UniverseMachine: Predicting Galaxy Star Formation over Seven Decades of Halo Mass with Zoom-in Simulations

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Abstract

We apply the empirical galaxy–halo connection model \textsc{UniverseMachine} to dark-matter-only zoom-in simulations of isolated Milky Way (MW)–mass halos, along with their parent cosmological simulations. This application extends \textsc{UniverseMachine} predictions into the ultrafaint dwarf galaxy regime ($10^5 M_\odot \lesssim M_\text{halo} \lesssim 10^7 M_\odot$) and yields a well-resolved stellar mass–halo mass (SMHM) relation over the peak halo mass range of $10^8$–$10^{15} M_\odot$. The extensive dynamic range provided by the zoom-in simulations allows us to assess specific aspects of dwarf galaxy evolution predicted by \textsc{UniverseMachine}. In particular, although \textsc{UniverseMachine} is not constrained for dwarf galaxies with $M_\text{halo} \lesssim 10^{8} M_\odot$, our predicted SMHM relation is consistent with that inferred for MW satellite galaxies at $z = 0$ using abundance matching. However, \textsc{UniverseMachine} predicts that nearly all galaxies are actively star-forming below $M_\text{halo} \sim 10^7 M_\odot$, and that these systems typically form more than half of their stars at $z \lesssim 4$, which is discrepant with the star formation histories of Local Group dwarf galaxies that favor early quenching. This indicates that the current \textsc{UniverseMachine} model does not fully capture galaxy quenching physics at the low-mass end. We highlight specific improvements necessary to incorporate environmental and reionization-driven quenching for dwarf galaxies, and we provide a new tool to connect dark matter accretion to star formation over the full dynamic range that hosts galaxies.

\textit{Unified Astronomy Thesaurus concepts:} Dark matter (353); Dwarf galaxies (416); Galaxy evolution (594); Computational methods (1965)

1. Introduction

Hierarchical structure formation via cold dark matter (CDM) collapse in a flat-\Lambda CDM cosmology model (White & Rees 1978; Blumenthal et al. 1984; Lahav et al. 1991; Cole et al. 1994) has become the standard paradigm for galaxy formation over the past few decades. Dwarf galaxies, which are tracers of the small-scale structures of $\Lambda$CDM (with peak halo mass $M_{\text{peak}} \lesssim 10^{11} M_\odot$), have shown diverse and initially surprising features in observations compared to the predictions from CDM theory and numerical simulations (see Bullock & Boylan-Kolchin 2017 for a review). It is crucial to understand the detailed formation mechanisms of dwarf galaxies, as well as the evolution of dwarf galaxies and the (sub)halos in which they form. This understanding could have a profound impact on our ability to test galaxy formation and the flat-$\Lambda$CDM paradigm by fully harnessing observations across the full range of galaxy mass scales. Key features of dwarf galaxies such as star formation histories (SFHs; Mateo 1998; Gallazzi et al. 2005; Tolstoy et al. 2009; Geha et al. 2012; Weisz et al. 2014a, 2014b, 2015) and quenched (non-star-forming) fractions as a function of stellar mass (McConnachie 2012; Karachentsev & Kaisina 2013; Fillingham et al. 2016; Mao et al. 2021) have been studied extensively in observations.

To connect the observed properties of galaxies to the dark matter (sub)halos in which they reside, two approaches of modeling the galaxy–halo connection have been widely adopted:

(i) models that are motivated by the underlying physics related to galaxy formation and gravity governing both dark matter and baryons (gas and stars), such as hydrodynamic simulations (see Vogelsberger et al. 2020 for a review) and semianalytic models (SAMs; see Henriques et al. 2015; Yates et al. 2021; Jiang et al. 2021 for some recent examples), or (ii) models that are motivated by empirical relations between galaxies and dark matter halos such as subhalo abundance matching and halo occupation distribution methods (see Somerville & Davé 2015; Wechsler & Tinker 2018 for reviews). Although these classes of models have each been effective for studying many aspects of galaxy–halo connection modeling, they possess different limitations when applied to the low-mass end of the observable galaxy population. The former approach relies on the assumed underlying physical subgrid or SAMs for baryons, which require high resolution (and thus demanding computational resources to resolve dwarf galaxies in cosmological volumes) and are less easily adaptable to be improved by observational constraints. The latter approach is more flexible owing to its statistical description and thus can more easily adapt to new measurements, but it makes strong assumptions on the number and density of central and satellite galaxies in connection to their host (sub)halos. All approaches can require calibration of systematics such as orphan galaxies (e.g., Springel et al. 2005b; Pujol et al. 2017; Nadler et al. 2019), although the numerical aspects of this are different for the different modeling types.

The empirical forward modeling approach (e.g., Behroozi et al. 2013a; Moster et al. 2013; Rodríguez-Puebla et al. 2017;
Moster et al. 2018; Behroozi et al. 2019) has inherited some merits from both branches above (we refer to this approach as an "empirical model" in the rest of the paper). Current empirical models paint the star formation rates (SFRs) of galaxies onto dark matter halos in N-body simulations using flexible mathematical formulae. These have the advantage of requiring fewer assumptions about the underlying galaxy formation processes than do hydrodynamic simulations and SAMs. They are also more flexible in connecting galaxy and halo properties than standard abundance matching and halo occupation distribution models.

In this work, we use the empirical model UNIVERSEMACHINE (Behroozi et al. 2019, hereafter B19) to study the galaxy–halo connection in the low-mass dwarf galaxy regime. The model parameterizes the distribution of galaxies’ SFRs as a function of halo mass (maximum circular velocity \( v_{\text{max}} \)), halo accretion rate (change in \( v_{\text{max}} \) over time), and redshift. The SFRs of galaxies are drawn randomly from these distributions and then painted onto halos. This process is conducted self-consistently to match a comprehensive set of observational constraints at the intermediate-to-high mass end: stellar mass functions (stellar mass \( M_*/M_\odot \in [10^7, 10^{12}] \)), redshift \( z \in [0, 8] \), galaxy quenched fractions (\( M_*/M_\odot \geq 10^9 \), \( z \leq 4 \)), the cosmic SFH (\( z \leq 10 \)), specific SFRs (SFR per unit stellar mass, \( M_* \geq 10^5 M_\odot \), \( z \leq 8 \)), UV luminosity functions (\( M_* \geq 10^8 M_\odot \), \( z \in [4, 8] \)), and galaxy clustering information from auto- and cross-correlations of different galaxy populations (\( M_*/M_\odot \in [10^{10}, 10^{12}] \), redshift \( z \leq 1 \)) (see Section 3 and Appendix C in B19 for more details), among others. The model also accounts for short-timescale SFR variations, stellar-to-high-mass end: stellar mass functions to high-mass end: stellar mass functions connection in the low-mass dwarf galaxy regime. The model

The UNIVERSEMACHINE Data Release 1 (UM DR1) was calibrated using the Bolshoi–Planck cosmological simulation (Klypin et al. 2016; Rodríguez-Puebla et al. 2016) with the above-mentioned set of observational data with stellar masses \( M_* \geq 10^5 M_\odot \) (corresponding to peak halo masses \( M_{\text{peak}} \geq 10^{10} M_\odot \)). The dark matter resolution of \( \sim 10^9 M_\odot \) for the Bolshoi–Planck simulation is not ideal for studying the dwarf galaxy regime (\( M_* \leq 10^9 M_\odot \) and \( M_{\text{peak}} \geq 10^{11} M_\odot \)). UNIVERSEMACHINE can be run on higher-resolution, large-volume cosmological simulations, as was done in Behroozi et al. (2020) to predict observables for the JWST, but this approach cannot gain much resolution without an equivalent sacrifice in volume and sample statistics.

We take an exploratory approach in this work that extrapolates the UNIVERSEMACHINE model into the dwarf galaxy regime by applying it to zoom-in simulations of Milky Way (MW)–sized halos (\( M_{\text{vir}} \approx 10^{12} M_\odot \)). These simulations resolve subhalos down to \( \sim 10^5 M_\odot \), corresponding to the halos that host the smallest-known galaxies, ultrafaint dwarf (UFD) galaxies with stellar masses as low as \( M_* \sim 10^5 M_\odot \). By qualitatively comparing the extrapolated UNIVERSEMACHINE predictions to observational constraints, we can identify specific limitations—especially pertaining to quenching physics—that the DR1 model failed to capture. Thus, we provide a framework for exploring the impact of reionization and environmental quenching mechanisms on dwarf galaxies in the context of a dark matter accretion-based model for galaxy assembly.

Since UNIVERSEMACHINE is currently constrained only at the intermediate-to-high mass end, quenching mechanisms for dwarf galaxies are not explicitly included in the DR1 version of the model. In particular, the model assumption that correlates galaxy SFR with halo accretion rate may break down at the epoch of reionization; in this epoch, photoionization in dwarfs with \( M_* \lesssim 10^6 M_\odot \) likely prevents gas from cooling (Thoul & Weinberg 1996; Bullock et al. 2000; Benson et al. 2002; Alvarez et al. 2012; Brown et al. 2014). It is also important to investigate whether the current modeling of environmental quenching primarily through parameterized galaxy quenched fractions constrained at high stellar masses is sufficient to capture galaxy evolution in the dwarf regime. Recent and ongoing observations of dwarf galaxies in the low-redshift universe (e.g., from the SAGA Survey, Geha et al. 2017; Mao et al. 2021; and satellites in the Local Volume, Carlsten et al. 2021, 2020a; Davis et al. 2021), as well as near the MW (e.g., from the Dark Energy Survey; Drlica-Wagner et al. 2015, 2020; Nadler et al. 2020), along with upcoming observations that will extend such observations in both the local and distant universe (e.g., from campaigns including the Vera C. Rubin Observatory, JWST, and the Nancy Grace Roman Space Telescope), promise to deliver tighter observational constraints on the model assumptions regarding dwarf galaxy evolution.

This paper is organized as follows: In Section 2, we introduce the dark matter simulations underlying this work. In Section 3, we describe our method for applying UNIVERSEMACHINE to zoom-in and cosmological simulations and describe the halo mass functions, stellar mass–halo mass (SMHM) relations, and matched evolution histories of systems in both resolution levels. In Section 4, we study the low-mass end of the SMHM relation, its redshift evolution, the SFRs matched across our simulation resolution levels, and the predicted quenched fractions for central and satellite galaxies. We discuss future modeling directions in Section 5, and we summarize our main findings and discuss the outlook for empirically modeling the low-mass end of the galaxy–halo connection in Section 6.

2. Simulations

2.1. The Chinchilla Suite

We begin by introducing the dark-matter-only simulations on which we base our UNIVERSEMACHINE analyses. The Chinchilla simulation suite is a set of dark-matter-only N-body simulations run with the L-GADGET code (an N-body-only variation of the GADGET-2 code; Springel 2005) under a flat \( \Lambda \)CDM cosmology with parameters \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) \((h = 0.7)\), \( \Omega_m = 0.286 \), \( \Omega_\Lambda = 0.714 \), \( n_s = 0.96 \), and \( \sigma_8 = 0.82 \). Dark matter halos are identified using the phase-space halo finder ROCKSTAR (Behroozi et al. 2013b) with a virial overdensity threshold of \( \Delta_{c,\text{vir}} \approx 99.2 \) at \( z = 0 \), while merger trees are constructed using CONSISTENT-TREES (Behroozi et al. 2013c). Halos contained within the virial radius of a more massive nearby halo are defined as subhalos; other halos are defined as host halos.

Here we use only the two smallest cosmological boxes in the suite, first introduced in Mao et al. (2015). These boxes both have a side length of 125 Mpc \( h^{-1} \) with periodic boundary conditions. The higher-resolution box has 2048\(^3\) resolution elements with a dark matter particle mass of \( m_{\text{DM}} = 1.80 \times 10^7 M_\odot h^{-1} \) (denoted as C125-2048 hereafter) and a softening length of 0.5 kpc \( h^{-1} \) (Plummer-equivalent force softening scale). The lower-resolution box has 1024\(^3\) resolution elements with particle masses of \( m_{\text{DM}} = 1.44 \times 10^8 M_\odot h^{-1} \) (denoted as C125-1024 hereafter) and a
softening length of 1.0 kpc h⁻¹. The boxes are initialized with the same set of initial conditions generated using 2LPTIC (Croccetc et al., 2006) implementing the matter power spectrum from CAMB, although C125-2048 starts at z = 199, while C125-1024 starts at z = 99. Their halo catalogs and merger trees both start from a scale factor of a = 0.075 (z ≈ 12.3) with 100 snapshots down to a = 1 (z = 0).

2.2. The MW Zoom-ins

The 45 MW-size halos chosen for the zoom-in resimulations were isolated hosts selected from the parent box C125-1024, with host halo masses in the range of $M_{\text{vir}}/M_\odot < 10^{12.1 \pm 0.03}$ (Mao et al. 2015). This mass range is consistent with the latest halo mass constraints of the MW inferred from the proper motion of globular clusters in Gaia DR2 (1.3 ± 0.3) × 10¹² $M_\odot$ from Posti & Helmi 2019; 1.54 ± 0.73 × 10¹² $M_\odot$ from Watkins et al. 2019. The initial conditions for each individual zoom-in halo are then generated with MUSIC (Hahn & Abel 2011) to achieve the equivalent resolution of 8192³ elements in an initial Lagrangian region of ~ 10Rvir centered on the MW host, while matching to the parent box on large scales. The high-resolution particles in the zoom-in region have masses of $m_{\text{DM}} = 2.82 \times 10^5 M_\odot h^{-1}$ and softening lengths of 170 pc h⁻¹.

The halo catalogs and merger trees for the zoom-ins begin at $a = 0.05$ (z = 19) with 236 snapshots down to $a = 1$ (z = 0). At z = 0, roughly 90% of the total mass within $r_{90} \approx 3$ Mpc of each MW host halo consists of high-resolution particles. Thus, the zoom-in simulations provide well-resolved subhalos in their infalling, splashback, accreted, and disrupted evolution phases far beyond the MW virial radius (∼ 300 kpc). We summarize the key properties of our 45 MW zoom-in simulations and their two parent boxes in Table 1.

### Table 1
Basic Information for Our 45 MW Zoom-in Simulations and Their Two Parent Boxes

| Simulation | Box Size (Mpc h⁻¹) | Resolution Elements | Particle Mass (M_\odot h⁻¹) | Softening Scale (kpc h⁻¹) |
|------------|------------------|---------------------|-----------------------------|---------------------------|
| Zoom-ins   | ...              | 8192³ (equivalent)  | 2.82 × 10⁵                 | 0.17                      |
| c125-2048  | 125              | 2048³               | 1.80 × 10⁵                 | 0.50                      |
| c125-1024  | 125              | 1024³               | 1.44 × 10⁵                 | 1.00                      |

3. Methods and Validation

We now overview the fundamental aspects of the empirical galaxy–halo connection model UNIVERSE MACHINE (Section 3.1). We present the halo mass function and the UNIVERSE MACHINE-predicted SMHM relation across the three simulation resolutions in Section 2, highlighting our procedure for applying UNIVERSE MACHINE to zoom-in simulations (Section 3.2). We study the dark matter halo evolution and predicted SFHs of matched objects in the zoom-in resimulations and their parent boxes (Section 3.3).

#### 3.1. UNIVERSE MACHINE Model

UNIVERSE MACHINE® (B19) is an empirical galaxy–halo connection model that self-consistently predicts the SFRs of galaxies inside dark matter halos given the halo mass (parameterized by the maximum circular velocity $v_{\text{max}}$).

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9 https://camb.info/
10 https://bitbucket.org/pbehroozi/universemachine
and traced for their orphan galaxy after disruption\(^{11}\) to 10, 35, and 60 km s\(^{-1}\) for the joint 45 zoom-ins, C125-2048, and C125-1024, respectively, following the resolution cuts defined in Appendix B.

3.2. Applying UNIVERSE_MACHINE to Zoom-ins and Chinchilla

We present the halo mass function and the SMHM relation derived from applying the UM DR1 model to 45 MW zoom-ins and their Chinchilla parent boxes. We also discuss challenges involved in applying UNIVERSE_MACHINE to zoom-in simulations and the steps taken to overcome them.

The left panel of Figure 1 shows the halo mass functions of the three simulation resolutions. We follow previous works (e.g., Behroozi et al. 2013a; Garrison-Kimmel et al. 2014) by using peak halo mass, the maximum value of the halo virial mass along the main progenitor branch in its merger tree, for all halo masses. The peak halo mass does not depend on subhalo mass loss due to tidal stripping after infall and correlates better with stellar mass than present-day virial mass (e.g., Behroozi et al. 2013a; Moster et al. 2013; Reddick et al. 2013). The joint zoom-in halo number density \(n\) is calculated as the average number density in the 45 zoom-in region sets by the zoom-in region volume factors in the initial Lagrangian spaces. We note that our 45 zoom-in MW halos are isolated and tend to live in slightly underdense environments, with the average matter density (measured within a sphere with radius of 20 Mpc \(h^{-1}\) centered on the host halo) \(\sim 0.87\times\) the mean matter density of the parent cosmological boxes.

The three resolution boxes show overall consistent halo mass functions in the peak halo mass range of \(M_{\text{peak}}/M_\odot \in [10^{10}, 10^{11}]\), and the two cosmological boxes extend all the way up to the cluster mass scale of \(\sim 10^{15} M_\odot\) (with their Lagrangian volumes the same as their box sizes). At the low-mass end, the joint mass function of the 45 MW zoom-in resolutions extends the dynamic range of our joint halo mass function far below \(\sim 10^5 M_\odot\), where both cosmological boxes are poorly resolved. The zoom-ins cut off right above the MW halo mass of a few times \(10^{12} M_\odot\), and the hump at that mass reflects the selection of MW-sized host halos in the zoom-in regions. An estimate of the MW halo mass derived from Gaia data (Watkins et al. 2019), which is consistent with other recent MW halo mass constraints, is shown for comparison.

In the right panel of Figure 1, we show the SMHM relations for the three simulation resolutions with the UM DR1 model applied to each box. The median SMHM relations coincide well (for both the normalization and slope) in the halo mass range \(M_{\text{peak}}/M_\odot \in [10^{10}, 10^{11}]\), where the halo mass functions are also converged. The most striking feature of the SMHM relation at the low-mass end is that all three resolutions follow a power-law relation with the same slope that extends from the knee of the relation at around \(10^{12} M_\odot\) down to the resolution limit of each simulation. This suggests that the SMHM relation in the zoom-ins is an extrapolation of the SMHM relation in the UM DR1 model, which is constrained down to \(M_{\text{peak}} \sim 10^{11} M_\odot\). We discuss the implications of our predicted SMHM relation in Section 4. We also quote and show the observational value of the MW stellar mass (Licquia & Newman 2015), along with the three dwarf galaxy regimes as defined in Bullock & Boylan-Kolchin (2017) for comparison. This work defines bright dwarfs as galaxies with stellar mass in the range of \(M_*/M_\odot \in [10^9, 10^{10}]\), classical dwarfs with stellar masses of \(M_*/M_\odot \in [10^7, 10^9]\), and UFDs with stellar masses of \(M_*/M_\odot \in [10^5, 10^7]\). We convert the stellar masses in these three regimes back to the peak halo mass intervals using the median SMHM relation in the joint zoom-ins and show them as the shaded regions in the left panel of Figure 1. The MW zoom-ins provide sufficient resolution to model the smallest-known galaxies, down to the lower mass limit of the UFDs, a regime that is crucial for studies of galaxy formation (Willman 2010; McConnachie 2012; Bechtol et al. 2015) and dark matter microphysics (Nadler et al. 2021).

Applying the UNIVERSE_MACHINE model to zoom-in simulations is nontrivial for several technical reasons. In particular,
individual zoom-in realizations of single host halos lead to poor sampling of the halo mass function at halo masses around the MW host and also provide only a few realizations of the most massive subhalos. This renders UNIVERSEMACHINE’s ranking algorithm, which assigns higher SFR to halos with higher accretion rates ($A_{\text{vmax}}$, the change in $v_{\text{max}}$ over one dynamical timescale) based on the full span of accretion rates at fixed halo mass, more susceptible to stochasticity, leading to biased rank predictions. We illustrate in Appendix A how we overcome this by joining 45 MW zoom-ins together to achieve a halo distribution that is largely consistent with the parent cosmological boxes. In summary, we implement two important changes when applying UNIVERSEMACHINE to zoom-in simulations as opposed to cosmological boxes.\textsuperscript{12}

1. We join the ROCKSTAR halo catalogs together for a large sample of zoom-in boxes at every simulation snapshot, such that each distinct (sub)halo is included exactly once in the joint halo catalog. In our case, this is equivalent to packing all 45 MW zoom-in halos together into one cosmological box with the same size as their parent boxes.

2. UNIVERSEMACHINE performs halo ranking with a spline interpolation step. We carry out this step with the joint halo catalog. Ranks produced in this manner will be more accurate owing to the more comprehensive sampling of the halo mass function, especially at the high-mass end.

In this way, we join a large number of zoom-in simulations to self-consistently extend UNIVERSEMACHINE predictions into the UFD galaxy regime. We note that the rank distributions, described in Appendix A and shown in Figure A1, are approximately self-similar when expressed in terms of particle number. Thus, step 1 could potentially be circumvented by scaling a given rank distribution to match those shown in Figure A1. This analytic procedure would yield approximate, unbiased ranks for halos in higher-resolution simulations and is useful for simulation suites that do not include a substantial number of high-resolution simulations.

3.3. Validation: Matched Subhalo Evolution

In the previous subsection, we showed that the halo mass function and the SMHM relation are consistent across the zoom-in and cosmological boxes. Since our three different resolution simulations share the same initial conditions, we now illustrate UNIVERSEMACHINE predictions in detail by studying the dark matter growth and SFHs of matched (sub)halos across the three boxes.

Figure 2 shows the projected dark matter density maps for the zoom-in MW halo No. 416 and its matched counterparts in the two parent boxes.\textsuperscript{13} The images were made assuming the MW host halo center at an angular diameter distance of 1.75 Mpc $h^{-1}$ from the observer, and the vertical aperture of the images is 15°. The images were created using the state-of-the-art multi-transparent-layer phase-space tessellation method described in Kaehler (2017, 2018).

To demonstrate the consistency in the evolution history of individual (sub)halos, we select five different subhalos in the zoom-in simulation along with the MW host halo and match them to corresponding low-resolution counterparts in the parent boxes. Particularly, our selection of (sub)halos in the zoom-in consists of the MW host halo with $M_{\text{peak}} = 10^{12.04} M_\odot$, while our subhalos (numbered 1 to 5) have peak halo masses $\log_{10}(M_{\text{peak},i}/M_\odot) = [11.32, 10.90, 10.17, 9.12, 10.16]$, respectively. Our choice of the subhalos covers a variety of different dwarf galaxy regimes: Subhalo 1 is an LMC analog (Nadler et al. 2020), Subhalo 2 is another bright dwarf, Subhalo 3 is a bound (within $R_{\text{vir}}$ of the MW host) classical dwarf dimmer than the LMC, Subhalo 4 is a UFD with no counterparts in the parent boxes, and Subhalo 5 is a splashback classical dwarf (i.e., a system previously inside but currently outside of the MW $R_{\text{vir}}$, which appears to be inside $R_{\text{vir}}$ in projection). Since we selected these subhalos based on their $M_{\text{peak}}$ values and classified them using the halo mass range in the left panel of Figure 1, their stellar masses as labeled in the right column of Figure 3 do not strictly follow the definition in Bullock & Boylan-Kolchin (2017) owing to scatter in the SMHM relation. Seen in the dark matter density maps in Figure 2, the locations of the matched subhalos in the projected dark matter density maps agree well in the two parent boxes but are noticeably different in the zoom-in, which could be explained by the differences in the orbital phases of subhalos across different resolutions as discussed below.

In Figure 3, we present the evolution history of the six individual (sub)halos selected in the zoom-in, along with their matched counterparts in the two parent boxes. The left column shows the evolution of $v_{\text{max}}$ (a halo mass proxy free from pseudo-evolution due to cosmic expansion; e.g., Conroy et al. 2006; Diemer et al. 2013), the middle column shows the evolution of $R_{\text{vir}}$ of the MW host and the 3D distance of the subhalos to the host $r_{3D}$ in units of the MW virial radius $R_{\text{vir}}$, and the right column shows the evolution of the intrinsic SFR values (uncorrected for observational effects) given by UNIVERSEMACHINE. The triangles in the left and right panels with the same color as the evolution curves indicate the infall times (the first crossing of the MW host $R_{\text{vir}}$, shown by the horizontal line in the middle column) of the subhalos in each resolution. The horizontal lines in the left column indicate the resolution limits in $v_{\text{Mpeak}}$ that we estimate for the zoom-in (10 km s$^{-1}$), C125-2048 (35 km s$^{-1}$), and C125-1024 (60 km s$^{-1}$) boxes based on the analysis in Appendix B.

For the MW host and Subhalos 1, 2, 3, and 5, the matched counterparts in the parent boxes have generally consistent $v_{\text{max}}$ evolution features on timescales $\gtrsim 1$ Gyr. The history of Subhalo 4 (UFD) is well resolved in the zoom-in, but not so in the two parent boxes. Peaks in the $v_{\text{max}}$ evolution curve generally indicate mergers, and this is captured well across the three resolutions for the MW host, Subhalo 1, and Subhalo 2. The lower-mass Subhalo 3 (which is unresolved in C125-1024) and Subhalo 5 (which is marginally resolved in C125-1024) show less correspondence in the short-timescale variability of $v_{\text{max}}$ across different resolutions. Since the intrinsic SFR at fixed $v_{\text{max}}$ and redshift is mostly determined by $\Delta v_{\text{max}}$, the SFR history in the right panel also shows short-timescale differences (uncorrelated between time steps to model local variations in the ISM) in the three resolutions, while the long-term evolution agrees to first order as a result of the convergence in halo growth.

\textsuperscript{12} Detailed steps can be found in the “Running on Different Simulations” section on https://bitbucket.org/pbchoozi/universemachine/src/main/. The two changes mentioned in the text are made in step 1 and step 4.

\textsuperscript{13} This is one of the MW-like halos that includes a realistic Large Magellanic Cloud (LMC) analog system, and it was used in Nadler et al. (2020) to fit the observed MW satellite galaxy population.
growth (long-term correlation dominated by the $v_{\text{max}}$ evolution).

We note that the growth of the MW host and the infall times of the subhalos in the zoom-in are systematically earlier than their counterparts in the parent boxes. The $R_{\text{vir}}$ of the MW host in the zoom-in appears to suddenly increase owing to the infall of Subhalo 1, which crosses the MW $R_{\text{vir}}$ at $z \approx 0.06$. Although this could potentially bias the $r_{3D}/R_{\text{vir,host}}$ values of the zoom-in subhalos from row two to six, we have checked and confirmed that $r_{3D}$ itself also evolves systematically earlier in the zoom-in. Given that the evolution of objects in C125-2048 is not coherently ahead of their counterparts in C125-1024, the phenomenon of earlier-evolving zoom-in (sub)halos is not a pure resolution effect. Furthermore, it results in changes to the orbital phases and subhalo identity between the zoom-in and cosmological boxes (i.e., Subhalo 1 is within the MW virial radius in the zoom-in but has not accreted in the parent boxes, and Subhalo 5 is a splashback subhalo in the zoom-in but is found within the MW host halo’s virial radius in the parent boxes). Since the UM DR1 model does not explicitly model environmental quenching using tidal or ram pressure stripping, our results are only minutely affected by this artifact thanks to the agreement in the $v_{\text{max}}$ evolution across the three resolutions. Nevertheless, future improvements of the UM DR1 model and other SAMs of satellite galaxy evolution based on zoom-in simulations would be affected by this evolution systematic. We leave a careful numerical investigation of this issue to future work.

In summary, UNIVERSE MACHINE applied to the Mao et al. (2015) MW zoom-ins and parent cosmological simulations agrees well in different resolutions on a halo-to-halo basis for the halo ($v_{\text{max}}$) and galaxy ($\text{SFR}_{\text{raw}}$) growth, with the caveat that host halo $R_{\text{vir}}$ growth and subhalo accretion times are systematically earlier in the zoom-ins. This difference does not significantly affect the main results in this work.

4. Results

We now focus on the galaxy properties derived from applying UNIVERSE MACHINE to zoom-ins, including the predicted SMHM relation and evolution (Section 4.1), SFHs (Section 4.2), and quenched fraction of galaxies as a function
of stellar mass (Section 4.3). We summarize the main takeaways in Section 4.4.

4.1. Stellar Mass–Halo Mass Relation

Figure 4 shows the low-mass end of the SMHM relation obtained by applying UNIVERSEMACHINE to the 45 MW zoom-in simulations (solid blue line and shaded region), compared to other recent models and inferences of the low-mass SMHM relation. The SMHM relation predicted by running UNIVERSEMACHINE on our zoom-in simulations is almost an exact power-law extrapolation of the high-mass-constrained UM DR1 model down to the zoom-in halo mass resolution limit ($\sim 5 \times 10^7 M_\odot$).

The slope and scatter of the SMHM for the UM DR1 model applied to zoom-ins are in excellent agreement with the SMHM relation inferred from state-of-the-art MW satellite observations using the Dark Energy Survey (DES) and Pan-STARRS combined with an abundance matching approach (Nadler et al. 2020). This agreement might have been expected, given that...
UNIVERSEMACHINE is tuned to match the global stellar mass function (down to $M_* \sim 10^7 M_\odot$), and Nadler et al. (2020) find that the MW satellite luminosity function is consistent with a power-law extrapolation of the faint end of the GAMA luminosity function (Loveday et al. 2015). However, this agreement does not imply that the UM DR1 model captures all of the relevant physical processes that lead to this SMHM relation in the real universe. As we discuss in Section 5, the predicted SFHs (Section 4.2) and quenched fractions (Section 4.3) for dwarf galaxies indicate that the UNIVERSEMACHINE faint-end SMHM relation evolves too strongly at late times.

We also compare our result for the SMHM relation to the results of several other models, including other abundance matching models (Garrison-Kimmel et al. 2014, 2017; labeled as GK14 and GK17, respectively) informed by the Local Group satellite and field galaxy populations, as well as several recent empirical modeling results (Behroozi et al. 2013a; Moster et al. 2013, 2018; Jethwa et al. 2018; Rodríguez-Puebla et al. 2017; labeled as RP). The UNIVERSEMACHINE SMHM prediction has a shallower slope at the low-mass end compared to models that introduce a large scatter in the faint-end SMHM relation (Garrison-Kimmel et al. 2017). This is encouraging, as recent observational analyses (Carlsten et al. 2020b) find that the steep faint-end SMHM relation of Garrison-Kimmel et al. (2017) tends to underpredict the abundance of bright satellites ($M_{\text{peak}} > 10^{11} M_\odot$) in the local universe. The UM DR1 model agrees reasonably well with most of the models that are constrained at higher masses and extrapolated down to the dwarf galaxy mass range. Our result has a steeper SMHM relation slope than the Behroozi et al. (2013a) slope extrapolated from higher masses but is shallower than the Moster et al. (2013, 2018) slopes, which are close to Garrison-Kimmel et al. (2017).

As demonstrated in Section 3.3 (Figure 3), the dark matter halo assembly history is well resolved for objects in the MW zoom-in simulations up to redshift $z \sim 8$.14 Therefore, we can robustly trace the the SMHM relation back in time to visualize its evolution (Figure 4, right panel). The median SMHM relation ($M_*$ at fixed $M_{\text{peak}}$) evolves over an order of magnitude from $z = 8$ to $z = 0$ for peak halo masses below $\sim 10^9 M_\odot$, and there is a mild trend for the slope to steepen with decreasing redshift. We note that the upper limit on the scatter in galaxy luminosity at fixed halo properties inferred from MW satellite observations (Nadler et al. 2020) can be used to inform the maximum degree of evolution allowed in the SMHM relation. In Sections 4.4 and 5, we discuss how the SMHM relation evolution is meaningful even though there are limitations in the SFHs predicted by the UM DR1 model.

At all redshifts we consider, the SMHM relations for the zoom-ins shown here are consistent with direct power-law extrapolations of the high-mass end SMHM relations that result from applying UNIVERSEMACHINE to the Bolshoi-Planck simulation (B19). This results from the fact that UNIVERSEMACHINE scales the SFR of star-forming galaxies as a double power law with $v_{\text{max}}$, which reduces to a single power law with respect to $M_{\text{peak}}$ at the low-mass end ($M_* < 10^8 M_\odot$, $M_{\text{peak}} < 10^{11} M_\odot$). Naturally, the time integration of the SFR (evaluating $M_*(t)$) will preserve a power-law relation of the total stellar mass $M_*$ and the peak halo mass $M_{\text{peak}}$, while the change in the SMHM relation slope reflects the time evolution of the underlying halo growth rate. At fixed $v_{\text{max}}$ (halo mass) and redshift, the scatter in SFR is determined by the instantaneous accretion rate of the halo ($\Delta v_{\text{max}}$), which in turn leads to scatter in the SMHM relation at fixed halo mass.

These results extend the peak halo mass range of the SMHM evolution from $10^7 M_\odot$ in Behroozi et al. (2013) to $10^{12} M_\odot$. As shown in Figure 12 of Behroozi et al. (2020), the trend of decreasing $M_*/M_{\text{peak}}$ at fixed $M_{\text{peak}}$ that we observe from $z = 8$ to $z = 2$ in the right panel of Figure 4 begins as early as $z \sim 14$ and is mainly driven by the different evolution rates of halo and galaxy number densities at high redshifts. Upcoming JWST observations will significantly reduce the uncertainties in halo and galaxy number density evolution as early as $z \sim 10$, providing unprecedented constraints on the amplitude and evolution of the high-redshift SMHM relation. However, the

14In particular, the $v_{\text{max}}$ values of these halos are always above the $v_{\text{Mpeak}}$ resolution floor as defined in Appendix B.
progenitors of systems with present-day absolute UV magnitudes fainter than $M_{UV} \sim -18$ are not observable at early times, even with JWST (Boylan-Kolchin et al. 2015). Our framework for predicting galaxy growth at the faint end is therefore crucial for understanding the evolution of these extreme systems and its interplay with the onset, duration, and strength of reionization.

4.2. Star Formation Histories

We break down the evolution of the SMHM relation discussed above by studying the SFHs for galaxies of different masses as predicted by UNIVERSEMACHINE. The cumulative SFHs (all stars ever formed in the galaxy, not accounting for stellar mass loss, quantified by $M_*/M_{*0}$, the evolution of the galaxy stellar mass in units of their final $z=0$ stellar mass) for galaxies in eight different stellar mass bins are shown in Figure 5. The galaxies are binned based on their $z=0$ stellar mass, and we trace their total stellar mass evolution back along their CONSISTENT-TREES accounting for their full merger history. In the inset panels, we only include galaxies from the simulations with well-resolved low-mass halos or sufficient statistics for high-mass halos. The median and 68% scatter of the SFHs (modeled as all stars ever formed) inferred for dwarf galaxies in the Local Group (Weisz et al. 2014a) are shown in the left panels for comparison.

The SFH at the three resolution levels agrees well in the high stellar mass bins for both the median and the scatter (right column). In the $M_{*}/M_\odot \in [10^{10}, 10^{11}]$ bin, the zoom-in galaxies tend to systematically form stars later than their counterparts in the parent boxes. A factor that leads to this difference is that there are no massive MW-mass satellites in the joint 45 MW zoom-ins (prevalent in hosts much more massive than the MW) compared to the parent boxes. We have checked that the consistency between the three resolutions improves in this stellar mass bin if we only include central galaxies from the two parent boxes. Another contribution to this difference might come from our selection of isolated MW-mass halos only, as a recent study using the FIRE simulation found earlier SFHs for central galaxies in Local Group—like environments compared to isolated MW halos, due to earlier halo mass accretion in the former (Garrison-Kimmel et al. 2019).

For lower stellar mass galaxies (left column), we compare the joint zoom-in SFHs and the SFHs from the lower-resolution C125-2048 box. We also plot the observed SFHs of dwarf galaxies from Weisz et al. (2014a) (starting from $z=5.5$, look-back time $\sim 12.59$ Gyr). The zoom-in galaxies tend to show earlier star formation than their parent box counterparts when we go from the $M_{*}/M_\odot \in [10^{7}, 10^{8}]$ bin to the $M_{*}/M_\odot \in [10^{9}, 10^{10}]$ bin. Here, resolution effects kick in such that the zoom-in simulations resolve halo growth earlier than the parent box, while their late-time star formation converges at low redshift. Compared to the inferred SFHs of Local Group dwarf galaxies from Weisz et al. (2014a), the rapid early star formation of the zoom-in dwarf galaxies at $z \gtrsim 3$ is marginally consistent with these observed galaxies.

The UM DR1 model predicts that the zoom-in dwarf galaxies only form $\sim 50\%$ of their present-day stellar mass in this early phase, and their star formation gets stalled by the slackened halo growth from $z=2$ to 1, before forming the other half of their stellar mass at low redshift ($z \lesssim 1$). This finding is valid for centrals and satellites alike and is discrepant with the inferred late-time SFHs of dwarf galaxies in the Local Group within the similar stellar mass ranges, especially for UFDs ($M_* \lesssim 10^5 M_\odot$), which are thought to quench their star formation at high redshifts ($z \gtrsim 5$) via reionization (e.g., Bullock et al. 2000; Barkana & Loeb 2001; Benson et al. 2002; Rodriguez Wimberly et al. 2019). The differences of UNIVERSEMACHINE with the Local Group observations in the UFD regime are robust; their object-to-object scatter does not overlap, and it cannot be accounted for by observational uncertainties ($\lesssim 0.2$ in $M_{*}/M_{*0}$) at $z \lesssim 0.5$ (Weisz et al. 2014a).

Even though updated stellar evolution models (e.g., Dotter et al. 2017) that account for atomic diffusion and gravitational settling could lead to slightly younger stellar ages, the tension between our SFHs and the Local Group dwarf SFHs cannot be fully resolved. It is not surprising that UNIVERSEMACHINE predicts a different SFH than observed dwarfs since no constraints were placed on the cosmic SFHs of low-mass galaxies ($M_* \lesssim 10^5 M_\odot$) in the fitting of the UM DR1 model. Similar late-time star formation that is discrepant from the Local Group dwarfs was predicted in Leitner (2012) when the observed SFR$-M_*$ relation was extrapolated down to the dwarf galaxy regime.

In the top two panels of the left column in Figure 5, we also show the evolution of $v_{\text{max}}$ for all galaxies, the centrals-only sample, and the satellites-only sample in the two lowest SFH stellar mass bins. At $z \gtrsim 4$, $v_{\text{max}}$ increases steadily in both stellar mass bins and fuels the rapid early star formation owing to halo growth. However, at $z \lesssim 2$, $v_{\text{max}}$ remains almost constant for centrals, and it decreases mildly on average for the subhalos hosting satellite galaxies owing to tidal stripping after infall, which leads to an almost nonevolving $v_{\text{max}}$ distribution for all galaxies in both stellar mass bins. This suggests that the late-time star formation observed at $z \lesssim 0.5$ in these low-mass bins is not driven by (sub)halo dark matter accretion at late times. Instead, the late-time star formation in these small halos results from a significant increase in the efficiency of their star formation, while little change occurs in their halo mass.

This phenomenon is due to the specific form of coupling that the UNIVERSEMACHINE model assumes between SFR and $v_{\text{max}}$, which behaves unreasonably when extrapolated to the low halo masses we examine here. The UNIVERSEMACHINE model parameterizes the SFR coupling to $v_{\text{max}}$ of star-forming galaxies in the form of a broken power law (see Equation (4) in B19):

$$SFR_{\text{SF}} \propto \left[ \frac{v_{\text{max}}}{v_0} \right]^\alpha \left[ 1 + \left( \frac{v_{\text{max}}}{v_0} \right)^\beta \right]^{-1},$$

(1)

where $v_0$, $\alpha$, and $\beta$ are model parameters, and we have assumed $v_{\text{peak}} \approx v_{\text{max}}$ since $v_{\text{max}}$ is almost constant at $z \lesssim 2$. The power-law slopes $\alpha$ and $\beta$ account for the different star formation efficiencies in low- and high-mass galaxies owing to different feedback and quenching mechanisms, whereas the normalization $v_0$ sets the location of that transition. The evolutions of the $\alpha$ and $\beta$ values in the UM DR1 model are mostly constrained by the decreasing specific SFR (star formation efficiency) of observed galaxies with $M_* \gtrsim 10^9 M_\odot$ (see Figure 3, right panel in B19), which corresponds to halo masses of $M_{\text{peak}} \gtrsim 2 \times 10^{11} M_\odot$. The underlying physics here encompasses the AGN feedback (Wyithe & Loeb 2003; Di Matteo et al. 2005; Springel et al. 2005a; Fabian 2012;
Figure 5. Cumulative SFHs of galaxies in eight $z = 0$ stellar mass bins derived by applying UNIVERSEMACHINE to our three simulation resolution levels. Curves and shaded regions indicate the median and 68% scatter of the SFH distribution for systems in our zoom-in simulations (blue) and the C125-2048 (red) and C125-1024 (green) parent boxes. In each stellar mass bin, we only include the simulation(s) that are well resolved and that sample the corresponding halo mass range. The observed median SFHs of dwarf galaxies in the Local Group (Weisz et al. 2014a) are shown for comparison in the left column (shaded gray regions indicate the 68% scatter). We also show the median SFH for only central or satellite galaxies in the top two panels of the left column, as well as these halos’ (nonorphans, $\geq 93\%$ subhalos in these two mass bins) $v_{\text{max}}$ evolution in the inset panels. Triangles of the same color as the solid curves indicate the redshift at which the median $v_{\text{max}}$ of the subhalos for galaxies in a given resolution and stellar mass bin rises above the resolution limits (Appendix B).
Kormendy & Ho 2013) and merger-driven quenching in massive galaxies (Nipoti et al. 2009b, 2009a; Remus et al. 2013; Wellons et al. 2016), which becomes more effective in massive halos at low redshift and reduces the efficiency at which a halo can convert its gas into stars.

The best-fit UM DR1 model values for \((v_0, \alpha, \beta)\) are (137.72 km s\(^{-1}\), −6.135, −1.813) at \(z = 0\). At \(z \lesssim 0.5\), \(v_0\) remains almost constant, while both \(\alpha\) and \(\beta\) increase steadily toward \(z = 0\). For the galaxies in the three highest stellar mass bins \(\left(\mathcal{M}_* \geq 10^9 \mathcal{M}_\odot\right)\) in Figure 5, most of their host (sub)halos satisfy \(v_{\text{max}} \gtrsim 120 \text{ km s}^{-1}\), i.e., \(\left(\frac{v_{\text{max}}}{v_0}\right) \gtrsim 1\). With the parameterization in Equation (1), even if \(v_{\text{max}}\) remains almost constant at \(z \lesssim 0.5\) for these massive galaxies, the UM DR1 model predicts that SFRs decrease with time toward \(z = 0\) owing to the increase in \(\alpha\) and \(\beta\) values, which is evident in the right column of Figure 5.

However, directly extrapolating this model down to lower-mass galaxies \(\left(\mathcal{M}_* < 10^8 \mathcal{M}_\odot\right)\) could result in \(\left(\frac{v_{\text{max}}}{v_0}\right) < 1\), which would lead to increasing SFR values from \(z \sim 0.5\) to \(z = 0\) owing to increasing values of \(\alpha\) and \(\beta\), even though \(v_{\text{max}}\) remains constant at low redshift. This effect can be seen in Figure 5 (left panel) and becomes stronger as stellar mass decreases. As the model predicts all galaxies to be star-forming below \(\mathcal{M}_* \sim 10^7 \mathcal{M}_\odot\) (see Section 4.3 and Figure 6), the late-time star formation is evident for both centrals and satellites. This effect is smaller for satellites owing to the mild decrease of \(v_{\text{max}}\) at \(z \lesssim 2\), due to tidal stripping after being accreted.

These findings reflect the fact that the global stellar mass function extends smoothly from \(\mathcal{M}_* \gtrsim 10^9 \mathcal{M}_\odot\) down to \(\mathcal{M}_* \lesssim 10^7 \mathcal{M}_\odot\), leading to a realistic SMHM relation (Figure 4). However, extending the SFR\(\left(v_{\text{max}}\right)\) coupling constrained by high-mass galaxy star formation efficiency, where quenching is driven by AGN feedback and mergers, does not fit in the dwarf galaxy regime, where quenching is driven by stripping, stellar feedback, and reionization (e.g., Bullock et al. 2000; Barkana & Loeb 2001; Benson et al. 2002; Rodriguez Wimberly et al. 2019) and results in the unrealistic SFHs at \(z \lesssim 1\) (Figure 5, left column).

We discuss the implications of model improvements based on this discrepancy, along with the quenched fractions (next section) predicted by UNIVERSE-MACHINE for dwarf galaxies, in Section 5.

4.3. Quenched Fractions

Another crucial observational constraint used to constrain the UM DR1 model is the quenched fraction \(f_{\text{Quench}}\) of galaxies as a function of stellar mass, which sets the transition from the star-forming main sequence to the quenched red sequence of galaxies (Dekel & Birnboim 2006; Faber et al. 2007; Noeske et al. 2007). The definition of “quenched” in the model is given by a set of redshift-dependent criteria that depend on both the specific SFR (SFR per unit stellar mass; Moustakas et al. 2013) and \(UVJ\)-band colors (Muzzin et al. 2013). We follow the definition in Appendix C6 of B19 and adopt specific SFR \(< 10^{-11} \text{ yr}^{-1}\) as the criterion for classifying quenched galaxies at \(z = 0\).

The \(f_{\text{Quench}}-\mathcal{M}_*\) relations for all galaxies, centrals, and satellites are shown in Figure 6. The classification of galaxies into “star-forming” or “quenched” forms a binomial distribution in each stellar mass bin. We show \(2\sigma\) bootstrap errors (from 500 resamplings), as well as the 95% confidence Wilson score interval (Wilson 1927), for the three categories of zoom-in galaxies. For brevity, the small bootstrap standard deviations in the two parent boxes are not shown owing to the abundant sampling of galaxies at the well-resolved halo masses. The three resolutions agree in the overall trend of the \(f_{\text{Quench}}-\mathcal{M}_*\) relation, although the zoom-in results show significant scatter toward high masses owing to limited statistics. Similar to the \(\mathcal{M}_*/\mathcal{M}_* \in [10^{10}, 10^{11}]\) bin in Figure 5, the zoom-ins begin to miss out on MW-mass satellites and lead to an \(f_{\text{Quench}}\) value that is biased high, although the Wilson score interval remains consistent at the \(2\sigma\) level with the parent boxes. This also leads
to the spike at $\sim 10^{10} M_\odot$ in the top panel when combined with the centrals.

The $f_{\text{Quench}} - M_*$ relation including both central and satellite galaxies in the top panel of Figure 6 suggests that the $f_{\text{Quench}} - M_*$ relation is a simple extension of the UM DR1 model constrained at higher masses down to the UFD regime in the form of an error function (see Section 3.2 in B19). Comparing the lower two panels, the satellites generally have higher quenched fractions at fixed stellar mass compared to centrals above $M \sim 10^7 M_\odot$ in both the zoom-ins and the parent boxes. However, the classical and UFDs below this mass are all predicted to be star-forming regardless of their central or satellite identity. Recent observations (McConnachie 2012; Karachentsev & Kaisina 2013; Weisz et al. 2015; Mao et al. 2021) suggest that satellite galaxies around MW-mass hosts in the Local Group and low-redshift universe are at least $\sim 60\%$ quenched at $\sim 10^7 M_\odot$, with higher quenched fractions toward lower stellar masses. This trend around MW hosts is also reproduced in hydrodynamic zoom-in simulations (Simpson et al. 2018; Akins et al. 2021), although these simulations have their own issues of overquenching field galaxies compared to observations (Dickey et al. 2020). We indicate the mass ranges of specific data sets (field centrals, Geha et al. 2012; SAGA Survey satellites, Mao et al. 2021; Local Group dwarfs, Weisz et al. 2014a) that could be used to constrain future UNIVERSE-MACHINE model improvements.

The discrepancy between UNIVERSE-MACHINE and observations reveals that extending the error-function-like parameterization of $f_{\text{Quench}} - M_*$ for higher-mass galaxies to lower stellar masses is insufficient to capture the correct satellite quenched fractions in the dwarf regime. Because the UM DR1 model predicts that all low-mass galaxies are star-forming, a more realistic treatment of observational selection functions is not expected to ease this tension. This implies that a different parameterization for the dwarf galaxy quenched fractions is necessary, in addition to the single-error-function module that fully described the observational constraints at $M_* \gtrsim 10^9 M_\odot$ in B19. As a consequence of not quenching dwarf galaxies with $M_* \lesssim 10^7 M_\odot$, the DR1 model fails to decouple SFR from halo growth scaled as Equation (1) and forces these low-mass galaxies into a late star-forming epoch ($z \lesssim 1$) to match the global stellar mass function at different redshifts, which would have been otherwise prevented if most of these dwarfs had been quenched (quenched galaxies in UNIVERSE-MACHINE take on a median SFR of $10^{-11.8} \text{yr}^{-1}$ with a 0.3 dex scatter, regardless of halo mass or halo accretion rate).

4.4. Discussion

Summarizing the main results of this section, UNIVERSE-MACHINE predicts a low-mass SMHM relation that is a power-law extrapolation of the SMHM relation at $M_* \gtrsim 10^9 M_\odot$. This relation is already in place at $z = 8$ and evolves over an order of magnitude to a slope and scatter consistent with the abundance-matching-inferred MW satellite SMHM relation at $z = 0$. The consistency in the SMHM relation with the SMHM relation inferred from MW satellite observations (Nadler et al. 2020) follows from the fact that the UM DR1 model matches global stellar mass functions across different redshifts. However, as the SFR($v_{\text{max}}$) coupling is mostly constrained by the specific SFR evolution of high-mass galaxies ($M_* \gtrsim 10^9 M_\odot$), the model forces all dwarf galaxies ($M_* \lesssim 10^7 M_\odot$) to actively star-forming below $z \sim 1$, regardless of their central or satellite identity. As a consequence, the path through which the dwarfs evolve onto this SMHM relation is inconsistent with that for observed dwarf galaxies.

Although the dwarf galaxy SFHs predicted by UNIVERSE-MACHINE are not realistic, the predicted evolution of the SMHM relation is reasonable given that UNIVERSE-MACHINE matches the global stellar mass function down to $M_* \sim 10^7 M_\odot$. As shown in the right panel of Figure 4, the SMHM relation evolves by an order of magnitude in stellar mass at fixed $M_{\text{peak}}$ from $z = 8$ to $z = 0$. Even if we implement improvements to the DR1 model to enforce SFHs that resemble those observed for dwarf galaxies, stellar masses at $z > 4$ are only required to change by factor of $\sim 2$ at these high redshifts owing to the very rapid early-phase star formation (Figure 5 left column). Therefore, future improvements to the predicted dwarf galaxy SFHs will not significantly affect the predicted faint-end SMHM evolution.

Preliminary results using the predicted SFHs in Section 4.2 indicate that the present-day UFDs’ progenitors were not the major contributors ($\sim 5\%$) to the ionizing-photon budget during reionization. This subdominant role is consistent with empirical modeling that connects Local Group dwarf galaxy SFHs to high-redshift progenitors based on their abundances and SFHs (Boylan-Kolchin et al. 2015; Weisz & Boylan-Kolchin 2017). Since the current UM model may underpredict SFHs during reionization (more discussion in Section 5), this predicted reionization contribution may slightly increase in future work but is expected to remain subdominant.

Thus, UNIVERSE-MACHINE arrives at a faint-end SMHM relation in agreement with the SMHM relation inferred from MW satellites (Section 4.1) despite its unrealistic predictions for dwarf galaxy SFHs (Section 4.2) and quenched fractions (Section 4.3). This implies that the DR1 model does not fully capture the physical processes that govern dwarf galaxy evolution, which is unsurprising given that it was only constrained using data for higher-mass galaxies. We now discuss how UNIVERSE-MACHINE might be improved to account for the physics that quenches star formation in the low-mass regime.

5. Implications for Model Improvements

The results in the previous section demonstrate specific shortcomings of the UM DR1 model when applied to low-mass objects that were previously investigated. In particular, although UNIVERSE-MACHINE predicts an SMHM relation in good agreement with that inferred from abundance matching and other empirical models, it arrives at this SMHM relation in an unrealistic manner, with all dwarf galaxies actively forming stars at $z = 0$. To more fully constrain the diverse range of physical processes that influence galaxy formation and evolution, UNIVERSE-MACHINE and other empirical models must self-consistently predict both the slope and scatter of the SMHM relation and the detailed evolution of particular galaxies along this relation over time.

Given the factors summarized in Section 4.4, further improvements of the UM DR1 model call for at least implicit incorporation of environmental quenching effects to produce nonzero $f_{\text{Quench}}$ values for dwarf satellites, thereby decoupling their SFR from halo growth at late times. This change would in principle mostly affect classical and bright dwarfs ($M_* / M_\odot \in [10^7, 10^8]$) in a mass-dependent fashion, and it should also accommodate the short quenching timescale ($\lesssim 2$ Gyr) inferred for galaxies with $M_* \lesssim 10^8 M_\odot$ from Local Group dwarfs (Wetzel et al. 2015). Meanwhile, for
UFs (M_u/M_⊙ ≤ 10^5), an effective model that captures quenching due to reionization physics (e.g., UV heating that prevents gas cooling) could likewise decouple dark matter accretion and star formation. Implementing such a model and constraining it by comparing to the early-quenching SFHs of Local Group dwarf galaxies will offer insights into the timing and efficiency of reionization quenching. Both the environmental and the reionization quenching effects can potentially be modeled by an f_{Quench}−M_u parameterization that increases with decreasing stellar mass for M_u ≤ 10^4 M_⊙, opposite to the parameterization at higher masses (M_u ≥ 10^6 M_⊙) in B19.

With these two changes implemented, the stellar masses of dwarf galaxies could be underestimated owing to the removal of late-time (z ≤ 1) star formation. To maintain an SMHM relation that matches constraints from Local Group dwarf galaxies, these changes necessitate that low-mass (sub)halos form stars more efficiently than high-mass halos at high redshifts (z ≥ 5), superseding the fiducial scaling of SFR with halo growth assumed in the UM DR1 model. This is consistent with the efficient high-redshift star formation inferred from Local Group dwarf galaxies (Madau et al. 2014). However, even if we consider the UFDs that should be most affected by reionization and quench before z ~ 4, they already form ~50% of their present-day stellar mass in the early star formation phase predicted by the UM DR1 model owing to rapid halo growth. Thus, a slight increase (a factor of few) in the early SFR would be sufficient to reproduce SFH consistent with Weisz et al. (2014a) while largely maintaining the SMHM relation. Additional information for the galaxy stellar age distribution as a function of halo mass may also provide quantitative constraints on the star formation efficiency of dwarf (sub)halos relative to their more massive counterparts at high redshift (Khimey et al. 2020).

As discussed in Section 4.4, the current UM model predicts that local UFDs’ progenitors contributed only ~5% to the total ionization budget during reionization. This may represent a slight underestimate due to the finite resolution of our simulations and the current UM model underpredicting UFD star formation efficiencies at z > 4. However, even with improved modeling and increased resolution, we anticipate that the UFD progenitors’ contribution to reionization will be ≤10%, as the required increase in SFR to match Local Group SFHs is only factor of ~2 at z > 4. In order to make robust predictions for the UFD contribution to reionization, it is necessary to account for systematics in the mass dependence of the initial mass function (IMF), as well as the spatial and temporal stochasticity of the UV photon escape fraction. These effects will be investigated further in future work.

In all, more accurate predictions of the earliest star formation epoch in the universe given by UM will rely on incorporating dwarf galaxy constraints into the model. To emphasize, we advocate that SFH and f_{Quench} are essential factors that impact the galaxy–halo connection at the low-mass end, and empirical models that build on the UNIVERSEMACHINE framework need to carefully account for their mass-dependent behavior to predict galaxy evolution consistent with the real universe. Although we do not attempt to directly constrain the UNIVERSEMACHINE model on dwarf galaxy scales in this work, we summarize two future directions for this work motivated by our current findings:

1. **Refitting the UNIVERSEMACHINE model**: We plan to carry out a detailed exploration of the UM DR1 model posterior space, including a study of parameter covariances, as well as the flexibility of the current model to allow for early star formation in dwarf galaxies while maintaining appropriate scaling relations at higher masses (e.g., stellar mass functions, cosmic SFH, quenched fractions, and auto- and cross-correlations).

2. **Implementing dwarf galaxy quenching mechanisms**: In parallel, we plan to explore effective models of environmental quenching and reionization by implementing a more sophisticated model of the redshift-dependent f_{Quench}−M_u relation. Environmental quenching could potentially be constrained with observed quenched fractions in Sloan Digital Sky Survey field centers (Geha et al. 2012) and SAGA+Local Group satellites (Weisz et al. 2014a; Mao et al. 2021) hand in hand, while the impact of reionization could potentially be constrained by Local Group UFDs (Weisz et al. 2014a). This approach can be generalized to improve other aspects of the model at low masses that are inflexible owing to the current parameterization based on high-mass galaxies only.

In addition to these plausible improvements, upcoming z ~ 10 JWST observations will significantly reduce uncertainties on the high-redshift SMHM relation for the progenitors of the brightest dwarf galaxies (Behroozi et al. 2020). Boosting the SFRs of dwarf galaxies at early times compared to the UM DR1 model as required by this study would suggest an increase in the detectability of these systems at redshifts, thereby impacting predictions for JWST. Combined with our methodology to extend galaxy evolution predictions down to the UFD galaxy regime, these high-redshift observations will further constrain the strength and timing of reionization, which holds far-reaching consequences for our understanding of dwarf galaxy formation and evolution.

**6. Conclusions and Outlook**

We applied the empirical galaxy–halo connection model UNIVERSEMACHINE (Behroozi et al. 2019) to cosmological zoom-in simulations of MW-mass halos, along with their parent boxes. Our study is based on a joint sample of 45 MW halo zoom-in resimulations in the halo mass range of 10^{12.1 ± 0.03} M_⊙ selected from the parent cosmological boxes of the Chinchilla simulations (C125-1024 and C125-2048; Mao et al. 2015). This work provides a framework for studying the galaxy–halo connection over the full range of observed galaxy masses, and it exposes specific aspects of the UM DR1 model that break down in the dwarf galaxy regime. The main findings of this work can be summarized as follows:

1. We have applied the empirical galaxy–halo connection model UNIVERSEMACHINE to a set of 45 MW-mass zoom-in simulations, achieving seven decades of halo mass resolution and modeling SFHs for the full range of galaxy masses when combined with their parent cosmological simulations (Figure 1).

2. The UM DR1 model predicts an SMHM relation that is consistent with observational constraints from MW satellites at z = 0, including for UFD galaxies (Figure 4, left panel).

3. Our predicted SMHM relation evolves roughly an order of magnitude from z = 8 to z = 4 and evolves more mildly from z = 4 to the present (Figure 4, right panel).

4. The UM DR1 model predicts significant late-time star formation in dwarf galaxies (a quenched fraction near 0%
for \( M_\ast \lesssim 10^7 M_\odot \) and is discrepant with the SFHs and quenched fractions inferred for Local Group dwarfs (Figures 5–6).

5. We identify modifications to UNIVERSEMACHINE, including environmental and reionization-driven quenching mechanisms for dwarf galaxies, that must be implemented in specific stellar mass regimes (\( \lesssim 10^7 M_\odot \)). Such models may simultaneously yield SFH and SMHM relation predictions in agreement with dwarf galaxy observations (Section 5).

This work lays crucial methodological foundations (especially for ranking subhalos; Section 3.3 and Appendix A) for applying UNIVERSEMACHINE to zoom-in simulations and constraining it at the low-mass end. Our work demonstrates that scaling galaxy SFR with (sub)halo dark matter accretion rate can yield reasonably realistic SMHM relations and match the evolution of the global stellar mass function down to the UFD galaxy regime. However, as discussed in Sections 4 and 5, our findings also reveal that this comes at the cost of predicting significant late-time star formation in dwarfs and not quenching the dwarf satellites at low redshifts (\( z \lesssim 1 \)). These limitations arise owing to the unconstrained nature of the UM DR1 model in the dwarf galaxy regime. Identifying these limitations in the current version of the UNIVERSEMACHINE model demonstrates that it is necessary to model quenching differently in low-mass dwarfs (\( M_\ast \lesssim 10^7 M_\odot \)) than in their more massive counterparts (\( M_\ast \gtrsim 10^7 M_\odot \)), marking a significant transition of the underlying quenching physics with halo mass. As a major focus of upcoming work, a more comprehensive picture that captures the life cycle of star formation in dwarf galaxies will be built using detailed modeling of environmental and reionization quenching mechanisms, as well as exploring the flexibility of the UM DR1 model to encompass diverse SFHs in dwarfs.

Apart from these two pertinent directions, comparison with hydrodynamic simulations (see Vogelsberger et al. 2020 for a review) on both cosmological and zoom-in scales could also provide valuable information. For example, recent results (Garrison-Kimmel et al. 2019) from the FIRE Simulation reproduce the stellar mass function and SFHs of dwarf galaxies around MW-mass hosts reasonably well, while showing minimal environmental dependence in their SFHs. Comparing UNIVERSEMACHINE to these results can shed light on the details regarding the diversity of SFHs and quenching processes given their power to self-consistently follow the baryonic evolution in galaxies with hydrodynamics.

Another prospect of our future work is to account for the systematic biases introduced into the SMHM relation by stochastically populating the stellar IMF in UFDs (Applebaum et al. 2020). Determining the origin of the earlier evolution of subhalos (Figures 2 and 3) in zoom-in simulations is also crucial for understanding the systematics of environmental quenching effects due to the change in subhalo orbital phases.

The methodology we have developed can easily be generalized to other mass scales (e.g., using cluster scale zoom-in resimulations), enabling empirical studies of the galaxy–halo connection that benefit from the dynamic range achieved by zoom-in simulations. We have demonstrated that combining the UNIVERSEMACHINE model with zoom-in dark matter simulations offers a powerful, high-resolution approach to study the relation between dark matter accretion and star formation. We expect that this methodology, combined with the model improvements highlighted here and with new observations that inform the abundance and evolution of dwarf galaxies, will play a key role in future studies of the galaxy–halo connection over large dynamic ranges.

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Appendix A
Subhalo Ranking

As briefly discussed in Section 3.3, correctly ranking subhalos in zoom-in simulations is nontrivial and is a crucial step for applying UNIVERSEMACHINE. This involves mapping the halo accretion rate \( \Delta_{\text{vmax}} \) to galaxy SFR at fixed halo mass \( v_{\text{max}} \). The definition of \( \Delta_{\text{vmax}} \) follows from Equation (1) in B19:

\[
\Delta_{\text{vmax}} = \frac{v_{\text{max}}(z_{\text{now}})}{v_{\text{max}}(\max(z_{\text{dyn}}, z_{\text{peak}}))},
\]

where \( z_{\text{now}} \) is the redshift when \( \Delta_{\text{vmax}} \) is measured, \( z_{\text{dyn}} \) is the redshift one dynamical timescale ago from \( z_{\text{now}} \), and \( z_{\text{peak}} \) is the redshift at \( M_{\text{peak}} \). The ranks of \( \Delta_{\text{vmax}} \) are essentially their probits according to the cumulative distribution function (CDF), which is assumed to be Gaussian. The probits are further mapped to the ranked percentiles of SFR by the UM DR1 model via a rank correlation parameter \( r_c \) (see Equation (18) in B19) with some random Gaussian scatter.

Shown in Figure A1 are the rank distributions of \( \Delta_{\text{vmax}} \) as a function of the peak halo particle number \( (M_{\text{peak}}/m_{\text{DM}}) \) for the 45 joint zoom-ins (left panel) and the individual MW zoom-in halo No. 416 (right panel). The colored curves denote the isodensity contours of the rank distributions in the three
resolutions, while the grayscale map shows the binned rank versus peak halo particle number for the zoom-ins (all subhalos in the left panel, and only those in Halo no. 416 on the right). We notice from the left panel that the contours for the subhalo ranks we obtain in the joint zoom-ins are close to those obtained in the two parent boxes. This is an interesting feature that could be useful when multiple zoom-ins are not available.

Wehrle et al. 2002; Diemer & Kravtsov 2015

Comparing the left and right panels, the most significant difference comparing the rank distributions of the joint and individual zoom-ins is that the joint zoom-ins’ ranks have a much better coverage at the high ($\gtrsim 10^5$) and low ($\gtrsim 10$) particle numbers, where the individual zoom-ins easily miss out on these rare objects owing to finite sampling for high-mass objects or halo finder cutoff for low-mass objects. In the range of $10^4-10^3$ particles where most subhalos dwell, the joint zoom-ins also sample the tails of the CDF more accurately ($\gtrsim 4\sigma$). In practice, if the tails are not sampled properly by applying UNIVERSEMAchine to an individual zoom-in, the code can break down owing to the presence of rapidly growing ($>+7\sigma$) or heavily tidal-stripped ($<-7\sigma$) subhalos before fully evolving to $z=0$. Therefore, it is crucial to join multiple zoom-in realizations for obtaining unbiased ranks of the subhalos when applying empirical models like UNIVERSEMAchine to zoom-in simulations in general.

Appendix B
Resolution Cuts

Although our results are hardly affected by resolution effects on our galaxy and halo samples, we emphasize that one should be cautious when interpreting the results involving a significant proportion of (sub)halos near the resolution limit of the simulation. Numerical resolution mainly affects the density profiles of dark matter halos by decreasing the central region density and henceforth decreasing the $v_{\text{max}}$. In Figure B1 we show the $M_{\text{vir}}-M_{\text{peak}}$ and $V_{\text{Mpeak}}-V_{\text{peak}}$ relations for our three different resolution simulations. Scattered dots indicate individual (sub)halos, while the dark and light shaded regions indicate the $1\sigma$ and $2\sigma$ intervals of the corresponding distributions, respectively.

Conventionally, halos with more than 100 particles at $z=0$ are thought to be well resolved. However, (sub)halos may experience mass loss due to tidal interactions in the cosmic environment; therefore, one must also include (sub) halos that have well-resolved evolution histories but currently stripped below the traditional resolution limit. We propose that a reasonable resolution cut for our set of simulations is to select (sub)halos above the upper bound of the $2\sigma$ interval of $V_{\text{Mpeak}}$ at the peak halo mass, which is 100 times that of the particle mass resolution. These values are indicated by the red dotted–dashed lines in the lower panels of Figure B1 (C125-1024 $\sim 60$ km s$^{-1}$, C125-2048 $\sim 35$ km s$^{-1}$, and zoom-ins $\sim 10$ km s$^{-1}$). This procedure deliberately selects subhalos with stellar mass ($\propto V_{\text{peak}}$) that upscatters in the SMHM relation (which is acceptable for dark-matter-related properties). One could potentially also cut conservatively on $M_{\text{peak}}$ with $>200\times$ the particle mass resolution if one is particularly interested in (sub)halos with stellar masses near the $V_{\text{Mpeak}}$ resolution limit.
Figure B1. Peak halo mass $M_{\text{peak}}$ vs. the maximum circular velocity at peak halo mass $V_{\text{peak}}$, and the virial mass $M_{\text{vir}}$ at $z = 0$ for all (sub)halos in C125-1024, C125-2048, and the joint MW zoom-ins at $z = 0$. Dark and light shaded regions indicate the 68% (1σ) and 95% (2σ) intervals for the distributions. The vertical dashed line in each panel indicates 100× the mass resolution, while the red dotted–dashed lines indicate the adopted $V_{\text{peak}}$ cut for well-resolved halos in the three different resolutions. This selects most of the halos with more than 100 particles not only at their peak mass but also at their present-day $M_{\text{vir}}$ for all three resolutions.

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16
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