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 ($\lambda$) 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
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, $M_{\text{LG}}$, which has been estimated to be $\log[M_{\text{LG}}/M_\odot] = 12.72$ with a $2\sigma$ 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
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 $\Lambda$CDM cosmology with the key parameters of $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n_s = 1.0$, $\sigma_8 = \ldots$
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.

From the Millennium-II FoF catalogs at \( z = 0 \), we first select those group-size halos whose FoF masses, \( M_h \), are in the \( 2\sigma \) 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.

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 $\sigma_r$ 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, $V_{\text{max}}$, averaged over the subhalos whose host
halos belong to each bin of $M_{s2}/M_{s1}$. The Millennium-II substructure catalog provides information on $V_{\text{max}}$ for each subhalo, which is a good indicator of the subhalo mass. Figure 6 plots the average value of $V_{\text{max}}$ 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 $\langle V_{\text{max}} \rangle$. As can be seen, there is only very weak, if any, correlation between $V_{\text{max}}$ and $M_{s2}/M_{s1}$ with the mean value of $V_{\text{max}}$ around $50 \text{s}^{-1} \text{km}$, 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 $\lambda$ which is conveniently defined as $\lambda = j/(\sqrt{2}V_{\text{vir}}R_{\text{vir}})$ [19] where $R_{\text{vir}}$ 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 $z = 0$.

$V_{\text{vir}}$ is the circular velocity measured at $R_{\text{vir}}$, $j$ 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 $R_{\text{vir}}$ is related to the spherical radius $R_{\text{max}}$ at which the subhalo’s circular velocity curve reaches its maximum as $R_{\text{vir}} = R_{\text{max}}/0.18$ [20], while $V_{\text{vir}}$ can be calculated from the virial mass $M_{\text{vir}}$ and the virial radius $R_{\text{vir}}$ as $V_{\text{vir}} = \sqrt{G M_{\text{vir}} / R_{\text{vir}}}$ where $G$ is the Newtonian constant. Using these relations along with information on $j$, $V_{\text{max}}$ and $R_{\text{max}}$ provided in the Millennium-II substructure catalog, we compute the dimensionless spin parameter $\lambda$ 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 $\sigma_\lambda$ 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 $\lambda$ 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 $\lambda$ and $M_{s2}/M_{s1}$ is not due to any mass bias.

The bottom panel of Fig. 7 shows one standard deviation scatter of $\lambda$ (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 $\lambda$ is much wider than the range of the detected trend in $\lambda$ with $M_{s2}/M_{s1}$, it does not necessarily mean that the correlation between $\lambda$ and $M_{s2}/M_{s1}$ is not meaningful since the spin parameter $\lambda$ is well known to be widely scattered following the log-normal distribution [19]. The presence of the correlation between $\lambda$ 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 $\lambda_c$ is some threshold of the spin parameter.

Now that a signal of correlation between $\lambda$ 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. $M_{s2}/M_{s3}$.

It is interesting to examine whether or not $\lambda$ 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
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 $\lambda$ 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 $N_p \geq 200$. 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
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 $\lambda$ 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 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 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.
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.
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.

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

[1] van den Bergh, S., The local group of galaxies, 1999 Astron. & Astrophys. rev. 9 273
[2] Karachentsev, I. D. and Kashibadze, O. G., Masses of the local group and of the M81 group estimated from distortions in the local velocity field, 2006 Astrophys. 49 3
[3] McMillan, P. J., Mass models of the Milky Way, 2011 Mont. Not. Roy. Astron. 414 2446 [arXiv:1102.4340]
[4] Li, Y.-S. and White, S. D. M., Masses for the Local Group and the Milky Way, 2008 Mont. Not. Roy. Astron. 384 1459 [arXiv:0710.3740]
[5] Klimentowski, J. and et al., The grouping, merging and survival of subhaloes in the simulated Local Group, 2010 Mont. Not. Roy. Astron. 402 1899 [arXiv:0909.1916]
[6] Knebe, A. et al., Renegade subhaloes in the Local Group, 2011 Mont. Not. Roy. Astron. Soc. 417 L56 [arXiv:1107.2944]
[7] Fouquet, S., Hammer, F., Yang, Y., Puech, M. and Flores, H., Does the dwarf galaxy system of the Milky Way originate from Andromeda?, 2012 Mont. Not. Roy. Astron. 427 1769 [arXiv:1209.4077]
[8] Pawlowski, M. S., Pflamm-Altenburg, J. and Kroupa, P., The VPOS: a vast polar structure of satellite galaxies, globular clusters and streams around the Milky Way, 2012 Mont. Not. Roy. Astron. 423 1109 [arXiv:1204.5176]
[9] Ibata, R. A. and et al., A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy, 2013 Nature 493 62
[10] Libeskind, N. and et al., Cosmic vorticity and the origin of halo spins, 2012 [arXiv:1212.1454]
[11] Pasetto, S. and Chiosi, C., Tidal Effects on the Spatial Structure of the Local Group, 2009 Astron. & Astrophys. 499 385 [arXiv:0902.3581]
[12] Jimenez, R., Heavens, A. F., Hawkins, M. R. S. and Padoan, P., Dark galaxies, spin bias and gravitational lenses, 1997 Mont. Not. Roy. Astron. 292 L5 [astro-ph/9709050]
[13] Jimenez, R., Padoan, P., Matteucci, F. and Heavens, A. F., Galaxy formation and
evolution: low-surface-brightness galaxies, 1998 Mont. Not. Roy. Astron. 299 123 [astro-ph/9804049]

[14] Mo, H. J., Mao, S. and White, S. D. M., The formation of galactic discs, 1998 Mont. Not. Roy. Astron. 295 319 [astro-ph/9707093]

[15] Vasiliev, E. O.; Vorobyov, E. I.; Shchekinov, Yu. A., Cooling and fragmentation of gas in rotating protogalaxies, 2010 Astron. Rep. 54 890

[16] Boylan-Kolchin, M., Springel, V., White, S. D. M., Jenkins, A. and Lemson, G., From Resolving cosmic structure formation with the Millennium-II Simulation, 2009 Mont. Not. Roy. Astron. 398 1150 [arXiv:0903.3041]

[17] Springel, V., White, S. D. M., Tormen, G. and Kauffmann, G., Populating a cluster of galaxies I. Results at z=0, 2001 Mont. Not. Roy. Astron. 328 726 [astro-ph/0012055]

[18] Lemson, G. and the Virgo Consortium Halo and Galaxy Formation Histories from the Millennium Simulation: Public release of a VO-oriented and SQL-queryable database for studying the evolution of galaxies in the ΛCDM cosmogony, 2006 [astro-ph/0608019]

[19] Bullock, J. S. and et al., A Universal Angular Momentum Profile for Galactic Halos, 2001 Astrophys. J. 555 240 [astro-ph/0011001]

[20] Muldrew, S. I., Pearce, F. R. and Power, C., The accuracy of subhalo detection, 2011 Mont. Not. Roy. Astron. 410 2617 [arXiv:1008.2903]

[21] Maccio, A. V. et al., Concentration, spin and shape of dark matter haloes: scatter and the dependence on mass and environment, 2007 Mont. Not. Roy. Astron. 378 55 [astro-ph/0608157]

[22] Macci, A. V., Dutton, A. A. and van den Bosch, F. C., Concentration, spin and shape of dark matter haloes as a function of the cosmological model: WMAP1, WMAP3 and WMAP5 results, 2008 Mont. Not. Roy. Astron. 391 1940 [arXiv:0805.1926]

[23] Corbelli, E., Dark matter and visible baryons in M33, 2003 Mont. Not. Roy. Astron. 342 199 [astro-ph/0302318]

[24] Kim, J. H. and Lee, J., How Does the Surface Density and Size of Disk Galaxies Measured in Hydrodynamic Simulations Correlate with the Halo Spin Parameter?, 2013 Mont. Not. Roy. Astron. doi: 10.1093/mnras/stt632 [arXiv:1210.8321]

[25] Boylan-Kolchin, M., Bullock, J. S., and Kaplinghat, M., Too big to fail? The puzzling darkness of massive Milky Way subhaloes, 2011 Mont. Not. Roy. Astron. 415 L40 [arXiv:1103.0007]

[26] Boylan-Kolchin, M., Bullock, J. S., and Kaplinghat, M., The Milky Way’s bright satellites as an apparent failure of CDM, 2012 Mont. Not. Roy. Astron. 422 1203 [arXiv:1111.2048]