

## THE LOCAL GROUP IN THE COSMIC WEB

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### ABSTRACT

We explore the characteristics of the cosmic web around Local Group(LG) like pairs using a cosmological simulation in the  $\Lambda$ CDM cosmology. We use the Hessian of the gravitational potential to classify regions on scales of  $\sim 2$  Mpc as a peak, sheet, filament or void. The sample of LG counterparts is represented by two samples of halo pairs. The first is a general sample composed by pairs with similar masses and isolation criteria as observed for the LG. The second is a subset with additional observed kinematic constraints such as relative pair velocity and separation. We find that the pairs in the LG sample with all constraints are: (i) Preferentially located in filaments and sheets, (ii) Located in a narrow range of local overdensity  $0 < \delta < 2$ , web ellipticity  $0.1 < e < 1.0$  and prolateness  $-0.4 < p < 0.4$ . (iii) Strongly aligned with the cosmic web, in particular for pairs in filaments/sheets the pair orbital angular momentum tends to be perpendicular to the filament direction or the sheet plane. A stronger alignment is present for the vector linking the two halos, which lies along the filament or the sheet plane. We show that the first and second results are expected trends with the LG total mass. However, the strong alignments with the cosmic web cannot be explained by a simple mass dependency. Additionally, we fail to find a strong correlation of the spin of each halo in the pair with the cosmic web. Applied to the observed LG, there is a potential conflict between these alignments and recent claims of an universal subhalo accretion direction. This highlights the relevance of achieving a precise characterization of the place of the LG in the cosmic web in a the cosmological context provided by  $\Lambda$ CDM.

*Subject headings:* galaxies: Local Group — dark matter

### 1. INTRODUCTION

The spatial and kinematic configuration of the Local Group (LG) galaxies is very uncommon in the local Universe and in cosmological simulations. The LG is dominated by two big spirals: MW and M31, the next most-luminous galaxy is M33 which is  $\sim 10$  times less massive than M31, followed by several dozen less luminous dwarf galaxies, up to a distance of  $\sim 3$  Mpc. The velocity vector of M31, with a low tangential velocity is consistent with a head-on collision orbit toward the MW (Cox & Loeb 2008; van der Marel et al. 2012b; Sohn et al. 2012).

Another feature of the Local Group is the relatively low velocity dispersion of nearby galaxies up to  $\sim 8$  Mpc (Sandage & Tammann 1975; Aragon-Calvo et al. 2011, and references therein). The environment around the Local Group has density quite close to the average density of the universe (Klypin et al. 2003; Karachentsev 2005). In addition, the closest massive galaxy cluster, the Virgo Cluster, is  $\approx 16.5$  Mpc away (Mei et al. 2007).

This combination of features makes LG analogues uncommon. Using numerical simulations González et al. (2014) found less than 2% MW-sized halos reside in a pair similar to MW-M31 and in a similar environment. Furthermore, if we select pairs constrained within  $2\sigma$  error from current observational measurements of the velocity components and distance to M31, there are only 46 systems in a cubic volume of  $250 h^{-1}$  Mpc side, giving a number density  $\sim 1.0 \times 10^{-6}$  Mpc<sup>3</sup>, comparable to the abundance of massive clusters. A similar abundance

was found by Forero-Romero et al. (2011) by comparing the formation history of LG pairs in constrained simulations with the results of unconstrained cosmological simulations.

Forero-Romero et al. (2013) also studied MW-M31 pairs in numerical simulations finding the typical quantities characterizing the orbital parameters of the LG are rare among typical pairs, but not sufficiently rare to challenge the  $\Lambda$ CDM model. Another set of criteria for LG analogues was used by Li & White (2008), but despite differences in the definitions and resulting fraction of LG analogues, results are in agreement with a low pairs frequency as well.

To better understand the properties of the LG and how this uncommon pair configuration can be explained in the cosmological context, an immediate question arises: What else can we say of the environment of the LG on larger scales?

Observationally, the LG is located in a diffuse and warped filament/wall connecting Virgo Cluster with Fornax Cluster, some nearby galaxies and groups members of this large structure are the Maffei group, NGC 6744, NGC 5128, M101, M81, NGC1023, Cen A group (Courtois et al. 2013). At this scale, there is no evident alignment of the MW-M31 orbital plane with any local filament or the Virgo-Fornax direction. However, if we look in a smaller volume below scales of  $\sim 6$  Mpc, there is a clear alignment of the MW-M31 orbit with a local plane of galaxies as shown by Figure 3 in Courtois et al. (2013).

We can then ask, to what extent is this an expected configuration in  $\Lambda$ CDM? In particular, which are the typ-

ical/preferred locations of these systems within the Cosmic Web?

In this paper we study the large scale environment of LG analogues in the context of  $\Lambda$ CDM. We use the Bolshoi simulation to explore in what structures they reside and if there is any correlation or alignment with the cosmic web. The large scale environment is defined by the cosmic web components identified by Forero-Romero et al. (2009), and we use the LG analogues computed by González et al. (2014).

This paper is organized as follows. In Section 2 we present the N-body cosmological simulation and the algorithm to define the cosmic web, next in Section 3 we describe the sample of LG analogues extracted from the simulation. In Section 4 we present our results to wrap up with a discussion and conclusions in Section 5.

## 2. SIMULATION AND WEB FINDING ALGORITHM

### 2.1. The Bolshoi simulation

We use the Bolshoi simulation of  $\Lambda$ CDM cosmology:  $\Omega_m = 1 - \Omega_\Lambda = 0.27$ ,  $H_0 = 70$  km/s/Mpc,  $\sigma_8 = 0.82$ ,  $n_s = 0.95$  (Klypin et al. 2011), compatible with the constraints from the WMAP satellite (Hinshaw et al. 2013). The simulation followed the evolution of dark matter in a  $250h^{-1}$  Mpc box with spatial resolution of  $\approx 1h^{-1}$  kpc and mass resolution of  $m_p = 1.35 \times 10^8 M_\odot$ . Halos are identified with the BDM algorithm (Klypin & Holtzman 1997). The BDM algorithm is a spherical overdensity halo finding algorithm and is designed to identify both host halos and subhalos.

### 2.2. Cosmic web identification

The web finding algorithm is based on the tidal tensor computed as the Hessian of the gravitational potential field

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

where  $r_i$ ,  $i = 1, 2, 3$  refers to the three spatial comoving coordinates and  $\phi$  is the gravitational potential renormalized to follow the Poisson equation  $\nabla^2 \phi = \delta$  where  $\delta$  is the matter overdensity.

This tensor is real and symmetric, which means that it can be diagonalized. We denote its eigenvalues as  $\lambda_1 \geq \lambda_2 \geq \lambda_3$  and their corresponding eigenvectors  $\hat{e}_1$ ,  $\hat{e}_2$  and  $\hat{e}_3$ . The web classification compares each one of the three eigenvalues to a threshold value  $\lambda_{th}$ . If the three, two, one or zero eigenvalues are larger than this threshold the region is classified as peak, filament, sheet or void, respectively. Because this tensor is also known as the tidal tensor we refer to it as the Tweb algorithm.

Forero-Romero et al. (2009) performed a detailed study for the topology of the cosmic web and its visual counterpart as a function of the parameter  $\lambda_{th}$ . They found that reasonable results in terms of the volume fraction occupied by voids, the visual inspection and the halo populations in each web type can be reached by values of  $0.2 < \lambda_{th} < 0.4$ . In this paper we choose the value of  $\lambda_{th} = 0.3$  to proceed with our analysis. This is only relevant to the classification of the simulation into web elements. Other results are completely independent of this choice. Nevertheless we have checked that the main

conclusions of this work do not depend on the precise choice of  $\lambda_{th}$ .

The algorithm to compute the potential is grid based. First we interpolate the mass into a cubic grid with a Cloud-In-Cell (CIC) scheme and smooth it with a gaussian kernel in order to reduce the grid influence in the computations that follow. Then we obtain the gravitational potential using FFT methods and use finite differences to compute the Hessian at every point in the grid. In our case we have used a grid size and a gaussian smoothing with two times larger as the typical separation between the two halos in the Local Group. The purpose of this choice is to have both halos in the pair a common environment. In this paper we use a grid spacing of  $s = 0.97 h^{-1}$  Mpc, corresponding to a  $256^3$  grid in the Bolshoi volume. The scale for the gaussian smoothing uses the same value.

We use the matter overdensity, ellipticity and the prolateness to further characterize the web. These quantities are defined in terms of the eigenvalues as follows

$$\delta = \lambda_1 + \lambda_2 + \lambda_3, \quad (2)$$

$$e = \frac{\lambda_3 - \lambda_1}{2(\lambda_1 + \lambda_2 + \lambda_3)}, \quad (3)$$

$$p = \frac{\lambda_1 + \lambda_3 - 2\lambda_2}{2(\lambda_1 + \lambda_2 + \lambda_3)}. \quad (4)$$

We also measure the alignment of the LG halos with respect to the cosmic web defined by their eigenvectors. To this end we characterize each LG pair by two vectors. The first is  $\hat{n}$ , the axis along the orbital angular momentum of the pair, normal to its orbital plane; the second is  $\hat{r}$ , the vector that connects the halos in the pair which can be related to the alignment of the radial velocities to the web. We quantify the alignment using the absolute value of the cosinus of the angle between the two vectors of interest  $\mu = |\hat{e}_i \cdot \hat{n}|$  or  $\mu = |\hat{e}_i \cdot \hat{r}|$ , where  $i = 1, 2, 3$ .

The data of the BDM halos and the Tweb is publicly available through a database located at <http://www.cosmosim.org/>. A detailed description of the database structure was presented by Riebe et al. (2013).

## 3. LOCAL GROUP ANALOGUES

To construct a sample of the MW-M31 pairs at  $z \approx 0$ , we use a series of simulation snapshots at  $z < 0.1$  (since the last  $\approx 1.3$  Gyr) spaced by  $\approx 150 - 250$  Myr. This is done because a particular configuration of MW and M31 is transient and corresponds to a relatively small number of systems at one snapshot. By using multiple snapshots we can increase the sample of systems in such configuration during a period of time in which secular cosmological evolution is small.

The LG analogues or the General Sample (GS) in this paper are pairs selected in relative isolation, and in a wide range of masses from  $M_{200c} = 5 \times 10^{11} M_\odot$  to  $5 \times 10^{13} M_\odot$ . Isolation criteria include pair members closer than 1.3 Mpc, and with no massive neighbors within 5 Mpc. In addition, we require that pairs have no Virgo-like neighbor halo with mass  $M_{200c} > 1.5 \times 10^{14} M_\odot$  within 12 Mpc. We have 5480 pairs under these general criteria. A full description of the selection criteria can be found in González et al. (2014, 2013).

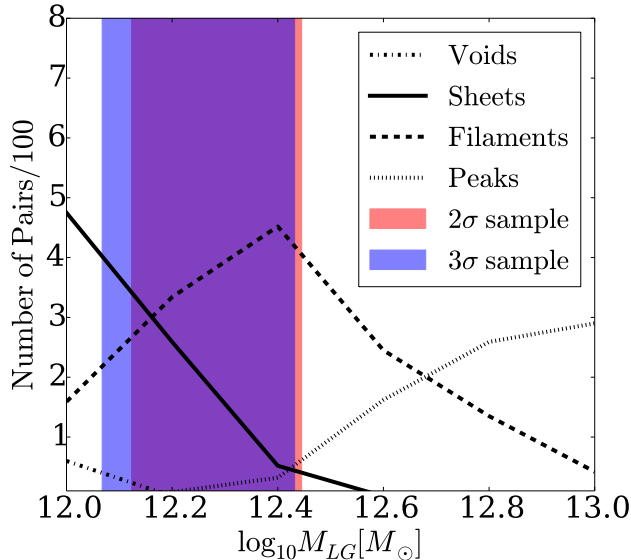


FIG. 1.— Mass distribution of pairs in different environments for the general sample. The shaded regions show the 68% confidence interval of the mass ranges for  $2\sigma$  and  $3\sigma$  samples.

We also define two subsets of restricted samples (RS) more closely related to the MW-M31 dynamics according to the tolerance in additional constraints. A sample named  $2\sigma$ , corresponding to LG analogues constrained by two times the observational errors in the orbital values (radial velocity, tangential velocity, and separation), and a more relaxed sample named  $3\sigma$  for LG analogues constrained by three times observational errors accordingly. The number of pairs in each sample is 46 and 120 respectively, notice we have less pairs than in González et al. (2014), since we removed pairs which are too close at  $z = 0$ , i.e. their virial radii overlap, also we removed a couple of pairs that merged or change their mass more than 20% at present time since they were detected at  $z < 0.1$ .

#### 4. RESULTS

##### 4.1. The preferred environment for LGs

The first result we explore is the kind of environment occupied by our LGs, and use as reference sample the GS where pairs are much more relaxed in mass and kinematic constraints. We find that the pairs in the GS are located across all different environment without any strong preferences; 1/3 are located in sheets, 1/4 in peaks, 1/4 in filaments and the remaining 1/6 in voids.

The situation in the  $2\sigma$  and  $3\sigma$  samples is very different. By and large the LGs in these samples are located in filaments and sheets. In both samples,  $\sim 50\%$  of the pairs can be found in filaments while  $\sim 40\%$  are in sheets. These absolute numbers in each environment for each sample are presented in Table 1.

We find that the difference between the GS and the RS can be explained by the total pair mass. In González et al. (2014) the mass range covered by  $2\sigma$  and  $3\sigma$  samples is very narrow and it is used to constraint the LG mass. We show in Table 1 that a subset of the GS having a similar mass range than the RS reproduces similar environment fractions. The correlation between halo

mass and their environment is a well known result (Lee & Shandarin 1998).

Figure 1 summarizes this correlation between environment and total pair mass. Each line represents the mass distribution of pairs in the four different environments for the GS. High mass pairs tend to be located in peaks and filaments while less massive ones in voids and sheets. The shaded regions represent the 68% confidence intervals of the mass distributions of  $2\sigma$  and  $3\sigma$  samples.

##### 4.2. Web Overdensity, Ellipticity and Prolateness

We now characterize the preferred place of the pair samples in terms of the web overdensity, ellipticity and anisotropy as defined in Section 2.

Figure 2 shows the dependency of these three characteristics on the total pair mass for the different samples. GS is represented by the solid lines with the associated errors covered by the shaded region. The symbols represent the results for the  $2\sigma$  and  $3\sigma$  samples. In three cases it is evident that the range of values for the  $2\sigma$  and  $3\sigma$  samples are completely expected from the mass constraint alone.

The left panel shows the overdensity dependence on pair mass. Higher mass pairs are located in high density regions. The  $2\sigma$  and  $3\sigma$  samples having a narrower mass range as shown in previous figure, are consequently located within a narrower range of overdensities  $0.0 < \delta < 2.0$  peaking at  $\delta \sim 1$ . This is also consistent with the fact that these samples are mostly found in filaments and sheets.

Middle and right panels show web ellipticity and absolute prolateness dependence on mass. Again we notice that within the  $2\sigma$  and  $3\sigma$  mass range, the average ellipticity and prolateness does not differ significantly from the GS expectation. In the RS samples the pairs are located in a narrow range for ellipticities  $0.1 < e < 1.0$  and absolute prolateness  $|p| < 0.4$ .

##### 4.3. Alignments with the cosmic web

We now study different alignments of the LG with respect to the cosmic web.

**Orbital Angular Momentum.** Figure 3 shows the cumulative distribution of  $\mu \equiv \hat{e}_i \cdot \hat{n}$  for the three eigenvectors  $i = 1, 2, 3$ . Lines in each panel correspond to different samples. The straight line across the diagonal shows the expected result for vectors with randomly distributed directions.

There are two important features in Figure 3. First the alignments themselves. There is a strong anti-alignment signature between  $\hat{n}$  and the third eigenvector. With respect to the second eigenvector the distribution is consistent with no alignment. While for the first eigenvector there is a strong alignment, an expected result considering the results with the other eigenvectors and keeping in mind that they are orthonormal. Second, the alignment strength changes for the different samples. For the anti-alignment with  $\hat{e}_3$  the signal strengthens as we move from the GS to the  $3\sigma$  into the  $2\sigma$  sample.

Quantitatively, the anti-alignment feature found with the  $\hat{e}_3$  vector means that for  $2\sigma$  sample,  $\sim 50\%$  pairs have  $|\mu| < 0.2$  ( $> 78$  degrees angle), and  $\sim 75\%$  pairs have  $|\mu| < 0.4$  ( $> 66$  degrees angle). These signals do not change significantly on different environments

Sample	Peak $n$ (%)	Filament $n$ (%)	Sheet $n$ (%)	Void $n$ (%)
$2\sigma$	4 (8.7)	24 (52.2)	17 (36.7)	1 (2.2)
$3\sigma$	10 (8.3)	58 (48.3)	47 (39.2)	5 (4.2)
General	1312 (23.9)	1472 (26.9)	1769 (32.3)	927 (16.9)
General ( $12.1 < \log_{10} M_{LG}/M_{\odot} < 12.3$ )	8 (1.4)	334 (55.5)	259 (43.0)	1 (0.1)

TABLE 1

NUMBER OF PAIRS IN THE FOUR DIFFERENT KINDS OF ENVIRONMENTS FOR EACH OF THE THREE SAMPLES PRESENTED IN SECTION 3. IN PARENTHESIS THE SAME NUMBER AS A PERCENTAGE OF THE TOTAL POPULATION. THE LAST LINE IN THE TABLE CORRESPONDS TO THE GENERAL SAMPLE WITH AN ADDITIONAL MASS CUT FOR THE TOTAL PAIR MASS.

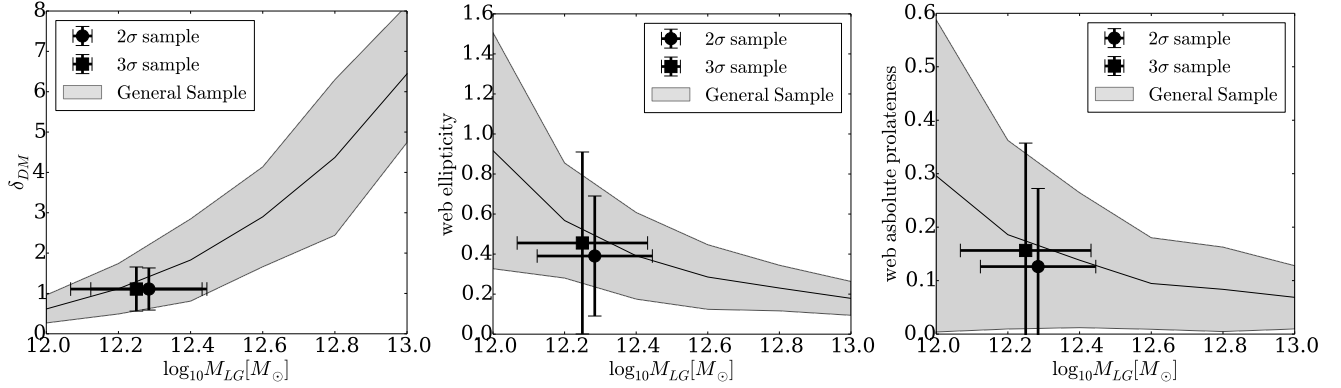


FIG. 2.— Mass dependency of the average dark matter overdensity (left), web ellipticity (middle) and web absolute value prolateness (right) at the pair location.

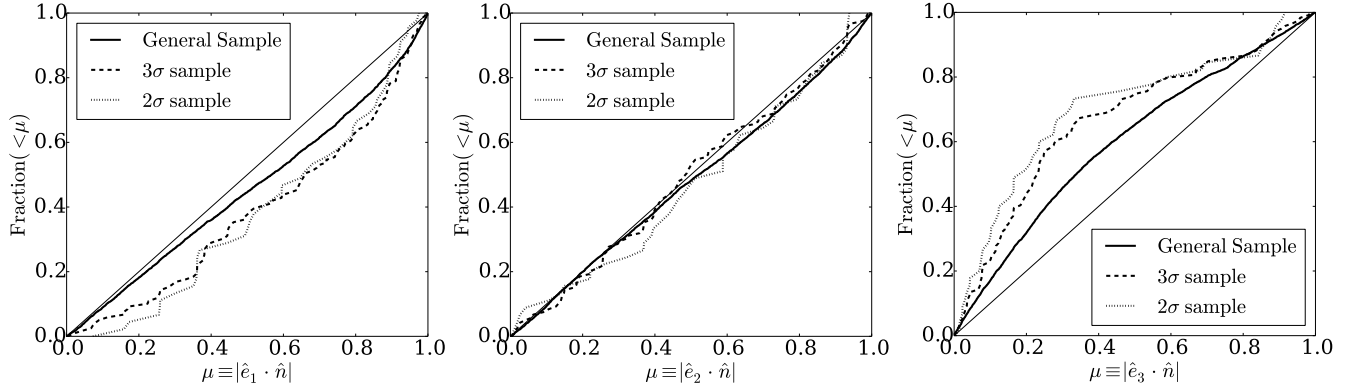


FIG. 3.— Cumulative distributions for the alignment between the normal vector to the pair orbital plane,  $\hat{n}$ , and the three eigenvectors in the Tweb.

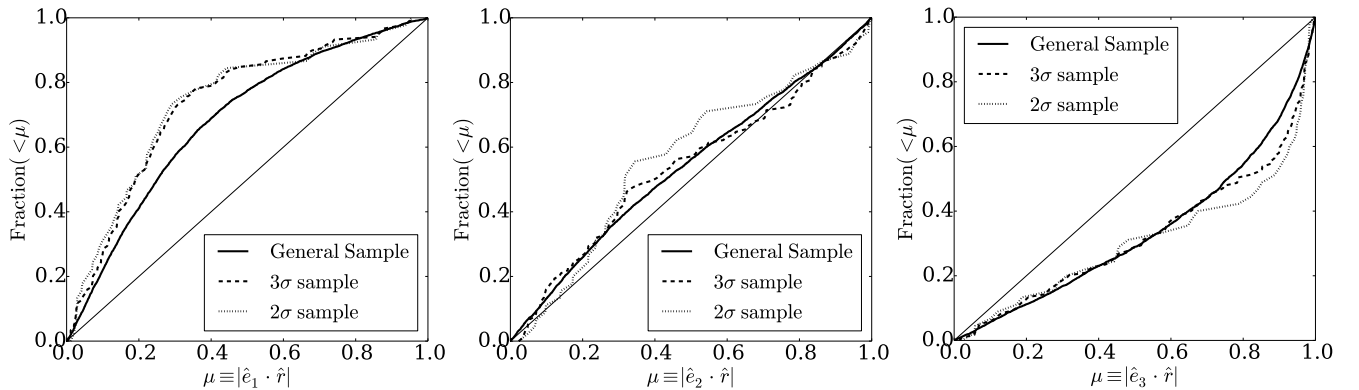


FIG. 4.— Cumulative distributions for the alignment between the vector linking the two halos in the pair,  $\hat{r}$ , and the three eigenvectors in the Tweb.

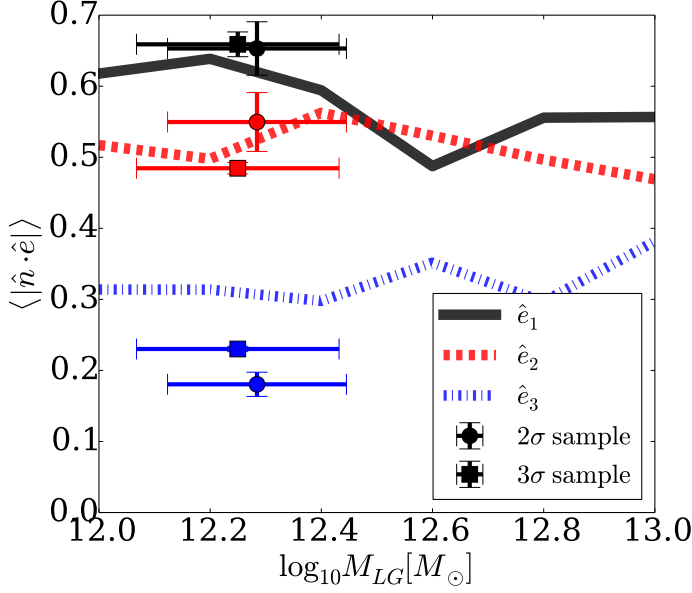


FIG. 5.— Mass dependency of the median value for the dot product between the normal vector  $\hat{n}$  and each one of the eigenvectors. The lines show the trends for the general sample.

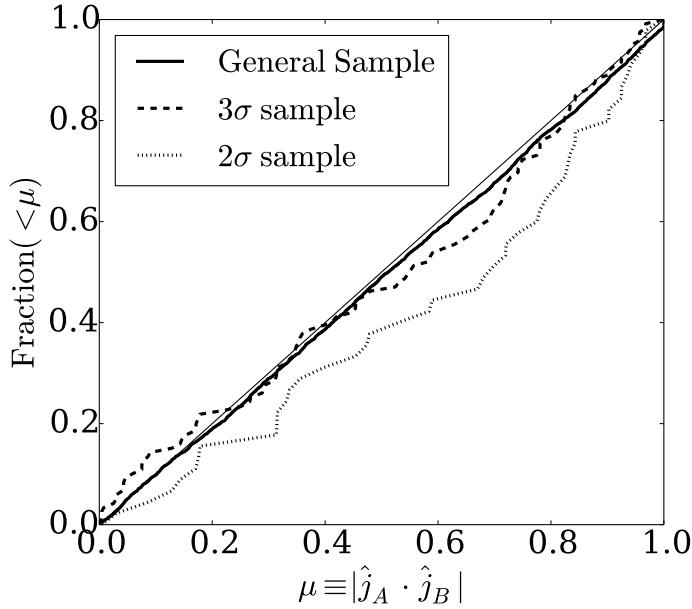


FIG. 6.— Alignment between the two angular momentum vectors of the two halos in the pair.

as has been already show in different alignment studies with similar (Libeskind et al. 2013) or identical (Forero-Romero et al. 2014) web finding techniques as ours. In particular, these trends hold for pairs in filaments and walls. If we consider only pairs in filaments, we have that the pair orbital angular momentum tends to be perpendicular to the filament direction, in the case of sheets it tends to lie perpendicular to the sheet plane.

Can the increase of the alignment strength in the different samples be explained as a consequence of different mass dependencies as in the results in the previous section? The answer is no. In Figure 5 we show the median of  $\mu \equiv \hat{e}_i \cdot \hat{n}$  in different mass bins. Lines show the me-

dian  $\mu$ -mass relation for the three eigenvectors in the GS, dots represent the results for the  $2\sigma$ - $3\sigma$  samples. Around the total mass  $1.5 - 2.0 \times 10^{12} M_\odot$  in the RS samples, the median of  $\mu$  decreases as we tighten constraints on the pairs, but not as a result of the narrowing mass selection.

We explored the main differences between the GS and RS samples which can be producing this alignment strength feature, and we have that RS samples contrain the tangential velocity, then pair orbits are more eccentric as we tighten pair constraints, and for GS sample there is no tangential velocity constraint at all. Therefore, to study any relation between orbit eccentricity and alignment, we computed for each halo pair in all samples, an approximate orbit eccentricity assuming a two body orbit with masses set as the virial masses and initial conditions given by current velocity vector and separation. We found that eccentricity is not responsible for this alignment feature by selecting a subsample of GS having the same eccentricity than  $2\sigma$ - $3\sigma$  samples, and we found no increase in the alignment of this subsample with GS.

**Radial Vector.** Figure 4 presents the results for the eigenvectors alignments with respect to the vector connecting the two halos. In this case we find that the vector  $\hat{r}$  is strongly aligned along the direction defined by  $\hat{e}_3$  and anti-aligned along  $\hat{e}_1$ ; correspondingly the signal along  $\hat{e}_2$  is rather weak.

We also find a stronger signal as we move into more restrictive samples, although the signal from the GS is already very significant. Quantitatively, the alignment feature with  $\hat{e}_3$  means that for the  $2\sigma$  and  $3\sigma$  samples,  $\sim 50\%$  pairs have  $|\mu| > 0.8$  ( $< 36$  degrees angle) and  $\sim 25\%$  pairs have  $|\mu| > 0.95$  ( $< 18$  degrees angle). Similar to the previous case of the  $\hat{n}$  vector, the increasing strenght of the  $\hat{r}$  alignment cannot be explained by a selection on mass.

Considering that the  $2\sigma$  and  $3\sigma$  samples correspond to pairs moving along the radial direction, we can say that the motion of the LG halos is mostly done along the  $\hat{e}_3$  vectors. This is consistent with recent results that report a strong alignment of halo's peculiar velocities along that direction (Forero-Romero et al. 2014).

**Halo Spin.** We also explore the alignment of the angular momentum (spin) of each pair member  $\hat{j}_A$  and  $\hat{j}_B$  with each other, the orbital angular momentum and with the cosmic web.

Figure 6 shows the cumulative distribution of dot product between angular momentum of the two halos. We find a slight alignment of spin vectors for the  $2\sigma$  sample with a median around  $|\mu| \sim 0.7$  (45 degrees). However, we found no significant alignment with the orbital angular momentum nor the cosmic web. This is also consistent with recent results that show that the spin alignment of halos of masses around  $10^{12} M_\odot$  is very weak (Forero-Romero et al. 2014).

In the LG, the angle between MW and M31 spin is  $\sim 60^\circ$  ( $|\mu| = 0.5$ ) and the angles between spins and orbital angular momentum are  $\sim 33^\circ$  ( $|\mu| = 0.83$ ) and  $\sim 76^\circ$  ( $|\mu| = 0.24$ ) for MW and M31 respectively (van der Marel et al. 2012a). This is consistent with our results of no strong alignment.

## 5. DISCUSSION AND CONCLUSIONS

The mass range of the LG pairs is tightly correlated with the properties of the web in which they reside, as shown in Table 1 and Figure 1. This confirms that the local overdensity, the trace of the tidal tensor, is the dominant web parameter that define the abundance and properties of halos (Lee & Shandarin 1998; Lemson & Kauffmann 1999; Sheth & Tormen 2004; Fakhouri & Ma 2009; Alonso et al. 2014). Other quantities derived from the tidal tensor play a secondary role defining properties such as its formation history.

In our case, the fact that the preferred LG total mass is around  $1 - 4 \times 10^{12} M_{\odot}$  implies that the preferred environment are filaments and sheets with an overdensity close to the average value. Correspondingly, the values for the ellipticity and prolateness are also well defined for the LG pairs given its correlation with the total mass.

We conclude that the typical LG environment and its characteristics is a robust results depending mostly on the LG total mass.

However, the alignments with the cosmic web are mass-independent and seem to be stronger once the kinematic constraints are imposed on the GS pairs. There is a clear anti-alignment between the third eigenvector and the orbital angular momentum vector, meaning that this vector is perpendicular to filaments and the sheets, We also found that the vector joining the LG halos are aligned with the third eigenvector. This means that the pair is aligned with the filaments and lies on the sheets and its motion is done along these directions.

These alignment features are in agreement with the scenario that pairs created in-situ or falling into a filament/wall align their orbits with the large scale structure in a relaxation process where pair members tend to moves along the slowest collapsing directions.

The most interesting feature is that these alignments are tighter as we narrow the kinematic conditions of the LG towards the observed values. A deeper understanding requires the study of the full formation history and coevolution with the cosmic web, a task beyond the scope of the work presented here.

These alignments for the LG pairs could be in contradiction with findings (Zentner et al. 2005; Bailin et al. 2008; Libeskind et al. 2014) that report a universal trend where the eigenvector  $\hat{e}_3$  (i.e. the filament direction) marks the infall direction for substructures. The Milky Way satellites are located at high galactic latitudes, almost perpendicular to the vector pointing towards the Andromeda Galaxy, which is the direction that we find

aligned with  $\hat{e}_3$ .

If the alignment we find in this paper holds, this would imply that infall in the case of the Milky Way is perpendicular to  $\hat{e}_3$ , in contradiction to the accretion along filaments. If the universal accretion along filaments holds, that would imply that the Andromeda galaxy is located perpendicular to  $\hat{e}_3$ , in contradiction with the strong alignment found in this paper.

This apparent contradiction can be solved if one considers that the subhalo infall properties depend on the environment at *the merger time*, while the alignments for yet unvirialized pairs such as the LG depend on the current state of the cosmic web. This also explain the absence of a strong alignment with halo spin, because it reflects past configurations of the web, not the current one. From this perspective, a joint consideration of the alignments between the dominant halos in the LG and their satellites, which also feature strong signals (Kroupa et al. 2005; Conn et al. 2013), should inform us about the structural evolution of the cosmic web.

Our results also raise the need to observationally constrain the alignments of LG pairs with their cosmic web environment. To this end one could use mass reconstructions from large surveys (Wang et al. 2009; Muñoz-Cuartas et al. 2011; Wang et al. 2014; Nuza et al. 2014) or filament finders (González & Padilla 2010; Sousbie 2011) to select a LG sample to quantify the alignments with the filamentary structure. This allows not only a direct quantification of how common are the LG alignments but also provides a new test of  $\Lambda$ CDM.

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