The In-situ Origins of Dwarf Stellar Outskirts in FIRE-2

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Abstract

Extended, old, and round stellar populations reminiscent in structure to the stellar halos of massive galaxies (Lin & Faber 1983; Minniti & Zijlstra 1996; Minniti et al. 1999; Zaritsky et al. 2000; Aparicio & Tikhonov 2000; Aparicio et al. 2000; Hidalgo et al. 2003; Bernard et al. 2007; Stinson et al. 2009; Strader et al. 2012; Nidever et al. 2019a,b; Pucha et al. 2019; Kado-Fong et al. 2020). Recently, it has been shown that high-mass dwarfs (10^8.5 < M_⋆ < 10^9.0 M_☉) can form a thick stellar & HI disk (Roychowdhury et al. 2013; van der Wel et al. 2014; Nath Patra 2020) in conjunction with a round stellar halo (Kado-Fong et al. 2020).

1. INTRODUCTION

Extended, old, and round stellar halos appear to be ubiquitous around high-mass dwarf galaxies (10^8.5 < M_⋆ < 10^9.0 M_☉) in the observed universe. However, it is unlikely that these dwarfs have undergone a sufficient number of minor mergers to form stellar halos that are composed of predominantly accreted stars. Here, we demonstrate that FIRE-2 (Feedback in Realistic Environments) cosmological zoom-in simulations are capable of producing dwarf galaxies with realistic structure, including both a thick disk and round stellar halo. Crucially, these stellar halos are formed in-situ, largely via the outward migration of disk stars. However, there also exists a large population of “non-disky” dwarfs in FIRE that lack a well-defined disk/halo and do not resemble the observed dwarf population. These non-disky dwarfs tend to be either more gas poor or to have burstier recent star formation histories than the disky dwarfs, suggesting that star formation feedback may be preventing disk formation. Both classes of dwarfs underscore the power of a galaxy’s intrinsic shape – which is a direct quantification of the distribution of the galaxy’s stellar content – to interrogate the feedback implementation in simulated galaxies.

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lar halo assembly at low masses (\(M_{\star} \approx 10^9 M_\odot\)) are gener-
ically rounder at larger radius regardless of environment. They further show that the majority of isolated dwarfs
host thick disks near their centers, while red satellite
dwarfs are more spheroidal (following the familiar color-
morphology bimodality seen at higher masses). Because
dwarfs do not typically accrete sufficient stellar mass to
form an ex-situ stellar halo that would be detectable in
current-generation widefield imaging (e.g. Purcell et al.
2007), both the dominance of this disk to halo structure
in the isolated dwarf sample and the presence of spheroidalstellar outskirts regardless of environment suggest that the formation of low-mass stellar outskirts is a primarily in-situ process. Thus, in order to match observations, simulated dwarfs should have both a young stellar disk and an old, round stellar halo. This requirement is especially relevant for a stellar halo produced largely by star formation feedback, as under-regulated or over-active star formation feedback has been shown to be capable of disrupting the disk in dwarf galaxies (El-Badry et al. 2018a,b; Smith et al. 2020). The requirement to match galaxy structure places a new constraint on the feedback physics implemented in simulations – there must be sufficient energy to heat the old stellar population, producing a round stellar halo, while simultaneously maintaining a young stellar disk.

The FIRE\(^1\) project combines both the resolution needed to study the detailed structure of dwarf galaxies
and the cosmological context necessary to understand
the formation of that structure. In this work, we examine the three-dimensional stellar structure of a set of isolated dwarf galaxies (\(10^8 \lesssim M_{\star}/M_\odot \lesssim 10^{10}\)) in the FIRE-2 simulation suite (Hopkins et al. 2018). We first determine whether or not the FIRE simulations reproduce the disk-halo systems observed to be the dominant population in observations, and then we examine the origin of these stellar halos. In Section 2, we summarize the basic properties of the FIRE simulations (Section 2.1) and our intrinsic shape measurement method (Section 2.2). We present our main findings in Section 3, then discuss those results in Section 4. In particular, a comparison of this study to previous theoretical works can be found in Section 4.1, while a discussion of the origin of stellar halos in the FIRE dwarfs and the context of non-disky dwarfs is found in Section 4.2 and Section 4.3, respectively.

2. METHODS

Here we give a brief overview of the FIRE simulation
suite and the sample of FIRE galaxies included in this
work. We then detail the method used to compute the
intrinsic shape of the simulations.

2.1. The FIRE Simulations

Due to the low masses and small sizes of dwarf galaxies,
studying their detailed structure requires high resolution simulations. Moreover, their shallow potential wells make the structure of dwarf galaxies relatively more sensitive to the details of the implementation of

\(^1\)http://fire.northwestern.edu
Figure 1. A schematic diagram to illustrate movement in the $B/A$ vs. $C/A$ plane. The red, green, and blue points show the position of an archetypal spheroid, prolate ellipsoid, and disk, respectively. The axis ratios are $(B/A,C/A) = (0.9,0.9)$, $(0.1,0.1)$, and $(0.9, 0.1)$ for the three cases. The observed 1σ distribution of the dwarf sample in Kado-Fong et al. (2020) as measured at $1R_{\text{eff}}$ and $4R_{\text{eff}}$ are shown by blue and red ellipses, respectively. At right, we show a three-dimensional representation of the ellipsoid that corresponds to each case in the corresponding color. We additionally show the principal axes A, B, and C as grey, gold, and magenta lines in each panel.

Feedback from star formation, such as stellar winds and supernovae, than the structure of more massive galaxies. Thus, while realistic feedback prescriptions are crucial to understanding the structural properties of low mass galaxies, such galaxies are also among the most sensitive tests of these same feedback prescriptions (e.g. Brooks & Zolotov 2014; Hu et al. 2016; Wheeler et al. 2017; Hu 2019; Wheeler et al. 2019; Dashyan & Dubois 2020; Smith et al. 2020). Furthermore, cosmological simulations are necessary to properly capture the significant effect of reionization on these small galaxies (e.g. Bovill & Ricotti 2009; Boylan-Kolchin et al. 2015; Weisz & Boylan-Kolchin 2017; Fitts et al. 2017; Graus et al. 2019a). Cosmological simulations also supply the variety of environments (e.g. Garrison-Kimmel et al. 2019; Jahn et al. 2019) and assembly histories (e.g. Fitts et al. 2017) needed to study the dwarf population, especially given the relatively large impact that interactions even with purely dark subhalos can have on the star formation histories of dwarfs (Starkenburg et al. 2016).

We use simulations from the FIRE project, specifically the suite of cosmological-baryonic zoom-in simulations run with the FIRE-2 version of the code (Hopkins et al. 2018) along with some variations described below. All simulations use the Meshless-Finite-Mass (hereafter MFM) mode of the GIZMO\(^2\) gravity+magnetohydrodynamic code (Hopkins 2015), which automatically provides adaptive spatial resolution, conservation of mass, energy, and momentum, and excellent shock-capturing and conservation of angular momentum, reproducing advantages of both smoothed-particle hydrodynamics (SPH) and Eulerian adaptive mesh refinement (AMR) schemes. Gravity is solved

\(^2\)http://www.tapir.caltech.edu/~phopkins/Site/GIZMO.html
Figure 2. The surface density of young stars (left column, star particles with ages less than 2 Gyr), old stars (middle column, star particles with ages greater than 12 Gyr), and HI (right column) for an example dwarf with a disk-halo structure, m11h (MHD+). The rows show the projection along the y-axis, x-axis, and z-axis, such that the z-axis is aligned with the disk minor axis.
Figure 3. The intrinsic shape of the young and old stellar populations for the three subsets of the sample we consider in this work. In each panel, the green filled circles show the intrinsic shape of the young (ages less than 2 Gyr) stellar population and the orange squares show the intrinsic shape of the old stellar population (ages older than 12 Gyr). Lines connect the measurements for each individual galaxy. The blue and red ellipses show the observed 1σ distribution of the dwarf sample of Kado-Fong et al. (2020) at 1R_{eff} and 4R_{eff}, respectively. At left a comparison sample of high-mass (M_* > 10^{10} M_\odot) galaxies is shown; these galaxies host a clear disk-halo transition between their young and old stellar populations, where the youngest stars are assembled in a thin disk and the oldest populate a spheroidal stellar halo. The center panel shows the sample of dwarf galaxies that host a disk halo system; the disks in these dwarfs are thicker (higher C/A) than those of the higher mass galaxies, while the old stellar components are less round (lower C/A). Finally, at right, we show the non-disky dwarfs in the sample, which are characterized by the lack of a young stellar disk, as well as the lack of a monotonic increase in C/A and the presence as a significant change in B/A function of age.

We use simulations run with three different variations of the FIRE physics engine, denoted in the “Run Type” column of Table 1 as (Hydro+, no MD), (Hydro+, MD), (MHD+), and (CR+) to explore the sensitivity of our conclusions to small changes in the baryonic physics implemented in the simulations. Runs marked (Hydro+, no MD) and (Hydro+, MD) use the core FIRE physics described in full in Hopkins et al. (2018) with and without metal diffusion (MD). Runs marked (Hydro+, MD) in Table 1 use the physics described above, but also include the numerical implementation of turbulent metal diffusion described in Escala et al. (2018). We do not expect the metal diffusion to affect the properties included in this work, and so both (Hydro+) designations may be treated interchangeably in this work – we propagate the presence of metal diffusion in the naming scheme for completeness. In brief, radiative heating and cooling is treated from 10 – 10^{10} K, including free, photo-ionization/recombination, Compton, photoelectric & dust collisional, cosmic ray, molecular, and metal-line & fine-structure processes (following each of 11 tracked species independently), and accounting for photo-heating both by a UV background (Faucher-Giguère et al. 2009) and local sources, as well as self-shielding. In the UV background model used for the present simulations, reionization occurs at z ~ 10, significantly earlier than current empirical constraints (see, e.g. Planck Collaboration et al. 2020). Star forma-
tion occurs only in gas identified as self-gravitating according to the Hopkins et al. (2013) criterion, which is also molecular and self-shielding (following Krumholz \\
Gnedin 2011), Jeans unstable, and exceeds a minimum density threshold \( n_{\text{min}} = 1000 \text{ cm}^{-3} \). Once a star particle forms, the simulations explicitly follow several different stellar feedback mechanisms, including (1) local and long-range momentum flux from radiation pressure (in the initial UV/optical single-scattering, and re-radiated light in the IR), (2) energy, momentum, mass and metal injection from SNe (Types Ia and II) and stellar mass loss (both OB and AGB), and (3) photo-ionization and photo-electric heating. Every star particle is treated as a single stellar population with known mass, age, and metallicity from which all feedback event rates, luminosities, energies, mass-loss rates, and other relevant quantities are tabulated directly from stellar evolution models (starburst99; Leitherer et al. 1999), assuming a Kroupa (2001) IMF.

Runs marked (MHD+) again use the same physics as the (Hydro+) runs but solve the equations of ideal magneto-hydrodynamics (MHD) as described and tested in Hopkins \\
Raives (2016) and Hopkins (2016), with anisotropic Spitzer-Braginskii conduction and viscosity as described in Hopkins (2017), Su et al. (2017), and Hopkins et al. (2020). Runs marked (CR+) include all of the physics implemented in the (MHD+) runs, with the addition of the magnetohydrodynamic treatment of cosmic rays described in Chan et al. (2019), Hopkins et al. (2020), and Ji et al. (2020).

These simulations are uniquely well-suited to study the connection between the formation of dwarf galaxies and their structure. The combination of physics implementations in the (Hydro+) runs have already been shown to reproduce the mass-size relation of observed galaxies across \( \gtrsim 5 \) orders of magnitude in stellar mass (El-Badry et al. 2016; Chan et al. 2018; Hopkins et al. 2018). The sample includes a large range of different assembly histories (9 in total for the dwarf sample) that give rise to a wide variety of present-day galaxy morphologies, from thin disks to UDG-like (El-Badry et al. 2018c). We note that in the FIRE simulations, the resolved ISM produces star formation histories that are generically bursty for dwarf galaxies (e.g. Sparre et al. 2017; Faucher-Giguère 2018; Flores Velázquez et al. 2021), an effect which can be suppressed in lower-resolution simulations that use simplified ISM prescriptions. The mass of the individual star particles is sufficiently small to support the assumption that each represents a single-age, single-metallicity stellar population while still being large enough to fully sample the IMF at the high-mass end (Sanderson et al. 2020). The inclusion of turbulent metal diffusion additionally reproduces the observed dependence of the width of abundance spreads on stellar mass in dwarfs (Kirby et al. 2013; Escala et al. 2018). Comparing runs with additional physics to the (Hydro+) runs for identical initial conditions allows us to both confirm that these variations do not strongly influence the structure of dwarfs, and set a bound on the degree of scatter due to stochastic supernova feedback for a fixed assembly history.

### 2.2. Intrinsic Shape Measurements

We parameterize the three dimensional shapes of the sample using the ratio of the semi-principal axis diameters A, B, and C where \( A \geq B \geq C \). The ratios of these axes, B/A and C/A, give a quantitative description of the intrinsic shape of each galaxy; in Figure 1, we show three extreme cases in both B/A vs. C/A space at left and as wireframe renderings at right. In particular, we show a prolate galaxy in green (\( C/A \sim B/A \ll 1 \)), a disky galaxy in blue (\( C/A \ll B/A \sim 1 \)), and a spheroidal galaxy in red (\( C/A \sim B/A \sim 1 \)). For context, we also show the 1σ contours of the observed dwarfs sample of Kado-Fong et al. (2020) in blue (measurements at \( R_{\text{eff}} \)) and red (measurements at \( 4R_{\text{eff}} \)).

Making structural measurements for age-separated stellar components of low-mass halos requires simulations of sufficiently high resolution. Even at the mass resolution of the FIRE simulations studied in this work, we use cumulative (i.e. the shape of the stars within a given radius), rather than differential (the shape of the stars at a given radius), intrinsic shape measurements in order to overcome instability due to low stellar densities in the outskirts of the dwarfs, though we note that the total density remains well-resolved. This is a qualitatively different approach than what is used in integrated light measurements of intrinsic shape, where the galaxy intrinsic shape distribution is inferred at fixed radius (Padilla \\
Strauss 2008; van der Wel et al. 2014; Kado-Fong et al. 2020). The need for a cumulative measure of the intrinsic shape will also lead us to measure intrinsic shapes as a function of stellar age instead of galactocentric radius, comparing in particular the young (ages \( < 2 \) Gyr) and old (ages \( > 12 \) Gyr) stellar populations (see Section 3.1). Based on observations of nearby dwarfs, this age separation is expected to correlate with the observational differential shapes (see, e.g. Zaritsky et al. 2000; Aparicio \\
Tikhonov 2000; Aparicio et al. 2000; Hidalgo et al. 2003; Demers et al. 2006; Bernard et al. 2007; Stinson et al. 2009; Strader et al. 2012; Nidever et al. 2019b,a; Pucha et al. 2019). However, we note that the age-separated populations that we use in this work are not the exact equivalent to the radially-separated
## Table 1. Basic Properties of the FIRE-2 Galaxies Included in this Work

<table>
<thead>
<tr>
<th>Run Name</th>
<th>$M_{\text{vir}}$</th>
<th>$R_{\text{vir}}$</th>
<th>$M_{*,90}$</th>
<th>$R_{50,*}$</th>
<th>Morphology</th>
<th>Baryonic particle mass</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>m11a (Hydro+, no MD)</td>
<td>0.39</td>
<td>0.89</td>
<td>0.11</td>
<td>2.79</td>
<td>non-disky</td>
<td>2.1</td>
<td>(1)</td>
</tr>
<tr>
<td>m11a (CR+)</td>
<td>0.39</td>
<td>0.89</td>
<td>0.05</td>
<td>1.27</td>
<td>non-disky</td>
<td>2.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11b (CR+)</td>
<td>0.40</td>
<td>0.90</td>
<td>0.09</td>
<td>2.29</td>
<td>disky</td>
<td>2.1</td>
<td>(1)</td>
</tr>
<tr>
<td>m11b (MHD+)</td>
<td>0.40</td>
<td>0.90</td>
<td>0.07</td>
<td>2.29</td>
<td>disky</td>
<td>2.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11b (Hydro+, no MD)</td>
<td>0.40</td>
<td>0.90</td>
<td>0.11</td>
<td>2.54</td>
<td>disky</td>
<td>2.1</td>
<td>(1)</td>
</tr>
<tr>
<td>m11b (Hydro+, no MD)</td>
<td>0.40</td>
<td>0.90</td>
<td>0.07</td>
<td>2.29</td>
<td>disky</td>
<td>2.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11c (CR+)</td>
<td>1.37</td>
<td>1.35</td>
<td>0.78</td>
<td>2.79</td>
<td>non-disky</td>
<td>2.1</td>
<td>(2)</td>
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<tr>
<td>m11c (MHD+)</td>
<td>1.41</td>
<td>1.36</td>
<td>1.16</td>
<td>3.21</td>
<td>non-disky</td>
<td>2.1</td>
<td>(4)</td>
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<td>1.37</td>
<td>1.35</td>
<td>0.84</td>
<td>3.00</td>
<td>non-disky</td>
<td>2.1</td>
<td>(4)</td>
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<td>m11d (CR+)</td>
<td>2.71</td>
<td>1.70</td>
<td>1.55</td>
<td>4.12</td>
<td>non-disky</td>
<td>7</td>
<td>(2)</td>
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<tr>
<td>m11d (MHD+)</td>
<td>2.75</td>
<td>1.71</td>
<td>5.03</td>
<td>5.71</td>
<td>non-disky</td>
<td>7</td>
<td>(2)</td>
</tr>
<tr>
<td>m11d (Hydro+, MD)</td>
<td>2.72</td>
<td>1.70</td>
<td>4.06</td>
<td>6.97</td>
<td>non-disky</td>
<td>7.1</td>
<td>(2)</td>
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<tr>
<td>m11e (Hydro+, MD)</td>
<td>1.43</td>
<td>1.38</td>
<td>1.46</td>
<td>3.84</td>
<td>non-disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11e (CR+)</td>
<td>1.40</td>
<td>1.36</td>
<td>0.65</td>
<td>3.28</td>
<td>non-disky</td>
<td>7.1</td>
<td>(4)</td>
</tr>
<tr>
<td>m11e (MHD+)</td>
<td>1.45</td>
<td>1.38</td>
<td>1.25</td>
<td>4.55</td>
<td>non-disky</td>
<td>7.1</td>
<td>(4)</td>
</tr>
<tr>
<td>m11h (CR+)</td>
<td>1.76</td>
<td>1.47</td>
<td>2.87</td>
<td>3.60</td>
<td>disky</td>
<td>7</td>
<td>(5)</td>
</tr>
<tr>
<td>m11h (MHD+)</td>
<td>1.81</td>
<td>1.49</td>
<td>4.44</td>
<td>3.46</td>
<td>disky</td>
<td>7</td>
<td>(2)</td>
</tr>
<tr>
<td>m11h (Hydro+, MD)</td>
<td>1.80</td>
<td>1.48</td>
<td>3.62</td>
<td>4.13</td>
<td>disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11i (Hydro+, MD)</td>
<td>0.69</td>
<td>1.08</td>
<td>0.93</td>
<td>3.79</td>
<td>non-disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11i (CR+)</td>
<td>0.63</td>
<td>1.05</td>
<td>0.22</td>
<td>2.88</td>
<td>non-disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11i (MHD+)</td>
<td>0.68</td>
<td>1.07</td>
<td>0.58</td>
<td>3.68</td>
<td>disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11l (MHD+)</td>
<td>1.45</td>
<td>1.38</td>
<td>1.87</td>
<td>3.04</td>
<td>non-disky</td>
<td>7</td>
<td>(2)</td>
</tr>
<tr>
<td>m11l (Hydro+, MD)</td>
<td>1.41</td>
<td>1.36</td>
<td>0.63</td>
<td>2.62</td>
<td>non-disky</td>
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<td>(2)</td>
</tr>
<tr>
<td>m11v (CR+)</td>
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<td>1.74</td>
<td>2.59</td>
<td>8.27</td>
<td>non-disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11v (MHD+)</td>
<td>2.20</td>
<td>1.58</td>
<td>2.51</td>
<td>3.52</td>
<td>disky</td>
<td>7.1</td>
<td>(2)</td>
</tr>
<tr>
<td>m11f (CR+)</td>
<td>4.30</td>
<td>1.98</td>
<td>12.02</td>
<td>3.56</td>
<td>non-dwarf</td>
<td>12</td>
<td>(2)</td>
</tr>
<tr>
<td>m11f (MHD+)</td>
<td>4.75</td>
<td>2.04</td>
<td>31.74</td>
<td>2.57</td>
<td>non-dwarf</td>
<td>12</td>
<td>(2)</td>
</tr>
<tr>
<td>m11g (CR+)</td>
<td>5.35</td>
<td>2.13</td>
<td>11.00</td>
<td>4.80</td>
<td>non-dwarf</td>
<td>12</td>
<td>(3)</td>
</tr>
<tr>
<td>m11g (MHD+)</td>
<td>6.05</td>
<td>2.21</td>
<td>49.02</td>
<td>2.78</td>
<td>non-dwarf</td>
<td>12</td>
<td>(2)</td>
</tr>
<tr>
<td>m12l (Hydro+, no MD)</td>
<td>10.46</td>
<td>2.66</td>
<td>70.60</td>
<td>2.89</td>
<td>non-dwarf</td>
<td>7.1</td>
<td>(2)</td>
</tr>
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</table>

Note—Virial mass ($M_{\text{vir}}$) is measured within the Bryan & Norman (1998) virial radius of the halo at $z = 0$. $M_{*,90}$ and $R_{*,50}$ are the stellar mass and radius enclosing 90% and 50% of the stellar mass within 30 kpc of the galaxy center, respectively. “Baryonic particle mass” denotes the initial mass of gas & star particles in the simulation. “Hydro+” indicates runs with the core physics suite with and without metal diffusion (“MD”), while “MHD+” indicates runs that also include treatment for magnetic fields and fully anisotropic conduction and viscosity. “CR+” indicates runs that also include treatment of cosmic rays in addition to the physics described by MHD+. Morphological classifications are discussed in Section 3.1. References: (1) Chan et al. 2018, (2) Hopkins et al. 2020, (3) Hopkins et al. 2018, (4) El-Badry et al. 2018c, (5) Wetzel et al. 2016.
stellar populations of Kado-Fong et al. (2020). The simulated and observed measurements also differ in that the observed measurements of the galaxy projected shapes are used to infer the intrinsic shape distribution of the galaxy population (whereas the simulated values are direct intrinsic shape measurements of individual galaxies), and that the simulated measurements are mass-weighted in bins of stellar age (whereas the observed measurements are light-weighted at fixed radii). Thus, the emphasis of this work will be on the change in galaxy properties, rather than a direct quantitative comparison between the observed and simulated measurements.

As mentioned above, unlike in observations, in simulations we are able to directly measure the intrinsic shape of the galaxies in our sample. To do so, we compute the reduced moment of inertia tensor $\mathbf{I}$ from the set of star particles at distances less than $R_{\text{max}} = 50$ kpc for the simulated galaxies with $M_{\text{halo}} \sim 10^{11} M_\odot$ and $R_{\text{max}} = 70$ kpc for the galaxy with $M_{\text{halo}} \sim 10^{12} M_\odot$. The reduced moment of inertia tensor $\mathbf{I}$ is given by

$$
\mathbf{I} = \begin{bmatrix}
I_{xx} & I_{xy} & I_{xz} \\
I_{yx} & I_{yy} & I_{yz} \\
I_{zx} & I_{zy} & I_{zz}
\end{bmatrix}
$$

where each element is computed from the star particles (of mass $m_k$) as

$$
I_{ij} = \sum_{r_k < R_{\text{max}}} m_k(r_k^2 \delta_{ij} - q_k^i q_k^j),
$$

for $i, j \in (x, y, z)$ and where $r_k = (q_k^x, q_k^y, q_k^z)$ is the distance from the principal halo center. $\delta_{ij}$ is the Kronecker delta. The eigenvalues $\lambda_1$, $\lambda_2$ and $\lambda_3$ of this matrix are the inverse squares of the semi-principal axis diameters $A$, $B$, and $C$ of the Poinsot ellipsoid that corresponds to the moment of inertia tensor:

$$
\frac{B}{A} = \sqrt{\frac{\lambda_1}{\lambda_2}}, \quad \frac{C}{A} = \sqrt{\frac{\lambda_1}{\lambda_3}}.
$$

This method is, in principle, sensitive to the choice of $R_{\text{max}}$ and emphasizes the contribution of particles at large $r$ (see Equation 2). We test the effect of our choice of intrinsic shape measurement method as follows. First, though we choose a larger $R_{\text{max}}$ for the higher mass halo, we would derive the same shape parameters $B/A$ and $C/A$ to within $\Delta(B/A) \sim \Delta(C/A) \sim 0.01$ at $R_{\text{max}} = 50$ kpc. Furthermore, although we adopt a fixed value of $R_{\text{max}} = 50$ kpc for the dwarf galaxies considered in this work, we find that varying $R_{\text{max}}$ does not qualitatively affect our results down to $R_{\text{max}} \sim 10$ kpc. Finally, we fit two dimensional Sérsic profiles to projections of each galaxy along its principal axes, and find no evidence for a systematic offset between the Sérsic fits and moment of inertia-derived axis ratios. Thus, although the moment of inertia method potentially overemphasizes star particles at large distances, we find that our results are not impacted by this bias in practice.

Observational works indicate that dwarfs in this mass range should host a central thick disk (see, e.g. van der Wel et al. 2014) with a round extended stellar component (Kado-Fong et al. 2020) that is populated by intermediate/old stars (see Stinson et al. 2009, and citations therein). If a disk-halo system is indeed present in the FIRE dwarfs, we should be able to detect the same transition from disk to halo when computing the intrinsic shape in bins of stellar age – we demonstrate that this transition is indeed detectable in mock HSC data in Section 3.2. We visualize an example of such a divide in Figure 2, which shows the projected density of the dwarf galaxy m11h-mhdcv in young stars (left column, blue) old stars (middle column, red) and neutral hydrogen (right column).

3. RESULTS

3.1. The Intrinsic Shapes of the FIRE Dwarf Galaxies

We present the main results of this section in Figure 3. In each panel, we show the intrinsic axis ratios of the simulated galaxies, B/A and C/A, where C ≤ B ≤ A. At left, for reference, we show the well-defined stellar disk and halo systems of the high-mass ($M_\odot > 10^{10} M_\odot$) reference sample (m11f, m11g, and m12i, see Table 1). The intrinsic shapes of young star particles (youngest 25th percentile) and old star particles (oldest 25th percentile) are shown in blue and red, respectively. In this panel, the young stars clearly are assembled in a well-formed disk (C < B ∼ A), and the old stars occupy a round stellar halo (A ∼ B ∼ C). Similarly, in the middle panel, we show the dwarf galaxies in our sample that have a clear disk-halo system. These galaxies are characterized by substantial increases in C/A as a function of age along with relatively little evolution in B/A compared to C/A over the same comparison, and were categorized by visual inspection of the galaxies’ stellar components. Although the oldest (ages greater than 12 Gyr) stars may not dominate the light in the outskirts of the FIRE-2 dwarfs, we see the same trend towards a more spheroidal shape when comparing the young (ages less than 2 Gyr) and intermediate (ages between 2 and 12 Gyr) star particles.
We note that the young stellar disks in these dwarfs tend to be thicker (higher $C/A$) than the disks in the higher mass galaxies – this phenomenon is in good agreement with previous observational findings (Padilla & Strauss 2008; Sánchez-Janssen et al. 2010; Kado-Fong et al. 2020). Both the high-mass and dwarf disks are largely axisymmetric, maintaining a $B/A \sim 1$ in both their young and old stellar populations. Though the old stellar population is significantly rounder than the young stellar disks of these dwarfs, the dwarf stellar halos are not as round (meaning $C/A$ approaching unity) as those of the old stellar population in the high-mass comparison sample. This is again consistent with the observations of Kado-Fong et al. (2020), who find that dwarfs have an average minor-to-major axis ratio $\langle C/A \rangle \sim 0.5$ at $4R_{\text{eff}}$, significantly flatter than the outer stellar halo of the Milky Way ($C/A \gtrsim 0.8$, Das & Binney 2016; Iorio et al. 2018). This may be due to a difference in the formation mechanism of dwarf stellar halos and massive galaxy stellar halos, which we will explore in later sections.

The evolution of $C/A$ as a function of age is also markedly different between the disky dwarfs and high-mass reference sample. In Figure 4, we show the change in $C/A$ from the minimum $C/A$ for each disky dwarf (purple) and high-mass galaxy (grey). Because $C/A$ increases monotonically as a function of age for both these groups, this is equivalent to showing the change in $C/A$ from the $C/A$ of the youngest ($t < 2$ Gyr) star particles. The $x-z$ projections as a function of age for one such disky dwarf (top) and one high-mass galaxy (bottom) are shown at right. The figure serves to illustrate two main points: first, the overall change in $C/A$ is systematically smaller for the disky dwarf sample. Second, the high-mass galaxies approach their maximum $C/A$ values more rapidly as a function of age, with a sharp increase in $C/A$ at $5 \lesssim t_{\text{age}} \lesssim 8$ Gyr and relatively little change beyond that. This can also be seen qualitatively in the stark change in shape between the $[4,6]$ Gyr and $[6,8]$ Gyr surface densities of the high-mass galaxy. The dwarf galaxies, meanwhile, increase in $C/A$ gradually as a function of age.

Finally, in the right panel of Figure 3, we show the intrinsic shapes of the non-disky dwarfs in our sample. Although we refer to these galaxies as “non-disky” dwarfs, this morphological class refers to galaxies that lack a young stellar disk and do not show a monotonic increase in $C/A$ as a function of stellar age. These dwarfs do not have a well-defined disk-halo structure, and appear to be significantly different in intrinsic shape to the population of observed galaxies from Kado-Fong et al. (2020)\(^3\). The lack of a well-defined disk in particular may point to an overly vigorous or bursty star formation history, preventing the formation of a rotationally supported disk at low redshift. El-Badry et al. (2018b) found in particular that the ability of FIRE galaxies to form a gaseous disk and maintain a fairly quiescent (less bursty) star formation history is linked to the accretion of high angular momentum gas at low redshifts, wherein low-mass FIRE galaxies struggle to build up stores of this high angular momentum gas due to both efficient gas removal via star formation feedback and inefficient cooling of high angular gas in the circumgalactic medium.

While the star formation feedback and/or cooling prescription may lead to a lack of a disk-halo structure in some dwarfs, those same prescriptions are capable of creating dwarf stellar disk-halo systems that are remarkably similar in structure to the observed population. Thus, in this work we will examine the two facets of the sample separately, examining first the dwarf stellar halo (in the simulated galaxies that do form disks) and then the origin of the non-disky dwarfs.

As a final note, we find that there is no change in the morphological classification of the galaxy as a func-

\(^3\) We quantify the possibility of an existent but minority non-disky dwarf population in the observations of Kado-Fong et al. (2020) in Appendix A and discuss this idea further in Section 4.3.

### Table 2. Mean Intrinsic Shape Ratios of the FIRE-2 Dwarf Sample

<table>
<thead>
<tr>
<th></th>
<th>$\langle C/A \rangle_{\text{young}}$</th>
<th>$\langle C/A \rangle_{\text{old}}$</th>
<th>$\langle N \rangle_{\text{young}}$</th>
<th>$\langle N \rangle_{\text{old}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-dwarfs</td>
<td>0.95 ± 0.02</td>
<td>0.69 ± 0.04</td>
<td>9.6 × 10^5</td>
<td>9.2 × 10^5</td>
</tr>
<tr>
<td>Disky Dwarfs</td>
<td>0.82 ± 0.03</td>
<td>0.50 ± 0.04</td>
<td>6.3 × 10^4</td>
<td>8.6 × 10^4</td>
</tr>
<tr>
<td>Non-Disky Dwarfs</td>
<td>0.55 ± 0.05</td>
<td>0.42 ± 0.02</td>
<td>9.9 × 10^4</td>
<td>9.6 × 10^4</td>
</tr>
</tbody>
</table>

Note—Mean intrinsic shape measurements (denoted by $\langle \rangle$) and the associated error on the mean for the sample considered in this work, divided by morphology. $(N)$ refers to the number of star particles used in the shape computation for the old (ages greater than 12 Gyr) and young (ages less than 2 Gyr) stellar populations.
tion of the physics implementation for the majority of the dwarfs in the sample. That is, it appears that the $z = 0$ stellar intrinsic structure is largely unaffected by the additional physics implemented in the (MHD+) and (CR+) runs as described in Section 2.1. However, we do find that two galaxies, m11i and m11v, are disky in their (MHD+) runs and non-disky in their (CR+) or (Hydro+) runs. A further investigation of the physical origin of the morphological difference for these two galaxies is of interest, but beyond the scope of this work.

3.2. The Origin of Dwarf Halo Stars

In Figure 5, we show for a selection of galaxies the maximum distance of the star particles from the host halo center since $z \sim 6.2$ as a function of the present-day distance. This figure acts to visualize the contributions to the young (top, blue) and old (bottom, red) stellar populations by in-situ and ex-situ components: in-situ star particles flare out from the 1:1 line, while accreted star particles occupy horizontal bands that correspond to the maximum distance of the progenitor system over the time considered. We have chosen to show two dwarf galaxies that host a disk-halo system (m11b-mhdcv and m11h-mhdcv), along with one dwarf that does not host a disk (m11c-res2100) and a Milky Way-mass galaxy (m12i,7100) as a set of examples that span the range of masses and morphologies of the sample.

As expected, the young stellar populations in all the galaxies shown in Figure 5 are dominated by in-situ contributions. However, the difference in how the dwarfs and the MW-mass galaxy have assembled their old stellar populations is apparent. Whereas the old star particles in the dwarfs (and therefore their stellar halos) are dominated by in-situ star particles, the old stellar population in the MW-mass galaxy is completely dominated by accreted star particles. We find no significant difference between the accreted halo fraction of the non-disk dwarf dwarfs and disky dwarfs, though the sample size is too small to straightforwardly extrapolate this behavior to the general dwarf population.

The diagnosis of halo star particle origin that we use in this work is not meant to produce exact ex-situ fractions, but is instead aimed to identify bulk changes in halo formation mechanism. We test our $\Delta R > 15$ kpc threshold against a cut in formation distance, which has been used in prior work with the FIRE simulations to track ex-situ contributions (Sanderson et al. 2018) and has been showed to produce accreted fractions in agreement with subhalo tracking from merger trees for MW-like galaxies in FIRE-2 (Necib et al. 2019). We compare these two ex-situ flagging methods for the disky dwarf m11h (Hydro+, MD) and the high mass galaxy m12i (Hydro+, no MD), and find that our $\Delta R$ cut produces accreted fractions consistent to within 10% of those based on a cut on formation distance. We also consider the effect that our choice of a threshold cut at $\Delta R = 15$ kpc plays on our estimated ex-situ fractions, and find that a cut of $\Delta R = 30$ kpc changes the estimated ex-situ fractions by no more than 12%, and does not affect the trend with stellar mass shown in Figure 5. We also find that this trend holds when we consider all stars in the outskirts, regardless of age ($R(z=0) > 0.1R_{\text{vir}}$, open points in Figure 5). Indeed, the divergent behavior seen in Figure 5 between the dwarf and massive galaxy stellar halos is consistent with the supposition that the stellar halos of massive galaxies are dominated by ex-situ stars, while the dwarf stellar halos are largely in-situ structures.

The thick and in-situ nature of the dwarf stellar outskirts in FIRE-2 also draws a clear structural similarity to the thick disks in more massive galaxies. Though the origin, existence, and nature of thick disks in the Milky Way and beyond is still a matter of significant debate (see, e.g. Yoachim & Dalcanton 2006; Bovy et al. 2012; Belokurov et al. 2020; Agertz et al. 2021; Park et al. 2021), it is straightforward to make an internal comparison between the dwarf stellar outskirts and massive thick disks within the context of the FIRE-2 simulations. It has been demonstrated that the thickened shape of the thick disks in the more massive FIRE-2 galaxies is due to an inherently broader configuration of star formation during a bursty phase of star formation at lookback times of $t_{\text{bf}} \gtrsim 5$ Gyr (Yu et al. 2021). It is thus of interest to examine whether the shape of the FIRE-2 dwarf stellar populations are set by stellar migration or by a change in the star formation configuration as a function of cosmic time. To address this, we show in Figure 6 the evolution of vertical scale height (as derived from an exponential fit to the stellar surface density along the $z$-axis) between the current time and the formation time for the star particles in a disky dwarf galaxy (m11h) and a massive galaxy (m12i) as a function of star particle age.

We first consider the massive FIRE-2 galaxy; Figure 6 demonstrates that the star particles in this galaxy show a negligible change in vertical scale height between $z = z_{\text{form}}$ and $z = 0$. We exclude star particles with ages greater than 10 Gyr for the massive galaxy in this figure, as these stars are expected to be dominated by ex-situ stars (see Figure 5) and the majority of the massive FIRE-2 thick disks are assembled at times more recent than 10 Gyr (Yu et al. 2021). This lack of scale height evolution is consistent with the results of Yu et al. (2021), who find that the thick disks in these massive galaxies are formed as thick disks from birth, rather than
Figure 4. *At left:* the change in minor-to-major intrinsic axis ratio C/A as a function of stellar age, in bins of 2 Gyr. We show the change in C/A over the minimum C/A across all age bins (because of the monotonic increase in C/A as a function of age for these galaxies, this is equivalent to the change in C/A over the youngest age bin). Dwarf disks are shown in purple, while high-mass disks are shown in grey. Not only are the old stellar populations of the dwarf disks less spheroidal than their high-mass counterparts, d(C/A)/d(age) is markedly smaller in the dwarfs than the high-mass galaxies. *At right:* the stellar surface density of an example dwarf (top two rows) and massive galaxy (bottom two rows) in bins of 2 Gyr. As at left, while the dwarf stellar population thickens gradually with increasing age, there is a sharp transition between the thin disk and round stellar halo in the more massive galaxy – this contrast is consistent with the differing origin of the dwarf and massive stellar outskirts, wherein dwarf stellar halos are produced via in-situ migration of star particles rather than the accretion of satellites.

3.3. The Observability of the FIRE-2 Dwarf Stellar Halos

As discussed in Section 2.2, the way in which we measure the intrinsic shape of the FIRE-2 dwarfs is significantly different than the measurement methods applied to observations in Kado-Fong et al. (2020). Thus, it is of interest to quantify the extent to which the stellar halos around the FIRE dwarfs would be observable in Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP), the imaging survey used by Kado-Fong et al. (2020). This test will help to understand the extent to which the FIRE-2 dwarf stellar halos and observed dwarf stellar outskirts track the same physical structure.

In order to quantify the observability of the FIRE-2 dwarf stellar halos, we generate mock observations of the sample in this work using the Flexible Population Synthesis (FSPS) package (Conroy et al. 2009; Conroy & Gunn 2010) to generate simple stellar populations over a grid of stellar ages (between $10^5$ and $10^{10}$ yr) and metallicities (in the range $-4 < \log_{10}(Z/Z_\odot) < 1$). We then compute the stellar mass-to-light ratio in the HSC i-band for each model spectrum. Each star particle in the simulated dwarfs is then assigned an HSC i-band mass-to-light ratio based on its age and metallicity via linear interpolation of the model grid; this process allows us to compute surface brightness and light-weighted age maps for each galaxy in our sample. Following Sandersson et al. (2018), we construct these maps via a simple binning of star particles with a box size of 0.25 kpc on a side.

We show these surface brightness and light-weighted age maps in Figure 7 for a set of galaxies that span the stellar masses and morphologies of the sample at
find that the FIRE-2 galaxies with stellar masses of 10^{8.5} \leq M_\star \leq 10^{9}\,M_\odot have a mean (standard deviation of) max R_{HSC,\,obs} of 3.6 (0.8) \, R_{\text{eff, HSC}}, and the galaxies with stellar masses of 10^{9} < M_\star < 10^{9.6}\,M_\odot have a mean (standard deviation of) max R_{HSC,\,obs} of 4.1 (1.7) \, R_{\text{eff, HSC}}. These values are consistent with the spatial limit of the HSC imaging for the dwarfs in Kado-Fong et al. (2020).

As shown in Figure 7, in the cases where a young stellar disk is formed (i.e. excluding the non-disky dwarfs due to the lack of an analogous population in the observations), the mock HSC observations extend beyond the young stellar disk into the rounder and older stellar outskirts. This finding supports our initial assertion in Section 2.2 that the age-separated intrinsic shape measurements in the simulated galaxies and the radially-separated intrinsic shapes inferred from the observed dwarf population are tracing the same physical structure.
Figure 6. For a massive (grey, $M_{\text{halo}} \sim 10^{12}M_\odot$) and dwarf (purple, $M_{\text{halo}} \sim 10^{11}M_\odot$) disk galaxy, we show the change in the exponential stellar scale height $h_z$ as a function of age. For the star particles with a given age, the solid curves show the current, $z = 0$ scale height of those star particles, while the dashed curves show the scale height of the same single-aged population at $z = z_{\text{form}}$. We exclude stars older than 10 Gyr, as in the massive galaxy they are likely to be dominated by ex-situ stars which should not be well-described by an exponential distribution at birth. Whereas the stars in the massive galaxy show a negligible change in vertical scale, the dwarf stars are consistently more extended at current times than they were at their formation time. This is consistent with the picture in which the dwarf stellar outskirts are populated by stars that have been heated to larger radii after their formation. In contrast, the massive galaxy FIRE-2 thick disks are formed due to an overall change in the configuration of star formation as a function of cosmic time (see Yu et al. 2021).

3.4. Properties of the Disky and Non-Disky Dwarfs

Though diagnosing, in detail, the formation path of non-disky dwarfs is not the main aim of this paper, it is informative to compare their global properties to those of the disky FIRE dwarfs and to observed dwarf galaxies.

It is known that the dwarfs in FIRE are, on average, somewhat lower in their HI gas fractions as compared to observed dwarfs (El-Badry et al. 2018a). Here we expand upon this trend to demonstrate that the gas content of the FIRE-2 dwarfs are also linked to their three dimensional structure. To do so, we compare the HI gas content of the FIRE simulations to that of the observed sample of Bradford et al. (2015). We compute the HI and stellar masses within 200 kpc of the galaxy center to derive the HI gas fractions of the FIRE-2 galaxies (though we note that a choice of 50 kpc from galaxy center would change the HI gas fractions by a few percent at most, and generally much less). Drawn from Sloan Digital Sky Survey (SDSS) spectroscopically confirmed targets with Arecibo Legacy Fast ALFA (ALFALFA) 21cm observations, this sample consists of isolated galaxies with stellar masses $10^7 \lesssim M_\star/M_\odot \lesssim 10^{11}$. We compare this isolated HI sample to the FIRE galaxies in Figure 8; the observed galaxies are shown in grey scatter, while the simulated galaxies are shown by the crosses (colored by morphology, as indicated). Notably, while the disky dwarfs lie on the main relation found by Bradford et al. (2015), the non-disky dwarfs are systematically more gas-poor at fixed stellar mass than the observed galaxies.

Next, we contrast the star formation histories (SFH) of the non-disky and disky dwarfs. In Figure 9, we show at left the fraction of stellar mass built in starbursts over the last 2 Gyr versus the galaxy’s stellar mass. We define a starburst as the snapshots for which

$$\frac{\langle \text{SFR} \rangle_{10\text{Myr}}}{\langle \text{SFR} \rangle_{1\text{Gyr}}} > 1.5.$$ (4)

We find that the FIRE dwarfs that succeed in forming disks are those that are either particularly gas rich (as seen in Figure 9; for easy comparison we outline the galaxies where the HI gas fraction exceed 0.7 with a dashed circle) or have particularly non-bursty recent star formation histories for their stellar mass. To visualize the difference in star formation histories, we show the SFH for a non-disky dwarf at top (green), and a disky dwarf with a low burst fraction at bottom (purple). Though both are highly bursty at high redshift, the disky dwarf becomes significantly less bursty at low redshift.

4. DISCUSSION

In the previous section, we showed that the FIRE dwarfs host stellar outskirts that are assembled from in-situ star particles, a distinctly different formation pathway than the stellar halos of more massive galaxies. Here, we place our results into the context of simulations of dwarf galaxies at large, and compare the simulated dwarf properties to those of observed dwarf galaxies.

4.1. Comparison to Other Simulations

As the FIRE simulation suite are a set of cosmological zooms, we will first contextualize our results via comparison to similar studies done on cosmological and non-cosmological simulations.

Because of the high resolution necessary to study the stellar outskirts of low-mass halos, there are relatively few cosmological simulations that make similar structural measurements on dwarf galaxies to which we can
Figure 7. Mock HSC-i band surface brightness maps (top row) and HSC-i light-weighted age maps (bottom row) for an example set of galaxies which span the mass and morphologies studied in this work. From left to right, we show: m11h (CR+), a disky dwarf at the high end of the dwarf stellar mass range ($M_\star < 3 \times 10^7 M_\odot$), m11b (MHD+), a disky dwarf at the low end of the dwarf stellar mass range ($M_\star < 7 \times 10^6 M_\odot$), m11c (Hydro+, no MD), a non-disky dwarf, and m11g (MHD+), a massive galaxy ($M_\star = 5 \times 10^{10} M_\odot$). The lime contour in each panel is an isophote at $\mu_i = 28.5$ mag arcsec$^{-2}$, the approximate surface brightness limit of the HSC-SSP i-band for galaxy outskirts. The values written in lime at the bottom of the top row of panels show the approximate maximum radius that HSC-SSP observations would be able to reach for each galaxy, as a function of the i-band effective radius of the galaxy (as determined by a single two-dimensional S\'ersic fit).

compare. Pillepich et al. (2019) use TNG50, the highest resolution volume of the IllustrisTNG simulations (Pillepich et al. 2018), to present mass-weighted intrinsic shape measurements made in an ellipsoidal aperture at twice the half-mass radius, 2$R_{1/2,\text{mass}}$, with a thickness of 0.4$R_{1/2,\text{mass}}$. TNG50 reaches a baryonic mass resolution of $8.5 \times 10^4 M_\odot$ and a DM mass resolution of $4.5 \times 10^5 M_\odot$ (about an order of magnitude lower resolution in both baryons and dark matter than the galaxies studied in this work) and a minimum gravitational force softening of 74 pc for the gas (compared to $\sim 2$ pc for the galaxies in this work). TNG50 contains approximately $\sim 5500$ dwarf galaxies with stellar masses in the range $10^8 < M_\star / M_\odot < 10^{10}$. The intrinsic shape of the dwarf galaxies in TNG50 is strong a dependence on stellar mass, with the $10^9 < M_\star / M_\odot < 10^{10}$ galaxies characterized by thick disks and the $10^8 < M_\star / M_\odot < 10^9$ dwarfs significantly more spheroidal. We see no such trend with mass in the FIRE simulation suite. It is of interest that the high-mass TNG50 dwarfs form thick disks, even in the old stellar population. This is in contrast to the FIRE dwarfs that succeed in forming thick disks; the FIRE stellar disks are dominated by young stars, while the old stellar populations that dominate the stellar mass budget maintain largely spheroidal shapes at all radii (for cumulative measurements). Observations indicate that high-mass dwarfs should generically host stellar disks, as they do in TNG50 (Kado-Fong et al. 2020), but also find morphological differences as a function of age in resolved star studies, as is seen in FIRE (Zaritsky et al. 2000; Aparicio & Tikhonov 2000; Aparicio et al. 2000; Hidalgo et al. 2003; Demers et al. 2006; Bernard et al. 2007; Stinson et al. 2009; Strader et al. 2012; Nidever et al. 2019b,a; Pucha et al. 2019).

It is also informative to compare to higher resolution, non-cosmological simulations of dwarf galaxies. In particular, Smith et al. (2020) examine the effect of photoionization and photoelectric heating from young stars on the efficacy of supernova feedback and the resultant impact on the SFH and disk structure. They find that the inclusion of photoionization significantly damps the burstiness of the simulated dwarf SFH, and that runs that include only SNe feedback result in superbubbles that significantly disrupt the gaseous disk. It is important to note that the galaxy studied in Smith et al. (2020) is initialized with both a stellar and gas disk, and is significantly lower in stellar mass ($M_\star \sim 10^7 M_\odot$) than the galaxies studied in this work; it is observationally uncertain whether galaxies in this mass range are generally disky (Kado-Fong et al. 2020; Carlsten et al. 2021). However, their finding that over-vigorous star formation feedback can disrupt the disk is in line with...
The HI gas fraction $M_{\text{HI}}/(M_\star + M_{\text{HI}})$ versus stellar mass for the simulated FIRE galaxies (marked as crosses) and the observed sample of (Bradford et al. 2015, light grey scatter). The FIRE galaxies are colored by morphology, as indicated. The FIRE-2 dwarfs tend to be overly HI-depleted compared to observed galaxies (see also El-Badry et al. 2018c), so the gas rich end of the FIRE dwarfs are the most consistent with observations. In particular, the galaxies that successfully form disks have HI gas fractions consistent with the observed relation, while the non-disky dwarfs are systematically gas depleted relative to the Bradford et al. (2015) sample.

our finding that it is the bursty and gas poor FIRE dwarfs that do not form young stellar disks.

Finally, it has been noted that dark matter particles may induce numerical heating in the stellar component of simulated galaxies. We do not expect this numerical heating to significantly affect our results – the resolution of the FIRE-2 dwarfs surpasses the dark matter particle mass limit estimated by Ludlow et al. (2021) at which numerical heating accounts for no more than 10% that of the virial velocity ($m_{\text{DM}} \lesssim 4.5 \times 10^4 M_\odot$; the maximum particle mass of the FIRE dwarfs is $m_{\text{DM}} = 3.8 \times 10^4 M_\odot$). Indeed, for the massive FIRE galaxy m12i, Ludlow et al. (2021) estimates that the change in scale height attributable to numerical heating is only 70 parsec, which is much smaller than the change in scale height observed in the FIRE dwarfs (see Figure 6).

4.2. A Divergent Path of Low-mass Stellar Halo Formation

Due to the steepening stellar-to-halo mass relation at low masses, it has long been thought unlikely for dwarf galaxies to assemble a significant stellar halo population via the accretion of satellite galaxies. Thus, the observed presence of extended old (Lin & Faber 1983; Minniti & Zijlstra 1996; Minniti et al. 1999; Zaritsky et al. 2000; Aparicio & Tikhonov 2000; Aparicio et al. 2000; Hidalgo et al. 2003; Demers et al. 2006; Bernard et al. 2007; Stinson et al. 2009; Strader et al. 2012; Nidever et al. 2019a,b; Pucha et al. 2019) and round (Kado-Fong et al. 2020) stellar outskirts around dwarf galaxies points to a different mode of stellar halo formation at low masses.

In this work, we have shown that the FIRE-2 dwarf galaxies are capable of producing an extended old and round stellar population in conjunction with a young stellar disk, and we find that the stellar outskirts of the FIRE dwarfs reproduce several key qualities of observed high-mass dwarf stellar halos.

First, in a marked contrast to the ex-situ stellar halos of massive galaxies, these dwarf stellar halo populations are dominated by in-situ stars that occupy an increasingly spheroidal component as a function of age. This behavior explains the apparent ubiquity of round stellar outskirts around high-mass dwarfs ($M_\star > 10^{8.5} M_\odot$), as feedback should be a generic process in all galaxies that proceeds regardless of accretion history or environment. The existence of an old, in-situ population in the outskirts of the FIRE dwarfs is not surprising, as it has been shown that the radial migration of stars due to baryon-driven potential fluctuations operates most strongly in FIRE dwarfs in this mass range (El-Badry et al. 2016; Graus et al. 2019b). This feedback-driven migration has previously been suggested as a formation mechanism for in-situ stellar halos (Stinson et al. 2009; Maxwell et al. 2012). Star formation feedback-driven size fluctuations have also recently been found via correlations between size and star formation rate in both the FIRE-2 dwarfs and a sample of nearby dwarfs from the Local Volume Legacy Survey (Emami et al. 2021).

Furthermore, the old stellar population of the FIRE dwarfs, though largely spheroidal compared to the young stellar disk populations, are significantly more flattened (a lower minor-to-major intrinsic axis ratio $C/A$) than are the halos of the higher mass FIRE galaxies. This is again due to their in-situ formation mechanism, wherein the disk gradually thickens into the halo as the stars age. These preferentially flatter dwarf stellar halos are in good agreement with observations of dwarf stellar outskirts, which find that dwarf stellar outskirts at 4 effective radii are preferentially flatter than the Milky Way at the same distance. Indeed, the mean $C/A$ of the young stellar population of disky dwarfs in FIRE ($\langle C/A \rangle = 0.21 \pm 0.03$, where $\langle \rangle$ denotes the sample mean, see Table 2) is similar to the maximum a posteriori estimate of the mean $C/A$ of the massive dwarf population inferred by Kado-Fong et al. (2020) ($\langle C/A \rangle = 0.30 \pm 0.01$ for dwarfs of stellar mass.
First, the production of non-disky dwarfs at $z = 0$ could stem from the implemented physics of the FIRE-2 simulations. That the non-disky dwarfs tend to be gas-poor with a bursty recent SFH (see Figure 9) suggests that the star formation feedback prescription in FIRE may be preventing the formation of both stellar and gaseous disks in these non-disky dwarfs (see also El-Badry et al. 2018b). It is also notable that observed high redshift dwarfs lack a well-defined disk; Zhang et al. (2019) found that high-$z$, high-mass dwarfs are characterized by triaxial prolate ellipsoids at high redshift ($z \gtrsim 1$) and transition to thick-disk structures at low-z (see also Ceverino et al. 2015, for a similar transition in simulated dwarfs). It is thus possible that the FIRE-2 dwarfs are failing to undergo this transition at the appropriate cosmic time. At the same time, the existence of the disky dwarfs, which also host in-situ stellar halos, indicates that it is possible to form disk-halo structures with this feedback prescription. Interestingly, El-Badry et al. (2018a) also showed that the low-mass FIRE galaxies tend to be overly dispersion-supported due to inefficient accretion of high angular momentum gas, with the same trend that rotation-supported gas disks occupy galaxies with less bursty recent star formation histories. This interplay between the gaseous structure, stellar structure, and recent star formation history of the FIRE dwarfs point to a link between the way in which star formation proceeds in these dwarfs and their ability to form a young stellar disk. Indeed, the idea that star formation feedback can significantly influence dwarf structure is well-established in regards to both the baryonic morphology (see, e.g. Governato et al. 2007; Smith et al. 2019, 2020) and in the dark matter halo (the core-cusp problem; see, e.g. Peñarrubia et al. 2012; Pontzen & Governato 2012). Indeed, as the most easily observable leg of this set, the stellar structure of galaxies in the dwarf mass regime could prove to be a powerful tool to constrain the feedback prescrip-

**Figure 9.** At left, the fraction of stellar mass built up in bursts (defined as time periods where $\langle \text{SFR}_{10\text{Myr}}\rangle / \langle \text{SFR}_{1\text{Gyr}} \rangle > 1.5$) versus stellar mass for the sample of FIRE dwarfs. The purple points show disky dwarfs, while the green points show the non-disky dwarfs, and the grey points show the non-dwarfs. The low-mass dwarfs that have HI gas fractions of greater than $0.7$ are shown with a dashed outline. We find that the dwarfs that are able to form a young stellar disk have either particularly quiescent (non-bursty) recent star formation histories, or are particularly gas rich relative to the other simulated galaxies. At right we show the star formation history for a non-disky dwarf (top, m11d) and a disky dwarf (bottom, m11h). In each panel we show the 10 Myr-averaged and Gyr-averaged star formation rates as the light and dark curves, respectively. We also show vertical lines at $t_{lb} = 2$ Gyr, the time period over which the burst mass fraction is computed.

$10^9 < M_*/M_\odot < 10^{9.6}$ and $\langle C/A \rangle = 0.32 \pm 0.02$ for dwarfs of stellar mass $10^{8.5} < M_*/M_\odot < 10^9$, see Table 1 of Kado-Fong et al. 2020). However, we stress that because of the differences in the intrinsic shape measurement method (differential versus cumulative) and the exact stellar populations being measured (i-band light-weighted versus age-separated), we are not emphasizing here the apparent agreement in the numerical value of $\langle C/A \rangle$ between the observed and simulated dwarfs. Rather, we point to the difference in $\langle C/A \rangle$ of the simulated (observed) dwarfs and simulated (observed) high-mass galaxies as the key observational constraint on the difference in the assembly mode of their stellar halos.

### 4.3. The Non-Disky Dwarfs

Although the FIRE simulations succeed in producing dwarfs with a disk-halo structure that well-reflects the observations, it must be noted that these disky dwarfs are not the dominant mode of dwarf stellar structure in the FIRE simulations. Indeed, most of the dwarfs in the sample have significantly lower values of B/A than observed dwarfs, and do not host a clear young stellar disk. To better understand this discrepancy, we suggest three possibilities below.

First, the production of non-disky dwarfs at $z = 0$ could stem from the implemented physics of the FIRE-2 simulations. That the non-disky dwarfs tend to be gas-poor with a bursty recent SFH (see Figure 9) suggests that the star formation feedback prescription in FIRE may be preventing the formation of both stellar and gaseous disks in these non-disky dwarfs (see also El-Badry et al. 2018b). It is also notable that observed high redshift dwarfs lack a well-defined disk; Zhang et al. (2019) found that high-$z$, high-mass dwarfs are characterized by triaxial prolate ellipsoids at high redshift ($z \gtrsim 1$) and transition to thick-disk structures at low-z (see also Ceverino et al. 2015, for a similar transition in simulated dwarfs). It is thus possible that the FIRE-2 dwarfs are failing to undergo this transition at the appropriate cosmic time. At the same time, the existence of the disky dwarfs, which also host in-situ stellar halos, indicates that it is possible to form disk-halo structures with this feedback prescription. Interestingly, El-Badry et al. (2018a) also showed that the low-mass FIRE galaxies tend to be overly dispersion-supported due to inefficient accretion of high angular momentum gas, with the same trend that rotation-supported gas disks occupy galaxies with less bursty recent star formation histories. This interplay between the gaseous structure, stellar structure, and recent star formation history of the FIRE dwarfs point to a link between the way in which star formation proceeds in these dwarfs and their ability to form a young stellar disk. Indeed, the idea that star formation feedback can significantly influence dwarf structure is well-established in regards to both the baryonic morphology (see, e.g. Governato et al. 2007; Smith et al. 2019, 2020) and in the dark matter halo (the core-cusp problem; see, e.g. Peñarrubia et al. 2012; Pontzen & Governato 2012). Indeed, as the most easily observable leg of this set, the stellar structure of galaxies in the dwarf mass regime could prove to be a powerful tool to constrain the feedback prescrip-
tions in conjunction with requirements for cored/cuspy dark matter profiles.

Second, it is possible that observations are missing a significant population of non-disky dwarfs due primarily to surface brightness sensitivity limits. We find that the non-disky dwarfs are not systematically lower in stellar surface density (within the stellar half-light radius) than the disky dwarfs. However, there is evidence that the FIRE dwarfs with more bursty star formation also have lower surface brightnesses (Chan et al. 2018). It is thus plausible that observed samples preferentially include disky dwarfs.

Explaining the lack of observational analogues to non-disky dwarfs in FIRE as being due to observational incompleteness would also necessitate the existence of a substantial and likely dominant population of low surface brightness dwarfs at \(10^8 \lesssim M_\star/M_\odot \lesssim 10^{10}\). A forthcoming probe of the distance and stellar mass distribution of a sample of low surface brightness galaxies will help to directly address this question (Greco et al., in preparation). However, observational studies of the intrinsic shapes of low surface brightness galaxies (Kado-Fong et al. 2021) and ultra diffuse galaxies in clusters (Burkert 2017; Rong et al. 2019) indicate that although LSBGs are relatively round, they do not show significantly lower values of B/A than spectroscopic dwarf samples, as is the case for the non-disky dwarfs. We thus find it unlikely that the non-disky dwarfs represent a dominant low surface brightness population that are undetected in current generation surveys. Similarly, because the non-disky galaxies lack a disk at all stellar age bins considered, we find it unlikely that the difference in observed and simulated intrinsic shape distributions originates from a difference between light-weighted differential and age-binned, mass-weighted cumulative shapes. We note that some of the non-disky dwarfs are consistent with previous inferred shapes for cluster ultra diffuse galaxies (Rong et al. 2019). It is of interest, but beyond the scope of this work, to ask whether these galaxies differ from the general set of non-disky dwarfs.

A last possibility is that, because the FIRE suite represents a relatively small number of dwarf galaxies, non-disky dwarfs may be a smaller proportion of the total dwarf population than is reflected in the FIRE suite. Part of this discrepancy could be due to bias in the dwarfs chosen for the suite. Galaxies in FIRE zooms are selected to be isolated, and to have small Lagrangian regions, and so it is possible that there is some systematic bias in the sample that causes them to be more non-disky. However, observational results do not indicate that non-isolated dwarfs are more non-disky (Kado-Fong et al. 2020); further investigation into the behavior of the FIRE zoom suite as a function of environment would be enlightening, but is outside the scope of this work.

To place a limit on the sensitivity of the observational methods of Kado-Fong et al. (2020) to a morphologically distinct non-disky population, we construct a toy model wherein we simulate a mock galaxy population composed of a disky and non-disky population and rerun our observational analysis, as detailed in Appendix A. We find that the hypothetical presence of a small minority \((\lesssim 10%)\) of galaxies with non-disky shapes would not affect the observationally inferred intrinsic shape parameters. However, the fraction of non-disky galaxies in FIRE-2 greatly exceeds this 10% threshold. Thus, we find that the over-representation of non-disky dwarfs in the simulated sample is unlikely to be explained by observational uncertainties or by Poisson fluctuations \((N_{\text{non-disky}} = 10 \pm 3)\).

5. CONCLUSIONS

In this work, we have shown that the FIRE-2 simulation suite is capable of reproducing the young, thick stellar disk and old, round stellar halo observed to be the dominant structural configuration of high-mass \((10^{8.5} < M_\star/M_\odot < 10^{9.6})\) dwarf galaxies. These dwarf halos bear an observational resemblance to the accreted stellar halos of higher mass galaxies, but as we show in Section 3.2, the dwarf stellar halos in FIRE are built up by the migration of in-situ stars. The FIRE galaxies that succeed in forming a disk-stellar halo system also succeed in reproducing a number of characteristics of observed dwarfs: their stellar halos are more flattened (lower \(C/A\)) than the stellar halos of the higher mass galaxies in FIRE (see Figure 3), appear ubiquitously around dwarfs that form disks, and have HI gas fractions in good agreement with observed galaxies (see Figure 8). These dwarfs demonstrate that dwarf stellar halo formation via the heating of disk stars is able to reproduce several properties of observed dwarf galaxies – such an in-situ pathway appears necessary to explain the commonality of dwarf stellar halos in observational samples.

However, the majority of the dwarfs in FIRE are not disk-halo systems. The rest of the dwarfs in this work are instead “non-disky” systems, here meaning that the dwarf is significantly non-disky in shape \((A \sim B \sim C)\), without a clear disk-halo transition (see Figure 3). We find that these non-disky dwarfs tend to be depleted in

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4 Though the results of Burkert (2017) appear to be in good agreement with the non-disky dwarf population, we caution that Burkert (2017) did not allow for triaxiality in their model, and their results are therefore constrained to either B/A=C/A or B/A=1.
HI for their stellar mass and have highly bursty recent star formation histories compared to the disky dwarfs. These differences may suggest that the galaxies are unable to form a disk due to over-vigorous star formation or star formation feedback.

Both classes of FIRE dwarfs demonstrate that intrinsic shapes are a useful tool to understand whether simulations are able to produce realistic galaxy structures. This is particularly important for low-mass galaxies where the details of the star formation history, star formation feedback, and gas accretion are expected to play a significant role in shaping the overall stellar content and structure (both due to the shallower potential well and the lower fractional contribution by accreted stars).

Future observational works targeting the low surface brightness universe will be able to determine whether there exists a counterpart to the non-disky dwarfs in FIRE that has been out of reach of previous observational studies (Greco et al., in preparation). Indeed, a great deal of theoretical and observational work remains necessary to understand the population of low mass galaxies beyond the Local Universe; among other open questions, the details of their star formation histories (Chan et al. 2015), their capacity to self-quench (Geha et al. 2012; Dickey et al. 2020), and the emergence of ultra diffuse galaxies (Chan et al. 2018; Greco et al. 2018; Wright et al. 2020; Kado-Fong et al. 2021) remain areas of active study for both observational and theoretical efforts. All three of these questions are tied intrinsically to the morphology (and more generally, the structure) of the dwarf population – future observational studies of the intrinsic shape of the dwarf population and other structural parameters will thus help to shed light on a number of open questions in dwarf evolution and stellar assembly.

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REFERENCES

APPENDIX

A. PLACING LIMITS ON THE PRESENCE OF A NON-DISKY MINORITY POPULATION

In the FIRE simulations, we find two distinct morphological classes of dwarf galaxies – those that are able to form young stellar disks and a round old stellar halo, and those that are characterized by highly non-disky shapes at all ages. In the observational analysis of Kado-Fong et al. (2020), the intrinsic shape population was modeled as a single multivariate Gaussian. It is thus of interest to make an estimate of the maximum fraction of non-disky galaxies that could be present in a dwarf sample without affecting the inferred observational intrinsic shape distribution. Here, we present mock trials to argue that no more than 10% of a non-disky population drawn from the FIRE non-disky dwarfs could exist in a disky population dominated by the FIRE disky dwarfs without changing the results of the observational inference method used in Kado-Fong et al. (2020).

To do so, we first briefly summarize the observational inference method; a full explanation can be found in Section 4 of Kado-Fong et al. (2020). As was demonstrated by Simonneau et al. (1998), it can be shown that the projected axis ratio \( b/a \) of an ellipsoid is an analytic function of its intrinsic axes ratios, \( B/A \) and \( C/A \), and the observer’s viewing angle \((\theta, \phi)\). A given intrinsic axis ratio distribution can then be quickly turned into a distribution of projected ellipticities, assuming that the viewing angle is distributed uniformly over a sphere. This ellipticity distribution can then be used, in conjunction with adopted flat priors over the relevant shape parameters, to infer the distribution of intrinsic shapes for a galaxy sample given a chosen functional form for that distribution via Markov Chain Monte Carlo sampling (MCMC via emcee, Foreman-Mackey et al. 2013). Kado-Fong et al. (2020) adopted a multivariate Gaussian for the inference with parameters \( \mathbf{\alpha} = \{\mu_B, \mu_C, \sigma_B, \sigma_C\} \), where \( \mu_X \) and \( \sigma_X \) are the mean and standard deviation of the Gaussian characterizing the axis ratio \( X/A \) distribution, respectively. This choice enforces a singly-peaked distribution in intrinsic shape space.

To investigate the impact of a minority population of non-disky galaxies, we invoke the following toy model. First, to characterize our two underlying intrinsic shape distributions, we measure the mean and covariance matrices of the non-disky and disky FIRE dwarfs separately. Then, we generate a sample from those shape distributions with a given fraction of non-disky galaxies ranging between 0 and 1, and infer the intrinsic shapes of the resulting ellipticity distribution using the same framework as Kado-Fong et al. (2020). The mock samples are of size \( N=4600 \), selected to be approximately equal to the largest mass bin of Kado-Fong et al. (2020). Figure 10 shows the evolution of the inferred shape parameters as a function of the non-disky fraction in the mock sample. As expected, we find that the mean \( B/A \) decreases and mean \( C/A \) increases as the non-disky fraction increases. Interestingly, although the inferred mean shapes of the pure disk population are in good agreement with the true values of the FIRE sample, the inferred mean shapes of the pure non-disky population are somewhat less non-disky than the true values of the FIRE sample. This is likely due to a significant covariance between \( B/A \) and \( C/A \) in the non-disky sample that is not captured by the model.

To quantify the non-disky fraction at which the mock observational inference changes significantly from the results for a pure disk \( (f_{\text{non-disky}} = 0) \) sample, we compute the \( \ell_2 \) norm between the mean values of each sample and the pure disk sample. The uncertainty \( \sigma_{\ell_2} \) is the propagation of errors where we adopt the standard deviation of the MCMC chains as the uncertainty on the estimates of the shape parameters. We show the results of this analysis in Figure 11 – we find that the inferred parameters change significantly when the non-disky fraction exceeds \( f_{\text{non-disky}} = 0.1 \). Thus, though it is possible for a sub-population of morphologically distinct galaxies to exist undetected within a generally disky population, this possible fraction is much smaller than the realized \( \sim 60\% \) non-disky fraction seen in the FIRE galaxies.

B. PROJECTION GALLERY OF DISKY AND non-disky DWARFS

To give the reader a wider sense of the morphologies spanned by the FIRE dwarfs, we show the \( z = 0 \) projections of young stars, old stars, and HI in the same format as Figure 2 for the disky dwarf m11b (Hydro+, no MD) in Figure 12 and the non-disky dwarf m11c (Hydro+, no MD) in Figure 13.
Figure 10. The maximum a posteriori (solid curves) and standard deviation (shaded regions) estimates of the observational intrinsic shape parameters as a function of the fraction of the mock sample that is drawn from the non-disky galaxy distribution. The solid black line (region) in each panel shows the maximum a posteriori estimate (standard deviation) of the $f_{\text{non-disky}} = 0$ sample. Clockwise from top left, we show: $\mu_B$, the mean axis ratio $B/A$, $\mu_C$, the mean axis ratio $C/A$, $\sigma_B$, the standard deviation of $B/A$, and $\sigma_C$, the standard deviation of $C/A$. As the non-disky fraction increases, the mean $B/A$ decreases and mean $C/A$ increases, consistent with a more non-disky shape overall.
Figure 11. The L2-norm, $\ell_2$, calculated between the inferred shape parameters of the mock observational sample as a function of the mock sample that is drawn from the non-disky galaxy distribution. The errors reflect the propagation of errors using the standard deviation of the MCMC chains as the uncertainty on the inferred shape parameters.
Figure 12. Projections of young stars (left), old stars (middle), and HI gas (right) for the disky dwarf m11b (Hydro+, no MD) in the same format as Figure 2.
Figure 13. Projections of young stars (left), old stars (middle), and HI gas (right) for the non-disky dwarf m11c (Hydro+, no MD) in the same format as Figure 2.