The Formation of Ultra-Diffuse Galaxies from Passive Evolution in the RomulusC Galaxy Cluster Simulation

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ABSTRACT

We study the origins of 122 ultra-diffuse galaxies (UDGs) in the RomulusC zoom-in cosmological simulation of a galaxy cluster (M200 = 1.15 × 1014 M⊙), one of the only such simulations capable of resolving the evolution and structure of dwarf galaxies (M⋆ < 109 M⊙). We find broad agreement with observed cluster UDGs and predict that they are not separate from the overall cluster dwarf population. UDGs in cluster environments form primarily due to the quenching of star formation from ram pressure stripping and the subsequent passive evolution of their stellar population which results in very low surface brightness dwarf galaxies. We predict that there is little difference between UDGs and non-UDGs in terms of their dark matter halo masses and spins, their z = 0 colors, nor their evolution over time. UDGs are typically larger dwarf galaxies well before in-fall into the cluster and have had their star formation quenched for longer, typically due to entering the cluster earlier. We find that in most respects cluster UDG and non-UDGs alike are similar to isolated dwarf galaxies, although they are typically larger in size. This is due, in part, to the fact that cluster dwarf galaxies grow from higher angular momentum gas compared to isolated dwarf galaxies.

Key words: galaxies:clusters:general – galaxies:evolution – galaxies:dwarf

1 INTRODUCTION

Recent advancements in detecting low surface brightness galaxies, led by observatories such as Dragonfly and Subaru, have revealed a population of very diffuse, low luminosity galaxies with stellar masses consistent with dwarf galaxies. They are numerous and found primarily in cluster and group environments (van Dokkum et al. 2015; van der Burg et al. 2016; Román & Trujillo 2017a; Greco et al. 2018), with significant populations detected in the Coma, Virgo, and Fornax clusters (Miños et al. 2015; Koda et al. 2015; Muñoz et al. 2015; Mowla et al. 2017), as well as lower mass galaxy groups and even Milky Way-mass halos (Román & Trujillo 2017b; Mancera Piña et al. 2018). In some cases, these ultra-diffuse galaxies (UDGs) have very unique properties, such as large numbers of globular clusters for their stellar mass (van Dokkum et al. 2017) or dynamical masses that are dominated by stars out to large radii (van Dokkum et al. 2018b, 2019b). The question of whether such galaxies can form in ΛCDM and what processes are required to produce them may have important implications to galaxy formation theory (e.g. Di Cintio et al. 2017), and potentially even the nature of dark matter (e.g. Wasserman et al. 2019).

Idealised simulations (e.g. Yozin & Bekki 2015; Dutta Chowdhury et al. 2019), analytic and semi-analytic models (e.g. Amorisco & Loeb 2016; Ogiya 2018; Rong et al. 2017; Carleton et al. 2019), and cosmological simulations (e.g. Di Cintio et al. 2017; Chan et al. 2018; Jiang et al. 2019; Liao et al. 2019; Martin et al. 2019) have all been utilized in attempts to understand the origin of UDGs and their properties, often coming to different conclusions. A dynamical origin to UDGs has been proposed by several groups, which would have UDGs forming from tidal heating and/or stripping due to interactions with the galaxy cluster environment (e.g. Ogiya 2018; Jiang et al. 2019; Liao et al. 2019). However, recent observations of UDGs have shown little to no evidence of tidal interactions (Mowla et al. 2017). Another possibility is that UDGs reside in halos with particularly high spin (Amorisco & Loeb 2016), and indeed cosmological simulations of iso-
lated galaxies have shown that angular momentum is an important component to forming low surface brightness galaxies (Di Cintio et al. 2019). Cosmological simulations have also shown that bursty feedback from supernovae, which lead to the formation of cored dark matter profiles (Governato et al. 2010, 2012; Pontzen & Governato 2012, 2013; Di Cintio et al. 2014), also lead to extended, diffuse stellar distributions and galaxies with UDG-like properties (Di Cintio et al. 2017). In this scenario, UDG formation does not require a dense environment, although the environment is likely important for reproducing other observed properties such as colors, gas content (or lack thereof), and stellar ages (Chan et al. 2018).

Self-consistently modeling UDG formation in dense environments is challenging for cosmological simulations because it requires simulating a massive halo, central galaxy, and circum-galactic/intracluster gas with enough resolution elements to study the internal structure of low mass galaxies. In general, smaller halos have been more accessible. Liao et al. (2019) simulate Milky Way-mass halos to reproduce observed abundances of UDGs in similar mass systems and find a combination of formation scenarios: tidal interactions can pull up an initially compact galaxy, while UDGs can form in isolation prior to in-fall. The latter only occurs for galaxies within high spin dark matter halos. Jiang et al. (2019) present results from a more massive galaxy group at significantly lower resolution with similar findings. Galaxies can be UDGs before in-fall into the group and survive to $z = 0$ while more compact galaxies may become UDGs due to tidal effects. However, such experiments using cosmological simulations of cluster environments have so far been limited either to low resolution simulations able to resolve only the most massive dwarf galaxies with $\sim 1$ kpc resolution and a few hundred particles (Martin et al. 2019) or semi-analytic-galaxy evolution models and dark matter only simulations (Carleton et al. 2019). Cosmological hydrodynamic simulations that resolve the internal structure of low mass dwarf galaxies in clusters are required to better understand UDG formation.

The Romulus simulations (Tremmel et al. 2017) consist of a 25 Mpc-per-side uniform volume simulation (Romulus25) as well as the RomulusC cosmological galaxy cluster simulation (Tremmel et al. 2019). Both are run with state-of-the art sub-grid physics and resolution. RomulusC is one of the highest resolution cosmological simulations ever completed of a galaxy cluster, comparable only to the recent TNG50 simulation, which also consists of a single cluster of similar mass (Nelson et al. 2019; Pillepich et al. 2019). It therefore represents an important opportunity for the first time, self-consistently study the evolution of dwarf galaxies ($M_* < 10^6 M_\odot$) in galaxy cluster environments. Galaxies in RomulusC with stellar and virial masses as small as $10^7 M_\odot$ and $3 \times 10^8 M_\odot$, respectively are resolved with more than 200 star particles and more than $\sim 10^8$ dark matter particles. We are also able to use Romulus25 to self-consistently compare properties of cluster dwarf galaxies to hundreds of isolated systems simulated with the same physics and resolution. In §2 we provide an overview of the simulation properties and our criteria for selecting galaxies as UDGs. In §3 we examine the $z = 0$ properties of UDGs predicted by RomulusC and compare with both observations and the overall cluster and isolated populations of dwarf galaxies. In §4 we study the evolution of dwarf galaxies in the cluster environment and examine its role in UDG formation. We discuss the implications and limitations of our results in §5 and we summarize the results in §6.

2 THE ROMULUSC SIMULATION

RomulusC (Tremmel et al. 2019) is a cosmological zoom-in simulation of a small galaxy cluster with $z = 0$ total virial mass of $1.5 \times 10^{14} M_\odot$, $R_{200} = 1033$ kpc, and $M_{200} = 1.15 \times 10^{15} M_\odot$. The initial conditions for RomulusC were extracted using the ‘zoom-in’ volume re-normalization technique of Katz & White (1993) to define a Lagrangian region associated with the most massive $z = 0$ halo of a 50 Mpc-per-side uniform volume dark matter-only simulation. The resulting ‘zoom-in region’ was re-simulated at higher resolution with full hydrodynamic treatment using the new Tree+SPH code CsAnGa (Menon et al. 2015) while maintaining the gravitational influence of the evolving large-scale structure of dark matter, which is modeled with much coarser resolution.

CsAnGa includes standard physics modules previously used in GASOLINE (Wadsley et al. 2004, 2008, 2017) such as a cosmic UV background (Haardt & Madau 2012) including self-shielding (Pontzen et al. 2008), star formation, ‘blastwave’ supernova (SN) feedback (Stinson et al. 2006), and low temperature metal cooling. CsAnGa implements an updated SPH routine that uses a geometric mean density in the SPH force expression, allowing for the accurate simulation of shear flows with Kelvin-Helmholtz instabilities (Ritchie & Thomas 2001; Menon et al. 2015; Governato et al. 2015). RomulusC includes an updated implementation of turbulent diffusion (Wadsley et al. 2017), which results in a realistic intracluster medium (ICM) (Wadsley et al. 2008; Tremmel et al. 2019) and metal distributions within galaxies (Shen et al. 2010). Finally, a time-dependent artificial viscosity and an on-the-fly time-step adjustment (Saitoh & Makino 2009) system allow for more realistic treatment of weak and strong shocks (Wadsley et al. 2017).

RomulusC is run with the same hydrodynamics, sub-grid physics, resolution, and cosmology as the Romulus25 simulation (Tremmel et al. 2017). The cosmology is ΛCDM with cosmological parameter values following the recent results from Planck ($Ω_0 = 0.3086$, $Λ = 0.6914$, $h = 0.6777$, $σ_8 = 0.8288$; Planck Collaboration et al. 2016). The simulation has a Plummer equivalent force softening of 250 pc (a spline softening of 350 pc is used, which converges to a Newtonian force at 700 pc). Unlike many similar cosmological runs, the dark matter particles are oversampled relative to gas particles, such that the simulation is run with initially 3,375 times more dark matter particles than gas. The result is a dark matter particle mass of $3.39 \times 10^7 M_\odot$ and gas particle mass of $2.12 \times 10^4 M_\odot$. This will decrease numerical effects resulting from two-body relaxation and energy equi-partition, which occur when particles have significantly different masses, both of which can affect the structure of simulated galaxies (Ludlow et al. 2019). This increased dark matter resolution also allows for the ability to track the dynamics of supermassive black holes within galaxies (Tremmel et al. 2015). Romulus25 has been shown to reproduce important galaxy and supermassive black hole scaling relations (Tremmel et al. 2017; Ricarte et al. 2019).
UDGs in RomulusC

Figure 1. **Example UDGs and non-UDGs selected from RomulusC.** (Top) Surface brightness profiles, corresponding Sersic fits, and UVJ images of six example UDGs extracted from RomulusC and (Bottom) the same information for four non-UDG dwarf galaxies (M\(\star\) < 10\(^9\) M\(\odot\)) from the same simulation. The UDG examples include the ones with the most stellar mass (7.7 \times 10^{8} M\(\odot\), top left), largest effective radius (5.6 kpc, top right), largest Sersic index (1.74, middle left), lowest central surface brightness (28.1 mag/arcsec\(^2\), middle right), farthest z = 0 distance to cluster center (1489 kpc, bottom left), and closest distance to cluster center (153 kpc, bottom right). For the non-UDG dwarfs, the top examples fail both size and surface brightness criteria for being a UDG. The bottom left is the non-UDG dwarf galaxy with the smallest effective radius (1.04 kpc) and on the bottom right is the non-UDG dwarf with the highest central surface brightness (21.4 mag/arcsec\(^2\)).
2.1 Sub-grid physics

2.1.1 Star formation and gas cooling

Star formation and associated feedback from supernovae are crucial processes that require sub-grid models in cosmological simulations like RomulusC. As in previous work (Stinson et al. 2006) for runs at this resolution, star formation (SF) is regulated with parameters that encode star formation efficiency in dense gas, the coupling of SN energy to the ISM, and the physical conditions required for star formation:

(i) The normalization of the SF efficiency, \( c_s = 0.15 \), and formation timescale, \( \Delta t = 10^7 \) yr, are both used to calculate the probability \( p \) of creating a star particle from a gas particle that has a dynamical time \( t_{dyn} \):

\[
p = \frac{m_{gas}}{m_{star}} (1 - e^{-c_s \Delta t / t_{dyn}}).
\]

(ii) The fraction of SN energy coupled to the ISM, \( \epsilon_{SN} = 0.75 \).

(iii) The minimum density, \( n_e = 0.2 \) cm\(^{-3}\), and maximum temperature, \( T_e = 10^4 \) K, thresholds beyond which cold gas is allowed to form stars.

Star particles form with a mass of \( 6 \times 10^5 \) \( M_\odot \), or 30% of the initial gas particle mass. We assume a Kroupa IMF (Kroupa 2001) with associated metal yields and SN rates. Feedback from SN uses the ‘blastwave’ implementation (Stinson et al. 2006), with thermal energy injection and a cooling shutoff period approximating the ‘blastwave’ phase of SN ejecta when cooling is inefficient.

Gas cooling at low temperatures is regulated by metal abundance as in Guédez et al. (2011) as well as SPH hydrodynamics that includes both thermal and metal diffusion as described in Shen et al. (2010) and Governato et al. (2015). An important limitation of the Romulus simulations is the lack of cooling from high temperature metal lines. For low mass galaxies such as those we focus on in this work, metal line cooling is sub-dominant due to both low metallicity and low virial temperature of the dark matter halos hosting the galaxies. However, massive halos like galaxy clusters will be affected by such choices. The choice to not include metalline cooling is outlined in more detail in Tremmel et al. (2019) and is due to the fact that, although RomulusC has the highest resolution for a cosmological simulation performed at this mass scale, it is still not enough to self-consistently simulate the multiphase ISM and, in particular, molecular cooling. Christensen et al. (2014) found that the inclusion of metal cooling without molecular hydrogen physics and more detailed models of star formation resulted in over-cooling in galaxies. While some simulations that are run at similar resolution to Romulus opt to include high temperature metal line cooling and instead boost the efficiency of stellar feedback (Shen et al. 2012; Dalla Vecchia & Schaye 2012; Schaye et al. 2015; Sokolowska et al. 2016, 2018), this will not necessarily result in realistic circumgalactic media nor realistic galaxies beyond bulk properties such as their final stellar and gas masses. Christensen et al. (2014) find that ISM models that include both metal lines and H\(_2\) physics result in galaxies with star formation histories and outflow rates more similar to primordial cooling runs than

1 \( R_\odot \) is defined as the radius enclosing a mean density of \( \Delta \times \rho_{crit} \), where \( \rho_{crit} \) is the critical density at \( z = 0 \), \( M_\odot \) is the mass enclosed within \( R_\odot \).

Figure 2. Size mass relation in Romulus. The g-band effective radius versus stellar mass for isolated galaxies from Romulus25 (grey) as well as clusters (blue) and UDGs (orange). In general, cluster galaxies follow the same relation as the isolated galaxies, which is slightly above the observed relation shown in red from Lange et al. (2016), the dashed portion representing an extrapolation of the observed relation. While non-UDG cluster dwarfs typically follow the relation down to \( 10^{7.5} \) \( M_\odot \), UDGs tend to lie well above the relation. Dwarf galaxies in the cluster lack the population of more compact (\( R_{eff} < 1 \) kpc) galaxies that exist in isolation, particularly at low mass (\(< 10^{7.5} \) \( M_\odot \)). Lange et al. (2016) use r-band to calculate the effective radius, but we confirm that the difference is negligible were we to fit the r-band profile instead.

To simulations with metal lines and no \( H_2 \). This will be particularly true for the low mass halos presented here, which would likely be more affected by artificially boosted SN feedback prescriptions. The structure of the ICM of the RomulusC cluster has been shown to be consistent with observations, despite the lack of metal-line cooling (Tremmel et al. 2019).

2.1.2 Black hole physics

Supermassive black hole (SMBH) formation, dynamics, growth, and feedback are implemented into all Romulus simulations and described in more detail in Tremmel et al. (2017), where it is shown that low mass galaxies are generally unaffected by SMBH feedback. While SMBH feedback certainly affects the evolution of the brightest cluster galaxy and other massive galaxies, it only marginally changes the overall structure of the ICM, even in the cluster core (Tremmel et al. 2019). While in this work we verify that interaction between dwarf galaxies and their environment is the most important process to forming UDGs in cluster environments, we will explore in more detail how the presence of SMBHs in dwarf galaxies may affect their final morphology and star formation history in future work (Sharma et al., in prep). We do confirm that the presence of a SMBH is not required to form a UDG, nor to keep a galaxy from becoming a UDG.

For the sake of completeness, we will briefly review the implementation of SMBH physics in Romulus. SMBHs are seeded in cold (\( T < 10^4 \) K), dense (\( n > 15 \times n_e \)), and pristine (\( Z < 10^{-4} \)) gas, primarily in the first Gyr of the simulation. SMBH growth is modeled with a modified Bondi-Hoyle formalism that accounts for angular momentum supported gas. A fraction (0.2%) of the accreted mass is transferred to surrounding gas particles as thermal energy and the cooling of particles receiving this energy is turned off for the length of the SMBH’s timestep (generally \(< 10^8 \) yr). Accretion

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onto SMBHs is Eddington limited, assuming a radiative efficiency of 10%. SMBHs are allowed to move freely within their host galaxies, with unresolved dynamical friction accounted for in a sub-grid model (Tremmel et al. 2015), resulting in SMBH mergers that can be significantly delayed with respect to galaxy mergers (Tremmel et al. 2018a; Tremmel et al. 2018b).

2.1.3 Sub-grid parameter optimization

Free parameters within our sub-grid models for star formation, SN feedback, and SMBH growth and feedback, were optimized using dozens of zoom-in cosmological simulations run with the same resolution as RomulusC, as described in Tremmel et al. (2017). The parameter combination that resulted in galaxies that best matched four roughly orthogonal empirical relations were selected. The relations used were: 1) stellar mass-halo mass (Moster et al. 2013), 2) SMBH mass-stellar mass (Schramm & Silverman 2013), 3) HI mass-stellar mass (using ALFALFA data, see Cannon et al. 2011; Haynes et al. 2011), and 4) bulge-to-total ratio versus specific angular momentum (Obreschkow & Glazebrook 2014). Calibration was only performed on isolated galaxies at $z = 0$. Therefore, the evolution of galaxy properties (morphology, star formation history, etc) with redshift, as well as $z = 0$ properties of satellite galaxies, are purely predictions from the simulation and have in no way been optimized to match any observations.

2.2 Halo and Galaxy Extraction

Dark matter halos, sub-halos, and all of their baryonic content, including central galaxies, are extracted using the Amiga Halo Finder (Knollmann & Knebe 2009). In our analysis we only consider a halo or sub-halo resolved if it has a virial mass, as calculated by AHF, of at least $3 \times 10^9 M_\odot$, meaning that it contains at least $\sim 10^8$ dark matter particles. The centers of halos are calculated using the shrinking spheres approach (Power et al. 2003), which consistently traces the centers of the central galaxies within each halo. By nature of being a zoom-in simulation, the main halo and surrounding region in RomulusC are simulated at high resolution while the rest of the cosmological volume is sampled at much lower mass resolution. Galaxies near the boundaries of the simulation can become ‘contaminated’ with low resolution elements. We avoid including such galaxies in our analysis by requiring each galaxy to have less than 5% of its dark matter particles be contaminated by low resolution elements. We only include galaxies that, at $z = 0$, exist well within our zoom-in region, no more than 1.5 Mpc from the center of the cluster, while the zoom-in region extends out to $\sim 2$ Mpc.

Munshi et al. (2013) carefully analyzed simulated galaxies as an observer would view them, showing observers would underestimate the ‘true’ stellar mass of simulated galaxies by more than 40%. This is due to photometric estimates of stellar mass underestimating contributions from older populations and the utilization of aperture-based photometry. In addition, Munshi et al. (2013) find that the dark matter halo mass is $\sim 20\%$ lower in simulations that include baryonic physics compared to those that do not. In order to perform a fair apples-to-apples comparison between our simulations and observations, when we refer to the stellar mass of our simulated galaxies, it is 60% of the total mass of star particles within the virial radius of the halo. Similarly, when comparing to abundance matching results, we correct the ‘true’ halo virial mass from the simulation to be what would be predicted from a dark matter only simulation by dividing by 0.8.

In our analysis we define dwarf galaxies to be any resolved galaxy with a post-correction stellar mass below $10^7 M_\odot$. In addition to galaxies from RomulusC, we also compare our cluster dwarf galaxies to the population of isolated dwarf galaxies in the RomulusC25 cosmological simulation. As discussed in §2, both simulations are run with the same resolution, sub-grid physics, and cosmology. When selecting for isolated galaxies, we select only galaxies that do not lie within the virial radius of another halo with

![Figure 3. Comparison with observed cluster UDGs. Scatter plots of properties of simulated cluster UDGs (orange) and other non-UDG cluster galaxies (blue) relative to observed properties of UDGs in cluster environments from van Dokkum et al. (2015) and Mowla et al. (2017) (black and grey diamonds respectively). For the latter we convert Subaru R-band magnitude to g-band assuming $g-R = 0.5$, as described in Mowla et al. (2017). Also shown are isolated galaxies extracted from RomulusC5 (black points). UDGs in RomulusC match well in general with observed galaxies, though the simulation has fewer large ($> 3$ kpc), low central surface brightness ($> 25$ mag/arcsec$^2$) UDGs. UDGs in RomulusC do not inhabit a well separated region of $R_{eff} - \mu_0 - M_g$ space compared to the rest of the galaxy population, but are rather just the low surface brightness portion of a roughly continuous population.](image-url)
larger virial mass. We also employ an additional criteria motivated by the results from Geha et al. (2012), where each isolated dwarf galaxy must be at least 1.5 Mpc away from any galaxy with stellar mass greater than $2.5 \times 10^{10} M_{\odot}$. Dwarf galaxies at closer distances to such massive galaxies are likely to be affected by their environment and should not be considered isolated. Galaxies and their host halos are extracted from the simulation in the same way as in RomulusC.

### 2.3 Selection of UDGs in RomulusC

For each resolved, uncontaminated galaxy in RomulusC at $z = 0$, we generate surface brightness profiles in V and B bands due to the stellar populations, where stellar emission is calculated using tables generated from population synthesis models (http://stev.oapd.inaf.it/cgi-bin/cmd; Marigo et al. 2008; Girardi et al. 2010). From Johnson V and B bands, we generate g-band surface brightness profiles following the conversion from Jester et al. (2005). The profiles are integrated within circular annuli, assuming only stars within each given dark matter halo contribute and absorption from gas and dust is unimportant. This latter assumption is safe for dwarf galaxies, which typically have low metallicities (e.g. van Zee 2000). The profiles are then fit to a single Sersic profile (Sérsic 1963) of the following form:

$$\Sigma(r) = \mu_e + 2.5(0868n - 0.142) \left( \frac{r}{R_{eff}} \right)^{-1/n} - 1.$$

We fit each galaxy using a least squares fit on Sersic index, $n$, effective radius, $R_{eff}$, and the surface brightness at the effective radius, $\mu_e$. In order to both match the angular resolution of typical UDG observations (e.g. van Dokkum et al. 2015; Mowla et al. 2017) and avoid fitting to structure below the resolution limit of the simulation, we create and then fit our surface brightness profiles using radial bins of 300 pc. We fit out to the first radial bin with surface brightness lower than 32 mag/arcsec$^2$, a typical limit for the most sensitive low surface brightness observations (e.g. van Dokkum et al. 2014). We place a further limitation on the radial bins used in this fit that they extend no further than the closest companion galaxy. At this resolution, it is difficult to resolve satellite galaxies at such low masses so this is a constraint rarely applied. Following van Dokkum et al. (2015), we classify a galaxy as being a UDG if it meets each of two criteria based on the single Sersic fits we generate: 1) it has an effective radius ($R_{eff}$) that is greater than 1.5 kpc, and 2) it has a central surface brightness ($\mu_e$) greater than 24 magnitudes/arcsec$^2$. Note that $\mu_e$ is different from $\mu_0$, that we fit to in Eqn. 2. Rather, this is the value of the surface brightness from the Sersic fit (Eqn. 2) evaluated at $r = 0$.

Each profile and Sersic fit is generated as if the observer is looking at the galaxy face-on. Galaxy re-orientations are performed based on the angular momentum of gas particles within the inner 5 kpc of the halo or, when there are less than 100 such particles, all (gas, stars, and dark matter) particles within the inner 5 kpc. The rationale behind this is that we want to capture all galaxies that could potentially be categorized as a UDG and, by orienting in this way, we maximize the effective size and minimize the surface brightness of all of our galaxies. This way, when we select UDGs, we will be selecting all galaxies that would potentially be categorized as such were they to be viewed at random inclinations.

We find a total of 122 galaxies that fit our adopted definition of UDG within 1.5 Mpc of the center of the cluster at $z = 0$ and 80 within $R_{200}$. Example images, surface brightness profiles, and Sersic fits are shown in Figure 1. This predicted abundance is a factor of $\sim 2 - 3$ higher than many estimates for low mass clusters such as RomulusC (van der Burg et al. 2017; Román & Trujillo 2017b; Mancera Piña et al. 2018). We do, however, stress that this is an upper limit as we do not account for the effect of random

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**Figure 4. Colors of Cluster Dwarf Galaxies in RomulusC.** Left: The Distribution of $g - i$ colors of UDG (orange) and non-UDG (blue) dwarf galaxies in RomulusC. Right: Dwarf galaxy $g - i$ colors for cluster UDGs and non-UDGs (same colors) as a function of total g-band magnitude. The dashed line and grey region represent the mean $g - i$ color from van Dokkum et al. (2015) and associated standard deviation. The overwhelming majority of dwarf galaxies in RomulusC are quenched and red. The colors of UDGs are similar to those in observations of Coma UDGs. UDGs and non-UDGs have similar colors at a given magnitude. The fact that our UDG population has slightly bluer colors, with an average of 0.7 compared to 0.8 from the van Dokkum et al. (2015) sample, is due to the lower mass, dimmer galaxies included in our simulation. In van Dokkum et al. (2015) there is only one galaxy with $M_g > -13$. Several UDGs in the more complete Mowla et al. (2017) sample exist at such low magnitudes, but $g - i$ colors have not been included for those galaxies yet. Were we to disregard these lower mass galaxies, the average UDG color would be more similar to the van Dokkum et al. (2015) sample.
Table 1. Number of total dwarf galaxies and UDGs in different mass bins in RomulusC. The errors in UDG fraction are Poisson errors.

| log(M_0 [M_⊙]) | N_{total} | N_{udg} | UDG Fraction |
|-----------------|-----------|---------|--------------|
| 7 – 7.5         | 64        | 41      | 0.65 ± 0.1   |
| 7.5 – 8         | 45        | 37      | 0.82 ± 0.14  |
| 8 – 8.5         | 43        | 31      | 0.72 ± 0.13  |
| 8.5 – 9         | 49        | 13      | 0.36 ± 0.1   |

orientation which can make galaxies appear less diffuse. If galaxies have a low axes ratio, doing a full GaFit analysis may also decrease some effective radii. Some numerical effects may also artificially boost our population of UDGs. We discuss all of this further in §6.

3 PROPERTIES OF UDGs IN ROMULUSC

3.1 UDG morphology and colors

Figure 2 shows the size-mass relation for RomulusC galaxies as well as isolated dwarf galaxies from the Romulus25 simulation. In terms of their size, UDGs are not a unique population compared to non-UDGs. Rather, they represent, particularly at stellar masses below ~ 2 × 10^9 M_⊙, the larger galaxies among the overall distribution of cluster dwarf galaxies. Cluster galaxies follow the same relation as the isolated galaxies, although they lack the smallest galaxies at any given stellar mass. This is contrary to observations that find
significant populations of dwarf galaxies in clusters with effective radii below 1 kpc (e.g. Gavazzi et al. 2005; Eigenthaler et al. 2018; Venhola et al. 2019a).

The isolated galaxy population is consistent with the empirical relation from Lange et al. (2016) at stellar masses above $10^{10.5}$ M$_\odot$. Although biased slightly high on average, the RomulusC25 isolated galaxies are within a factor of two of the empirical relation. Non-UDG cluster galaxies match well to the Lange et al. (2016) results while the UDGs are above it. At the lowest masses ($M_* < 10^{10.5}$ M$_\odot$), the deviation from the (extrapolated) empirical relation for both cluster and isolated dwarf galaxies is more significant. It is likely that the observations from Lange et al. (2016) are insensitive to the lowest surface brightness galaxies, which by design we do not exclude from our simulated sample. This may contribute to the slight bias of our simulated galaxies toward higher effective radius in both environments. For galaxies with $M_* < 10^{10.5}$ M$_\odot$, resolution effects are likely important in determining their larger sizes, as we discuss further in §5.

Figure 3 plots the effective radius, central surface brightness, and total g-band magnitude ($M_g$) for simulated cluster galaxies from RomulusC and isolated galaxies from RomulusC25 alongside the observed sample of Coma cluster UDGs from van Dokkum et al. (2015) and Mowla et al. (2017). Cluster UDGs do not inhabit a unique region in $R_{\text{eff}} - M_\text{g}$ space compared to cluster and isolated dwarf galaxies, though there are more large, low surface brightness, low-luminosity galaxies in the cluster compared to the field. There is an overall good agreement between the observed UDGs and those in RomulusC. The most noticeable, though minor, difference is the lack of galaxies in RomulusC with low ($M_\text{g} > 25$ mag/arcsec$^2$) central surface brightness and $R_{\text{eff}} > 5$ kpc.

Figure 4 shows the distribution of UDG and non-UDG dwarf galaxy colors in RomulusC. Dwarf galaxies we classify as UDGs and non-UDGs have similarly red colors, with dimmer, lower mass galaxies typically being bluer, consistent with observations of cluster dwarf galaxies (Boselli et al. 2014; Eigenthaler et al. 2018). The $g-i$ colors are slightly bluer than the average UDG color presented in van Dokkum et al. (2015) ($g-i = 0.8 \pm 0.1$), but this difference is due to the inclusion of lower luminosity, bluer galaxies from RomulusC. The RomulusC UDG population deviates from the typical color of observed UDGs below $M_\odot = -13$, where there is only one UDG in the van Dokkum et al. (2015) sample.

The right-hand panels of Figure 5 compare the distribution in $R_{\text{eff}}$ and Sersic index of cluster UDG and non-UDG dwarf galaxies, as well as isolated galaxies from RomulusC25. Other than the fact that UDGs are not allowed to have small effective radii by definition and are therefore more likely to have larger sizes, cluster UDGs do not look significantly different from non-UDGs or field galaxies in terms of $R_{\text{eff}}$ and are essentially identical in terms of their Sersic index distribution. As mentioned above, we see that RomulusC lacks dwarf galaxies with $R_{\text{eff}} < 1$ kpc that exist in isolation. Overall, these results indicate that UDGs are not a unique population of galaxies, but rather a sub-set of the ambient dwarf galaxy population in our simulations. Further, their morphology is not significantly altered by the cluster environment compared to isolated galaxies. We also compare to observed UDG morphologies from Mowla et al. (2017). While we find overall good agreement with observed cluster UDGs, RomulusC UDGs have slightly larger sizes and larger Sersic indices.

3.2 Location, dynamics, and infall time

Figure 6 plots the cluster-centric distance and radial velocity of cluster galaxies. The small number of dwarf galaxies that have yet to cross $R_{200}$ by $z = 0$ are shown as diamonds. There is also a significant population of ‘splashback’ galaxies that have already crossed $R_{200}$ but their orbits have taken them back outside of it. Most of these galaxies happen to be moving outward (positive radial velocities), but some are on their way back inward.

There is no difference between the phase space location of UDGs, non-UDGs, and more massive galaxies, though there is a difference between their in-fall times, defined as the time a galaxy first crosses $R_{200}$ of the cluster. The upper panel in Figure 7 plots the distribution of in-fall times for UDG and non-UDG dwarf galaxies in RomulusC. The small number of dwarfs that have yet to cross $R_{200}$ are not included. UDGs are more likely to have fallen in at earlier times. The lower panel in Figure 7 shows the fraction of galaxies that are UDGs at $z = 0$ as a function of in-fall time. More than 80% of the dwarf galaxies that in-fall before $z = 0.5$ become UDGs by $z = 0$. This falls to ~50% for galaxies that have fallen into the cluster more recently.

Figure 8 plots the distribution of both $z = 0$ cluster-centric distances and the minimum distance attained by cluster dwarf galaxies. Again, only those that have already crossed $R_{200}$ are included. The final distance distributions are nearly identical, but there is a difference in the minimum distance to cluster center attained throughout their orbital evolution. The difference is relatively small and is mostly due to the different in-fall times. UDGs reach closer into the cluster environment because they tend to have crossed $R_{200}$ earlier (see Figure 7). Selecting only galaxies with in-fall times later than $z = 0.5$, the effect is diminished. An earlier in-fall means that the cluster was smaller with a shorter dynamical time and these galaxies had more opportunity to pass closer to cluster center due to more repeated passages. It is not a requirement for UDGs to have passed close to cluster center. For example, ~30% of UDGs have never passed closer than 0.5 $R_{200}$ to the cluster center.

Figure 6. Distance and radial velocity for cluster galaxies. UDGs (orange), non-UDG dwarf galaxies (blue), and more massive galaxies (black) all inhabit the same regions in phase space within the cluster environment at $z = 0$. The solid line denotes $R_{200}$ at $z = 0$. The diamond points represent galaxies that have not yet fallen inward of $R_{200}$. Several galaxies are splashback galaxies that have moved back outside $R_{200}$ after their initial in-fall.
3.3 Dark matter halos

Figure 9 plots the relationship between stellar mass and halo virial mass at $z = 0$ (small points) for ROMULUSC galaxies. Plotted in larger points is the relation for these same galaxies at the time they reach their peak halo mass. Prior to in-fall, cluster galaxies are consistent with the same abundance matching relations as isolated galaxies in ROMULUSC25 (Tremmel et al. 2017). While these galaxies often in-fall much earlier than $z = 0$, we expect the stellar mass halo mass relation to remain relatively constant with redshift (Behroozi et al. 2013). Because the ROMULUS simulations were calibrated to match the Moster et al. (2013) relation for isolated $z = 0$ galaxies, this result is not purely a prediction of the simulation. What it does is that, prior to in-fall, UDGs and non-UDGs alike had halo masses consistent with the isolated galaxy population of ROMULUSC25. Following in-fall, halos lose dark matter from tidal stripping, but the central galaxy remains unaffected, pushing the galaxies to the left of the abundance matching relations.

At the time of peak halo mass, UDGs in ROMULUSC have stellar masses as high as $6.3 \times 10^9 \, M_\odot$ and halo virial masses as high as $6.5 \times 10^{10} \, M_\odot$, corresponding to a mass of $8.2 \times 10^{10} \, M_\odot$ in a dark matter only simulation (Munshi et al. 2013). While it is often difficult to make concrete observational conclusions about the halo mass of UDGs, Dragonfly 44 is thought to occupy a relatively massive halo based on its large velocity dispersions (van Dokkum et al. 2016), though current estimates place its most likely dynamical mass to be not much beyond $10^{11} \, M_\odot$ (van Dokkum et al. 2019b). The large populations of globular clusters observed in several UDGs (van Dokkum et al. 2017) has been used as an argument that they come from more massive halos than their stellar masses would normally imply. Our results do not support this picture, as both UDGs and non-UDGs inhabit average mass DM halos for their stellar mass at the time of in-fall.

Other UDGs have been reported to have much lower dynamical masses than expected, with dark matter sub-dominant compared to stars in terms of total mass, or potentially missing all together (van Dokkum et al. 2018a, 2019a). We do not attempt to extract such halos from the simulation, as we place strict boundaries on which halos we consider well resolved based on the number of dark matter particles they have. It is also unclear whether our halo finder would be properly optimized to find such systems.

It is possible that these observed galaxies do have dark matter, but heavily cored dark matter profiles. Our galaxies do not form heavily cored dark matter profiles due to their resolution being too low (see §5 for more discussion on this). There is some decrease to the dark matter density in the centers of cluster satellite halos due to tidal stripping (see §4.1), but not enough to form resolved cores. The typical dark matter density profile inside 1 kpc for cluster dwarf galaxies is cuspy with a slope of approximately $-1.5$.  

Figure 7. Galaxy In-fall Times. Top: The cumulative distribution of in-fall times for UDGs (orange) and non-UDG dwarf galaxies (blue). Bottom: The fraction of dwarf galaxies that are UDGs at $z = 0$ as a function of in-fall time. The grey shaded region represents the 68% binomial confidence interval (Cameron 2011). Low mass galaxies crossing $R_{200}$ at $z > 0.5$ are about two times more likely to become UDGs by $z = 0$ than galaxies that in-fall at $z < 0.5$.

Figure 8. Final and Minimum Cluster-centric Distances for Dwarf Galaxies. The distribution of final (bottom) and minimum (top) distances each UDG (orange) and non-UDG (blue) dwarf galaxy attains relative to cluster center in ROMULUSC. We derive the minimum distance relative to $R_{200}$ as calculated for the cluster progenitor at each snapshot. The overall distribution at $z = 0$ is the same for both populations while UDGs have gotten preferentially closer to the center of the cluster throughout their orbital evolution. This is mostly a function of in-fall time, rather than an indication of an important evolutionary channel. In-fall for UDGs is preferentially earlier compared to the non-UDG population (see Figure 7). When we limit the sample to galaxies that in-fall at $z > 0.5$ (dotted lines), we see this difference becomes less significant.
Despite the lack of dark matter cores, UDGs still exist in ROMULUS. While this is not a prediction of the simulation, but a resolution effect, it shows that dark matter profiles are not required to form UDGs. The formation of UDGs in this simulation occurs through a formation channel that is unique to that presented in Di Cintio et al. (2017).

4 THE ORIGIN OF UDGs IN GALAXY CLUSTERS

4.1 The evolution of cluster dwarf galaxies

In this section we explore the origin of UDGs in galaxy clusters by tracking ROMULUS galaxies back in time and examining how their key morphological properties change as they interact with the cluster environment. Because UDGs in our simulation span two orders of magnitude in stellar mass. To ensure that we control for any differences in evolution as a function of mass we split galaxies into three stellar mass bins: $10^7 < M_* < 10^{10}$, $10^{10} < M_* < 10^{11}$, and $10^{11} < M_* < 10^{12}$. Each bin contains approximately one-third of the total UDG population.

We track several properties back in cosmic time and plot their evolution relative to $t_{\text{fall}}$, the first time when each galaxy crosses $R_{200}$, and $t_{\text{quench}}$, the time at which star formation ceases in the inner 1 kpc of each galaxy. Figures 10, 11, and 12 plot such evolutionary tracks for Sersic index ($n$), $R_{\text{eff}}$, and central surface brightness ($\mu_0$) respectively. The thick blue and orange lines represent the mean values at each time for non-UDGs and UDGs (at $z = 0$), respectively, and the shaded regions the standard deviation at any given time. The thin lines represent individual galaxies and the stars the values at $z = 0$. The mean values are only calculated for times that include at least 3 galaxies. Some galaxies fail to track back in time, due to the halo finder failing to recover their progenitor halo during a step. This can happen either due to a close interaction with the cluster center or with another cluster member galaxy that causes the halo finder to be unable to separate the two halos. The galaxies included on these plots are those that trace back to at least $t = 2$ Gyr in simulation time and prior to both in-fall and quenching. These criteria remove ~20 – 30% of dwarf galaxies in each bin. We stress that at earlier times the galaxies are much less massive and so are resolved with fewer particles, making some of the earliest morphological properties uncertain, particularly at our lowest stellar mass bin.

For Sersic $n$ (Figure 10) there is little difference in the mean evolution between UDG and non-UDG dwarf galaxies in all mass bins. There is a gradual decrease in $n$ from ~2 at early times to ~1 that is most apparent at low mass.

The effective radius (Figure 11) tends to increase with time, particularly at larger masses. Following in-fall into the cluster, the effective radius increases by a typical value of ~20 – 30% compared to its value at in-fall with the most extreme cases increasing by ~50% (the same is true when taken relative to $t_{\text{quench}}$). For high mass galaxies, the evolution in size with time is most apparent, but also the least important as all galaxies in the simulation with stellar masses above $10^8 M_\odot$ have effective radii large enough for UDG classification long before in-fall or quenching. Both UDGs and non-UDGs at $z = 0$ have similar evolutionary histories with respect to effective radius at the highest masses. For lower mass galaxies, the effective radius is a critical factor in determining their $z = 0$ status as UDGs. For the two lower mass bins, both UDG and non-UDG galaxies increase their effective radius over time, but UDGs are often large enough to be considered UDGs long before they quench or in-fall past $R_{200}$. At any given time galaxies that will become UDGs are more likely to have larger radii compared to galaxies that will not become UDGs in the two lower mass bins.

The reason for the increase in effective radius after in-fall and quenching is in part due to the tidal stripping of dark matter. In Figure 13 we plot the dark matter density inside the inner 0.5 kpc of dwarf galaxies over time relative to its value at in-fall. While, as discussed in §3.3, we do not form cored dark matter profiles from supernovae feedback, we do see a decrease in dark matter density typically ~25 – 50% by $z = 0$. As shown in Figure 9, a significant amount of mass in dark matter gets stripped from these galaxies as they interact with the cluster. This tidal stripping can affect the dark matter in the core, as dark matter particles that make up the core often have more radial orbits that take them out to larger distances and therefore susceptible to tidal stripping (Zolotov et al. 2012). While this isn’t extreme enough to form large dark matter cores, it is able to decrease the density an appreciable amount.

Star orbits are generally unaffected by stripping, but will puff up to larger radii due to the decrease dark matter density (Arraki et al. 2012). The stellar mass within the inner 0.5 kpc of the galaxies are also decreasing with time (see Figure 14), most of which is likely from wind mass loss during stellar evolution. Gas is also being stripped away from the galaxy due to ram pressure (see Figure 15). All of these effects in tandem will decrease the binding energy of stars and cause the orbits to widen. Tidal heating due to more extreme tidal interactions with the cluster center or other galaxies may also contribute. However, only a subset of UDGs and non-UDGs exhibit the dramatic changes in effective radius one would expect from such interactions. Regardless of the details causing this gradual and overall
relatively minor increase in effective radius after in-fall. UDGs and non-UDGs follow similar evolutionary tracks indicating that this effect does not play an important role in determining a galaxy’s status as a UDG by $z = 0$.

Substantial evolution is seen in the central $g$-band surface brightness, $\mu_{0g}$, for both UDG and non-UDG galaxies in the cluster as shown by Figure 12. The highest mass dwarf galaxies have much higher surface brightness prior to in-fall into the cluster. The same is true for lower mass dwarf galaxies but many, particularly those in the lowest mass bin, begin to see substantial change well before in-fall. More enlightening is the evolution in $\mu_{0g}$ with respect to $t_{\text{quench}}$ (lower panels in Figure 12). Prior to quenching the central surface brightness is relatively constant, but following the shutdown of star formation $\mu_{0g}$ declines steadily with time. This decline corresponds to as much as 1-3 magnitudes/arcsec$^2$ by $z = 0$. For all UDGs at all masses this evolution is important for bringing them below the threshold set by our selection criteria. For the lowest mass bins, every galaxy falls below this threshold by $z = 0$ (which is why the galaxy size becomes the most important criteria for determining their status as a UDG). For the highest mass bin the opposite is true: all galaxies are large enough to be UDGs so the central surface brightness is the determining factor in their final classification.

One possible cause for the decline in $\mu_{0g}$ is a decrease in the central stellar density. We test this idea in Figure 14, showing the evolution in the stellar density within the inner 0.5 kpc of each dwarf galaxy. Prior to the quenching of star formation, the central stellar density increases as more stars form. Once star formation ceases, the stellar density declines by $\sim 25 - 50\%$ typically, though it can be as high as 75% in some cases. This is partially related to the decrease in dark matter density (Figure 13) causing stars to puff up, but the strong connection to $t_{\text{quench}}$ likely means other effects are important. Specifically, stellar evolution in the simulation has star particles lose $\sim 30 - 40\%$ of their mass in winds. This can account for a significant portion of the mass loss we see here, keeping in mind that after $t_{\text{quench}}$ this mass loss is permanent. While the galaxy is still star forming the effect of winds is overshadowed by new star formation, sometimes from the very gas lost by the previous generation of stars. After in-fall this gas will be easily stripped away from the galaxy. As we discuss in §5, resolution effects may also contribute to this decline in central stellar density. However, this is a relatively modest change compared to the 1-3 orders of magni-

Figure 10. Evolution in Sersic index for cluster dwarf galaxies. This figure shows the evolution of the Sersic index, $n$, over cosmic time for cluster dwarfs. The average evolutionary track for UDGs (thick orange line) and non-UDGs (thick blue line) in RomulusC, only including galaxies that have fallen inward of $R_{200}$ and can be traced back to at least 2 Gyr after the Big Bang. The stars represent the $z = 0$ values. The average is only calculated at times with at least 3 galaxies in that group. The times are plotted relative to the in-fall time (top) and quenching time (bottom). The shaded regions show the standard deviation at each time and the thin lines show individual trajectories. Galaxies are more concentrated at earlier times, with $n$ typically falling from 2 to 1. There is no apparent change in evolution associated with either quenching or falling into the cluster.
tude change seen in the central surface brightness of dwarf galaxies of all masses, meaning that this cannot be the major cause. Rather, the most important effect is the passive evolution of an aging stellar population (beyond the mass loss from stellar winds).

As the dwarf galaxies fall into the cluster environment, ram pressure strips them of their gas and quenches star formation. Once quenched, the stellar population ages and dims. Figure 15 shows how this process works in more detail for the most massive UDG in our sample. On the top we show the gas column density at four snapshots as the galaxy first crosses inward of R_{200}. Below that, we show the evolution of its star formation rate, which declines over the next Gyr and fully quenches at 8.06 Gyr, approximately 1 Gyr after the initial in-fall. On the bottom we show the evolution of the surface brightness profile at five different times. Before in-fall, the galaxy is star forming with a central surface brightness 1 magnitude brighter than the UDG threshold. After crossing R_{200}, gas begins to feel more ram-pressure. As gas in the outskirts gets stripped initially, gas closer to the center compresses, driving star formation often in the centers of galaxies (Fujita & Nagashima 1999; Bekki & Couch 2003; Kronberger et al. 2008). We see this effect here, with the central surface brightness initially increasing (compare the blue dashed and green dotted lines). However, this is only temporary because it doesn’t take long for all the gas to be stripped away. Once the galaxy is fully quenched (red dot-dashed line) it has a lower surface brightness due to lack of bright, young stars and continuous passive evolution. Approximately 700 Myr after quenching, the galaxy reaches z = 0 it has decreased surface brightness by another order of magnitude (black solid line). Prior to quenching, the shape of the surface brightness profile does change due to, first, a compression of star forming gas and then a slight expansion as cold, star forming gas is stripped away from the center. After quenching, the surface brightness profile evolves in roughly the same way at all radii, decreasing its overall normalization as the stars passively evolve.

Passive evolution is not unique to the cluster environment, as shown in Figure 16. Central surface brightness values of galaxies in isolation follow the same trend with stellar age as galaxies in RomulusC. Galaxies with older stellar populations at their centers have lower central surface brightness. The cluster environment is important mainly as a way to quench star formation in low mass galaxies, which are generally star forming in isolation.
4.2 Angular momentum and galaxy sizes

We have established in the previous section that the sizes of dwarf galaxies increase slightly with time, but such processes are not substantially important for determining the UDG population at $z = 0$. However, Figures 2 and 5 show that, compared to field galaxies, cluster dwarfs are more likely to be large, with the cluster lacking dwarfs of sizes below 1 kpc that exist in isolation. This makes galaxies in the cluster environment inherently more likely to become UDGs. In §5 we discuss the extent to which the lack of small galaxies at the lowest masses may be a resolution effect, but we stress that both RomulusC and Romulus25 have the same resolution and physics and so we can self-consistently compare isolated and cluster dwarf galaxies to better understand why their sizes could be different.

Previous work has theorized that angular momentum is important for determining the sizes of galaxies and that low surface brightness galaxies reside preferentially in halos with larger spin (e.g. Dalcanton et al. 1997; Di Cintio et al. 2019). A similar argument has been made with respect to the origin of UDGs (e.g. Amorisco & Loeb 2016). To study the effect of angular momentum on the sizes of galaxies in cluster and field environments in the Romulus simulations, we use the dimensionless spin parameter, $\lambda^*$ (Bullock et al. 2001). AHP calculates this parameter for each halo in the simulation at all times, accounting for the angular momentum of all halo particles ($\lambda_{\text{tot}}$) as well as just gas particles ($\lambda_{\text{gas}}$). This dimensionless parameter is convenient because it is redshift independent, allowing us to directly compare the spins of halos and gas at different times. However, it is also important to take into account the fact that cluster galaxies are subject to environmental effects that strip away dark matter, as well as all gas, from low mass galaxies. It is reasonable that the final halo spins may not fully represent the effect that angular momentum has on the halo as the galaxy is forming most of its stars. In Figure 11 we show that for lower mass dwarfs galaxies that are larger at $z = 0$ (i.e. UDGs) are also larger at earlier times. In order to capture a potential trend between angular momentum and the formation of dwarf galaxies, we use values for $\lambda_{\text{tot}}$ and $\lambda_{\text{gas}}$ calculated at $t_{50}$, the time at which 50% of the stars have formed in the galaxy. By doing this we sample the state of the halo and potential star forming gas during a period when the galaxy is still growing and ensure that the gas and dark matter have not yet been significantly stripped by the cluster environment.

The top panels of Figure 17 plot the distributions of $\lambda_{\text{tot}}$ at $t_{50}$ for non-UDG cluster dwarfs (blue) and for UDGs (orange) in our...
three mass bins. We also show the distribution for the population of isolated dwarf galaxies in Romulus25 (black, solid). While UDGs do tend to have slightly higher spin values than non-UDGs, the difference is small and both are similar to the overall population of isolated dwarf galaxies. The lower panels of Figure 17 are scatter plots showing the relationship between the final effective radius and the spin parameter measured at $t_{50}$. Galaxy sizes tend to increase toward larger spin parameters, with a stronger relationship at higher masses, but the correlation is relatively weak as the halos do not have a large diversity of spin parameters within any mass bin. Controlling for spin parameter cluster dwarf galaxies are still typically larger, lacking the smaller dwarf galaxies present in isolation in all three mass bins.

Figure 18 is similar to Figure 17 but for $A_{gas}^\prime$, the spin parameter calculated only for gas particles, at $t_{50}$. Compared to total spin, there is a more significant difference in the gas spin distribution for isolated compact ($R_{eff} < 1$ kpc; dashed, black) and large ($R_{eff} > 2$ kpc; dotted, black) dwarf galaxies in all three mass bins. This can also be seen in the scatter plots on the bottom, where there is a more pronounced dependence of $R_{eff}$ on $A_{gas}^\prime$ (and overall more diversity among galaxies at all mass bins). Similar to total spin, the UDGs have a slight tendency to have higher gas spin values than non-UDGs in the cluster. At the two lower mass bins, even non-UDGs are more likely to have higher gas angular momentum compared to isolated dwarfs. This lack of low angular momentum gas at low masses can explain, in part, the lack of compact dwarf galaxies in RomulusC. Galaxies with low spin parameters ($A_{gas}^\prime \sim 0.03$) and $M_\star < 10^8 M_\odot$ make up a large portion of the most compact isolated dwarf galaxies.

Still, the scatter plot on the bottom of Figure 18 shows that even controlling for gas spin isolated galaxies tend to be smaller than cluster galaxies. This difference goes away, however, if we control for the fact that cluster dwarfs are preferentially quenched with much older stellar populations. The black points on the scatter plot show that, for a given gas spin parameter at $t_{50}$, isolated dwarf galaxies with older stellar populations in their centers (a mass-weighted age of $> 7.5$ Gyrs within the inner 1 kpc) have larger sizes, more comparable to cluster dwarf galaxies. While gas angular momentum may contribute to the lack of small galaxies, particularly at low mass, the quenching of star formation also results in dwarfs with larger effective radii. This is likely a combination of 1) younger central stellar populations being brighter and pushing the effective radius inward and 2) wind mass loss and dark matter tidal stripping decreasing the inner mass density over time and puffing the galaxy up, as we describe in §4.1. This may also be partially due to a resolution effect which we discuss further in §5.
UDGs in RomulusC

5 DISCUSSION

In this section we will review our results in light of other observational and theoretical work and discuss various numerical effects that may have influenced our results.

5.1 The role of quenching and passive evolution in creating UDGs

UDGs in the RomulusC simulation are formed through interactions with their dense cluster environment, but not through tidal interactions as has been suggested in previous work (e.g. Ogiya 2018; Carleton et al. 2019). Rather, we find that the cluster environment is crucial in shutting off star formation in low mass galaxies via ram pressure stripping (as seen in Figure 15). Jiang et al. (2019) also find that ram-pressure, rather than tidal stripping, is the main mechanism through which gas is removed from low mass galaxies in groups. Star formation in the more massive dwarfs often remains present longer (~ 1 – 2 Gyr) after in-fall, but lower mass galaxies can quench Gyrs before in-fall. Figure 6 shows a handful of UDGs that have not yet fallen inward of R200. In Tremmel et al. (2019) we find a significant population of galaxies that quench prior to in-fall and, of these, 71% were once within the virial radius of another halo. Indeed observations have shown a significant population of quenched galaxies at large cluster-centric distances (Fujita 2004; Haines et al. 2015). Simulations have shown that galaxies can also be quenched by the larger scale ICM without being a satellite prior to in-fall (Bahé et al. 2013; Zinger et al. 2018). It is possible that there may be other observational signatures in cluster dwarf galaxies such that their history of being pre-processed by another halo may be inferred, which we leave to future work. One limitation to this is that our zoom-in region only extends to ~ 2R200 at z = 0. Future cosmological cluster simulations will be needed to better understand the formation of UDGs at larger cluster-centric distances.

While we do see an evolution in effective radius for galaxies prior to in-fall into the cluster, which agrees with previous studies (e.g. Jiang et al. 2019; Liao et al. 2019), we find that this evolution is often relatively minor (~ 30% increase typically) and does not play a significant role in determining the final UDG population, as both UDGs and non-UDGs experience similar relative increases.
Figure 15. Ram Pressure, Quenching, and the Passive Evolution of Surface Brightness. Here we show the evolution of an example UDG selected from Romulus-C for its $z = 0$ properties. This example galaxy is a relatively massive ($M_\star(z = 0) = 10^{8.53} M_\odot$) system with otherwise typical morphology for UDGs at this mass in the simulation ($n = 1.01$, $R_{e\,eff} = 4.3$ kpc, and $\mu_0 = 25$ mag/arcsec$^2$). The top panel shows four snapshots of the gas column density in the galaxy (with the colors on a scale from $3 \times 10^{19}$ to $5 \times 10^{21}$ m$^{-2}$) as it is crossing $R_{200}$ for the first time. Tails forming from ram pressure stripped gas are seen in all four panels. The middle panel shows the star formation history of the galaxy as a function of time, with the four snapshots marked as vertical dashed lines. The first snapshot after in-fall, which corresponds to the leftmost image in the top panel, occurs at 7.12 Gyr and within 1 Gyr star formation is quenched in the galaxy, with the last remnants of dense gas being pushed away by ram pressure. The bottom panel plots the surface brightness profile of the galaxy at five different times: 1 Gyr before in-fall (blue, dashed), at in-fall (green, dotted), at the time star formation fully quenches (red, dot-dash), the time when the galaxy would first be considered a UDG (orange, solid), and the profile at $z = 0$ (black, solid). The inner surface brightness profile increases just after in-fall, likely due to the compression from ram pressure pushing more gas to the center to form stars. Once the galaxy is quenched we can already see a significant change in the surface brightness within 10 kpc and, as the galaxy is no longer forming new stars, the surface brightness continues to drop roughly evenly across all scales until the galaxy would be considered a UDG. As the galaxy passively evolves, the surface brightness decreases further and the galaxy remains ultra diffuse at $z = 0$. 

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in effective radius after in-fall. The Sersic index does not evolve significantly after in-fall and the quenching of star formation, further evidence that passive evolution is the most important aspect to galaxy evolution post in-fall. Similar to the results from Chan et al. (2018), we find that dwarf galaxies can easily be large enough while still relatively isolated (i.e. well before in-fall into the cluster) but that the cluster environment is important for quenching star formation, which leads to decreased central surface brightness and redder colors more consistent with observed cluster UDGs. An important difference is that we find that none of our dwarf galaxies have low enough central surface brightness to be considered UDGs prior to quenching. This may have to do with the different, more explosive feedback prescriptions used in the FIRE simulations, as well as the higher resolution that is capable of resulting in cored dark matter profiles.

Our prediction that the passive evolution of aging stellar populations is the main mechanism for forming UDGs agrees with observations of UDGs in clusters. Román & Trujillo (2017b) find populations of both red UDGs and blue UDGs, with the latter having slightly higher surface brightness than what would be considered a UDG under our definition. They then predict the surface brightness profiles for the blue UDGs after 6 Gyr of passive evolution and find similar properties to the red UDGs, specifically a much lower central and average surface brightness. This is essentially the exact scenario predicted by ROMULUSC, where quenching results in a decrease in central surface brightness due to passive evolution. As in the observed sample in Roman & Trujillo (2017b), there is little evolution in morphology (as traced by the Sersic index) during this process. This scenario is also consistent with the fact that there is little evidence for tidal distortions in the stellar distributions of UDGs in the Coma cluster (Mowl a et al. 2017). A small subset of UDGs in Coma have been found to have metallicities, ages, and star formation histories consistent with normal dwarf galaxies, along with kinematics consistent with recent in-fall into the cluster (Alabi et al. 2018; Ferré-Mateu et al. 2018). While we do find that there are plenty of UDGs that have recently fallen into the cluster, plenty more have fallen in much earlier (z > 0.5). Due to the importance of passive evolution, dwarf galaxies in ROMULUSC that fall into the cluster earlier are more likely to become UDGs.

One reason why our results may differ from previous theoretical work on satellite UDG formation is that these studies were focusing on UDGs in less massive host halos (e.g. Jiang et al. 2019; Liao et al. 2019). Smaller halos have shorter dynamical times and earlier formation times. It is therefore more likely for dwarf galaxies to in-fall earlier and make several passes around the halo and get preferentially close to the central galaxy. This may make tidal stripping and heating more important to a satellite galaxy’s evolution. There is also the issue of resolution. Even though ROMULUSC is a larger system it is run with resolution better than those for simulations of lower mass groups (e.g. Jiang et al. 2019). As we will discuss in §5.4 resolution can also play an important role in the evolution of galaxy structure and lead to the spurious formation of UDGs in simulations. While ROMULUSC is certainly not excluded from this caveat, it is less susceptible to such effects compared to some previous simulations.

Previous simulations have predicted that isolated galaxies can evolve to have properties that fit the definition of UDGs, showing that bursty star formation and efficient stellar feedback can make galaxies more diffuse over time (Di Cintio et al. 2017; Chan et al. 2018). In particular, Di Cintio et al. (2017) show the connection between UDGs and prominent dark matter cores, which also form as a result of supernovae feedback. In ROMULUSC we find that the interactions with the cluster environment and the subsequent quenching of star formation is critical to creating galaxies with low enough central surface brightness to be considered UDGs. However, this is not to say that we do not predict they should form in isolation. In future work (Wright et al., in prep) we will study the formation of UDGs in lower mass halos and in isolation, comparing the formation channels in different environments. We also note that the ROMULUS simulations do not have the resolution to form dark matter cores and so the formation channel we predict should be considered completely independent of that from Di Cintio et al. (2017). In reality, the bursty star formation and ram pressure stripping/quenching processes can work in tandem to create a population of low surface brightness dwarf galaxies.

5.2 Angular momentum and galaxy sizes

We show in §4.2 that cluster galaxies tend to form from higher angular momentum gas, which is connected in part to their tendency to be larger than isolated galaxies. The connection between angular momentum and low surface brightness galaxies has already been shown for isolated galaxies (Di Cintio et al. 2019) and it has been proposed as a way of forming UDGs as well (Amorisco & Loeb 2016; Liao et al. 2019). We study this connection using the dimensionless gas spin parameter, $I_{v0}$ measured at $r_{50}$, the time at which half of the stars in the galaxy have formed. Ex-situ star formation makes this connection complicated, but we confirm that using $I_{v0}$ and $r_{50}$ yield qualitatively similar results although $r_{50}$ does show the most significant difference between cluster and field galaxies.

UDGs in ROMULUSC formed with similar $I_{v0}$ compared to the overall dwarf galaxy population, yet this overall population does tend to have higher angular momentum gas at $r_{50}$ compared to isolated galaxies. As explained in Di Cintio et al. (2019), higher gas angular momentum keeps star formation at larger radii and leads
Figure 17. Total spin parameter at \( t_{50} \). Top: The distribution of total halo spin at \( t_{50} \), the time at which 50% of the stars formed in the galaxy, for non-UDG cluster dwarf galaxies (blue) and for cluster UDGs (orange). Also plotted for each mass bin are the spin distributions for isolated dwarf galaxies from Romulus25 (black, solid). Additionally, we plot the distribution of spin for isolated galaxies that, at \( z = 0 \), have large (\( R_{\text{eff}} > 1 \) kpc) and small (\( R_{\text{eff}} < 1 \) kpc) sizes. There is not a significant difference in the spin distributions of UDGs and non-UDGs and both are similar to the overall spin distribution of isolated dwarf galaxies. Bottom: Effective radius as a function of total spin parameter at \( t_{50} \) for non-UDG cluster galaxies (blue), UDGs (orange), and isolated dwarf galaxies (grey). At low mass there is no significant dependence of final size on the spin parameter at \( t_{50} \), but there is at higher masses.

to a lower mean surface brightness and larger effective radius. Still, the effect of passive evolution on aging stellar populations also contributes significantly to galaxy sizes at \( z = 0 \). We note that we do see a relationship between total halo spin and galaxy size, but that this becomes increasingly noisy at low mass. The relationship between gas spin and galaxy size is more apparent. While it makes sense that halo spin should determine, in part, the angular momentum available to gas, the additional processes that affect the evolution of gas (cooling, feedback, etc) can contribute to its decoupling from halo spin. Looking at either total or gas spin parameter, we find that our results contrast those from Amorisco & Loeb (2016) who find that UDGs have significantly higher halo spin compared to average dwarf galaxies. Despite hints that gas angular momentum is important for creating larger galaxies in cluster environments, the values for both \( \lambda_{\text{tot}} \) and \( \lambda_{\text{gas}} \) are not significantly different from the average, isolated dwarf galaxy.

The origin of the difference in gas angular momentum among cluster and isolated dwarf galaxies is still uncertain and we leave this to future work. It is possible that these galaxies have expelled their lower angular momentum gas (e.g. Brook et al. 2011; Christensen et al. 2016), but that doesn’t explain the environmental dependence. It is possible that the galaxies in cluster environments are more likely to accrete higher angular momentum gas. Recently, Tadaki et al. (2019) showed evidence for high rates of gas accretion in proto-cluster environments, but the star formation rates were comparable to field galaxies. This lower star formation efficiency could be due to gas accreting with higher angular momentum. Such gas would spend more time at the outskirts of the galaxy at lower densities rather than quickly falling to the center where densities would increase faster.

5.3 Choice of UDG definition

We chose to define our UDG population based on the definition used in van Dokkum et al. (2015) as well as several other works. However, there are other definitions that have been used in the literature for various bandpasses. All definitions generally require an ef-
Figure 18. Gas spin parameter at $t_{50}$. The same as Figure 17, but for the spin just of the gas in each dwarf galaxy halo at $t_{50}$. In all mass bins UDGs are more likely to have high spin compared to non-UDG dwarf galaxies. In the two lowest mass bins, the non-UDG cluster dwarf galaxy population also has higher spin compared to the overall isolated dwarf population in RomulusC. The difference is more pronounced when compared to the spin distribution of compact ($R_{e f f} < 1$ kpc, dashed) isolated dwarf galaxies. Low mass galaxies with low angular momentum gas make up a substantial part of the compact isolated dwarf galaxy population and these galaxies are less likely to exist in the cluster environment. The bottom panels show a slight dependence of $R_{e f f}$ at $z = 0$ on $\lambda _{gas}^\prime$ becoming more important for higher mass dwarfs. The trend is more pronounced compared to $R_{e f f}$ (Figure 17) and the halos have more diversity in gas spin compared to total spin. At a given $\lambda _{gas}^\prime$, value the cluster environment still lacks compact dwarfs relative to the field. This difference goes away if we consider only isolated galaxies with old (> 7Gyr) stellar populations in their central 1 kpc (black points). Both gas angular momentum and a lack of recent star formation in their centers contribute to the lack of compact cluster dwarf galaxies in RomulusC.

The effective radius of $\sim 1.5$ kpc or similar. A common alternative definition involves using the mean surface brightness within $R_{e f f}$, rather than the central surface brightness (Koda et al. 2015; van der Burg et al. 2016; Ferré-Mateu et al. 2018). At a fixed stellar mass, $R_{e f f}$ and mean surface brightness are directly related to one another: larger galaxies have a lower mean surface brightness. In this way, the central surface brightness is a more orthogonal criteria to the effective radius which is why we choose to adopt it in this work. Following van der Burg et al. (2016), were we to define galaxies as UDGs using their r-band properties such that $24.4 < (\mu (R_{e f f})) < 26$ mag/arcsec$^2$ as UDGs, most of our high mass dwarf galaxies would be classified as UDGs while most of our low mass galaxies would lie below the allowed range of surface brightness. Overall, our results on the origin of UDGs remain largely unchanged were we to change to this definition. The sizes of galaxies only slightly change over time (see Figure 11). Passive evolution after galaxies quench will result in a decrease in both central and mean surface brightness over time (see the bottom panel in Figure 15). In future work we will examine in more detail the effect of different UDG definitions, galaxy orientation, and the use of a more detailed surface brightness fit using GalFit on our predicted UDG population. We will also make predictions for the axis ratio and predict any secondary effects of environment on these more detailed morphological parameters.

5.4 Resolution effects

While RomulusC is state-of-the-art for cosmological simulations of halos of this mass, the spatial and mass resolution are still low compared to zoom-in cosmological simulations of isolated galaxies and it is important to understand how this might affect our results.
5.4.1 The lack of compact dwarf galaxies

The RomulusC simulation notably lacks compact dwarf galaxies ($R_{\text{eff}} < 1$ kpc) in the cluster environment, despite the fact that many such galaxies have been observed (Gavazzi et al. 2005; Eigenthaler et al. 2018; Venhola et al. 2019b). Many simulations, including some at higher resolution, have had difficulty creating small low mass galaxies in isolation or as satellites (e.g. El-Badry et al. 2016; Lupi et al. 2017; Jiang et al. 2019; Chan et al. 2018). While this can often be attributed to feedback and/or ISM sub-grid models, in Romulus the issue is at least partially due to resolution. With a spline kernel softening length of 350 pc, structures well below 1 kpc are difficult to resolve. Further, the relatively low resolution and simple ISM physics means that star formation must be allowed to occur at relatively low densities. All together, this means that it is difficult to generate very dense structures in the simulation such that more than half of a galaxy’s mass is within < 1 kpc from the galaxy center. This lower limit to structure can be seen in the flattening of the size-mass relation (Figure 2) at stellar masses lower than $\sim 10^{7.5}$ $M_{\odot}$. The flattening occurs just above 1 kpc and results in our lowest mass galaxies being a factor of ~2 times larger than the empirical relation.

The fact that star forming gas cannot form dense stellar structures in our simulation due to limited spatial resolution and a low density threshold for star formation results in a lack of compact galaxies. It also makes it easier to form UDGs, as galaxies are more likely to be large and lack a dense nucleus. How much this affects our UDG predictions is unclear, but it is likely contained to mostly the lowest masses ($M_{\star} < 10^{7.5}$ $M_{\odot}$). At higher masses our galaxies match much better to the observed size-mass relation. If most low mass galaxies are more compact, it would be more difficult to form UDGs and we would therefore overpredict the number of low mass UDGs in the cluster. However, the result connecting central surface brightness to the quenching of star formation remains robust to such resolution effects.

5.4.2 Two body interactions and energy equipartition

Galaxies resolved with only a few hundred star particles (like those in our lowest mass bin) are subject to effects related to two-body relaxation and energy equipartition among different mass particles. Even though dark matter particles have similar mass to gas particles in the Romulus simulations, star particles form with only 30% of their parent gas particle mass. It may be the case that the decrease in central stellar mass densities (see Figure 14) and increase in galaxy sizes (see Figure 11) are results of this effect, which causes the puffing up of stars relative to the more massive dark matter particles, particularly in quiescent galaxies. However, the change we see in central density is only ~30% on average and can mostly be explained by wind mass loss from aging stellar populations as well as the decreasing dark matter mass density (see Figure 13). According to Ludlow et al. (2019), energy equipartition should result in an increase in the sizes of galaxies over time, becoming more prominent in lower mass galaxies that are resolved with fewer star particles. However, we see just as much if not more evolution in effective radius for more massive dwarf galaxies (see Figure 11) that are resolved with several thousand star particles as we do at our lowest mass bin. It is therefore unlikely that our simulated dwarf galaxies are suffering from this effect.  

5.4.3 Resolution and ram pressure stripping

Dense, molecular gas would be more resistive to ram pressure stripping in the cluster environment, but such dense gas is unresolved in the simulation. Therefore even though at this resolution ram pressure stripping itself is well resolved (Roediger et al. 2015), the fact that star forming gas is less dense will make it artificially more efficient at being stripped from galaxies interacting with the cluster environment. Further, feedback taking place in low density gas in low mass galaxies may be too efficient at disturbing the cold gas and make it even more susceptible to being stripped even in relatively low density environments (Schaye et al. 2015; Bahé et al. 2017). Using RomulusC25 we confirm that in isolation we do not produce a significant population of quenched dwarf galaxies above a stellar mass of $10^{7.5}$ $M_{\odot}$. Only at our lowest masses ($M_{\star} < 10^{7.5}$ $M_{\odot}$) do we begin to see significant evidence of such overquenching.

It is likely that the limited resolution for the ISM means that ram pressure stripping and the subsequent quenching of star formation may happen too quickly, particularly for the lowest mass galaxies. In reality the multiphase ISM would be more resistant to ram pressure, with star forming gas surviving for longer periods after infall. However, we do not expect this to have a significant impact on our results. Many of the UDGs have been within the cluster environment for a long time already and would likely have been stripped no matter what. At low masses the evolution in central surface brightness happens such that the galaxies are well below the threshold for being UDGs, so a delay in their quenching would only be a secondary effect. This may mean that the population of UDGs that have fallen in more recently is overestimated, but they are in the minority. More massive galaxies, which depend more closely on the evolution of $\mu_\star$ for being considered UDGs, may be less likely to be considered UDGs at $z = 0$ if they quench later, but this will not qualitatively affect our conclusions as to their origin or evolution.

5.4.4 The lack of dark matter cores

Feedback from supernovae can affect the distributions of both stars and dark matter in dwarf galaxies, but this requires simulations that can resolve individual, dense star-forming regions (Governato et al. 2010, 2012; Pontzen & Governato 2012, 2013; Di Cintio et al. 2014; El-Badry et al. 2016; Dutton et al. 2019). As already discussed at length, the limited resolution attainable for such a massive simulation as RomulusC means that the multiphase ISM cannot be resolved and stars must form in gas with lower density and higher temperature thresholds. This affects the environment in which supernovae explode and their spatial distribution throughout the galaxy. This low resolution model is incapable of forming cored dark matter profiles (e.g. Genina et al. 2018; Bose et al. 2019; Dutton et al. 2019), which some simulations predict is an important part of forming UDGs (Di Cintio et al. 2019). While the lack of dark matter cores is not a prediction of the simulation, but a result of its lower resolution, the fact that UDGs still form in RomulusC means that the formation channels we predict in this work are unique compared to that of Di Cintio et al. (2019) where bursty star formation, efficient feedback, and cored dark matter profiles are critical. In reality, it is likely that a combination of both processes are important for shaping the UDG population in both isolation and in clusters. It is possible that a cuspier dark matter profile contributes to the lack of tidal evolution of dwarf galaxies in RomulusC (Carleton et al. 2019) as there is more binding energy to hold the galaxies
together. It is possible that, with a heavily cored profile, cluster dwarfs experience more evolution in their central densities and effective radii due to various tidal interactions. Still, we show in this work that such interactions are not required to form UDGs in the first place. The lack of dark matter cores may also contribute to the Sersic indices that are slightly larger than observed UDGs (see Figure 5). More central mass concentration could mean more concentrated stellar distribution and therefore higher Sersic index.

5.5 Classification and predicted number of UDGs in low mass clusters

Using our criteria for UDG classification, we identify 80 UDGs within $R_{200}$ of the $10^{14} M_\odot$ RomulusC galaxy cluster, approximately twice as many as observations have found for halos of this mass (Román & Trujillo 2017b; van der Burg et al. 2017). It is important to note that our classifications are done assuming a face-on observer, where galaxies have the least surface brightness. Were they to be observed at different viewing angles, these galaxies may not be classified as UDGs so this number should be considered an upper limit. We also calculate surface brightness profiles using simple radial bins, rather than performing a full analysis with GalFit. It is unlikely that this would have a large effect on our results, but it could mean that we overestimate the effective radius for our galaxies with lower axis ratios. In future work we will both examine the effect of galaxy orientation and perform a more detailed analysis with GalFit to classify galaxies and extract axis ratios.

Our results are also sensitive to the definition of UDG. It is important to note that many of the UDGs in RomulusC are low mass with very low surface brightness, such that they may not be detected at all in some surveys. Rather than placing restrictions on central surface brightness, many groups instead define UDGs based on the mean surface brightness measured within the effective radius, $\langle \mu(R_{eff}) \rangle$. Adopting the criteria of van der Burg et al. (2016) that defines UDGs as having $24.4 < \langle \mu(R_{eff}) \rangle < 26$ mag/arcsec$^2$ and $R_{eff} > 1.5$ kpc, where $\mu_0$ is the surface brightness in the r-band, we would get 51 UDGs. Using this criteria, most of our low mass galaxies would be undetected and many non-UDG dwarfs at higher masses would be considered UDGs. The limit on the mean surface brightness is important. Were we to take our fiducial UDG classified galaxies and apply the additional criteria of $\langle \mu(R_{eff}) \rangle < 27$ mag/arcsec$^2$ to approximate observational limits, our 80 UDGs would decrease to 50 within $R_{200}$ and once again exclude the majority of our lowest mass dwarf galaxies. The effective radius is similar between g and r-bands so the main effect of adopting different criteria is really the range of allowed mean surface brightness. Taking into account observational limitations in detecting objects with low mean surface brightness means that the number of large, diffuse dwarf galaxies in RomulusC is similar to observations.

Our results are insensitive to our specific selection criteria for UDGs. We show in Figures 10, 11, and 12 that the evolution of UDGs and non-UDG dwarf galaxies are very similar. Figure 15 demonstrates that the passive evolution of the quenched galaxies affects the mean surface brightness as well as $\mu_0$. For massive galaxies there is little difference in the evolution in $R_{eff}$. When each galaxy does or does not cross the UDG threshold depends mostly on how long it has been quenched. The same qualitative results will hold true for the mean surface brightness.

6 SUMMARY AND CONCLUSIONS

We have selected galaxies from the RomulusC cosmological zoom-in simulation of a galaxy cluster that fit the criteria of van Dokkum et al. (2015) for being considered ultra-diffuse ($R_{eff} > 1.5$ kpc, $\mu_0 > 24$ mag/arcsec$^2$). The UDGs in RomulusC match well with the observed properties of cluster UDGs. Our simulated UDGs are all dwarf galaxies, so we compare the population of UDGs to the overall population of dwarf galaxies in the cluster ($M_\star < 10^8 M_\odot$). We leverage the fact that we can trace all galaxies back in time to better understand the role of environment in forming the UDG population. We also compare to the population of isolated dwarf galaxies from the Romulus25 simulation.

- UDGs in galaxy clusters form from dwarf galaxies that experience ram pressure stripping as they travel through the hot, dense cluster environment. This results in the quenching of star formation. The subsequent passive stellar evolution is the cause of their low surface brightness at $z = 0$.

- The central surface brightness decreases by 1-3 orders of magnitude following the quenching of star formation. The evolution is similar for UDGs and non-UDGs. Prior to quenching, UDG progenitors are 1-2 magnitudes brighter than what is required for UDG classification. The evolution in surface brightness cannot be accounted for by decreasing central stellar densities, which fall by typically only 30% over the course of the simulation after star formation is quenched.

- Passive evolution of stars results in a relationship between stellar age and central surface brightness that is the same in the cluster environment as it is for isolated galaxies. Dwarfs with older stellar populations have lower central surface brightness.

- The evolution of galaxy morphology is similar for UDGs and non-UDGs. UDG progenitors tend to be slightly larger (at low mass) and have slightly lower central surface brightness (at high mass) than non-UDG progenitors. Dwarf galaxies that fall into the cluster earlier ($z > 0.5$) are approximately twice as likely (> 80%) to become UDGs as those that fall in later.

- The classification of lower mass dwarf galaxies ($M_\star < 10^8 M_\odot$) as UDGs depends mostly on their effective radius, while for higher mass dwarfs ($M_\star > 10^8 M_\odot$) the classification depends on their central surface brightness.

- UDGs are not a separate population compared to non-UDG dwarf galaxies in terms of absolute magnitude, central surface brightness, and effective radius. Rather, they are part of a continuous distribution of dwarf morphologies. UDGs also have similar positions and velocities relative to the center of the cluster as non-UDGs and have similar Sersic indices compared to both non-UDG cluster dwarfs and isolated dwarfs.

- Both UDGs and non-UDG dwarf galaxies are, at the time of their maximum halo mass, consistent with the stellar-mass halo mass relation. UDGs have dark matter halos with peak virial mass below $10^{11} M_\odot$. Tidal stripping results in decreased halo masses and central dark matter densities at $z = 0$, but does not affect their final stellar mass.

- Both UDGs and non-UDGs have similar halo spin values at
t_{ff}$, the time at which 50% of the galaxy’s final stellar mass has assembled. Cluster dwarf galaxies and isolated galaxies also have similar values for total halo spin at $t_{ff}$. Cluster UDGs are more likely to have slightly higher gas spin values at $t_{ff}$ compared to isolated galaxies.

- The effective radius of all dwarf galaxies increases typically by $\sim 30\%$ after quenching and in-fall into the cluster. This evolution is the result of a decrease in central mass density due to the tidal stripping of dark matter, wind mass loss from stellar evolution, and ram pressure stripping of gas. At low masses, where the final effective radius strongly determines their classification, UDGs typically have larger effective radii compared to non-UDGs Gyrs before quenching or in-fall.

- Cluster dwarf galaxies lack the population of more compact dwarfs ($R_{\text{eff}} < 1$ kpc) seen in isolation in Romulus25. Partly this is due to the fact that they are mostly quenched and have had their dark matter stripped (see above). Another difference is that cluster galaxies form their stars from higher angular momentum gas compared to isolated galaxies.

These results show that UDGs form in clusters through passive evolution of a population of quenched dwarf galaxies and the formation of a dark matter core or a high spin halo is not a requirement in their formation. They also support the notion that UDGs are, in general, just a sub-sample of the overall dwarf galaxy population, rather than a unique type of galaxy with a unique evolutionary path. Although the overall population of UDGs is not unique in terms of their evolution compared to non-UDGs, there may be individual cases where UDGs are created more violently through mergers or close interactions. We leave it to future work to examine individual cases in the RomulusC simulation, though it is clear from Figures 10-14 that there are plenty of candidates for such unique evolutionary paths. In Wright et al. (in prep) we will build on these results and examine the population of UDGs in lower mass halos and in isolation using the Romulus25 simulation in order to compare formation channels in different environments.

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