

# 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 and their apparent co-rotation seem to challenge current galaxy formation models (Pawlowski et al. 2014). Pawlowski et al. (2012) compared the kinematic structure of the MW satellites against DM only simulation of high resolution halos from the Via Lactea and Aquarius projects and could not find a similar kinematic structure (i.e. the orbital poles of the MW satellites) in the simulations. Additionally, a few months after the discovery of the M31 plane of satellites, Bahl and Baumgardt (2013) looked for similar structures in the MilleniumII dark matter only cosmological simulations, and found that planar structures are common (they found them in around 2 per cent of host halos). Nevertheless these results were contradicted by the works of Ibata et al. (2014) and Pawlowski et al. (2014) who, analyzing the same cosmological simulations with methods closer to those used to analyze the observational data, found that planar structures such as that observed in M31 are extremely rare (less than 0.02 per cent or 0.004 per cent respectively). But satellite galaxies are not particularly good tracers of the underlying dark matter structure (Sawala 2014), and indeed anisotropic distributions of the satellites have been found in the APOSTOLE simulations that include baryonic physics (Sawala et al. 2016), although the Milky Way remains an extreme case. These results were contested by Pawlowski et al. (2015) who claim that the anisotropies found are a product of using a metric that ignores the radial position of the galaxies. In CLUES, a high resolution constrained Local Group simulation, Gillet et al. (2015) found M31-like planes but again, the observed M31 plane remains an extreme case, and this seems to be corroborated by Cuatun et al. (2015), who, despite finding a great variety of planes in simulations remarks that the observed M31 plane has an "unusually large radial extent".

In addition to these plane-finding efforts in cosmological simulations, many works have focused on the possible formation processes that led to planar structures and on the alignments of these structures with the cosmic web. In a pioneer work Libeskind et al. (2011) measured the infall direction of satellites in a DM only constrained simulation of one pair of LG halos and found that there is a definite infall direction. Using cosmological dark

matter only simulations Libeskind et al. (2014) showed that the preferential infall direction was along cosmic filaments, result that was also obtained by Lee & Choi (2015). This result was further confirmed by Tempel et al. (2015), who measure the angle between satellites and the direction defined by filaments (Bissous filament finder) to find a signal both in the SDSS galaxy catalog and in the semi-analytic galaxies in the Millennium Simulation. Additionally, an analysis of the cosmic flow data set by Libeskind et al. (2015) reveals that four out of the five satellite planes observed in the Local Group are aligned with a filament. Additionally, Libeskind et al. (2016) use the SDSS DR10 catalog to study galaxy pairs and 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.

Early filamentary accretion has been proposed as the formation mechanism for the Andromeda thin plane of satellites (Buck et al 2015), with early formed galaxies accreting their mass via cold thin filaments. This formation mechanism results naturally in thin planes, but a follow up work shows that these are not kinematically coherent structures (Buck et al. 2015). These results are from dark matter only simulations, so it would be interesting to see if they still hold for simulations that include baryonic physics, since it was shown by Gonzales et al 2015 that satellites accreted via filaments are destroyed faster than those that are not.

In a more general numerical study, 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.

Planes in simulations tend to be transient structures (not kinematically coherent) and that poses two problems: one is why do we see planes in all the galaxies were we can actually make the measurements if they are transient? Problem with the MW plane for which some of the dwarfs have proper motion measurements. Another problem: explicacin de Buck 2015 sera rara entonces...

## 2. NUMERICAL SETUP

### 2.1. Illustris simulation

In this work we use the publicly available results from the Illustris simulation (Vogelsberger et al. 2014). This cosmological simulation, performed using the quasi-Lagrangian code AREPO, follows the coupled evolution of dark matter and gas, and includes parametrizations to account for the effects of gas cooling, photoionization, star formation, stellar feedback, black hole and super massive black hole feedback. Vogelsberger et al. 2014 use a  $75Mpc/h$  simulation box, with  $\Lambda$ CDM cosmology initial conditions starting at a redshift  $z = 127$  and consistent with WMAP-9 measurments.

### 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  $0.75h^{-1}\text{Mpc} < R_{AB} < 1.50h^{-1}\text{Mpc}$  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. 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  $250^3 h^{-3} \text{Mpc}^3$ . 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. (Hahn et al. 2007; Forero-Romero et al. 2009). This method computes a cartesian grid the tensor  $T_{ij}$ ,

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

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 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 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  $\lambda_{th}$ .

In this study we compute these eigenvalues and eigen-

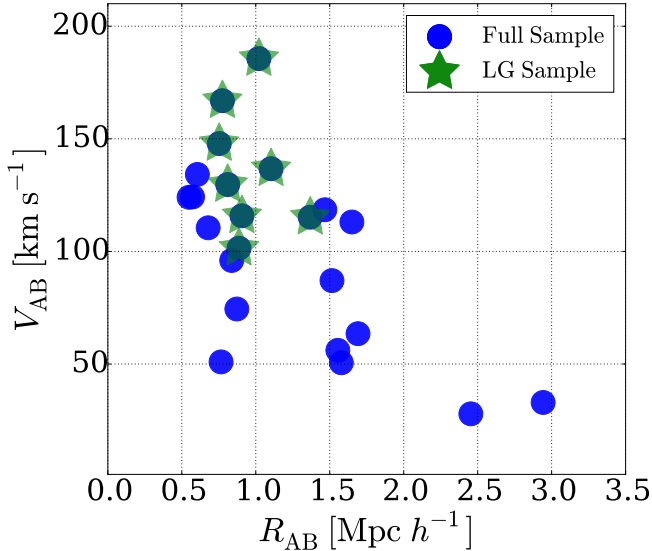


FIG. 1.— Halo pair samples used in this paper located in the plane of relative comoving velocity  $V_{AB}$  versus relative distance  $R_{AB}$  between the two halos in the pair. The R&V sample is the closest to the separation and kinematic conditions observed in the Local Group.

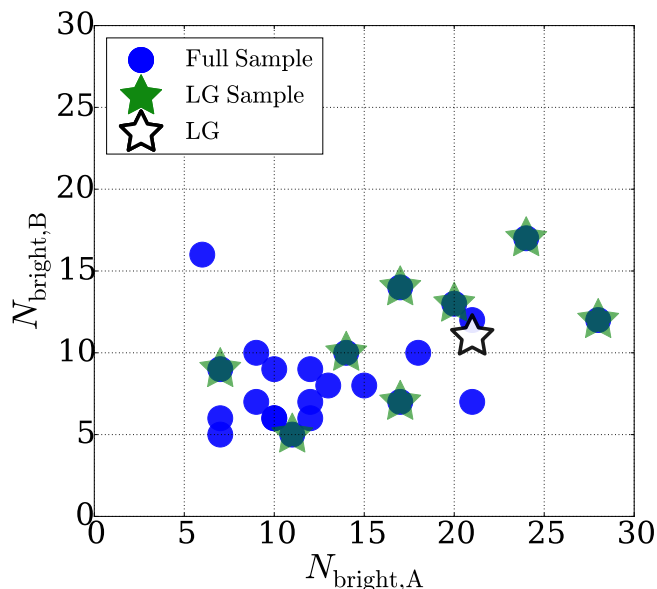
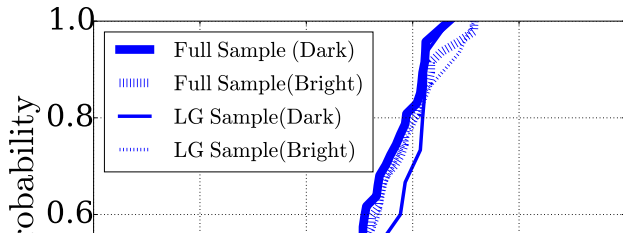


FIG. 2.— Number of bright substructures ( $M_B < -9$ ) and dark matter substructures. This resolution corresponds to  $\sim 1$  Mpc  $h$ . We interpolate the DM density on that mesh using a Cloud-In-Cell (CIC) scheme. We proceed to smooth the density field with a gaussian window with a physical scale 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 context (Forero-Romero et al. 2013; Forero-Romero & González 2015).



#### 2.4. Characterization of spatial distributions

In this paper, our aim is to study alignments: of the satellite population with the axis that unites them, etc... To do this, we fitted a triaxial spheroid to both the satellite (bright) and the dark matter (dark) subhalo distributions, to get both their semi-major and semi-minor axis. With this geometrical information we can study the alignments of the two distributions with the cosmic web, and also with the vector that unites the halo pair that host these substructures.

### 3. RESULTS

Some papers claim that once baryonic physics is included more planar distributions are found. First we investigate if there is a difference in the bright and dark distribution in terms of their flatness. In Figure 3 we can see that indeed the bright distribution is flatter than the dark distribution.

We then try to fit planes to both the dark and bright distributions in order to test if it is indeed easier to find thinner planes in the bright distribution. We find that the bright planes are thinner. But is there a physical reason for that? Apparently not, since the thinness of the fitted planes seems to be only due to number of objects: number of bright satellites is smaller than of dark subhalos and that results naturally in thinner fitted planes.

A second test is to look if there is any evidence of alignments between the distribution of satellites and the axis that unites the main halos that form the pair.

### 4. DISCUSSION

Difference between bright and dark distributions are only due to number.

We find significant alignments between distributions and H1H2 axis. But this alignments are the opposite as the one observed for the Local Group!!!

### 5. ACKNOWLEDGEMENTS

Gracias.

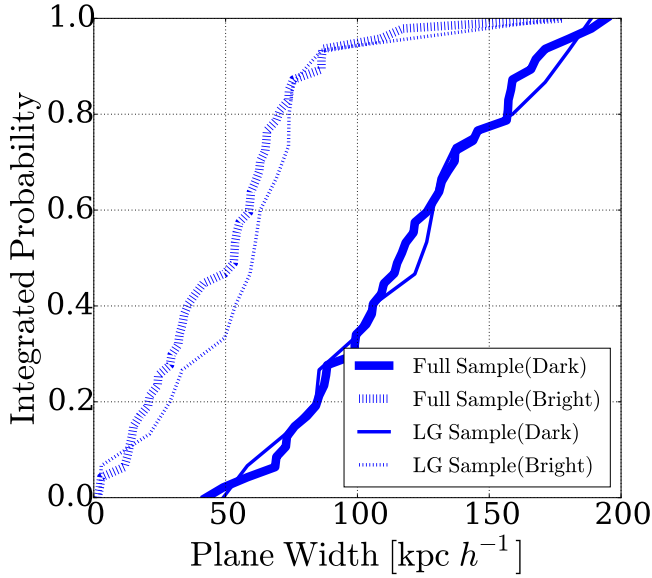


FIG. 4.— Plane width for the best planes in the luminous and dark cases.

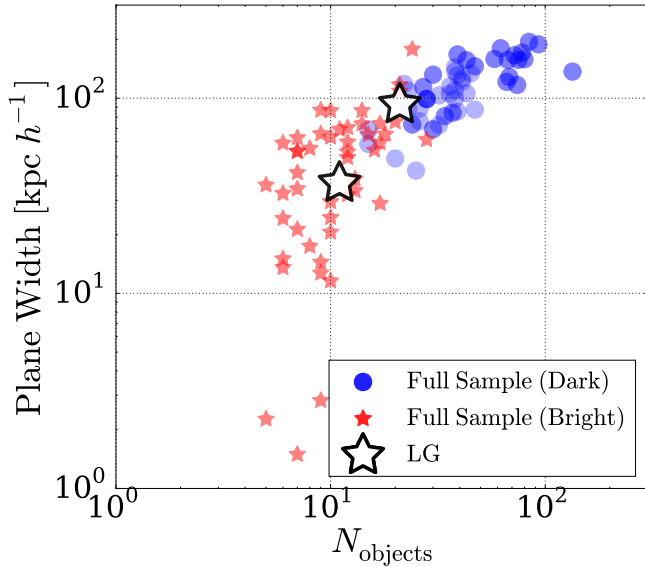


FIG. 5.— Plane width as a function of objects used to find the plane.

#### REFERENCES

- Forero-Romero, J. E., & González, R. 2015, *ApJ*, 799, 45
- Forero-Romero, J. E., Hoffman, Y., Bustamante, S., Gottlöber, S., & Yepes, G. 2013, *ApJ*, 767, L5
- Forero-Romero, J. E., Hoffman, Y., Gottlöber, S., Klypin, A., & Yepes, G. 2009, *MNRAS*, 396, 1815
- Hahn, O., Porciani, C., Carollo, C. M., & Dekel, A. 2007, *MNRAS*, 375, 489
- Lee, J., & Choi, Y.-Y. 2015, *ApJ*, 799, 212
- Libeskind, N. I., Guo, Q., Tempel, E., & Ibata, R. 2016, *ArXiv e-prints*
- Libeskind, N. I., Knebe, A., Hoffman, Y., & Gottlöber, S. 2014, *MNRAS*, 443, 1274
- Libeskind, N. I., Knebe, A., Hoffman, Y., Gottlöber, S., Yepes, G., & Steinmetz, M. 2011, *MNRAS*, 411, 1525
- Lynden-Bell, D. 1976, *MNRAS*, 174, 695
- Pawlowski, M. S., Famaey, B., Merritt, D., & Kroupa, P. 2015, *ApJ*, 815, 19
- Pawlowski, M. S., Kroupa, P., Angus, G., de Boer, K. S., Famaey, B., & Hensler, G. 2012, *MNRAS*, 424, 80
- Sawala, T., Frenk, C. S., Fattahi, A., Navarro, J. F., Bower, R. G., Crain, R. A., Dalla Vecchia, C., Furlong, M., Helly, J. C., Jenkins, A., Oman, K. A., Schaller, M., Schaye, J., Theuns, T., Trayford, J., & White, S. D. M. 2016, *MNRAS*, 457, 1931
- Shao, S., Cautun, M., Frenk, C. S., Gao, L., Crain, R. A., Schaller, M., Schaye, J., & Theuns, T. 2016, *ArXiv e-prints*
- Tempel, E., Guo, Q., Kipper, R., & Libeskind, N. I. 2015, *MNRAS*, 450, 2727

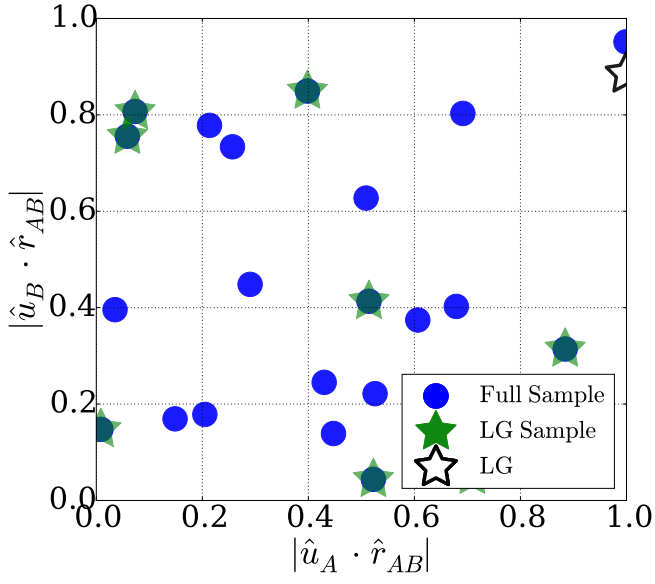


FIG. 6.— Alignment of the mayor axis with the vector connecting the two halos.

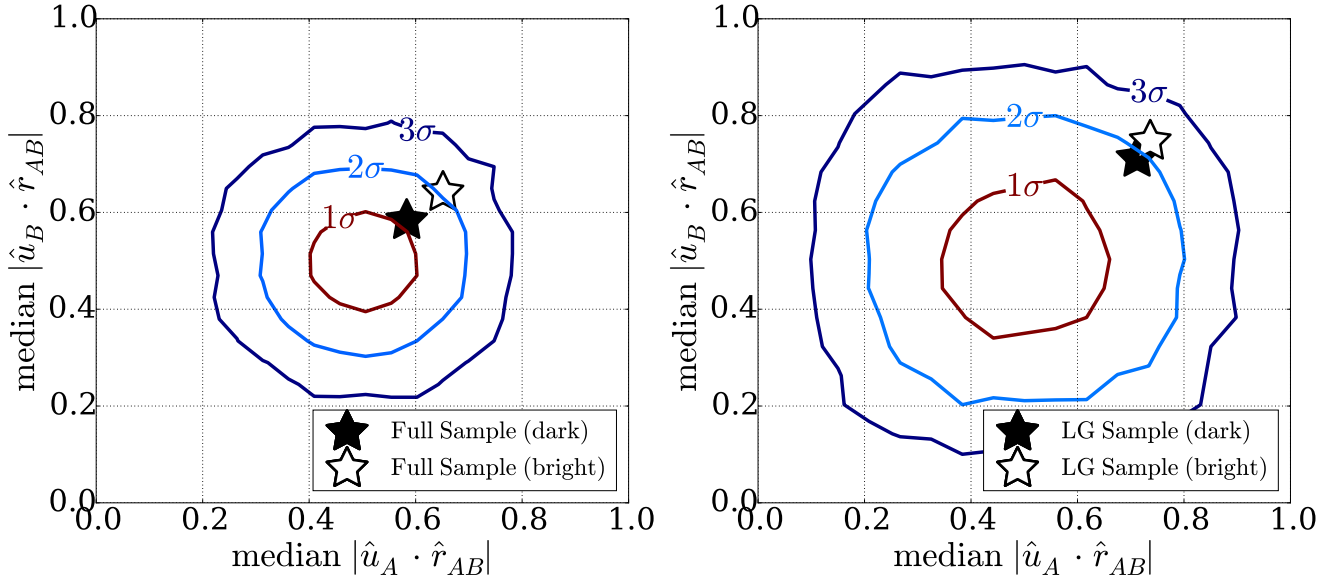


FIG. 7.— Significance of alignments for both samples.