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Analysis of bulk void regions

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ABSTRACT

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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. ...

Relevant information about previous works and current state of the art.

2 THE SIMULATION

As it was previously mentioned, we use an unconstrained cosmological simulation, the Bolshoi simulation, to identify the possible large scale environment of the Local Group. This is a similar approach to the one already used by **[reference here]**.

The Bolshoi simulation 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 $m_{\rm p} = 1.4 \times 10^8 h^{-1}{\rm M}_\odot$. We identify halos with two algorithms, the Friends-of-Friends **[reference here]** algorithm and the Bound Density Maximum algorithm.

3 ALGORITHMS TO QUANTIFY THE COSMIC WEB

3.1 The tidal web (T-web)

The first algorithm we use to identify the cosmic web is based upon 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 also use 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 value λ_{th} allows for the local classifica-

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tion 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}. Below we shall discuss a novel approach to define an adequate threshold value based on the visual impression of void regions, furthermore we study other possible values based on other visual features of the cosmic web.

3.3 The cosmic web in Bolshoi

Both established schemes to quantify the cosmic web depend on continuous and smooth physical quantities, i.e the peculiar velocity field and the density field. To calculate these quantities, a discretization over the volume of the simulation is performed, so all the properties are reduced to single values associated to discrete cells. According to this, we divide the overall volume into $(256)^3$ cells, so each cell has an associated comoving cubic volume of 0.98 Mpc h^{-1}. Finally, in order to reduce possible effects due to the discretization process, a gaussian softening is performed between neighbour cells.

Once defined the numerical details about both classification schemes, we shall analyse the dependence on the threshold value λ_{th} for each one. For this, we shall use the distribution of dark matter halos as tracer of the underlying matter field in order to be more consistent with available observational data. In Figure 1 we calculate fractions of halos within each one of the defined environments based upon the FOF catalogue of the simulation and for an extensive λ_{th} range. Then we look for some key feature that could indicated us a possible optimal value of the λ_{th} value. One first step forward our quest is the behaviour of the V-web scheme compared with the T-web. As was previously established by **Hoffman et al. (2012)** and as can be seen in Figure 1, V-web scheme is significantly more sensible to variations of the λ_{th} value, since all fractions of halos for the V-web change significantly in the range $[0, 0.4]$, whereas, for the T-web scheme, fractions change smoothly throughout all λ_{th} range covered. From this, it is then expected that the optimal λ_{th} value for the V-web scheme is less than the T-web value.

The more notorious characteristic of Figure 1 is the behaviour of the fraction of halos within sheet regions for both web schemes, increasing until a local maximum, and then decreasing. The increasing or decreasing rate of the fraction of halos for some region could be interpreted as a measure of the degree of non-linearity of such region for some specific λ_{th} value. For example, filaments and knots, that are the most non-linear regions of the universe, have a negative rate for all covered λ_{th} range. In the case of voids, the situation is completely opposite, where fractions of halos increase in everywhere. If we think in terms of the underlying matter field of the cosmic web, λ_{th} is just a cutting parameter between high non-linear regions (filament and knots) and low non-linear (voids and sheets). Furthermore, if we take into account that dark matter halos are much more likely to form in high non-linear regions, it is expected the obtained behaviour of fractions of halos for voids, filaments and knots as we increase the λ_{th} value. However, the behaviour of the fraction of halos in sheets is less clear, increasing for low λ_{th} values (like voids) and decreasing for higher λ_{th} values (like filaments and knots). This indicates us the transitional character of sheet regions in the cosmic web. Our proposal here is to select as optimal λ_{th} the value where the fraction of sheets reaches a local maximum, so sheets are completely taken as intermediate transitional and neutral zones regarding the degree of non-linearity. According to this, we find for the T-web scheme a optimal value $\lambda^T_{opt} = 0.36$ and for the V-web scheme $\lambda^V_{opt} = 0.20$. In figure 2 we show the visual impression of the cosmic web along with the density field for different λ_{th} values including the optimal values.

4 FINDING BULK VOIDS

Following the recent growing interest in studying galaxy formation in low-density regions, we use a method based on a FOF-like algorithm to find extended regions of voids. To achieve this, we build the input catalogue for the FOF method with the coordinate of the center of every cell marked as void according to the web classification scheme adopted, furthermore we set an adequate linking length to connect even diagonal neighbour cells.

Following the work of **Forero-Romero et al. 2008**, we also perform a percolation analysis in order to select the best threshold parameter that reduces percolation in cells, thereby accounting for physical bulk void regions. In Figure **??** we show the obtained result of our percolation analysis for both web schemes. In both cases, it can be noticed that the volume of the largest void region is minimized and the volume distribution of voids is relatively flat at $\lambda_{th} = 0.0$, what means percolation is completely reduced for this threshold value. So, in spite of the previously established λ_{th} optimal values for each scheme, we shall use $\lambda_{th} = 0.0$ just for the detection of bulk void regions. Moreover, due to the domination of the large scale visual impression by voids, it is inevitable the presence of the percolation phenomenon, so the current chosen threshold value for percolation is justified because though voids are necessarily connected among them, we are just interested in detecting bulk regions.

Next, we shall calculate the reduced inertia tensor of each void region in order to determinate their principal directions of inertia and analyse the size-shape distribution of voids.

$$\tau_{ij} = \sum_l \frac{x_{l,i}x_{l,j}}{R_l^2} \tag{4}$$

where l is an index associated to each cell of to the current region, i and j indexes run over each spatial direction and finally R_l is defined as $R_l^2 = x_{l,1}^2 + x_{l,2}^2 + x_{l,3}^2$, all positions are measured from the respective center of mass of the region.

The eigenvalues of the reduced inertia tensor, i.e. the principal moments of inertia, are used to quantify the shape of void regions. They are denoted as τ_1, τ_2 and τ_3 such that $\tau_1 \leqslant \tau_2 \leqslant \tau_3$. In Figure **??** we show the computed distributions for τ_1/τ_2 and τ_2/τ_3, where we rather calculate histograms for these ratio quantities instead of each single value in order to avoid using an arbitrary normalization. For both schemes, it can be noticed that the shape-distribution is completely spread out, thereby indicating a non-preferred geometry of void regions, which is in agreement with the well established highly anisotropy of matter flows associated to this type of region **[reference here]**. Because of that, we shall look for possible alignments between the plane of rotation of halo pairs and the principal directions of inertia of the nearest void regions.

5 STATISTICS OF VOIDS AND INFLUENCE OVER DARK MATTER HALOS

6 CONCLUSIONS

ACKNOWLEDGMENTS

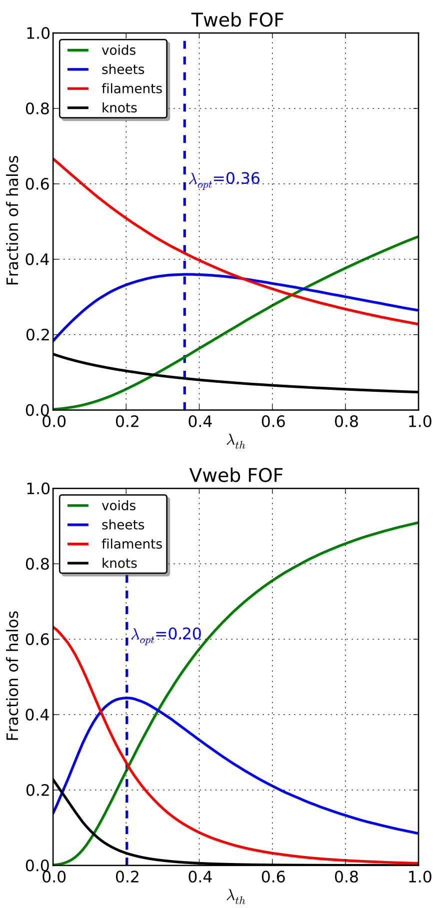

Figure 1. Mean density parameter for each one of the defined environments according to the chosen λ_{th} value and for both classification schemes. Tweb (green lines) and Vweb (blue lines). The mean density parameter is calculated by averaging all the values of the cells determined as a certain type of environment according to its eigenvalues. The optimal parameters found are $\lambda^{T}_{opt} = 0.326$ and $\lambda^{V}_{opt} = 0.188$.

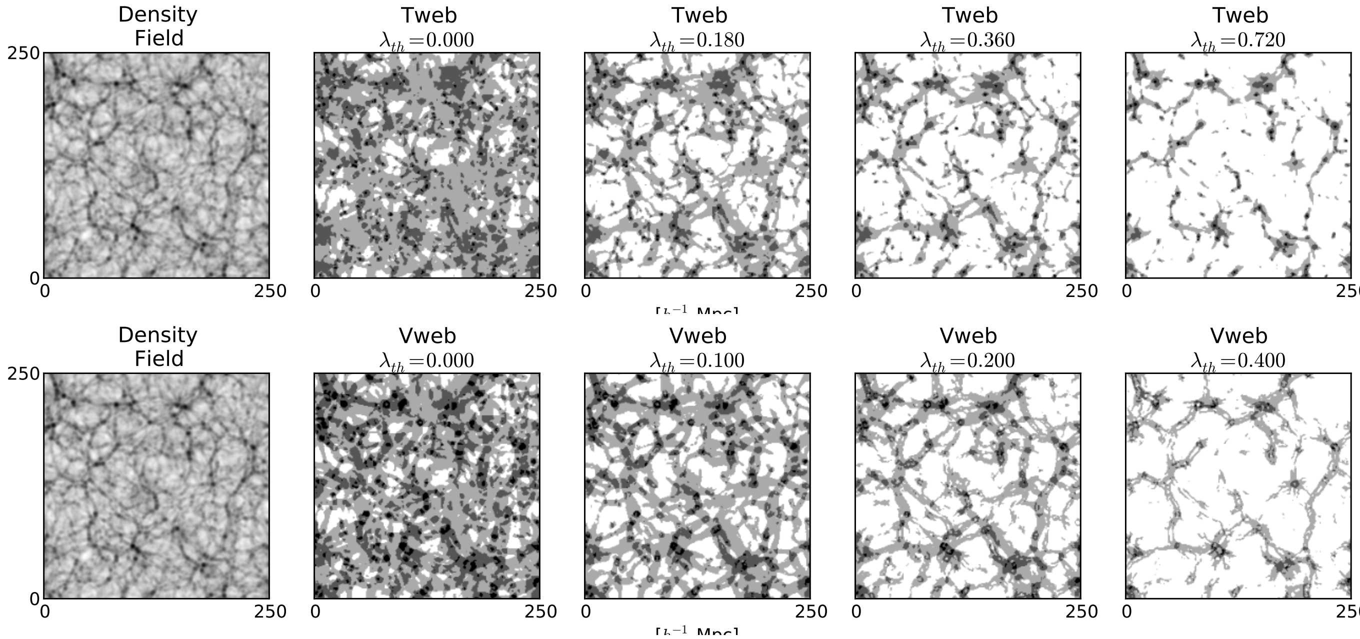

Figure 2. Visual impression of the density field (left panels), and of each classification scheme with the λ_{th} values obtained by our criteria (others panels). The color convention for each environment is (white) - void, (light gray) - sheet, (gray) - filament, (black) - knot. For each web scheme, it has been used the previously established optimal threshold as a reference value, so plots are done with the next values $\lambda_{th} = 0.0$, $\lambda_{th} = \lambda_{opt}/2$, $\lambda_{th} = \lambda_{opt}$ and $\lambda_{th} = 2\lambda_{opt}$.