Extreme Stellar Populations in the Universe: 
Backsplash Dwarf Galaxies and 
Wandering Stars

Maureen Teyssier

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ABSTRACT

Extreme Populations: Backsplash Dwarf Galaxies and Wandering Stars

Maureen Teyssier

We demonstrate that stars beyond the virial radii of galaxies may be generated by the gravitational impulse received by a satellite as it passes through the pericenter of its orbit around its parent. These stars may become energetically unbound (escaped stars), or may travel to further than a few virial radii for longer than a few Gyr, but still remain energetically bound to the system (wandering stars). Larger satellites (10-100% the mass of the parent), and satellites on more radial orbits are responsible for the majority of this ejected population. Wandering stars could be observable on Mpc scales via classical novae, and on 100 Mpc scales via SNIa. The existence of such stars would imply a corresponding population of barely-bound, old, high velocity stars orbiting the Milky Way, generated by the same physical mechanism during the Galaxy’s formation epoch. Sizes and properties of these combined populations should place some constraints on the orbits and masses of the progenitor objects from which they came, providing insight into the merging histories of galaxies in general and the Milky Way in particular.
We distinguish between Local Group field galaxies which may have passed through the virial volume of the Milky Way, and those which have not, via a statistical comparison against populations of dark matter haloes in the Via Lactea II (VLII) simulation with known orbital histories. Analysis of VLII provides expectations for this escaped population: they contribute 13 per cent of the galactic population between 300 and 1500 kpc from the Milky Way, and hence we anticipate that about 7 of the 54 known Local Group galaxies in that distance range are likely to be Milky Way escapees. These objects can be of any mass below that of the Milky Way, and they are expected to have positive radial velocities with respect to the Milky Way. Comparison of the radius-velocity distributions of VLII populations and measurements of Local Group galaxies presents a strong likelihood that Tucana, Cetus, NGC3109, SextansA, SextansB, Antlia, NGC6822, Phoenix, LeoT, and NGC185 have passed through the Milky Way. Indeed, several of these galaxies – especially those with lower masses – contain signatures in their morphology, star formation history and/or gas content indicative of evolution seen in simulations of satellite/parent galactic interactions. Our results offer strong support for scenarios in which dwarfs of different types form a sequence in morphology and gas content, with evolution along the sequence being driven by interaction history.

We use the Via Lactea II cosmological N-body simulation of the formation of Milky Way and M31 Analogues, to explore the expected properties of intergalactic light (light found beyond the virial radii of galaxies) in poor groups and around isolated galaxies. We find that the luminosity fraction of intergalactic light is 1%. This is similar to observational measurements of intergalactic light in poor groups. We expect this result to
be observationally verifiable through observations of supernovae Ia by blind, repeated surveys like Pan-STARRS and LSST.

We find the major contributors to the intergalactic light are the largest mass satellite haloes due to the low stellar fraction expected in smaller mass haloes. The intergalactic light produced by the most massive satellites has a much smaller spatial extent than that produced by lower mass satellites, meaning that baryon prescriptions designed to suppress star formation in low mass satellites also shrink the spatial extent of intergalactic light. It may be possible to use observations of the large quantity of intergalactic red giants, that we expect in the Local Group, to define the spatial extent of the intergalactic light, and thereby place limits on the total star formation in progenitor satellites in the Local Group.
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Chapter 1

Introduction

Hierarchical structure formation is a process in which smaller structures accumulate to form larger structures: individual galaxies may create galaxy clusters, and smaller galaxies (e.g. dwarfs) may create larger galaxies. This formation process is one of complex dynamical interactions which leave behind signatures in dwarf spheroidal galaxies, tidal remnants, and intergalactic light.

Spectacular advances in observational capabilities have made it possible to find these typically low surface brightness tracers of interaction. The Two Micron All Sky Survey and Sloan Digital Sky Survey dramatically increased the number and volume of stars catalogued, resulting in the discovery of new dwarf galaxies (e.g. Zucker et al. 2004; Willman et al. 2005; Belokurov et al. 2006; Irwin et al. 2007), and tidal tails (e.g. Majewski et al. 2003; Belokurov et al. 2005). Upcoming surveys, like Pan-STARRS (Kaiser et al. 2002), LSST (Ivezic et al. 2008; LSST Science Collaborations et al. 2009) and SkyMapper (Keller et al. 2007), will probe even lower surface brightness structures in increasing volumes of
space.

In this text, instead of focussing on the structures that are created, we focus on the structures that are altered or destroyed, on the remnants. Simulations make it possible to follow the process of the build up of structure, and the accompanying process of destruction of progenitors and creation of remnants. With simulations, it becomes possible to understand the physics in play throughout the history of specific objects that create observable remnants. By tying the simulations and the observations together, it is possible to form an understanding of galactic evolution. Faint remnants of galaxy interactions are mostly easily found in our own Local Group, making it an ideal test bed for this area of study. With the aim of understanding remnants, we research the most extreme, most transformative and destructive dynamical interactions between a satellite galaxy, and a Milky Way-like Galaxy.

As a satellite passes through the potential of a Milky Way-like Galaxy, changing gravitational forces from the larger potential alter the orbits of the stars within the satellite. This dynamical heating of stellar orbits means an increase in orbital energy and spatial randomization. Any or all of the following outcomes may be a direct result. Dark matter and stars once belonging to the satellite are lost to the Milky Way Galaxy (tidal stripping). Heating of orbits causes the satellite to expand (tidal stirring, Klimentowski et al. 2009). The satellite may pass the center of the Milky Way Galaxy closely and quickly enough that some of the stars feel an impulsive force strong enough to eject them from the entire satellite/Milky Way system (tidal impulse, Teyssier et al. 2009). To sum: during a galactic interaction, stars from the satellite can either remain in the satellite, move to the Milky
Way-like Galaxy, or be lost from the system altogether.

We choose to focus primarily on the populations of stars that undergo a tidal impulse and are ejected into the local field. In Chapter 2, we examine whether it’s possible to create an intergalactic population of stars in the Local Group via interactions between a Milky Way-like object and a dwarf galaxy. We summarize observations of stars outside of galaxies- mostly observations of intra cluster light (Section 2.1). We find that the most massive satellites on the most radial orbits would create this population. These stars may become energetically unbound (escaped stars), or may travel to further than a few virial radii for longer than a few Gyr, but still remain energetically bound to the system (wandering stars). Larger satellites (10-100% the mass of the parent), and satellites on more radial orbits are responsible for the majority of this ejected population. Wandering stars could be observable on Mpc scales via classical novae, and on 100 Mpc scales via SNIa. The existence of such stars would imply a corresponding population of barely-bound, old, high velocity stars orbiting the Milky Way, generated by the same physical mechanism during the Galaxy’s formation epoch. Sizes and properties of these combined populations should place some constraints on the orbits and masses of the progenitor objects from which they came, providing insight into the merging histories of galaxies in general and the Milky Way in particular.

By focussing on the population of stars ejected into the local field, we also focus on the subset of satellites with energetic enough orbits to produce it. This subset of satellites includes a population of ‘backsplash’ galaxies, which travel back into the local field after a close interaction with the Milky Way, carrying morphological signatures of
that interaction. The characteristics of each galaxy interaction (e.g. mass ratio, relative orbital energies and eccentricities) determines what happens to the majority of the stars in the satellite. What happens to the majority of the stars determines the extent of the satellites morphological change, on a scale from non-existant, to dramatic or destroyed. In this way, galactic morphology is dependent on environment.

In Chapter 3, we distinguish between Local Group field galaxies which may have passed through the virial volume of the Milky Way, and those which have not, via a statistical comparison against populations of dark matter haloes in the Via Lactea II (VLII) simulation with known orbital histories. Analysis of VLII provides expectations for this escaped population: they contribute 13 per cent of the galactic population between 300 and 1500 kpc from the Milky Way, and hence we anticipate that about 7 of the 54 known Local Group galaxies in that distance range are likely to be Milky Way escapees. These objects can be of any mass below that of the Milky Way, and they are expected to have positive radial velocities with respect to the Milky Way. Comparison of the radius-velocity distributions of VLII populations and measurements of Local Group galaxies presents a strong likelihood that Tucana, Cetus, NGC3109, SextansA, SextansB, Antlia, NGC6822, Phoenix, LeoT, and NGC185 have passed through the Milky Way. Many of these dwarfs have a lower HI mass fraction than the majority of dwarfs lying at similar distances to either the Milky Way or M31. Indeed, several of these galaxies – especially those with lower masses – contain signatures in their morphology, star formation history and/or gas content indicative of evolution seen in simulations of satellite/parent galactic interactions. Our results offer strong support for scenarios in which dwarfs of different types form a
sequence in morphology and gas content, with evolution along the sequence being driven by interaction history.

In Chapter 4, we revisit the creation of an intergalactic stellar population during the buildup of a Milky Way-like halo. We find the major contributors to the intergalactic light are the largest mass satellite haloes, \( \sim 10^{10}M_\odot \), due to the low stellar fraction expected in smaller mass haloes. The intergalactic light produced by the most massive satellites has a much smaller spatial extent than that produced by lower mass satellites, meaning that baryon prescriptions designed to suppress star formation in low mass satellites also shrink the spatial extent of intergalactic light. It may be possible to use observations of the large quantity of intergalactic red giants, that we expect in the Local Group, to define the spatial extent of the intergalactic light, and thereby place limits on the total star formation in progenitor satellites in the Local Group.

Finally, in Chapter 5 we summarize our conclusions and outline future work on the high velocity populations in the Milky Way that also may result from an interaction between a dwarf satellite and the Milky Way.
Chapter 2

Wandering Stars: an Origin of Escaped Populations

2.1 Introduction

One of the triumphs of the last decade is orders of magnitude increase in the numbers of stars catalogued by large sky surveys such as the Sloan Digital Sky Survey and the Two Micron All Sky Survey. These catalogs contain significant samples of stars out to $\sim 100$ kpc from the center of the Galaxy, allowing these regions to be probed through number counts to far lower surface brightness than previously possible and resulting in the discovery of numerous new dwarf satellite galaxies (e.g. Willman et al. 2005; Belokurov et al. 2006), as well as tidal tails from dwarf galaxies possibly disrupted long ago (e.g. Majewski et al. 2003; Belokurov et al. 2005).

We move from this decade of large sky surveys into a decade of continual all-sky
surveying with the introduction of the Panoramic Survey Telescope & Rapid Response System (Pan-STARRS, see Kaiser 2004) and the prospect of the Large Synoptic Survey Telescope (LSST, see Ivezic 2007). These surveys will be sensitive to ever fainter magnitude objects and hence probe ever lower surface brightness structures in ever increasing volumes of space. The repeated nature of these surveys also adds the extra dimension of time, enabling large-sample statistical studies of variable phenomena in a way that was not previously possible. For example, Shara (2006) points out that LSST will detect many new classical novae (hereafter CN). While interesting in their own right, the special relationship between the peak brightness and decline time relationship of CN, coupled with their high luminosity, will allow us to map a volume out to 40 Mpc from Earth. This will be the first map of stars between galaxies and outside of clusters or groups of galaxies (i.e. intercluster stars) ever produced. But should we expect to find anything there?

Red giant stars, planetary nebulae and classical novae have been detected outside of galaxies but within clusters (i.e. intracluster light - hereafter ICL, for example see Willman et al. 2004; Neill et al. 2005). These populations are thought to begin their lives in galaxies: stars are liberated from their original hosts during galactic collisions, galactic harassment and tidal shredding, which generate tails of debris that can be ripped from the galaxy system by the tidal field of the cluster (Moore et al. 1996). This evolutionary picture is confirmed by the general agreement of observations and simulations on the level of ICL (Murante et al. 2004), which photometric studies define as 0 – 50% of the total cluster light (Arnaboldi 2004; Feldmeier et al. 2004; Willman et al. 2004). The same dynamical processes can be appealed to on smaller scales to explain the existence of ICL around
2.1: Introduction

less massive, looser clusters and galaxy groups (Arnaboldi 2004), as well as diffuse stellar halos around individual galaxies (Bullock & Johnston 2005). Thus stellar halos and the ICL can be thought of as testaments to galactic interactions during the epochs of galaxy and cluster formation.

We explore whether dynamical interactions could plausibly lead to stars beyond the virial radii of the parent galaxy, group or cluster, and, if so, what the existence of such a population might tell us about the nature of hierarchical structure formation. Spergel & Hernquist (1992) have already shown that N-body simulations of mergers of massive galaxies can give rise to unbound particles that form a gaussian tail to the energy distribution, in agreement with a statistical mechanical description of violent relaxation. Here, we develop a simple description of interactions that allows us to illustrate how the size of the escaped population should depend on the mass ratio and orbits of the progenitor systems. In §2.2 we establish that a tidal impulse at perigalacticon is a viable path for stars from satellite dwarf galaxies to escape from the combined dark matter potentials of the parent and satellite galaxies. In §2.3 we first use restricted three-body simulations to test the mechanism described in §2.2 and then analyze N-body results to establish trends, and quantitative expectations for the escaping population. In §2.4 we discuss the implications of our results for future surveys of giant stars, CN, supernovae and high velocity stars. In §2.5 we summarize our conclusions.
2.2 Mechanism for Escape

Consider a satellite orbiting in a parent potential $\Phi(r)$, at radius $r$ from the center of the parent, moving with velocity $v$, along an orbit of energy $E = \frac{1}{2}v \cdot v + \Phi(r)$. As the satellite orbits, a star at position $x$ relative the center will experience a slightly different acceleration due to the parent than the satellite as a whole. In the impulsive regime, the resultant relative velocity change between the star and the satellite can be approximated as $\Delta v \sim \Delta a_{\text{peri}}t_{\text{enc}}$ where $t_{\text{enc}} = r_{\text{peri}}/v_{\text{peri}}$ is the duration of an encounter of pericentric distance $r_{\text{peri}}$ and speed $v_{\text{peri}}$, and $\Delta a_{\text{peri}}$ is the difference in acceleration experienced by the satellite and star at pericenter. Expanding $\Delta v$ in powers of $x$ we have:

$$\Delta v \sim a_{\text{peri}}t_{\text{enc}} = (x \cdot \nabla)\Phi(r)t_{\text{enc}} \sim -GM_{\text{peri}}\left(\frac{x}{|r_{\text{peri}}|^{3}} - 3 \frac{r_{\text{peri}}(x \cdot r_{\text{peri}})}{|r_{\text{peri}}|^{5}}\right)t_{\text{enc}} \quad (2.1)$$

where $M_{\text{peri}}$ is the enclosed mass of the parent at pericenter. The first and second terms in equation (2.1) are responsible for stretching along $r$ and compression perpendicular to $r$, respectively.

This impulsive velocity change corresponds to a change in orbital energy

$$\Delta E = v \cdot \Delta v + \frac{(\Delta v)^{2}}{2} \quad (2.2)$$

When summed over all stars in the entire satellite, the first term in equation (2.2) typically vanishes due to symmetry, and the last term represents the dynamical heating. In contrast, for an individual star, the last term is usually negligible compared to the first. The maximum increase in orbital energy will be for stars barely bound to (i.e. at large $r_{\ast} = |x|$)
and trailing the satellite along its orbit (i.e. where the direction of the impulse $\Delta v$ is aligned with the direction of orbital motion for the maximum positive energy change in this dot product term). In this case:

$$\Delta v \sim \frac{2GM_{\text{peri}}}{r_{\text{peri}}^3} r_{\text{enc}} \sim \frac{2GM_{\text{peri}}}{r_{\text{peri}}^2} v_{\text{peri}}.$$ \hspace{1cm} (2.3)

Such a trailing star could move to an an orbit that escapes entirely from the combined parent-satellite system if $\Delta E \sim v_{\text{peri}} \Delta v > |E|$ or

$$\Delta v > \frac{|E|}{v_{\text{peri}}}.$$ \hspace{1cm} (2.4)

In combination, equation (2.4) and equation (2.3) yield a constraint on the minimum extent of stars in the satellite system for an escaping population to be produced: $r_\star > r_{\text{peri}}$, where

$$r_{\text{peri}} \approx \frac{|E|}{2GM_{\text{peri}}/r_{\text{peri}}}.$$ \hspace{1cm} (2.5)

We examine whether equation (2.4) will be satisfied for any realistic galactic encounters by estimating $r_{\text{peri}}$ for orbits in a Milky Way-like parent halo that follows a Navarro-Frenk-White potential of virial mass $m_{\text{vir}} = 1.4 \times 10^{12} M_\odot$, virial radius of $r_{\text{vir}} = 273$ kpc and characteristic radius $r_c = 20.7$ kpc. The functional form of the NFW is:

$$m(r) = m_c \left( \log \left( \frac{r + r_c}{r_c} \right) - \frac{r}{r + r_c} \right)$$ \hspace{1cm} (2.6)

where the mass within distance $r$ is $m(r)$ and $m_c = 4\pi\delta_c \rho_c r_c^3$ is the mass within the
characteristic radius (Navarro et al. 1994). Fig. 2.1 shows contours of $r_{*,\min}$ as a function of circularity, $I_{\text{frac}} = \frac{I}{I_{\text{circ}}}$, and fractional binding energy parameter, $\eta = \frac{R_{\text{circ}}}{r_{\text{vir}}}$, for a satellite orbit of energy $E$ and angular momentum $J$. $I_{\text{circ}}$ and $R_{\text{circ}}$ are the radius of a circular orbit of the same energy $E$. Satellite orbits become more loosely bound with increasing $\eta$ and more eccentric with decreasing $I_{\text{frac}}$. From Fig. 2.1, $r_{*,\min}$ depends weakly on binding energy, but strongly on orbital eccentricity. For any $\eta$ or $I_{\text{frac}}$, more massive (i.e. of greater stellar extent) satellites are likely to create a greater number of E/W stars than a smaller satellite. A satellite on an eccentric orbit will contribute more stars than the same satellite on a less eccentric orbit. The lowest contours on Fig. 2.1 overlap with the typical extent of stars in Local Group dwarf galaxies. As we observe satellites which meet criteria in Fig. 2.1 today, logically, this is indeed a plausible mechanism for ejecting stars from a Milky-Way-sized halo during its formation epoch.

Analogous calculations performed for an NFW potential on cluster scales, with $M_{\text{vir}} = 1 \times 10^{14} M_\odot$, show contours of similar shape but more than a factor 10 increase in amplitude. While these scales are much greater than the sizes of typical galactic disks, these results do allow that the same mechanism may liberate the most loosely bound parts of galaxies from the cluster — the stellar halos of spirals and the outer edges of ellipticals.
Figure 2.1: Estimated minimum light radius [kpc] of the satellite necessary for unbinding tracer particles from perigalacticon of a Milky-Way-size halo as a function of binding energy (parameterized by $\eta$ — see text) and orbital eccentricity ($J_{\text{frac}} = 0$ for radial orbits and $J_{\text{frac}} = 1$ for circular orbits).
2.3 Illustrations of Escape

2.3.1 Restricted 3-Body Simulations

A restricted 3-body code follows the orbits of stars as a dark matter satellite orbits its parent galaxy. Stars may (“escaped” stars — E) or may not (“wandering” stars — W) become energetically unbound from the parent-satellite system, but the two classes are likely to be observationally indistinguishable; a wandering star can take a jaunt beyond the virial radius that lasts for a significant fraction of the age of the universe. Note— the intention in this section is not to estimate the size of the E/W population, but to confirm the predicted escape mechanism (§2.2).

Our restricted 3-body model consists of two orbiting, analytical, nonevolving NFW dark matter halos, and 10,000 massless “tracer” particles which represent stars around the smaller of the two halos (the “satellite”). Simulations are performed in two pieces — orbits for interacting NFW halos are calculated first, then tracer particles are run in the changing potential. The code uses leapfrog integration. Orbital precision is ensured by comparing results for the same parameter sets calculated with orders of magnitude change in time resolution.

The Milky Way-like (as described in §2.2) parent NFW is identical in all runs. Simulations run with satellites of various characteristic masses ($m_c$, of 10\%, 1\%, and .1\% of the parent) and scale radii ($r_c$, of 7 kpc, 3 kpc, and 1 kpc, drawn from distributions seen at $z = 0$ in cosmological simulations — Bullock et al. 2001) are placed on orbits with various $R_{\text{circ}}$ (130 kpc, 200 kpc) and $\eta$ (.05, 0.1, 0.5). Parent and satellite dark matter halos are
truncated at their respective tidal radii at initial apogalacticon.

Since we are interested in generating escaping stars, massless particles are not chosen to reproduce a fixed density distribution, but rather to explore regions of phase-space that are most likely to be stripped. They are placed randomly with a spatially uniform distribution around the satellite, out to its tidal radius. Their velocities are initially spatially isotropic, with amplitudes forming a uniform energy distribution up to the escape energy of the satellite at a given radius $E_{\text{esc, sat}}(r)$, i.e. the vast majority of stars should escape from the satellite. We eliminate particles unbound within the first $1/10$ of the orbit; they are uninteresting for analysis of evolution near pericenter.

Figure 2.2 is an example satellite from these runs, with $m_c$ 10% that of the parent, on an orbit with $R_{\text{circ}} = 200$ kpc and $\eta = 0.05$. The satellite is mostly stripped of it’s initially uniform cloud of test particles (gray) by pericenter. Test particles that are ahead of the satellite along its orbit at the first pericenter form a cloud around the center of the parent potential by second apocenter. From the dot product term in Equation 2.2, we expect that the impulse results in the maximum energy loss. In contrast, black crosses highlight the positions of the subset of particles that from the E/W population — defined as those that are ejected and remain outside the virial radius of the system for more than 2 Gyears. While this subset follows the same isotropic distribution as the non-escapers at apocenter, they clearly lag the satellite along its orbit at pericenter, so from the same dot product term in Equation 2.2, we expect them to have the maximum orbital energy increase and therefore be the most likely to escape. Every run which generates wandering stars demonstrates this behavior, confirming the dynamical picture proposed in §2.2; the
E/W population can be ejected by an impulsive velocity change at pericenter aligned with the orbital motion.

Figure 2.2: Projection of particle positions in a 3-body simulation onto the orbital plane. Future E/W particles are marked with black stars. The center of the satellite is a diamond, its orbit is dark grey. The parent NFW is represented by a light grey triangle with its orbit shown in light grey.
2.3.2 N-Body Simulation

While the restricted 3-body models successfully illustrate the mechanism for generating E/W stars, they are of limited use in assessing the size of this population or trends in progenitor properties for four reasons: satellites do not self-consistently lose mass as they orbit; star particles are not embedded deep within their host dark matter halos; parent potentials do not grow; and satellite’s orbits do not evolve due to dynamical friction with the parent. (Note- none of these effects would invalidate our description of the formation mechanism.)

We turn our attention to cosmological N-body simulations (Bullock & Johnston 2005) of satellite accretion, where mass loss from the satellite is modelled self-consistently, stars are distributed more realistically, an estimate of dynamical friction is explicitly included, and parent potentials grow analytically. The original aim of these simulations was to examine the formation of the stellar halo of the Milky Way. The set includes 11 stellar halo models, each formed from the superposition of simulations of individual satellite accretions, whose masses, accretion times and orbits were chosen at random from cosmologically motivated distributions. Gravitational influence of the parent galaxy is calculated from analytic functions which represent disk, bulge and dark matter halo components and that grow smoothly over time (tied to a randomly generated accretion history) to form a Milky Way type galaxy today. Dark matter in each satellite is represented by $10^5$ equal-mass particles, with positions and velocities initially chosen to follow an equilibrium NFW distribution. Masses and scales of these NFW halos are drawn from those seen in fully self-consistent cosmological simulations of structure formation. Stars
are “painted-on” by assigning a variable mass-to-light ratio to each dark matter particle in such a way that they follow an equilibrium King model, whose total luminosity, spatial and velocity scales are normalized to match observed scaling relations of Local Group dwarf galaxies.

Our 11 stellar halo models all contain an E/W population with an average of 5.5% (and ranging between 2.5 and 10%) of the stars beyond the virial radius of the host today. Since these models only follow the stellar halo component of the Galaxy (∼ $10^9 M_\odot$ in stars), this represents a much smaller fraction of the total light of the Galaxy — of order 0.05%. This is a lower limit to the E/W population since it does not include those that might be contributed from the parent galaxy, or from disk components of satellites during more major mergers.

We ask what type of interactions are responsible for the E/W population in these simulations. In Figure 2.3 we look at the fraction of stars defined as E/W, averaged over all 11 stellar halo models as a function of satellite mass and orbital properties. The solid line plots the cumulative fraction of E/W stars (i.e. number of E/W divided by the total number of stars falling in to the parent) from all satellites less than a given mass. The dot-dashed/dotted/dashed lines are the subset of satellites with $J_{frac} < 0.25/0.5/0.75$ — the orbit distribution for these satellites was originally nearly uniform in $J_{frac}$. This figure confirms the trends anticipated in §2.2; the bulk of the E/W population is produced by: (i) larger mass satellites since they are intrinsically more extended and more stars satisfy the criterion $r_* > r_{*, min}$; and (ii) satellites on more eccentric orbits with smaller pericenters that minimize $r_{*, min}$. In particular, by comparing the solid and dashed lines we see that for all
masses, much more than 50% of the population is produced from the 50% of objects on the most eccentric orbits. Also, at the very lowest masses the dot-dashed line converges with the total: smaller satellites need to be on increasingly eccentric orbits in order to contribute to the E/W population.

2.4 Discussion

Our results indicate the plausible existence of a population of isolated stars thrown out beyond the virial radii of Milky-Way-size dark matter halos. We expect that most of this population was generated during the epoch of structure formation on various scales. While these results should be confirmed by simulations of structures forming in a fully self-consistent cosmological context, our estimates suggest a lower limit of 0.05% of stars could be in this population of E/W stars, and this number could be revised significantly upwards once the contribution from the disk component in equal-mass mergers is included.

There are promising avenues for detecting such a population. Shara (2006) has pointed out that near-future all-sky, repeated surveys should be able to map the distribution of CN out to the Virgo cluster. Assuming an E/W population of ~10% (from the levels of ICL) he calculates a detection rate of 100’s to thousands during the first few years of LSST for a typical stellar population. Such surveys would also be sensitive to SNIa, an even brighter, though rarer, variable phenomena: extragalactic SNIa (Green 2009; Smith 1981; Gal-Yam et al. 2003) may not have been truly represented in more targeted observations.

While our discussion has focussed on stars, numerical simulations of structure for-
Chapter 2: Wandering Stars: an Origin of Escaped Populations

Figure 2.3: Solid line shows the cumulative fraction of the E/W population (i.e. number of E/W divided by the total number of stars falling in to the parent) contributed by satellites less than a given mass. The dot-dashed line shows the most, dotted, and dashed lines shows the contribution from satellites on orbits that are increasingly circular.

Information on both cluster and individual galaxy scales have also noted that satellite galaxies can sometimes be accreted onto parent potentials in groups (Rudick et al. 2006; Li & Helmi 2008). A low mass satellite, initially only loosely bound to an infalling group could
potentially be ejected by the same mechanism described in §2.2. Indeed, populations of galaxies at several virial radii away from their prior parent (dubbed backsplash galaxies by Gill et al. 2005) have been seen in many simulations (Gill et al. 2005; Ludlow et al. 2009). Moreover, there are now dwarf galaxies observed within the Local Group to be moving at close to or even above escape speed (Majewski et al. 2007; Chapman et al. 2007).

Lastly, an interesting implication of our results is that, accompanying our E/W population, there must be a population of stars that are kicked to barely bound orbits. At their apocenters, these would contribute to our “wandering” population, but as they oscillated back through the Milky Way they could be detectable as old high-velocity stars (HVS) in the stellar halo, left over from the epoch of galaxy formation. Current surveys have concentrated on mapping the young HVS population, in part because they are easy to select photometrically (i.e. from unusual blue colors and faint magnitudes at high Galactic latitude, see Brown et al. 2006). This young population is thought to originate from multiple-star encounters with the Galactic Center black hole — though Abadi et al. (2009) have shown using N-body simulations that such speeds can be produced in satellite/parent galaxy encounters, presumably by the mechanism we describe analytically here. Systematic surveys of the stellar halo velocity distribution of the older (redder) population are just now producing results (Kollmeier et al. 2009) and could provide an interesting additional limit on the E/W population.
2.5 Conclusions

We’ve outlined how tidal interactions can eject stars which are loosely bound to a satellite galaxy to beyond the virial radius of the satellite’s parent. We determined that more massive satellites contribute the most to this escaped (entirely unbound from the satellite/parent system) or wandering (bound, but traveling beyond 2 virial radii for more than ~Gyr) population of stars, as do satellites on highly radial orbits. The majority of this population of stars originated during the epoch of galaxy formation, when large interacting satellites were more frequently infalling on radial orbits, approximately from a redshift of around 4 to 3. If this is indeed the case, we expect an old, uniform (to first order) population of escaped and wandering stars to exist beyond a few virial radii of the Milky Way. Subcategories (e.g. classical novae, supernovae) of this population should be detectable by LSST and Pan-STARRS. We estimate a lower limit of 0.05% of stars to be members of this population. An accurate number prediction warrants further investigation using full cosmological simulations which follow interacting subhalos as they form the parent halo.
Chapter 3

Identifying Local Group Field Galaxies that have interacted with the Milky Way

3.1 Introduction

Dwarfs within the approximate 300 kpc virial radii of the Milky Way (MW) and M31 are preferentially small, gas-poor spheroids, compared to their field counterparts which are typically larger, gaseous, and irregularly shaped (e.g. van den Bergh 1994; Grebel et al. 2003; Grcevich & Putman 2009; Weisz et al. 2011). This position-morphology relationship, first noted by Einasto et al. (1974), appears universal, as it is found in other galaxy groupings as well (e.g. Skillman et al. 2003; Bouchard et al. 2009). The position-morphology relationship is attributed to a transformation of gas-rich dwarf irregular galaxies into gas-poor dwarf spheroidals via environmental effects. That the cumulative environmental
effects encountered during a passage through a larger potential are sufficient to transform the morphology of a dwarf is very well motivated by simulations (e.g. Mayer et al. 2001b,a, 2006; Kravtsov et al. 2004).

Environmental effects each leave a multitude of signatures on a galaxy. Tidal stirring has been shown to convert stellar components from disks to bars and finally to pressure supported spheroidal systems (e.g. Klimentowski et al. 2009). Shocking and ram-pressure stripping of gas (Sofue 1994; Grebel et al. 2003; Mayer 2010) leaves signatures in the satellite’s star formation history, either as starbursts (Hernquist 1989; Barnes & Hernquist 1996; Mihos & Hernquist 1996) or as starvation and quenching of the star formation (see Kawata & Mulchaey 2008, for a low mass group). Tidal shock heating is known to disrupt or destroy star clusters (Kruijssen et al. 2011).

Although initially it appeared that these effects might only be highly effective within 50 kpc of a MW-size object (Sofue 1994; Grebel et al. 2003), recent studies including other effects [e.g. tidal effects with UV background Mayer et al. (2006), resonant stripping D’Onghia et al. (2009)] show that such a close passage may not be necessary for a morphological transformation.

There are objects that do not fit the rough distance-morphology relationship, because they exist outside the virial radius of the nearest large galaxy, but nevertheless exhibit a morphology that suggests strong interactions (e.g. Tucana). However, interaction with a Milky-Way-size object is not the only way to affect changes in dwarfs: dwarf-dwarf interactions (or even mergers) have been shown to stimulate bursts of star formation, and to create irregular morphologies (Méndez et al. 1999; Bekki 2008; Besla et al. 2012);
interactions between dark satellites and dwarf galaxies can also trigger starbursts or a transformation to a spheroidal morphology (Helmi et al. 2012); episodic star formation (Gerola et al. 1980) of the bursty (e.g. Davies & Phillipps 1988) or quiescent variety (e.g. Barbuy & Renzini 1992) has been shown to reduce high gas content and lower metallicity through the interaction of stellar feedback and the interstellar medium; and small galaxies can ionize and blow out (via stellar feedback and including supernova feedback) enough gas to shut off a star formation episode (e.g. De Young & Heckman 1994; Brinks & Walter 1998).

Knowledge of the past orbit of a dwarf would be helpful in determining whether prior interaction with the MW is sufficient to explain the properties of objects like Tucana or whether alternative explanations (such as dwarf-dwarf encounters or internal effects) need to be invoked. Unfortunately, drawing direct, clear connections between the current morphology of an observed object and its past orbit is limited by our observational perspective. It is difficult or impossible to measure more than the angular position, distance and line-of-sight velocity for field dwarfs, and these quantities have been shown to be insufficient to determine a complete, accurate, orbital history for objects in the Local Group (Lux et al. 2010).

However, there is precedence for using distance and velocity measurements to draw a connection between morphology and rough orbital history on the larger scale of galaxy clusters. These clusters exhibit a high incidence of so-called ‘backsplash galaxies’, defined to be objects on extreme orbits that have taken them through the inner $0.5 R_{\text{vir}}$ of a larger potential and subsequently carried them back outside $R_{\text{vir}}$. 
Gill et al. (2005) demonstrated in simulations how a population of backsplash galaxies might be probabilistically separated from those infalling to the cluster for the first time using their observed velocities. Subsequent observations demonstrate that galaxies selected using this approach indeed exhibit unusual or unique morphologies (Balogh et al. 2000; Sanchis et al. 2002; Solanes et al. 2002; Sato & Martin 2006; Mahajan, Mamon & Raychaudhury 2011).

Owing to the approximately self-similar clustering of dark matter, the research done on clusters provokes questions about the existence and nature of backsplash galaxies on a smaller scale, specifically in the Local Group. Theoretical work on these scales suggests the existence of satellites on extreme orbits around potentials about the size of the MW. Around galaxy potentials, Sales et al. (2007a) identifies an ‘associated’ population of haloes which have at some point passed through the virial volume of the main halo. Of these, ~6 per cent have apocentric radii greater than 50 per cent of their turnaround radius, and a few have been ejected as far as 2.5 $R_{\text{vir}}$. (Similar populations have also been seen in simulations analysed by Warnick et al. 2008; Ludlow et al. 2009; Wang et al. 2009; Knebe et al. 2011, .)

Data samples which further inform the extent to which morphology and gas content can be related to dynamical history are growing rapidly. The study of Local Group objects has recently been invigorated by an influx of new members: SDSS enabled an expansion in the volume probed by star count surveys, which resulted in the discovery of numerous new dwarf satellite galaxies of both the MW and M31 (e.g. Zucker et al. 2004; Willman et al. 2005; Belokurov et al. 2006; Irwin et al. 2007). Moreover, new observational surveys, such
as DES (Bernstein et al. 2011), SkyMapper (Keller et al. 2007), Pan-STARRS (Kaiser et al. 2002), and LSST (Ivezic et al. 2008; LSST Science Collaborations et al. 2009), will be even more sensitive to faint magnitude and low surface brightness objects, and are expected to reveal even lower surface brightness objects over even larger volumes of space (Tollerud et al. 2008).

Motivated by this confluence of theoretical analyses, recent observational discoveries and promising new surveys, this paper makes connections between dynamically distinct histories for subhaloes seen in a cosmological simulation of structure formation (Via Lactea II, hereafter VLII), and properties of Local Group dwarf galaxies. More specifically, we establish that it is possible to distinguish field populations which may have passed within the MW-like halo of VLII from those which have not, using observable properties at \( z = 0 \) (radial distance, line-of-sight velocity and mass). The \( z = 0 \) distributions of these observable properties for haloes in VLII are given in Section 3.3. The simulated populations can be used to categorise the orbital histories of Local Group field objects (Section 3.4). Assuming that morphology is a result of environmental changes over time, we can connect morphology to orbit. Finally, we discuss whether this rough orbital characterisation provides insight into the morphologies and gas content of nearby field objects in the Local Group (Section 3.5). The methods we employ, and details of the VLII simulation itself, are described in Section 3.2.
Figure 3.1: The Via Lactea II simulation: A projection of the mass in a 3 Mpc cube onto the X–Z plane. Note the central MW-size halo, and the less massive halo above and to the left (described in Section 3.2.2). In the central panel we have over-plotted contours delineating regions containing less than 0.5 per cent (magenta), 5 per cent (red), and 50 per cent (blue) lower resolution particles in projection. In the right panel we have over-plotted the positions of weakly associated (red) and backsplash (blue) haloes.

3.2 Methods

VLII is one of the highest resolution cosmological simulations of the formation and evolution of the dark matter halo of a MW-like galaxy. The simulation resolves in the initial conditions at $z_i = 104$ the Lagrangian region of a halo with a $z = 0$ virial mass and radius of $1.70 \times 10^{12} M_\odot$ and 309 kpc with just over one billion high resolution particles of mass $4,100 M_\odot$. The surrounding density field is sampled at lower resolution with 29 million and 17 million particles of mass $2.6 \times 10^5 M_\odot$ and $1.3 \times 10^8 M_\odot$, respectively. The total computational domain of the simulation is $(40 \text{ Mpc})^3$. During the evolution, 400 output files, evenly spaced in cosmic time were saved. Diemand et al. (2006) ran the 6DFOF (sub)halo finder on a subset of 27 output files. The $\sim 20,000$ most massive haloes at $z = 4.56$ were linked to their descendant haloes, and their orbits around the host halo traced forward in

$^1$Here we define virial quantities relative to a density of 92.5 times the critical density (Bryan & Norman 1998).
3.2: Methods

For more detailed information about the VLII simulation and its subhalo population we refer the reader to Diemand et al. (2008), Kuhlen et al. (2008), Madau et al. (2008), Zemp et al. (2009), and Kuhlen et al. (2012).

The properties of the VLII simulation make it ideal for our purposes: the small particle mass allows us to follow a large range of halo masses, and trace haloes through order of magnitude changes in mass; the high frequency of outputs allow an accurate assessment of the subhalo interactions with the host halo potential; and the large volume allows us to track subhaloes to large distances beyond the host’s virial radius. This last point is one of the distinguishing features of our present work. While previous analyses of the VLII simulation focused on the properties of the subhaloes within the host halo’s virial volume, we here consider a population of haloes that at some point passed through the main halo but are found considerably beyond its virial radius at \( z = 0 \). The left panel of Fig. 3.1 shows a projection along the y-axis of a \((3 \, \text{Mpc})^3\) region centred on the main host halo at \( z = 0 \).

However, we exercise caution when using this dataset. Below the galactic scale, baryon and dark matter distributions deviate, due to many of the processes discussed in Section 3.1. VLII is a purely dark matter simulation, so we use it only to determine the observeables we expect to be independent of baryonic processes on the subgalactic scale — namely, the location and velocity of galactic-scale objects. For example, in simulations which superpose a more realistic matter distribution to represent baryons towards the center of a Milky-Way like object, the number of haloes has been shown to be depleted by about a factor of two within the inner 30kpc of the main halo due to disk shocking
Chapter 3: Field Galaxies that have interacted with the Milky Way

Figure 3.2: The fraction of high– (blue), intermediate– (magenta), and low-resolution– (red) particles contributed to the number of particles (solid lines) and their total mass (dotted) in spherical shells, as a function of distance from the main halo’s centre. The main halo’s virial radius of 309 kpc is indicated with a solid vertical line.

(D’Onghia et al. 2010). This destruction takes a few Gyrs. We analyse a subset of haloes which are found at distances of more than 400 kpc at z=0, a very small number of which would remain within 30 kpc for the required destruction time, so we do not expect this effect to change our results.

3.2.1 Subhalo Analysis

In all Figures, we define a subhalo’s mass as

$$M_{V_{\text{max}}} = \frac{V_{\text{max}}^2 R_{\text{max}}}{G},$$

(3.1)
where $V_{\text{max}}$ is the maximum circular velocity and $R_{\text{max}}$ is the radius at which $V_{\text{max}}$ occurs. This mass is not to be confused with the subhalo’s tidal mass or its total gravitationally bound mass. Instead it reflects the mass contained within $R_{\text{max}}$, which is a quantity that for subhaloes is more robustly determined in numerical simulations, but is typically lower than either of the other less well defined masses.

For most of the dark matter haloes in the $z = 4.56$ snapshot we were able to identify any surviving core at $z = 0$ by following the orbits derived by Diemand et al. (2006). For a small number of haloes that passed very close to the centre of the main halo we found it necessary to identify the position and velocity of the surviving halo by finding the average location of the particles that were members of the progenitor object weighted by their $z = 4.56$ internal potential energy (i.e. so the derived quantities are biased towards the remaining core). We were then able to match this location to a halo identified by the group finder in the $z=0$ snapshot.

### 3.2.2 A Second Host Halo and M31 Analog

In addition to the main host halo that is the focus of the VLII simulation, a second massive halo (hereafter Halo2) of comparable size to the main halo is apparent in the top left of the projection in Fig. 3.1. To obtain the mass of this halo at $z=0$, we determined the number of bound particles using the potential solver described in Hernquist & Ostriker (1992). The method begins with the assumption of a basic potential, that is then harmonically modified with the contribution of every particle. Once the final potential is calculated, unbound particles are discarded. We iterated this process until the total mass remained
constant, to find a total gravitationally bound mass of $6.5 \times 10^{11} M_\odot$ with a virial radius of 225 kpc. The distance of the second halo from the main halo is 833 kpc, and they are approaching each other with a speed of 60 km s$^{-1}$. Overall, we consider Halo2 to be a fortuitous analog to M31, which lies a distance of 785 kpc from the MW (McConnachie et al. 2005), is approaching at 122 km s$^{-1}$ (de Vaucouleurs et al. 1991), and has a mass of $1.2^{+0.9}_{-0.7} \times 10^{12} M_\odot$ (Tollerud et al. 2012).

### 3.2.3 Contamination with Lower Resolution Particles

At large distances from the main host halo, contamination from lower resolution particles becomes unavoidable. The middle panel of Fig. 3.1 shows contours delineating regions containing less than 0.5 per cent, 5 per cent, and 50 per cent lower resolution particles by number in projection, and Fig. 3.2 shows profiles of the fraction contributed by high, intermediate, and low resolution particles to the total mass and total number of particles as a function of three-dimensional radius. Throughout our region of interest ($\lesssim 1500$ kpc from the main halo centre) the contamination remains below a few percent by number, but can reach up to almost 50 percent by mass. However, owing to their larger gravitational softening lengths (4.2 and 200 times the high resolution softening length of 40 pc), the dynamical influence of lower resolution particles on highly resolved structures is minimal, and masses, positions, and velocities of such haloes can be accurately determined even in regions subject to non-negligible contamination.
3.2.4 Subhalo Nomenclature

To examine the relationship between orbital histories and $z = 0$ mass, radial distance and velocity, we separate the haloes in the VLII simulation into basic categories based on whether they have passed deeply, shallowly or not at all through the virial radius of the main halo. We employ the following commonly used nomenclature for these categories:

**associated** Haloes which have passed within half the virial radius of the main halo, and exited by $z=0$, are ‘backsplash’ haloes. Haloes which have only passed through outskirts of the halo (within 0.5-1 virial radius), and exited by $z=0$, are ‘weakly associated’.

**unassociated** Haloes which remain outside the virial radius of the main halo to $z=0$ are ‘unassociated’ haloes.

**subhaloes** Haloes found within the virial radius at $z=0$, we simply call ‘subhaloes’.

3.3 Results I: Distribution of subhaloes in VLII

In this Section we examine the VLII halo population to determine if there are observable differences between their orbital history categories.

3.3.1 Halo Category Statistics

Since we are interested in observable results, we eliminate from the VLII halo catalogue haloes that were not massive enough to allow for gas to condense and star formation
Table 3.1: Halo counts for the most massive (presumably star-forming) halo categories in VLII. Categories are defined in Section 3.2.4.

to occur. For this purpose we reject haloes that never reach a mass of $M_{\text{vir}}(z) > 10^7 M_\odot$, similar to the approach taken in Rashkov et al. (2012). There are 13,512 haloes above this mass cut, and these are the only haloes we consider in the following analysis.

Of the 13,512 massive haloes, 5,999 (44 per cent) are at some point found within the redshift-dependent virial radius, $R_{\text{vir,host}}(z)$, and the majority of these (5,352, 89 per cent) deeply penetrate the main halo, passing within half $R_{\text{vir,host}}(z)$. A small fraction of the deeply penetrating haloes (695, 13 per cent) are found outside $R_{\text{vir,host}}$ at $z=0$, and are therefore ‘backsplash’ haloes. Additionally, 647 haloes pass through the host’s virial volume, but never enter the central 0.5 $R_{\text{vir,host}}(z)$. A larger fraction of the shallowly penetrating haloes, almost half (312), make their way back outside $R_{\text{vir,host}}$ by $z=0$ to become ‘weakly associated’ haloes.

The majority of haloes that pass within $R_{\text{vir,host}}(z)$ are completely destroyed and have no identifiable $z = 0$ remnant (3,458; 58 per cent). Only about a quarter (1,534) of haloes survive within $R_{\text{vir,host}}$ to $z=0$, and are thus ‘subhaloes’. (The remaining 1007, or 17 per cent are the weakly associated and backsplash haloes.) There are also 7,513 haloes in our
catalogue that never enter the main halo’s virial volume at all and are hence ‘unassociated’ haloes not likely to have been affected by the main halo. These halo statistics are summarised in Table 3.1.

The fraction of associated haloes to total simulation haloes we find (10 per cent) is slightly larger than the 9-4 per cent quoted for increasing halo masses in Wang et al. (2009), despite simulation differences. There are several plausible explanations for this difference. VLII’s analysis focuses solely on the high resolution area around two haloes between $10^{11}$ and $10^{12} \ M_{\odot}$, while analysis in Wang et al. (2009) covers $\geq 22,000$ haloes in that mass range in a $(100h^{-1}$ Mpc)$^3$ volume. Hence, their value of 9-4 per cent is a very robust average, whereas our system could be an outlier due to, perhaps, the proximity of our two main haloes. Wang et al. (2009) also find that the fraction of associated haloes decreases with increasing satellite halo mass. This trend, in combination with our ability to trace much lower satellite halo masses (the particle mass in Wang et al. (2009) is $6.2 \times 10^8 \ M_{\odot}$), likely accounts for our slightly higher associated fraction.

We now volume-limit the $z=0$ halo results to make them more readily comparable to the Local Group sample examined in the remainder of the paper. Taking the haloes within 1.5 Mpc ($\sim 5 \ R_{\text{vir,host}}$) decreases the number of unassociated haloes from 7,513 to 6,888. Of the potentially star-forming subhaloes (corresponding to theoretically predicted dwarf galaxies) found between 1 and 5 virial radii (see Subsection 3.3.3 for justification of radius limit) at $z = 0$, $\sim 13$ per cent have passed within the virial radius of the main halo during their history. Considering that there exist at least 54 Local Group galaxies in this radius range, we expect that $\sim 7$ of these are examples of associated galaxies that have
passed within the virial volume of the MW in the past.

### 3.3.2 Host halo membership subhaloes at \( z = 0 \)

We briefly discuss the membership of subhaloes at \( z = 0 \), as defined by an orbital energy calculation with respect to either the MW-like main halo or Halo2.

Note that, despite being outside the virial radius (and in some cases far outside) most of the associated subhaloes are still gravitationally bound to the main halo at \( z = 0 \). A minority of the backsplash and weakly associated subhaloes, 7 per cent and 17 per cent respectively, have become unbound from both the main halo and Halo2. Remarkably, a small fraction of the associated haloes, 5 per cent and 4 per cent of strongly and weakly associated respectively, are bound to Halo2 but not to the main halo, and thus appear to have been captured by Halo2, making these objects so-called “renegade haloes” (Knebe et al. 2011).

We note that Halo2, the second largest halo in the VLII simulation, has it’s own associated, unassociated and subhalo populations. Apart from the renegade haloes mentioned above, these are encompassed within the main halo’s unassociated population. Our analysis could be duplicated from the perspective of Halo2, and those results would be particularly interesting if transverse velocities of more Local Group Field objects were known.
3.3: Results I: Distribution of subhaloes in VLII

Figure 3.3: TOP: A comparison of the radial distance from backspash haloes to the central, most massive halo at redshift $z=4.56$, and redshift $z=0$. Backsplash haloes are coloured with the log of their infall mass. Distances are shown in Mpc and in virial radii of the main halo. The virial radius of the halo is shown at redshift $z=0$ (vertical, dashed line). Haloes are scattered to 5 virial radii. BOTTOM: Quantity of haloes as a function of $z=0$ radial distance for backspash (solid), weakly associated (dot-dashed) and unassociated haloes (dashed).
3.3.3 Spatial Distributions

Figure 3.3 shows the radial distance from VLII haloes to the centre of main halo compared between $z=4.56$ and $z=0$. Weakly associated haloes have been scattered out to 1.5 Mpc [$5 \times R_{\text{vir}}(z = 0)$], and backsplash haloes are found past 1.2 Mpc at $z=0$. The backsplash haloes are plotted as squares and are colour-coded by infall mass, the mass that they had just prior to their first crossing of $R_{\text{vir,host}}(z)$. A trend of decreasing infall mass with distance from the host halo, as may be expected from multi-body interactions with the host halo, is not readily apparent (see §3.3.4). Histograms of the $z = 4.56$ and $z = 0$ distances for the two populations are shown in the left and bottom panels of the figure. We find that the radial distribution of associated (weakly + backsplash) haloes is well fit by a simple power law: $dN/dR \propto R^{-3.7}$.

It is somewhat surprising that associated haloes are found as far out as $5 R_{\text{vir}}$. The analytic analysis of a cluster halo by Mamon et al. (2004) should roughly scale down to a galaxy size halo, so backsplash haloes in both cluster and galaxy simulations should only be found out to $\sim 2.5 R_{\text{vir}}$ at $z=0$. This was seen in simulations of isolated galaxy potentials (Sales et al. 2007a). However, Wang et al. (2009) and Ludlow et al. (2009) have also found associated haloes to large distances, $4R_{200}$ and $5R_{200}$, respectively. As shown in the right panel of Fig. 3.1, the associated haloes in VLII fill an elongated volume of space, oriented toward Halo2. Perpendicular to the elongated axis, associated haloes are found out to only $2.5 R_{\text{vir,host}}$, approximately the value predicted by Mamon et al. (2004) for an isolated halo.

It appears that the unexpectedly large radial extent of associated haloes in VLII may
Figure 3.4: Distributions of \( \log(M_{\text{infall}}) \) of the associated haloes as a function of their \( z = 0 \) distance from the main halo, in bins of 100 kpc width. The median of \( \log(M_{\text{infall}}) \) is given by the red line, the box extends from the 25th to the 75th percentile, the whiskers (dashed lines) from the 12.5th to the 87.5th percentile, and haloes outside this range are shown as individual crosses. There is no evidence for an inverse relation between \( M_{\text{infall}} \) and distance.

be due to the strong anisotropy of cosmological infall and the presence of Halo2, which itself is still infalling along one of the three main filaments feeding the main halo. This could also account for the large extent of the associated objects found in Wang et al. (2009); Ludlow et al. (2009). (Assuming that some of the parent galaxies in Ludlow et al. (2009) had strong filaments or a companion in the 1-2Mpc range, beyond their isolation criteria of 1Mpc.)
3.3.4 Mass Distributions

Previous work on the ejection of subhaloes from a galaxy potential considered a slingshot effect (Sales et al. 2007b) and a tidal impulse (Teyssier et al. 2009). Sales et al. (2007b) examined the origin of the two most dynamically extreme objects, one with a $z=0$ distance of $2.5R_{\text{vir}}$ and the other with a velocity of $2V_{\text{vir}}$, and found both to have originated from pairs of objects, one of which received an energetic impulse from the host potential at pericentre. Teyssier et al. (2009) describe the same mechanism in a different way, focusing on a distribution of objects (a satellite or a group of satellites) instead of a pair of objects (see also Ludlow et al. 2009).

Both of these mechanisms predict an inverse correlation between mass and distance, because the smaller, more peripheral members of an infalling group experience the largest energy gain during the group’s pericentre passage. We expect to see this signature if these mechanisms are solely responsible for the associated halo population in the VLII simulation. We split the associated halo sample by $z = 0$ distance into bins of 100 kpc width, and look at the distributions of $\log(M_{\text{vmax}})$ at infall, within each bin (Fig. 3.4). Neither the median of the distributions nor its scatter exhibit any noticeable trends with distance. We don’t view this absence of inverse correlation between mass and distance to be strong evidence that the mechanisms described above aren’t occurring. Rather, it indicates that other dynamical processes also have a comparable effect on the ejection of subhaloes to beyond the virial radius. These other processes could include dynamical interactions that occur on multiple levels, in conjunction with the main potential i.e. subhalo-subhalo, subhalo-group, or group-group interactions. Regardless, our analysis
does not indicate that one should expect a mass-distance bias in the associated dwarfs around the MW.

### 3.3.5 Velocity Distributions

In Fig. 3.5 we show the means and standard deviation of the radial velocity distributions in the same 100 kpc $z = 0$ distance bins, for each of our four subhalo categories: backsplash, weakly associated, unassociated haloes, and subhaloes (with increasingly darker shades of Gray). Beyond the virial radius, and up to 1.5 Mpc, the unassociated haloes are inflowing (negative radial velocity), either onto the main halo, or onto Halo2, which we have marked with an X on the figure. The weakly associated and backsplash haloes are outflowing with approximately the Hubble Flow (diagonal dashed line) or even higher radial velocities. Wang et al. (2009) also finds a velocity offset for the associated population. On average VLII associated populations have radial velocities that are 50 - 100 km s$^{-1}$ higher than the unassociated haloes. This offset is much larger than observational uncertainties in velocity. These results raise the exciting possibility of using this radial velocity signature to observationally assign a likelihood of being an associated halo, to actual Local Group dwarf galaxies. In §3.4 we do exactly that, by comparing the locations of real Local Group dwarf galaxies in the $v_r - r$ plane with the predictions from the VLII simulation.
### Properties of Local Group Objects

<table>
<thead>
<tr>
<th>Common Name(s)</th>
<th>$D_{\text{helio}}$ [kpc]</th>
<th>$V_{\text{helio}}$ [km s$^{-1}$]</th>
<th>$D_{\text{gsr}}$ [kpc]</th>
<th>$V_{\text{gsr}}$ [km s$^{-1}$]</th>
<th>Class</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix Dwarf</td>
<td>406.0</td>
<td>56.0</td>
<td>401.0</td>
<td>-37.0</td>
<td>dIrr/dSph</td>
<td>Hidalgo et al. (2009); Cote et al. (1997)</td>
</tr>
<tr>
<td>LeoT</td>
<td>415.0</td>
<td>35.0</td>
<td>421.0</td>
<td>-69.0</td>
<td>dIrr/dSph</td>
<td>de Jong et al. (2008); Irwin et al. (2007)</td>
</tr>
<tr>
<td>NGC6822 (DDO209)</td>
<td>489.0</td>
<td>-57.0</td>
<td>486.0</td>
<td>57.0</td>
<td>Irr</td>
<td>Wyder (2003); Irwin et al. (2007)</td>
</tr>
<tr>
<td>IC10</td>
<td>715.0</td>
<td>-348.0</td>
<td>711.0</td>
<td>-137.0</td>
<td>dIrr</td>
<td>Kim et al. (2009); Huchra et al. (1999)</td>
</tr>
<tr>
<td>IC1613 (DDO8)</td>
<td>748.0</td>
<td>-234.0</td>
<td>740.0</td>
<td>-150.0</td>
<td>Irr</td>
<td>Rizzi et al. (2007); Lu et al. (1993)</td>
</tr>
<tr>
<td>LGS3</td>
<td>769.0</td>
<td>-287.0</td>
<td>762.0</td>
<td>-146.0</td>
<td>dIrr/dSph</td>
<td>A, Huchtmeier et al. (2003)</td>
</tr>
<tr>
<td>Cetus</td>
<td>755.0</td>
<td>-87.0</td>
<td>747.0</td>
<td>-23.0</td>
<td>dSph</td>
<td>A, Grecevich &amp; Putman (2009)</td>
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<td>LeoA (DDO69)</td>
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<td>24.0</td>
<td>815.0</td>
<td>-21.0</td>
<td>dIrr</td>
<td>Tammann et al. (2008); Huchtmeier et al. (2003)</td>
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<tr>
<td>Tucana</td>
<td>890.0</td>
<td>194.0</td>
<td>887.0</td>
<td>96.0</td>
<td>dSph/dE4</td>
<td>Bernard et al. (2009); Fraternali et al. (2009)</td>
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<tr>
<td>Aquarius (DDO210)</td>
<td>1071.0</td>
<td>-141.0</td>
<td>1066.0</td>
<td>-12.0</td>
<td>dIrr/dSph</td>
<td>Karachentsev et al. (2002); Koribalski et al. (2004)</td>
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<tr>
<td>WLM (DDO221)</td>
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<td>-122.0</td>
<td>958.0</td>
<td>-57.0</td>
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<td>Gieren et al. (2008); Koribalski et al. (2004)</td>
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<tr>
<td>SagDIG</td>
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<td>1037.0</td>
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<td>1062.0</td>
<td>-9.0</td>
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<td>362.0</td>
<td>1296.0</td>
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<td>dIrr/dSph</td>
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</tr>
<tr>
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<td>403.0</td>
<td>1266.0</td>
<td>179.0</td>
<td>Irr/bar</td>
<td>Dalcanton et al. (2009); Lauberts &amp; Valentijn (1989)</td>
</tr>
<tr>
<td>Name</td>
<td>RA</td>
<td>Dec</td>
<td>Dist</td>
<td>Type</td>
<td>References</td>
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<tr>
<td>SextansA (DDO75)</td>
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<td>324.00</td>
<td>1387.0</td>
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<td>Dalcanton et al. (2009); Koribalski et al. (2004)</td>
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<td>SextansB (DDO70)</td>
<td>1390.00</td>
<td>300.00</td>
<td>1397.0</td>
<td>dIrr</td>
<td>Dalcanton et al. (2009); Huchtmeier et al. (2003)</td>
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</tr>
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<td>VV124 (UGC4879)</td>
<td>1360.00</td>
<td>-29.00</td>
<td>1364.0</td>
<td>dIrr/dSph</td>
<td>Jacobs et al. (2011); Kirby et al. (2012)</td>
<td></td>
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<tr>
<td>M31</td>
<td>785.00</td>
<td>-300.00</td>
<td>779.00</td>
<td>SA(s)b</td>
<td>A, de Vaucouleurs et al. (1991)</td>
<td></td>
</tr>
<tr>
<td>AndXVI</td>
<td>525.00</td>
<td>-367.00</td>
<td>518.00</td>
<td>dSph?</td>
<td>Ibata et al. (2007); Letarte et al. (2009)</td>
<td></td>
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<tr>
<td>NGC185</td>
<td>616.00</td>
<td>-202.00</td>
<td>611.00</td>
<td>dSph/dE3p</td>
<td>A, Bender et al. (1991)</td>
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<tr>
<td>AndII</td>
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<td>645.00</td>
<td>dSph</td>
<td>A</td>
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<tr>
<td>NGC147 (DDO3)</td>
<td>675.00</td>
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<td>670.00</td>
<td>dSph/dE5</td>
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<td>Majewski et al. (2007)</td>
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<td>-368.00</td>
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<td>dSph</td>
<td>A</td>
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<td>AndIII</td>
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<td>-314.00</td>
<td>742.00</td>
<td>dSph</td>
<td>A, Karachentseva &amp; Karachentsev (1998)</td>
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<td>AndX</td>
<td>760.00</td>
<td>-164.00</td>
<td>754.00</td>
<td>dSph</td>
<td>Zucker et al. (2004)</td>
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<td>AndVII</td>
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<td>758.00</td>
<td>dSph</td>
<td>A, Karachentsev et al. (2001)</td>
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<td>765.00</td>
<td>-209.00</td>
<td>759.00</td>
<td>dE</td>
<td>A, Zucker et al. (2004)</td>
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<td>AndXV</td>
<td>770.00</td>
<td>-323.00</td>
<td>764.00</td>
<td>dSph?</td>
<td>Ibata et al. (2007); Letarte et al. (2009)</td>
<td></td>
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<tr>
<td>AndV</td>
<td>774.00</td>
<td>-397.00</td>
<td>769.00</td>
<td>dSph</td>
<td>A, Mancone &amp; Sarajedini (2008)</td>
<td></td>
</tr>
<tr>
<td>AndXXII</td>
<td>794.00</td>
<td>-127.00</td>
<td>787.00</td>
<td>dSph?</td>
<td>Martin et al. (2009); ?</td>
<td></td>
</tr>
<tr>
<td>M32 (NGC221)</td>
<td>817.00</td>
<td>-200.00</td>
<td>811.00</td>
<td>cE2</td>
<td>Fiorentino et al. (2010)</td>
<td></td>
</tr>
</tbody>
</table>
AndXII     &  830. & -525. & 823. & -349. & dSph? & B, Chapman et al. (2007); ? \\
AndXXI     &  859. & -362. & 853. & -151. & dSph? & Martin et al. (2009); ? \\
M33 (NGC598) &  884. & -179. & 877. & -36. & SA(s)cd & Martin et al. (2009) \\
AndXVIII   &  1355. & -332. & 1349. & -121. & dSph? & McConnachie et al. (2008); ? \\

Table 3.2: Choice of distance and velocity are shown in both heliocentric and galactocentric reference frames. Details for reference frame conversion are found in §3.4. In the sources column, A refers to McConnachie et al. (2005) and B refers to Martin et al. (2006).
Our confidence in assigning associated halo status to observed dwarf galaxies hinges on how well separated the associated and unassociated populations are in the $v_r - r$ plane. Around $d \sim 850$ kpc the presence of Halo2 leads to an increase in the radial velocity dispersions in both halo categories, such that the distributions significantly overlap. However, spatial information can be used to increase the distinction between the populations. Selecting haloes with large angular separation from the centre of Halo2 (from a vantage point at the centre of the main halo) significantly decreases overlap in the radial velocity distribution between associated and unassociated haloes, and leads to a more appropriate analysis for some Local Group objects that also lie more than $90^\circ$ from Halo2.

There is no significant difference between the $v_r - r$ distributions of backsplash and weakly associated haloes, making it impossible to distinguish between weakly associated and backsplash haloes with this method. Unfortunately, we cannot thereby separate objects we expect to have undergone more dramatic changes in their morphology (backsplash) from those with relatively more minor transformations (weakly associated). Note that this distinction may be less important in the resonant stripping model proposed by D’Onghia et al. (2009), in which heavy stripping and morphological transformation can occur even for subhaloes without close pericentre passages, provided that they enter the host halo on a retrograde orbit.

### 3.4 Comparison of Simulation Results to Observations

To briefly recap the main results of §3.3, from an analysis of the subhalo population in the VLII simulation, we expect that: (i) $\sim 13$ per cent of the Local Group field dwarfs have
Figure 3.5: The mean radial velocity per radial distance bin for four populations of haloes: subhaloes remaining within the virial radius of the central halo at \( z=0 \) (squares), haloes which have never entered the virial radius of the central halo (triangles), haloes which have passed within 0.5-1 virial radii of the central halo (diamonds), and haloes which have previously passed within 0.5 virial radii of the central halo (star), are shown on the radial distance vs. radial velocity plane at redshift 0. The 68 per cent confidence region for the subhalo, unassociated, weakly associated and backsplash populations is shown in darkest grey, dark grey, medium grey and light grey, respectively. The solid vertical line is the virial radius of the central halo at \( z=0 \), and the dashed line shows the Hubble Flow.
passed through the virial volume of the MW; (ii) these associated dwarfs can be found out to 5 $R_{\text{vir}}$ ($\approx 1.5$ Mpc); (iii) the associated dwarf population does not necessarily exhibit any strong trends in mass with distance; (iv) associated dwarfs are likely to have positive radial velocities with respect to the MW, of order or greater than the Hubble Flow, and in contrast to unassociated haloes which typically have negative radial velocities out to $\sim 1.5$ Mpc; and lastly (v) it’s possible that there are so-called renegade satellites around M31, i.e. MW escapees that have become bound to M31.

In the following, we identify Local Group field objects which may be associated with the MW by comparison of their dynamical properties with those of the populations in VLII. We then augment our argument for the plausibility of their association by including the observed properties of the objects, including stellar population ages, and gas content.

### 3.4.1 Radial Distance and Velocity Comparison

As discussed in §3.3.5, the separation between the associated and unassociated populations from VLII in the $v_r - r$ plane makes it possible to use these same properties of Local Group field objects to predict the likelihood that they are either associated or unassociated with the MW. Velocity and distance measurements of Local Group objects with sources are summarised in Table 3.2. Errors in measurement are as reported by the source, or as found in NED. The distances and velocities in Table 3.2 are converted from the heliocentric reference frame to the galactocentric reference frame, for comparison to VLII data. The following assumptions are made: the Solar System lies at a distance of 8.3 kpc from the galactic centre (Gwinn et al. 1992). The local rotation speed is $\Theta_0 = 236$ km s$^{-1}$; the speed
Figure 3.6: The observed radial distances (kpc) and velocities (km s$^{-1}$) in the galactocentric frame are over-plotted on the 1$\sigma$ distributions of the simulated halo populations from VLII (weakly associated, backsplash, unassociated, and subhalo in increasingly dark shades of grey). Note that of the galaxies with large negative velocity (less than -100 km/s) all (except AndXVIII) lie within the full distribution of the VLII haloes. Moreover, M31’s actual mass could be up to a factor of 2 larger than that of our M31-analogue. It’s true velocity dispersion thus could be a factor of $\sqrt{2}$ larger, accounting for the dwarfs that fall on the lower edges of the VLII distribution.
### Fractional Likelihood of being ‘associated’ to the MW

<table>
<thead>
<tr>
<th>Name</th>
<th>Likelihood per bin (Haloes per bin)</th>
<th>Morphology</th>
<th>Mass [10^6 M_⊙]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total pop. 45° away 90° away</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC3109</td>
<td>1.00 (2) 1.00 (2) 1.00 (2)</td>
<td>Irr</td>
<td>6550</td>
</tr>
<tr>
<td>NGC6822</td>
<td>0.64 (50) 0.87 (15) –</td>
<td>Irr</td>
<td>1640</td>
</tr>
<tr>
<td>SextansB</td>
<td>1.00 (3) 1.00 (3) 1.00 (3)</td>
<td>dIrr</td>
<td>885</td>
</tr>
<tr>
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<td>1.00 (3) 1.00 (3) 1.00 (3)</td>
<td>dIrr</td>
<td>395</td>
</tr>
<tr>
<td>NGC185</td>
<td>0.56 (84) – –</td>
<td>dSph/dE3p</td>
<td>130</td>
</tr>
<tr>
<td>Phoenix</td>
<td>0.70 (77) 0.70 (56) –</td>
<td>dIrr/dSph</td>
<td>33</td>
</tr>
<tr>
<td>Antlia</td>
<td>1.00 (2) 1.00 (2) 1.00 (2)</td>
<td>dIrr/dSph</td>
<td>12</td>
</tr>
<tr>
<td>Leo T</td>
<td>0.70 (77) 0.70 (56) 0.74 (38)</td>
<td>dIrr/dSph</td>
<td>8</td>
</tr>
<tr>
<td>Tucana</td>
<td>0.36 (22) 1.00 (2) 1.00 (2)</td>
<td>dSph</td>
<td>N/A</td>
</tr>
<tr>
<td>Cetus</td>
<td>0.17 (95) 0.60 (27) –</td>
<td>dSph</td>
<td>N/A</td>
</tr>
<tr>
<td>M33</td>
<td>0.01 (110) – –</td>
<td>SA(s)cd</td>
<td>5 × 10^4</td>
</tr>
<tr>
<td>NGC147</td>
<td>0.17 (95) – –</td>
<td>dSph/dE5</td>
<td>110</td>
</tr>
<tr>
<td>LeoA</td>
<td>0.02 (161) 0.17 (18) 0.17 (18)</td>
<td>dIrr</td>
<td>80</td>
</tr>
<tr>
<td>Pegasus</td>
<td>0.02 (47) – –</td>
<td>dIrr/dSph</td>
<td>58</td>
</tr>
<tr>
<td>Aquarius</td>
<td>0.02 (47) 0.00 (27) –</td>
<td>dIrr/dSph</td>
<td>5</td>
</tr>
<tr>
<td>AndII</td>
<td>0.05 (60) – –</td>
<td>dSph</td>
<td>N/A</td>
</tr>
<tr>
<td>AndX</td>
<td>0.02 (161) – –</td>
<td>dSph</td>
<td>N/A</td>
</tr>
<tr>
<td>AndIX</td>
<td>0.02 (161) – –</td>
<td>dSph</td>
<td>N/A</td>
</tr>
<tr>
<td>AndXXII</td>
<td>0.02 (161) – –</td>
<td>dSph</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 3.3: The fractional likelihood that the object is ‘associated’ (passed through the virial radius of the MW) is defined by comparison of the galactocentric velocity and galactocentric distance of Local Group objects to VLII data. Analysis is repeated for objects with angular separation of more than 45° and more than 90°. These additional analyses use subsets of the VLII populations which fit there same angular constraints. Objects given in the lower panel have less than 50 per cent likelihood that they are associated with the MW. Total mass values are taken from Mateo (1998), or from Brown et al. (2007) for LeoA, Corbelli (2003) for M33, and Simon & Geha (2007) for LeoT.
of a closed orbit at the position of the Sun relative to the Galactic center (Bovy et al. 2009). The relative motion of the Sun is \((U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25) \text{ km s}^{-1}\) (Schönrich et al. 2010).

Fig. 3.6 repeats Fig. 3.5 with the Local Group data over-plotted. It is clear from this Figure that there are several examples of field objects in the Local Group that fall in the region outlined by associated haloes in VLII and hence are likely to have interacted with the MW some time in the past. The \(\sim 50 - 100 \text{ km s}^{-1}\) separation between the objects that are obviously bound to the second massive (Andromeda-like) halo and those objects found above the Hubble Flow is much larger than known observational uncertainties. We note that while there is a M31 Analogue in VLII, it lacks M33. Moreover, structures on scales larger than the Local Group are also not necessarily distributed the same way and this may influence the details of our result.

For a more quantitative determination of whether an object is likely to be associated with the MW, we divide the radial velocities and distances of the associated and unassociated VLII halo populations into bins of size 100 kpc and 50 km s\(^{-1}\). The fraction of haloes in a \(v_r - r\) bin that are ‘associated’ gives a rough estimate of the likelihood of an observed Local Group dwarf in the same bin having interacted at some time in the past with the MW. These likelihoods are listed in Table 3.3 for our most likely associated halo candidates.

Note that the simple radial distance and velocity test does not take into account the full spatial distribution of Local Group objects. In Figure 3.6, several observed objects lie in regions of the \(v_r - r\) plane where the wings of the radial velocity distributions of associated
and unassociated populations overlap due to the presence of Halo2 (as discussed in §3.3.5). However, some of these objects lie at large angular separations from M31 (e.g. Tucana). To address this issue we also performed comparisons of the most isolated dwarfs (more than $45^\circ$ and more than $90^\circ$ from Andromeda) against the VLII distributions for all haloes more than $45^\circ$, or $90^\circ$ respectively, from Halo2. These corrected likelihood estimates are included in Table 3.3.

From Table 3.3 we expect that the following Local Group Objects have with high likelihood (>50 per cent) at some point in time passed through the virial radius of the MW: NGC3109, SextansA, SextansB, Antlia, Cetus, Tucana, NGC6822, Phoenix, LeoT, and NGC185. Note that the zero-velocity radius of the Local Group is 0.96 Mpc (Karachentsev et al. 2009). This radius cut-off has been used in the past to exclude the Antlia Group (Antlia, NGC3109, SextansA and SextansB) from membership in the Local Group of Galaxies (Courteau & van den Bergh 1999). If these objects are not currently members, our results indicate that they were likely to be in the past. The rest of the objects found in Table 3.2 have a likelihood of association with the MW that is very low or zero. The fractional likelihood that the following objects are associated is less than 1 per cent: IC10, IC1613, LGS3, WLM, SagDIG, NGC205, AndI, AndII, AndIII, AndV, AndVII, AndXI, AndXII, AndXIII, AndXIV, AndXV, AndXVI, AndXVIII, AndXXI, VV124.

3.4.2 Discussion of Local Group Morphologies for Associated Objects

We now discuss whether the associated objects identified in this paper have any signatures of a past interaction with the MW. As described in Section 3.1, we expect that the passage
through the larger potential of the MW will affect a morphological transformation of objects in the Local Group. Indeed, recent work using SDSS has shown that quenching of galaxies with stellar mass $M_\star < 1 \times 10^9 M_\odot$ does not occur beyond 1.5 Mpc of a more massive galaxy (like M31 or the MW). This is strong evidence that an interaction with a massive galaxy is necessary for quenching (Geha et al. 2012), and by extension, that galaxies which have interacted with a MW-like object, can carry a morphological signature of that interaction, and be found out to 1.5Mpc, which is the same distance range found in this paper.

Possible signatures of association include low gas mass fraction due to gas stripping, a dynamically heated old population of stars, a barred or spheroidal stellar component due to tidal stirring, and a star formation history that is bursty due to gas inflows or starvation. The strength of these transformation signatures depends on both the duration and depth of any pericentric encounter with the MW, the mass of the dwarf, and to a lesser extent, whether it is a member of an infalling group. While tidal effects scale with the relative densities of the parent and satellite galaxies (and hence are not necessarily mass-dependent), the importance of shock heating and ram-pressure stripping of gas does depend on the depth of the satellite’s potential well.

The similarity in the distributions of backsplash and weakly associated haloes in VLII suggests there is no easy way to assess the nature of pericentric passages from the locations and velocities of field dwarfs. However, we do have information on their masses. Moving from most to least massive, the 10 objects which have greater than 50 per cent likelihood of association with the MW, are: irregulars, dwarf irregulars, a dwarf elliptical/spheroidal,
‘transition’ objects, and dwarf spheroidals. Since transformations are stronger in smaller galaxies, we might expect that the effects of a passage through the MW could have resulted in just this sequence in morphologies.

We use gas detections from Grcevich & Putman (2009) to create Figure 3.7, which shows detected HI mass fraction vs. distance to MW or M31 (see their Fig.3), but also includes in a colour coding the likelihood of association with the MW. From this figure it is apparent that HI gas fractions for objects with a high likelihood of association are lower than those for field objects at a given distance from the MW. This trend supports our findings, and provides further evidence that associated objects may have been stripped during their passage past the MW.

Finally, there are cases where we also see hints of past interactions in the stellar populations of these objects. Most obviously Tucana and Cetus both have an old population, with no contributions from younger stars, presumably because star formation was truncated as gas was stripped during the encounter. Antlia, NGC6822, Leo T, NGC 185 and Phoenix have all have extended old haloes, no population of intermediate-age stars, and a dynamically cold, young core (Hwang et al. 2011; McQuinn et al. 2010). In these cases, the encounter could have stripped gas to delay any ongoing star formation and heated the old population. Subsequent re-accretion of gas (or retention of a small amount of gas), funnelled to the centre by residual tidal distortions, could have formed the young population.

Overall, we conclude that these combined morphological, gas content and stellar populations signatures suggest that some, if not all of the objects we identify as ‘associated’
Figure 3.7: Detected HI masses over total masses with distance to the MW in kpc. Colors represent the fractional likelihood that an object is associated with the MW. Leo T, Phoenix Dwarf, Antlia, Sextans A and Sextans B all show low mass fractions (for their distances) and high likelihoods that they have had an interaction with the MW.

indeed had some past interaction with the MW.
3.5 Summary of Major Results

We demonstrate that with just the line-of-sight distance and velocity, we can obtain a rough interaction history for field objects in the Local Group via comparison with VLII populations. We separate field haloes in VLII into categories: associated haloes have been within the virial radius of the main MW-like halo, unassociated haloes have not.

We find \( \sim 13 \) per cent of field haloes in the simulations to have passed through the virial volume of the MW-like halo at some point during their histories. These associated haloes could be found out to \( 5 R_{\text{vir}} \). This suggests that, for the Local Group, of the 54 known galaxies within this distance range, we expect at least 7 to have interacted with the MW. Further analysis of VLII suggest that these associated objects are likely to have positive radial velocities with respect to the MW of order or greater than the Hubble Flow, which will make them distinguishable from the unassociated populations. From our analysis we do not expect a mass-distance bias in the associated dwarfs around the MW. About 4 per cent of the MW-associated haloes may have become renegade haloes bound to M31.

The separation between the associated and unassociated populations in the distance-velocity plane in VLII was applied in the Local Group to identify field dwarfs that may be associated with the MW: Tucana, Cetus, Antlia, NGC3109, SextansA, SextansB, NGC6822, Phoenix, LeoT and NGC185. Several of these objects have signatures in their morphology, gas content, or stellar populations that could be the result of their passage through the MW. This possibility should be considered when analyzing transformative internal and external effects for these objects. Overall we conclude that our simple test provides
strong support for scenarios in which the gas-poor, dwarf spheroidal objects in the field result from the transformation of gas-rich irregulars during past interactions with MW or Andromeda.
Chapter 4

Diffuse light from Wandering Stars around Milky Way-like Galaxies

4.1 Introduction

Hierarchical structure formation requires that smaller structures aggregate to form larger structures, e.g. galaxies build clusters, and dwarf galaxies build Milky Way-sized galaxies. The diffuse light found around these structures is a by-product of their growth and evolution, and specifically of processes such as galactic collisions, harassment, and tidal shredding (Moore et al. 1996). Diffuse light is, therefore, universal. Just as intergalactic light exists between cluster galaxies, and within a cluster potential, it is expected between galaxies and within the potential of the Local Group. It has been observed as intracluster light in large clusters like the Coma Cluster (Bernstein et al. 1995) and Abell 1689 (Fisher, Illingworth & Franx 1995), as intragroup light in galaxy groups M81 (Feldmeier et al. 1995).
Chapter 4: Diffuse light around Milky Way-like Galaxies

2003) and Leo I (Castro-Rodríguez et al. 2003), and as halo light in many systems, but particularly around our own Milky Way (e.g. Belokurov et al. 2005).

Most of what is known about diffuse light beyond the virial radii of individual galaxies, comes from studies of clusters. Cluster simulations confirm (e.g. González-García, Stanghellini & Manchado 2010; Rudick, Mihos & McBride 2007; Sommer-Larsen 2006; Willman et al. 2004) that the stellar contribution, resulting from dynamical effects, matches to an order of magnitude the quantity of light observed in clusters. This is useful not only in confirming the formation mechanism of intergalactic light, but is also in constraining the contribution from possible background contaminants (background galaxies, quasars) to low levels.

As intergalactic light is a by-product of dynamical structure evolution, it is expected that the quantity of this light depends on the overall size of the system, i.e. galaxy clusters have both more material and the potential for more dynamical interactions than smaller systems. As expected from this line of thought, increasing amounts of diffuse light are found in richer environments (Murante et al. 2004). Rich clusters like the Coma Cluster and Abell 1689 have a large fraction of intracluster light; \(\sim 50\%\) (Bernstein et al. 1995) and \(\sim 30\%\) (Tyson & Fischer 1995), respectively as compared to the significantly smaller fractions found in galaxy groups M81 (\(< 3\%\), Feldmeier et al. 2003) and Leo I (1.6\%, Castro-Rodríguez et al. 2003). However, even among systems on the same mass scale, the fraction of diffuse light will change depending on the dynamical age of the system. For example, measurements for the fraction of diffuse light in the Virgo cluster is 10-20\% (Feldmeier et al. 2004)(much less than that of the Coma Cluster or Abell 1689), consistent
with the idea that Virgo is a dynamically young cluster (Tully & Shaya 1984; Binggeli, Tammann & Sandage 1987). These observations of structures that vary in age, total mass and interaction history make it clear that intergalactic light is unique to its environment and history.

Not only can the fraction of diffuse light (as a function of group/cluster size) be used to gauge dynamical age, but the individual properties of the stars can be used to do this as well, and more. This stellar population is as diverse as that found in the galaxy the stars originated in; individual planetary nebulae, novae, supernovae Type Ia, red giants and globular clusters have been detected in intracluster light (e.g. Arnaboldi et al. 2002; Arnaboldi 2003; Feldmeier et al. 2004; Gal-Yam et al. 2003; Neill et al. 2005; Lee et al. 2011). Wandering globular clusters provide information on the origins of globular clusters and the first dwarf galaxies (Lee et al. 2011; Conselice 2005). Analyses of intracluster planetary nebulae and intracluster red giants both indicate that the intracluster light in the Virgo cluster may have originated mostly in the cluster’s spiral galaxies (Okamura et al. 2002; Feldmeier et al. 2004; Durrell et al. 2002).

The majority of galaxies do not exist in clusters, but in poor groups or isolated galaxies. Diffuse light near isolated galaxies (in galaxy haloes) has been studied extensively. It has long been known that our Galaxy is surrounded by a diffuse stellar halo, containing approximately 1% of the total luminosity, with its origin traditionally attributed to either stars formed in-situ (Eggen, Lynden-Bell & Sandage 1962) or accreted (Searle & Zinn 1978), or some combination of the two (Abadi, Navarro & Steinmetz 2006; Carollo et al. 2007; Zolotov et al. 2010; Nissen & Schuster 2012). Studies of nearby stellar halos have
been revolutionized by tracing their extent and structure using star counts. The Milky Way’s stellar halo has been mapped over the entire SDSS footprint in detail using main sequence turnoff stars to 40kpc (Belokurov et al. 2005), with tracer populations detected out to 200kpc along more restricted lines of sight (Deason et al. 2012). Maps of red giant stars have been produced stretching to greater than 150 kpc around M31’s stellar halo (Ibata et al. 2007), as well as M33 and NGC891 (Ibata, Mouhcine & Rejkuba 2009).

 theoretical work indicates that it is possible to have diffuse light extend beyond the halo, and beyond the virial radius, of isolated galaxies. Teyssier et al. (2009) (hereafter T09) demonstrated that it is possible to remove stars from the expected Local Group dark matter potentials via the dynamical interaction of a Milky Way-like dark matter potential and a dwarf size halo. However, T09 is based on idealized simulations without subhalo-subhalo interactions or a M31 Analogue. This paper aims to place wandering stars in a more realistic context, in order to accurately establish the expected quantity for the population of stars beyond the virial radius of a Milky Way-like galaxy.

 Additional motivation comes from observational advances. In the past, observational restrictions have limited study of this intergalactic stellar population, to large intracluster populations. New observational tools and studies, such as Pan-STARRS and LSST, will make it possible to probe stellar populations beyond the virial radii of isolated galaxies and galaxies in poor groups. We expect that the intergalactic intergroup counterparts to intracluster supernovae Type Ia will be found at cosmological distances. Classical novae will be observeable to 40 Mpc. Red giants may be a useful tracer of intergalactic light in the Local Group.
We will predict the order of magnitude of light beyond the virial radius of a Milky Way-like galaxy. This estimate allows us to make predictions for the observability of this population both in the Local Group (with Red Giants) and on cosmological scales (with supernovae Type Ia). Since the existence of this population is a natural by-product of structure formation, and we have an expected approximate level of light from observations of poor groups, its absence or overabundance would be deeply disturbing. We also know that this intergalactic light should vary (at a level less than an order of magnitude, from the observations described above) due to the history of individual objects. We examine the dependence of the intergalactic population on the mass of the progenitor satellites.

In the following, Section 4.2 describes our model, our methods of halo and particle selection, and baryon assignment. In Section 4.3, we quantify the total intergalactic baryon mass spatially, and as a function of radius. We quantify the total intergalactic light from our model. We then describe the possible use of intergalactic red giants in the Local Group, and the level of expected intergalactic supernovae on cosmological scales. In Section 4.4 we describe the quantity, distribution and origin of subhalos which have created the intergalactic population in our model. Section 4.5 summarizes our results.

4.2 Methods

We describe the N-body simulation (Via Lactea II, hereafter VLII) that was used in our study, our selection of the dark matter haloes formed from particles within it, and the assignment of light we apply to these particles to trace the spatial distribution of baryons.
4.2.1 Via Lactea II

VLII is a high resolution ΛCDM cosmological dark matter particle simulation. It is among the highest resolution cosmological simulation of a MW size halo available, making it ideal to our purpose. It follows the growth of a $1.1 \times 10^{12} M_\odot$ mass dark matter halo (hereafter the ”MW Analogue”), tracing a billion particles from a redshift $z = 104$ to 0, with 400 snapshot outputs. VLII has three resolution levels; the majority of particles are high resolution particles, with a mass of $4.1 \times 10^3 M_\odot$. Lower resolution particles have masses 256 times greater, and 256 times something greater still. Contamination by lower resolution particles is not a significant fraction of the population in the volume we examine (Teyssier, Johnston & Kuhlen 2012, Figure 1).

The large extent of the high resolution volume also includes a ”M31 Analogue” dark matter halo with the following characteristics: a gravitationally bound mass of $6.5 \times 10^{11} M_\odot$, a central distance of 833 kpc from the center of the MW Analogue, and velocity toward the MW Analogue of 60 km/s.

The small particle mass and high frequency of outputs in VLII make it possible to trace a range of halo masses, and to trace halos through changes in mass, as well as subhalo and particle interactions. The large $z=0$ volume allows tracking of the most distant particles after their interaction with the main halo. In addition to snapshots, VLII has $\sim 20,000$ subhalos above a Vmax of 4 km/s which were identified via the 6DFOF finder and tracked from formation to destruction, or to redshift $z = 0$. 
4.2.2 Halo Treatment

Following the methodology described in Teyssier, Johnston & Kuhlen (2012) which is similar to that of Rashkov et al. (2012), we ignore all but the subset of haloes which could host stars, by requiring haloes to reach a peak mass \( M_{\text{vir}}(z) > 10^7 M_{\odot} \) at some point during their evolution. Recent work has found that baryon mass assignment is most accurate when assigned a mass fraction dependent on \( V_{\text{peak}}^{\text{max}} \) (Reddick et al. 2012), which is the peak value of \( V_{\text{max}} \) over the history of the halo. \( V_{\text{max}} \) is the maximum circular velocity and \( R_{\text{max}} \) is the radius at which the maximum velocity occurs, fit to a NFW profile with the critical overdensity defined as in Bryan & Norman (1998). As a consequence of Reddick et al. (2012), VLII haloes are assigned a baryon fraction dependent on \( M_{\text{vir}} \) or \( M_{200} \) derived from \( V_{\text{peak}}^{\text{max}} \).

We use the term ‘intergalactic light’ to mean any light that is outside the virial radius of the closest galaxy. This forces the light to be well away from the halo of the galaxy, so there is no confusion as to where the light originates.

4.2.3 Baryon Prescriptions

The high resolution and large volume of VLII necessitates that it is a dark matter only simulation, making the assignment of baryons to the dark matter particles a necessary evil. This baryonic assignment roughly approximates the z=0 distribution of the stellar component, not the gaseous component. The total stellar mass a halo is assumed to produce is determined from its peak mass using a prescription and assigned equally to the ten percent most energetically bound particles in a halo at \( z = 4.56 \) based on the logical
Figure 4.1: The baryon mass assigned to a dark matter halo as a function of its peak mass via the Behroozi12 or Rashkov12 prescriptions (Section 4.2.3). Note the steeper slope that suppresses star formation in low mass haloes in the Rashkov12 prescription.
assumption that the vast majority of star formation over the haloes lifetime will occur deep within the well of the halo. This redshift is around the beginning of the cosmological interaction period in VLII. For a discussion of the cosmological interaction period of galaxies, and the galactic merger rate, see Martel, Barai & Brito (2012). Assignment to the ten percent most bound particles produces $z = 0$ half-light radii between $\sim 200-300$ pc in the surviving haloes. The minimum half-light radius is 190 pc, up to about one kpc. This is a good match to Local Group dwarfs, which have half-light radii between 120pc up to one kpc (e.g. see Martin et al. 2006, 2009; Willman et al. 2005; Irwin et al. 2007). Changing the assignment to the one percent most bound particles shifts the entire distribution down approximately 50pc.

The many problematic issues which surround assigning light to dark matter simulations include the following:

- Star formation histories are directly dependent on the interactions and environments that a galaxy encounters over it’s history- this is highly individual, and difficult to account for in simulations where baryons must be assigned to dark matter particles.

- The mass-to-light ratio at high redshift is observed only for massive haloes $10 < \log_{10}(M_{DM}[M_\odot]) < 15$ in cluster environments (e.g. Behroozi, Wechsler & Conroy 2012). The mass-to-light ratio for smaller haloes must be extrapolated from this curve.

Due to these issues, we restrict our conclusions to order of magnitude estimate.

Owing to the problems with assigning baryons to dark matter distributions, we compare results from two very different prescriptions which are used to assign a baryon
mass fraction to dark matter haloes in VLII. The prescription used in Rashkov et al. (2012) (hereafter Rashkov12, See Equation 4.1) for subhaloes has a theoretical origin. It is based on prescriptions from Koposov et al. (2009) and Kravtsov (2010). The stellar mass is tagged at infall (which is assumed to be the peak mass) and scales as a power law of the halo mass. This prescription strongly suppresses baryon assignment in haloes below $10^8 M_\odot$. It appears to recover the mass and number of dwarf spheroidals observed within the virial radius of the MW.

$$M_* = 1.6 \times 10^{-5} M_{200} (V_{\text{peak}}/V_{\text{max}}) \left( \frac{M_{200}(V_{\text{max}})}{10^9 M_\odot} \right)^{1.8}$$

(4.1)

Behroozi, Wechsler & Conroy (2012) (hereafter Behroozi12) derives their prescription from observations of galaxy clusters at redshifts of $z = 0 - 8$, allowing them to find baryon fraction for dark matter haloes in the mass range $10 < \log_{10}(M_{DM}[M_\odot]) < 15$. Abundance matching is used to recursively fit the prescription output to observations at many redshifts. There is a knee in the shape of the stellar-mass-to-halo-mass curve at a virial mass of $10^{12} M_\odot$, for redshifts below $z = 6.0$ (See 4.2). We extend the slope below $10^{12} M_\odot$ to $10^7 M_\odot$ and fit a power law to come up with this prescription (Equation 4.2) for a baryon fraction per dark matter halo:

$$M_* = 2 \times 10^{-2} M_{\text{vir}} (V_{\text{peak}}/V_{\text{max}}) \left( \frac{M_{\text{vir}}(V_{\text{max}})}{10^{12} M_\odot} \right)^{0.4}$$

(4.2)

The Behroozi12 prescription has a much shallower slope at lower halo mass.
Figure 4.2: From Behroozi12, Figure 7: Evolution of the derived stellar mass as a function of halo mass.

<table>
<thead>
<tr>
<th>Mass [$M_\odot$]</th>
<th>Prescription</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^9$</td>
<td>Baryons from Rashkov12</td>
</tr>
<tr>
<td>$1 \times 10^9$</td>
<td>Baryons from Behroozi12</td>
</tr>
<tr>
<td>$3 \times 10^{10}$</td>
<td>Dark Matter Mass</td>
</tr>
</tbody>
</table>

Table 4.1: The extrapolated mass of the stellar component found outside all virial radii at a redshift of 0, for both the Rashkov12 and Behroozi12 prescriptions. The given dark matter mass is the mass of the dark matter particles outside all virial radii at $z = 0$, and which were among 10% most bound particles in a halo at high redshift. Note that the intergalactic contribution from the Rashkov12 prescription is the largest (See Section 4.4 for discussion.)
Figure 4.3: LEFT: The particles found outside all halo virial radii, which were among the 10% most bound particles to haloes at high redshift (solid line). These particles are binned with distance to the central MW-like halo. The subset of the aforementioned particles which have a lower resolution, meaning that they have a higher dark matter particle mass, are also shown (dot-dashed line). These low resolution particles are a negligible fraction of the entire population at all radial distances. RIGHT: Baryon mass prescriptions applied to the VLII haloes at high redshift result in a mass assignment to the particle profile (left) creating the mass profiles (right). Mass profiles are shown as a function of distance from the central MW size dark matter halo in VLII. Three mass profiles result from the Behroozi12 mass prescription (solid line), the Rashkov12 prescription (dashed line). Also shown is the dark matter mass for the particles shown in the left panel (dotted).

4.3 Results I: Intergalactic Light in poor groups and around isolated Milky Way-like Galaxies

To contribute to intergalactic light, particles assigned baryons must fall outside the virial radii of all baryon-hosting halos, of MW/M31 size or lower, in the VLII $z = 0$ snapshot.

Figure 4.3, left panel, plots the number of dark matter particles which were among the ten percent most bound per halo at high redshift, but are outside all virial radii at $z=0$,
4.3: Results I: Intergalactic Light in poor groups and around isolated Milky Way-like Galaxies

The difference in the radial distribution arising from each prescription is striking — this result is even more strongly apparent in Figure 4.5, which shows a spatial projection of the intergalactic baryonic mass profile for the Rashkov12 (left panel), and the Behroozi12 (right panel) prescriptions. Moreover, the intergalactic light is highly anisotropic. The majority of the mass, regardless of the mass prescription, lies between the MW Analogue...
Figure 4.5: Projection of the mass profile of intergalactic stars onto the X-Z plane in our models. Left: The baryon assignment (described in 4.2.3) is from Rashkov12. The steep slope of the Rashkov12 prescription creates a much less diffuse distribution. Most of the intergalactic mass is concentrated between the MW and M31, or around M31, with the exception of two streams. RIGHT: The baryon assignment (described in 4.2.3) is extrapolated from Behroozi12.

and the M31 Analogue. This is expected: the orientation of the ejected intergalactic light reflects the direction of the orbit of the halo in which it originated, and most halos less massive than the M31 Analogue and the MW Analogue travel down filaments oriented toward the space between them. Figure 4.5 also makes it apparent that the majority of intracluster baryon mass is due to interactions with the two largest mass haloes- so although VLII is missing an M33 analogue, it’s still reasonable to use the simulation to gain an order of magnitude estimate for light in the Local Group.

Table 4.1 summarizes the total mass in the intergalactic populations, showing that the total stellar population is of order $10^9 M_\odot$. This order of magnitude estimate isn’t strongly
dependent on the slope of the baryon assignment model; although the baryons are strongly suppressed in the Rashkov12 prescription, as compared to Behroozi12, it makes less than an order of magnitude difference in the total mass of wandering stars. Although the strong suppression of baryons in low mass haloes in the Rashkov12 prescription makes less than an order of magnitude difference in the total mass of the wandering star population, it does make a difference in the total effective extent of the population. In this way, the quantity and extent of the observable wandering star populations could differentiate between mass functions for low mass haloes.

Previous work, e.g. Rashkov12, has shown that the appropriate mass-to-light ratio for contributing stellar populations is $M/L = 3$. From this and the VLII data, galaxies in the Local Group should have between $0.33 - 1.7 \times 10^9 L_\odot$ of diffuse light. From this data, the luminosity fraction of diffuse light from starlight in the Local group is approximately 1% (See Section 4.5 for comparison to galaxy cluster and group observations).

As in observations of intragroup and intracluster light, we would expect that this light be likewise made up of stellar populations which include: classical novae, planetary nebulae, supernovae Type Ia, red giants, and globular clusters.

### 4.3.1 Tracers of Light Detectable in and Around the Local Group

Intergalactic red giants have been found in clusters (Virgo Ferguson, Tanvir & von Hippel 1998), in the M81 galaxy group (Durrell et al. 2004), and recently in the Local Group. Palladino et al. (2012) has found 667 candidates of intragroup solar-metallicity M giants at distances of 300 kpc to 1.1 Mpc in the SDSS DR7 dataset (however, there could be
significant contamination by nearby L-dwarfs in their sample).

Using an intergalactic red giant population that extends out to \( \gtrsim 2 \text{Mpc} \) to differentiate between dwarf prescriptions with or without heavy suppression is an intriguing possibility because the Rashkov12 and Behroozi12 prescriptions create different spatial distributions (Figure 4) and different radial profiles (Figure1,right). The Palladino candidates are found using many color cuts, velocity cuts, etc. that make it difficult to estimate the entire population of which they are a tiny part. The Palladino candidates also do not quite have a large enough distance range to make it possible to differentiate between the Rashkov12 and Behroozi12 descriptions.

We predict a large population of intergalactic red giants in and around the Local Group. A simple luminosity-specific stellar evolutionary flux of a non-star-forming population should be \( \sim 2 \times 10^{-11} \text{ stars yr}^{-1} \text{L}_\odot^{-1} \) in the K band, independent of age or initial mass function. The lifetime of red giants is of order 100Myr, so we expect \( \sim 2 \times 10^{-3} \text{ red giants L}_\odot^{-1} \), and about 2,000,000 red giants in the diffuse light created by Local Group galaxies. Figure 4.6 shows the number of intergalactic Local Group red giants under these assumptions as functions of distance and apparent magnitude. We expect that many of the observed M giants are part of this intergalactic population.

Palladino et al. (2012) notes that their observed population is anisotropic, which is also true for the VLII population. Figures 4.7 and 4.8 show projections of the intergalactic VLII population using the Behroozi12 or Rashkov12 prescriptions, but scaled down for a red giant population. The projection is onto VLII galactic longitude and latitude and shows the quantity of red giants for an apparent limiting magnitude of \( m = 21, 23, 24 \).
or 25. There is no extinction from a disk—the orientation is arbitrary. The red giant population is concentrated in the direction of VLII’s M31 Analogue. If suppression of star formation in the lowest mass galaxies is strong enough to approximate that of the Rashkov12 prescription, then we expect only a handful of clumps of tens or hundreds of red giants and a concentration in the direction of M31. However, if star formation for the lowest mass galaxies is closer to the Behroozi12 prescription, there should be concentrations of tens to hundreds of red giants covering a large fraction of the sky. The overdensity in the distribution of intergalactic stars between the MW Analog and the M31 Analog (Figure 4.5) may mean that the immediate importance of the intergalactic red giant population may be as contaminants in observations of M31. However, its possible that continued detection of this population could be used to map out the intergalactic population.

4.3.2 Tracers of Light Detectable on Cosmological Scales

The majority of galaxies (~70% for z = 0 – 2, Behroozi12) are isolated or exist in poor groups, as opposed to existing in galaxy cluster environments. An interesting test of our results is to find the number of supernovae Type Ia (SNeIa) detectable in the intergalactic population of these poor groups, and in the few Mpc around isolated galaxies. Past supernovae surveys which targeted galaxies were not sensitive to this population. Blind, repeated surveys should be able to find these intergalactic supernovae. From this work, intergalactic light is ~1% of the light in the MW galaxy, hence ~1% of the supernovae should be intergalactic. The current generation of surveys (e.g. PTF) are cataloguing
Figure 4.6: Number of red giants in the intergalactic light of the Local Group from the Rashkov12 and Behroozi12 prescriptions described in this paper. The number of red giants is shown as functions of distance and apparent magnitude, based on the assumptions given in Section 4.3.1.
4.4 Results II: The Contributing Dark Matter Halo Population

We examine mass trends in the halo population responsible for the intergalactic light in our model. We find that the most massive haloes are critical to forming this population, even though only about a third of them make any contribution at all.
Figure 4.8: Projections in galactic longitude and latitude of the number of red giants in VLII using the Rashkov12 prescription, and based on the assumptions given in Section 4.3.1. Projections show the number of red giants that are visible to a given limiting magnitude ($m = 21, 23, 24, \text{ or } 25$).

Figure 4.9 shows the total mass of wandering stars binned by the peak mass of its progenitor halo. The profile marked ‘ten percent’ is the total dark matter mass of the particles which were the ten percent most bound, but are currently intergalactic particles at a redshift $z = 0$. The Behroozi12 and Rashkov12 profiles are the result of baryonic mass assignment to the ‘ten percent’ particles. With the application of the baryon prescriptions, the intergalactic contribution declines sharply with decreasing peak halo mass. The reason for this can be seen in Figure 4.10, which shows that the average mass in wandering stars in the same mass decades recovers the original baryonic mass-assignment used. The waver in the Rashkov12 power law in Figure 4.10 results from the conversion from $M_{200}$
Figure 4.9: The total intergalactic mass from all haloes falling within a $v_{\text{peak}}$ mass range at a redshift $z=0$. The histogram labeled ‘ten percent’ is the total (dark matter) mass of the particles which were among the ten percent most bound at high redshift. The histograms labeled ‘Behroozi12’ and ‘Rashkov12’ are the baryonic masses for this same particle population, weighted as described in Section 4.2.3.
to $M_{\text{vir}}$.

With the halo-mass trends in Figures 4.9 and 4.10, it is apparent that the very different distributions in the left vs. the right panels of Figure 4.5 is due to the mass of the haloes generating the intergalactic light. Massive satellite haloes generate intergalactic light which is mostly within the 50 kpc beyond the virial radii of the MW or M31 Analogue. Less massive satellite haloes can generate intergalactic light that spreads a Megaparsec further (Figure 4.5, right panel).

Figure 4.9 shows that the total level of intergalactic light is strongly dependent on highest mass haloes, and by extension, dependent on the mass assigned these haloes. Figure 4.10 shows that the Rashkov12 prescription, when compared observational results from Behroozi12 and to the known dark matter and baryon mass of the MW, over-predicts the mass fraction at the high mass end. This results in a total mass estimate that is 5 times higher than that derived via the Behroozi12 prescription.

Not all haloes that became massive enough to host baryons contribute to the intergalactic population at $z = 0$. Figure 4.11 shows the fraction of these massive haloes, in different mass bins, which do contribute some fraction of their (previously most tightly bound) particles to the intergalactic population. Although the highest mass haloes contribute the most baryons to the intergalactic mass (Figure 4.9), these particles originated in only 40% of the haloes at this high mass end. Lower mass haloes are more likely (50 – 60%) to contribute baryons, but their total contribution is orders of magnitude less (how many orders of magnitude less depends on the baryon mass prescription).

Previous work finds that creation of intergalactic light in high mass galaxies is strongly
Figure 4.10: The average mass of wandering stars from a halo of a given peak mass. The three prescriptions (described in 4.2.3) are shown. This approximately recovers the slope of the law used to assign baryonic mass to the halo.
Figure 4.11: The fraction of haloes in a peak mass range that contribute intergalactic light. The error shown is the fractional uncertainty.
dependent on the mass ratio of the galaxy interaction which liberated it. (Martel, Barai & Brito 2012) shows that small mass ratios \( M_{frac} < 1.2 \) most likely result in a merger. Intermediate mass ratios \( 1.2 < M_{frac} < 10 \) generally result in tidal destruction with some fragments escaping the potential of the system, resulting in intergalactic light. Large mass ratios \( M_{frac} > 10 \) result in tidal destruction with eventual reaccretion of fragments onto the more massive galaxy (Martel, Barai & Brito 2012; Ciardullo et al. 2004). By applying these findings to this work, its plausible that the intermediate mass ratio between the largest satellites and the MW/M31 Analogues resulted in the production of the intergalactic baryons that are focussed around the MW/M31 Analogue as in Figure 4.5, left panel. The intergalactic mass lying further afield in Figure 4.5, is from intermediate mass interactions between haloes within their infalling group.

Using Rashkov12, the the contribution from low mass haloes is insignificant. Using Behroozi12, the total contribution from haloes in mass ranges \( 10^7 M_\odot < M_{vir} < 10^{11} M_\odot \) increases from \( 5 \times 10^6 \) to \( 10^8 M_\odot \) (Figure 4.1).

### 4.5 Conclusions

Analysis of the VLII simulation shows that \( \sim 1\% \) of the light in the Local Group is intergalactic light. This result is expected due to observations of other galaxy groups and clusters, which show that the smaller the group, the smaller the fraction of intergalactic light. For comparison, Castro-Rodríguez et al. (2003) finds that the Leo I group hosts 1.6\% intergalactic light.

However, our result differs from the results of Teyssier et al. (2009), which estimates a
level of 0.1% intergalactic light. VLII differs in several ways from the Bullock & Johnston (2005) simulations used to derive that estimate. Bullock & Johnston (2005) contains no major mergers, and neglects satellite-satellite interactions. Since the radial extent of stars within a satellite is an important part of whether the tidal impulse is sufficient to remove stars from a combined system, we think that the dynamical heating from satellite-satellite interactions within groups -present in VLII- accounts for this higher estimate. We also find that satellites with much smaller stellar radii than required by Teyssier et al. (2009) were able to contribute baryonic mass to intergalactic light. We also attribute this to the effects of satellite-satellite interactions.

Our result of \( \sim 1\% \) intergalactic light around MW like galaxies should be verifiable through observational counts of intergalactic supernovae Ia around these systems, which we expect to be found by blind, repeated surveys like Pan-STARRS and LSST. This is the same order of magnitude of light found in the galactic halo, but in a much larger volume of space. The level of intergalactic light is strongly dependent on the high mass end \((M_{\text{vir}}(V_{\text{peak}}^{\text{max}}) > 10^{10}M_\odot)\) of the mass function. It is not sensitive to the contribution from the many, many lower mass haloes due to the low stellar fraction expected in smaller haloes.

The intergalactic light produced by the most massive satellites has a much smaller spatial extent than that produced by lower mass satellites, meaning that baryon prescriptions designed to “supress star formation” in low mass satellites also shrink the spatial extent of intergalactic light. We expect a large quantity of intergalactic red giants in the Local Group. It may be possible to use observations of intergalactic red giants, to define the spatial extent of the intergalactic light, and thereby place limits on the total star
formation in progenitor satellites in the Local Group.
Chapter 5

Conclusion

5.1 Thesis Summary

Dynamically extreme interactions can produce unique populations. Just studying one type of dynamical interaction - one between a satellite and a Milky Way-like galaxy - can provide insights into both backsplash galaxies and intergalactic light in a Local Group context. Our major conclusions include the following:

- several Local Group field dwarfs, which have morphologies indicative of a major interaction, are also at positions/velocities that indicate that they are likely to have interacted with Milky Way
- satellites on similarly extreme orbits about the Milky Way can create a population of wandering stars within and beyond the Local Group
- the extent of Red Giants within the Local Group could be used as a constraint on
baryonic populations in low mass dark matter halos

- blind time-domain surveys should now be able to find intergalactic SNeIa within a few Mpc surrounding Milky Way-size galaxies

These populations (backsplash galaxies, intergalactic light) promise to provide insight into the formation and evolution of galactic systems. As computational capabilities increase, higher resolution simulations will make it possible to track baryons as well as dark matter particles. At the same time, observational capabilities are also increasing. The combination of these two will allow us to address some poorly-understood questions about where baryons can collect and form stars, expanding the possibilities for research into ‘extreme’ populations.

5.2 Future work in high velocity populations in the Milky Way

In addition to creating intergalactic stars, a satellite galaxy on a highly energetic orbit, and with a passage close to the center of the Milky Way potential, can create a population of high velocity stars and stellar ‘clouds’. These stars were stripped from the satellite galaxy, but not energetically enough to leave the potential of the Milky Way. They continue to oscillate within it; at apogalacticon they form a ‘cloud’ of stars that were similarly stripped. Approaching perigalacticon they are an old population of high velocity stars.
5.2: Future work in high velocity populations in the Milky Way

5.2.1 Distinguishing between three separate high velocity populations

The first high velocity star was discovered in 2005 (Brown et al. 2005). Subsequent highly targeted searches have yielded about 20 stars with velocities above 300km/s (e.g. Brown et al. 2007; Kollmeier et al. 2009). The high velocity stellar population discovered thus far has strong and unusual characteristics which may ‘point’ to specific creation mechanisms.

Possible creation mechanisms for high velocity populations are: 1. a 3-body interaction including a central super-massive black hole, 2. the scattering of matter from a satellite galaxy off the central potential of the MW, 3. a binary star system in which one of the stars goes supernova. Each of these three mechanisms probe very different structural baryonic and dark matter components of the MW (e.g. galactic center vs. the halo or the disk), so understanding and separating the high velocity populations belonging to each mechanism is essential to our ability to make fundamental contributions to our understanding of the MW. This is complicated by the fact that our understanding of the population created by mechanism 2 is far from complete. To derive meaningful scientific conclusions from these populations it is first necessary to understand their origin, and then possibly to separate the three populations. Happily, we expect signatures of the creation mechanism to remain in the resultant high velocity star (HVS) populations, which we now describe for each of the mechanisms in the following:

Mechanism 1: A high velocity star can be created during a 3-body encounter in which one member of a close stellar binary receives a high velocity kick as a result of an encounter with the super-massive black hole (SMBH) at the center of the MW (Hills 1988; Sari, Kobayashi & Rossi 2010). An interaction between a star and a super-
massive/intermediate mass black hole binary at Galactic center can also produce HVSs (Sesana, Madau & Haardt 2009; Levin 2006). Yu, Lu & Lin (2007) estimates that the rate of HVS generation would be 10-5 per year. These HVSs would be rotating slowly (López-Morales & Bonanos 2008). The resulting HVS population, generated by an interaction with the central SMBH, would have purely radial velocities, be slow rotators, and have very specific spatial and temporal distributions created by features in the Galactic Center.

**Mechanism 2:** The gravitational impulse received by a satellite galaxy, as it passes through the pericenter of its orbit around its parent, can be sufficient to create HVSs in the parent galaxy (Teyssier et al. 2009; Abadi et al. 2009). Analytic estimates (Teyssier et al. 2009, hereafter T09) indicate that material at larger satellite radii is more likely to receive the highest velocity kick. This implies that high velocity dark matter, which makes up the majority of material in satellites at the largest radii, would be preferentially created, although N-body simulations from the same paper, T09, show that it is feasible that substantial high velocity baryonic component is also created. This is also supported by work with VLII (in process). We expect the high velocity matter created by satellite interactions to include dark matter and stars. This population of HVSs would most likely have a spatially anisotropic angular distribution (T09, Abadi et al. 2009, in prep), and would be at least as old as the last close satellite interaction with the MW. Since the gravitational impulse is biased toward stars at large satellite radii (T09), these HVSs would not be expected to have purely radial velocities. The included HVSs are expected to be old, have non-radial velocities, normal rotation, and have an anisotropic spatial distribution.
5.2: Future work in high velocity populations in the Milky Way

**Mechanism 3:** A binary star system with an uneven mass ratio evolves until the more massive member goes supernova (SN). The subsequent energy kick transforms the remaining member into a high velocity star. These ‘runaway’ stars have a maximum velocity of 300 km/s for a $3M_\odot$ star (e.g. Bromley et al. 2009). They are expected to be biased toward the Galactic disk (Bromley et al. 2009). Runaway stars have a lower velocity range than the other two mechanisms and a spatial bias toward low Galactic latitudes. The velocity limit and spatial bias may make this population separable from those created by mechanisms 1 and 2.

5.2.2 Possible scientific implications from high velocity populations

**Setting limits on the interaction history of the MW:** The HVS population created via satellite interaction is expected to be at least as old as the time since the last satellite interaction. Old high velocity stars in the halo are difficult to detect. Kollmeier et al. (2010); Kollmeier et al. (2009) analyses of SDSS and SEGUE-2 set upper limits on the quantity of old HVSs. By using the VLII simulation to determine the types of satellite interactions which generate HVSs and the quantity of HVSs created, and comparing this dataset to the extreme velocity population expected in GAIA, its possible to set a limit on when the last satellite interaction occurred.

**Setting limits on the properties of accreted satellites:** The minor merger history of the Milky Way is largely unknown. Satellite remnants, like the Sagittarius stream, provide clues into this history, but only low eccentricity orbits create tidal streams. High eccentricity orbits produce high velocity matter and ‘tidal clouds’ at the apocenters of
their orbits (Johnston et al. 2012). Detection of local M giant stars (which are too sensitive to recent merger events) having an unusual radial velocity (Sheffield et al. 2012) is interpreted as a high velocity flow that is tidal debris from a satellite on an eccentric orbit about the MW (Johnston et al. 2012). Since cosmological simulations show that satellite orbits are typically eccentric (Wetzel, Cohn & White 2009), further investigation of high velocity matter, as remnants of satellites on eccentric orbits, will increase our knowledge of the minor merger history of the MW. Using VLII, it is possible to predict the properties of these high velocity stellar flows, and to tie these debris remnants to the overall properties of the satellites which created them, filling in gaps of the interaction history of the MW.

**Stellar tracers of dark matter debris flows and implications for dark matter detection:** If observations of local stellar flows, like the Sheffield M giants (Sheffield et al. 2012), also strongly trace bulk motions of high velocity dark matter flows, there are important implications for experiments of dark matter direct detection. Kuhlen, Lisanti & Spergel (2012) analyzed the VLII dark matter velocity distribution in a thin shell at the Galactic radius of the Sun, and found significant debris flows at Earth-frame velocities of greater than 450 km/s. This flow will create a distinctive recoil energy spectrum and a broadening of the distribution of incidence in direct detection experiments. In VLII, tying the stellar component to the dark matter flows is essentially a question of the coherence of the dark matter debris flows; do the particles that were most tightly bound trace the same velocity structure as the bulk flows. By using VLII to establish, with some level of confidence, that high velocity stars are tracers for strong high velocity dark matter flows, results from direct detection experiments can be linked to dynamical measurements of subpopulations
of local stars.

**HVSs as a powerful probe of the triaxiality of the galactic potential**: HVSs generated by mechanism 1, could be used to measure the triaxiality of the Galactic potential, because they are assumed to have a purely radial velocity. Deviation from a purely radial velocity would most strongly depend on the triaxiality of the MW, so measurement of a small tangential velocity component can be used to infer the shape of the potential (Gnedin et al. 2005). Although HVSs which are generated via interaction with a SMBH are expected to have a purely radial velocity, HVSs generated via satellite interaction aren’t. Therefore, the validity of using HVSs as a probe of the triaxiality of the Galactic potential is based on an assumption which cannot be proven sound until the HVSs generated via satellite interaction have a characterized parameter space which can be used to rule them out.

**HVSs as a probe of the structure in the center of the galaxy**: Anisotropic angular distributions in the HVS population (which are generated via SMBH interaction) could be tracers of structures in the galactic center. Zhang, Lu & Yu (2010) posits the existence of a young stellar disk existing within 5 pc of the central SMBH. The HVSs, which were fed to the SMBH from the young stellar disk, would have a spatial distribution creating two circles on the plane of the sky. However, anisotropic angular distributions of HVSs could also be the result of satellite interactions. HVSs generated via satellite interactions act as a contaminant when using HVSs to probe the Galactic center.
5.2.3 Observational Tools

Large sky surveys, such as SDSS, have resulted in orders of magnitude increase in the number of stars cataloged out to 100 kpc from Galactic Center (GC) and followed up with spectroscopic surveys. One result of this, is that it is feasible to characterize the high velocity stellar population of the Milky Way for the first time. The first high velocity star was discovered in 2005 (Brown et al. 2005). Subsequent highly targeted searches have yielded about 20 stars with velocities above 300 km/s (Brown et al. 2007; Kollmeier et al. 2009). The high velocity stellar population discovered thus far has strong and unusual characteristics which may ‘point’ to specific creation mechanisms. Ongoing analysis of SDSS data (the SDSS radial velocity catalog is not complete, in contrast to the photometric survey), and other surveys, such as RAVE, will greatly increase the number of stars with accurate velocity measurements. RAVE, scheduled to finish the end of this year, will provide accurate velocities for 500,000 stars. This explosion of data makes it feasible to greatly increase the high velocity stellar dataset.

5.2.4 Simulation Tools

It is necessary to use the highest resolution simulation available to trace the kinematics of particles at stellar mass scales. VLII is among the highest resolution cosmological simulations of a Milky Way-like object available. The particle mass is only $4.1 \times 10^3 M_\odot$, allowing the high velocity component to be tracked by statistically relevant numbers of particles, and making it possible to track satellites as small as the lowest mass dwarf galaxies. The dataset of high velocity dark matter particles can be pulled directly from
VLII, traced to high redshift and its original host halo. Preliminary analysis has found 2.8 million particles above 400 km/s in the Milky Way Analog, and particle velocities up to 580 km/s. Kuhlen, Lisanti & Spergel (2012) also found high velocity matter.
Chapter 6

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