

Cosmic web alignments with the shape, angular momentum and peculiar velocities of dark matter halos

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ABSTRACT

We study the alignment of dark matter halos with the cosmic web as described by the tidal and velocity shear fields. We focus on the alignment of their shape, angular momentum and peculiar velocities. We use a cosmological N-body simulation that allows to study dark matter halos spanning almost five orders of magnitude in mass (10^9 - 10^{14}) $h^{-1}M_{\odot}$ over spatial scales of $(0.5$ - $1.0)h^{-1}\text{Mpc}$ to define the cosmic web. After varying the numerical parameters in our experiments we find that the halo shape and the tidal field web presents the strongest alignment along filaments and walls with a signal that gets stronger as the halo mass increases; in the case of the velocity shear only massive halos $> 10^{12}h^{-1}M_{\odot}$ tend to have their shapes be perpendicular to filaments and walls. For the angular momentum we find alignment signals only for halos more massive than $10^{12}h^{-1}M_{\odot}$ both in the tidal and velocity shear webs where the preferences are to be perpendicular to filaments or parallel to walls, respectively. Finally, the peculiar velocities show a strong alignment for all halo masses to move along filaments and walls in the tidal web, while in the velocity shear the same alignment is present but weaker and only for halos less massive than $10^{12}h^{-1}M_{\odot}$. Most of the different signals between the two web description are due to the fact that the main directions of stronger tidal tension and velocity shear coincide for halos below $10^{12}h^{-1}\text{Mpc}$ but are perpendicular to each other for halos more massive than this threshold.

Key words: methods: N-body simulations, galaxies: haloes, cosmology: theory, dark matter, large-scale structure of Universe

1 INTRODUCTION

There is a long observational tradition studying galactic properties as a function of its large scale environment. In these situations the environment definition is based on quantities easily accesible to observations such as the number density. With the advenment of large surveys the visibility of the cosmic web is clear. As a consequence, in order to capture this filamentarity, the environment definition started to be more complex, involving shear properties of the galaxy density field or the reconstructed dark matter density field.

The emergence of this web like structure is a great success of large scale structure growth models based on gravitational instability. Using numerical simulations allows the time description of such structure together with the formation of the virialized dark matter halos, which in turn should host observable galaxies. The finding of gas filaments that feed galaxies is another theoretical hint that strenghten the

expected connection between galactic properties and their place in the cosmic web.

Using high resolution simulations it has been established that halos of a given mass for earlier in denser regions; concentration, spin and shape also depend on the local density. In the last decade new algorithms have implemented cosmic web classifications that go beyond the local density by defining a location to be a peak, sheet, filament or void depending on the symmetry properties of the local dark matter distribution.

There analytical frameworks, such as tidal torque theory, that aim at describing how galaxies gain angular momentum and expect a correlation of this quantity with the cosmic web. The observational studies that try to measure such correlations actually try to use as a proxy the observed shape of galaxies. In this respect it is useful to have a theoretical baseline for the correlations of angular momentum and shape with the cosmic web.

In the same spirit of describing the place of galaxies within the cosmic web, there has been an revival of surveys that measure the cosmic flow patterns in the Local Universe. Assuming the correspondence between the divergence of the cosmic flow velocity field and the local matter overdensity (valid in the linear regime) one could construct accurate maps of the matter density from peculiar velocities. From this perspective is interesting to look at the expected alignment of the peculiar velocities.

There is large tradition of alignment measurements of shape and angular momentum. The main result of these previous studies is that shape alignment is a robust measurement regardless of the methods and simulations. On the other hand, the results for the angular momentum differ in the degree of the alignment. In this paper we review most of these studies and offer our own study with complementary numerical techniques and simulations. We also present for the first time in the literature new results for the alignment of peculiar velocities with large scale structure.

The structure of this paper is the following. In §2 we present the theoretical antecedents for the alignment studies we present in this paper. In §3 we present the N-body cosmological simulation and halo catalogs next to describe in §4 the two web-finding algorithms we use. In §6 we present our main results about the alignment of shape, spin and peculiar velocities with respect to the cosmic web. We continue with a discussion of these results in §7 paying special attention to resolution effects and the conditions that might drive the strong alignment signals observed in the precedent section. In §8 we present our conclusions.

2 THEORETICAL CONSIDERATIONS: NOTATION AND PRECEDENTS

There is abundant literature on the issue of shape and angular momentum alignment of dark matter haloes with respect to the cosmic web. In this paper we focus our attention on results published during the last decade that have made use of large N-body dark matter only cosmological simulations. There are many works that have addressed this problem using observational data from large surveys such as the Sloan Digital Sky Survey (SDSS), however we choose to narrow our discussion to simulation based studies which are prone to comparison.

Out of the three alignments that we study in this paper -shape, angular momentum and peculiar velocity- only the first two have received wide attention in the literature, being angular momentum the most popular with twice the number of studies for shape alignment.

These alignments are often measured from the distribution of the $\mu = |\cos \theta|$ where θ is the angle between the two axes of interest. This is often directly measured as the absolute value of the dot product between the two unit vectors along the directions being tested, for instance in the case of angular momentum one would compute $\mu = |\hat{j} \cdot \hat{n}|$. In the case of shape alignments the major axis is the chosen direction to compare against the cosmic web.

For an isotropic distribution of the vector around the direction defined by \hat{n} the μ distribution, ranging between 0 and 1, should be flat and its mean value should be $\langle |\mu| \rangle = 0.5$. If a distribution is biased towards 1 ($\langle |\mu| \rangle > 0.5$) we call

this an statistical alignment along \hat{n} , while in the case of a bias towards 0 ($\langle |\mu| \rangle < 0.5$) we talk about an anti-alignment, meaning an perpendicular orientations with respect to the \hat{n} direction.

Trowland et al. (2013) presented a parameterization for the μ distribution in the case of angular momentum alignment based on theoretical considerations by Lee et al. (2005) (Eq. 6 in the Appendix A). Under this parameterization it was found a unique correspondence between the full shape of the $|\mu|$ distribution and its average. In this paper we use that result to only present the results for the average $\langle |\mu| \rangle$.

Table 1 and Table 2 summarize recent results found in the literature for shape and angular momentum alignment. The Appendix A includes a detailed description of the definitions, algorithms and simulations used in each one of these studies. In these tables the first column describe the reference, the second column summarizes the web finding method with a single name, the third scale associates an spatial scale to the web finding methods, in most cases it corresponds to the grid size or smoothing scale used to interpolate the underlying matter density or velocity field; The fourth column indicates along which web element (filament or wall) was measured the alignment; the fifth column indicates the strength of the alignment/anti-alignment, $++/--$ indicate a strong alignment/anti-alignment while $+/-$ indicate a weaker signal; the last column indicates whether the described signal is present within a defined range of halo mass.

These results can be summarized in three important points:

- The halo mass of $1 - 5 \times 10^{12} h^{-1} M_{\odot}$ is a threshold mass between behaviours of no-alignment, alignment or anti-alignment.
- Halo shape provides a strong alignment signal along filaments and sheets, more so for massive haloes.
- Halo spin tends to be oriented perpendicular to filaments and parallel to sheets, but it is a weaker than shape alignment.

A novel aspect of our study is the use of a single computational volume of a high resolution simulation to study the alignments. Equally important, is our focus to quantify to what extent these results depend on the method used to define the cosmic web and the numerical choices to implement the algorithms.

3 N-BODY SIMULATION AND HALO FINDING

In this paper we use the Bolshoi simulation that follows the non-linear evolution of a dark matter density field on cosmological scales. The volume is a cubic box with $250 h^{-1} \text{Mpc}$ on a side, the matter density field is sampled with 2048^3 particles. The cosmological parameters in the simulation correspond to the results inferred from WMAP5 data (Dunkley et al. 2009), which are also consistent with the more recent results of WMAP9 (Hinshaw et al. 2013). These parameters are $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, $\sigma_8 = 0.82$, $n_s = 0.95$ and $h = 0.70$ for the matter density, cosmological constant, normalization of the power spectrum, the slope in the spectrum of the primordial matter fluctuation and the dimen-

Author	Web Method	Spatial Scale	Along	Alignment	Mass dependence
Forero-Romero et al. (2014)	T-Web	$0.5 - 1h^{-1}\text{Mpc}$	filament	++	$> 10^{12}h^{-1}M_{\odot}$
			filament	+	$< 10^{12}h^{-1}M_{\odot}$
			wall	++	$> 10^{12}h^{-1}M_{\odot}$
			wall	+	$< 10^{12}h^{-1}M_{\odot}$
Forero-Romero et al. (2014)	Vp-Web	$0.5 - 1h^{-1}\text{Mpc}$	filament	--	$> 10^{12}h^{-1}M_{\odot}$
			filament	none	$< 10^{12}h^{-1}M_{\odot}$
			wall	--	$> 10^{12}h^{-1}M_{\odot}$
			wall	none	$< 10^{12}h^{-1}M_{\odot}$
Libeskind et al. (2013)	V-Web	$1h^{-1}\text{Mpc}$	filament	++	$> 10^{12}h^{-1}M_{\odot}$
			filament	+	$< 10^{12}h^{-1}M_{\odot}$
			wall	++	all masses
Zhang et al. (2009)	Hessian density field	$2.1h^{-1}\text{Mpc}$	filament	++	$> 10^{12}h^{-1}M_{\odot}$
			filament	+	$< 10^{12}h^{-1}M_{\odot}$
Aragón-Calvo et al. (2007)	Hessian density field	-	wall	++	$> 10^{12}h^{-1}M_{\odot}$
		-	wall	+	$< 10^{12}h^{-1}M_{\odot}$
		-	filament	++	$> 10^{12}h^{-1}M_{\odot}$
		-	filament	+	$< 10^{12}h^{-1}M_{\odot}$

Table 1. Shape alignment with the cosmic web. Summary of theoretical results provided by methods similar to ours.

Author	Web Method	Spatial Scale ($h^{-1}\text{Mpc}$)	Along	Alignment	Mass dependence
Forero-Romero et al. (2014)	T-Web	$0.5 - 1$	filament	none	$< 10^{12}h^{-1}M_{\odot}$
			filament	-	$> 10^{12}h^{-1}M_{\odot}$
			wall	none	$< 10^{12}h^{-1}M_{\odot}$
			wall	none	$> 10^{12}h^{-1}M_{\odot}$
Forero-Romero et al. (2014)	Vp-Web	$0.5 - 1$	filament	none	$< 10^{12}h^{-1}M_{\odot}$
			filament	none	$> 10^{12}h^{-1}M_{\odot}$
			wall	none	$< 10^{12}h^{-1}M_{\odot}$
			wall	+	$> 10^{12}h^{-1}M_{\odot}$
Libeskind et al. (2013)	V-Web	1	filament	-	$> 10^{12}h^{-1}M_{\odot}$
			filament	+	$< 10^{12}h^{-1}M_{\odot}$
			wall	++	all masses
Trowland et al. (2013)	Hessian density	$2 - 5$	filament	-	$> 5 \times 10^{12}h^{-1}M_{\odot}$
			filament	+	$< 5 \times 10^{12}h^{-1}M_{\odot}$
Codis et al. (2012)	Morse Theory & T-Web	$1 - 5$	filament	--	$> 10^{12.5}h^{-1}M_{\odot}$
			filament	++	$< 10^{12.5}h^{-1}M_{\odot}$
			wall	++	all masses
Zhang et al. (2009)	Hessian density	2.1	filament	++	if anticorrelated with shape
			filament	--	if correlated with shape
Aragón-Calvo et al. (2007)	Hessian density	-	wall	++	$> 10^{12}h^{-1}M_{\odot}$
		-	wall	+	$< 10^{12}h^{-1}M_{\odot}$
		-	filament	-	$> 10^{12}h^{-1}M_{\odot}$
		-	filament	+	$< 10^{12}h^{-1}M_{\odot}$
Hahn et al. (2007)	Tidal Web	2.1	filament	-	none
			wall	+	$< 10^{12}h^{-1}M_{\odot}$
			wall	++	$> 10^{12}h^{-1}M_{\odot}$

Table 2. Spin alignment with the cosmic web. Summary of theoretical results provided by methods similar to ours.

sionless Hubble constant. With this conditions the mass of each dark matter particle in the simulation corresponds to $m_p = 1.4 \times 10^8 h^{-1} M_\odot$. A more detailed description of the simulation can be found in (Klypin et al. 2011).

In this paper we use groups found with a Friends-Of-Friends (FOF) halo finder using a linking length of $b = 0.17$ times the mean interparticle separation. This choice translates into halos with a density of 570 times the mean density at $z = 0$. The measurements for the shape, angular momentum and peculiar velocity are done using the set of particles in each dark matter halo. The definition we use in this paper for the shape comes from the diagonalization of the reduced inertia tensor.

$$\mathcal{I}_{lm} = \sum_i \frac{x_{i,l} x_{i,m}}{R_i^2}, \quad (1)$$

where i is the particle index in the halo and l, m run over the three spatial indexes and $R_i^2 = x_{i,1}^2 + x_{i,2}^2 + x_{i,3}^2$, where the positions are measured with respect to the center of mass.

The spin is calculated as

$$\vec{J} = \sum_i m_p R_i \vec{v}_i, \quad (2)$$

where the velocities are also measured with respect to the center of mass velocity. Finally the peculiar velocity of a halo is computed as the center of mass velocity.

The halo data used in this paper is publicly available through the MultiDark database¹ and is thoroughly described in Riebe et al. (2013).

4 WEB FINDING ALGORITHMS

We use two algorithms to define the cosmic web in cosmological N-body simulations. Both are based on the same algorithmic principle, which determines locally a symmetric tensor which can be diagonalized to yield three real eigenvalues $\lambda_1 > \lambda_2 > \lambda_3$ and their corresponding eigenvectors \mathbf{e}_1 , \mathbf{e}_2 and \mathbf{e}_3 . This allows for a local classification into one of the following four web types: void, sheet, filament and peak depending on the number of eigenvalues larger than a given threshold λ_{th} is 3, 2, 1 or 0, respectively.

We use two different symmetric tensors. The first is the shear tensor, defined as the Hessian of the gravitational potential, normalized in such a way as to be dimensionless:

$$T_{\alpha\beta} = \frac{\partial^2 \phi}{\partial r_\alpha \partial r_\beta}, \quad (3)$$

where ϕ is the gravitational potential rescaled by a factor $4\pi G \bar{\rho} = 3/2 \Omega_m H_0^2$ in such a way that the Poisson equation can be written as $\nabla^2 \phi = \delta$, where δ is the matter overdensity, $\bar{\rho}$ is the average matter density, H_0 is the Hubble constant at present time and Ω_m is the matter density parameter. A detailed presentation of this algorithm can be found in (Forero-Romero et al. 2009).

The second tensor is the velocity shear:

$$\Sigma_{\alpha\beta} = -\frac{1}{2H_0} \left(\frac{\partial v_\alpha}{\partial r_\beta} + \frac{\partial v_\beta}{\partial r_\alpha} \right), \quad (4)$$

where v_α correspond to the components of the peculiar co-moving velocities. With this definition the trace of the shear tensor is minus the divergence of the velocity field normalized by the Hubble constant $-\nabla \cdot \mathbf{v}/H_0$. A detailed description of this algorithm can be found in (Hoffman et al. 2012).

4.1 Numerical considerations

In this paper we compute the cosmic web on cubic grids of two different resolutions 256^3 and 512^3 . For the T-Web we interpolate first the matter density field using a Cloud-In-Cell (CIC) scheme. Then we smooth using a Gaussian kernel with a spatial variance equal to the size of one grid cell. This smoothed matter density field is transformed into Fourier space to solve the Poisson equation and find the gravitational potential ϕ . The Hessian is computed a finite differences method. Finally, the eigenvalues and eigenvectors are computed on each grid point.

For the V-Web we interpolate first the momentum density field over a grid using the CIC scheme and then apply a gaussian smoothing with a spatial variance of one grid cell. We use the matter density field, which is also CIC interpolated and gaussian smoothed, to normalize the momentum field. This ratio between the momentum and matter density field is what we consider as the velocity field to compute the shear tensor on each grid point. In this case we also compute the eigenvalues and eigenvectors on each grid point.

5 OUR NUMERICAL EXPERIMENTS

In this paper we use the data and the methods described above to perform two kinds of measurements: the preferential alignment and the average value of the angle along the eigenvectors of interest.

We note that we measure alignments along the eigenvectors of the cosmic web without defining first whether each point corresponds to a filament or a wall. Our motivation is two-fold. First, partitioning the simulation into web elements implies an choice as to what value to use for the parameter λ_{th} ; although, this has been done before we consider that

5.1 Preferential Alignment

The first measurement is a rough approximation to find out along which axes are halos aligned. We call this Preferential Alignment (PA).

We use the fact that for a given vector under study \hat{a} and the tree eigenvectors the following identity holds

$$(\hat{s} \cdot \hat{e}_1)^2 + (\hat{s} \cdot \hat{e}_2)^2 + (\hat{s} \cdot \hat{e}_3)^2 = 1. \quad (5)$$

Using this we know that all halos can be splitted into three groups:

(i) Halos with $(\hat{s} \cdot \hat{e}_1)^2 > (\hat{s} \cdot \hat{e}_2)^2$ and $(\hat{s} \cdot \hat{e}_1)^2 > (\hat{s} \cdot \hat{e}_3)^2$, which can be considered to aligned mostly along \hat{e}_1 .

¹ <http://www.multidark.org/MultiDark/>

- (ii) Halos with $(\hat{s} \cdot \hat{e}_2)^2 > (\hat{s} \cdot \hat{e}_1)^2$ and $(\hat{s} \cdot \hat{e}_2)^2 > (\hat{s} \cdot \hat{e}_3)^2$, which can be considered to aligned mostly along \hat{e}_2 .
- (iii) Halos with $(\hat{s} \cdot \hat{e}_3)^2 > (\hat{s} \cdot \hat{e}_1)^2$ and $(\hat{s} \cdot \hat{e}_3)^2 > (\hat{s} \cdot \hat{e}_2)^2$, which can be considered to aligned mostly along \hat{e}_3 .

If the halo population does not show any preferential alignment, then all the halos must be evenly distributed along these three populations. On the contrary, if there is more than one third of the halo population in one of these sets, then we can talk about a preferential alignment along one of the axis. However, this statistic does not give a precise answer on the degree of the alignment

5.2 Average Alignment Angle

We emphasize that all the quantities that we compute in this paper are independent of any threshold on the eigenvalues that could be used to make a web clasification into web types. Instead, we focus on the alignments with respect to the eigenvectors regardless of the web type. In this context we recall that the eigenvector \hat{e}_1 is vector perpendicular to the plane defining a sheet and also a filamente and that \hat{e}_3 is the vector that marks the direction of a filament and lies on the plane of a sheet. Therefore we focus on quantifying the degree of alignment along these two eigenvectors.

This experiment complements the results obtained by the PA satistic by computing the average and standard deviation of $|\langle \hat{s} \cdot \hat{e}_1 \rangle|$ and $|\langle \hat{s} \cdot \hat{e}_3 \rangle|$. We perform this tests in diffetet populations split into different mass bins logarithmically spaced between $1 \times 10^9 h^{-1} \text{M}_\odot$ and $1 \times 10^{14} h^{-1} \text{M}_\odot$.

In a separate test we make the same measurements but this time splitting the halo sample by other properties such as: circularity, concentration, local matter density, spin and triaxiality. In this case we take the upper and lower 30% of the halos according to each property and measure the strenght of the alignment by the average value of $|\langle \hat{s} \cdot \hat{e}_1 \rangle|$ and $|\langle \hat{s} \cdot \hat{e}_3 \rangle|$.

6 RESULTS

6.1 Preferential Alignment

Figure 1 presents all the results for the preferential alignment (PA) summarizing to a good extent the main results of this paper.

For shape alignment and the Tweb (upper row, right column) we find a strong preferential alignment along the third eigenvector \vec{e}_3 . This signal incresases steadily with mass and is almost independent of the grid resolution. At high masses between 70% and 100% of the halos have their major axis aligned along \vec{e}_3 which means that they mostly lie along filaments and sheets.

The shape alignment and the Vweb (upper row, left column) gives a different perspective. Firstly, there seems to be little evidence for an alignment for masses below $10^{11} - 10^{12} h^{-1} \text{M}_\odot$, depending on the grid resolution. Secondly, the alignment at higher masses goes along the first eigenvector \vec{e}_1 meaning that they mostly lie perpendicular to the filaments and sheets. In the discussion section we clarify this result that at first might seem puzzling.

For the angular momentum alignment and the Tweb (middle row, right column) we find that at low masses

$< 10^{12} h^{-1} \text{M}_\odot$ no evidence for any alignment. At higher masses $> 10^{12} h^{-1} \text{M}_\odot$ there is weak signal of preferential alignment along the first and second eigenvectors, between 35% to 45% of the halos are aligned with respect to \vec{e}_1 and \vec{e}_2 . Correspondingly, between 10% to 20% of the halos are aligned along respect to \vec{e}_3 . This means that most of the halos are perpendicular to the filaments and do not have a clear alignment with respect to walls.

The angular momentum in the Vweb (middle row, left column) presents a a signal of alignment along the second eigenvector \hat{e}_2 , between 45% to 60% of the halos are aligned along that direction. While there is a minority of halos aligned with \vec{e}_1 . There a clear change in trends around $10^{11} h^{-1} \text{M}_\odot - 10^{12} h^{-1} \text{M}_\odot$ depending on the grid resolution; below that mass range there is no evidence for alignment while at higher masses appear all the trends we describe. This means that most of the halos tend to lie along walls but do not have a clear alignment with respect to filaments.

The peculiar velocities show a weak but consistent alignment along the third eigenvector \vec{e}_3 of the Tweb for all masses below $10^{13.0} h^{-1} \text{M}_\odot - 10^{13.5} h^{-1} \text{M}_\odot$ depending on the grid resolution. 45% of the halos are aligned while only 25% are aligned along the first eigenvector \vec{e}_1 . This suggests that halos tend to move along filaments and parallel to the walls, except at higher masses where the alignments get randomized. In contrast, the peculiar velocities with respect to the Vweb show the same trend but weaker and only for low mass halos $< 10^{12}$.

In the next subsections we present a complementary account of this results by presenting quantitative results of the average angle between vector pairs describing the alignments discussed so far.

6.2 Shape Alignment

Figure 2 presents the main results for the angles between the first and third eigenvectors and the major shape axis as a function of halo mass.

In the case of the Vweb (left column) we have a clear alignment with respect to the first eigenvector at high masses $> 10^{12} h^{-1} \text{M}_\odot$, with values $|\langle \cos \theta \rangle| \approx 0.8$ well above the expected value of 0.5 for random distribution. With respect to the third eigenvector we measure an anti-alignment with $|\langle \cos \theta \rangle| \approx 0.3$. For low masses $< 10^{12} h^{-1} \text{M}_\odot$ we do not detect any alignment signal. This is consistent with the PA results of massive halos perpendicular to filaments and parallel to walls.

The Tweb (right column) show alignment trends starting at masses of $10^{10} h^{-1} \text{M}_\odot$, two orders of magnitude less than the V-web. In this case we measure an alignment along the third eigenvectors and an antialignment along the first eigenvector. In the later case at the highest masas $|\langle \cos \theta \rangle| \approx 0.8$ while in the former $|\langle \cos \theta \rangle| \approx 0.2$. This strong alignment/antialignment signal mirrors the interpretation from the PA results that describe halos lying parallel both to filaments and walls.

6.3 Angular Momentum Alignment

We now take a look at the angular momentum alignment. Figure 3 shows the results as a function of halo mass following the same panel distributio as in Figure 2. In all cases

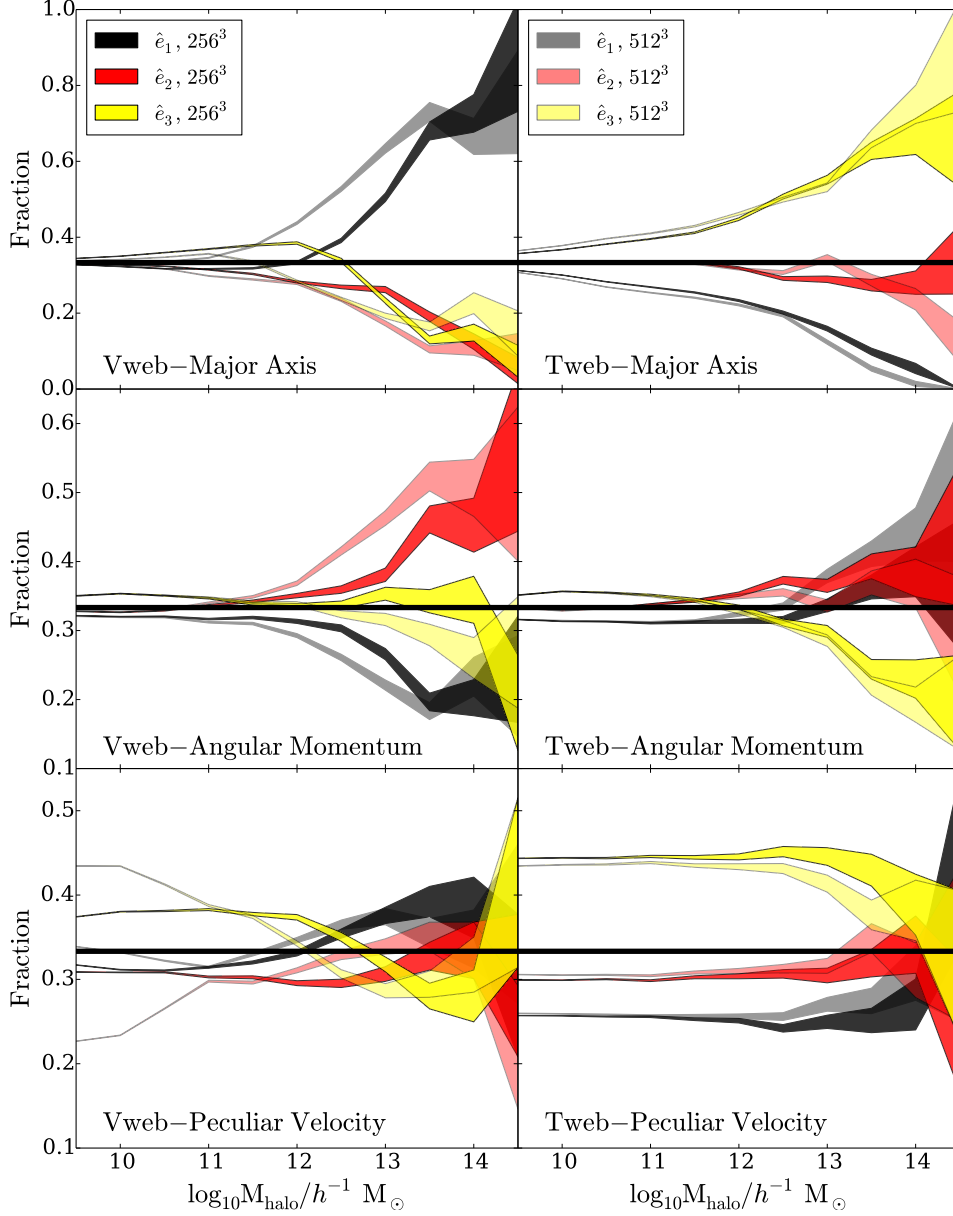


Figure 1. Fraction of halos in a mass bin that show a preferential alignment with respect to an eigenvector. Each row presents one of the three properties studied in this paper: shape (major axis), angular momentum and peculiar velocity. Left column presents the results against the Vweb and the right the Tweb. Strong colors refer to 256^3 grid resolutions and lighter colors to a 512^3 grid. The thick black horizontal line at 0.33 corresponds to the expected fraction for a random vector field.

we see that these alignment trends are weaker than shape alignments. For the Vweb low mass halos $< 10^{12} h^{-1} M_{\odot}$ do not show any preferential alignment with the cosmic web. Halos more massive than this threshold have their angular momentum slightly perpendicular to the direction defined by the first eigenvector and uncorrelated to the third eigenvector. This translates into a weak tendency for the angular momentum to lie parallel to walls.

In the case of the Tweb, the alignment for low mass halos $< 10^{12} h^{-1} M_{\odot}$ is also absent. More massive halos present a weak alignment along first eigen vector and anti-alignment with the third eigenvector. This provides a quantitative expression of the results derived from the preferential align-

ment whereby the angular momentum is weakly perpendicular to filaments.

6.4 Peculiar velocity Alignment

Figure 4 shows the results for peculiar velocities alignments. In the case of the Vweb, the peculiar velocities show a weak signal of alignment ($|\langle \cos \theta \rangle| \approx 0.55$) along the third eigenvector for low masses $< 10^{12} M_{\odot}$ and a weak antialignment at higher masses. The strength of the alignment also shows clear dependency on the grid size used to compute the web.

The Tweb shows a stronger alignment with the third eigenvector at all masses with $|\langle \cos \theta \rangle| \approx 0.6$ and an an-

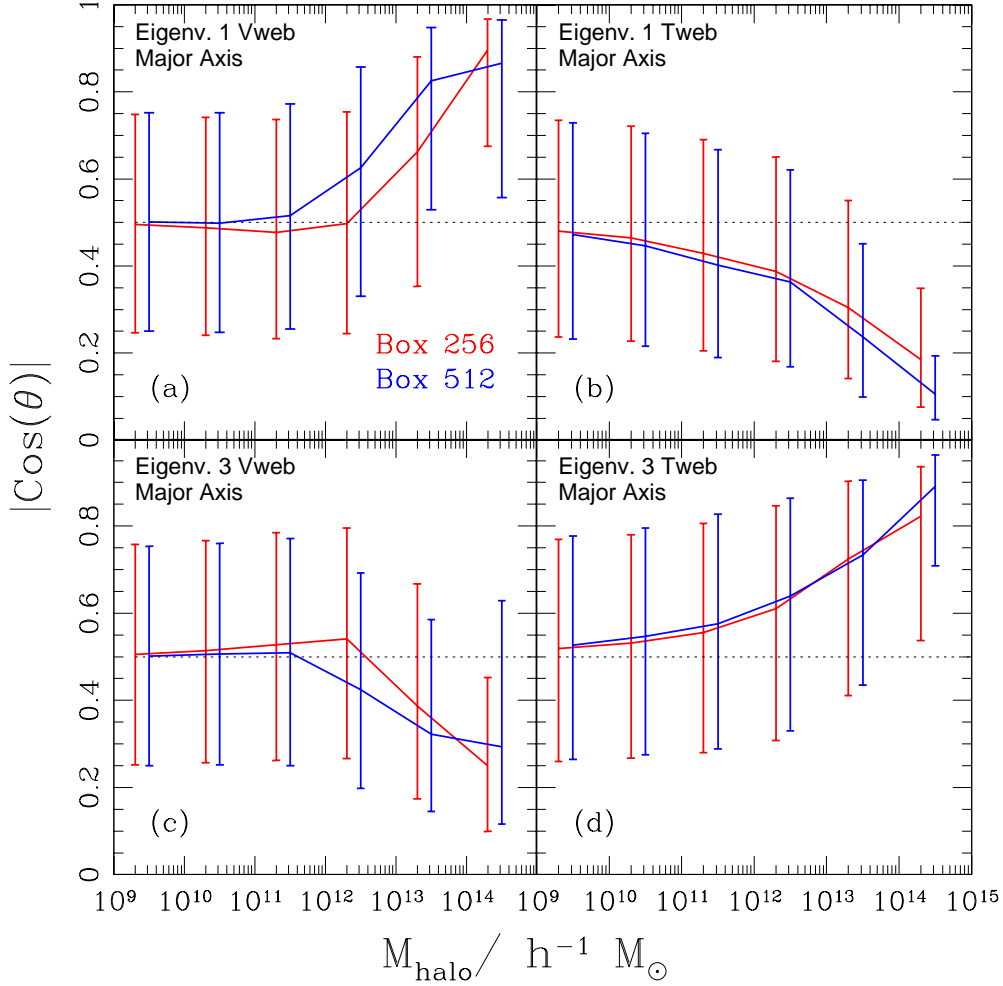


Figure 2. Median of $\cos \theta$ quantifying the shape alignment for the Vweb (left) and the Tweb (right) at two different grid resolutions. In the upper (lower) panels the angle θ is measured between the halo major axis and the first (third) eigenvector.

tialignment with the first eigenvector with $|\langle \cos \theta \rangle| \approx 0.4$. In contrast to the Vweb results, these trends remain basically unchanged at all masses and grid resolutions, with only minor change for halos masses $> 10^{13} h^{-1} M_{\odot}$.

In the first place we wish to directly compare the results of the two algorithms. For the two algorithms we have the information for the eigenvectors and the eigenvalues on exactly the same positions defined by the grids. This allows us to compute the pair-wise alignment between the eigenvectors in the two web finders.

We are mainly interested in the alignment of the web with the halos. Therefore we restrict our analysis to the grid cells that are occupied by halos. If we had decided to perform this kind of analysis on all the grid cells, the statistics would be dominated by the void regions, because they dominate in number the fraction of cells in the simulation.

6.5 Interweb Alignment

Perhaps the most striking result so far is that the two webs give different results for the alignment of massive halos. This is not completely unexpected given that the two algorithms are based on different physical premises to obtain the direc-

tions defining the eigenvectors. However, we investigate the origin of the different alignment statistics by studying the inter-web alignment.

Figure 5 shows the values for $|\langle \cos \theta \rangle|$ between the two \vec{e}_1 eigenvectors in the Tweb and the Vweb. The Figure shows that there is an alignment, $|\langle \cos \theta \rangle| \approx 1.0$, for low mass halos and an antialignment, $|\langle \cos \theta \rangle| \approx 0.2$ for massive.

The transitional scale is located around $(10^{11.5} - 10^{12.5}) h^{-1} M_{\odot}$ depending on the grid resolution. The coarse grid (256³) shows the transition at higher masses than the fine grid (512³). We also note that the alignment is weaker in the finer grid, ($|\langle \cos \theta \rangle| \approx 0.7$) than in the coarser grid ($|\langle \cos \theta \rangle| \approx 1.0$).

These two facts (alignment at low masses and low grid resolution) points towards an explanation in terms of the linear / non-linear growth of structure. When the alignment is present on linear scales the divergence of the velocity field is proportional to the overdensity, i.e. the trace of the shear field is proportional to the trace of the tidal field.

On the scale where the halos more massive than $10^{13} h^{-1} M_{\odot}$ are located, the relationship between the velocity shear and the tidal field changes. There, the fastest momentum-weighted collapse direction (defined by the V-

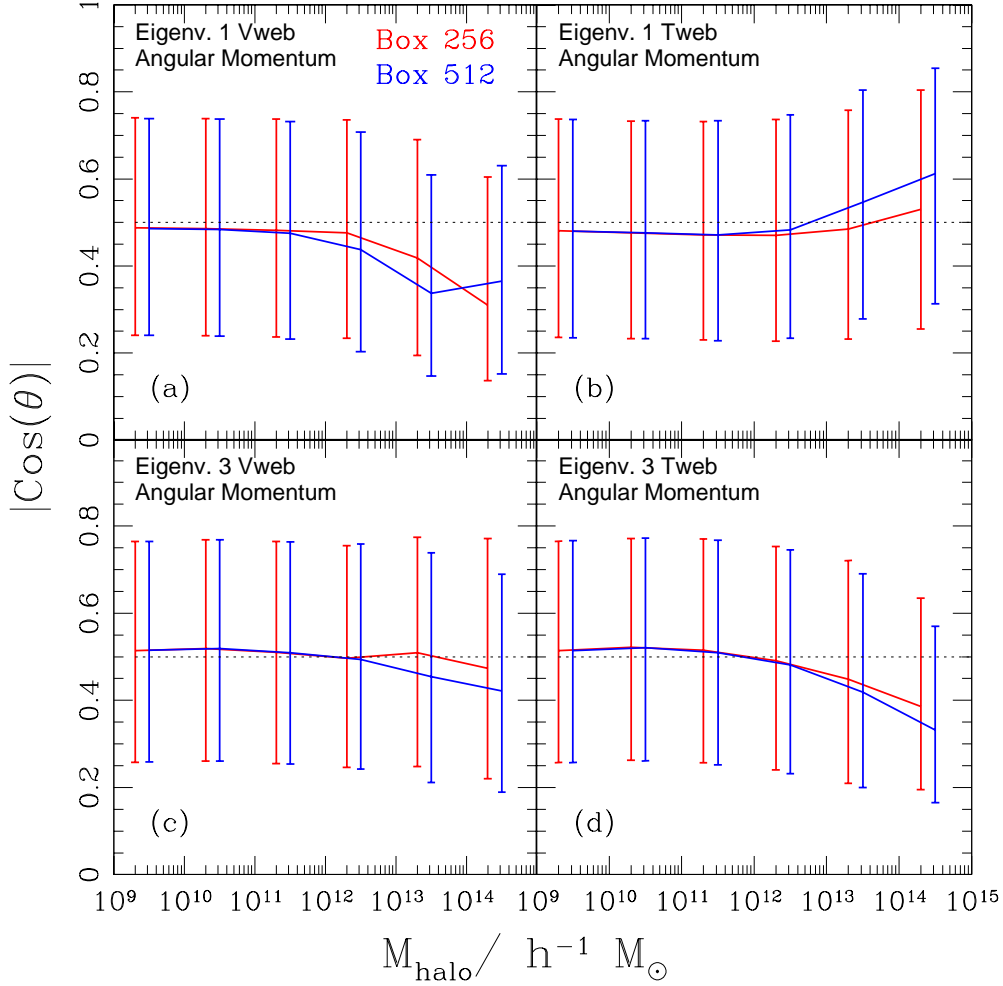


Figure 3. Median of $|\cos\theta|$ quantifying the angular momentum alignment for the Vweb (left) and the Tweb (right) for two different grid resolutions. In the upper (lower) panels the angle θ is measured between the first (third) eigenvector and the angular momentum vector.

web) is perpendicular to the direction where the tidal compression is the highest.

6.6 What drives the alignment

We wish to understand what other selection criteria on halo properties can produce a stronger local alignment for the shape, spin and peculiar velocities. We split the halo population into low and high mass halos imposing a cut at $M_{\text{halo}} = 10^{11} h^{-1} M_{\odot}$. This allows us to have robust statistics on the high mass end. We have also computed these results for a cut at $M_{\text{halo}} = 10^{12} h^{-1} M_{\odot}$ and checked that the results we report below are not affected by this change.

For each mass interval we perform cuts in the following properties: spin, concentration, triaxiality, circularity and density. We measure the web alignments in two sets, each one including the 30% of halos in the lower/higher end of the corresponding property.

Possible conclusion. Prolateness follow concentration. In the Tweb Angular momentum alignment is influenced by spin at higher masses. In the Vweb angular momentum alignment is influenced by all

factors. In the peculiar velocity alignment only spin seems to have an effect.

7 DISCUSSION

We do not find a strong signal for the alignment of spin and the cosmic web. A significant correlation signal has been recently measured between the spin and the cosmic vorticity (Libeskind et al. 2013; Laigle et al. 2013). This two facts are consistent with spin being produced by the non-symmetric part of the shear and tidal tensors.

8 CONCLUSIONS

We have examined the alignment of shape, angular momentum and peculiar velocity of dark matter halos with respect to the cosmic web. We use publicly available data from two algorithms implemented on a large cosmological N-body simulation to study halo populations spanning five orders of magnitude in mass. The first algorithm uses the tidal field

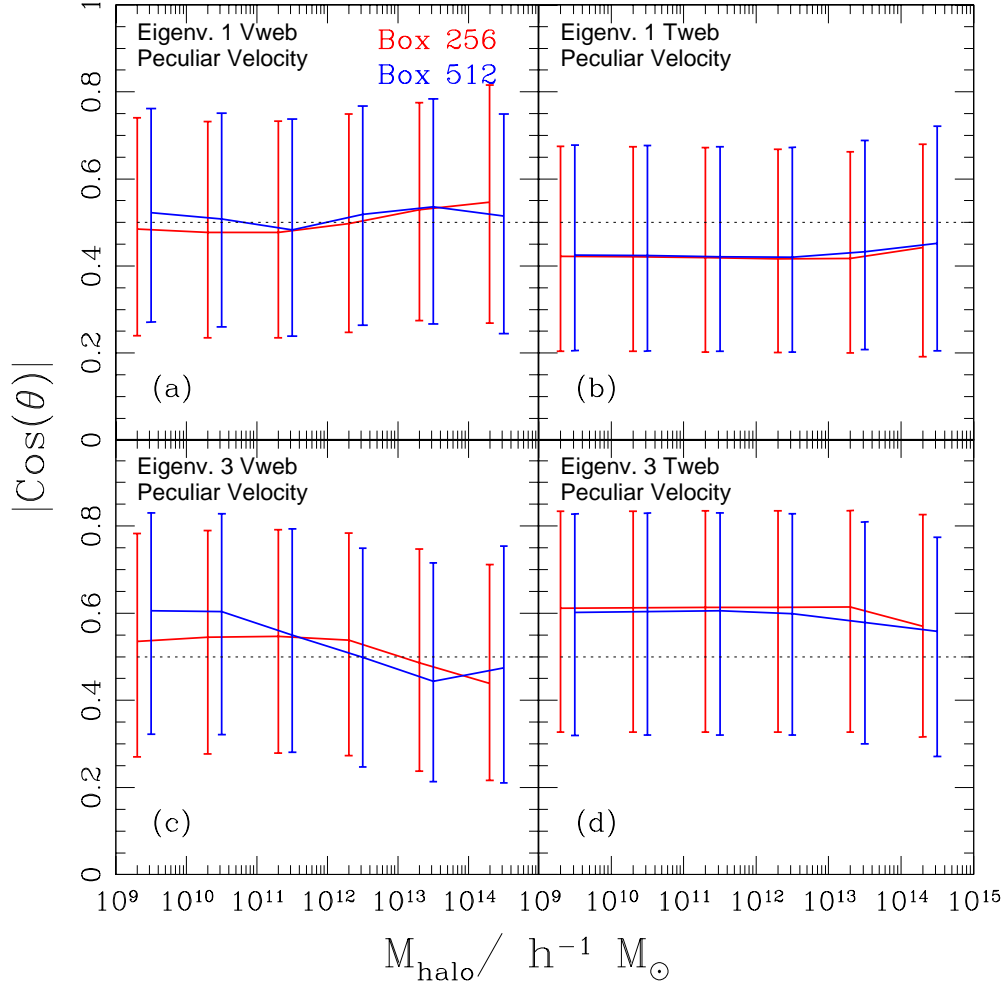


Figure 4. Median of $|\cos \theta|$ quantifying the peculiar velocity alignment with the Vweb (left) and the Tweb (right) for two different grid resolutions. In the upper (lower) panels the angle θ is measured between the first (third) eigenvector and a halo's peculiar velocity.

and the second the velocity shear, both present local results on scales of $0.5h^{-1}\text{Mpc}$ to $1.0h^{-1}\text{Mpc}$.

We quantify the alignments in two complementary ways. The first one measures the fraction of halos in a population that is preferentially aligned with either one of the eigenvectors \vec{e}_1 , \vec{e}_2 or \vec{e}_3 . The second method measures the average value of the angle between an eigenvector and the quantity of interest. These two measurements give us a complete picture for the different degrees of alignment in the cosmic web.

We find that the strongest alignment occurs for the halo shape with respect to the Tweb. In this case the halos tend to align with the third eigenvector, \vec{e}_3 , meaning that they lie along filaments and walls. This trend gets stronger as the halo mass increases and agrees with all the results published so far. Instead, for the Vweb, there is only an anti-alignment for halos more massive than $10^{12}h^{-1}\text{M}_\odot$, a result that is presented here for the first time.

A much weaker alignment signal is present for the angular momentum. In the Tweb only the most massive halos $> 10^{12}h^{-1}\text{M}_\odot$ are anti-aligned with respect to the filaments, while for the Vweb the massive halos are alignment with sheets. These results broadly agree with the published

literature. Nevertheless, in the same publications there is an alignment/anti-alignment signal reported at lower halo masses $< 10^{12}h^{-1}\text{M}_\odot$ that we do not detect in our measurements.

A new result from our study is the alignment for the peculiar velocities. Here we find a relatively strong signal of alignment along the direction defined by the third eigenvector and perpendicular to the first. This signal is very strong in the Tweb for all masses below $< 10^{13}h^{-1}\text{M}_\odot$. This can be interpreted as a flow parallel to walls and filaments. In the case of the Vweb similar signal, albeit weaker, is present only for the low mass halos $< 10^{12}h^{-1}\text{M}_\odot$.

The different behaviour for the alignments of massive halos in the Tweb and the Vweb was tracked to a corresponding anti-alignment between the eigenvectors in the two web grids for massive halos $> 10^{12}h^{-1}\text{M}_\odot$. For low mass halos the directions defined by the two webs point in the same direction. This trends can be interpreted as non-linear effects that appear in the two different physical descriptions for the cosmic web.

We also performed a simple study to find evidence of halo properties, other than mass, in driving the alignments. We find that in the case of shape, halos located in high

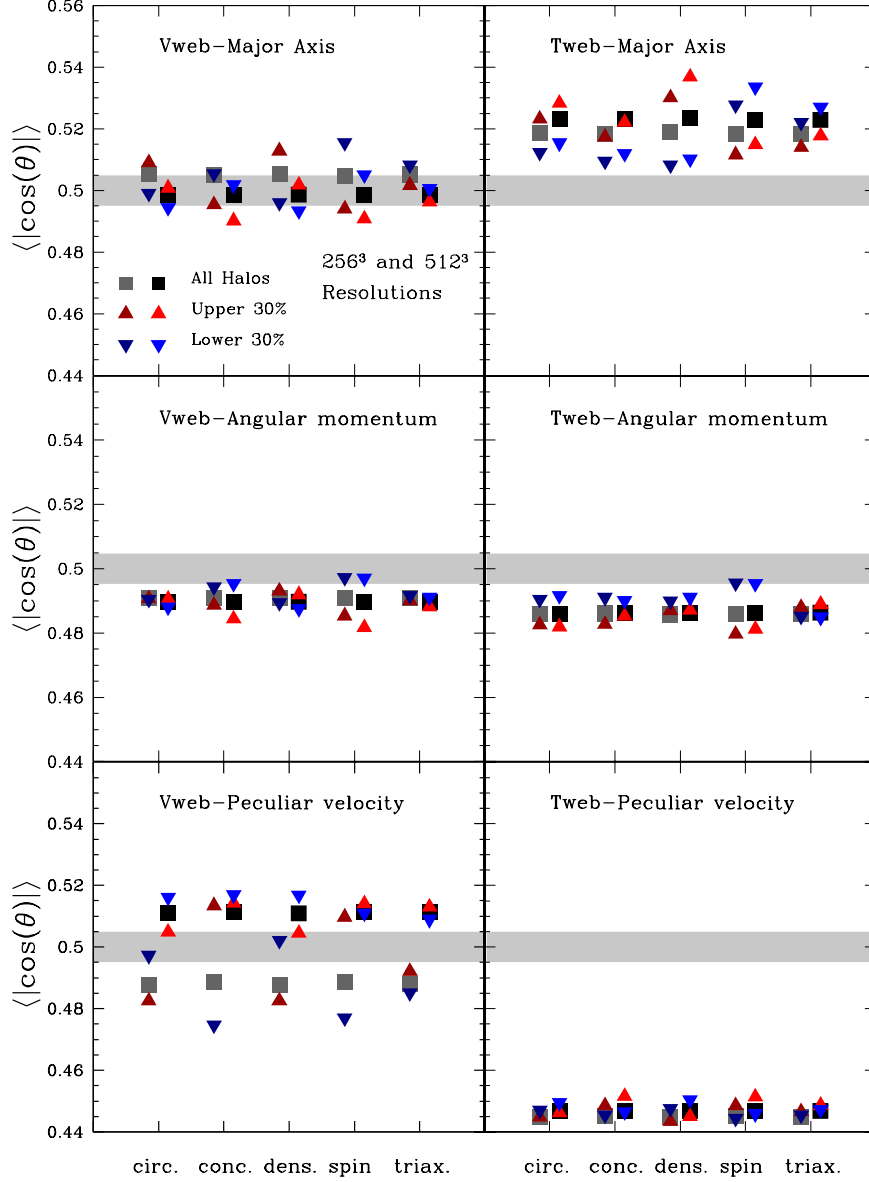


Figure 6. The alignment is always taken with respect to the third eigenvector.

density regions or with a low value of the reduced spin parameter tend to show a stronger signal. This trend is more pronounced in the Tweb than in the Vweb. Concerning angular momentum we find that the antialignment signal is stronger for halos with high spin values. In the peculiar velocities we do not find any effect in the Tweb alignments, and the results for the Vweb show a wide variations with grid resolution that impedes driving any strong conclusion.

ACKNOWLEDGMENTS

APPENDIX A. DETAILED DESCRIPTION OF PREVIOUS THEORETICAL RESULTS

The tidal connection between voids in simulations (Platen et al. 2008), the alignment of observed galaxies with the inferred tidal field (Lee & Erdogdu 2007; Jones et al. 2010).

There are other kind of alignment statistics based on modifications of the correlation (Paz et al. 2008; Faltenbacher et al. 2009) that go beyond a local computation and therefore are not reviewed in detail in this paper.

- Libeskind et al. (2013)

They study the shape and angular momentum alignments with the cosmic web defined by the velocity shear tensor method described in this paper. Libeskind et al. (2013) used the Bolshoi simulation and the halo catalogs we use in this work. Results are reported for three mass bins $M_{\text{vir}} < 10^{11.5} h^{-1} M_{\odot}$, $11^{11.5} < M_{\text{vir}} < 12^{12.5} h^{-1} M_{\odot}$ and $M_{\text{vir}} > 12^{12.5} h^{-1} M_{\odot}$. The identification of the cosmic web is done on a grid of 256^3 with a gaussian smoothing of $\sim 1 h^{-1} \text{Mpc}$ over the velocity field. The way they compute this smoothed velocity field differs from our computation.

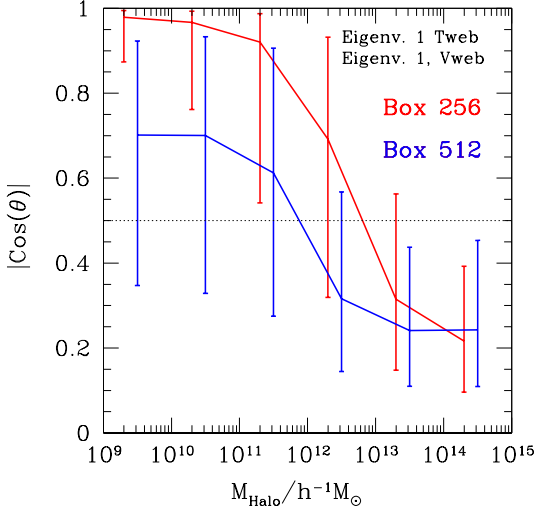


Figure 5. Median of the interweb alignment for the two grid resolutions as a function of the dark matter mass corresponding to the halos where the measurement was made. The error bars indicate the lower and upper quartiles (Figure in color in the web version).

We do it based on the momentum density field while ? do not take into account the mass in each cell.

The alignment signal for the angular momentum is weak while the shape alignment signal is very strong. The shape alignment is such that the eigenvector corresponding to the smallest eigenvalue is aligned with the major axis. This effect is stronger for more massive halos. In other words the major axis of a halo is aligned with a filament, and lies on the plane that define a sheet. The angular momentum is anti-aligned with the filament for massive halos and weakly aligned for low mass halos.

- Trowland et al. (2013)

They used the Millennium Run, which has 2160^3 particles in a volume of $500h^{-1}\text{Mpc}$ on a side. This corresponds to a particle mass of $8.6 \times 10^8 h^{-1}M_\odot$. The catalog uses both halos and subhalos identified with SUBFIND. Only halos with more than 500 particles were kept to get a robust computation for the spin. The angular momentum is defined as the sum of the angular momentum of each particle with respect to the center of mass.

The method to define the filamentary structure is based on the eigenvalues of the hessian of the density. However, the analysis is performed on a box of $300h^{-1}\text{Mpc}$ on a side. Four different gaussian smoothing scales are used: 2.0, 3.0 and $5.0h^{-1}\text{Mpc}$.

By fitting the following functional form to the $\cos(\theta)$ distribution

$$P(\cos \theta) = (1 - c) \sqrt{1 + \frac{c}{2}} \left[1 - c \left(1 - \frac{3}{2} \cos^2 \theta \right) \right]^{-3/2}, \quad (6)$$

they are able to quantify the degree of alignment ($c < 0$) or anti-alignment ($c > 0$). This parameterization is based on theoretical expectations of Tidal Torque Theory (TTT) (Lee et al. 2005). At $z = 0$, the reported value is $c = 0.035 \pm 0.004$, where the uncertainty was calculated using bootstrapping and resampling.

When the halo sample is divided between low mass and high mass halos with a transition scale $M_* = 5.9 \times 10^{12}M_\odot$, there is a weak alignment signal of the angular momentum against the principal filament axis for halos above that mass, for halos below that scale there is a weak anti-alignment.

- Codis et al. (2012)

They studies the alignment of the angular momentum dark relative to the surrounding large scale structure and to the tidal tensor eigenvalues.

They use a dark matter simulation with 4096^3 DM particles in a cubic periodic box of $2000h^{-1}\text{Mpc}$ on a side, which corresponds to a particle mass of $7.7 \times 10^9 M_\odot$. Halos are identified using a FoF algorithm with a linking length of 0.2 keeping all halos with more than 40 particles, which sets the minimum halo mass to be $3 \times 10^{11}M_\odot$. In their work the particles were sampled on a 2048^3 grid and the density field was smoothed with a gaussian filter over a scale of $5h^{-1}\text{Mpc}$ corresponding to a mass of 1.9×10^{14} . The skeleton was computed over 6^3 overlapping subcubes and then reconnected.

The filament finder algorithm is based on Morse theory and defines a Skeleton to be the set of critical lines joining the maxima of the density field through saddle points following the gradient. They also compute the hessian of the potential over the smoothed density field to get their eigenvectors.

The angular momentum of the halo is defined as $m_p \sum_i (r_i - \bar{r}) \times (v_i - \bar{v})$ where \bar{r} is the center of mass of the halo and \bar{v} is the average velocity.

They measure the alignment with each one of the eigenvectors. With respect to the minor eigenvector \vec{e}_3 (the filament direction) there is anti-alignment for masses $M > 5 \times 10^{12}M_\odot$ and alignment for masses $< 5 \times 10^{12}M_\odot$; with respect to the intermediate eigenvector \vec{e}_2 there is a strong alignment at high masses and no alignment for low masses; with respect to the major eigenvector \vec{e}_1 (normal to the wall plane) there is an anti-alignment signal at all masses. The results from the Skeleton algorithm are in agreement with the results from the Tidal web. The transitional mass is weakly dependent on the smoothing scale, varying between $1 - 5 \times 10^{12}h^{-1}M_\odot$ for smoothing scales between $1.0 - 5.0h^{-1}\text{Mpc}$.

- (Zhang et al. 2009)

They studied the angular momentum and shape alignment against filaments. They used a dark matter simulation with 1024^3 DM particles in a periodic box of $100h^{-1}\text{Mpc}$ on a side. The particle mass is $6.92 \times 10^7 h^{-1}M_\odot$. Dark matter haloes are found using a FOF algorithm with a linking length of 0.2 times the interparticle distance. Only halos with more than 500 particles are retained for further analysis. The angular momentum is measured with positions respect to the center of mass and the shape is determined using the non-normalized moment of inertia tensor.

The environment is found using the hessian of the density. The density field was interpolated over a 1024^3 grid and then smoothed with a Gaussian filter of scale $R_s = 2.1h^{-1}\text{Mpc}$. There are two methods to define the direction of a filament. The first method uses the eigenvalues of the hessian density; they take the filament direction to be the eigenvector corresponding the single positive eigenvalue of the hessian. The second method used a line that connects the two terminal halos in a filament segment.

For the method that uses the eigenvectors, they find that the strenght of the angular momentum alignment decreases with halo mass. For the shape they study the alingment of the major axis with the filament. They find an alignment signal in all mass bins, with an stronger effect for more massive halos.

In a final experiment they measure the angular momentum alignment in four different samples split by the strength of the shape alignment. They find that halos anti-aligned in shape, show a strong angular momentum correlation; and a strong angular momentum anti-alignment for halos with a strong shape alignment.

- (Aragón-Calvo et al. 2007)

They used the Multi-Scale Morphology Filter to describe th filamentary structure. The method is based on the Hessian matrix of the density field, which is computed from the particle distribution using a Delaunay tessellation field estimator (DTFE). This allows them to identify clusters, filaments and walls.

They used a simulation with 512^3 particles in a cubic box of $150h^{-1}\text{Mpc}$. The mass per particle is $2 \times 10^9 h^{-1} M_\odot$. Halo identification is done with the HOP algorithm. They keep halos with more than 50 particles and less than 5000, defining a mass range of $1 - 100 \times 10^{11} h^{-1} M_\odot$. The principal axes of each halo are computed from the non-normalized inertia tensor. The inertia tensor and the angular momentum are computed with respect to the center of mass of the halo.

They compute two angles, one with respect to the direction defining the filaments and the other the walls. Their results make a distinction between halos of more massive and less massive than $10^{12} h^{-1} M_\odot$. The angular momentum tends to lie along the plane of the wall, with a stronger alignment for massive halos. The effect for filaments is weaker, low mass halos tend to alight along the filament, while high mass halos tend to be anti-aligned.

For the shape they find a very strong alignment along filaments. In walls the major axis lies along the wall. Both alignments are stronger for massive halos.

- (Hahn et al. 2007)

They used the Tweb method applied on three simulations each of 512^3 particles, with sizes $L_1 = 45h^{-1}\text{Mpc}$, $L_2 = 90h^{-1}\text{Mpc}$ and $L_3 = 180h^{-1}\text{Mpc}$, this corresponds to particle masses of $4.7, 38.0, 300 \times 10^7 h^{-1} M_\odot$. Halo identification was done with a FOF algorithm with 0.2 times the interparticle distance. They considered halos of at least 300 particles.

The web is obtained for a grid of 1024^3 cells, the density field is obtained with a CIC interpolation and smoothed using a Gaussian Kernel. All the results correspond to a smoothing scale of $R_s = 2.1h^{-1}\text{Mpc}$.

They report on the angle between the halo angular momentum vector and the eigenvector corresponding to perpendicular directions to the sheets and the direction of the filaments. This is divided into two halo populations according to mass; low mass $5 \times 10^{10} - 1.0 \times 10^{12}$ and high mass $> 10^{12}$. They find a weak anti-alignment for filaments and a stronger anti-alignment in the case of the sheets. For the sheets the effect is stronger for the massive bin. The anti-alignment along filaments is weak regardless of the mass. They do not report any other significant statistic, but recognize that they suffer from small-number statistics in voids.

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