877 ⁺¹³⁸ ₋₉₇	8.3 ± 0.4	QSO B0003+1553	66 ± 26	Interacting
UGC 9126	14:15:40.1	+16:32:59.0	43 ± 2	2575 ⁺⁹⁷ ₋₁₂₉	9.2 ± 0.2	SDSS J141542.90+163413.8	17.8 ± 0.8	Isolated
UGC 7485	12:24:22.2	+21:09:36.0	24.01 ± 0.08	1183.0 ^{+1.0} _{-0.9}	8.9 ± 0.2	4C21.35	105.9 ± 0.3	Isolated
LEDA 1722581	08:35:37.1	+25:00:15.0	80.55 ^{+0.06} _{-0.11}	5158 ⁺⁴ ₋₈	8.8 ± 0.2	FBQS J083535.8+245940	15.19 ^{+0.01} _{-0.02}	Interacting
<i>LEDA 1722581-em</i>	08:35:36.7	+25:00:15.0	80.7 ^{+0.4} _{-0.2}	5166 ⁺³² ₋₁₄	8.37 ± 0.02			
PGC 1818175	12:17:08.2	+27:47:42.9	16.9 ± 0.1 ^f	971 ⁺⁶ ₋₁₅	8.4 ± 0.2	RX J1217.2+2749	12.99 ± 0.08	Interacting
UGC 5427	10:04:41.0	+29:21:51.5	10 ⁺¹ ₋₂	447 ⁺³⁹ ₋₁₈	8.0 ^{+0.2} _{-0.3}	Ton 28	80 ⁺⁸ ₋₁₆	Isolated
NGC 5486	14:07:25.0	+55:06:10.5	25 ⁺³ ₋₄	1345 ⁺³⁵ ₋₃₆	9.2 ± 0.2	QSO J1407+5507	12 ⁺¹ ₋₂	Group
dw1408+56	14:08:41.0	+56:55:38.0	32.2 ^{+0.9} _{-1.3}	2163 ⁺⁶⁰ ₋₉₇	7.9 ± 0.2	WISEA J140854.15+565743.3	25.8 ^{+0.7} _{-1.0}	Isolated
UGC 4527	08:44:24.0	+76:55:04.6	10.96 ± 0.03	725 ± 4	7.6 ± 0.2	VII Zw 244	7.23 ± 0.02	Isolated

^a New and interacting satellites of QUEST Dwarfs, which are also analyzed in this work, have their names italicized.

^b See Section 5.3.3 for details regarding distance inference.

^c See Section 5.3.2 for details regarding redshift measurements.

^d See Section 5.3.5 for details regarding measurements of M_{star} .

^e See Section 5.3.8 discussions on the environment of these dwarfs.

^f The Cosmicflows-3 (Kourkchi et al., 2020) model does not increase monotonically around 970 km s⁻¹, so we adopt the mean of the potential model velocities.

we combine absorption probes of the CGM content and constraints on interstellar medium (ISM) of the galaxies, stellar populations, and star formation histories to directly link the different components of the baryon cycle.

The initial Quasars to Understand Environments around, and STar formation in, Dwarfs – or QUEST Dwarfs – sample is made up of > 60 dwarf galaxies with background FUV sightlines projected within $\sim R_{\text{vir}}$. In this paper, we preview the science enabled by this large and diverse dataset, looking in detail at 14 systems, and highlight the ability to connect the chemical and physical properties of galaxies to the conditions of their CGM. All new data and data products presented here are available for easy download via the QUEST Dwarfs website¹, with archival data linked.

In Section 5.2, we describe the data used in this paper and how the larger QUEST Dwarfs sample was constructed. We detail the analyses of the first release sub-sample of galaxies presented here in Section 5.3. In Section 5.4, we expand on the analysis of the galaxies’ larger environments, including measurements of their circumgalactic media. In Sections 5.5 and 5.6, we discuss and then summarize our results.

5.2 Sample Selection & Data

The QUEST Dwarfs are all selected from Cosmicflows-3 (Tully et al., 2016), the Paudel et al. (2018) catalog of merging dwarf galaxies, and the 50 Mpc Galaxy Catalog (50 MGC; Ohlson et al., 2024) on the following criteria:

1. low inferred stellar mass with $M_{\text{star}} \leq 10^9 M_{\odot}$ based on an initial mass-to-light ratio conversion given their broadband photometry and inferred distance in the literature (see Section 5.3.5 for the mass inference);
2. line-of-sight velocity distinguishable from the Milky Way – $v \gtrsim 300 \text{ km s}^{-1}$, which helps

1. <https://questdwarfs.github.io>

prevent confusion with absorption features due to high velocity Milky Way clouds; and

3. available high-quality FUV absorption spectra of background source(s)² at small impact parameters (d_{proj}), allowing for characterization of the CGM and galaxy’s larger gaseous environment (see Section 5.2.2 below).

The combined QUEST Dwarfs sample contains > 60 dwarf galaxies which span environments, star formation histories, and more than three decades in mass.

The sub-sample analyzed here consists of 14 galaxies with available high-quality multi-wavelength imaging and spectroscopic data, either retrieved from public archives or obtained ourselves. It showcases the range of science possible with these combined datasets. A gallery of color composite images of these galaxies are presented in Figure 5.1, while the galaxy name and coordinates are presented in columns (1) through (3) of Table 5.1 which also lists the corresponding QSO sightline and projected distance (d_{proj}) in columns (7) and (8).

Combining optical spectroscopy with broad-band photometry provides constraints on the galaxies’ stellar populations, star formation histories, and ISM metallicities. These complementary data enable a unified study of the low-mass baryon cycle by linking the stellar populations, ISM, and CGM within the same galaxy sample. In this section, we briefly describe the available observations. A summary of the optical imaging and spectroscopic data is presented in Table 5.2. The remaining QUEST Dwarfs will be presented in future data releases, with accompanying observations and derived data products made publicly available as each sample is published.

2. We will explore the subsample of systems that, like PGC 4143 introduced here, have multiple associated sightlines in a future work (Polzin et al. in preparation).

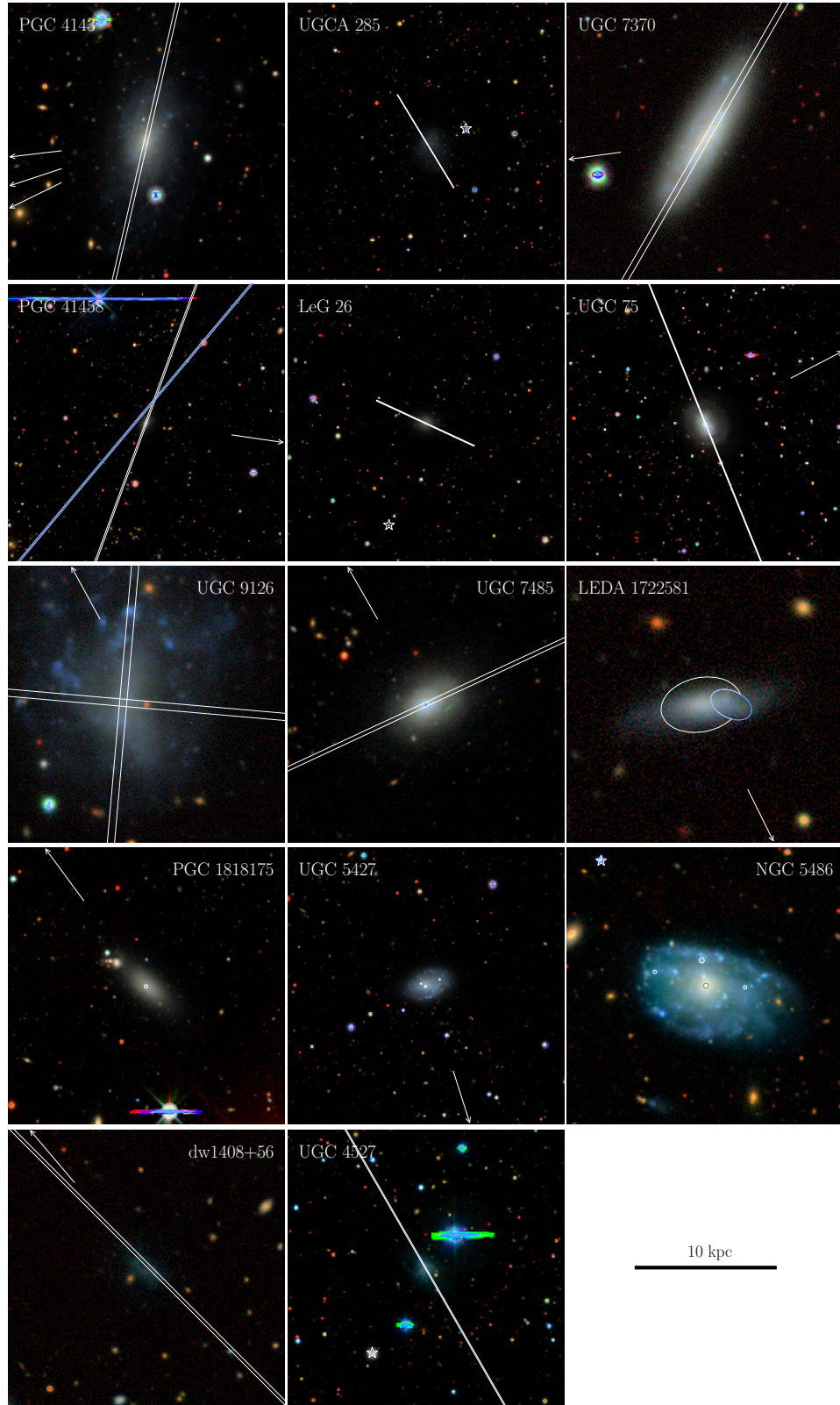


Figure 5.1: *(Caption next page.)*

Figure 5.1: (*Previous page.*) Cutouts of the QUEST Dwarfs first release sample from the Dark Energy Camera Legacy Survey (Dey et al., 2019) in *grz*. The scale bar applies to all postage stamps. QSOs in frame are marked with a star symbol; otherwise, arrows point toward the relevant sightline. The footprint of the slit, fiber, or IFU region used for optical spectroscopy is overplotted on each galaxy. The ancillary targets, PGC 41458b and LEDA 1722581-em, are marked by a blue slit and an extraction region, respectively. The central pointing of NGC 5486, which is largely excluded from analyses because of strong P Cygni-like features, is shown in gray.

Table 5.2: Spectral and high-resolution imaging coverage of the first release QUEST Dwarfs galaxies sample.

Galaxy	<i>HST</i> /WFPC2	<i>HST</i> /ACS	Optical spectrum
PGC 4143	-	-	Magellan/IMACS
UGCA 285	-	F814W	Keck/LRIS
UGC 7370	-	-	Magellan/IMACS
PGC 41458	-	-	Magellan/IMACS
LeG 26	-	-	Keck/LRIS
UGC 75	F300W, F814W	-	Magellan/IMACS
UGC 9126	-	-	Magellan/IMACS
UGC 7485	-	-	Magellan/IMACS
LEDA 1722581	-	F814W	SDSS MaNGA
PGC 1818175	-	-	SDSS
UGC 5427	-	F606W, F814W	SDSS
NGC 5486	-	F555W, F814W	SDSS
dw1408+56	-	-	MMT/Binospec
UGC 4527	-	-	MMT/Binospec

5.2.1 Optical Galaxy Spectra

As summarized in Table 5.2, optical spectra for eight dwarf galaxies in the first release sample were obtained ourselves, while the remaining six galaxies have existing data in either the Keck archive or from the Sloan Digital Sky Survey (e.g., York et al., 2000)³.

3. The final flux-calibrated, median-combined 1-D spectra from this paper are available via the QUEST Dwarfs website and GitHub.

Magellan/IMACS

We observed UGC 75 on the Inamori-Magellan Areal Camera and Spectrograph (IMACS; Dressler et al., 2011) on Magellan I on 2022 November 15, taking three exposures of UGC 75 of 600 s, 1800 s, and 1200 s respectively, totaling 3600 s. We also observed PGC 4143 with IMACS on 2022 November 16 for a total of 2400 s across two 1200 s exposures. UGC 7370 was observed with IMACS for 2400 s (2×1200 s) on 2023 March 22. UGC 9126 was observed on both 28 April and 2 May 2025, integrating for 3600s (3×1200 s) each day – the slit was oriented along the galaxy’s major axis on 28 April and along the galaxy’s minor axis on 2 May. PGC 41458 and its smaller companion, which we will refer to here as PGC 41458b, were each observed on 2 May 2025 for a total of 3600s (3×1200 s). These spectra were all taken with IMACS’s f/4 channel using the $2''.5$ -wide long slit to maximize signal from our low surface brightness targets and the 300 l mm^{-1} grating blazed at $6650 \text{ \AA}$. Nominally, this grating covers from $\sim 3700 - 9700 \text{ \AA}$ with a spectral FWHM of $\sim 17 \text{ \AA}$ (or $R \sim 390$).

UGC 7485 was observed on 2024 11 February using the f/2 channel on IMACS with the $2''.5$ long slit and the 400 l mm^{-1} grism blazed at $4730 \text{ \AA}$. This instrument setup has a similar wavelength range to the other IMACS observations used here, covering $3900\text{-}8500 \text{ \AA}$ at $R \sim 420$ (FWHM $\sim 11 \text{ \AA}$), though we only use data from the redder chip in this analysis with wavelengths longer than $4500 \text{ \AA}$.

In each case, with the exception of the second UGC 9126 pointing on 2 May 2025, the slit position angle was aligned with the major axis of the galaxy to maximize coverage of any spatial variation in the resulting spectra.

We reduce these data using a proprietary IDL-based pipeline built for Magellan analysis. Using the sky-subtracted spectra, we create a combined 2D spectral image for each target on a by-pointing basis, taking the inverse variance-weighted average for two exposures or median for three or more exposures, and mask cosmic rays and artifacts from the sky subtraction. We define our boxcar spectral extraction region to include the full spatial extent of the

galaxies, so that the resultant one-dimensional spectrum is summed across the extended stellar body of the target with wavelength corrected to vacuum. Therefore, the recovered properties based on these longslit spectra in Section 5.3 are integrated over the galaxy.

MMT/Binospec

dw1408+56 and UGC 4527 were both observed with MMT’s Binospec optical spectrograph (Fabricant et al., 2019) using the 1.5" single slit mode with the 270 l mm⁻¹ grating blazed at 6500 Å, which covers roughly 3850–9150 Å. The slit was aligned with the major axis of each target galaxy to maximize spatial coverage. No additional binning was applied and the science frames have a spectral dispersion of 1.3 Å pix⁻¹ and a spatial resolution of 0.24 arcsec pix⁻¹.

Binospec, like other MMT instruments, uses queue scheduling. UGC 4527 was observed on 2025 March 31 for a total of 3600s across three 1200s exposures. dw1408+56 was observed on 2025 April 27 for a total of 4800s across four 1200s exposures.

We independently extract the trace of UGC 4527 from the co-added and sky-subtracted, flux-calibrated two-dimensional spectra produced by MMT’s automated Binospec pipeline (Chilingarian et al., 2015). Due to anomalous issues with the automatic wavelength calibration on the night of 27 April 2025, we reran the MMT/Binospec pipeline⁴ for dw1408+56. We largely use the pipeline’s default parameters, but we turn off the sky line illumination correction and, given the low surface brightness of dw1408+56, the “bright” source flag.

Keck/LRIS

UGCA 285 was previously observed for a total of 600s with the Keck I’s Low Resolution Imaging Spectrograph (LRIS; Oke et al., 1995) on 2016 January 9 under program U050LA (PI: Prochaska). Data were taken with the 1" long slit using the 400 l mm⁻¹ grism blazed

4. https://bitbucket.org/chil_sai/binospec/src/master/

at $3400\text{\AA}$ (blue) and the 600 l mm^{-1} grating blazed at $7500\text{\AA}$ (red) with the D560 dichroic, covering $1760\text{--}8400\text{\AA}$. The slit was angled along the galaxy’s major axis with $\text{PA} = 31.2^\circ$. Collected data underwent 2×2 binning, resulting in a spatial resolution of $0.27\text{ arcsec pix}^{-1}$ and a spectral dispersion of $2.18\text{ \AA pix}^{-1}$ (blue) and $1.6\text{ \AA pix}^{-1}$ (red).

LeG 26 was observed with Keck/LRIS on 2003 April 26 for program U21L (PI: Bolte) using the $1''.5$ long slit. Data are not binned spatially ($0.135\text{ arcsec pix}^{-1}$) or spectrally and cover from approximately $3040\text{--}8630\text{\AA}$, with the 600 l mm^{-1} grism blazed at $4000\text{\AA}$ (blue, $0.63\text{ \AA pix}^{-1}$), the 600 l mm^{-1} grating blazed at $7500\text{\AA}$ (red, $0.80\text{ \AA pix}^{-1}$), and the D560 dichroic. There are three separate exposures of 900 s each.

We reduced these data, obtained via the Keck Observatory Archive, with `PypeIt` (Prochaska et al., 2020), using the default parameters for LRIS reduction with the following exceptions: we turn off automatic trace extraction due to the low surface brightness of these sources and define both a broad FWHM and low SNR for source detection to avoid oversubtracting signal during the sky modeling step. On the blue side, there are no lamp-on flats from the relevant night for UGCA 285, so pixel-level flat-fielding is not completed.

We extract the trace using an unweighted boxcar, which we flux calibrate manually rather than using the `PypeIt` “fluxing” step. We mask bad pixels in the two-dimensional spectra and median combine the three LeG 26 exposures before recovering two one-dimensional spectra per galaxy, one from the blue side of the spectrograph and one from the red. The individual blue and red 1D spectra are then concatenated to form a final science spectrum joined according to the considerations described in Perley (2019). We note that the LeG 26 blue-side flux calibration is somewhat uncertain and necessitated rescaling to match the continuum level ascertained from the red detector; while no rescaling is necessary between red and blue detectors for UGCA 285, a slight bias correction is applied to its associated blue detector data.

Table 5.3: Details of QSO sightlines and their spectral coverage.

QSO	z_{QSO}	COS Grating	$\langle S/N \rangle_{\text{COS}}$	COS PID	$\langle S/N \rangle_{\text{FUSE}}$	FUSE PID
LBQS 0107-0232	0.727	G160M	10.3	11585	-	-
LBQS 0107-0235	0.957	G130M, G160M	12.8	11585	-	-
QSO J0110-0218	0.956	G130M, G160M	11.5	11585	-	-
LBQS 1230-0015	0.471	G130M, G160M	10.5	11598, 12486	-	-
QSO B1217+023	0.240	G130M, G160M	13.5	13852	-	-
LEDA 169472	0.116	G130M	12.7	14071	-	-
2MASS J10512569+1247462	1.281	G130M, G160M	6.0	12603, 14777	-	-
QSO B0003+1553	0.450	G130M, G160M	21.9	12038	-	-
SDSS J141542.90+163413.8	0.743	G130M	15.8	12486	-	-
4C21.35	0.432	G130M, G160M	20.6	13008	-	-
FBQS J083535.8+245940	0.331	G130M, G160M	12.3	12025	3.1	P207
RX J1217.2+2749	0.395	G130M	8.0	14772	-	-
Ton 28	0.330	G130M, G160M	19.5	12038	2.5	P207 ^a
QSO J1407+5507	1.027	G130M	12.0	12486	-	-
WISEA J140854.15+565743.3	0.336	G130M	11.7	13314	-	-
VII Zw 244	0.131	G130M, G160M	21.6	11520	8.7	G020

^a These data are not used in our analysis due to low SNR.

SDSS

PGC 1818175, UGC 5427, and NGC 5486 have existing optical spectra taken as part of the Sloan Digital Sky Survey (SDSS; Blanton et al., 2017) at Apache Point Observatory. The SDSS spectrograph (and BOSS spectrograph) fibers are $3''(2'')$ in diameter and often target brighter, star-forming or HII regions in the galaxies, making it hard to assess the overall properties of the galaxies. As a means of mitigating this lack of spatial averaging, we analyze all available SDSS spectra from multiple positions, taking the sum of line strengths and luminosity-weighted average of fit properties derived from the different pointings where possible to ascertain the *galaxy's* more global properties.

PGC 1818175 was observed once (spectroscopic object ID 2511998754664507392), targeting the central region of the galaxy. The fiber covers the bluest, most apparently star-forming portion of the galaxy.

UGC 5427 has three SDSS spectra available from different pointings. Spectroscopic object ID 2195517795251283968 encompasses a star-forming region near the center of the galaxy, ID 7283574696637126656 is relatively central, but not focused on a specific bright clump, and ID 12779137532475758592 is pointed at the galaxy's outskirts.

There are four SDSS spectroscopic object IDs associated with NGC 5486. The fiber for spectroscopic ID 1490826493520013312 targeted the center of the galaxy, but the resulting spectrum shows broad P Cygni-like line profiles that are not easily fit by a generic model. In this analysis, we use IDs 9489301150144681984, 9488057877522569216, and 1491909507004000256, which each target one of the galaxy's brighter star forming regions.

LEDA 1722581⁵, at $d_{\text{proj}} = 15$ kpc to the sightline of FBQS J083535.8+245940, was

5. This galaxy has a massive neighbor, NGC 2611, at $d_{\text{proj}} = 60$ kpc from the QSO sightline based on an updated distance (see § 5.3.3). NGC 2611 is, therefore, four times farther away from the QSO sightline than LEDA 1722581. The absorption features identified in the spectrum of FBQS J083535.8+245940 (Section 5.4 and Table 5.6) were previously attributed to NGC 2611 (Stoeckel et al., 2013). However, following the association criterion described in Section 5.3.8, we consider LEDA 1722581 the more likely host because of its substantially closer proximity to the QSO sightline.

observed as part of the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA; Bundy et al., 2015) integral field survey (MaNGA ID 1-385149), which bundles BOSS fibers to simultaneously gather spatial and spectral information about targeted galaxies. We use data cubes processed with the MaNGA Data Analysis Pipeline (Westfall et al., 2019; Belfiore et al., 2019) via **Marvin** (Cherinka et al., 2019) to access the spaxel-level $H\alpha$ line intensity map. We then segment the object into two different regions, one that is cospatial with the stellar continuum, and one that is slightly offset and appears primarily in $H\alpha$ and *GALEX* FUV emission, which we refer to as LEDA 1722581-em here. We analyze the co-added spectra from each of these regions separately.

5.2.2 FUV QSO Spectra

Each of the dwarf galaxies in the QUEST Dwarf sample has at least one background quasar at projected separation $d_{\text{proj}} \lesssim 100$ kpc at their inferred distance, for which there exist archival FUV absorption spectra obtained using the Cosmic Origins Spectrograph (COS; Green et al., 2012) on board the *Hubble Space Telescope* (*HST*). Three of the QSOs also have archival FUV spectra obtained using the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*; Moos et al., 2000). A summary of these FUV spectra are presented in Table 5.3. *FUSE* spectra cover a wavelength range from 905 to 1187 Å with a full-width-at-half-maximum spectral resolution of $\text{FWHM} \approx 15 \text{ km s}^{-1}$ in line-of-sight velocity. *HST*/COS spectra typically cover a wavelength range from 1140 to 1780 Å with a velocity resolution of $\text{FWHM} \approx 18 \text{ km s}^{-1}$. Together, these FUV spectra provide spectral coverage for a suite of H I and ionic transitions that are necessary for constraining the chemical and physical conditions of the diffuse CGM (e.g., Chen & Zahedy, 2026). The extended wavelength coverage from *FUSE* is particularly useful for constraining the neutral hydrogen column density, $N(\text{HI})$, based on the strengths of higher-order Lyman series absorption lines.

Both *FUSE* and *HST*/COS spectra were processed and co-added using custom software

we developed to account for wavelength-calibration errors and to optimize the signal-to-noise (S/N) in the final combined spectra. Details regarding data processing of the FUSE and *HST*/COS spectra are described in Qu et al. (2026) and Chen et al. (2020), respectively. The median S/N of the coadded FUSE spectra along three QSO sightlines ranges from $\langle S/N \rangle_{\text{med}} \approx 2.5$ to $\langle S/N \rangle_{\text{med}} \approx 8.7$ per resolution element, while the median S/N of individual coadded *HST*/COS spectra ranges from $\langle S/N \rangle_{\text{med}} \approx 6$ to $\langle S/N \rangle_{\text{med}} \approx 22$ per resolution element (see Qu et al., 2026, and Table 5.3 for details).

5.2.3 Galaxy Imaging

The QUEST Dwarfs are covered by multiwavelength archival data from a variety of sources, allowing us to directly characterize the morphology, stellar populations, and recent star formation history of the galaxies in this sample.

Optical Survey Imaging

All of the QUEST Dwarfs were observed by either the Dark Energy Camera Legacy Survey (DECaLS; Dey et al., 2019) or the complementary ancillary imaging in the DECam Local Volume Exploration Survey (DELVE; Drlica-Wagner et al., 2021). The 14 primary galaxies analyzed here are all included in DECaLS (see Figure 5.1), and we use DR9 *grz* “bricks” with approximately native resolution ($0.262'' \text{ pix}^{-1}$) to derive the integrated photometric properties of each dwarf galaxy.

High-resolution Imaging

About half of the QUEST Dwarfs have archival high-resolution imaging, which enables detailed study of the galaxies’ stellar populations. Of this first release sub-sample, five galaxies have space-based imaging taken with the *Hubble Space Telescope* (PIDs 9124, 12546, 13024, and 17070; see Table 5.2).

We download CTE-corrected individual exposure image files from the Barbara A. Mikulski Archive for Space Telescopes, which we “tweak”, co-add, and “drizzle” via `Drizzlepac` (Fruchter et al., 2010; Hoffmann et al., 2021). This allows us to derive a consistently drizzled PSF for use with the resulting co-added and mosaiced images starting from the same data and processing.

Ultraviolet Imaging

Most of the QUEST Dwarfs are covered by *GALEX* (Martin et al., 2005) ultraviolet imaging. We use these data to derive a self-consistent star formation rate (SFR) on ~ 100 Myr timescales (e.g., Kennicutt, 1998; Calzetti, 2013; Flores Velázquez et al., 2021). With our optical spectra enabling direct measurement of the SFR on $\lesssim 10$ Myr timescales via the $H\alpha$ line, these ultraviolet data give us the opportunity to probe the recent star formation history of dwarf galaxies. The expectation is that star formation in this mass regime is generally feedback-regulated and somewhat bursty, which makes the combined dataset particularly valuable for constraining star formation properties. Simultaneously, each star formation indicator comes with caveats for use in the extremely low-mass, low-metallicity regime, which includes many of the QUEST Dwarfs: some particularly low-mass dwarf galaxies may not exhibit $H\alpha$ emission due to the intrinsic stochasticity in sampling the high-mass end of the stellar initial mass function in particularly low-mass galaxies (e.g., Applebaum et al., 2020), and low-metallicity galaxies tend to be bluer and more UV-bright regardless of their SFR (e.g., Kennicutt & Evans, 2012; Sanders et al., 2013). It is therefore important to examine the recent star formation history of dwarf galaxies in greater detail and using multiple tracers.

5.3 Properties of QUEST Dwarf Galaxies

To better understand the correspondence between galaxy and halo absorber properties, we analyze available images and spectra to infer key physical and chemical quantities for these dwarf galaxies, including broad-band photometry, radial velocity, distance, stellar metallicity, star formation history, stellar mass, ISM metallicity, and environment. Here we describe the steps for inferring these quantities.

5.3.1 Integrated Photometric Properties of Galaxies

All of the galaxies in this sub-sample are covered by DECaLS (Dey et al., 2019) DR9 imaging, and we fit for each galaxy’s structural and photometric properties in *grz* filters. We use cube-by-cube PSFEx (Bertin, 2011, 2013) PSF models for Legacy Survey photometry.

To mask non-target galaxy features in the images, we use segmentation maps from SEP (Bertin & Arnouts, 1996; Barbary, 2016), and run `pysersic` (Pasha & Miller, 2023) to fit simple Sérsic models jointly to the galaxies’ *grz*-band light profiles. In the couple of cases where the galaxies’ morphologies necessitate more complex modeling than a single Sérsic profile, we use a “double” Sérsic model, where only the profiles’ centers and position angles are shared. These structural parameters are then used in aperture photometry of the deepest available *GALEX* FUV imaging, defining the ellipse from which we extract each galaxies’ FUV flux based on $\gtrsim 2\times$ the effective radius recovered from the `pysersic` for to DECaLS imaging. Our targets are covered by both the main *GALEX* surveys and guest investigator programs, including PIDs 25, 40, and 104. All integrated photometry is reported in columns (1) through (4) of Table C.1, along with the best-fitting morphological parameters of a single Sérsic model in columns (5) through (8) for each galaxy.

For the five galaxies also covered by *HST*, we model the galaxies’ light profiles more carefully with GALFIT (Peng et al., 2010). We use `spike` (Polzin, 2025) with TinyTim (Krist et al., 2011) to generate resampled instrument- and filter-dependent *HST* point spread func-

tions at the locations of UGCA 285, UGC 75, LEDA 1722581, UGC 5427, and NGC 5486. The drizzled *HST* PSFs are then fed to **GALFIT**. Because these galaxies stellar populations are resolved, structural parameters are first fit for *HST* imaging smoothed with a Gaussian kernel and integrated magnitudes are then force fit for the original (unsmoothed) imaging.

5.3.2 Radial Velocities of Galaxies

To ensure the accuracy of the wavelength calibration we re-zero point the wavelength axis based on the location of the atmospheric A-band absorption feature in our newly extracted spectra, which results in a $2\text{\AA}$ correction applied globally to the extracted LeG 26 spectrum. For our broad $2.5''$ longslit data, we also correct for spatial variation within the slit, offsetting the wavelength array so that the measured *cz* accounts for the potentially irregular line profiles associated with structure in the observed galaxies. All such corrections are at the $\lesssim 1\text{\AA}$ level, while the FWHM of the corrected data varies between $\sim 11\text{--}17\text{\AA}$.

We then measure the radial velocity of each galaxy in this sample using available optical spectra and a simple reduced χ^2 minimization scheme. Template spectra are **FSPS** (Conroy et al., 2009; Conroy & Gunn, 2010; Johnson et al., 2024) simple stellar populations (SSPs) spanning both metallicity ($-2.5 \leq [\text{Fe}/\text{H}] \leq 0$) and age ($0.5 - 10$ Gyr) and smoothed to approximate each instrument’s spectral resolution. We report the median best fit velocity across templates with a heliocentric correction applied and confidence intervals defined by the 16th and 84th percentiles of the distribution of velocities returned across templates.

Where there are independent spectra at multiple pointings associated with the same galaxy, we take the average best fit velocity across pointings as the “integrated” *cz*. For UGC 9126, the spectrum taken along the minor axis is much noisier than the spectrum taken along the major axis; we adopt the major axis velocity.

In the few cases where no good fit to the (largely Balmer) absorption lines is possible and no alternative pointing exists, we use full spectral fitting (see Section 5.3.4) to measure

the galaxy’s cz . The best-fit cz of each galaxy is presented in column (5) of Table 5.1.

5.3.3 *Inferring Distances*

We infer the distance to every galaxy presented here from either its radial velocity or, where possible, a redshift-independent distance calibrator. Most galaxies in the first release QUEST Dwarfs sample do not have redshift-independent distances from either the Tip of the Red Giant Branch (TRGB; e.g., Lee et al., 1993) or surface brightness fluctuations (SBFs; Tonry & Schneider, 1988). For the subset with *HST* imaging, we measure the SBF distance. The best estimated distances are presented in column (4) of Table 5.1.

Radial Velocity Distances

We use the Cosmicflows-3 Distance-Velocity Calculator (Kourkchi et al., 2020) to compute local velocity field- and cosmology-corrected distances from galaxy radial velocities. We adjust the output distances to use $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ in lieu of the higher $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ used by default in the Cosmicflows-3 model.

Where possible, however, we adopt redshift-independent TRGB or SBF distances, whether from the literature or newly measured here, for the galaxies in this sample. For galaxies within $cz \lesssim 1500 \text{ km s}^{-1}$, the galaxy’s peculiar velocity and any potential group velocity represent a significant source of uncertainty on the inferred radial velocity distance, as these velocity components may dominate over the Hubble flow.

Surface Brightness Fluctuation Distances

Four of the dwarf galaxies presented here have archival *HST*/ACS F814W imaging, which allows us to apply existing surface brightness fluctuation distance calibrations (Blakeslee et al., 2010; Carlsten et al., 2019) that have been shown to recover accurate distances for younger stellar populations to put a redshift-independent constraint on the galaxies’ distances.

Table 5.4: Salient SBF measurements for each galaxy with high-resolution imaging. Note that imaging was done with either *HST*/WFPC2 or ACS (see Table 5.2).

Galaxy	$\bar{M}$	m_{SBF}	D_{SBF} (Mpc)
UGCA 285	-2.2 ± 0.3	$27.5^{+0.1}_{-0.3}$	9^{+1}_{-2}
UGC 75	-3 ± 1	$25.22^{+0.06}_{-0.18}$	5 ± 2
UGC 5427	-2.3 ± 0.2	$27.7^{+0.2}_{-0.3}$	10^{+1}_{-2}
NGC 5486	-2.5 ± 0.2	$29.48^{+0.05}_{-0.20}$	25^{+3}_{-4}

We find and apply a conversion between $(g - z)^{\text{DECam}}$ and F475W-F814W using the colors of simple stellar populations in MIST as was done in, e.g., Cohen et al. (2018) and Carlsten et al. (2019). More details of this conversion are in Appendix C.3.

For UGC 75, which has archival multi-band *HST*/WFPC2 imaging, we use the F814W SBF relation from Ajhar et al. (1997). Though Ajhar et al. (1997) calibrated the F814W SBF signal for PC imaging, this relation has been shown to work for WF imaging, as well (Morris & Shanks, 1998). As above, we find a conversion between $(g - z)^{\text{DECam}}$ and the standard $V - I$ (F555W–F814W) color on which that relation relies.

From the TRGB, UGC 5427 was previously measured to be at 7.7 ± 0.77 Mpc (Tully et al., 2013). We verify this distance, deriving a SBF distance of 10^{+1}_{-2} Mpc from the F814W *HST*/ACS imaging. For consistency with the treatment of the rest of our sample, we adopt the SBF distance in our analysis.

Results are shown in Table 5.4. For the galaxies imaged with *HST*/ACS, we adopt the Carlsten et al. (2019) SBF relation given the blue color of the target galaxies, but note that distance results from Blakeslee et al. (2010) are consistent with those reported here. LEDA 1722581’s variance power spectrum is background-dominated at all scales (using the updated SBF equation from Foster et al., 2024); as there is no way to recover the SBF signal, it is not included in our reported results. Fortunately, LEDA 1722581 is in the regime where the galaxy should be securely in the Hubble flow.

5.3.4 Spectral Fitting

We use the **Bagpipes** (Carnall et al., 2018, 2019) SED fitting code to estimate the metallicity and star formation history (SFH) from the observed optical spectra. To consistently fit SFHs for a wide range of galaxies, like those in the QUEST Dwarfs sample, we select the Iyer et al. (2019) non-parametric SFH model, which is an improvement on the Dense Basis SFH fitting introduced in Iyer & Gawiser (2017). We allow **Bagpipes** to fit for the SFH in seven time bins with a Dirichlet prior (Leja et al., 2017, 2019). Based on the tests in Iyer et al. (2019), we adopt $\alpha = 5$, where α is the Dirichlet prior parameter that defines the correlation between the resulting time bins, essentially tuning the smoothness or stochasticity of the star formation history.

All spectra are given the same priors fixed at their measured redshift⁶ and are fit with the **MultiNest** (Feroz & Hobson, 2008; Feroz et al., 2009; Feroz & Skilling, 2013) algorithm implemented via **PyMultiNest** (Buchner et al., 2014). We adopt flat priors for velocity dispersion ($1 - 1000 \text{ km s}^{-1}$) SFR ($10^{-6} - 1 \text{ M}_{\odot} \text{ yr}^{-1}$), stellar metallicity ($10^{-2} - 1 Z_{\odot}$), and stellar mass formed ($10^4 - 10^{10} \text{ M}_{\odot}$), with the latter three flat priors defined in $\log_{10}$.

We include a nebular emission component in the spectral fit, but fix the ionization parameter to $U = 10^{-3}$, which is both standard and consistent with the value **Bagpipes** returned in tests where we allowed this value to vary. Additionally, following Carnall et al. (2019), we add a white noise component to the spectrum, which functionally rescales the spectroscopic errors and results in somewhat more “realistic” confidence intervals associated with the posterior distributions from the fit. We directly mask the atmospheric A- (7600-7630 Å) and B-bands (6860-6890 Å) in the input spectra to mitigate the impact of their absorption on the spectral fits. We do not include a dust model in the spectral model as the QUEST Dwarfs are low-mass and relatively low-metallicity, which suggests that they should also be

6. Where we rely on **Bagpipes** to recover the redshift, we use a flat prior of $0 \leq z \leq 0.005$. This is the case for UGCA 285, UGC 7485, and UGC 4527, where the SNR and/or wavelength coverage is not sufficient below 5000 Å to directly measure the galaxies’ cz from Balmer absorption lines.

Table 5.5: Derived spectral and photometric properties.

Galaxy (1)	$\log M_h/M_\odot$ (2)	R_{vir} (kpc) (3)	$\log Z/Z_\odot^a$ (4)	$12 + \log \text{O}/\text{H}$ (5)	$\log \text{sSFR}_{\text{H}\alpha}/\text{yr}^{-1}$ (6)	$\log \text{sSFR}_{\text{UV}}/\text{yr}^{-1}$ (7)	$\log \text{H}\alpha/\text{UV}$ (8)	SFH ^b (9)
PGC 4143	10.90	88.87	$-0.953^{+0.010}_{-0.003}$	8.40 ± 0.18	-10.595 ± 0.005	-10.6 ± 0.2	0.0 ± 0.2	B
UGCA 285	10.16	50.12	$-0.07^{+0.05}_{-0.08}$	8.62 ± 0.19	-10.07 ± 0.05	$-10.6^{+0.2}_{-0.4}$	$0.5^{+0.2}_{-0.4}$	S
UGC 7370	11.13	105.59	$-1.40^{+0.05}_{-0.06}$	8.41 ± 0.18	-10.060 ± 0.005	-10.5 ± 0.2	0.5 ± 0.2	B
PGC 41458	10.21	52.03	$-1.63^{+0.11}_{-0.08}$	8.56 ± 0.40	-12.464 ± 0.003	$-11.7^{+0.2}_{-0.4}$	-0.7 ± 0.4	Q
PGC 41458b	10.21	45.02	$-0.009^{+0.006}_{-0.014}$	8.83 ± 0.14^c	$-12.3^{+0.7}_{-2.2}$	< -11.94	> -0.33	Q
LeG 26	10.25	54.04	$-0.05^{+0.03}_{-0.06}$	8.31 ± 0.19	$-11.15^{+0.06}_{-0.097}$	-11.6 ± 0.2	$0.5^{+0.2}_{-0.5}$	Q
UGC 75	10.58	69.28	$-1.45^{+0.05}_{-0.06}$	8.37 ± 0.18	-10.195 ± 0.002	...	...	S
UGC 9126	11.04	98.79	-0.99 ± 0.05	8.14 ± 0.18	-9.58 ± 0.01	-9.9 ± 0.2	0.3 ± 0.2	E
UGC 7485	10.90	88.87	$-0.72^{+0.06}_{-0.02}$	8.29 ± 0.18	$-9.460^{+0.008}_{-0.009}$	-10.5 ± 0.2	1.1 ± 0.2	S
LEDA 1722581	10.85	85.55	-1.19 ± 0.04	8.36 ± 0.18	-10.300 ± 0.004	-10.8 ± 0.2	0.5 ± 0.2	S
LEDA 1722581-em	10.62	71.41	$-1.26^{+0.04}_{-0.06}$	8.31 ± 0.18	-9.722 ± 0.004	-10.01 ± 0.08	0.29 ± 0.08	S
PGC 1818175	10.64	72.39	$-0.93^{+0.05}_{-0.06}$	8.86 ± 0.35	-11.7 ± 0.1	$-11.8^{+0.3}_{-0.2}$	$0.1^{+0.3}_{-0.2}$	Q
UGC 5427	10.41	60.93	-1.30 ± 0.02	8.28 ± 0.18	-9.68 ± 0.01	$-9.8^{+0.2}_{-0.3}$	$0.1^{+0.2}_{-0.3}$	E
NGC 5486	11.04	98.79	-1.43 ± 0.03	8.25 ± 0.18	-8.716 ± 0.009	-9.9 ± 0.2	1.1 ± 0.2	E
dw1408+56	10.36	58.48	$-0.73^{+0.04}_{-0.03}$	8.41 ± 0.18	-9.92 ± 0.02	-10.0 ± 0.2	0.1 ± 0.2	E
UGC 4527	10.21	52.03	$-1.58^{+0.11}_{-0.08}$	8.27 ± 0.18	-10.18 ± 0.01	-10.1 ± 0.2	-0.1 ± 0.2	B

^a The stellar metallicity is reported based on the **Bagpipes** posterior. Note that we used a flat prior defined from $-2 \leq \log Z/Z_\odot \leq 0$, so especially low-metallicity galaxies may be strongly constrained by the lower bound we adopted on the prior. Additionally, the two galaxies observed with Keck/LRIS – UGCA 285 and LeG 26 – are found to be best fit by more metal-rich, near $Z = Z_\odot$, models; given flux calibration concerns for these two galaxies, it is possible that the metallicity of the stellar population is inferred erroneously.

^b The summarized star formation history designated here is from the qualitative character of the SFH returned by **Bagpipes** (see Section 5.3.4 and Appendix C.2): *sustained* (S), *bursty* (B), *quiescent* (Q), and *episodic* (E).

^c Gas-phase metallicity determined from the O_{32} strong line relation presented in Curti et al. (2017) as the N_2 line ratio is out of range due to H α being a near non-detection.

dust-poor (e.g., Fisher et al., 2014; De Vis et al., 2019; Li et al., 2019).

The best-fit stellar metallicity of each galaxy is presented in column (4) of Table 5.5, and we characterize the extended SFH returned by **Bagpipes** (see Appendix C.2) in column (9) of Table 5.5. We divide those returned SFHs into four categories: *sustained*, where star formation is roughly constant over the galaxy’s lifetime; *bursty*, where there is a clear gap between episodes of star formation; *quiescent*, where the recent star formation rate has fallen off precipitously and the specific star formation rate is now below 10^{-11} yr^{-1} ; and *episodic*, where the star formation history is more complex and does not fit neatly into one of the other categories. Given the extensive available data, we infer stellar mass from broadband imaging which captures the total star light and is therefore not subject to slit losses (see Section 5.3.5), and, where available, we additionally constrain the recent SFH from *GALEX* photometry and emission line fitting (Appendix C.1); as such, no spectrophotometric or aperture correction is applied when fitting the data with **Bagpipes**. The optical spectra and their **Bagpipes** fits are shown in Appendix C.2.

5.3.5 Inferring Mass

We adopt the distances derived in Section 5.3.3 to convert the galaxies’ integrated magnitudes (see Section 5.3.1 and Table C.1) to absolute magnitudes and apply the color-based photometric stellar mass calibration for low-mass galaxies presented in de los Reyes et al. (2025, their equation 13). This relation is intended to minimize mass-dependent systematic over- and under-prediction of galaxy stellar mass, which can otherwise bias inferred masses by up to $\sim$ half a dex. Note that the QUEST Dwarfs’ stellar masses are reported with an uncertainty of 0.2 dex on top of the photometric and distance uncertainties, which encompasses the intrinsic scatter of the de los Reyes et al. (2025) relation and is consistent with the typical systematic error on color-based stellar mass estimates.

Independent stellar continuum is not detected for LEDA 1722851-em, the H α -bright

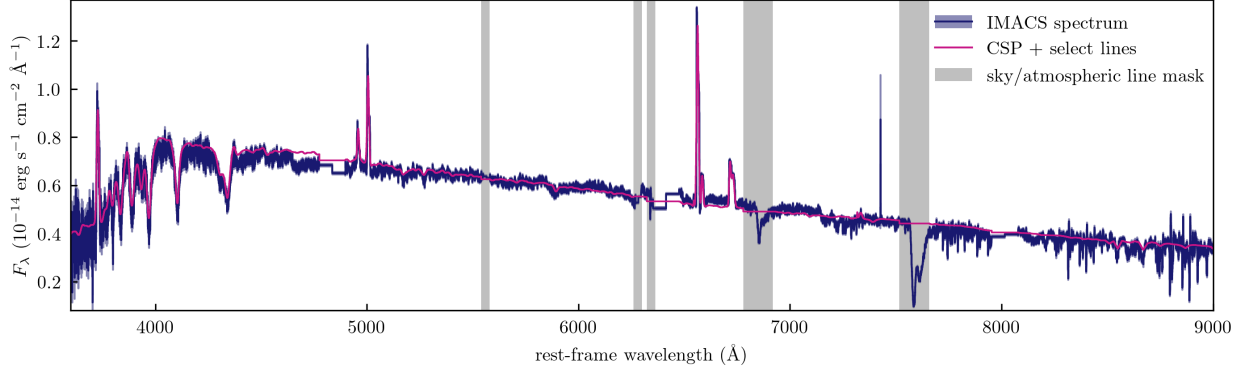


Figure 5.2: The optical spectrum of UGC 75 (dark blue), overplotted by the CSP model with the nebular lines we fit added (pink). Note that for illustration purposes the normalization of the CSP model is set *globally* here with the line properties adjusted accordingly.

region associated with LEDA 1722581. Instead, we report here the **Bagpipes** inferred mass of $2.3 \times 10^8 M_{\odot}$ for that companion object, which is just a factor of $\lesssim 3$ lower than the stellar mass inferred for the main body of LEDA 1722581 by **Bagpipes**. For the main body of LEDA 1722581, M_{star} estimated from integrated MaNGA spectroscopy using **Bagpipes** is consistent with M_{star} inferred from photometry ($\log M_{\text{star}}/M_{\odot} = 8.8$). The results are presented in column (6) of Table 5.1.

To infer the halo mass of these galaxies, we use the dwarf galaxy stellar mass-halo mass relation (SHMR) from Manwadkar & Kravtsov (2022), which is consistent with both Read et al. (2017) and Nadler et al. (2020) for dwarf galaxies and can also be reliably extrapolated to higher stellar and halo masses, where it is consistent with e.g., the Behroozi et al. (2013) SHMR. The virial radius, R_{vir} , which we define here as R_{200c} , is then computed for each galaxy, assuming $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The inferred halo mass and halo radius of each galaxy are presented in columns (2) and (3) of Table 5.5.

5.3.6 Deriving Star Formation Histories

In addition to the star formation history derived from the **Bagpipes** SED fitting (see Appendix C.2) we measure the (specific) SFR at both $\sim 100 \text{ Myr}$ and $\sim 10 \text{ Myr}$ with FUV

photometry and the $H\alpha$ line respectively. We use the integrated FUV photometry (Section 5.3.1) and our distance estimates (Section 5.3.3) to infer the galaxy’s global SFR on ~ 100 Myr timescales using equation 3 of Lee et al. (2009). We then convert this SFR to a specific SFR, sSFR, normalizing by the stellar mass from Section 5.3.5. The shorter timescale sSFR is derived from the equivalent width of the $H\alpha$ line as described in Section 5.3.7 below. These specifically measured star formation rates are compared against the **Bagpipes** SFHs in Figures C.2 through C.5.

The ratio between integrated $H\alpha$ and FUV fluxes has been used as a proxy for the burstiness of dwarfs’ star formation histories (e.g., Lee et al., 2009; Weisz et al., 2012; Perry et al., 2025). As we do not have narrow-band $H\alpha$ imaging for the QUEST Dwarfs, we instead adopt $\log(\text{sSFR}(H\alpha)/\text{sSFR}(\text{FUV}))$ here, which should be proportional to the flux ratio⁷. Critically, the sSFRs we compare are not computed over the same area – the FUV-inferred sSFR is based on independent estimates of SFR from integrated *GALEX* imaging and M_{star} , while the $H\alpha$ -inferred sSFR is estimated from the spectral line – which introduces an additional spatial explanation for discrepancies between the two sSFRs independent of temporal burstiness. We report $H\alpha$ -inferred and FUV-based sSFRs, as well as the ratio of the two quantities in columns (6)–(8) of Table 5.5, respectively.

5.3.7 Measurements of Spectral Features

We measure the equivalent widths (EWs) and fluxes of a suite of optical nebular lines, including $[\text{OII}]_{3728}$, $H\beta$, $[\text{OIII}]_{4960}$, $[\text{OIII}]_{5008}$, $H\alpha$, and $[\text{NII}]_{6585}$. For each galaxy, we use a low-order polynomial to approximate the local continuum and use stellar phase metallicity and non-parametric star formation history from the **Bagpipes** fitting to create complex stellar population (CSP) models of only stellar continuum and absorption with **FSPS** against which lines can be fit. To account for potentially imperfect flux calibration across the entire

7. Though the sSFR is not linear with respect to the $H\alpha$ equivalent width in Belfiore et al. 2018, that non-linearity is attributed to the stellar mass correction, in-keeping with other relations where $\text{SFR} \sim F(H\alpha)$.

Table 5.6: Measured absorption features.

Galaxy	d_{proj}/R_{200}	$\log N_{\text{HI}}/\text{cm}^{-2}$	$\log N_{\text{SiII}}/\text{cm}^{-2}$	$\log N_{\text{CIV}}/\text{cm}^{-2}$	$\log N_{\text{SiIII}}/\text{cm}^{-2}$	$\log N_{\text{SiIV}}/\text{cm}^{-2}$	$\log N_{\text{CIV}}/\text{cm}^{-2}$
PGC 4143	0.570	...	...	...	...	...	$13.42^{+0.07}_{-0.08}$
	0.607	14.7 ± 0.1	< 12.89	13.4 ± 0.2	...	$12.975^{+0.07}_{-0.075}$	13.3 ± 0.1
	0.629	$14.21^{+0.08}_{-0.06}$	< 11.92	< 13.05	...	...	< 12.875
UGCA 285	0.061	> 14.37	< 11.85	< 12.73	...	< 12.83	$13.709^{+0.07}_{-0.085}$
UGC 7370	0.767	$14.42^{+0.03}_{-0.02}$	< 11.96	< 12.60	...	< 12.37	$13.78^{+0.05}_{-0.06}$
PGC 41458	0.251	$13.58^{+0.08}_{-0.07}$	< 12.00	< 12.985	< 11.90	< 12.12	...
LeG 26	0.161	> 14.56	13.3 ± 0.2	$14.03^{+0.08}_{-0.09}$	$13.19^{+0.06}_{-0.065}$	13.16 ± 0.08	$14.24^{+0.12}_{-0.08}$
UGC 75	0.949	$13.55^{+0.05}_{-0.06}$	< 12.02	...	< 11.52	< 12.06	< 12.24
UGC 9126	0.180	19.81 ± 0.01	$14.1^{+0.2}_{-0.1}$	> 14.64	...	13.34 ± 0.04	...
UGC 7485	1.192	$13.22^{+0.07}_{-0.09}$	< 12.15	< 12.51	< 11.77	< 11.97	< 12.30
LEDA 1722581	0.178	> 15.56	14.40 ± 0.04	> 15.58	> 14.12	14.13 ± 0.02	$15.1^{+0.5}_{-0.1}$
PGC 1818175	0.179	> 14.84	< 12.46	$13.8^{+0.1}_{-0.2}$	< 12.75	< 12.90	...
UGC 5427	1.316	$13.90^{+0.045}_{-0.04}$	< 11.61	< 12.87	< 11.63	< 11.94	< 12.92
NGC 5486	0.119	> 15.14	15.0 ± 0.3	> 14.99	> 13.82	13.67 ± 0.03	...
dw1408+56	0.441	> 13.81	< 11.69	< 13.51	...	12.8 ± 0.1	...
UGC 4527	0.139	> 14.76	12.4 ± 0.1	13.47 ± 0.05	$13.16^{+0.04}_{-0.03}$	12.85 ± 0.03	$13.58^{+0.04}_{-0.05}$

range of the fit, the normalization of the CSP component is re-evaluated in each spectral fitting region. Measurements of line fluxes and equivalent widths are presented in Table C.2 and an example of the results of this fitting is shown in Figure 5.2.

We infer gas-phase metallicities for the QUEST Dwarfs based on their observed N_2 index with $N_2 \equiv \log \text{NII}/\text{H}\alpha$, following (Pettini & Pagel, 2004, see also Kewley et al. 2019 for a review). The results are presented in column (5) of Table 5.5. From the equivalent width of $\text{H}\alpha$, $\text{EW}(\text{H}\alpha)$, we infer sSFR using the empirical, MaNGA-derived $\text{EW}(\text{H}\alpha)$ -sSFR relation from Belfiore et al. (2018). This sSFR is then independent of any slit- or fiber-loss and agnostic to each galaxy’s estimated stellar mass (column 6 of Table 5.5)

The strength of the 4000Å break (D_n4000) can be used as a diagnostic for the age of a galaxy’s stellar population (Bruzual A., 1983; Hamilton, 1985). However, the age-dependence of D_n4000 becomes weaker with decreasing stellar metallicity (e.g., van den Bergh, 1963; Paulino-Afonso et al., 2020). We measure D_n4000 here, adopting the red and blue continuum definitions from Balogh et al. (1999). These measurements are presented in the rightmost column of Table C.2.

5.3.8 *Environment*

Using the galaxy distance and mass derived in Sections 5.3.3 and 5.3.5, we examine the “neighborhood” around the QUEST Dwarfs. We show these galaxies in the context of their immediate environments (± 2 deg) using the 50 MGC (Ohlson et al., 2024) and the DESI DR1 (DESI Collaboration et al., 2025) catalog to find galaxies within 300 km s^{-1} of the target dwarf galaxy’s measured radial velocity. For these non-target sources, we use the “best” stellar mass from the 50 MGC where available, or, for galaxies that are only in the DESI catalog, we compute the stellar mass using catalog photometry⁸ and the de los Reyes

8. Though “fragmentation” or “shredding” remains a problem for automated photometry of nearby galaxies in large surveys, we adopt the DESI catalog values as any correction for this effect would be beyond the scope of our analysis. The determination of the environments of QUEST Dwarfs is only minimally impacted

et al. (2025) relation. We follow Section 5.3.5 and use the Manwadkar & Kravtsov (2022) SHMR to infer halo masses of these neighboring galaxies and compute their R_{vir} based on R_{200c} for $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

We show the QUEST Dwarfs’ environments in Figure C.1. Galaxies are placed into one of three categories based on their environments. *Isolated* galaxies are $\gtrsim 2R_{\text{vir}}$ from their nearest neighbor. *Group* galaxies are in close associations with other galaxies or are part of known groups. Galaxies are categorized as *interacting* if their virial radius overlaps significantly with the virial radius of a close neighbor (in both projected distance and velocity). Note that there is significant variety in the environment of *group* and *interacting* systems.

In such complex environments, a fundamental challenge is determining which galaxy is physically associated with an observed absorber. In an extensive study, Qu et al. (2023) showed that CGM absorption properties in group environments are primarily driven by the galaxy closest to the QSO sightline, rather than by the most massive galaxy or by mass-weighted group properties. Guided by this finding, we associate each absorber with the galaxy closest to the QSO sightline in the analysis below.

5.4 Properties of the CGM around QUEST Dwarfs

The core aim of the QUEST Dwarfs sample is to connect properties of the CGM, derived from absorption spectroscopy of FUV-bright background quasars, to the galaxies’ ISM and stellar populations. To determine the CGM properties of QUEST Dwarfs, we perform an absorption-line search in the FUV spectra of the background QSOs described in Section 5.2.2. Specifically, we search for a suite of strong ionic lines from Si, C, and O as well as hydrogen near the galaxies’ central radial velocities. Prominent FUV absorption transitions of the diffuse CGM covered by *HST*/COS include H I Lyman series, C II 1334, C IV 1548,

by the stellar mass of non-target galaxies; instead, given their projected positions, even significantly revised non-target galaxy mass estimates would not affect the environment classification here.

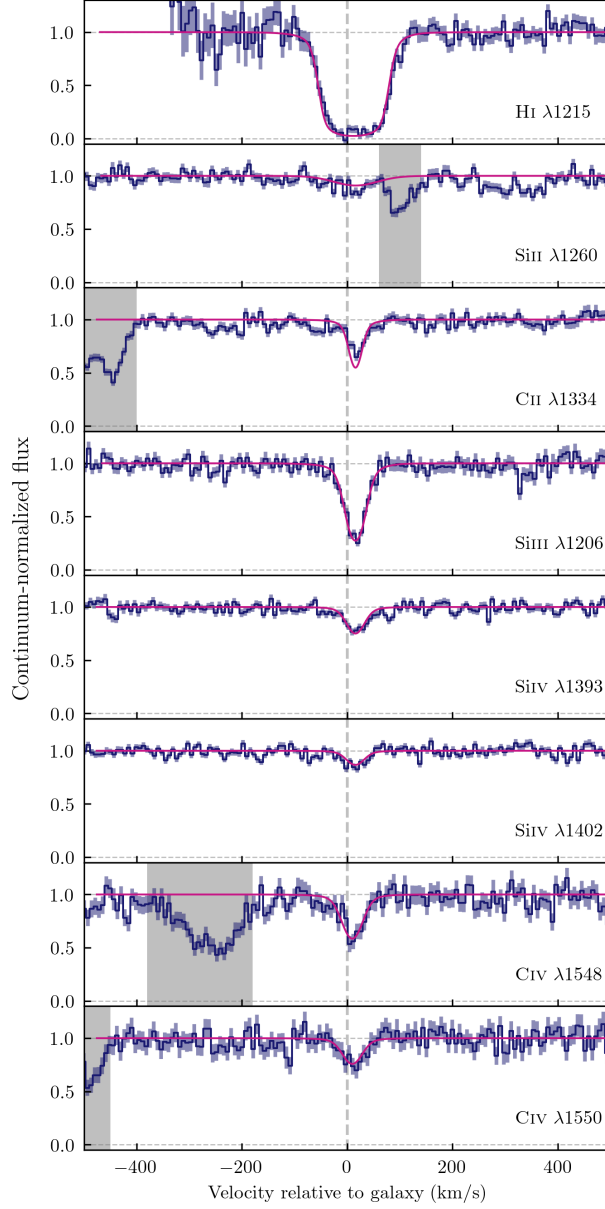


Figure 5.3: A suite of absorption transitions identified at $d_{\text{proj}} \approx 7$ kpc (or $\approx 0.14 R_{200}$) from UGC4527, a dwarf galaxy of $\log M_{\text{star}}/M_{\odot} \approx 7.6$ at $z = 0.00242$ (or $cz \approx 725$ km s $^{-1}$; see Table 5.1). Zero velocity corresponds to the systemic redshift of the galaxy (see Section 5.3.2 and Table 5.1). In addition to H I at the top, we detect moderately strong ionic transitions due to Si II, C II, Si III, Si IV, and C IV (from top to bottom). Gray regions demarcate absorption not associated with the relevant line, while best-fit Voigt profile models are overplotted in pink.

1550, Si II 1260, 1304, 1526, Si III 1206, and Si IV 1392, 1402 (see Figure 5.3 for an example and Figures C.7, C.8, and C.9 for the full sample). We perform a Voigt profile analysis of all absorption features following the steps described in Qu et al. (2026) and adopting the minimum number of components necessary to capture the observed asymmetries of the absorption profiles.

Along all but two of the QUEST Dwarfs sightlines, H I Ly α absorption is detected at the redshifts of the dwarfs. For LeG 26, the Ly α absorption is contaminated by strong and complex absorption features due to Ne IV 543 originating in the high-speed outflows from the background QSO, 2MASS J10512569+1247462. In addition, the sightline toward LBQS 0107–0232 around PGC 4143 has no COS G130M data available for placing constraints at wavelengths below 1450 Å (see Table 5.3). Incidentally, this dwarf has two additional sightlines probing its CGM at two other locations, and both exhibit a strong Ly α absorption feature. Because Ly α is a strong transition and, in seven cases, saturated, and the available *FUSE* spectra are not of sufficiently high quality to constrain $N(\text{HI})$ based on the flux discontinuity at the Lyman limit, we are only able to place a $2\text{-}\sigma$ lower limit to $N(\text{HI})$ for these saturated Ly α absorbers. For the remaining eight sightlines through seven dwarf halos, we can determine $N(\text{HI})$, and its associated $1\text{-}\sigma$ uncertainties based on the Voigt profile analysis. For each H I absorber, we search for associated ionic transitions and perform a Voigt profile analysis, using the consistent line centroid of the H I line. In cases when the ionic transitions are not detected, we report a $2\text{-}\sigma$ upper limit to the underlying ionic column densities for a fixed Doppler velocity width of 15 km s^{-1} (typical of the line widths observed in low-ionization transitions; see e.g., Zahedy et al., 2019, 2021; Qu et al., 2022), using a Bayesian framework described in Qu et al. (2022, see also Zahedy et al. 2021). We report all available column density measurements and their associated uncertainties in each dwarf galaxy halo in Table 5.6. The absorption profiles for different absorption species detected in the vicinity of UGC4527 are presented in Figure 5.3 for illustration. The remaining sightlines

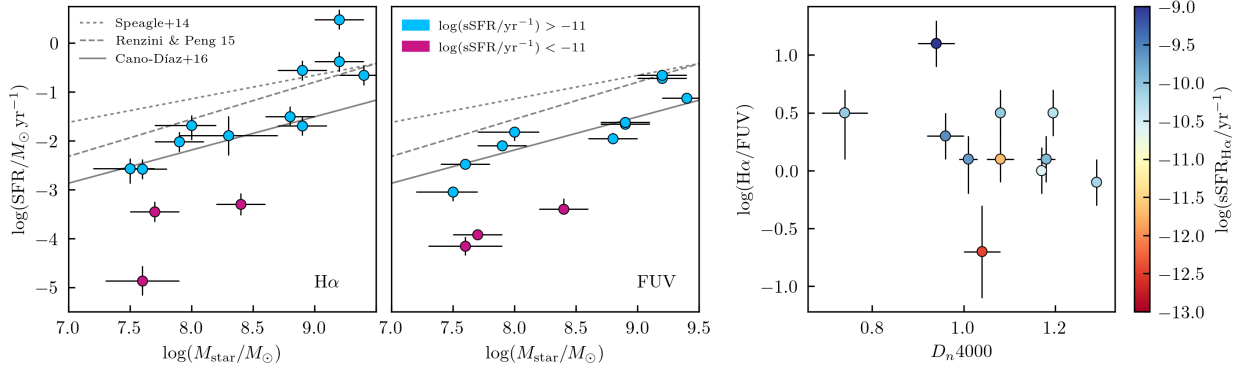


Figure 5.4: Summary of the star formation histories of the first release QUEST Dwarfs sample. The best-fit $z = 0$ star-forming sequence from Speagle et al. (2014), Renzini & Peng (2015), and Cano-Díaz et al. (2016) compared to the presented sample of galaxies. $H\alpha$ -derived SFRs are shown at left, and FUV SFRs are shown in the central panel. Galaxies are colored according to whether they are star-forming (blue) or quiescent (pink). The recent star formation history of each galaxy, as described by $\log(H\alpha/FUV)$, compared to the measured $4000\text{\AA}$ line break is shown at right. As expected, more quiescent with $\log sSFR/\text{yr}^{-1} < -11$ exhibit a significant $4000\text{-\AA}$ break. However, little correlation is found between D_n4000 and individual SFR indicators.

are presented in the Appendix for completeness.

Note that absorption measurements of C II, C IV, Si II, and Si III associated with UGC 7485 in the FUV spectrum of QSO 4C21.35 (PG1222+216) were previously reported by Zheng et al. (2024), with non-detections for both H I and Si IV. We measure the H I absorption directly and place more stringent upper limits on the remaining ions, C II, C IV, and Si II-Si IV. Although the data presented here are archival, all other sightlines are newly analyzed for absorption by the target dwarf galaxies.

5.5 Discussion

A primary goal of the QUEST Dwarfs program is to establish a dataset that enables comprehensive studies of the baryon cycle in low-mass galaxies, from star formation and feedback within galaxies to the interplay between their interstellar media, stellar populations, and gaseous halos. As an initial step, we have constructed the first release QUEST Dwarfs sam-

ple of 14 galaxies, measured their spectral and photometric properties, and placed sensitive constraints on their CGM based on available archival FUV spectra of the background QSOs. Here we first place the QUEST Dwarfs sample in the broader context of the larger galaxy population by examining fundamental scaling relations, including the stellar and gas-phase mass–metallicity relations (MZR) and the star-forming main sequence (e.g., Noeske et al., 2007), to assess whether the sample exhibits the expected trends observed in nearby galaxies. We then continue to investigate the connections between galaxy properties and CGM absorption properties.

5.5.1 *Star formation and chemical enrichment in QUEST Dwarfs*

We first examine the star formation history of the first release QUEST Dwarfs by comparing the inferred SFR and stellar mass in Figure 5.4 (two left panels). In comparison to published relations for the local galaxy populations from Speagle et al. (2014), Renzini & Peng (2015), and Cano-Díaz et al. (2016), 11 of the 14 galaxies in this first-release sample are consistent with expectations from the star-forming main sequence, while three are qualified quiescent galaxies with $\log \text{sSFR}/\text{yr}^{-1} < -11$. While FUV-inferred SFRs, which are expected to reflect the mean SFR on time scales of 100 Myr or longer, tend to be systematically lower⁹ than the $\text{H}\alpha$ -inferred SFRs, the division between quiescent and star-forming in the QUEST Dwarfs sample remains clear.

We also compare $\log(\text{H}\alpha/\text{FUV})$ and D_n4000 in the right panel of Figure 5.4. The ratio between $\text{H}\alpha$ and FUV continuum is adopted as a proxy for tracking the recent star formation history of the galaxies. At the same time, D_n4000 is often used as an indicator of stellar population age (e.g., Bruzual A., 1983), although it is also sensitive to stellar metallicity

9. Both $\text{H}\alpha$ and the FUV star formation rates may need to be revised downward to account for sub-solar $[\text{Fe}/\text{H}]$, with rough estimates suggesting that for a galaxy with $[\text{Fe}/\text{H}] = -1$, FUV SFRs are overestimated by 0.07 dex and $\text{H}\alpha$ SFRs are overestimated by 0.4 dex (Kennicutt & Evans, 2012). Given uncertainties on these corrections, we do not adopt them here; however, corrections of that nature alleviate some of the discrepancy between the two SFR indicators, while making tighter the correlation between $\log \text{H}\alpha/\text{FUV}$ and D_n4000 .

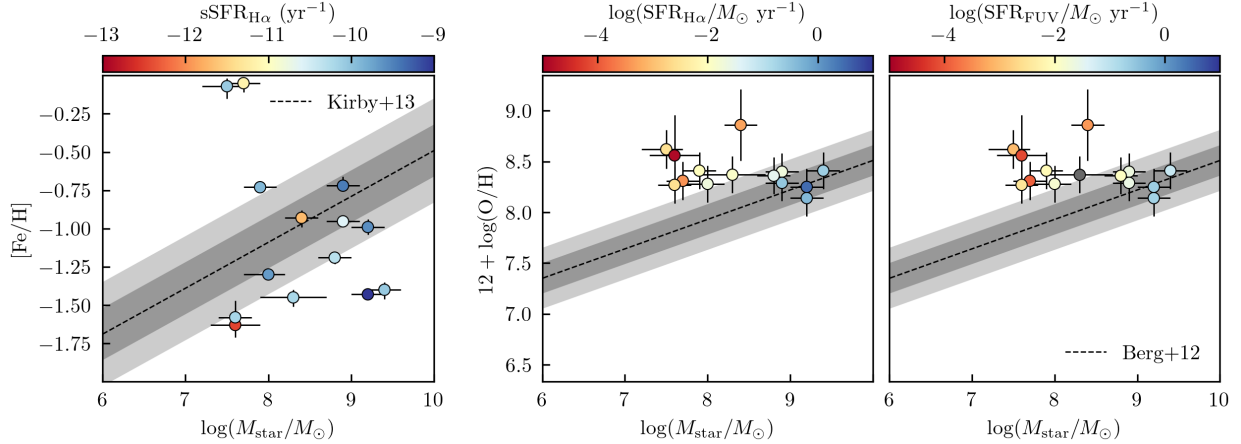


Figure 5.5: The low-mass stellar (Kirby et al., 2013, left) and gas-phase (Berg et al., 2012, middle and right) mass-metallicity relation compared to the metallicities reported for the first release subsample of QUEST Dwarf galaxies, at *left* colored by the specific star formation rate over the last ~ 10 Myr, *middle* colored by SFR over the last ~ 10 Myr, and *right* colored by SFR over the last ~ 100 Myr. Note that the two very high $[\text{Fe}/\text{H}] \sim 0$ galaxies only have Keck/LRIS spectra available, for which the calibrations on the blue side are uncertain. As **Bagpipes** takes the shape of the continuum into account in fitting, those metallicities are likely more uncertain than is expressed by the error bar. Gas-phase metallicity scales inversely with star formation rate.

given that the flux discontinuity is a result of line blanketing of a large number of metal lines (e.g., Balogh et al., 1999). Notably, there is little correlation between the D_n4000 and individual SFR indicators for these galaxies, nor with $\log \text{H}\alpha/\text{FUV}$ (see Tables 5.5 and C.2, and Figure 5.4). Such a lack of correlation between D_n4000 and the star-formation indicators may reflect the combined effects of age and metallicity, as D_n4000 is sensitive to both stellar population age and metal-line blanketing (e.g., Balogh et al., 1999). The broad range of stellar metallicities in the QUEST Dwarfs sample ($-2 \lesssim [\text{Fe}/\text{H}] \lesssim 0$, see Table 5.5) may therefore contribute to the observed scatter.

In Figure 5.5, we compare the stellar metallicity, $[\text{Fe}/\text{H}]$, fit by **Bagpipes** and ISM gas-phase metallicity $12 + \log(\text{O}/\text{H})$ inferred from the N_2 line ratio following Pettini & Pagel (2004) to well-established mass-metallicity relations (Berg et al., 2012; Kirby et al., 2013). Considering the stellar and ISM gas-phase MZR is necessary as they exhibit

different slopes in this low-mass regime. The stellar MZR in the QUEST Dwarfs sample follows the declining trend observed in nearby field dwarfs (e.g., Kirby et al., 2013), with the exception of UGCA 285 and LeG 26. Both galaxies’ analysis was done with archival LRIS data that have uncertain blue flux calibrations, resulting in poorly constrained continuum shapes below $\sim 5000 \text{ \AA}$. Combined with degeneracies between stellar metallicity and star formation history in the `Bagpipes` fits, this likely contributes to the observed metallicity offsets of $\lesssim 0.3$ dex.

The inferred gas-phase metallicities measured for star-forming galaxies in our sample show a flat distribution with an apparent floor at $12 + \log(\text{O}/\text{H}) \approx 8.0$, although they are consistent with the Berg et al. (2012) MZR given relatively large measurement uncertainties. The constant gas-phase metallicity over the stellar mass range in our sample may be a result of applying integrated nebular line fluxes across the full extent of the galaxies (see Section 5.2). In the presence of metallicity variations or metallicity gradients (e.g., Sánchez et al., 2014; Li et al., 2025) within individual galaxies, the integrated ion line fluxes could be influenced by the most metal-enriched regions with the strongest [N II] lines. We will explore such potential bias in follow-up spatially resolved studies (e.g., Bardon Soto et al., 2026, in preparation). For quiescent galaxies, our gas-phase inferred metallicities are more likely upper limits, even when measurements of the N_2 ratio can be made. At the same time, the N/O ratio may flatten at low metallicities (e.g., Strom et al., 2018), though the regime in which this seems to occur is $\gtrsim 0.2$ dex below our galaxies’ apparent $12 + \log(\text{O}/\text{H})$ floor.

In summary, the QUEST Dwarfs sample is broadly representative of low-metallicity field dwarf galaxies. Most galaxies in the sample lie on the star-forming main sequence, while three are classified as quiescent based on their low specific star formation rates. The stellar and gas-phase metallicities are generally consistent with established mass–metallicity relations for nearby dwarf galaxies, although the current sample size and measurement uncertainties limit a more detailed assessment of intrinsic scatter and secondary trends.

5.5.2 *The correlation between CGM properties and galaxy properties*

Having established the star formation histories of the QUEST Dwarfs, we next examine the connection between galaxies and the surrounding CGM through the distribution of chemically enriched gas. Silicon is particularly well suited for this purpose because the available FUV spectra encompass the dominant ionization states, Si II, Si III, and Si IV (e.g., Muratov et al., 2017). The combined column densities of these ions provide a nearly ionization-independent measure of the silicon content of the CGM, allowing us to investigate how the metal budget and its spatial distribution relate to the stellar and ISM properties of the host galaxies (see also Johnson et al., 2017; Zheng et al., 2020; Fox et al., 2026).

Figure 5.6 presents the total silicon column density as a function of halo-radius-normalized projected distance, $d_{\text{proj}}/R_{\text{vir}}$, for the nine sightlines in which constraints on all three dominant silicon ions, Si II, Si III, and Si IV, are available. For comparison, we also include dwarf galaxies from previous studies. To explore the physical drivers of the observed spatial distribution, the data are color-coded by stellar mass, recent star formation history ($\log[\text{H}\alpha/\text{FUV}]$), and gas-phase metallicity ($12 + \log(\text{O}/\text{H})$) in the left, middle, and right panels, respectively.

The inclusion of the QUEST Dwarfs has increased by nearly a factor of three the number of available probes of the inner CGM ($d_{\text{proj}} < 0.3 R_{\text{vir}}$) in low-mass halos, enabling a more robust characterization of the radial distribution of metals. Consistent with previous studies, the total silicon column density, combining Si^+ , Si^{2+} , and Si^{3+} , declines rapidly with increasing halo-radius-normalized projected distance. Four of the 10 sightlines within $0.3, R_{\text{vir}}$ exhibit a total silicon column density exceeding $\log N(\text{Si II-IV}) = 13.5$, corresponding to a covering fraction of $\kappa_{\text{Si}} = 0.40^{+0.20}_{-0.18}$, whereas only one of the 16 sightlines at $0.3 \leq d_{\text{proj}}/R_{\text{vir}} \leq 1$ exceeds this threshold, corresponding to $\kappa_{\text{Si}} = 0.06^{+0.13}_{-0.05}$. In contrast, strong $\text{Ly}\alpha$ absorption remains common throughout the halo. Ten of the 11 sightlines within $0.3, R_{\text{vir}}$ exhibit $N(\text{H I}) > 10^{14} \text{ cm}^{-2}$, corresponding to a covering fraction

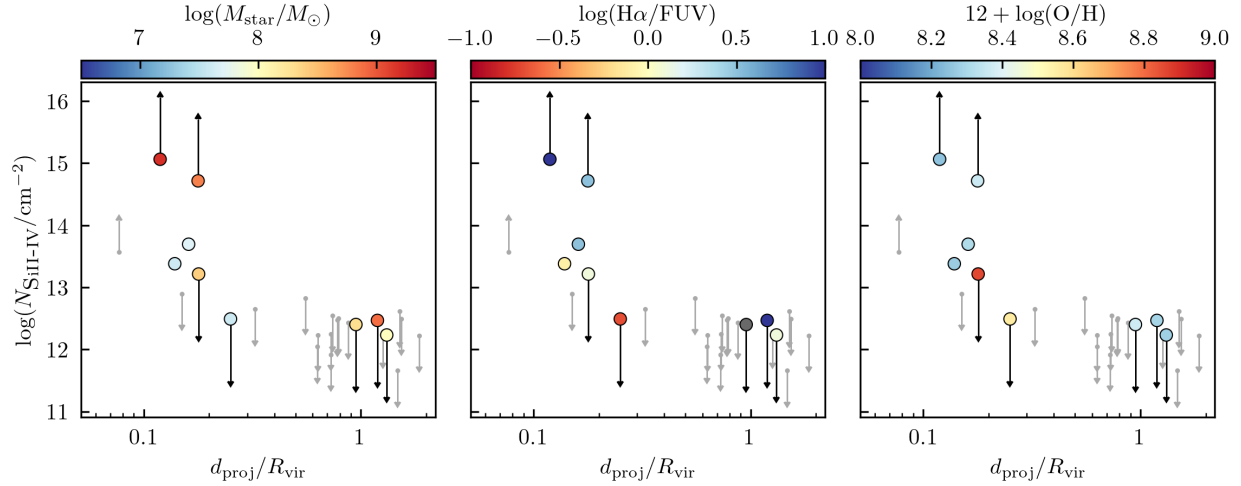


Figure 5.6: The total column density of Si from sightlines where all of Si II, Si III, and Si IV can be measured as a function of d_{proj}/R_{200} . We use total Si as a proxy for the overall metal content of the CGM. The panels are colored by stellar mass (*left*), recent star formation history ($\log(\text{H}\alpha/\text{FUV})$; *center*), and gas-phase metallicity ($12 + \log(\text{O}/\text{H})$; *right*). Literature values for dwarf galaxies outside of the Local Group (from Bordoloi et al., 2014, 2018; Liang & Chen, 2014; Johnson et al., 2017, 2026; Zheng et al., 2024; Mishra et al., 2024) are shown as light gray points.

of $\kappa_{\text{HI}} = 0.91^{+0.07}_{-0.18}$, while 18 of the 24 sightlines at $0.3 \leq d_{\text{proj}}/R_{\text{vir}} \leq 1$ satisfy the same criterion, yielding $\kappa_{\text{HI}} = 0.75^{+0.09}_{-0.12}$. For a halo gas density that declines with radius (e.g., Zahedy et al., 2019; Qu et al., 2023), the neutral fraction of hydrogen should also decrease outward. The observed H I distribution therefore likely underestimates the true extent of the total hydrogen reservoir, implying that the contrast between the radial distributions of metals and gas is even stronger than suggested by the H I measurements alone. Together, these results indicate that chemically enriched cool gas is preferentially concentrated in the inner CGM, while the diffuse hydrogen reservoir extends well beyond R_{vir} .

Superimposed on this radial trend, a clear dependence on stellar mass emerges: at a fixed $d_{\text{proj}}/R_{\text{vir}}$, more massive galaxies tend to exhibit higher silicon column densities, in agreement with expectations from cosmological simulations (e.g., Schaye et al., 2015; Zheng et al., 2024; Piacitelli et al., 2025). While previous observational studies have reported mixed evidence regarding the role of stellar mass in regulating CGM metal absorption (e.g., Zheng

et al., 2024), the first-release QUEST Dwarfs sample substantially improves coverage within $0.3 R_{\text{vir}}$, where the mass dependence becomes particularly apparent. Together, these results suggest that both projected distance and galaxy mass play important roles in determining the silicon content of the CGM, with distance governing the overall radial decline and stellar mass setting the normalization of the silicon column density profile.

At the same time, galaxies with elevated $\log(\text{H}\alpha/\text{FUV})$, indicative of recent enhancements in star formation activity, and perhaps also lower gas-phase metallicities appear to exhibit higher silicon column densities. However, because SFR and stellar mass are strongly correlated along the star-forming main sequence (Figure 5.4), we cannot determine from the current sample whether these trends reflect an independent dependence on recent star formation history or are simply a manifestation of the stellar-mass dependence discussed above. An additional quantity to consider is the possible azimuthal dependence of metal column density relative to the minor axis of star-forming disks, where conical outflows may elevate the observed metal content (see e.g., Bordoloi et al., 2011; Péroux et al., 2020). However, our sample remains too small for drawing a definitive conclusion. While the QSO sightline appears to pass close to the minor axis of LEDA 1722581, one of the two galaxies with the strongest total observed silicon column densities, NGC 5486 appears to be nearly face-on and a robust measurement of the azimuthal alignment is challenging (see e.g., Venkat et al., 2025).

5.5.3 *Chemical enrichment in the vicinities of low-mass dwarf galaxies*

The QUEST dwarf sample also provides a preliminary estimate of the total Si (and metal) mass residing in the inner halo of dwarf galaxies. In all, there are seven sightlines within $1/3 R_{\text{vir}}$ with measurements or limits on three of silicon ionization stages, Si II, Si III, and Si IV (see Figure 5.6), including both the QUEST Dwarfs and the existing dwarf galaxy literature sample outside of the Local Group. Because of the correlation between galaxy

stellar mass and absorber strength described in Section 5.5.2, we divide these galaxies into “low-mass” ($\log M_{\text{star}}/M_{\odot} < 8$) and “high-mass” ($\log M_{\text{star}}/M_{\odot} \geq 8$) populations, with each bin containing three and four sightlines respectively. For the low-mass subsample with a median stellar mass of $\langle \log M_{\text{star}}/M_{\odot} \rangle_{\text{med}} = 7.6$ and corresponding $R_{\text{vir}} = 52.0$ kpc, two of the three sightlines have $N_{\text{Si}} > 10^{13} \text{ cm}^{-2}$, corresponding to a covering fraction of $\kappa_{\text{Si}} \sim 0.66$ for gas exceeding this N_{Si} threshold. We estimate a total enclosed Si mass of $\log M_{\text{Si II-IV}}(< 0.3 R_{\text{vir}})/M_{\odot} \approx 3.2$, which is comparable to the silicon ion mass found in dwarf CGM by Zheng et al. (2024) for a nearby dwarf galaxy sample with a median stellar mass of $\langle \log M_{\text{star}}/M_{\odot} \rangle_{\text{med}} \approx 8$ but a factor of three greater than what is reported in the inner halo ($d_{\text{proj}}/R_{\text{vir}} \leq 0.15$) of the Local Group dwarf Sextans B by Fox et al. (2026). While the three ionization stages combined are commonly assumed to recover nearly the total underlying silicon abundance, up to 50% of silicon may reside in higher ionization stages in photoionized gas with densities below $n_{\text{H}} = 0.001 \text{ cm}^{-3}$ (e.g., Chen et al., 2017). Applying this ionization correction to the observed mass in Si II–IV, we infer a total silicon mass of $\log M_{\text{Si}}(< 0.3, R_{\text{vir}})/M_{\odot} \approx 3.5$ around a dwarf galaxy of $\log M_{\text{star}}/M_{\odot} \approx 7.6$. Assuming a solar-like abundance pattern (Asplund et al., 2009), this total silicon mass corresponds to a total metal mass of $\log M_{\text{Z}}(< 0.3, R_{\text{vir}})/M_{\odot} \approx 4.8$ in these low-mass halos.

The high-mass subsample with $\langle \log M_{\text{star}}/M_{\odot} \rangle_{\text{med}} = 8.6$ and $R_{\text{vir}} = 78.9$ kpc has two of four sightlines with $N_{\text{Si}} > 10^{14.5} \text{ cm}^{-2}$, corresponding to a covering fraction of $\kappa_{\text{Si}} \sim 0.5$ for these high Si column density absorbers. We estimate a total enclosed mass of $\log M_{\text{Si II-IV}}(< 0.3 R_{\text{vir}})/M_{\odot} \approx 4.9$ or $M_{\text{Si}}(< 0.3 R_{\text{vir}})/M_{\odot} \approx 5.2$ after accounting for silicons in still higher ionization stages. This is a factor of $\sim 3 - 10$ higher than what was found in Johnson et al. (2017) but similar to the Si mass inferred for the Local Group dwarf IC 1613 with $M_{\text{star}} \approx 10^8 M_{\odot}$ (see e.g., Zheng et al., 2020). This corresponds to $\log M_{\text{Z}}(< 0.3 R_{\text{vir}})/M_{\odot} \approx 6.5$ for high-mass dwarf galaxies.

Adopting the nucleosynthetic yields summarized in Vincenzo et al. (2016), we find that

for low-mass dwarf galaxies, the cool CGM probed by low-ions contains $\approx 3\%$ of the total metals produced over the lifetime of the galaxy; for high-mass dwarf galaxies, these numbers are a factor of ~ 5 higher, with the inner cool CGM retaining $\approx 16\%$ of the total metals produced by the galaxies. We note, however, that the multiphase nature of the CGM (e.g., Chen & Zahedy, 2026) precludes a complete baryon census from any single ion. A global ionization gradient, in which low-ionization absorption declines more rapidly with radius than higher-ionization species (e.g., Liang & Chen, 2014, see also Figure 5.7 below), requires multiple ionic tracers to probe the increasingly larger volume at greater halo radii. Indeed, O VI surveys have uncovered substantial reservoirs in the outer CGM and beyond, with the mass in O⁵⁺ alone comparable to that traced by the low ions (see McQuinn et al., 2026, for a recent review). Given an O⁵⁺ fraction of at most $\approx 20\%$, these observations imply a substantially larger metal reservoir in the highly ionized CGM. At large radii, however, absorption measurements are increasingly susceptible to contamination from correlated halos projected along the line of sight (Ho et al., 2021). Together, these considerations highlight the challenge of achieving a complete metal census across the full spatial and ionization extent of the CGM.

We also examine the spatial distributions of individual ionic species. Figure 5.7 presents the column densities of H I, Si II, C II, Si III, Si IV, and C IV as a function of halo-radius-normalized projected distance, $d_{\text{proj}}/R_{\text{vir}}$, from top left to bottom right. The data points are color-coded by stellar mass, while analogous figures color-coded by $\log(\text{H}\alpha/\text{FUV})$ and gas-phase metallicity are presented in Appendix C.4.

Consistent with previous studies of more massive halos, neutral hydrogen is detected throughout the halo and beyond R_{vir} , indicating the presence of an extended reservoir of circumgalactic gas. In contrast, low-ionization species such as Si II, C II, and Si III are preferentially found in the inner CGM at $d_{\text{proj}} \lesssim 0.3 R_{\text{vir}}$, where the largest column densities are observed (e.g., Liang & Chen, 2014). Higher-ionization species, particularly Si IV and C IV,

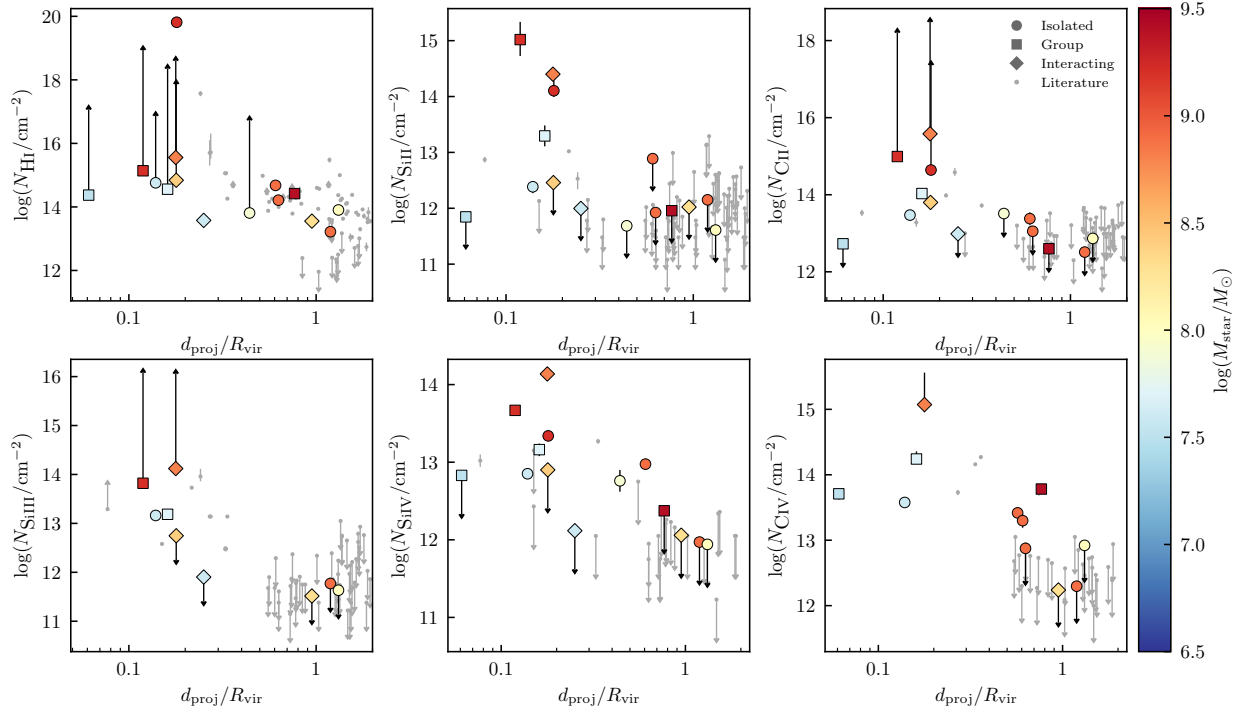


Figure 5.7: The column density of different ions along the sightlines near our first release subsample of QUEST Dwarf galaxies. With this preview of just $\sim 20\%$ of our full sample, we are beginning to meaningfully populate the absorption properties of the inner CGM ($d_{\text{proj}}/R_{\text{vir}} \lesssim 0.5$) of dwarf galaxies. Literature data are from the high SNR ($S/N > 8$) subset of the Zheng et al. (2024) compilation (Bordoloi et al., 2014, 2018; Liang & Chen, 2014; Johnson et al., 2017), Mishra et al. (2024), and Johnson et al. (2026), showing only dwarf galaxies outside of the Local Group.

exhibit a substantially shallower radial decline and remain detectable to larger projected distances. Together, these trends point to a systematic ionization gradient within the CGM, in which cool, low-ionization gas is concentrated toward the inner halo while more highly ionized gas occupies a larger fraction of the halo volume (see also Chen et al., 2001; Kong et al., 2026). Notably, the stellar-mass dependence is visible in nearly every ion, especially for Si II, C II, and C IV.

In summary, our analysis suggests that both halo-scale and galaxy-scale processes govern the metal-bearing CGM of dwarf galaxies. The spatial distributions of individual ions reveal a multiphase structure, with low-ionization species concentrated toward the inner halo and

higher-ionization species extending to larger projected distances. Galaxies with larger stellar masses also consistently exhibit stronger metal absorption at fixed $d_{\text{proj}}/R_{\text{vir}}$, indicating that stellar mass plays an important role in setting the overall metal content of the CGM. While there are tentative indications that recent star formation activity and gas-phase metallicity may also influence absorber strength, the current sample does not permit disentangling these effects from the strong covariance among galaxy mass, star formation, and chemical enrichment. The inferred metal masses should therefore be regarded as uncertain lower limits on the total CGM metal budget, particularly given its multiphase nature (see, e.g., Faucher-Giguère & Oh, 2023). While Si II–Si IV primarily trace cool, photoionized gas at $T \sim 10^4$ K, more highly ionized species such as O VI probe lower-density and warmer gas (e.g., Chen & Zahedy, 2026) and may account for $\approx 40\%$ of the metal budget around dwarf galaxies with $\log M_{\text{star}}/M_{\odot} \approx 8.4$ (e.g., Johnson et al., 2017) with an approximately equal mass traced by O VI beyond the projected virial radius (Tchernyshyov et al., 2022; Mishra et al., 2024).

At the same time, a continuous distribution of gas density and temperature likely produces some overlap between the material traced by low and high ions, complicating a simple accounting of metals across different phases. The full QUEST Dwarfs sample will substantially improve both the statistical power and parameter-space coverage needed to establish a more complete census of metals across the multiphase CGM, disentangle the roles of galaxy mass, star formation, and chemical enrichment, and distinguish among the physical processes that regulate the baryon cycle in dwarf galaxies.

5.6 Conclusions

We present initial results on the CGM properties in low-mass halos using the first-release QUEST Dwarfs sample, which contains 14 out of the main sample of > 60 dwarf galaxies with stellar mass $M_{\text{star}} \leq 10^9 M_{\odot}$ at $z \approx 0.001\text{--}0.16$. Every dwarf galaxy in the QUEST Dwarfs

sample has at least one absorption probe of its circumgalactic medium at projected distances $d_{\text{proj}} < 100$ kpc. In addition, extensive multi-wavelength imaging and spectroscopic data are available for these galaxies from both public archives and our own observations to facilitate a comprehensive stellar population synthesis study for constraining the star formation history, stellar age, metallicity, and ISM gas phase metallicity. This initial “first release” sample is selected to demonstrate the extent of science possible with this integrated dataset. We summarize the main findings below.

- The “first release” sample is broadly representative of low-metallicity field dwarf galaxies. Eleven galaxies in the sample lie on the star-forming main sequence, while three are classified as quiescent based on their low specific star formation rates. The inclusion of the first-release QUEST Dwarfs increases by nearly a factor of three the number of available probes of the inner CGM ($d_{\text{proj}} < 0.3 R_{\text{vir}}$) in low-mass halos beyond the Local Group.
- The total silicon column density, combining Si II, Si III, and Si IV, declines with increasing halo-radius-normalized projected distance, indicating that chemically enriched gas is concentrated toward the inner CGM. In addition, at a fixed $d_{\text{proj}}/R_{\text{vir}}$, more massive galaxies tend to exhibit higher silicon column densities.
- The stellar-mass dependence is visible in nearly every ion, and is especially apparent for Si II, C II, and C IV. It suggests that both projected distance and galaxy mass play important roles in determining the metal content of the CGM, with distance governing the overall radial decline and stellar mass setting the normalization of the metal column density profile.
- The spatial distributions of individual ions reveal a multiphase structure, with low-ionization species concentrated toward the inner halo and higher-ionization species extending to larger projected distances.

- While there are tentative indications that recent star formation activity and gas-phase metallicity may also influence absorber strength, the current sample does not permit disentangling these effects from the strong covariance among galaxy mass, star formation, and chemical enrichment. We anticipate that the full QUEST Dwarfs sample will substantially improve the statistical power and parameter-space coverage needed to disentangle these effects and distinguish among the different physical scenarios.
- Based on a preliminary division of literature and QUEST Dwarfs galaxies with Si II–Si IV measurements into “low-mass” ($\log M_{\text{star}}/M_{\odot} < 8$) and “high-mass” ($\log M_{\text{star}}/M_{\odot} \geq 8$) populations, we find that the cool CGM retains $\sim 3\%$ of the metals produced by low-mass dwarfs, compared to $\sim 16\%$ for high-mass dwarfs.

CHAPTER 6

FORECASTING GALAXY CLUSTER H I MASS RECOVERY WITH CHIME AT REDSHIFTS 1 AND 2 VIA THE ILLUSTRISTNG SIMULATIONS

Polzin et al. (2024c) presented as part of a thesis to the Department of Astronomy and Astrophysics, The University of Chicago, in partial fulfillment of the requirements for the Ph.D. degree.

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6.1 Introduction

The Canadian Hydrogen Intensity Mapping Experiment (CHIME; CHIME Collaboration et al. 2022a) is a cylindrical drift-scan interferometer operating between 400-800 MHz at the Dominion Radio Astrophysical Observatory in Penticton, Canada. CHIME was designed to use the redshifted 21 cm emission of neutral hydrogen to measure large scale structure via a low spatial resolution, high spectral resolution survey (referred to as intensity mapping; Battye et al. 2004; Chang et al. 2008; Wyithe & Loeb 2008; Peterson et al. 2009; Shaw et al. 2015) at frequencies corresponding to $2.5 > z > 0.8$. To this end, maps from CHIME cover ~ 60 per cent of the Northern sky daily with sub-degree angular resolution ($0.52^\circ - 0.26^\circ$ for the synthesized beam), which translates to physical scales of $50 - 10$ Mpc (Newburgh et al., 2014; CHIME Collaboration et al., 2022a).

Although the $2.5 > z > 0.8$ redshift range was selected for CHIME observations to constrain models of Dark Energy, it also corresponds to a rich era in galaxy evolution when the overall star formation efficiency is at its peak (‘Cosmic Noon’; e.g., Madau & Dickinson

2014). At these redshifts, the number density of quenched galaxies, or galaxies in which star formation has ceased, increases dramatically (e.g. Faber et al., 2007). Since the abundance of neutral hydrogen in galaxies is a robust indicator of the existing reservoir of star-forming gas content, instruments like CHIME are extremely valuable for looking at trends in this reservoir at these specific cosmic times, and could possibly be used to quantify the average H I mass of a target population from stacks.

CHIME’s redshift band and sensitivity to neutral hydrogen could provide a new probe of the integrated H I content of galaxy clusters spanning the earliest assembling clusters around $z \sim 2$ to the quenching of star formation around $z \sim 1$. At high redshift, galaxy clusters are generally thought to be gas-rich and contain large reservoirs of neutral hydrogen (e.g., Francis et al., 2001; Battye et al., 2004). There are ongoing and planned experiments aimed at studying the evolution of cluster H I in individual galaxy clusters. The Five-hundred-meter Aperture Spherical radio Telescope (FAST, Jiang et al., 2019, 2020; Qian et al., 2020) should be able to measure the H I signal from individual neutral hydrogen-rich galaxy clusters out to $z \sim 1.5$ (Ai et al., 2017). However, even the best-case projected integration times for FAST to reach the required depth are on the order of hours to days, depending upon cluster redshift, which limits potential survey scope. Data from CHIME can be used to better understand the average reservoir of neutral gas in dense environments at the population level. Such measurements potentially have the power to statistically distinguish the role of AGN feedback in driving the evolution of clusters’ neutral hydrogen reservoir and confirm whether it follows model predictions as a function of redshift (e.g., Villaescusa-Navarro et al., 2016; Tremmel et al., 2019; Dong et al., 2023).

Due to poor spatial resolution, experiments like CHIME cannot directly measure the flux from a galaxy, galaxy group, or galaxy cluster. Instead, data from CHIME has been stacked in voxels (RA, Dec, z) on known source locations from eBOSS (Dawson et al., 2016) to detect cosmological neutral hydrogen in emission line galaxies (ELGs), luminous

red galaxies (LRGs), and quasars (QSOs) (CHIME Collaboration et al., 2023), and has been correlated with Lyman-alpha emitters to detect a decrement of neutral hydrogen in absorber systems (CHIME Collaboration et al., 2024). These detections highlight that the CHIME data set in principle has access to the aggregate quantity of neutral hydrogen in sources at these intermediate redshifts. Catalogs of hundreds of clusters are already available from optical, X-ray, and CMB surveys spanning this redshift range (e.g., Bleem et al., 2015; Wen & Han, 2021; Hilton et al., 2021; Wen & Han, 2022; Bulbul et al., 2024), and with upcoming experiments like Simons Observatory (Ade et al., 2019) and CMB-S4 (Abazajian et al., 2016) coupled with follow-up enabled by *JWST*, Roman, and Lynx, we expect this number to grow substantially (Mantz et al., 2019), with thousands of clusters expected to be detected at $z \sim 1$ and hundreds expected to be detected at $z \sim 2$ with CMB-S4.

In preparation for cross-correlating CHIME data with galaxy cluster (or other) catalogs to answer questions related to galaxy evolution, or, more specifically, the evolution of the gaseous medium in and around galaxies, it is important to understand which objects actually contribute to the measured H I flux in stacked data. Our low spatial resolution ensures that we are able to measure the integrated flux from objects that fall in the beam; however, that low resolution comes with the caveat that we are not able to resolve individual objects and/or their immediate environments. Instead, structures surrounding our target objects are also likely to be included in the beam and in our stacking analyses. It is essential that we understand how much surrounding ancillary objects contaminate our stacked flux measurements. In this paper, we use the Illustris TNG300 suite of simulations of large scale structure and its neutral hydrogen content to estimate whether CHIME could be used to measure the H I content in galaxy clusters across this interesting epoch.

We assume the general cosmological parameters from Planck Collaboration et al. (2016) used by the TNG300 simulation (Pillepich et al., 2018; Springel et al., 2018; Nelson et al., 2018; Naiman et al., 2018; Marinacci et al., 2018) of the IllustrisTNG project (Nelson et al.,

2019b), $h = 0.6774$, $\Omega_M = 0.3089$, and $\Omega_\Lambda = 0.6911$, and we adopt the H I – H₂ transition prescription from Gnedin & Kravtsov (2011) to assign H I masses to each halo.

The structure of this paper is as follows: in Section 6.2, we discuss the simulated data that facilitates this analysis; in Section 6.3, we go through the steps of our stacking analysis; in Section 6.4, we lay out an example means of recovering M_{HI} from CHIME galaxy cluster stacks; and in Section 6.5, we consider the broad applicability of this work.

6.2 Simulating CHIME observations

In this section we describe how we generate a mock CHIME observation of an IllustrisTNG simulation field. This paper is meant to describe a proof-of-concept reconstruction, and so we do not follow the simulation template procedure outlined in CHIME Collaboration et al. (2023), which was used to find parameter errors on model parameters such as the 21 cm power spectrum ($P_{\text{HI},g}$), the bias of galaxy and 21 cm fields (b_g , b_{HI}), etc., and included effects such as fingers-of-god, nor do we include processing steps such as filtering and weighting. Instead, we adopt a less rigorous approach of convolving projections of the TNG300 volume with the synthesized CHIME beam shape and using that as a proxy for the stacking measurement to understand whether CHIME can in principle recover H I information from high redshift clusters.

6.2.1 TNG300 simulation from the IllustrisTNG project

We select the TNG300 simulation, part of the Illustris suite of cosmological simulations, as the parent simulation for generating our mock CHIME maps due its large volume, native inclusion of H I, and relevant redshift coverage. In the TNG300 simulation, the evolution of the gas content - both molecular and atomic hydrogen - is tracked for every sufficiently massive ($M_{\text{star}} \geq 5 \times 10^{10} M_\odot$ or $M_{\text{gas}} \geq 10^9 M_\odot$) subhalo across environments.

The TNG300 *Molecular and atomic hydrogen (HI+H2) galaxy contents* catalogs (Diemer

et al., 2018, 2019) provide the neutral hydrogen mass of each subhalo at two discrete redshifts, $z = 1$ and $z = 2$, that also overlap with the CHIME observation band. Since $z = 1.5$ (568 MHz) falls into the radio frequency interference-afflicted 500 – 585 MHz sub-band and is inaccessible to us in analysis of real CHIME data, we do not include it in our mock data analysis either. We select the Gnedin & Kravtsov (2011, alternately referred to as GK11) H I model from those included in the *Molecular and atomic hydrogen (HI+H2) galaxy contents* catalogs; the similarity of TNG300 H I abundances to observations is discussed further in Diemer et al. (2019).

With the tabulated neutral hydrogen masses for each sufficiently massive subhalo from catalogs at $z = 1$ (710 MHz) and at $z = 2$ (473 MHz), we construct mock high-resolution maps, which are then smoothed with the CHIME synthesized beam to simulate observational data.

6.2.2 Constructing a beam-like convolutional kernel

To generate the low-resolution CHIME intensity maps from high-resolution TNG300 simulations, we require a frequency-dependent synthesized beam model of CHIME. The cylindrical design of the CHIME reflector has a different cross-sectional beam profile in the North-South (N-S) and East-West (E-W) directions.

We assume an approximate form of the N-S beam shape, inspired by the triangular window function that resulted from the baseline-dependent inverse variance weighting scheme described in CHIME Collaboration et al. (2023). The triangular window function is given by:

$$W(y) = \frac{1 - |y/y_{\max}|}{\sum 1 - |y/y_{\max}|} \quad (6.1)$$

where y is the physical distance along the North-South direction in units of wavelength and $y_{\max}$ is the longest North-South baseline in units of wavelength. The N-S beam model is the Fourier transform of this window function. As is standard in radio interferometry, this

produces baseline-dependent, frequency-dependent scale on the sky.

We use the synthesized E-W beam model from CHIME Collaboration et al. (2023) at 710 MHz ($z = 1$), with a few simplifications: we have limited the beam to hour angles less than $\pm 4^\circ$ which neglects the effects of aliasing; this beam is computed by beamforming to declination $\delta = 0^\circ$, and we use only the Y -polarized beam and include only inter-cylinder baselines (baselines that span more than one cylinder). The full form of the synthesized beam is described in more detail in Section 4.3.4 of CHIME Collaboration et al. (2023). For the E-W beam at 473 MHz ($z = 2$), we use full width at half maximum (FWHM) $\propto 1/\nu$ to re-scale the 710 MHz ($z = 1$) beam model. We also interpolate the beam function to a coarser grid-size to convolve more easily with the simulations.

The two-dimensional, synthesized beam is then the outer product of the N-S and E-W cross-sections. Although this does not capture the rich structure of the CHIME beam (CHIME Collaboration et al., 2022b), the simplified beam is sufficient for the explorations in this paper as we focus here on the polarization-independent flux measured in the primary component of the synthesized beam. These beam models, both synthesized and cross-sectional, are shown in Fig. 6.1.

6.2.3 Generating mock intensity maps

Here we outline the procedure adopted to generate mock intensity maps from the simulated data. Assuming that the H I gas is optically thin in the sources we are examining, we use the formalism from Wild (1952) to derive the neutral hydrogen intensity from H I mass (Draine, 2011):

$$\left(\frac{F_{\text{obs}}}{\text{Jy MHz}} \right) = 2.022 \times 10^{-8} \left(\frac{M_{\text{HI}}}{M_\odot} \right) \left(\frac{d_L}{\text{Mpc}} \right)^{-2} \quad (6.2)$$

The observed flux, F_{obs} , is defined as the flux density integrated over the frequency range of the relevant CHIME sub-band. This flux should be equivalent to Stokes I , which combines the two linear polarizations for total intensity ($I = X^2 + Y^2$); for the purposes of this paper,

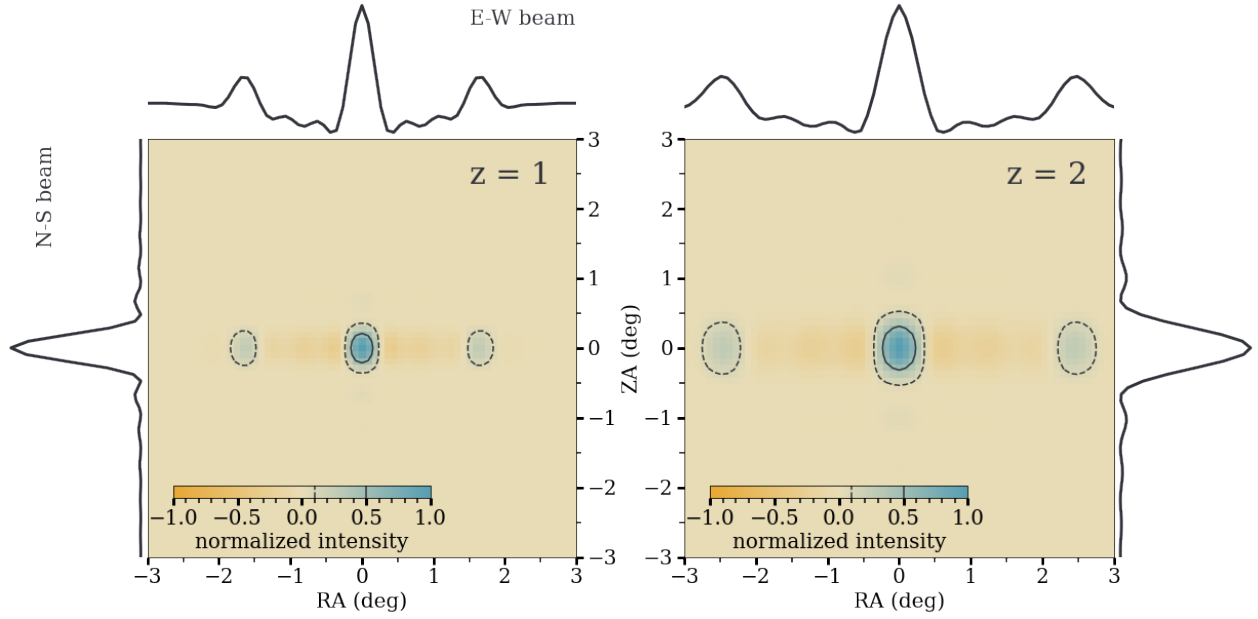


Figure 6.1: We show the cross section of synthesized beam models used in this paper along the E-W (x axis) and N-S (y axis) direction, sampled at the resolution of the stacked CHIME maps ($5'.3$ in RA and $5'.7$ in zenith angle). The synthesized beam models are used as convolutional kernels to go from a TNG300 gas mass map to a CHIME-like intensity map. *Left*: Shown for the 710 MHz ($z = 1$) synthesized beam model, which is the outer product of the E-W and N-S models. *Right*: Shown for the 473 MHz ($z = 2$) synthesized beam model.

we use the CHIME measured Y polarization beam as a proxy for the Stokes I beam due to its well-understood behavior in these two redshift regimes, noting that the two instrumental polarizations are shown to return consistent results in CHIME Collaboration et al. (2023), so that any difference in the X - and Y -polarized beams should have a negligible impact on the analysis in this work.

The luminosity distance, d_L , is defined consistent with our chosen cosmology and the simulation volume – for $z = 1$, $d_L = 6.8 \times 10^3$ to 7.0×10^3 Mpc and for $z = 2$, $d_L = 1.59 \times 10^4$ to 1.60×10^4 Mpc. We convert to flux density in Jy by dividing off the width of the CHIME frequency sub-band (0.390 MHz), which assumes that we know the spectral position of targets to within $dz \lesssim 0.001$ at $z = 1$ and $dz \lesssim 0.002$ at $z = 2$. In stacking, see Section 6.3, we assume that all objects in the mock intensity map are at $z = 1 \pm dz$ or $2 \pm dz$. Selecting a different range in redshift/frequency will impact the noise properties of the stacks as well as the observed flux. Foreground filtering strongly attenuates the signal with increasing bandwidth. To approximate this effect in our mock observations, we apply a corrective factor of 0.2 to the flux, corresponding to the mean foreground filtering attenuation between catalogs used in CHIME Collaboration et al. (2023). This is for our narrowest CHIME band, comparable to the precision of a spectroscopic catalog. More advanced foreground filtering may allow for a greater tolerance in dz in the future.

We deposit the flux from each TNG300 subhalo onto a grid matching the angular scale of CHIME map pixels ($5'.3$ in RA and $5'.7$ in Dec). The CHIME hybrid beamformed maps have a zenith angle-dependent pixel size; here we choose the highest resolution pixel scale ($5'.3 \times 5'.7$) corresponding to $ZA = 0^\circ$. Included H I sources will be further smoothed by later convolution with the low angular resolution CHIME beam.

Given the limited angular extent of each TNG300 slice at $z = 1$ and $z = 2$, we tile rotated (and flipped) versions of the same projected map to create a larger map to smooth and stack. Since we also permute the projected maps from the existing $(300 \text{ Mpc})^3$ simulation

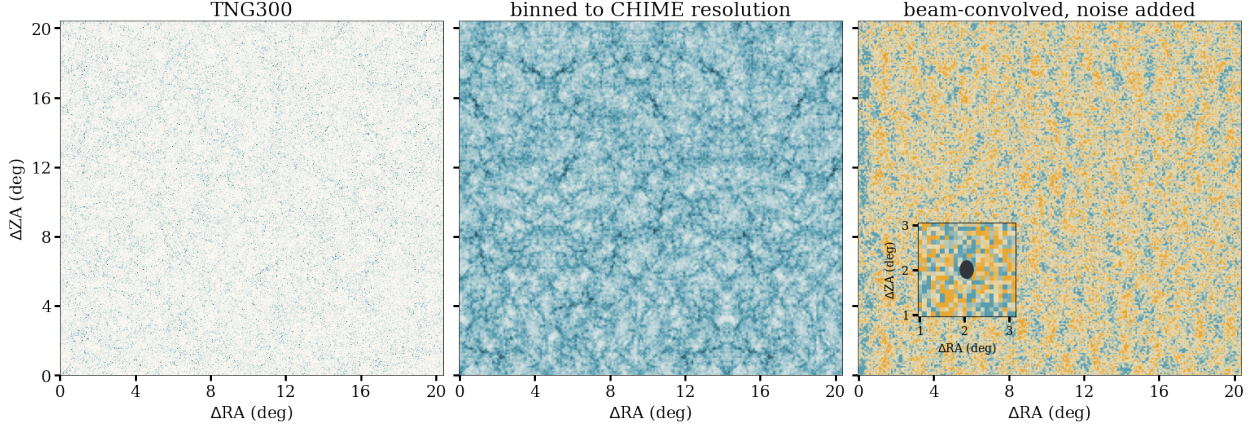


Figure 6.2: An example zoom-in region of a neutral hydrogen map at different points in processing. The leftmost panel offers a higher resolution look at the spatial distribution of TNG300 galaxies as mapped by their normalized H I flux. The middle panel shows those same galaxies binned to reflect the spatial resolution of CHIME. The rightmost panel shows the middle panel convolved with the CHIME beam (see Fig. 6.1) with CHIME-like noise added. The inset panel shows a zoomed-in region of the beam-convolved map overlaid with an ellipse representing CHIME’s primary beam FWHM. The portion of the map used here is 4 per cent of the full $z = 1$ tile that is used in our mock stacking analyses.

volume with respect to the reference position used in calculating F_{obs} , the final tiled map encompasses 384 times the area of a single projected simulation slice, totalling $\sim 4100 \text{ deg}^2$ at $z = 1$ and $\sim 1900 \text{ deg}^2$ at $z = 2$. (See Appendix D.1 for more details.) It is this larger intensity map that is then convolved with the CHIME beam model. The mock sky coverage is comparable to the extent of the eBOSS fields used in CHIME Collaboration et al. (2023). We add Gaussian noise with $\sigma = 0.6 \text{ mJy}$ (CHIME Collaboration et al., 2023) to the beam-convolved map in order to better replicate CHIME observations.

Fig. 6.2 shows the progression from the higher resolution native TNG300 mock intensity map to the beam-smoothed mock intensity map with realistic noise. We note that we do not include foreground emission, frequency masking from radio frequency interference, or point source removal. Instead, the results we present provide a proof-of-principle extraction of astrophysical neutral hydrogen in clusters from intensity mapping experiments like CHIME.

6.3 Mock stacking analyses

We stack the signal from the simulated H I maps for the two redshifts separately. For each source in the simulation, we create a two-dimensional, $6^\circ \times 6^\circ$ cutout in RA and Dec, following Section 4.7 of CHIME Collaboration et al. (2023). These cutouts are then directly co-added, returning a ‘stacked’ signal from the average of the co-added signals (see Fig. 6.3 for an example). The intensity map area of our $z = 1$ mock is comparable to the area used in the eBOSS/LRG and QSO cross-matched stacks from CHIME Collaboration et al. (2023), while the area of our $z = 2$ mock is comparable to the area used in the eBOSS/ELG cross-matched stack. We do not expect that the z -dependent difference in area impacts our ability to compare mock stacking analyses across redshifts, given that the signal we are measuring is innately normalized by virtue of averaging the stacks.

In order to isolate the contribution to the H I signal from galaxy clusters and their constituent galaxies, we create separate stacks based on our cluster population-specific maps at each redshift in addition to the full map used for much of the analysis: mass-selected galaxy clusters only and radius-selected galaxy clusters only. The specific maps and stacks are as follows:

1. *all galaxies*; stacked on all galaxies¹
2. *field galaxies*; stacked on field galaxies
3. *cluster galaxies*; stacked on cluster galaxies
4. *all clusters*; stacked on all galaxy clusters with the centre of the stack defined by the centre of mass of the halo.
5. *mass-selected clusters*; stacked on mass-selected galaxy clusters with haloes with a mass $\geq 10^{14} M_\odot$ at $z = 0$ as traced by central galaxy membership at $z = 0, 1$, and 2.

1. This first stack is intended to be more easily compared with the analysis done in CHIME Collaboration et al. (2023).

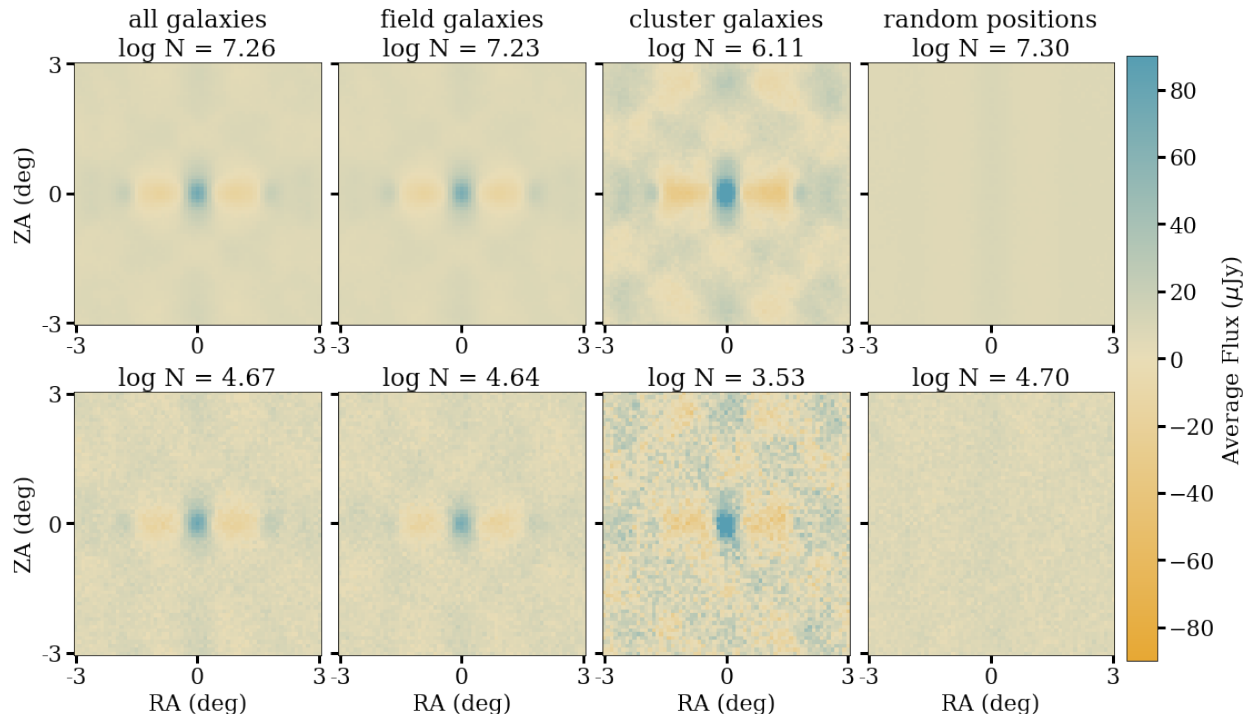


Figure 6.3: Output stacks at $z = 1$ for different galaxy populations ($M_{\text{star}} \geq 10^{10} M_{\odot}$). To demonstrate that the signal we are measuring is real, we also stack on randomly generated positions (*rightmost panels*). *Top*: The “true” stacks from TNG300, using all of the massive galaxies in simulation volume. *Bottom*: Stacks based on N randomly sample massive galaxies from the full catalogs. This less well-sampled *all galaxies* stack is directly comparable to the weighted eBOSS/QSO stack from CHIME Collaboration et al. (2023). The galaxy stacks are then sliced to make the $z = 1$ panels of Fig. 6.4.

6. *radius-selected clusters*; stacked on radius-selected galaxy clusters with haloes with comoving $R_{200} > 0.75 h^{-1}$ Mpc, independently determined for $z = 1$ and $z = 2$.

7. *random positions*; stacked on N random locations.

The two cluster selection criteria are intended to ensure that we are accounting for proto-clusters that should be present at $z = 2$ as expected in the Λ CDM cosmology (mock catalog construction is detailed further in Appendix D.2).

We define field galaxies as subhaloes which do not belong to a group designated as a cluster (due to either mass or radius selection).

Though all galaxies down to TNG300’s mass resolution limit for the *Molecular and atomic*

hydrogen galaxy contents catalog ($M_{\text{star}} \geq 5 \times 10^{10} M_{\odot}$ or $M_{\text{gas}} \geq 10^9 M_{\odot}$) are included in the maps, those maps are only stacked on galaxies with $M_{\text{star}} \geq 10^{10} M_{\odot}$ (as defined by the *SubhaloStellarPhotometricsMassInRad* group catalog field); this roughly corresponds to the lowest mass bin in the eBOSS ELG sample (e.g. Guo et al., 2019).

We show example stacks in Fig. 6.3. The top row includes stacks (i) - (iii) and (vii) on the full catalog returned for the simulation volume, and the bottom row shows the same stacks for a more realistic number of randomly selected galaxies in the simulation volume. These realistic stacks are directly comparable to those in CHIME Collaboration et al. (2023), including the same number of target galaxies. The amplitude of the stacked signal is equivalent between the full catalog and realistic stacks, with the noise properties varying as predicted based on the number of targets used in each stack. The implications of stacking on unresolved target source is described in Section 6.4.

6.4 Results

6.4.1 Neutral hydrogen environment

The results of stacks (i) - (iii) are shown in Fig. 6.4, where it is apparent that the measured average neutral hydrogen flux is higher from galaxies associated with clusters than from field galaxies. We found this was explained by the crowded cluster environment causing 'source confusion': the CHIME beam is large enough to encapsulate all galaxies in the cluster², such that we are adding the flux from all galaxies in the cluster each time we stack on a single galaxy in the cluster. This means we measure the aggregate H I emission from all galaxies, not the average H I per galaxy, in these stacks. As a result, environments with more galaxies have a higher stacked signal than environments with fewer galaxies (such as the field galaxies). This is consistent with Fig. 6.5, which shows the results for stacks (iv) -

2. The primary beam has a resolution of $\approx 10 - 20$ Mpc, while clusters are $\approx 0.5 - 1$ Mpc in radius in this redshift range.

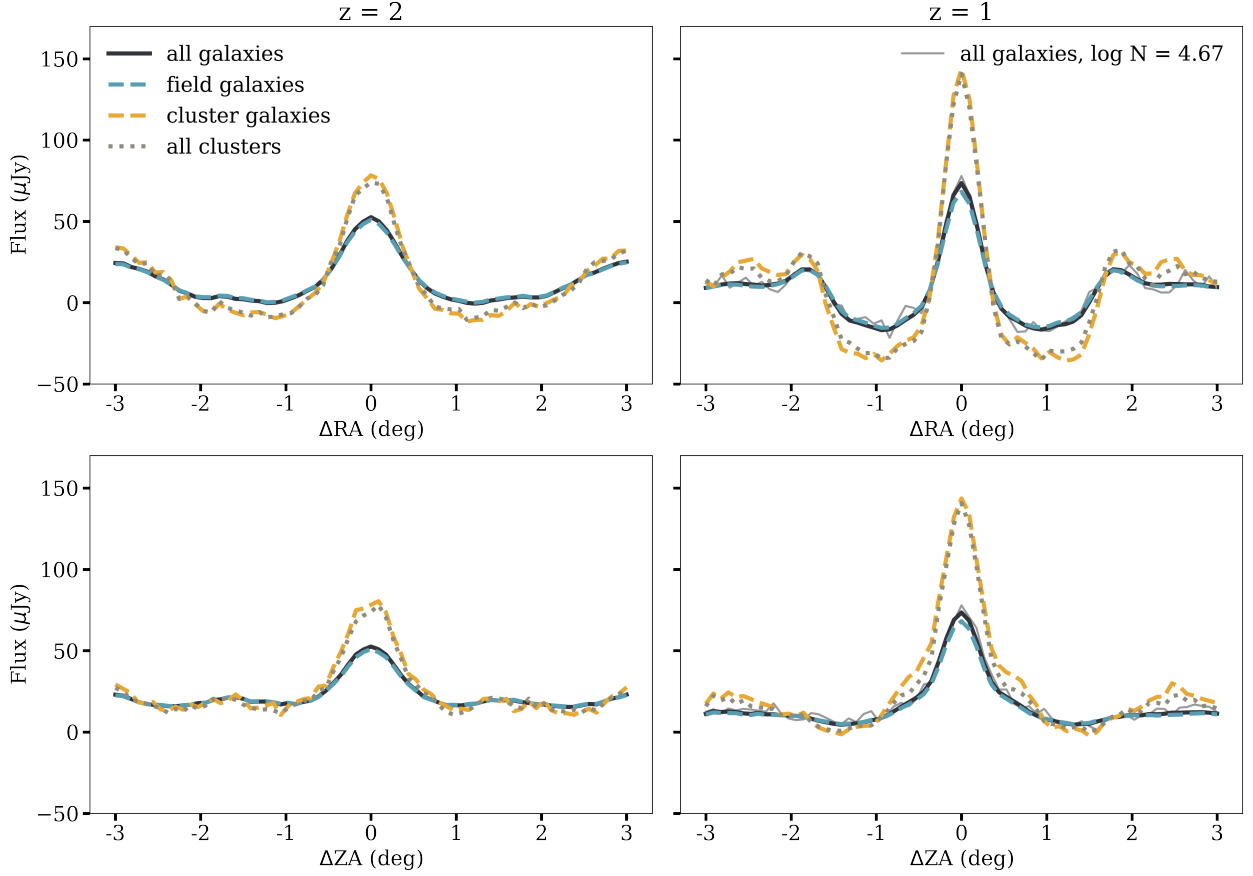


Figure 6.4: The results of our stacking, as described in Section 6.3, on the locations of all individual galaxies/subhaloes in the TNG300 volume that meet our minimum $M_{\text{star}} \geq 10^{10} M_{\odot}$ threshold. The upper panel shows the stacks sliced along the central pixel in ZA, and the bottom panel shows the stacks sliced along the central pixel in RA. At left, we show the $z = 2$ stacks and at right, we show the $z = 1$ stacks. The disparity between stacks on field and cluster galaxies is likely due to more galaxies in the crowded cluster environments falling into the CHIME beam. That is, stacking on cluster galaxies returns the H I signal from the galaxy clusters themselves. This is shown by the dotted “all clusters” curve matching the flux returned by stacking on cluster galaxies. Alongside the full $z = 1$ stacks, we also show a less well-sampled *all galaxies* stack that is directly comparable to the weighted eBOSS/QSO stack from CHIME Collaboration et al. (2023). It is apparent that the measured peak flux is the same between this stack and the “true” *all galaxies* stack, while the noise properties are somewhat different.

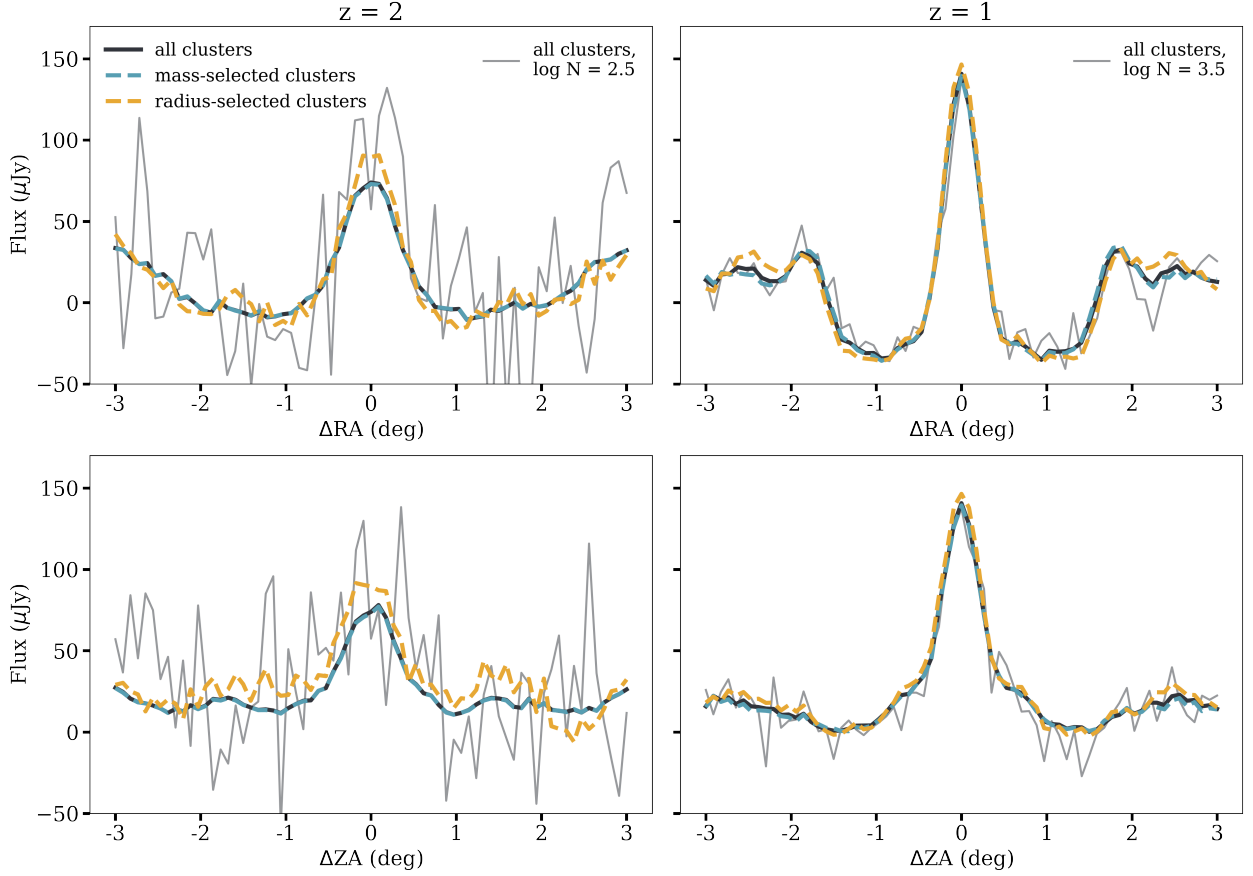


Figure 6.5: The results of our stacking, as described in Section 6.3, on the locations of cluster-identified haloes. The upper panel shows the stacks sliced along the central pixel in RA, and the bottom panel shows the stacks sliced along the central pixel in Dec. At left, we show the $z = 2$ stacks and at right, we show the $z = 1$ stacks. Solid and dashed lines show results for the full map stacked on galaxy cluster locations. At $z = 2$ ($z = 1$), the black curve shows the stack on 106752 (118656) clusters, the blue curve shows the stack on 105984 (106368) mass-selected clusters, and the yellow curve shows the stack on 9984 (61440) radius-selected clusters in the full CHIME-like map. In addition to the “true” stacks based on all relevant sources in the TNG300 volume, we underplot example cross-sections from stacks based on 300 $z = 2$ and 3000 $z = 1$ clusters randomly selected from the full catalog (shown in gray). These stacks are consistent with the number of clusters we anticipate will be in catalogs facilitated by next-generation instruments. Notably, the shape and amplitude of the cross-sections are preserved despite the increased noise due to the small sample sizes.

(vi).

Fig. 6.4 shows the results from stacking on all galaxies in the sample at a redshift $z = 1$. That simulation is comparable in number of galaxies and mean redshift to the published CHIME results for the QSO and ELG samples. We find that the flux associated with the *all galaxies* sample indeed has a flux peak value within a factor of a few of the CHIME results from stacking on the eBOSS/QSO catalog with median $z \sim 1.2$, which is enough consistency to not impact the conclusions drawn in this paper. The disparity between the CHIME Collaboration et al. (2023) peak flux and the one measured here may come from differences in approach between simulations and real data, such as the potential for increased background flux in our convolved maps due to flattening over the entire simulation volume. In addition, we recover the shape of the co-added signal, whose negative value on each side of the peak was shown in the CHIME data and attributed to the synthesized beam which we also use in this paper.

We confirm that the cluster galaxy flux traces galaxy cluster H I by overplotting the cluster stacks on the cluster-member galaxy stacks in Fig. 6.4 where it can be seen that the stack on cluster galaxies matches the stack from cluster centre positions only. As noted above, this is a consequence of measuring the aggregate emission from all sources in the beam in the stacks. Conversely, the stack on field galaxies have lower measured average flux because the lower number counts mean there is less aggregate H I emission from that region. The field galaxy flux is comparable to the *all galaxies* flux. Because the sample size of field galaxies is $\sim 100\times$ larger than the sample size of cluster galaxies, the *all galaxies* signal is dominated by the field galaxies.

This same statistical effect is driving the similarity of the mass-selected cluster stack and the *all cluster* stack in Fig. 6.5 – at $z = 2$, 99 per cent of clusters are included in the mass-selected sample and at $z = 1$, 90 per cent of clusters are in the mass-selected sample. The very different flux between radius-selected clusters (which are selected for their properties at

$z = 1$ and 2 respectively) and mass-selected clusters (selected for their properties at $z = 0$) at $z = 2$ is indicative of the fact that radius-selected clusters are intrinsically larger and more assembled on average than mass-selected clusters at the same redshift and so radius-selected clusters are denser and will have more aggregate H I emission in the CHIME beam than the mass-selected cluster. The mass-selection criterion is intended to include proto-clusters in our analysis, as a result they are smaller and contain less H I. Thus, it is possible to look at the relative H I content of different populations of clusters (categorized based on their initial detection method or other properties) even without fully understanding an instrument’s flux calibration. This opens up opportunities to look at the ratio of average H I content between populations. If the frequency-dependent flux calibration is determined, this can also allow comparisons between redshifts.

6.4.2 *Mass recovery for complete TNG300 catalogs*

The quantity of neutral hydrogen in the intergalactic medium directly informs the evolution of the galaxies in this environment. We can use this mock CHIME analysis to study whether we can use H I flux measurements from galaxy clusters to infer their atomic neutral hydrogen mass at intermediate redshifts. As a test of this application, we compare the H I mass inferred from the stacked signal within CHIME’s primary beam and the mean H I mass of the subhaloes (Fig. 6.6) and haloes (Fig. 6.7) that were used in the construction of our mock intensity maps.

For galaxy clusters, the flux in the averaged stacks exhibit similar trends to the mean H I mass of the included haloes (i.e., that mass-selected and radius-selected clusters have approximately the same signal at $z = 1$, while at $z = 2$, radius-selected clusters have higher stacked flux and higher mean H I; Fig. 6.5 and Fig. 6.7), thus allowing us to estimate the neutral hydrogen mass from the stacked data. Using even a rough conversion to infer the mass, we find that this can be accomplished by inverting equation (6.2) and accounting for

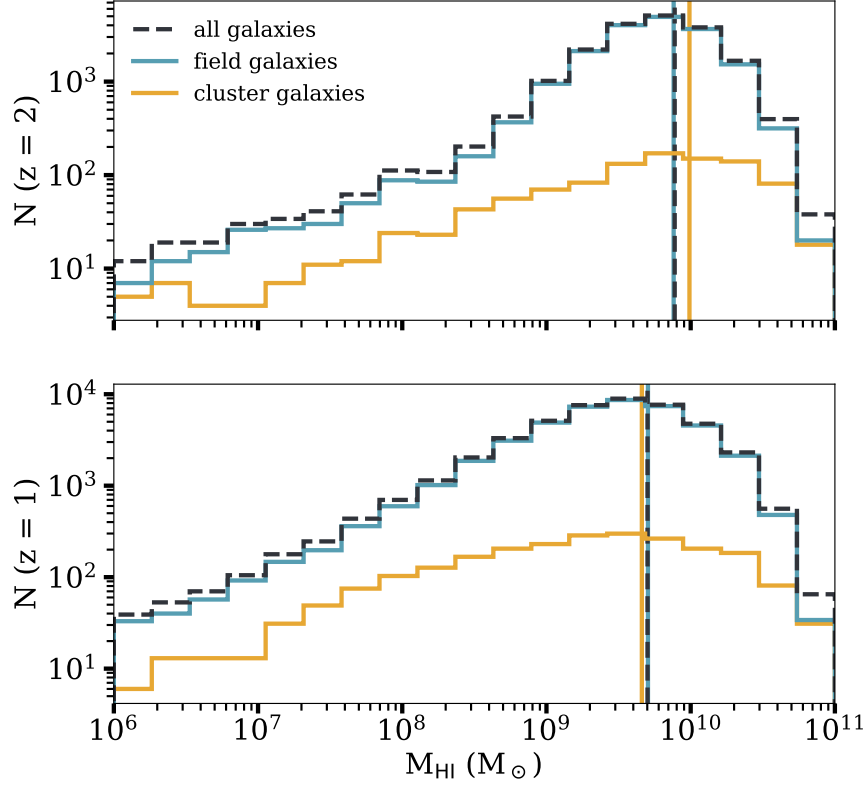


Figure 6.6: The intrinsic neutral hydrogen mass distribution from TNG300 in each of three subhalo populations – all galaxies (subhaloes), field galaxies, and cluster member galaxies – for the galaxies included in the stacks at $z = 2$ (top) and $z = 1$ (bottom). The mean H I mass for each population is shown as a vertical line. As with other analyses in this paper, we limit each sample to only include galaxies with $M_{\text{star}} \geq 10^{10} M_{\odot}$, in-keeping with the stellar mass limit of the eBOSS galaxies. Note that the overall normalization changes between the top and bottom panels.

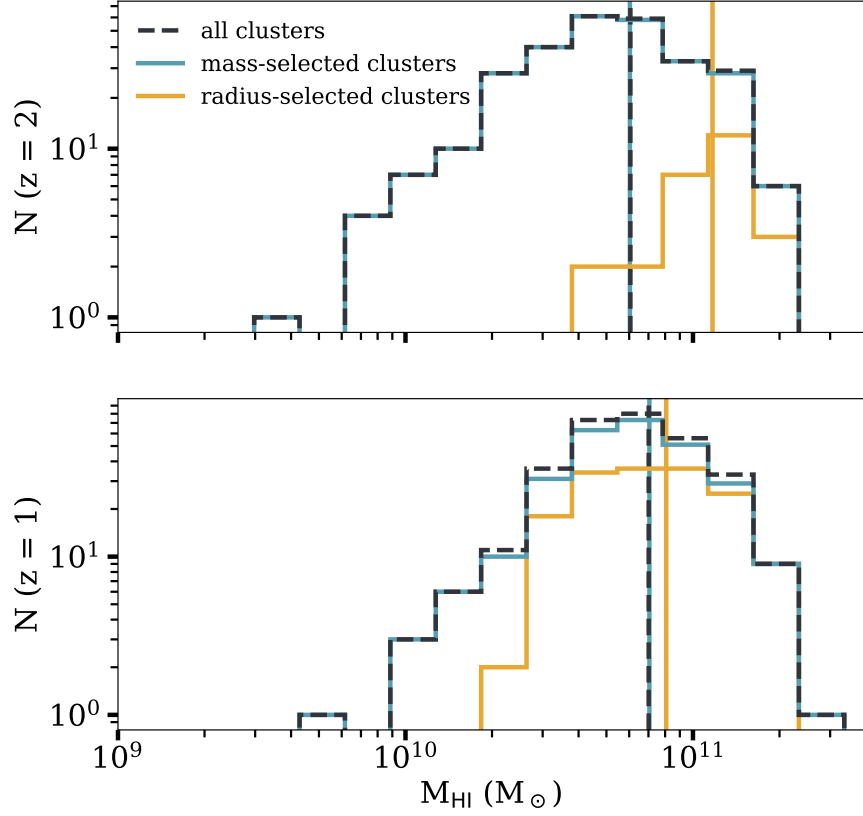


Figure 6.7: The intrinsic total neutral hydrogen mass distribution from TNG300 in each of three halo populations – all clusters (haloes), mass-selected galaxy clusters, and radius-selected galaxy clusters – for the clusters included in the stacks at $z = 2$ (top) and $z = 1$ (bottom). The mean H I mass for each population is shown as a vertical line.

the differences in spatial coverage at $z = 1$ and 2:

$$\frac{M_{\text{HI}}}{M_{\odot}} \approx \frac{4.945 \times 10^7}{C(z)} \left(\frac{F_{\text{pk,sub}}}{\text{Jy MHz}} \right) \left(\frac{\langle d_L \rangle}{\text{Mpc}} \right)^2 \quad (6.3)$$

where $\langle d_L \rangle$ is the average luminosity distance of the stacking targets, $F_{\text{pk,sub}}$ is the flux measured in the central pixel of a background-subtracted stack, and C is a single redshift-dependent conversion factor. We generate a background stack to subtract by stacking on N random locations. For the purposes of our calibration here, we select N equal to the length of the catalog from which the original stack was created, and note that choosing too small a number may result in the inferred mass changing with repeated measurements. To consistently measure $F_{\text{pk,sub}}$ for stacks with very different noise properties (primarily defined by the number of targets), we fit a Gaussian profile

$$F(x) = n \exp\left(-0.5 \left(\frac{x - \mu}{\sigma_z} \right)^2\right) \quad (6.4)$$

to the central slice in both RA and ZA, fixing σ_z and μ individually for each slice. μ is simply the central pixel in the slice and σ_z is based on the mean σ measured from slices of the well-sampled stacks that include all of the clusters in the simulation volume at $z = 1$ and 2. Given CHIME's asymmetric primary beam shape, we find $\sigma_{\text{RA},z=1} = 1.62 \pm 0.01$ pix, $\sigma_{\text{RA},z=2} = 2.41 \pm 0.04$ pix, $\sigma_{\text{ZA},z=1} = 2.73 \pm 0.04$ pix, and $\sigma_{\text{ZA},z=2} = 3.08 \pm 0.06$ pix. Here x is in pixels and n is the maximum amplitude of the curve. $F_{\text{pk,sub}}$ is simply the average of n_{RA} and n_{ZA} ³, which is useful in mitigating some of the effects of noise on the measured peak.

C accounts for the large beam and low resolution characteristic of 21 cm intensity mapping

3. For stacks based on large catalogs (with $N_{\text{targets}} \gg 1000$), this Gaussian fitting method is comparable to using $F_{\text{pk,sub}}$ taken directly from the amplitude of the central pixel of the background-subtracted stack. The approach we detail in Section 6.4 has the advantage of being more consistent across sample sizes, though it is slightly more computationally intensive due to the fitting.

experiments, and can be expressed generically as

$$C(z) = f_{\text{ff}} f_{\text{nt}} (1+z)^{-2} \frac{A_{\text{pix},z}}{\langle A_{\text{HI}} \rangle_z} \quad (6.5)$$

A more specific expression for $C(z)$ with CHIME is

$$C(z) = f_{\text{ff}} f_{\text{nt}} (1+z)^{-2} (5.3 \times 5.7) \frac{r_{\text{amin},z}^2}{\pi \langle R_{\text{HI}} \rangle_z^2} \quad (6.6)$$

Here $A_{\text{pix},z}$ is the physical area of a pixel at z , which for CHIME is $(5.3 \times 5.7) r_{\text{amin},z}^2$, where $r_{\text{amin},z}$ is the proper scale of 1 arcmin at a redshift, z . $\langle A_{\text{HI}} \rangle$ corresponds to the average proper area covered by the clusters' H I, taking $\langle A_{\text{HI}} \rangle \approx \pi \langle R_{\text{HI}} \rangle^2$. Here we assume that the radial extent of cluster H I is $1.2 R_{200}$, though there is evidence that it may extend to at least $1.25 R_{200}$ at $z = 1$ (Villaescusa-Navarro et al., 2016). As we noted earlier, we assume $f_{\text{ff}} = 0.2$, which is the fraction of flux that survives foreground filtering – in reality, this value may be somewhat different based on the conditions of the filtering and the input catalog; in CHIME Collaboration et al. (2023), the CHIME stacks on three different eBOSS catalogs have f_{ff} between 0.15 and 0.3 with a mean of 0.2.

We adopt $\langle R_{200} \rangle$ for the galaxy clusters in the TNG300 at each of $z = 1$ and 2 in estimating $C(z)$. We find that $\langle R_{200} \rangle_{z=2} = 0.527 h^{-1}$ and $\langle R_{200} \rangle_{z=1} = 0.763 h^{-1}$ cMpc respectively in TNG300. f_{nt} is the fraction of the stacked flux that is attributable to non-target sources such as field galaxies. We measure this quantity by looking at the relative power in the cluster stacks used throughout this analysis and cluster stacks on cluster-only maps that do not include field galaxies and are constructed based on the individual cluster populations (i.e., mass-selected or radius-selected). In our noiseless CHIME-like TNG300 maps, across cluster populations and redshifts (accounting for the differing pixel size), $f_{\text{nt}} = 6.4 \pm 0.2$, which we adopt here, noting that this value should be similar to the real one for CHIME's angular resolution and beam size given the accuracy of the TNG300

clustering, but is likely not exact. At $z = 2$, there are $139\times$ more field galaxies than cluster galaxies and those field galaxies contain $56\times$ more mass than the cluster galaxies. At $z = 1$ there are $62\times$ as many field galaxies as cluster galaxies, with the field galaxies containing $47\times$ more H I than cluster galaxies by mass. In this context, the small correction with $f_{\text{nt}} = 6.4$ is further indication that we are actually measuring the H I signal from the clusters on which we are stacking. There is negligible redshift evolution in f_{nt} , though the different cluster populations have slightly different values of f_{nt} associated with them, likely due to their differing extents and H I masses – $f_{\text{nt, mass-selected}} = 6.9 \pm 0.5$ and $f_{\text{nt, radius-selected}} = 5.8 \pm 0.3$ – the averaged value of $f_{\text{nt}} = 6.4$ results in sufficiently accurate mass estimates. This gives us $C_{z=2} = 18.75$ and $C_{z=1} = 8.26$. C could potentially be further tuned by assuming a different $R_{200}(z)$ or extent of H I within the halo.

For the stacks and expression we use here, these simple conversion factors put us within a factor of $\lesssim 1.25$ of the measured mean mass in the simulation. At $z = 2$, we find $\langle M_{\text{stack}} \rangle / \langle M_{\text{sim}} \rangle = 1.26 \pm 0.02$, 1.24 ± 0.02 , and 0.86 ± 0.03 for all galaxy clusters, mass-selected galaxy clusters, and radius-selected galaxy clusters respectively. At $z = 1$, where we stack on many more radius-selected clusters in particular: $\langle M_{\text{stack}} \rangle / \langle M_{\text{sim}} \rangle = 1.000 \pm 0.009$, 0.982 ± 0.009 , and 0.93 ± 0.01 respectively for all galaxy clusters, mass-selected galaxy clusters, and radius-selected galaxy clusters. The presented range includes the effect of noise, taking the uncertainty to be the width of the distribution of mass estimates after 1000 realizations of randomly generated background stacks. The underprediction of the radius-selected galaxy cluster mass at $z = 2$ is driven by our single assumed average R_{200} being somewhat too small for the selection criterion, which is why the radius-selected clusters at $z = 1$ are better matched. As mentioned above, $C(z)$ can be refined by considering a different $\langle R_{200} \rangle$ for a particular redshift, or even more specifically, for the target clusters at each redshift. Similarly, the overprediction of mass in mass-selected clusters (and our full cluster sample given the preponderance of mass-selected clusters) at $z = 2$ is likely the result of that se-

lection criterion being defined at $z = 0$ and then traced back along the Main Progenitor Branch, so that this sample includes protoclusters in addition to already evolved clusters. As a result, the gas properties and distribution of the still-assembling higher z mass-selected clusters may be somewhat different than radius-selected clusters at the same redshift or true clusters at $z = 1$ (e.g., Dong et al., 2023). This is consistent with the slight increase in M_{HI} in mass-selected clusters from $z = 2$ to $z = 1$ as seen in Fig. 6.7.

Though the mass recovery strategy we employ here is simple, it serves as an example of how one might go about deriving a cluster H I mass from stacked 21 cm data. In the case that the fraction of non-target contamination (f_{nt} here) and the instrument’s flux amplitude calibration are not known to a sufficient degree to infer H I mass directly, it is still possible to infer the relative mass between tracers and/or redshifts. Using the background-subtracted stacks described above and, if comparing across redshifts, the $A_{\text{pix},z}/\langle A_{\text{HI}} \rangle_z$ correction⁴, it is straightforward to return the inferred mass ratio between two independently selected cluster samples. For example, one could then compare the evolution of Sunyaev-Zel’dovich-selected clusters (e.g., Sunyaev & Zeldovich, 1972; Planck Collaboration et al., 2014; Bleem et al., 2015; Hilton et al., 2021) to the evolution of X-ray-selected clusters using only a pixel size normalization (without assuming f_{nt} or $\langle R_{\text{HI}} \rangle$) even without having a fully accurate flux calibration in place.

6.4.3 The extent of H I in $z = 2, 1$ TNG300 clusters

One innate limitation of this analysis is that the mass resolution of the *Molecular and atomic hydrogen (HI+H2) galaxy contents* catalog limits us to looking at the gas content of the most

4. To arrive at this corrective factor, we assume that (i) the distribution and properties of galaxies and clusters in TNG300 are comparable to those in the real universe, (ii) the H I masses in the *Molecular and atomic hydrogen (HI+H2) galaxy contents* catalogs are realistic, (iii) equation (6.2) is accurate for all source types, and (iv) the CHIME beam is correct (noting that we already use a Y -polarized beam in this analysis instead of the actual $X+Y$ -polarized beam). With this in mind, we urge some caution in extrapolating this factor to other experiments, suggesting instead that this analysis should be repeated for different beams, as in the scenario where assumptions (1)-(3) are true, (4) ensures that the correction is only informative for the CHIME dataset.

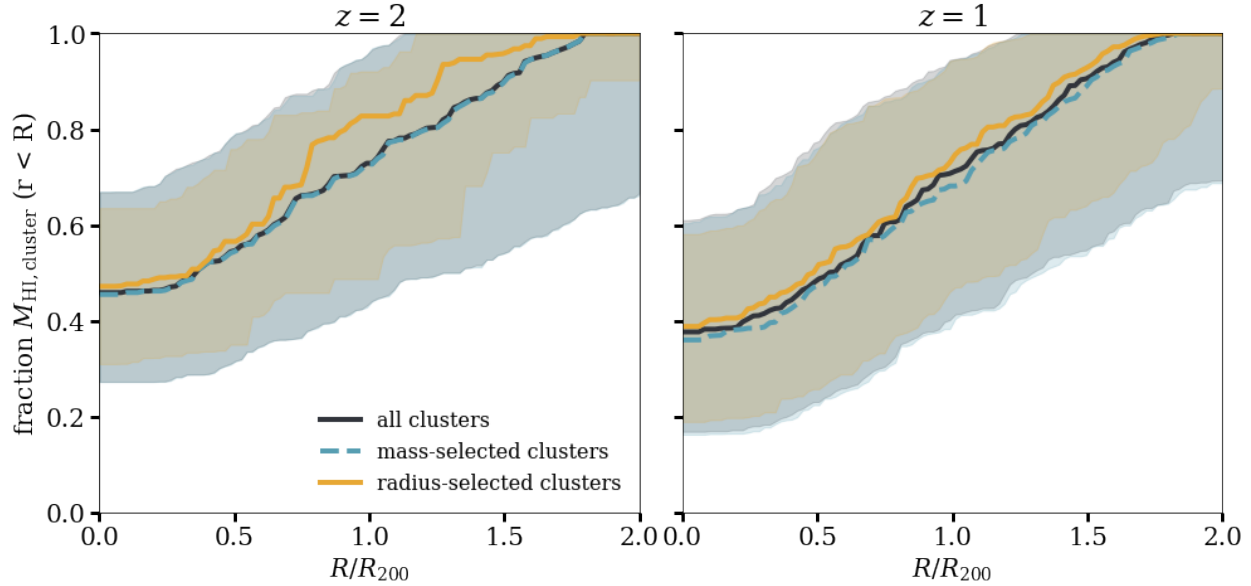


Figure 6.8: The cumulative normalized H I mass as a function of R/R_{200} for clusters included in our stacks. The lines show the median $M_{\text{HI}}/M_{\text{HI,tot}}$ vs. R/R_{200} with the shaded regions corresponding to the 16th and 84th percentile across clusters at that redshift. As the clusters evolve with time, more mass is concentrated in the cluster outskirts with most H I mass within $2 R_{200}$.

massive galaxies. These massive galaxies generally experience the most efficient quenching in cluster environments (e.g. Foltz et al., 2018; Pintos-Castro et al., 2019), and in that sense, we are adequately exploring what happens to the neutral hydrogen in galaxy clusters. However, it is not clear that we are sensitive to the gaseous intracluster medium (ICM) or the diffuse cluster outskirts in this simulation using the existing *Molecular and atomic hydrogen (HI+H2) galaxy contents* catalogs, since they tie H I mass to individual subhaloes rather than to the larger halo; the ICM is generally thought to be too hot and ionized to contain substantial amounts of neutral hydrogen, but the clusters’ outskirts may house cool gas (Kravtsov & Borgani, 2012).

To better understand where the mass is in the clusters we target in this analysis, we look at the cumulative distributions of H I mass with radius (normalized to R_{200}) in Fig. 6.8. It is apparent that ~ 40 per cent of the mass in the clusters is outside of R_{200} , with ~ 80 per cent of the total M_{HI} contained in $1.2 R_{200}$. In the roughly 2.5 Gyr between $z = 2$ and

$z = 1$, there is already apparent evolution in the amount of mass concentrated in the centre of the cluster rather than in the outskirts, with lower redshift clusters generally having more neutral hydrogen in their outskirts. This is consistent with observations at $z = 0$, where *most* neutral hydrogen is observed in the cluster outskirts at $R \gtrsim R_{200}$ (e.g., Giovanelli & Haynes, 1985; Yoon et al., 2012).

Given that the spatial extent of H I (and the fraction of M_{HI} within $1.2 R_{200}$) is similar at $z = 2$ and $z = 1$, the direct comparison of the relative H I mass at these two redshifts is feasible. This suggests that CHIME will be able to place observational constraints on the evolution of clusters' H I reservoir between $z = 2$ and $z = 1$, and even a normalized flux ratio will prove diagnostic between redshifts.

6.4.4 *Minimum sample size for accurate mass recovery*

We have established that it is possible to recover the H I mass when stacking on all of the galaxy clusters in our CHIME-like TNG300 map. In reality, though, there are only a limited number of known galaxy (proto-)clusters at $z = 2$ and $z = 1$ that fall within CHIME's sky coverage. We consider a handful of scenarios, stacking on limited samples of clusters.

To do this, we randomly sample N clusters from the full catalogs without replacement (though we note that the full catalog is based on target locations in the tiled map and includes the same TNG300 clusters in different locations and at different distances), looking explicitly at samples containing 3000, 1000, 300, 100, and 30 clusters. We iterate over the selection and mass estimate 1000 times for each sample size and distinct cluster population (i.e., all clusters, mass-selected clusters, and radius-selected clusters) to place stronger constraints on the accuracy while mitigating bias. Due to this randomization, some stacks may be based on catalogs of less massive, less luminous clusters at large distances, making it possible that small, but thoughtfully selected catalogs will yield more consistent results in reality.

Our results are in Table 6.1, and are indicative of the expectation that stacking on

Table 6.1: $\langle M_{\text{HI,stack}} \rangle / \langle M_{\text{HI,sim}} \rangle$ for stacks on N galaxy clusters. Here *all* denotes that the sample was drawn from a catalog containing all galaxy clusters, *mass-selected* indicates that the sample was drawn from a catalog of mass-selected galaxy clusters, and *radius-selected* indicates that the sample was drawn from a catalog of radius-selected galaxy clusters. The column without a label uses every cluster in the catalog in the stack.

Sample		$N = 3000$	1000	300	100	30
<i>all</i> , $z = 2$	1.26 ± 0.02	1.3 ± 0.2	1.2 ± 0.3	1.2 ± 0.5	1.3 ± 0.9	1 ± 2
<i>all</i> , $z = 1$	1.000 ± 0.009	1.00 ± 0.08	1.0 ± 0.1	1.0 ± 0.3	1.0 ± 0.4	1.1 ± 0.8
<i>mass-selected</i> , $z = 2$	1.24 ± 0.02	1.2 ± 0.2	1.3 ± 0.3	1.3 ± 0.5	1.2 ± 0.9	1 ± 2
<i>mass-selected</i> , $z = 1$	0.982 ± 0.009	0.98 ± 0.08	1.0 ± 0.1	1.0 ± 0.2	1.0 ± 0.4	1.0 ± 0.8
<i>radius-selected</i> , $z = 2$	0.86 ± 0.03	0.86 ± 0.08	0.9 ± 0.1	0.9 ± 0.3	0.8 ± 0.5	0.9 ± 0.9
<i>radius-selected</i> , $z = 1$	0.93 ± 0.01	0.93 ± 0.06	0.9 ± 0.1	0.9 ± 0.2	0.9 ± 0.4	0.9 ± 0.7

more targets does not impact the measured flux, but does affect the noise properties of the stacks. We find that it is possible to recover $\langle M_{\text{HI}} \rangle$ of the stacked galaxy clusters from a sample at $z = 1$ or $z = 2$ with $\sim$ hundreds of targets. This is consistent with the size of current $z \gtrsim 1$ galaxy cluster catalogs (e.g., Balogh et al., 2021; Wen & Han, 2021; Hilton et al., 2021; Wen & Han, 2022; Bulbul et al., 2024; Klein et al., 2024), though many of these clusters are only assigned a photometric z . While we include only a single corrective factor to approximate the impact of foreground filtering in this proof-of-concept analysis, we note that the redshift uncertainties need to be less than or comparable to the velocity dispersion of galaxy clusters ($dz \lesssim 0.005$) to avoid significant attenuation of the signal (CHIME Collaboration et al., 2023), even for projected improvements in foreground filtering. (The loss of flux contributed by high-velocity H I associated with narrower band stacks should be secondary to the mitigation of signal loss due to filtering, though thorough investigation of this point is beyond the scope of this paper.) This constraint means that a primary limitation will be building sufficiently large catalogs of clusters with spectroscopic redshift measurements. There is significant promise that the next generation of instruments that are beginning to come online now will substantially expand intermediate-to-high redshift cluster catalogs (Mantz et al., 2019; Zhang et al., 2020; Cerardi et al., 2024) and offer opportunities for spectroscopic confirmation of existing $z \gtrsim 1$ galaxy cluster candidates. The timing could

not be better for CHIME to be equipped to carry out these analyses.

Additionally, we tested a scenario with a CHIME-like signal level at $z = 1$ where we could do a direct comparison and found that it did not significantly impact the result that a mass could be recovered for samples with $N \gtrsim 100$ clusters. Instead, this somewhat lower flux case had mildly increased errors, consistent with the slightly lower SNR, that placed the lower bound on N closer to 300, but which were not large enough to make mass recovery impossible in the $N = 100$ case. Spectroscopic cluster catalogs at this redshift are expected to include hundreds-to-thousands of clusters, so this difference in required sample size is essentially negligible.

6.5 Summary & Conclusions

In this work, we discuss the possibility of cosmology experiments like CHIME providing an avenue for us to measure the integrated H I content of clusters at $z = 2 - 1$.

To summarize our results:

- Stacks on cluster galaxies show substantially more H I flux than stacks on field galaxies (Fig. 6.3 and Fig. 6.4). This is likely due to the large beam covering the entire cluster, making the stack sensitive to the cluster’s neutral hydrogen content.
- Radius-selected clusters contain, on average, more neutral hydrogen mass than mass-selected clusters at both $z = 2$ and $z = 1$ (see Fig. 6.5 and Fig. 6.7). Because they are selected for their properties at $z = 2$ or 1 rather than their evolved properties at $z = 0$, radius-selected clusters are intrinsically larger and more massive than mass-selected clusters at the same redshift.
- We recover from TNG300 the evolution of galaxy clusters to have more H I in their outskirts from $z = 2$ to $z = 1$ (Fig. 6.8). This is consistent with low redshift observations of galaxy clusters, for which most neutral hydrogen mass is measured outside at

$$R \gtrsim R_{200}.$$

- It is possible to recover a mean cluster M_{HI} from stacks as long as there are $N \gtrsim 100$ clusters in the sample (Table 6.1). This is promising for understanding the properties of high redshift galaxy clusters given current catalogs and the forecast for expanded samples anticipated from next-generation instruments. Similarly, this approach can be used to infer the H I mass ratio between redshifts and/or cluster selection criteria even without a robust instrument flux calibration. Comparison between redshifts to derive a relative abundance requires a simple normalization for the change in pixel proper scale, while comparison between cluster catalogs at the same redshift can be done directly without correction. We note, though, that depending on the exact protocol for converting between measured flux and H I content, assumptions like those about the neutral hydrogen volume filling factor or the spatial extent of the typical galaxy clusters may introduce additional redshift dependence that complicates mass ratio recovery across redshifts.

The primary limitations in measuring the evolution of neutral hydrogen in intermediate-to-high redshift galaxy clusters and protoclusters are the instrument sensitivity and resolution compared to the scale and H I mass of the target objects (Battye et al., 2004; Giovanelli et al., 2005). Since CHIME is able to study the average, stacked H I content of clusters that are not resolved by the beam, these results may also have applications for other instruments of comparable resolution and sky coverage. For instance, the CHIME synthesized beam and the GMRT primary beam have similar angular extents in the same redshift range (e.g. Chowdhury et al., 2022), and the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX, Newburgh et al., 2016; Crichton et al., 2022) will offer a direct complement to CHIME, mapping the H I signal in the Southern sky with the same frequency coverage and spatial resolution. As catalogs of galaxy clusters at $z \geq 1$ grow, 21 cm experiments offer a promising avenue to study the evolving H I reservoir in clusters and proto-clusters. Such

studies should also be able to provide constraints on the character and strength of feedback mechanisms that are active in cluster environments as a function of redshift.

Data Availability

Data used in this paper are publicly available as part of TNG300 simulation (Pillepich et al., 2018; Springel et al., 2018; Nelson et al., 2018; Naiman et al., 2018; Marinacci et al., 2018) from the IllustrisTNG project⁵ (Nelson et al., 2019b). Additionally, our beams, catalogs, tiled intensity maps, and analysis code are available on GitHub⁶.

5. <https://www.tng-project.org/data/downloads/TNG300-1/>

6. <https://github.com/avapolzin/CHIMExIllustrisTNG>

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

In this dissertation, I present my recent efforts, using a combination of constraining observations and detailed numerical simulations, to shape our end-to-end understanding of the baryon cycle in low-mass galaxies with a particular eye toward elucidating the multi-scale processes that regulate star formation. The primary conclusions from each chapter are broken out here:

- In Chapter 2, I introduce new simple analytic prescriptions to model the non-equilibrium H I-H₂ transition at low metallicities¹, based on new single-metallicity runs of a realistic isolated disk galaxy simulation. I also discuss the nature of star-forming gas, noting that the star formation rate decouples from the abundance of molecular gas at $Z \lesssim 0.1 Z_{\odot}$.
- In Chapter 3, I examine the dependence of the star formation rate per free-fall time (or approximately the fraction of gas that is converted into stars) on the cloud-scale properties of the interstellar medium. I report that the star formation efficiency is universally ~ 0.01 , with the regulation of that value driven by the interplay between feedback (from stars, supernovae) and turbulence in the ISM.
- In Chapter 4, I characterize COSMOS-dw1, a quenched, isolated dwarf galaxy. Because COSMOS-dw1 has a relatively young stellar population (~ 1 Gyr) and no ongoing star formation, I posit that stellar feedback is responsible for the galaxy’s quiescence. COSMOS-dw1 was discovered serendipitously in the well-studied COSMOS field, further suggesting that the number density of feedback-regulated low-mass galaxies may be higher than previously thought².

1. See <https://github.com/avapolzin/hih2> for a readily available Python implementation.

2. In the last five years, the number of identified quenched, isolated dwarf galaxy candidates has increased significantly. A regularly updated list is available at https://avapolzin.github.io/projects/quench_list/.

- In Chapter 5, I preview our QUEST Dwarfs program, which integrates measurements of galaxies’ stellar populations, ISM, and CGM. The first release subsample shared here includes just $\sim 20\%$ of the overall sample. I report that, consistent with expectations from simulations, more massive galaxies exhibit higher absorber column densities at a given projected distance, and in-keeping with a multiphase view of the CGM, higher ionization chemical species extend farther into the galaxies’ halos. Further, I make a preliminary estimate of the metal budget of the CGM, finding that just $\sim 3\%$ of the total metals in low-mass ($\log M_{\star}/M_{\odot} < 8$) dwarfs are retained in the cool phase, while that value rises to $\sim 16\%$ for high-mass ($\log M_{\star}/M_{\odot} \geq 8$) dwarfs.
- In Chapter 6, I use mock observations generated from cosmological simulations and a model for the H I-H₂ transition to demonstrate that 21 cm experiments can provide insight into the reservoir of star-forming material available in galaxy cluster environments. This proof-of-concept analysis, suggests that existing instrumentation and datasets can place critical constraints on the aggregated gas content of galaxy clusters at intermediate redshifts.

There is additional ongoing work that extends naturally from the chapters of this dissertation, which is not presented here. I briefly describe these continuing projects and their relation to the studies included in this thesis.

Modeling star formation in low-metallicity galaxies. Given the results of Chapters 2 and 3, which demonstrate that star formation is driven by cold, dense gas generally rather than any particular chemical species, tying models of star formation to H₂ abundance will either (a) overpredict the H₂ fraction in the gas when chemical equilibrium is assumed, while matching expected star formation rates or (b) underpredict star formation, when using non-equilibrium H I-H₂ models that accurately reflect the gas chemistry.

As an alternative, I am currently calibrating a set of analytic prescriptions that recover the star formation efficiency and the depletion time of gas on a range of scales as a simple

function of gas density, metallicity, and ionizing radiation field, which can be used to model star formation in simulations. Specifically, these prescriptions can be used without relying on H_2 abundance, while retaining the uniformity of the star formation efficiency per free-fall time on cloud scales.

Analyzing a statistical sample of CGM absorbers. The work presented in Chapter 5 represents just $\sim 20\%$ of the overall QUEST Dwarfs sample, which is, in total, made up of > 60 galaxies with almost 70 associated FUV-bright background sightlines. The QUEST Dwarfs more than double the number of dwarf galaxies in the literature with constraints on the metal content of the CGM, putting us in the regime where we can begin to make statistical statements about the chemistry and kinematics of the gaseous halos and their correlation with various dwarf galaxy properties. The QUEST Dwarfs were selected exclusively based on the presence of archival FUV spectroscopy of nearby background sightlines, so the included galaxies are remarkably diverse.

I am analyzing the spectroscopy and imaging associated with the remaining galaxies in the sample to characterize their stellar populations, star formation histories, metallicities, and environments. In addition to publishing the full complement of QUEST Dwarfs, I am interested in examining the baryon cycle in subsets of these galaxies, binning the sample by mass, star formation, environment, and chemistry to better understand the complex interplay between star formation, feedback, and the gas in and around galaxies.

Directly characterizing the chemistry of stars' natal clouds. As I am writing this, the *Hubble Space Telescope* is preparing to observe two FUV-bright stars in the low-metallicity Local Group galaxy IC 1613. These two stars are targeted as part of Cycle 33 *HST* program, PANCHO³ (HST GO-18074), which aims to directly measure the column densities of cold H I and H_2 in the immediate vicinity of young stars using absorption spectroscopy. Such observations will directly test the predictions about the nature of star-

3. PANCHO – Piloting a Novel Calibration for H_2 Observations – is a pun, with the acronym for our *pilot* program inspired by the pioneering aviatrix Pancho Barnes.

forming gas laid out in Chapter 2 by placing constraints on the localized molecular hydrogen fraction. Simultaneously, obtaining high signal-to-noise FUV spectroscopy of young, massive stars creates an opportunity to better understand the stars themselves and their impact on their immediate surroundings. Because IC 1613 is so nearby, spatially resolved optical spectroscopy is also possible on $\sim$ pc scales. In tandem with our absorption study of the two massive stars in IC 1613, we will use a combination of simulations and integral field spectroscopy to constrain the impact of radiative feedback and stellar winds on the gas in the immediate vicinity of O- and B-type stars.

What remains. There are a number of interesting research directions that traverse the baryon cycle and connect scales. I am most interested in relating star formation to feedback; testing the energetics of stellar, supernova, and AGN feedback; and relating feedback to galaxy-scale properties, disentangling different mechanisms via their impact on galaxies and the CGM. To those ends, I have already started collecting integral field data for some fascinating work that marries these various themes by directly mapping the chemistry and kinematics of gas in the target galaxies and their inner halos, though I will withhold further details until the ultimate publication of that work. On the more theoretical side of things, I am working on forward modeling realistic simulations to aid in the physical interpretation of secondary tracers of star formation or gas content; the suite of simulations used in Chapters 2 & 3 are among the only ones that reproduce the detailed and highly localized characteristics of star formation and feedback observed in real galaxies (in this case, the decorrelation of young stars and cold gas on small scales). Specifically, using basic chemical networks and the simulations' existing radiative transfer properties, I plan to reproduce the *intrinsic* distribution of CO and C II within the simulated galaxies. I will then compare those maps against CO isotopologue lines and 158 micron [CII] line from forward modeled mocks to work to determine the correspondence between what is observed and the intrinsic gas content, assessing validity of the commonly used tracers of molecular gas and star formation

rate respectively. Such efforts to forward model simulations and compare mock observables to the simulated ground truth are one critical avenue to bridge the gap between observational and theoretical work.

APPENDIX A

MODELING MOLECULAR HYDROGEN IN LOW METALLICITY GALAXIES

A.1 Implementation of other HI-H₂ models

Given that there are different formulations of the HI-H₂ transition models which we use in comparisons in Section 2.5, we offer details of how f_{H_2} and F_{H_2} were computed as a function of density and column density for each model.

A.1.1 GK11 and GD14

For both GK11 and GD14 models, we follow the model as presented in the original papers (Gnedin & Kravtsov, 2011; Gnedin & Draine, 2014). We set the scale in GD14 to be the size of the simulation’s grid cells.

For the projected case of GK11, we use the high density approximation

$$\Sigma_{\text{HI}} = 2 \Sigma_c = 40 \text{ M}_{\odot} \text{ pc}^{-2} \frac{\Lambda^{4/7}}{D_{\text{MW}}} \frac{1}{\sqrt{1 + U_{\text{MW}} D_{\text{MW}}^2}} \quad (\text{A.1})$$

to compute

$$f_{\text{H}_2} = 1 - \frac{\Sigma_{\text{HI}}}{\Sigma_{\text{H}}} \quad (\text{A.2})$$

Here we assume that $\Sigma_{\text{H}} = \Sigma_{\text{H}_2} + \Sigma_{\text{HI}}$, consistent with a nonexistent or negligible amount of ionization. If the expression produces $\Sigma_{\text{HI}} > \Sigma_{\text{H}}$, we set $f_{\text{H}_2} = 0$. We note that assuming $\Sigma_{\text{HI}} \simeq \Sigma_c$ results in somewhat better agreement between GK11 and the location of the HI-H₂ transition in the simulation, particularly at low Z , though we do not show it here, opting instead to use the formulation from the paper.

In the case of GD14, we follow their Equations 8 - 10 directly and compute molecular

fraction as $f_{\text{H}_2} = R_{\text{mol}}/(1 + R_{\text{mol}})$.

A.1.2 The KMT09b and K13 models

We use the KMT09b model (Krumholz et al., 2009b) rather than the model presented in Krumholz et al. (2009a) due to its better accuracy at low molecular fractions, consistent with the low Z regime. The KMT09b model uses surface density of the atomic-molecular complex $\Sigma_{\text{comp}} = c\Sigma_{\text{gas}}$ with the clumping factor $c \rightarrow 1$ on scales ~ 100 pc. We approximate $\Sigma_{\text{comp}} \approx \Sigma_{\text{H}}$, since the grid cells in the simulation with $f_{\text{H}_2} \geq 10^{-5}$ are generally smaller than 100 pc. We note that this is not a perfect approximation since this expression for Σ_{comp} should be averaged on ~ 100 pc scales. In the volumetric case, to compute Σ_{H} from n_{H} , we take $\Sigma_{\text{H}} = (n_{\text{H}}/\text{cm}^{-3})(L/\text{cm})(m_p/\text{g})$, which we then convert to units of $M_{\odot} \text{pc}^{-2}$. Similarly in the K13 model, we compute Σ_0 in the same way as Σ_{H} .

We largely follow Krumholz (2013) for the implementation of the K13 model. In order to compute f_{H_2} , we first need to compute $n_{\text{CNM,hydro}}$, which relies on P_{th} . P_{th} is a function of $R_{\text{mol}} = f_{\text{H}_2}/(1 - f_{\text{H}_2})$. We ultimately iterate over this step 10 times, following the more efficient approach in Diemer et al. (2018), where f_{H_2} is initialized at 0.5 and is averaged as it advances through the iteration so that for step i , $f_{\text{H}_2,i} \approx 0.3f_{\text{H}_2,i-1} + 0.7f_{\text{H}_2,i}$.

We also adopt a clumping factor, $f_c = 1$. For Figure 2.10 we adopt the median density $\rho_{\text{SD}} = 0.1 M_{\odot} \text{pc}^{-2}$ in our simulation in regions where $f_{\text{H}_2} \geq 10^{-5}$ and ρ_{SD} is non-zero. As in Diemer et al. (2018, §C.4), we find no significant difference between using different constant values of ρ_{SD} , but that using different values on a cell-by-cell basis (as we do in Figure 2.11, where ρ_{SD} is computed directly from the simulation) has a significant effect.

A.1.3 The S14 model

We follow the simple Diemer et al. (2018, §C.5) formulation for the S14 model (Sternberg et al., 2014; Bialy & Sternberg, 2016). To convert the number density to column

density, we assume $N_{\text{H}}/\text{cm}^{-2} = (n_{\text{H}}/\text{cm}^{-3})(L/\text{cm})$ for comparison with our volumetric model. In the same vein, when comparing with our projected model, we take $n_{\text{H}}/\text{cm}^{-3} = (N_{\text{H}}/\text{cm}^{-2})(1.54 \times 10^{21}/\text{cm})^{-1}$, which corresponds to the approximate height of the disk (~ 500 pc).

APPENDIX B

ON THE UNIVERSALITY OF STAR FORMATION EFFICIENCY

B.1 Turbulence-free star formation

To better understand the mechanism driving the uniformity of the star formation efficiency with varying ISM properties (metallicity, UV field strength, and surface density of gas and stars), we re-run five of the single metallicity simulations ($Z = 0.01, 0.03, 0.1, 0.3$, and $1 Z_{\odot}$) from the same initial conditions as the fiducial simulations introduced in Section 3.2, turning off subgrid turbulence and any tracking of turbulent energy. The non-turbulent virial parameter, $\alpha_{\text{vir,nt}}$, is then defined taking $\sigma_{\text{tot}} = c_s$, rather than $\sigma_{\text{tot}} = \sqrt{\sigma_t^2 + c_s^2}$ as in the default Padoan et al. (2012) model (see Eq. 3.2), effectively isolating the behavior and effects of thermal motions in star-forming gas. After the runs each proceed for ~ 100 Myr (approximately a crossing time), ϵ_{ff} is then recomputed using $\alpha_{\text{vir,nt}}$ for the non-turbulent case. We denote this non-turbulent star formation efficiency per free-fall time as $\epsilon_{\text{ff,nt}}$. Similarly, the turbulence-free star formation rate is defined as $\dot{M}_{\star} = \epsilon_{\text{ff,nt}} M_{\text{gas}}/t_{\text{ff}}$.

All other analysis is done in the same way as in Section 3.3.1, and we do not change any of the physics associated with star formation or feedback within the simulation. For direct comparison between Figure 3.6 and B.1, we make the same cut of $\alpha_{\text{vir}} \leq 15$, with cells weighted by their star formation rates.

The dependence of $\epsilon_{\text{ff,nt}}$ on gas phase metallicity is shown on the left in Figure B.1. In the turbulence-free case, ϵ_{ff} dependence on metallicity is noticeably stronger than in the fiducial simulations. This is likely due to the importance of thermal motions in defining $\alpha_{\text{vir,nt}}$. Even selecting only for star-forming regions ($\alpha_{\text{vir}} \leq 15$), low metallicity gas will be warmer than higher Z gas given the less efficient cooling in low metallicity gas. In this case, the thermal motions defined by c_s will be greater in low Z gas, increasing $\alpha_{\text{vir,nt}}$ and driving

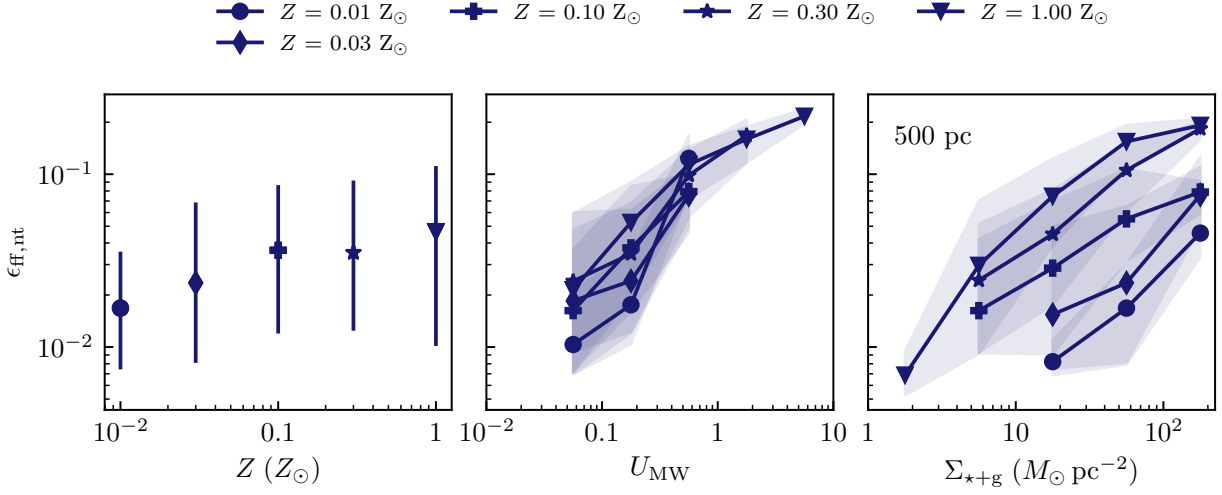


Figure B.1: The same as the top row of Figure 3.6, but with turbulence turned off. The now-strong dependence of the star formation efficiency on metallicity and baryon surface density is apparent. (Note that the range of ϵ_{ff} shown here is larger than in Figure 3.6.)

$\epsilon_{\text{ff,nt}}$ down compared with ϵ_{ff} . This leads to ϵ_{ff} varying increasing steadily with increasing gas phase metallicity.

Likewise, Figure B.1 shows that in the simulations without subgrid turbulence ϵ_{ff} depends significantly on the local UV flux and gas surface density (the middle and right panels). The middle panel of Figure B.1. The figure shows that $\epsilon_{\text{ff,nt}}$ increases with increasing U_{MW} and surface density of gas and stars (averaged on 500 pc) due to the positive correlation between U_{MW} and density and star formation rate. The significant dependence of the efficiency on metallicity at specific values of U_{MW} and surface density are also apparent in these panels.

Note that stellar feedback still operates in the runs without turbulence. Thus, as gas cools and reaches higher densities star formation rate increases and so does associated stellar feedback. The feedback prevents runaway collapse and disperses star-forming regions.

APPENDIX C

THE LOW-MASS BARYON CYCLE IN QUEST DWARF GALAXIES: SAMPLE DEFINITION AND FIRST RESULTS

C.1 Photometric and spectral properties of QUEST Dwarfs

As discussed in Section 5.3, we measure broadband FUV and optical photometry of the sample galaxies based on a 2D surface brightness profile analysis of archival imaging data. We also measure nebular line fluxes and equivalent widths, along with the strength of the 4000 Å discontinuity, using available optical spectra. All the measurements are presented in Tables C.1 and C.2 below. The environmental properties of each galaxy (see § 5.3.8) are presented in Figure C.1.

C.2 Full spectral fitting

We use `Bagpipes` to fit the full spectrum of each QUEST Dwarf galaxy, using a non-parametric star formation history model. The results of that fitting are shown in Figures C.2 through C.5. The fit star formation histories are shown at right, where they offer *qualitative* insight into the galaxies’ evolution. For instance, LEDA 1722581 and its H α -selected counterpart appear to have evolved in parallel despite the latter’s lack of independent stellar continuum, and PGC 41458 and PGC 41458b have comparable star formation histories, pointing to their co-evolution, though the lower mass satellite PGC 41458b has a more stochastic SFH. Similarly, UGC 75 and UGC 7485, which are both shell galaxies, have consistent inferred star formation histories.

The choice of $\alpha = 5$ for the Dirichlet prior on the star formation history, which we adopt as optimal from Iyer et al. (2019), effectively smooths the SFH, leading to much less bursty behavior among our seven time bins than may be suggested from FUV and

Table C.1: Photometric properties of the galaxies in the QUEST Dwarfs first release sample as obtained from survey imaging. All magnitudes AB.

Galaxy	g	r	z	FUV	n	b/a	PA (deg)	r_{eff} (arcsec)
PGC 4143	14.682 ± 0.002	14.140 ± 0.003	13.784 ± 0.003	17.72 ± 0.02	1.660 ± 0.005	$0.5802^{+0.0009}_{-0.0008}$	$-14.46^{+0.04}_{-0.05}$	26.91 ± 0.07
UGCA 285	$16.261^{+0.003}_{-0.002}$	$15.85^{+0.03}_{-0.05}$	15.61 ± 0.04	19.4 ± 0.1	0.655 ± 0.008	$0.881^{+0.008}_{-0.011}$	8^{+1}_{-2}	$19.2^{+0.6}_{-0.8}$
UGC 7370	14.486 ± 0.001	13.940 ± 0.002	13.576 ± 0.002	$17.49^{+0.06}_{-0.05}$	0.817 ± 0.002	0.2828 ± 0.0003	-29.37 ± 0.02	$20.31^{+0.06}_{-0.05}$
PGC 41458	16.725 ± 0.002	16.095 ± 0.004	15.719 ± 0.004	22.1 ± 0.1	1.354 ± 0.006	0.574 ± 0.002	$-27.4^{+0.1}_{-0.2}$	13.29 ± 0.03
PGC 41458b	17.78 ± 0.01	$17.19^{+0.02}_{-0.04}$	16.67 ± 0.01	> 23.8	0.71 ± 0.01	$0.97^{+0.01}_{-0.04}$	-24^{+4}_{-6}	12 ± 1
LeG 26	16.403 ± 0.002	$15.798^{+0.006}_{-0.008}$	15.419 ± 0.007	21.483 ± 0.003	0.884 ± 0.003	$0.811^{+0.004}_{-0.005}$	79.7 ± 0.5	$14.28^{+0.06}_{-0.07}$
UGC 75 ^a	$12.8458^{+0.0006}_{-0.0005}$	12.359 ± 0.003	$12.015^{+0.005}_{-0.006}$	...	1.251 ± 0.004	0.547 ± 0.001	26.02 ± 0.06	26.7 ± 0.3
UGC 9126	14.924 ± 0.001	14.526 ± 0.003	14.279 ± 0.004	16.92 ± 0.05	0.652 ± 0.004	$0.9994^{+0.0003}_{-0.0006}$	26.02 ± 0.06	42 ± 4
UGC 7485	14.907 ± 0.002	14.387	14.078 ± 0.003	$17.90^{+0.08}_{-0.07}$	1.000 ± 0.003	0.719 ± 0.002	1.5 ± 0.2	$30.38^{+0.09}_{-0.10}$
LEDA 1722581	17.549 ± 0.003	17.085 ± 0.004	16.800 ± 0.005	$21.4^{+0.3}_{-0.2}$	1.478 ± 0.005	0.671 ± 0.002	$-59.69^{+0.08}_{-0.09}$	$14.46^{+0.05}_{-0.04}$
LEDA 1722581-em ^b	...	...	...	20.6 ± 0.2	1.157 ± 0.008	0.326 ± 0.001	-82.16 ± 0.08	6.56 ± 0.02
PGC 1818175	15.734 ± 0.002	15.137 ± 0.003	14.751 ± 0.003	$21.6^{+0.5}_{-0.3}$	...	...	...	...
UGC 5427	14.669 ± 0.002	14.034 ± 0.004	14.084 ± 0.004	16.517 ± 0.009	1.145 ± 0.003	0.490 ± 0.001	-76.49 ± 0.06	17.73 ± 0.03
NGC 5486 ^a	$13.7678^{+0.0010}_{-0.0007}$	$13.326^{+0.002}_{-0.003}$	$13.328^{+0.005}_{-0.004}$	15.598 ± 0.006	$0.723^{+0.001}_{-0.002}$	0.611 ± 0.002	-76.49 ± 0.06	19.20 ± 0.06
dw1408+56	17.977 ± 0.005	$17.551^{+0.009}_{-0.014}$	17.96 ± 0.02	$19.7^{+0.2}_{-0.1}$	0.65 ± 0.01	0.573 ± 0.002	70.5 ± 0.2	25.2 ± 0.4
UGC 4527	$16.158^{+0.006}_{-0.007}$	$15.755^{+0.008}_{-0.009}$	16.150 ± 0.009	$18.35^{+0.09}_{-0.08}$	$3.81^{+0.04}_{-0.05}$	$0.9995^{+0.0004}_{-0.0009}$	70.5 ± 0.2	10 ± 1
					0.925 ± 0.008	$0.569^{+0.005}_{-0.006}$	51.6 ± 0.4	12.52 ± 0.06
					0.805 ± 0.003	0.814 ± 0.002	30.0 ± 0.3	14.71 ± 0.08

^a These galaxies are best fit by the combination of two Sérsic models with a fixed PA. We list parameters for both models here, with g , r , z , and FUV magnitudes coming from the combined profile. The top row includes the parameters for the primary Sérsic profile, which, for UGC 75 and NGC 5486 contain $(77.8^{+0.7}_{-0.8})\%$ and $(71.5 \pm 0.6)\%$ of the flux respectively, and the bottom row includes parameters for the secondary profile.

^b The FUV magnitude is determined from the same region used in extracting the MaNGA spectrum. LEDA 1722581 is correspondingly masked, so FUV flux is attributed to only one of LEDA 1722581 or LEDA 1722581-em.

Table C.2: Individual spectral line and index measurements for the QUEST Dwarfs first release sample. For galaxies spectra from with multiple independent pointings, reported values are summed. Lines that are not included in the wavelength coverage of the spectra are denoted “...”

Galaxy	[OII]3727 (erg s ⁻¹) <i>W</i> ₃₇₂₇ (Å)	H β ₄₈₆₁ (erg s ⁻¹) <i>W</i> ₄₈₆₁ (Å)	[OIII]4959 (erg s ⁻¹) <i>W</i> ₄₉₅₉ (Å)	[OIII]5007 (erg s ⁻¹) <i>W</i> ₅₀₀₇ (Å)	H α ₆₅₆₃ (erg s ⁻¹) <i>W</i> ₆₅₆₃ (Å)	[NII]6584 (erg s ⁻¹) <i>W</i> ₆₅₈₄ (Å)	<i>D_n</i> 4000
PGC 4143	(1.62 ± 0.08) × 10 ⁻¹⁴ 14.0 ± 0.8	...	(2.2 ± 0.1) × 10 ⁻¹⁵ 1.20 ± 0.08	(5.2 ± 0.1) × 10 ⁻¹⁵ 2.92 ± 0.08	(1.53 ± 0.01) × 10 ⁻¹⁴ 9.25 ± 0.08	(2.5 ± 0.1) × 10 ⁻¹⁵ 1.51 ± 0.07	1.17 ± 0.01
UGCA 285 ^a	(1.5 ± 0.3) × 10 ⁻¹⁴ 27 ± 7	(0.3 ± 1.0) × 10 ⁻¹⁵ 0.5 ± 1.7	n.d.	(0.9 ± 1.8) × 10 ⁻¹⁵ 2 ± 3	(1.34 ± 0.06) × 10 ⁻¹⁴ 23 ± 2	(4.1 ± 0.4) × 10 ⁻¹⁵ 6.9 ± 0.3	0.74 ± 0.05
UGC 7370	(1.59 ± 0.03) × 10 ⁻¹³ 20.1 ± 0.5	...	(3.30 ± 0.07) × 10 ⁻¹⁴ 3.16 ± 0.07	(6.96 ± 0.06) × 10 ⁻¹⁴ 6.68 ± 0.07	(2.198 ± 0.004) × 10 ⁻¹³ 23.5 ± 0.2	(3.78 ± 0.04) × 10 ⁻¹⁴ 4.05 ± 0.05	1.080 ± 0.008
PGC 41458	(1.3 ± 0.5) × 10 ⁻¹⁵ 1.1 ± 0.4	(5 ± 2) × 10 ⁻¹⁶ 0.5 ± 0.2	(3 ± 1) × 10 ⁻¹⁶ 0.3 ± 0.1	(2 ± 1) × 10 ⁻¹⁶ 0.2 ± 0.1	(3 ± 2) × 10 ⁻¹⁶ 0.355 ± 0.02	(8 ± 5) × 10 ⁻¹⁷ 0.09 ± 0.06	1.04 ± 0.04
PGC 41458b	(1.1 ± 0.3) × 10 ⁻¹⁴ 16 ± 5	(-6 ± 2) × 10 ⁻¹⁶ -3 ± 1	(4 ± 1) × 10 ⁻¹⁶ 2.3 ± 0.7	(0.7 ± 1.6) × 10 ⁻¹⁶ 4 ± 1	(8 ± 7) × 10 ⁻¹⁷ 0.5 ± 1.1	(2.1 ± 0.5) × 10 ⁻¹⁶ 1.5 ± 0.4	0.9 ± 0.1
LeG 26 ^a	...	(-1.0 ± 0.5) × 10 ⁻¹⁶ -0.3 ± 0.2	(1.3 ± 0.4) × 10 ⁻¹⁶ 0.4 ± 0.1	(3.6 ± 0.8) × 10 ⁻¹⁶ 1.2 ± 0.3	(7.8 ± 0.6) × 10 ⁻¹⁶ 3.5 ± 0.3	(9 ± 2) × 10 ⁻¹⁷ 0.4 ± 0.1	...
UGC 75	(6.3 ± 0.1) × 10 ⁻¹⁴ 14.5 ± 0.3	...	(1.37 ± 0.02) × 10 ⁻¹⁴ 2.04 ± 0.03	(4.25 ± 0.02) × 10 ⁻¹⁴ 6.34 ± 0.05	(9.94 ± 0.02) × 10 ⁻¹⁴ 18.56 ± 0.08	(1.47 ± 0.01) × 10 ⁻¹⁴ 2.75 ± 0.03	1.126 ± 0.004
UGC 9126 ^b	(3.9 ± 0.2) × 10 ⁻¹⁴ 18 ± 3	(1.04 ± 0.04) × 10 ⁻¹⁴ 9.3 ± 0.6	(1.24 ± 0.04) × 10 ⁻¹⁴ 11.1 ± 0.7	(3.89 ± 0.04) × 10 ⁻¹⁴ 34.4 ± 0.8	(4.21 ± 0.03) × 10 ⁻¹⁴ 54 ± 1	(1.9 ± 0.2) × 10 ⁻¹⁵ 2.5 ± 0.6	0.96 ± 0.04
UGC 7485	...	(9.82 ± 0.05) × 10 ⁻¹⁴ 14.3 ± 0.3	(1.145 ± 0.005) × 10 ⁻¹³ 16.4 ± 0.3	(3.498 ± 0.005) × 10 ⁻¹³ 49.4 ± 0.8	(3.756 ± 0.005) × 10 ⁻¹³ 67 ± 1	(3.99 ± 0.05) × 10 ⁻¹⁴ 7.1 ± 0.2	...
LEDA 1722581	(2.87 ± 0.02) × 10 ⁻¹⁵ 23 ± 0.5	(6.72 ± 0.05) × 10 ⁻¹⁶ 3.35 ± 0.03	(4.05 ± 0.06) × 10 ⁻¹⁶ 2.02 ± 0.03	(1.307 ± 0.006) × 10 ⁻¹⁵ 6.51 ± 0.04	(2.582 ± 0.005) × 10 ⁻¹⁵ 15.5 ± 0.1	(3.74 ± 0.04) × 10 ⁻¹⁶ 2.24 ± 0.03	1.195 ± 0.003
LEDA 1722581-em	(3.68 ± 0.01) × 10 ⁻¹⁵ 49.2 ± 0.9	(1.032 ± 0.004) × 10 ⁻¹⁵ 0.43 ± 0.08	(6.60 ± 0.04) × 10 ⁻¹⁶ 6.70 ± 0.05	(2.009 ± 0.004) × 10 ⁻¹⁵ 20.3 ± 0.1	(3.344 ± 0.004) × 10 ⁻¹⁵ 42.4 ± 0.3	(3.83 ± 0.03) × 10 ⁻¹⁶ 4.87 ± 0.04	1.102 ± 0.003
PGC 1818175	...	(2 ± 2) × 10 ⁻¹⁷ 0.3 ± 0.2	(1.1 ± 0.5) × 10 ⁻¹⁷ 0.15 ± 0.07	(4 ± 1) × 10 ⁻¹⁷ (0.6 ± 0.2)	(8 ± 1) × 10 ⁻¹⁷ 1.4 ± 0.2	(4 ± 2) × 10 ⁻¹⁷ (0.6 ± 0.3)	1.08 ± 0.03
UGC 5427	> 1.33 × 10 ¹⁵ 24 ± 2	(1.73 ± 0.04) × 10 ⁻¹⁵ 11.7 ± 0.6	(4.0 ± 0.3) × 10 ⁻¹⁶ 2.7 ± 0.6	(1.45 ± 0.04) × 10 ⁻¹⁵ 9.9 ± 0.7	(4.65 ± 0.06) × 10 ⁻¹⁵ 46 ± 1	(4.6 ± 0.2) × 10 ⁻¹⁶ 4.5 ± 0.6	1.01 ± 0.02
NGC 5486	> 5.35 × 10 ⁻¹⁵ 51 ± 2	(6.24 ± 0.07) × 10 ⁻¹⁵ 43.9 ± 0.9	(6.44 ± 0.07) × 10 ⁻¹⁵ 46 ± 2	(1.94 ± 0.02) × 10 ⁻¹⁴ 138 ± 3	(1.92 ± 0.01) × 10 ⁻¹⁴ 245 ± 4	(1.62 ± 0.03) × 10 ⁻¹⁵ 20.7 ± 0.8	0.94 ± 0.04
dw1408+56	...	(8.3 ± 0.7) × 10 ⁻¹⁶ 5.6 ± 0.4	(2.6 ± 0.7) × 10 ⁻¹⁶ 1.8 ± 0.5	(9.0 ± 0.6) × 10 ⁻¹⁶ 6.2 ± 0.4	(4.07 ± 0.09) × 10 ⁻¹⁵ 30 ± 1	(7 ± 1) × 10 ⁻¹⁶ 5.6 ± 0.9	1.18 ± 0.02
UGC 4527	...	(1.0 ± 0.1) × 10 ¹⁵ 1.6 ± 0.2	(-6 ± 1) × 10 ⁻¹⁶ -1.0 ± 0.2	(-3 ± 1) × 10 ⁻¹⁶ -0.5 ± 0.2	(9.4 ± 0.1) × 10 ⁻¹⁵ 19.2 ± 0.4	(9 ± 1) × 10 ⁻¹⁶ 1.8 ± 0.3	1.29 ± 0.01

^a Measurements of line *fluxes* at $\lambda < 5600\text{\AA}$ and the *D_n*4000 are significantly less robust for these galaxies due to the quality of the blue-side flux calibration from archival LRIS data. These numbers are italicized in the table.

^b [NII] is not detected in one of the two UGC 9126 pointings, so the value reported here is derived only from the spectrum along the major axis. N₂ is therefore computed only from the major axis spectrum for the metallicity estimate of this galaxy.

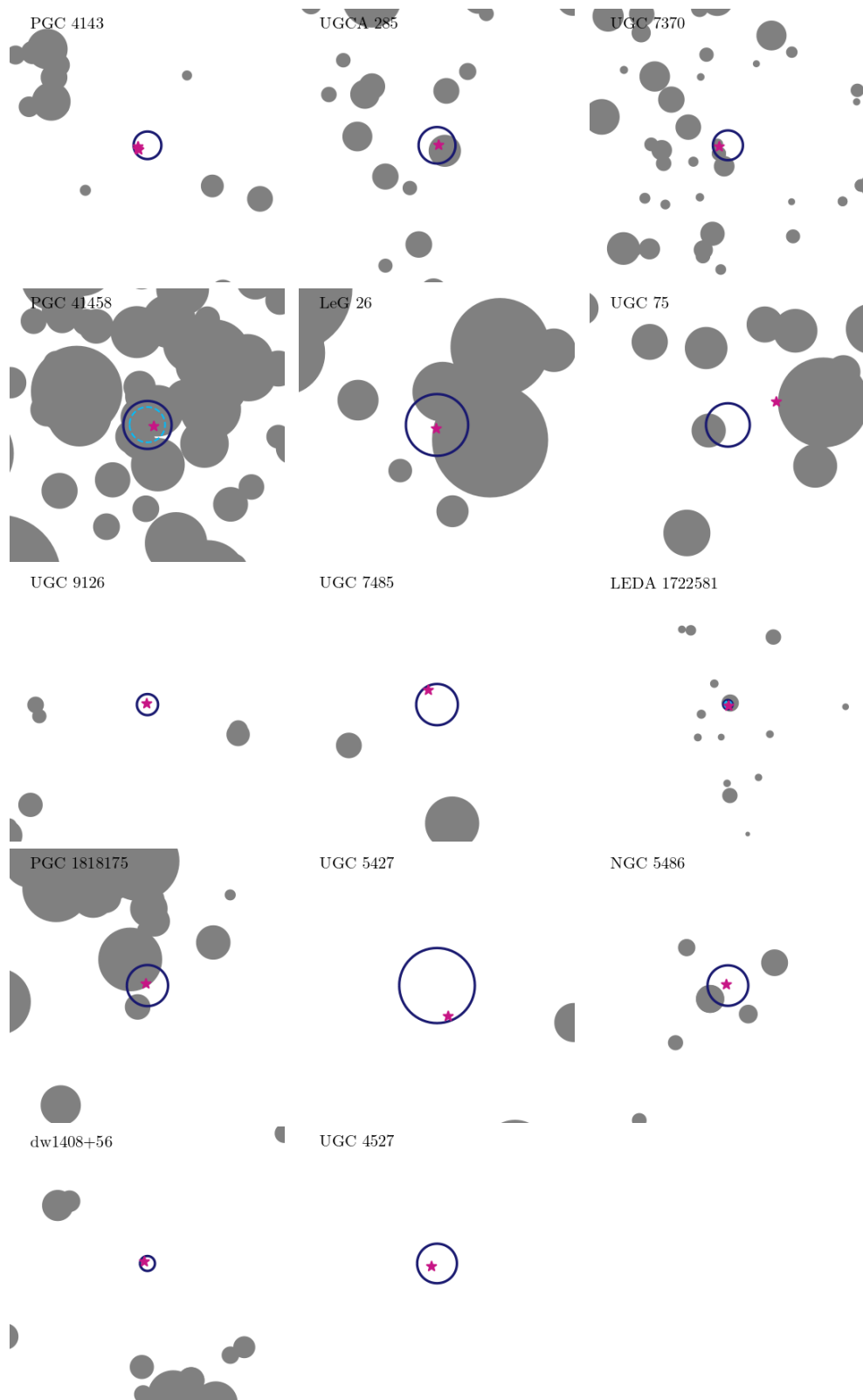


Figure C.1: *(Caption next page.)*

Figure C.1: (*Previous page.*) The cosmic “neighborhood” of each QUEST Dwarf. Each panel spans $4 \times 4 \text{ deg}^2$ and shows in gray the virial coverage of all galaxies within $\pm 300 \text{ km s}^{-1}$ as selected from the 50 MGC (Ohlson et al., 2024) and DESI DR1 (DESI Collaboration et al., 2025) catalogs. The virial radius of the each QUEST Dwarf is shown in navy blue and QSO sightlines are denoted with pink stars. For PGC 41458 and LEDA 1722581, we mark the virial radius of their interacting companions with light blue dashed circles.

$\text{H}\alpha$ SFR indicators. As such, *quantitative* analysis of galaxies’ SFHs comes from the direct photometric (FUV) and line ($\text{H}\alpha$ and D_n4000) measurements. We focus only show the last 8 Gyr of each galaxy’s SFH, where a combination of absorption features (including the Balmer series) and emission lines best constrain stellar population ages and ongoing star formation.

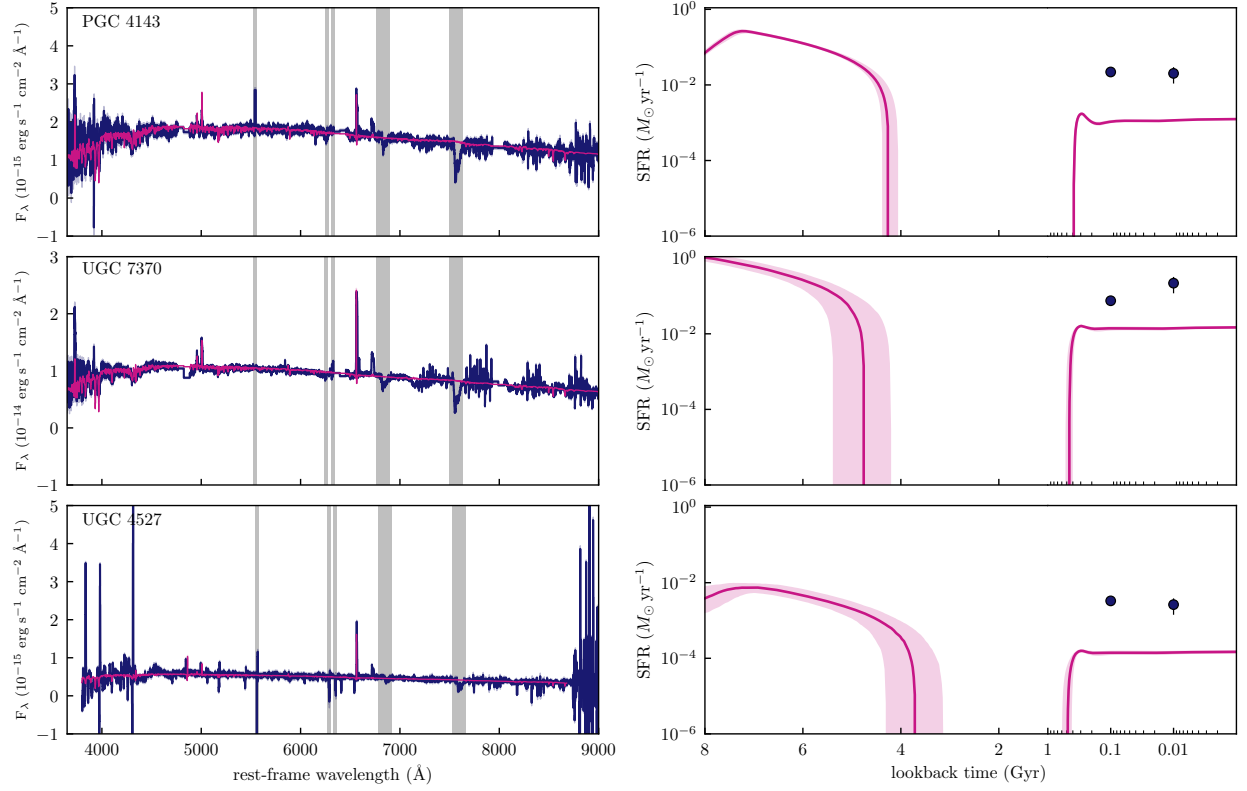


Figure C.2: *Left:* Optical spectra (blue) and **Bagpipes** best fit model spectra (pink) for galaxies with a “bursty” SFH. Note that the scaling is different spectrum-to-spectrum. Regions of the spectrum that are masked due to atmospheric features or sky lines are grayed out. *Right:* Star formation histories recovered from **Bagpipes** fitting (pink); where the measurements are available, we also show the H α and FUV SFRs (see Section 5.3.6) on timescales of 10 and 100 Myr respectively.

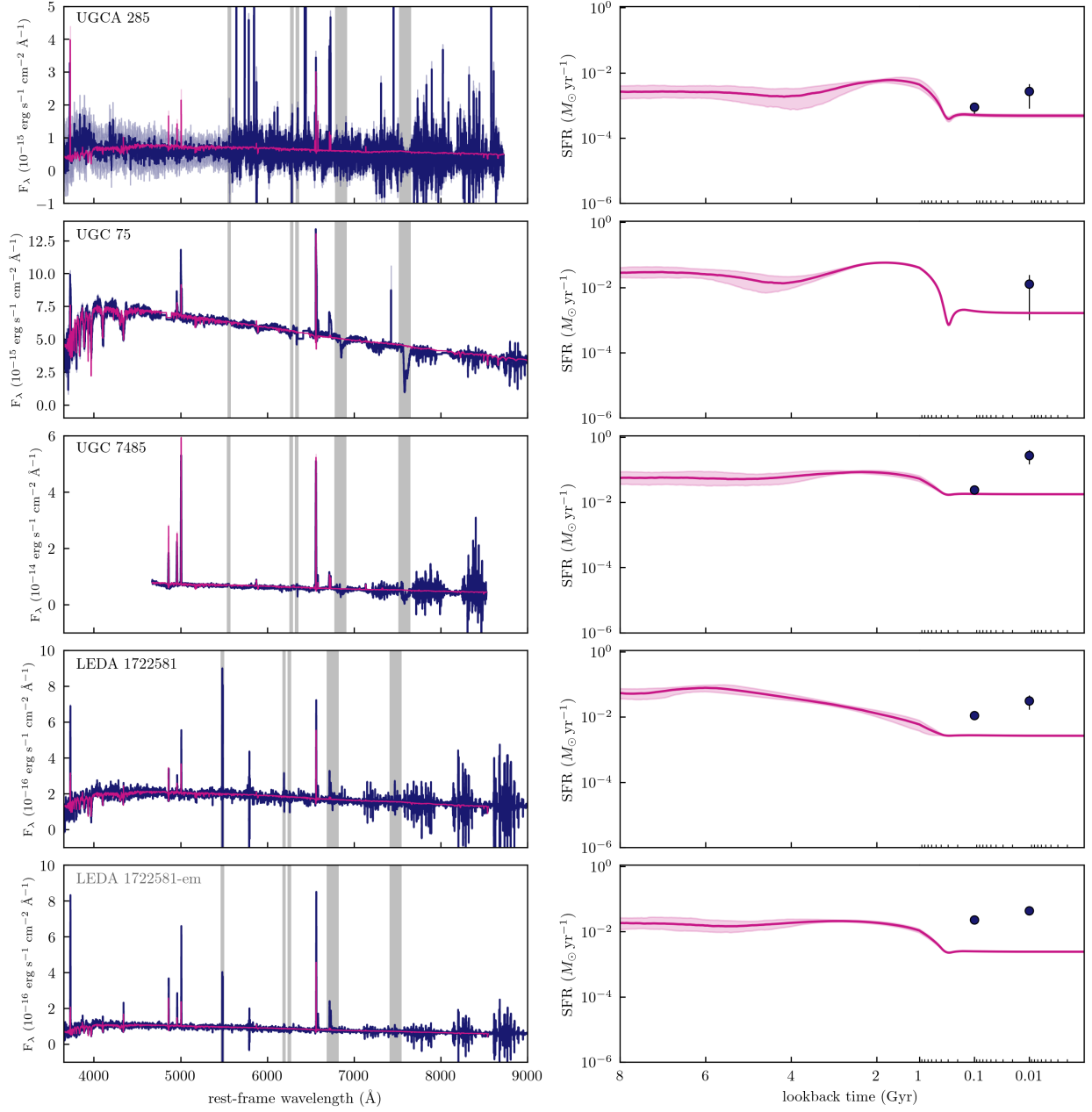


Figure C.3: Same as Figure C.2, for galaxies with an “sustained” SFH. For galaxies with multiple spectroscopic pointings, we select a representative spectrum and fit to display here.

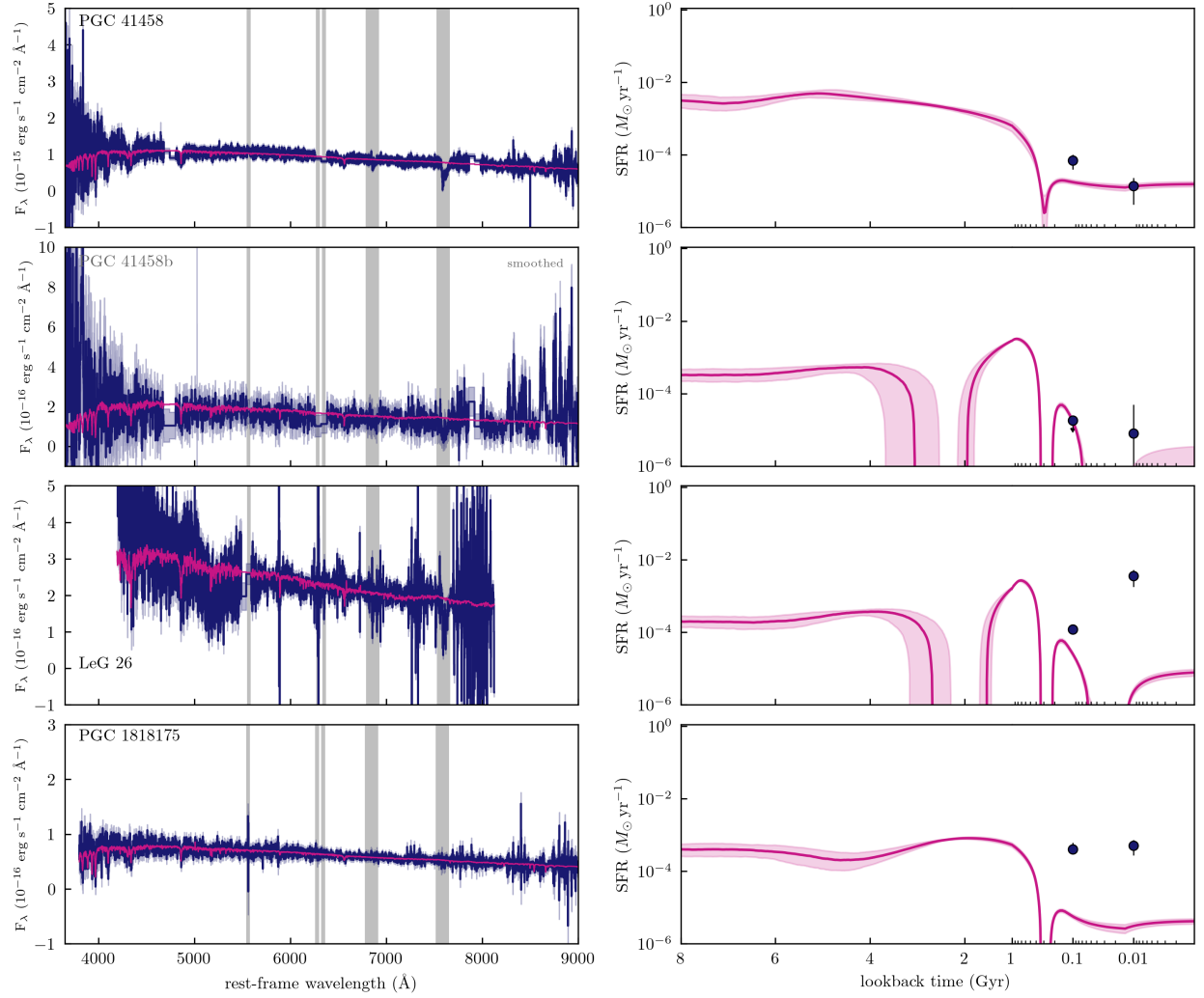


Figure C.4: Same as Figure C.2, for galaxies with an “quiescent” SFH. For galaxies with multiple spectroscopic pointings, we select a representative spectrum and fit to display here.

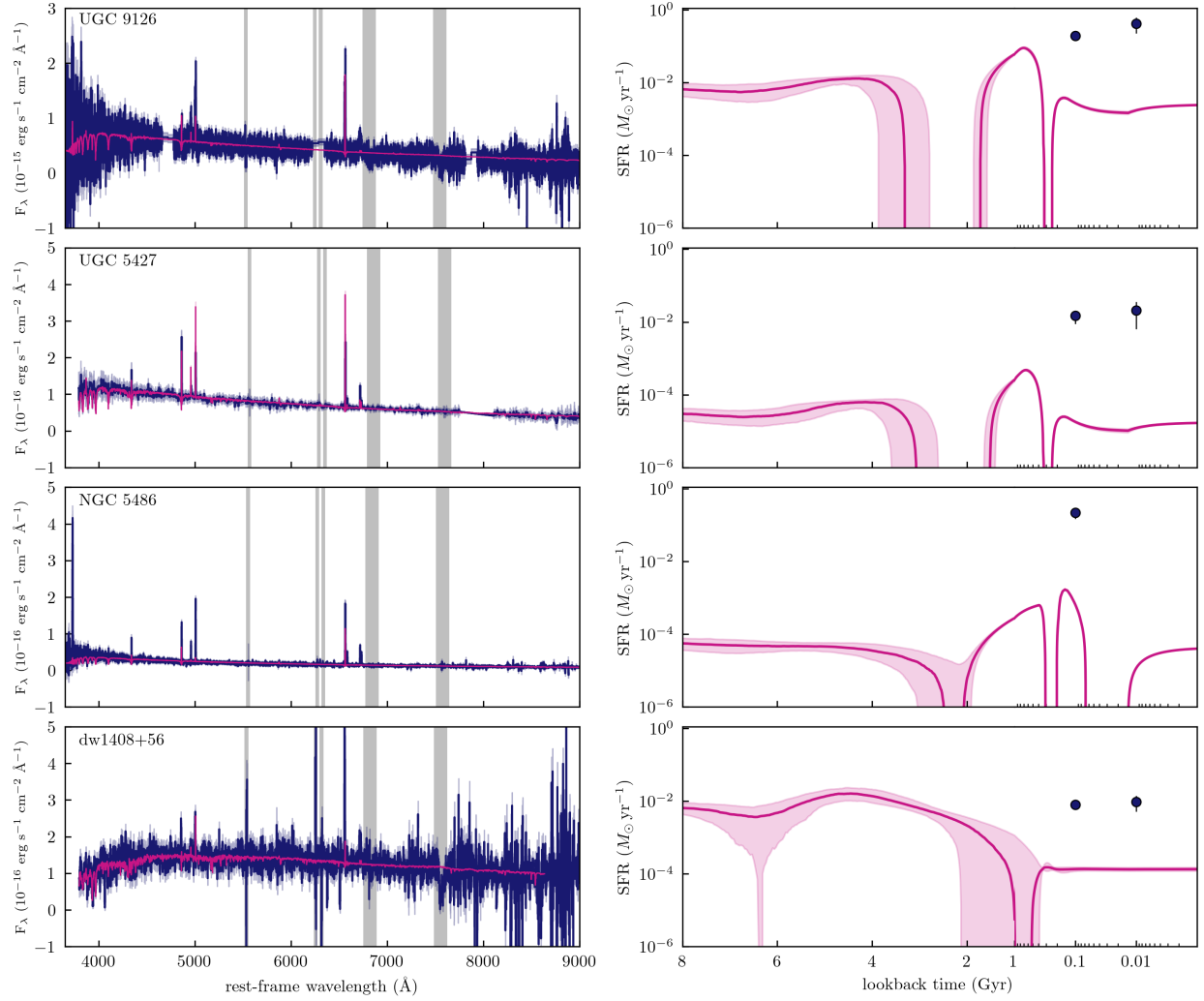


Figure C.5: Same as Figure C.2, for galaxies with an “episodic” SFH. For galaxies with multiple spectroscopic pointings, we select a representative spectrum and fit to display here. Note that there is no correction made for slit or fiber loss, so the *Bagpipes* SFH for UGC 5427 and NGC 5486 deviates particularly from the “integrated” H α and FUV SFRs.

C.3 Photometric color conversions for SBF

Following e.g., Cohen et al. (2018) and Carlsten et al. (2019), we compare photometry for simple stellar populations in *HST*/ACS, *HST*/WFPC2, CFHT MegaCam, and DECam bands using photometry from MIST isochrones (Dotter, 2016; Choi et al., 2016). We use the AB magnitude color for every MIST SSP with an age ≤ 13 Gyr, spanning $-4 \leq [\text{Fe}/\text{H}] \leq 0.5$, to directly relate DECam $g - z$ to each of *HST*/ACS WFC F475W-F814W, *HST*/WFPC2 F555W-F814W, and CFHT MegaCam $g - i$ to predict $\bar{M}$ for comparison with the magnitude of the SBF signal (Ajhar et al., 1997; Blakeslee et al., 2010; Carlsten et al., 2019).

As dwarf galaxies are generally bluer, we explicitly fit for all SSPs with $(g - z)^{\text{DECam}} \leq 1.5$. We find the following color conversions:

$$(F475W - F814W)^{\text{ACS}} = 0.0154x^2 + 0.8366x + 0.0034 \quad (\text{C.1})$$

and

$$(g - i)^{\text{CFHT}} = 0.0113x^2 + 0.7078x + 0.0033 \quad (\text{C.2})$$

and

$$(F555W - F814W)^{\text{WFPC2}} = 0.0129x^2 + 0.6068x + 0.4000 \quad (\text{C.3})$$

where $x = (g - z)^{\text{DECam}}$. These relations have $\sigma_{(F475W-F814W)^{\text{ACS}}} = 0.03$, $\sigma_{(g-i)^{\text{CFHT}}} = 0.04$, and $\sigma_{(F555W-F814W)^{\text{WFPC2}}} = 0.01$ for $(g - z)^{\text{DECam}} \leq 1.5$ and $\sigma_{(F475W-F814W)^{\text{ACS}}} = 0.02$, $\sigma_{(g-i)^{\text{CFHT}}} = 0.03$, and $\sigma_{(F555W-F814W)^{\text{WFPC2}}} = 0.01$ for $(g - z)^{\text{DECam}} \leq 1$, noting that there are fewer blue SSPs against which to compare, so the larger scatter among redder stellar populations is likely driven by the wider range of individual age and metallicity combinations that result in those photometric colors.

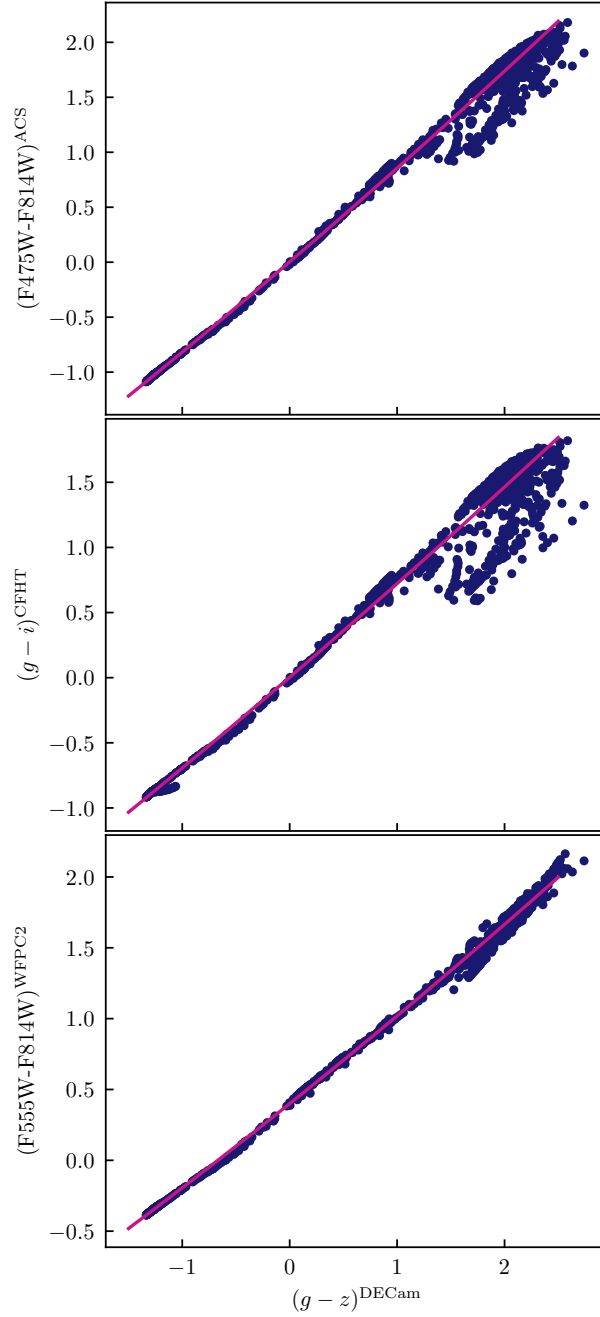


Figure C.6: Synthetic photometry from MIST for simple stellar populations at a variety of ages (10^5 yr - 13 Gyr) and metallicities ($-4 \leq [\text{Fe}/\text{H}] \leq 0.5$). The color indices of each SSP are shown as blue dots, and our fit to these points is shown in pink (Eqs. C.1, C.2, and C.3). *Top:* *HST*/ACS F475W-F814W compared to DECam $g-z$. *Middle:* CFHT MegaCam $g-i$ compared to DECam $g-z$. *Bottom:* *HST*/WFPC2 F555W-F814W compared to DECam $g-z$.

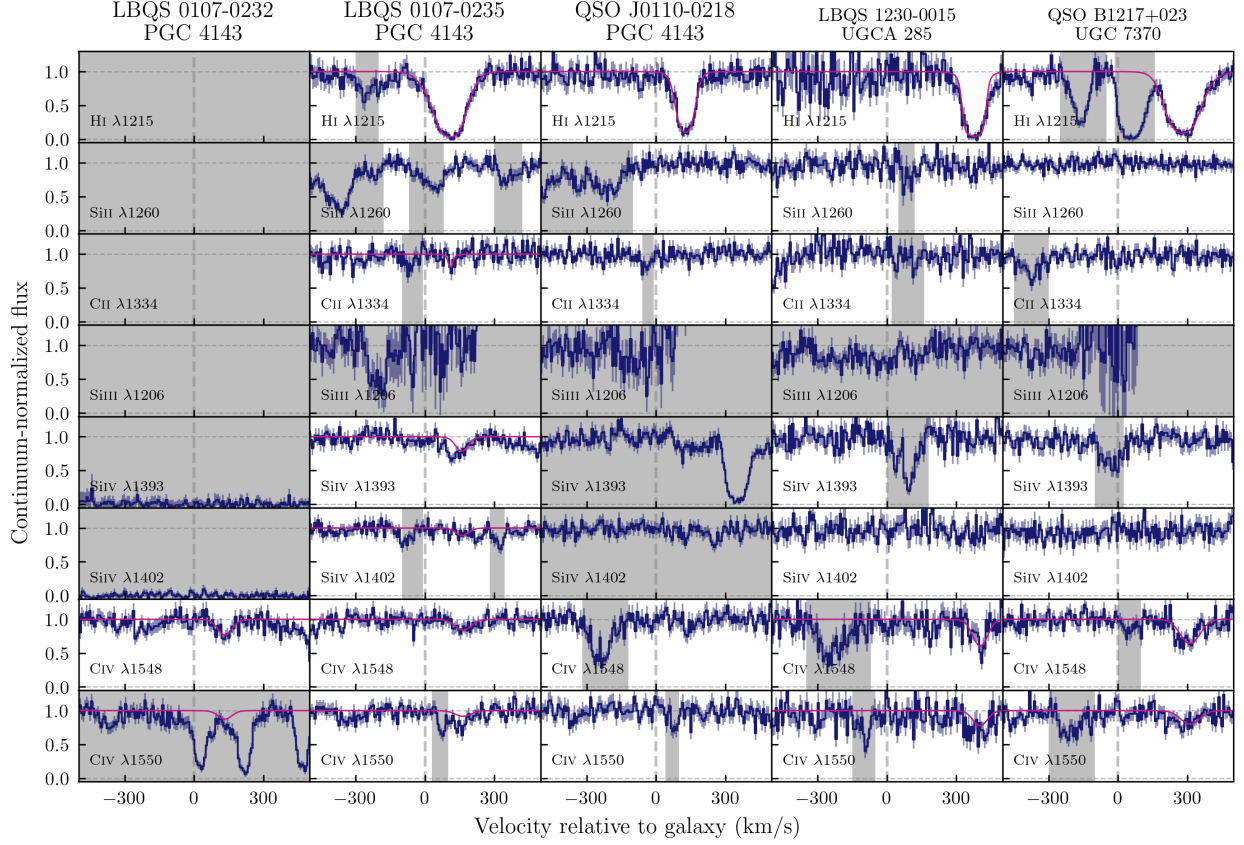


Figure C.7: Same as Figure 5.3 for the sightlines associated with PGC 4143, UGCA 285, and UGC 7370. Note that complete non-detections where it is not possible to place a limit on the line strength (due, in general, to wavelength coverage, the Lyman limit, or significant contamination) are denoted by a grayed out panel.

C.4 Ion-to-ion column densities in the dwarf CGM

Individual ion column density measurements (detailed in Table 5.6), color-coded based on M_{star} have been shown in Figure 5.7. Here we present the underlying FUV absorption spectra (Figures C.7, C.8, and C.9) and the ionic column density density profiles with the measurements color-coded by $\log(\text{H}\alpha/\text{FUV})$ (Figure C.10) and $12 + \log(\text{O}/\text{H})$ (Figure C.11).

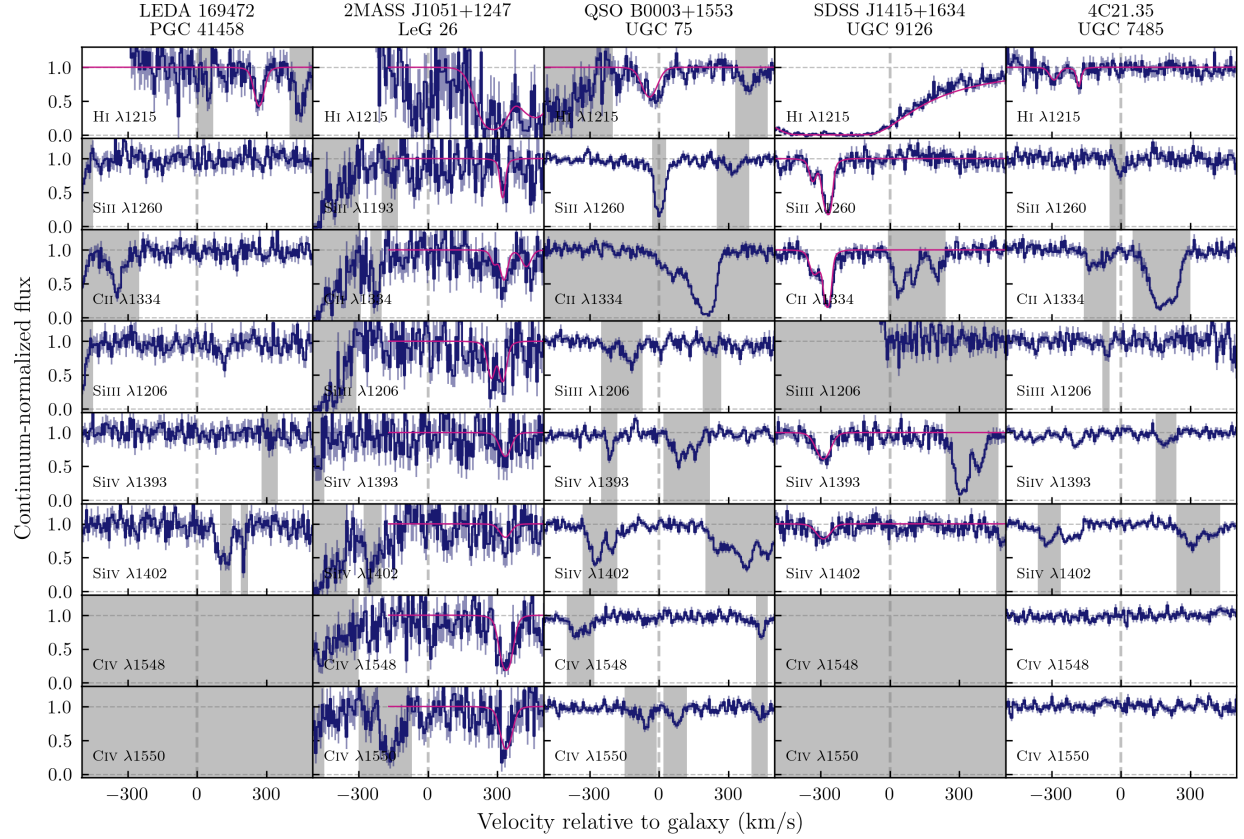


Figure C.8: Same as Figure 5.3 for the sightlines associated with PGC 41458, LeG 26, UGC 75, UGC 9126, and UGC 7485. Note that the Si II measurement for LeG 26 comes from Si II $\lambda 1193$ instead of Si II $\lambda 1260$.

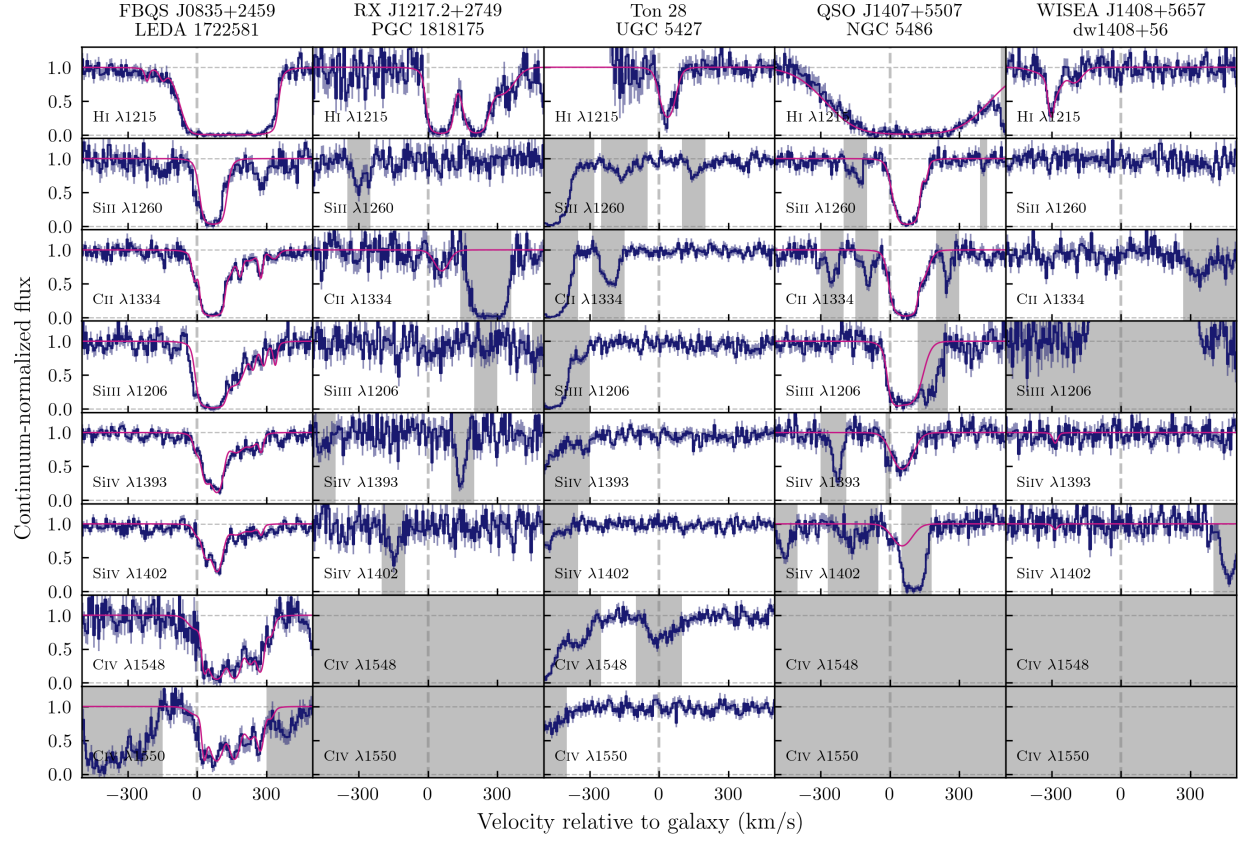


Figure C.9: Same as Figure 5.3 for the sightlines associated with LEDA 1722581, PGC 1818175, UGC 5427, NGC 5486, and dw1408+56.

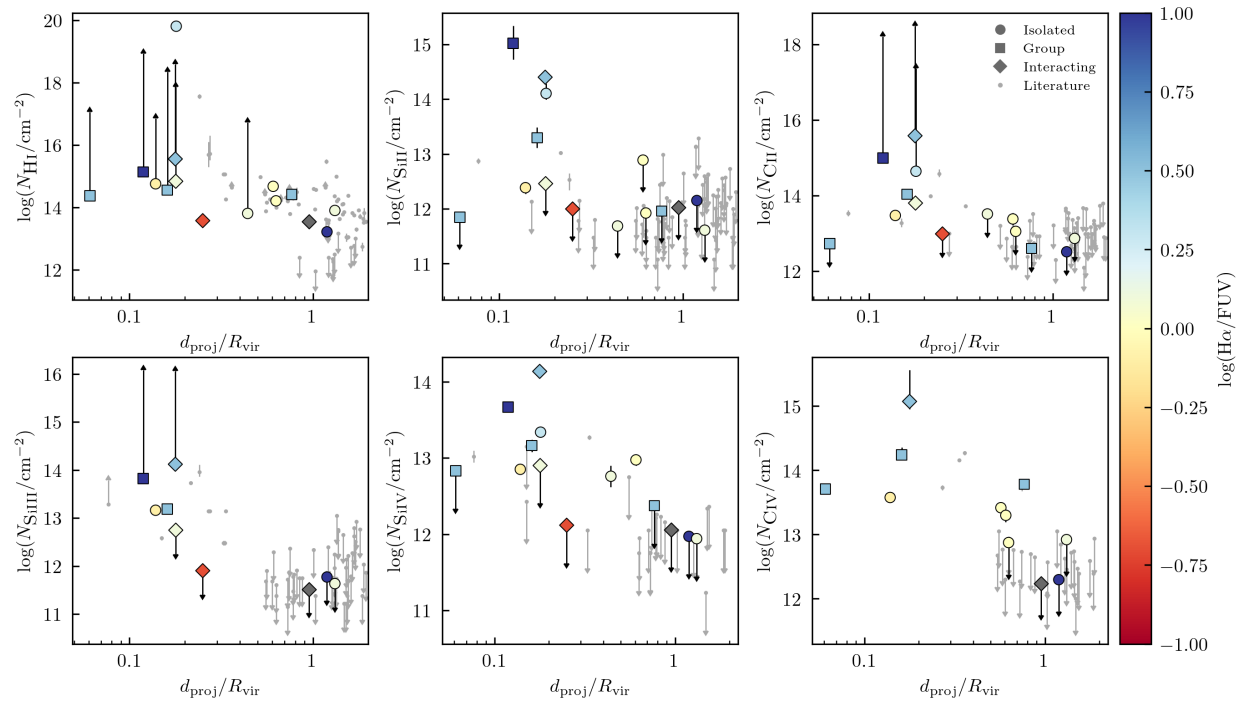


Figure C.10: Same as Figure 5.7, but with QUEST Dwarf galaxies colored by their $\log(\text{H}\alpha/\text{FUV})$.

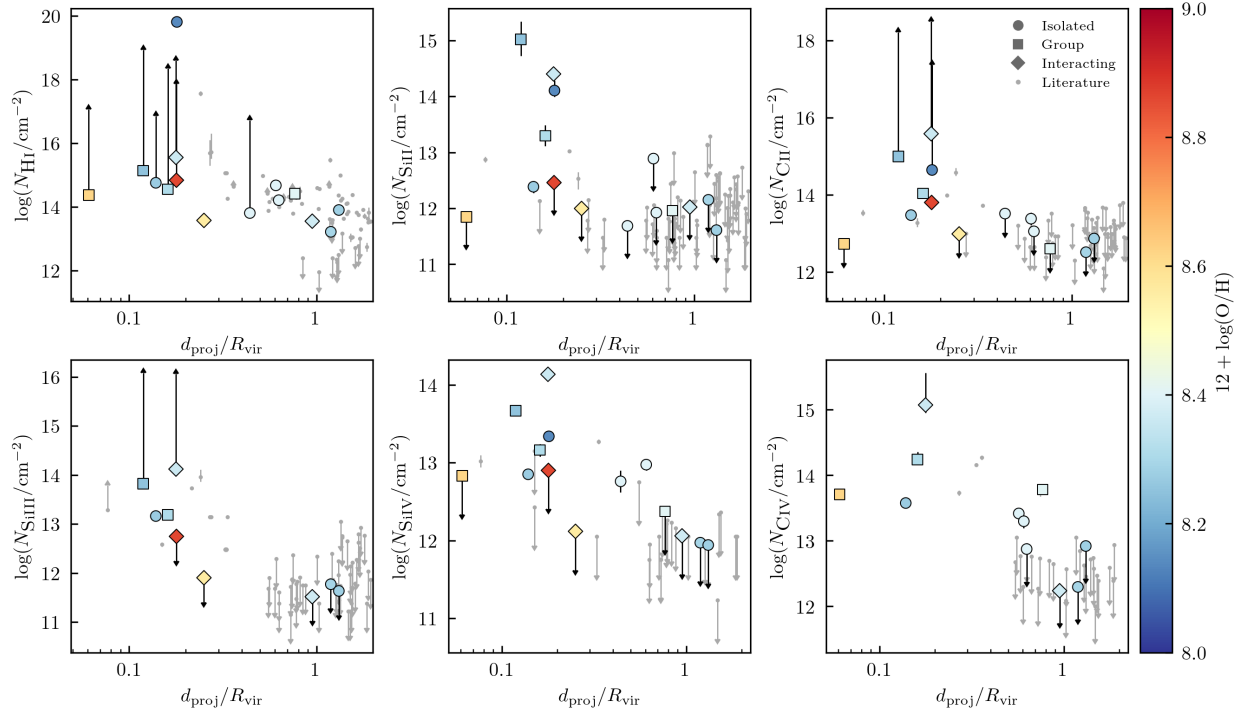


Figure C.11: Same as Figure 5.7, but with QUEST Dwarf galaxies colored by $12 + \log(\text{O}/\text{H})$.

APPENDIX D

FORECASTING GALAXY CLUSTER H I MASS RECOVERY WITH CHIME AT REDSHIFTS 1 AND 2 VIA THE ILLUSTRATING SIMULATIONS

D.1 Making a tiled map from the simulation volume

The volume is projected along a single axis, with the galaxy’s luminosity distance defined by $d_L(z)$ plus its location along the collapsed, projected axis of the volume. We iterate through different projections of the simulation volume in order to construct a larger map that better replicates the angular coverage of real CHIME data.

We generate sub-tiles from all possible projections of the simulation volume from flipping and rotating projected maps, and combine together eight such sub-tiles into the tiled map, which is later convolved with the CHIME beam and used in our analysis. The eight sub-tiles are generated in the same way, but each of the sub-tiles has a different subset of the axes flipped for all permutations. We show this in Fig. D.1.

While this does lead to some repeated projections in the full tiled map, any repetition is mitigated by the neighboring projections being similarly affected generating differences on larger scales which will be affected by beam-convolution and, ultimately, the addition of noise.

D.2 Mock catalog creation

As so much of this analysis rests on the catalogs of (mass- or radius-selected) clusters that we use for stacking, we will go into this catalog creation in greater detail for those interested. (The salient points for the analysis itself are included in the main body of the text and all of code used to generate our catalogs is publicly available.)

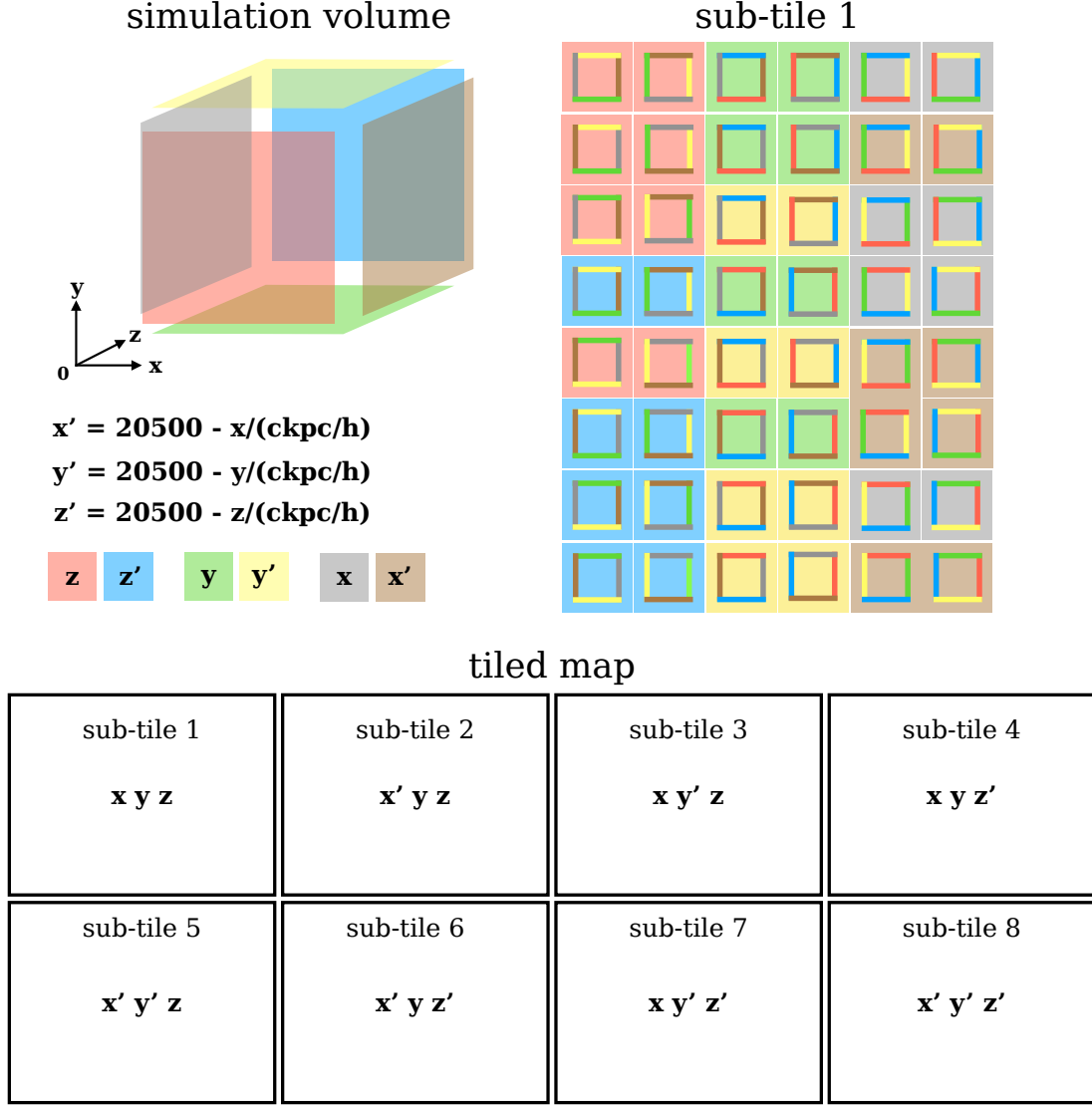


Figure D.1: The various permutations of the simulation volume that make up our individual sub-tiles and, in turn, the full tiled map that we use to simulate CHIME observations. The *simulation volume* color codes the different faces of the volume, which are perpendicular to the projection in each case. The face color indicates the side from which d_L is computed for each target (e.g., for the red face $d_L = d_L(\text{redshift}) + z$, where z is the distance along that axis, while for the blue face $d_L = d_L(\text{redshift}) + [20500 - z/(\text{ckpc}/h)]$). *Sub-tile 1* shows the way different flipped and rotated projections are combined to generate the sub-tiles (using the top left sub-tile as an example). The open squares indicate the orientation of the projection using the face's edges. The *tilled map* demonstrates how the different sub-tiles are ultimately combined, with x' indicating that the x-axis has been flipped for all of the projections in the sub-tile (and so on for y' and z'). In the case of sub-tile 2 then, the red square second from the top and from the left suggests that the simulation volume is projected along the z -axis and included in the sub-tile as x vs. y .

D.2.1 Mass-selected galaxy clusters

In generating the mass-selected galaxy cluster sample, we start by selecting those haloes with $M_{200} \geq 10^{14} M_{\odot}$ within the $z = 0$ group catalog and then track their central subhalo back from $z = 0$ to $z = 2$ or 1 , using the Main Progenitor Branch of the TNG300 SubLink merger trees via the API. For these (sub)haloes, we store M_{200} at $z = 0$, as well as the group ID and position of the massive progenitor halo at $z = 1, 2$.

We check whether the 3 haloes that are already more massive than $10^{14} M_{\odot}$ at $z = 2$ and 50 haloes that meet the same condition at $z = 1$ are included by this approach. Oddly, a portion are not – 8 of the massive haloes at $z = 1$ are not returned by this check for massive haloes at $z = 0$. This seems to be an effect of using central membership to trace haloes at different snapshots. These eight massive haloes all evolve so that their centrals are part of a massive halo at $z = 0$, but are not part of the main progenitor branch of the massive halo’s central subhalo at $z = 0$.

Before any permutations of the simulation volume, the mass-selected galaxy cluster sample contains 276 haloes at $z = 2$ and 277 haloes at $z = 1$, down from 280 haloes with $M_{200} \geq 10^{14} M_{\odot}$ at $z = 0$.

D.2.2 Radius-selected galaxy clusters

Selecting clusters by their radius at $z = 1$ or 2 is somewhat more straightforward. We define radius-selected galaxy clusters at each redshift as haloes with $R_{200} \geq 0.75 h^{-1} \text{ cMpc}$. (See also D’Aloisio et al. 2009 for a more in-depth discussion of proto-cluster and cluster structure.)

There are 26 haloes at $z = 2$ and 160 haloes at $z = 1$ that match this criterion.

D.2.3 Overlap between cluster catalogs

Our definitions of mass- and radius-selected galaxy clusters are not mutually exclusive. At $z = 1$, 128 haloes are included in both samples. This dually defined population drops to 24 haloes at $z = 2$.

The overlapping designations for these haloes do not impact our analyses, but we note that this may be of interest in examining the discrepancy between the observed H I flux of mass- and radius-selected clusters or to those looking to assess the validity of one cluster definition over another.

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