AN INVESTIGATION INTO THE EFFECTS OF BARYONS ON SATELLITE GALAXIES IN COSMOLOGICAL SIMULATIONS

By

SHEEHAN H. AHMED

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ABSTRACT OF THE DISSERTATION

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By SHEEHAN H. AHMED

Dissertation Director:
Alyson M. Brooks

Cosmological N-body simulations are essential tools in verifying and analyzing the details of the Lambda Cold Dark Matter (ΛCDM) paradigm of the Universe. In this work I analyze the effects of baryons in these simulations by comparing cosmological, zoom-in simulations with baryons (gas and stars) to their dark matter-only counterparts, specifically focusing on the statistics and kinematics of satellite galaxies. Initially I investigate the formation of planes of satellites around Milky Way-sized galaxies and compare them to the satellite planes around the Milky Way and Andromeda. Then I focus on the masses and velocities of satellite galaxies around dwarf galaxies (100 to 1000 times less massive than the Milky Way) and quantify the parameters that control the differences that exist in these satellites between the dark matter-only and the baryonic simulations.
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Chapter 1

Introduction

The current picture of the Universe is what is termed as the ΛCDM (Lambda-Cold Dark Matter) cosmological model. Discoveries over many decades have pointed firmly at the fact that the majority of matter in the Universe only interacts only through gravity and is dark, starting with Fritz Zwicky in 1933 (Zwicky 1933). This is the CDM part of ΛCDM. More recent discoveries (Riess et al. 1998) have shown that the majority of the energy budget of the Universe belongs to what is termed as "Dark Energy", which is causing the Universe to accelerate in its expansion, making up the Λ. Baryonic matter consists of the small, remaining part.

While there have been many testable analytic predictions that come out of the ΛCDM (e.g. the Press-Schechter formalism of galaxy formalism (Press & Schechter 1974), the CDM power spectrum (Peebles 1982, Blumenthal et al. 1984), etc), various observables in the Universe arise out of the non-linear and non-analytical parts of the paradigm. In these cases, N-body simulations have been instrumental in reaching and verifying the current understanding of the Universe. These are simulations of small or large-scale structures present in the Universe composed of a dynamical system of particles interacting mainly through gravity. They can be used to study structure formation, clustering and formation of galaxies and even different models of dark matter. In this introduction, I will briefly go over the details of why dark matter is such a compelling idea and the basics of N-body simulations as they are used in cosmological astrophysical studies.

1"Baryons" in astrophysics is a blanket term that encompasses normal, non-dark matter, such as baryons and leptons; you, me, planets, stars and most things humanity cares about.
1.1 The $\Lambda$CDM paradigm

As stated above, The $\Lambda$CDM paradigm describes a three-component universe dominated primarily by Dark Energy (a property that causes the universe to accelerate), followed by Dark Matter (a form of matter that only interacts through gravity) and then “baryonic” matter (normal matter, that includes baryons and leptons). Since measurements tend to indicate that the geometry of space-time in the universe is flat, there is a critical density that the three components must add up to. Latest data from the Wilkinson Microwave Anisotropy Probe (WMAP) indicates that the three components form 71.35%, 24.02%, and 4.63% of the critical density respectively (Bennett et al. 2013).

Motivation for the inclusion of dark matter came during the 1930s when it was noticed that the mass from luminous matter would not account for the gravitational mass inferred from motion for various systems. In 1933, Fritz Zwicky observed that the velocity dispersions in galaxy clusters (then known as “extragalactic nebulae”) required anywhere between 10 to 100 times the mass of the observed luminous galaxies in the clusters to keep them bound. Eventually, detailed measurements of rotation curves of galaxies showed that the circular velocities of galaxies at the outer edges were much higher than what would be expected due to the observed luminous matter inside (assuming a certain mass-to-light ratio) (Bosma 1978). This led to the conclusion that there must be a significant matter content in the universe which seems to exert a gravitational force, exists superimposed or around luminous matter but is not luminous itself. This component of matter, which had no electromagnetic interactions and was only “observable” through gravity was termed as Dark Matter (DM). The “cold” part of $\Lambda$CDM comes from the fact that dark matter needs to be composed of non-relativistic particles to match with current observations of the spatial clustering of galaxies.

Since then there have been many more concrete examples of the existence of Dark Matter. Most notable has been the observations of the ”Bullet Cluster” (Clowe et al. 2006).
The Bullet Cluster consists of two large clusters containing stars, gas and presumably dark matter colliding. The gas can interact with each other through collisions (the stars are sparse enough to pass by each other without interacting other than through gravity), they lose energy and end up settling at the center of the collision. However, through observations of gravitational lensing (whereby light from a distant source is bent by the gravitational field around matter Walsh et al 1979), it was seen that the majority of the mass of the system lie in the outskirts where no visible matter can be seen. The collisionless and dissipationless dark matter parts of the clusters passed by each other and ended up at the edges of the system at current times. This provided "direct empirical proof of the existence of dark matter" (Clowe et al. 2006).

Separately, observations of cosmic dimming (where light from distant supernovae are dimmer than expected if the Universe were expanding at a constant rate) using Type Ia supernovae as standard candles eventually led to the conclusion (Riess et al. 1998) that the expansion of the universe has been accelerating recently. This effect is introduced into the Friedmann equation, which is an exact solution to Einstein’s field equations of general relativity, as a cosmological constant Λ (Peebles & Ratra 2003). This acceleration is attributed to the mysterious “Dark Energy” which permeates the whole Universe, acting as an agent which is causing the expansion of the Universe to accelerate.

The ΛCDM model can successfully predict a lot of different observations really well including the cosmic microwave background fluctuations (Spergel et al. 2003), the large-scale clustering of galaxies at present times (Eisenstein et al. 2005), the number densities of galaxy clusters and the baryon fractions within them (Allen et al. 2004), etc. ΛCDM does very well in matching the observations of the large-scale structures of the universe such as galaxies and the numbers, sizes and distributions of their dark matter haloes (Somerville & Davé 2015). These, and much more, have cemented the ΛCDM model as a successful paradigm for the Universe.
1.2 Cosmological N-body simulations

To create non-analytic predictions from the ΛCDM, Cosmological N-body simulations are the perfect tool. They provide a framework to test theoretical assumptions, predict the formation of large scale structures including galaxies and also allow for mock observations to be generated that can then be compared to real observations. While N-body simulations can be used to simulate and study isolated systems (e.g. the formation of spiral arms, merger between only two galaxies, etc), I will be focusing on cosmological simulations where significant portions of the observable Universe are simulated. In the simplest cosmological simulation, a box is populated with a large number of particles in a lattice, where each particle represents a large mass of dark matter. This lattice is then perturbed using a power spectrum derived from large scale galaxy surveys and weak lensing surveys which informs how much the lattice should be perturbed at different length scales. This perturbation power spectrum is termed as the initial conditions for the simulation. Once the initial conditions are set, the simulation can be allowed to go forwards in time and these small density fluctuations amplify with slightly high density regions gathering more particles through gravity over time and slightly underdense regions becoming larger voids as time passes. Eventually significant large scale structures consisting of sheets and filaments form and the intersection points of these structures, dark matter haloes form. These haloes contain the galaxies we see all around us today (Kuhlen et al. 2012; Mayer et al. 2008).

Initially due to computational constraints, cosmological simulations consisted of dark matter only, under the assumption that the insignificant fraction of baryons would not have a significant effect on large scale structures. Recently with advances in computational power, cosmological simulations with baryonic matter have become increasingly common and the effect of baryons on these simulations, especially on small scales, is a closely studied topic. Baryonic matter introduced into simulations include gas, which consists of small particles than can dissipate energy through metal line cooling and stars, which form from the gas particles and can inject energy into their surrounds through supernovae explosions. The
simulations used in this work all use Smoothed Particle Hydrodynamics (SPH) to model the gas “fluid”. SPH involves modeling a fluid with discrete particles and applying a smoothing kernel over certain scales to average out the properties of the fluid (Monaghan 1992; Evrard 1988; Monaghan & Gingold 1983; Gingold & Monaghan 1977).

1.3 Issues with \( \Lambda \)CDM

\( \Lambda \)CDM, while quite accurate in its predictions of large scale structure and clustering has a number of issues on small scales. A few notable ones include:

- The cusp-core problem: The centrally peaked density profiles of smaller dark matter haloes (de Blok 2010) seen in simulations appear more flattened (cored) (Oh et al. 2012) in real galaxies. Possible solutions include flattening of the cuspy profile due to supernovae feedback from the presence of baryons (Governato et al. 2010) and due to dynamical friction from clumpy baryonic matter (Nipoti & Binney 2015).

- Missing satellites problem: Dark matter haloes around the mass of the Milky Way and Andromeda contain thousands of subhaloes around them (Moore et al. 1999) while observations show orders of magnitudes fewer satellites. Of the many proposed solutions, the presence of baryons can drastically reduce the number of massive subhaloes (due to enhanced tidal stripping due to a baryonic disc and suppressed star formation by photo-heating) (Brooks et al. 2013).

- Too big to fail problem: Abundance matching (whereby observed galaxies are matched to an ordered set of dark matter haloes) indicate that there must be many large “dark haloes”, dark matter haloes that have “failed” to acquire baryonic matter, around the Milky Way (Boylan-Kolchin et al. 2011). One of the proposed solutions to this problem involves the suppression of \( v_{max} \) of satellites due to feedback from baryons (which reduces the total number of large haloes and brings them down towards observations) (Sawala et al. 2016).
Many of these problems are most apparent on smaller scales where baryonic physics and feedback processes become important factors \cite{Brooks2014} and many of their proposed solutions involve baryons. Thus one of the key focuses of this work is to quantify how exactly baryons affect satellites in N-body simulations. It is also important to note that quite a few of these “issues” with ΛCDM are slowly being resolved as both simulations and observations get better.

1.4 Dwarf Galaxies

To probe the effects of baryonic matter it is important to look at structures in the scales where the feedback effects of baryonic matter become important, such as dwarf galaxies. Dwarf galaxies are usually defined as gravitationally bound collections of around 10,000 to a billion stars (as opposed to ~100 billion for normal galaxies) and are found orbiting larger galaxies such as the Milky Way and in greater numbers in the voids between them.

In the chapters that follow, I look at various aspects of cosmological simulations on small scales, mostly involving the statistics and kinematics of dwarf galaxies and how the presence of baryonic matter effects them. This is done through the direct comparison of dark-matter only to dark-matter+SPH simulations.
Chapter 2  
Planes of Satellites

2.1 Introduction

The 11 classical satellites of the Milky Way have been known to lie on a thin plane with polar alignment for some time now (Lynden-Bell 1976). More recently, they have been shown to exist in a rotationally coherent structure (e.g., Metz et al. 2008, 2009; Pawlowski et al. 2013), and newly found ultra-faint dwarfs also lie in the plane (Pawlowski et al. 2015b). Early hints of a similar plane in Andromeda (Koch & Grebel 2006) have recently been shown to be a highly significant thin plane (Conn et al. 2013) with 13 of 15 of Andromeda’s satellites possibly rotating in the same direction (Ibata et al. 2013). Ibata et al. (2014a) also reported the possible discovery of planar structures outside of the Local Group, with 20 out of 22 massive nearby galaxies possibly having co-rotating planes like that of Andromeda (though see Cautun et al. 2015b; Phillips et al. 2015).

There have been a number of investigations using N-body simulations that have tried to quantify whether satellite planes are common in Lambda Cold Dark Matter (ΛCDM) cosmology. Studies of high-resolution N-body simulations do suggest anisotropies due to filamentary accretion from the cosmic web (D’Onghia & Lake 2008; Li & Helmi 2008; Libeskind et al. 2005, 2014; Lovell et al. 2011; Goerdt et al. 2013; Tempel et al. 2015; Buck et al. 2015b). Filamentary infall is generally found to lead to alignment with the parent halo’s angular momentum, preferentially orienting the satellites along the outer halo’s major axis. Assuming the inner and outer halo are aligned, and the disc lies along the halo’s major axis, this orientation would lead to satellites preferentially orbiting in the same plane as the
While this orientation seems to be in agreement with observations of relatively massive, red, spheroidal galaxies (Brainerd et al. 2005; Yang et al. 2006; Bailin et al. 2008; Welker et al. 2015), it is at odds with the known satellite planes around the Milky Way, where the plane is almost perpendicular with the Galactic disc, and Andromeda, whose plane is tilted $\sim 38^\circ$ from the disc (Ibata et al. 2013). In simulations where polar planes of satellites are found around disc galaxies, the disc is oriented with the minor axis of the halo (Libeskind et al. 2007). Non-polar planes like in Andromeda may indicate that the angular momentum of the inner and outer dark matter halo are not aligned (Faltenbacher et al. 2007; Deason et al. 2011; Shao et al. 2016).

Despite the fact that planar satellite distributions have been found in ΛCDM simulations (Libeskind et al. 2009; Deason et al. 2011; Gillet et al. 2015; Buck et al. 2015a; Cautun et al. 2015a; Sawala et al. 2016), there is controversy regarding whether these planes resemble those found around the Milky Way and Andromeda. In particular, the thinness of the observed planes and the number of apparent co-rotating satellites are rarely as significant in simulations as observed (Pawlowski et al. 2014). From their measurements, Ibata et al. (2013) claim a low likelihood of the satellite plane of Andromeda forming by chance.

Conflicting conclusions have been drawn from satellite arrangements in the same simulations studied by different authors. While multiple authors have claimed that vast, thin planes like the one observed around Andromeda are common in the Millenium-II simulation (Wang et al. 2013; Bahl & Baumgardt 2014), others (Ibata et al. 2014b; Pawlowski et al. 2014) claim from the same simulation that Andromeda-like planes are very rare.

Nearly all of the simulation studies to date on planar satellites have made use of dark matter-only simulations. Sawala et al. (2014) claimed to find prominent planes in baryonic simulations of Milky Way-mass galaxies, but did not compare to a dark matter-only version to see if baryonic physics makes planes more prominent (also, their claim of significant planes has been refuted using the same data by Pawlowski et al. 2015a). There are multiple
reasons why we might expect the baryonic satellite distribution to be different than in an exact same simulation using dark matter-only. For example, many authors have found that satellites that may survive in a dark matter-only run are completely destroyed in a baryonic run by the presence of the disc (e.g., D’Onghia et al. 2010; Romano-Díaz et al. 2010; Zolotov et al. 2012; Brooks & Zolotov 2014; Wetzel et al. 2016). Additionally, Read et al. (2009) found that the presence of a disc preferentially dragged massive merging satellites into the disc plane, where they are tidally destroyed. Might these trends somehow tend to leave planes? In particular, would the effect of a disc preferentially destroy in-plane satellites, and be more likely to leave polar planes?

To address these questions, in this chapter we look at four high-resolution “zoom-in” simulations of Milky Way-mass galaxies, run both dark matter-only and with baryons, in order to investigate the existence and formation of significant planes. This chapter is organized as follows: Section 2.2 presents the details of our simulations and dataset while section 2.2.1 explains how our luminous satellite population was chosen. Section 2.3 discusses the orbital distribution of the entire subhalo population (not just luminous satellites). This is followed by Section 2.4 where we detail our plane detection method, and the quantitative significance of the resulting planes in Section 2.4.2. Section 2.5.1 discusses the characteristics of individual planes, and we examine the role of filamentary accretion in creating coherently rotating planes in Section 2.5.2. In Section 2.6 we demonstrate that baryons create different planes than found in dark matter-only runs. Finally, we summarize in Section 2.7.

### 2.2 Simulation Data

The simulations used in this work were run at high-resolution using the N-body + SPH (smoothed particle hydrodynamics) code GASOLINE (Wadsley et al. 2004). The four Milky Way mass (\(\sim 10^{12} M_\odot\)) haloes that are used in this chapter were selected from a uniform resolution, dark matter-only box, 50 comoving Mpc on each side. The initial conditions for
this box used a WMAP Year 3 cosmology (Spergel et al. 2007) with $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$, $H_0 = 73$ km s$^{-1}$, and $\sigma_8 = 0.77$. The work here looks only at zoomed-in regions of these four haloes which were resimulated at higher resolution both with and without baryons (Katz & White 1993). During the resimulation, the highest resolution particles are introduced to the region that ends up within several virial radii of the selected halo while the rest of the box is kept at low resolution. Maintaining the 50 Mpc box allows for large-scale transfer of angular momentum. The force resolution for the high resolution region is 173 pc. The high-resolution dark matter particles have masses of $1.3 \times 10^5$ M$_\odot$, while the gas particles start with $2.7 \times 10^4$ M$_\odot$ (Shen et al. 2010) and a model of H$_2$ creation and destruction by Lyman-Werner radiation, and shielding of HI and H$_2$ described in Christensen et al. (2012). To simulate reionization, a uniform UV background turns on at $z = 9$ (Haardt & Madau 2001). For the sub-grid feedback model, $10^{51}$ erg of thermal energy is deposited by Type II supernovae into the surrounding gas and cooling is disabled for a period of time equal to the momentum conserving phase of the blastwave (Stinson et al. 2006).

The overall merger histories of the four haloes in this study are quite different from each other. The heaviest, h239, has a busy merger history full of small mergers spread out in time. h258 has an almost 1:1 co-rotating merger at around $z=1$ which leads it to have a measurable dark disc (Governato et al. 2009; Read et al. 2009). h277, which is the closest analog to the Milky Way (Loebman et al. 2014) has a very quiescent life while h285 has a violent merger history with multiple simultaneous mergers. It also has a counter-rotating major merger between $z=0.8$ and $z=1.4$ which leads it to have counter-rotating dark matter in its inner regions (Sloane et al. 2016). Halo masses$^1$ and virial radii for the four dark matter-only simulations and their SPH counterparts are listed in Table 2.1.

Two of these four galaxies (h258 and h277) were studied by Zolotov et al. (2012) and

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$^1$As discussed in Munshi et al. (2013) and Sawala et al. (2012), SPH halo masses are generally lower than the same halo in a dark matter-only run. At Milky Way masses, this is primarily due to the fact that feedback removes material, and thus fitting to the same overdensity leads to a slightly smaller virial radius, as can be seen in Table 2.1. For the one galaxy in Table 2.1 in which the SPH run appears more massive, it is due to infalling substructure in the SPH case that isn’t yet infalling in the dark matter-only run.
Table 2.1: Properties of parent haloes

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$m_{\text{vir}}$ ($10^{12} , M_\odot$)</th>
<th>$r_{\text{vir}}$ (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>h239</td>
<td>0.930</td>
<td>253</td>
</tr>
<tr>
<td>h239+SPH</td>
<td>0.924</td>
<td>252</td>
</tr>
<tr>
<td>h258</td>
<td>0.817</td>
<td>242</td>
</tr>
<tr>
<td>h258+SPH</td>
<td>0.780</td>
<td>238</td>
</tr>
<tr>
<td>h277</td>
<td>0.748</td>
<td>235</td>
</tr>
<tr>
<td>h277+SPH</td>
<td>0.695</td>
<td>230</td>
</tr>
<tr>
<td>h285</td>
<td>0.726</td>
<td>233</td>
</tr>
<tr>
<td>h285+SPH</td>
<td>0.935</td>
<td>253</td>
</tr>
</tbody>
</table>

Brooks & Zolotov (2014), who showed that the resulting satellite luminosity functions are in good agreement with those for the Milky Way and Andromeda. They were also the first Milky Way-mass simulations to simultaneously reproduce both the luminosities and velocities of satellite populations seen around the Milky Way and Andromeda. In Fig. 2.1 we show the satellite stellar mass function of our four baryonic simulations compared to the observed satellite stellar mass functions for the Milky Way and Andromeda and all are relatively good matches.

### 2.2.1 Identifying Satellites

To identify haloes and subhaloes in our simulations we use the ROCKSTAR Phase-Space Based Halo Finder at all time steps. ROCKSTAR uses a modified friends-of-friends algorithm in six dimensions which allows for a better tracking of substructure as it interacts with its parent halo (Behroozi et al. 2013). Halo and subhalo data from ROCKSTAR is then fed through the merger tree and halo catalog generator Consistent Trees (Behroozi et al. 2013) to create complete merger trees. A lower limit of 64 dark matter particles is imposed on the data since below 64 particles the mass function fails to converge (Brooks et al. 2007). This gives us confidence on the physical properties of haloes and subhaloes down to a virial mass of $\sim 10^7 \, M_\odot$. All subhaloes that exist within $1.5 \times r_{\text{vir}}$, (listed in Table 2.1), of the parent halo at $z = 0$ are considered to be part of the system. The virial radius corresponds to the virial overdensity definition from Bryan & Norman (1998) which
Figure 2.1: Stellar mass function of the luminous satellite population around our four DM+SPH galaxies compared to those around the Milky Way and Andromeda. Milky Way data collected from McConnachie [2012] and Bechtol et al. [2015a]. Lower cutoff of x-axis is a result of our selection criterion of subhaloes that contain more than $2 \times 10^4 \, M_\odot$ in stellar mass at $z = 0$ (more than 3 star particles).

is equal to 360 times the background density at $z=0$, but evolves with redshift.

In order to identify planes of satellites, we must first identify luminous satellites. In the baryonic run, this is easily done using subhaloes that contain stars. However, a different method must be used for the dark matter-only simulations. Satellites are more commonly destroyed in baryonic runs due to the presence of a disc [D’Onghia et al. 2010; Zolotov et al. 2012], so it is not possible to simply identify all of the same subhaloes in the baryonic run that were found in the dark matter-only run. Moreover, we wish to evaluate whether those studies that use dark matter-only simulations would pick out different planes than in observations or studies that use baryonic simulations. Hence, for the dark matter-only runs we use a commonly-employed method to identify the subhaloes that likely contain the most luminous satellites [Ibata et al. 2014b; Gillet et al. 2015], and make no use of the fact that we know which haloes have luminous, surviving satellite counterparts in the baryonic runs. We employ the following methods to pick out subhaloes that would correspond to luminous
Figure 2.2: Hammer projections of the subhalo angular momentum (AM) vectors compared to that of their parent halo. The lines show the PDF of $\cos \theta$, where $\theta$ is the angle between the angular momentum vector of the orbit of a subhalo and the AM vector of the parent halo. The red line is the histogram of the whole sample of $N$ subhaloes while blue and green are the 200 and 30 most massive subhaloes at $z=0$, respectively. Column 1 is with respect to the angular momentum of the DM halo in the DM-only runs, while columns 2 and 3 are the DM halo AM and gas disc ($<5$ kpc) AM, respectively, of the SPH runs. Spatial clustering of the tips of the subhalo AM vectors are shown in black dots, with the red diamond corresponding to the parent halo AM and the blue diamond representing the opposite. See Sec. 2.3 for interpretation.
satellites at \( z = 0 \) in the Universe:

- **Dark matter-only simulations**: From the surviving subhaloes at \( z = 0 \), we pick out the 30 that were most massive at infall, under the assumption that these correspond to the 30 most luminous satellites at \( z = 0 \). Infall is defined as when the virial radius of the subhalo intersects with the virial radius of the parent halo for the first time. We chose 30 subhaloes because this provides a similar number to the observed satellite counts in both the Milky Way and Andromeda (see Fig. 2.1).

- **Dark matter + SPH simulations**: We select subhaloes that contain more than \( 2 \times 10^4 \) \( \text{M}_\odot \) in stellar mass at \( z = 0 \) (a minimum of 4 star particles), because this picks out approximately 25-35 subhaloes for each of our galaxies (i.e., comparable numbers to the known luminous satellites in M31 or the Milky Way). This stellar mass lower limit also ensures that ultra-faint satellites are included in the luminous sample, since ultra-faints are members of the observed planes in M31 and the Milky Way. We verified that selecting all satellites with \( V \)-band magnitude brighter than \( -5 \) provides a sample consistent with our stellar mass selected sample. Note that our selection may include subhaloes that have been substantially tidally stripped but still have a significant stellar mass, so that they are not necessarily the most massive satellites at \( z = 0 \), but are the most luminous.

Table 2.2 shows the total number of subhaloes and selected luminous satellites in our simulations, \( N_{\text{subhaloes}} \) and \( N_{\text{sats}} \), compared to the known values in the Milky Way and Andromeda. In Appendix 3.1 we discuss the effects of employing different selection criteria than listed above. However, none of our conclusions below are altered if we use different selection criteria.
Table 2.2: Plane statistics, with $\Delta = 20$ kpc, $N_{\text{planes}} = 20000$ and $N_{\text{sims}} = 2000$. Column 1 lists the name of the galaxy simulation. Column 2 lists the total number of subhaloes in the simulation that are within 1.5 $r_{\text{vir}}$. Column 3 lists the number of satellites that were selected in our “observational” sample. For the dark matter-only runs, this is the top 30 by mass at infall. For the baryonic runs, this includes all subhaloes with $M_{\text{star}} > 2 \times 10^4$ $M_\odot$ at $z = 0$. Columns 4 and 5 list the number of subhaloes in the maximum plane and the subset of those that are co-rotating, respectively. Columns 6, 7 and 8 are the positional p-value, kinetic p-value and their product, the total p-value of the maximum plane, respectively. Columns 9 and 10 are the average r.m.s. thickness and radial extent of the maximum plane with 2$\sigma$ standard errors around the mean. Column 11 is the angle between the plane’s rotation vector and the dark matter halo angular momentum vector for the dark matter-only runs or the inner gas disc angular momentum vector for the SPH runs. Milky Way and Andromeda numbers collected from Ibata et al. (2013), Gillet et al. (2015), Pawlowski et al. (2015b) and Torrealba et al. (2016).

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$N_{\text{subhaloes}}$</th>
<th>$N_{\text{sats}}$</th>
<th>$N_{\text{max}}$</th>
<th>$N_{\text{cor}}$</th>
<th>$p_{\text{pos}}$(%)</th>
<th>$p_{\text{kin}}$(%)</th>
<th>$p_{\text{tot}}$(%)</th>
<th>$\sigma_{\perp}$(kpc)</th>
<th>$\sigma_{\parallel}$(kpc)</th>
<th>$\psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>h239</td>
<td>823</td>
<td>30</td>
<td>13</td>
<td>8</td>
<td>7.55</td>
<td>58.1</td>
<td>4.39</td>
<td>14.0±2.8</td>
<td>200.8±53.6</td>
<td>62.7°</td>
</tr>
<tr>
<td>h239+SPH</td>
<td>881</td>
<td>42</td>
<td>15</td>
<td>8</td>
<td>3.45</td>
<td>100.0</td>
<td>3.45</td>
<td>11.6±3.4</td>
<td>197.2±52.9</td>
<td>37.8°</td>
</tr>
<tr>
<td>h258</td>
<td>1066</td>
<td>30</td>
<td>10</td>
<td>8</td>
<td>71.5</td>
<td>10.9</td>
<td>7.81</td>
<td>12.9±3.4</td>
<td>176.7±45.4</td>
<td>35.0°</td>
</tr>
<tr>
<td>h258+SPH</td>
<td>769</td>
<td>28</td>
<td>10</td>
<td>7</td>
<td>69.9</td>
<td>34.4</td>
<td>24.0</td>
<td>13.6±3.7</td>
<td>184.8±51.2</td>
<td>17.1°</td>
</tr>
<tr>
<td>h277</td>
<td>714</td>
<td>30</td>
<td>12</td>
<td>6</td>
<td>57.9</td>
<td>100.0</td>
<td>57.9</td>
<td>10.1±3.0</td>
<td>165.8±47.4</td>
<td>41.9°</td>
</tr>
<tr>
<td>h277+SPH</td>
<td>438</td>
<td>23</td>
<td>10</td>
<td>6</td>
<td>8.75</td>
<td>75.4</td>
<td>6.60</td>
<td>9.7±2.7</td>
<td>197.3±53.9</td>
<td>65.7°</td>
</tr>
<tr>
<td>h285</td>
<td>654</td>
<td>30</td>
<td>15</td>
<td>8</td>
<td>31.4</td>
<td>100.0</td>
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<td>11.9±3.4</td>
<td>89.9±26.6</td>
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</tr>
<tr>
<td>h285+SPH</td>
<td>601</td>
<td>28</td>
<td>10</td>
<td>8</td>
<td>68.2</td>
<td>10.9</td>
<td>7.46</td>
<td>8.6±2.5</td>
<td>154.4±53.6</td>
<td>31.7°</td>
</tr>
</tbody>
</table>

| MW      | 48                       | 11                | 8                 |                  |                     |                     |                     |                     |                     |       |
| M31 (Gillet2015) | 27                     | 14                | 12                | 1.60             | 1.3                 | 0.0208              | 12.5                | 154.7               |       |
| M31 (Ibata2013)  | 27                     | 15                | 13                | 0.13             | 0.74                | 0.00096             | 12.6                | 191.9               |       |
2.3 Orbital Properties of All Subhaloes

Before we examine the distribution of only these most massive/luminous haloes, we first look at the general characteristics of all $N_{\text{subhaloes}}$ in our sample for each simulated galaxy (all subhaloes with $\geq 64$ particles within $1.5 \times r_{\text{vir}}$ of the parent halo). Orbital information for all subhaloes is shown in Fig. 2.2. For each of our galaxies, the colored lines in column 1 shows the angular momentum vectors of the subhalo orbits with respect to the parent halo’s angular momentum in the dark matter-only simulation. The colored lines in columns 2 and 3 show the same information with respect to either the dark matter angular momentum or gas disc angular momentum, respectively, in the baryonic simulation. The dark matter angular momentum vectors of the parent halo are calculated by summing the angular momenta of all dark matter particles within the virial radius, while the gas disc angular momentum vector is calculated similarly by using all gas particles within a 5 kpc radius.

The insets in each panel of Fig. 2.2 show the actual spatial clustering of the tips of the subhalo angular momentum vectors in a Hammer-Aitoff projection. The red and blue diamonds represent the parent halo (or disc) angular momentum vector and its opposite, respectively. The angle between the parent halo’s dark matter halo and disc angular momentum vectors in the SPH simulations is noted as $\phi$ in column 3.

$\theta$ is the angle between the angular momentum vector of a subhalo’s orbit and the angular momentum vector of the parent halo. Therefore $\cos \theta$ ranges from -1, where the subhalo orbit is completely opposite to the average rotation of the parent halo (or disc), through 0, where the subhalo orbit is perpendicular to the rotation of the parent, to 1, where the subhalo rotation lines up with the parent halo (or disc) rotation. The probability density graph which shows the distribution of subhaloes with a certain value of $\cos \theta$ is represented by three lines: red, blue, and green corresponding to the whole population, most massive 200, and most massive 30 subhaloes at $z = 0$, respectively. This breakdown helps distinguish any mass dependent properties of subhalo orbit orientation, but none is seen.
Generally, the subhaloes have a slight tendency to rotate either aligned or anti-aligned with the halo’s angular momentum. However, the trend is weak in all simulations except h258 where the subhaloes tend to heavily favor rotating with the parent halo, as seen in the clustering of points around the red parent angular momentum vector. Because the disc and halo angular momentum vectors are also nearly aligned in h258, the subhaloes also are aligned with the angular momentum vector of the disc. The angular momentum vector of the disc of h285 is almost completely anti-aligned with the dark matter halo’s angular momentum in the SPH run (by $162^\circ$). This results in the subhalo alignment trend being reversed when compared to the dark matter halo angular momentum vector versus the disc vector in the SPH run. This scenario is a result of a large counter-rotating merger in the history of h285. The alignment trend in the other three galaxies is the strongest when every subhalo in our sample is selected. Selecting for the most luminous satellites still keeps the general trend, albeit more weakly.

2.4 Plane Detection

2.4.1 Plane detection algorithm

The plane detection method used in this work follows the procedure used by Gillet et al. (2015) and subsequently Buck et al. (2015a). Twenty thousand random planes, defined by their normal vectors, all passing through the centre of the parent halo, are generated at $z = 0$. The number of subhaloes that fall within a distance $\Delta = 20$ kpc of these planes are recorded and are considered part of the plane. Just as in Gillet et al. (2015), $\Delta$ is chosen to be roughly $3 \times$ the root mean square (r.m.s.) thickness of the M31 plane to capture planes of similar thickness in our simulations (which range from 8.6 to 14.0 kpc, comparable to the 12.5 kpc of Andromeda, see Table 2.2). The plane with the highest number of subhaloes is termed the maximum plane, and the number of subhaloes in that plane is labelled $N_{\text{max}}$. This is the plane that is selected and its kinematics are studied. The algorithm is run multiple times on each parent halo to make sure that the number of
random planes generated is enough to pick out the same max plane on every iteration. If more than one plane is detected with the same maximum number of subhaloes, the one with the most co-rotating subhaloes (largest $N_{\text{cor}}$) is chosen as the maximum plane. Co-rotation is a binary value with subhaloes either rotating with or against the plane depending on which side their angular momentum vector falls.

The plane detection method leads to unique and robust planes. Planes with 1 or 2 fewer subhaloes than the maximum plane always turn out to be the maximum plane with a few members missing because the test plane used to detect this second plane was slightly offset from the one that detected the maximum plane. The next plane down from the maximum plane always has significantly fewer subhaloes, with one exception\footnote{h277 dark matter-only had another plane with the same $N_{\text{max}}$ but smaller $N_{\text{cor}}$.}. Thus, in general there is no ambiguity in what the maximum plane is for a given simulation.

### 2.4.2 Significance of detected planes

We now proceed to quantify how statistically significant these planes are against a random distribution. To generate a random distribution of maximum planes, positional information for test subhalo populations are created conforming to the radial distribution of subhaloes present in each of the parent haloes. The satellite radial distribution for our cosmologically simulated galaxies is seen in Fig. 2.3. The SPH runs have a less centrally concentrated satellite population when compared to their corresponding dark matter-only runs. This can be attributed to the fact that subhaloes in the SPH runs have a higher chance of being destroyed the closer they are to the disc \cite{Donghia2010, Schewschenko2011, Brooks2013, Brooks2014, Wetzel2016}. In general (apart from h239) not only are the SPH runs less concentrated, but the subhalo numbers are reduced overall, see Table 2.2.

Fig. 2.3 also illustrates that the cumulative radial distributions of our subhaloes in the SPH simulations qualitatively match the observations of the Milky Way and Andromeda,
barring the effects of incomplete surveys that reduce the number of “faint” subhaloes present around the Milky Way at higher radii (for a detailed discussion, see Yniguez et al. 2014).

For this comparison, we use all known satellites of the Milky Way and Andromeda that have \( M_{\text{star}} > 2 \times 10^4 \, M_\odot \) (McConnachie 2012; Bechtol et al. 2015a). No assumption is made about the stellar mass of the subhaloes selected from the dark matter-only run, other than that the 30 most massive subhaloes at infall are likely to correspond to the 30 most luminous satellites.

Figure 2.3: Cumulative radial distribution of satellites using our selection methods at \( z=0 \) (30 most massive at infall in the dark matter-only runs, all satellites with \( M_{\text{star}} > 2 \times 10^4 \, M_\odot \) in the SPH runs). Colors represent different parent haloes; solid lines are baryonic runs while dashed lines are dark matter-only runs. Milky Way and Andromeda satellites with \( M_{\text{star}} > 2 \times 10^4 \, M_\odot \) are shown in thicker black and gray bold lines, respectively (McConnachie 2012, Bechtol et al. 2015a). Grey dotted line shows the Andromeda satellites from Conn et al. (2012) as used by Gillet et al. (2015) in their analysis. In general, the SPH simulations have a less centrally concentrated population of subhaloes.

Next the plane finding algorithm is run on a large number (\( N_{\text{sims}} = 2000 \)) of test cases where \( N_{\text{sats}} \) is randomly sampled from a radial distribution that matches the radial distributions of each parent halo in order to build up a statistical probability distribution function (pdf) of finding a plane with a certain number of subhaloes given that radial distribution. This is illustrated in Fig. 2.4 where we can see that the most likely number
Figure 2.4: Probability distribution function of the maximum plane generated from 2000 instances of subhalo positions following the radial subhalo distributions in our simulations (Figure 2.3). Peak indicates the number of subhaloes most likely to be found in the maximum plane.

of subhaloes found in the maximum plane with $\Delta = 20$ kpc is somewhere between 10-15.

With these pdfs we can find the probability of finding $n$ or more satellites in a plane given a population of $N$ satellites, i.e. the positional p-value, where,

$$p_{pos} = p(X \geq n) = \sum_{n}^{N} pdf. \quad (2.1)$$

Since our method forces a binary choice on the rotation direction on any given subhalo (depending on whether their angular momentum vector falls either on one side of the plane or the other), we can easily also find the kinematic p-value which is the probability of finding $k$ or more plane satellites corotating given that the plane contains $n$ satellites.

$$p_{kin} = p(X \geq k) = 2 \times \sum_{k}^{n} p(i) \quad (2.2)$$

with $p(i)$ being the binomial distribution:
\[ p(i) = \binom{n}{i} \lambda^i (1 - \lambda)^{n-i} \]  

(2.3)

where \( \lambda = 0.5 \).

The total probability of finding \( n \) out of \( N \) satellites with \( k \) co-rotating given a certain radial distribution is found by multiplying \( p_{pos} \) and \( p_{kin} \) together. The results are presented in Table 2.2.

Looking at the p-values of our galaxies in Table 2.2, the first thing to note is that there is generally no correlation in the p-values between the dark matter-only and the SPH versions, i.e. a smaller p-value in the dark matter-only simulation does not imply similar results in the corresponding SPH simulation or vice versa. However, we show in Section 2.6 that this is because the planes picked out in the dark matter-only runs and the SPH runs are different. This is the first effect that results from including baryons: a different set of satellites are inside the halo at \( z = 0 \). Because of this, the dark matter-only versions of the runs cannot be compared directly to their SPH counterparts. In the remainder of this section, we simply treat them as additional examples of planes of satellites.

Examining the total p-values of our galaxies in Table 2.2, we find that over 50 per cent of our sample have p-values below 10 per cent. While this value is nowhere near as significant as in the Milky Way or M31, it is much lower than the p-values found in the simulations studied by Gillet et al. (2015) using the same method (where the lowest p-value was \( \sim 14 \) per cent). In three of our haloes, this low p-value results from low positional p-values, and in the two others it results from low kinematic p-values. In no case is there a simulation plane with both a low \( p_{pos} \) and a low \( p_{kin} \), which is the case in M31. Because of this, none of our galaxies have planes as significant as M31.

Included in Table 2.2 are the numbers of satellites that make up the planes in the Milky Way (Pawlowski et al. 2015b, Torrealba et al. 2016) and Andromeda. We include two different estimates of p-values for Andromeda (Ibata et al. 2013, Gillet et al. 2015).
Our smallest p-value is still substantially higher than the estimated p-value of the plane of satellites observed around Andromeda of 0.0208 per cent (Gillet et al. 2015). Cautun et al. (2015a) recently suggested that the significance of the satellite planes observed around the Milky Way and Andromeda may have been overestimated by around an order of magnitude because the significance of the planes are very sensitive to small changes in the sample selection criteria. However, even if the Milky Way and Andromeda planes are less significant than previously estimated, the significance of our planes is still much lower.

The total numbers of satellites found in our planes are comparable to the Milky Way and M31 values (this is a result of choosing \( \Delta = 20 \) kpc). Importantly, we can identify that the reason that some galaxies have low positional p-value is due to the fact that their satellites are less radially concentrated. For example, the baryonic versions of h239 and h277 are the least radially concentrated within \( \sim 150 \) kpc (see Figure 2.3). Because all of our planes are made to pass through the centre of the halo and have a thickness \( \Delta = 20 \) kpc, as the satellite distribution becomes more centrally concentrated the number of satellites that make up the plane tends to increase. In our random distributions with similar radial concentrations, it becomes much more difficult to pack as many satellites into the maximum plane as the radial concentration decreases. Hence, the significance of the haloes being in a planar structure increases compared to random if the satellites are less radially concentrated.

This is the second effect that results from including baryons: if inclusion of baryons makes the satellite distribution less radially concentrated (as seen in Figure 2.3), then planes of satellites will be more significant compared to a random distribution when baryons are included.

In fact, this is part of the reason that Andromeda has such a high positional p-value. As an example, \( N_{\text{sats}} \) and \( N_{\text{max}} \) for the dark matter-only h285 run are similar to those for M31, but their \( p_{pos} \) values are quite different, with our simulation planes being much less significant. The reason for this can be seen clearly in Fig. 2.3 where the satellite distribution for h285 dark matter-only is much more centrally concentrated than the satellite distribution.
used in Gillet et al. (2015) from Conn et al. (2012). This makes it much easier to find planes with the same number (or higher) of satellites in our dark matter-only h285, thus lowering their significance (leading to a higher $p_{pos}$ value). Note as well that the updated method of distance finding in Conn et al. (2012) leads to a much less centrally concentrated satellite distribution in M31 than earlier works, like those compiled in McConnachie (2012). Using the distribution from McConnachie (2012) leads to a lower $p_{pos}$ for M31.

Our less centrally concentrated satellite radial distribution is also the reason why we find lower $p$-values than Gillet et al. (2015). Although they examine multiple methods of defining satellites to comprise their maximum planes, in all but one case their resulting satellite radial distribution is more concentrated than in Andromeda. Their least concentrated distribution is also the one that leads to the lowest $p_{pos}$ for M31.

Hence, it is easier for us to find relatively significant planes in terms of positional $p$-value. On the other hand, it is harder for us to find significant co-rotating planes. Our highest fraction of co-rotating satellites in a maximum plane is 80 per cent. This is slightly higher than in the Milky Way, but not as high as in Andromeda. Those planes with 80 per cent co-rotating satellites have the lowest $p_{kin}$, but many of our planes have $\sim$50 per cent co-rotating, significantly lower than that of Andromeda. As we will examine in more detail in Sections 2.5.1 and 2.5.2 and in Figure 2.5, our ability to achieve relatively high significance in a few cases is only due to our binary definition of co-rotating. In reality, we never achieve a true fraction of co-rotating satellites higher than $\sim$50 per cent. Although we only have a binary definition in M31, in the Milky Way proper motion data has been used to show that 8 of the 11 satellites in the plane seem to be truly co-rotating (Pawlowski et al. 2015b). Hence, in no case do we produce any satellite plane that is as coherently rotating as that seen in the Milky Way.
Figure 2.5: Each panel shows an Aitoff-Hammer projection of the sky from the centre of our simulated galaxies. Blue circles show the position of subhaloes and the corresponding orange triangles show the tips of the angular momentum vectors of their orbit around the galactic centre projected onto the sky. The numbers are labels for the subhaloes in decreasing order of virial mass at z=0 with 0 being the heaviest. The filled points indicate the subhaloes making up the maximum plane. A clustering of the angular momentum vectors indicate that those subhaloes are coherently rotating. This can most clearly be seen in the SPH versions of h285 and h239 and in the dark matter-only versions of h239 and h277. Red (and blue) diamonds indicate the angular momentum (antiparallel-) vector of the parent halo as in Fig. 2.2. Note that the clustering does not usually correlate with the angular momentum vector of the parent halo, indicating that the maximum plane is usually offset from the rotation of the dark matter halo or disc. \( \psi \) is the angle between the maximum plane's rotation vector and the dark matter halo angular momentum vector for the dark matter-only runs or the inner gas disc angular momentum vector for the SPH runs.
2.5 Coherency of Planes

2.5.1 Details of Individual Planes

Fig. 2.5 shows us the position and angular momentum vectors of the most luminous and maximum plane subhaloes in our simulations as projected onto the night sky in an Aitoff-Hammer projection as seen from the centres of the galaxies. The projection plots are oriented such that (1) the maximum planes lie along the equator and (2) the angular momentum vectors of subhaloes that move along the plane cluster near the poles. The subhaloes are labelled in decreasing order of their virial mass at z=0 out of the whole population. Each blue circle shows the position of the selected subhaloes that are being analysed for that simulation and the corresponding orange triangles show where the tips of the angular momentum vectors of their orbit around the galactic centre project onto the sky. The filled points indicate the subhaloes making up the maximum plane and only these are labelled. The angle between the plane’s rotation axis and the dark matter angular momentum axis for the dark matter-only simulations or the inner gas disc angular momentum axis for the SPH simulations is listed as $\psi$ in Table 2.2.

Looking at the make-up of the maximum plane for each simulation gives us insight into their formation process. For the dark matter-only version of h239, both subhalo pairs 29 & 48 and 18 & 55 fall into the parent halo together with the same trajectories. However, the former pair stay relatively together throughout the simulation and end up in close proximity in the projection view in Fig. 2.5. Due to slight differences in orbital radii and velocities, subhaloes 18 and 55, even though they keep similar trajectories till $z=0$, end up away from each other in proximity. The orbital coherence of both pairs can be seen in the clustering of their angular momentum vectors in Fig. 2.5. The rest of the maximum plane is split evenly between subhaloes that are in coherent orbits with these two pairs but had their own individual infall trajectories and other subhaloes that are crossing the plane by chance at $z=0$. 
For the baryonic version of h239, a cluster of subhaloes (1, 6, 25, 62 & 63) falls into the parent halo and ends up with similar positions (projected and real) and trajectories at $z=0$. These subhaloes make up the bulk of the maximum plane and, barring subhalo 6, also the coherently rotating part of the maximum plane. Four of these satellites are accreted close to $z = 0$. Subhaloes 1 and 63 have infall times of 12.9 and 13.5 Gyr, respectively, while subhaloes 6 and 25 are just about to come into the virial radius of the parent halo as the simulation ends at $z = 0$. Subhalo 62, while part of the group, has an early infall time of 5.6 Gyr but is actually a “splashback” subhalo coming back from its apocentre (Gill et al. 2005; Ludlow et al. 2009; Wang et al. 2009; Teyssier et al. 2012). Subhaloes 2 and 92, though having similar trajectories and positions, have a velocity vector directed out of the plane and are only transient parts of the plane. Subhaloes 10 & 12 also fall in together $\sim 12$ Gyr following a distinct accretion filament. These filaments are discussed in greater detail in Section 2.5.2.

Note that, despite the fact that both the dark matter-only and baryonic versions of h239 have pairs of subhaloes falling in together to make up the maximum planes, they are not the same subhaloes. We discuss in Section 2.6 that there is very little overlap in the subhaloes that constitute the maximum planes in the dark matter-only and baryonic simulations, in all cases.

The dark matter-only version of h258 lacks any significant coherent portion of the maximum plane and is mostly made up of rogue subhaloes that form a transient plane at $z = 0$. For the baryonic version of h258, only subhaloes 44 and 46 fall in together, but due to the latter’s close encounter with the core of the parent halo, they end up with substantially different positions and trajectories. The coherent part of the maximum plane (subhaloes 14, 20, 24 & 44) have their angular momentum vectors deviating slightly from the normal of the plane, indicating that they will slowly move out of the maximum plane as time progresses.

For the h277 dark matter-only halo, subhaloes 4, 6, and 10 fall in as a large sheet and mostly retain their similar positions and trajectories due to their late infall times (not yet
fallen in, 11.9 Gyr and 13.7 Gyr respectively). They are counter-rotating with respect to the other set of subhaloes that are moving coherently (by chance), 2, 33 and 47. The rest are transients. The baryonic version of h277 has a maximum plane defined by subhaloes 7 & 35 (co-rotating) and 26 (counter-rotating). Subhaloes 7 and 35 had very early infall times of 2.6 Gyr but keep their coherent formation (subhalo 26 infalls at 10.3 Gyr). The rest are all transients in tilted orbits.

The dark matter-only version of h285 has a plane made mostly of transients with little or no coherence. A few clusters that showed early coherence and infall lose those properties by \(z = 0\). On the other hand, the baryonic version of h285 has a strongly coherent maximum plane with three early infall subhaloes, 18, 25 & 118 (infall times of 4.2 Gyr, 3.5 Gyr and 3.5 Gyr respectively). These three subhaloes keep their coherent rotation till \(z = 0\) (their relative positions spread out due to slightly different orbital radii and speeds). Along with another coherent pair (19 & 38), half of the maximum plane of subhaloes in the baryonic h285 run have a very tightly clustered set of angular momentum vectors implying that they will hold the structure of the plane for a long time.

### 2.5.2 Relation to Filamentary Accretion

Looking at the traced-back positions of the plane subhaloes, we find that groups of them that are within close proximity of each other have similar infall times and follow similar trajectories. In this section, we investigate the role of filamentary accretion in contributing to the maximum planes, in particular the coherence of rotation in the planes. The angular momentum vectors of the plane subhaloes confirm that many instances of these planes are transient, and are only a feature that is dependent on the time we are looking at it. This is seen clearly in Fig. 2.5 in every instance where a subhalo in the maximum plane does not have its angular momentum vector near either pole of the projection. Some subhaloes will keep moving coherently, but the whole plane may not exist at a different time.

A good example of how filamentary accretion can lead to the formation of coherent
Figure 2.6: Snapshots of integrated dark matter density (left panel) and integrated gas density (right panel) around the baryonic h239 simulation at $t = 11.59$ Gyr. Subhaloes that will belong to the maximum plane at $z = 0$ are highlighted in blue. Subhaloes mentioned in the text are labelled. Accretion filaments are highlighted in orange and distances are in physical units. In this galaxy, the maximum plane is built by a pair of filaments that contribute most of the plane satellites.

Figure 2.7: Snapshots of the integrated dark matter density around h258 in the dark matter-only run at $t = 2.58$ Gyr (left panel) and $t = 7.73$ Gyr (right panel). Subhaloes that will belong to the maximum plane at $z = 0$ are highlighted in blue. Distances are in physical units. No distinct filamentary accretion of subhaloes can be seen at either time. At $z = 0$, this halo has no coherently rotating plane of satellites.
Figure 2.8: Snapshot of integrated dark matter density around h285 DM at $t = 2.91$ Gyr. Subhaloes that will belong to the maximum plane at $z = 0$ are highlighted in blue. Accretion filaments are highlighted in orange and distances are in physical units. While multiple distinct filaments can be seen, the maximum plane subhaloes do not have a strong affiliation with any one of them. At $z = 0$, this halo has no coherently rotating plane of satellites.

Figure 2.9: Snapshots of integrated dark matter density (left panel) and gas density (right panel) around the baryonic version of h285 at $t = 3.55$ Gyr. Subhaloes that will belong to the maximum plane at $z = 0$ are highlighted in blue. Subhaloes mentioned in the text are labelled. Accretion filaments are highlighted in orange and distances are in physical units. The same filamentary structures as those in Fig. 2.8 are seen, but in this case the maximum plane subhaloes mainly come from two filaments that are close to each other. This configuration leads to a maximum plane at $z = 0$ that is strongly coherent in its rotation.
planes is illustrated in Fig. 2.6. The left and right panels are snapshots of the integrated
dark matter and gas densities respectively of the SPH run of h239 at 11.59 Gyr. Recall from
Fig. 2.5 that both versions of h239 contain maximum planes with a cluster of coherently
co-rotating satellites. The orange regions in Fig. 2.6 highlight the two major filaments
through which most of the maximum plane subhaloes (highlighted in blue) infall. The
labelled subhaloes all end up rotating coherently in the maximum plane (or in the case of
subhalo 12, counterrotating). The rest of the maximum plane elements come from another
distinct filament or have no association with any major filamentary structures.

As a counter example, both versions of h258 lack a coherently rotating maximum plane
at $z = 0$. Fig. 2.7 shows the infalling maximum plane subhaloes at 2.58 Gyr (left panel)
and 7.73 Gyr (right panel) in the dark matter-only run. While there are wide, sheet-like
infalling dark matter structures, the distinct and narrow filaments that are seen for h239
in Fig. 2.6 are not present. This configuration leads to a very transient, and non-coherent
plane.

Further examples that strengthen the picture being painted above are found in the h285
dark matter-only and h285 baryonic runs. Recall from Fig. 2.5 that the maximum plane in
the dark matter-only run is very transient, while the maximum plane in the baryonic run has
a majority of its satellites coherently rotating. Fig. 2.8 shows that, even though there are
distinct filamentary accretion structures present, the maximum plane subhaloes in the dark
matter-only h285 halo come in through all of them. On the other hand, we can see in Fig. 2.9
that even though the baryonic h285 has the exact same filamentary structures at a similar
time, the majority of the coherent satellites of the maximum plane come in through two
narrow filaments that are close to each other and another diametrically opposite filament,
rather than through multiple as in the dark matter-only case. From these examples, it
appears that maximum planes that accrete their satellites through multiple (more than
two) sets of filaments do not lead to rotational coherence. If, however, a maximum plane
is built from satellites that are accreted primarily through two filaments (or two sets of
filaments), this can lead to a more coherently rotating plane. Previous work has noted that filamentary accretion can lead to planar satellite structures (see Introduction), but here we refine the results. Coherent rotation seems to more strongly arise if only two filaments contribute to the majority of planar satellites, as is the case in h239 and the baryonic h285 simulations. While a maximum plane can still be defined in other cases, the plane does not contain a large number of coherently rotating subhaloes. This is seen, for example, in the dark matter-only h258, where a large number of subhaloes fall in through many different filaments. It is also seen in the dark matter-only h285, where amorphous accretion makes it very difficulty for the maximum plane to have any coherent rotational structure at $z = 0$.

Finally, we note that the maximum plane is not aligned with the angular momentum vector of the dark matter halo or baryonic disc in any of our galaxies (this can be seen by the fact that the clustering of the satellite orbital angular momentum vectors in Fig. 2.5 do not cluster around the blue or red points). As was noted in Fig. 2.2, the angular momentum of the baryonic disc in our simulations is always either aligned, or nearly anti-aligned in h285, with the dark matter halo angular momentum. Despite that, the maximum plane is usually at an angle to them ($\psi$, listed in Table 2.2).

None of our planes are polar, like that of the Milky Way, but neither are they completely aligned with the disc. As was mentioned before (see discussion of Fig. 2.2), generally the angular momentum vectors of all the subhaloes (before selecting for a luminous population) do show preference to align (or anti-align) with the DM halo or baryonic disc. In h258, the subhaloes were strongly aligned in the direction of the disc. The satellite planes of the Milky Way and Andromeda are not aligned with their discs. We see here that, even if the majority of subhaloes tend to align with the disc (e.g., h258), the maximum plane does not. It is suggestive that something similar could be happening in real galaxies.
Table 2.3: Overlaps in subhaloes between DM and SPH simulations. Overlap number pairs are DM $\rightarrow$ SPH and SPH $\rightarrow$ DM correspondences respectively. See section 2.6 for details. $N_{\text{destroyed}}$ indicates the number of subhaloes that have been fully disrupted in the baryonic run that have surviving counterparts in the dark matter-only run.

<table>
<thead>
<tr>
<th></th>
<th>h239</th>
<th>h258</th>
<th>h277</th>
<th>h285</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sats , overlap}}$</td>
<td>18,20</td>
<td>11,16</td>
<td>13,14</td>
<td>5,9</td>
</tr>
<tr>
<td>$N_{\text{max , overlap}}$</td>
<td>4,4</td>
<td>1,3</td>
<td>2,3</td>
<td>2,2</td>
</tr>
<tr>
<td>$N_{\text{destroyed}}$</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>

2.6 Comparison of DM-only and DM+SPH simulations

Being able to compare the same simulation with and without baryons lets us have a unique perspective on how baryons affect subhaloes and plane formation. Since our dark matter-only and SPH simulations start from the same initial conditions, it is natural to compare a subhalo from the dark matter-only simulation with its counterpart from the SPH simulation at $z = 0$. To find counterparts, we track all the dark matter particles in a subhalo in the dark matter-only simulation and find which subhalo the majority of the same particles reside in the SPH simulation.

In our analysis, we check how many such correspondences occur in our total luminous subhalo selection, and in the maximum plane subhaloes. This is shown in Table 2.3. $N_{\text{sats \, overlap}}$ lists how many of the same subhaloes exist in the total luminous satellite population between DM and SPH simulations. The two numbers are, first, the correspondence when starting from the dark matter-only run and tracing to the SPH run, and second, the correspondence when starting from the SPH run and tracing to dark matter-only run, respectively. $N_{\text{max \, overlap}}$ lists the same numbers, but for only the maximum plane subhaloes.

While our selection method picks out anywhere from 23 to 42 luminous satellites in the SPH run, and 30 in all dark matter-only runs, the number of overlapping haloes is anywhere from 5 to 20. This difference is due to two facts. First, the two methodologies used to identify luminous satellites (30 most massive at infall in the dark matter-only simulations,
and all satellites with stellar mass above \( 2 \times 10^4 \, M_\odot \) in the SPH runs) pick out slightly different subhaloes. On top of that, the luminous population in the SPH simulation can be significantly different than the one in the dark matter-only simulation. In particular, a surviving subhalo in the dark matter-only run is more likely to be entirely disrupted in the SPH run [Brooks & Zolotov 2014]. The trend in the number of overlapping haloes in Table 2.3 goes in this direction: we are less likely to find subhaloes in the SPH run that exist in the dark matter-only run than to find subhaloes in the dark matter-only run that exist in the SPH run. This trend can be explained if the dark matter-only run contains subhaloes that have been fully destroyed in the SPH run. \( N_{\text{destroyed}} \) in Table 2.3 indicates the number of subhaloes that have been fully disrupted in the baryonic run that have surviving counterparts in the dark matter-only run.

In all four cases, the proportion of overlap in the luminous satellite populations (50-57 per cent) is greater than the proportion of overlap in the max plane population (7-30 per cent). This indicates that there are distinctly different maximum planes being picked out by the plane finding algorithm in the SPH simulations compared to the dark matter-only simulations. While the general statistics of the maximum plane stays relatively constant between the DM-only and DM+SPH simulations, the individual members of the planes are different.

The presence of baryons changes the formation history, infall times and interactions with the parent haloes enough that by \( z = 0 \), the dark matter-only and SPH versions of any given subhalo have different trajectories. This is in line with the findings of Schewtschenko & Macciò (2011), who conclude that baryonic subhaloes have in general a later infall time than their dark matter-only counterparts, leading to different positions and velocities at \( z = 0 \).

To test the robustness of this claim, we modified our selection criterion for luminous satellites and reran our plane detection algorithm. In the SPH simulations we only chose satellites that corresponded to an existing one in the dark matter-only luminous population.
Running the plane analysis algorithm on these also led to distinctly different maximum planes with minimal overlap between the dark matter-only and SPH planes (no more than 2-3 overlapping satellites in the maximum planes in all cases). Thus, the different planes identified between the two versions are not an effect of the method being used to select the luminous satellite population. Instead, it is primarily the changes in formation and infall history introduced by the presence of baryons that leads to a different satellite configuration at $z = 0$.

The fact that the two versions of the simulations consistently lead to different maximum planes indicates that no study to date that has examined the formation of satellites planes using dark matter-only simulations has studied a realistic population of satellites. The planes studied in dark matter-only simulations are not the same planes that result in the presence of baryons. In order to study satellite planes with a realistic position, mass, and luminosity distribution, baryonic simulations are necessary.

Finally, we examined the trajectories of the satellites that are fully destroyed in the SPH run in order to test whether there is any geometrical dependence on the destruction, e.g., are satellites that have orbits aligned with the disc plane preferentially destroyed over other satellite orbits? Indeed, we find that more than 75 per cent of all of the destroyed satellites have orbits that appear to be dragged toward the disc plane prior to their destruction. Such disc-plane dragging was also demonstrated in Read et al. (2009). Another $\sim$25 per cent of the satellites instead seem to have radial paths that take them directly through the disc plane and they are quickly disrupted thereafter. Intriguingly, all of the destroyed satellites have surviving counterparts in the dark matter-only run with positions at $z = 0$ that are less than 100 kpc in height from the plane of the disc in the baryonic run, though they are not confined to this distance in other dimensions. This seems to indicate that these counterparts have a preference for orbits that are on a path more closely aligned with the disc plane in the baryonic run.
2.7 Conclusions

We have examined the impact of including baryonic physics in forming planes of satellites around Milky Way-mass galaxies, like the planes observed in both the Milky Way and Andromeda. We have studied the satellite planes that form in both dark matter-only runs and baryonic runs of the same haloes, to explicitly assess the impact of baryons. The presence of baryons has two effects. First, it changes the satellite composition of the resulting planes. The majority of satellites that contribute to a plane are different in the baryonic version of a simulation than in a dark matter-only version. This is true even if the same satellites are used across both the baryonic and dark matter-only runs. The resulting distribution of the satellites in the baryonic run is different enough that the maximum plane (the plane that maximizes the number of member satellites) is always different in the two versions. However, the second effect of baryons is perhaps the most important in terms of understanding the significance of the planes observed around the Milky Way and Andromeda. Inclusion of baryons makes the satellite distribution less radially concentrated (see Figure 2.3), leading to planes of satellites with higher significance compared to a random distribution.

To understand the effect of baryons on the planar significance, it is important to note that all of our planes pass through the centre of the halo, by definition. Thus, as radial concentration decreases, it becomes much less likely to create a planar distribution when randomly populating the halo with satellites, even using the same radial distribution. Because of this, the significance of planar structures increases compared to random when the satellites are less radially concentrated. When there are more centrally concentrated satellites, it becomes much easier to find as many (or more) satellites in the maximum plane in a random distribution. The presence of a disc in baryonic simulations tends to destroy satellites that pass near the centre of the galaxy (see Section 2.6 and Table 2.3) and this effect makes the planes in baryonic simulations more likely to be of higher significance.
Hence, it is critical to study simulations that include baryons if one wishes to understand the origin of highly significant planes. Additionally, dark matter-only simulations lead to different plane satellite members, making it again critical to use baryonic simulations if one wishes to study the satellite members that contribute to significant planes.

Low radial concentration is part of the reason why the satellite plane in M31 has such high significance. M31 has a satellite distribution that is less concentrated near the galaxy centre. In our simulations, we can find relatively low positional $p$-values due to low radial concentration. However, to be as truly significant as the observed plane in Andromeda, we must also have a low kinematic $p$-value. Although we have some simulations that produce low $p_{\text{kin}}$, we never find a case where both low $p_{\text{kin}}$ and low $p_{\text{pos}}$ occur together. Hence, none of our simulated galaxies have planes as significant as M31 or the Milky Way.

In every simulation, we can easily identify a group of satellites that form a planar structure. Notably, this plane is usually unique. Our plane detection method consistently identifies a plane containing the maximum number of dwarfs. Trying to define planes with different configurations leads to a plane with many fewer subhaloes. In this sense, it is easy to identify planes of satellites in simulations. However, it is much more rare to be able to identify a plane with a large fraction of co-rotating satellites. This is true despite the fact that we define co-rotation as a simple binary choice: the orbital angular momentum vectors of the satellites point to one side of the plane or the other. When true co-rotation is examined (e.g., satellites whose orbital angular momentum vectors cluster together near the poles in Fig. 2.5), the number of coherently rotating satellites is even smaller. In reality, all of the defined planes contain transient satellites that appear to be spatially coincident with the plane, but that have an orbit that will eventually move them out of the plane. Even our most coherently rotating planes contain some transients, and in some cases the entire plane can be made of transients.

We also investigate the role of large-scale filamentary structure in forming satellite planes. For those planes that do contain a significant fraction of co-rotating satellites,
the coherently rotating satellites seem to be accreted primarily through no more than two sets of filaments. When more than two sets of filaments contribute, or if there are no well-defined filaments in general, then coherent rotation of the plane does not exist.

Overall, a simulated galaxy must be able to produce a satellite plane that is both positionally significant (with low radial concentration) and kinematically significant (with more than $\sim 80$ per cent co-rotating) in order to match the highly significant satellites planes observed around the Milky Way and Andromeda. Such a simulation has yet to be published.
Chapter 3

Dwarfs around dwarfs

3.1 Introduction

Galaxy formation within the Cold Dark Matter (CDM) paradigm is hierarchical. Hence, satellites of dwarf galaxies is a robust prediction of CDM, including satellites of satellites around galaxies like the Milky Way. Targeted surveys exist to identify satellites of dwarf galaxies and test numbers against CDM predictions, with some candidates already identified (e.g., Sand et al. 2015, Carlin et al. 2016). Some of the newly discovered dwarfs in the Dark Energy Survey (DES, Bechtol et al. 2015b, Drlica-Wagner et al. 2015, Kim & Jerjen 2015, Kim et al. 2015, Koposov et al. 2015, Luque et al. 2017) are thought to potentially be satellites of the Magellanic Cloud system (D’Onghia & Lake 2008, Deason et al. 2015, Yozin & Bekki 2015, Jethwa et al. 2016, Sales et al. 2017). Additionally, Dooley et al. (2016) recently pointed out that the Solitary Local dwarfs survey (Solo), which has surveyed all of the isolated dwarfs within 3 Mpc of the Milky Way (Higgs et al. 2016) has probably already seen satellites of these dwarf galaxies, though spectroscopic confirmation is required and will be time consuming.

Previous studies have made predictions for the probability of finding a luminous satellite around a dwarf galaxies of $\sim 10^{10} \, M_\odot$ in halo mass (Sales et al. 2013, Wheeler et al. 2015), suggesting a 35-50% probability. However, the actual numbers are strongly dependent on how stars populated halos of a given mass. Dooley et al. (2016) used a range of stellar mass-to-halo mass relationships, combined with a model for reionization that predicts the fraction of halos that contain stars as a function of halo mass, in order to explore a range of
probabilities for finding a luminous satellite for every isolated dwarf in the Solo survey. In a companion paper (Munshi et al., in prep.), we demonstrate that the chosen star formation recipe can have a severe effect on the resulting stellar mass-to-halo mass relation and fraction of luminous halos at a given mass, and can thus dramatically alter predictions for the number of luminous satellites expected around dwarfs. In this paper, we focus on a related topic: is the evolution of dwarf galaxies altered compared to predictions from dark matter-only simulations if baryonic effects are included?

In particular, we focus on whether the inclusion of baryonic physics alters the expected masses (and therefore velocities) of satellites around dwarf galaxies. Many recent authors have demonstrated that including baryons in a massive galaxy like the Milky Way can alter the evolution of its satellites (e.g., Penarrubia et al. 2010, Zolotov et al. 2012, Brooks & Zolotov 2014, Wetzel et al. 2016, Garrison-Kimmel et al. 2017). Because baryons can cool to the center of their dark matter halo, the inclusion of baryons puts more mass at the center of massive halos. This leads to stronger tidal forces on orbiting satellites, causing more mass to be stripped from the satellites than predicted in dark matter-only simulations. However, it is not clear that this same effect should happen on the scale of dwarf galaxies. Milky Way galaxies are generally thought to retain most of their baryons, despite galactic winds (Muratov et al. 2015, Christensen et al. 2016, e.g.). Dwarf galaxies, on the other hand, lose many of their baryons in winds and are generally dark matter-dominated at $z = 0$ (Christensen et al. 2016, Wang et al. 2017). They do not generally show signs of adiabatic contraction (Dutton et al. 2016). Hence, the ability to alter satellite mass evolution that occurs at Milky Way parent masses is not necessarily expected to occur on the scale of dwarf galaxy parent halos.

However, the simulation of Munshi et al. (2017) contained some satellites of dwarf galaxies that had been substantially stripped of mass after infall, losing more than 90% of their original dark matter mass. If such mass loss is common and not expected in dark matter-only simulations, then the predicted velocity dispersions for dwarf galaxy satellites such as
the DES dwarfs may be substantially lowered.

Additionally, there are other baryonic effects that have been observed in simulations that may alter satellite evolution. For example, Schewtschenko & Macciò (2011) found that the infall times of subhalos are delayed when baryonic effects are included, not due to differences in the evolution of the parent halo’s $r_{\text{vir}}$ but most likely due to excess pressure support due to hot gas in low-density regions. Also, Munshi et al. (2013) and Sawala et al. (2013) showed that the masses and virial radii of dwarf galaxies are smaller in runs with baryons than in dark matter-only runs (due to baryon mass loss through feedback). Thus, we explore the evolution of satellites of dwarf galaxies in detail in this paper by making a direct comparison between a cosmological, zoomed-in simulation that contains many dwarf galaxies run with and without baryons.

This paper is outlined as follows: in Section 3.2 we describe the simulated dwarf volumes and our selected sample. In Section 3.3 we present comparison of the masses, velocities, and mass loss between dwarfs in a dark matter-only simulation and dwarfs in a baryonic simulation. These physical processes behind these results are discussed in Section 3.4. We summarize in Section 3.5 and discuss some implications of our findings.
Table 3.1: Columns 1 & 2 are the halo IDs in DM+SPH and DM-only runs, respectively. Columns 3 & 5 are the corresponding virial masses with Column 4 being the DM+SPH stellar mass. Columns 6 & 7 are the corresponding virial radii. Columns 8 & 9 are the corresponding number of subhaloes within the virial radius with more than 64 particles.

<table>
<thead>
<tr>
<th>HaloID</th>
<th>HaloID</th>
<th>$m_{\text{star}}$ ($10^7 M_\odot$)</th>
<th>$m_\text{vir}$ ($10^{10} M_\odot$)</th>
<th>$m_\text{vir}$ ($10^{10} M_\odot$)</th>
<th>$r_\text{vir}$ (kpc)</th>
<th>$r_\text{vir}$ (kpc)</th>
<th>$N_{\text{subs}}$</th>
<th>$N_{\text{subs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5.44</td>
<td>1.83</td>
<td>2.52</td>
<td>68.1</td>
<td>75.7</td>
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<td>263</td>
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<td>3</td>
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<td>59.8</td>
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<td>177</td>
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<td>58.0</td>
<td>62.2</td>
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<td>52.8</td>
<td>58.5</td>
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<td>0.81</td>
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<td>0.11</td>
<td>0.61</td>
<td>0.77</td>
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<td>0.44</td>
<td>33.2</td>
<td>42.4</td>
<td>29</td>
<td>57</td>
</tr>
</tbody>
</table>
3.2 Simulations

The simulations used in this paper were run using the N-body + SPH (smoothed particle hydrodynamics) code CHANGA ([Menon et al. 2015]) in a fully cosmological ΛCDM dark matter-only box with sides of 25 co-moving Mpc each. CHANGA uses the charm++ run-time system which allows it to scale well to a larger numbers of cores. CHANGA also uses an improved implementation of SPH and models gas physics at the hot-cold interface more realistically ([Keller et al. 2014], [Wadsley et al. 2017]). The cosmology used was the WMAP Year-3 cosmology with $\Omega_0 = 0.26$, $\Lambda = 0.74$, $h = 0.73$, $\sigma_8 = 0.77$ and $n = 0.96$.

This zoomed-in simulation, nicknamed “Captain Marvel”, is centered on a “sheet” of dwarf galaxies in the field. The highest mass dwarf in the sheet has an $m_{\text{vir}} \sim 2.5 \times 10^{10} M_\odot$. This region was resimulated at higher resolution both with (DM+SPH) and without (DM-only) baryons. The resimulation involves introducing the highest resolution particles in a region roughly 1500 kpc in diameter while the rest of the box is kept at low resolution. This allows us to analyze our selected haloes (which are all chosen from within the high-resolution region) in detail while also allowing for the large-scale transfer of angular momentum throughout the 25 Mpc box. The high-resolution dark matter particles have a mass of $6.7 \times 10^3 M_\odot$ and gas particles begin at $\sim 1410 M_\odot$, but turn 30% of their mass into a star particle each time a star particle is formed. The high resolution region has a gravitational force resolution of 65 pc.

This is the same volume referenced in [Munshi et al. 2017] but run with different physics. In [Munshi et al. 2017], gas can cool via primordial cooling plus metal line cooling, and star formation happens stochastically when cold gas ($T < 10^4$ K) reaches a density of 100 amu/cc. In this version of the simulation, we follow the formation formation and destruction of molecular hydrogren, $H_2$, as described in [Christensen et al. 2012]. This

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1Individual halos are identified using AMIGA’s HALO FINDER (AHF, Gill et al. 2004, Knollmann & Knebe 2009), available for download at http://popia.ft.uam.es/AHF/Download.html. We use the Bryan & Norman (1998) virial radius, $r_{\text{vir}}$, (and consequently $m_{\text{vir}}$) definition which is approximately 100 times $\rho_{\text{crit}}$ at $z = 0.$
allows the additional cooling of gas via molecular cooling down to 10 K as well as self-
shielding of molecular gas, and star formation is restricted to occurring only in the presence
of H$_2$. This effectively eliminates the need for a density threshold for star formation, as it
ensures that all stars are formed from gas with densities above 100 amu/cc. The gas must
also be colder to form stars, \( T < 10^3 \) K.

As in Munshi et al. (2017), metals are diffused through the interstellar medium following
Shen et al. (2010). A uniform, time-dependent UV field mimics the reionization history of
the Universe following Haardt & Madau (2012). We adopt the "blastwave" supernova
feedback approach (Stinson et al. 2006). Massive stars deposit mass, thermal energy, and
metals into nearby gas when they evolve into supernovae. The thermal energy deposited
amongst those nearby gas neighbors is $1.5 \times 10^{51}$ ergs per supernova. Cooling is turned off
for gas particles within the blastwave radius until the end of the momentum-conserving
phase. This model keeps gas hydrodynamically coupled at all times, and has been shown
to form galaxies that match a large range of observed scaling relations (Brooks et al. 2007;

This simulation also has a novel implementation of supermassive black holes (SMBHs)
which includes physically motivated models for SMBH formation. The decay of the SMBH
orbit is realistically modeled (Tremmel et al. 2015) and sub-grid parameters that regulate
feedback from these SMBHs have been calibrated using a comprehensive set of $z = 0$
scaling relations as detailed in (Tremmel et al. 2017). It is not expected that SMBHs play a
substantial role in the evolution of the dwarf galaxies studied here, but this will be examined
in detail in future works.

In this work, we study the satellites of dwarf galaxies. The parent halos are chosen to
have \( m_{\text{vir}} \geq 10^9 \) M$_\odot$ and be within the high-resolution region in the DM+SPH simulations
and the corresponding haloes in the DM-only simulation. This mass is within a factor of a
few of an initial or unstripped mass for the Small Magellanic Cloud as discussed in Bekki &

\[^2m_{\text{vir}} \text{ includes both DM and baryons in DM+SPH simulations}\]
Table 3.2: Properties of luminous satellites at $z = 0$

<table>
<thead>
<tr>
<th>HaloID</th>
<th>Parent HaloID</th>
<th>$m_{\text{vir}}$ (M$_\odot$)</th>
<th>$m_{\text{gas}}$ (M$_\odot$)</th>
<th>$m_{\text{star}}$ (M$_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71</td>
<td>6</td>
<td>$1.39 \times 10^8$</td>
<td>$1.83 \times 10^4$</td>
<td>0</td>
</tr>
<tr>
<td>167</td>
<td>4</td>
<td>$5.24 \times 10^7$</td>
<td>0</td>
<td>$6.27 \times 10^3$</td>
</tr>
<tr>
<td>455</td>
<td>1</td>
<td>$1.43 \times 10^7$</td>
<td>0</td>
<td>$3.89 \times 10^4$</td>
</tr>
</tbody>
</table>

Stanimirović (2009) ($m_{\text{vir}} \sim 6.5 \times 10^9$M$_\odot$). Subhaloes of these haloes are defined as those that are found within $r_{\text{vir}}$ at $z = 0$ down to those containing a minimum DM particle count of 64 particles (a halo mass of $4.3 \times 10^5$M$_\odot$). Our initial selection consists of 10 haloes in the DM+SPH simulation and 9 corresponding ones in the DM-only simulation since two of the DM+SPH haloes end up merging in the DM-only simulation by $z = 0$. Since one of the main goals of this work is to directly compare subhaloes between the DM+SPH and DM-only simulations, it is preferable to only include the ones that exist in similar environments at $z = 0$ and thus the above mentioned two parent subhaloes in the DM+SPH simulation and the corresponding single subhalo in the DM-only simulation, along with all subhaloes within their virial radii, are excluded from the comparison. The final complete sample consists of 8 parent haloes in both the SPH+DM and DM-only simulations and their subhaloes. The properties of these parent subhaloes at $z = 0$ are listed in Table 3.1.

Within this sample of subhaloes around the 8 parent haloes are three that contain baryonic material. These are subhaloes 71, 167 and 455 around parent haloes 6, 3 and 1 respectively. Their properties at $z = 0$ are listed in Table 3.2.

It is important to note that if any subhaloes were destroyed due to baryonic and stripping processes before $z = 0$, they would not be counted as part of our sample. This may affect the interpretation of certain results and is discussed more in 3.4.1.

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Although subhalo 71 is able to retain more than $10^4$M$_\odot$ in gas, most of it is ionized. Only 18 M$_\odot$ is in neutral HI gas, and this subhalo would thus be nearly impossible to detect. We include it here only as an example of a subhalo that is able to retain baryonic material, even if it is undetectable.
3.2.1 Well-matched subhalo sample

In some analysis below, we compare the global properties of the subhalo population in each of the two runs (SPH+DM and DM-only). For certain analyses, we require a direct comparison between the subhalo populations of the DM+SPH and DM-only simulations. In these cases, we do not use the total population of subhaloes within the virial radius at \( z = 0 \) in each simulation, but rather, use a “well-matched” sample. These are around 70% of the total sample of subhaloes within the virial radii of the parent haloes that have a direct and unambiguous counterpart between the SPH+DM and the DM-only simulations.

To find a direct counterpart, we take all the dark matter particles belonging to a subhalo in the DM+SPH simulation and find and rank which subhaloes those particles are in in the DM-only simulation. The highest rank goes to the subhalo in the DM-only simulation containing the most dark matter particles from the subhalo in the DM+SPH simulation. We then apply the same procedure to this highest ranked DM-only subhalo and find its DM+SPH counterpart. If the counterpart from running the procedure from DM-only to DM+SPH match the original DM+SPH subhalo we started with, then it is well-matched.

However, there are more complex situations that commonly arise. Sometimes the highest ranking DM-only subhalo while going from DM+SPH→ DM-only is a parent halo in the DM-only simulation (i.e. most of its dark matter particles are part of the DM-only parent halo at \( z = 0 \)) . This is a common situation where the DM+SPH subhalo has a different merger history in the DM-only simulation. In that case we look at the second highest ranked match in the DM-only simulation. We then re-map that subhalo back to the DM+SPH simulation and if we return to the original DM+SPH subhalo then we consider those two subhaloes to be well-matched as well.

Likewise, sometimes a DM+SPH subhalo maps onto a DM-only subhalo but going from that DM-only subhalo back to the DM+SPH simulation leads to a parent halo. This is another case where the merger histories in the two simulations differ. This might arise when a bigger DM-only subhalo is stripped in the DM+SPH simulation leaving a smaller
subhalo behind. In this case if the second highest ranked match going from DM-only → DM+SPH matches the original DM+SPH subhalo, we consider the two subhaloes to be well-matched.

While there are a myriad of other combinations possible in terms of mapping and remapping, these three are the only ones we consider for our well-matched sample, giving us unambiguous matches and first-order stripping cases. This ensures that any cases where a subhalo is stripped by the parent halo in the sister simulation is still part of the sample as long as there is a reasonable counterpart. Thus, in the well-matched sample a relative majority of the dark matter particles in an DM+SPH halo are found in the counterpart DM-only halo and vice versa.

3.3 Results

In this section we present the properties of our subhalo samples (both global and well-matched) at $z = 0$ and at infall, and we investigate the amount of mass loss that has occurred between infall and $z = 0$. In Section 3.4 we interpret these results.

3.3.1 Current time

We initially compare the differences between halo mass and $v_{max}$ in the subhalo population between the two simulations at $z = 0$. The top left panel of the top half of Fig. 3.1 shows the cumulative mass distribution (for all subhaloes) and the mass at $z = 0$ as a function of infall mass of the subhalo in the DM-only simulation (for well-matched haloes). We frequently use DM-only infall mass as a pseudo-unique identifier for subhaloes when comparing between the two simulations. The left panel shows that the overall cumulative mass distributions closely follow each other with the DM-only simulation having more subhaloes. The bottom left panel is the ratio of the number of subhaloes in the DM-only simulation to the DM+SPH

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4This helps factor out any effects due to other identifier values (e.g., mass at infall in their respective simulations) being different between the SPH and DM-only simulations and avoids the hassle of using unique halo identifier numbers that do not have physical significance.
simulation in bins of $m_{\text{vir}}$.

The right panel of Fig. 3.1 shows that a given DM+SPH subhalo generally has lower mass than its DM-only counterpart at $z = 0$, as might be inferred from the left panels. We find that the DM+SPH halos on average are 89% of the mass of their DM-only counterparts, though there is significant scatter (see Figure 3.6 below as well). Lower halo masses in SPH versions of simulated halos is in line with previous findings (Munshi et al. 2013; Sawala et al. 2013).

The bottom half of Fig. 3.1 similarly has three panels. The top left panel shows the cumulative distribution function of $v_{\text{max}}$ at $z = 0$. The top left panel shows the ratio of the number of subhaloes in the DM-only simulation to the DM+SPH simulation in bins of $v_{\text{max}}$. The bottom left panel ratio stays generally above 1 meaning that for all values of $v_{\text{max}}$ there are more subhaloes in the DM-only run. The right panel shows how $v_{\text{max}}$ varies with infall mass in the DM-only simulation. $v_{\text{max}}$ is also seen to be lower in the DM+SPH simulation. This is important to note since it is possible for a DM+SPH halo to be lower in mass but still have the same $v_{\text{max}}$ if it has a higher concentration. A lower $v_{\text{max}}$, as in this case, proves that the mass is lower as a function of radius between the two runs and not just due to a smaller outer radius for the baryonic runs.

3.3.2 Infall

Similar to Section 3.3.1 we investigate the differences in $m_{\text{vir}}$ and $v_{\text{max}}$ at infall time of the subhaloes. Infall is defined as when the center of the subhalo crosses the virial radius of its parent halo (note that infall time can vary for any pair of well-matched subhalos between the SPH+DM and DM-only runs). In Fig. 3.2 we see that both the masses and $v_{\text{max}}$ values of the subhaloes in the SPH+DM simulation are less than of those in the DM-only simulation at infall.

The high mass end of the cumulative distributions show a discrepancy between the two runs for both $m_{\text{vir}}$ and $v_{\text{max}}$ at infall, unlike at $z = 0$. At $z = 0$, the CDF for $m_{\text{vir}}$ appears
to converge while that of \(v_{\text{max}}\) does not. This implies that before infall, \(m_{\text{vir}}\) and \(v_{\text{max}}\) track each other quite well but stripping affects each of those values differently after infall (similar to results in [Kravtsov et al. 2004]).

The right panels in Fig. 3.2 for both \(m_{\text{vir}}\) and \(v_{\text{max}}\) are similar to the right panels in Fig. 3.1, but the mass discrepancy is slightly larger at infall. We find that, on average, the DM+SPH halos are 75% of the mass of their DM-only counterparts at infall. We investigate the difference in \(v_{\text{max}}\) in more detail in Section 3.4.2 and Figure 3.6.

### 3.3.3 Mass loss after infall

Fig. 3.3 compares the mass loss after infall between subhaloes in the DM+SPH and DM-only simulations. The left panel compares the log difference in mass at infall and \(z = 0\) for subhaloes in the DM+SPH simulation vs those in the DM-only simulation for the well matched subsample. This gives a direct comparison between the mass loss after infall of a given subhalo in both simulations. The diagonal line separates the regions of higher DM-only mass loss (lower right) and higher DM+SPH mass loss (upper left). There is a higher concentration of points below the dividing line (70% of well-matched subhaloes lie under the one-to-one line), implying that generally for a given subhalo, the total amount of mass stripped after infall is greater in the DM-only simulation than in the DM+SPH one. This result is somewhat surprising because earlier studies have shown that the presence of baryons can lead to enhanced tidal stripping of satellites ([Peñarrubia et al. 2010] [Zolotov et al. 2012], [Arraki et al. 2014], [Wetzel et al. 2016], [Garrison-Kimmel et al. 2017]). We investigate the source of the extra stripping in the DM-only halos in the next Section.

### 3.4 Discussion

Above, we showed that the DM+SPH simulations were lower in mass than their DM-only counterparts. However, we found that the discrepancy in mass was greater at infall, i.e., DM-only haloes were even more massive than their DM+SPH counterparts at infall than at
Consistent with this, we showed that the DM-only halos appear to lose more mass after infall. In this section, we discuss the physical processes leading to these trends.

### 3.4.1 Mass loss after infall

The left panel of Fig. 3.3 shows that, on average, subhaloes in the DM-only run suffer a larger fractional mass loss due to stripping compared to their DM+SPH counterparts. This also leads to a larger total stripping since the DM-only subhaloes have a greater mass on average at infall. To investigate why there is higher tidal stripping in the DM-only simulation subhaloes, we first start by formulating a toy model. When a massive object moves through a collisionless system, it experiences a drag force called “dynamical friction.” As particles get accelerated towards the massive object, the subhalo leaves a wake of accelerating particles behind it which causes a higher density of matter to exist there compared to ahead of it, thus slowing it down. This causes the orbits of subhaloes in simulations to decay as time passes. In a static collisionless system where a subhalo exists within the body of the parent halo, there is a certain radius inside the subhalo’s extent where the gravitational force from the parent halo and the centrifugal force balance the gravitational binding force of the subhalo. This is known as the “tidal radius.” A simple model can assume that any mass that is part of the subhalo outside of this radius will eventually be stripped and become part of the parent halo.

An approximation of the tidal radius is derived in [Mo et al. (2010)](Mo2010) where

\[ R_t \sim \frac{1}{\sqrt{2}} \frac{\sigma_{sat}}{\sigma_{halo}} r. \]

\( \sigma_{sat} \) and \( \sigma_{halo} \) are the velocity dispersions within the virial radius of the subhalo and the parent halo respectively (at infall in our case), while \( r \) is the distance of the subhalo from the center of the parent halo. In our model, we use the pericentre distance \( r_{peri} ^5 \), as

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5This is not the true pericentre distance, however, which would require interpolating the subhalo orbits to find the minimum distance. We simply take the minimum distance of a subhalo to the parent halo’s
$r$, assuming that the maximum amount of stripping occurs when the subhalo is closest to the center of the parent halo.

Next we fit an Navarro-Frenk-White (NFW) profile \cite{Navarro1996} to the subhalo at infall using its $m_{\text{vir}}$, $r_{\text{vir}}$ and $r_{v_{\text{max}}}$. Although recent simulations have shown that baryonic processes can transform an NFW dark matter density profile (with a cusp) into one with a core \cite[e.g.,][]{Read2005, Governato2010, Governato2012, Pontzen2012, Teyssier2013, Chan2015}, most of our subhaloes are dark and retain an NFW profile. Our few subhaloes that retain baryons do not have sufficient stellar mass to substantially transform their halos with injected supernova energy \cite{Penarrubia2012, Maxwell2015, Read2016}. Once the NFW profile is fitted we can use the the tidal radius to infer the $m_{\text{vir}}$ at $z = 0$ assuming everything outside the tidal radius gets removed.

The results of this toy model are shown in the right panel of Fig. 3.3. The predicted mass loss lies in the same range as the mass loss seen in the simulation data and also generates a slight bias towards the subhaloes in the DM-only simulation to having a greater mass loss after infall (64% of the subhaloes lie under the one-to-one line). Thus, this toy stripping model seems to explain the simulation results well. We next investigate what factor in the tidal stripping equation is responsible for this result.

Previous studies have shown that simulations with baryonic physics tend to have subhaloes with slightly later infall times ($\sim$0.7 Gyr, \cite{Schewtschenko2011}). Earlier infall times would allow a subhalo to experience more tidal stripping. The left panel of Fig. 3.4 shows that there is a general trend of earlier infall times having a larger mass loss after infall. The right panel of Fig. 3.4 shows the difference between infall times in the DM-only simulation and the DM+SPH simulation for well matched subhaloes as a function of infall time in the DM-only simulation. There is significant scatter, especially for smaller haloes, between the two simulations because there is some degree of randomness in the simulations, centre from the simulation snapshots available to us. The true $r_{\text{peri}}$ may lie between two snapshots.
but on average DM-only infall times are earlier by about 0.6 Gyr, in line with the findings of Schewtschenko & Macciò (2011).

Equation 3.1 has two factors that control the tidal radius: \( r \) (in our case, \( r_{\text{peri}} \)) and the ratio of \( \sigma_{\text{sat}}/\sigma_{\text{halo}} \). Looking at the values from the simulations that go into the toy model, we get more insight into why there is more stripping in subhaloes in the DM-only simulation. Fig. 3.5 shows the difference in the pericentre distance for each well-matched subhalo between the DM-only and DM+SPH simulations as a function of the difference in infall times. On average the subhaloes in the DM-only simulations have a smaller pericentre distance, contributing to the calculation of a smaller tidal radius which leads to more mass stripped, according to Equation 3.1. The ratio of dispersion velocities, \( v_{\text{disp}} \), of a subhalo and its parent at infall is slightly higher for subhaloes in the DM-only simulation (contributing to a larger tidal radius and less mass stripped), but the reduced \( r_{\text{peri}} \) overrides this effect.

It is possible that the pericentre distances are generally smaller in the DM-only simulation due to the earlier infall times of its subhaloes. A subhalo falling in earlier may have a greater chance for its orbit to decay to a smaller radius. It is also possible that there were subhaloes in the DM+SPH run that came close to the parent center and were destroyed (due to enhanced stripping in baryonic systems as mentioned previously). This would have left their close-approaching, but not destroyed, DM-only counterparts behind. The effects of these, however, would not show up in our well-matched sample but might have an effect in the global sample plots. To confirm these requires further investigation.

### 3.4.2 Mass discrepancy at infall

The above discussion demonstrates that, although inclusion of baryons leads to enhanced tidal stripping of satellite galaxies around massive galaxies like the Milky Way (Peñarrubia et al. 2010; Zolotov et al. 2012; Wetzel et al. 2016; Garrison-Kimmel et al. 2017), the same effect is not observed in satellites of simulated dwarf galaxies. The DM+SPH subhaloes at \( z = 0 \) are lower in mass than their DM-only counterparts, but this effect is instead driven by
the fact that the DM+SPH subhaloes are already lower mass at the time of their accretion. Here we discuss the origin of their lower masses.

The majority of DM+SPH subhaloes in Captain Marvel do not contain baryons (but the parent halos do, as seen in Table 3.1). Given the low masses of the subhaloes, they likely lost their baryons through heating from the UV background. Only subhaloes 71, 167, and 455 having any baryonic content at $z = 0$, and only two of those have stars. The two with stars could have lost additional material due to supernova feedback. The lack of baryonic mass alone would cause the infall $v_{\text{max}}$ values of the subhaloes in the DM+SPH simulation to be reduced by a factor of $\sqrt{1 - \text{baryonic fraction}} = \sqrt{1 - 0.174} = 0.909$ compared to their DM-only counterparts. The left panel of Fig. 3.6 shows this ratio vs the $v_{\text{max}}$ at infall in DM-only. The red line shows the predicted ratio due to the lack of baryonic mass while the black line shows the average of the data points. The average lies below the prediction indicating that the subhaloes in the DM+SPH environment have a lower $v_{\text{max}}$ at infall than can be accounted for by just the lack of baryonic mass in them.

The reduced mass is most likely due to preventative feedback. Preventative feedback reducing the total amount of material ever accreted onto the haloes. The presence of baryonic physics introduces various sources of feedback (supernovae and SMBHs, for example), but the dominant heating for most of these halos (since they completely lack baryons) should be heating by the UV background. Christensen et al. (2016) traced the total number of gas particles ever accreted onto halos as a function of galaxy mass, in simulations that use very similar physics to this work. They found that the amount of material accreted to the halo dips below the cosmic baryon fraction for halos smaller than $\sim 2 \times 10^{10} \, M_\odot$, and continues to decline. Their lowest mass halos were $\sim 3 \times 10^{9} \, M_\odot$ in halo mass, which is much larger than many of the subhalos studied here. However, at these low masses only 20% of the cosmic baryon fraction is accreted to the halos, and the trend was still declining. The general effect of this is to slow the growth history of haloes in DM+SPH runs, leading to the greater than

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\footnote{Assuming that baryons are uniformly distributed throughout the halo, which is not necessarily true.}
expected mass discrepancy at infall.

In the left panel of Fig. 3.6, it is interesting to note that while there is a large amount of scatter in the y-axis for the smaller subhaloes, the larger ones very consistently straddle the average and have a very consistent infall $v_{\text{max}}$ ratios of SPH haloes to DM-only halos. The right panel shows the same plot but at $z = 0$ and has significant scatter over all ranges, most likely due to effects of various orbital parameters leading to different amounts of stripping.

3.5 Conclusions

We investigated and compared the properties of subhaloes around 8 dwarf haloes with $2 \times 10^9 < m_{\text{vir}}/M_\odot < 2 \times 10^{10}$ both at $z = 0$ and at infall and between the DM-only and DM+SPH runs. We found that the halo masses are lower in the DM+SPH versions of the haloes, but that this discrepancy is already in place at infall. In fact, the DM-only haloes tend to lose more mass after infall because they have smaller $r_{\text{peri}}$, possibly because they infall to their parent halos earlier than in the DM+SPH run. Despite this mass loss, the DM+SPH haloes maintain lower masses at $z = 0$.

Comparisons of $m_{\text{vir}}$ and $v_{\text{max}}$ distributions indicate that the presence of baryons causes stripping to take place over extended radii through the subhaloes rather than just at the edges. This is in line with previous work that found that dark matter mass is not stripped strictly from the outside in, due to the fact that dark matter particles in the simulations can have highly elliptical orbits, spending more time at apocenter. Thus, as mass is stripped from the outside, the overall effect is to remove mass that contributes across a range of radii (Peñarrubia et al. 2008; Zolotov et al. 2012).

At infall, the mass discrepancy in $v_{\text{max}}$ between the DM-only and DM+SPH subhaloes cannot be explained as purely due to a loss of the baryonic fraction of mass. Instead, it can most likely be attributed to slower growing haloes in the DM+SPH simulation due to preventative feedback effects.

One goal of this work was to ascertain whether any change in halo masses in a DM+SPH
simulation would affect the predictions for the probability of finding satellites around dwarf galaxies. Dooley et al. (2016) used abundance matching to make such predictions for the Solo survey. In abundance matching, a dark matter-only mass function is assumed to correlate one-to-one with an observed luminosity function. Dooley et al. (2016) adopt relations that assign a stellar mass to a given halo mass at the time of infall for satellites in the Caterpillar suite of dark matter-only simulations. Although the baryonic simulations are lower mass at infall, since the abundance matching adopts the DM-only mass the results should be unaffected as long as the “correct” stellar mass is assigned.

However, we have shown that the subhaloes of the dwarf galaxies have a later infall time, of $\sim 0.6$ Gyr. This allows luminous subhaloes to continue to form stars (if they are still forming stars) for an additional period of time, growing the stellar mass of the galaxy. In the dwarfs studied here, though, all of the luminous satellites contain ultra-faint galaxies that stopped forming their stars prior to infall. Hence, the predictions of Dooley et al. (2016) would again remain unaffected in this mass range. However, more massive dwarfs (like the LMC) should contain higher stellar mass satellites, which may be star forming up until infall, and the delayed infall could alter the stellar masses at infall. This remains to be studied further, as we have no LMC mass objects in this sample.

Another goal of this work was to discover if the satellites of dwarf galaxies should have lower velocities than predicted by DM-only simulations. Indeed, the DM+SPH subhaloes do have lower velocities. We predict that, on average, observed satellites of dwarfs will be 90% lower in velocity than predicted by DM-only runs (see Figure 3.6), though the scatter in this result is significant as it depends strongly on the orbital parameters of the satellite around the parent halo.
Figure 3.1: Top half: Top left panel shows the cumulative distribution function (CDF) of the masses of all subhaloes around our sample of dwarf haloes at $z = 0$. Red line indicates DM+SPH simulation while the black line is for the DM-only simulation. Bottom left panel plots ratio of the number of subhaloes in DM-only over the number of subhaloes in DM+SPH in bins of $m_{\text{vir}}$. Right panel shows $z = 0$ masses of the well-matched subsample of subhaloes as a function of their infall masses in the DM-only simulation. These figures demonstrate that the DM+SPH subhaloes are less massive than their DM-only counterparts at $z = 0$. 

Bottom half: Same three panels as in the top but with $v_{\text{max}}$ instead of $m_{\text{vir}}$. Interestingly the high mass end of the $m_{\text{vir}}$ CDF converges between the two runs while the $v_{\text{max}}$ CDF does not. The right panels show distinctly that corresponding subhaloes between the two runs have both higher $m_{\text{vir}}$ and $v_{\text{max}}$ values in the DM-only run at $z = 0$. 

Figure 3.2: **Top half:** Top left panel shows the cumulative distribution function of the masses of all subhaloes around our sample of dwarf haloes at infall. Red line indicates DM+SPH simulation while the black line is for the DM-only simulation. Bottom left panel plots ratio of the number of subhaloes in DM-only over the number of subhaloes in DM+SPH in bins of $m_{\text{vir}}$. Right panel shows infall masses of the well-matched subsample of subhaloes as a function of their infall masses in the DM-only simulation. These figures demonstrate that the DM+SPH subhaloes are less massive than their DM-only counterparts at infall, not just at $z = 0$. **Bottom half:** Same three panels as in the top but with $v_{\text{max}}$ instead of $m_{\text{vir}}$. Both the $v_{\text{max}}$ CDF and $m_{\text{vir}}$ CDF show a separation at the high mass/velocity ends at infall. These figures demonstrate that the DM-only subhaloes already had higher masses than their SPH+DM counterparts at infall.
Figure 3.3: **Left panel:** Difference between log mass at infall and $z = 0$ for DM+SPH subhaloes vs DM-only subhaloes. Diagonal line indicates line of equal mass loss between the two simulations. 70% of the well-matched subhaloes are clustered under the one-to-one diagonal, indicating that subhaloes in the DM-only simulation generally experience higher mass loss than their DM+SPH counterparts. **Right panel:** Same as left panel but with mass loss calculated using the toy model (see Section 3.4.1). The results of the toy model span the same range as data from simulation and 64% of the subhaloes lie under the one-to-one line where DM-only subhaloes have more mass loss, providing a good match with simulation results.
Figure 3.4: Left panel: Plot of subhalo mass loss after infall vs infall time in their respective simulations. Mass loss increases with earlier infall times and DM-only subhaloes show a marginally larger mass loss vs the DM+SPH ones. Solid lines show best fit 3rd order polynomials to clarify trend since a large amount of scatter is present. Right panel: The difference in $t_{infall}$ between corresponding subhaloes in the DM+SPH and DM-only simulations for the well matched subsample as a function of infall time in the DM-only simulation. The average lies in the negative, meaning that subhaloes tend to infall slightly earlier (by 0.6 Gyr on average) in the DM-only simulation. Solid diagonal lines limit the bounds of the physically possible values of the difference.
Figure 3.5: Left panel: Plot of the difference in pericentre distance of a subhalo vs difference in infall time between the DM-only and DM+SPH simulations. Red dot is the average of both axes showing earlier infall times and smaller $r_{peri}$ for subhaloes in the DM-only simulation. Right panel: Ratio of the velocity dispersion of subhaloes to their parent in the DM-only simulation vs those in the DM+SPH simulation. Even though this factor works opposite to the increased mass loss seen in DM-only subhaloes, the smaller $r_{peri}$ values dominate.
Figure 3.6: *Left panel:* The ratio of $v_{\text{max}}$ of DM+SPH subhaloes to the $v_{\text{max}}$ of their DM-only counterparts for the well-matched sample at infall plotted against the mass at infall in the DM-only simulation. Red line shows the $\sqrt{1 - \text{baryonic fraction}}$ to indicate where points would lie if the mass difference at infall was only due to the lack of the excess baryonic mass in the DM+SPH simulation. Black line shows the mean y-value of the points. Apart from a large scatter for smaller subhaloes, the points generally tend to lie under the red line indicating that the presence of baryons cause mass loss and reduction in mass accreted overall through preventative feedback effects even before stripping begins (Christensen et al. 2016). *Right panel:* Same as right panel but y-axis is now the ratio at $z = 0$. Red and black lines are also the same as before. By $z = 0$, differing merger histories of subhaloes result in a large scatter seen at all mass ranges. This indicates that the kinematics of counterpart subhaloes are very different between DM-only and DM+SPH simulations leading to different amounts of stripping.
Chapter 4
Conclusions

4.1 Planes of Satellites

In Chapter 2, we investigated whether the inclusion of baryonic physics influences the formation of thin, coherently rotating planes of satellites such as those seen around the Milky Way and Andromeda. We searched for planes of satellites around four different Milky Way-mass simulations, each run both as dark matter-only and with baryons included. In all haloes (both dark matter-only and baryonic), we were able to identify a planar configuration that significantly maximizes the number of satellites that are members of a plane. We found that the member satellites that make up this maximum plane are consistently different between the dark matter-only and baryonic versions of the same run. In the baryonic runs, satellites are more likely to be destroyed through interactions with the disc, and substructure tends to infall later. Hence, studying satellite planes in dark matter-only simulations is misleading, because they will be composed of different satellite members than those that would exist if baryons were included. Additionally, we found that the destruction of satellites in the baryonic runs leads to less radially concentrated satellite distributions, a result that is critical to making planes that are statistically significant compared to a random distribution. Since all planes pass through the centre of the galaxy, it is much harder to create a plane containing a large number of satellites from a random distribution if the satellites have a low radial concentration. We identified Andromeda’s low radial satellite concentration as a key reason why the plane in Andromeda is highly significant. Despite this, when co-rotation is considered, none of the satellite planes identified for the simulated
galaxies are as statistically significant as the observed planes around the Milky Way and Andromeda, even in the baryonic runs. We also found that co-rotation in both types of runs can be attributed to the accretion of satellites along a maximum of two sets of filaments from the cosmic web. When more than two sets of filaments contribute, or if there are no well-defined filaments, there is a lack of coherent rotation in the satellite plane at $z = 0$. In summary, although baryons clearly do influence the formation of satellite planes and their statistical significance, we do not reproduce the high significance of the observed planes of satellites, thus leaving the current planar structure around the Milky Way still an anomaly.

4.2 Satellites of Dwarfs

In Chapter 3 we looked at the population of subhaloes around 8 dwarf galaxies to investigate how their masses and velocities differ at infall and at $z = 0$ between dark matter-only and baryonic simulations. We also investigated mass loss after infall in these subhaloes. We discovered that subhaloes in the baryonic runs tend to have smaller masses and velocity dispersions both at infall and at current time compared to their dark matter-only counterparts. We also saw evidence of stripping occurring throughout subhaloes in the baryonic runs rather than just at the edges. Unexpectedly, the subhaloes in the dark matter only runs had higher mass losses after infall compared to their baryonic counterparts. Further exploration using a toy model replicated the results from the simulations very well, and shed light on the fact that the dark matter-only subhalos lost more mass because they have a closer pericentre distance than the baryonic subhaloes. It may well be possible that the pericentre distances are smaller in the dark matter-only simulation due to those subhaloes having earlier infall times but this cannot be conclusively proven without more detailed investigations.
4.3 Summary

Baryons, while only making up $\sim 5\%$ of the Universe clearly have a significant effect, especially on smaller scales, as illustrated by the cases investigated in this work. Simulations show us that the presence of baryons can completely change merger histories, enhance stripping and even cause certain counterintuitive results to emerge. While baryons are not the only solution to all the problems that still exist within the $\Lambda$CDM paradigm, they have enough of an effect that they cannot be ignored in N-body simulations.
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.1 Appendix: Details of Satellite Selection Criteria

In addition to the methods mentioned in Section 2.2.1, we tested various selection criteria for choosing luminous satellites in both our DM-only and DM+SPH simulations.

For the DM-only simulations, we alternatively tried selecting the 30 most massive subhaloes at $z = 0$ instead of the 30 most massive at infall. Roughly 80 per cent of the most massive subhaloes at $z = 0$ are also in the sample selected by 30 most massive at infall. We also investigated the effect that using as few as 25 subhaloes and as many as 40 subhaloes had on our results. While changing the total number selected does change $N_{sats}$ and
$N_{\text{max}}$ proportionally, in all cases the alternative selections have no significant effect on our $p$-values nor the conclusions drawn about filamentary accretion.

Alternatively, we tested selecting subhaloes with a $v_{\text{max}}$ (maximum value of the rotation curves) at $z = 0 > 15.0$ km s$^{-1}$ in the dark matter-only runs, and identified the surviving counterparts in the baryonic run. This selection is identical to that used in Zolotov et al. (2012) and Brooks & Zolotov (2014), which yielded a satellite sample that produced realistic luminosity functions and velocity dispersions. However, this method was designed originally to capture primarily classically bright dwarf spheroidals ($M_V$ brighter than $-8$ mag). It led to too few luminous dwarfs compared to the number observed around the Milky Way and M31. Again, we note that even in the case of requiring the dark matter-only and baryonic satellites to be counterparts of each other, the resulting planes are different due to the different infall times and orbital evolution in the two runs.

In the baryonic runs, we are able to select luminous satellites directly. However, as the number of star particles decreases, the star formation history in any individual galaxy is less likely to be converged. Subhaloes with more than 5 star particles are more likely to have converged star formation histories. However, selecting satellites with more than 5 star particles decreased the number of luminous satellites by up to 10 in most of the galaxies, making the numbers far fewer than observed in the Milky Way or M31. We settled on a minimum of 4 star particles (corresponding to a lower stellar mass cutoff of $M_{\text{star}} > 2 \times 10^4$ M$_{\odot}$) as a compromise that yielded a reasonable number of luminous satellites. Decreasing to 3 or more star particles resulted in adding anywhere between 8-20 more subhaloes, yielding more satellites than we needed and resulting in a questionable convergence of the star formation history in the least luminous satellites.