The virial mass distribution of ultra-diffuse galaxies in clusters and groups

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\begin{abstract}
We use the observed abundances of ultra-diffuse galaxies (UDGs) in clusters and groups and \textsc{lcdm} subhalo mass functions to put constraints on the distribution of present-day halo masses of satellite UDGs. If all of the most massive subhaloes in the cluster host a UDG, UDGs occupy all subhaloes with $\log M_{\text{sub}}/M_\odot \gtrsim 11$. For a model in which the efficiency of UDG formation is higher around some characteristic halo mass, higher fractions of massive UDGs require larger spreads in the UDG mass distribution. In a cluster with a virial mass of $10^{15} M_\odot$, the 90\% upper limit for the fraction of UDGs with $\log M_{\text{sub}}/M_\odot > 12$ is 7\%, occupying 70\% of all cluster subhaloes above the same mass. To reproduce the observed abundances, however, the mass distribution of satellite UDGs has to be broad, with $> 30\%$ having $\log M_{\text{sub}}/M_\odot < 10.9$. This strongly supports that UDGs are part of a continuous distribution in which a majority are hosted by low mass haloes. The abundance of satellite UDGs may fall short of the linear relation with the cluster/group mass $M_{\text{host}}$ in low-mass hosts, for stringent constraints on the UDG virial mass distribution.
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\textbf{Key words:} galaxies: dwarf — galaxies: structure — galaxies: formation — galaxies: haloes — galaxies: clusters

1 INTRODUCTION

The suggestion that surface brightness limited surveys may significantly underestimate the total number of galaxies is at least twenty years old. Using a very simple model based on a standard \textsc{lcdm} framework, Dalcanton et al. (1997) predicted the existence of an extremely abundant population of low surface brightness (LSB) galaxies, potentially extending to surface brightness levels of $\mu \gtrsim 30$ mag/arcsec\textsuperscript{2}. Reaching these depths remains exceptionally challenging and great effort is currently being devoted to push to ever fainter limits, to probe a yet largely unexplored regime of the galaxy formation process.

LSB galaxies, including faint cluster galaxies, have been the object of numerous studies (e.g., Binggeli et al. 1985; Ferguson 1989; Davies et al. 1994; Impey & Bothun 1997; Conselice et al. 2002, 2003; Adami et al. 2006; Penny et al. 2009; Ferrarese et al. 2012; Yamanoi et al. 2012), and the significant abundance of Ultra-diffuse galaxies (UDGs) in clusters (e.g., van Dokkum et al. 2015; Koda et al. 2015; Muñoz et al. 2015; van der Burg et al. 2016; Román & Trujillo 2017a; Janssens et al. 2017; Lee et al. 2017; Vennola et al. 2017) has confirmed the above prediction. With mean surface brightnesses within their effective radius $R_e$ of $(\mu) \gtrsim 24.5$ mag/arcsec\textsuperscript{2}, UDGs have stellar masses of dwarf galaxies ($\log M_*/M_\odot \sim 7.5 \div 8.5$), but $R_e > 1.5$ kpc, quite larger than what is common among bright galaxies with similar stellar mass. Within the framework considered by Dalcanton et al. (1997), UDGs owe their remarkable sizes to the high angular momentum of their dark matter halos (see also e.g., Mo et al. 1998; Dutton et al. 2007). Although simplistic, this scenario reproduces the abundance of UDGs in clusters and their size distribution (Amorisco & Loeb 2016), and predicts that most UDGs are hosted by low-mass haloes ($\log M_{\text{sub}}/M_\odot \sim 10.3 \div 11.3$ for a normal stellar-to-halo mass relation, Amorisco & Loeb 2016). Stellar feedback has been proposed as alternative cause of the UDGs extended sizes (Di Cintio et al. 2016), which would also require that most UDGs are hosted by low-mass haloes ($\log M_{\text{sub}}/M_\odot \sim 11$). Galaxies with the properties of UDGs have been obtained in recent hydrodynamical simulations (Di Cintio et al. 2016; Chan et al. 2017), but clear predictions for their population properties are not yet available.

It remains possible, however, that a fraction of UDGs is hosted by haloes that are considerably more massive than suggested by the scenarios above, and potentially as massive

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as the Milky Way (MW) halo. It has been proposed that some UDGs may be ‘failed’ $L_{\star}$ galaxies, with a different formation pathway. Failure could be caused by gas stripping and/or extreme feedback processes, that may have halted their star formation. UDGs would then fall significantly short of the stellar-to-halo mass relation and be hosted by ‘over-massive haloes’ (e.g., van Dokkum et al. 2015, 2016; Beasley et al. 2016). The only direct measurement of the virial mass of UDGs, based on the stacked weak lensing signal of $>700$ systems, can not rule out this possibility (Sifón et al. 2017). Indirect arguments on the mass of UDG hosting haloes appear to confirm that a majority have low mass haloes ($< 2 \times 10^{11} M_\odot$; Beasley et al. 2016; Beasley & Trujillo 2016; Peng & Lim 2016; Amorisco et al. 2016; Román & Trujillo 2017a). A few notable exceptions could however be interpreted as due to a fraction of systems with higher virial masses. These exceptions include the high GC abundance of some Coma UDGs (van Dokkum et al. 2016, 2017, together with some less extended LSB galaxies, Amorisco et al. 2016) and the central stellar velocity dispersion of a couple of Coma UDGs (van Dokkum et al. 2016, 2017). In fact, if UDGs comply with the same scaling relations of normal galaxies, the heterogeneity of surface brightness values and sizes would suggest a mix of halo masses (Zaritsky 2017).

It is therefore important to try and constrain the distribution of UDG virial masses. In this Letter, we concentrate on satellite UDGs, and constrain their present-day subhalo masses using literature measurements of their cluster and group abundances (Koda et al. 2015; Muñoz et al. 2015; van der Burg et al. 2016, 2017; Román & Trujillo 2017a,b; Janssens et al. 2017). Section 2 describes the data and our simple model. Section 3 details our statistical analysis and collects results. Section 4 discusses them and lays out the Conclusions.

2 THE ABUNDANCE OF UDGs

Significant effort has been put into measuring the abundance of UDGs in galaxy clusters (e.g., van der Burg et al. 2016; Román & Trujillo 2017a; Janssens et al. 2017; Lee et al. 2017; Venhola et al. 2017). These results have confirmed the initial finding of van der Burg et al. (2016) that the relation between the number of UDGs, $N_{\text{UDG}}$, and the virial mass of the host cluster, $M_{\text{host}}$, is approximately proportional to the mass of the host (the dashed line shows the slope of a linear relation in this plane). As we will show, these high abundances put strong constraints on the distribution halo masses of satellite UDGs, and so does the apparent linearity of this relation. The subhalo abundance per unit parent mass is not independent of parent mass when $M_{\text{sub}}/M_{\text{host}} \sim 1$: abundances are strongly suppressed for subhaloes above $M_{\text{sub}}/M_{\text{host}} \sim 0.1$ (e.g., Gao et al. 2004; Giocoli et al. 2008). This causes potentially observable deviations from linearity in the relation between $M_{\text{host}}$ and $N_{\text{UDG}}$ when the mix of UDG halo masses includes a significant fraction of massive haloes. We formalise these concepts in the following.

2.1 Model UDG abundances

We model the mean differential mass function of subhaloes with mass $M_{\text{sub}}$, $\langle N(M_{\text{sub}}) \rangle$, in a parent halo or cluster of mass $M_{\text{host}}$ with a fitting function based on: i) the results of Boylan-Kolchin et al. (2010) (hereafter BK10) and ii) the mentioned independence of the subhalo abundance per unit parent mass on the parent mass itself. The subhalo mass function in MW-mass haloes ($12 \leq \log M_{\text{host}}/M_\odot \leq 12.5$) has been measured with high precision by BK10, using the Millennium-II Simulation (Boylan-Kolchin et al. 2009). We adopt the functional form and parameters suggested by these authors (their eqn. (8)) and refer to this function as

$$\frac{d\langle N \rangle}{d\log M_{\text{sub}}} \bigg|_{M_{\text{host}} = M_{\text{MW}}} = \mathcal{N}(M_{\text{sub}}),$$

Figure 1. UDG abundances in groups and clusters as measured by Koda et al. (2015); Muñoz et al. (2015); van der Burg et al. (2016, 2017); Román & Trujillo (2017a,b); Janssens et al. (2017). The dashed line shows the slope of a linear relation. The orange shading displays the 10-to-90% confidence region for the mean $N_{\text{UDG}}$-$M_{\text{host}}$ relation obtained from our analysis, the yellow shaded region shows the 1-$\sigma$ scatter around it.

ducer the collection of data presented by vdB17: over $\sim 4$ orders of magnitude in $M_{\text{host}}$, $N_{\text{UDG}}$ is approximately proportional to the mass of the host (the dashed line shows the slope of a linear relation in this plane). As we will show, these high abundances put strong constraints on the distribution halo masses of satellite UDGs, and so does the apparent linearity of this relation. The subhalo abundance per unit parent mass is not independent of parent mass when $M_{\text{sub}}/M_{\text{host}} \sim 1$: abundances are strongly suppressed for subhaloes above $M_{\text{sub}}/M_{\text{host}} \sim 0.1$ (e.g., Gao et al. 2004; Giocoli et al. 2008). This causes potentially observable deviations from linearity in the relation between $M_{\text{host}}$ and $N_{\text{UDG}}$ when the mix of UDG halo masses includes a significant fraction of massive haloes. We formalise these concepts in the following.

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Interestingly though, abundant UDG population have been detected in galaxy groups (Román & Trujillo 2017b; van der Burg et al. 2017, hereafter RT17 and vdB17), extending the same approximately linear relation valid in massive clusters (see also Trujillo et al. 2017). Figure 1 reproduces the collection of data presented by vdB17: over $\sim 4$ orders of magnitude in $M_{\text{host}}$, $N_{\text{UDG}}$ is approximately proportional to the mass of the host (the dashed line shows the slope of a linear relation in this plane). As we will show, these high abundances put strong constraints on the distribution halo masses of satellite UDGs, and so does the apparent linearity of this relation. The subhalo abundance per unit parent mass is not independent of parent mass when $M_{\text{sub}}/M_{\text{host}} \sim 1$: abundances are strongly suppressed for subhaloes above $M_{\text{sub}}/M_{\text{host}} \sim 0.1$ (e.g., Gao et al. 2004; Giocoli et al. 2008). This causes potentially observable deviations from linearity in the relation between $M_{\text{host}}$ and $N_{\text{UDG}}$ when the mix of UDG halo masses includes a significant fraction of massive haloes. We formalise these concepts in the following.

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$$\frac{d\langle N \rangle}{d\log M_{\text{sub}}} \bigg|_{M_{\text{host}} = M_{\text{MW}}} = \mathcal{N}(M_{\text{sub}}),$$

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This is a power-law with index $a = -1.935$ for $M_{\text{sub}}/M_{\text{MW}} \ll 1$ with an exponential truncation for subhalo masses $M_{\text{sub}} \gtrsim 10^{13} M_\odot$. To calculate the differential mass function of subhaloes with mass $M_{\text{sub}}$ in any parent of mass $M_{\text{host}}$ we scale eqn. (1) using that the subhalo mass function is independent of the parent mass:

$$\frac{d<N>}{d \log M_{\text{sub}}} = \frac{M_{\text{host}}}{M_{\text{MW}}} N' \left( \frac{M_{\text{sub}}}{M_{\text{host}}} \right) \frac{N'(m_0)}{N'(M_{\text{MW}} m_0/M_{\text{host}})}, \quad (2)$$

This uses that the shape of the truncation at high subhalo to parent mass ratio is also independent of the parent mass (see e.g. Giocoli et al. 2008). In eqn. (2), $m_0$ is any subhalo mass satisfying $m_0 \ll M_{\text{MW}}$. The mass function $N'$ has been measured using all central haloes with virial mass between $10^{12} M_\odot$ and $10^{14} M_\odot$. We therefore estimate the mean value $M_{\text{MW}}$ (needed in eqn. (2)) and the relative uncertainty (necessary for our statistical analysis, see the following section) using a standard halo mass function with a slope of $-1.9$, which returns $\log M_{\text{MW}} / M_\odot = 12.23 \pm 0.14$. For any cluster or group, eqn. (2) allows us to calculate the mean number of subhaloes in any given mass interval. A fraction of these subhaloes will host UDGs.

Before introducing a model for the fraction of UDG as a function of halo mass, in Figure 2 we compare the measured UDG abundances with the total mean number of massive subhaloes above some threshold mass $M_{\text{sub}} > 10^{-4} M_{\text{MW}}$.

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Data points are the same as in Fig. 1 and the coloured lines display $\langle N_{\text{sub}}(> M_{\text{sub}}) \rangle$ for the threshold masses $M_{\text{sub}} = \{10.5, 11, 11.5, 12, 12.5\}$. In order to roughly reproduce the observed abundances, all available subhaloes more massive than log $M_{\text{sub}} \sim 11$ need be occupied by UDGs. This would leave no halo with log $M_{\text{sub}} > 11$ for the non-UDG galaxies that also populate the same clusters/groups, showing that many UDG hosting subhaloes ought to have lower masses. In this extreme case, the fraction of UDGs hosted by haloes with $M_{\text{sub}} > 10^{12} M_\odot$ is of 11.5%. The same upper limit is of 39% for the largest UDGs, with $R_{e} > 2.5$ kpc, the abundance of which we estimate using the observed abundances in Fig. 2 and the size distribution measured by van der Burg et al. (2016).

Next, we introduce a simple model for the fraction of subhaloes hosting UDGs, as a function of the present-day subhalo mass. We take that the physical mechanism responsible for forming UDGs is more efficient around some particular mass: the fraction of subhaloes with mass $M_{\text{sub}}$ hosting UDGs has a gaussian shape, $G(M_{\text{sub}})$. Therefore, the differential UDG mass function is

$$\frac{d(N_{\text{UDG}})}{dM_{\text{sub}}} = \frac{d(N)}{dM_{\text{sub}}} \cdot G(M_{\text{sub}}) \cdot f_{\text{max}} \exp \left[-\frac{1}{2} \left( \frac{\log M_{\text{sub}}/\bar{m}}{\zeta} \right)^2 \right], \quad (3)$$

where $\bar{m}$, $\zeta$, and $f_{\text{max}}$ are free parameters of the model. The parameter $\bar{m}$ is the mass at which the fraction of UDGs is largest, $f_{\text{max}}$, with $f_{\text{max}} \leq 1$. Notice that the value $\bar{m}$ is strictly larger than the mean UDG halo mass, and their difference quickly increases with the spread $\zeta$. Due to the steepness of the subhalo mass function, at fixed $\bar{m}$, an increase in $\zeta$ implies higher counts of satellite UDGs through a larger fraction of low-mass subhaloes. By taking the model parameters to be constant across parent halos, by construction, eqn. (3) results in a linear relation between $N_{\text{UDG}}$ and $M_{\text{host}}$ when $\bar{m} \ll M_{\text{host}}$. $N_{\text{UDG}}$ may however drop below the linear relation when considering parent haloes with low enough mass.

Figure 2 shows the mean UDG abundances, $\langle N_{\text{UDG}} \rangle$, corresponding to our model mass distribution (3) for a selection of pairs $(\log \bar{m}, \zeta)$. All displayed models adopt $f_{\text{max}} = 1$. By comparing with the observed abundances:

- We confirm there are more than enough low mass haloes to host the observed cluster and group UDGs. If $(\log \bar{m}, \zeta) = (10, 0.3)$, then a fraction $f_{\text{max}} < 1$ is needed. This remains true if $(\log \bar{m}, \zeta) = (10.75, 0.3)$, for which some deviation from linearity in the $N_{\text{UDG}} - M_{\text{host}}$ relation can be noticed at log $M_{\text{host}}/M_\odot \lesssim 12$.
- A model with $(\log \bar{m}, \zeta) = (12, 0.3)$, corresponding to a median UDG halo mass log $M_{\text{UDG, 50}}/M_\odot = 11.8$, cannot reproduce the observed abundances, despite $f_{\text{max}} = 1$.
- While keeping log $\bar{m} = 12$, this can be ameliorated by increasing the value of the spread $\zeta$, as shown by the model $(\log \bar{m}, \zeta) = (12, 0.75)$. This however corresponds to

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1 To explore how any uncertainty on the slope $a$ influences our results we also consider a mass function with $a = -1.86$ (e.g. Jiang & van den Bosch 2016; van den Bosch & Jiang 2016). Other parameters are unchanged and we impose that the number of subhaloes with mass $M_{\text{sub}} > 10^{-4} M_{\text{MW}}$ is the same.

2 Throughout this Letter, whenever comparing to the observed abundances, we correct model subhalo counts by a factor 1/0.8, to account that observations measure overdensities in cylindrical apertures. This correction factor assumes UDGs have an NFW spatial distribution in the cluster/group with a concentration of $c = 6$ (see vdB17).
a dramatic decrease in the median UDG halo mass, with $\log M_{\text{UDG,50}}/M_{\odot} = 10.8$.

3 STATISTICAL ANALYSIS

We now quantify the qualitative constraints above within a proper statistical framework. We take that, as shown by BK10, the scatter in the subhalo mass function is wider than Poissonian, and that it approaches a fractional intrinsic scatter of $s_1 = 18\%$ for large values of $\langle N \rangle$. Here $s_1 = \sigma_1/\langle N \rangle$, where $\sigma_1$ is the intrinsic scatter in $\langle N \rangle$. As suggested by BK10, we adopt that the probability distribution of observing $N_{\text{UDG}}$ UDGs in a cluster of mass $M_{\text{host}}$, $P(N_{\text{UDG}}|\langle N_{\text{UDG}}(M_{\text{host}})\rangle)$, is a Negative Binomial\(^3\) (see eqns. (13-15) in BK10).

The observed abundances we use in this analysis are either abundances for a single cluster or group, or mean abundances in samples of clusters or groups of similar mass. For the latter, we numerically construct the relevant probability distribution starting from the $P$ above (the parent samples are often not large enough to invoke the central limit theorem). For all of the used measurements we take account of the uncertainty in the group/cluster mass (as well as of the uncertainty in $M_{\text{DM}}$, see Sect. 2.1). We take an uncertainty of 0.1 dex for the groups in vdB17 and, for the one group from RT17 lacking a mass uncertainty we adopt the same fractional uncertainty of the lowest-mass group in the same study. If, for simplicity, we still refer to the resulting probability distributions with the symbol $P$, the likelihood of the measured abundances $N_{\text{UDG,i}}$ is

$$L = \prod_i P(N_{\text{UDG,i}}|\langle N_{\text{UDG}(M_i)} \rangle)$$

where the function $\langle N_{\text{UDG}(M)} \rangle$ depends on the model parameters $(f_{\text{max}}, \bar{m}, \varsigma)$.

3.1 Results

As discussed in the previous Section, the model parameters $\bar{m}$ and $\varsigma$ are not readily interpreted. We therefore start by casting our results in terms of $M_{\text{UDG,30}}$ and $M_{\text{UDG,85}}$, respectively the 30% and 85% quantile of the UDG virial mass distribution. As these are a function of the cluster mass $M_{\text{host}}$, unless otherwise specified, we take log $M_{\text{host}} = 15$. In other words, we refer to the case in which the tail at high masses of the UDG virial mass distribution is fully populated. The left panel of Figure 3 shows the distribution of models accepted by our MCMC chains in the $(M_{\text{UDG,85}}, M_{\text{UDG,30}})$ plane. We only accept models that have log $M_{\text{UDG,30}} > 9.5$. Models that lie close to the line $M_{\text{UDG,85}} = M_{\text{UDG,30}}$, shown as a black dashed line, have negligible scatter in the distribution of UDG halo masses (i.e. small values of $\varsigma$). As a consequence, high values of $f_{\text{max}}$ are required, as indicated by the colour coding. As $M_{\text{UDG,85}}$ increases from log $M_{\text{UDG,85}} = 9.5$, even when $f_{\text{max}} = 1$, some minimum spread is necessary to reproduce the high observed abundances, and models depart from the $M_{\text{UDG,85}} = M_{\text{UDG,30}}$ locus. While log $M_{\text{UDG,85}} \lesssim 11$, all values $0 < f_{\text{max}} < 1$ are allowed, corresponding to different values of $M_{\text{UDG,30}}$, in a one-to-one relation. All of these models result in identical - and very close to linear - $N_{\text{UDG}}$-$M_{\text{host}}$ relations. In this analysis these models are degenerate because the observed abundances do not suggest significant deviations from linearity. When log $M_{\text{UDG,85}} > 11.3$, only high UDG fractions, $f_{\text{max}} \gtrsim 0.7$ are allowed, and the mass distribution is required to be broad, with log $M_{\text{UDG,30}} < 10.9$ (or log $M_{\text{UDG,30}} < 11.15$ if $a = -1.86$). This is mirrored in the right panel of the same Figure, which shows the accepted models in the plane of the model parameters, $(\log \bar{m}, \varsigma)$, color-coded by $M_{\text{UDG,85}}$. The UDG abundances alone cannot constrain these parameters, but the paucity of massive subhaloes imposes a marked correlation between them, corresponding to a tight upper limit on the fraction of massive UDGs.

In Fig. 1, we show the resulting marginalised $N_{\text{UDG}} - M_{\text{host}}$ relation. The orange shading identifies the 10-to-90% confidence region for the mean UDG abundance. The data are fully consistent with an exactly linear relation, although some deviation in low mass groups is allowed. The yellow shaded region shows the scatter around the mean, comprising both Poisson and intrinsic scatter. Figure 4 shows the marginalised posteriors for the cumulative mass distribution of subhaloes hosting UDGs (10, 50 and 90% quantiles). The three panels refer to hosts of different virial mass, respectively log $M_{\text{host}} = 13$, 14, and 15 in the left, central and right panels. In a massive cluster with log $M_{\text{host}} = 15$, at 90% probability, 50% of all UDGs are hosted by subhaloes with $M_{\text{sub}} < 10.8$ ($M_{\text{sub}} < 11.05$ if $a = -1.86$), 90% by

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\(^3\) Though notice that this distribution becomes in fact sub-Poissonian for $(N) \lesssim 2$ (Jiang & van den Bosch 2017).
subhaloes with $M_{\text{sub}} < 11.8$ ($M_{\text{sub}} < 12.1$ if $a = -1.86$). In a group with $\log M_{\text{host}} = 13$, at 90% probability, 50% of all UDGs are hosted by subhaloes with $M_{\text{sub}} < 10.7$ ($M_{\text{sub}} < 10.8$ if $a = -1.86$), 90% by subhaloes with $M_{\text{sub}} < 11.6$ ($M_{\text{sub}} < 11.75$ if $a = -1.86$).

Fig. 5 shows the 10, 50 and 90% quantiles for the inferred fraction of subhaloes with $M_{\text{sub}} > 12$ that are occupied by UDGs, $N_{\text{UDG}}(\log M_{\text{sub}} > 12)/N(>12)$, as a function of the fraction of UDGs with similarly massive subhaloes, $N_{\text{UDG}}(\log M_{\text{sub}} > 12)/N_{\text{UDG}}$. As in Fig. 4, panels refer to hosts with virial mass $\log M_{\text{host}}/M_\odot \in \{13, 14, 15\}$. In a massive cluster with $\log M_{\text{host}} = 15$, if more than 5% (more than 8.5% if $a = -1.86$) of all UDGs have massive subhaloes, $\log M_{\text{sub}} > 12$, more than 50% of subhaloes with the same mass are occupied by UDGs. In a group with mass $\log M_{\text{host}} = 13$, no accepted model has $N_{\text{UDG}}(>12)/N_{\text{UDG}} > 4\%$ ($N_{\text{UDG}}(>12)/N_{\text{UDG}} > 6\%$ if $a = -1.86$), and if more than 2% (more than 2.5% if $a = -1.86$) of all UDGs are similarly massive, more than 50% of massive haloes in groups are occupied by UDGs.

4 SUMMARY AND CONCLUSIONS

In this Letter, we have used the observed abundances of satellite UDGs in clusters and groups to constrain the present-day mass distribution of their dark matter subhaloes. If all of the most massive subhaloes available in the cluster host a UDG, all subhaloes with $M_{\text{sub}}/M_\odot \gtrsim 11$ would be occupied by UDGs, leaving no room for the non-UDG galaxies in the cluster. This implies a sharp upper limit to the fraction of UDGs hosted by massive haloes with $\log M_{\text{sub}} > 12$, which is of 11.5%.

We introduce a model in which the efficiency of UDG formation is a function of halo mass, and the probability for a subhalo to host a UDG is maximum around some characteristic subhalo mass, taken to be constant across clusters and groups. This simple assumption may more easily describe the scenario in which UDGs are formed in the field (e.g., Amorisco & Loeb 2016; Di Cintio et al. 2016; Chan et al. 2017) rather than the case in which UDGs are normal galaxies at first and expand after infall due to satellite-specific processes such a harassment and tidal stirring. However, we find that the currently available UDG abundances cannot constrain the parameters of this model, so that our specific choice has negligible impact on our results. Instead, as a consequence of the limited number of massive subhaloes, we find that the fraction of UDGs with high virial mass and the spread in the UDG mass distribution are strongly correlated. For instance, if 15% of all UDGs in a massive cluster have $\log M_{\text{sub}} > 11.5$, the spread of the distribution is such that >30% has $\log M_{\text{sub}} < 10.9$. No model in which 15% of all UDGs in a massive cluster have $\log M_{\text{sub}} > 11.8$ can reproduce the observed abundances. This translates in a fraction of UDGs with $\log M_{\text{sub}} > 12$ that is <7% at 90% probability, and corresponding to a cluster in which ~70% of all subhaloes with $\log M_{\text{sub}} > 12$ are occupied by UDGs. An analysis that folds in constraints for the fraction of satellite galaxies in clusters and groups that are UDGs vs non-UDGs is beyond the scope of the present Letter and is left for future studies. If we take that 50% of all massive subhaloes in Coma host UDGs, <16 out of the 332 UDGs counted by Koda et al. (2015) may be massive. If so, the mass distribution has to be broad, with >110 UDGs having $\log M_{\text{sub}} < 10.8$.

This strongly supports a number of observational arguments suggesting that UDGs are part of a continuous distribution in which a majority have low mass haloes. These include:

- the seamless continuity of the properties of UDGs with respect to those of the numerous – though relatively more compact – LSB dwarfs (e.g., Koda et al. 2015; Wittman et al. 2017; Venhola et al. 2017);
- the fact that a majority of UDGs has normal GC systems for their stellar mass (Beasley et al. 2018; Beasley & Trujillo 2016; Peng & Lim 2016; Amorisco et al. 2016) and that a minority of systems with enhanced GC abundances exist among UDGs as well as among LSB dwarfs (Amorisco et al. 2016);
- the fact they do not appear to significantly deviate from...
the mass-metallicity relation of bright dwarf galaxies (Gu et al. 2017; Pandya et al. 2017).

Finally, this analysis shows that it is extremely useful to better assess the properties of UDGs in low-mass groups, as UDG abundances in this regime constrain the actual shape of the UDG virial mass distribution. We have shown that, in proceeding towards lower mass groups, the linearity of the relation between the UDG abundance \( N_{\text{UDG}} \) and the group mass \( M_{\text{host}} \) is expected to break, with mean abundances falling short of the linear relation. This discrepancy quantifies the weight and shape of the high mass tail of the UDG virial mass distribution. Interestingly, the results of vdB17 appear to hint to similar deviations from linearity, with low mass groups (log \( M_{\text{host}} \) ∼ 12) featuring a UDG in only 1 out of ∼ 10 cases. However, as confirmed by our analysis, this is currently not statistically significant. Larger samples will elucidate the behaviour of the \( N_{\text{UDG}}-M_{\text{host}} \) relation at low group masses, allowing for better constraints on the UDG virial mass distribution and therefore more stringent tests for formation models.

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REFERENCES

Adami, C., Schidegger, B., Ulmer, M., et al. 2006, AA, 459, 679
Amorisco, N. C., & Loeb, A. 2016, MNRAS, 459, L51
Amorisco, N. C., Monachesi, A., Agnello, A., & White, S. D. M. 2016, arXiv:1610.01595
Beasley, M. A., Romanowsky, A. J., Pota, V., et al. 2016, arXiv:1602.04002
Beasley, M. A., & Trujillo, I. 2016, arXiv:1604.08024
Binggeli, B., Sandage, A., & Tammann, G. A. 1985, AJ, 90, 1681
Boylan-Kolchin, M., Springel, V., White, S. D. M., Jenkins, A., & Lemson, G. 2009, MNRAS, 398, 1150
Boylan-Kolchin, M., Springel, V., White, S. D. M., & Jenkins, A. 2010, MNRAS, 406, 896
Chan, T. K., Kereš, D., Wetzel, A., et al. 2017, arXiv:1711.04788
Conselice, C. J., Gallagher, J. S., III, & Wyse, R. F. G. 2002, AJ, 123, 2246
Conselice, C. J., Gallagher, J. S., III, & Wyse, R. F. G. 2003, AJ, 125, 66
Dalcanton, J. J., Spergel, D. N., & Summers, F. J. 1997, ApJ, 482, 659
Davies, J., Phillips, S., Disney, M., Boyce, P., & Evans, R. 1994, MNRAS, 268, 984
Di Cintio, A., Brook, C. B., Dutton, A. A., et al. 2016, arXiv:1608.01327
Dutton, A. A., van den Bosch, F. C., Dekel, A., & Courteau, S. 2007, ApJ, 654, 27
Ferguson, H. C. 1989, AJ, 98, 367
Ferrarese, L., Côté, P., Cuillandre, J.-C., et al. 2012, ApJS, 200, 4
Gao, L., White, S. D. M., Jenkins, A., Stoehr, F., & Springel, V. 2004, MNRAS, 355, 819
Giocoli, C., Tormen, G., & van den Bosch, F. C. 2008, MNRAS, 386, 2135
Greco, J. P., Greene, J. E., Price-Whelan, A. M., et al. 2017, arXiv:1704.06681
Impey, C., & Bothun, G. 1997, ARAA, 35, 267
Janssens, S., Abraham, R., Brodie, J., et al. 2017, ApJL, 839, L17
Jiang, F., & van den Bosch, F. C. 2016, MNRAS, 458, 2848
Jiang, F., & van den Bosch, F. C. 2017, MNRAS, 472, 657
Koda, J., Yagi, M., Yamanoi, H., & Komiyama, Y. 2015, ApJL, 807, L2
Lee, M. G., Kang, J., Lee, J. H., & Jang, I. S. 2017, ApJ, 844, L57
Gu, M., Conroy, C., Law, D., et al. 2017, arXiv:1709.07003
Mo, H. J., Mao, S., & White, S. D. M. 1998, MNRAS, 295, 319
Muñoz, R. P., Eigenthaler, P., Puzia, T. H., et al. 2015, ApJL, 813, L15
Pandya, V., Romanowsky, A. J., Laine, S., et al. 2017, arXiv:1711.05272
Peng, E. W., & Lim, S. 2016, ApJL, 822, L31
Penny, S. J., Conselice, C. J., de Rijcke, S., & Held, E. V. 2009, MNRAS, 393, 1054
Román, J., & Trujillo, I. 2017, MNRAS, 468, 703
Román, J., & Trujillo, I. 2017, MNRAS, 468, 4039
Sifón, C., van der Burg, R. F. J., Hoekstra, H., Muzzin, A., & Herbonnet, R. 2017, arXiv:1704.07847
Trujillo, I., Roman, J., Filho, M., & Sánchez Almeida, J. 2017, ApJ, 836, 191
van den Bosch, F. C., Tormen, G., & Giocoli, C. 2005, MNRAS, 359, 1029
van den Bosch, F. C., & Jiang, F. 2016, MNRAS, 458, 2870
van der Burg, R. F. J., Muzzin, A., & Hoekstra, H. 2016, arXiv:1602.00002
van der Burg, R. F. J., Hoekstra, H., Muzzin, A., et al. 2017, arXiv:1706.02704
van Dokkum, P. G., Abraham, R., Merritt, A., et al. 2015, ApJL, 798, L45
van Dokkum, P., Abraham, R., Brodie, J., et al. 2016, ApJL, 828, L6
van Dokkum, P., Abraham, R., Romanowsky, A. J., et al. 2017, ApJL, 844, L11
Venholo, A., Peletier, R., Laurikainen, E., et al. 2017, arXiv:1710.04616
Wittmann, C., Lisker, T., Ambachew Tilahun, L., et al. 2017, MNRAS, 470, 1512
Yamanoi, H., Komiyama, Y., Yagi, M., et al. 2012, AJ, 144, 40
Zaritsky, D. 2017, MNRAS, 464, L110