

# THE SPATIAL DISTRIBUTION OF LOCAL GROUP SATELLITES IN A COSMOLOGICAL CONTEXT

VERÓNICA ARIAS<sup>1</sup>, JAIME E. FORERO-ROMERO<sup>2</sup>

<sup>1</sup>Departamento de Física, Universidad de los Andes, Cra. 1 No. 18A-10, Edificio Ip, Bogotá, Colombia

*Submitted for publication in ApJ*

## ABSTRACT

We focus on the spatial distribution of bright ( $M_V < -8$ ) satellites and pairs of galaxies with similar masses, isolation and kinematic configurations as the Local Group.

*Subject headings:* Galaxies: halos — Galaxies: high-redshift — Galaxies: statistics — Dark Matter — Methods: numerical

## 1. INTRODUCTION

Since the early works of (el que libeskind dice que habl de eso primero) and Lynden-Bell (1976), the observed anisotropic distribution of satellite galaxies in the Local Group has been a key point in the discussion of galaxy formation models within  $\Lambda$ CDM cosmology. These pioneer papers described that the then known satellite galaxies of the Milky Way (MW) were distributed roughly following the plane that contained the Magellanic clouds and their stellar tails. This anisotropic distribution was further studied in the work of Pawlowski et al. (2012), where they included all the known MW satellite galaxies (XXX more than in the original Lynden-Bell paper) as well as some MW globular clusters, and found that they are all contained in what they call a "Vast Plane Of Satellites" (VPOS). This structure is around 30kpc thick and is perpendicular to the stellar disc of the MW galaxy. This plane of satellites was considered a rarity until the PAndAS survey of the Andromeda (M31) galaxy and its halo (missing reference on the survey) provided a complete sample of the satellite galaxy population (above a XXXX magnitude) of our neighboring galaxy, allowing their consistent distance estimations (Conn et al. 2012). In a groundbreaking work, Ibata et al. (2013) found that 15 out of the 30 satellites are in a planar structure that is 15kpc thick and has an extension of 400kpc. Additionally, from line of sight velocity measurements, they found that the structure has an apparent coherent rotation, with the satellites south of M31 moving away from us and those north of M31 coming towards us. This apparent organized rotation of satellite galaxies was also statistically found to occur in diametrically opposed pairs of satellites from the SDSS (Ibata et al. 2014), although this results were contested in a follow up paper by Cuatun et al. (2014).

These discoveries of the planes in M31 and the MW were followed by the remark from Shaya et al. (2013) that the other satellite galaxies in M31 could be part of a second plane, further reinforcing the idea that satellites in the local group are not isotropically distributed. Despite the challenges in estimating distances to the satellites galaxies, Tully et al. managed to go beyond the local group and found two planes of satellites galaxies in Centaurus A, making a clearer case for the planes of satellites: in all the galaxies where distance measurements could be performed evidence of satellite

planar structures have been found.

These observed planes present a challenge for current galaxy formation models (Pawlowski et al. 2014)

A comparison of the distribution of satellite galaxies around Andromeda and the results of  $\Lambda$ CDM simulations (Bahl and Baumgardt 2013) Encuentran planos en Millenium II.

A thousand shadows of Andromeda: rotating planes of satellites in the Millennium-II cosmological simulation (Ibata et al 2013) dicen que el paper de Bahl y Baumgardt está mal y que no hay planos en millenium II

Co-orbiting satellite galaxy structures are still in conflict with the distribution of primordial dwarf galaxies (Pawlowski et al 2014)

Co-orbiting planes of sub-halos are similarly unlikely around paired and isolated hosts (Pawlowski et al 2014) Vast planes of satellites in a high resolution simulation of the Local Group: comparison to Andromeda (Gillet et al 2014). finds a plnes similar to that of M31 in Clues simulations.

Planes of satellite galaxies: when exceptions are the rule (Cautun et al 2015) encuentra que 10 por ciento de los halos tienen planos iguales o más prominentes que los del LG.

### 1.1. Posibles orígenes de los planos:

Preferential accretion (Libeskind et al 20??)

Alignments with the cosmic web (Tempel et al 20??)

The vast thin plane of M31 co-rotating dwarfs: an additional fossil signature of the M31 merger and of its considerable impact in the whole Local Group (Hammer et al 2013) Major merger in M31-MW system plane galaxies are tidal dwarfs (n-body simulations)

Kroupa tiene todo un carretazo de que las dwarfs son todas tidal dwarfs

MIRAR lo que está haciendo Pierre Alan Duc con tidal dwarfs porque en una conferencia este a;o habló de un posible escenario intermedio...

Evidence for Early Filamentary Accretion from the Andromeda Galaxy's Thin Plane of Satellites (Buck et al 2015)

Alignments between galaxies, satellite systems and haloes (Cautun et al 2016) NO LO HE LEIDO...

### 1.2. Problemas con esas explicaciones:

The Vast Polar Structure of the Milky Way and Filamentary Accretion of Sub-Halos (Pawlowski et al 2012)

Paper de Collins (2013 y 2016) donde explica que no hay diferencias en las propiedades de los on-plane y los off-plane satellites

Problemas con la estabilidad a largo plazo de los planos: Bowden et al 2012, Gonzales et al 2015...

The Plane Truth: Andromeda analog thin Planes of Satellites are not kinematical coherent structures (Buck et al 2015)

### 1.3. Previous studies of Local Group satellites

(?) Measure the infall direction of satellites in a DM only simulation of one pair of LG halos in a constrained simulation. There is a definite infall direction but it's not quantified in terms of the cosmic web.

(?) Compare the kinematic structure of the MW satellites against DM only simulation of high resolutions halos from the Via Lactea and Aquarius projects. Cannot find a similar kinematic structure (i.e. the orbital poles of the MW satellites) in the simulations.

(?) Measure the infall direction of satellites with respect to the V-web. They do it in a DM cosmological simulation (64 Mpch, 1024 3 particles). They find that infall is done along the e3 (i.e. filament) direction.

(?) They measure the angle between satellites and the direction defined by filaments (Bissous filament finder) to find a signal both in SDSS and the semi-analytic galaxies in the Millennium Simulation.

(?) Detection of alignment of satellites along the direction defined by filaments (velocity shear cosmic web) on the SDSS DR7.

(?) Uses the APOSTLE simulation (12 pairs) to study the spatial anisotropy the 11 brightest satellites. The anisotropy is quantified the reduced inertia tensor. Still the MW is more anisotropic than all but one of the 24 halos. The analysis is not very thorough and do not show the resulting distribution. Does not compare the results of using DM information only.

(?) argue that the result from (?) is a product of using a metric that ignores the radial position of the galaxies. They use the ELVIS suite to compare the two analysis methods: reduced vs. full inertia tensor.

(?) Use the eagle simulation to study the alignment of satellites with respect to the central galaxy. They find a weak alignment. Around 20% of the systems have a misalignment angle larger than the value observed for the Milky Way. They do not study DM only simulations and do not narrow down the signal to pairs.

(?) Using SDSS DR10 studied galaxy pairs. They find that satellites tend to accumulate towards the companion galaxy. There are up to  $\sim 10\%$  more satellites in the space between the pair than expected from an uniform distribution

## 2. NUMERICAL SETUP

### 2.1. Illustris simulation

### 2.2. Sample Selection

We select all halos with maximum circular velocities in the range  $150 \text{ km s}^{-1} < V_{\text{max}} < 350 \text{ km s}^{-1}$ . We exclude

sub-halos from this selection. From this set we construct a sample of pairs as follows. For each halo  $A$  we find its closest halo  $B$ , if halo  $A$  is also the closest to halo  $B$ , the two halos are considered as a pair. Another way to phrase this selection is that pairs do not have neighbors closer than the pair's distance. We exclude the pairs that are closer than There are 53 pairs with those conditions in the simulation.

We extract from the simulation spheres of  $2 h^{-1} \text{Mpc}$  radius around the pair's center of mass. We use this information to exclude all the pairs that have separations smaller than the sum of their virial radii, i.e. we exclude interacting pairs. This reduces to 49 the number of pairs in the sample.

We count the number of galaxies with  $M_V < -9$  inside the virial radius of each halo, including the central galaxy. We only keep pairs where both halos have 5 bright galaxies at least. This reduces the sample to 24 pairs. We call this sample the Full Sample.

From the Full Sample we build a second sample based on the pairs' kinematics. Figure 1 shows the co-moving separation and relative speed between the two halos in the pair. The stars in the Figure represent the pairs with a separation in the range  $0.75 h^{-1} \text{Mpc} < R_{AB} < 1.50 h^{-1} \text{Mpc}$  and relative velocity in the range  $V_{AB} > 100 \text{ km s}^{-1}$ , which are close to the Local Group Observed values. We call this sample the LG Sample.

The number of pairs in the Full Sample is consistent with previous calculations. ? performed a study of the LG kinematics using a cosmological N-body simulation as a benchmark. In their study, using criteria similar to ours to define the Full Sample, they found 1923 pairs in a volume of  $250^3 h^{-3} \text{Mpc}^3$ . With the same number density we expect to find 52 pairs in the volume of the Illustris simulation, which is very close to the actual number of 49 pairs.

In the same study they found 158 pairs with broad kinematic characteristics, similar to the definition of our LG sample. This represents a reduction of a factor of 12 from their General Sample. With those numbers in mind we would expect to keep at least 4 pairs in the Illustris volume. Given that our conditions are slightly more relaxed (we do not ask for isolation criteria from massive halos) we end up with a larger sample size, but still consistent with the fact that LG-like pairs are scarce.

### 2.3. Cosmic Web environment

We place the pairs in our sample into the cosmic web as quantified by the deformation tensor. (??). This method computes a cartesian grid the tensor  $T_{ij}$ ,

$$T_{ij} \equiv \frac{\partial^2 \phi}{\partial r_i \partial r_j} \quad (1)$$

where  $\phi$  is a pseudo-gravitational potential that follows the Poisson equation  $\nabla^2 \phi = -\delta$  and the  $r_i$  coordinates correspond to a cartesian system with  $i = 1, 2, 3$ .

This tensor is symmetric and can be diagonalized. Its eigenvalues ( $\lambda_1 > \lambda_2 > \lambda_3$ ) and corresponding eigenvectors ( $\hat{e}_1, \hat{e}_2, \hat{e}_3$ ) define the degree and direction of stability around the neighborhood where the tensor was computed. This allows the classification of that region either as a peak, filaments, sheets and voids in the case of three, two, one or zero eigenvalues larger than a given

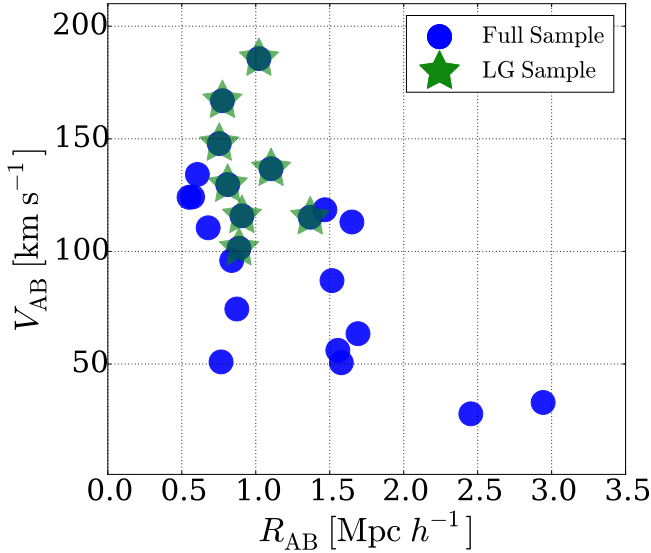


FIG. 1.— Halo pair samples used in this paper located in the plane of relative comoving velocity  $V_{AB}$  versus relative distance  $R_{AB}$  between the two halos in the pair. The R&V sample is the closest to the separation and kinematic conditions observed in the Local Group.

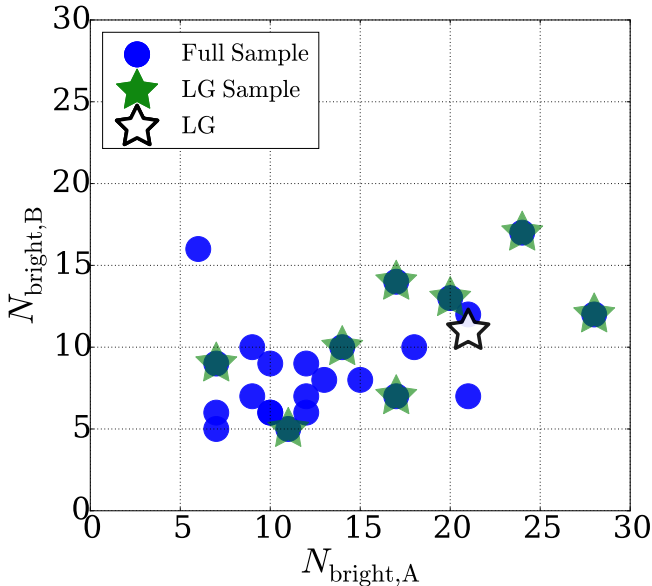


FIG. 2.— Number of bright substructures ( $M_B < -9$ ) and dark matter substructures.

threshold  $\lambda_{th}$ .

In this study we compute these eigenvalues and eigenvectors over the dark matter component of the Illustris-3 simulation on a cubic mesh of 74 cells on a side. This resolution corresponds to  $\sim 1$  Mpc  $h$ . We interpolate the DM density on that mesh using a Cloud-In-Cell (CIC) scheme. We proceed to smooth the density field with a gaussian window with a physical scale equal to the cell size.

We choose this interpolation and smoothing scale for two reasons. First, because it corresponds to the typical pair separation in our sample. Second, because it allows a direct comparison with other results in the literature that used the same methodology to quantify the cosmic web environment for Local Group pairs in a cosmological

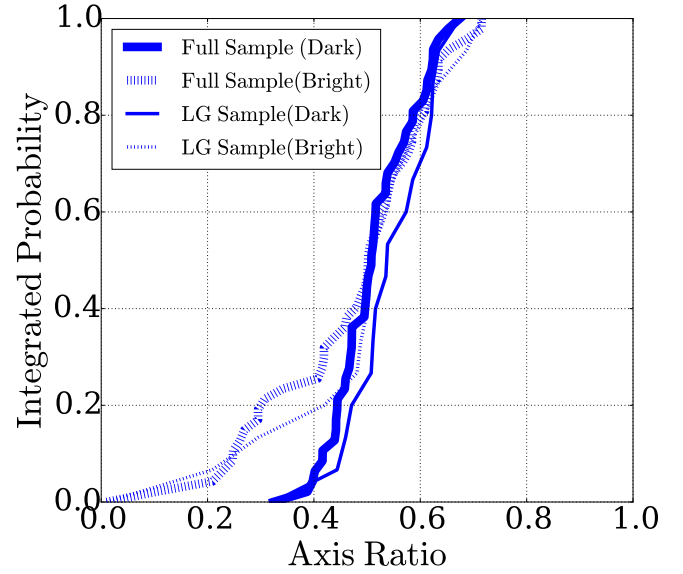


FIG. 3.— Axis ratio of luminous satellites versus the axis ratio for dark subhalos.

### 3. RESULTS

### 4. METHOD

### 5. DISCUSSION

### 6. ACKNOWLEDGEMENTS

Gracias.

Simulation papers:

- Bahl and Baumgardt 2013 "A comparison of the distribution (...)":  
MillenniumII and a semi-analytic model  
Baryonic mass cut:  $2.8 \times 10^4 M_\odot$   
PAndAS like field  
With orphan galaxies: planes are common (40%) but overall distribution is different from that of M31 (more radially concentrated).  
Excluding some orphan galaxies: overall distribution closer to M31's and finds planes.  
Conclusion: M31 like planes are not uncommon in MillenniumII simulations. Co-rotating structures are not stable structures. Plane of M31 could be a statistical fluctuation in an otherwise more spherical distribution.  
Simulation: Millennium II ()  
Gas: NO  
Resolution: sub-halos  $2 \times 10^8 M_\odot$  (orphan galaxies have less than 20 particles and could be tidally disrupted)  
Number of host halos: 1511 with orphan galaxies, 112 excluding orphan galaxies (mass between  $1.1 \times 10^{12} M_\odot$  and  $1.7 \times 10^{12} M_\odot$ ), younger than 10 Gyr and satellites smaller than  $7 \times 10^{10} M_\odot$   
Planes: yes (40% with orphan galaxies 2% without)  
co-rotation: yes (in 2% of the halos ???)  
Stable: No  
Note: PAndAS data has satellites with baryonic masses down to  $2.9 \times 10^4 M_\odot$  and they take that as a lower limit for their data.

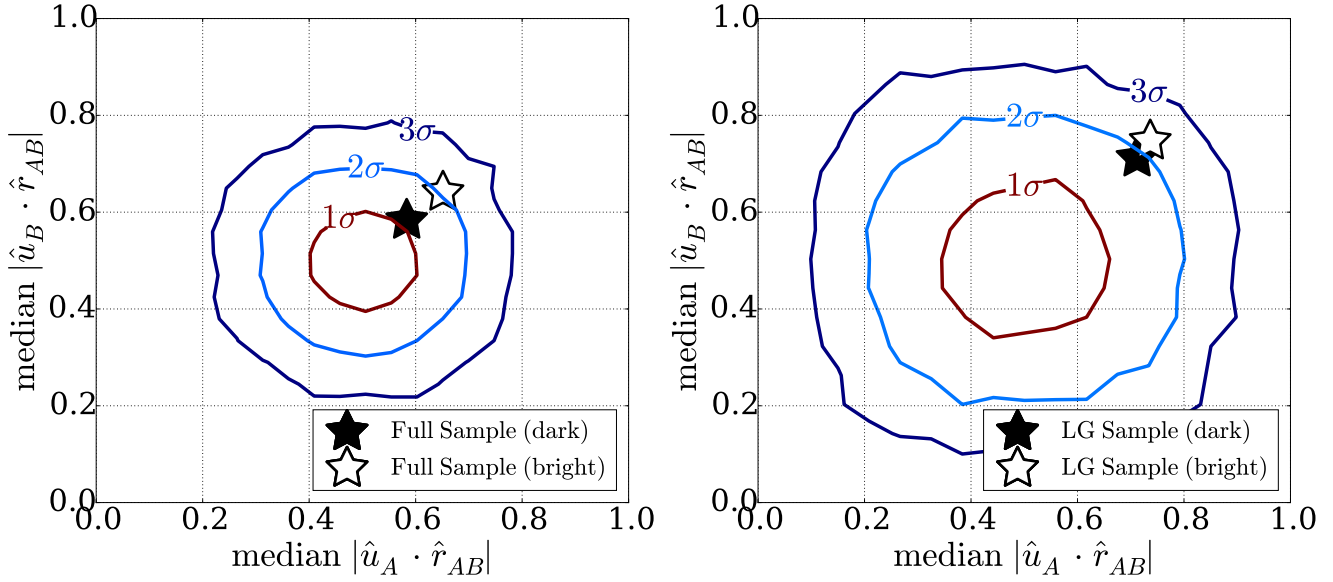


FIG. 4.— Significance of alignments.

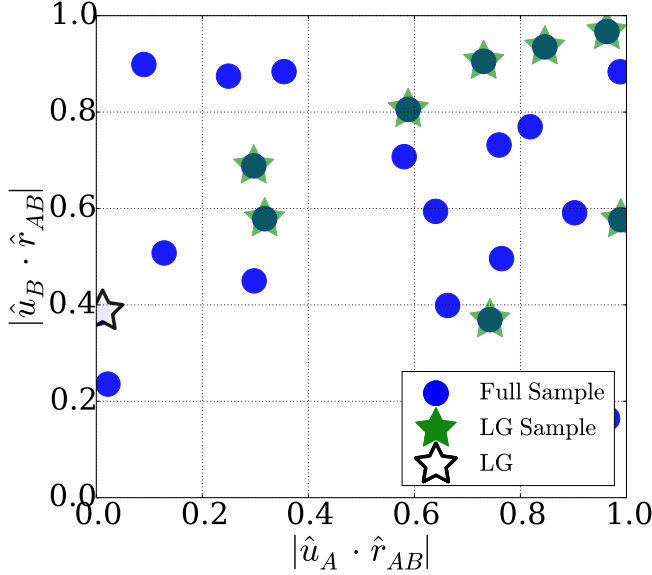


FIG. 5.— Alignment of the mayor axis with the vector connecting the two halos.

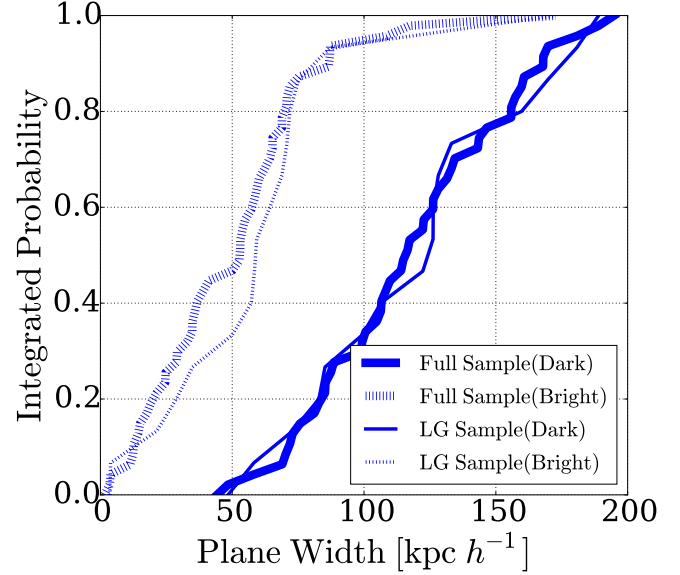


FIG. 6.— Plane width for the best planes in the luminous and dark cases.

- Ibata et al 2014 "A thousand shadows (...)":  
MilleniumII and a semi-analytic model (Guo)  
Same analysis as in PAndAS data  
Conclusion: M31 like planes are NOT common in MilleniumII simulations.  
Simulation: Millenium II ()  
Gas: NO  
Resolution: sub-halos  $2 \times 10^8 M_\odot$  (orphan galaxies have less than 20 particles and could be tidally disrupted)  
Number of host halos: 679 (I assume with orphan galaxies) (mass between  $1.1 \times 10^{12} M_\odot$  and  $1.7 \times 10^{12} M_\odot$ , younger than 10 Gyr and satellites smaller than  $7 \times 10^{10} M_\odot$  they also use LG upper mass limit, and an isolation criteria).  
Planes: no (with orphan galaxies only 0.04% of the system fulfill the thinness, extension and co-rotation criteria, and NONE does if orphans

are not included. If co-rotation is not included then 2% fulfill the thinness and extension criteria)  
co-rotation: only 0.04% with orphans and NONE without orphans  
Note: they use the 679 host halos and study them from different viewing angles

- Pawlowski et al 2014 "Co-orbitingsatellite galaxy structures are still in conflict with (...)":  
MilleniumII and a semi-analytic model (Guo)  
Same analysis as in PAndAS data  
Same analysis as in Wang et al. 2013  
Conclusion: M31 and MW like planes are NOT common in MilleniumII simulations.  
Simulation: Millenium II ()  
Gas: NO  
Resolution: sub-halos  $2 \times 10^8 M_\odot$  (orphan galaxies

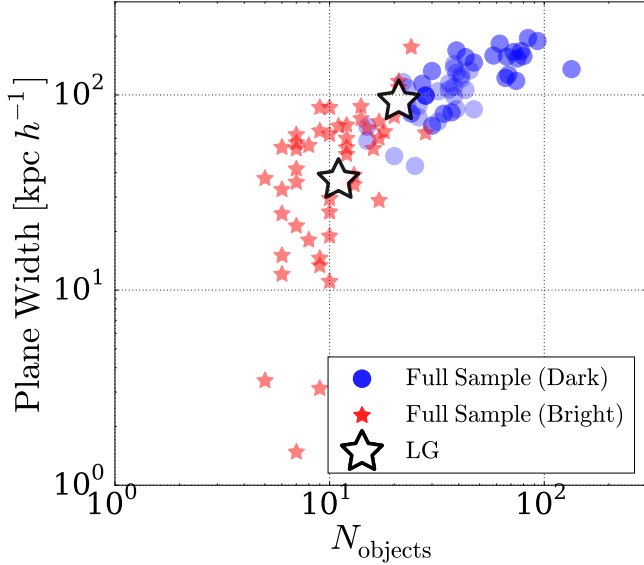


FIG. 7.— Plane width as a function of objects used to find the plane.

have less than 20 particles and could be tidally disrupted)

Number of host halos: 1825 (mass between  $1.1 \times 10^{12} M_{\odot}$  and  $1.7 \times 10^{12} M_{\odot}$ , younger than 10 Gyr and satellites smaller than  $7 \times 10^{10} M_{\odot}$  they also use LG upper mass limit, and an isolation criteria).

Planes: no (M31: 0.09% fulfill the thinness, extension and co-rotation criteria. MW: 0.2%)

Note: they use the host halos and study them from different viewing angles so they end up with 15000 samples. They always consider orphan galaxies for comparison purposes. For one test they randomize the sample and find M31 like planes in only 0.002 per cent of the cases and MW like planes in 0.06% of the cases.

MIRAR Wang et al. 2013 que busca MWlike planes en MilleniumII y encuentra que 13% de los halos tienen planos

- Cautun et al. 2015 "Planes of satellite galaxies: when exceptions are the rule":  
MilleniumII and a semi-analytic model (Guo 2013)  
CoCo and a semi-analytic model (Guo 2015)  
Conclusion: planar structures are very common in  $\Lambda$ CDM (10%)  
Simulation 1: Millenium III rescaled to WMAP  
Simulation 2: CoCo (Higher resolution than MilleniumII)  
Gas: NO  
Resolution 1: sub-halos  $2 \times 10^8 M_{\odot}$  (orphan galaxies have less than 20 particles and could be tidally disrupted)  
Number of host halos: 2849 (MilleniumII) and 63 8COCO halos) (selection criteria: "we adopted a broader mass range to account for the large uncertainty in the mass measurements and also for possible systematic effects").  
Resolution 2: sub-halos  $\approx 2 \times 10^6 M_{\odot}$  (75 times higher mass resolution and four times better spatial resolution)

Planes: yes (10%)

Note: They found a great variety of plane and the M31 plane lies in general within the scatter of the simulated planes however it seem to have an "unusually large radial extent".

Note 2: they find that each halos has a different planar configuration showing that the low incidence of the M31 plane is not in contradiction with simulations. This contradicts the Pawlowski et al. 2014 conclusions

- Sawala et al. 2014 "The chosen few: the low mass halos that host faint galaxies":  
Conclusion: Some "effects make dwarf galaxies highly biased tracers of the underlying dark matter distribution."  
Simulation: 12 cosmological volumes as zoom" simulations extracted from the Dove simulation. They require that each box has to have two halos (MW and M31 like)  
Gas: Yes (they also compare their results with DM only simulations)  
Resolution : sub-halos  $1 \times 10^7 M_{\odot}$   
Number of host halos: 2 times 12 (pairs of galaxies).  
Planes: They do not look for them
- Libeskind et al. 2012 "The universal nature of subhalo accretion":  
Conclusion: "the preferential infall of subhaloes is effectively universal in the sense that its always aligned with the axis of weakest collapse of the velocity shear tensor. It is the same shear tensor that dictates the structure of the cosmic web and hence the shear field emerges as the key factor that governs the local anisotropic pattern of structure formation."  
Simulation: DM-only N-body simulation of 10243 particles in a  $64h^{-1}$  Mpc box.  
Gas: NO  
Resolution : particle  $1.89 \times 10^7 h^{-1} M_{\odot}$   
Resolution : halos  $1 \times 10^9 h^{-1} M_{\odot}$   
Number of host halos: not mentioned.  
Planes: They do not look for them. They look and find preferential directions for accretion
- Libeskind et al. 2015 "Planes of satellite galaxies and the cosmic web":  
Conclusion: "The analysis reveals that the Local Group and Centaurus A reside in a filament stretched by the Virgo cluster and compressed by the expansion of the Local Void. Four out of five thin planes of satellite galaxies are indeed closely aligned with the axis of compression induced by the Local Void. (...) "  
Simulation: Observational paper uses the cosmic flow data set.  
Gas: No aplica
- Tempel et al. 2015 "The alignment of satellite galaxies and cosmic filaments: observations and

simulations”:

Conclusion: ”A statistically significant alignment between satellite galaxy position and filament axis in observations is confirmed. We find a qualitatively compatible alignments by examining satellites and filaments similarly identified in the Millennium simulation, semi-analytical galaxy catalogue. We also examine the dependence of the alignment strength on galaxy properties such as colour, magnitude and (relative) satellite magnitude, finding that the alignment is strongest for the reddest and brightest central and satellite galaxies. ”

Simulation: MillenniumII compared to Observational data (SDSS).

Gas: No

Alignments: yes both in simulations and in observations

Note: they make a statistical analysis of alignments in projected data.

- Sawala et al. 2015 ”The APOSTLE simulations: solutions to the Local Group’s cosmic puzzles”:

Conclusion: ”Applying the Eagle code to the LG environment, we find that our simulations match the observed abundance of LG galaxies, including the satellite galaxies of the MW and Andromeda. Due to changes to the structure of halos and the evolution in the LG environment, the simulations reproduce the observed relation between stellar mass and velocity dispersion of individual dwarf spheroidal galaxies without necessitating the formation of cores in their dark matter profiles. Satellite systems form with a range of spatial anisotropies, including one similar to that of the MW, confirming that such a configuration is not unexpected in  $\Lambda$ CDM”

Simulation: They use the EAGLE code to simulate the Apostle set of simulations (a suite of cosmological hydro- dynamic simulations of twelve volumes selected to match the kinematics of the Local Group (LG) members).

halo selection: In particular, we focus on pairs of halos that match the separation, approach velocity, and relative tangential velocity of the Milky Way (MW) and Andromeda (M31). From a large cosmological simulation, we have selected twelve pairs of halos with combined virial masses of  $2.3 \pm 0.6 \times 10^{12} M_{\odot}$ , compatible with the most recent dynamical constraints

Resolution : re-simulated each LG volume at several resolutions, both as dark matter only (DMO) simulations, and as hydrodynamic simulations

Gas: Yes (they also compare with DM only simulations)

planes: yes (they find ”anisotropic configurations: BUT not typical ”)

Note: they select MW-M31-like pairs, including kinematical constraints

- Gillet et al. 2015: ”Vast planes of satellites in a high resolution simulation of the Local Group: comparison to Andromeda”:  
CLUES project and a semi-analytic model

Conclusion: ”The structure of the simulated satellite systems is strongly non-random and contains planes of satellites, predominantly co-rotating, with, in some cases, sizes comparable to the plane observed in M31 by Ibata et al.. However the latter is slightly richer in satellites, slightly thinner and has stronger co-rotation, which makes it stand out as overall more exceptional than the simulated planes, when compared to a random population”

Simulation: CLUES

Gas: NO

Resolution : DM particle  $2.1 \times 10^5 h^{-1} M_{\odot}$

Resolution : gas particle  $4.42 \times 10^4 h^{-1} M_{\odot}$

Resolution : halos  $4.2 \times 10^6 h^{-1} M_{\odot}$

Number of host halos: 2 (one pair)

Planes: yes

co-rotation: kind of

Stable: No

note: they use 5 different methods to choose the satellites and 3 different volumes.

- Pawlowski et al. 2012: ”Can filamentary accretion explain the orbital poles of the Milky Way satellites?”:

Aquarius and Via Lactea Simulations

Conclusion: they find that the simulations cannot reproduce the angular momentum coherence of the satellites in the MW and that ”this indicates that the formation as tidal dwarf galaxies in a single encounter is a viable, if not the only, process to explain the phase-space distribution of the MW satellite galaxies.”

Simulation: Aquarius and Via Lactea

Gas: NO

Resolution : ?

Number of host halos: 8

Planes: they look for alignments in the orbital poles and found none in the cosmological simulations

co-rotation: no

note: they compare what they find in simulations with an isotropic distribution and with merger scenarios.

- Pawlowski et al. 2014: ”Co-orbiting planes of sub-halos are similarly unlikely around paired and isolated hosts”:

They use the Elvis simulations to study the satellite population of paired vs isolated galaxies.

Conclusion: The observed flattening and the observed orbital alignment are each reproduced by only 0.2 to 2 per cent of paired and isolated systems incorporating the obscuration of satellites by randomly oriented galactic discs.

Simulation: Elvis

Gas: NO

Resolution : ?

Number of host halos: 24 paired and 24 isolated host halos (4800 analyzed realizations).

Planes: 0.2 to 2 per cent

co-rotation: 0.2 to 2 per cent

note: co-rotation and alignments together are only

observed in ONE of 4800 realizations.