The beginning and the end of star formation in faint field dwarf galaxies

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ABSTRACT
We use the APOSTLE suite of cosmological simulations to examine the role of the cosmic ionizing background in regulating star formation (SF) in low-mass LCDM halos. In agreement with earlier work, we find that, after reionization, SF can only proceed in halos whose mass exceeds a redshift-dependent “critical” virial mass determined by the structure of LCDM halos and the thermal pressure of UV-heated gas. This critical mass increases from $M_{\text{crit}} \sim 10^8 M_\odot$ at $z \sim 11$ to $\sim 10^{9.7} M_\odot$ at $z = 0$, roughly following the average mass growth history of halos in that mass range. This implies that most halos above or below critical at present have remained so since early times. In particular, the halos of most galaxies today were already above-critical (and thus forming stars) at high redshift, providing a simple explanation for the ubiquitous presence of ancient stellar populations in dwarfs, regardless of luminosity. It also implies that $M_{\text{crit}}$ today represents a “threshold” mass below which the fraction of “dark” halos increases steeply. Sub-critical halos may still host luminous galaxies if they were above-critical at some point in the past. SF ceases if a halo falls into the sub-critical regime; depending on each halo’s accretion history this can occur over a wide range of times, explaining why SF in many dwarfs seems to continue well past the reionization epoch. It also suggests a tantalizing explanation for the episodic nature of SF in some dwarfs, which, in this interpretation, would be linked to temporary halo excursions above the critical boundary. In the simulations, $M_{\text{crit}}(z)$ cleanly separates star-forming from non-star-forming systems at all redshifts, indicating that the ionizing UV background, and not stellar feedback, is what regulates the beginning and the end of SF in the faintest dwarfs. Galaxies in sub-critical halos should make up a sizable population of faint field dwarfs, distinct from those in more massive halos because of their lack of ongoing star formation. Although few such galaxies are known at present, the discovery of this population would provide strong support for our results.

Key words: dark matter; galaxies: formation; galaxies: evolution; galaxies: dwarf; galaxies: kinematics and dynamics; globular clusters: general;

1 INTRODUCTION

The Lambda Cold Dark Matter (LCDM) paradigm for structure formation makes a number of well-defined and robust predictions for the formation and evolution of dark matter halos. In particular, LCDM predicts a power-law halo mass function at the low-mass end that is much steeper than the galaxy stellar mass function at the faint end. This discrepancy places strong constraints on the galaxy mass-halo mass relation at the faint end, and is usually explained by arguing for a steady decrease in galaxy formation “efficiency” with decreasing halo mass, so that, effectively, no luminous galaxies form below some “threshold” halo mass (see; the excellent review of Bullock & Boylan-Kolchin 2017, and references therein).

The origin of this threshold is usually ascribed to the effects of high-energy photons responsible for cosmic reionization (Rees 1986; Ikeuchi 1986; Efstathiou 1992), which heated gas throughout the Universe at early times, preventing its collapse, and the subsequent onset of star formation, in the shallow potential wells of low-mass halos (Quinn et al. 1996; Thoul & Weinberg 1996; Navarro & Steinmetz 1997).

Although the importance of reionization has long been recognized as a mainstay of LCDM dwarf galaxy formation models (see; e.g., early work by Couchman & Rees 1986; Chiba & Nath 1994; Bullock et al. 2000; Benson et al. 2002; Somerville 2002), there is still disagreement about how it translates in practice into regulating the onset of star formation in low-mass halos and whether it actually implies the actual presence of a minimum “threshold” halo mass for galaxy formation, (see; e.g., Wheeler et al. 2019; Nadler et al. 2020).

For example, it would be natural to expect in this scenario that reionization should have had a defining effect on the formation of dwarf galaxies, and that these effects may have left a recognizable imprint in the star formation history (SFH) of dwarfs. Since cosmic reionization is widely thought to have happened rather early and abruptly, early models suggested that it should have left a similarly abrupt signature in the SFHs of the faintest dwarfs, namely a sharp truncation in their star formation at the time of reionization (Gnedin & Ostriker 1997; Ricotti et al. 2002).

However, exquisite panoramic data from HST, coupled with the latest stellar population synthesis models, have revealed that even...
non-star-forming dwarfs dominated by old stellar populations seem to have had protracted star formation activity extending well past the epoch of reionization (Weisz et al. 2011, 2014a,b; Gallart et al. 2015; Skillman et al. 2017). Indeed, only a few extremely faint satellites of the Milky Way (MW) seem to have a stellar population consisting solely or mainly of stars formed pre-reionization (Brown et al. 2014). How does then reionization affect star formation in a dwarf, and how do those effects compare to others, driven perhaps by environment or feedback? Does reionization actually play a defining role in ending star formation activity in a dwarf?

A similar set of questions are posed by other properties of dwarf galaxies, such as the ubiquitous presence of ancient stellar populations (Weisz et al. 2014a; Skillman et al. 2017, and references therein). These suggest that the onset of star formation happened very early, and almost simultaneously, in all dwarfs, regardless of their present-day luminosity. This is somewhat surprising in the context of a “threshold” for galaxy formation, since presumably systems of different mass would reach such threshold at different times.

In addition, if reionization, or more generally speaking, the ionizing UV background, was indeed partly responsible for curbing star formation in at least some dwarfs, it may also play a role explaining the wide variety of dwarf SFHs, which vary from systems that formed all their stars at early times, to systems where star formation is long-lasting and still ongoing, to systems punctuated by episodes of star formation separated by relatively quiescent periods (Mateo 1998; Grebel & Gallagher 2004; Tolstoy et al. 2009; Simon 2019).

Dwarf galaxy properties are also known to vary greatly as a function of environment. For example, only two of the satellites of the Milky Way are currently forming stars (the Magellanic Clouds; the rest are all quiescent dwarf spheroidals, or dSphs, see; e.g., McNamara 2012), but most “field” dwarfs outside the virial radius of a more massive host appear to be actively forming stars at present (Geha et al. 2012). This clear environmental dependence may reflect, however, a subtle mass dependence; indeed, most satellites in the Milky Way are intrinsically much fainter than the majority of field dwarfs studied so far. How are the effects of the ionizing background modulated by environmental effects, and how do they depend on galaxy mass?

Early work on these topics focused mainly on the statistics of the dwarf population, and aimed mainly at establishing the characteristic “filtering” mass of halos whose baryonic content is severely affected by reionization (e.g., Gnedin 2000; Okamoto et al. 2008), rather than on the effects of reionization on the star formation history of individual dwarf systems. This has started to change, however, especially as cosmological hydrodynamical simulations start to tackle the low-mass halo regime (Simpson et al. 2013; Shen et al. 2014; Benítez-Llambay et al. 2015; Jean et al. 2017; Fitts et al. 2017; Macciò et al. 2017; Wheeler et al. 2019; Wright et al. 2019; Munshi et al. 2019; Applebaum et al. 2021; Rey et al. 2022; Gutcke et al. 2022), and as theoretical modeling considers the evolving thermodynamics of photoionized gas in a hierarchically evolving population of cold dark matter halos.

The mass function and redshift evolution of the latter population are well understood now. It is also widely accepted that the mass profile of virialized halos is well approximated at all times and for all masses by the Navarro-Frenk-White profile (hereafter, NFW, Navarro et al. 1996, 1997), with parameters that are well specified for LCDM at all redshifts (see; e.g., the “mass-concentration relation” of Ludlow et al. 2016, and references therein).

Before star formation begins in earnest, the properties of (primordial) gas in such halos are also amenable to theoretical modeling. This is particularly true after reionization, when gas heating by UV background photons, together with gas cooling from collisional excitation of H and He line emission, lead to a tight link between gas density and temperature. This “equation of state” may be used, assuming hydrostatic equilibrium, to infer the gas and temperature profile of gas in halos of arbitrary mass, enabling simple assessments regarding which systems can start forming stars, and when.

In particular, UV-heated gas in equilibrium in an NFW halo is expected to follow a density profile that is well-specified for all halo masses and redshifts. In our analysis we assume that the dark matter dominates gravitationally the system. This profile, coupled with a suitably specified criterion (e.g., total gas halo content, or a threshold central density), can be used to infer which halos may be susceptible to begin forming stars. This procedure translates into a well-defined, redshift-dependent characteristic “critical” halo mass, $M_{\text{crit}}(z)$, above which galaxy formation can begin (Benítez-Llambay & Frenk 2020, hereafter BL20).

Halos below critical are simply filled with tenuous, photo-heated gas supported by their own pressure, and they would remain “dark” if their halos remain sub-critical at all times. We shall refer to such systems hereafter as RELHICs (short for “REionization-Limited HI Clouds”) following Benítez-Llambay et al. (2017, hereafter BL17).

If this criterion is indeed applicable, $M_{\text{crit}}(z)$ may be combined with the mass accretion history of an individual halo to ascertain when star formation begins (Benítez-Llambay & Fumagalli 2021, hereafter BL21). Importantly, the same criterion also implies that star formation would cease, should the halo become sub-critical at a later time. This suggests that the effects of an ionizing background on systems close to the critical boundary may be variegated and spread over time, depending on the vagaries of each halo’s individual mass accretion history.

We address here the validity of this scenario, using cosmological hydrodynamical simulations of the APOSTLE project (Sawala et al. 2016; Fattahi et al. 2016). These simulations use the EAGLE code (Schaye et al. 2015; Crain et al. 2015) to evolve volumes tailored to resemble the Local Group of Galaxies and its surroundings, and contain hundreds of low-mass halos, both isolated (“field”) systems as well as sub-halos embedded within the virial boundaries of more massive systems. For simplicity, our analysis focuses on field systems only, since sub-halos are likely affected by environmental effects, such as tidal and ram-pressure stripping, which may overwhelm or confuse the effects of the ionizing background.

We also restrict much of our analysis to times after the epoch of reionization, which was assumed to be $z_{\text{reion}} \approx 11.5$ in APOSTLE runs. As we discuss below, the onset of star formation before reionization is artificially curtailed by the adoption in EAGLE/APOSTLE of an effective polytropic equation of state (PEoS) in regions of high gas density. This PEoS is adopted to prevent spurious fragmentation in star-forming regions, but it also imposes an effective ceiling on the gas density of early-collapsing clumps which delays the onset of star formation in many of them. Our analysis therefore is best applied to the interpretation of the evolution of isolated low-mass systems that did not yet start forming stars by $z_{\text{reion}}$.

Despite these caveats and limitations, we believe that our analysis sheds interesting new insights into the role of reionization and an ionizing background in the regulation of star formation of dwarfs. This paper is organized as follows. We begin with a brief description

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1 We define the virial radius, $r_{200}$, of each halo as that enclosing a region of mean density equal to 200 times the critical density for closure, $\rho_{\text{crit}} = 3H(z)^2/8\pi G$, where $H(z)$ is Hubble’s “constant”. We denote values computed within or at the virial boundary with a “200” subscript.
of the APOSTLE simulations in Sec. 2, before describing our analytical “critical” mass modeling in Sec. 3. We contrast these analytic results with APOSTLE results in Sec. 4 and conclude with a brief discussion and summary in Sec. 5.

2 THE APOSTLE SIMULATIONS

The APOSTLE2 simulation suite consists of a set of 12 zoom-in cosmological hydrodynamical simulations. The volumes were selected from the DOVE N-body simulation (Jenkins 2013), with the intent of reproducing the Local-Group environment. Each volume has a pair of halos with mass and kinematic properties similar to those of the Milky Way-Andromeda system (Fattahi et al. 2016). We use in our analysis the five volumes run at the highest mass resolution, with particle masses \( m_{\text{gas}} = 1 \times 10^4 M_\odot \) and \( m_{\text{dm}} = 5 \times 10^4 M_\odot \), and a gravitational softening length of 134 pc.

The APOSTLE simulations were performed using a modified version of P-GADGET3 code (Springel 2005) developed for the EAGLE cosmological simulation (Crain et al. 2015; Schaye et al. 2015). The adjustable numerical parameters used in APOSTLE were the same as in the EAGLE reference runs. We briefly describe some aspects relevant to our analysis below, and refer the reader to the reference EAGLE papers for full details. APOSTLE adopts the WMAP-7 cosmological parameters (Komatsu et al. 2011).

2.1 Radiative cooling, UV-background, and cosmic reionization

Radiative cooling and photoheating rates are calculated following the procedure outlined by Wiersma et al. (2009). The ionization state of the gas is calculated using the CLOUDY code (Ferland et al. 1998), under the assumption the gas is dust-free, optically thin, and in ionization equilibrium. The gas is exposed to the time evolving, but spatially uniform, cosmic microwave and X-ray/UV-background from Haardt & Madau (2001). The evolution of the background field is dependent on the parameterization of the reionization epoch in the simulation, which occurs at \( z_{\text{reion}} = 11.5 \). Before reionization, \( z > 11.5 \), the cosmic microwave background is modelled using the Haardt & Madau (2001) spectrum at \( z=9 \), cropping energies above 1 Ryd. For \( z < 11.5 \), the full, time evolving, Haardt & Madau (2001) spectrum is applied. To account for the fact that the gas is not optically thin prior to reionization, an extra 2 eV per proton mass are added, which ensures intergalactic gas is quickly ionized and heated to \( \approx 10^6 K \). For hydrogen, this is done at \( z = 11.5 \), while for helium the extra energy is distributed in redshift with a Gaussian centered at \( z = 3.5 \), of width 0.5.

2.2 Star-formation

Like EAGLE, the APOSTLE simulations are not intended to resolve the multi-phase ISM or cold molecular gas complexes \( (T << 10^4 K) \). In order to prevent numerical instabilities on such small scales, the simulation imposes a minimum pressure floor on the gas, which takes the form of a “polytropic equation of state” (PEoS),

\[
P_{\text{EOs}} = P_0 \left( \frac{P_e}{P_0} \right)^\Gamma,
\]

with \( \Gamma = 4/3 \) and where \( P_0 = 1.1 \ g \ cm^{-1} \ s^{-2} \) and \( P_0/m_p = 0.1 \ cm^{-3} \). In practice, this forces high-density gas to have a temperature that simply reflects the effective pressure of the unresolved ISM, and cannot be trusted for other physical considerations, such as calculating neutral hydrogen fractions in post-processing.

Given the limitations modelling cold molecular gas, star formation is only allowed to proceed at gas densities exceeding the threshold above which a cold phase is expected to form. This is chosen to be \( 10^4 \ cm^{-3} \) for primordial gas but allowed to decrease with increasing metallicity, \( Z \), in enriched gas regions (Schaye 2004);

\[
n_{\text{thr}}(Z) = \min \left[ 10^{-1} \ cm^{-3} \left( \frac{Z}{0.002} \right)^{-0.64}, 10 \ cm^{-3} \right].
\]

For the systems we focus on in this paper, the latter threshold is the more important of the two, since it is the one applicable to primordial/lowl metallicity gas.

Finally, because gas density in the early universe was very high, a simple density threshold would have allowed star-formation at very high redshifts. For this reason, an overdensity requirement is also imposed, with gas density having to exceed 57.7 times the cosmic mean. This choice of overdensity requirement does not significantly affect the results (Schaye et al. 2015), largely due to the imposition of the PEoS, which prevents gas from reaching high densities in low mass systems at high redshift.

2.3 Stellar Feedback

Stellar particles are treated as simple stellar populations (SSPs) with a Chabrier (2003) initial mass function (IMF) in the mass range 0.1-100\( M_\odot \). The energy feedback from SNIa is implemented following Dalla Vecchia & Schaye (2012), where stellar particles will release their feedback energy in a stochastic manner to individual gas particles nearby. The energy given to each gas particle is fixed such that \( \Delta T = 10^{7.5}K \), with the probability that any gas particle be heated proportionally to the total amount of energy released by the SSP, which corresponds to the release of \( 10^{51} \) erg per supernova, and assumes that stars with masses 6-100\( M_\odot \) explode via this channel.

2.4 Halo finder

Substructures in the simulation are identified using the SUBFIND groupfinder (Springel et al. 2001; Dolag et al. 2009). Halos are first identified by running a friends-of-friends algorithm (FoF; Davis et al. 1985) on the dark-matter particles, with a linking length 0.2 times the mean interparticle separation. Gas and stellar particles are then assigned to the same FoF group as their nearest dark-matter particle. SUBFIND, using all particles, then recovers gravitationally bound substructures within each FoF group, which we refer to as subhaloes. In this work we only study the properties of the main (“central”) subhalo of each FoF halo.

We use in our analysis all central halos found within a spherical volume with 3 cMpc radius, centered on the barycenter of the two main halos in each volume. The barycenter is calculated for each snapshot, spanning the redshift range from 0 to 20. We restrict our analysis to halos with \( M_{200} > 10^7 M_\odot \), or the equivalent of about 200 dark matter particles. In practice, we shall see that no halos below \( 10^8 M_\odot \) are able to form stars in these APOSTLE runs, so our analysis concerns mainly halos resolved with an equivalent of at least 2000 dark matter particles.

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3 CRITICAL VIRIAL MASS FOR STAR FORMATION

Our modeling of the minimum “critical” virial mass needed for the onset of star formation in a halo follows closely the model described in detail by BL20. Post-reionization, the model assumes that the density profile of gas in a CDM halo in thermal equilibrium with the cosmic microwave and UV/X-ray backgrounds may be computed assuming hydrostatic equilibrium of gas. For simplicity, dark halos are assumed to be spherically symmetric, and well approximated by NFW profiles. The validity of these assumptions has been tested by BL17 and BL20 using cosmological hydrodynamical simulations.

In terms of dimensionless variables, we may write the equation of hydrostatic equilibrium as,
\[
\frac{\dot{T}}{\dot{\rho}} + \frac{dT}{d\bar{r}} \frac{d\bar{\rho}}{d\bar{r}} = -\frac{\dot{M}(\bar{r})}{\bar{r}^2},
\]

(3)
where \(\dot{\rho} = \rho/\bar{\rho}_{\text{bar}},\) \(\bar{T} = T/T_{200},\) \(\dot{M} = M/M_{200},\) \(\bar{r} = r/r_{200},\) and \(\bar{\rho}_{\text{bar}} = \rho_{\text{crit}}\Omega_0\). Here the halo virial temperature is defined as \(T_{200} = (\mu m_p/k_B) V_{200}^2\) where \(\mu, m_p\) and \(k_B\) are the mean molecular weight\(^3\), the proton mass, and Boltzmann’s constant, respectively. \(V_{200}\) is the halo circular velocity at \(r_{200}\), defined by \(\gamma^2_{200} = GM_{200}/r_{200}\).

For the dark-matter enclosed mass profile, we use the equation,
\[
\dot{M}(\bar{r}) = \frac{\ln(1 + c\bar{r}) - c/(1 + c)}{\ln(1 + \bar{c}) - c/(1 + \bar{c})},
\]
(4)
which follows the NFW density profile, with concentration parameter \(c = r_{200}/r_s\). The concentration, \(c(M_{200}, z)\), is a function of mass and redshift. We use here the parameterization proposed by Ludlow et al. (2016), applied to the WMAP-7 LCDM cosmological model adopted here.

To solve equation 3 for \(\rho\), we require a temperature-density (\(T-\rho\)) relation for the intergalactic gas, as well as a boundary condition. The “equation of state” relating \(T\) and \(\rho\) depends on the properties of the ionizing background and its dependence on redshift, as discussed briefly in the next subsection. For the boundary condition, we assume two different behaviours prior to and after reionization. After reionization, we assume that the density of gas at infinity (\(r \rightarrow \infty\)) is equal to the average baryonic density of the Universe (\(\bar{\rho}_{\text{bar}}\)). This boundary condition was also used by Benitez-Llambay et al. (2017), and shown to be adequate for approximating the total gas mass enclosed in low mass LCDM halos at \(z = 0\).

Prior to reionization, the inter-galactic medium is not pressurised and we cannot assume that our \(T-\rho\) relation is applicable beyond the virial radius. Therefore, prior to reionization we choose a boundary condition where the gas density at the virial radius is set so that the total enclosed gas mass within \(r_{200}\) equals the universal baryon fraction (i.e., \(M_{\text{gas}}(r < r_{200}) = \bar{\rho}_{\text{bar}} M_{200}\)).

Once the gas density profile is known, a criterion for the onset of star formation needs to be specified, which in turn sets the minimum value of the halo mass needed for star formation to begin. After reionization, BL20 adopted a criterion based on the total gas content within the virial boundary of a halo, obtained by integrating \(\rho(r)\). Beyond some redshift-dependent minimum mass, \(M_{\text{crit}}(z)\), the gas content exceeds \(f_{\text{bar}} M_{200}\); the total baryonic mass expected within \(r_{200}\) according to the universal baryon fraction, \(f_{\text{bar}} = \Omega_{\text{bar}}/\Omega_M\). The theoretical total gas mass quickly diverges for masses greater than \(M_{\text{crit}}\), indicating that pressure alone cannot stop gas from flowing to the centre of a halo, where it should turn into stars. Prior to reionization, BL20 assume that the critical mass simply corresponds to the atomic cooling limit mass, or \(T_{200} = 7 \times 10^3\) K.

We adopt here a different criterion, based on the central (maximum) density of the gas. This criterion is better attuned to the choices made in cosmological hydrodynamical simulations, which often rely on a minimum “threshold” gas density for star formation to proceed. Although different, the two criteria actually give similar results for \(M_{\text{crit}}(z)\), as we discuss in Sec. 3.4.

3.1 Temperature-density relation

The temperature-density relation of photoionized gas is shown, at various redshifts, in Fig. 1, and is characterized by two different regimes after reionization. At low densities the temperature rises steeply, as a result of photoheating. This rise tracks the loci where the photoheating timescale equals the age of the Universe at that redshift, and therefore it shifts to higher densities at earlier times.

The maximum of each curve corresponds to a density where the photoheating rise meets the loci where photoheating and radiative cooling timescales are comparable. At larger densities, the \(T-\rho\) curve drops from its maximum and approaches roughly \(10^4\) K, the minimum temperature needed to collisionally excite the Ly-\(\alpha\) transition (see; e.g., Haehnelt et al. 1996; Theuns et al. 1998, and references therein).

The sharp upturn in temperature at high density (shown by dashed lines) corresponds to the imposed pressure minimum of the PEOs, which applies only to high-density gas in the APOSTLE/EAGLE simulations (see Sec. 2.2). This PEOs is implemented as a single pressure-density relation, but manifests itself as two different \(T-\rho\) relations, before and after \(z_{\text{reion}}\), because of the change in molecular weight that occurs at reionization. As we shall see below, the adoption

\(^3\) Unless otherwise noted, we assume a constant \(\mu = 0.6\), as appropriate for a fully ionized gas of primordial composition.

Figure 1. Gas temperature-density relation assumed in our modeling at different redshifts. At high densities, dashed lines indicate the polytropic equation of state (PEoS) adopted in the APOSTLE/EAGLE simulations. In this regime, solid lines assume that the gas is isothermal. Prior to reionization, our model assumes that, at low densities, the gas inside the virial radius of critical halos is isothermal at \(10^3\) K (thick red line). Densities above the APOSTLE star-formation threshold (\(n_H = 10^{13} \text{cm}^{-3}\)) are highlighted in light blue.

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of a PEoS curtails (artificially) the ability of low-mass halos to form stars before reionization.

Prior to reionization, our model assumes the gas is isothermal at $10^4$ K within the virial radius, for densities not affected by the PEoS. To highlight that the isothermal assumption does not apply outside the virial radius, the line shown in Fig. 1 is truncated at $n_H = 10^{-3} \text{ cm}^{-3}$.

### 3.2 Analytic gas density profiles

Using Eq. 3 we may now compute the gas density profile of a “dark” (RELHIC) halo at any redshift, using the appropriate $T$-$\rho$ relation, as shown in Fig. 1. We illustrate this in Fig. 2, where the dashed curve in the top panel shows the total gravitational acceleration profile, $a(r) = G M(r)/r^2$, of an APOSTLE RELHIC at $z = 0$. The dots in the bottom panel indicate the gas profile of this same RELHIC. The NFW profiles of three halos with the same virial mass ($M_{200} = 10^{9.65} M_\odot$), but different concentrations ($c = 5, 10, \text{ and } 15$), are also shown with thick colored lines. For the appropriate concentration ($c \approx 10$), the gas profile computed by solving Eq. 3 matches the density profile of the simulation data remarkably well\footnote{In order to best fit the data of this example RELHIC, we set a boundary condition equal to the RELHIC gas density at $r = r_{200}$, instead of the condition at infinity which we use in the critical mass modeling.} (see Fig. 5 in BL17 for another example).

The shaded region in the bottom panel of Fig. 2 indicates densities above the star formation threshold assumed for primordial gas in APOSTLE. At fixed halo mass, the resulting density profile is highly dependent on halo concentration; for $c = 10$ the gas in the halo would remain in hydrostatic equilibrium without forming stars, whereas for $c = 15$ a halo of the same mass would begin forming stars at its center. This illustrates that not only halo mass, but also concentration, determine which halos will host luminous galaxies and which will remain “dark”.

We examine next the role of the PEoS imposed on high-density gas in APOSTLE. Fig. 3 shows the gas density profiles of two halos at two different redshifts, computed including the PEoS (dashed lines) or not (solid). Concentrations for each halo are computed from the average concentration expected from the Ludlow et al. (2016) mass-concentration-redshift relation. The adoption of a PEoS clearly depresses the central gas densities. This is true in particular prior to reionization where the PEoS renders most halos below $\sim 10^8 M_\odot$ (artificially) ineligible for star formation. Indeed, as we shall see below, all APOSTLE halos that begin forming stars at $z > 2_{reion}$ exceed a virial mass of $\sim 10^8 M_\odot$, a likely artificial result of the PEoS.

### 3.3 Halo concentration and central gas density

To isolate the effects of concentration on the gas profile, we adopt the $T$-$\rho$ relation without a PEoS in this section. In Fig. 4 we summarise the effects of concentration on gas properties. The top panel shows, as a function of halo mass at $z = 0$, the impact on the central gas density (defined as $n_c$, or the density at $r = 0.01 r_{200}$) of varying the average halo concentration about the value, $c \approx 13$, expected for LCDM (Ludlow et al. 2016). Average-concentration halos (solid black curve) are expected to become eligible for star formation for virial masses exceeding $10^{8.63} M_\odot$, but this boundary varies somewhat for lower or higher-than-average concentration halos.

The variation in terms of “critical” mass, however, is not large,
only about a factor of ~ 2 for concentrations between 5 and 20. We conclude that, although halo concentration plays a role in determining which halos are expected to remain “dark” or to host luminous systems, it appears to be secondary compared with the role of halo mass.

Indeed, this is shown in the bottom panel of Fig. 4, which is analogous to the top, but plots the total gas mass expected within the virial radius, and how it varies with halo concentration. For average-concentration halos (solid black curve) the total gas mass is seen to match the expected total baryonic content of the halo at $M_{200} \sim 10^{9.65}M_\odot$ and to diverge rapidly at higher masses: gas in such halos is unable to stay in hydrostatic equilibrium and would collapse to the centre and trigger the onset of star formation. This is, indeed, the rationale for the “critical mass” for star formation advocated by BL20.

Comparing the top and bottom panels of Fig. 4 shows that defining the “critical mass” either by total gas content or central gas density gives similar results (within a factor of ~ 2; note that none of these curves include the effects of the EAGLE PEoS). This provides further evidence for the robustness of the concept of critical mass. In addition, it explains the good agreement reported by BL21 between the BL20 critical mass (derived using total gas mass) and the results of cosmological simulations using the EAGLE code, where star formation is triggered once gas density goes above a minimum threshold value.

Finally, we explore in Fig. 5 how the central gas density varies as a function of redshift for halos of different mass, as labeled. Solid curves use the $T_\rho$ relations of Fig. 1, and assume average concentrations for each halo. The dashed curves correspond to models that include the PEoS modification at high gas densities implemented in EAGLE/APOSTLE. The intersection of each curve with the central density threshold of $n_c = 10$ cm$^{-3}$ corresponds to the redshift at which that mass equals $M_{\text{crit}}$, the “critical” mass in APOSTLE.

Each of these curves assumes the concentration-mass-redshift dependence of Ludlow et al. (2016). The critical mass clearly decreases systematically with redshift, driven primarily by the increase in gas density and the evolution of the $T_\rho$ relation. The critical mass is also sensitive to the PEoS assumption, particularly at high redshifts where the difference between the two sets of lines grows.

3.4 Critical mass model comparison: BL20 vs APOSTLE

We are now ready to compute a critical mass as a function of redshift that can be compared directly with the results of the APOSTLE simulation. This is shown by the black dashed curve in Fig. 6, which traces the halo mass that hosts a system with $n_c = 10$ cm$^{-3}$, the APOSTLE primordial gas threshold for star formation. The black dashed curve assumes average concentrations from the Ludlow et al. (2016) $c(M, z)$ relation, and the $T_\rho$ relations (including the effects of EAGLE’s PEoS) shown in Fig. 1.

We compare our APOSTLE model with the critical mass curve from BL20, shown by the thick magenta curve in Fig. 6. This curve is computed using the total gas mass criterion illustrated in the bottom panel of Fig. 4. Following BL20, the model adopts, for simplicity, a constant concentration of $c = 10$, and that the critical mass is approximated by the atomic cooling mass, with $T_{200} = 7 \times 10^3$ K, prior to reionization.

The most notable change between the black and magenta lines is that the jump to lower $M_{\text{crit}}$ at $z > z_{\text{reion}}$ expected from BL20 is affected when introducing the PEoS and the different boundary condition. These changes reduce substantially the central gas densities that the gas may reach in halos near the critical boundary before reionization. Because of this, we expect only APOSTLE halos that exceed $10^{7.7} - 10^{8.2}M_\odot$ to be able to start forming stars before reionization in our APOSTLE runs. Note that this is higher than either the critical boundary expected either from the H-cooling limit (set at 7000 K; magenta curve) or from $H_2$-cooling, indicated by the blue dotted line (Tegmark et al. 1997).

4 RESULTS

4.1 The onset of star formation in APOSTLE halos

We begin by analysing how well the critical mass model presented in the previous section describes the onset of star formation in the APOSTLE simulation. This is shown in Fig. 7, where we plot the virial mass of a halo at the time it forms its first star. Individual systems are shown with squares, colored by their concentration, computed from the ratio between maximum circular velocity, $V_{\text{max}}$, and $V_{200}$, assuming NFW profiles. The critical mass curves from BL20 (solid magenta) and from our APOSTLE fiducial model (black) are also shown.

Despite the simplicity of the critical mass model, it appears to capture well the main trends highlighted in Figure 7. In particular, it is clear that the minimum mass needed to ignite star formation increases steadily with decreasing redshift, and that the boundary is well approximated by the dashed black line. There seems to be no jump in the mass needed to start forming stars at reionization (as pre-
implies that the oldest stars in the great majority of central field dwarfs at present day started forming stars after systems with present-day virial masses to the distribution of ages of the oldest stars in all APOSTLE luminous systems date to lookback times at least as old as \( z = 279 \) Gyrs. We show three critical mass curves as a function of redshift: solid purple curve (dashed curves). Each curve corresponds to halos of different virial mass, as listed in the legend. Each of these halos becomes “critical” at the redshift where they cross the star-formation threshold. The reionization redshift is shown by the black vertical line. Densities above the star-formation threshold of APOSTLE are highlighted by the shaded blue region.

Although the large majority of dwarfs begin forming stars very early, there is a discernible population of dwarfs that first ignited more recently, about 4-8 Gyrs ago. This trace population corresponds to dwarfs with uncommon mass accretion histories, which first reached the critical mass fairly recently. Such population has been analyzed in detail by BL21, and we refer the interested reader to that work for further details.

Why do the great majority of luminous dwarfs in APOSTLE start forming stars early on, regardless of luminosity? The reason may be traced to the mass growth history of individual halos with masses close to the critical mass of \( \sim 10^{9.7} M_\odot \) at \( z = 0 \). We show three such mass accretion histories (i.e., the redshift evolution of the mass of the most massive progenitor of a system identified at \( z = 0 \)) with blue curves in Fig. 7. Two of these, shown in solid blue, correspond to halos hosting luminous galaxies at present, and they start forming stars roughly at the time (identified by open blue circles) that their accretion histories intersect the critical mass curve: systems that cross the critical mass boundary earlier also start forming stars earlier. Indeed, the bottom (dashed) blue curve corresponds to a system that never crosses the critical boundary and that remains “dark” at \( z = 0 \). This result echoes earlier analyses reported by Fitts et al. (2017), Macciò et al. (2017), and BL21.

The grey histogram in the right-hand panel of Fig. 7 shows the \( z = 0 \) halo mass distribution of all luminous galaxies in APOSTLE. There is a clear peak at the critical mass \( \sim 10^{9.7} M_\odot \), and a sharp decline towards lower masses: indeed, basically all halos below \( 10^9 M_\odot \) remain “dark”.

This decline may be traced to the typical accretion histories of halos in this mass range, which is roughly parallel to the evolution of the critical mass. In other words, most halos that are today above critical have been so since early times, and the same is true for most...
sub-critical halos. Indeed, “sub-critical” halos hosting stars at $z = 0$ are the exception, as they were above critical at some point in their past history, before their mass growth slowed enough to fall under the critical boundary by the present time. One example of this is shown by the bottom solid blue curve in Fig. 7.

### 4.2 Halo mass growth history and the modulation of star formation

The discussion of the previous subsection makes clear that APOSTLE halos can only begin forming stars once their mass histories take them into the “above-critical” regime. What happens if they happen to fall below critical at later times? We explore this in Figure 9, where we plot the mass accretion history of two illustrative examples. Blue solid curves indicate the mass evolution of the most massive progenitor, whereas the black dashed curve delineates the critical mass boundary. The orange curves track the gas content of each halo.

The blue shaded region brackets the interval between the youngest and oldest star formed in each system. The system on the left climbs above critical at $z \sim 7$ and remains so until the present. It starts forming stars soon after becoming critical and is still forming stars at $z = 0$. On the other hand, the example on the right depicts a halo that climbs above critical at $z \sim 6$ but becomes sub-critical soon thereafter, at $z \sim 2$. As the shaded region indicates, this halo only forms stars for as long as its mass remains above critical.

Note that the same process could, in principle, explain why some galaxies may stop forming stars for a relatively long time before reigniting, or why some have experienced several distinct episodes of star formation separated by quiescent periods. These cases have been reported in simulations by, e.g., Benítez-Llambay et al. (2015, 2016) and Wright et al. (2019), although the latter authors interpreted their results in terms of environmental effects, rather than as a result of a critical mass imposed by the ionizing background. We plan to analyze further the relation between episodic star formation and mass accretion histories in a future contribution.

The discussion above suggests that it is the interplay between mass growth history and the critical boundary that determines, to a large extent, the star formation activity of a dwarf. Feedback may also play a role, as seen by the sudden decrease in gas mass (orange line) that accompanies the onset of star formation (Fig. 9), but it appears to be less important overall; despite continuously forming stars, the system on the left-hand panel of Fig. 9 retains some gas (and forms stars) until today. This result suggests that the critical mass should delineate, on average, a clear boundary between star-forming and quiescent systems, an issue we examine next.

### 4.3 Star-forming vs quiescent dwarfs

Fig. 10 examines the star formation properties of APOSTLE dwarfs at $z = 0$. The upper panel shows the stellar mass-halo mass relation, colored blue (star-forming) if star formation is still ongoing and red (quiescent) if no stars have formed in the past 0.5 Gyr. The vertical dashed line indicates the critical mass, and clearly separates the two dwarf populations: most halos above critical host galaxies where star formation is ongoing, whereas sub-critical halos host almost exclusively quiescent dwarfs. The distinction between these two populations is less clear using stellar mass, although there is a clear trend for the faintest dwarfs to be quiescent.
There have been a number of suggestions for truncating star formation in field dwarfs, notably the loss of its surrounding gaseous halo due to ram-pressure effects from the cosmic web (Benítez-Llambay et al. 2013) or from potential grazing passages through the virial radius of a more massive system (e.g., Teyssier et al. 2012). These may be contrasted with our scenario by examining the gas content of the quiescent population in APOSTLE, which would be largely absent if ram-pressure effects were the dominant mechanism. We explore this in Fig. 11, where we plot the gas mass of each APOSTLE central halo at $z = 0$ as a function of halo virial mass.

Blue and red circles indicate star-forming and quiescent dwarfs, respectively, while the semi-transparent light-blue symbols indicate the (more numerous) “dark” RELHIC systems. The green curve indicates, for reference, the total baryon mass of a halo, $f_{\text{bar}} M_{200}$, whereas the cyan curve indicates the total gas mass expected by integrating eq. 3 for the gas density profile. As expected, the cyan curve tracks, on average, the total gas mass of a halo in the sub-critical regime.

Note that most quiescent galaxies still retain a large amount of gas, typically one or two orders of magnitude more than the stars they have been able to form. These systems thus appear to be quiescent not because of gas removal by feedback or environmental effects, but rather because their halo masses are below critical and thus unable to compress the gas to high enough central densities to ignite star formation.

This constitutes a robust and simple prediction of our model that should be testable by observations. In other words, our modeling predicts the existence of a sizable population of quiescent field dwarfs at the faint-end of the luminosity function. Such dwarfs are quite rare in the Local Group, with few known examples: the Cetus (Whiting et al. 1999) and Tucana (Lavery & Mighell 1992) dSphs, and two more distant dwarfs, KKR 25 (Karachentsev et al. 2001; Makarov et al. 2012), and KKS 3 (Karachentsev et al. 2015). They also seem to be rare in the local Universe; Geha et al. (2012) report the existence of a “threshold of $M < 10^9 M_\odot$ below which quenched galaxies do not exist in the field”. Their survey, however, only extends down to $M < 10^7 M_\odot$ before becoming severely incomplete. As shown in Fig. 10, the population of quiescent field dwarfs predicted by our analysis is expected to become prominent at much lower stellar masses.

APOSTLE is not the only simulation suite where these two populations of dwarfs have been seen. The bottom panel of Fig. 10 is analogous to the top, but includes results from five recent cosmological hydrodynamical simulations of dwarf galaxy formation (Jeon et al. 2017; Fitts et al. 2017; Wheeler et al. 2019; Wright et al. 2019; Rey et al. 2022). Remarkably, although each of these simulations adopt different recipes for star formation/feedback and disparate treatments of the interstellar medium, taken together they seem to agree with our main conclusion: there is a critical halo mass that separates star-forming from quiescent dwarfs. Note again that the separation is much less clear in $M$ than it is in virial mass, highlighting the fact that it is the critical mass imposed by the ionizing UV background, and not stellar feedback, the main culprit for the origin of these two populations.

The existence of a population of faint, quiescent dwarfs inhabiting sub-critical halos is thus an intriguing prediction from our modeling that should be possible to verify in the near future. The quiescent isolated dwarf ($M_* \approx 2 \times 10^9 M_\odot$) recently discovered by Polzin et al. (2021), together with the newly identified Tucana B ultra-faint dwarf (Sand et al. 2022), could very well be the archetypes of a whole population still awaiting discovery.

### 4.4 Star formation end times

As discussed in Sec. 1, cosmic reionization is often assumed to imply a sharp and very early truncation of star formation in faint dwarfs. Although this description may apply to low mass halos well below the...
critical boundary, we have seen that this is not the case for most field dwarfs inhabiting near-critical halos at $z = 0$. In such systems, the ionizing UV background seems to regulate the end of star formation somewhat indirectly, and in conjunction with the accretion history of a halo. It is therefore interesting to ask, for dwarfs that have ceased forming stars at present (i.e., those in “sub-critical” halos), when they experienced the last episode of star formation.

We show this in the bottom panel of Fig. 8, where the red and blue histograms delineate the distribution of the youngest star particle in all APOSTLE galaxies with $M_{200} < 10^{11} \, M_\odot$ at $z = 0$. Those shaded in blue indicate star-forming systems, whereas those in red correspond to the quiescent population at the present time. Clearly, there is a large diversity of “quenching” times, driven by the large diversity of individual halo mass accretion histories at fixed halo mass. This is another robust prediction for the quiescent population of isolated dwarfs that could be addressed in future observational studies.

4.5 Redshift dependence of the quiescent population

If our modeling is correct, then the quiescent population of dwarfs we discussed above should exist at all redshifts, although the boundary between quiescent and star-forming should shift to lower masses at increasing redshift, tracking the evolution of the critical mass. We explore this in Fig. 12, where we show the differential halo mass function (averaged over the five APOSTLE volumes) at different redshifts. The solid black lines indicate the dark halo mass function, and the cyan curve denotes halos that have remained dark at each redshift. Green corresponds to all luminous galaxies, split between star-forming (blue) and quiescent (i.e., those that did not form any stars in the most recent 0.5 Gyrs, in red) populations. The vertical dashed line indicates the critical mass according to our model (black curve in Fig. 6).

The quiescent population is mostly contained below the critical mass threshold at all redshifts, indicating that the critical mass model is still a valid threshold for star-formation at other redshifts. The differentiation between populations becomes less neat at higher redshift, with an increasing function of sub-critical halos hosting star-forming dwarfs. This is most likely because our definition of “star-forming” uses a fixed time window of 0.5 Gyr to categorize systems, which represents a significant fraction of the universe’s age at earlier times.

Another result illustrated by Fig. 12 is that, at all redshifts, $M_{\text{crit}}$ represents a characteristic “threshold” for galaxy formation, in the sense that the fraction of “dark” halos grows sharply below that mass. Indeed, the number density of luminous galaxies peaks at about the critical mass, so that, in terms of sheer numbers, the majority of luminous field galaxies in any given volume should be faint dwarfs inhabiting halos near the critical boundary.

5 SUMMARY AND CONCLUSIONS

We have examined the onset of star formation in low-mass halos identified in the APOSTLE cosmological hydrodynamical simulations. Star formation begins once the mass of a halo reaches a characteristic “critical” mass that may be derived using a simple model that combines the NFW mass profile of LCDM halos and the thermodynamics of gas heated by the cosmic ionizing background.

The model assumes hydrostatic equilibrium to derive the gas density profile at various redshifts, and identifies the critical mass where the central gas density equals the gas density threshold for star forma-
implying that, in general, halos above- or sub-critical at present remain so since early times. This implies that the critical mass at $z = 0$ represents a "threshold" below which the fraction of halos harboring luminous systems drops sharply.

- For the same reason, dwarf galaxies at $z = 0$, regardless of their luminosity, became able to form stars quite early, providing a simple and appealing explanation for the ubiquitous presence of ancient stellar populations in all known dwarfs.

- Sub-critical halos can still host luminous galaxies, but only if they were above critical at some point in the past. However, they are expected to be quiescent, forming a sizable population of non-star-forming dwarfs at the very faint end of the field galaxy stellar mass function. Very few such galaxies have been discovered in the field so far, but the discovery of this population would provide strong evidence in support of this scenario.

- Halos whose accretion histories cross the critical boundary several times during their evolution may host several distinct episodes of star formation, without need for environmental effects, a result that may help to explain the puzzlingly episodic nature of star formation observed in some dwarfs.

Although this simple scenario accounts for the main features of the star formation history of the faintest dwarfs in APOSTLE, it is important to note some of its caveats and limitations as well. We have focused exclusively on isolated systems, mainly because of simplicity, but note that environmental effects such as ram-pressure and tidal stripping may dominate in dwarfs that are satellites of more massive systems.

Therefore, it is important to exercise care when applying these results to the interpretation of the star formation histories of dwarfs in the Local Group, where satellites make up the majority of systems studied observationally in detail so far.

We also note that the use of a “polytropic equation of state” (P$\text{EoS}$) in EAGLE/APOSTLE artificially reduces the ability of low-mass halos to form stars prior to reionization. This rather crude numerical treatment of high-density gas means that our conclusions, however appealing, must be treated with care, and should be scrutinized further in future simulation work with more sophisticated treatments of the interstellar medium. Nevertheless, we believe that many of the conclusions highlighted above will prove of lasting value, and will provide a useful interpretive framework for future work.

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