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THE SPATIAL DISTRIBUTION OF LOCAL GROUP SATELLITES IN A COSMOLOGICAL CONTEXT

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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 ΛCDM cosmology. These pioneer papers described that the then known satellite galaxies of the Milky May (MW) were distributed roughly following the plane that contained the Magelanic 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 ΛCDM 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 dwrafs 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 doferencias 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*

(Libeskind et al. 2011) 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.

(Pawlowski et al. 2012) 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.

(Libeskind et al. 2014) 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.

(Tempel et al. 2015) 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.

(Lee & Choi 2015) Detection of alignment of satellites along the direction defined by filaments (velocity shear cosmic web) on the SDSS DR7.

(Sawala et al. 2016) 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.

(Pawlowski et al. 2015) argue that the result from (Sawala et al. 2016) is a produc 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.

(Shao et al. 2016) 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.

(Libeskind et al. 2016) 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 km s^{-1} $< V_{\rm max} <$ 350 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}Mpcin 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 $0.75h^{-1}$Mpc $< R_{AB} <$ $1.50h^{-1}$Mpc and relative velocity in the range $V_{AB} > 100$ 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. Forero-Romero et al. (2013) 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} 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. (Hahn et al. 2007; Forero-Romero et al. 2009). This method computes a cartesian grid the tensor T_{ij},

$$T_{ij} \equiv \frac{\partial^2 \phi}{\partial r_i \partial r_j} \tag{1}$$

where ϕ 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 and 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

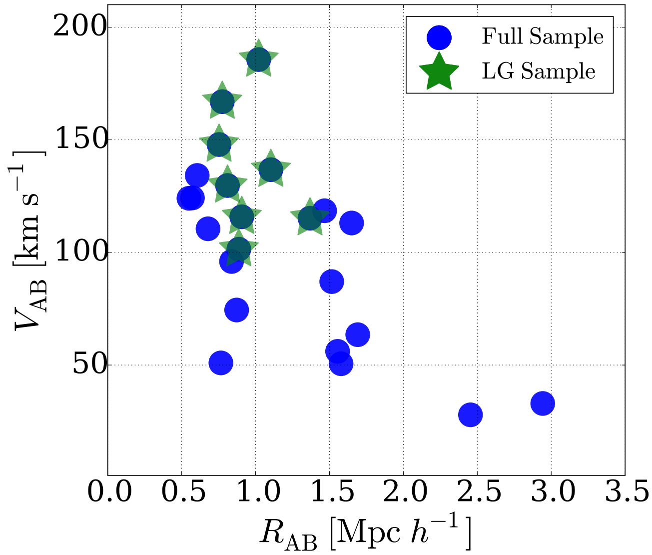

FIG. 1.— Halo pair samples used in this paper located in the plane of relative comoving velocity V_{AB} versus relative distance R_{AB} between the two halos in the pair. The R&V sample is the closest to the separation and kinematic conditions observed in the Local Group.

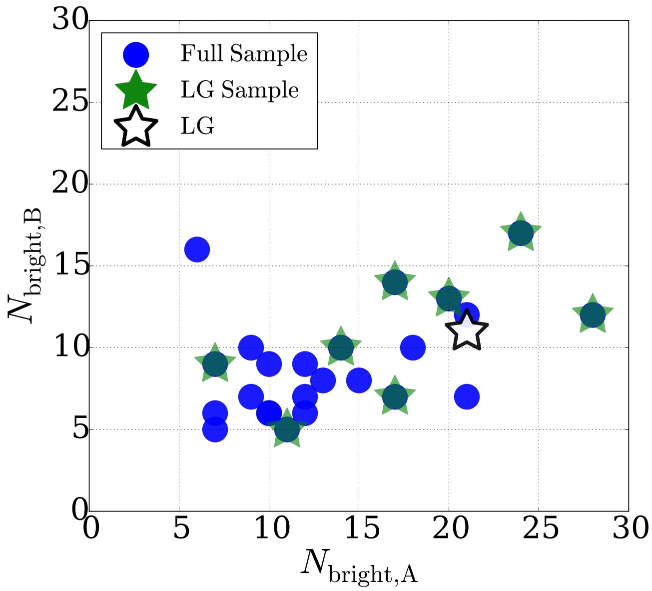

FIG. 2.— Number of bright substructures ($M_B < -9$) and dark matter substructures.

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 threshold λ_{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 ~ 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

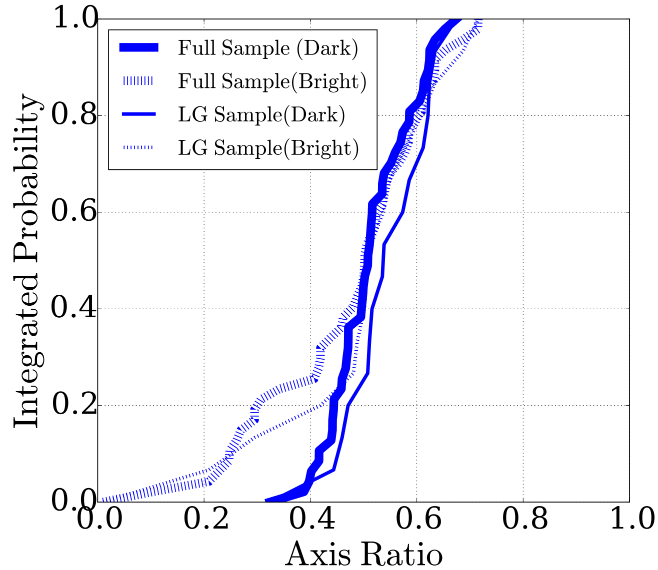

FIG. 3.— Axis ratio of luminous satellites versus the axis ratio for dark subhalos.

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 (Forero-Romero et al. 2013; Forero-Romero & González 2015).

3. RESULTS

4. METHOD

5. DISCUSSION

6. ACKNOWLEDGEMENTS

Gracias.

Simulation papers:

- Bahl and Baumgardt 2013 "A comparison of the distribution (...)":
  MilleniumII and a semi-analytic model
  Baryonic mass cut: $2.8\times10^4 M\odot$
  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 MilleniumII simulations. Co-rotating structures are not stable structures. Plane of M31 could be a statistical fluctuation in an otherwise more spherical distribution.
  Simulation: Millenium II ()
  Gas: NO
  Resolution: sub-halos $2\times10^8 M\odot$ (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 $1.1\times10^{12} M\odot$ and $1.7\times10^{12} M\odot$), younger that 10 Gyr and satelites smaller than $7\times10^{10} M\odot$
  Planes: yes (40% with orphan galaxies 2% without)
  co-rotation: yes (in 2% of the halos ???)
  Stable: No

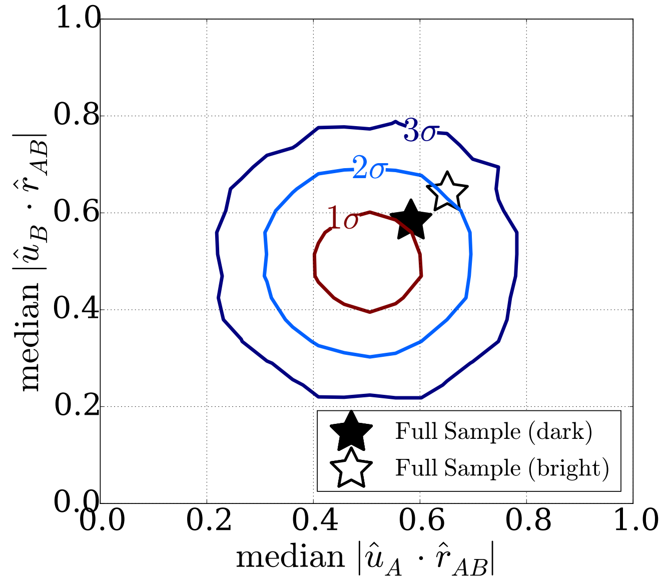

FIG. 4.— Significance of alignments.

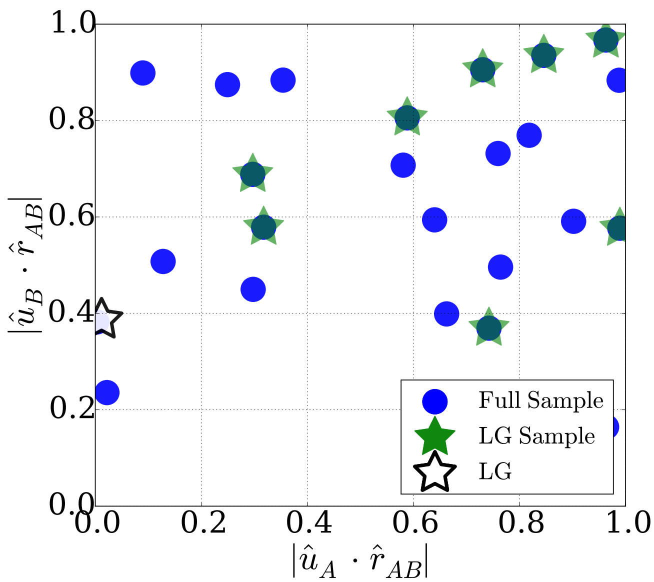

FIG. 5.— Alignment of the mayor axis with the vector connecting the two halos.

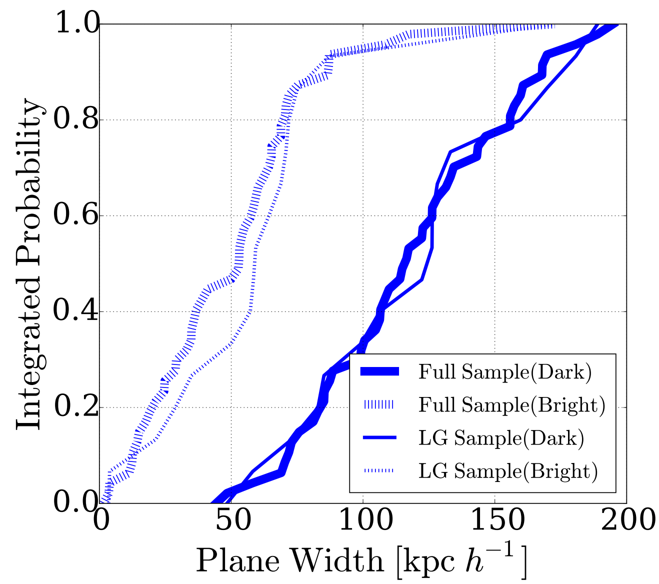

FIG. 6.— Plane width for the best planes in the luminious and dark cases.

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.

- 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 that 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

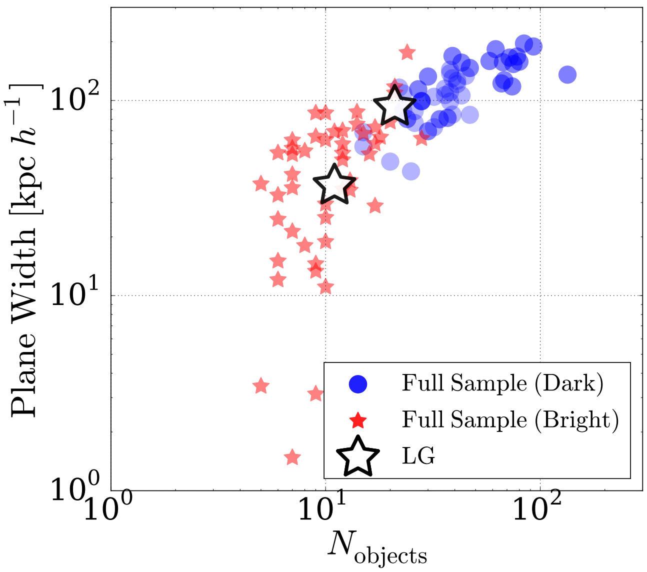

FIG. 7.— Plane width as a function of objects used to find the plane.

Conclusion: M31 and MW like planes are NOT common in MilleniumII simulations.
Simulation: Millenium II ()
Gas: NO
Resolution: sub-halos $2\times10^8 M\odot$ (orphan galaxies have less than 20 particles and could be tidally disrupted)
Number of host halos: 1825 (mass between $1.1\times10^{12} M\odot$ and $1.7\times10^{12} M\odot$, younger that 10 Gyr and satellites smaller than $7\times10^{10} M\odot$ 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 ΛCDM (10%)
Simulation 1: Millenium IIi rescaled to WMAP
Simulation 2: CoCo (Higher resolution than MilleniumII)
Gas: NO
Resolution 1: sub-halos $2\times10^8 M\odot$ (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 $\approx 2\times10^6 M\odot$ (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

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