Living with Neighbors. IV. Dissecting the Spin–Orbit Alignment of Dark Matter Halos: Interacting Neighbors and the Local Large-scale Structure

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Abstract

Spin–orbit alignment (SOA; i.e., the vector alignment between the halo spin and the orbital angular momentum of neighboring halos) provides an important clue to how galactic angular momenta develop. For this study, we extract virial-radius-wise contact halo pairs with mass ratios between 1/10 and 10 from a set of cosmological N-body simulations. In the spin–orbit angle distribution, we find a significant SOA in that 52.7% ± 0.2% of neighbors are on the prograde orbit. The SOA of our sample is mainly driven by low-mass target halos (<10^{11.5} h^{-1} M_{\odot}) with close merging neighbors, corroborating the notion that tidal interaction is one of the physical origins of SOA. We also examine the correlation of SOA with the adjacent filament and find that halos closer to the filament show stronger SOA. Most interestingly, we discover for the first time that halos with the spin parallel to the filament experience most frequently prograde polar-interaction (i.e., fairly perpendicular but still prograde interaction; spin–orbit angle ~70°). This instantly invokes the spin-flip event and the prograde-polar interaction will soon flip the spin of the halo to align it with the neighbor’s orbital angular momentum. We propose that SOA originates from the local cosmic flow along the anisotropic large-scale structure, especially that along the filament, and grows further by interactions with neighbors.

Unified Astronomy Thesaurus concepts: N-body simulations (1083); Dark matter (353); Galaxy kinematics (602); Cosmic web (330); Large-scale structure of the universe (902); Galaxy dark matter halos (1880); Galaxy encounters (592); Galaxy interactions (600)

1. Introduction

Recent observations have revealed that the halo spin is associated with the large-scale structure (LSS). According to the tidal torque theory (Peebles 1969; White 1984; Vitvitska et al. 2002; Peirani et al. 2004; Bett et al. 2007, 2010; Stewart et al. 2013; Zavala et al. 2016; Zjupa & Springel 2017), the spin–LSS alignment can be explained by the tidal torque of the ambient anisotropic matter distribution giving rise to galaxy rotation. Numerical simulations have shown that, for instance, less (more) massive halos in filaments tend to have a spin parallel (perpendicular) to the filament’s spine (Aragón-Calvo et al. 2007; Hahn et al. 2007; Codis et al. 2015; Laigle et al. 2015; Wang & Kang 2017). Galaxy observations also confirm this spin–LSS alignment (Tempel & Libeskind 2013; Blue Bird et al. 2020; Welker et al. 2020; see also Kravlis et al. 2019). On the other hand, recent studies have reported a possible link between the spin (and the shape) of centrals and the spatial distribution of their satellites. Such spin–satellite alignment is found among dark matter halos (Wang et al. 2014; Kang & Wang 2015) and among galaxies (Brainerd 2005; Yang et al. 2006; Augustsson & Brainerd 2010; Dong et al. 2014; Tempel et al. 2015; Velliscig et al. 2015a; Shao et al. 2016; Wang et al. 2018b). The alignment depends on the mass (Velliscig et al. 2015a), morphology (Wang et al. 2010), and color of the central galaxies (Wang et al. 2018b) and on the color of the satellites (Dong et al. 2014). The spin–satellite alignment indicates that the galaxy (or halo) spin is regulated by tidal interaction. Taking the two types of alignments together, it has been suggested that the angular momentum of a galaxy evolves with nonlinear events such as mergers and accretions along the local LSS (Porciani et al. 2002; Vitvitska et al. 2002; Peirani et al. 2004; Hetznecker & Burkert 2006; Hahn et al. 2007; Cervantes-Sodi et al. 2010; Stewart et al. 2013; Rodriguez-Gomez et al. 2017; Peng & Renzini 2020).

Motivated by this concept of spin–LSS and spin–satellite alignments, we explore the alignment between the spin of a halo and the orbital angular momentum of its neighbor, which we refer to as the spin–orbit alignment (SOA). Our working hypotheses are (a) that the neighbor’s orbital angular momentum can be converted into the internal angular momentum of the central galaxy (e.g., Aubert et al. 2004; Bailin & Steinmetz 2005), and (b) that interacting neighbors preferentially coming along the LSS (Wang & Kang 2018) have orbital angular momenta reflecting the local matter flow. We expect that dark matter halo pairs will display SOA, and then the halo spin will get faster within a strong tidal field (Wang et al. 2011) such as in a pair system (Johnson et al. 2019; see also Cervantes-Sodi et al. 2010). Previous studies have found corotating satellites with their host clusters (in simulations; Warrick & Knebe 2006) and with the isolated galaxies hosting them (in observations; Herbert-Fort et al. 2008; but see also Hwang & Park 2010). Moon et al. (2021, hereafter Paper III) proposed that SOA can be developed by interactions with neighboring galaxies. Some studies have found spin–alignment in interacting pairs (Mesa et al. 2014; Koo & Lee 2018) although it is still controversial (Cervantes-Sodi et al. 2010; Buxton & Ryden 2012; Lee 2012). This work focuses on SOA for dark matter halos with virial-radius-wise interacting neighbors using a set of cosmological N-body simulations. We intend to address the question of which physical parameter dominantly influences the halo spin. To this end, we measure the SOA and examine its dependence on the halo mass, pairwise distance, interaction type, large-
scale density, distances from the nearest filament and node, and the angle between the halo spin vector and the filament axis.

The present series of papers investigates both observationally and theoretically the impact of interacting neighbor galaxies (or halos) on galactic properties. Moon et al. (2019, Paper I) revealed how strongly the nearest neighbor affects the star formation activity of galaxies using a comprehensive galaxy pair catalog from the Sloan Digital Sky Survey (York et al. 2000). An et al. (2019, hereafter Paper II), using a set of cosmological N-body simulations, found that flyby-type interactions substantially outnumber merger-type interactions toward z = 0, and that the flyby contributes to the galactic evolution more significantly than ever at the present epoch. Paper III found a strong SOA of close galaxy pairs using IllustrisTNG simulation data (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018), and the results imply that the interacting neighbor compels the spin vector of its target to be aligned with its orbital angular momentum. This fourth paper is an extension of Paper II and Paper III. By extending the simulation data set of Paper II, we aim to understand the buildup process of galactic angular momentum via the SOA on a larger scale of a few hundred kiloparsecs compared to $<100\, h^{-1}$ kpc explored by Paper III. Moreover, this paper is the first of its kind to quantitatively investigate the association of the SOA with the LSS.

Throughout the paper, we assume that the dark matter halo spin represents the galaxy spin. The spin vector (or minor axis) of dark matter halos has been, however, reported to be somewhat misaligned with the spin vector (or major axis) of baryonic components (so-called galaxy–halo misalignment). The degree of the misalignment depends on the halo and galaxy properties (Bailin et al. 2005; Velliscig et al. 2015b; Ganeshaiah Veena et al. 2019). Despite the presence of galaxy–halo misalignment, the mean angle offset between the two components’ vectors (25°–50°; Bailin & Steinmetz 2005; Shao et al. 2016; Chiari et al. 2017) is smaller than the offset (57°) expected from the random distribution. We further suppose that tidal interaction eventually adjusts the halo spin to align with the galaxy spin because tidal interaction affects the spin orientation (Hetznecker & Burkert 2006; Cervantes-Sodi et al. 2010; Wang et al. 2011; Johnson et al. 2019). This implies that the SOA makes the present galaxy–halo alignment stronger, an effect similar to that of satellite galaxies on the galaxy–halo alignment of their central galaxies (Shao et al. 2016). To be more conservative, we measure the halo spin vector only in the central region of the target halo. Many simulation studies have found that a galaxy is more closely associated with the inner part of its host halo than with the outer halo (Bailin et al. 2005; Bett et al. 2010; Shao et al. 2016). Therefore, we use the SOA for dark matter halos as a representative of the SOA for galaxies.

This paper is organized as follows. Section 2 describes our simulations, the halo and pair sample selection, and the measurement method of the SOA. Section 3 shows the spin–orbit angle distributions and estimates their dependence on various parameters. In Section 4 we discuss the physical causes of SOA, linking it to both interactions with neighbors and the LSS. We summarize our results in Section 5.

### 2. Data and Analysis

#### 2.1. Halo Pair Sample and Subsamples

We perform a series of cosmological N-body simulations using the parallel tree particle-mesh code `GOTPM` (Grid-of-Oct-Trees-Particle-Mesh; Dubinski et al. 2004). There are 14 simulations in total, each of which has the same mass resolution of $M_p = 1.55 \times 10^8 \, h^{-1} \, M_\odot$, but 10 simulations have a box with a side length of $L_{\text{box}} = 64 \, h^{-1} \, \text{Mpc}$ while 4 simulations have $L_{\text{box}} = 128 \, h^{-1} \, \text{Mpc}$. All simulations are based on the Wilkinson Microwave Anisotropy Probe 9 year cosmology (Bennett et al. 2013) but apply different sets of random numbers to take into account the cosmic variance (see Paper II for details).

We employ the `ROCKSTAR` (Robust Overdensity Calculation using K-space Topologically Adaptive Refinement; Behroozi et al. 2013) halo-finding algorithm to build a halo catalog. In the 14 simulations, we choose the target halos with a halo mass range of $10^{10.8} \, h^{-1} \, M_\odot$ to $10^{13.0} \, h^{-1} \, M_\odot$ (a total of 585,739 halos at $z = 0$) and identify the halos with interacting neighbors using the same criteria fully described in Paper II except for the mass ratio. In particular, the mass ratio range is 1/10 to 10 (while we adopted 1/3–3 in Paper II), and the distance ($d_{\text{in}}$) between the target halo (hereafter, we use a subscript $t$) and its neighbor (hereafter, we use a subscript $n$) should be smaller than the sum of the virial radii of the two halos ($d_{\text{in}} < R_{\text{vir},t} + R_{\text{vir},n}$). In this study, one target halo can have multiple neighbors, and we count all the neighbors with different orbital configurations. The total number of paired neighbors is defined by

$$N_{\text{sample}} \equiv \sum_i N_{n,i},$$

where $N_{n,i}$ is the number of neighbors that belong to the $i$th target halo. At $z = 0$, we have found $N_{\text{sample}} = 282,098$ interacting neighbors around $N_t = 195,699$ target halos with the mass ratio and distance conditions (on average, 1.44 interacting neighbors per target halo). In Paper II, we found that the number fraction of our multiple interactions is about five times higher than the observation by Darg et al. (2011), due to our distance criterion ($\sim300 \, h^{-1} \, \text{kpc}$) being longer than theirs (30 kpc).

Next, we break down the pair sample according to the halo mass, environment, and total energy of the pair system. First, we use the virial mass, which is calculated according to the definition of Bryan & Norman (1998). Second, we define the environmental parameter ($P_{\text{env}}$) as the percentile rank of the total mass of halos that are more massive than $10^{9.8} \, h^{-1} \, M_\odot$ within a comoving distance of $5 \, h^{-1} \, \text{Mpc}$ from the target halo. Finally, with the total energy ($E_{\text{in}}$, the sum of the kinetic and potential energy) of the pair system, we classify the interacting neighbors into mergers ($E_{\text{in}} < \Delta E$) and flybys ($E_{\text{in}} \geq \Delta E$), where $\Delta E$ is the capture criterion used in Gnedin (2003). Gnedin presumed that some pairs with $0 < E_{\text{in}} < \Delta E$ are merged ultimately due to the energy loss induced by the dynamical friction.

We also measure the distances from the nearest filament and the nearest node, with respect to the center position of the target halos. For the measurement, we extract filamentary structures from the distribution of all targets and neighbors using a publicly available code, `DisPerSE` (Sousbie 2011; Sousbie et al. 2013).
From a smoothed density field constructed by a mass-weighted Delaunay tessellation, the code identifies a ridge line by linking the density maximum to another maximum passing through a saddle point. At the same time, identified ridge lines have a persistence that represents the significance level of the lines. In this study, we take 7σ as the proper persistence threshold to investigate the correlation of the SOA with the filaments. If we use a lower (higher) threshold, the filamentary structures become more complicated (sparser) as shown in Codis et al. (2018), who dealt with correlations of the filament’s properties with the persistence threshold. In Figure 1, we display the distribution of halos and filaments in three consecutive slabs with a thickness of 8 h⁻¹ Mpc. Seemingly discrete filaments are due to the projection effect, i.e., they are not actually broken but spread over the other slabs.

2.2. Spin–Orbit Angle Measurements

To quantify the SOA, we first measure the spin–orbit angle (θSL), i.e., the angle between the spin vector of a target halo (S) and the orbital angular momentum vector of its neighbor (L). Prior to the vector measurement, we take into account the definition of the position and velocity of a halo, to minimize the effect of tidal stripping during contact interaction. The halo’s position and velocity are calculated by using the bound member particles in the innermost region (about 10% of the halo radius; see Behroozi et al. 2013 for details). We then measure the spin vector as a sum of the angular momenta of the bound member particles in the innermost region instead of the whole member particles (S ≡ Sₚ ≠ Sₛ). This helps us to better trace the galaxy spin (e.g., Shao et al. 2016). The vector L (≡ dᵣ × Vᵣ) is the cross product of the center position of a neighbor halo from the target halo center (dᵣ) and the relative velocity (Vᵣ) with consideration of the Hubble flow.

We note that the halo spin vector measurement can be contaminated by the neighbor’s orbital angular momentum (see Moon et al. 2021 for details). According to the halo-finding algorithm, if two interacting halos are so close that their virial radii overlap with each other, the larger halo takes the outskirts of the smaller halo as well as its own member particles (e.g., Muldrew et al. 2011). Such misidentification hinders an accurate spin vector measurement. We remedy the problem by using the core spin vector instead of the whole spin vector, but for very close pairs it is unavoidable.

Figure 2 shows the median cosine of offset angles (cos θ_SL) between the core spin vector (Sₚ) and the whole spin vector (Sₛ) of our target halos as a function of pairwise distance normalized to the target halo’s virial radius (dᵣ / Rᵥₜ). Overall, the median offset angle for distant pairs (dᵣ > 1.5Rᵥₜ) is almost constant regardless of the halo mass, mass ratio, and interaction type. For close pairs (dᵣ < 1.5Rᵥₜ), the trend depends on the interaction type and mass ratio. In cases of larger merging neighbors (Mᵣ / Mₜ > 1) and flyby neighbors, the median value of cos θ_SL is almost constant. In contrast, in cases of smaller merging neighbors (Mᵣ / Mₜ < 1), the median offset angle decreases at 0.8Rᵥₜ < dᵣ < 1.5Rᵥₜ and increases at dᵣ < 0.8Rᵥₜ with decreasing distance—that is, as the neighbors get close to their targets, the inaccurate assignment of the outskirts of the neighbors results in the erroneous measurement of the whole spin vector (0.8Rᵥₜ < dᵣ < 1.5Rᵥₜ) and even of the core spin vector (dᵣ < 0.8Rᵥₜ). This can cause an unreal strong SOA. To avoid such faulty measurement, we exclude close pairs in the sample with pairwise distances smaller than 0.8Rᵥₜ. The size of our sample is reduced to 84,014 neighbors in 70,766 target halos.

The next step is to quantify the strength of the SOA and its error, by adopting the method of Yang et al. (2006). For the analysis of three-dimensional alignment, we measure the directional cosine (cos θ_SL) between the SOA’s constituent vectors. The frequency of interacting neighbors relative to the uniform distribution at a given spin–orbit angle is then defined as

\[ n(\cos \theta_{SL}) = \frac{N(\cos \theta_{SL})}{\langle N_{\text{rand}}(\cos \theta_{SL}) \rangle}. \]

where N(\cos θ_{SL}) is the number of neighbors at a given cos θ_{SL} and \langle N_{\text{rand}}(\cos θ_{SL}) \rangle is the mean value of N_{\text{rand}}(\cos θ_{SL}) obtained from 100 random isotropic samples with the same number of neighbors. If the halo spin is preferentially aligned with the orbital angular momentum of the neighbor at a given cos θ_{SL}, n(\cos θ_{SL}) is greater than 1; n(\cos θ_{SL} ≈ 1) > 1 (θ_{SL} ≈ 0°) is called prograde alignment and n(\cos θ_{SL} ≈ -1) > 1 (θ_{SL} ≈ 180°) is called retrograde alignment. Random alignment is represented as n(\cos θ_{SL}) = 1 at all ranges of cos θ_{SL}. 

Figure 1. Distribution of halos (gray circles) and filaments (red lines) in three back-to-back slabs with a Z-direction thickness of 8 h⁻¹ Mpc in one of our simulations at z = 0. The filaments are extracted from the distribution of all halos including targets and neighbors by means of DisPerSE (Sousbie 2011; Sousbie et al. 2011) with a persistence threshold of 7σ. The radius of the circles indicates twice the virial radius of the halos.
3. Results

3.1. Spin–Orbit Angle Distribution

We examine the SOA for interacting neighbors of our target halos at $z = 0$. Figure 3 shows the spin–orbit angle distribution for our whole pair sample. The alignment amplitude ($n(\cos \theta_{SL})$) increases with $\cos \theta_{SL}$. Compared to the random distribution, the number of highly prograding neighbors is 11% higher and the number of highly retrograding neighbors is 8% lower: $n(0.75 < \cos \theta_{SL} < 1.0) = 1.11 \pm 0.01$ and $n(-1.0 < \cos \theta_{SL} < -0.75) = 0.92 \pm 0.01$. The prograde alignment is thus noticeable while the retrograde alignment is insignificant.

To further demonstrate the existence of alignments, we measure the prograde fraction ($f_{\text{prog}}$), which is defined as

$$f_{\text{prog}}(\%) \equiv \frac{N_n(\cos \theta_{SL} > 0)}{N_n(\text{total})} \times 100,$$

where $N_n(\cos \theta_{SL} > 0)$ is the number of interacting neighbors on the prograde orbit ($\cos \theta_{SL} > 0$) and $N_n(\text{total})$ is the total number of interacting neighbors. If the prograde fraction is greater than 50% (a predicted value from the random distribution), prograde alignment exists. For our pair sample, the prograde fraction is 52.7% $\pm$ 0.2%, indicating that significant prograde alignment is present with a significance level of $>13\sigma$.

Such an alignment is consistent with previous findings from simulations (Warnick & Knebe 2006; L’Huillier et al. 2017) and observations (Herbert-Fort et al. 2008; Lee et al. 2019a, 2019b). Lee et al. (2019b) found a coherence between the galaxy spin and neighbors’ motion even up to a scale of several megaparsecs (800 kpc in Lee et al. 2019a), beyond our distance criterion (on average 300 $h^{-1}$ kpc). We can thus formulate two hypotheses: one is that SOA is caused by interactions with neighbors and the other is that SOA is brought about by the local LSS. Our hypotheses are based on previous findings: (a) the flipping of the spin direction coincides with interactions (Bett & Frenk 2012, 2016); (b) the halo spin is associated with the local LSS (Aragón-Calvo et al. 2007; Codis et al. 2012; Tempel & Libeskind 2013; Forero-Romero et al. 2014; Zhang et al. 2015; Wang et al. 2018a); and (c) satellites are accreted along the local LSS (Libeskind et al. 2005; Kang & Wang 2015). In the following sections, we will investigate the dependence of SOA on various parameters and discuss the physical causes of SOA.
3.2. Dependence of Spin–Orbit Alignment

3.2.1. Dependence on the Halo Mass and Environmental Parameter

Figure 4 shows the prograde fraction as a function of the target halo mass for three different environment subsamples. The bottom panels show the change of the fraction along with the environmental parameter for three different mass subsamples. Each subsample has 10 bins with the same sample size. In all panels, horizontal dashed lines at $f_{\text{prog}} = 50\%$ indicate the value expected from the random distribution. The error bars along the $x$-axis are the standard error of the median (i.e., the ratio of the median absolute deviation to the square root of the sample size; $\text{err(x)} \equiv \text{Med}(|x - \text{Med}(x)|)/\sqrt{N_{\text{sample}}}$) and they are all smaller than the symbol size. The error bars along the $y$-axis are the standard error from the binomial distribution ($\text{err(y)} \equiv \sqrt{f_{\text{prog}}(1-f_{\text{prog}})/N_{\text{sample}}}$). Dotted lines show the linear fit to the subsamples using error-weighted orthogonal distance regression, and the slope ($\beta$) of the fitted line is given at the bottom of each panel.

![Figure 4. Prograde fraction ($f_{\text{prog}}$) for all interacting neighbors. The top panels show the prograde fraction as a function of the target halo mass for three different environment subsamples. The bottom panels show the change of the fraction along with the environmental parameter for three different mass subsamples. Each subsample has 10 bins with the same sample size. In all panels, horizontal dashed lines at $f_{\text{prog}} = 50\%$ indicate the value expected from the random distribution. The error bars along the $x$-axis are the standard error of the median (i.e., the ratio of the median absolute deviation to the square root of the sample size; $\text{err(x)} \equiv \text{Med}(|x - \text{Med}(x)|)/\sqrt{N_{\text{sample}}}$) and they are all smaller than the symbol size. The error bars along the $y$-axis are the standard error from the binomial distribution ($\text{err(y)} \equiv \sqrt{f_{\text{prog}}(1-f_{\text{prog}})/N_{\text{sample}}}$). Dotted lines show the linear fit to the subsamples using error-weighted orthogonal distance regression, and the slope ($\beta$) of the fitted line is given at the bottom of each panel.](image)

For the given environmental parameters (top panels of Figure 4), the prograde fraction tends to slightly decrease from $\sim 54\%$ to $\sim 51\%$ with increasing halo mass. The mass dependence of $f_{\text{prog}}$ is statistically significant in low- and high-density environments (at the $1.2\sigma$ and $1.9\sigma$ levels, respectively), with little dependence for intermediate-density environments. The decreasing trend is due to the fact that low-mass halos are so vulnerable to interactions with their neighbors that their spin vectors seem easily aligned with the neighbors’ orbital angular momenta. Such high $f_{\text{prog}}$ for low-mass halos is consistent with Paper III.

For the given halo masses (bottom panels of Figure 4), the prograde fraction is almost constant regardless of the large-scale density ($\lesssim 1\sigma$). This seems due to the fact that for higher density, two competing factors arise: interactions with neighbors happen more frequently (e.g., Paper II) but neighbors infall more isotropically (e.g., Wang et al. 2018b). This weak dependence is consistent with that for high-mass galaxies in Paper III. Although they found an environmental dependence on the SOA for less massive galaxies, their mass range is below ours since the mass resolution in our simulations is about 20 times lower than TNG100’s.

3.2.2. Dependence on the Mass Ratio

Figure 5 shows the prograde fraction as a function of the mass ratio ($M_{n}/M_{t}$). To minimize the mass dependence of $f_{\text{prog}}$, we divide our sample into two subsamples: lower-mass ($M_{L10} < 11.5$) and higher-mass ($M_{L10} \geq 11.5$). In the two mass ranges, the prograde fraction does not change significantly as the mass ratio varies. Interestingly, for a mass ratio of $1/10–1/$
3, there is a clear difference in $f_{\text{prog}}$ between the lower- and higher-mass halos. The sample with this mass ratio range likely governs the mass dependence of $f_{\text{prog}}$ in that $f_{\text{prog}}$ for lower-mass halos is higher than that for higher-mass halos as shown in Figure 4.

In Figure 5, for the other mass ratio ranges, the values of $f_{\text{prog}}$ for the low- and high-mass subsamples are the same within the errors. This is due to (a) a dependence of the merger timescale on the mass ratio (for the mass ratio of 1/3–3) and (b) the incompleteness of identification of two close halos (for the mass ratio of 3–10). First, the merging time for $1/3 < M_\text{m}/M_\text{t} < 3$ is shorter than that for $M_\text{m}/M_\text{t} < 1/3$ and $M_\text{m}/M_\text{t} > 3$ (Binney & Tremaine 1987; Lacey & Cole 1993; Boylan-Kolchin et al. 2008; Jiang et al. 2008). A short interaction time is insufficient to bring about the mass dependence of $f_{\text{prog}}$. Next, a smaller target halo with $M_\text{m}/M_\text{t} > 3$ seems to be embedded in its larger neighbor before the spin vector of the target is aligned with the neighbor’s orbital angular momentum, and thus the prograde fraction appears not to depend on the mass. This is due to the nature of the halo-finding algorithm. As the two halos get quite close to each other, the smaller halo is identified as a part of the larger neighbor rather than as one separate halo (e.g., Muldrew et al. 2011). This hinders an examination of SOA caused by close neighbors with $M_\text{m}/M_\text{t} > 3$ as the smaller halo spuriously disappears.

### 3.2.3. Dependence on the Pairwise Distance

Figure 6 shows the prograde fraction as a function of the pairwise distance normalized to the virial radius of the target halo ($d_{\text{tn}}/R_{\text{vir}, t}$). For the analysis, we divide our sample into lower-mass and higher-mass subsamples as in the previous section. In addition, each subsample has eight bins with the same number of interacting neighbors.

We find a different trend between lower-mass ($M_{L10} < 11.5$) and higher-mass target halos ($M_{L10} \geq 11.5$). For the lower-mass halos, as the pairwise distance increases, the prograde fraction decreases with a significance level of 2.7σ. This indicates that the halo spin is preferentially aligned with the orbital angular momentum of the neighboring halo in cases of close neighbors. We note that such preferential alignment simply implies a positive correlation on the ensemble average at $z = 0$, not the evolution of the spin direction with the pairwise distance. To confirm the time evolution of spins, we should use the merger tree data for each halo pair.

For the higher-mass halos ($M_{L10} \geq 11.5$), there is a marginally increasing trend of a 1.1σ significance level, and it is opposite to that for the lower-mass halos. This is because, at our distance range, the spin orientation of the high-mass halos seems more difficult to change than that of the low-mass halos. We speculate that, at $d_{\text{tn}} < 0.8R_{\text{vir}, t}$, the dependence of $f_{\text{prog}}$ on the pairwise distance would emerge if we could use an advanced method such as tracking particle IDs to separate a close pair into two halos. On the other hand, the marginal increase at farther distance is likely associated with the LSS. The halo mass $M_{L10} = 11.5$ is close to the spin-flip mass ($M_{\text{flip}} = 10^{11.5–12.0} h^{-1} M_\odot$; e.g., Codis et al. 2012; Ganeshiaah Veena et al. 2018). For halos with a mass greater than the spin-flip mass, the spin directions have changed over cosmic time and become more linked to the cosmic flow through the filament. This will have made the SOA stronger. In Section 3.2.5 and 3.2.6, we will further analyze the association of SOA with the LSS.

### 3.2.4. Dependence on the Interaction Type

In Figure 7, we compare the spin–orbit angle distributions for merging neighbors (left panel) and flybying neighbors (right). The merger sample shows a stronger prograde alignment than the flyby sample. As the directional cosine of the spin–orbit angle increases, the difference in $n(\cos \theta_{SLO})$ between the merger and flyby samples turns from negative $(0.91 – 0.96 = –0.05)$ to positive $(1.15 – 1.03 = 0.12)$. In other words, merging neighbors are more preferentially on
the prograde orbit than flybying neighbors while flybying neighbors’ orbits are closer to being random. This trend holds true even for the subsample with $M_{L,10} < 11.5$ and $d_{tn} < 1.5 R_{\text{vir},t}$ that shows a strong SOA in Sections 3.2.1 and 3.2.3. In the whole sample (subsample), the prograde fraction for merging neighbors is 1.6% (1.1%) higher than that for flybying neighbors with a significance level of 5σ (3σ). We attribute the stronger prograde alignment for merging neighbors to their duration of interaction being longer than that of flybying neighbors. In other words, flybying neighbors mainly have a shorter interaction duration to exchange the tidal torque, due to their higher relative velocities compared to those of merging neighbors (e.g., Paper II).

On the other hand, the small difference in the spin–orbit angle distribution between the whole sample and the subsample indicates that the stronger SOA for merging neighbors compared to the SOA for flybying ones can be detected even at a farther distance. This is a natural feature according to two facts: (a) the spin direction is induced by the tidal effect of the local cosmic flow (e.g., Dubinski 1992; Forero-Romero et al. 2014) and (b) distant merging neighbors better reflect the local flow than close ones do (e.g., Welker et al. 2018). A merger thus forms SOA by coming along the flow even from the beginning of the interaction. By contrast, a flybying neighbor would move irrespective of the flow, and such movement seems to imprint a nearly flat feature in the flyby’s spin–orbit angle distribution. Hence, the SOA for flybying neighbors is inherently weak.

### 3.2.5. Dependence on the Distance to the Nearest Node and Filament

In this section and the next, we focus on the contribution of the LSS to the SOA. For a pure analysis, we minimize the neighbor interaction effect on the SOA by restricting our sample to the subsample with $M_{L,10} > 11.5$ and $d_{tn} > 1.5 R_{\text{vir},t}$ which has the weakest prograde alignment. We also compare the LSS effects between merging and flybying neighbors since they may have different origins as mentioned in Section 3.2.4.

The subsample size is reduced once again for an examination of dependence on the distance from the nearest filament because we exclude halos residing around the node within $2.0 h^{-1}$ Mpc as used in previous studies on filaments (e.g., Kraljic et al. 2018).

Figure 8 shows the prograde fraction as a function of the distances from the nearest node ($d_{node}$; top panels) and the nearest filament ($d_{filament}$; bottom). In the top left panel, the prograde fraction for merging neighbors does not depend on $d_{node} (< 1\sigma)$ and remains constant at $\sim 53\%$. Such a constant $f_{\text{prog}}$ seems to suggest that merging neighbors come along the same filament and interact with their target halos. This is in line with the observation that the major axes of Virgo cluster galaxies are aligned with the axes of filaments connected to the cluster (Kim et al. 2018). In the top right panel, the prograde fraction for flybying neighbors increases with $d_{node} (3.5\sigma)$. In other words, flybying neighbors closer to the node have a more random incidence angle when entering their target halo. This suggests that flybying neighbors come from different filaments. The node is an environment involved with a number of filaments. If one neighbor moves along a filament different from its own and encounters its target halo, its relative velocity is so high that the neighbor will be a flybying neighbor. Since filaments are manifold around the node, the SOA would disappear.

In the bottom left panel of Figure 8, the prograde fraction for merging neighbors decreases with distance from the nearest filament. The trend has a significance level of 3.2σ. The higher prograde fraction for halos closer to the filament has two possibilities: (a) if the spin vector of the halo is parallel to the filamentary spine, its neighbor moves perpendicularly to the spine, or (b) if the spin vector is perpendicular to the filament, the neighbor moves along the spine. The halos of our subsample are massive ($> 10^{11.5} h^{-1} M_{\odot}$) and thus their spin orientations are largely perpendicular to the filament (e.g., Codis et al. 2012). Hence, the second possibility seems more plausible. In the bottom right panel, for flybying neighbors, $f_{\text{prog}}$ decreases with decreasing $d_{filament}$. This is consistent with
the trend found between $f_{\text{prog}}$ and $d_{\text{node}}$ although the significance level is 1.1σ. The low $f_{\text{prog}}$ at small $d_{\text{filament}}$ is due to the center of the filament being an intricate intersection of cosmic flow like the node environment.

The correlation of $f_{\text{prog}}$ with $d_{\text{node}}$ and $d_{\text{filament}}$ is a combination between the neighbor interaction effect and the pure node and filament effect. Due to the high number density of halos around the node and filament, interactions with multiple neighbors are frequent, burying the node and filament effect on the SOA under the neighbor interaction effect. Also our criterion of $d_{\text{filament}} > 1.5R_{\text{vir,t}}$ excludes target–neighbor pairs residing close to the node and filament, which prohibits examining the dependence of the SOA on their environment. To disentangle the two effects, we will scrutinize the SOA with respect to the cosmic web structure. In the following section, we will further investigate the SOA’s correlation with the angular alignment between the spin direction and the filament axis given that the filamentary structure is anisotropic unlike the spherically symmetric node.

### 3.2.6. Dependence on the Degree of Spin–Filament Alignment

Figure 9 shows the median of the directional cosine (i.e., the spin–filament angle $\cos \theta_{SF}$) between the spin vector of a halo ($S$) and the axis of its nearest filament ($F$) as a function of the halo mass (left panel) and the distance from the nearest filament (right). To see the pure correlation of the halo spin with the filament, we exclude the node sample with $d_{\text{node}} < 2.0h^{-1}$ Mpc.

In the left panel, the median value of $\cos \theta_{SF}$ decreases with the halo mass. The trend is consistent with previous findings in both simulations (e.g., Aragón-Calvo et al. 2007; Codis et al. 2012; Ganeshaiah Veena et al. 2018) and observations (e.g., Welker et al. 2020): the lower-mass (higher-mass) halo prefers to have a spin parallel (perpendicular) to the nearest filamentary spine. The mass for which the median value crosses 0.5 is approximately $10^{11.5}h^{-1}M_{\odot}$. This is smaller than the well-known spin-flip mass ($10^{11.5}−10^{12.0}h^{-1}M_{\odot}$; e.g., Codis et al. 2012) and is attributed to the use of the inner halo spin. Ganeshaiah Veena et al. (2018) found that the spin-flip mass...
for the inner halo spin is lower than that for the whole halo spin. We have verified that the spin flip occurs at $\sim 10^{11.5} \, h^{-1} M_\odot$ when considering the whole halo spin. The spin-flip phenomenon holds true for halos close to the filament ($d_{\text{filament}} < 1.0 \, h^{-1} \, \text{Mpc}$). Their median value of $\cos \theta_{SF}$ is slightly smaller than that for the whole sample. This indicates that the spin flip happens more frequently as the halos are closer to the filament.

In the right panel of Figure 9, the degree of spin–filament alignment depends on the distance from the nearest filament as well. The median value of $\cos \theta_{SF}$ increases with $d_{\text{filament}}$ regardless of the halo mass. This indicates that, as $d_{\text{filament}}$ increases, the averaged halo spin vector turns from being perpendicular to the filament into being parallel to the filament.

In view of the mass dependence of the spin–filament alignment, the spin vectors of lower-mass halos are thought to be parallel to the filament. However, lower-mass halos close to the filament ($d_{\text{filament}} \lesssim 1.0 \, h^{-1} \, \text{Mpc}$) have experienced the spin flip, despite a median value of $\cos \theta_{SF}$ that is higher than that for the higher-mass halos. The difference in the fraction of spin-flipped halos between two mass ranges appears to generate the mass dependence of the spin–filament alignment. Hence, the halo spin vector is largely perpendicular to the filament when the halo resides close to the filament.

Figure 10 shows the spin–orbit angle distribution depending on the spin–filament angle. We use the filament sample ($d_{\text{node}} > 2.0 \, h^{-1} \, \text{Mpc}$ and $d_{\text{filament}} < 1.0 \, h^{-1} \, \text{Mpc}$) with far neighbors ($d_{\text{in}} > 1.5 R_{\text{vir,t}}$). The sample is divided into two sub-samples: "parallel" ($\cos \theta_{SF} \geq 0.8$ or $\theta_{SF} \leq 37^\circ$; solid lines) and "perpendicular" ($\cos \theta_{SF} < 0.4$ or $\theta_{SF} \geq 66^\circ$; dotted lines). The sizes of the subsamples are given in the legend box and the prograde fractions are given at the bottom of the panels.
subsamples: “parallel” \(\cos \theta_{SL} \geq 0.8\), i.e., \(\theta_{SL} \leq 37^\circ\) and “perpendicular” \(\cos \theta_{SL} \leq 0.4\), i.e., \(\theta_{SL} \geq 66^\circ\) with respect to the filament axis used in Welker et al. (2018).

For merging neighbors (left panel), the parallel subsample has a maximum amplitude at \(\cos \theta_{SL} \sim 0.4\). The excess at \(0.2 < \cos \theta_{SL} < 0.6\) is significant: \(n(\cos \theta_{SL}) = 1.26 \pm 0.07\). At \(\cos \theta_{SL} > 0.4\), the amplitude dramatically decreases with \(\cos \theta_{SL}\). By contrast, the perpendicular subsample shows a flat spin–orbit angle distribution with a slight increase at both ends. The prograde fraction for the perpendicular subsample is lower than that for the parallel subsample. This indicates that the halos of the parallel subsample interact largely with neighbors on a nearly perpendicular but prograde orbit. Hence, the neighbors coming along the filament lead to a high prograde fraction for halos close to the filament. The difference between the two merger subsamples appears to represent different states before and after the spin flip. Therefore, if the spin vector of a halo is parallel to the filament, the halo confronts the spin flip soon by its neighbor with an orbital angular momentum perpendicular to the spin. After the spin flip, the SOA at \(\cos \theta_{SL} > 0.5\) develops as the frequency of nearly perpendicular interactions decreases.

For flybying neighbors (right panel of Figure 10), the parallel subsample has a different spin–orbit angle distribution from that for merging neighbors. The distribution has a minimum value at \(\cos \theta_{SL} = 0.0\) and dramatically increases. Such a prograde alignment diminishes for the perpendicular subsample. Their high relative velocities (Gnedin 2003; Paper II) imply that flybying neighbors move along the fastest-collapsing direction. When the spin vector of a halo is parallel to the filament, it should be aligned with the orbital angular momentum of the flybying neighbor. The filament axis is however the slowest-collapsing direction under the definition of the cosmic web (Cautun et al. 2014). A halo with a spin perpendicular to the filament encounters neighbors coming both from the outskirts of the filament and along the filament, and thus the SOA is broken.

### 4. Discussion

We have shown that the spin vector of a halo is strongly aligned with the orbital angular momentum vector of its neighbor (see Figure 3). We have found three interesting facts about SOA: (1) halos with close neighbors show stronger SOA than do halos with far neighbors (see Figure 6); (2) merging pairs show stronger SOA than do flybying pairs (see Figure 7); and (3) halos close to the filament show stronger SOA than do halos far from the filament (see Figure 8). The first two suggest that the formation of SOA is led by the interaction, whereas the last one implies that it is led by the LSS. We discuss the link between SOA and the two physical causes: interaction with neighbors (Section 4.1) and the LSS (Section 4.2).

#### 4.1. Linking SOA to Interaction with Neighbors

SOA is stronger for halos with closer neighbors than for those with farther neighbors (see Figure 6). We attribute this to the tidal effect of interactions with neighbors. With a closer neighbor, the neighbor’s orbital angular momentum could modify the target’s spin vector to be more aligned with itself. This is because the magnitude of the neighbor’s orbital angular momentum is on average greater than the internal angular momentum of the target (Hetznecker & Burkert 2006). The neighbor interaction effect on the SOA holds true for the SOA of galaxies (Paper III). In the same vein, Cervantes-Sodi et al. (2010) found that the spin directions of two galaxies in a pair are more parallel for smaller pairwise distance. Lee et al. (2020) showed that paired galaxies with stronger SOA physically resemble each other more (in terms of color) than paired galaxies with weaker SOA. These results imply that interacting neighbors affect a number of physical properties of their target halos. We note that the stronger SOA for closer neighbors is detectable for low-mass target halos because they are more sensitive to the interaction than high-mass halos. This entails a mass dependence on the SOA (see Figure 4). Despite the weak SOA for high-mass halos, the interaction effect on the SOA would be more prominent if we could use neighbors with distances shorter than our criterion of \(0.8R_{\text{vir}}\).

Merging neighbors make the SOA stronger than flybying neighbors do. Although both types of interaction tidally affect target halos, there is a difference in interaction duration between mergers and flybys. The duration of mergers is longer than that of flybys. A merger exerts a strong tide during an interaction and converts the orbital angular momentum of a neighbor into the spin of its target halo (Hetznecker & Burkert 2006), and then the two vectors become aligned (Fernando et al. 2017). We thus suggest that SOA grows mainly by prolonged interactions with merging neighbors. By contrast, a flyby has a shorter duration of interaction than a merger due to a relatively rapid velocity (Gnedin 2003; Paper II). The instantaneous interaction causes only a limited conversion from the external angular momentum into the internal.

In Figure 11, we further examine the effect of neighbor interaction on the halo spin. We measure the specific angular momentum \(j_{\text{core}} = |S|/M_{\text{halo}}\) of the core region of a halo, where \(S\) is the internal angular momentum of the halo core as used in the analysis of this study. The left panel shows the specific angular momentum as a function of the halo mass. Compared to halos without neighbors, those with neighbors have, on average, a slightly higher \(j_{\text{core}}\), and it is consistent with previous findings (e.g., Lee & Lemson 2013; Johnson et al. 2019). Although the increase in \(j_{\text{core}}\) is statistically significant, the difference between the two subsamples is quite small. This is because there are multiple drivers of the rise in \(j_{\text{core}}\), such as the halo mass, pairwise distance, interaction type, and degree of SOA.

In the right panel of Figure 11, we investigate how much the specific angular momentum increases depending on the degree of the SOA, which is one of the drivers of the increase in \(j_{\text{core}}\). Compared to the median value of \(j_{\text{core}}\) for halos without neighbors, the median value of \(j_{\text{core}}\) is higher for halos with neighbors, regardless of their orbital configuration. This seems due to the fact that the presence of interacting neighbors is associated with the growth of \(j_{\text{core}}\) via matter accretion along the local cosmic flow (Johnson et al. 2019). The result rather differs from our initial expectation that prograde interaction raises \(j_{\text{core}}\) but retrograde interaction lowers it. Nonetheless, highly prograding neighbors (\(\cos \theta_{SL} \geq 0.5\)) enhance \(j_{\text{core}}\) more than highly retrograding neighbors (\(\cos \theta_{SL} \leq -0.5\)). Such an increasing trend gets stronger for lower-mass halos because they are so susceptible that their spin vectors can easily change. The fast rotation induced by prograde interaction may hold true not only for dark matter halos but for galaxies (Lagos et al. 2018). Specifically for a disk galaxy, continuous prograde
accretion is required to maintain the angular momentum of its disk (Sales et al. 2012; Peng & Renzini 2020).

Interacting neighbors tidally affect both the direction and magnitude of the halo spin. Whereas the spin direction becomes aligned with the specific direction during the interaction, the spin magnitude can either increase or decrease depending on the orbital configuration. This makes it difficult to detect the neighbor interaction effect on the spin magnitude. This holds true even in view of the spin parameter ($\lambda$; Peebles 1969; Bullock et al. 2001). Hetznecker & Burkert (2006) found that $\lambda$ instantaneously increases during the merger process but then decreases to even lower than its value before the merger. Merger and flyby interactions ultimately lead to slow-rotating halos (e.g., Cappellari et al. 2011) by reducing the internal energy of the halo (Hetznecker & Burkert 2006). Quantifying the interaction effect on the SOA and the halo spin will require individually tracing the direction and magnitude of the halo spin during the interactions.

### 4.2. Linking SOA to the LSS

This paper is the first of its kind to demonstrate the link of SOA to the LSS. We propose that the LSS is one of the physical causes of SOA based on the tidal torque theory (Peebles 1969). As the tidal torque by the primordial density fluctuation regulates the halo spin direction to be perpendicular to the cosmic flow (e.g., Wang et al. 2011), SOA can emerge naturally. Our results show that the halo spin is well aligned even with a distant neighbor’s orbital angular momentum, which represents the local cosmic flow along the filament for merging neighbors and toward the filament for flybying neighbors. In other words, the regulation of the spin direction by the LSS entails SOA.

We examined the correlation of SOA with the degree of spin–filament alignment (see Figure 10). Most interestingly, we discovered for the first time that halos with a spin parallel to the filament experience most frequently prograde-polar merging interactions with $\cos \theta_{\text{SL}} \simeq 0.4$ (i.e., $\theta_{\text{SL}} \simeq 70^\circ$). This is a piece of evidence supporting the notion that merging neighbors move along the filament, as shown in previous studies (Libeskind et al. 2011; Shi et al. 2015; Musso et al. 2018). This is logically consistent with Tempel & Tamm (2015) and Lima et al. (2018), who observed that the orientation of galaxy pairs is aligned with the spine of the nearest filament. The distribution of farther satellites is also better aligned with the filament than with the major axis of their centrals (Dong et al. 2014; Welker et al. 2017, 2018). We suggest that at the beginning of the interaction, the orbital angular momentum of a neighbor representing the cosmic flow is aligned with the halo spin, and then the alignment starts to evolve with the interaction.

The frequent occurrence of prograde-polar interactions for halos residing in the filament is associated with the spin-flip phenomenon in the filament. Halos that formed with the local filament initially have a spin parallel to the filamentary spine, but soon face the cosmic flow along the filament (Codis et al. 2015). Neighbors following the cosmic flow are candidates for misaligned interactions, and gradually affect the magnitude and direction of the halo spin (Bett & Frenk 2012, 2016). The interactions incline the halo spin toward a perpendicular direction with respect to the initial angular momentum by converting the neighbor’s orbital angular momentum into the target halo’s spin (e.g., Aubert et al. 2004; Bailin & Steinmetz 2005). In this vein, our Galaxy seems to be currently undergoing spin flip. Libeskind et al. (2015) revealed that the Galaxy resides in the local filament and has a plane of satellites perpendicular to its disk plane. If our Galaxy has a spin parallel to the filament, the satellite galaxies are in the process of inflow along the local filament, and in turn, their orbital angular momenta are perpendicular to the Galactic rotation axis. With the combination of the observational findings and theoretical hypotheses, we infer that the satellite galaxies will induce the spin flip of our Galaxy. The formation of the initial SOA is thus strongly linked to the cosmic flow along the LSS.

Based on the notion of the spin flip, we propose a scenario about how the spin direction of galaxies around the filament evolves. In the outskirts of a filament, the spin direction tends to be random with respect to the filament regardless of the mass. After falling onto the filamentary line, galaxies gravitationally interact with neighbors coming along the

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**Figure 11.** Left: Specific angular momentum ($j_{\text{core}} \equiv |S|/M_{\text{halo}}$) of the core region of halos as a function of the halo mass. We compare the median values of $j_{\text{core}}$ between two subsamples: halos without neighbors (black circles) and halos with neighbors (red triangles). The subsamples have 12 bins with an equal width along the $x$-axis. The error bars are the standard error of the median and they are all smaller than the symbol size. Contours denote 1, 2, and 3$\sigma$ of the subsamples’ distributions. Right: Difference in the median value of $j_{\text{core}}$ between halos with neighbors (symbols) and those without neighbors (dotted horizontal line). The halos with neighbors are divided into two subsamples: highly prograde ($\cos \theta_{\text{SL}} \geq 0.5$; blue squares) and highly retrograde ($\cos \theta_{\text{SL}} \leq -0.5$; red diamonds). The subsamples have five bins with an equal width along the $x$-axis. The error bars are the standard error of the median, and those along the $x$-axis are all smaller than the symbol size.
filamentary line (Wang et al. 2005, 2014; Libeskind et al. 2014; Shi et al. 2015; Wang & Kang 2017) and their spin directions change into being perpendicular to the filament. This process imprints prograde-polar alignment in the spin–orbit angle distribution. On the other hand, the degree of spin flip in the filament depends on the halo mass (see the right panel of Figure 9): the more massive the halo is, the lower the median value of $\cos \theta_{0\text{F}}$ is. This seems due to the difference in infall history: more massive galaxies enter the filament earlier than less massive ones. The galaxy spin flip in our scenario has been observed in both simulations (e.g., Kraljic et al. 2020) and observations using integral field spectroscopy (e.g., Welker et al. 2020). We note that the galaxy spin is more vulnerable than the halo spin due to hydrodynamic effects (such as disk instability and stellar feedback) as well as gravitational effects. The SOA for galaxies is stronger than that for dark matter halos (Paper III) while the intrinsic alignment for galaxies is weaker than that for dark matter halos (Chisari et al. 2017; Codis et al. 2018). Such differences coincide with the galaxy−halo misalignment induced by various physical causes (Bailin & Steinmetz 2005; Velliscig et al. 2015b; Shao et al. 2016; Chisari et al. 2017). The galaxy spin, however, has followed and will be aligned with the halo spin after all (Okabe et al. 2020). In addition, we used the spin direction measured only in the inner part of the halo because the inner halo spin better represents the galaxy spin (Bailin et al. 2005; Bett et al. 2010; Shao et al. 2016). Hence, it is legitimate to address the SOA phenomenon using dark matter halos, and the SOA of halos is crucial to understanding the evolution of the galaxy spin.

4.3. Angular Momentum Transfer to the Core Radius

We have discussed the formation and evolution of dark matter halos’ SOA in view of the tidal effect of both interacting neighbors and the anisotropic LSS. The halo spin used in this paper is defined as the spin of the inner region of the halo (see Section 2.2). Our definition of the halo spin enables us (a) to avoid contamination by false-member assignment of the halofinding algorithm by which part of the member particles of the interacting neighbor are technically assigned to the outskirts of the target halo and (b) to link the SOA for dark matter halos to that for galaxies. Despite these advantages and our new findings, the question remains whether the external tidal force directly affects the inner halo region.

Figure 12 shows the offset angle ($\theta_{S,\text{aS}}$) between the spin direction measured within a certain radius ($S_{< R}$) and that measured within the virial radius ($S_{v}$). We divide the target halo sample into three subsamples: (a) target halos without interacting neighbors that have a distance smaller than $R_{v} + R_{n}$, (b) those with distant neighbors that meet the distance criterion imposed in our target−neighbor pair sample ($0.8R_{v} < d_{\text{in}} < R_{v} + R_{n}$), and (c) those with close neighbors that have a distance smaller than our minimum distance criterion ($0.8R_{n}$). The halo spin directions are measured within 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 times the virial radius. Errors are the standard error of the median value but are smaller than the symbol size. The dotted lines in (b) and (c) are for the target halos without neighbors shown in (a). Vertical dashed lines represent the median value of the core radii of the subsamples, and the values are approximately 0.13 $R_{v}$.

Figure 12. Offset angles between the spin direction of each target halo measured within a specific radius ($S_{< R}$) and that measured within the virial radius ($S_{v}$). The target halo sample is divided into three subsamples: (a) target halos without neighbors that have a distance smaller than $R_{v} + R_{n}$, (b) those with distant neighbors that meet the distance criterion imposed in our target−neighbor pair sample ($0.8R_{v} < d_{\text{in}} < R_{v} + R_{n}$), and (c) those with close neighbors that have a distance smaller than our minimum distance criterion ($0.8R_{n}$). The halo spin directions are measured within 0.1, 0.2, 0.4, 0.6, 0.8, and 1.0 times the virial radius. Errors are the standard error of the median value but are smaller than the symbol size. The dotted lines in (b) and (c) are for the target halos without neighbors shown in (a). Vertical dashed lines represent the median value of the core radii of the subsamples, and the values are approximately 0.13 $R_{v}$.
whole halo spin direction during the virialization of the halo (Pichon et al. 2011). In other words, the tidal interactions with the neighbor and the anisotropic LSS first influence the outskirts of the halo, and then the inner part of the halo is affected. There will be a time lag in transferring the angular momentum from the outer region to the inner region. To prove our speculation, we will investigate the time evolution of SOA in a forthcoming paper in this series.

5. Summary and Conclusion

In an attempt to understand how galactic angular momenta develop, we have analyzed the SOA between the spin of a target halo and the orbital angular momentum of its neighbor using cosmological dark matter simulations. We selected a target–neighbor pair sample with a target halo mass of $10^{10.8} - 10^{13.0} M_\odot$, a mass ratio of 1/10–10, and a pairwise distance ranging from 0.8 $R_{\text{vir},t}$ (i.e., a criterion to prevent an artificial SOA by false member particle assignment) to the sum of the virial radii of the paired halos ($R_{\text{vir},t} + R_{\text{vir},n}$). To quantify the SOA, we measured the spin–orbit angle between the halo spin vector and the neighbor’s orbital angular momentum vector. For a more detailed interpretation, we examined the dependence of SOA on both parameters related to interactions with neighbors (i.e., the halo mass, mass ratio, pairwise distance, and interaction type) and those related to the LSS (i.e., the large-scale density, the distances from the nearest filament and node, and the degree of spin–filament alignment). Our main results are summarized as follows:

1. The spin of a target halo is well aligned with the orbital angular momentum of its neighbor whose mass ranges from one-tenth of the target’s mass to 10 times this mass (Figure 3). For all of the target–neighbor pair sample, the amplitude of the alignment ($n(\cos \theta_{SOA})$) monotonically increases from 0.92 at $\cos \theta_{SOA} < -0.75$ to 1.11 at $\cos \theta_{SOA} > 0.75$ (1.0 for random alignment), and the prograde fraction ($f_{\text{prograde}}$) is $52.7\% \pm 0.2\%$ (50% for random alignment). The significant prograde alignment comes from the tidal effects by both the interacting neighbor and the anisotropic LSS.

2. SOA gets stronger by interaction with neighbors, in view of the higher prograde fraction (up to 56%) for less massive halos with close, merging neighbors compared to that for more massive halos with distant, flybying neighbors (Figures 4, 6, and 7). This is attributed to two facts: (a) a less massive halo is more susceptible to tidal interaction, and (b) a close, merging neighbor has affected the halo spin direction for a longer duration of the interaction. The neighbor’s orbital angular momentum is thus gradually turned into the internal angular momentum of the target halo.

3. Halos closer to the filament and with merging (flybying) neighbors have a stronger (weaker) SOA than those farther from the filament (Figure 8) while the SOA shows no dependence on the large-scale density. More interestingly, halos with the spin parallel to the filament experience merger interactions most frequently with neighbors on the prograde-polar orbit ($\cos \theta_{SOA} \approx 0.4$) and flyby encounters most frequently with neighbors on the prograde orbit ($\cos \theta_{SOA} \approx 1.0$) (Figure 10). Among the interactions, the prograde-polar merger interaction turns the direction of the halo spin from being parallel to the filament into being perpendicular, i.e., the spin-flip phenomenon.

Our results lead us to conclude that SOA originates from tidal effects by anisotropic matter distribution such as that of the filament and then grows by tidal interactions with neighbors. We conjecture that the contributions of the two physical causes (i.e., neighbor interaction and the LSS) to SOA are more or less comparable. It is, however, hard to quantitatively compare the contributions because a galaxy comes along the cosmic flow generated by the LSS and at the same time the galaxy, as a neighbor, tidally affects its target halo. Hence, the two physical origins are linked to each other. To disentangle them, we will explore the evolution of SOA by tracing the spin direction and magnitude during interaction with neighbors depending on the trajectories with respect to the filament.

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