Technische Universität München
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A comparison of the distribution of satellite galaxies around Andromeda and the results of ΛCDM simulations

Ein Vergleich der Verteilung von Satellitengalaxien um Andromeda und den Resultaten von ΛCDM-Simulationen

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Chapter 1

Introduction

The nature of dark matter is one of the major problems in modern physics. Whereas there is observational evidence for it (e.g. galaxy rotation curves, galaxy clusters, gravitational lensing or the cosmic microwave background), it is still unclear of which particles dark matter is composed.

The current 'standard model' of cosmology is the ΛCDM-model. It assumes that cold dark matter (CDM) is the dominating form of matter (see Fig. 1.1). Besides the assumption that dark matter consists of nonrelativistic particles, the nature of dark matter is not specified. Nevertheless studying the implications of the model is a promising approach to constraint the nature of dark matter.

To test the ΛCDM-model large cosmological simulations considering only gravitationally interacting collisionless dark matter are run. The Millennium simulations are among the largest ΛCDM simulations (Springel et al., 2005; Boylan-Kolchin et al., 2009; Guo et al., 2013). They have shown that the ΛCDM-model is broadly consistent with the observations especially on large scales. But there remain some unsolved mismatches between observation and simulation.

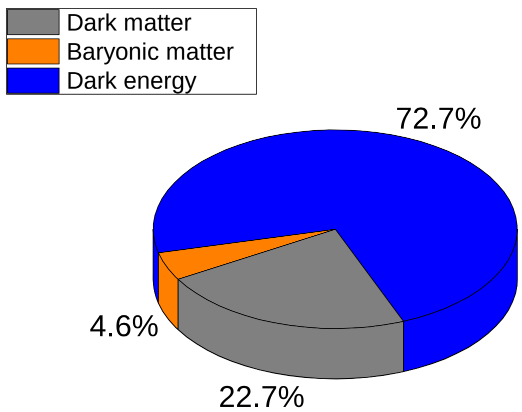

Figure 1.1: Today's mass-energy distribution of the universe (according to Jarosik et al. 2011).

Most of them are related to dwarf galaxies and thereby to dark matter. Dwarf galaxies have a significantly lower number of stars ($\sim 10^{10}$ stars) as 'big' galaxies like the Milky Way or the Andromeda galaxy ($\sim 10^{11}$ stars) and are dominated by dark matter (large mass-to-light ratios). They often orbit around big host galaxies (like the Milky Way or Andromeda) and are therefore often referred as satellite galaxies. Galaxies are supposed to form in dark matter halos, an accumulation of dark matter (Mo et al., 2010, chap. 2). Due to gravitational attraction gas falls into the halo. When the baryon density is high enough, the formation of stars starts. The same is supposed for the formation of satellite galaxies. Since they are located in the halo of their host galaxy (host halo), their own halo is named as subhalo.

One major problem in the context of dwarf galaxies is the so-called 'missing satellite problem' (Bullock, 2010). It refers to the fact that the simulations predict too high numbers of subhalos and thereby to high numbers of satellite galaxies around big host galaxies like the Milky Way. The number of observed satellite galaxies around the Milky Way and the Andromeda galaxy is significantly lower than the predicted number. This might be due to incomplete observations, the non consideration of baryonic processes or a lag of understanding of the formation of galaxies.

An other discrepancy referring to dwarf galaxies and their dark matter halo is the so-called cuspy halo problem (de Blok, 2010). Observations indicate that the density of dark matter in dwarf galaxies is nearly constant in the center of a dwarf galaxy's halo. In contrast ΛCDM simulations predict cusped density profiles ($\rho(r) \sim r^{-1}$). A subtle interplay between baryons and dark matter which is not considered in the simulation might eliminate the cusps.

This thesis focus on a third problem: The existence of planar structures in the distribution of satellite galaxies orbiting big host galaxies. Due to observational constraints we only have detailed knowledge about the distribution of satellite galaxies around the Milky Way and the Andromeda galaxy and both of them are known to be anisotropic.

The origin of these anisotropies has not been explained within the framework of the ΛCDM-model yet and it is unclear, if this is possible. The large-scale ΛCDM simulations are an ideal testing ground for the ΛCDM-model. Therefore a search for planar structures similar to the observed ones in the simulation data is a good check to see, if the formation of such structures can be explained within the ΛCDM-model or if not. This thesis deals only with the satellite distribution around the Andromeda galaxy.

In the course of the work on this project, the following publication emerged.

Chapter 2

Publication

2.1 Abstract

Ibata et al. (2013) recently reported the existence of a vast thin plane of dwarf galaxies (VTPD) orbiting around Andromeda and demonstrated that such a plane is very unlikely to be found if the underlying dwarf galaxy distribution around Andromeda is spherically symmetric. In the present paper we investigate whether such a configuration can be reproduced within the standard cosmological framework. To this end, we search for similar thin planes of co-rotating satellite galaxies around Andromeda-like host haloes in the Millennium II simulation scaled to WMAP7 parameters combined with a semi-analytic model of galaxy formation (Guo et al., 2013). To avoid the missing satellite problem and to reproduce the effect of observational selection criteria, we use a baryonic mass cut off of $1.4 \times 10^4 \mathrm{M}_{\odot}$, a spatial distance cut and a reduction of the data to a PAndAS like field. We find that thin planes are common in Millennium II haloes, about ~ 20 per cent of all haloes with the same total number of satellite galaxies within a PAndAS like field have thin planes of 15 satellites with a lower rms than found by Ibata et al. (2013) for Andromeda. A significant fraction of these haloes also has an equal or higher number of co-rotating satellites compared to what is seen in Andromeda, showing that Andromeda-sized DM haloes are rotating. The radial distributions of satellite galaxies are also in statistical agreement to the dwarf galaxy distribution seen around Andromeda. By excluding dwarf galaxies with a mass weighted age of less than 10 Gyr, the fraction of Millennium II haloes featuring thin planar structures rises to more than 43 per cent. We therefore conclude that the existence of the VTPD around Andromeda is not in conflict with the standard cosmological paradigm. An analysis of the formation history and further evolution of planar structures in the Millennium II simulation shows that the VTPD around Andromeda is most likely only a statistical fluctuation of an underlying more spherical galaxy distribution.

2.2 Introduction

The distribution of the classical satellite galaxies around the Milky Way is highly anisotropic with most of them being located in a thin plane roughly perpendicular to the disc of the Milky Way (Kroupa et al., 2005). Metz & Kroupa (2008) found that the clustering of the orbital poles indicates a rotationally support of the disc formed by satellite galaxies. Libeskind et al. (2005), Zentner et al. (2005), Libeskind et al. (2009), Lovell et al. (2011) and Wang et al. (2013) used large-scale cosmological N-body simulations and tried to find similar anisotropic distributions of satellite galaxies. Libeskind et al. (2005) noted that in all six of their simulations of dark matter haloes the 11 brightest satellites are distributed along thin, disc-like structures and that this distribution reflects the preferential infall of satellites along the spines of a few filaments of the cosmic web. Zentner et al. (2005) found that if selecting the subhaloes expected to be luminous, the distribution of the subhaloes around the three simulated Milky Way-sized dark matter haloes is consistent with the observed Milky Way satellites due to the preferential accretion of satellites along filaments and the evolution of satellite orbits within prolate, triaxial potentials. Libeskind et al. (2009) simulated 436 haloes and found that the angular momenta of at least three of the eleven brightest satellites point approximately towards the short axis of the satellite distribution in a significant fraction of the haloes. This result is supported by Lovell et al. (2011), who found that quasi-planar distributions of coherently rotating satellites, such as those inferred in the Milky Way and other galaxies, arise naturally in simulations of a ΛCDM universe. Wang et al. (2013) examined 1686 Milky Way-like haloes found in the Millennium II simulation (Boylan-Kolchin et al., 2009) and six haloes simulated by the Aquarius project (Springel et al., 2008). They noted that 5-10 per cent of the satellite distributions are as flat as the Milky Way's and that this can be best understood as the consequence of preferential accretion along filaments of the cosmic web and the accretion of a single rich group of satellites. Nevertheless Pawlowski et al. (2012) argued that CDM simulations do not reproduce the clustering of the orbital poles of the Milky Way satellites.

The distribution of satellite galaxies around Andromeda is also known to be anisotropic (Koch & Grebel, 2006; McConnachie & Irwin, 2006). Ibata et al. (2013) and Conn et al. (2013) recently noted the existence of a vast thin plane of dwarf galaxies (VTPD) orbiting around the Andromeda galaxy. They analysed 27 satellites examined by the Pan-Andromeda Archaeological Survey (PAndAS, McConnachie et al. 2009) and found that 15 out of the 27 satellites are located in a thin plane with root mean square thickness of 12.6 ± 0.6 kpc. In addition, 13 of these 15 satellites are supposed to share the same sense of rotation around Andromeda (Ibata et al., 2013). Ibata et al. (2013) found that the existence of this thin plane is highly significant. By assigning a random angular orientation inside the PAndAS area to each satellite galaxy, Ibata et al. (2013) found that in 0.13 per cent of all cases a plane as thin as the original plane is found. Ibata et al. (2013) discussed accretion of satellite galaxies and the in-situ formation as two scenarios to create such a thin plane. They argue that both do not seem to be able to explain the existence of a thin plane.

A possible clustering of the orbital poles of Andromeda's satellites can not be examined since the proper motions of the Andromeda satellites are not yet known. Nevertheless the large number of co-rotating satellites located in a thin plane is a remarkable similarity between the Andromeda galaxy and the Milky Way and might point to a similar formation history (Hammer et al., 2013). This idea is backed by the observations of Ibata et al. (2013) that the identified plane is approximately aligned with the pole of the Milky Way's disk and is co-planar to the position vector between the Milky Way and Andromeda. On the other hand it is of course possible that Andromeda and the Milky Way formed independently and that the alignment is just random. Hence the question remains, whether standard galaxy formation models within the current cosmological framework are sufficient to understand the formation of the Andromeda and Milky Way satellite distributions.

We try to answer this question here for Andromeda. Our approach is to search for similar structures in the Millennium II simulation (Boylan-Kolchin et al., 2009), and to examine their formation and evolution. Guo et al. (2013) scaled the Millennium II data to match the cosmological parameters derived by WMAP7 (Jarosik et al., 2011) and ran a semi-analytic galaxy formation model using the formalism of Guo et al. (2011) over the re-scaled data. The main difference between the approaches by Libeskind et al. (2005) and Zentner et al. (2005) and the approach used here is the number of examined host haloes. The Millennium II simulation provides a large sample of Andromeda like host haloes. This high number makes it possible to quantify the commonness of such structures more effectively. In addition we investigate the formation history of some haloes featuring a thin plane. Due to the rescaling the scaled Millennium II simulations does not stop at present time. Therefore we are also able to examine the further evolution of thin planes. The approach presented here can be used to test whether galaxy formation within the ΛCDM paradigm is sufficient to explain the formation of such structures. Our paper is organised as follows: In section 2 we discuss our method for selecting Andromeda like satallite distributions from the Millenium II simulation. In section 3, we present the results that we obtained using this method. We end with a conclusion and discussion of the results in section 4.

2.3 Methods

The scaled version of the Millennium II simulation was created by Guo et al. (2013) using the algorithm of Angulo & White (2010). This algorithm involves first a re-assignment of length, mass and velocity units, followed by a relabelling of the time axis and finally a rescaling of the amplitudes of individual large-scale fluctuation modes. The re-scaled simulation has a box size of 104.3 Mpc/h containing 2160^3 particles with masses of $8.5024 \times 10^6 M_\odot$/h. It uses the following cosmological parameters: matter density $\Omega_m = 0.272$, baryon density $\Omega_b = 0.045$, dark energy density $\Omega_\Lambda = 0.728$, Hubble parameter h = 0.704, scalar spectral index $n_s = 0.961$ and fluctuation amplitude at 8 h^{-1}Mpc $\sigma_8 = 0.807$. We use the data derived by a semi-analytic galaxy formation model run on the scaled Millennium II data here. Guo et al. (2013) used the semi-analytic galaxy formation model developed by Guo et al. (2011) which considers the influence of gas infall (both cold and hot, primordial and recycled), shock heating, cooling, star formation, stellar evolution, supernova feedback, black hole growth, AGN feedback, metal enrichment, mergers and tidal and ram-pressure stripping.

Due to the relatively large dark matter particle mass in Millennium II, satellite halos fall below the resolution limit of 20 particles if their mass drops below $2\times10^8 M_\odot$ (Boylan-Kolchin et al., 2009). In this case, Guo et al. (2011) assume that galaxies are still bound and determine the position of each galaxy by tracking the most bound particle before the disruption of the subhalo. The accuracy of this model can be questioned, in particular it is uncertain if these 'orphan galaxies' are still bound or are tidally disrupted. The positions and velocities of the orphan galaxies might also not be accurate. Simulations with higher resolution are necessary to solve this problem as indicated by Guo et al. (2011), In the following, we assume that these 'orphan galaxies' still exist and take them into account in our analysis.

In a first step, we query possible host haloes from the Millennium II database. The observed virial mass of Andromeda is $\sim 1.4\times10^{12} M_\odot$ (Watkins et al., 2010), therefore we select all haloes from Millennium II with a virial mass between $1.1 \times 10^{12} M_\odot$ and $1.7 \times 10^{12} M_\odot$. We exclude haloes whose mass weighted age according to the semi-analytic calculations of Guo et al. (2013) is higher than 10 Gyr, since the average stellar age of stars in the disc of Andromeda is supposed to be less than 10 Gyr (Brown et al., 2006). We reject any host halo which has a satellite galaxy with a baryonic mass higher than $7 \times 10^{10} M_\odot$ within a spatial distance of 500 kpc, because such galaxies are not found near Andromeda and might disturb the distribution of dwarf galaxies around the host halo. 1825 haloes fulfil these requirements and are regarded as host haloes.

The resolution of the Millennium II simulation is high enough to resolve sub-haloes down to masses of $\sim 2 \times 10^8 M_\odot$ (Boylan-Kolchin et al., 2009) and thereby dwarf galaxies. We retrieve all relevant parameters (virial and baryonic masses, positions, velocities) of dwarf galaxies around each host halo. These dwarf galaxies are used to search for planes of satellite galaxies.

Faint dwarf galaxies are hard to detect. Dwarf galaxies in the PAndAS field have baryonic masses down to about $3 \times 10^4 M_\odot$ (McConnachie, 2012). To take care of this mass limit in our analysis we remove all dwarf galaxies with a baryonic mass less than $1.4 \times 10^4 M_\odot$ from the data.

Ibata et al. (2013) only considered satellites between 60 to 500 kpc from the Andromeda galaxy. Hence we select only satellites with a distance lower than 500 kpc and higher than 60 kpc to the corresponding host halo. They also examined only satellites within the PAndAS area (McConnachie et al., 2009). Due to the luminous disk of Andromeda they discarded satellites within a projected distance of 32 kpc as well. We approximate the PAndAS area as a sphere with a radius of 250 kpc. Since there is no particular line of sight from which satellite galaxies are seen in the Millennium II simulation, we choose one randomly. We assign an approximated PAndAS area to each line of sight and exclude all satellites outside this area. We also discard all satellites within a projected distance of 32 kpc to take obscuration due to a luminous disk into account. For haloes where too many satellites are excluded, we choose a new line of sight three times until a sufficient number of satellite galaxies is found. If after three tries we still cannot find enough satellite galaxies, we discard the whole halo.

We end up with a list of satellite galaxies with baryonic masses greater than $1.4 \times 10^4 M_\odot$ which are located in a PAndAS like area for each host halo having an average virial mass of $10^{12} M_\odot$. We find that haloes in the Millennium II simulation have on average 97 subhaloes fulfilling the requirements described above in a PAndAS like field. In order to perform a comparable analysis to that of Ibata et al. (2013), we select the 27 satellites with the highest baryonic mass to end up with the same absolute number of satellites as Ibata et al. (2013).

Ibata et al. (2013) searched for the plane which gives the lowest root mean square distance r_{per} of the satellite galaxies perpendicular to the plane. For the calculation of r_{per} they only considered those 15 satellite galaxies which are closest to the plane. They mentioned that the number 15 was chosen only because the plane thickness increases significantly if a larger number of satellites is chosen.

When measuring the plane thickness, Ibata et al. (2013) took distance errors to individual galaxies into account. They calculated a r_{per} value of 12.6 ± 0.6 kpc for the Andromeda satellite distribution and we adopt this value as the value of r_{per} for Andromeda in this paper. We also use the 15 nearest satellites for the calculation of the best fitting plane for the Millennium II haloes to ensure comparability.

We characterize the satellite distribution around each halo by two different numbers. First, we calculate the root mean square distance r_{per} of the satellites to the best fitting plane using the method of Ibata et al. (2013) descriped above. Second, we calculate the root mean square distance r_{par} of the satellites projected in the plane to the center of the host halo. For the calculation of both r_{per} and r_{par}, we use only the 15 satellites which are closest to the best fitting plane. It is important to compare the radial concentration of the satellite distributions of the Millennium II haloes and the satellite distribution around Andromeda since it is of course more likely to find planes with low values of r_{per} in more radially concentrated galaxy distributions. We use r_{par} to measure the radial concentration. The r_{par} value of the Andromeda satellite distribution turns out to be 167.5 kpc.

We examine furthermore the sense of rotation of the satellites belonging to the best fitting plane. We calculate the sense of rotation of each satellite galaxy relative to the best fitting plane and determine the number of co-rotating and counter-rotating galaxies. The number of co-rotating galaxies is then given by the maximum of the two numbers.

All the methods described before only use data from the snapshot closest to the present age of the universe. To learn about the formation of thin planes, we consider all haloes with an r_{per} value lower than 14 kpc and with 13 or more co-rotating satellites. We trace back the 15 satellites closest to the corresponding best fitting plane of these haloes to $z \sim 0.5$ corresponding to a time $\sim$ 5.2 Gyr before present time ($T - T_H \sim -5.2$ Gyr) by querying their first progenitors and calculating the value of r_{per} at every snapshot. The first progenitor is the most massive progenitor of the satellite in the majority of cases. We refer the readers to De Lucia & Blaizot (2007) for a detailed description of the algorithm choosing the first progenitor. If a first progenitor does not exist for a satellite, we reduce the number of satellites considered in the calculation of r_{per} to the remaining number of satellites. A reduction of the number of considered satellites alleviates finding a good fitting plane to the remaining ones. In consequence lower r_{per} values are more likely.

In addition, we follow the further evolution of the 15 satellites by pursuing their descendants until $z \sim -0.29$ and calculating the value of r_{per} at every snapshot. This is possible because the scaled version of the Millennium II simulation does not stop at $z = 0$ but at $z \sim -0.29$ corresponding to $T - T_H \sim 5.0$ Gyr. Due to mergers and the fact that not all haloes can be resolved in all snapshots, the number of satellites can also decrease if following the further evolution. In this case we reduce the number of satellites considered in the calculation of r_{per} to the remaining number of satellites as in the case of the first progenitors.

2.4 Results

The main result of our analysis is that vast thin planes are common in the Millennium II simulation. In total 1120 haloes remain after imposing the various selection criteria. Of these 1120 haloes, 20 per cent have an r_{per} value equal to or smaller than the r_{per} value of Andromeda. 4 per cent of all haloes also have an r_{per} value equal to or smaller than the r_{per} value of Andromeda and a number of co-rotating satellites equal to or higher than the number of co-rotating satellites for the VTPD (see Fig. 2.1). These values are in stark contrast to a spherical distribution (inside

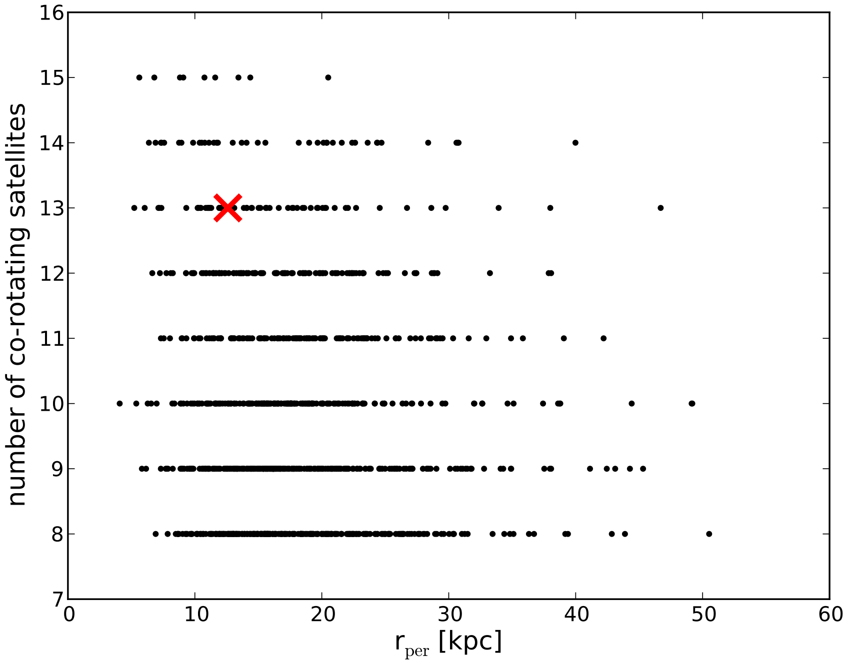

Figure 2.1: The root mean square distance r_{per} of the satellites to the best fitting plane plotted against the number of co-rotating satellites. The black dots show individual haloes and their satellite systems from the Millennium II simulation, the red cross marks the position of the satellite system of Andromeda. 20 per cent of the Millennium II haloes have an r_{per} value equal to or smaller than the r_{per} of Andromeda.

the PAndAS area), for which Ibata et al. (2013) found that only 0.13 per cent of all distributions have a smaller r_{per} value than Andromeda.

A valid objection to the good fit obtained in Fig. 2.1 could be that the Millennium II haloes are biased by a more radially concentrated distribution. In order to test if this is the case, we plot in Fig. 2.2 the distribution of the root mean square distance perpendicular to the best-fitting plane (r_{per}) vs. the root mean square distance to the host halo in the best fitting plane (r_{par}). Fig. 2.2 shows that if at all, this is the case for only a part of the haloes since 82 per cent of all Millennium II haloes have a larger r_{par} than Andromeda. In addition, 13 per cent of the haloes have a smaller r_{per} and a higher r_{par} than Andromeda. Fig. 2.2 shows also that there is a lower limit for r_{par} for any given r_{per}. Haloes with a low r_{par} value have more likely also a small r_{per}

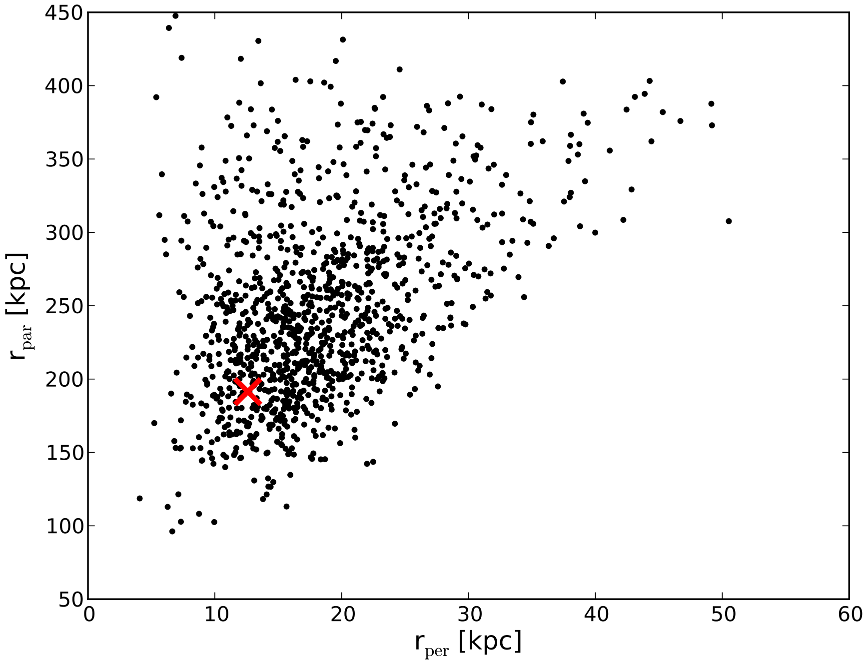

Figure 2.2: The root mean square distance $r_{\rm per}$ of the satellites to the best fitting plane plotted against the root mean square distance of the satellites projected in the best fitting plane to the center of the host halo ($r_{\rm par}$). The black dots show individual haloes and their satellite systems from the Millennium II simulation, the red cross marks the position of the satellite system of Andromeda. 13 per cent of the Millennium II haloes have a smaller $r_{\rm per}$ and a higher $r_{\rm par}$ than Andromeda.

value, because finding a thin plane is more likely if the distribution is more radially concentrated. The good agreement of the Millennium II haloes with Andromeda's satellite system is confirmed by Fig. 2.3, which shows that the radial distribution of satellites in haloes with an $r_{\rm per}$ value between 11 kpc and 15 kpc is similar to the one of Andromeda (a K-S test yields on average a probability of ~ 24 per cent that a profile from Millennium II and the profile of Andromeda's satellite distribution are drawn from the same distribution). The distributions match especially well at small distances (below 150 kpc) and at large distances (beyond 300 kpc) likely due to the distance cuts. For intermediate distances, a slight discrepancy between the radial distribution of Millennium II satellites and the Andromeda satellites is recognizable since the Millennium II haloes tend to be further away from the center of their host

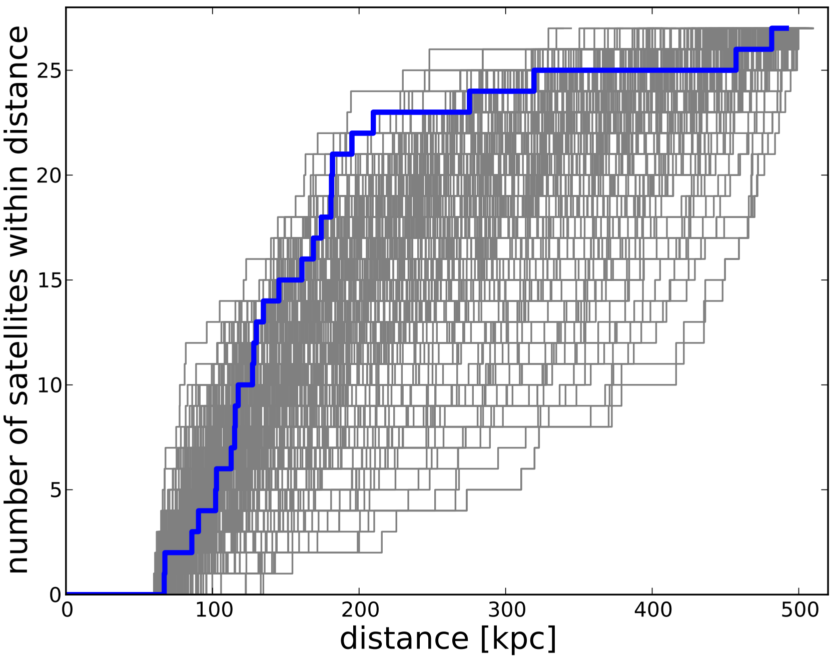

Figure 2.3: Cumulative plot of the number satellites within a certain distance from the center of the host halo. The grey thin lines mark the profiles for Millennium II haloes with an r_{per} value between 11 kpc and 15 kpc. The blue thick line is the profile of the satellite distribution around Andromeda.

halo than the Andromeda satellites. Nevertheless we conclude that the distribution of satellite galaxies in the Millennium II simulation is consistent with the distribution seen around Andromeda.

Since it is known that re-ionization suppresses star formation (Wyithe & Loeb, 2006) and since this might not be fully considered in the semi-analytic model of Guo et al. (2011), we use an additional age cut to see how the formation time of galaxies affects the final results. In order to do this, we remove all satellite galaxies with a mean stellar age less than 10 Gyr from the data set before applying the other selection criteria. In this case Andromeda like haloes are even more numerous. 1187 haloes remain after imposing the selection criteria described above. In 43 per cent of these haloes the root mean square distance perpendicular to the best fitting plane (r_{per}) calculated by again considering only the best-fitting 15 satellites out of a total sample of 27 is smaller than 12.6 kpc. 9 per cent of all haloes have an r_{per} value equal to or smaller than the r_{per} value of Andromeda and a number of co-rotating satellites equal to or higher than the number of co-rotating satellites for the VTPD (see Fig. 2.4). 66 per cent of the haloes have a higher r_{par} value than Andromeda and 19 per cent of the haloes a smaller r_{par} and a higher r_{per} than Andromeda (see Fig. 2.5). Fig. 2.6 shows that the radial distributions of the haloes with an r_{per} value between 11 kpc and 15 kpc match the radial distribution of Andromeda (a K-S test yields on average a probability of $\sim$ 26 per cent that a profile from Millennium II and the profile of Andromeda's satellite distribution are drawn from the same distribution). A slight discrepancy is again recognizable between 150 kpc and 300 kpc. The satellites in the Millennium II haloes tend to be further away from the center of their host halo than the Andromeda satellites in this distance range, similar to the case without the age cut.

We finally examine whether the Millennium II haloes tend to have a larger number of co-rotating satellites compared to a distribution of galaxies with a random orbital orientation. Figure 2.7 shows the fraction of haloes as a function of the number of co-rotating satellites for the Millennium II haloes - with and without a lower age cut of 10 Gyr for the satellite galaxies - and for a distribution with random orbital orientations. The Millennium II haloes (9.9 co-rotating satellites on average for the distribution without the age cut and 10.3 co-rotating satellites on average for the distribution with the age cut) have a significantly higher number of co-rotating satellites on average than expected for a halo of satellite galaxies with random orbital orientations (9.1 co-rotating satellites on average), showing that in Millennium II, dark matter halos with a mass similar to the virial mass of Andromeda are mildly rotating. The difference between the haloes with and without the age cut is also statistically significant.

In order to understand if the satellite planes found in the Millennium II simulation are real structures, made up of satellite galaxies with tightly aligned orbital planes, we investigate the formation and further evolution of these planes. Fig. 2.8 depicts the formation and further evolution of thin planes ($r_{per} < 14$ kpc) with 13 or more co-rotating satellites from $z \sim 0.5$ (5.2 Gyr before the present time) up to the end of the simulations at $z \sim -0.3$ (corresponding to $T - T_H = 5.0$ Gyr). The root mean square distance r_{per} of the satellites to the best fitting plane decreases slightly from an average value of $r_{per} \sim 80$ kpc to $r_{per} \sim 30$ kpc from $T - T_H \sim -5.0$ Gyr to $T - T_H \sim -0.5$ Gyr. From $T - T_H \sim -0.5$ Gyr to 0 Gyr, r_{per} drops rapidly from on average ~ 30 kpc to values below 14 kpc before increasing again to average values of ~ 30 kpc in ~ 0.5 Gyrs. From ~ 0.5 Gyr to ~ 5 Gyr the average r_{per} values are roughly constant. Individual values fluctuate heavily. Despite the heavy fluctuations, the r_{per} values are nearly always significantly higher than at $z = 0$ when the satellite galaxies belonging to the planes were selected. Consequently, the satellite galaxies can not be tightly aligned in an orbital plane. The timescale over which the average r_{per} values are small (about 1 Gyr), agrees roughly with the orbital

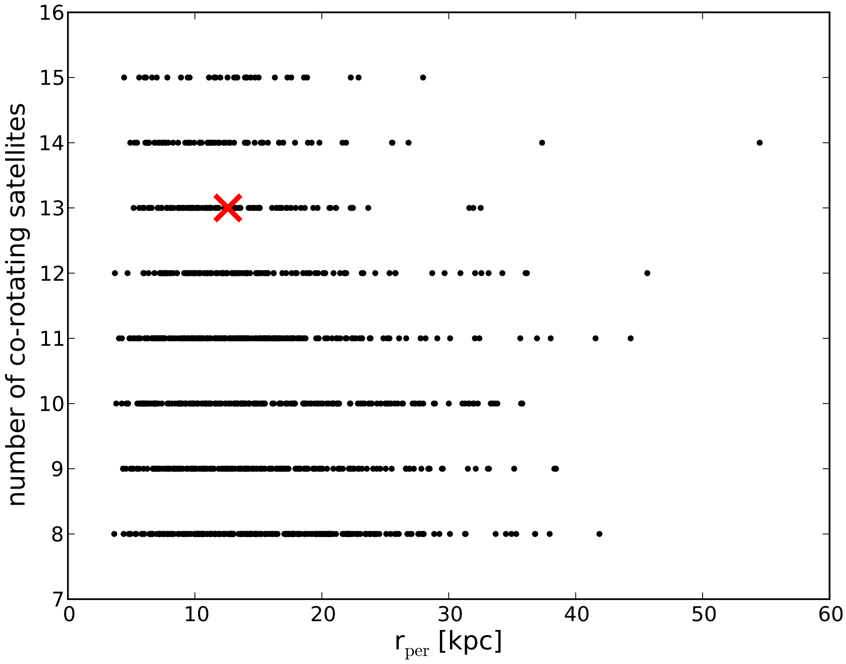

Figure 2.4: Same as Fig. 2.1 but only selecting satellite haloes whose mass averaged age is larger than 10 Gyr. 43 per cent of the Millennium II haloes have an r_{per} value equal to or smaller than the r_{per} value of Andromeda.

time of the satellites around their host haloes. We therefore conclude that the thin planes which we have identified in the Millennium II simulations are most likely statistical fluctuations of an underlying more spherical galaxy distribution.

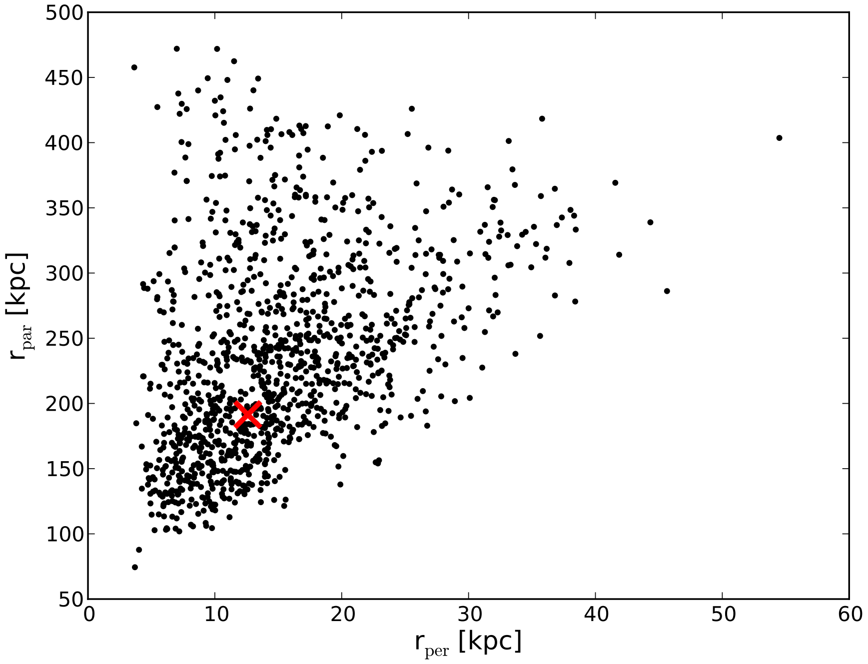

Figure 2.5: Same as Fig. 2.2 but only selecting satellite haloes whose mass averaged age is larger than 10 Gyr. 19 per cent of the Millennium II haloes have a smaller r_{per} and a higher r_{par} than Andromeda.

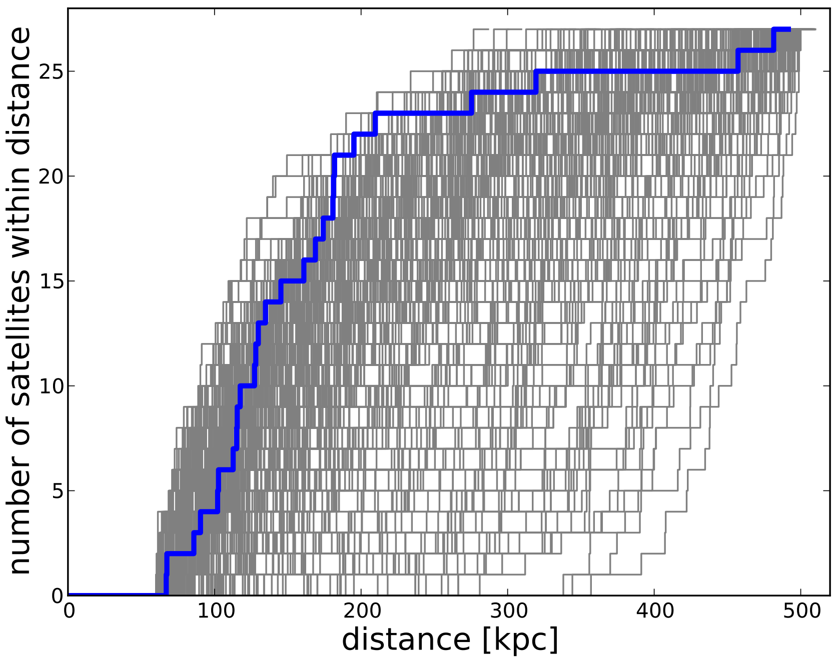

Figure 2.6: Same as Fig. 2.3 but only selecting satellite haloes whose mass averaged age is larger than 10 Gyr.

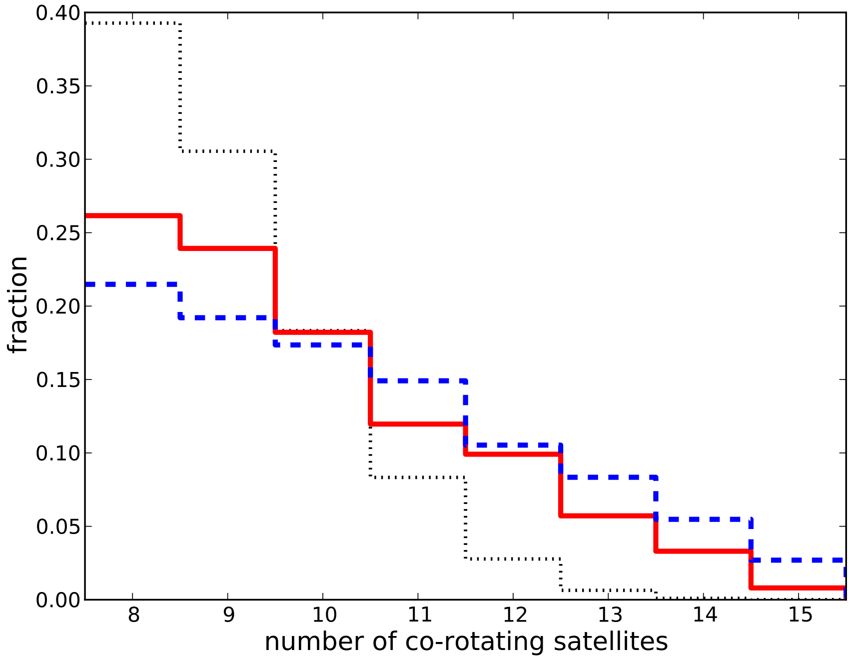

Figure 2.7: Distribution of haloes over the number of co-rotating satellites. The dotted, black line shows the distribution if orbital orientations are randomly distributed (9.1 co-rotating satellites on average). The red solid line marks the distribution for the Millennium II haloes if all dwarfs are considered (9.9 co-rotating satellites on average). The blue dashed line marks the distribution for the Millennium II haloes in the case that only dwarfs with a mean stellar age higher than 10 Gyr are considered (10.3 co-rotating satellites on average).

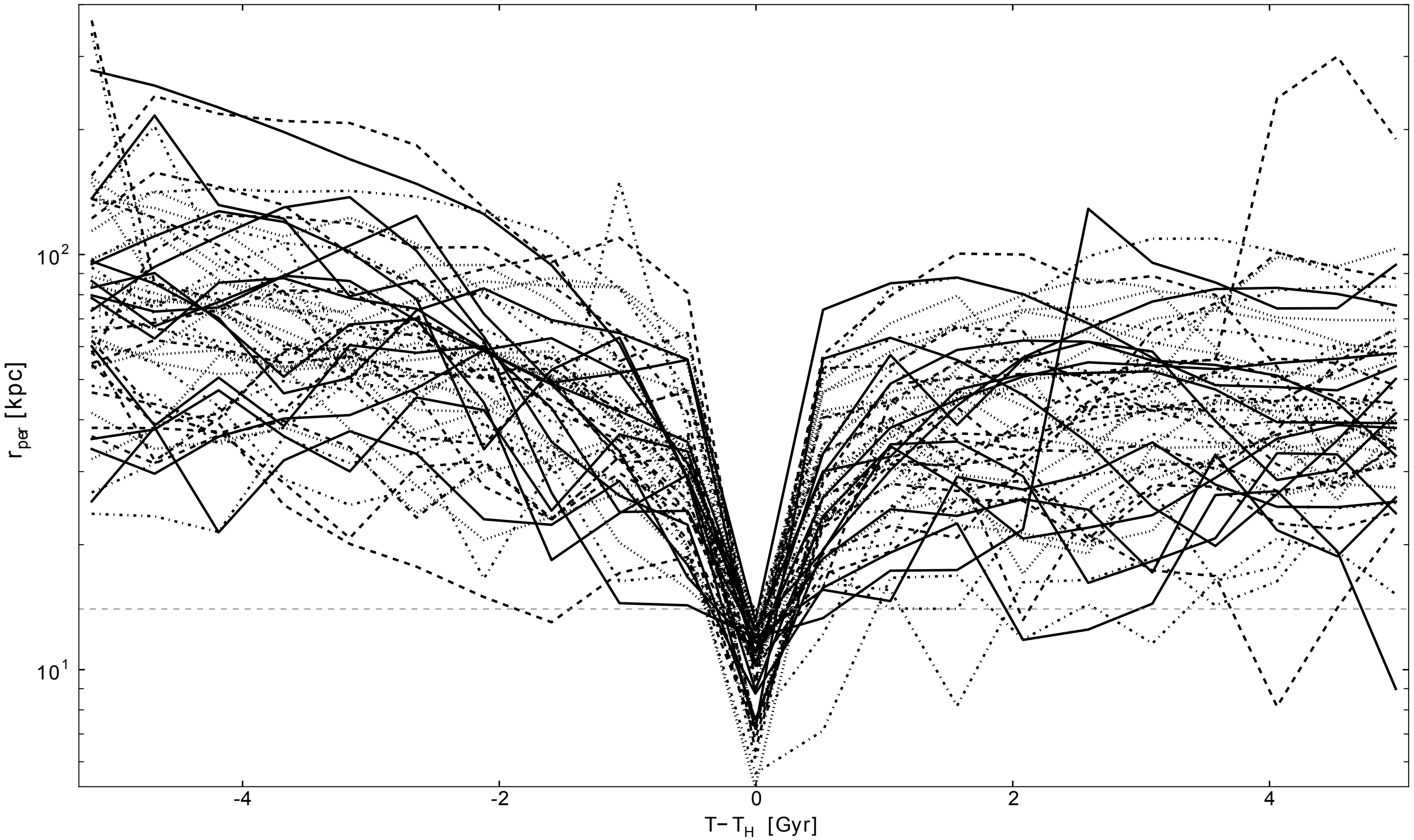

Figure 2.8: Time evolution of the rms distance $r_{\rm per}$ of the 15 galaxies which lie closest to the best fitting plane at time $T = T_H$ for all haloes that have $r_{\rm per} < 14$ kpc at $T = T_H$ and 13 or more co-rotating satellites. The horizontal dashed line marks $r_{\rm per} = 14$. $r_{\rm per}$ drops below 14 kpc and increases again within ± 0.5 Gyr. Outside these time intervals it is much larger.

Ibata et al. (2013) considered 15 galaxies out of a total of 27 galaxies in the PAndAS field only because this number maximises the contrast with a random distribution while at the same time representing a large as possible fraction of the whole satellite population. In the following we compare the distribution of Millennium II haloes with the full distribution of Andromeda satellites in the PAndAS field in order to obtain an unbiased comparison between both data sets. If we consider all 27 satellites in the calculation of the root mean square distance r_{per} of the satellites to the best fitting plane, we find that for 22 per cent of the Millennium II haloes r_{per} is lower than for Andromeda (r_{per} = 60.1 kpc for Andromeda). 8 per cent of all haloes have an r_{per} value equal to or smaller than the 60.1 kpc and a number of co-rotating satellites equal to or higher than the number of co-rotating satellites for all satellites within the PAndAS area (18 co-rotating satellites). 93 per cent of the Millennium II haloes have a higher r_{par} value than Andromeda and 18 per cent a smaller r_{per} and a higher r_{par} than Andromeda (r_{par} = 189.9 kpc for Andromeda if considering all 27 satellites). The large fraction of haloes with a higher r_{par} value than Andromeda is due to the fact that the satellites in the Millennium II haloes are less radially concentrated. Nevertheless we conclude that the whole satellite population of Andromeda is also consistent with the distribution of satellite galaxies in the Millennium II simulation.

The analysis presented so far has used data derived by re-scaling the Millennium II simulation to match WMAP7 data. Such a re-scaling is supposed to reproduce the mass power spectrum of the target cosmology to better than 3 per cent on small scales (Angulo & White, 2010). In order to be sure that the final results are not falsified by the scaling we examine additionally the unscaled version of the Millennium II simulation using the same approach as for the scaled version. The results are in good agreement with the results for the scaled version (24 per cent of the haloes have a smaller r_{per} value than Andromeda and 4 per cent a smaller r_{per} value than Andromeda and 13 or more co-rotating satellites). Hence our results seem robust against the adopted cosmology.

2.5 Conclusion and discussion

We have compared the observed distribution of Andromeda satellite galaxies, and especially the vast thin plane of co-rotating dwarf galaxies (VTPD) found by Ibata et al. (2013), with a large number of galaxy haloes taken from the Millennium II simulation. The large sample of considered haloes provides high statistical significance. After imposing several selection criteria (mass cuts, age cuts, distance cuts, PAndAS area, cluster exclusion) to ensure comparability to the results of Ibata et al. (2013) we find planes which are thinner than the VTPD for 20 per cent of the Millennium II haloes. We also find that this good agreement is not due to a mismatch of the radial distributions between the Millennium II haloes and the satellite system of Andromeda. Haloes with 13 or more co-rotating satellites orbiting in a thin plane, as observed for the Andromeda satellite system, are also not rare, since we find them in about 4 per cent of all investigated haloes. In addition, the number of co-rotating satellites for the Millennium II haloes is significantly higher than expected if the sense of rotation would be random. The reason for this is that a significant fraction of Millennium II halos is mildly rotating. This is in agreement with the results obtained by Libeskind et al. (2009) and Lovell et al. (2011) for the distribution of Milky Way dwarf satellite galaxies. If we compare the Millennium II haloes with the full distribution of Andromeda satellites, we find that in 22 per cent of the Millennium II haloes the satellites are located in planes thinner than observed. We conclude that the satellite distributions around Millennium II haloes are consistent with the one around Andromeda. Our analysis shows that the flattened satellite distribution and the mild rotation are mainly due to the old (mass weighted stellar age larger than 10 Gyr) satellite galaxies in the Millennium II simulation.

The work presented here strongly relies on the semi-analytic modelling of Guo et al. (2011) and in particular on the inclusion of the so-called 'orphan galaxies' into our analysis. If we do not consider 'orphan galaxies', we do not find Millennium II haloes with planes as thin as the VTPD around Andromeda. This might be related to the limited mass resolution of the Millennium II simulation (Guo et al., 2011), however a reliable answer to this question requires higher resolution simulations.

Several theories have been suggested to explain the formation of thin planes of satellite galaxies. Libeskind et al. (2005) found that the flat distribution of dwarf galaxies around the Milky Way can be explained by the anisotropic accretion of matter along filaments. Zentner et al. (2005) came to a similar conclusion. Dekel & Birnboim (2006) and Dekel et al. (2009) developed a scenario in which galaxy formation is driven by cold streams along cosmic filaments. Goerdt & Burkert (2013) found that cold mode accretion streams can explain the formation of the VTPD. Similarly Sadoun et al. (2013) found that the satellites belonging to the VTPD could have all been accreted from an intergalactic filament. In contrast, Hammer et al. (2013) modelled Andromeda as an ancient, gas-rich major merger and found that the formation of tidal dwarf galaxies in tails arising from galaxy interactions can explain the VTPD. A similar scenario has been suggested as the explanation for the plane of satellite galaxies around the Milky Way by Metz & Kroupa (2008) and Metz et al. (2009).

Our results offer a third possible explanation for the VTPD since it might just be a random statistical fluctuation of an underlying more spherical galaxy distribution. This is indicated by the steep decrease, respectively increase, of the root mean square distance r_{per} of the Millennium II satellites to the best fitting plane. A possible instability of the VTPD was also discussed by Bowden et al. (2013), who found that a thin satellite disc can persist over cosmological times ($\sim$ 5 Gyr) if and only if it lies in the planes perpendicular to the long or short axis of a triaxial halo, or in the equatorial or polar planes of a spheroidal halo. A measurement of the proper motions of Andromeda's satellites would allow to distinguish between the different scenarios but may be very difficult to do.

We have regarded Andromeda's satellite system as an isolated system. The closeness of the Milky Way could indicate however a common formation history (Hammer et al., 2013). Shaya & Tully (2013) and Pawlowski et al. (2013) investigated the distribution of all dwarf galaxies in the Local Group. Shaya & Tully (2013) analysed the formation of four planes containing most of the Local Group dwarfs and found that the key to the formation of the planar structures in the Local Group is the evacuation of the Local Void and consequent build-up of the Local Sheet, a wall of this void. Pawlowski et al. (2013) found that the satellites that do not belong to either Andromeda or the Milky Way can be fitted by two planes and proposed that major galaxy interactions are the key for the understanding of the formation of the four identified planes of Local Group satellite galaxies. Despite this ongoing debate, we conclude that as far as we regard Andromeda's satellite system as an isolated system, the existence of a VTPD is not in conflict with the standard cosmological framework.

Chapter 3

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