EVIDENCE FOR EARLY FILAMENTARY ACCRETION FROM THE ANDROMEDA GALAXY’S THIN PLANE OF SATELLITES

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ABSTRACT

Recently it has been shown that a large fraction of the dwarf satellite galaxies orbiting the Andromeda galaxy are surprisingly aligned in a thin, extended, and kinematically coherent planar structure. The presence of such a structure seems to challenge the current Cold Dark Matter paradigm of structure formation, which predicts a more uniform distribution of satellites around central objects. We show that it is possible to obtain a thin, extended, rotating plane of satellites resembling the one in Andromeda in cosmological collisionless simulations based on the Cold Dark Matter model. Our new high-resolution simulations show a correlation between the formation time of the dark matter halo and the thickness of the plane of satellites. Our simulations have a high incidence of satellite planes as thin, extended, and as rich as the one in Andromeda, and with a very coherent kinematic structure when we select high concentration/early forming halos. By tracking the formation of the satellites in the plane we show that they have mainly been accreted onto the main object along thin dark matter filaments at high redshift. Our results show that the presence of a thin, extended, rotating plane of satellites is not a challenge for the Cold Dark Matter paradigm, but actually supports one of the predictions of this paradigm related to the presence of filaments of dark matter around galaxies at high redshift.

Key words: dark matter – galaxies: dwarf – galaxies: formation – galaxies: individual (M31 Andromeda) – galaxies: kinematics and dynamics – methods: numerical

1. INTRODUCTION

The success of the currently favored model of structure formation, the Cold Dark Matter model, lies in its outstanding accordance with observations on large scales (Tegmark et al. 2004; Springel et al. 2005). However, over the last years several problems on galactic and sub-galactic scales have been reported, e.g., the missing satellite (Klypin et al. 1999; Moore et al. 1999) and cusp-core (Moore 1994; Boylan-Kolchin et al. 2011) problems. A potential solution to these issues lies in an inappropriate comparison between observations and simulations that only consider the dark matter component. Cosmological simulations that include baryonic physics have been shown to be able to ease those problems and to bring the CDM model in agreement with observations (Benson et al. 2007; Governato et al. 2010; Macciò et al. 2010; Brooks & Zolotov 2014; Di Cintio et al. 2014).

Recent observations of dwarf satellite galaxies around Andromeda (Koch & Grebel 2006; McC Connachie & Irwin 2006; Ibata et al. 2013), and possibly also around the Milky Way (Metz et al. 2008), have suggested these satellites align in a rotationally supported disk. Ibata et al. (2013) found that 15 out of 27 satellites in the Pan-Andromeda Archaeological Survey (PAndAS; McC Connachie et al. 2009) lie in a thin plane with thickness (12.6 ± 0.6) kpc. Furthermore, using line-of-sight velocities, they reported 13 of the satellites in the plane corotate. This kind of spatial and kinematic alignment is not easily found in Cold Dark Matter simulations (Ibata et al. 2014; Pawlowski & McGaugh 2014; Pawlowski et al. 2014), though it is not impossible (Libeskind et al. 2009; Ibata et al. 2014). Furthermore, there are other studies that have searched for planes of satellites in hydrodynamical simulations (Lovell et al. 2011; Gillet et al. 2015, and references therein). There have been indications that filamentary accretion of subhalos can lead to anisotropic spatial distributions of them (Libeskind et al. 2009, 2014; Lovell et al. 2011). Nevertheless, none of the previous studies were able to closely reproduce the parameters of Andromeda’s plane of satellites (number of members, thickness, corotation, and extension). Since the accretion and distribution of dwarf galaxies is primarily governed by the global gravitational potential, which is dominated by the dark matter distribution; this issue has raised (again) the question of whether the Cold Dark Matter model is correct or, conversely, needs to be revised.

In this paper we present new high-resolution “zoom-in” dark matter-only simulations of Andromeda-sized dark matter halos that reveal thin rotating planes of subhalos like those in the case of Andromeda. The key insight that enables us to solve this puzzle is that halos formed through filamentary accretion should form earlier and thus can be selected by their higher-than-average present day dark halo concentrations.

This paper is organized as follows. In Section 2 we present the simulations, including the host halo selection criteria and our plane finding algorithm. In Section 3 we present the results of our study, and in Section 4 we present our conclusions.

2. SIMULATIONS

We performed 21 high-resolution “zoom-in” dark matter-only simulations using the N-body code {	extsc{pkdgrav2}} (Stadel 2001, 2013). We select Andromeda-like mass halos (5 × 10^{11} < M_{\text{200}} [h^{-1} M_{\odot}] < 1.5 × 10^{12}), where the halo mass is defined with respect to 200 times the critical density of the universe. The halos were selected from three cosmological boxes of sides 30, 60, and 80 h^{-1} Mpc from Dutton & Macciò (2014), which used cosmological parameters from the Planck Collaboration et al. (2014): \Omega_m = 0.3175, h = 0.671, \sigma_8 = 0.8344, n = 0.9624.

Initial conditions for zoom-in simulations were created using a modified version of the {	extsc{grafic2}} package (Bertschinger 2001)
We select roughly equal numbers of high-mass dark matter particles per halo with particle masses of \( \sim 10^7 \) \( h^{-1} M_{\odot} \). The solid one is halo A, the dashed one is halo B.

Figure 1. Left panel: concentration–mass relation. This diagram shows the concentration as a function of mass of the high-resolution halos. The solid line is the average relation from Dutton & Macciò (2014). The dashed line indicates the 1\( \sigma \) scatter of this relation. Color coding shows the division of the halos into high, average, and low concentration. Right panel: mass growth vs. concentration. The plot shows the concentration at \( z = 0 \) as a function of mass at \( z = 2 \) in terms of the present day mass. Strongly growing halos (late forming) are located on the left, while least growing halos (early forming) are located on the right. The color coding shows the division of the halos into high, average and low concentration. The halos with satellite planes coming closest to the values of Andromeda are marked by black circles. The solid one is halo A, the dashed one is halo B.

2.1. Halo Concentration and Formation Time

Aside from halo mass, the only other selection criteria for our objects is the concentration, which is a proxy for halo formation time (Wechsler et al. 2002). The right panel of Figure 1 shows the concentration at \( z = 0 \) as a function of the mass growth since \( z = 2 \). The clear correlation validates our approach of using the concentration as a first proxy for the halo formation time.

The reasoning behind such a choice is that, at a fixed mass at the present time, early forming halos are more likely to form at the nodes of intersections of a few filaments of the cosmic web, while typical halos tend to reside inside such filaments (Dekel et al. 2009). One then might expect that, rare, early forming halos would accrete satellites from a few streams that are narrow compared to the halo size, while typical halos accrete satellites from a wide angle in a practically spherical pattern.

In the left panel of Figure 1 we show the concentration–mass relation of our high-resolution halos. Here the concentration is defined as \( c_{200} = R_{200}/r_{-2} \), where \( R_{200} \) is the virial radius, and \( r_{-2} \) is the radius where the logarithmic slope of the density profile is \(-2\). We select roughly equal numbers of high (red points), average (black points), and low (blue points) concentration halos (see Figure 1).

The solid line is the power-law fit from Dutton & Macciò (2014), while the dashed ones show the 1\( \sigma \) intrinsic scatter of 0.11 dex around the mean. Our high concentration halos have, on average, an offset of about 2\( \sigma \) from the mean relation. This means these halos are the rarer 2.3% of the whole population. In a random sample of halos it would thus require \( \sim 40 \) simulations to recover such a rare halo. This helps to explain why previous high-resolution simulations were unable to reproduce the observed properties of the satellite distribution around the Andromeda galaxy: they simply did not sample enough halos to find the rarer earliest forming ones.

2.2. Satellite Selection

Our simulations reveal hundreds of resolved subhalos that have to be matched to actual luminous galaxies. Galaxy formation models robustly predict the luminous subhalos to be the ones most massive at infall times (Kravtsov et al. 2004; Conroy et al. 2006; Vale & Ostriker 2006). Thus, we select a sample of the 30 most massive subhalos at the time of the accretion, where we restrict our analysis to subhalos within the virial radius of the host halo (\( \sim 200 \) kpc).

Although observations around Andromeda use a special selection function given by the peculiarities of the PAndAS (McConnachie et al. 2009), we choose not to reproduce the selection function for a number of reasons. First, it requires surface-brightness information that we do not have in our (dark matter only) simulations. Second, the PAndAS footprint is unique to the Andromeda galaxy, being non-circular, and including a region around its most massive satellite M33. Thus, it would not make sense to apply the same footprint to a cosmological simulation. Third, the spatial depth of the survey is somewhat uncertain due to the difficulty of measuring accurate distances to the satellites. Rather, we apply a simple, reproducible, and physically motivated selection criteria. For our satellite population we select the most massive subhalos (at the time of infall) within the \( z = 0 \) virial radius, \( R_{\text{vir}} \). Choosing satellites within the virial radius leaves us with a larger volume (\( \sim R_{\text{vir}}^3 \)) compared to the observations, hence we use 30 satellites instead of 27. Furthermore, there is some arbitrariness in the number of satellites related to Andromeda. Nine known satellites (two that lie inside the PAndAS field, and seven that lie outside) were not considered by Ibata et al. (2014) or Conn et al. (2013). Nevertheless we experimented with sample sizes of 25, 27, and 30 satellites and found no major differences in the plane statistics.
2.3. Plane Finding Algorithm

In order to find planes in the distribution of subhalos we generate a random sample of planes defined by their normal vector. All planes include the center of the main halo. To uniformly cover the whole volume we generate 100,000 random planes with a fixed thickness of $2\Delta = 40\, h^{-1}\, \text{kpc}$. After specifying a plane, we calculate the distance of every satellite to this plane. A satellite is considered to lie in the plane if its distance to the plane is smaller than $\Delta$. For each plane we calculate the number of satellites in the plane and its root-mean-square thickness $\sigma_{\text{rms}}$. We then select for every number of satellites in the plane the one that is thinnest and richest to analyze for kinematics (for further details see also Conn et al. 2013; Ibata et al. 2014; Gillet et al. 2015).

The plane of satellites around Andromeda can be characterized by four parameters including the number of satellites in the plane ($N_{\text{in}}$), the number of corotating satellites ($N_{\text{corot}}$), the thickness of the plane ($\sigma_{\text{rms}}$), and its extension. For Andromeda these values are $N_{\text{in}} = 15$, $N_{\text{corot}} = 13$, $\sigma_{\text{rms}} = 12.6 \pm 0.6\, \text{kpc}$, and a projected diameter of $\sim 280\, \text{kpc}$.

3. RESULTS

3.1. Plane Thickness versus Halo Concentration

In a first step of our analysis, we investigated the correlation between concentration (as a proxy of halo formation time) and thickness of the plane. Figure 2 shows the plane thickness as a function of the number of satellites in the plane, with line colors coded according to halo concentration. There is a clear dependence of plane thickness on the concentration of the halo. The thinnest planes are only found in the highest concentration (red lines), and hence earliest forming halos. Furthermore, only high concentration halos have planes as thin as observed in Andromeda (assuming 15 members). The smooth relation between plane thickness and number of satellites in the plane suggests that there is an arbitrariness in the number of satellites chosen to be in the plane. We do not see clear evidence of two distinct spatial structures such as a planar and spherical distribution of satellites. We further note that an investigation of the satellite distribution does not reveal a more concentrated satellite distribution in high concentration halos, which might trivially explain the dependence of plane thickness on concentration that we find.

3.2. Corotation versus Number of Satellites in plane

Figure 3 shows the outcome of our plane finding algorithm for the two (early forming) halos best matching the values of Andromeda (halo A: $N_{\text{in}} = 15$, $N_{\text{corot}} = 14$, $\sigma_{\text{rms}} = 15.8\, \text{kpc}$, diameter $\sim 220\, \text{kpc}$; and halo B: $N_{\text{in}} = 15$, $N_{\text{corot}} = 13$,

Figure 2. Minimal rms thickness, $\sigma_{\text{rms}}$, of planes as a function of number of satellites in the plane. Each line represents a different dark matter halo. Red lines show high concentration halos, blue lines show low concentration halos, and black lines show average concentration halos. The thinnest planes occur in the highest concentration halos. The blue dot shows the rms value of the plane of satellites observed around Andromeda (Ibata et al. 2013; Conn et al. 2013). The gray area represents a nominal uncertainty in the number of satellites in the plane around Andromeda of $\pm 1$.

Figure 3. Number of corotating satellites vs. number of satellites in the plane for the two best-matching high-concentration halos (halo A (left) and halo B (right)). The points are color coded by the rms thickness ($\sigma_{\text{rms}}$) of each plane. The squares mark the values observed for Andromeda (15 in plane, 13 corotating), while the gray shaded area marks the uncertainty of $\pm 1$ satellite in the plane and $\pm 1$ corotating satellite. The dots show the values of the planes found for this halo.
For every value of the number of satellites in the plane, \( N_{\text{in}} \), the plots show the number of corotating satellites, \( N_{\text{corot}} \). Every dot in the plot represents a different plane. In both halos one can find planes with up to 12 members that have a 100% corotation fraction. One can always find planes with no coherent kinematics (i.e., a corotation fraction of 50%). The points are color coded according to the thickness of the plane \( \Delta_{\text{rms}} \). As would be expected, planes with more satellites tend to be thicker. The thickness of the plane is also independent of the corotation fraction to the first order, except at the highest corotation fractions.

This figure also shows that there is some arbitrariness in choosing the best plane from a simulation. For example, for halo A (left panel in Figure 3, and upper panel of Figure 4), we can find a plane with 15 satellites and 14 corotating (one more than Andromeda). If we restrict to a plane of 14 satellites (instead of 15) we still find a large corotating fraction (\( N_{\text{corot}} = 13 \)) but in a thinner plane \( \Delta_{\text{rms}} = 13.9 \text{kpc} \), which is consistent with the Andromeda value.

\( \Delta_{\text{rms}} = 12.9 \text{kpc}, \sim 450 \text{kpc} \). For every value of the number of satellites in the plane, \( N_{\text{in}} \), the plots show the number of corotating satellites, \( N_{\text{corot}} \). Every dot in the plot represents a different plane. In both halos one can find planes with up to 12 members that have a 100% corotation fraction. One can always find planes with no coherent kinematics (i.e., a corotation fraction of 50%). The points are color coded according to the thickness of the plane \( \Delta_{\text{rms}} \). As would be expected, planes with more satellites tend to be thicker. The thickness of the plane is also independent of the corotation fraction to the first order, except at the highest corotation fractions.

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We are also able to find a thin plane even richer in number of satellites and coherent motion as the one found around Andromeda. For example, in halo A we are able to find planes consisting of up to 17 satellites from which 13 share the same rotation direction (see left panel in Figure 3).

### 3.3. Visual Impression of Planes Matching Andromeda

Figure 4 shows one particular projection of two early forming halos with plane parameters coming closest to the ones observed around Andromeda. The left-hand side shows the spatial extension and the kinematics of the system, clearly revealing a thin but radially extended plane with coherent motion of the satellites around their host. The right-hand side shows a dark matter density map of the host halos, with the two satellite populations superimposed, one in the plane (green circles) and one outside of the plane (black circles). Such distinct planes were reported before in CDM simulations (Ibata et al. 2014; Pawlowski et al. 2014; Gillet et al. 2015), but never as rich as the ones found here.
It is worth noting that previous simulation studies were
either limited by the capability of resolving enough (sub)
structures, e.g., the Millennium II simulation (Boylan-Kolchin
et al. 2009) or, conversely, were limited by very low number
statistics of host halos (Gillet et al. 2015), moreover the halos
were not selected according to formation time. Since we are
able to find planes as rich as the one around Andromeda in at
least 3 out of our 20 simulations, the rarity of the planes can be
explained by the rareness of early forming halos.

3.4. Formation Scenario

We now move to the question of where this spatial and
kinematic coherence come from. By tracing the satellites in the
plane back to a redshift of $z = 3$ we reveal that the accretion of
the satellites are along dark matter filaments. This can be seen
in Figure 5 where we show a density plot of the main halo and
its substructure at redshift $z = 3$, the satellites in the plane
indicated by green circles and the satellites outside of the plane
by white circles. Providing two different projections, these
plots prove the connection between accretion along filaments
and the property of being in a kinematically coherent plane at
redshift $z = 0$.

The presence of a plane of satellites in Andromeda seems
then to suggest an (unusual) early formation epoch for this
galaxy. Such a scenario is consistent with other observational
evidences. For its stellar mass ($\sim 10^{11} M_\odot$), Andromeda lives in
a lower mass dark matter halo than typical galaxies of the same
mass (Moster et al. 2010). At these stellar masses the majority
of galaxies are bulge-dominated and non star forming, while
Andromeda is disk-dominated and star forming, consistent with
an early mass accretion history, devoid of recent major
mergers. A similar line of reasoning also suggests an early
formation epoch for the Milky Way.

Figure 5. High redshift ($z = 3$) density plots of satellite distribution ending up in the plane and outside of the plane of halo A. The left panel shows density plots of $x$–$y$
and $x$–$z$ projections of satellites ending up in the plane at $z = 0$, while the right panel shows density plots of the $x$–$y$ and $x$–$z$ projections of satellites ending up outside
of the plane. The upper panel shows that satellites ending up in the plane are accreted along two filaments coming from opposite sides of the main halo, which set a
preferred infall direction. While satellites not ending up in the plane are accreted from everywhere. Comparison with the lower panel clearly shows that satellites
ending up in the plane lie within the filaments such that their projection collimates in the center of the halo, while halos not ending up in the plane scatter around the
main halo indicating that they are not part of the filaments.
4. CONCLUSION

We have explored the connection between the formation time of a host dark matter halo and the alignment and coherent kinematics of its subhalos using 21 high-resolution (10 million particles) cosmological N-body simulations. Our key new result is that high concentration (earlier forming) halos tend to have thinner and richer planes. Our simulations show that the presence of a thin, rotating, and extended plane of satellites like the one observed around the Andromeda galaxy is not a challenge for the Cold Dark Matter paradigm. Conversely, it supports one of the key predictions of such a model, namely the presence of large filaments of dark matter around galaxies at high redshift and the web-like nature of cosmic structures in the universe.

The connection between the formation time with the satellite distribution at the present time that we report in this paper opens a new possibility of constraining the topology of the dark matter accretion pattern.

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