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The place of the local group in the cosmic web

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ABSTRACT

We present a theoretical study Local Group in a cosmological context. The principal objective is to find a coherent sample of LG systems in the unconstrained simulation Bolshoi based upon the properties of hand construted LG systems in the constrained simulations CLUES. We obtain a privileged environment for these systems and significant bias in some of their properties. (**draft!**)

Key words: galaxies: high-redshift - galaxies: star formation - line: formation

1 INTRODUCTION

The spatial distribution of galaxies describes a web-like pattern, the so-called cosmic web. Today it is understood that such configuration is driven by gravitational instabilities. ...

The study of the influence of the cosmic web on galaxy properties start with the seminal work of Dressler **[reference here]** and extends to recent works using large observational surveys that look for signatures of the web into the evolution of galaxy populations. With the advention of more detailed observations and sophisticated computational models it is now within our reach to understand what physical processes dominate.

This makes that the mass assembly history of a galaxy is deeply connected with its position in the cosmic web. There is an extensive body of literature on the effects of the web environment on the observable properties of galaxies.

This environmental study is also of paramount importance to understand the formation of our Galaxy. In our local neighborhood, the observations of dwarf galaxies around the Milky Way (MW) and the Andromeda galaxy (M31) show filamentary and disk-like patterns that can be linked to a preferential infall direction, very likely connected with the cosmic web where the Local Group (LG) of galaxies is embedded.

In this paper we quantify the velocity shear environment of DM halo pairs representative of the principal members of the Local Group (LG), the Milky Way (MW) and Andromeda galaxy (M31). We perform this study in two kinds of cosmological simulations: unconstrained simulations from random phases in the initial conditions, together with constrained simulations, which have been setup as to reproduce the large scale structure of the local universe ($\sim 30h^{-1}$Mpc around the local group) on scales of $\sim 5h^{-1}$Mpc .

We pay special attention to the correlation of the present velocity shear environment with the assembly and the kinematics properties of the pairs. The motivation to have that focus is that it has been previously shown that the LG present in three different realizations of the constrained simulations have assembly histories biased towards early formation times and absence of major mergers (ratio 1:10) in the last 10 Gyr. In the case of the kinematic properties, recent observational constrains to the galactocentric tangential velocity of M31 has enabled to establish how typical is the LG in a cosmological context **[reference to Forero-Romero 2013-1]**, that is why we focus here how a specific kind of host environment biases these kinematics properties.

2 THE SIMULATIONS

We use two sets of simulations two identify the possible large scale environment of the Local Group. This is similar approach to the one already used by **[reference here]**. The first set of simulations are constrained, that aim at reproducing the large scale environment around the local group as described by observations. The second simulations is an unconstrained cosmological volume that serve us as a benchmark of the results obtained from the constrained realizations. In the following subsections we describe the most relevant characteristics of these two simulations.

2.1 The CLUES simulations

The CLUES simulations have constrained initial conditions. The design goal was being able to reproduce in a N-body

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simulation the density distribution in the local universe on scales of ~ 5 Mpc as accurate as the observations allow. A full description of the methods and results in the CLUES project was done by **[reference here]**, a summary of the cosmological volumes we use in this paper was presented by **Forero-Romero et al. 2011.**

The most relevant technical details are the following. We use three DM only simulations done in cubic volumes of $64h^{-1}$Mpc (comoving) on a side. The matter field is sampled with 1024^3 particles, the integration was performed using the Tree-PM MPI N-body code Gadget2 **[reference here]**. The cosmological parameters are consistent with a WMAP5 and WMAP7 cosmologies with $\Omega_{\rm m} = 0.28$, $\Omega_\Lambda = 0.72$, $h = 0.73$, $n = 0.73$ and $\sigma_8 = 0.817$ **[reference to Komatsu]** for the matter density, cosmological constant, dimensionless Hubble parameter, spectral index of primordial density perturbations and normalization for the power spectrum. With these parameters the mass of each particle in the simulation is $m_{\rm p} = 1.89 \times 10^7 h^{-1}{\rm M}_\odot$.

2.2 The Bolshoi simulation

The Bolshoi simulations follows the non-linear evolution of a dark matter density field on a cubic volume of size $250h^{-1}$Mpc sampled with 2048^3 particles. The cosmological parameters in the simulation are $\Omega_{\rm m} = 0.27$, $\Omega_\Lambda = 0.73$, $h = 0.70$, $n = 0.95$ and $\sigma_8 = 0.82$ for the matter density, cosmological constant, dimensionless Hubble parameter, spectral index of primordial density perturbations and normalization for the power spectrum. The mass of each particle in the simulation is $m_{\rm p} = 1.4 \times 10^8 h^{-1}{\rm M}_\odot$.

2.3 Halos and Merger Trees

We identify halos with a Friends-of-Friends (REF) algorithm. These catalogues also provide the basis for the mass aggregation history studies. All the results presented here must be interpreted in term of host halos, without any information of the substructure. In particular the merger of two FOF halos corresponds to the epoch of first overlap, and not to the fusion and/or disruption of an accreted subhalo with a dominant halo.

The linking length is $b = 0.17$ times the mean interparticle separation. All objects with 20 particles or more are considered a bona fide halo and are included in the construction of the merger tree, this corresponds to a minimum halo mass of $M_{\rm min} = 3.78 \times 10^8\ h^{-1}{\rm M}_\odot$in the CLUES volumes and $M_{\rm min} = 2.70 \times 10^9 h^{-1}{\rm M}_\odot$in the Bolshoi simulation.

The halo identification for the CLUES simulation was done for 80 snapshots in the redshift range $0 < z < 7$ more or less evenly spaced in look-back time. For Bolshoi we use the information of XX snapshots in the same redshift range.

3 ALGORITHMS TO FIND THE COSMIC WEB

3.1 The tidal web - T-web

The first algorithm we use to identify the cosmic web is based on the diagonalization of the tidal tensor, defined as the Hessian of a normalized gravitational potential

$$T_{\alpha\beta} = \frac{\partial^2\phi}{\partial x_\alpha \partial x_\beta} \tag{1}$$

where the physical gravitational potential has been rescaled by a factor $4\pi G\bar{\rho}$ in such a way that ϕ satisfies the following equation

$$\nabla^2\phi = \delta, \tag{2}$$

where $\bar{\rho}$ is the average density in the Universe, G is the gravitational constant and δ is the dimensionless matter overdensity.

3.2 The velocity web - V-web

We use the a kinematical method to define the cosmic-web environment in the simulation. The method has been thoroughly described in XXX and applied to study the shape and spin alignment in the Bolshoi simulation here XX. We refer the reader to these papers to find a detailed description of the algorithm, its limitations and capabilities. Here we summarize the most relevant points for the discussion.

The V-web method for environment finding is based on the local shear tensor calculated from the smoothed DM velocity field in the simulation. The central quantity is the following dimensionless quantity

$$\Sigma_{\alpha\beta} = -\frac{1}{2H_0}\left(\frac{\partial v_\alpha}{\partial x_\beta} + \frac{\partial v_\beta}{\partial x_\alpha}\right) \tag{3}$$

where v_α and x_α represent the α component of the comoving velocity and position, respectively. $\Sigma_{\alpha\beta}$ can be represented by a 3×3 symmetric matrix with real values, that ensures that is possible to diagonalize and obtain three real eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$ whose sum (the trace of $\Sigma_{\alpha\beta}$) is proportional to the divergence of the local velocity field smoothed on the physical scale $\mathcal{R}$.

The relative strength of the three eigenvalues with respect to a threshold values λ_{th} allows for the local classification of the matter distribution into four web types. Voids, sheets, filaments and peaks, which correspond to regions with 3, 2, 1 or 0 eigenvalues with values larger than λ_{th}. In this paper we do not perform an definitive classification into web types, instead we express the results respect to the relative strength of the eigenvalues and in a range of λ_{th}. To choose a suitable range we propose a new quantity analogous to expression 3, but built with the physical velocity field w_α and physical coordinates r_α, the physical local shear tensor, defined as

$$\Pi_{\alpha\beta} = -\frac{1}{2H}\left(\frac{\partial w_\alpha}{\partial r_\beta} + \frac{\partial w_\beta}{\partial r_\alpha}\right) \tag{4}$$

evaluating this quantity in current epoch, we obtain the next relation between both tensors

$$\Pi_{\alpha\beta} = \Sigma_{\alpha\beta} - \delta_{\alpha\beta} \tag{5}$$

Using this relations, we can establish the two extreme λ_{th} values to present our results. The first one $\lambda_{th} = 0$, it is obtained assuming that the sign of each eigenvalue indicates the nature of collapse in the respective direction, what is valid in the strong non-linear scale where the peculiar velocity field is mainly dominant. The upper limit $\lambda_{th} = 1$ is obtained using the same previous argument, but using the eigenvalues of the the physical tensor, what is valid in the weak non-linear scale, where the hubble flow is still dominant.

We consider *a posteriori* the possible web type interpretation that could be feasible within a range of thresholds for the eigenvalues.

3.3 The Web in Bolshoi and CLUES

... Resolution and Smoothing

... Database

4 LOCAL GROUP SAMPLE DEFINITION

In order to establish an adequate set of criteria to define LG samples in unconstrained simulations, we proceed from the the general dark halo catalogues, constructed using the FOF scheme with a linking length of $b = 0.17$. These samples are defined for all simulation and will be referred as General Halos (GH) samples. To be consistent with the observationally determined mass range of halos that host disk-form galaxies, we select the halos in the mass range $5 \times 10^{11} < M_h/h^{-1}\mathrm{M}_\odot < 5 \times 10^{12}$, referred here as Individual Halos (IH) samples.

As a primal approach to define gravitational bounded halo pairs we select all halo pairs in IH samples that satisfied to be the closest to each other, they constitute the Pairs (P) samples. To keep the concordance with previous works in LG selection algorithms ([**references here**]), we define here the next list of conditions that have to fulfill a pair system in order to construct the Isolated Pairs (IP) samples. All these considerations are based upon the relative dynamics of the Milky Way and M31, and its isolation from massive structures:

(i) The Local Group is considered to be a pair of halos with dark matter masses in the range $5 \times 10^{11} < M_h/h^{-1}\mathrm{M}_\odot < 5 \times 10^{12}$.
(ii) The distance between the center of the two halos should be less than $0.7h^{-1}$Mpc .
(iii) The relative physical velocity between the two halos has to be negative.
(iv) The distance to any halo more massive than any of the pair members must be less than XXh^{-1}Mpc .
(v) The distance to cluster-like halos with masses larger than XXh^{-1}Mpc must be larger than XXh^{-1}Mpc .

In the case of a constrained simulation on can include an additional constrain

(vi) The Local Group pair must be located in the right environment with respect to the XX Cluster.

From these conditions it is possible to construct three different samples. A sample of pairs, following conditions 1 to 3. A second sample of isolated pairs, that additionally fulfill conditions 4 and 5, and a sample third sample of LGs that fulfills condition 6. The samples of pairs and isolated pairs can be constructed from the Bolshoi and CLUES simulations. However, by construction, the LGs sample can only be extracted from the constrained simulation.

Sample description	CLUES 1	CLUES 2	CLUES 3	Bolshoi
GH	56632	57707	56799	432000
IH	1493	1490	1493	88068
P	386	380	387	23037
IP	20	12	18	1256
LG	1	1	1	–
CLG	1	2	3	17

Table 1. Size of the samples in each simulation. The relation between the size of the samples scales as the relation between the volumes of each respective simulation, approximately 1/60 for the CLUES simulations respect to Bolshoi.

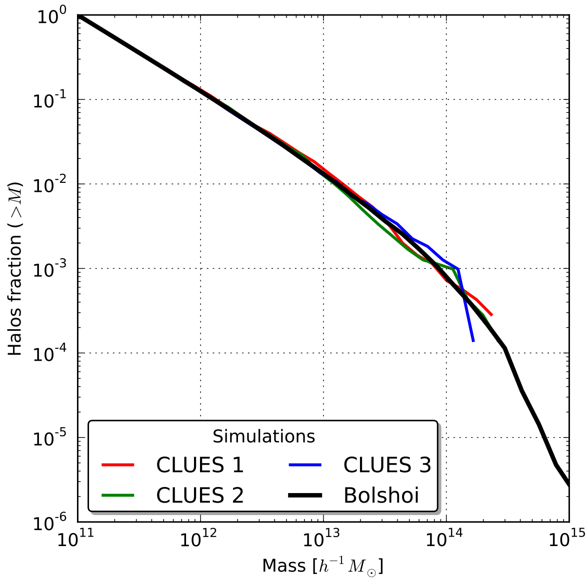
5 FINDING A LOCAL GROUP ENVIRONMENT

In this section we prepare some numerical experiments with the halos samples and their environment, with special emphasis on the isolated pairs and LG samples. All this in order to find for environment correlations and common properties between LG systems.

5.1 Comparison of the two simulations

Prior to study of isolated and LG samples and to determinate possible correlations between their properties, it is necessary to establish the equivalence between all simulations that we will use, with the aim to eliminate effects due to construction process of each one.

In first place, we analyse the mass distribution of individual halos and in next figure we show the integrated mass function (IMF) for halos sample with $M \geq 1 \times 10^{11} M_\odot$.



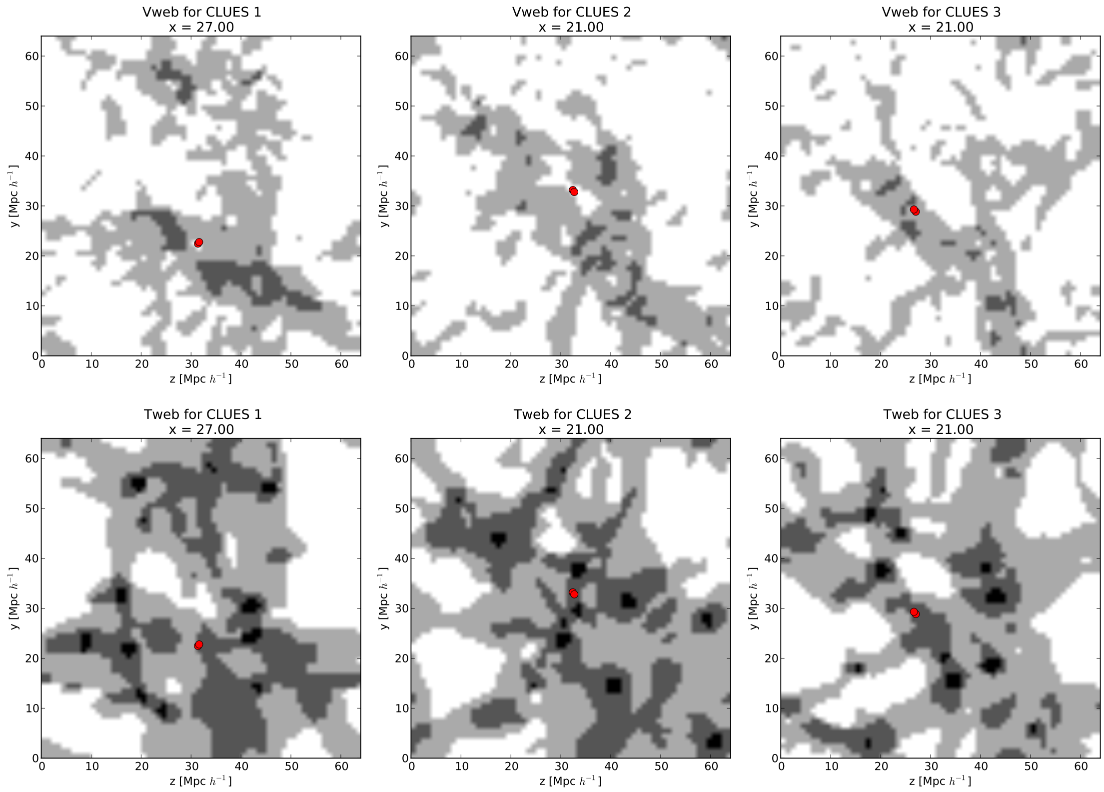
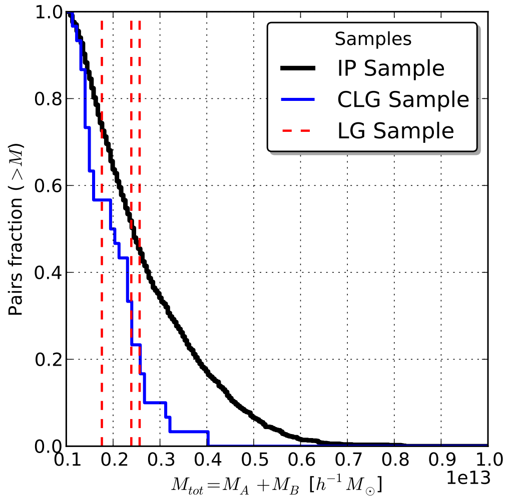
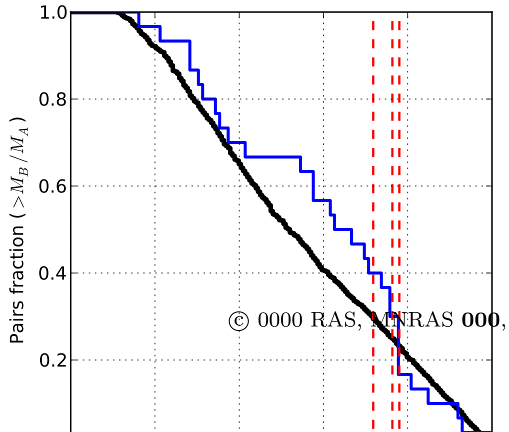


Figure 1. Environment of LG systems in each CLUES simulation, according to V-web scheme (upper figures) and to T-web scheme (lower figures).

Figure 2: Integrated mass function of individual halos of each simulation used. In the center-left, with vertical dot lines, the individual masses of each LG system in CLUES simulations are represented.



Although in high masses the IMF of each simulation are slightly different, in low mass region, where the most halos of our interest are, the IMFs are quite similar indicating that the sample of halos in each simulation have the same mass distribution, while the small differences are due to finite size of samples. Another aspect in the figure 2 is the position of LG halos, they are distributed across the mass range of halos that we have set (see in section 4), indicating that there is not an apparent condition with their individual masses.



	$\boldsymbol{\lambda_1}$	$\boldsymbol{\lambda_2}$	$\boldsymbol{\lambda_3}$
Minim value	1.77×10^{-1}	-6.29×10^{-3}	-1.98×10^{-1}
Maxim value	3.49×10^{-1}	1.21×10^{-1}	-8.85×10^{-2}

Table 2. Extreme values for each eigenvalues to construct LG samples.

Figure 3: Integrated distribution of mass ratio index for isolated pairs sample (a).

The situation is quite different respect to mass ratio index of isolated pairs sample (MRI). In the figure 3 (a) we show the integrated distribution of MRI, where the approximately linear behaviour indicates an uniformly distribution. The interesting aspect here is the closeness between the LG sample values, indicating a possible common property in these systems, even though this could be established a priori by construction. In the 3 (b) is plotted the integrated distribution of total pair mass, and again like the IMF, there is not a preferential value.

Once established the concordance between the defined samples, we proceed to analyse the distribution of the eigenvalue of shear velocity tensor 3, for this we assume that the halos are good tracers of the environment properties and therefore we evaluate each eigenvalue in the center mass of each halo, mapping of this way the complete distribution (figure 4). The black curves correspond to the unconstrained simulation (Bolshoi) and the color curves to the constrained simulations (CLUES), aditionally we calculate the cosmic variance, showed in purple curves, dividing the Bolshoi volume in smaller parts with a size comparable to the CLUES volume ($64h^{-1}$ Mpc of side). What is interesting here is the clear difference between the eigenvalues distributions of the both types of simulations, inclusively the constrained distributions does not match between the cosmic variance, indicating that although both simulations were made with the same cosmology (see subsections 2.1 and 2.2), the constrained simulations have a significantly different environment properties (spatial matter distribution) compared to the average expected from a random volume with the same comoving size.

5.2 Defining the LG environment

With the aim of constructing a sample of LG systems in Bolshoi simulations, we use the eigenvalues of the three LG systems in each CLUES simulation and choose a range for each one based in the extreme values of the six halos, this with the expectation of reproducing the LG specific conditions in constrained simulations. This criteria can be thought as a first approximation to establish a more faithful sub-sample into the isolated pairs. In table 2 we show the used extreme values for each eigenvalue of local shear tensor.

As a self-consistency test, we apply this criteria to CLUES simulations and find, on average, three LG systems in each one. But to avoid confusion, we keep defining the LG sample as the three initial pairs. Finally, we construct the LG sample of Bolshoi, where the sample size is illustrated in Table 1.

Once we have established the equivalence of samples in each simulation and have defined the LG samples, we proceed to calculate correlations between halo samples and their environment. As was mentioned in section 3.2, we do not use an specific value of eigenvalue threshold λ_{th}, instead of this, we explore a relatively wide range of this parameter (i.e. $0 \leq \lambda_{th} \leq 1$) and calculate distributions respect to each eigenvalue individually.

At first place, we calculate the environment of each LG system in CLUES simulations, for this we use the λ_{th} scheme to classify it in void, sheet, filament or knot (see 3.2), with λ_{th} into the threshold range. Figure **??** is obtained.

At first place, we calculate the integrated distribution of each eigenvalue for individual halos, isolated pairs and LG samples. For this, we associate to each halo a value of environment (set of eigenvalues) according to its center of mass position in a smoothed grid (256^3 cells for Bolshoi and 64^3 for CLUES, or equivalently a resolution of 1.0Mpc h^{-1} per cell, according to the physical size of the pairs.)

6 RESULTS

6.1 Bias induced on kinematic and dynamics properties

... Total Mass
... Radial vs. tangential velocities
... Angular Momentum
... Total Mechanical energy.
... Reduced Spin

6.2 Bias induced on the Mass Assembly Histories

... Last major merger. Formation Time. Assembly Time.

6.3 Pair Alignment with the Cosmic Web

... Separation.
... Relative velocity.
... Angular Momentum.

7 CONCLUSIONS

ACKNOWLEDGMENTS

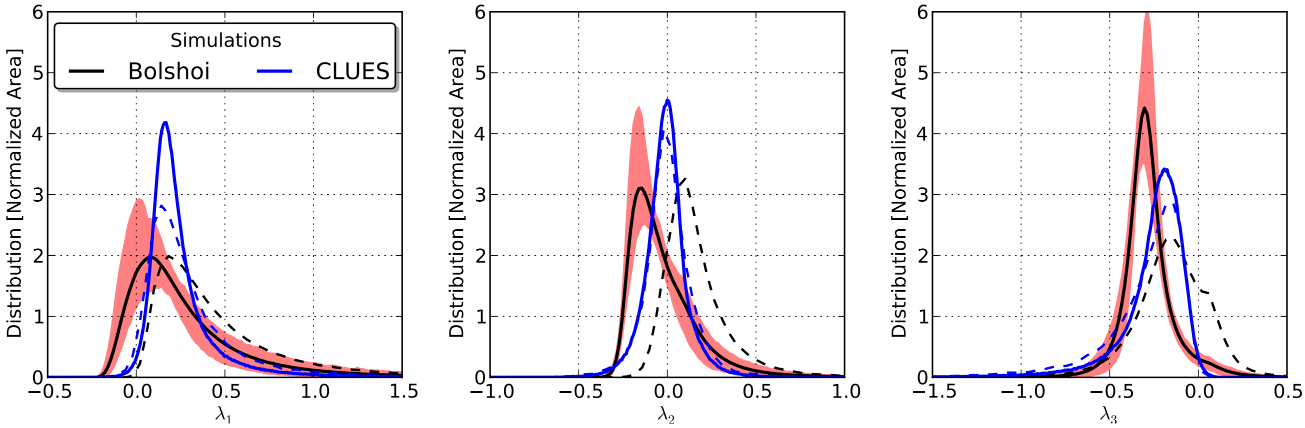


Figure 4. Integrated distribution of mass ratio index for isolated pairs sample (a).