arXiv:2311.03632 arXiv:2401.11707

Gauging the Initial Misalignment between the Inertia and Tidal Tensors in the IllustrisTNG Simulations: A Key Regulating Factor for Galactic Halo Spins

Jun-Sung Moon and Jounghun Lee

Astronomy Program, Department of Physics and Astronomy, Seoul National University; jsmoon.astro@gmail.com

Abstract

According to the linear tidal torque theory, the generation of halo angular momentum requires an initial misalignment between the protogalactic inertia tensor and the initial tidal field. Here, we introduce a new parameter, denoted by τ, to measure the degree of such an initial misalignment at the protogalactic sites. To determine the values of τ, we analyze the IllustrisTNG cosmological simulations by tracing all member particles of galactic halos at z = 0 back to the initial condition at z = 127. The probability density functions of τ are perfectly modeled by the Gamma distributions, and their shape and scale parameters have universal values on a particular spatial scale, regardless of halo mass and redshift. We find that τ shares significant mutual information with halo properties at z = 0, including the spin parameter, formation epoch, stellar-to-total mass ratio, and fraction of random motion. The spin parameter exhibits the strongest dependence on τ, even indicating that τ plays a more decisive role than halo masses and environments. The halo spin alignments with the local tidal fields also depend on τ, with τ-dependent spin transitions occurring at two different thresholds. These findings suggest that the initial condition plays a significant role in galaxy evolution and that τ should be a key factor regulating the strength and orientation of the current halo spins.

Initial Misalignment (τ)

- **The τ parameter quantifies the misalignment between the protogalactic inertia tensor and the initial tidal field.**
- For the inertia tensor ($\boldsymbol{I}$) in the principal frame spanned by three eigenvectors ($\hat{\boldsymbol{t}}$) of the tidal field ($\boldsymbol{T}$),

$$\tau \equiv \left(\frac{\boldsymbol{I}_{12}^2 + \boldsymbol{I}_{23}^2 + \boldsymbol{I}_{31}^2}{\boldsymbol{I}_{11}^2 + \boldsymbol{I}_{22}^2 + \boldsymbol{I}_{33}^2}\right)^{1/2}$$

- If the inertia tensor is perfectly aligned with the tidal tensor, the off-diagonal components of $\boldsymbol{I}$ are zero and τ = 0.
- The more the two tensors are misaligned, the larger τ becomes.
- A non-zero value of τ is a necessary condition for the galaxy angular momentum along $\hat{\boldsymbol{t}}_\alpha$ in the tidal torque theory (e.g., Lee & Pen 2000; Schäfer 2009).

$$\boldsymbol{J}_1 \propto \boldsymbol{I}_{23}(\boldsymbol{T}_{22} - \boldsymbol{T}_{33}),\quad \boldsymbol{J}_2 \propto \boldsymbol{I}_{31}(\boldsymbol{T}_{33} - \boldsymbol{T}_{11}),\quad \boldsymbol{J}_3 \propto \boldsymbol{I}_{12}(\boldsymbol{T}_{11} - \boldsymbol{T}_{22})$$

IllustrisTNG Simulation

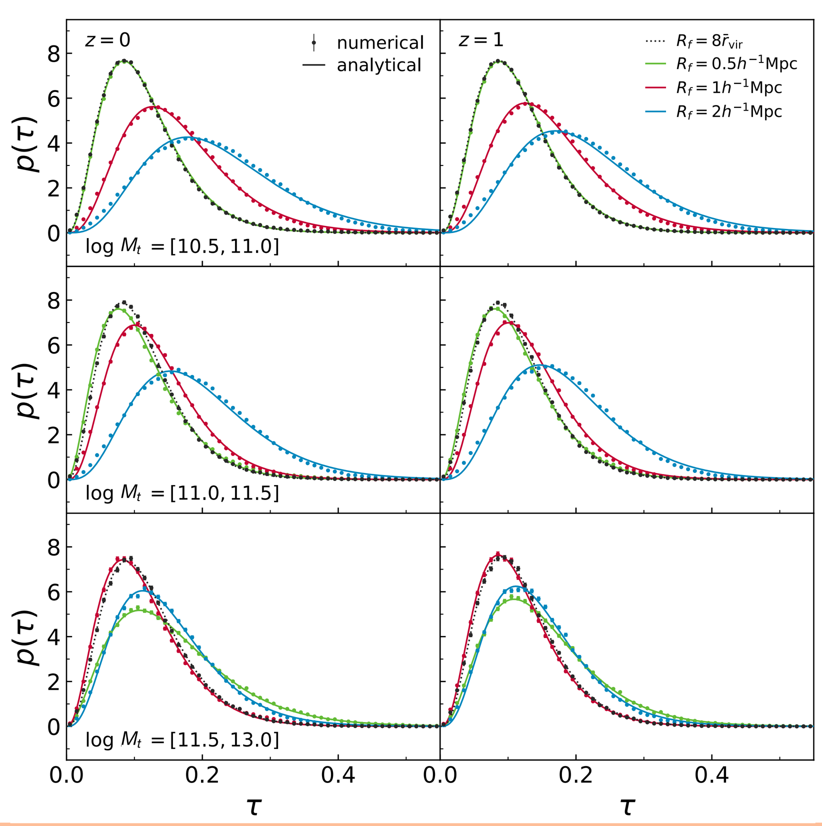
- **We utilize the TNG300 run in the IllustrisTNG project,** a cosmological hydrodynamical simulation (Nelson et al. 2019).
- Central subhalos with $10^{10.5} \le M_t/(h^{-1}M_\odot) \le 10^{13}$ are selected.
- The constituent DM particles of each subhalo at z = 0 are traced back to the initial condition at $z_{ini} = 127$.
- The inertia tensor ($\boldsymbol{I}$) is calculated from the initial positions ($\boldsymbol{x}$) of the DM particles with respect to their center of mass ($\bar{\boldsymbol{x}}$).

$$\boldsymbol{I}_{\alpha\beta} = \sum_i m_i(\boldsymbol{x}_{i,\alpha} - \bar{\boldsymbol{x}}_\alpha)(\boldsymbol{x}_{i,\beta} - \bar{\boldsymbol{x}}_\beta)$$

- The tidal field ($\boldsymbol{T}$) at $\bar{\boldsymbol{x}}$ is obtained in the Fourier space from the density field (δ) with a smoothing scale (R_f).

$$\boldsymbol{T}_{\alpha\beta}(\boldsymbol{k}) = k_\alpha k_\beta \delta(\boldsymbol{k}) \exp\left(-|\boldsymbol{k}|^2 R_f^2/2\right)/|\boldsymbol{k}|^2$$

τ Distributions



$$p(\tau; k, \theta) = \frac{1}{\Gamma(k)\theta^k}\tau^{k-1}\exp\left(-\frac{\tau}{\theta}\right)$$

Figure 1. Distributions of τ (filled circles) with the best-fit gamma distributions (solid lines) in three different halo mass ranges (M_t) and four smoothing scales (R_f) at two different redshifts (z). **The PDFs are well approximated by the gamma distributions and have a universal shape on $R_f = 8r_{vir}$.**

Correlation with Halo Properties

- **We examine the correlation between τ and four basic halo properties:** spin parameter (λ; Bullock et al. 2001), formation epoch (a_f), stellar mass-to-total mass ratio (M_*/M_t), and fraction of random motion in kinetic energy (K_{rd}/K_t; Sales et al. 2012)

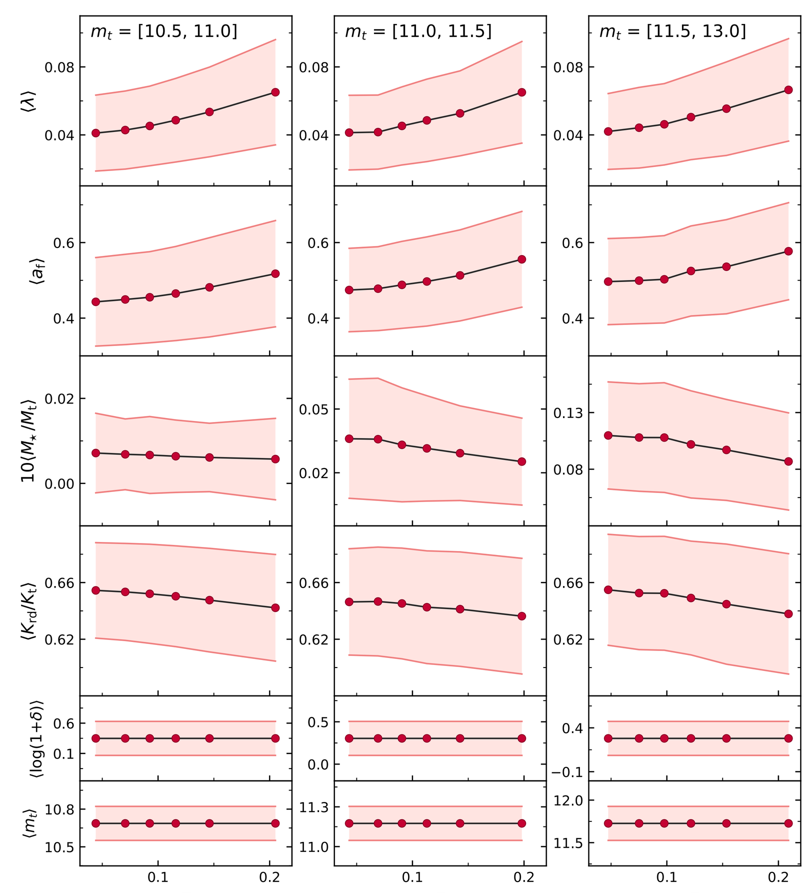


Figure 2. Mean halo properties (the top four panels) as a function of τ when the halo mass (M_t) and environmental overdensity (δ) are controlled to be the same (the bottom two panels). The shaded areas indicate 1σ scatters, while the errors of the means are too small to be visible. **On average, λ increases, a_f becomes later, M_*/M_t decreases, and K_{rd}/K_t reduced, as τ increases.**

- **Mutual information (MI) is a measure of the correlation between two variables,** which quantifies the amount of information that the two variables share (e.g., Shannon 1948; Sarkar et al. 2021).

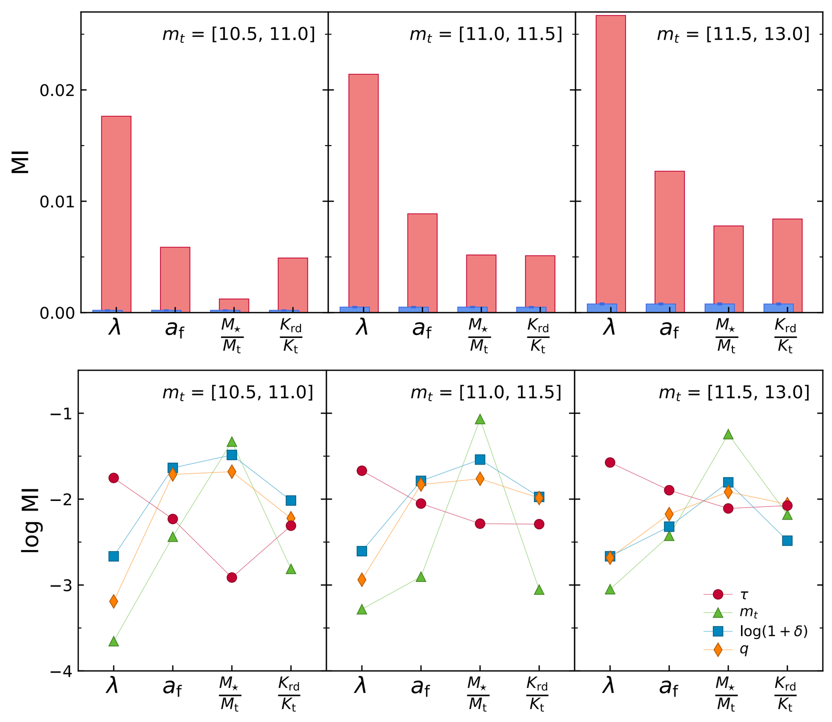


Figure 3. Top: MIs between τ and the halo properties (red). The mean MIs from the random data (blue) are shown for comparison. Bottom: Comparisons among the MIs with τ (red circles), M_t (green triangles), δ (blue squares), and q (tidal anisotropy; orange diamonds). **τ shares a large amount of MI with halo properties, especially λ.**

τ-Dependent Spin Transition

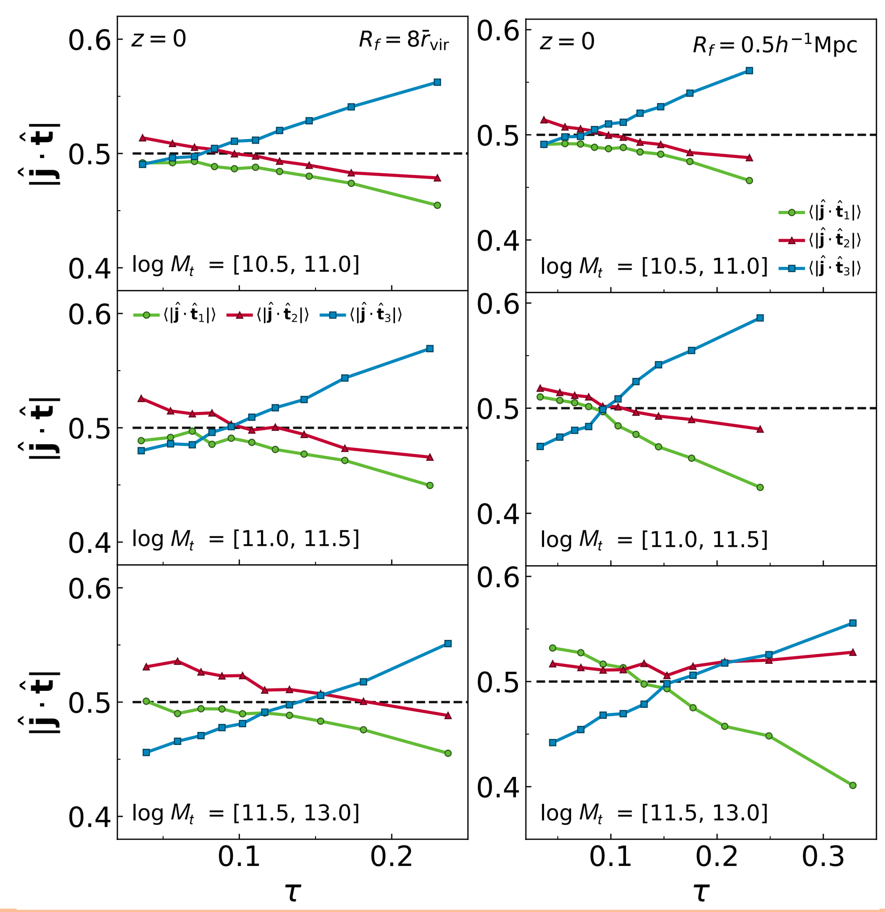


Figure 4. Mean cosine angles between the halo spins (**j**) and the major (**t**$_1$; green circles), intermediate (**t**$_2$; red triangle), and minor (**t**$_3$; blue squares) principal axes of the local tidal fields on the scale of $R_f = 8r_{vir}$ (left) and $R_f/(h^{-1}\mathrm{Mpc}) = 0.5$ (right), respectively. The horizontal dashed lines indicates random orientations. **The halo spin alignment depends on τ: the spin transits from t_3 to t_2 as τ decreases in all mass ranges.**