Dark-matter-deficient galaxies in hydrodynamical simulations

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ABSTRACT
Low-mass galaxies are expected to be dark-matter-dominated even within their central regions. Recently, two observations reported two dwarf galaxies in a group environment with very little dark matter in their central regions. We explore the population and origins of dark-matter-deficient galaxies (DMDGs) using two state-of-the-art hydrodynamical simulations, the EAGLE and Illustris projects. For all satellite galaxies with $10^9 < M_* < 10^{10} \, M_\odot$ in groups with $M_{200} > 10^{13} \, M_\odot$, we find that about 2.6 per cent of them in EAGLE, and 1.5 per cent in Illustris are DMDGs with dark matter fractions below 50 per cent inside two times the half-stellar-mass radius. We demonstrate that DMDGs are highly tidally disrupted galaxies, and that because dark matter has a higher binding energy than stars, mass loss of the dark matter is much more rapid than that of stars in DMDGs during tidal interactions. If DMDGs were confirmed in observations, they are expected in current galaxy formation models.

Key words: methods: numerical – galaxies: evolution – dark matter.

1 INTRODUCTION
In the standard ΛCDM framework, cold dark matter is the dominant mass budget of the Universe, but it can be less important at small scales. For example, for Milky Way–like galaxies and more massive ones, while dark matter dominates the total mass budget within the virial radius of their dark matter haloes, the central regions of these galaxies are dominated by baryons. Low-mass systems, for example dwarf galaxies, however, have a shallower potential and suffer more from various physical processes, for instance stellar feedback and UV ionization heating, and so cannot make stars as efficiently as high-mass systems. As a result, the central regions of dwarf galaxies are predicted to be dark-matter-dominated. This expectation has been confirmed in observations of the dark matter distributions of many nearby dwarf galaxies and also by modern hydrodynamical simulations (e.g. Schaller et al. 2015; Sawala et al. 2016).

However, recent observations suggest that some of these low-mass galaxies may have very low dark matter fractions. For example, DDO 50, a galaxy in the catalogue of LITTLE THINGS (Oh et al. 2015), has a stellar mass very close to the total dynamical mass, indicating a baryonic mass fraction 10 times higher than that of normal dwarf galaxies with the same maximum circular velocity (see also Oman et al. 2016). In another recent observation by van Dokkum et al. (2018), a low-surface-brightness galaxy, NGC 1052-DF2, was shown to reside in a system with only a subdominant amount of dark matter. These latter authors carried out a dynamical analysis of the globular clusters of this system and showed that, within a radius of 7.6 kpc, the total mass is $3.4 \times 10^9 \, M_\odot$ while the stellar mass is $2 \times 10^8 \, M_\odot$. This implies that the dark matter mass is at least 400 times lower than in other galaxies of the same mass, but the results remain controversial (Martin et al. 2018; Blakeslee & Cantiello 2018; Wasserman et al. 2018; Laporte, Agnello & Navarro 2019).

In this short paper, we make use of two sets of state-of-the-art hydrodynamical simulations, the EAGLE (Schaye et al. 2015; Crain et al. 2015) and Illustris (Genel et al. 2014; Vogelsberger et al. 2014a,b) projects, to explore whether or not dark-matter-deficient galaxies (DMDGs) are allowed in current galaxy formation models. If the answer is yes, what is the physical origin of the formation of these DMDGs?

The structure of this paper is as follows. In Section 2 we briefly describe the simulation data used in this work, and in Section 3 we determine the fraction of DMDGs in our galaxy samples. We then explore the formation history of DMDGs in Section 4, and we summarize our results in Section 5.

2 SIMULATIONS
The numerical simulations used in this study comprise two large hydrodynamical galaxy formation simulations, the Illustris and EAGLE projects. Below we briefly describe these simulations.

2.1 Illustris simulations
The Illustris project (Genel et al. 2014; Vogelsberger et al. 2014a,b; Sijacki et al. 2015; Nelson et al. 2015) consists of a series of cosmo-
logical hydrodynamical simulations performed with a moving-mesh code, AREPO (Springel 2010). The simulations assume a standard cosmological model with \( \Omega_m = 0.7274, \Omega_b = 0.2726, \Omega_{\Lambda} = 0.0456, \sigma_8 = 0.809, n_s = 0.963 \) and \( H_0 = 70.4 \text{ km s}^{-1} \text{ Mpc}^{-1} \). In this study, we make use of the Illustris-1 simulation (hereafter Illustris), which follows the evolution of a cosmic volume of \( (106.5 \text{ Mpc})^3 \) from redshift \( z = 127 \) to \( z = 0 \). The mass resolutions are \( m_{\text{DM}} = 6.26 \times 10^9 \text{ M}_\odot \) for dark matter particles, and \( m_b = 1.6 \times 10^6 \text{ M}_\odot \) for typical baryonic elements. The softening length for dark matter particles is fixed to \( \epsilon_{\text{DM}} = 1.42 \text{ kpc in comoving units, whereas the softening length for stars is limited to a maximum physical scale of } \epsilon_{\text{star}} = 0.71 \text{ kpc}. Haloes and subhaloes are identified with the friends-of-friend (FOF, Davis et al. 1985) and the SUBFIND (Springel et al. 2001) algorithm, respectively. The merger trees of subhaloes are constructed by the SUBLINK algorithm; see Rodriguez-Gomez et al. (2015) for details.

### 2.2 EAGLE simulations

The EAGLE project (Crain et al. 2015; Schaye et al. 2015) comprises a suite of hydrodynamical simulations performed with an N-body Tree-PM smoothed particle hydrodynamics code, GADGET-3 (Springel, Di Matteo & Hernquist 2005). The data from the simulation have been publicly released; see McAlpine et al. (2016) for details. In this work, we use the reference model run Ref-L0100N1504 (hereafter EAGLE), which follows the evolution of a volume of \( (100 \text{ Mpc})^3 \). The particle masses for the initial gas and dark matter particles are \( m_b = 1.8 \times 10^6 \text{ M}_\odot \) and \( m_{\text{DM}} = 9.7 \times 10^6 \text{ M}_\odot \), respectively. The simulation adopts a comoving softening length of \( 2.66 \text{ kpc at early time, and switches to a fixed value of } 0.7 \text{ kpc in physical scale at } z = 2.8 \) for dark matter and baryonic particles.

We also use the Ref-L0025N0752 run (hereafter EAGLE-highres), which has a higher mass resolution of \( m_b = 2.26 \times 10^6 \text{ M}_\odot \) and \( m_{\text{DM}} = 1.21 \times 10^6 \text{ M}_\odot \), but a smaller volume of \( (25 \text{ Mpc})^3 \). The softening length for EAGLE-highres is \( 1.33 \text{ comoving kpc initially, and is fixed to } 0.35 \text{ physical kpc after } z = 2.8 \). All runs adopt a flat \( \Lambda \text{CDM cosmology with parameters given by } \text{Planck results, namely } \Omega_m = 0.307, \Omega_b = 0.693, \Omega_{\Lambda} = 0.04825, n_s = 0.9611, \sigma_8 = 0.8288 \) and \( H_0 = 67.77 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Planck Collaboration et al. 2014a,b). Similar to the Illustris simulations, haloes and subhaloes in the EAGLE simulations are identified by FOF and SUBFIND algorithms. The merger trees of subhaloes are constructed by the D-Trees algorithm (Jiang et al. 2014).

### 3 DARK MATTER FRACTION OF SATELLITE GALAXIES

Because the reported dark-matter-deficient dwarfs were discovered in group of galaxies, we select satellite galaxies in galaxy group environments to see whether or not they exist in modern cosmological hydrodynamical simulations. More specifically, we select satellite galaxies (belonging to FOF) with stellar mass \( 10^9 < M_\star < 10^{10} \text{ M}_\odot \) (containing at least 500 star particles) from host haloes with halo masses \( M_{200} > 10^{13} \text{ M}_\odot \), and measure the dark matter fraction, \( f_{\text{DM}} = M_{\text{DM}}(< 2R_2)/M_{\text{tot}}(< 2R_2) \), within two times the half-stellar-mass radius, \( R_h \). Because EAGLE-highres has a mass resolution \( \sim 10 \) times better than that of the other two runs, we select its satellite galaxies with \( 10^9 < M_\star < 10^{10} \text{ M}_\odot \) in order to have a similar effective resolution for stars. Throughout this paper, \( M_{200} \) is defined as the mass enclosed in \( R_{200} \), within which the average density of a halo is 200 times the critical density of the Universe.

In Fig. 1, we show the dark matter fraction \( f_{\text{DM}} \) of our sample galaxies as a function of their halo-centric distances. Results for the Illustris and EAGLE simulations are shown in the left and the right panel, respectively. While dark matter dominates the total mass budget of the majority of satellite galaxies within \( 2R_h \) for all simulations, a few per cent of galaxies have \( f_{\text{DM}} \) below 50 per cent. Here, we define the DMDGs as galaxies with \( f_{\text{DM}} \) below 50 per cent. In Table 1, we list the fractions of DMDGs in all satellite galaxies from the Illustris and EAGLE simulations. About 1.5 per cent of the Illustris satellite galaxies have dark matter fractions less than 50 per cent within \( 2R_h \), while the fraction is about 2.6 per cent in the EAGLE simulation. We note that there are galaxies with \( f_{\text{DM}} = 0 \) in Illustris. These galaxies are probably tidal dwarf galaxies formed in the tidal tails of interacting galaxies (Ploeckinger et al. 2018); we neglect these galaxies in the rest of this paper.

Fig. 2 presents two examples of DMDGs (one from Illustris and one from EAGLE-highres). For each galaxy, we show the projected distributions of star and dark matter particles (upper panels), the cumulative mass profiles (middle panels), and the spherically averaged density profiles of different components (lower panels).
Table 1. Fraction of satellite galaxies with $f_{\text{DM}} < 0.5$ in haloes with $M_{200} > 10^{13} M_\odot$.

<table>
<thead>
<tr>
<th>Stellar mass limit ($M_\odot$)</th>
<th>Illustris</th>
<th>EAGLE</th>
<th>EAGLE-highres</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^9 &lt; M_* &lt; 10^{10}$</td>
<td>1.5%</td>
<td>2.6%</td>
<td>3.2%</td>
</tr>
<tr>
<td>$10^8 &lt; M_* &lt; 10^{10}$</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$10^9 &lt; M_* &lt; 10^{10}$</td>
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<tr>
<td>$10^8 &lt; M_* &lt; 10^{10}$</td>
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</tbody>
</table>

Figure 2. Two representative DMDGs from the Illustris (left) and EAGLE-highres (right) simulations. The top panels show the projected star and dark matter particles of each galaxy. The middle panels plot the enclosed mass as a function of radius for stellar (red), dark matter (black) and total (grey) mass. The bottom panels show the density profiles of each component. The green dotted vertical lines indicate the half-stellar-mass radii. The blue dotted line in the middle and bottom panels show the results for Navarro-Frenk-White (NFW, Navarro, Frenk & White 1997) haloes with masses determined by the mean $M_* - M_{200}$ relationship in the corresponding simulations ($M_{200} = 1.06 \times 10^{11} M_\odot$ (left) and $5.51 \times 10^{10} M_\odot$ (right)). The concentrations are calculated from the concentration–mass relationship taken from Dutton & Macciò (2014), and the blue shaded regions represent one sigma of concentration.

panels). It can clearly be seen that there are more stars than dark matter particles within about two times the half-stellar-mass radius.

4 FORMATION HISTORY OF DMDGS

To understand the origin of these simulated DMDGs, we trace their formation histories back to early time to see their evolution. In Fig. 3, we present the evolution of the density profiles of the dark matter, stars and gas of a representative DMDG selected from EAGLE at three epochs, $z = 0.1$, 1.0 and 2.0. Dark matter dominates over stars and gas over all radial ranges at earlier times, but eventually it becomes subdominant at $z \approx 0$. The shape of the dark matter profile does not change much between $z = 1.0$ and $z = 0.1$, while its amplitude drops by a factor of 10. This suggests that the mass loss of dark matter occurs at all scales, consistent with Frings et al. (2017), who used idealized simulations and found that the whole dark matter profile of a satellite decreases owing to tidal forces after infall. In the same redshift range, the amplitude of the stellar profile
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Figure 3. Evolution of the density profiles of different components for a DMDG selected from the EAGLE simulation. The dashed and solid lines denote the profiles of stars and dark matter, respectively. The black, red and blue lines distinguish results for different redshifts as labelled in the figure. The black vertical line indicates $2R_h$ of the galaxy at $z = 0$.

Figure 4. Mass (left axis) and velocity dispersion ($\sigma$) (right axis) of the dark matter and star components as a function of redshift for the DMDG shown in Fig. 3. The mass and dispersion at each redshift are calculated within 2.34 physical kpc ($2R_h$ of the galaxy at $z = 0$). The black and red solid lines represent the enclosed mass results for the dark matter and stars, respectively. The blue vertical line indicates the infall time of the satellite galaxy.

decreases by only 10–50 per cent. Apparently, the mass loss of dark matter is more rapid than that of stars.

This can also be seen in Fig. 4, where we plot the mass growth history (left axis) of the same galaxy. Here the masses of galaxies are defined as the enclosed mass within a fixed 2.34 physical kpc ($2R_h$ of the galaxy at $z = 0$). The blue vertical line indicates the infall time of the satellite galaxy, which is defined as the redshift when the galaxy enters into $R_{200}$ of its parent halo. Clearly, both the enclosed dark matter and the stars within the range decrease rapidly after the infall redshift $z_{\text{infall}} \sim 2$, yet dark matter loses mass at a much higher rate than the stellar component. In the end, for both components, only a few per cent of their initial masses remain.

What causes the galaxy to lose dark matter more rapidly than stars? One possibility is that dark matter and star particles have different energy distributions. To verify this, in the same figure we plot the velocity dispersion of dark matter particles and star particles within the same $r$ range. The velocity dispersion of the dark component is about 30 per cent higher than that of stars at early time, and the difference increases significantly at later times, which may be induced by the tidal shocking (e.g. Gnedin & Ostriker 1997; Gnedin, Hernquist & Ostriker 1999a; Gnedin, Lee & Ostriker 1999b; Kazantzidis et al. 2011; Prieto & Gnedin 2008). This supports the expectation that dark matter particles are dynamically ‘hotter’ than stars and so are prone to be tidally disrupted. We demonstrate this further below.

We select all the star/dark matter particles within 2.34 physical kpc of the galaxy at $z = 2.01$ ($z_{\text{infall}}$), at which the galaxy enters into the virial radius of its parent halo. Then we plot their specific binding energy distributions in Fig. 5 as dashed lines. Different colours distinguish the distributions of different components. Here, the specific binding energy $sE$, namely the energy per mass, of

Figure 5. In the top panel, the dotted histograms show the mass-weighted and normalized specific binding energy distributions of dark matter (black) and star (red) particles within 2.34 physical kpc at $z = 2.01$ for the DMDG shown in Fig. 3. The solid histograms show results for the dark matter and star particles remaining bound at $z = 0$. The lower panel shows the fraction of mass that still remains bound at $z = 0$ in each specific binding energy ($sE$) bin.
We show the fraction of mass that still remains bound at binding energy remain at the present day. In the lower panel of this figure, we show the specific energy distribution of the particles that remain to be bound at $z = 0$ in the same plot, with solid lines. Compared with the results at $z = 2$, only the particles with low binding energy remain at the present day. In the lower panel of this figure, we show the specific energy distribution of the particles that remain to be bound at $z = 0$ as a function of $sE_i$. Clearly, particles with higher binding energy tend to be tidally disrupted. The tidal origin of DMDGs has been discussed in the literature (Ogiya 2018; Chang, Macciò & Kang 2013; Yu, Ratra & Wang 2018). Ogiya (2018) argued that the more rapid mass loss of dark matter could be explained if a galaxy has a cored mass distribution before infall. We find that both EAGLE and Illustris simulations have a cuspier dark matter distribution in dwarf galaxies. Recent studies demonstrate that this may be due to the low gas-density threshold for star formation (e.g. Benitez-Llambay et al. 2018; Bose et al. 2019; Dutton et al. 2019). Therefore, cored profiles are not a necessary condition to form DMDGs. Up to now, we have focused the discussion on one typical DMDG example. In Appendix A, we show 11 additional examples, five from Illustris, five from EAGLE, and one from EAGLE-highres. In addition, we also show the stacked results of Illustris and EAGLE in Appendix A. Our conclusions do not change when considering all DMDGs in the sample.

The galaxy discussed above apparently experiences strong tidal interactions with its host. Do all DMDGs experience such strong tidal interactions? In Fig. 6, we plot the distribution of $r_{\text{min}}$ for the DMDGs in the EAGLE and Illustris simulations, and compare it with that for normal satellite galaxies. Here $r_{\text{min}}$ is an approximation of the pericentre distance, which is defined as the minimal distance of the galaxy from its parent halo in its history. Generally, a smaller $r_{\text{min}}$ corresponds to stronger tidal interactions. We find that DMDGs have a very different $r_{\text{min}}$ distribution from normal satellite galaxies; that is, in the EAGLE (Illustris) simulation, the $r_{\text{min}}$ of DMDGs tends to be distributed in the very inner region of the host haloes with a median value of $r_{\text{min}}/R_{200} = 0.046$ (0.062), which is significantly smaller than that of normal satellite galaxies, namely $r_{\text{min}}/R_{200} = 0.411$ (0.381).

Although the pericentre distance is usually a good estimator of the degree of tidal interaction, the tidal stripping strength also depends on other orbital parameters, such as the orbital energy at infall, the time spent in the host halo and the eccentricity of orbit, and the properties of the satellite, such as its stellar mass and its compactness (see e.g. Frings et al. 2017; Fattahi et al. 2018; Buch et al. 2019; Li, Gao & Wang 2019). Instead of exploring each of these parameters, we directly compare in Fig. 7 the mass-loss fractions of DMDGs and normal satellite galaxies. The mass-loss fraction is calculated as the total SUBFIND mass loss of the satellites since their infall. It is easy to see that DMDGs all suffer significant mass loss. The median mass-loss fraction for DMDGs is 98.7 per cent (98.4 per cent), while it is 64.8 per cent (48.7 per cent) for normal satellite galaxies in the EAGLE (Illustris) simulation. All these results strongly suggest that DMDGs are highly tidally disrupted galaxies.

5 CONCLUSIONS

We used two sets of state-of-the-art hydrodynamical cosmological simulations to investigate whether or not DMDGs are allowed in current galaxy formation models. Our results can be summarized as follows.

For satellite galaxies in galaxy groups/clusters, 1.5 percent of galaxies have dark matter fractions below 50 per cent within two times the half-stellar-mass radius in the Illustris simulation, while this percentage is slightly higher in the EAGLE simulation, namely 2.6 per cent.

We traced the formation histories of DMDGs back to earlier times, and found that these DMDGs were not originally dark-matter-deficient but became so at later times owing to strong tidal interactions with the central galaxies of their hosts. During the interactions, because the binding energy of dark matter in these DMDGs is significantly higher than that of stars, the mass loss of...
dark matter is much more rapid than that of stars, meaning that they are dark-matter-deficient at the present day. Compared with normal satellite galaxies in group/clusters, the median value of $r_{\text{min}}/R_{200}$ of DMDGs is on average two times closer to their central galaxies; DMDGs also lose a much larger fraction of their original masses than normal satellite galaxies. These results suggest that DMDGs are highly disrupted systems, and if DMDGs were confirmed in observations, they are expected in current galaxy formation models.

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APPENDIX A: ADDITIONAL EXAMPLES

Here we provide 11 additional examples, five from Illustris (Fig. A1), five from EAGLE (Fig. A2), and one from EAGLE-highres (Fig. A3). Each row denotes one DMDG. The columns from left to right are similar to in Figs 4, 3 and 5, respectively. We also show the stacked results of Illustris and EAGLE in Figs A4 and A5, respectively.
Figure A1. Evolution of DMDG examples selected from Illustris. Each row denotes one DMDG. The columns from left to right are similar to in Figs 4, 3 and 5, respectively.
Figure A2. Similar to Fig. A1, but selected from EAGLE.
Figure A3. Similar to Fig. A1, but selected from EAGLE-highres.

Figure A4. Stacked results for DMDGs within different $z_{\text{infall}}$ bins for Illustris. Each row represents the stacked results of DMDGs in the same $z_{\text{infall}}$ bin. Left columns are similar to Fig. 4, but the lines show the mean value of the DMDGs. Middle columns are similar to Fig. 3, but the lines show the mean density profiles. Right columns are similar to Fig. 5, but histograms show the stacked distribution of the specific binding energy ($sE$), which is normalized by the mean $sE$ of the star particles of each galaxy before stacking.
Figure A5. Similar to Fig. A4, but for EAGLE.

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