The Effect of Massive Neutrinos on the Galaxy Spin Flip Phenomenon

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The galaxy spin flip refers to the phenomenon that the spin axes of galaxies with masses above a certain threshold tend to be preferentially aligned perpendicular to the hosting large-scale filaments, while low mass or early type galaxies tend to have their spin axes aligned parallel to such structures. Extensive work has so far been conducted to understand this phenomenon under the assumption of cold dark matter and suggested that its origin should be closely related to the nonlinear evolution of the galaxy angular momentum in the anisotropic cosmic web. We present, for the first time, a numerical examination of this phenomenon assuming the presence of massive neutrinos, finding a clear and robust dependence of the threshold mass for the spin flip on the total neutrino mass. Our physical explanation is that the presence of more massive neutrinos retard the nonlinear evolution of the cosmic web, which in turn allows the galaxy spin vectors to better retain their memories of the initial tidal interactions even in the highly nonlinear regime. Our finding in principle implies that the statistical alignment of galaxy spins with the large-scale structures can be used as a probe of the total neutrino mass.

Introduction. The total mass of neutrino species, \( \sum m_\nu \), whose non-zero value was confirmed by the detection of neutrino flavor oscillations [1] is of vital importance not only in particle physics but also in cosmology. In the former, the non-zero value of \( \sum m_\nu \) is the most conclusive counter proof against the standard model of particle physics [1]. In the latter, the presence of massive neutrinos (like the sterile neutrinos), has a significant effect on the growth of structure in the universe. Under the assumption that such massive particles partially constitute the dark matter (DM) that permeates the universe, their ability to free stream out of primordial potential wells effectively causes a suppression of the density power spectrum on a scale determined by \( \sum m_\nu \) [2, 3].

In fact, a close coaction of particle physics with cosmology is required to constrain \( \sum m_\nu \), since laboratory experiments have a capacity of putting only a lower limit on \( \sum m_\nu \) [1]. The optimal way to determine the upper limit of \( \sum m_\nu \), which is most crucial to the physical understanding of their properties, is to resort to cosmological observables that reflect well the growth history of the universe [2]. According to the latest and most reliable observations of the cosmic growth history, the upper limit of \( \sum m_\nu \) is as low as \( \sum m_\nu \lesssim 0.12 \text{ eV} \), under the assumption of a flat \( \Lambda \)CDM (cosmological constant \( \Lambda \)+cold DM) universe [4].

In modified gravity (MG) models, however, more massive neutrinos above this constraint can still survive the observational test, since the stronger clustering caused by a fifth force of MG could compensate for the suppression of the small-scale powers in the presence of massive neutrinos [5]. A new independent diagnostics of massive neutrinos (\( \nu \)) is required to break this intricate degeneracy between the \( \Lambda \)CDM cosmology and the MG+\( \nu \) models. A prerequisite for finding such a diagnostics is to understand what effect(s), other than suppression of small-scale power, the presence of massive neutrinos can have and to look for an observable susceptible to the other effect(s) of \( \nu \), if any.

Here, we attempt to identify one such probe by investigating how the presence of massive neutrinos affects the mass at which the DM halos change their spin orientations with respect to the tidal eigenvectors [6]. The occurrence of the galaxy spin flip was first witnessed in numerical works which investigated the orientations of halo spins with respect to surrounding large-scale structures as defined by the eigenvectors of the local tidal tensors and found that the spin vectors of the galactic halos having masses lower (higher) than a certain threshold were oriented parallel (perpendicular) to the directions of minimum compression [7–9]. To date, detection of an observational evidence for such a spin flip was reported only twice in the literature [10].

A multitude of scenarios has been put forth to explain what causes the occurrence of the spin flip and why it occurs at a particular threshold mass [11]. Although the origin and underlying mechanism has yet to be fully understood, it is now generally accepted that the evolutionary processes in the cosmic web is largely responsible for the occurrence of the galaxy spin flip [11]. Meanwhile, a recent numerical analysis hinted that the presence of massive neutrinos affects the degree of the anisotropy of the cosmic web [12]. Given this result and recalling that the strength and tendency of the tidally induced spin alignments of galaxies depends sensitively on the anisotropy of the surrounding web environments [6–8], we propose a hypothesis that the threshold mass for the halo spin flip may also depend on \( \sum m_\nu \), speculating that this dependence, if detected, might be useful to break the aforementioned cosmic degeneracy. The goal of this Letter is to test this hypothesis against N-body simulations performed for the \( \nu \)CDM models whose initial conditions are different only in \( \sum m_\nu \).

Throughout this Letter, we will use the following notations to denote the relevant quantities: \( \mathbf{J} = (J_i) \) (spin vector of a DM halo), \( \mathbf{J} = (\langle \mathbf{J} \rangle) \) (direction of \( \mathbf{J} \)), \( \mathbf{T} = (T_{ij}) \) (smoothed tidal shear tensor), \( \mathbf{T} = (\langle \mathbf{T} \rangle) \) (traceless version of \( \mathbf{T} \) rescaled by \( |\mathbf{T}| \)), \{\( \lambda_i \)\} \( i = 1 \) (eigenvalues of \( \mathbf{T} \) in a decreasing
Numerical Analysis and Results. Our numerical investigation relies entirely on the publicly available data from the Cosmological Massive Neutrino Simulations (MassiveNuS) performed on a cosmological box of comoving 512 h⁻¹Mpc aside, containing 1024³ particles with individual mass of 10¹⁰ h⁻¹M☉ [13]. A total of 101 νCDM models having unequal initial conditions were adopted by the MassiveNuS as the background cosmologies, among which three models, with \( \sum m_\nu = 0.0, 0.1 \) and 0.6 eV, are selected for our analysis since they share the same initial conditions other than \( \sum m_\nu \). For each of the three selected νCDM models, we divide the simulation box into a grid of 256³ cells and determine the raw density contrast, \( \delta(x) \), at the location of each grid cell, \( x \), by applying a cloud-in-cell algorithm to the particle distribution at \( z = 0 \). Performing the Fast Fourier Transformation (FFT) of \( \delta(x) \), we obtain its Fourier amplitude, \( \delta(k) \), at each Fourier-space wave vector, \( k = (k_x, k_y, k_z) \). An inverse FFT of \( \hat{T}_{ij}(k) \equiv \hat{k}_i \hat{k}_j \delta(k) \exp \left[ -k^2 R_f^2 / 2 \right] \) returns, \( T_{ij}(x) \), the tidal field smoothed by a Gaussian window function on the scale of \( R_f \).

The MassiveNuS also provides a catalog of bound objects identified by the Rockstar algorithm [14], which includes not only the distinct halos but also their substructures. Eliminating the substructures from the catalog and selecting the distinct galactic halos in the mass range of \( 0.5 \leq M_h / (10^{12} h^{-1} M☉) \leq 10 \), we locate the grid point, \( x_h \), where each selected halo resides. Then, we calculate \( \hat{T}(x_h) \) by subtracting the trace from \( \hat{T}(x_h) \) and rescaling it by its magnitude. Finding \( \{ \hat{\lambda}_i \}^3_{i=1} \) and \( \{ \hat{e}_i \}^3_{i=1} \) at the location of each halo through a similarity transformation of \( \hat{T}(x_h) \), we compute the projection of \( \hat{J} \) onto each tidal eigenvector as \( \cos \theta_i = | \hat{J} \cdot \hat{e}_i | \) for \( i \in \{ 1, 2, 3 \} \) and then determine the ensemble average, \( \langle \cos \theta_i \rangle \), as a function of \( \log M_h \). The case of \( \langle \cos \theta_1 \rangle \) is slightly larger than \( \langle \cos \theta_i \rangle < 0.5 \) corresponds to the alignment of \( \hat{J} \) with the direction parallel (perpendicular) to \( \hat{e}_i \), while the case of \( \langle \cos \theta_1 \rangle > 0.5 \) corresponds to no alignment (i.e., \( \hat{J} \) is random with respect to \( \hat{e}_i \)). The more strongly \( \hat{J} \) is aligned with \( \hat{e}_i \), the higher value \( \langle \cos \theta_i \rangle \) has than 0.5. The linear tidal torque theory (TTT) [15] predicts \( \langle \cos \theta_2 \rangle > 0.5 \), \( \langle \cos \theta_2 \rangle \sim 0.5 \) and \( \langle \cos \theta_2 \rangle < 0.5 \) in the proto-galactic stages, regardless of \( M_h \) [16].

Figure 1 plots \( \langle \cos \theta_1 \rangle \) (green lines), \( \langle \cos \theta_2 \rangle \) (red lines) and \( \langle \cos \theta_3 \rangle \) (blue lines) versus \( \log M_h \), for the two cases of \( \sum m_\nu = 0.0 \text{ eV} \) (top panel) and \( \sum m_\nu = 0.6 \text{ eV} \) (bottom panel). For this plot, we set \( R_f = 5 h^{-1} \text{Mpc} \), leaving out the results for the case of \( \sum m_\nu = 0.1 \text{ eV} \), which turn out to be almost the same as those for the case of \( \sum m_\nu = 0.6 \text{ eV} \). The errors are calculated as one standard deviation in the mean value as \( [ \langle \cos^2 \theta_i \rangle - \langle \cos \theta_i \rangle^2 ]^{1/2} \). As can be seen, the two νCDM models yield a similar trend. As \( M_h \) decreases, the value of \( \langle \cos \theta_1 \rangle \) almost monotonically diminishes down to 0.5, while the values of \( \langle \cos \theta_2 \rangle \) and \( \langle \cos \theta_3 \rangle \) mildly increase.

In the entire mass range of the distinct galactic halos from the MassiveNuS, the value of \( \langle \cos \theta_2 \rangle \) (\( \langle \cos \theta_1 \rangle \)) remains higher (lower) than 0.5. Whereas, the value of \( \langle \cos \theta_3 \rangle \) (\( \langle \cos \theta_3 \rangle \)) switches its sign midway, which leads to \( \langle \cos \theta_3 \rangle \) to equal \( \langle \cos \theta_2 \rangle \) at a certain threshold mass, \( M_{\text{flip}} \). The two νCDM models differ significantly from each other in the value of \( M_{\text{flip}} \), yielding \( M_{\text{flip}} \approx 1.3 \times 10^{12} h^{-1} M☉ \) for the case of \( \sum m_\nu = 0.0 \text{ eV} \) and \( M_{\text{flip}} \approx 1.0 \times 10^{12} h^{-1} M☉ \) for the case of \( \sum m_\nu = 0.6 \text{ eV} \). In other words, the presence of more massive neutrinos has an effect of rendering the spin flip to occur at lower mass scales.

Since the spin-flip phenomenon was known to be the most prominent in the filamentary environment [9], we refollow the whole procedure but with only those halos located in the grid points at which the filament condition of \( \lambda_2 \geq 0 \), \( \lambda_3 < 0 \) is satisfied [6]. Figure 2 plots the same as Figure 1 but using only the filament halos. As can be seen, the spin flips of the filament halos occur at higher mass scales than those of all halos for both of the νCDM cosmologies. We find \( \langle \cos \theta_2 \rangle \sim \langle \cos \theta_3 \rangle \) at \( M_{\text{flip}} \approx 3.0 \times 10^{12} h^{-1} M☉ \) for the case of \( \sum m_\nu = 0.0 \text{ eV} \) and at \( M_{\text{flip}} \approx 1.5 \times 10^{12} h^{-1} M☉ \) for the case of \( \sum m_\nu = 0.6 \text{ eV} \), respectively, which confirms the existence of stronger \( \sum m_\nu \)-dependence of \( M_{\text{flip}} \) in the filament environments.

It is worth mentioning here the advantages of defining \( M_{\text{flip}} \) as a threshold mass at which \( \langle \cos \theta_2 \rangle \sim \langle \cos \theta_3 \rangle \). The previous works conventionally defined \( M_{\text{flip}} \) as the threshold mass at which \( \langle \cos \theta_3 \rangle = 0.5 \). However, this conventional defini-
tion of $M_{\text{flip}}$ does not take into proper account the possibility that $\mathbf{J}$ can be simultaneously aligned with both of $\mathbf{e}_2$ and $\mathbf{e}_3$ (i.e., $\langle \cos \theta_2 \rangle > 0.5$ and $\langle \cos \theta_3 \rangle > 0.5$). If the $\mathbf{J}$-$\mathbf{e}_2$ alignment is stronger than the $\mathbf{J}$-$\mathbf{e}_3$ alignment (i.e., $\langle \cos \theta_2 \rangle > \langle \cos \theta_3 \rangle > 0.5$), then $\mathbf{J}$ would appear to be aligned perpendicular to the elongated axes of the filaments (i.e., the directions of minimum compression) in spite of $\langle \cos \theta_3 \rangle > 0.5$. The neglect of this possibility would result in a spurious value of $M_{\text{flip}}$. Suppose that $\langle \cos \theta_2 \rangle > \langle \cos \theta_3 \rangle > 0.5$ at a given mass $M_h$. According to our definition, we would properly conclude $M_{\text{flip}} < M_h$, while the conventional method based only on $\langle \cos \theta_3 \rangle$ would spuriously claim $M_{\text{flip}} > M_h$.

To investigate whether or not the $\sum m_\nu$-dependence of $M_{\text{flip}}$ is robust against the variation of $R_f$, we smooth $\mathbf{T}$ on two different scales and redetermine $\langle \cos \theta_3 \rangle$ by repeating the whole process for each $\nu$CDM model. Figures 3-4 show the same as Figure 2 but for the cases of $R_f = 2 \, h^{-1}\text{Mpc}$ and $10 \, h^{-1}\text{Mpc}$, respectively. As can be seen, although the decrease (increase) of $R_f$ induces the decrease (increase) of $M_{\text{flip}}$ for both of the $\nu$CDM cosmologies, a signal of the dependence of $M_{\text{flip}}$ on $\sum m_\nu$ is robustly detected, regardless of $R_f$.

It is found that, on the smaller smoothing scale of $R_f = 2 \, h^{-1}\text{Mpc}$, $\langle \cos \theta_2 \rangle \sim \langle \cos \theta_3 \rangle$ at $M_{\text{flip}} \approx 1.1 \times 10^{12} \, h^{-1} \, M_\odot$ for the case of $\sum m_\nu = 0.0 \, \text{eV}$ and that $\langle \cos \theta_2 \rangle \geq \langle \cos \theta_3 \rangle$ with $\langle \cos \theta_3 \rangle \approx 0.5$ in the whole mass range for the case of $\sum m_\nu = 0.6 \, \text{eV}$, which implies $M_{\text{flip}} < 0.5 \times 10^{12} \, h^{-1} \, M_\odot$ for the latter case (Figure 3). In other words, in the presence of more massive neutrinos, the galactic halos with $M_h \geq 0.5 \times 10^{12} \, h^{-1} \, M_\odot$ embedded in the short filaments of length $2 \, h^{-1}\text{Mpc}$ show no spin flips. It is also found that in these short filaments, $\langle \cos \theta_3 \rangle < \langle \cos \theta_1 \rangle < 0.5$ at $M_h \leq M_{\text{flip}}$ where $M_{\text{flip}} \approx 5 \times 10^{12} \, h^{-1} \, M_\odot$ for the case of $\sum m_\nu = 0.0 \, \text{eV}$ and $M_{\text{flip}} \approx 3 \times 10^{12} \, h^{-1} \, M_\odot$ for the case of $\sum m_\nu = 0.6 \, \text{eV}$.

In the filaments on the scale of $R_f = 10 \, h^{-1}\text{Mpc}$ $M_{\text{flip}} \approx 3.5 \times 10^{12} \, h^{-1} \, M_\odot$ for the case of $\sum m_\nu = 0.0 \, \text{eV}$ and $M_{\text{flip}} \approx 2.2 \times 10^{12} \, h^{-1} \, M_\odot$ for the case of $\sum m_\nu = 0.6 \, \text{eV}$ (Figure 4). Note that the two $\nu$CDM cosmologies differ in the sign of $\langle \cos \theta_3 \rangle$ at the highest mass bin. The value of $\langle \cos \theta_3 \rangle$ is higher than 0.5 in the entire mass range for the
case of $\Sigma m_\nu = 0.0 \text{ eV}$, while it drops below 0.5 at the highest mass bin $5 \leq M_h/(10^{12} h^{-1} M_\odot) < 10$ for the case of $\Sigma m_\nu = 0.6 \text{ eV}$.

In a similar manner, we also examine if the $\Sigma m_\nu$-dependence of $M_{\text{flip}}$ can be found in the sheets ($\lambda_1 > 0, \lambda_2 < 0$), voids ($\lambda_1 < 0$), and knots ($\lambda_3 > 0$) [6]. In the sheets on the scale of $R_f = 2 h^{-1}\text{Mpc}$ (Figure 6), we witness an occurrence of the spin flip of different kind, $\langle \cos \theta_2 \rangle > \langle \cos \theta_3 \rangle \sim 0.5$, at $M_h \geq M_{\text{flip}} \approx 7 \times 10^{12} h^{-1} M_\odot$, while $\langle \cos \theta_3 \rangle > \langle \cos \theta_2 \rangle > 0.5$ at $M_h \geq M_{\text{flip}}$ for the case of $\Sigma m_\nu = 0.6 \text{ eV}$, which results cannot be described by the linear TTT. In contrast to the filament halos, this spin flip of second kind describes the tendency that the sheet halos are preferentially aligned with $\hat{e}_3$ at $M_h > M_{\text{flip}}$ but with $\hat{e}_2$ at $M_h < M_{\text{flip}}$. Noting that the spin flip of second kind occurs only in the presence of massive neutrinos but not for the case of $\Sigma m_\nu = 0.0 \text{ eV}$, we speculate that a detection of its occurrence would in principle confirm $\Sigma m_\nu \neq 0$. Since both of $\hat{e}_2$ and $\hat{e}_3$ lie in the sheet plane normal to $\hat{e}_1$, however, it may be difficult to distinguish between the $\hat{J} \cdot \hat{e}_2$ and the $\hat{J} \cdot \hat{e}_3$ alignments in practice.

In the knots on the scale of $R_f = 1 h^{-1}\text{Mpc}$ (Figure 7), we find that the increment of $\Sigma m_\nu$ from 0.0 to 0.6 eV induces $M_{\text{flip}}$ to change from $\approx 5 \times 10^{12} h^{-1} M_\odot$ to $3 \times 10^{12} h^{-1} M_\odot$. It turns out that the knot halos has a higher $M_{\text{flip}}$ than the filament halos on the same smoothing scale $R_f = 2 h^{-1}\text{Mpc}$ for both of the $\nu$CDM cosmologies. The results from the knots on the larger scales of $R_f = 5 h^{-1}\text{Mpc}$ and $10 h^{-1}\text{Mpc}$ as well as from the voids are found to carry large uncertainties due to poor number statistics and thus omitted here.

**Discussion and Conclusions.** Analyzing the numerical data from the MassiveNuS [13] and exploring the intrinsic spin alignments of the galactic halos with the eigenvectors of the

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**FIG. 5:** Same as Figure 2 but for the case of the sheet halos.

**FIG. 6:** Same as Figure 3 but for the case of the sheet halos.

**FIG. 7:** Same as Figure 3 but using the knot halos.
local tidal fields in the presence of massive neutrinos, we have detected a clear signal of the $\sum m_{\nu}$-dependence of $M_{\text{flip}}$ at which the spin flips occur. The signal has been found to be most prominent in the filaments, being robust against the scale variation. Our result has revealed the potential of $M_{\text{flip}}$ as a powerful probe of $\sum m_{\nu}$, which seems inconsistent with the claim of [18] that the intrinsic alignments of the galaxy spins fail to discriminate the ΛCDM cosmology from the alternatives including the warm DM models.

We interpret the detected signal of the $\sum m_{\nu}$-dependence of $M_{\text{flip}}$ as an evidence for a retarding effect of massive neutrinos on the nonlinear evolution of the tidal fields. On the scales above their free streaming lengths, $l_p$, the massive neutrinos experience not only gravitational clustering but also tidal torque forces from the surroundings, which can be well described by the linear tidal torque theory. On the scales below $l_p$, the massive neutrinos, while freely streaming, carry over information on the larger-scale tidal influences to the galactic scales, leading the galactic halos to retain better the initial memory of the $J$-e$^{-2}$ alignments even on the low-mass scales. This effect of massive neutrinos on $M_{\text{flip}}$ should be distinct from that of suppressing the small-scale density powers, since the intrinsic galaxy alignment and spin flip phenomenon concern mostly not the magnitudes but the directions of the tidal fields. Henceforth, we speculate further that the detected $\sum m_{\nu}$-dependence of $M_{\text{flip}}$ might play a role in breaking the aforementioned cosmic degeneracy between the ΛCDM and the MG+ν cosmologies, in which direction our future work will head.

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