

# Halo alignments with large scale tidal and velocity fields

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26 February 2013

## ABSTRACT

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

## 1 INTRODUCTION

## 2 THEORETICAL ANTECEDENTS

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

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

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

(Libeskind et al. 2013) (Codis et al. 2012) (Faltenbacher et al. 2009) (Paz et al. 2008) (Platen et al. 2008) (Lee & Erdogdu 2007)

- (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  $150h^{-1}\text{Mpc}$ . The mass per particle is  $2 \times 10^9 h^{-1}\text{M}_\odot$ . 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  $1 - 100 \times 10^{11} h^{-1}\text{M}_\odot$ .

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  $10^{12} h^{-1}\text{M}_\odot$ .

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 tends 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 tends to lie perpendicular to the wall, while the other axis then tends 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  $L_1 = 45h^{-1}\text{Mpc}$ ,  $L_2 = 90h^{-1}\text{Mpc}$  and  $L_3 = 180h^{-1}\text{Mpc}$ , this corresponds to particle masses of 4.7, 38.0,  $300 \times 10^7 h^{-1}\text{M}_\odot$ . 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  $R_s = 2.1h^{-1}\text{Mpc}$ .

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 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.

(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

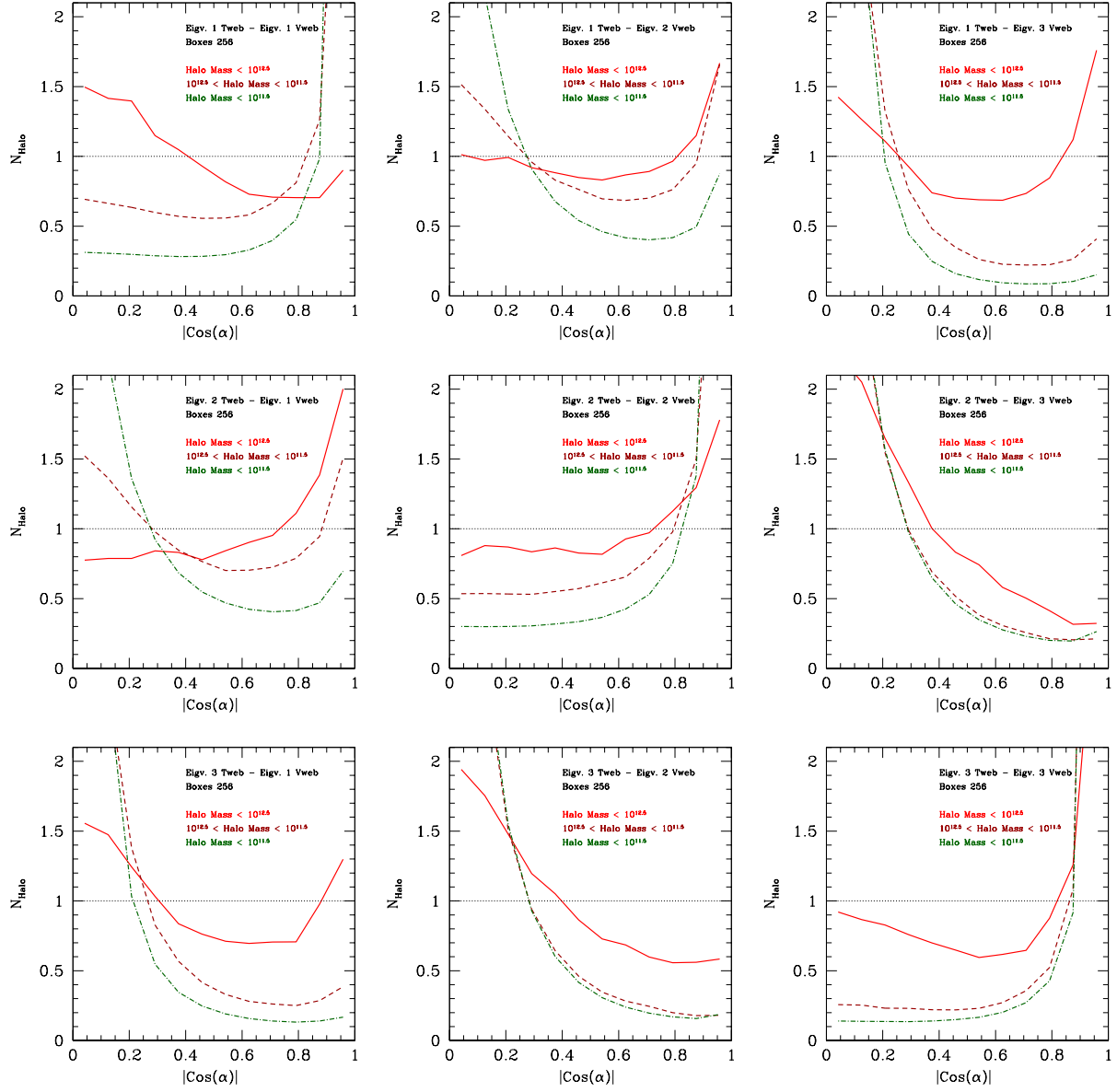
### 6 DISCUSSION

### 7 CONCLUSIONS

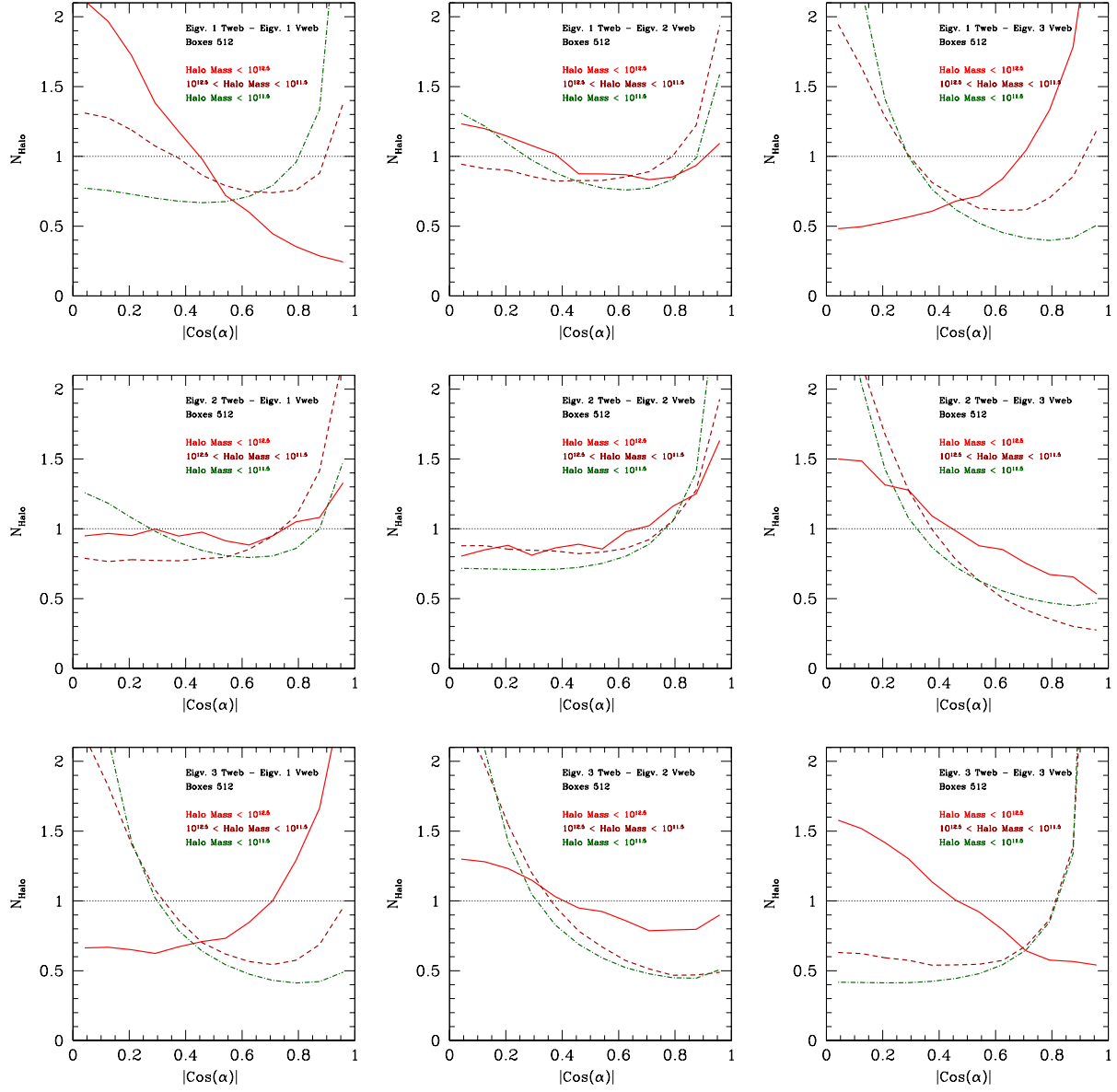
### ACKNOWLEDGMENTS

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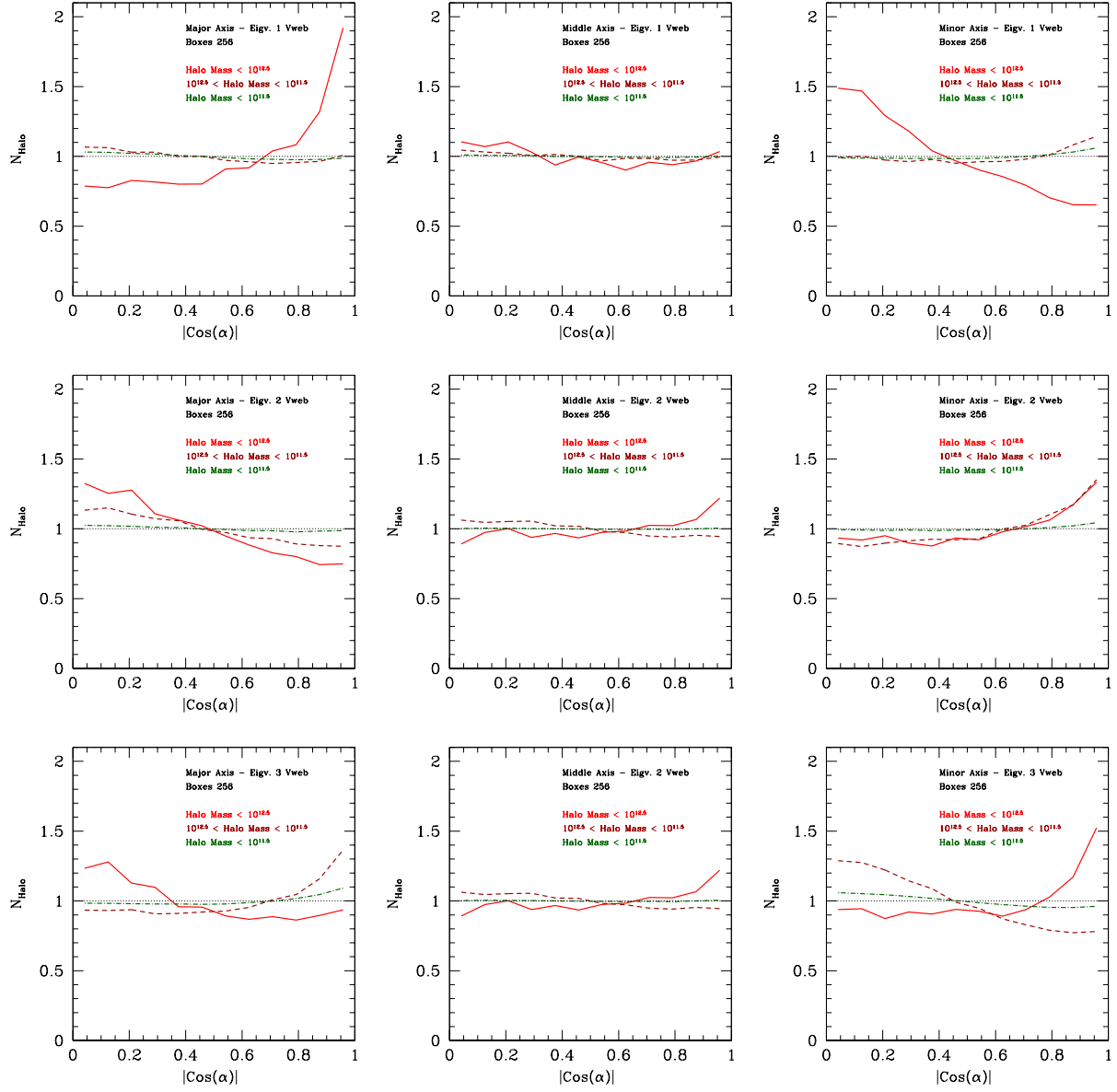
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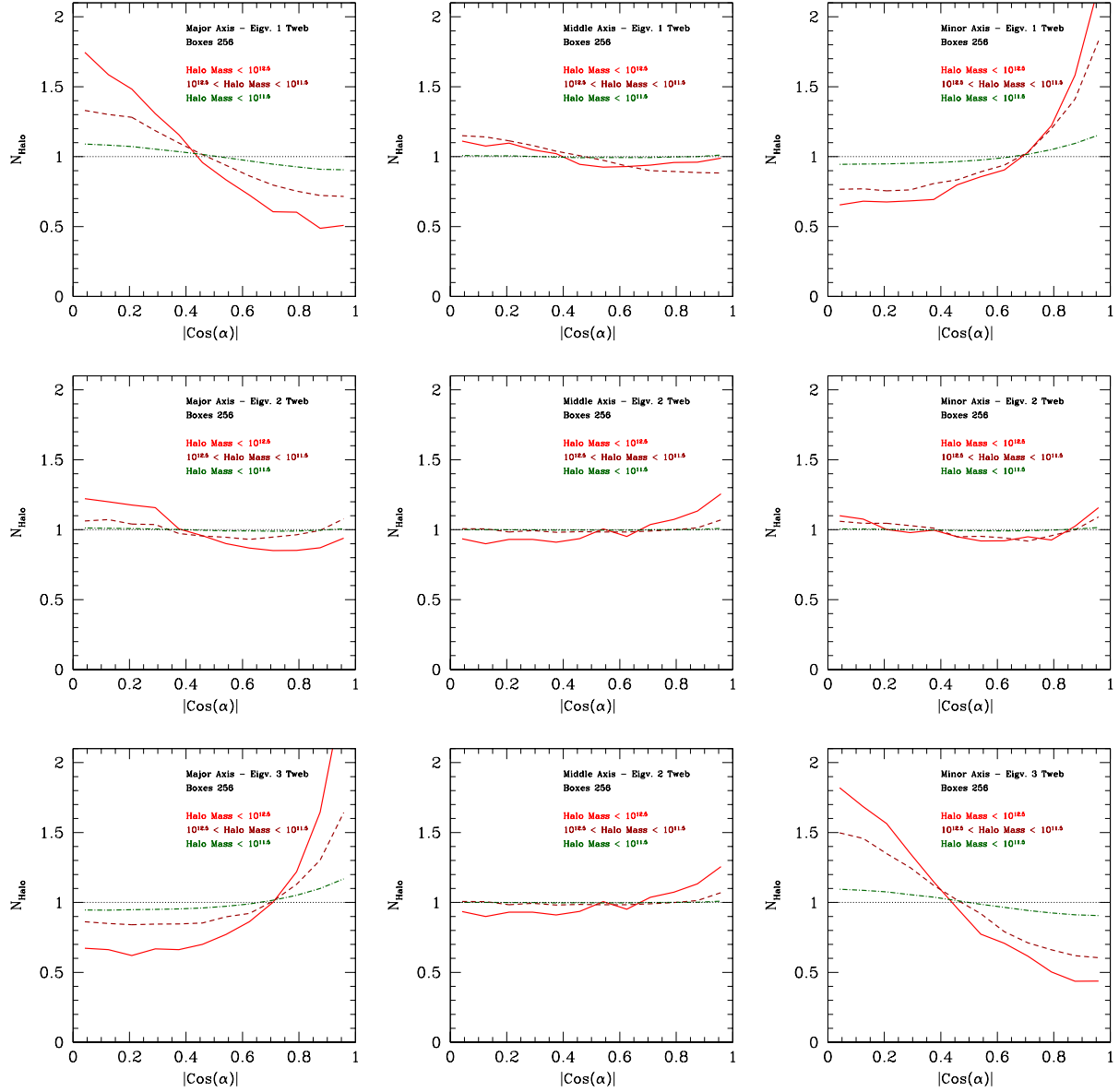
**Figure 1.** Interweb alignment for  $256^3$  grid resolution.



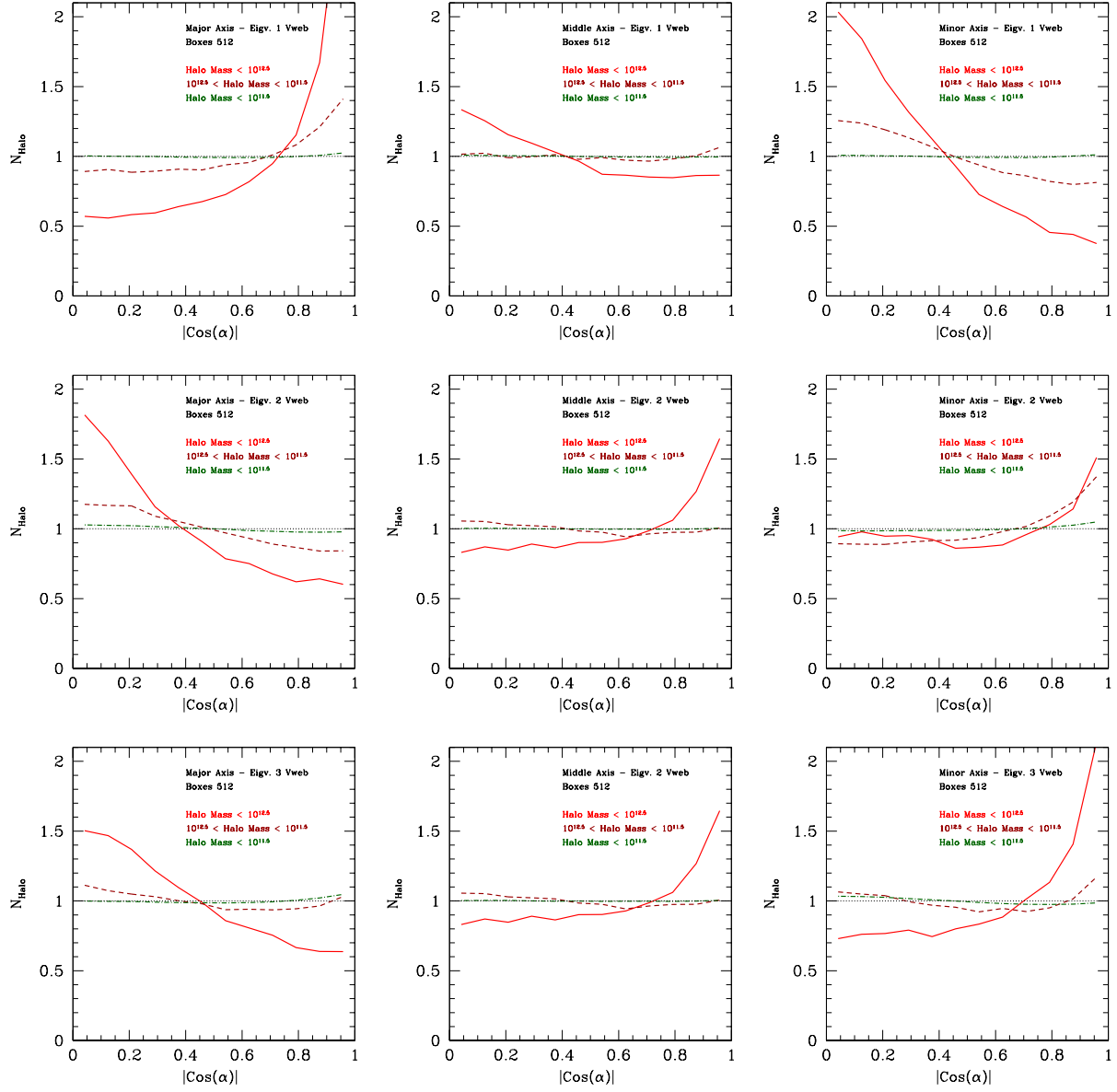
**Figure 2.** Interweb alignment for  $512^3$  grid resolution.



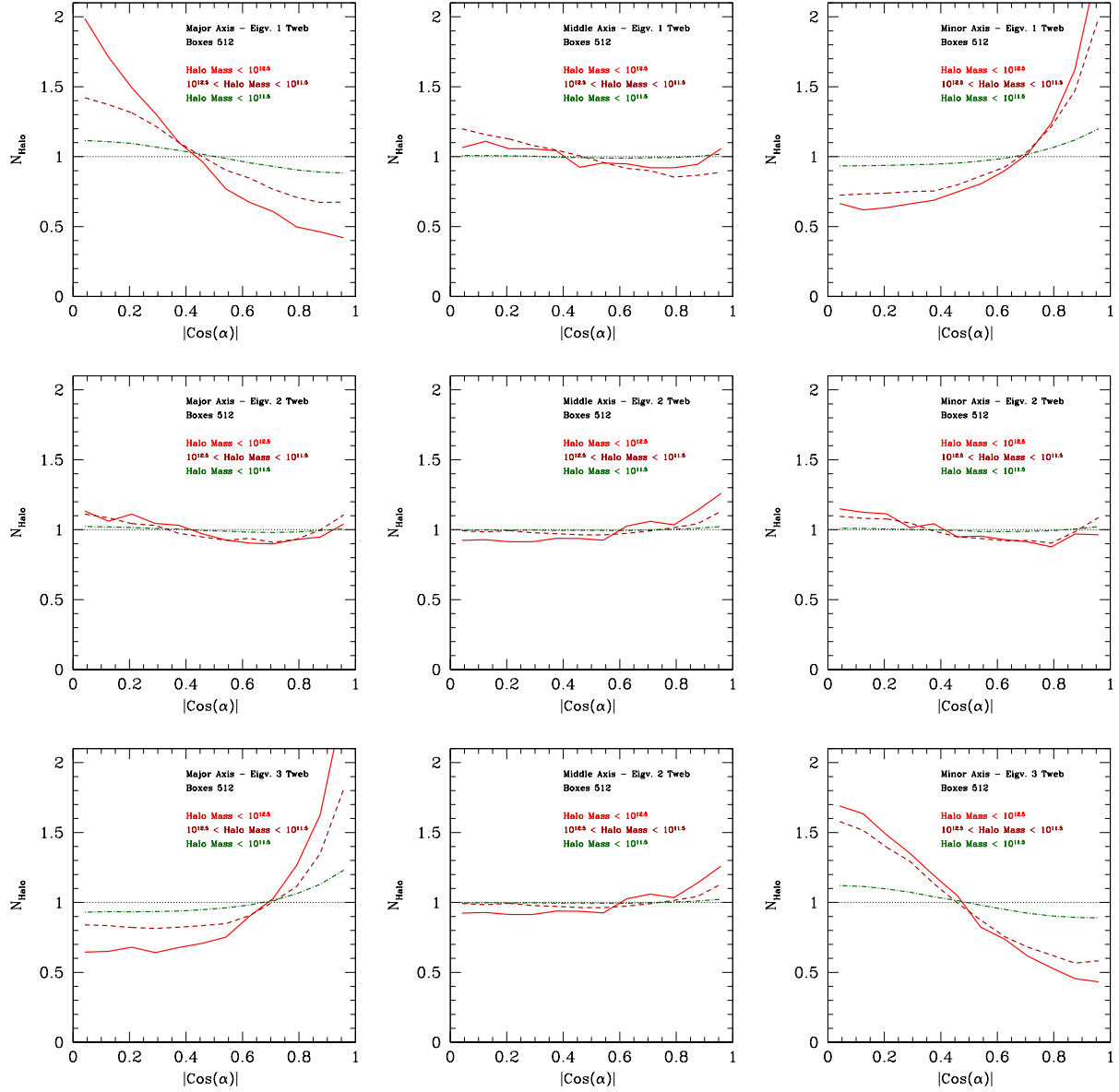
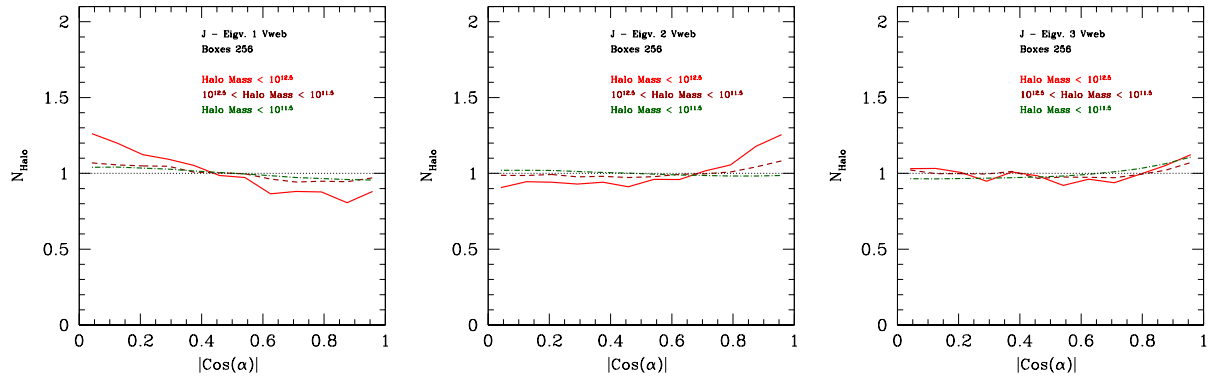
**Figure 3.** Shape alignment for the vweb at  $256^3$  resolution.



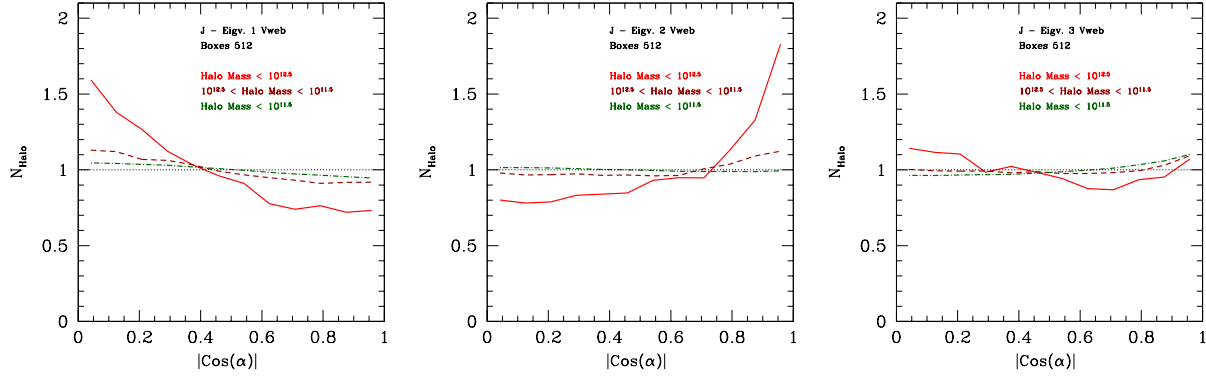
**Figure 4.** Shape alignment for the tweeb at  $256^3$  resolution.



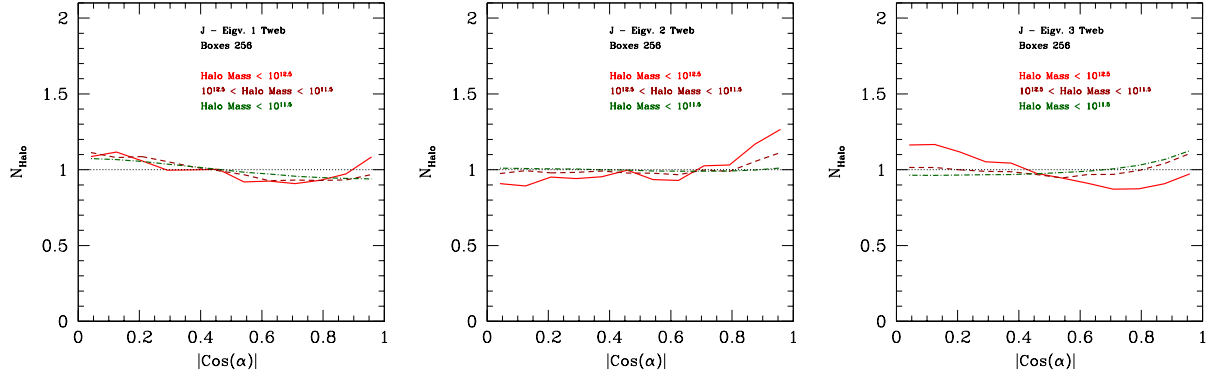
**Figure 5.** Shape alignment for the vweb at  $512^3$  resolution.

Figure 6. Shape alignment for the tweb at  $512^3$  resolution.Figure 7. Angular momentum alignment with the Vweb for  $256^3$  grid resolution.

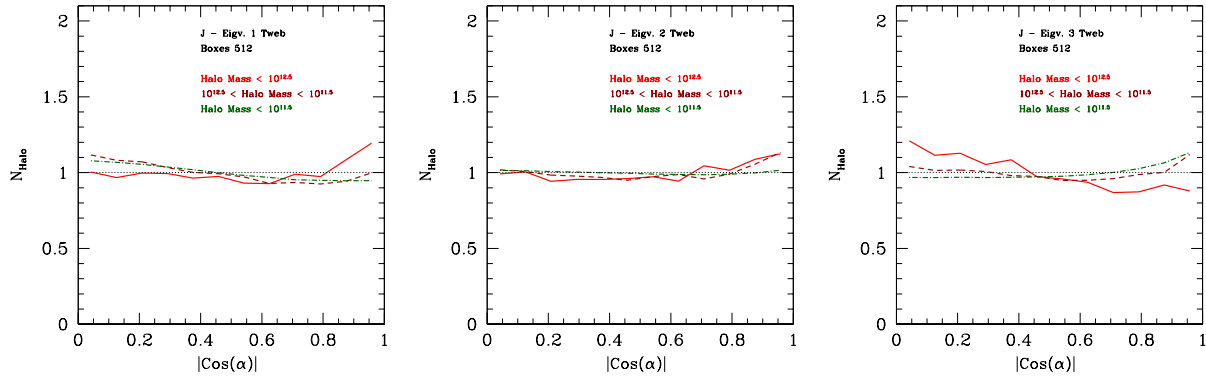




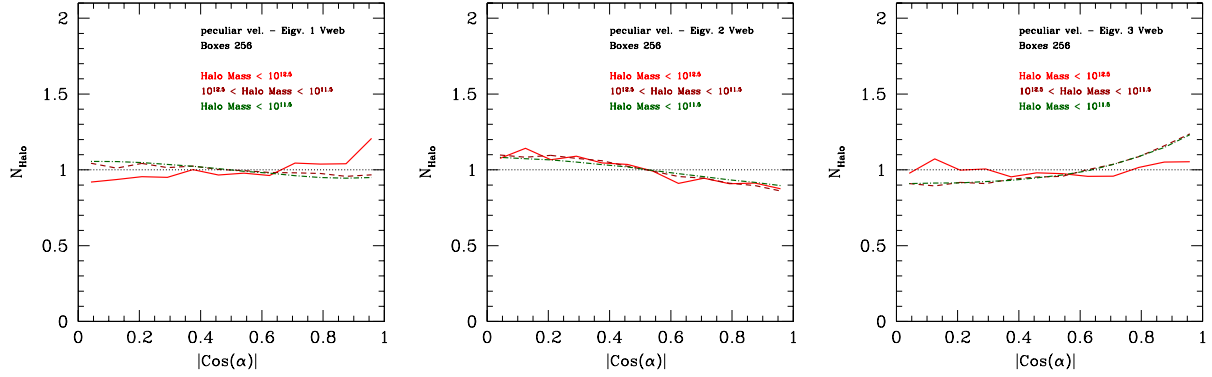
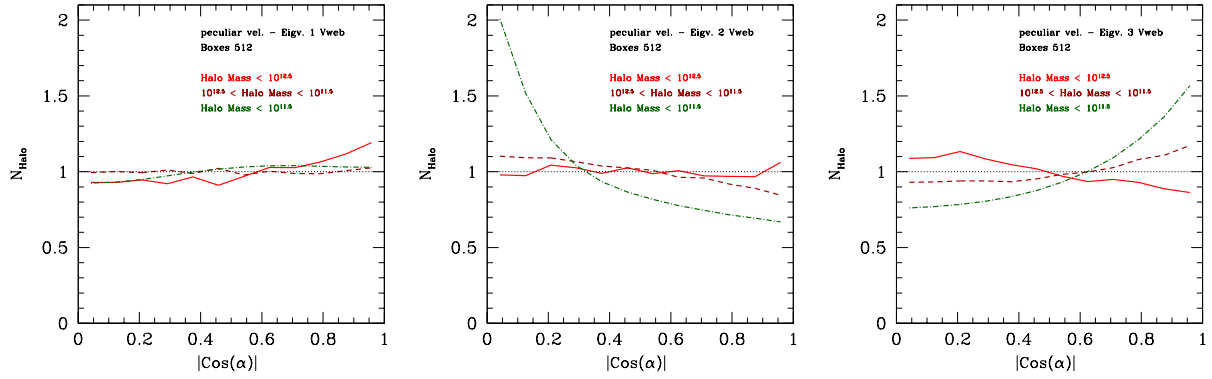
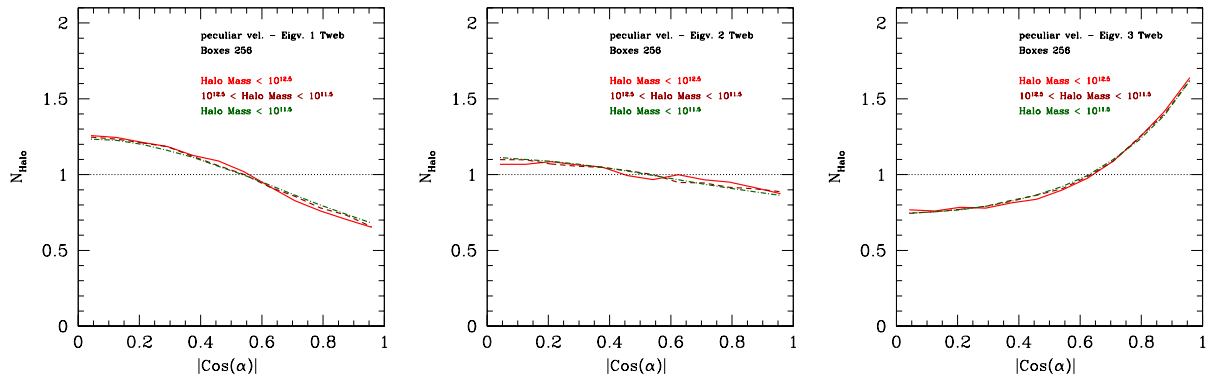
**Figure 8.** Angular momentum alignment with the Vweb for  $512^3$  grid resolution.

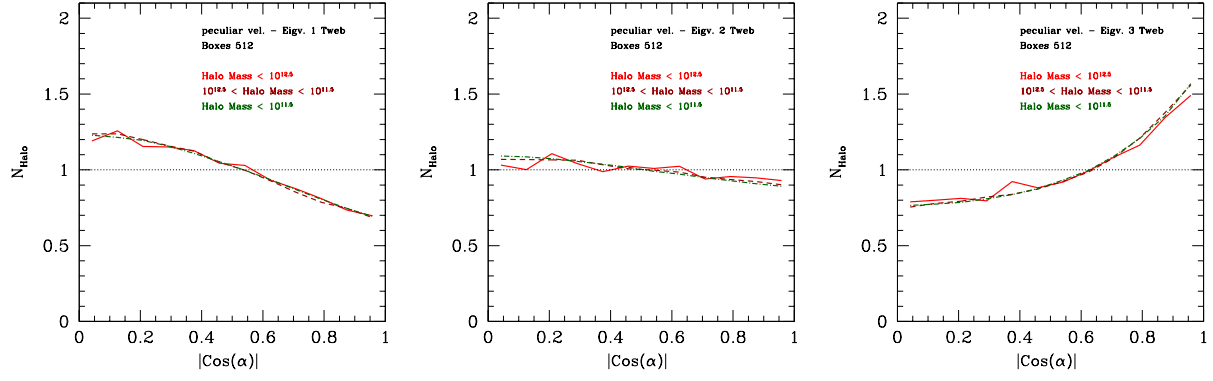


**Figure 9.** Angular momentum alignment with the Tweb for  $256^3$  grid resolution.



**Figure 10.** Angular momentum alignment with the Tweb for  $512^3$  grid resolution.

Figure 11. Peculiar velocity alignment with the Vweb for  $256^3$  grid resolution.Figure 12. Peculiar velocity alignment with the Vweb for  $512^3$  grid resolution.Figure 13. Peculiar velocity alignment with the Tweb for  $256^3$  grid resolution.



**Figure 14.** Peculiar velocity alignment with the Tweb for  $512^3$  grid resolution.