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The undiscovered ultra-diffuse galaxies of the Local Group

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ABSTRACT

Ultra-diffuse galaxies (UDGs) are attractive candidates to probe cosmological models and test theories of galaxy formation at low masses; however, they are difficult to detect because of their low surface brightness. In the Local Group (LG) a handful of UDGs have been found to date, most of which are satellites of the Milky Way and M31, and only two are isolated galaxies. It is unclear whether so few UDGs are expected. We address this by studying the population of UDGs formed in hydrodynamic constrained simulations of the LG from the HESTIA suite. For a LG with mass $M_{\rm LG}(<2.5\ {\rm Mpc}) = 8\times10^{12}\ {\rm M_\odot}$, we predict that there are 12 ± 3 UDGs (68 per cent confidence) with stellar masses $10^6 \leq M_* / {\rm M_\odot} < 10^9$, and effective radii $R_{\rm e} \geq 1.5$ kpc, in the field of the LG, of which 2^{+2}_{-1} (68 per cent confidence) are detectable in the footprint of the Sloan Digital Sky Survey (SDSS). Accounting for survey incompleteness, we find that up to 82, 90, and 100 per cent of all UDGs in the LG field would be observable in a future all-sky survey with a depth similar to the SDSS, the Dark Energy Survey, or the Legacy Survey of Space and Time, respectively. Our results suggest that there is a population of UDGs in the LG awaiting discovery.

Key words: galaxies: formation – Local Group – galaxies: dwarf – galaxies: luminosity function – galaxies: interactions

1 INTRODUCTION

Hierarchical models of galaxy formation predict the emergence of a large population of low-mass galaxies. Typically, they are dominated by sizable dark matter components that make them useful as discerning probes of cosmological models. The most valuable galaxies for this purpose are those that contain little baryonic material which is dispersed throughout a large volume. In recent years, hundreds of such faint and extended galaxies have been discovered in a variety of environments: within clusters of galaxies such as Coma, Virgo, and Fornax (van Dokkum et al. 2015; Koda et al. 2015; Martínez-Delgado et al. 2016; Román & Trujillo 2017); in galaxy groups (Trujillo et al. 2017); and in the field inbetween (e.g. Leisman et al. 2017). These extended objects have stellar masses and magnitudes typical of bright dwarf galaxies ($M_* = 10^{6-9}\ {\rm M_\odot}$ and $M_{\rm V} < -8$, respectively); however, they are significantly larger, with sizes approaching those of massive galaxies such as the Milky Way. As a result they have very low surface brightness, usually between $\mu_{\rm e} = 24$ and 28 mag arcsec^{-2}, earning them the sobriquet 'Ultra-Diffuse Galaxies' (UDGs).

The circumstances leading to the emergence of such diffuse galaxies are not understood fully and several scenarios have been proposed to explain their formation. These are divided broadly into two main categories: (i) internal processes that drive stars towards the outer regions of the galaxy, as could happen in haloes with high spin (Amorisco & Loeb 2016), and during episodes of powerful stellar feedback (Di Cintio et al. 2017; Chan et al. 2018); and, (ii) the disturbance caused by external mechanisms such as stripping and tidal heating (Carleton et al. 2019; Jiang et al. 2019; Tremmel et al. 2020; Benavides et al. 2021), and galaxy mergers (Wright et al. 2021). A compelling test of these proposals requires a large sample of UDGs, the catalogue of which has grown rapidly in recent years because of advances in instrumentation and observational techniques. However, UDGs remain challenging to detect so their census in the nearby Universe is likely far from complete.

Similarly, the census of dwarf galaxies within the Local Group is also incomplete (Garrison-Kimmel et al. 2014; Newton et al. 2018; Nadler et al. 2019; Drlica-Wagner et al. 2020; Fattahi et al. 2020b). Using the Di Cintio et al. (2017) definition of UDGs, only eight Local

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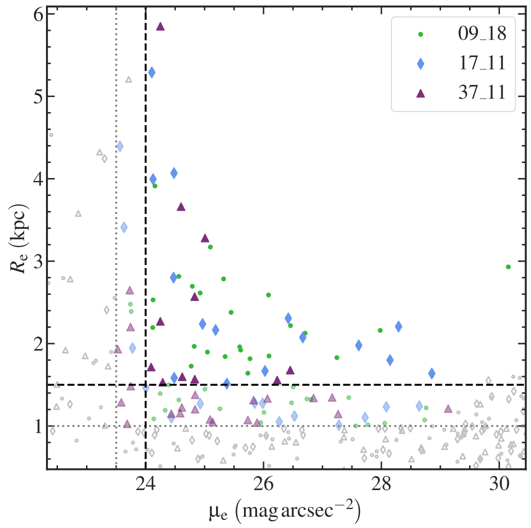

Figure 1. The two-dimensional effective radius, R_e, as a function of the r–band effective surface brightness, μ_e, of the field UDGs in the three high-resolution HESTIA simulations. The dashed lines show two of our selection criteria applied to the field haloes in the simulations. The galaxies that satisfy all of the selection criteria described in Section 2.1 are plotted with filled symbols, while unfilled symbols show the rest of the field galaxies. The faint filled symbols show galaxies that satisfy less stringent selection criteria (dotted lines) that are often used in the literature.

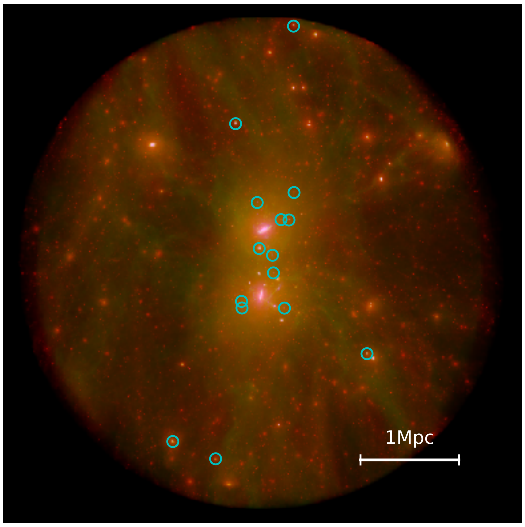

Figure 2. The projected mass-weighted densities of DM (red), gas (green), and stars (white) within 2.5 Mpc of the Local Group in the 17_11 simulation. The two bright galaxies at the centre are the analogues of the Milky Way and M31 and we mark the projected positions of the UDGs with light-blue circles.

Group galaxies satisfy the criteria: And II, And XIX, And XXXII, Antlia II, Crater II, Sagittarius dSph, WLM, and IC1613 (Collins et al. 2013; Kirby et al. 2014; Torrealba et al. 2016; Caldwell et al. 2017, see also McConnachie 2012 for observational data). Of these, six are satellites of the Milky Way and M31 and only two are found in the field. It is unclear whether the dearth of UDGs in the field of the Local Group arises primarily from environmental influences that prevent most galaxies from becoming UDGs, or if observational limitations are the main obstacle impeding their detection. Indeed, if such a UDG population exists it would be partly obscured by the foreground of Milky Way stars and the background of other galaxies, making it difficult to detect with current instruments. Therefore, in this *Letter* we use high-resolution simulations to quantify the number of UDGs that we expect to find in the field of the Local Group and study their potential detectability in current and forthcoming surveys.

2 METHODOLOGY

To estimate the size and properties of the population of UDGs in the field of the Local Group we require simulations that self-consistently model the formation and evolution of galaxies in this environment. The HESTIA suite does this (Libeskind et al. 2020), and consists of 13 zoom-in simulations of Local Group analogues that were run with the AREPO moving mesh code (Springel 2010) and the AURIGA galaxy formation model (Grand et al. 2017). Using estimates of the peculiar velocity field derived from observations (Tully et al. 2013), the initial conditions are constrained to reproduce the major gravitational sources in the neighbourhood of the Local Group. Consequently, at $z = 0$ the Local Group analogues are embedded in large-scale structure that is consistent with the observations when assuming the Λ+cold dark matter (ΛCDM) cosmological model (see e.g. Hoffman & Ribak 1991; Doumler et al. 2013; Sorce et al. 2016).

The Local Group analogues are simulated at 'low' and 'intermediate' resolution in a PLANCK 2014 cosmology (Planck Collaboration et al. 2014). Three were re-simulated at higher resolution using ~200M DM particles in a high-resolution region consisting of two overlapping spherical volumes with radii of 2.5 h^{-1} Mpc, each centred on the Milky Way and M31 analogues at $z = 0$. The spatial resolution achieved is 177 pc, and the effective masses of the DM and gas particles are $M_{\rm DM} = 2\times10^5$ M$_\odot$ and $M_{\rm gas} = 2.2\times10^4$ M$_\odot$, respectively. The simulations are labelled 09_18, 17_11, and 37_11, after the initial seed used, and their physical properties can be found in Libeskind et al. (2020, table 1). We use the Amiga Halo Finder (AHF) algorithm (Gill et al. 2004; Knollmann & Knebe 2009) to identify and characterize gravitationally bound structures in the simulations.

2.1 UDG selection criteria

The UDGs we study here are drawn from the population of field haloes in each high-resolution simulation. They are located within 2.5 Mpc of the centre of the Local Group at $z = 0$ and are outside R_{200} (the radius of the sphere enclosing a mean matter density of $\rho(< R_{200}) = 200\times\rho_{\rm crit}$, where $\rho_{\rm crit}$ is the critical density for closure) of all haloes that are at least as massive as the Milky Way analogue. We select UDGs from the field haloes by applying criteria similar to those described in Di Cintio et al. (2017): (i) the candidate has a total stellar mass, $M_* \leq 10^9$ M$_\odot$; (ii) it has a two-dimensional effective radius, which contains half of the total luminosity of the system, $R_e \geq 1.5$ kpc; and, (iii) it has effective surface brightness, μ_e=$\mu(<R_e) \geq 24$ mag arcsec^{-2}. Both R_e and μ_e depend on the luminosity of the galaxy, which we compute in the r–band while ignoring the effects of dust attenuation. We calculate these values by orienting the galaxy so that the gas disc is face-on to the observer and project the star particles into the plane of the disc. When a galaxy has no identifiable gas disc we take the simulation z-axis to be normal to the disc plane. To minimize the effects of the limited simulation resolution we also require that each UDG has at least 50 star particles.

In Fig. 1, we show two of the key selection criteria applied to the simulated field galaxies. The filled symbols show UDGs that satisfy the modified Di Cintio et al. criteria described above, and have stellar masses in the range $M_* = \left[10^6,\ 10^9\right]$ M$_\odot$. There are 24, 15, and 11 UDGs in the fields of the 09_18, 17_11, and 37_11 simulations, respectively. A detailed analysis of their formation histories will be conducted in a companion paper (Cardona-Barrero et al., in prep.).

In Fig. 2, we show the distribution of the UDGs in one repres-

Table 1. The $z = 0$ properties of the three simulations. We provide the total mass, M_{LG}, the number of field galaxies, $N_{field, tot}$, and the number of UDGs, $N_{UDG, tot}$, with $10^6 \leq M_* / M_\odot \leq 10^9$ within 2.5 Mpc of the midpoint of the primary haloes. Note the different observer position to that in Fig. 3.

Simulation	M_{LG} $(10^{13}\ M_\odot)$	$N_{field, tot}$	$N_{UDG, tot}$
09_18	1.23	79	24
17_11	1.03	58	15
37_11	0.77	50	11

entative high-resolution simulation (17_11; chosen arbitrarily). This shows the projected DM, gas, and stellar density in a spherical region with a radius of 2.5 Mpc centred on the midpoint of the Milky Way and M31 analogues. The distribution of UDGs throughout the volume is not uniform: at small radii the UDGs cluster close to the Milky Way and M31 analogues, whereas at larger radii they are affiliated preferentially with the large structures that compose the Local Group analogue and the filaments and sheets that deliver matter to it.

3 RESULTS

The total number of field galaxies, $N_{field, tot}$, within 2.5 Mpc scales with the total mass, M_{LG}, of the Local Group (see Fattahi et al. 2020a). This differs by a factor of 1.6 between the least- and most-massive simulations and causes $N_{field, tot}$ to vary between 50 and 79 (see Table 1). The total number of UDGs, $N_{UDG, tot}$, in each simulation varies between 11 and 24, and accounts for 22 – 30 per cent of the total population of field galaxies in the stellar mass range $10^6 \leq M_* / M_\odot \leq 10^9$. This is consistent with the results from the RomulusC galaxy cluster simulation that shows that a large fraction of low-mass galaxies at $z = 0$ are UDGs (Tremmel et al. 2020).

In Fig. 3, we show the cumulative radial distributions of field galaxies and field UDGs in each high-resolution volume with respect to the Milky Way analogue at $z = 0$. This choice of observer location is arbitrary and we find no significant differences between the distributions obtained when using the M31 analogue or the Milky Way–M31 midpoint. We also overlay the incomplete census of observed field galaxies in the stellar mass range described above. The observations are limited by incomplete sky coverage and insufficient sensitivity to low-surface brightness objects. The fraction of field galaxies that are UDGs decreases by a factor of two as a function of radius, except within 800 kpc of the observer (see the upper panel of Fig. 3). Here the volume available to host the UDGs grows more slowly with distance because we remove galaxies that are within R_{200} of the primary haloes. Consequently, the size of the population appears to be suppressed and is affected strongly by stochastic effects. We find 46 to 71 per cent of the total UDG population within 1 Mpc, most of which cluster close to the virial radii of the primary haloes. At larger radii, the UDGs are affiliated preferentially with the filaments and sheets that feed the growth of the Local Group (see also Fig. 2). This is in agreement with the results of Fattahi et al. (2020a), who used the APOSTLE simulations to show that most undiscovered dwarf galaxies should lie near the virial boundaries of the primary haloes.

3.1 Total luminosity functions

The luminosity functions of the UDGs within 2.5 Mpc of the centre of each Local Group analogue are shown in Fig. 4. All of the UDGs in the HESTIA simulations are as bright as the classical satellite galaxies of the Milky Way ($M_V < -8$); however, they are much more diffuse, which makes them difficult to detect in wide-area surveys using standard analysis techniques. To estimate how many UDGs could be observable in all-sky surveys with response functions similar to the Sloan Digital Sky Survey (SDSS; Blanton et al. 2017), the Dark Energy Survey (DES; Abbott et al. 2018), and the Legacy Survey of Space and Time (LSST; Ivezić et al. 2019), we apply the corresponding limiting surface brightness cuts in the r–band and discard UDGs that are too faint to be detected (Fig. 4, left panel). In this simplified scenario and averaging the results from the three simulations, up to 82 and 90 per cent of the UDG population is potentially detectable in all-sky surveys with SDSS- and DES-like surface brightness limits, respectively. A whole-sky LSST-like survey could detect the entire population.

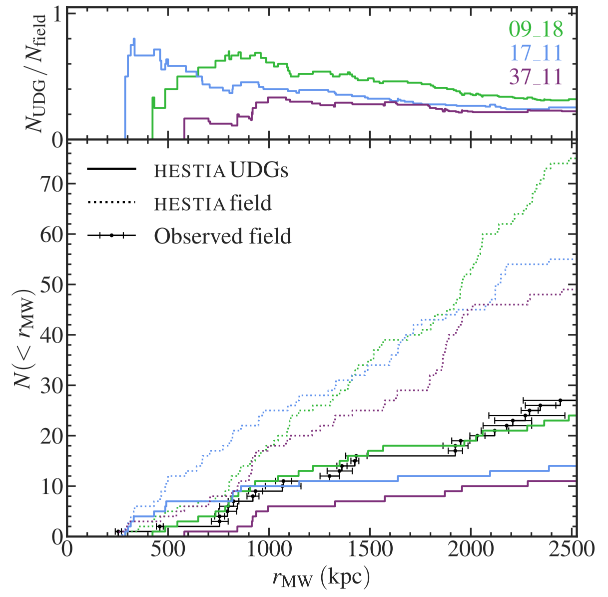

Figure 3. *Lower panel*: The radial cumulative distributions of UDGs (solid lines) and all field galaxies (dotted lines) with stellar masses, $10^6 \leq M_* / M_\odot < 10^9$, as a function of radius, r_{MW}, from the Milky Way analogue. We overlay the incomplete census of observed field galaxies as points with error bars showing the 68 per cent distance uncertainties (using data compiled by McConnachie 2012). Between 46 to 71 per cent of all field UDGs are within 1 Mpc of the MW. *Upper panel*: The fraction of field galaxies that are UDGs at $z = 0$.

In the right panel of Fig. 4, we plot the apparent V–band magnitude luminosity functions of the UDG populations. We generate luminosity functions for an observer located in the Milky Way and M31 analogues; however, there is little difference between them because the distributions of relative distances to the UDGs are similar. The magnitude limits of the surveys are marked with arrows and suggest that, on the basis of apparent magnitude alone, almost the entire UDG population is detectable in SDSS-, DES-, and LSST-like surveys. This illustrates that the most significant factor limiting the detection of UDGs is their diffuse nature, compounded by limitations in the survey response, and complications such as the obscuration of the sky by the Galactic disc, which we do not model here.

3.2 Mock luminosity functions

The HESTIA simulations predict that UDGs exist in the field of the Local Group at $z = 0$ and that a fraction of them are potentially detectable by surveys such as the SDSS. As very few field UDGs have been found to date, this suggests that several await discovery or that current models of galaxy formation do not accurately describe the physics at low masses. One test of this is to estimate how many UDGs

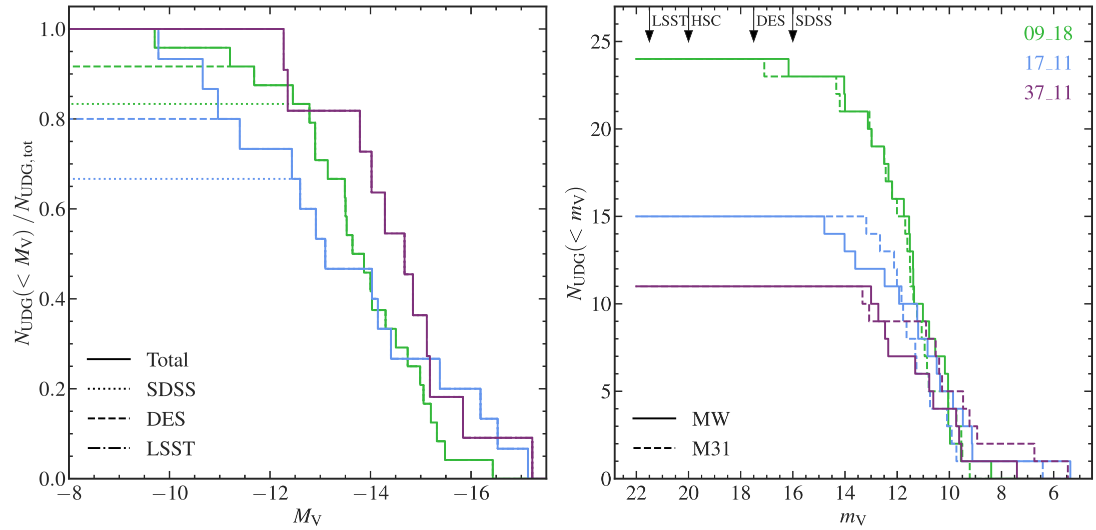

Figure 4. The total luminosity functions of field UDGs within 2.5 Mpc of each high-resolution Local Group simulation in the HESTIA suite. *Left panel*: We estimate the absolute V–band magnitude luminosity functions as a fraction of the total number of UDGs, $N_{\rm UDG,\,tot}$, likely to be observed in whole-sky SDSS-, DES-, and LSST-like surveys by applying a limiting surface brightness cut in the r–band (SDSS: 26.5 mag arcsec^{-2}, DES: 27.86 mag arcsec^{-2}, LSST: 31 mag arcsec^{-2}). In each simulation the LSST-like and 'Total' luminosity functions overlap; all curves overlap with this in the 37_11 simulation. *Right panel*: The cumulative number of field UDGs in the simulations as a function of apparent V–band magnitude, $m_{\rm V}$. The solid and dashed lines show the luminosity functions measured by observers in the Milky Way and M31 analogues, respectively. The vertical arrows indicate the faintest dwarf galaxies that could be detected in several past and future surveys: SDSS ($m_{\rm V}$ = 16), DES ($m_{\rm V}$ = 17.5), HSC ($m_{\rm V}$ = 20), and LSST ($m_{\rm V}$ = 21.5).

we expect to find in the footprints of current surveys such as the SDSS and whether they are, in principle, detectable using existing data sets.

To study this, we construct mock SDSS observations of the population of field UDGs in the three simulations. This requires an understanding of the observational selection function of low-mass galaxies obtained by an algorithmic search of the survey data. Modern approaches to search for low-mass galaxies in wide-area surveys commonly adopt one, or both, of two complementary techniques: (i) matched-filter searches that apply criteria to select samples of stars at a given distance and compare their spatial overdensity with the Galactic foreground (e.g. Koposov et al. 2008; Walsh et al. 2009), and; (ii) likelihood-based searches that model the properties of the stellar populations and incorporate observational uncertainties that are specific to the survey, such as the survey depth (e.g. Bechtol et al. 2015; Drlica-Wagner et al. 2015). These are powerful techniques to search large areas of the sky efficiently but they are less sensitive than other methods to find spatially extended and low-surface brightness galaxies. Approaches such as resolved star searches have been used very effectively to detect nebulous galaxies in small surveys like Hyper Suprime-Cam (HSC, Garling et al. 2020); however, they are impractical for wide-area sky searches. For this reason, in this study we use the selection function obtained by Koposov et al. (2008), who applied a matched-filter search to SDSS data.

Koposov et al. (2008) characterize the efficiency with which their algorithm detects galaxies with sizes up to 1 kpc at distances as far as 1 Mpc from the Sun. They do this using models of galaxies that are less spatially extended and closer than the field UDGs in the HESTIA simulations. Therefore, to apply their approach and estimate the HESTIA UDG detection efficiency in SDSS, we extend to larger effective radii at greater distances from the Milky Way the relationships they calculated for the parameters in their matched-filter algorithms. This means that the detectability of the most distant galaxies could be overestimated because we do not account for star-galaxy confusion that most likely dominates the signal at large distances. Furthermore, we also disregard the effects of dust attenuation on the UDGs, and their possible obscuration by the Milky Way at Galactic latitudes $|b| \leq 10°$, known as the Zone of Avoidance (ZoA). Our results should therefore be interpreted as an upper bound on the detectability of UDGs in the SDSS footprint when using this search algorithm. Using the analytic form provided by Koposov et al. (2008), the detection efficiencies, ϵ, of the UDGs in the SDSS are given by

$$\epsilon(M_{\rm V},\,\mu) = G\left(M_{\rm V} - M_{\rm V,\,lim}\right) G\left(\mu - \mu_{\rm lim}\right)\,, \tag{1}$$

where

$$G(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp -\frac{t^2}{2}\, dt \tag{2}$$

is the Gaussian integral. We infer the limiting absolute V–band magnitude, $M_{\rm V,\,lim}$, and the limiting surface brightness, $\mu_{\rm lim}$, at distances greater than 1 Mpc using a linear fit to the relationships in Koposov et al. (2008, fig. 12).

To generate a mock observation, we place an observer at the centre of one of the primary haloes. We model the mock survey as a conical volume with an opening angle of 14 555 deg^2, corresponding to the sky coverage of the SDSS, and orient it so that its apex coincides with the observer. To account for the effects of the viewing angle, we assign each UDG a random orientation with respect to the observer and recalculate $R_{\rm e}$ and $\mu_{\rm e}$. UDGs that fail the selection criteria described in Section 2.1 are discarded before the analysis proceeds. Using the relative distances of the UDGs with respect to the observer and the recomputed values of $\mu_{\rm e}$, we calculate ϵ using eq. (1). This represents the probability of detecting each UDG, and we use it to randomly select a set of UDGs that are detectable in the mock survey. As most galaxies have $\epsilon{\sim}1$ the effect of the random sampling is small.

We repeat this procedure for 15 000 pointings of the mock survey distributed evenly across the sky, and again for an observer in the second primary halo. We find that 30 000 mock observations in each high-resolution simulation produces results that are well-converged. Using these, we compute the medians and 68 per cent scatter of the field UDG luminosity functions that are detectable in SDSS (see Fig. 5). From this, in a SDSS-like survey we find 1 – 4 UDGs within 2.5 Mpc of the Milky Way analogues with $\mu_{\rm e}$ brighter than 26.5 mag arcsec^{-2} in the r–band.

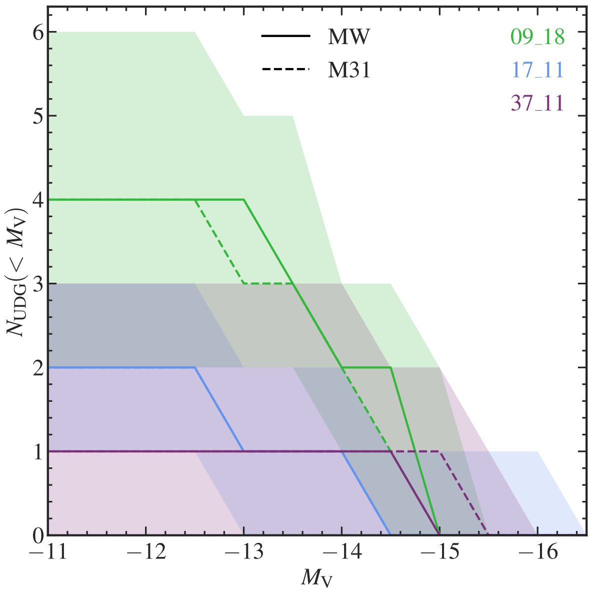

Figure 5. Mock SDSS observations of the population of field UDGs. The solid and dashed lines show the median predictions obtained by observers in the Milky Way and M31 analogues, respectively. The shaded regions represent the 68 per cent scatter in the Milky Way analogue luminosity functions over 15 000 mock observations.

As stated earlier, the total number of field galaxies depends strongly on $M_{\rm LG}$, which is different in each HESTIA simulation. To account for this, we rescale the total mass of each simulation to $M_{\rm LG}(<2.5\ {\rm Mpc}) = 8 \times 10^{12}\ {\rm M}_\odot$ and adjust the number density of field galaxies according to the LG mass–galaxy number density relationship in Fattahi et al. (2020a). Our choice of LG mass is motivated by current observational estimates of $M_{\rm LG}(<1\ {\rm Mpc}) = [3, 4.75] \times 10^{12}\ {\rm M}_\odot$ (Lemos et al. 2021; Carlesi et al. 2022; Hartl & Strigari 2022). We use the mass profiles of the simulated LGs to extrapolate these values to an outer radius of 2.5 Mpc and select the average mass. From this, we expect to find 52 ± 7 (68 per cent confidence, CL) field galaxies with stellar masses $10^6 \leq M_* / {\rm M}_\odot < 10^9$ within 2.5 Mpc of the centre of the Local Group. Of these, approximately one-quarter (12 ± 3) are UDGs, and 2^{+2}_{-1} (68 per cent CL) of them should be detectable in a re-analysis of the footprint of the SDSS. Using our selection criteria, no UDGs have been observed in the SDSS footprint to date. Disregarding the effects of dust attenuation, we estimate that the chance that there are no field UDGs detectable in the SDSS footprint is less than 12.8 per cent. In Table 2 we provide the predicted number of field galaxies and UDGs for different choices of $M_{\rm LG}$ and other UDG selection criteria.

4 DISCUSSION AND CONCLUSIONS

In this *Letter*, we provide quantitative predictions of the size and luminosity function of the Local Group field UDG population, and estimate how many could be detectable in dedicated searches of current data sets, and in future surveys. We produce these predictions using the populations of UDGs in the highest resolution hydrodynamic simulations from the HESTIA suite that are constrained to reproduce the local large-scale structure at $z = 0$. This is the first time that such spatially extended galaxies have been simulated self-consistently in such environments (see Figs 1 and 2). To obtain our results, we rescale the simulations to a common Local Group mass, $M_{\rm LG}(<2.5\ {\rm Mpc}) = 8 \times 10^{12}\ {\rm M}_\odot$, which is consistent with current estimates of $M_{\rm LG}(<1\ {\rm Mpc})$ from the Timing Argument (see Section 3.2). We predict that there are 12 ± 3 (68 per cent CL) low-surface brightness UDGs in the field of the Local Group with stellar masses, $10^6 \leq M_* / {\rm M}_\odot < 10^9$, and effective radii, $R_{\rm e} \geq 1.5$ kpc; and as many as 27 ± 5 when selecting UDGs with $R_{\rm e} \geq 1$ kpc. The UDGs account for approximately one-quarter and one-half, respectively, of the total population of 52 ± 7 (68 per cent CL) field galaxies with similar stellar masses. As many as 67 per cent of these systems are within 1 Mpc of the Milky Way–M31 midpoint and cluster close to these two primary haloes (see Fig. 3), in agreement with the results of Fattahi et al. (2020a).

All of the UDGs are as bright as the 'classical' satellite galaxies of the Milky Way (i.e. they are brighter than $M_{\rm V} = -8$; see Fig. 4); however, they are much more spatially extended and have $R_{\rm e} \geq 1.5$ kpc. Therefore they are very diffuse, and have faint effective surface brightnesses that make them difficult to detect against the foreground of Galactic stars and the background of distant galaxies. In the surveys that we consider, we find that the detectability of field UDGs is limited most strongly by their faint effective surface brightness; however, we also find that some field UDGs could be detectable in existing survey data sets and are awaiting discovery by dedicated follow-up searches of archival data (see Fig. 4). To estimate how many could be detectable, we generate mock SDSS observations of the field UDG populations in the three highest-resolution HESTIA simulations using survey response functions extrapolated from those described in Koposov et al. (2008). Using these, we predict that there are 1 – 4 UDGs detectable in the SDSS footprint (see Fig. 5). This is subject to the variation in the masses of the three Local Group volumes we use. When renormalizing these to $M_{\rm LG}(<2.5\ {\rm Mpc}) = 8 \times 10^{12}\ {\rm M}_\odot$, we find 12 ± 3 field UDGs within 2.5 Mpc of the Milky Way–M31 midpoint, of which 2^{+2}_{-1} are detectable in the footprint of the SDSS (see Section 3.2 and Table 2). A full-sky survey with a response function similar to that of the SDSS, DES, or LSST will detect up to 82, 90, or 100 per cent of the total field UDG population, respectively.

To generate mock SDSS observations, we used a simple model of the Koposov et al. (2008) SDSS response function. This depends on several physical properties of the galaxies such as their sizes and luminosities, and their physical locations, i.e. their heliocentric distances and projected positions on the sky. The latter are important because galaxies that are partially or totally obscured by the Milky Way can be more difficult to detect against the high-density Galactic stellar foreground, i.e. the ZoA. In HESTIA, we find that 15^{+12}_{-8} per

Table 2. The total number of field galaxies, $N_{\rm field,\,tot}$, UDGs, $N_{\rm UDG,\,tot}$, and the number of UDGs detectable in the SDSS footprint, $N_{\rm UDG,\,SDSS}$, for combinations of $M_{\rm LG}(<2.5\ {\rm Mpc})$ and UDG selection criteria. Our fiducial choice is in bold.

$M_{\rm LG}$ $(10^{12}\ {\rm M}_\odot)$	$R_{\rm e}$ (kpc)	μ_e (mag arcsec^{-2})	$N_{\rm field,\,tot}$	$N_{\rm UDG,\,tot}$	$N_{\rm UDG,\,SDSS}$
7	1.0	23.5	45 ± 7	26 ± 5	5^{+4}_{-3}
7	1.0	24.0	45 ± 7	24 ± 5	4^{+3}_{-2}
7	1.5	23.5	45 ± 7	13 ± 4	3 ± 2
7	1.5	24.0	45 ± 7	10 ± 3	2^{+2}_{-1}
8	1.0	23.5	52 ± 7	29 ± 5	6^{+4}_{-3}
8	1.0	24.0	52 ± 7	27 ± 5	5 ± 3
8	1.5	23.5	52 ± 7	15 ± 4	3 ± 2
8	**1.5**	**24.0**	$\mathbf{52 \pm 7}$	$\mathbf{12 \pm 3}$	$\mathbf{2^{+2}_{-1}}$
9	1.0	23.5	58 ± 8	33 ± 6	6^{+5}_{-3}
9	1.0	24.0	58 ± 8	30 ± 5	5 ± 3
9	1.5	23.5	58 ± 8	16 ± 4	3^{+3}_{-2}
9	1.5	24.0	58 ± 8	13 ± 4	2^{+2}_{-1}

cent (68 per cent CL) of the total UDG population is in the ZoA on average. We do not account for this when estimating the detection efficiencies of the UDGs, and we further assume that the UDGs do not suffer from dust extinction. Correcting for both of these effects would likely reduce the number of UDGs detectable in the surveys.

As we have shown, UDGs are challenging to observe because they are extremely diffuse. However, those that contain large reservoirs of neutral Hydrogen, such as most isolated observed UDGs as well as the simulated field UDGs in HESTIA (Cardona-Barrero et al., in prep.), could be detected more easily. In H I surveys the neutral Hydrogen could appear as ultra-compact high-velocity clouds (UCHVCs; Giovanelli et al. 2009; Adams et al. 2013). Recent searches for UCHVCs and other H I-bright systems using ALFALFA (e.g. Janesh et al. 2019), DES (Tanoglidis et al. 2021), and HIPASS (Zhou et al. 2022) have produced promising results that could expand the catalogue of targets for dedicated follow-up studies. Our results suggest that there is a population of low-surface brightness, spatially extended galaxies in the Local Group awaiting discovery.

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DATA AVAILABILITY

A repository of reduced data and scripts to produce the figures in this manuscript will be made available on GitHub and archived in Zenodo upon publication. Requests for access to the HESTIA simulation data should be directed to a CLUES Collaboration PI.

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