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Analysis of bulk void regions

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ABSTRACT

Key words: Cosmology: large-scale Structure of Universe, 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. ...

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 an 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. It can be noticed that the optimal values found reproduce well the visual impression.

As we have taken halos as tracers of the cosmic web, we analyse distributions of mass and peculiar velocity in order to assign typical values to each type of environment. In figure 3 we calculate both distributions for web schemes and using the FOF catalogue of the simulation. Thick lines correspond to the median of the distribution and filled regions limited by dashed lines correspond to quartiles Q_1 and Q_3, it means, 50% of all halos are within such regions for every λ_{th} value and for each type of environment. We rather use median and quartiles as measure of dispersion because there are some very unusual and extreme values that makes the usual analysis based upon means and standard deviations less reliable.

A first interesting feature of Figure 3 is the median mass for each region. In the case of the T-web, although dispersions of the distribution of mass for each environment are considerably overlapped each other, the median value is very well-differentiated among types of environment, indicating that it is possible to assign typical values of mass to each region, and being consistent with expectations, where low mass halos are typical in voids until high mass halos in knots. For the case of the V-web scheme, all medians and dispersions are completely overlapped, specially for values grater than the optimal λ_{th} value, indicating that it is not possible to assign typical mass ranges to each environment as quantified by this scheme. For peculiar velocities, this situation is opposite, where V-web scheme is much more adequate to assign typical distributions of velocity to each environment. Although T-web also makes a differentiation in the distributions of velocity, this is very slight compared with the V-web case. These results can be explained by appealing the physical origin of each web scheme. As T-web is based upon the Hessian matrix of the potential field, it is expected all quantities related to the potential, like density field and distribution of halos mass, are well-differentiated among each region, while for the V-web scheme, based upon the shear velocity tensor, all dynamical quantities, as the peculiar velocity field and the distribution of halos velocity are alike expected to be well-differentiated among regions as quantified by this scheme.

Finally, we also calculate typical distributions of the density and peculiar velocity fields in each type of environment, obtaining completely analogous results. Furthermore, we also use a BDM catalogue of the simulation, obtaining very similar conclusions.

4 FINDING BULK VOIDS

4.1 FOF void finder

Following the recent growing interest in studying galaxy formation in low-density regions as cosmological tests, we propose an scheme to find bulk voids by using the two defined web schemes. Initially, we explore a first simple method based on a FOF-like algorithm, where we build an 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, setting a linking length to connect 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. In Figure 4 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 at $\lambda_{th} = 0.0$, what means the percolation is completely reduced for this threshold value. However, according to our previous analysis, such value does not reproduce the visual appearance of the cosmic web, so it is out of consideration.

5 STATISTICS OF VOIDS AND INFLUENCE OVER DARK MATTER HALOS

6 CONCLUSIONS

ACKNOWLEDGMENTS

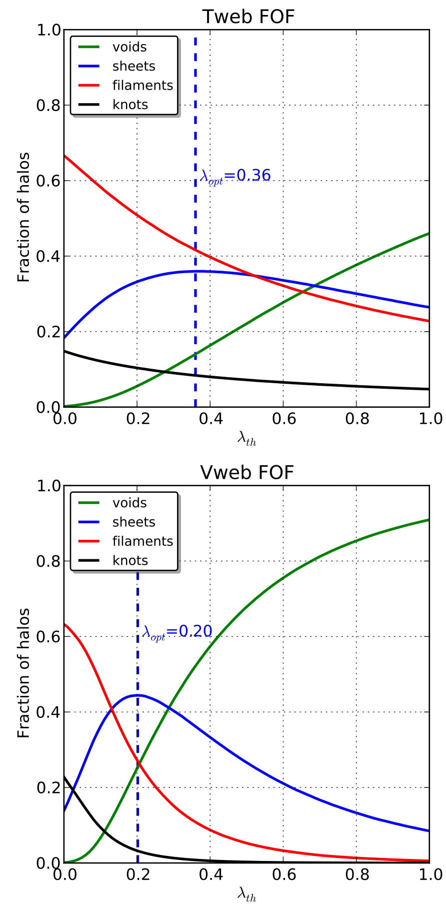

Figure 1. Fractions of halos embedded in each one of the defined environments according to the λ_{th} value. T-web scheme (upper panel) and V-web scheme (lower panel). The optimal parameters found are $\lambda^T_{opt} = 0.36$ and $\lambda^V_{opt} = 0.20$.

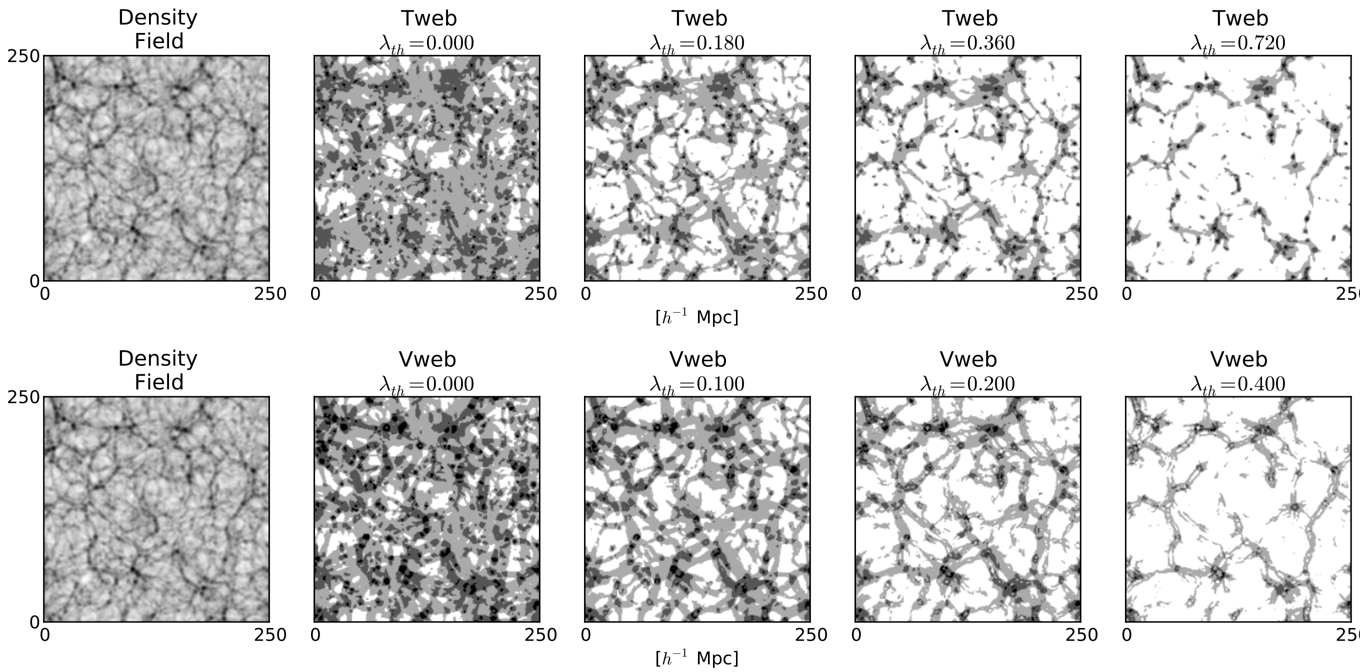

Figure 2. Visual impression of the density field (left panels), and of each classification scheme with the λ_{th} values obtained by our criteria (others panels). The color convention for each environment is (white) - void, (light gray) - sheet, (gray) - filament, (black) - knot. For each web scheme, 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 $\lambda_{th} = 2\lambda_{opt}$.

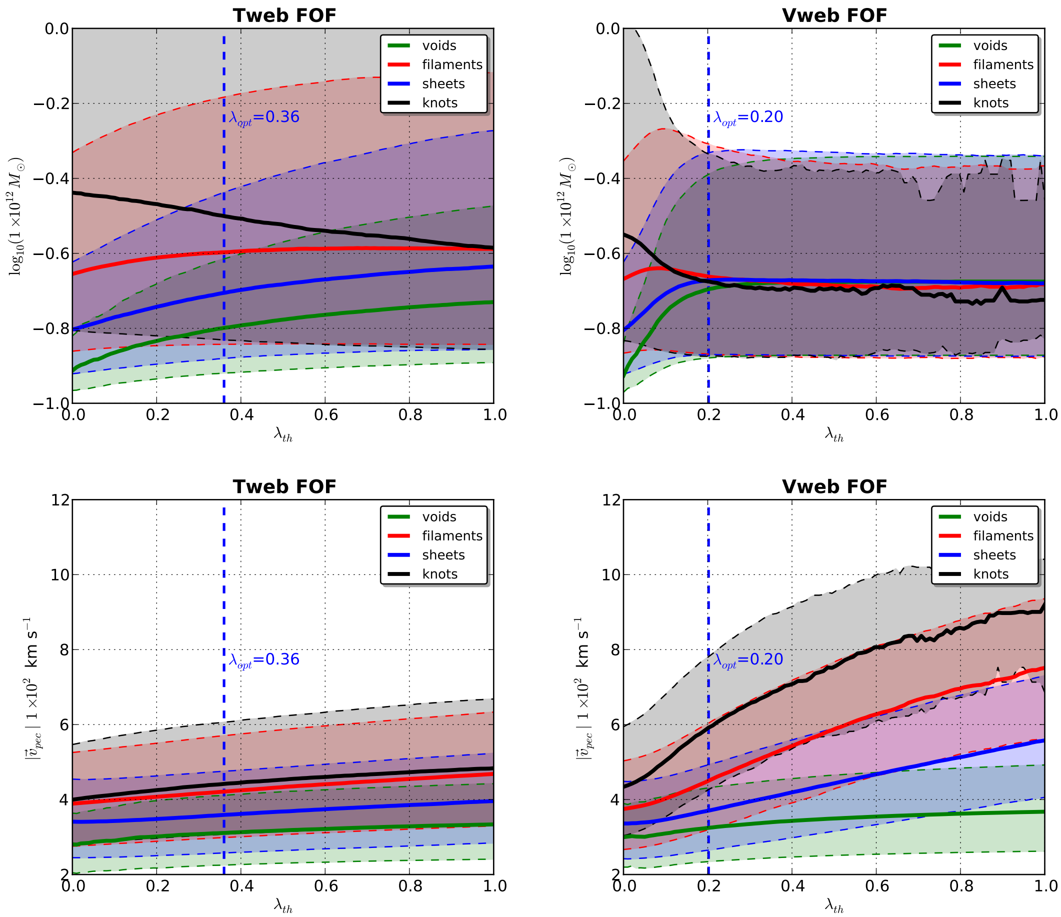

Figure 3. Distribution of masses of dark matter halos according the region where they are embedded for both web schemes (upper panels) and of peculiar velocity (lower panels).

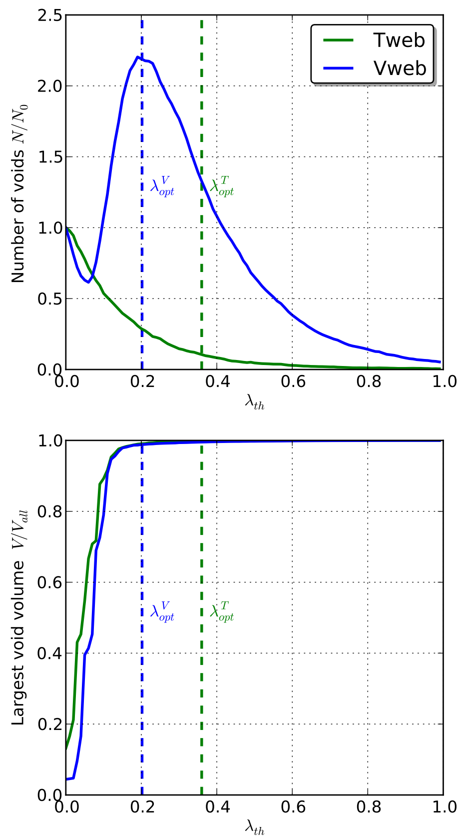

Figure 4. Percolation analysis of bulk void found by using FOF void finder algorithm. It is swept an extensive λ_{th} range for both web schemes. T-web (blue lines) and V-web (green lines). Plot of the largest volume (lower panel) and the number of bulk voids found (upper panel).

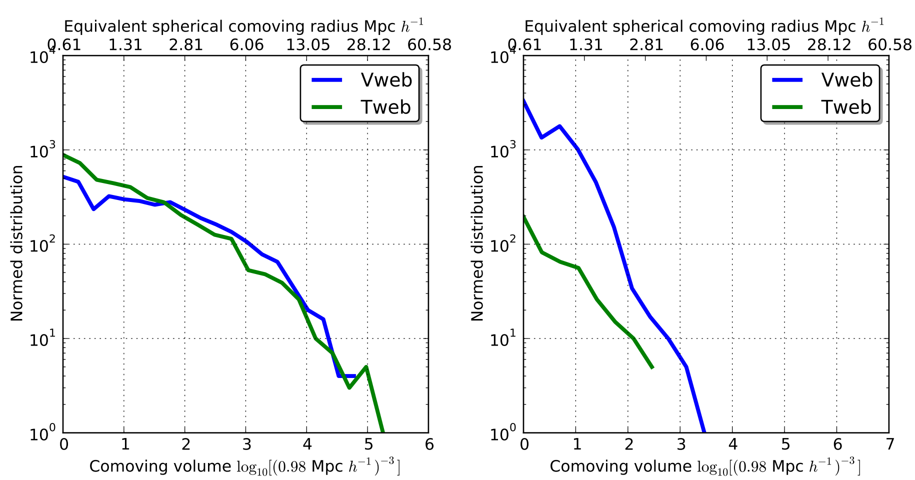

Figure 5. Percolation analysis of bulk void found by using FOF void finder algorithm. It is swept an extensive λ_{th} range for both web schemes. T-web (blue lines) and V-web (green lines). Plot of the largest volume (lower panel) and the number of bulk voids found (upper panel).