Hermeian dark matter haloes of the Local Group

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Key words: Local Group – Galaxy: evolution – galaxies: dwarf – galaxies: evolution – galaxies: interactions – dark matter

ABSTRACT

The Local Group is a unique environment in which to study the astrophysics of galaxy formation. The proximity of the Milky Way and M31 causes a large fraction of the low-mass halo population to interact with more massive dark matter haloes, which increases their concentrations and strips them of gas and other material. Some low-mass haloes pass through the haloes of the Milky Way or M31 at earlier times and is almost twice as concentrated as isolated field haloes. These ‘Hermeian’ haloes are distributed anisotropically at greater distances from the Local Group barycentre than the primary haloes and appear to cluster close to the Milky Way and M31 in projection. We show that some Hermeian haloes can host galaxies that are promising targets for indirect dark matter searches and are competitive with signals from other dwarf galaxies. Hermeian galaxies in the Local Group should be detectable by forthcoming wide-field imaging surveys.

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1 INTRODUCTION

The Local Group environment is an exceptional probe of fundamental theories, and models of galaxy evolution. The proximity of its constituent galaxies facilitates detailed observations that enable the comprehensive exploration of the physics of galaxy formation across several orders of magnitude in mass. Its population of faint galaxies has also proved to be a compelling test of cosmological models on small astrophysical scales, ruling out various dark matter (DM) candidates (e.g. Lovell et al. 2016; Enzi et al. 2020; Nadler et al. 2021; Newton et al. 2020) and revealing possible small-scale challenges to the prevailing paradigm (see Bullock & Boylan-Kolchin 2017; Pawlowski 2018, for recent reviews).

Over the last decade, self-consistent Local Group-like volumes have been modelled in detail using increasingly sophisticated simulations (e.g. Gottlöber et al. 2010; Libeskind et al. 2010; Garrison-Kimmel et al. 2014; Yepes et al. 2014; Carlesi et al. 2016; Sawala et al. 2016; Fattahi et al. 2016; Libeskind et al. 2020). They have revealed a dynamic environment that influences the growth of the Milky Way (MW) and Andromeda (M31) and has important effects on the evolution of the low-mass galaxy population (Benítez-Llambay et al. 2013). In particular, the simulations show that low-mass objects often interact with more massive haloes in the dense environment of the Local Group. The tidal interactions they experience increase the concentrations of their DM haloes (Li et al. 2013; Bakels et al. 2021) and baryonic processes efficiently strip gas from the galaxies they host.

Such ‘pre-processed’ haloes are commonly found in the vicinity of the two ‘primary’ hosts, which dominate the Local Group’s internal dynamics. Most are ‘backsplash’ haloes that fell into the halo of the MW or M31 at earlier times and passed back into the field, reaching distances many times the virial radius of the host by the present day (Gill et al. 2005; Moore et al. 2004; Knebe et al. 2011a). Backsplash haloes compose more than 10 per cent of field galaxies in the Local Group and could account for as many as half of all systems accreted by the MW and M31 (Ludlow et al. 2009; Teyssier et al. 2016; Fattahi et al. 2016; Libeskind et al. 2020).
et al. 2012; Garrison-Kimmel et al. 2014; Bakels et al. 2021; Green et al. 2021). Galaxies in backsplash haloes typically have higher quenched fractions and lower mass-to-light ratios and gas fractions than isolated field galaxies that have not experienced such halo–primary halo interactions (Knebe et al. 2011a; Simpson et al. 2018; Buck et al. 2019). There is evidence of these processes in some nearby dwarf galaxies, which could have passed close to the MW (e.g. Besla et al. 2007; Pawlowski & McGaugh 2014; Buck et al. 2019; Blaña et al. 2020; McConnell et al. 2021; Putman et al. 2021). The proximity of the MW and M31 during the assembly of the Local Group also facilitates the exchange of DM haloes between them. These ‘renegade’ haloes pass through one of the primary haloes and are then accreted into the other, potentially transferring baryonic material in the process (Knebe et al. 2011b). As many as half of the satellite galaxies in the MW and M31 could have experienced such interactions (Wetzel et al. 2015). Renegade haloes share many properties with other pre-processed haloes but differ in their spatial distribution, which is anisotropic and points towards the two host haloes. This is a result of their trajectory through the primary haloes of the Local Group (Libeskind et al. 2011).

Populations of highly concentrated DM haloes could be competitive probes with which to constrain the properties of the DM. Candidate particles that decay or annihilate with each other in regions of high DM density are predicted to emit electromagnetic radiation, typically in X-rays or gamma-rays. For annihilating DM, the luminosity of the radiation originating from these particle interactions scales strongly with halo mass and concentration (Sánchez-Conde & Prada 2014). Such signals have been claimed to be observed already in DM-dominated systems such as the Galactic centre (the so-called ‘GeV excess’; Goodenough & Hooper 2009; Calore et al. 2015; Daylan et al. 2016; Ackermann et al. 2017b), the centre of M31 (Ackermann et al. 2017a), and the Reticulum II dwarf galaxy (Geringer-Sameth et al. 2015). However, an astrophysical origin of the signal is also possible and has not been ruled out (Carlson & Profumo 2014; Petróvić et al. 2014; Bartels et al. 2016; Lee et al. 2016; Di Mauro & Winkler 2021). Gas-poor, pre-processed dwarf galaxies could therefore be attractive targets to break the degeneracy in the origins of the gamma-ray excesses.

In this paper, we describe a new class of concentrated DM halo, which is a promising target for indirect DM searches. These ‘Hermeian’ haloes interact with the haloes of both the MW and M31 during the assembly of the Local Group and have passed back into the field by $z = 0$. We study these using high resolution magnetohydrodynamic simulations of Local Group volumes from the HESTIA suite (Libeskind et al. 2020) and which we introduce in Section 2. These simulations are constrained by observations of the peculiar velocity field to reproduce realistic Local Group environments. In Section 3, we investigate how interactions with the primary haloes affect the evolution of the Hermeian haloes compared with the backsplash and field populations and describe their present-day properties by which they might be identified in observations. We also evaluate how Hermeian haloes would appear in observational searches for DM annihilation signals. We discuss these results and present concluding remarks in Section 4.

1 In Ancient Greek mythology, Hermes was the messenger of the gods and the protector of travellers and wayfarers. He also presided over the crossing of thresholds and boundaries and was often invoked alongside the goddess Hestia during times of change and transition.

2 This is the radius at which the mean enclosed matter density is $\rho(< R_{200}) = 200 \times \rho_{\text{crit}}$, where $\rho_{\text{crit}}$ is the critical density for closure.
the centre of the M31 analogue in the $R$ only concerned with when they cross inside poses this does not affect the classification of the haloes as we are markers. At mean galaxies are shown by thick solid lines and distinguishing Hermeian halo from the MW and M31 analogues. The dark Hermeian haloes contain low-mass galaxies, one of which retains a gaseous component, i.e. they are ‘dark’. However, four contain low-mass galaxies, one of which retains a gaseous component until $z = 0$. The four galaxies and 121 (over 90 per cent) of the total Hermeian population are found in the 17.11 simulation, so we report results only from this in the analysis that follows. We note that the 17.11 simulation is the most massive Local Group in the HESTIA suite and its primary haloes are closer together than in the other simulations. The lack of Hermeian haloes in the other simulations could be due to the lower masses and larger separations of the primary pairs, although differences in the orientation of the primaries with respect to the Large Scale Structure could also be important.

3 RESULTS

We find a total of 137 Hermeian haloes in the three high-resolution simulations of the Local Group in HESTIA. Over 97 per cent of these do not have any baryonic component, i.e. they are ‘dark’. However, four contain low-mass galaxies, one of which retains a gaseous component until $z = 0$. The four galaxies and 121 (over 90 per cent) of the total Hermeian population are found in the 17.11 simulation, so we report results only from this in the analysis that follows. We note that the 17.11 simulation is the most massive Local Group in the HESTIA suite and its primary haloes are closer together than in the other simulations. The lack of Hermeian haloes in the other simulations could be due to the lower masses and larger separations of the primary pairs, although differences in the orientation of the primaries with respect to the Large Scale Structure could also be important.

As discussed in Section 2, we identify Hermeian haloes in simulations by studying the past trajectories of present-day field haloes through the Local Group and select those that passed within $R_{200}$ of both host haloes. In Fig. 1, we plot the distance, $r_{\text{host}}$, of each Hermeian halo from the MW and M31 analogues. The dark Hermeian haloes are plotted as thin solid lines and the luminous Hermeian galaxies are shown by thick solid lines and distinguishing markers. At $z = 0$, most Hermeian haloes are at distances from the host halo much greater than $R_{200}$. Adopting a different halo definition, for example using $R_{50}$ that approximates the virial radius in the PLANCK 2013 cosmology, would likely have little effect on the classification of most Hermeian haloes but would remove some that are close to the $R_{200}$ boundary at $z = 0$. However, it would also expand the classification to include DM haloes that had more shallow, ‘grazing’ interactions with the host, which could affect the distributions of Hermeian halo properties (see Diemer 2021, for a detailed discussion about the consequences of adopting different definitions of the halo boundary).

There are two main epochs during which the Hermeian haloes interact with a host halo. The first is at $t_{\text{lookback}} = 9 - 6.5$ Gyr, when most Hermeian haloes experience pericentric passages with the M31 analogue and are gravitationally attracted towards the MW host halo. The second epoch is longer, beginning at $t_{\text{lookback}} = 5$ Gyr and finishing approximately 1 Gyr before the present day. Both epochs are dominated by the members of a large group containing three of the Hermeian galaxies that fell into the M31 analogue. Their interactions with this primary halo increased the dispersion of the trajectories of the group members, lengthening the second interaction epoch with the MW halo and broadening their angular dispersion relative to the MW host at $z = 0$. The latter is shown in Figs 2 and 3, which are discussed below. The remaining dark haloes and the fourth Hermeian galaxy, indicated in Fig. 1 by cross symbols, originate from the opposite side of the Local Group and traverse it in the opposite direction, interacting first with the MW analogue then being attracted towards M31.

There is a limited set of trajectories on which DM haloes can interact with both Local Group primary hosts and move into the field within a Hubble time. This restricts the spatial distribution of Hermeian haloes at $z = 0$. To characterize this we determine the angle, $\theta_{\text{mid}}$, formed by the field haloes and the M31 analogue with respect to the midpoint of the line connecting the two primary hosts. This is an arbitrary choice of basis that sets the M31 analogue at $\theta_{\text{mid}} = 0^\circ$ and the MW analogue at $\theta_{\text{mid}} = 180^\circ$. The field and backsplash halo populations have similar angular distributions in the Local Group; however, a larger proportion of backsplash haloes are close to the
MW–M31 line in the direction of the M31 analogue ($\theta_{\text{mid}} = 0^\circ$) and the Hermeian haloes are more strongly concentrated in the direction of the MW analogue ($\theta_{\text{mid}} = 180^\circ$). These features are related to each other by the large group infall onto the M31 analogue. In addition to supplying most of the Hermeian population, many of the DM haloes brought in by the group that did not escape towards the MW stayed close to the M31 host as backsplash haloes.

To strengthen our understanding of the spatial distribution of the Local Group field halo populations, the right panel of Fig. 2 shows their radial distributions relative to the midpoint of the MW–M31 line. Most field and backsplash haloes are within 1 Mpc of the LG midpoint and most commonly are at smaller distances than the two primary haloes (e.g. Libeskind et al. 2016; Pawlowski et al. 2017; Gong et al. 2019; Wan et al. 2020). There are no Hermeian haloes within 400 kpc of the centre of the Local Group and all of them are at greater distances than the MW and M31 analogues (with respect to the LG midpoint); the furthest of these is at a distance of 1.6 Mpc. Finding a halo at such large distances that has passed within the virial radii of both main haloes without being accreted is particularly surprising. Accounting for the angular distributions of the haloes discussed above, the Hermeian population is confined to two lobes at distances further from the Local Group barycentre than the MW and M31. Observational efforts to detect Hermeian haloes would be best focused in these areas.

To illustrate the spatial distribution of the Hermeian haloes more clearly, in Fig. 3 we plot the angular positions of the haloes relative to the midpoint of the line connecting the primary pair. Here, the dark Hermeian haloes (i.e. those without a baryonic component) are plotted with triangles and the four Hermeian galaxies, which retain stars and gas, are plotted with markers corresponding to those used in Fig. 1. The locations of the MW and M31 analogues are marked with filled and unfilled squares, respectively. As we showed in Fig. 2, most of the Hermeian haloes lie on the far side of the MW analogue with respect to the Local Group barycentre and close to the line connecting the primary pair. The large angular dispersion is a consequence of the scatter in the trajectories of the group members that was enhanced during their initial interactions with the M31 analogue, lengthening the epoch during which the haloes experienced their pericentric passages with the MW (see Fig. 1). Nearly 10 per cent of the Hermeian haloes closest to the MW analogue are at low galactic latitudes and would likely be obscured by the MW disk, i.e. the Zone of Avoidance. The Hermeian haloes closest to the M31 analogue are clustered much closer together in projection, although there are fewer objects in total and they do not all belong to one group.

As the Hermeian haloes pass through each Local Group primary, tidal forces suppress further accretion of matter and strip mass from their outer layers (e.g. Kravtsov et al. 2004; Peñarrubia et al. 2008; Warnick et al. 2008). Most of this mass loss occurs near pericentre (Zavala & Frenk 2019) concurrently with tidally induced shock heating that reduces the inner density of the infalling halo and increases its concentration (Hayashi et al. 2003; Kazantzidis et al. 2004). Here, we explore how these dynamical processes affect the properties of the haloes at $z = 0$. In the main panel of Fig. 4, we compare the concentrations, $c_{200}$, of the backsplash haloes (dashed contours and squares), dark Hermeian haloes (triangles), and the Hermeian galaxies (symbols as used in Fig. 1) with the rest of the field halo population (solid contours and points) as a function of their maximum

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Figure 2. **Left panel**: Probability distributions of the angles, $\theta_{\text{mid}}$, that the backsplash, Hermeian, and remaining field halo populations make with the vector towards M31 from the midpoint of the line connecting the MW and M31 analogues. In this basis, the M31 halo is at $\theta_{\text{mid}} = 0^\circ$ and the MW is at $\theta_{\text{mid}} = 180^\circ$. **Right panel**: Probability density functions of the distances, $r_{\text{mid}}$, of the haloes from the midpoint of the line. We multiply this by $\text{sgn} (\cos \theta_{\text{mid}})$, so that haloes in the direction of M31 (marked by the unfilled arrow) have positive values and haloes in the hemisphere containing the MW analogue (marked by the filled arrow) have negative values. In both panels, the properties of the Hermeian galaxies are indicated by the vertical dotted lines and markers corresponding to the same galaxies as in Fig. 1.
circular velocity, \( V_{\text{max}} \). This is a stable proxy for halo mass, even for objects that experienced some tidal stripping, and \( V_{\text{max}} \) correlates more strongly to certain observable properties (such as galaxy rotation curves) than the halo mass (see discussion in Knebe et al. 2013, section 1.2). As the field and backsplash populations are large, within the 99th percentiles we represent these populations using solid and dashed isodensity contours, respectively. The shaded region in the main panel shows isodensity contours for backsplash haloes that pass through one of the primary haloes exactly twice. We refer to these objects as the ‘\( N=2 \)’ backsplash population. Their interaction history is similar to that of the Hermeian haloes and their properties evolve in a similar manner. In all cases we exclude haloes for which AHF could not determine a concentration. In the upper and right panels of Fig. 4, we decompose the parameter space into probability distribution functions for each halo population. The field, (total) backsplash, and Hermeian halo populations are represented by thin solid lines, thick dashed lines, and thick solid lines, respectively.

The \( V_{\text{max}} \) functions of the Hermeian and backsplash populations in the upper panel of Fig. 4 are truncated compared with the field population. In the populations that interact with the host haloes, high-mass haloes with large \( V_{\text{max}} \) are strongly affected by tidal stripping that removes mass each time they descend deep into the potential of a Local Group primary. This truncates the upper ends of their \( V_{\text{max}} \) distributions to between \( V_{\text{max}} = 35 - 40 \text{ km s}^{-1} \), and the Hermeian distribution is affected more severely than the total backsplash population. The Hermeian galaxies are hosted by the four Hermeian haloes with the highest \( V_{\text{max}} \), which is consistent with expectations from galaxy formation models. At low \( V_{\text{max}} \), the limited resolution of the simulation prevents the full characterization of the low-mass halo population, producing a turnover in the \( V_{\text{max}} \) functions below \( V_{\text{max}} = 4 \text{ km s}^{-1} \). In this regime, the suppression of low-\( V_{\text{max}} \) backsplash and Hermeian haloes is enhanced because of their repeated interactions with the Local Group primaries. Although tidal stripping is less efficient at low halo masses, enough material is removed during pericentric passages that low-\( V_{\text{max}} \) haloes stop being identified by structure finders or are numerically disrupted (see discussion in e.g. Springel et al. 2008; Peharrubia et al. 2010; Onions et al. 2012; van den Bosch 2017; Newton et al. 2018; van den Bosch & Ogiya 2018; Green & van den Bosch 2019; Errani & Navarro 2020; Poulton et al. 2020; Green et al. 2021).

In the right panel of Fig. 4, we plot the \( c_{200} \) distributions of the halo populations. Independently of halo mass, we find that haloes that have interacted with one or both primary hosts (backsplash and Hermeian haloes, respectively) are more concentrated than field haloes, in agreement with previous work on the backsplash population (e.g. Li et al. 2013; Bakels et al. 2021). The medians of each distribution are marked with arrows and we find that the Hermeian haloes are nearly twice as concentrated as the field halo population and 18 per cent more concentrated than the backsplash population. We also mark the median of the ‘\( N=2 \)’ backsplash population with an arrow with a dashed outline. These haloes are 15 per cent more concentrated that the Hermeian haloes, and more than twice as concentrated as the field halo population. We perform Kolmogorov-Smirnov tests to compare the concentration distribution of the Hermeian haloes with those of the total backsplash, ‘\( N=2 \)’ backsplash, and field halo populations. In all cases, we reject that the distribution of Hermeian concentrations is drawn from the total backsplash, ‘\( N=2 \)’ backsplash, or field halo distributions, at 95 per cent confidence. The test statistics, \( D \), and \( p \)-values are: \( D_{\text{backsplash}} = 0.224; \quad p_{\text{backsplash}} = 9 \times 10^{-6}; \quad D_{\text{Hermeian}} = 0.153; \quad p_{\text{Hermeian}} = 0.006; \quad D_{\text{field}} = 0.548; \quad p_{\text{field}} = O\left(10^{-34}\right) \).

The four Hermeian galaxies are segregated in \( c_{200} \) according to their mass: the two most massive galaxies (marked by the star and diamond) lie closest to the expected halo mass–concentration relation according to their mass: the two most massive galaxies (marked by the star and diamond) lie closest to the expected halo mass–concentration relation.
The concentration, $c_{200}$, of field haloes as a function of maximum circular velocity, $V_{\text{max}}$. In the main panel, the isodensity contours enclose 5, 50, 90, and 99 per cent of the field halo and backsplash populations (solid and dashed lines, respectively) and haloes outside the 99th percentiles are plotted as points and squares, respectively. The shaded contours enclose 5, 50, and 99 per cent of the backsplash population that interacts with one of the primary haloes exactly twice (the ‘$N=2$’ backsplash population). The ‘dark’ Hermeian haloes are represented by triangles and the Hermeian galaxies are shown by the pentagon, cross, star, and diamond. The upper and right panels show, respectively, the $V_{\text{max}}$ and $c_{200}$ probability distributions of the field haloes (thins solid lines), the backsplash (thick dashed lines), and the ‘dark’ Hermeian (thick solid lines) populations. The $c_{200}$ probability distributions shown are for haloes with $V_{\text{max}} \leq 35 \text{ km s}^{-1}$, to match the $V_{\text{max}}$ range of the Hermeian population. The median values of these populations and the ‘$N=2$’ backsplash haloes are marked with arrows. In both panels, the masses and concentrations of the Hermeian galaxies are indicated by dotted lines and their corresponding symbols. There are 15,537 field haloes, 2,577 backsplash haloes, 120 ‘dark’ Hermeian haloes and four Hermeian galaxies. Haloes for which $\text{gpc}$ could not determine a concentration have not been plotted.

(Prada et al. 2012; Ludlow et al. 2016), whereas the two lowest-mass Hermeian galaxies (marked by the cross and pentagon) are much more concentrated at $z = 0$. While this is consistent with the effects of tidal interactions that we described above, the evolution of $c_{200}$ through time is degenerate with the pericentric distance of the Hermeian galaxy and could also depend on other properties. As we showed in Fig. 1, the two most massive Hermeian haloes have the largest pericentric distances, which minimises mass loss during their interactions with the hosts.

3.1 Prospects for indirect DM searches

Highly concentrated DM-dominated objects such as the Hermeian haloes can be excellent targets for indirect DM searches that look for DM annihilation products. In DM models where the particle annihilates and produces photons, the expected photon flux from a DM source, $\frac{d\Phi_\gamma}{dE}$, can be expressed as the product of two physically motivated terms:

$$\frac{d\Phi_\gamma}{dE} = \frac{d\Phi_{\gamma}^{pp}}{dE} \times J(\Delta \Omega).$$

The first term, $\frac{d\Phi_{\gamma}^{pp}}{dE}$, contains information about the DM particle properties and its interactions (e.g. its mass, annihilation cross-section and number of photons per annihilation) and, for Majorana DM particles, can be expressed as

$$\frac{d\Phi_{\gamma}^{pp}}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\text{DM}}^2} \frac{dN_\gamma}{dE},$$

where $m_{\text{DM}}$ is the mass of the DM particle, $\langle \sigma v \rangle$ is the thermally averaged DM annihilation cross-section, and $\frac{dN_\gamma}{dE}$ describes the energy distribution of the photons produced by the interactions. The second term in eq. (1), called the $J$-factor, $J(\Delta \Omega)$, encodes the astrophysical properties of the DM in the target system. If the DM particle interaction cross-section does not depend on the particle velocity, then the $J$-factor is independent of the DM model, making it useful to assess the suitability of Hermeian haloes as targets for indirect DM searches. The $J$-factor is calculated by

$$J(\Delta \Omega) = \int_{\Delta \Omega} \int_{\text{d.o.s.}} r_{\text{DM}}^2 \, d\Omega, \quad \text{d} \Phi_\gamma = \frac{\langle \sigma v \rangle}{8\pi m_{\text{DM}}^2} \frac{dN_\gamma}{dE} \times J(\Delta \Omega).$$

In detail, there is always a connection between both terms in eq. (1): the mass of the DM particle imposes a cut-off on the matter power spectrum that sets a minimum halo mass, $M_{\text{min}}$. For DM particles with $m_{\text{DM}} = 10^3 \text{ GeV}$, the minimum halo mass is approximately $M_{\text{min}} = 10^{-6} \text{ M}_\odot$ (Profumo et al. 2006; Bringmann 2009). The value of $M_{\text{min}}$ has important implications for the total annihilation signal (Sánchez-Conde & Prada 2014; Moliné et al. 2017).
and \( f \) in the signal due to the subhalo population inside the Hermeian haloes would produce very similar results. We expect that repeating the above calculations assuming an Einasto density profile with shape parameter \( \alpha = 0.16 \) at low-mass Hermeian galaxies have larger \( J \)-factors than the two low-mass Hermeian galaxies. The maximum \( J \)-factor among the Hermeians reaches a value of \( \log_{10} \left( J_T / \text{GeV}^2 \text{cm}^{-5} \right) = 17.59 \). This is comparable to the \( J \)-factors of other more traditional targets for gamma-ray DM searches, such as dwarf satellite galaxies, dark satellites, or galaxy clusters (Charles et al. 2016). However, this is significantly below the \( J \)-factors of the most promising nearby dwarf galaxies (Albert et al. 2017) that are usually considered to be among the best targets for indirect DM detection, though see the recent discussions in Facchinetti et al. (2020) and Grand & White (2021) about the likelihood of detecting an unambiguous signal in the smooth halo of the MW.

In addition to the \( J \)-factor, the detectability of DM haloes in gamma-ray searches also depends on the angular size, \( \alpha \), of the photon emission region. This is because the analysis of gamma-ray data from extended sources is significantly more complex than that for point-like sources (see the discussion in e.g. Ackermann et al. 2015b; Acciari et al. 2018). The angular size depends on both the distance to the source and the spatial extent of its photon emission, which scales inversely with halo concentration. In the right panel of Fig. 5, most Hermeian haloes have angular sizes \( \alpha < 0.1^\circ \) that are smaller than the typical angular resolution of current gamma-ray experiments such as Fermi LAT or MAGIC (Aleksić et al. 2016). Consequently, these objects will appear as point-like sources in gamma-ray telescopes and are promising can-

\[
J_T = \frac{1}{4\pi d^2} \int_Y \rho_{\text{DM}}^2(r) \, dV
= \frac{1}{d^2} \frac{M_{200} c_{200}^2}{f(c_{200})^2} \frac{200 \rho_{\text{crit}}}{9} \left( 1 - \frac{1}{(1 + c_{200})^3} \right),
\]

\( \rho_{\text{DM}} \) the distance from the Earth to the centre of the target system and \( f(x) = \ln(1+x) - x/(1+x) \). To quantify the strength of the DM signal from the Hermeian haloes, we calculate their total \( J \)-factors. In Fig. 5, we plot these as a function of the distance from the MW analogue (left panel) and of the angular size of the photon emission region (right panel), which we define as the angle subtended by twice the scale radius of the target. When assuming a NFW density profile, approximately 90 per cent of the annihilation flux originates within this region and it therefore represents a good proxy of the angular size that would be observed by gamma-ray telescopes. Recently, Wang et al. (2020) showed that an Einasto density profile with shape parameter \( \alpha = 0.16 \), fits the profiles of DM haloes more accurately than a NFW profile for halo masses spanning 20 orders of magnitude. We expect that repeating the above calculations assuming an Einasto profile would produce very similar results.

When calculating the \( J \)-factor we do not include any enhancement in the signal due to the subhalo population inside the Hermeian halo (the so-called subhalo boost, e.g. Kamionkowski et al. 2010; Sánchez-Conde & Prada 2014; Ando et al. 2019). Having been subhalos themselves in the past, Hermeian haloes experienced strong tidal interactions with both the MW and M31. This repeated tidal stripping not only increased their concentrations but also will have removed most of their substructure, especially in the outermost regions. As a result, the subhalo boost is expected to be of the order of only a few percent for these objects (Moliné et al. 2017).

The average total \( J \)-factor of the dark Hermeian population is \( \log_{10} \left( \tilde{J}_T / \text{GeV}^2 \text{cm}^{-5} \right) = 15.50^{+0.63}_{-0.75} \) and the four Hermeian galaxies have \( \log_{10} \left( J_T / \text{GeV}^2 \text{cm}^{-5} \right) = [16.62, 16.62, 17.05, 17.59] \), respectively. The \( J \)-factor is affected most strongly by the halo mass and is weakly sensitive to the distance of the Hermeian haloes from the primary halo. Consequently, six dark haloes have larger \( J \)-factors than the two low-mass Hermeian galaxies. The maximum \( J \)-factor among the Hermeians reaches a value of \( \log_{10} \left( J_T / \text{GeV}^2 \text{cm}^{-5} \right) = 17.59 \). This is comparable to the \( J \)-factors of other more traditional targets for gamma-ray DM searches, such as dwarf satellite galaxies, dark satellites, or galaxy clusters (Charles et al. 2016). However, this is significantly below the \( J \)-factors of the most promising nearby dwarf galaxies (Albert et al. 2017) that are usually considered to be among the best targets for indirect DM detection, though see the recent discussions in Facchinetti et al. (2020) and Grand & White (2021) about the likelihood of detecting an unambiguous signal in the smooth halo of the MW.

\[ \log_{10} \left( \tilde{J}_T / \text{GeV}^2 \text{cm}^{-5} \right) = 15.50^{+0.63}_{-0.75} \]
We discovered and described a new class of cosmic objects that passed within the virial radii of both Local Group hosts, the MW and M31, and became field haloes at $z = 0$. We call these ‘Hermeian’ haloes, named after Hermes from Ancient Greek mythology: the messenger of the gods, who presided over the crossing of thresholds and boundaries. These Hermeian haloes are similar to ‘backsplash’ haloes that experience more than one pericentric passage with the same host; however, Hermeian haloes pass through two different and massive haloes at two different epochs in their formation. Most Hermeian haloes are devoid of baryonic material at $z = 0$ as the gas and stellar content was stripped during their pericentric passages. The most massive Hermeian haloes can contain galaxies that survive close interactions with the primary hosts and retain their gaseous component. They could facilitate the exchange of baryonic material between the host haloes, making Hermeian haloes important participants in the evolution of the MW and M31 that affect observational proxies of the star formation histories of the main galaxies. These intergalactic messengers are potentially a source of external chemical proxies of the star formation histories of the main galaxies. These events or other chemical signatures, and the dynamical modelling of their nearby dwarf galaxies will help to establish the abundance and likely locations of Hermeian haloes in the Local Group (e.g. Teyssier et al. 2012; Buck et al. 2019; McConnachie et al. 2021). The members of the NGC 3109 association are interesting targets for further study because initial calculations suggest these galaxies could have experienced interactions with the MW, indicating that they are remnants of a similar group infall event. However, better proper motion measurements and additional dynamical modelling are needed to establish whether the association has also interacted with M31 (Shaya & Tully 2013; Pawlowski & McGaugh 2014).

The properties of Hermeian haloes are affected by tidal stripping and shock heating during their interactions with the Local Group primaries. These effects are strongest during pericentric passage and affect the $V_{\text{max}}$ distribution and concentrations of the Hermeian population (see Fig. 4). Compared with the isolated field halo population, the Hermeian haloes sample a narrower range in $V_{\text{max}}$. The truncation of the upper end of the distribution to $V_{\text{max}} > 35$ km s$^{-1}$ is a consequence of tidal stripping that removes mass efficiently from the outer layers of more massive haloes. Low-$V_{\text{max}}$ haloes are more susceptible to artificial disruption by numerical effects in the simulation that suppress the abundance of field haloes below $V_{\text{max}} = 4$ km s$^{-1}$. This turnover is more severe in the backsplash and Hermeian halo populations as tidal interactions dissolve some low-$V_{\text{max}}$ haloes during each pericentric passage. The same mechanisms also enhance the concentrations of the haloes while they travel through the Local Group hosts, changing the shape of the Hermeian concentration distribution function and making them almost twice as concentrated, on average, as isolated field haloes. We find a similar result for the population of back splash haloes that passed through a primary halo twice: on average, they are 14 per cent more concentrated than the Hermeian population and more than twice as concentrated as field haloes. However, their spatial distribution in the Local Group at $z = 0$ is less anisotropic than the Hermeian haloes, which makes searching for ‘N=2’ backsplash haloes in observations more challenging.

In the $17_\text{}_{\text{11}}$ HESTIA simulation most of the Hermeian haloes are created as part of a large group that falls into the M31 analogue at early times. This group travels through the Local Group from the direction of M31 towards the MW so that, at $z = 0$, the angular distribution of Hermeian haloes in the direction of the MW analogue ($\theta_{\text{mid}} = 180^\circ$) is enhanced. The remaining non-Hermeian haloes in the infalling group have three possible futures: (i) they avoid interacting with either host and remain as field haloes; (ii) they are captured by one of the host haloes and become a satellite, or; (iii) they experience at least one pericentric passage with a host and become back splash haloes. The backsplash haloes that fall in are spread throughout the Local Group at $z = 0$; however, most cluster close to the M31 primary, which enhances the angular distribution of backsplash haloes towards $\theta_{\text{mid}} = 0^\circ$ (see Fig. 2). The asymmetric enhancements of the angular distributions of the backsplash and Hermeian populations towards opposing poles of the MW–M31 line are a characteristic signature of the group infall. Evidence of similar major encounters in the MW or M31, for example from starburst events or other chemical signatures, and the dynamical modelling of their nearby dwarf galaxies will help to establish the abundance and likely locations of Hermeian haloes in the Local Group (e.g. Teyssier et al. 2012; Buck et al. 2019; McConnachie et al. 2021). The members of the NGC 3109 association are interesting targets for further study because initial calculations suggest these galaxies could have experienced interactions with the MW, indicating that they are remnants of a similar group infall event. However, better proper motion measurements and additional dynamical modelling are needed to establish whether the association has also interacted with M31 (Shaya & Tully 2013; Pawlowski & McGaugh 2014).

The Hermeian haloes are promising targets to detect signals of DM annihilation in gamma-ray experiments. We characterize their detectability by calculating their astrophysical $J$-factors and determine the angular sizes of their photon emission regions (see Fig. 5). The $J$-factors of the four Hermeian galaxies are comparable with those galaxies for additional follow-up. Further discoveries could be made in upcoming wide-field imaging surveys such as the Legacy Survey of Space and Time at the Vera C. Rubin Observatory (Ivezić et al. 2019).

The most massive Hermeian haloes can contain galaxies that survive pericentric passages and affect the $V_{\text{max}}$ distribution and concentrations of the Hermeian population (see Fig. 4). Compared with the isolated field halo population, the Hermeian haloes sample a narrower range in $V_{\text{max}}$. The truncation of the upper end of the distribution to $V_{\text{max}} > 35$ km s$^{-1}$ is a consequence of tidal stripping that removes mass efficiently from the outer layers of more massive haloes. Low-$V_{\text{max}}$ haloes are more susceptible to artificial disruption by numerical effects in the simulation that suppress the abundance of field haloes below $V_{\text{max}} = 4$ km s$^{-1}$. This turnover is more severe in the backsplash and Hermeian halo populations as tidal interactions dissolve some low-$V_{\text{max}}$ haloes during each pericentric passage. The same mechanisms also enhance the concentrations of the haloes while they travel through the Local Group hosts, changing the shape of the Hermeian concentration distribution function and making them almost twice as concentrated, on average, as isolated field haloes. We find a similar result for the population of backsplash haloes that passed through a primary halo twice: on average, they are 14 per cent more concentrated than the Hermeian population and more than twice as concentrated as field haloes. However, their spatial distribution in the Local Group at $z = 0$ is less anisotropic than the Hermeian haloes, which makes searching for ‘N=2’ backsplash haloes in observations more challenging.

4 DISCUSSION AND CONCLUSIONS

The set of trajectories that Hermeian haloes take through the Local Group is limited. This restricts their spatial distribution at $z = 0$ and favours a highly anisotropic configuration along the line connecting the MW with M31 (see Fig. 2). We find Hermeian haloes 400 kpc to 1.6 Mpc from the midpoint of this connecting line, and none between the primary hosts. That a halo at such large distances could have passed through both primary haloes without being accreted or dissolved by tidal stripping is particularly remarkable and speaks to the resilience of some haloes. When projected on the sky, the Hermeian haloes appear to cluster close to the projected positions of the MW and M31 (see Fig. 3). The tightly constrained spatial distribution will assist searches for observational signatures of the dark haloes, and also can be applied as a criterion to select candidate Hermeian...
from dwarf satellite galaxies but are much lower than the nearby dwarfs showing most promise for the detection of a DM signal. However, most of the Hermeian haloes would be point-like sources in current gamma-ray telescopes, which improves their detectability significantly. If the real Hermeian population is as large as the simulated one, a combined likelihood analysis of gamma-ray data would further increase the sensitivity to DM signals from these objects.

We find Hermeian haloes in all three high-resolution simulated Local Groups in the HESTIA suite. However, over 90 per cent of all the Hermeian haloes in these simulations, as well as all the Hermeian haloes that retain baryons at $z = 0$, are in just one HESTIA simulation (17_11). This Local Group has the most massive primary pair that is also 20 per cent closer together at $z = 0$ than in the other simulations. We note that the primaries in this simulation have masses consistent with observational constraints and a separation at $z = 0$ of 675 kpc, which is slightly less than the observed value of ~780 kpc (McConnachie et al. 2005; Conn et al. 2012; Riess et al. 2012). This suggests that the masses and spatial evolution of the Local Group primaries influence the creation of Hermeian galaxies. This is consistent with the results of Knebe et al. (2011b), who found that the greater proximity of the hosts during their evolution enhances the rate of exchange of low-mass satellites. We also show that the abundance of Hermeian haloes can be affected by group infall, which depends on the location and orientation of the primary haloes with respect to the Large Scale Structure. A quantitative statement about the properties that strongly affect the size of the Hermeian population would require the analysis of a large suite of constrained Local Group simulations, which we defer to future work.

Hermeian haloes are unique to paired-halo systems like the Local Group. Although rare, their high concentrations make them promising targets to detect DM annihilation signals. The highly anisotropic spatial distribution of the Hermeian haloes will assist in the search for these objects in observational campaigns, and analyses of DM annihilation signals could be enhanced further by carrying out a combined likelihood analysis of the separate sources. The trajectories of the Hermeian haloes through the Local Group primary haloes could also facilitate the exchange of baryonic material, affecting the evolution and star formation histories of the MW and M31 galaxies. The mass function of the Hermeian population is similar to that of the isolated field haloes, suggesting that there could be many Hermeian haloes that are not resolved in current simulations. Furthermore, the low-mass haloes that are resolved are more susceptible to artificial disruption from numerical effects, a process that is exacerbated during interactions with massive hosts. Therefore, higher resolution hydrodynamic simulations of constrained Local Group systems are needed to estimate the abundance of Hermeian haloes and galaxies in the Local Group. They will also help to understand better how Hermeian haloes affect the evolution of the baryonic component of the MW and M31 haloes and their satellites, and will also shed light on the potential of the Hermeian haloes for indirect DM searches. Some galaxies, such as those in the NGC 3109 association, are promising Hermeian candidates.

ACKNOWLEDGEMENTS

We thank Rob Grand, Christoph Pfrommer, and Stefan Gottlöber for valuable discussions on the draft manuscript. ON thanks Tom Rose for directing attention to Hermes from Ancient Greek mythology and his grammatical comments on the manuscript. ON also thanks Tom Rose, Thomas Callingham, and Calvin Sykes for their hospitality during the completion of this work. ON and NIL acknowledge financial support from the Project IDEXLYON at the University of Lyon under the Investments for the Future Program (ANR-16-IDEX-0005) and supplementary financial support from La Région Aquvergne-Rhône-Alpes. AK is supported by the Ministerio de Ciencia, Innovación y Universidades (MICIU/FEDER) under research grant PGC2018-094975-C21 and further thanks Low for i could live in hope. MASC acknowledges the support of the Atracción de Talento Investigador contract no. 2020-SAI/TIC-19725 granted by the Comunidad de Madrid in Spain. The work of MASC was additionally supported by the Spanish Agencia Estatal de Investigación through the grant PGC2018-095161-B-I00 and the IFT Centro de Excelencia Severo Ochoa, SEV-2016-0597. ET acknowledges support by ETAg grant PRG1006 and by EU through the ERDF CoE grant TK113.

Software: This research made use of Astropy (The Astropy Collaboration et al. 2013, 2018), matplotlib (Hunter 2007), numpy (van der Walt et al. 2011; Harris et al. 2020), python (van Rossum & Drake 2009), and scipy (Jones et al. 2011; Virtanen et al. 2020). We thank their developers for maintaining them and making them freely available.

DATA AVAILABILITY

The data used in this work were extracted from the HESTIA simulation suite. A data repository and scripts to produce the figures in this manuscript is available on GitHub 6 and archived in Zenodo (Newton 2021). Requests for access to the HESTIA simulation data should be directed to a CLUES Collaboration PI.

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6 Supplementary materials: https://github.com/Musical-Neutron/hermeian_paper_plots/
