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CLUSTERING DEPENDENCE ON HALO ANGULAR MOMENTUM GROWTH

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ABSTRACT: Although the tidal torque theory (TTT) naturally relates the origin and evolution of angular momentum with the characteristics of the environment in which dark matter (DM) halos are formed, and even though it is the most accepted model on the current paradigm, its validity range is limited to the early times of structure formation. In this work, we study and characterize systematic deviations from TTT predictions performing a statistical analysis on DM halos in a cosmological simulation. We find that the classification of DM halos according to their angular momentum growth results in samples (**W** and **L** halos) with different internal alignment and radically different spin parameter distributions. Based on this classification, we find a strong correlation between the angular momentum history and the well known mass dependent alignment between the angular momentum direction and the large-scale structure. Our study suggests that a secondary tidal torque mechanism could be acting during the non-linear stages of halo formation.

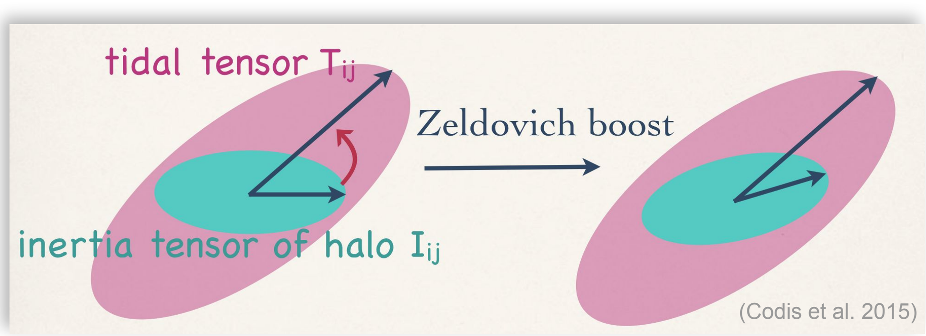
Basics of the TTT

$$\mathbf{J}(t) = \int_{V_L} [\mathbf{r}(\mathbf{q},t) - \mathbf{r}_{cm}(t)] \times \mathbf{v}(\mathbf{q},t)\rho_0 a^3(t) d^3q$$

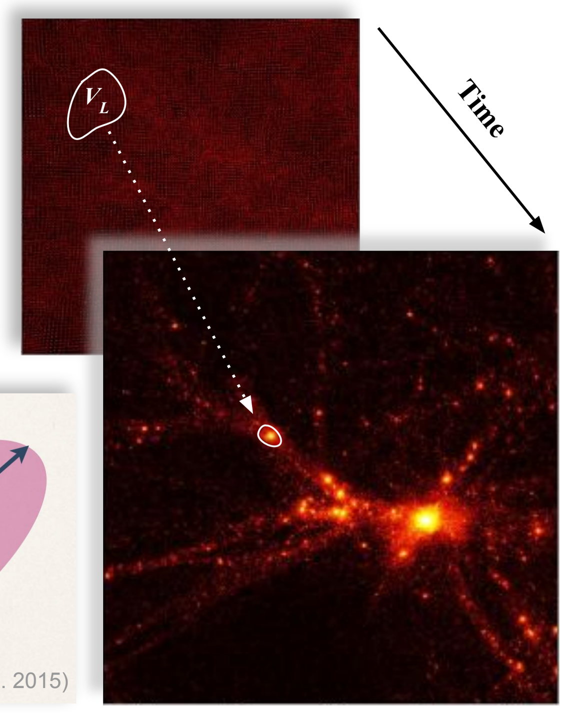
In an EdS Universe $t \propto a^{3/2}$

$$J_i(t) = a^2(t)\dot{D}^+(t)\epsilon_{ijk}T_{jl}I_{lk}$$

(White 1984)



(Codis et al. 2015)



The TTT process: The model states that most of the angular momentum of the matter inside a Lagrangian volume V_L (namely, a protohalo) is gained during the linear stage of structure formation, due to the misalignment between its inertia tensor $\boldsymbol{I}$ and the tidal shear field $\boldsymbol{T}$ exerted by the surrounding matter distribution. Using the Zeldovich approximation in order to boost the torquing, this scenario can be analytically described with an expression (White 1984) with separate dependence on position and time. The time-dependent factor grows proportional to the cosmic time t (proportional to $a^{3/2}$) in an EdS Universe.

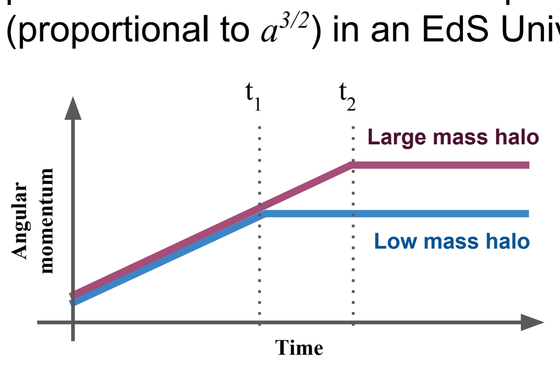


Fig. 1: The decoupling of the protohalo region from the general expansion of the Universe, when it turns around to non-linear collapse and virialization, makes the TTT process lose efficiency due to the reduction of the system inertia and the increasing separation with the neighbouring matter responsible for the tidal torque. Hence, from this point on, little angular momentum is expected to be tidally exchanged (Porciani et al. 2002), i.e. **angular momentum growth by tidal torquing should stop after turnaround**. As we know by the hierarchical theory, large mass halos collapse later in time, so, as the TTT mechanism is efficient for a longer period, their final angular momentum should be larger.

TTT implementation and halo samples

N_p	L [h^{-1}Mpc]	H_0 [km s^{-1} Mpc^{-1}]	$\Omega_M = 1 - \Omega_\Lambda$	σ_8	m_p [h^{-1} M$_\odot$]	l [$\bar{\nu}^{-1/3}$]	N_h
1024^3	1000	70,2	0,272	0,807	$7{,}21 \times 10^{10}$	0,17	2.730.590

Table 1: We list the parameters (Larson et al. 2011) and some features of the numerical simulation we runned to perform our analysis: the number of particles N_p, the side of the box L, the Hubble constant H_0, the mass density parameter Ω_M, the mass distribution on 8 h^{-1}Mpc scales σ_8 and the particle mass m_p. We also show the linking length l (in terms of the mean particle density $\bar{\nu}$) of our FoF algorithm and the number of halos N_h identified.

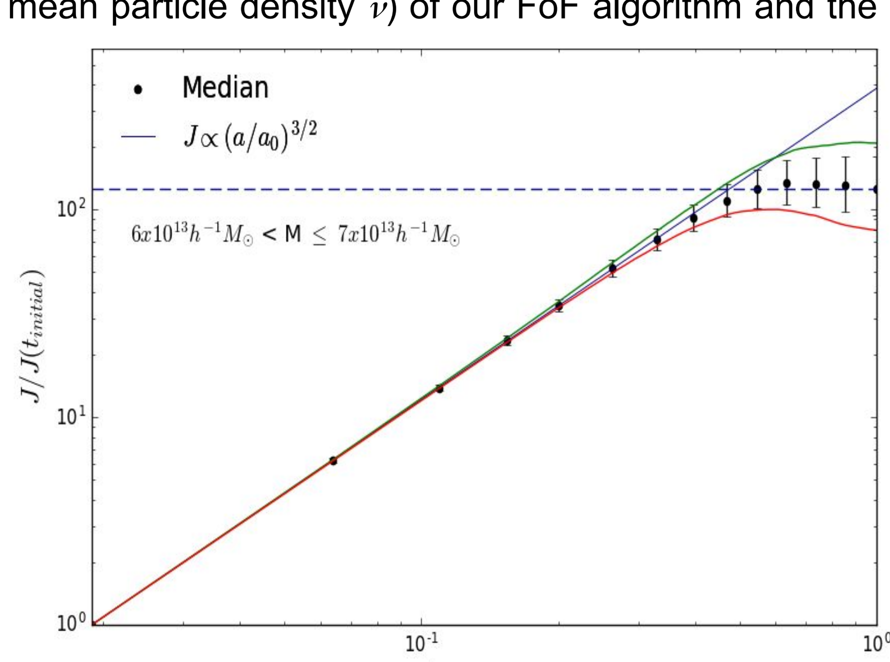


Fig. 2: The median evolution of the angular momentum for halos in a given mass range (black dots) against the TTT predictions (solid blue line). In order to compare and detect systematic deviations, we measure the angular momentum growth normalizing every value to its initial condition, and divide the population in mass bins to avoid biases arising from the different turnaround times. We can see an excellent agreement in the first stages of structure formation, but the scatter in the non-linear stages suggest that there are other process involved. We then define the **W** and **L** samples as the upper and lower terciles, respectively, in the final angular momentum growth distribution (medians in green and red solid curves).

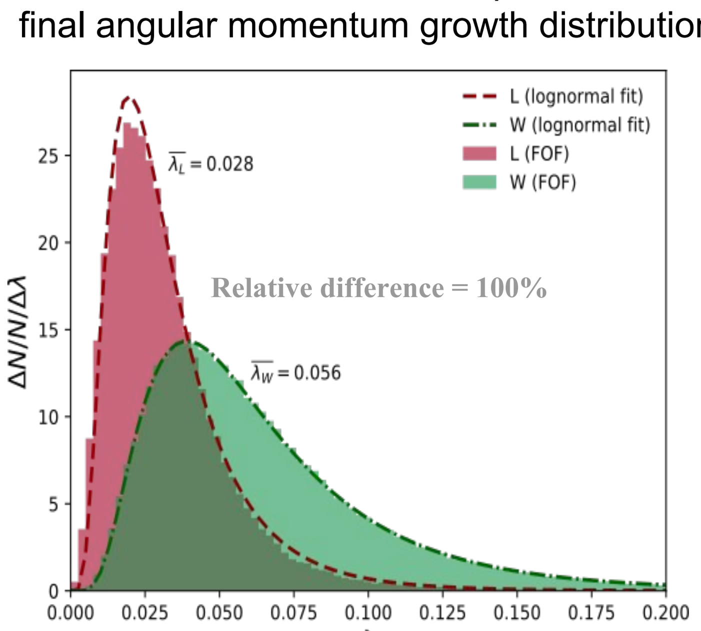


Fig. 3: Distribution at $z=0$ of the dimensionless spin parameter λ for halos in the **W** and **L** samples. The spin parameter measures the fraction of coherent rotation in a system compared to random motions and has a well known log-normal distribution that peaks at $\bar{\lambda}\sim0{,}04$ with a very low dependence on mass (Bullock et al. 2001; Vitvitska et al. 2002). Thus, halos with larger angular momentum growth show twice as mean rotational support as halos under the predictions in our TTT implementation.

RESULTS

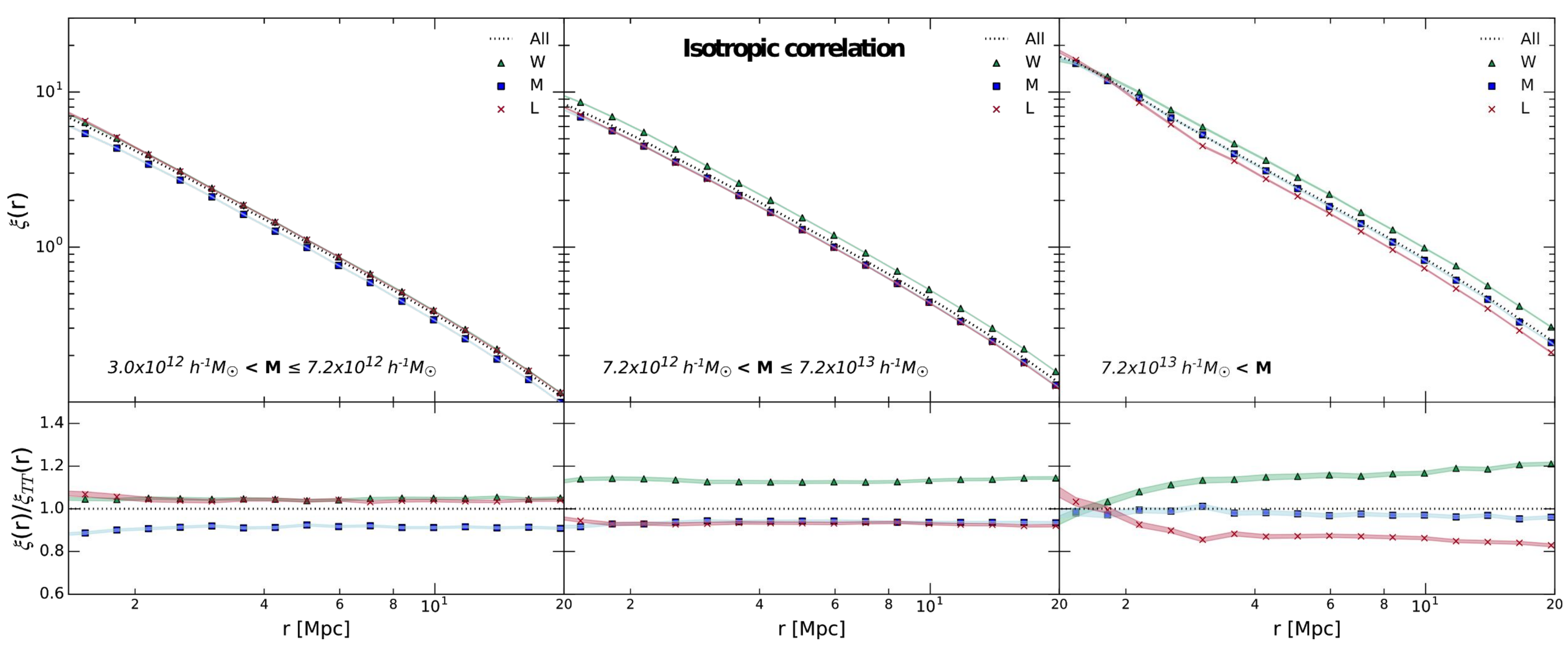


Fig. 2: Spatial two-point cross correlation function of the entire population (black dotted curve), the **W** (green triangles) and the **L** (red crosses) samples, for low, medium and large mass halos from left to right. The lower panel shows the normalization of each curve by the general correlation. Halos of the **W** sample show a stronger surrounding structure as mass increases.

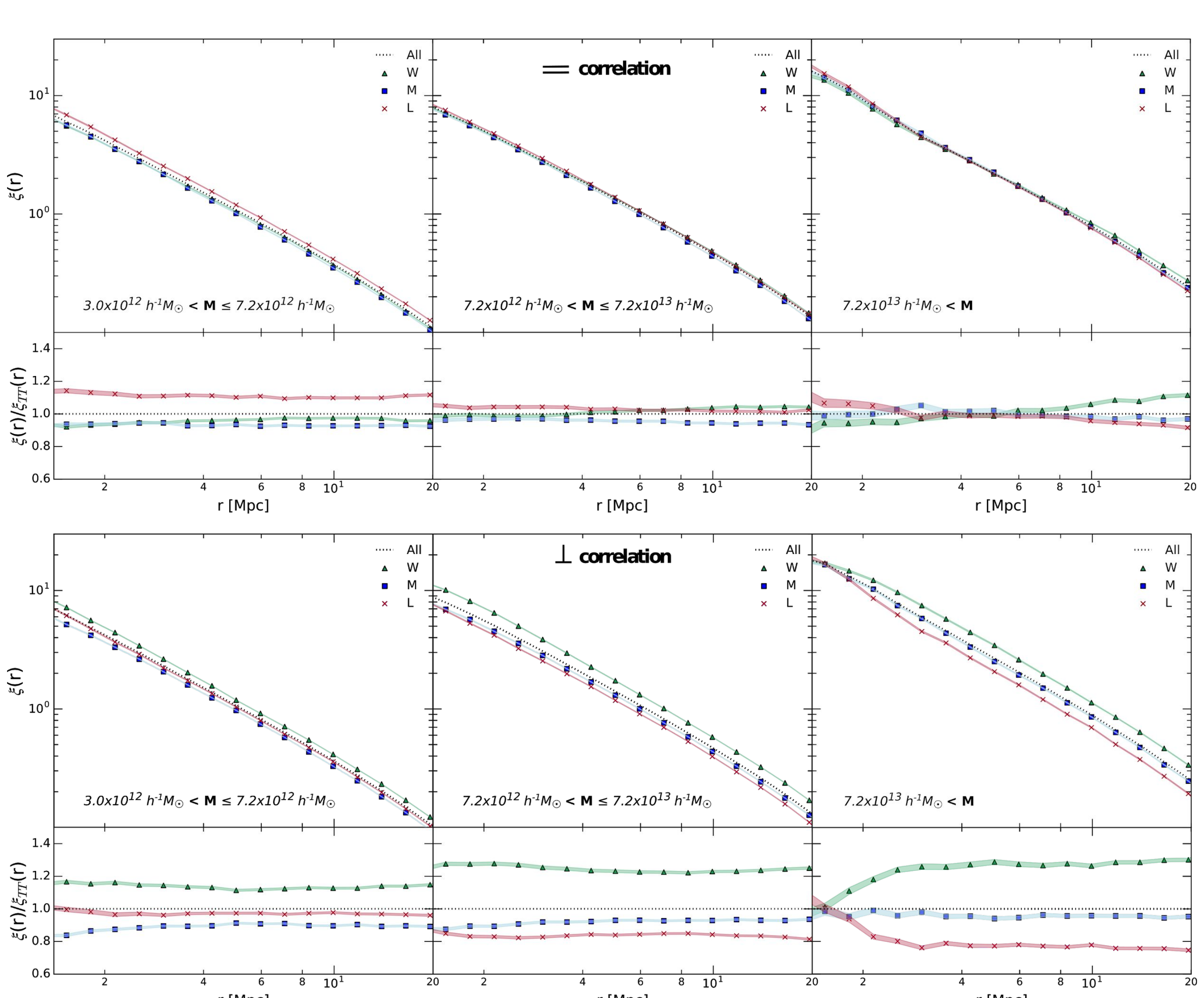


Fig. 3: The upper (lower) pannel shows the correlation function of each halo sample in the direction parallel (perpendicular) to the angular momentum. The difference in clustering detected in the isotropic correlation is due almost entirely to the perpendicular structure, which can produce secondary torques during the non-linear stages of structure formation.

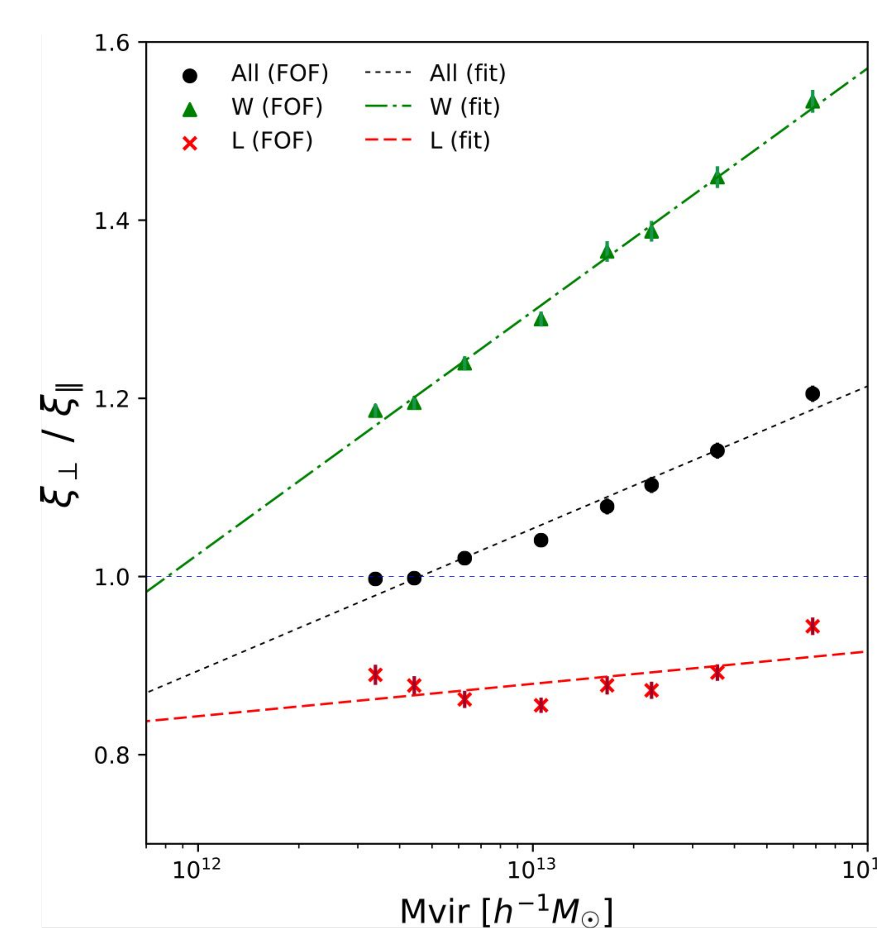


Fig. 4: Ratio of the anisotropical correlation functions for a single distance range (1 - 15 h^{-1}Mpc) on different mass bins. In the perpendicular direction, the **W** sample shows a stronger clustering as mass increases, which is well described by Codis et al. (2015). The **L** sample, however, shows an almost mass-independent trend of stronger clustering in the direction parallel to their angular momentum.

Conclusions

- We performed a statistical analysis of **deviations from the TTT predictions** in a numerical simulation with 2.730.590 DM halos, defining two samples according to their **angular momentum growth**: halos with an increase above (**W** sample) and under (**L** sample) the predictions of our TTT implementation.
- We found a clear trend of **more rotational support** in the **W** sample, which indicates that the non-TTT processes involved in their angular momentum acquisition also modeled their internal structure. This is consistent with the observed difference of alignment between angular momentum and shape for halos in both samples.
- Large mass halos of the **W** sample show a **stronger clustering** around them, particularly in the direction **perpendicular** to their angular momentum. This suggest that there could be a secondary tidal torque acting during the non-linear stages of structure formation on halos surrounded by a stronger perpendicular structure, perhaps due to a non-decoupled collapse.
- The known **mass-dependent relation between angular momentum and LSS**, described in Codis et al. (2015), is clearly observed in the **W** sample, but **is not consistent** with the mass-independent trend of stronger clustering in the direction parallel to the angular momentum showed by halos in the **L** sample. This requires further investigation and a probably a different approach.

References

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