

Halo alignments with large scale tidal and velocity fields

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ABSTRACT

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

Author Web Method Halo Finder SPIN SPIN

1 INTRODUCTION

2 THEORETICAL ANTECEDENTS

... There is abundant literature on the issue of shape and angular momentum alignment of dark matter haloe with respect to the cosmic we.

... This alignment is often measured from the distribution of the $\cos\theta$ where θ is the angle between the two axes of interest.

... Table 1 summarizes recent results found in the literature for shape and angular momentum alignment.

(Faltenbacher et al. 2009) (Paz et al. 2008) (Platen et al. 2008) (Lee & Erdogdu 2007)

- (Libeskind et al. 2013) Studies shape and spin alignment with the cosmic web defined by the velocity shear tensor method described in this paper.

The simulation has 2048³ particles in a box of 250 h^{-1} Mpc, corresponding to a particles mass of $1.3 \times 10^8 h^{-1} M_\odot$. Halos are found using a FOF halo finder with $b = 0.17$. The catalog only include halos more massive than $3 \times 10^9 h^{-1} M_\odot$.

The shape is defined from the reduced inertia tensor. Results are reported for three mass bins $M_{\text{vir}} < 10^{11.5} h^{-1} M_\odot$, $10^{11.5} < M_{\text{vir}} < 10^{12.5} h^{-1} M_\odot$ and $M_{\text{vir}} > 10^{12.5} h^{-1} M_\odot$.

The identification of the cosmic web is done on a grid of 256³ with a gaussian smoothing of $\sim 1 h^{-1}$ Mpc over the velocity field. The details of this smoothing are different from ours. This is described in detail in the Appendix.

The alignment signal of the spin is very weak while the shape alignment signal is very strong. The 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.

- (Trowland et al. 2013)

The simulation is the millennium simulation, which has 2160³ particles in a volume of 500 h^{-1} Mpc on a side. This corresponds to a particle mass of $8.6 \times 10^8 h^{-1} M_\odot$. The cata-

log uses both halos and subhalos which were identified with SUBFIND. Only halos with more than 500 particles were kept to get a robust computation for the spin. For each halo the spin 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 reported on a box of 300 h^{-1} Mpc on a side. Four different gaussian smoothing scales are used: 2.0, 3.0 and 5.0 h^{-1} Mpc.

The authors report a slight alignment signal of spin against the principal filament axis. By fitting the following functional form to the $\cos(\theta)$ distribution

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

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 an anti-alignment above this mass and an alignment below it.

- (Codis et al. 2012) Studies the alignment of the spin of dark matter halos relative to the surrounding large scale structure and to the tidal tensor eigenvalues.

They use a dark matter simulation with 4096³ DM particles in a cubic periodic box of 2000 h^{-1} 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 2048³ grid and the density field was smoothed with a gaussian filter over a scale of 5 h^{-1} Mpc corresponding to a mass of 1.9×10^{14} . The skeleton was computed over 6³ 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 spin 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 spin alignment with each one of the eigenvectors. With respect to the minor eigenvector e_1 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 e_2 there is a strong alignment at high masses and no alignment for low masses, with respect to the major eigenvector e_3 there is an anti-alignment signal at all masses. The results from the Skeleton algorithm are in perfect 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 $1.0 - 5.0 h^{-1} \text{Mpc}$.

- (Zhang et al. 2009) Study the spin and shape alignment against filaments.

They use a dark matter simulation with 1024^3 DM particles in a periodic box of $100 h^{-1} \text{Mpc}$ 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 $R_s 2.1 h^{-1} \text{Mpc}$. There are two methods to define the direction of a filament. The first method uses the eigenvalues of the hessian density, however they define the filament direction with 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.

The characterization of the alignment with the $\cos(\theta)$ statistic. For the method that uses the eigenvectors, they find that the strength of the spin alignment decreases with halo mass. For the shape they study the alignment of the major axis with the filament. They find an alignment signal in all mass bins, with a stronger effect for more massive halos.

In a final experiment they measure the spin alignment in four different samples that separated by the strength of the shape alignment. They find that halos anticorrelated in shape, show a strong spin correlation going to the extreme where there is a strong spin anticorrelation for halos with a strong shape correlation. This means that the halos with strong spin alignment are not the same halos showing strong shape alignment.

- (Aragón-Calvo et al. 2007) The method is the Multi-scale Morphology Filter which is based on the Hessian matrix of the density field, where the density field is computed from the particle distribution using a Delaunay tessellation field estimator (DTFE), which is self-adaptive. This allows them to identify clusters, filaments and walls.

The simulation has 512^3 particles in a cubic box of $150 h^{-1} \text{Mpc}$. 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 halo spins tend to lie on the plane of the wall. This is stronger for massive halos. The effect for filaments is weaker: low mass halos tend to lie parallel to their host filament, while high mass halos tend to be perpendicular.

There is a very strong effect for the principal axes of halos in filaments to be strongly correlated with the direction of the filaments. The minor axis tend to be perpendicular to the filament. This effect is stronger for larger halos.

The effect in walls is less strong, but still the minor axis tend to lie perpendicular to the wall, while the other axis tend to lie over the wall. The effect is stronger for massive halos.

They find that spins and shapes of dark matter halos are significantly correlated with each other and with the orientation of their host structures.

- (Hahn et al. 2007) The method is the Tweb. They use three simulations each of 512^3 particles, with sizes $L_1 = 45 h^{-1} \text{Mpc}$, $L_2 = 90 h^{-1} \text{Mpc}$ and $L_3 = 180 h^{-1} \text{Mpc}$, this corresponds to particle masses of 4.7, 38.0, $300 \times 10^7 h^{-1} M_\odot$. The normalization is $\sigma_8 = 0.9$. Halo identification was done with a FOF algorithm with 0.2 times the interparticle distance. They consider 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. In the rest of the paper all the results correspond to a smoothing scale of $R_s = 2.1 h^{-1} \text{Mpc}$.

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 in two halo populations: $5 \times 10^{10} - 1.0 \times 10^{12}$ and $> 10^{12}$. There is a weak anti-alignment in the case of the filaments and a stronger anti-alignment in the case of the sheets. For the sheets the effect is stronger for the massive bin. In the filaments the alignment 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).

They do not see any strong dependence of the environment in the shape. They do not measure the shape alignment.

- (Brunino et al. 2007)
- (Basilakos et al. 2006) Use a cosmological SPH+N-body simulation to measure the alignment of cluster halos with their parent supercluster. For both the cluster halos and parent super-cluster they define the shape via the non-normalized inertia tensor. They find that strength of the alignments increases with the degree of filamentarity of the supercluster.

The simulation has 2×512^3 particles in a box of side

$500h^{-1}\text{Mpc}$. The dark matter particle mass is $6.6 \times 10^{10}h^{-1}\text{M}_{\odot}$ while for SPH particles is $1.2 \times 10^{10}h^{-1}\text{M}_{\odot}$. The halo finding is done with a FOF algorithm with a linking length of 0.17 and keep objects with more than 100 particles.

- (Lee & Pen 2002) Observational measurement for the alignment of galaxy spin axes with the local tidal shear field. For the measurement of shear, we have used the Point Source Catalog Redshift (PSCz) survey (a complete redshift survey from the IRAS Point Source Catalog) data. This was done down to a radial comoving distance of $\sim 150h^{-1}\text{Mpc}$.

- (Hatton & Ninin 2001) DM matter only simulation. 256^3 particles, $100h^{-1}\text{Mpc}$, particle mass. Look for mutual alignment of angular momentum vectors, and alignment with structure. Halos on any scale by close pair statistics. They don't find any evidence for a statistically significant mutual alignment of haloes on any scale,

3 N-BODY SIMULATION AND HALO FINDING

... In this paper we use groups found with a FOF halo finder.

4 THE COSMIC WEB ALGORITHMS

4.1 The Tidal Web

4.2 The Velocity Web

4.3 Numerical considerations

... In this paper we compute the cosmic web on grids of two different resolutions 256^3 and 512^3 .

5 RESULTS

5.1 Interweb Alignment

... We compute the pair-wise alignment between the eigenvectors in the two web finders.

... We also compute the alignment between the eigenvectors in cells occupied by dark matter halos. This will be a key element in the interpretation of the results for halo-based alignments in the next sections: shape, angular momentum and peculiar velocities.

...

5.2 Shape Alignment

5.3 Angular Momentum Alignment

5.4 Peculiar velocity Alignment

6 DISCUSSION

7 CONCLUSIONS

ACKNOWLEDGMENTS

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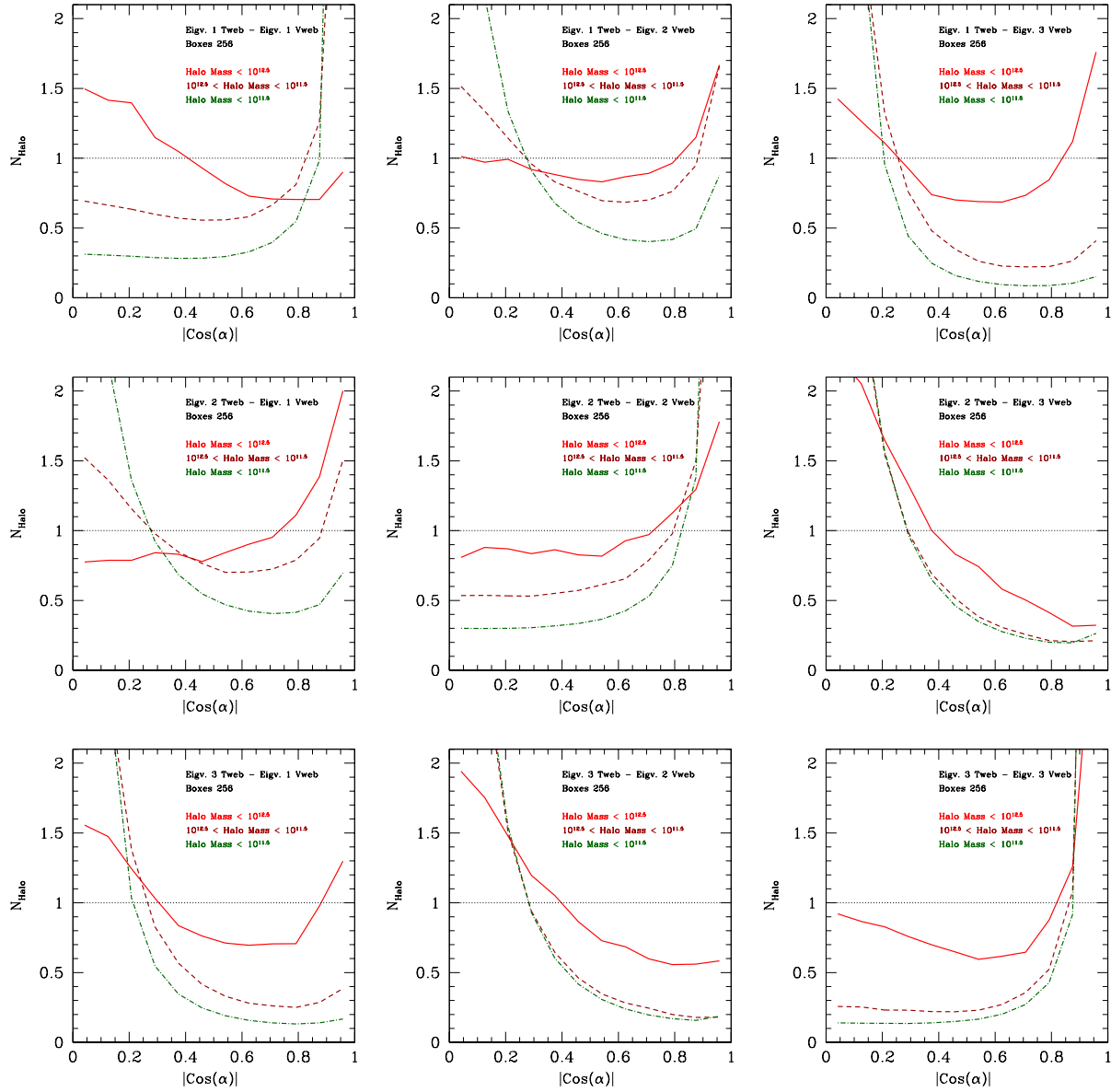


Figure 1. Interweb alignment for 256^3 grid resolution.

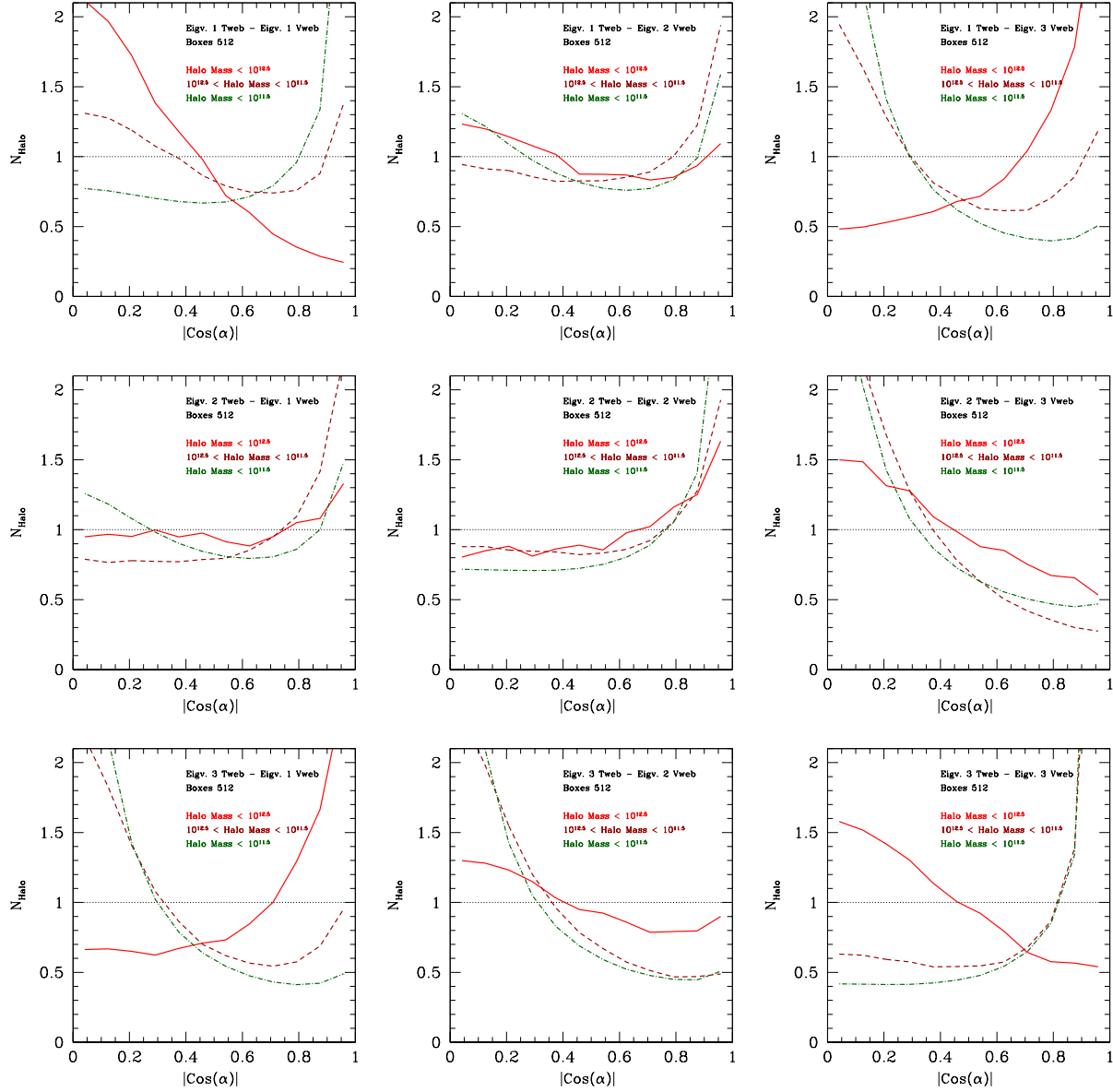


Figure 2. Interweb alignment for 512^3 grid resolution.

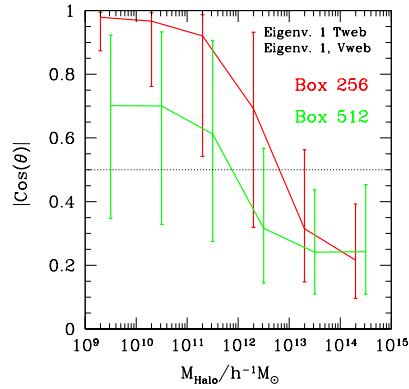


Figure 3. Median of the interweb alignment for the two grid resolution.

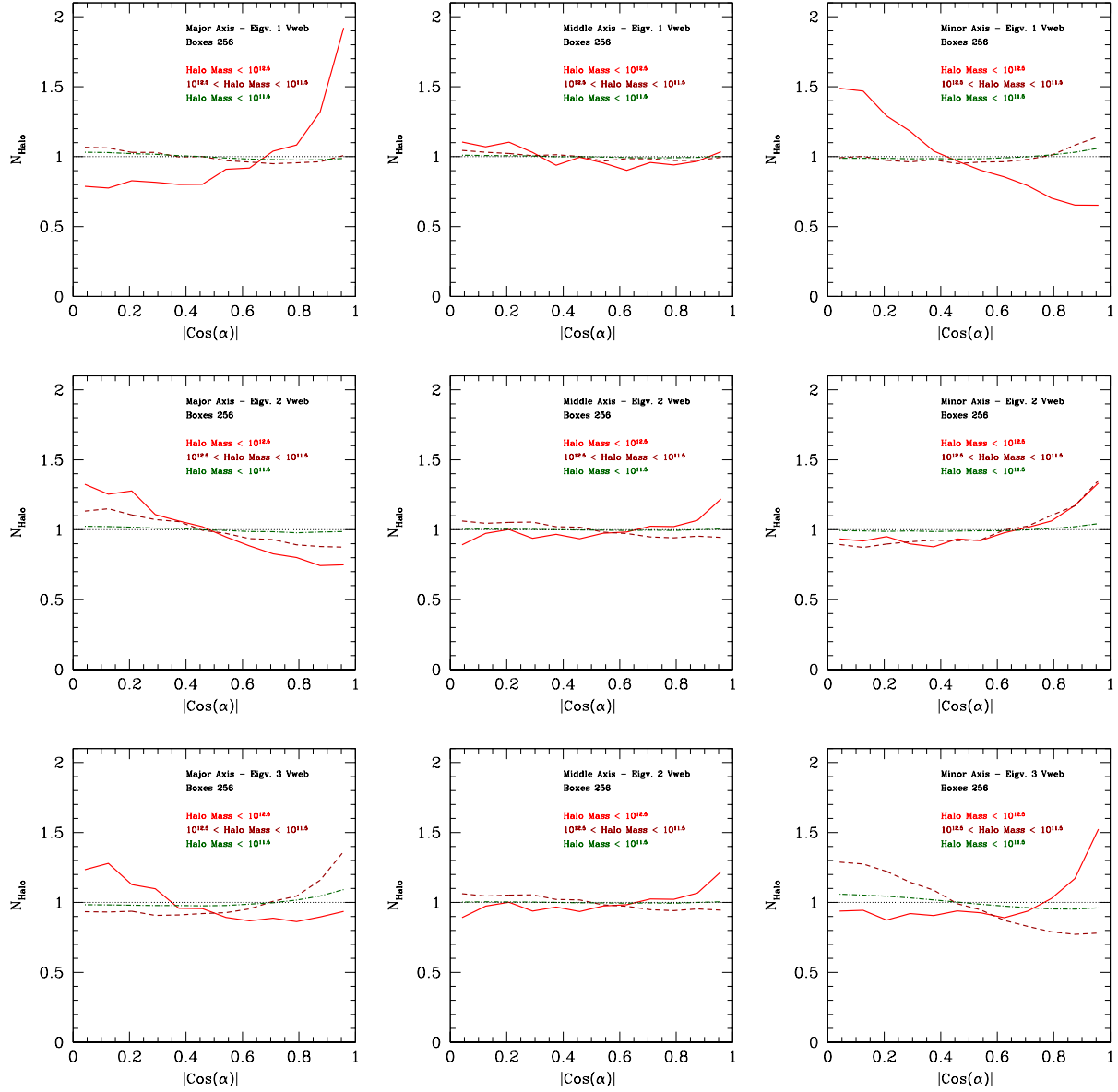


Figure 4. Shape alignment for the vweb at 256^3 resolution.

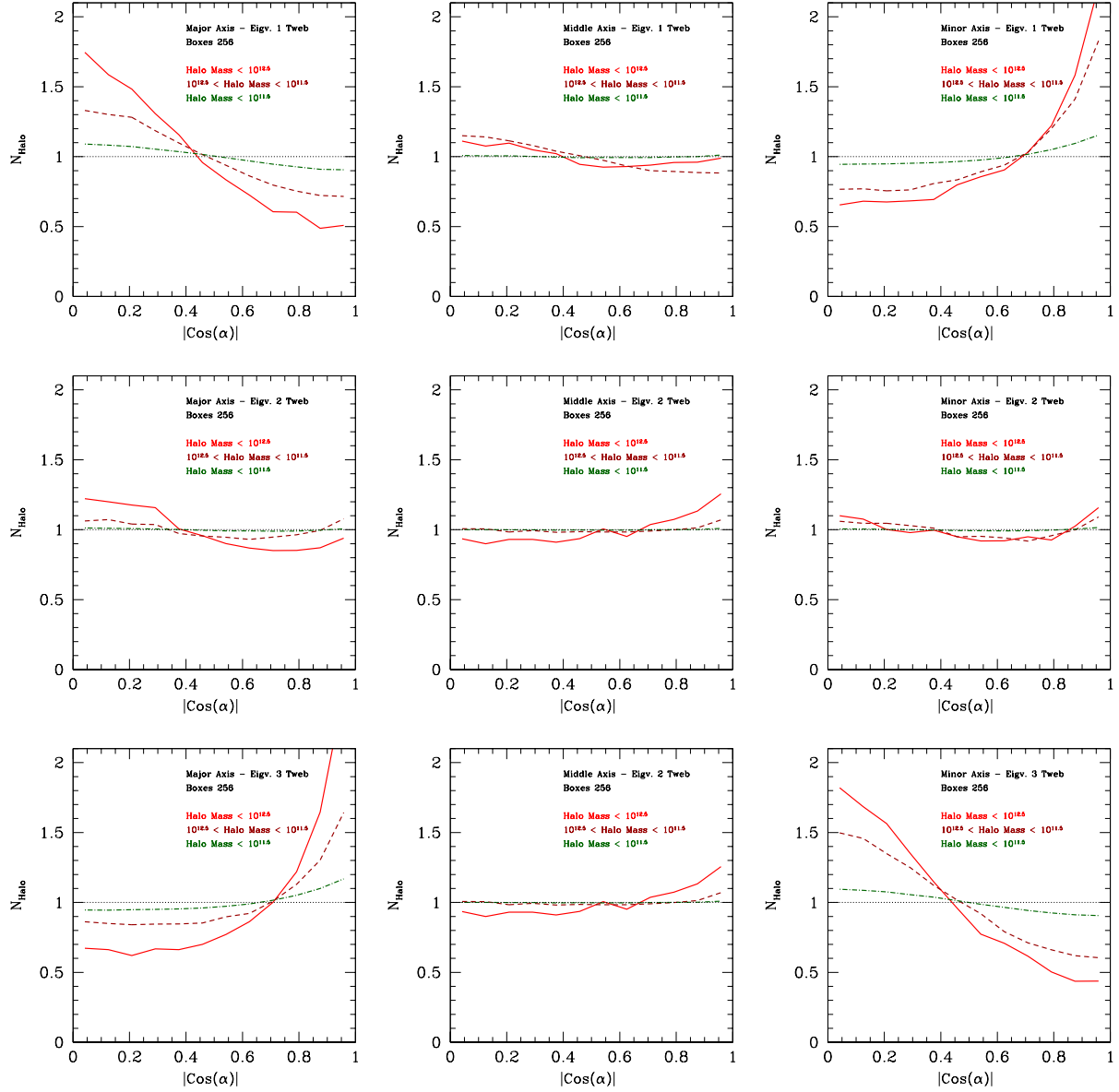


Figure 5. Shape alignment for the tweb at 256^3 resolution.

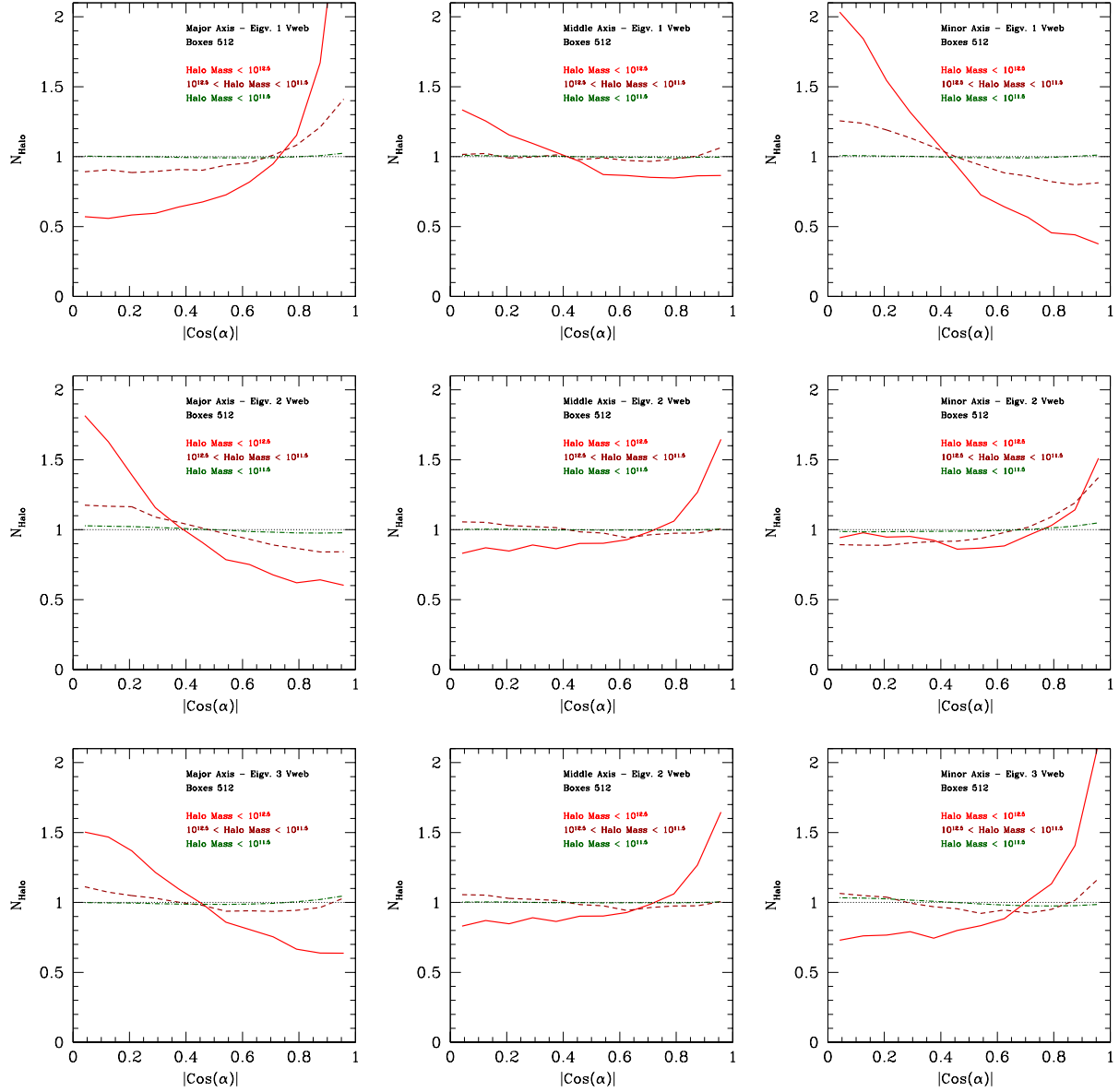


Figure 6. Shape alignment for the vweb at 512^3 resolution.

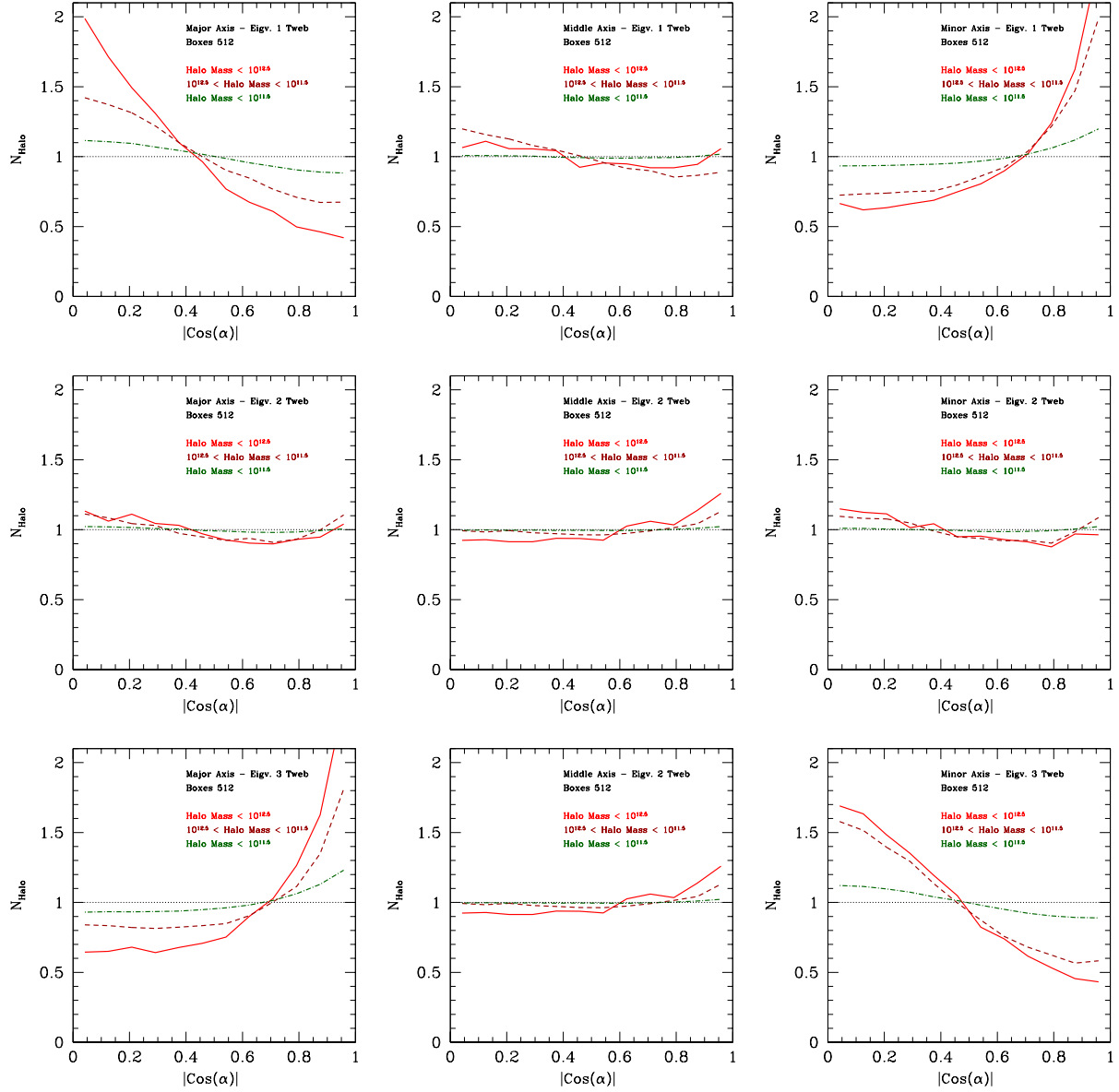


Figure 7. Shape alignment for the tweb at 512^3 resolution.

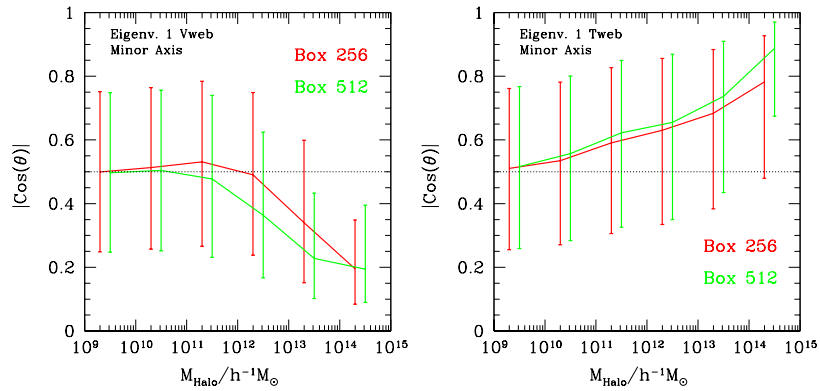


Figure 8. Median of the shape alignment for the two web and the two grid resolution.

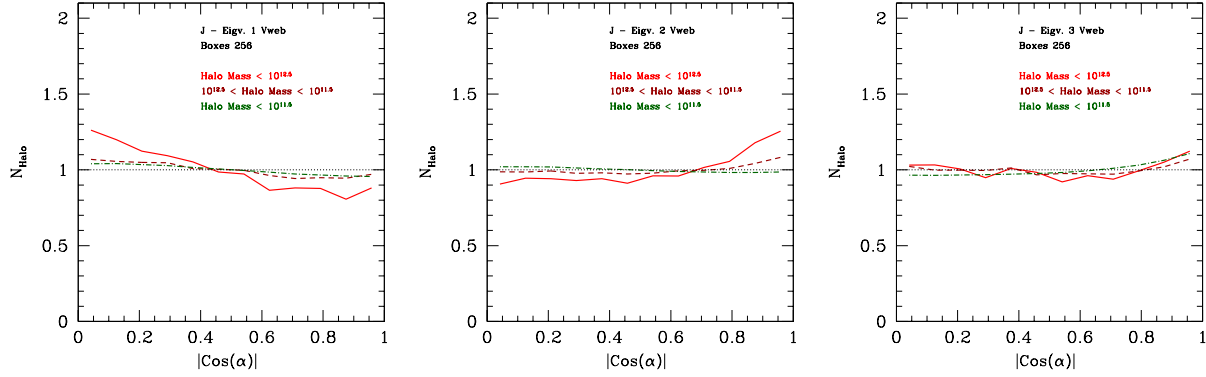


Figure 9. Angular momentum alignment with the Vweb for 256^3 grid resolution.

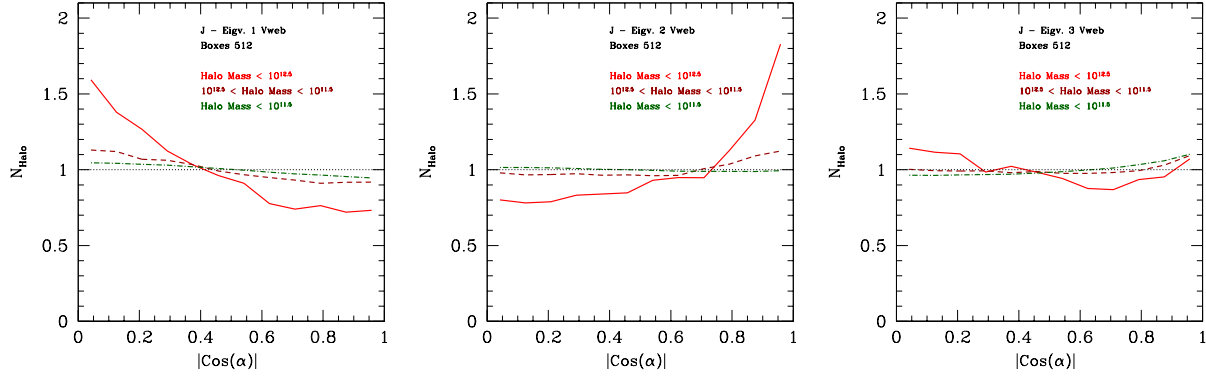


Figure 10. Angular momentum alignment with the Vweb for 512^3 grid resolution.

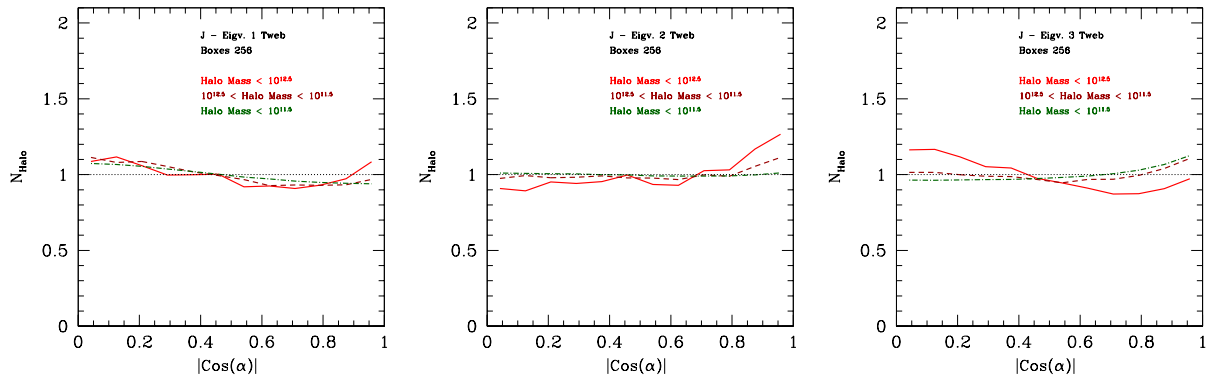


Figure 11. Angular momentum alignment with the Tweb for 256^3 grid resolution.

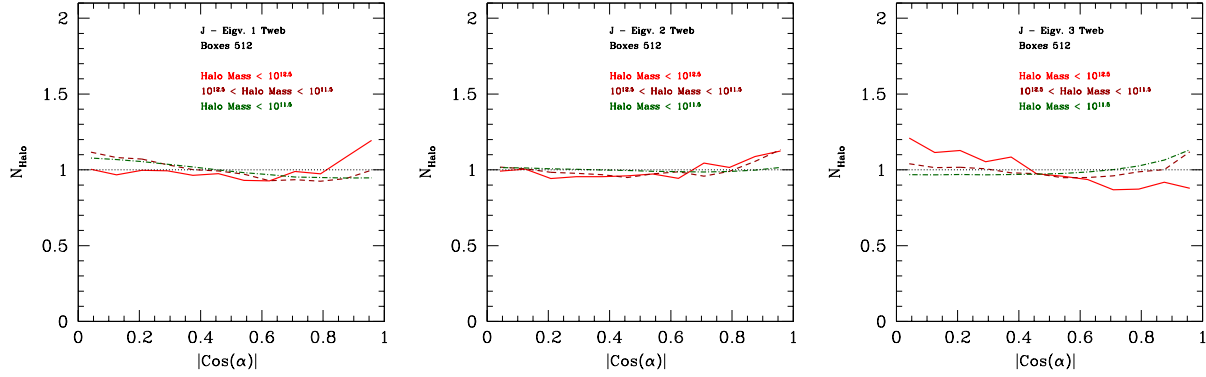


Figure 12. Angular momentum alignment with the Tweb for 512^3 grid resolution.

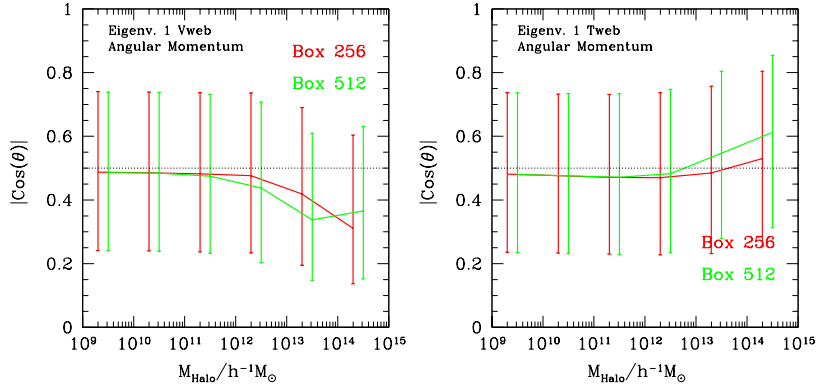


Figure 13. Median of the angular momentum for the two web and the two grid resolution.

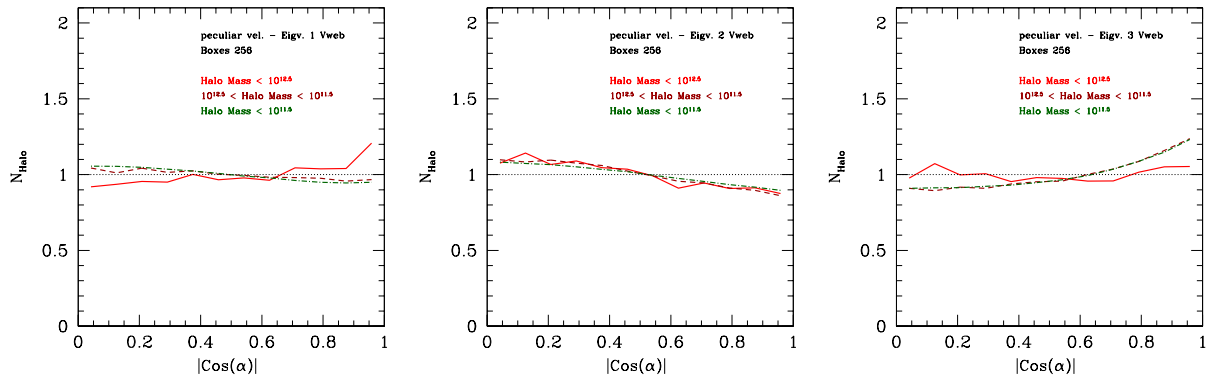
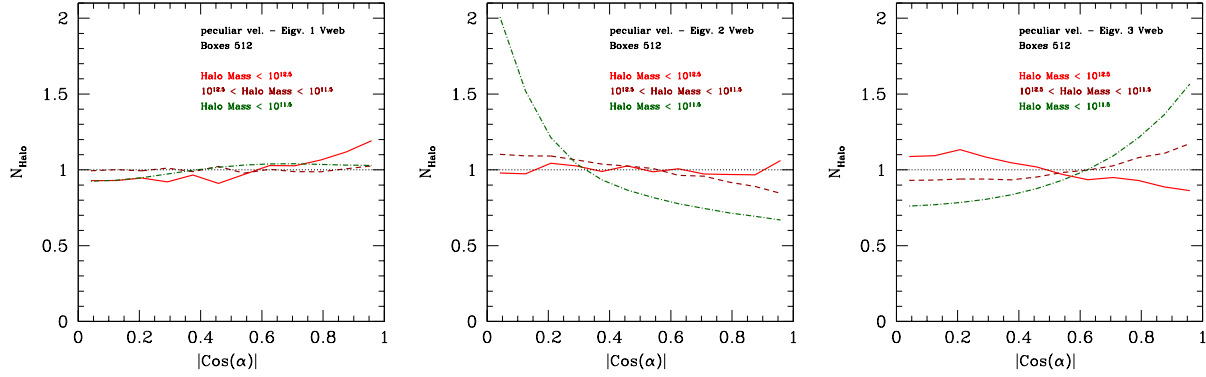
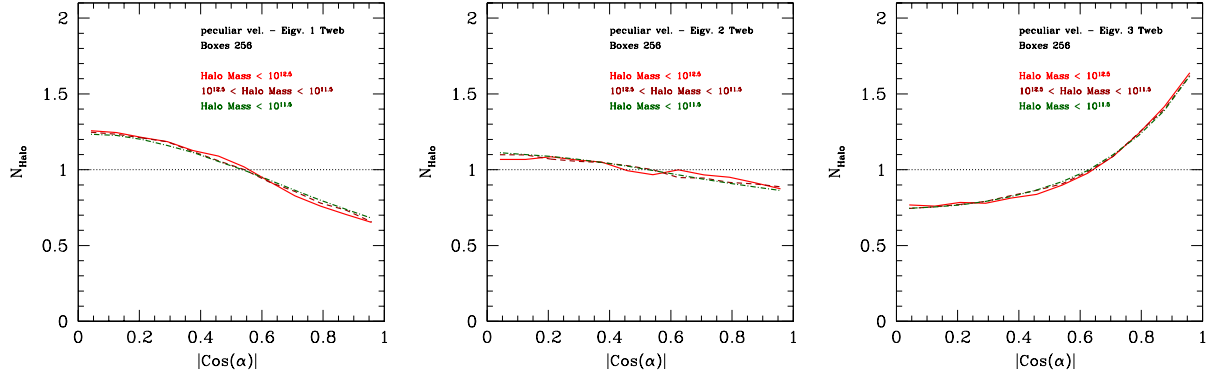
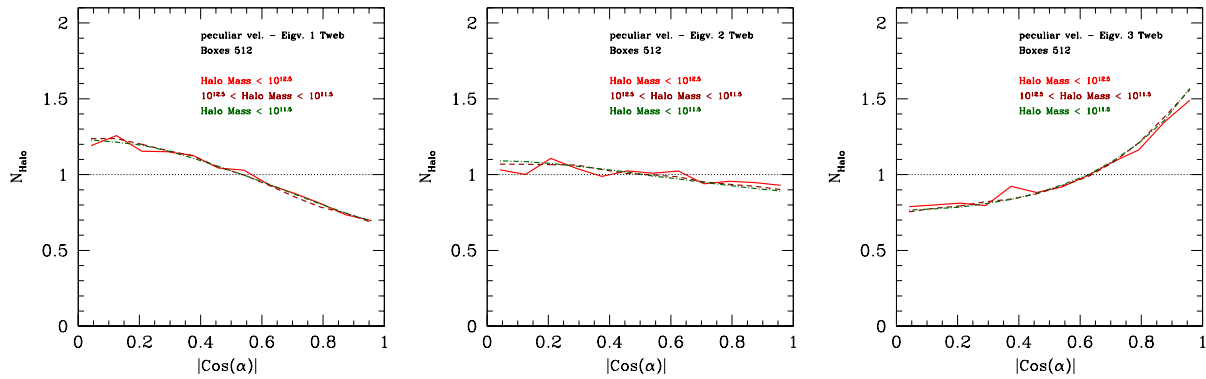


Figure 14. Peculiar velocity alignment with the Vweb for 256^3 grid resolution.

Figure 15. Peculiar velocity alignment with the Vweb for 512^3 grid resolution.Figure 16. Peculiar velocity alignment with the Tweb for 256^3 grid resolution.Figure 17. Peculiar velocity alignment with the Tweb for 512^3 grid resolution.

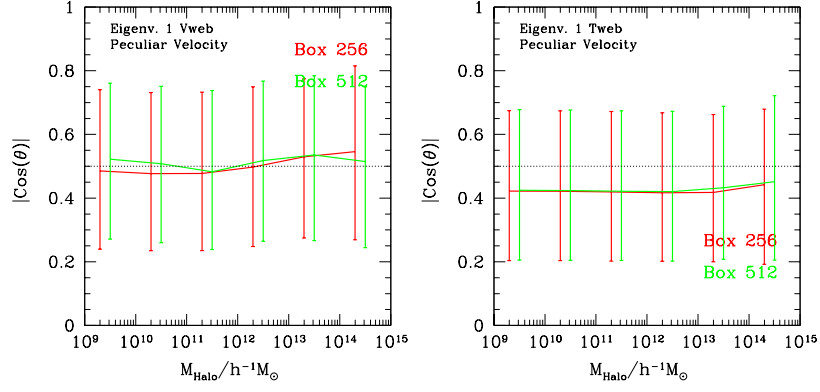


Figure 18. Median of the peculiar velocity for the two web and the two grid resolution.