LYRA. III. The Smallest Reionization Survivors

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Abstract

The dividing line between galaxies that are quenched by reionization ("relics") and galaxies that survive reionization (i.e., continue forming stars) is commonly discussed in terms of a halo mass threshold. We probe this threshold in a physically more complete and accurate way than has been possible to date, using five extremely high resolution ($M_{\text{target}} = 4 \times 10^9 M_\odot$) cosmological zoom-in simulations of dwarf galaxies within the halo mass range (1–4) × 10^6 M_\odot. The employed LYRA simulation model features resolved interstellar medium physics and individual, resolved supernova explosions. Interestingly, two out of five of the simulated dwarf galaxies lie close to the threshold mass but are neither full reionization relics nor full reionization survivors. These galaxies initially quench at the time of reionization but merely remain quiescent for ~500 Myr. At $z \sim 5$ they recommence star formation in a synchronous way and remain star-forming until the present day. The parallel timing indicates diverse consistent sound-crossing and cooling times between the halos. While the star formation histories we find are different, we show that they are directly related to the ability of a given halo to retain and cool gas. Whereas the latter is most strongly dependent on the mass (or virial temperature) of the host halo at the time of reionization, it also depends on its growth history, the UV background (and its decrease at late times), and the amount of metals retained within the halo.

Unified Astronomy Thesaurus concepts: Galaxy formation (595); Interstellar medium (847); Reionization (1383); Dwarf galaxies (416); Computational methods (1965); Galaxy quenching (2040); Population III stars (1285)

1. Introduction

Dwarf galaxies are observed to display a variety of star formation histories (SFHs, Weisz et al. 2014). Some SFHs show fairly continuous activity to the present day. Others are quenched at high redshift and then "rejuvenated" in the last few gigayears before the present day. Lastly, there are "reionization relics" that formed all their stars before the universe was reionized ($z \sim 8–7$) and have remained "red and dead" since. To obtain SFHs from observations, they can be reconstructed either from the color–magnitude diagram (CMD) or from the spectral energy distribution (SED). This has been done for known dwarf galaxies in and around the Local Group (LG), to a maximum distance of ~4 Mpc (McQuinn et al. 2010; Weisz et al. 2014; Olsen et al. 2021). Olsen et al. (2021) specifically find synchronized star formation (SF) across their sample, requiring a large-scale environmental cause or a general cosmological explanation. However, observations of such small systems are still only possible very close to the LG. Disentangling the contribution of reionization and environment is thus not easily possible for such faint systems.

From a theoretical point of view, there should be a cutoff mass for galaxy formation due to the heating effect of the photoionizing background (Rees 1986; Babul & Rees 1992; Efstathiou 1992). This was simulated in detail by various authors (e.g., Thoul & Weinberg 1996; Gnedin 2000; Benson et al. 2002; Hoefl et al. 2006; Okamoto et al. 2008; Hambrick et al. 2009), who find substantial gas mass loss and suppression of SF in low-mass halos due to the heating effect by the ultraviolet background (UVB). Okamoto et al. (2008) predict the characteristic, cutoff halo mass to be $M_c \sim 6.5 \times 10^5 M_\odot$ at $z = 0$.

However, the characteristic mass is dependent on redshift and is lower at higher redshift. Maccio et al. (2017) distinguish halos that remain dark or manage to form stars and propose that the ones that remain dark do so because their halos do not cross the characteristic mass at any time in their evolution. Dijkstra et al. (2004) revisit the Thoul & Weinberg (1996) model to show that dwarfs forming well before the peak of reionization ($z > 10$) will be less affected, thus reducing the threshold mass for these objects. This was modeled in detail by Benitez-Llambay & Frenk (2020), who calculated the redshift-dependent critical halo mass for SF before and after reionization. Assuming instantaneous reionization, they demonstrate a lower threshold mass before reionization, corresponding to the atomic hydrogen limit set by a virial temperature of $T_{200} \sim 7000$ K. After reionization, the threshold mass is set by the temperature of ionized hydrogen, $2 \times 10^4$ K. Once a halo is in thermal equilibrium with the background, the metallicity of the gas will not have much effect, since metal cooling lines are subdominant to hydrogen at this temperature. This critical mass theory connects the total mass growth history to the SFH, since halos are only expected to form stars when they are more massive than the critical mass. If their growth does not keep pace with the critical mass growth, then they are predicted to cease SF. Thus, we can call this a mass growth threshold.
These various models capture the general trends very well and have been substantiated by multiple galaxy formation simulations (i.e., Onorbe et al. 2015; Pereira Wilson et al. 2022). However, the evolution before reionization is unconstrained observationally, and theoretical predictions span three orders of magnitude for the pre-reionization cutoff mass, covering the range $10^5$–$10^8 \ M_{\odot}$. The lower end of this range is populated by models assuming that molecular hydrogen cooling leads to Population III SF (Machacek et al. 2001; Abel et al. 2002; Yoshida et al. 2003; Skinner & Wise 2020; Kulkarni et al. 2021). The upper end of the range is a result of assuming that atomic hydrogen is the dominant cooling channel, which happens when the virial temperature rises above $T_{200} = 7000 \ K$ (e.g., Tegmark et al. 1997; Benitez-Llambay & Frenk 2020). This translates to a mass threshold of around $10^8 \ M_{\odot}$ at $z = 8$.

However, since the critical mass is expected to be redshift dependent and have a discontinuity at reionization, the assumed timing of reionization becomes a decisive parameter here as well. For example, the Tegmark et al. (1997) model allows for SF in halos of $M_{\text{halo}} = 2 \times 10^9 \ M_{\odot}$ at $z = 30$. But this rises steeply to $10^{10} \ M_{\odot}$ by $z = 9$. New James Webb Space Telescope (JWST) candidate galaxies at $z \sim 9$–17 show high rest-frame UV luminosities (Harkane et al. 2022). The authors conclude that this can be explained by either a higher-than-expected star formation rate (SFR) surface density or a top-heavy stellar initial mass function (IMF). The former could indicate that the SF efficiency is higher pre-reionization because it is not suppressed by a UV background. The latter could indicate that Population III stars are indeed more massive on average than later stars.

The aim of most of the models presented above is to predict the first primordial collapse threshold. This means that metal line cooling and metal molecular cooling are not taken into account. So while this is an extremely interesting and important question, it really only applies for the very first, isolated and metal-free halos. However, the average $10^9 \ M_{\odot}$ halo at $z = 10$ is already expected to be the product of the assembly (merging) of many smaller halos. Thus, the SFH we would like to understand is actually a cumulative history of the SF in each of these individual smaller halos. To complicate matters, the evolution and SF of such a halo at high redshift are quickly influenced by metal production (i.e., Curti et al. 2023).

After the first (metal-free) Population III stars form, it is expected that their metal production will enrich the surrounding gas and contribute to further cooling (i.e., Wise et al. 2012). As shown in Jeon et al. (2017) and Gutcke et al. (2022), supernovae (SNe) from star-forming halos can eject metals beyond their own virial radii and enrich neighboring halos that otherwise would not be able to cool efficiently via either molecular hydrogen or hydrogen line cooling. Once enriched, the cooling in these small systems is boosted by metal lines. This process allows certain halos in the vicinity of larger neighbors with masses down to $\lesssim 10^9 \ M_{\odot}$ to host stars prior to reionization. Thus, the assembly of a single $>10^9 \ M_{\odot}$ halo can include a combination of primordial and pre-enriched halos.

Lastly, as the halo mass increases and the UVB decreases, some or most of the metals can be retained within the halo. Combined, this creates favorable conditions for gas accretion, gas cooling, and condensation. When the gas finally reaches the critical density for self-shielding, SF quickly reignites.

In this work, we aim to study the SFHs of the smallest dwarf galaxies that survive reionization and place their behavior in the theoretical context of the mass threshold models. While these models are generally valid, the detailed behavior of individual systems seems to be sensitive to various additional processes. In our analysis, we will attempt to disentangle the causes for the intermittent SF activity displayed by our simulations. Situations where multiple simulations demonstrate similar timing point to a cosmological cause that could be interpreted in terms of a larger-scale synchronicity.

The paper is organized as follows: In Section 2 we summarize the most relevant aspects of the simulation model. In Section 3.1 we present the SFHs of the five simulations. Then, in Section 3.2 we discuss how these histories came about through an analysis of the halos’ early evolution. In Section 3.3, we compare the $z = 0$ attributes of the simulations with observations of LG dwarf galaxies. Lastly, in Sections 4 and 5 we discuss our results in the context of other simulation work and present our main findings.

### 2. Model and Method

In the current study, we present the first sample of five cosmological simulations run to $z = 0$ using the LYRA galaxy formation model (Gutcke et al. 2021, 2022). LYRA is a comprehensive numerical model that includes a resolved interstellar medium (ISM) with a cooling prescription down to 10 K, individual (star-by-star) SF, resolved SN, and a subgrid model for Population III star enrichment at high redshift. These prescriptions are implemented in the cosmological, hydrodynamical moving-mesh code AREPO (Springel 2010; Pakmor et al. 2016; Weinberger et al. 2020). We direct the reader to these papers for a detailed description of the model and the code characteristics. Below, we will summarize the most relevant aspects for this study.

The UVB is implemented as an isotropic heating term following the rates presented in Faucher-Giguere (2020). H II reionization is set to $z = 7.8$ but is $>90\%$ complete by $z = 7.3$. He II reionization is $>90\%$ complete at $z = 3.0$. Gas is self-shielded from this heating following the fitting function presented in Rahmati et al. (2013). In practice, the self-shielding factor depends on the gas density and the redshift. The majority of gas will be fully self-shielded above $n_H \gtrsim 10^{-2} \ cm^{-3}$. To enable the compatibility of heating and cooling rates, we choose to use the metal and low-temperature cooling rates tabulated in Ploeckinger & Schaye (2020; “UVB dust1 CR0 G0 shield1”). These were computed using CLOUDY (Ferland et al. 2017) and use the Faucher-Giguere (2020) UVB as an input. Importantly, instead of the common “one-zone” model, these tables account for the full absorption of the incident radiation down to a fixed column density. We include these cooling rates from $z = 20$ at the lowest value tabulated. The simulations are started with zero metallicity; thus, no metal cooling can occur initially. Using the “100$\%$” case presented in Gutcke et al. (2022) as our fiducial model, we implement the enrichment by Population III stars in a subgrid manner. Running the halo finder SUBFIND (Springel et al. 2001) on the fly, the metallicity of the gas within the virial radius is increased from 0 to $10^{-4} Z_{\odot}$ when a halo crosses the mass threshold of $M_{\text{PopIII}} = 10^8 \ M_{\odot}$. Once the gas metallicity is $10^{-4} Z_{\odot}$ or higher, it is allowed to cool and form stars.

SF follows a Schmidt relation (Schmidt 1959):

$$M_\star = \varepsilon_{\text{SF}} \frac{M_{\text{gas}}}{t_{ff}},$$

where $\varepsilon_{\text{SF}}$ is the SF efficiency parameter and $t_{ff} = \sqrt{3\pi/(32G\rho)}$ is the freefall time of the gas cell with density

\[ \rho = \frac{\dot{M}}{4\pi r^2 c}, \]

where $\dot{M}$ is the gas accretion rate, and $c$ is the sound speed.
\( \rho \) and gravitational constant \( G \). Gas cells with \( T/K < 100 \) and \( 3 < \log(n_H/cm^{-3}) < 4 \) are eligible to form stars at an efficiency of \( \varepsilon_{SF} = 2\% \). When \( \log(n_H/cm^{-3}) > 4 \), the efficiency is increased to \( \varepsilon_{SF} = 100\% \).

Each individual star’s evolution is determined by its initial mass, metallicity, and age. Stars between 4 and \( 8 \, M_\odot \) return mass and metals to the ISM according to the asymptotic giant branch models of Portinari et al. (1998); above \( 8 \, M_\odot \), the stars either explode as SNe or simply shed their enriched shells without the additional injection of thermal energy and become direct collapse black holes (following Sukhbold et al. 2016).

The SN cooling radii are resolved at all densities relevant to this study (see Gutcke et al. 2021, for tests). These simulations do not include other types of feedback.

The initial conditions were taken from the EAGLE simulation (Schaye et al. 2015) following the method presented in Jenkins (2013). The final zoom-in initial conditions simulate the entire EAGLE box \( (L = 100 \, h^{-1} \, Mpc) \) at low resolution. Within this box, we define a high-resolution region that encompasses the complete Lagrangian region of a single dwarf galaxy. Within this region gas can be refined and de-refined, cool radiatively, and form stars. The DM mass resolution is \( \sim 80 \, M_\odot \), while the target gas cell mass is set to \( 4 \, M_\odot \). The gravitational softening length is 10 pc for DM and 4 pc for the gas and stars. The galaxies were chosen to fulfill an isolation criterion, namely to not interact with a larger galaxy for the duration of their lifetime. This is distinct from the population of LG dwarf galaxies that we use for comparison in Section 3.3. However, as shown in Arora et al. (2022), the difference between field dwarfs and LG dwarfs is most strongly seen in the metallicity of the circumgalactic medium (CGM), which we do not compare here.

3. Results

3.1. Star Formation Histories

In this work, we present a sample of five halos in the mass range \((1-4) \times 10^9 \, M_\odot \). Figure 1 shows stellar surface brightness maps at \( z = 0 \) for each of the five simulations. The general morphology is that of dwarf spheroidals (dSph), with a smooth extended distribution. However, there are two additional features of note in these mock images. First, the center of the main spheroid seems to show signs of nucleation, a central stellar overdensity distinct from the extended profile. Nucleation is seen in dwarf galaxies in both the Fornax Cluster (Munoz et al. 2015; Eigenthaler et al. 2018; Next Generation Fornax Survey) and the Virgo Cluster (Grant et al. 2005; Isaac Newton Telescope Virgo Survey). Second, there is a clear indication of luminous substructure associated with each halo. We summarize the general attributes of the five simulations in Table 1.

In Figure 2 we present the five SFHs as a function of redshift. More precisely, this is an initial-mass-weighted histogram of formation times of all stars within \( R_{200} \) at \( z = 0 \). It includes accreted stars but does not include stellar mass loss. The thin lines were computed using a bin width of 10 Myr (500 Myr for the thick lines). The halos are ordered from top to bottom by halo mass at \( z = 0 \). Halo A and Halo D show a similar SFH: they initially quench at \( z = 7.8 \), recommence SF at \( z \approx 5 \), and continue to form a significant fraction of their stars after reionization. Nevertheless, it should be pointed out that they are severely affected by reionization: first, because they initially are quenched for approximately 400–500 Myr before recommencing SF, and second, because the level of SF after reionization steadily decreases to values around \( 10^{-6} \) to \( 10^{-4} \, M_\odot \, yr^{-1} \), never again attaining the early (pre-reionization) value of \( \sim 10^{-2} \, M_\odot \, yr^{-1} \). Table 2 summarizes the rejuvenation time and redshift for Halos A, B and D.

Halo B is also initially quenched by reionization but has a single burst around \( z = 5 \), which reduces the central density such that no more stars are able to form at that time. However, 6 Gyr later the galaxy rejuvenates at around \( z = 0.3 \) at a rate of \( \sim 10^{-5} \, M_\odot \, yr^{-1} \). Halo C and Halo E are consistent with being reionization relics. Their SF ceases at \( z = 7.8 \), after which they are never again able to assemble sufficient gas to recommence forming stars. Interestingly, these two galaxies also form their first stars later than the other three galaxies. While Halo A, Halo B, and Halo D begin forming stars shortly after \( z = 20 \), these two halos do not host stars until around \( z = 16 \). We also note that the \( z = 0 \) halo mass is a good predictor neither of the final stellar mass nor of the shape of the SFH.

3.2. Why Do Certain Halos Survive Reionization?

In the following, we will investigate the cause of the quenching at reionization in more detail. Most importantly, we will focus on the reasons why two (three, if we include Halo B) of the halos recommence their star-forming activity, while the others do not.

Figure 3 presents the evolutionary behavior of the four more massive simulations, Halos A–D, in the time interval \( t = 0.2–1.7 \, Gyr \). Each panel shows data from one simulation. The top panel is the average hydrogen number density within the central 40 pc (colored line) and within \( R_{200} \) (black line). The middle panel is the cooling time of the entire halo (colored line) computed as

\[
\tau_{cool} = \frac{\rho}{du/dt},
\]

where \( u \) is the total internal energy of gas cells within the halo. We also show the dynamical time of the halo (black line), which is

\[
\tau_{dyn} = \left( \frac{3 \pi}{32 G \rho} \right)^{1/2},
\]

where \( \rho \) is the average total mass density within the halo. Finally, the bottom panel is the net gas flow rate across a spherical shell centered on \( R_{200} \) with a width of 0.1 \( R_{200} \). The gray bands indicate ongoing SF within the halo at that time. We note that the gray bands differ slightly from the SFHs in Figure 2, since the SFHs include all stars that reside within the main halo at \( z = 0 \). Due to late accretion of luminous substructure, some of these stars are not yet present in the halo at higher redshifts.

Before reionization, all four simulations show similar behavior: the cooling time is well below the dynamical time, and SF is fairly continuous. The central gas density varies but has peaks above \( 1 \, cm^{-3} \). The outflow and inflow rates are generally well matched, meaning that SF is self-regulated: external accretion fuels SF, and SNe drive outflows without preventing accretion. Thus, there is neither runaway cooling nor quenching. This self-regulation is strongly affected by the onset of reionization.
Figure 1. Mock V-band surface brightness maps for each simulation at $z = 0$. Each image is 1.4 kpc $\times$ 1.4 kpc. Notice that the color bar is rescaled for each image. The simulation is not rotated, only repositioned to place the halo in the center.
Hydrogen reionization begins at \( z = 8.3 \) and completes at \( z = 7.3 \), thus occurring at a mean redshift of \( z = 7.8 \) (black dashed line). During this time, all gas that is not self-shielded is heated to approximately \( 1.5 \times 10^4 \) K. In response to this sudden heating, unshielded gas in the ISM and the entire CGM must expand. As Shapiro et al. (2004) show, even the

### Table 1
Summary of Simulation Attributes

| Name  | \( M_{200} \) \((10^9 M_\odot)\) | \( M_* \) \((10^6 M_\odot)\) | \( R_{200} \) (kpc) | \( R_{1/2} \) (pc) | \( c_{\text{max}} \) | \( v_{\text{bulk}} \) (km s\(^{-1}\)) | \( \log (M_*) \) (M_\odot yr\(^{-1}\)) | \( f_{\text{Gyr}} \) | \( M_V \) | \( \log L_\odot \) | \( \log Z_\odot \) |
|-------|-----------------|----------------|---------------|--------------|----------|------------------|-----------------|-------------|--------|------------|----------|
| Halo A | 3.34            | 9.42           | 28.7          | 311.5        | 13.5     | 177.5            | -2.3            | 0.519      | -11.5   | 6.69       | -1.02    |
| Halo B | 2.82            | 1.26           | 29.8          | 483.2        | 12.7     | 146.6            | -3.2            | 0.992      | -8.8    | 5.79       | -2.60    |
| Halo C | 2.16            | 1.05           | 27.2          | 878.4        | 13.0     | 46.3             | -3.1            | 1.000      | -8.6    | 5.57       | -2.22    |
| Halo D | 1.72            | 1.59           | 25.3          | 119.6        | 24.8     | 120.0            | -2.8            | 0.830      | -9.0    | 5.65       | -1.47    |
| Halo E | 0.29            | 0.22           | 7.2           | 107.0        | 14.7     | 11.0             | -3.7            | 1.000      | -8.4    | 5.55       | -2.52    |

**Note.** Virial Mass at \( z = 0 \), Stellar Mass within \( R_{200} \) at \( z = 0 \), Virial Radius, Stellar Half-mass Radius, Concentration Parameter, Bulk Velocity of the Halo, Mean SFR until \( z = 4 \), Fraction of Stars Formed in the First 1Gyr, V-band Magnitude at \( z = 0 \), Luminosity at \( z = 0 \), and Mean Stellar Metallicity at \( z = 0 \).
self-shielded gas can eventually become photoevaporated. The expansion causes outflows, so there is less net accretion onto the central region. SF comes to a sudden halt in all halos owing to a lack of fuel. Cooling times of the gas increase above the dynamical time and even above the Hubble time (gray dotted line). The net flow rate may be outward owing to the last SNe driving outflows into the now-ionized medium, making the central gas density drop drastically.

Let us assume that the majority of gas is in hydrostatic equilibrium before the onset of reionization. The gas is neither isothermal nor in thermal equilibrium with an external radiation field (since there is none in this model). A pressure (and temperature) gradient across the halo supports the non-SF gas. We can approximate reionization as an instantaneous (non-adiabatic) heating process.

The sudden heating of the gas by reionization raises the pressure. To reestablish equilibrium, the gas in the halo will expand on the sound-crossing timescale, which is the time it takes to cross the halo when traveling at the local sound speed. It is straightforward to compute the adiabatic sound speed assuming an ideal gas:

$$c_s = \sqrt{\frac{k}{\mu m_p} T} \approx 18.4 \text{ km s}^{-1} \left( \frac{T}{1.5 \times 10^4 \text{ K}} \right)^{1/2},$$

where $\gamma = 5/3$ is the adiabatic index, $k_B$ is the Boltzmann factor, $T$ is the temperature, $m_p$ is the proton mass, and we assume a mean molecular weight of ionized hydrogen and singly ionized helium after reionization, $\mu = 2/(3X + 1) \approx 0.61$, where $X = 0.76$ is the primordial hydrogen mass fraction. The two halos with early rejuvenation, Halo A and Halo D, undergo the same quenching and recommencement of SF at approximately the same time. They have an average virial radius of $R_{200} \approx 3 \text{kpc}$ between $z = 7.8$ and 5. Thus, the sound-crossing time of these halos is $t_{sc} \approx 160 \text{ Myr}$ (see Table 2).

Due to the sudden heating and subsequent expansion, some gas may become unbound, as seen in the net outflow rates. However, most of the gas will cool and recollapse owing to gravity. The net flow rates reverse and inflow begins to dominate after around one sound-crossing time, driving gas back inside the virial radius. The initial expansions and subsequent recollapse can be seen as oscillation (or “breathing”) of the halo in response to reionization.

The total gas density (black line) in Halo B and Halo C steadily decreases immediately after reionization. There is photoevaporation of the gas at and beyond the virial radius. Accretion is halted and outflows dominate. However, within one sound-crossing time all four halos reestablish a central gas reservoir. The minimum density required to do this is the self-shielding threshold of $\sim 10^{-2} \text{ cm}^{-3}$. After that, the central gas densities (colored lines) either remain constant or rise steadily. This accretion occurs despite the total halo density (black lines) remaining constant or decreasing. This implies that most gas does not escape the halo but is initially suspended in the CGM until it is slowly reaccreted onto the central zone.

As the central densities increase, the cooling time decreases. Once it drops below the dynamical time again, SF can start again. This happens after $\sim 500 \text{ Myr}$ in Halo A, Halo B, and Halo D. The time required for this is a combination of the sound-crossing time and the time required for outward angular momentum transport and radiative cooling. We suggest that this $\sim 500 \text{ Myr}$ break results from intrinsic properties of these halos that are at the edge between quenching and survival. The fact that all three halos display the same behavior can be interpreted as synchronicity with a cosmological (reionization) cause.

Halo B shows a slightly different behavior than Halo A and Halo D after reionization. Already before reionization it shows a more bursty and sporadic SF with periods of lower gas densities. There is a final burst of SF at the time of reionization and some subsequent net outflow. However, the net flow does not turn around to become an inflow in the same way as in the other two halos. Instead, there is a low but persistent net outflow, meaning that the halo is photoevaporating at its boundary. So while we can see a slow increase in the central gas density, this is material from the CGM, not new accretion. The central density reaches a sufficiently high value that SF recommences but is interrupted after a single burst, sending the cooling time to values greater than the Hubble time. SF is quenched for the next 6 Gyr. Then, at $z \approx 0.3$, it recommences at a low rate.

Lastly, we will look at Halo C (which is very similar to Halo E and not shown here for simplicity). SF is quenched slightly before the peak of reionization, showing that the halo is especially sensitive to the external radiation field. The cooling time increases rapidly, and the net flow rates are very small (note that the $y$-axis is rescaled, showing no large-scale accretion. Interestingly, while this halo does not manage to form stars again, there is nevertheless an indication of activity around the same time that the other halos rejuvenate. The cooling time decreases below the Hubble time, and the gas density rises slightly. After this, the activity ceases.

Halos A–D were chosen to have $z = 0$ halo masses within a factor of two of each other. Nevertheless, their growth histories vary. In the top panel of Figure 4 we show the virial temperature of each halo as a function of redshift:

$$T_{500} = \frac{\mu m_p GM_{200}}{2k_B R_{200}},$$

where $M_{200}$ is the virial mass and $R_{200}$ is the virial radius. To guide the eye, we have also plotted the atomic cooling threshold of $10^4 \text{ K}$ and the quenching redshift of $z = 7.7$. The magenta line shows the IGM temperature, computed following Puchwein et al. (2015), namely the median gas temperature of IGM gas within 5% of the mean cosmic density. The IGM temperature begins to rise at $z = 8.3$ according to our UVB and reaches $10^4 \text{ K}$ by $z = 7.3$. Starting at $z = 4$, we begin to see He II reionization heating the IGM. After $z = 2$ the IGM temperature drops below $10^4 \text{ K}$ owing to the expansion of the universe.
Figure 3. Each of the four figures shows three panels as a function of time for one simulation, respectively: the top panels show gas density within 40 pc (solid colored) and within $R_{200}$ (black line). The middle panels show the cooling time measured within the virial radius (colored), the dynamical time of the halo (black), and the Hubble time (dotted). The bottom panels show the net mass flow rate (outflow rate minus inflow rate) across the spherical shell with radius $R_{200}$ and width $0.1 \times R_{200}$. The gray bands in each panel indicate when SF is ongoing. The black vertical dashed line shows the time of quenching ($z = 7.7$), which is just after the central reionization redshift ($z = 7.8$).
We see that Halo D displays the fastest early growth, rising above $10^4$ K as early as $z \approx 10$. This is also seen in the concentration parameter (see Table 1). The concentration is computed following Bullock et al. (2001) assuming an NFW profile shape (Navarro et al. 1997) and using the $r_{\text{max}}$ method:

$$c = 2.16 \frac{R_{200}}{r_{\text{max}}},$$

where $r_{\text{max}}$ is the radius at the peak of the rotation curve, $v_{\text{max}}$. Large concentration parameters are known to be indicative of early growth (Wechsler et al. 2002), since the central halo builds up early, when the universe was denser. The fact that this affects halo properties, such as SF, is known as assembly bias. Halo A also grows sufficiently that the virial temperature surpasses $10^4$ K before the onset of reionization, despite having a much lower concentration. Halo B and Halo C cross this threshold after reionization, while Halo E never grows sufficiently.

In the bottom panel of Figure 4, we also show the virial mass, $M_{\text{halo}}$, as a function of redshift for comparison. The colored lines are opaque when SF is off. The Population III halo threshold is plotted as a gray dashed line, and the black line shows the model from Benitez-Llambay & Frenk (2020). If the model were accurate, the colored lines would be opaque below the black line and colored above. Despite the simplicity of the model, this is indeed approximately true most of the time. However, close to the threshold the details of each halo alter the evolution.

Figure 5 shows the mass loading factor as a function of redshift for all five simulations. The mass loading factor is the ratio of the outflow rate over the mean SFR, where we have measured the mean value from the time of the first star to $z = 4$:

$$\eta_M = \frac{M_{\text{out}}}{\langle M_\ast \rangle}.$$  

Since all simulations have discontinuous SFHs, the mean SFR is lower than if we had only accounted for times of ongoing SF. Therefore, the mass loading factors shown are lower than the instantaneous values would be. The time-averaged mass loading factors from the time the first star forms to $z = 4$ for the simulations in alphabetical order are 33.7, 26.3, 3.7, 6.5, and 7.0. It is interesting to note that the mean values are above unity in all cases. This means that the halos are losing substantial gas mass throughout their evolution. We show this even more clearly in Figure 6, in terms of the baryon fraction across redshift. Until $z \approx 15$, all halos are consistent with hosting baryons at the cosmic baryon fraction (gray dashed line). Once SF sets in, mass loss occurs. While certain halos are able to regain higher fractions for some time, the final values tend to assume extremely low values of 1%–10% of the mean cosmic value. It is of interest to note that Halo E does not form new stars after $z \approx 7.7$ but nevertheless shows a mass loading above unity and a decreasing baryon fraction. This must therefore be attributed to photoevaporation due to the UVB.

### 3.3. What Are the $z = 0$ Properties?

Now that we have discussed the SFHs and the reason why certain halos survive reionization, let us turn to the $z = 0$ properties. Do these properties conform to LG observations? Do they betray their different histories?

First, in Figure 7 we look at the kinematics of the stars at $z = 0$. In the left panel, we show the peak value of the stellar rotation curve. The middle panel is the stellar velocity dispersion measured within the half-mass radius. To be precise,
this is the average of the three independent (x, y, and z) line-of-sight velocity dispersions. The right panel shows the ratio of these two values, giving us an indication of the dominant mode of support against gravitational collapse. In each panel, the gray data points are compiled measurements from LG dwarf observations. The rotation velocity of our five halos as a function of total stellar mass matches the data well. There is a distinct increase in velocity with increasing stellar mass that reflects the same trend seen in the data. In addition, the velocity dispersions in the central panel match the data. However, they seem to be slightly low in the simulations. This is likely caused by the “softened” treatment of gravitational N-body forces below the softening length, ε soft, which we have set to 4 pc in this work. This means that the gravitational acceleration acting on stars passing within ε soft of another particle is reduced, a choice made for computational efficiency. This can affect the estimated value of the velocity dispersion when interactions such as encounters closer than the softening length and binary stars interacting with a third star occur. Such interactions would cause an exchange of velocities and therefore increase the total dispersion of the system. Since they are not accounted for here, the velocity dispersion is on the low end of what is expected from observations. Finally, in the right panel we see that the four lower-mass systems are dispersion dominated (values below unity). Halo A, on the other hand, sits close to unity, consistent with the appearance of more rotation-dominated systems at these stellar masses in the observational data. 

Figure 8 shows the magnitude–metallicity relation for our simulations at z = 0 and the LG data from McConnachie (2012). The metallicity is the log-averaged z = 0 metallicity of all stars within R200. Our simulations span the range of metallicities in the data, between log Z/Z⊙ = −2.5 and −1. As Agertz et al. (2020) showed, the metallicity relation is a useful indicator for the strength of feedback. Metallicities above the relation indicate a too-weak feedback prescription, since metals are not ejected out of the ISM, instead accumulating and forming high-metallicity stars. On the other hand, if the feedback is too strong, then metals are preferentially ejected with the SN bursts and impoverish the ISM. The fact that this work spans the data is an encouraging indication that resolving the cooling radius for each SN self-consistently calibrates the strength of feedback.

It is unsurprising that the two halos that survive reionization also show the highest metallicities, since later SF produces more enriched stars. To show this in detail, we plot the age–metallicity diagram for Halo A in Figure 9. SF starts before reionization at the lowest metallicity allowed for SF, log Z/Z⊙ = −4. Within the first gigayear, the metallicity increases to > −2. After z = 4, no new stars form below log Z/Z⊙ = −1.5. However, the mean SFR is also reduced significantly. Recent Early Release Observations with the James Webb Space Telescope (JWST) using the Near-Infrared Spectrograph (NIRSpec) indicate a rapid buildup of metallicity at z > 7 (Arellano-Córdova et al. 2022). The metallicity buildup within our halos prior to the onset of reionization is also rapid, with the first solar-metallicity stars forming as early as z > 10.

Finally, we also show the size–magnitude relation in Figure 10. Colored diamonds give the stellar half-mass radii in the simulations. Again, the gray data points show LG dwarfs from McConnachie (2012). For comparison, black diamonds show Milky Way globular clusters (GCs) from Harris (1996; 2010 edition). Clearly, the simulated sizes are within expectations of the data. All five simulations are well placed within the classical dwarf regime (M20 > −6), not in the ultrafaint regime. The two halos with more recent SF have smaller sizes. This is due to the fact that younger stars, which are brighter and have not lost mass, are more centrally located. We show this in Figure 11 for Halo A. This is consistent with Figure 11(b) of Savino et al. (2019) for Tucana dSph. In Figure 12 we see that the central 0.5 kpc of Halo A are also dominated by a rotating disk, which is composed primarily of younger stars. This is in line with Figure 7, in which only Halo A shows signs of rotational support.

4. Discussion

Cosmological simulations at mass resolutions of < 10 M⊙ are not yet very common. But this level of resolution is crucial for the galaxy mass scale we study here, since it allows us to resolve the multiphase ISM and individual SN bursts without parameters tuned to match observations. We can compare our results with the EDGE simulations (Agertz et al. 2020) that have a mass resolution of 20 M⊙. In Rey et al. (2020, hereafter R20), the SFHs of four galaxies from this project were presented in detail. The authors show that reionization initially quenches all four. However, two are able to reignite SF at low rates after z = 1. These two cases are reminiscent of Halo B in our sample. Of the two quenched halos in R20, the “gas-rich” simulation is similar to Halo C presented here. While neither forms stars after reionization, they are very close to doing so.

R20 show that a small “genetic” modification that increases the final mass can incite this halo to rejuvenate. In our work, Halo C is the same initial condition as presented in Gutcke et al. (2022). In that paper, we showed that small modifications to the treatment of metals at high redshift (for example, setting M⊙/popIII = 107 M⊙) also had the effect of inducing rejuvenation. Thus, both of these halos seem to demonstrate properties at the extreme edge between survival and quenching. Minor model variations are able to tip the evolution in one direction or another. Both halos have very similar z = 0 total masses of 2.5 × 10⁹ M⊙ (R20) and 2.16 × 10⁹ M⊙ (Halo C). One additional point to note, however, is that the stellar masses of the two are almost a factor of two different: 5.9 × 10⁵ M⊙ (R20) and 1.05 × 10⁶ M⊙ (Halo C).

Wheeler et al. (2019) present FIRE dwarfs with a mass resolution of 30 M⊙. They show consistency with Onorbe et al. (2015), in which SF in ultrafaint dwarf galaxies is quenched by.

Figure 6. Baryon fraction normalized to the cosmic baryon fraction, Ωb/Ωm, as a function of redshift for each simulation. The vertical gray band indicates the time of hydrogen reionization.
reionization, but residual self-shielded gas allows stars to continue forming until \( z \sim 2.5 \). The lack of fresh accretion, which is caused by reionization, then prevents SF after \( z = 2 \). They also predict that all simulations producing classical dwarfs continue to form stars until at least \( z = 0.5 \).

These results are somewhat in conflict with our work here. This is primarily caused by quite different stellar masses in the same halo mass ranges. For example, the “m0930” simulation in the "m0930" simulation in Wheeler et al. (2019) has a halo mass of \( M_{\text{halo}} = 2.5 \times 10^9 \, M_\odot \), but only produces \( 1.2 \times 10^4 \, M_\odot \) in stars. For the same halo mass, this is two orders of magnitude lower than the stellar mass.

Figure 7. The peak of the stellar rotation curve, \( v_{\text{rot}} \), the 1D velocity dispersion within the half-mass radius, \( \sigma_* \), and their ratio as a function of total stellar mass. Gray data points with error bars show the LG dwarf observations (compiled by Wheeler et al. 2017). Halo A and Halo D are partially rotationally supported.

Figure 8. Metallicity as a function of V-band magnitude. Gray data points show LG dwarf observations from McConnachie (2012).

Figure 9. Age–metallicity relation for Halo A. The color bar shows the logarithm of the mean SFR in each bin of age and metallicity. Age bins are 500 Myr wide, while metallicity bins are 0.25 dex. Compare this figure to Figure 8(a) of Savino et al. (2019) showing the age–metallicity relation of Tucana dSph.

Figure 10. V-band magnitude as a function of stellar half-mass (light) radius, \( R_{1/2} \). Gray data points show LG dwarf observations from McConnachie (2012). Filled diamonds show half-mass radii. Small back diamonds also show the Milky Way GCs from Harris (1996). The gray shaded area represents sizes below the dark matter softening length of our simulations. The diagonal light-blue lines are lines of constant surface brightness.

Figure 11. Cumulative radial distribution of stars within \( R = 1 \) kpc for Halo A. The red line shows the distribution for stars formed before reionization, while the blue line is all stars formed afterward. Clearly, the younger stars are more centrally concentrated.
mass formed in our work here. This discrepancy is already set before the onset of reionization, since the SFR in our work is $\gtrsim 10^{-2} \, M_{\odot} \, yr^{-1}$, and all five galaxies form $\gtrsim 10^5 \, M_{\odot}$ before $z = 10$. "m09a03" on the other hand, forms stars at a rate of $\lesssim 10^{-4} \, M_{\odot} \, yr^{-1}$ before reionization, producing an order of magnitude fewer stars by the same time.

It is plausible that these large differences so early on in the evolution are caused by a combination of two model choices. For one, the FIRE model does not account for Population III enrichment. Possibly more importantly, the stellar feedback prescription is known to be very strong and bursty in the FIRE model. It is likely that this suppresses early SF too much in their model. This explanation is consistent with the extremely low metallicities presented in the same work. Encouragingly, the updated FIRE-3 model (Hopkins et al. 2022) appears to present altered predictions for precisely this halo mass range ($(1-5) \times 10^5 \, M_{\odot}$). Figure 9 of that paper shows stellar masses one order of magnitude higher in the new model, bringing their results in much closer agreement to ours. The remaining differences can be attributed to the additional feedback prescriptions included in FIRE-3, such as photoionization in H II regions, photoelectric heating, and cosmic-ray heating. Future work on the LYRA model will include these, and then a more conclusive comparison can be made.

### 5. Conclusions

We have carried out five ultra–high-resolution cosmological zoom-in simulations of dwarf galaxies in the mass range $(1-4) \times 10^7 \, M_{\odot}$. At $M_{\text{target}} = 4 \, M_{\odot}$, these simulations constitute the highest-resolution zoom-in simulations run fully cosmologically to $z = 0$ to date. Additionally, they include a resolved multiphase ISM and individually resolved SN explosions. As our galaxies were selected to form in isolation and distanced from larger neighbors, our simulations probe universal aspects of cosmological evolution and of the effects of reionization, without being influenced by additional effects caused by environment or infall.

The halo mass range chosen for our study covers the edge of where galaxy formation is expected. As such, it is unsurprising that only two out of the five simulations form a significant fraction of stars after reionization. To understand why these two survive while the other three remain quenched, we analyze the SFHs and the early evolution to $z = 4$ in detail. Our main results are as follows:

1. In the studied mass range, the $z = 0$ halo mass is not a good predictor for the survival after reionization.
2. Framing the evolution and SFH of dwarfs in terms of an evolving mass threshold is useful in a general sense but fails to capture the details of individual galaxies.
3. In our sample, halos that grow to $T_{200} > 10^4 \, K$ before reionization form stars after reionization.
4. The two surviving halos are initially quenched by reionization for around 500 Myr, before recommencing SF.
5. The nonadiabatic heating caused by reionization elicits an oscillation or breathing of the entire gas within the halo. Initially, the gas expands, then slows, and, if still bound, recollapses onto the halo. This final step can be followed by an SF episode.
6. Late-time ($z \sim 0.3$) reignition of SF occurs in one of our halos. The halo growth and gas accretion leading up to the reignition are concurrent with the drop of the strength of the UVB after $z = 2$.

To place our simulations in the context of LG dwarf galaxy observations, we also compare them to various $z = 0$ properties of our simulations. Our main findings are as follows:

1. The feedback strength resulting from resolved SNe produces a magnitude–metallicity relation as expected from observations.
2. Younger stars, when they exist, are more centrally concentrated and in a rotating disk.
3. Younger stars are more metal-rich, leading to a higher mean metallicity.
4. The LYRA model predicts that the examined halo mass range produces classical dwarfs, as opposed to ultrafaint dwarf galaxies.
Additionally, we would like to stress that this work is based on five simulations only. Hence, while this does constitute a small sample, certain evolutionary behavior may still be purely stochastic. In addition, while most of our model parameters are either set by first principles or directly motivated by observations instead of being calibrated for, there remains some room for modified parameter choices or assumptions. Some of the results presented here may be sensitive to the details of these choices.

Finally, our goals for the future are to expand the sample of simulations and the parameter space covered by this work, as well as to include additional physics, in particular magnetohydrodynamics and cosmic rays. Thus, we hope to present in forthcoming work refined predictions for dwarf galaxy properties as a function of halo mass and be able to either confirm or extend common extrapolations down into the low-mass galaxy regime.

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