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On the Spin Bias of Satellite Galaxies in the Local Group-like Environment

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Abstract. We utilize the Millennium-II simulation databases to study the spin bias of dark subhalos in the Local Group-like systems which have two prominent satellites with comparable masses. Selecting the group-size halos with total mass similar to that of the Local Group (LG) from the friends-of-friends halo catalog and locating their subhalos from the substructure catalog, we determine the most massive (main) and second to the most massive (submain) ones among the subhalos hosted by each selected halo. When the dimensionless spin parameter (λ) of each subhalo is derived from its specific angular momentum and circular velocity at virial radius, a signal of correlation is detected between the spin parameters of the subhalos and the main-to-submain mass ratios of their host halos at $z = 0$: The higher main-to-submain mass ratio a host halo has, the higher mean spin parameter its subhalos have. It is also found that the correlations exist even for the subhalo progenitors at $z = 0.5$ and 1. Our interpretation of this result is that the subhalo spin bias is not a transient effect but an intrinsic property of a LG-like system with higher main-to- submain mass ratio, caused by stronger anisotropic stress in the region. A cosmological implication of our result is also discussed.

Keywords: galaxy evolution, galaxy morphology, cosmological simulations

Contents

1 Introduction

The Local Group (LG) is a dumbbell-shaped group of galaxies which include the great Andromeda (M31), the Triangulum (M33) and the Magellanic Clouds (MC) as well as our home, the Milky Way (MW) [1]. The two centers of the dumbbell shaped LG are nothing but MW and M31 which are known to have very similar masses of $\sim 10^{12}\,h^{-1}M_{\odot}$ [2, 3]. These two prominent galaxies contribute most of the total mass of LG, $M_{\rm LG}$, which has been estimated to be $\log[M_{\rm LG}/M_{\odot}] = 12.72$ with a 2σ range of $[12.26,\ 13.01]$ based on the accurate measurements of the distance and pair-wise speed between MW and M31 [4]. The majority of the other LG member galaxies are the satellites of either MW or M31, having orders of magnitude lower masses. It is expected that MW and M31 will eventually form a large central galaxy through a major merger between them when LG completes its virialization.

An intriguing question to ask is if and how the presence of two prominent galaxies in the LG and their mutual interaction caused their satellite galaxies to possess any biased or anomalous properties compared with other typical group galaxies. Occurring rarely in the LG-like environment [5], the major merger event is one of those few mechanisms that can have a significant effect on the geometrical and physical properties of the subhalos. For instance, ref. [6] claimed that the major mergers of the M31 progenitors should be responsible for the change of the satellite hosts between M31 and MW. Ref. [7] also attributed the detected vast polar structures of the MW dwarf satellites [8] to the major mergers of the M31 progenitors [see also, 9].

Here, we suggest a scenario that the spin parameters of the LG member galaxies have higher mean value than the that of the typical group galaxies due to the high anisotropic stress in the LG site. According to the recent study of ref. [10], the evolution of the angular momentum of a galaxy in the nonlinear regime is driven primarily by the local vorticity effect. The dumbbell shape of LG and the ongoing gravitational interaction between its two prominent galaxies, MW and M31, reflects the enhanced anisotropic stress in the local region around LG, which must have originated from the external tidal effect [11]. Given that the spin parameter of a galactic halo is strongly correlated not only with its surface stellar density [24, and references therein] but also with the temperature and mass of its gas contents [15], understanding the

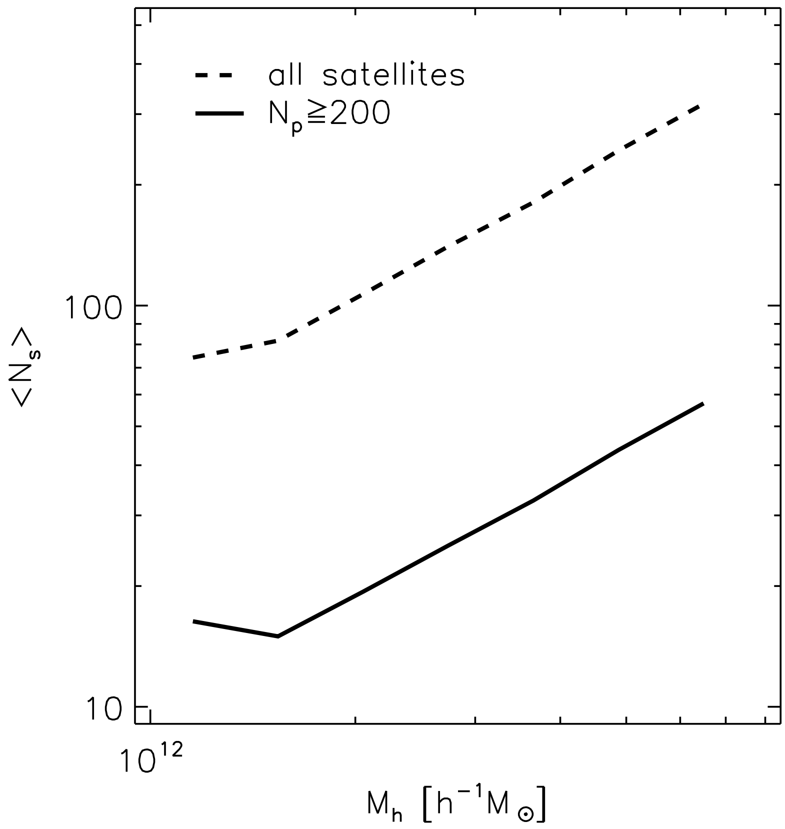

Figure 1. Mean numbers of the subhalos hosted by the group-size halos with mass M_h at $z = 0$. The solid and dashed lines represent the mean numbers of all subhalos and only those well resolved subhalos consisting of 200 or more particles, respectively.

spin parameter distributions of the LG member galaxies may provide a crucial key to explaining their physical properties as well as their evolution.

The goal of this Paper is to numerically test the above scenario by analyzing the data from the high-resolution N-body simulations. The contents of the upcoming sections are outlined as follows. In section 2 we describe the data from high-resolution N-body simulations and explain the numerical analysis of the simulation data. In section 3 we present the main result on the spin bias of the dark subhalos in the LG-like systems and its redshift dependence. In section 4 we discuss a physical interpretation of our result and its cosmological implication as well.

2 Main-to-submain mass ratios of group-size halos

For the numerical investigation we utilize the catalogs of dark matter halos and their subhalos resolved in the Millennium II simulations [16]. Under the assumption of a flat ΛCDM cosmology with the key parameters of $\Omega_m = 0.25,\ \Omega_\Lambda = 0.75,\ n_s = 1.0,\ \sigma_8 =$

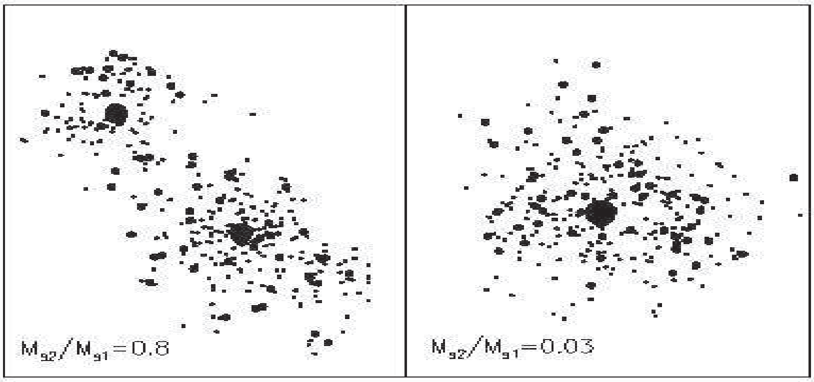

Figure 2. Spatial distributions of the subhalos in the two-dimensional projected space for the two different cases of the main-to-submain mass ratios at $z = 0$. In each panel the medium-size filled circles and the small filled circles correspond to the well-resolved subhalos with $N_p \leq 200$ and $N_p < 200$, respectively. The two large filled circles in the left panel correspond to the main and submain subhalos while the one large filled circle in the right panel corresponds to the single main subhalo.

0.9, $h = 0.73$, the Millennium-II simulations were performed at various epochs in a periodic box of linear size $100\,h^{-1}$Mpc with 2156^3 dark matter particles each of which has mass of $6.89\times10^6\,h^{-1}M_\odot$. The dark matter halos and their subhalos were identified by applying the friends-of-friends (FoF) and the subfind algorithms [17] to the particle data from the Millennium-II simulations, respectively. The full descriptions of the Millennium-II simulation and how to retrieve information from the halo catalogs are provided in refs. [16, 18], respectively.

From the Millennium-II FoF catalogs at $z = 0$, we first select those group-size halos whose FoF masses, M_h, are in the 2σ mass range of LG [4]: $10^{12.26} \leq M_h/M_\odot \leq 10^{13.01}$. A total of 2079 dark halos in the Millennium-II FoF catalog at $z = 0$ are found to satisfy this mass constraint. For each selected group-size halo, we extract their subhalos from the Millennium-II subhalo catalog at $z = 0$ but consider only those well-resolved ones consisting of 200 or more dark matter particles (N_p) for our analysis. Figure 1 plots the mean number of the well-resolved (all) subhalos versus the FoF masses of their host halos at $z = 0$ as solid (dashed) line. As can be seen, the mean numbers of the well-resolved subhalos with $N_p \geq 200$ increase monotonically with M_h but do not exceed 100 in the whole range of M_h.

We define the main and the submain subhalos of each halo as the most massive and the second to the most massive subhalos, respectively. Then, we assign each selected halo its unique value of the main-to-submain mass-ratio, M_{s2}/M_{s1}, where M_{s1} and M_{s2} denote the masses of the main and submain subhalos, respectively. If some halo has this mass-ratio close to unity, it is similar to the Local Group, having a dumbbell shape with two centers. Figure 2 illustrates the spatial distributions of the subhalos in the projected x-y plane for the two different cases of M_{s2}/M_{s1}. The left

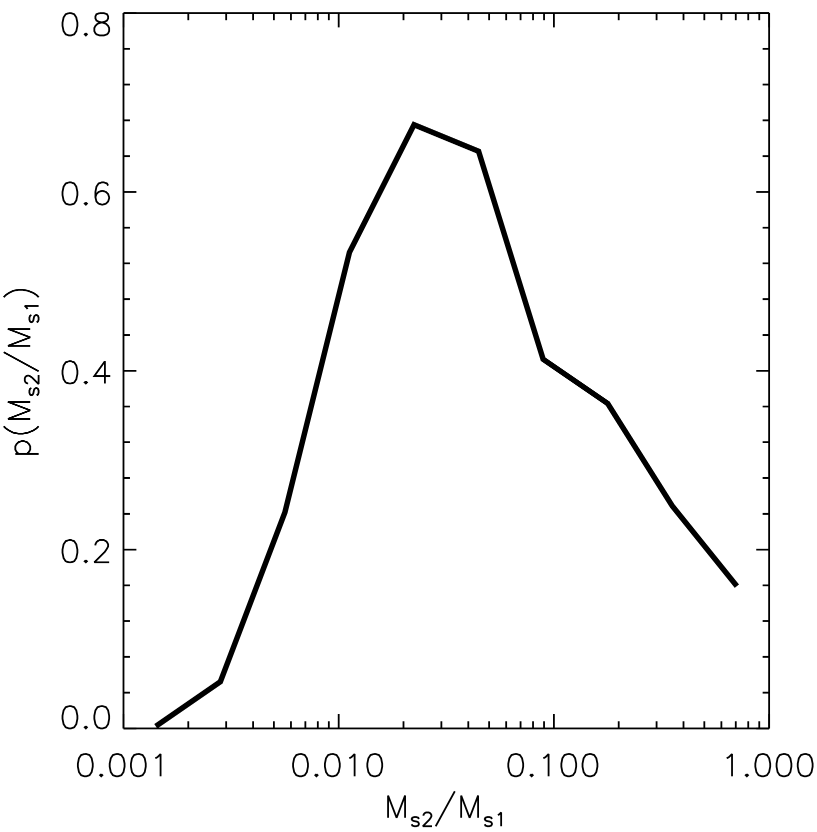

Figure 3. Probability density distribution of the main-to-submain mass ratios of the selected group-size halos at $z = 0$.

panel corresponds to the case that the main-to-submain mass ratio is close to unity with two prominent subhalos of comparable masses (largest filled circles). Note that most of the other subhalos for this case seem to be the satellites of these two prominent subhalos. The right panel corresponds to the case where the main-to-submain mass ratio is much smaller than unity with one single central dominant subhalo. In each panel, the medium and small-size filled circles represent the projected positions of the subhalos other than the prominent ones with $N_p \geq 200$ and $N_p < 200$, respectively. To see how rare the dumbbell-shaped systems are among the selected group-size halos, we bin the values of M_{s2}/M_{s1} and count the numbers of the group-size halos belonging to each bin to determine the probability density distribution of M_{s2}/M_{s1}, the result of which is shown in Fig. 3. As can be seen, the probability density reaches its maximum value around $M_{s2}/M_{s1} = 0.02$, dropping rapidly as M_{s2}/M_{s1} approaches unity.

To see if the distances between the main and the submain subhalos depend on their mass-ratios, we also calculate the mean main-between-submain distances averaged over those hosts belonging to each bin of M_{s2}/M_{s1}, the result of which is plotted in Fig. 4. The horizontal dotted line corresponds to the separation distance between

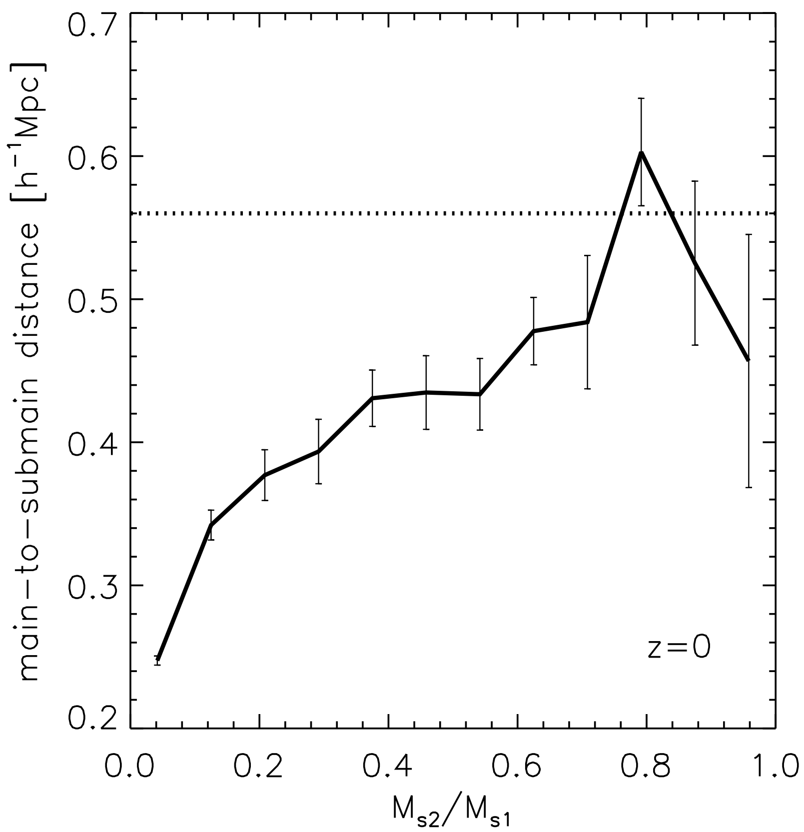

Figure 4. Separation distances between the main and the submain subhalos as a function of their mass ratios at $z = 0$. The horizontal dotted line corresponds to the separation distance between the MW and the M31.

the MW and the M31 [4]. As can be seen, the mean distance between the main and the submain subhalos increases as M_{s2}/M_{s1} increases. Note also that it matches the separation distance between MW and M31 when M_{s2}/M_{s1} has the value around 0.8, which indicates that those FoF halos with $M_{s2}/M_{s1} \geq 0.8$ are indeed similar to the LG.

To see if the main-to-submain mass-ratio of a host halo depends on its total mass, we bin the values of M_h and calculate the mean value of M_{s2}/M_{s1} averaged over those hosts belonging to each bin of M_h. Figure 5 plots the mean value of the main-to-submain mass ratios of the selected group-size halos as a function of its FoF mass. The errors represent one standard deviation σ_r in the measurement of $\langle M_{s2}/M_{s1}\rangle$ computed as $\sigma_r^2 = \left[\langle (M_{s2}/M_{s1})^2\rangle - \langle M_{s2}/M_{s1}\rangle^2\right]/(N_h - 1)$ where N_h denotes the number of those group-size halos belonging to each bin of M_h. As can be seen in Figure 5, the mean value, $\langle M_{s2}/M_{s1}\rangle$, does not vary strongly with the total mass, M_h.

To see if the mass distribution of the subhalos depends on the main-to-submain mass ratios of their host halos, we bin the values of M_{s2}/M_{s1} and calculate the mean value of the maximum circular velocity, $V_{\max}$, averaged over the subhalos whose host

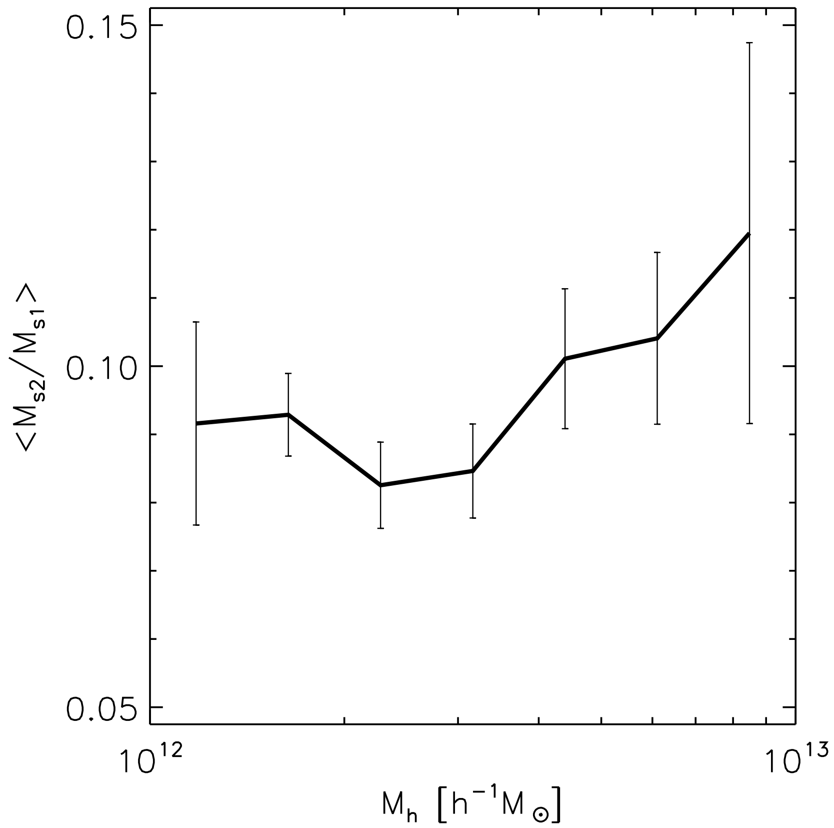

Figure 5. Mean main-to-submain mass ratios of the group-size halos as a function of their FoF mass at $z = 0$.

halos belong to each bin of M_{s2}/M_{s1}. The Millennium-II substructure catalog provides information on $V_{\rm max}$ for each subhalo, which is a good indicator of the subhalo mass. Figure 6 plots the average value of $V_{\rm max}$ as a function of the main-to-submain mass ratios of their host halos. The errors represent again one standard deviation in the measurements of $\langle V_{\rm max}\rangle$. As can be seen, there is only very weak, if any, correlation between V_{max} and M_{s2}/M_{s1} with the mean value of V_{max} around $50\,s^{-1}km$, regardless of the value of M_{s2}/M_{s1}.

3 Spin bias in the LG-like Environments

Now that the LG-like groups are found atypical in the respect that most of the group-size halos with masses comparable to that of LG have main-to-submain halo ratios much less than unity, we would like to investigate what environmental effect the atypical LG-like systems have on their subhalos. We are particularly interested in the environmental effect on the subhalo's dimensionless spin parameter λ which is conveniently defined as $\lambda = j/(\sqrt{2}V_{\rm vir}R_{\rm vir})$ [19] where $R_{\rm vir}$ represents the virial radius and

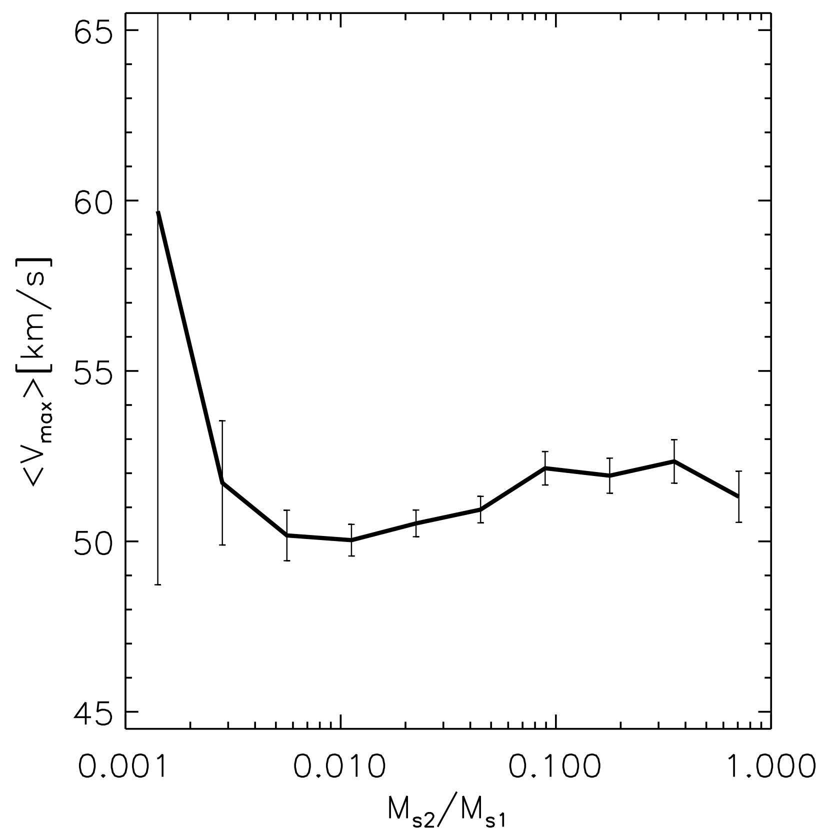

Figure 6. Mean circular velocity maximum of the subhalos as a function of their host halo's main-to-submain mass ratio at $z = 0$.

$V_{\rm vir}$ is the circular velocity measured at $R_{\rm vir}$, j is the magnitude of the subhalo's specific angular momentum (angular momentum per mass). For the subhalos identified by the SUBFIND algorithm, the virial radius $R_{\rm vir}$ is related to the spherical radius $R_{\rm max}$ at which the subhalo's circular velocity curve reaches its maximum as $R_{\rm vir} = R_{\rm max}/0.18$ [20], while $V_{\rm vir}$, can be calculated from the virial mass $M_{\rm vir}$ and the virial radius $R_{\rm vir}$ as $V_{\rm vir} = \sqrt{GM_{\rm vir}/R_{\rm vir}}$ where G is the Newtonian constant. Using these relations along with information on j, $V_{\rm max}$ and $R_{\rm max}$ provided in the Millennium-II substructure catalog, we compute the dimensionless spin parameter λ of each selected subhalo.

Binning the mass ratio M_{s2}/M_{s1} of each selected group-size halo and calculating the mean value of the spin parameters of those well-resolved subhalos whose host halos belong to each bin of M_{s2}/M_{s1}, we determine $\langle\lambda\rangle$ as a function of M_{s2}/M_{s1}, which is shown in the top panel of Fig. 7. The errors represent one standard deviation σ_λ in the measurement of $\langle\lambda\rangle$ computed as $\sigma_\lambda^2 = [\langle\lambda^2\rangle - \langle\lambda\rangle^2]/(N_h - 1)$ where N_h denotes the number of those group-size halos belonging to each bin of M_{s2}/M_{s1}. As can be seen, there exists a clear signal of correlation between λ and M_{s2}/M_{s1}: The higher main-to-submain mass ratio a host halo has, the higher mean spin parameters their subhalos

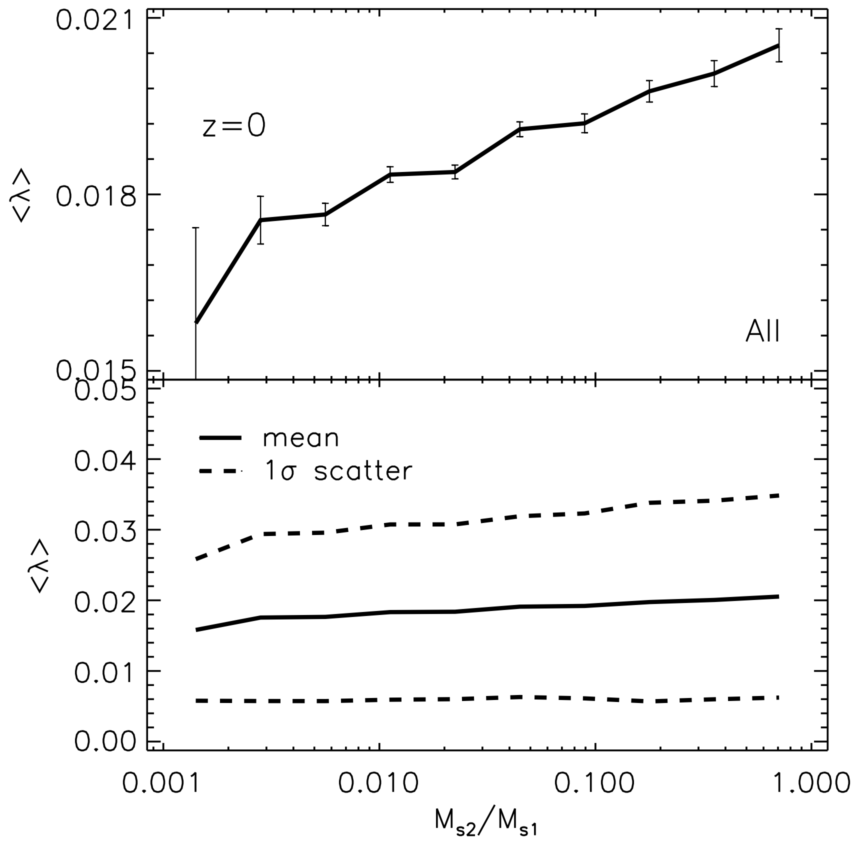

Figure 7. (Top panel): Mean spin parameter of the subhalos as a function of their host halo's main-to-submain mass ratio M_{s2}/M_{s1} at $z = 0$. (Bottom panel): Range of one standard deviation scatter (dashed line) of the spin parameters around its mean (solid line) vs. M_{s2}/M_{s1}.

have. Recalling that the main-to-submain mass ratio of a host halo has no mass bias (see Fig. 6) and that the subhalo spin parameters are insensitive to the subhalos' mass, we affirm that the correlation detected between λ and M_{s2}/M_{s1} is not due to any mass bias.

The bottom panel of Fig. 7 shows one standard deviation scatter of λ (dotted line), computed as $[\langle\lambda^2\rangle - \langle\lambda\rangle^2]^{1/2}$, around its mean value (solid line). Although the width of the scatter of λ is much wider than the range of the detected trend in λ with M_{s2}/M_{s1}, it does not necessarily mean that the correlation between λ and $M_{s2}/M_{s1}$is not meaningful since the spin parameter λ is well known to be widely scattered following the log-normal distribution [19]. The presence of the correlation between λ and M_{s2}/M_{s1} is important and meaningful because it implies that for the case of higher M_{s2}/M_{s1} the fraction of $\lambda \geq \lambda_c$ in the log-normal tail will be larger where λ_c is some threshold of the spin parameter.

Now that a signal of correlation between λ and M_{s2}/M_{s1} is detected, it is inter-

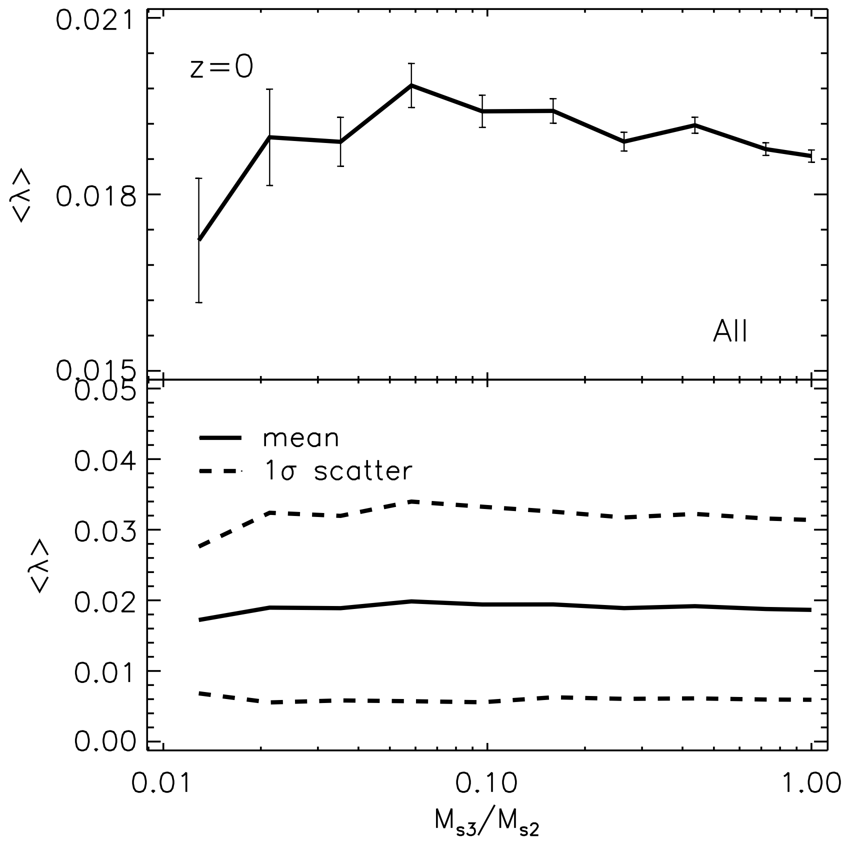

Figure 8. (Top panel): Mean spin parameter of the subhalos as a function of M_{s2}/M_{s3} at $z = 0$, where M_{s2} and M_{s3} represent the masses of the second and the third to the most massive subhalos belonging to a given host halo. (Bottom panel): Range of one standard deviation scatter (dashed line) of the spin parameters around its mean (solid line) vs. M_{s2}/M_{s3} .

esting to examine whether or not λ also depends on M_{s3}/M_{s2} where M_{s3} denotes the mass of the third to the most massive subhalo. We repeat the same calculation to determine $\langle\lambda\rangle$ but as a function of M_{s3}/M_{s2}, the result of which is shown in Fig. 8. As can be seen, the mean spin parameter of the subhalos depends weakly on M_{s3}/M_{s2}, reaching the maximum value at $M_{s3}/M_{s2} \approx 0.05$ and decreasing as M_{s3}/M_{s2} increases. This result implies that the LG may be the optimal environment for the highest spin parameters: In addition to its high value of $M_{s2}/M_{s1} \approx 0.8$ [2], the value of M_{s3}/M_{s2} of the LG is approximately 0.05 since the Triangulum galaxy (the third to the most massive member galaxy in the LG) has mass approximately $M_{s3} = 5 \times 10^{10}\, h^{-1}M_{\odot}$ [23].

Since it is only the central galaxies whose physical properties are known to depend on the spin parameters of their host halos [12–14], we repeat the whole calculations using only the central prominent subhalos, the result of which is shown in Fig. 9. As can be seen, we observe stronger correlation between the spin parameters of the central

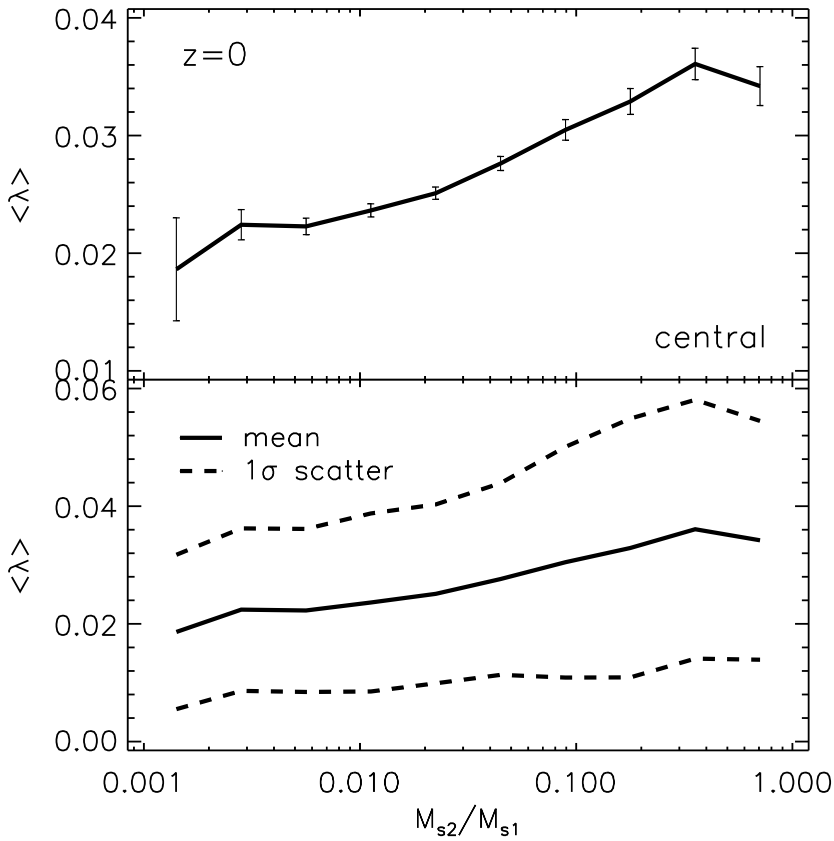

Figure 9. Same as Fig. 7 but only using the central prominent subhalos.

prominent subhalos and the main-to-submain mass ratios of their host halos. From this results, it can be inferred that the subsequent tidal stripping effect tends to reduce the strength of the correlation between the spin parameters of their subhalos and the main-to-submain mass ratios of their host halos.

Given that those host halos with higher M_{s2}/M_{s1} are likely to be recent merger remnants, it should be worth checking whether or not the observed correlation between λ and M_{s1}/M_{s2} is a transient effect. Locating the progenitors of the subhalos belonging to each host halo at higher redshifts, $z = 0.5$ and $z = 1$, in the Millennium Merger Tree catalog, we investigate the correlations between the spin parameters of the subhalo progenitors and the main-to-submain mass ratios of their descendant hosts at $z = 0$. Figure 10 shows the same as Fig. 7 but for the subhalo progenitors at $z = 0.5$ and $z = 1$ in the top and bottom panels, respectively. The results are obtained by considering only those well resolved subhalo progenitors with $N_{\rm p} \geq 200$. As can be seen, the mean spin parameters of the subhalo progenitors are correlated with the main-to-submain mass ratios of the descendant hosts and the strength of the correlations are similar to that observed at $z = 0$. Using only the central prominent subhalos, we repeat the whole calculations, the result of which is shown in Fig. 11. As can be seen, we

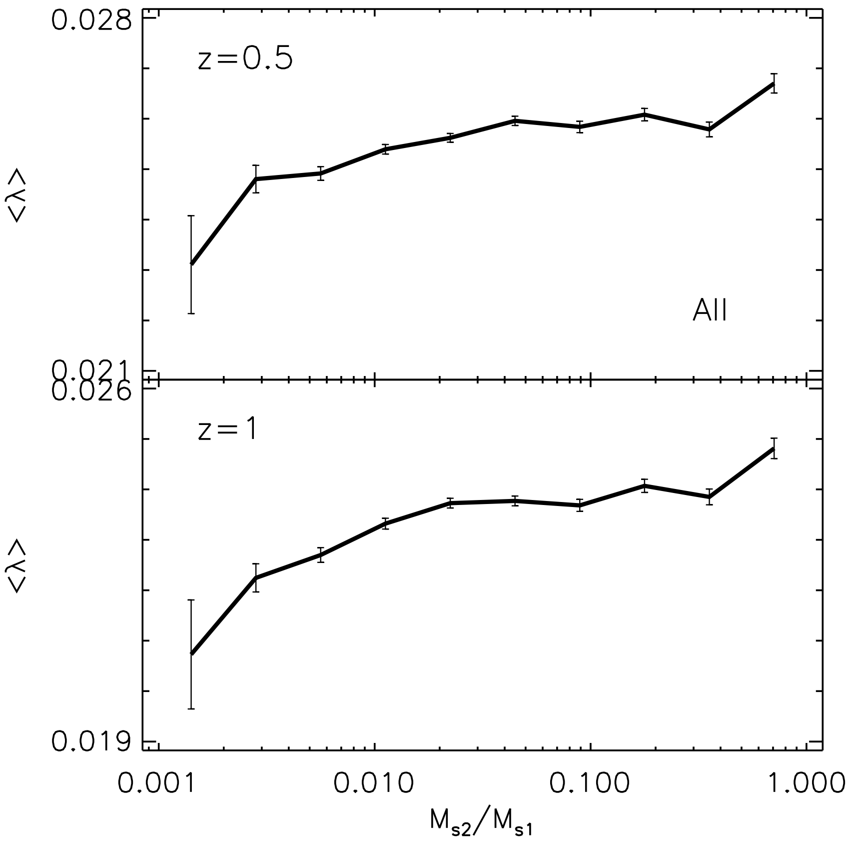

Figure 10. Correlations between the mean spin parameters of the subhalo progenitors and the main-to-submain mass ratios of the host halos at $z = 0.5$ and 1 in the top and bottom panels, respectively. .

observe stronger correlation between the spin parameters of the progenitors of the central prominent subhalos and the main-to-submain mass ratios of their descendant hosts. Noting the results shown in Fig. 10, we think that the observed trend in λ with M_{s2}/M_{s1} is not a mere transient phenomena due to the merging but an intrinsic effect of the anisotropic stress which increases with the main-to-submain mass ratios.

Previous theoretical studies asserted that the surface stellar density of a disc galaxy is inversely proportional to the spin parameter of its host halo and that a dark galaxy whose surface stellar density falls below $100\,\mathrm{pc}^{-2}$ forms in the critically fast spinning halos whose spin parameters exceeds some threshold of $\lambda_c \approx 0.06$ [12–14]. Very recently, ref. [24] performed a high-resolution hydrodynamic simulation to numerically confirm that the spin parameters are indeed strongly correlated with the surface stellar and gas densities of a disc galaxy. Their result revealed clearly that the halo's higher spin leads to the lower stellar and gas surface densities of its disk galaxy. To see how abundant the dark galaxies are in the LG-like systems, we calculate the number fraction of the prominent subhalos with $\lambda \geq \lambda_c = 0.06$ as a function of

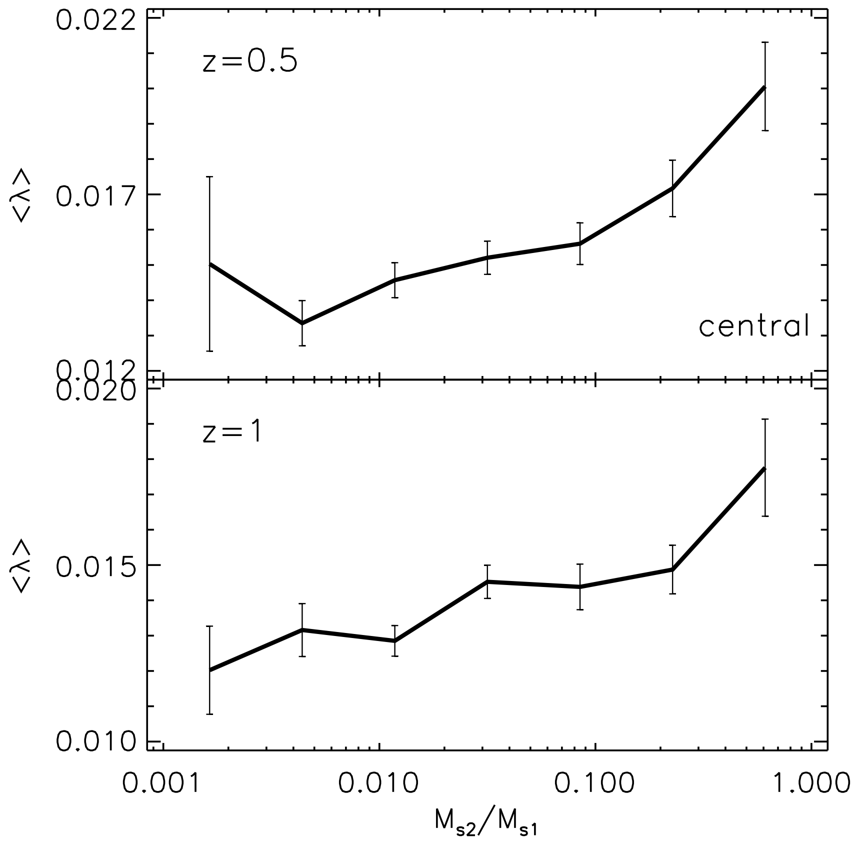

Figure 11. Same as Fig. 10 but only for the central prominent satellites.

the main-to-submain mass ratio, the result of which is plotted in Fig. 12. As can be seen, the fraction of the fast-spinning central subhalos with $\lambda \geq \lambda_c$ increases almost monotonically with the main-to-submain mass ratio. For the case of $M_{s2}/M_{s1} \geq 0.3$, approximately 18% of the central subhalos have $\lambda \geq \lambda_c$ while for the case of $M_{s2}/M_{s1} \leq 0.05$ only 2% of the central subhalos satisfy the condition.

4 Summary and discussion

By analyzing the halo and subhalo catalogs from the Millennium-II simulations, we have detected a clear signal of correlations between the main-to-submain mass ratios of group-size halos and the spin parameters of their subhalos at present epoch. We have also found that the central prominent subhalos exhibit stronger correlations and that the correlations with similar strength exist even for the subhalo progenitors at $z = 0.5$ and $z = 1$. We conclude that the observed high mean spin parameters of the subhalos in the LG-like groups are not transient merger remnants but likely to be intrinsic property of the LG-like systems induced by the high anisotropic stress in the local site.

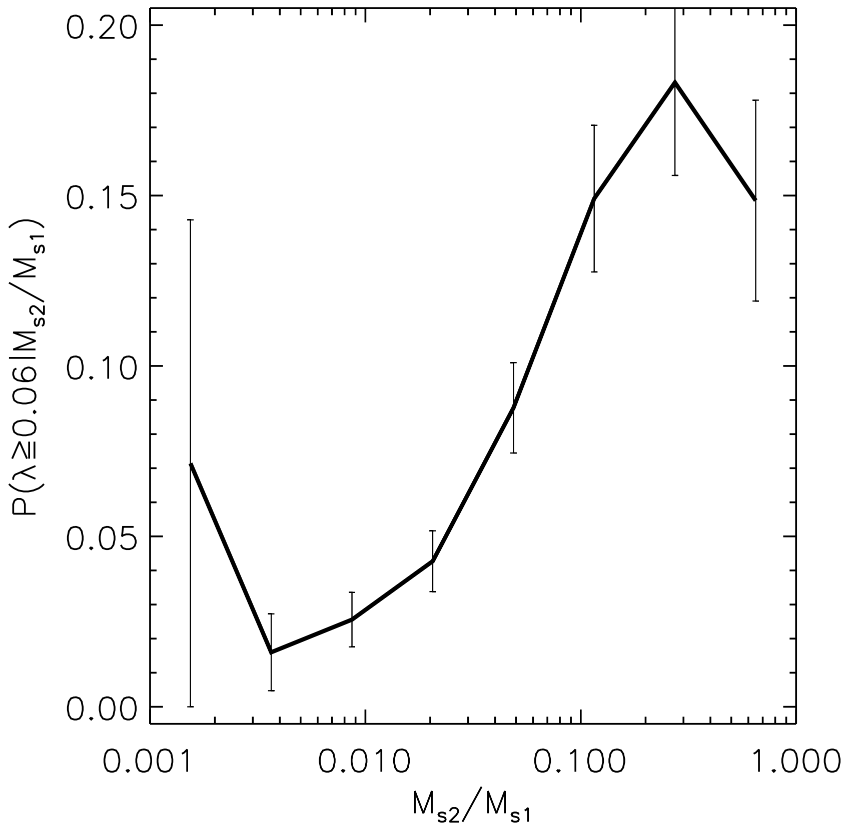

Figure 12. Number fractions of the central subhalos with $\lambda \geq 0.06$ versus the main-to-submain ratio of the host halos at $z = 0$.

An important implication of our result is that the LG member galaxies are biased toward the high spins and thus likely to have on average lower stellar and gas surface densities than the typical group galaxies [12–14, 24]. When the observed properties of the MW satellites are used to be compared with the predictions of ΛCDM cosmology the spin bias of the MW satellites should be taken into account. For instance, our result may help alleviate the tension between the observed satellite populations of the MW and the predictions of the ΛCDM cosmology [25, 26, and references therein] since the presence of more dark satellite galaxies due to their biased spins in the MW system could explain the lower abundance of the observed satellites of the MW. It is, however, worth mentioning here that the robustness of our result obtained from the Millennium-II simulations against the subhalo-finding algorithm will have to be tested further in the future before connecting it to the observed properties of galaxies. Especially the masses and spin parameters of the subhalos calculated using the number of DM particles can have large variations in their values at the consecutive time steps due to the limitation of the SUBFIND algorithm.

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