

SATELLITES OF LMCS: CLOSE FRIENDSHIPS RUINED BY MILKY WAY MASS HALOS

ALIS J. DEASON¹, ANDREW R. WETZEL^{2,3}, SHEA GARRISON-KIMMEL⁴, VASILY BELOKUROV⁵

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ABSTRACT

Motivated by the recent discovery of several dwarf galaxies near the Large Magellanic Cloud (LMC), we study the accretion of massive satellites onto Milky Way (MW)/M31-like halos using the ELVIS suite of N-body simulations. We identify 25 surviving subhalos near the expected mass of the LMC, and investigate the lower-mass satellites that were associated with these subhalos before they fell into the MW/M31 halos. Typically, 7% of the overall $z = 0$ satellite population of MW/M31 halos were in a surviving LMC-group prior to falling into the MW/M31 halo. This fraction, however, can vary between 1% and 25%, being higher for groups with higher-mass and/or more recent infall times. Groups of satellites disperse rapidly in phase space after infall, and their distances and velocities relative to the group center become statistically similar to the overall satellite population after 4 – 8 Gyr. We quantify the likelihood that satellites were associated with an LMC-mass group as a function of both distance and velocity relative to the LMC at $z = 0$. The close proximity in distance of the nine Dark Energy Survey candidate dwarf galaxies to the LMC suggest that $\sim 2 - 4$ are likely associated with the LMC. Furthermore, if several of these dwarfs nearby to the LMC are genuine members, then the LMC-group probably fell into the MW very recently, $\lesssim 2$ Gyr ago. If the connection with the LMC is established with the help of the follow-up velocity measurements, these “satellites of satellites” represent prime candidates to study the affects of group pre-processing on lower mass dwarfs.

Keywords: Galaxy: formation — Galaxy: halo — galaxies: dwarf — galaxies: Magellanic Clouds

1. INTRODUCTION

The Λ cold dark matter (Λ CDM) model predicts an abundance of substructure on all (observable) mass scales. Galaxy halos simply appear as scaled versions of galaxy clusters (Moore et al. 1999). Hundreds of subhalos are predicted to surround Milky Way (MW) mass halos (Klypin et al. 1999), which can be likened to a scaled down version of the thousands of substructure clumps associated with clusters. This trend, presumably, continues to smaller mass scales, whereby dwarf galaxies can also host several substructures. Recent discoveries of dwarf-dwarf accretion (Martínez-Delgado et al. 2012; Belokurov 2013) present tantalizing observational evidence for the existence of such “sub-structure of sub-structure”.

Despite the hierarchical nature of dark matter halos, we generally ignore the possibility that some of the MW satellites may have been part of a group of subhalos before they fell into the Galaxy. The relatively unexplored population of sub-subhalos or “satellites of satellites” is strongly linked to the most massive structures in the MW halo, as these are seen as the potential vehicles that dragged in several low mass dwarfs. For example, Wetzel et al. (2015) showed that a significant fraction ($\sim 30\%$) of low-mass subhalos ($M_{\text{star}} \lesssim 10^5 M_{\odot}$)

likely fell into a MW-type host as a satellite of a more massive subhalo, and $> 50\%$ were in a group before infall. The most likely culprit in our own Galaxy is the Large Magellanic Cloud (LMC). This massive dwarf already has one obvious companion, the Small Magellanic Cloud (SMC), but it likely had several other companions in the past.

Numerous works have attempted to connect the LMC to other known dwarfs in the MW. Lynden-Bell (1976) first suggested the idea of a “Greater Magellanic Galaxy”, and he later postulated the association of several of the classical dwarfs with the Magellanic complex (Lynden-Bell 1982; Lynden-Bell & Lynden-Bell 1995). More recently, D’Onghia & Lake (2008) suggested that seven of the MW satellites could have been part of a late infalling LMC group. In contrast, Sales et al. (2011) use an LMC-analog “case-study” in a cosmological simulation to show that most of the classical dwarfs show little evidence for an association with the LMC. However, the authors do prophetically state that “The dearth of satellites clearly associated with the Clouds might be solved by wide-field imaging surveys that target its surroundings, a region that may prove a fertile hunting ground for faint, previously unnoticed MW satellites”.

The discovery of very low luminosity galaxies ($L \lesssim 10^5 L_{\odot}$) in the MW (e.g. Willman et al. 2005; Belokurov et al. 2006, 2007) has, until recently, been restricted to the Sloan Digital Sky Survey (SDSS) footprint, as most of the “ultra-faint” dwarf population have been discovered using SDSS imaging. However, uncharted territory beneath declination $\delta = -30^{\circ}$ has very recently been explored with the first data release of the Dark Energy Survey (DES). Two independent groups (Bechtol et al. 2015; Koposov et al. 2015) unveiled eight and nine candidate dwarf galaxies correspondingly in the

¹ Hubble Fellow. Department of Astronomy and Astrophysics, University of California Santa Cruz, Santa Cruz, CA, USA; alis@ucolick.org

² TAPIR, California Institute of Technology, Pasadena, CA, USA

³ Observatories of the Carnegie Institution for Science, Pasadena, CA, USA

⁴ Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA, USA

⁵ Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, UK

DES data. Curiously, these satellites are mostly of the “ultra-faint” variety and are in close proximity to the LMC.

In Wetzel et al. (2015) we showed that most of the past satellites of an LMC-mass dwarf are likely lower mass subhalos, likened to the ultra-faints. Thus, the finding of several low luminosity dwarfs in close proximity to the LMC could potentially confirm a generic prediction of hierarchical structure formation. In this letter, we use cosmological simulations to study the satellite populations of LMC-mass dwarfs accreted onto MW/M31 mass halos, in order to understand the potential association between the newly discovered DES satellites and the LMC in a cosmological context.

2. NUMERICAL METHODS

2.1. *ELVIS Simulations*

To study the satellite populations of LMC-mass dwarfs, we use ELVIS (Exploring the Local Volume in Simulations), a suite of N -body zoom-in simulations that model the Local Group environment in a cosmological context (Garrison-Kimmel et al. 2014). ELVIS contains 48 dark matter halos of masses similar to the MW or M31 ($M_{\text{vir}} = 1 - 3 \times 10^{12} M_{\odot}$) within a zoom-in volume of radius $> 4 R_{\text{vir}}$ of each halo (corresponding to $r > 1.4$ Mpc) at $z = 0$. Half of the ELVIS halos reside in a paired configuration with separations and relative velocities similar to those of the MW-M31 pair, while the remainder are highly isolated halo mass-matched to those in the pairs.

ELVIS was run using GADGET-3 and GADGET-2 (Springel 2005) with initial conditions generated using MUSIC (Hahn & Abel 2011), within a Λ CDM cosmology with parameters based on *Wilkinson Microwave Anisotropy Probe* WMAP7 (Larson et al. 2011): $\sigma_8 = 0.801$, $\Omega_M = 0.266$, $\Omega_{\Lambda} = 0.734$, $n_s = 0.963$ and $h = 0.71$. The zoom-in regions are selected from a suite of simulations, each a cube with side length 70.4 Mpc. Within the zoom-in regions, the particle mass is $1.9 \times 10^5 M_{\odot}$ and the Plummer-equivalent force softening is 140 pc (comoving at $z > 9$, physical at $z < 9$). See Garrison-Kimmel et al. (2014) for more details on ELVIS.

2.2. *Finding and tracking subhalos*

ELVIS identifies dark matter (sub)halos with the six-dimensional halo finder ROCKSTAR (Behroozi et al. 2013a) and constructs merger trees using the CONSISTENT-TREES algorithm (Behroozi et al. 2013b). For each halo that is not a subhalo (within the virial radius of a more massive halo), we assign a virial mass, M_{vir} , and radius, R_{vir} , using the evolution of the virial relation from Bryan & Norman (1998) for our Λ CDM cosmology. At $z = 0$, this corresponds to an overdensity of $97(363) \times$ the critical (matter) density of the Universe.

For each (sub)halo, we assign its primary progenitor (main branch) as the progenitor that contains the most total mass summed from the (sub)halo masses over all preceding snapshots in that branch. We then compute the maximum (peak) mass, M_{peak} , ever reached by the main branch of a progenitor.

Throughout this work, we only consider subhalos with $M_{\text{peak}} > 10^8 M_{\odot}$ (or $M_{\text{star}} \gtrsim 5 \times 10^2 M_{\odot}$);

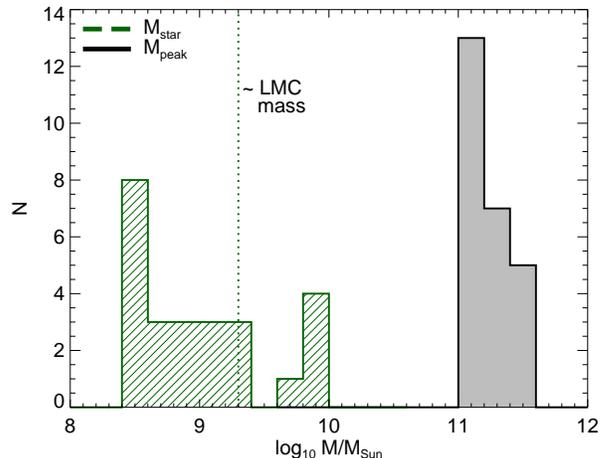


Figure 1. Distribution of peak subhalo mass, M_{peak} (solid gray), and stellar mass, M_{star} (hashed green), for the 25 satellites with $M_{\text{peak}} > 10^{11} M_{\odot}$ (masses near that expected for the LMC) in the MW/M31 hosts at $z = 0$ in the ELVIS simulation suite. These are the (surviving) “LMCs” that we will discuss in the remainder of the paper.

Garrison-Kimmel et al. (2014) show that the subhalo catalogs are complete down to this mass threshold.

2.3. *Sample of LMC-mass satellites*

We select a sample of LMC-mass satellites of MW/M31 hosts at $z = 0$ using all 48 (paired and isolated)⁶ halos in the ELVIS simulation suite. We select $z = 0$ satellites with $M_{\text{peak}} > 10^{11} M_{\odot}$ (or $M_{\text{star}} \gtrsim 3 \times 10^8 M_{\odot}$). This lower mass cut is approximately a factor of two lower than the LMC mass ($M_{\text{peak}} \sim 2 \times 10^{11}$ for $M_{\text{star}} \approx 2 \times 10^9$, van der Marel et al. 2002). Stellar masses are estimated for the dark matter subhalos using the $M_{\text{star}} - M_{\text{peak}}$ relation derived in Garrison-Kimmel et al. (2014). Note that we exclude the satellite in the Sonny & Cher paired simulation that has a mass comparable to its host halo ($M_{\text{peak}} \sim 7 \times 10^{11} M_{\odot}$).

A significant number of the host halos in ELVIS ($\sim 50\%$) do not have *any* satellites more massive than $M_{\text{peak}} > 10^{11} M_{\odot}$, while some halos have more than one LMC satellite. It is unlikely that relatively low mass MW/M31 halos with $M_{\text{vir}} \approx 10^{12} M_{\odot}$ host very massive satellites (see e.g. Boylan-Kolchin et al. 2010), so we are biased towards the more massive host halos in the ELVIS suite (typically $\langle M_{\text{vir}} \rangle \sim 2 \times 10^{12} M_{\odot}$). We also note that some of the paired halos were selected to have a satellite companion with mass similar to the LMC ($M_{\text{star}} \sim 10^9 M_{\odot}$, see Garrison-Kimmel et al. 2014). Thus, our sample is not an unbiased (random) selection of MW/M31 mass hosts.

Our final sample comprises 25 LMC-mass dwarf satellites at $z = 0$. Fig. 1 shows the distribution of their stellar and peak dark matter masses.

2.4. *Finding the (surviving) satellites of LMC dwarfs prior to infall onto the MW/M31 host*

We trace back all $z = 0$ satellites of MW/M31 hosts and identify those that were satellites of a surviving LMC

⁶ We find no significant differences in our results when just the paired halos are used.

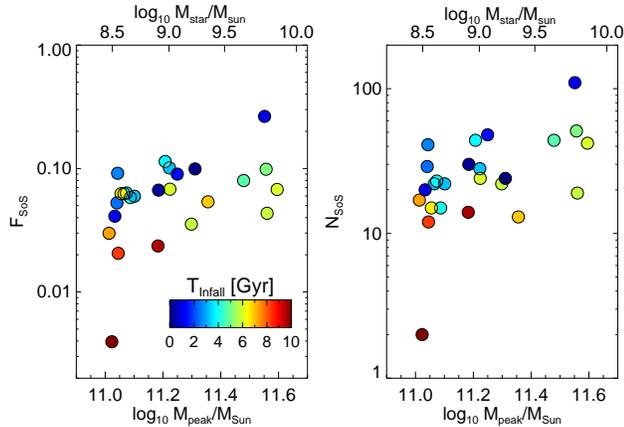


Figure 2. The fraction (left panel) and number (right panel) of satellites of MW/M31 hosts at $z = 0$ that were satellites of the surviving LMC dwarfs prior to its infall onto the MW/M31 host. The peak mass (stellar mass) of the LMCs is shown on the bottom (top) x-axis. The color scheme indicates the time since infall of the accretion events. Recent and/or massive accretion events contribute significant numbers of “satellites of satellites” to the present day satellite population.

dwarf anytime *before* infall onto the MW/M31 hosts. We impose that a subhalo must remain a satellite for at least two consecutive time-steps ($\Delta T \approx 400$ Myr) in the simulations to avoid counting particularly transient (and likely non-meaningful) crossings just within R_{vir} .

Note that the LMC dwarfs themselves are now also satellites of MW/M31 hosts, but prior to infall are the group centrals.

In total, we identify $N = 734$ MW/M31 satellites today that were once satellites of LMC dwarfs, where these “LMCs” are still intact today. These “satellites of satellites” comprise approximately 7% of the surviving satellite population of MW/M31 hosts at $z = 0$, and have typical stellar masses of $M_{\text{star}} = 10^3 - 10^5 M_{\odot}$ (comparable to the ultra-faint dwarf galaxy population). This fraction is lower than in Wetzel et al. (2015) because we only consider the subset of satellites that were satellites of a *surviving*⁷ LMC satellite before infall. In this work, we only consider subhalos within the MW/M31 hosts today, and do not include “field” subhalos (i.e. outside of R_{vir} today) that could have been associated with an LMC-mass host in the past. It is worth noting, however, that these associations do exist, and this could be an interesting population to study in future work.

3. RESULTS

3.1. Satellites of LMC-mass dwarfs

Fig. 2 shows the fraction (left panel) and number (right panel) of $z = 0$ satellites that were associated with a surviving LMC dwarf before infall onto the MW/M31, against the mass of the group central. The color scheme indicates the infall time⁸ of the accretion events onto the MW/M31 hosts (blue=recent infall, red=early infall).

⁷ Wetzel et al. (2015) show that approximately half of the overall population of group centrals have merged/disrupted by $z = 0$.

⁸ Throughout we use “infall time” to define the time *since* infall of a subhalo onto a host halo.

Unsurprisingly, more massive dwarfs have more abundant satellite populations. There is also a dependence on infall time onto the MW/M31 host. At a given mass, groups accreted more recently have more surviving members at $z = 0$.

3.2. Phase-space associations at $z = 0$

We now consider the current ($z = 0$) association in phase-space between the LMC dwarfs and their former satellite population. In Fig. 3 we show the median velocity (left panel) and 3D distance (right panels) between the “LMCs” and their past members as a function of infall time onto the MW/M31 hosts.

After infall, groups become more dispersed in phase-space over time (see also Sales et al. 2011). For comparison, we show the typical average velocity/distance difference between *all* satellites of MW/M31 hosts at $z = 0$ and the group centrals with the dotted lines. Groups accreted more than $\sim 5 - 6$ Gyr ago are well mixed in phase-space today. For illustration, the far-right panel of Fig. 3 shows the distribution of ΔR for one LMC-group with low median ΔR .

In the middle right panel, we show the median difference in configuration space for satellites with $\Delta R < 130$ kpc from the group central. This is a rough estimate for the maximum ΔR probed by the DES survey around the LMC (see Koposov et al. 2015 Fig. 20). The proximity of the DES satellites to the LMC is striking, especially compared to the general population of group members in the simulations. This proximity in configuration space not only suggests a likely association between the DES dwarfs and the LMC, but, if several of these dwarfs are genuine group members, then it implies a very recent infall time for the LMC-group. Note that the most recent observational constraints on the orbits of the LMC/SMC suggest a recent infall time for this group (see e.g. Besla et al. 2007; Boylan-Kolchin et al. 2011; Rocha et al. 2012; Kallivayalil et al. 2013).

Qualitatively, a picture similar to the above has been painted by the study of Sales et al. (2011). However, here we present the first *quantitative* evidence of a pronounced correlation between $z = 0$ scatter in the phase-space exhibited by the “satellites of the satellites” for a statistically significant sample of accretion configurations.

3.3. Likelihood of group-membership

Fig. 4 presents the probability of a past association with an LMC dwarf as a function of distance (left panel) and velocity (middle panels) from the massive group central. This now includes “interloping” satellites near the LMC at $z = 0$ that were not satellites of the LMC-mass host prior to MW/M31 infall. Dwarfs more closely related in configuration or velocity space are more likely to have been group members before infall. For example, $> 25\%$ of dwarfs within 50 kpc of the LMC dwarf today were likely associated with this dwarf before infall. Note that combining both position and velocity information allows a much easier distinction between previous members and the general satellite population. The top-right hand panel of Fig. 4 shows that $> 90\%$ of dwarfs within 50 kpc and 50 km s^{-1} of a LMC dwarf were likely once group members. For comparison, $\Delta R = 23 \pm 2$ kpc and $\Delta V_{3D} = 128 \pm 32 \text{ km s}^{-1}$ (Kallivayalil et al. 2013) for the LMC-SMC pair.

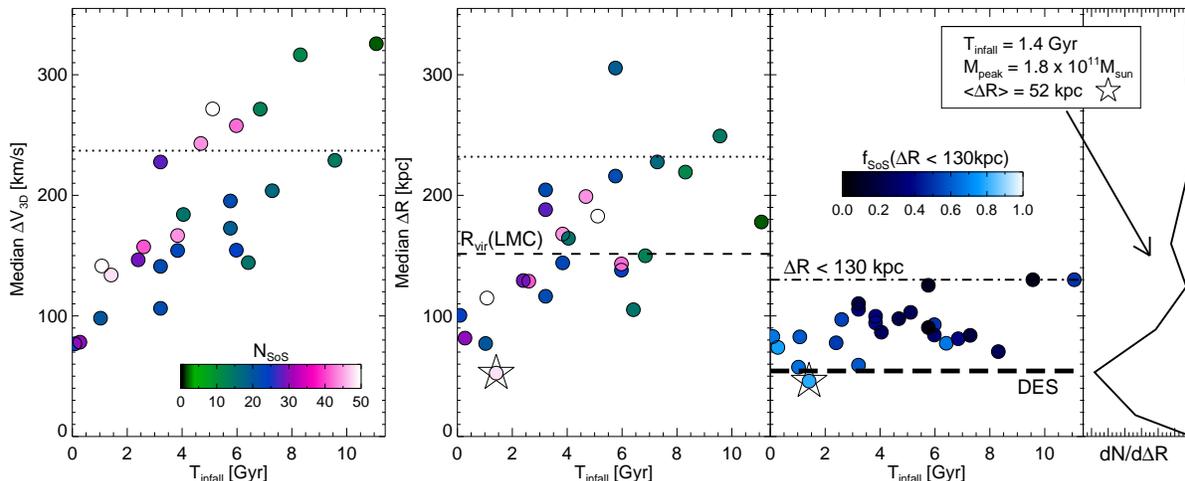


Figure 3. The median differences in 3D velocity (left panel) and 3D distance (right panels) at $z = 0$ between the LMC dwarfs and the satellites that were associated with them in a group before falling into the MW/M31 hosts. LMCs that fell in at early times have the largest differences in phase space with their satellites today. The colors indicate the number of surviving group members. The black dotted lines indicate the average velocity/radial difference between *all* satellites in MW/M31 hosts and the LMC satellite at $z = 0$. We also show the approximate virial radius for an LMC-mass subhalo with the short-dashed line. The middle right panel shows the median difference in configuration space for satellites with $\Delta R < 130$ kpc. This is a rough estimate for the maximum ΔR probed by the DES survey around the LMC. The colors indicate the fraction of surviving group members that have $\Delta R < 130$ kpc. The black dashed line shows the median distance between the DES dwarfs and the LMC. The furthest right panel shows the distribution of ΔR for one massive group (indicated by the star symbol) with low median ΔR .

We also show the radial velocity difference ($\Delta V_R = |V_{R,\text{SoS}} - V_{R,\text{LMC}}|$) between group members in the bottom panels. Clearly, 3D velocity information gives a much cleaner distinction between members and non-members. However, the combination of radial velocity information and 3D distance can be useful. For example, $> 25\%$ of dwarfs within 50 kpc are likely past group members, but this fraction rises to $> 50\%$ for dwarfs with $\Delta V_R < 150$ km s^{-1} .

The significance of infall time onto the MW/M31 host is further illustrated in Fig. 4. The red dashed and blue dotted lines show the fraction of past members as a function of radial and velocity difference for late ($T_{\text{infall}} < 2$ Gyr) and early ($T_{\text{infall}} > 5$ Gyr) accretion events, respectively. Groups accreted a long time ago are now phase-mixed, whereas the probability of being associated with a recently accreted LMC dwarf is strongly related to the proximity in phase-space.

We can use these relations shown in Fig. 4 to estimate the probability that the DES candidate dwarfs were once satellites of the LMC. The estimated probabilities are listed in Table 1. We also give the sum of these probabilities, which provides a rough estimate of the number of these dwarfs that are “satellites of satellites”. Using only 3D coordinate information, we find that two of the DES dwarfs were once satellites of the LMC. If we assume that the LMC-group fell in very recently ($T_{\text{infall}} < 2$ Gyr) then this number rises to four. The right-hand panels of Fig. 4 show that the inclusion of velocity information will enable a clearer distinction between members and non-members in the future.

Simon et al. (2015) and Walker et al. (2015) recently spectroscopically confirmed that the Ret 2 dwarf candidate is indeed a dwarf galaxy. Although this dwarf is in close proximity to the LMC ($\Delta R = 23.9$ kpc), the radial velocity measured by Simon et al. (2015) and

Table 1
The nine candidate dwarf galaxies from Koposov et al. (2015). We give the dwarf name, 3D distance from the LMC, and estimated probability of once being a satellite of the LMC based on this distance.

Name	ΔR [kpc]	$P_{\text{LMC sat}}$	$P_{\text{LMC sat}} (T_{\text{infall}} < 2 \text{ Gyr})$
Reticulum 2	23.9	0.38	0.65
Eridanus 2	337.4	0.02	0.01
Horologium 1	38.5	0.31	0.57
Pictoris 1	70.0	0.19	0.41
Phoenix 2	54.3	0.23	0.49
Indus 1	80.0	0.18	0.37
Grus 1	92.8	0.16	0.31
Eridanus 3	48.2	0.26	0.52
Tucana 2	36.7	0.32	0.58
Total:		2.0	3.9

Walker et al. (2015) for this dwarf is more disparate ($|\Delta V_R| = 160$ km s^{-1})⁹. This dwarf is shown by the purple star in the bottom right panel of Fig. 4. With distance information alone we estimated $P_{\text{LMC sat}} = 0.38$, but this additional radial velocity information only slightly reduces the probability of once being a satellite of the LMC to $P_{\text{LMC sat}} = 0.36$.

Note that we have not taken into account the presence of the SMC in the above analysis, and it is worth pointing out this potential caveat. It is beyond the scope of this work to quantify the affect of the LMC-SMC interaction on the orbits of lower-mass LMC satellites, but this could be a worthwhile avenue for further study.

4. CONCLUSIONS

We used the ELVIS simulation suite to study the surviving satellite population of LMC-mass dwarfs accreted

⁹ Note that this is the difference in line-of-sight velocity between Ret 2 and the LMC in the Galactic rest frame.

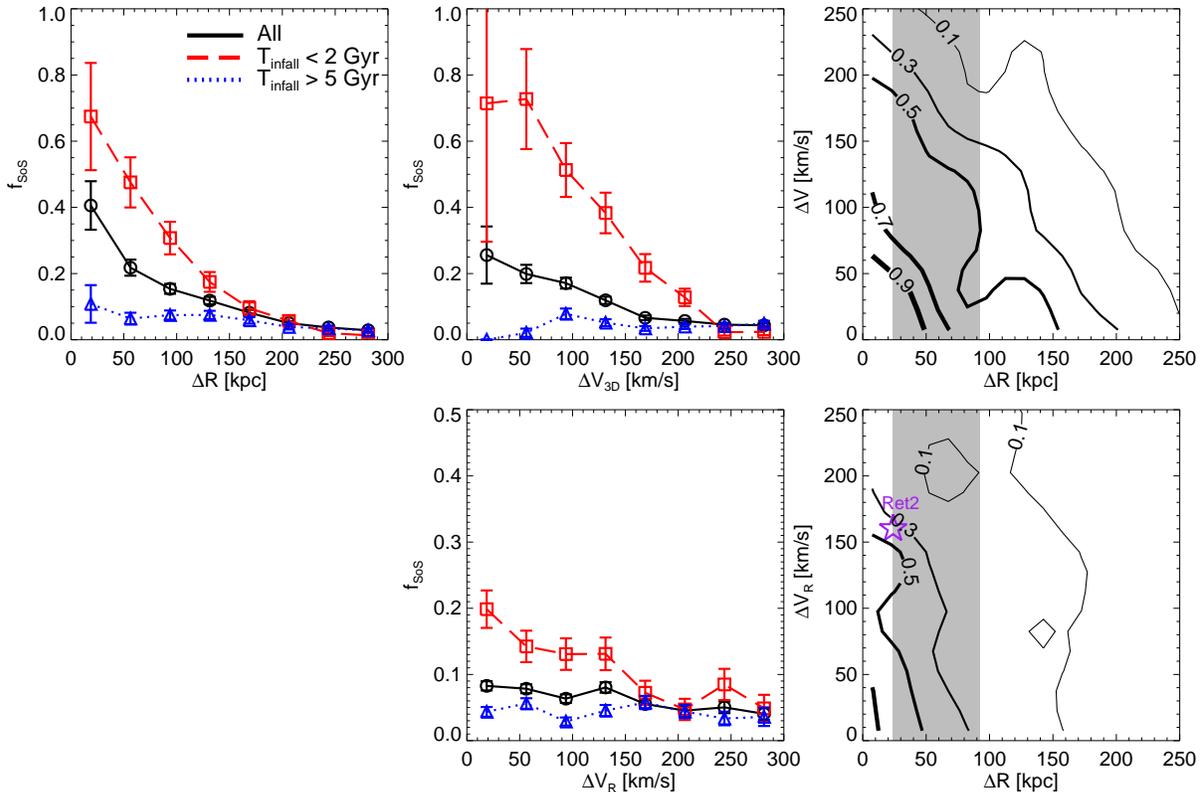


Figure 4. The fraction of all MW/M31 satellites at $z = 0$ that were a satellite of a surviving LMC dwarf before infall onto the MW/M31 host as a function of 3D distance (left panel) and velocity (middle panels) difference from the LMC today. The fractions when velocity and distance information are combined are shown by the contours in the right-hand panels. The gray bands in these right-hand panels indicate the range of ΔR for eight candidate DES dwarfs (excluding Eri 2). The purple star in the bottom-right panel indicates the (spectroscopically confirmed) Ret 2 dwarf (Simon et al. 2015; Walker et al. 2015). The dashed red and dotted blue lines are for groups accreted recently ($T_{\text{infall}} < 2$ Gyr) and early ($T_{\text{infall}} > 5$ Gyr), respectively. Only groups accreted recently show a close-proximity in phase-space at $z = 0$.

onto MW/M31 mass halos. A sample of 25 LMC-mass ($M_{\text{peak}} > 10^{11} M_{\odot}$) $z = 0$ satellites of MW/M31 hosts are selected, and we find the lower mass dwarfs that were associated with these massive dwarfs before they fell into the MW/M31 hosts. Our selection is motivated by the recent discovery of nine candidate dwarf galaxies in the vicinity of the LMC/SMC group. Our main conclusions are summarized as follows:

- Recent, massive accretion events likely “dragged in” a significant number of MW/M31 dwarfs. Typically, 7% of the surviving $z = 0$ satellite population were once associated with surviving LMC-mass dwarfs, but this fraction can vary between 1% and 25% depending on the mass and infall time of the group central.
- Groups of dwarfs quickly disperse in phase-space after infall onto MW/M31 mass hosts. We find that $z = 0$ MW/M31 satellites that were once satellites of a surviving LMC dwarf can typically have large differences in velocity or configuration space relative to their group central if they fell into the MW/M31 host more than 5 Gyr ago.
- The proximity of the candidate DES dwarfs to the LMC suggests that: (1) several were likely satellites of the LMC at some point in the past, and; (2) if

they are genuine “satellites of satellites”, then the LMC-group was likely accreted very recently ($\lesssim 2$ Gyr) for these dwarfs to retain such a close proximity in configuration space with the LMC. Distance information alone suggests that two to four of the newly discovered DES dwarfs were satellites of the LMC-group before infall.

- The DES dwarfs that were/are satellites of the LMC could be prime candidates to study the affects of group pre-processing. If the LMC-group fell in very recently onto the MW, then the members may have spent a significant amount of time in this group before joining the MW. In future work, we plan to study the affects of group pre-processing in more detail.

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