THE ACCRETION OF DARK MATTER SUBHALOS WITHIN THE COSMIC WEB: PRIMORDIAL ANISOTROPIC DISTRIBUTION AND ITS UNIVERSALITY

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ABSTRACT

The distribution of galaxies displays anisotropy on different scales and it is often referred to as galaxy alignment. To understand the origin of galaxy alignments on small scales, one must investigate how galaxies were accreted in the early universe and quantify their primordial anisotropy at the time of accretion. In this paper we use N-body simulations to investigate the accretion of subhalos, focusing on their alignment with halo shape and the orientation of mass distribution on the large scale, defined using the Hessian matrix of the density field. The large/small ($e_1/e_3$) eigenvalues of the Hessian matrix define the fast/slow collapse direction of matter on the large scale. We find that: (1) the halo major axis is well aligned with the $e_3$ (slow collapse) direction, and it is stronger for massive halos; (2) subhalos are predominantly accreted along the major axis of the host halo, and the alignment increases with the host halo mass. Most importantly, this alignment is universal; (3) accretion of subhalos with respect to the $e_3$ direction is not universal. In massive halos, subhalos are accreted along the $e_3$ (even more strongly than the alignment with the halo major axis), but in low-mass halos subhalos are accreted perpendicular to $e_3$. The transitional mass is lower at high redshift. The last result well explains the puzzling correlation (both in recent observations and simulations) that massive galaxies/halos have their spin perpendicular to the filament, and the spin of low-mass galaxies/halos is slightly aligned with the filament, under the assumption that the orbital angular momentum of subhalos is converted to halo spin.

Key words: galaxies: halos – cosmology: theory – dark matter – large-scale structure of universe – methods: statistical

1. INTRODUCTION

In the cold dark matter universe, structures emerge from the initial seed of perturbations via gravitational instability. On large scales, the mass distribution is characterized as the cosmic web (filaments, sheets, clusters, voids), which can be fairly described by a linear theory and the Zel’ dovich approximation (Zel’dovich 1970). On small scales, dark matter halos form by collapse of matter at the intersection of filaments, and they gradually merge and grow in a hierarchical and nonlinear way. The detail of the properties and mass distribution of dark matter halos on large scales can be accurately studied by N-body simulations (e.g., Springel et al. 2006). In such a formation scenario, it is naturally expected that the properties of halos are correlated with the large-scale structure (LSS). For example, the halo shape is well aligned with the cosmic filament (e.g., van Haarlem & van de Weygaert 1993; Aragón-Calvo et al. 2007b; Hahn et al. 2007b; Zhang et al. 2009; for a summary, see Forero-Romero et al. 2014), the halo spin originates from the tidal force force exerted by the mass distribution on large scales (White 1984), and its direction is well correlated with the cosmic web (e.g., Bond et al. 1996; van de Weygaert & Bertschinger 1996; Lee 2004; Bailin & Steinmetz 2005; Hahn et al. 2007b; Zhang et al. 2009; Libeskind et al. 2012). Most importantly, the alignment between halo spin and the LSS has a dependence on halo mass (e.g., Aragón-Calvo et al. 2007b; Hahn et al. 2007a; Codis et al. 2012; Trowland et al. 2013; Dubois et al. 2014; Zhang et al. 2015).

These theoretically predicted correlations of the halo properties with LSS are manifested by the distribution of galaxies inside dark matter halos, as galaxies are “luminous” tracers of merged halos formed at early times. For example, satellite galaxies are found to be aligned with the major axis of central galaxies, with a strong dependence on galaxy colors and halo mass (Brainerd 2005; Yang et al. 2006). Local dwarf satellites in the Milky Way and M31 are distributed anisotropically and most are in a large thin disk (Kroupa et al. 2005; Metz et al. 2007; Ibata et al. 2013). The shapes of luminous red galaxies are correlated with each other up to very large scales (e.g., Faltenbacher et al. 2007; Okumura et al. 2009; Li et al. 2013). Galaxy spin is also found to correlate with LSS although the measurements of galaxy spin are not straightforward (e.g., Trujillo et al. 2006; Jones et al. 2010). More interestingly, it has recently been found that the correlation of galaxy spin with LSS depends on galaxy type/mass, such that the spin of early-type galaxies is perpendicular to the surrounding filament, but late-type galaxies have their spin slightly parallel to the filament (Tempel & Libeskind 2013; Zhang et al. 2015), in amazingly good agreement with the theoretical expectations (e.g., Aragón-Calvo et al. 2007b).

The observed anisotropic distribution of galaxies on different scales raises the question of its origin. Some studies (e.g., Benson 2005; Libeskind et al. 2005; Wang et al. 2005) have shown that satellite galaxies are accreted anisotropically during the formation of dark matter halos, and this primordial anisotropy is the origin of the current anisotropic distribution of satellite galaxies. However, the observed distribution of galaxies within dark matter halos involves complicated baryonic processes (e.g., Kang et al. 2005; Vogelsberger et al. 2014) and galaxies have experienced nonlinear dynamical evolution inside dark matter halos. Along with the fact that the signal of the galaxy’s anisotropic distribution is much weaker, it is therefore difficult to infer how much of the currently observed anisotropic distribution of galaxies is from the
primordial anisotropy set on large scales before galaxies were accreted, and how much of it is from the nonlinear evolution inside the dark matter halo. For example, the anisotropic distribution of satellites with respect to central galaxies can be purely ascribed to the nonlinear evolution or the non-spherical nature of dark matter halos (e.g., Jing & Suto 2002; Kang et al. 2007; Dong et al. 2014; Wang et al. 2014; Debattista et al. 2015). For a recent review of galaxy alignments and their relation with the halo shape or the LSS, see Joachimi et al. (2015). The flip of the halo spin–LSS correlation (e.g., Aragón-Calvo et al. 2007b) has also attracted great attention recently. Using hydrodynamical simulations, it was found that the flip is related to the halo merger history and cold gas accretion during the formation of elliptical and spiral galaxies (e.g., Codis et al. 2012, 2015; Welker et al. 2014).

To understand the observed correlation of the galaxy distribution with the halo shape or the LSS in detail, one needs to trace galaxies back to the time of their accretion, to quantify the degree of primordial correlation with dark matter halos or the LSS at that time. This is often done by tracing subhalos back to early times using N-body simulations. In this paper we study the spatial alignment of subhalos with respect to the host halo shape and the LSS, and in a future paper we will focus on the velocity/spin correlation with LSS at the time of accretion. There have been only a few studies using this kind of approach. Benson (2005) found that subhalos are preferentially accreted in the planes defined by the major and middle axes of the host halos. Wang et al. (2005) also found that subhalos are accreted along the halo major axis and massive subhalos show a stronger trend. However, they both ignored the correlation with the LSS. Recently, Libeskind et al. (2014) and Shi et al. (2015) have found that subhalos are predominantly accreted along the filament, but their classification of the cosmic web is based on velocity shear or tidal field. In our paper we classify the cosmic web by means of the density field in order to classify the LSS environment, and our analysis goes to very low-mass halos. In particular, we will show that our results are helpful in explaining the puzzling non-universality in the correlation between halo/galaxy spin and LSS.

The paper is organized as follows. In Section 2 we introduce the simulations and the methods to quantify the halo shape and the LSS. In Section 3 we show how the halo shape is correlated with the LSS and the anisotropic distribution of accreted subhalos with respect to the halo shape and the LSS. Then, we present their dependence on halo mass and redshift. In Section 4 we summarize our results and briefly discuss how our results help to explain the correlation between the halo spin and the LSS.

2. N-BODY SIMULATION AND LSS CLASSIFICATION

In this work we use two N-body simulations with different box sizes. Both simulations are run with the Gadget-2 code (Springel 2005) using the same number of particles, 1024³, and the same cosmological parameters from the WMAP7 data (Komatsu et al. 2011), namely $\Omega_m = 0.73$, $\Omega_m = 0.27$, $h = 0.7$, and $\sigma_8 = 0.81$. The box sizes are 200 Mpc/$h$ and 65 Mpc/$h$, and the particle masses in these two simulations are $5.5 \times 10^8 M_\odot/h$ and $1.8 \times 10^7 M_\odot/h$, respectively. With the larger simulation box we get more well resolved massive halos, while the smaller box one allows us to resolve halos down to low masses, about $5 \times 10^9 M_\odot/h$. We note that in the following analysis the results for halos with mass below $10^{12} M_\odot$ are from the simulation with small box size (65 Mpc/$h$), and for massive halos we use the results from the 200 Mpc/$h$ simulation.

From the simulation output we first identify dark matter halos using the standard friend-of-friend (FOF) algorithm, and each FOF halo should contain at least 20 particles. Then, subhalos in each FOF halo are found using the SUBFIND algorithm (Springel et al. 2001) and their merger trees are also constructed. For details the readers can refer to Kang et al. (2005). We trace each subhalo back to the time when it was last identified as an independent FOF halo (labeled as $h$). In a very short time period (the next snapshot) the small halo $h$ will merge with a larger halo (host halo, labeled as $H$). By means of positions and velocities of the halos $h$ and $H$, we can obtain the time and position when halo $h$ crosses the virial radius of halo $H$ for the first time. Note that in the following, when we refer to the subhalo distribution at accretion, we are actually referring to either the distribution of the halo $h$ with respect to the host halo $H$, or with the large scale around the halo $H$ at the time when halo $h$ crosses the virial radius of $H$ for the first time.

For each FOF halo its virial mass is the mass enclosed within the virial radius inside which the mean density is $\Delta_c(z)$ times the critical density of the universe (Bryan & Norman 1998). To measure the shape of each halo, we follow the traditional method to calculate the normalized inertia tensor defined as (Bailin & Steinmetz 2005)

$$I_{ij} = \sum_n \frac{x_{i,n} x_{j,n}}{R_n^2},$$

where $x_{i,n}$ is the distance component of particle $n$ to the halo center, and the summation is over all particles inside the virial radius. The three eigenvectors of $I_{ij}$ define the orientation of the three axes of a halo, and the direction of the largest eigenvalue defines the major axis. Note that the minimum number of particles in each host halo $H$ is taken as 500, so the halo shape is more accurately determined (Jing & Suto 2002). We also tested the halo shapes (the three eigenvectors) using all particles of the FOF halo, and found that they agree quite well with those from those using the particles inside the virial radius.

To define the LSS environment around each halo, we follow the most used method (e.g., Aragón-Calvo et al. 2007a; Hahn et al. 2007b; Zhang et al. 2009) by calculating the Hessian matrix at the position of each halo. The Hessian matrix of the smoothed mass density field is defined as

$$H_{ij} = \frac{\partial^2 \rho_s(x)}{\partial x_i \partial x_j},$$

where $\rho_s(x)$ is the smoothed density with smoothing length $r_s$. There is a lack of systematic consensus on which smoothing length is the best to characterize the mass distribution on large scales (for partial discussions, see Hahn et al. 2007a; Forero-Romero et al. 2014). In most studies, a constant smoothing length ($\sim 0.5–2$ Mpc/$h$) is used at $z = 0$ (e.g., Hahn et al. 2007b; Zhang et al. 2009; Codis et al. 2012; Trowland et al. 2013). However, it is found that an evolving smoothing length is more physically reasonable and can better describe the evolution of the LSS environment (e.g., Hahn et al. 2007a; Libeskind et al. 2014). Following Hahn et al. (2007a), we adopt
a smoothing length roughly scaled as the virial radius of the typical mass for halo collapse at different redshifts (often written as $M_\text{vir}$). To be able to compare with other studies at $z = 0$, we adopt $r_\text{s} \sim 2/(1 + z)$ Mpc/$h$. Actually, we also found that our results are not significantly affected by using other constant smoothing lengths (1, 2, 5 Mpc/$h$) at all redshifts. We will show some comparisons in Figure 2 below.

The eigenvalues ($\lambda_1 > \lambda_2 > \lambda_3$) of the Hessian matrix define the LSS environment around a halo, and it is classified as cluster, filament, sheet, or void depending on the number of positive eigenvalues. For example, there is no positive eigenvalue for a cluster, one positive eigenvalue for a filament, and two for a sheet. This classification of halo environment well mimics the description of Zel’dovich theory (for a review, see Cautun et al. 2014). Basically, the eigenvector $e_1$ (corresponding to the largest eigenvalue $\lambda_1$) defines the fast collapse direction, and $e_3$ corresponds to the slowest collapse direction. For example, for a halo in a filament environment, $e_3$ gives the direction where the matter has not collapsed on large scales, and future mass accretion will mostly happen along $e_3$. As the matter distribution along $e_3$ has not strongly collapsed, the halo is less compressed along this direction, and this is why the halo major axis will then have a tendency to align with $e_3$, which has been shown in many studies (e.g., van Haarlem & van de Weygaert 1993).

Figure 1 illustrates the space configuration described above. The left panel shows the mass distribution around a selected host halo at $z = 1$, with virial radius denoted by the red circle. The blue circles denote the subhalos that will merge with the host halo in a short timescale. The yellow line shows the $e_3$ direction, which is seen to be well aligned with the mass distribution on large scales. The cyan line is the direction along the major axis of the host halo. The position angles of subhalos with respect to the cyan or yellow line are $\theta_\text{MA}$ and $\theta_\text{e3}$, respectively. The right panel shows the distribution of those accreted subhalos at $z = 0$; their anisotropic distribution with respect to the host major axis can also be seen in the plot.

With the above descriptions, we are able to derive the spatial distribution of subhalos with respect to the host halo and its LSS environment. The angular position of halo $h$ at the time of accretion with respect to the major axis of halo $H$ is labeled as $\theta_\text{MA}$, and the angle with respect to the slowest collapse direction ($e_3$) centered on $H$ is labeled as $\theta_\text{e3}$. For a random distribution, the expected value of $\langle |\cos(\theta)| \rangle$ is 0.5, and if $\langle |\cos(\theta)| \rangle$ is larger than 0.5, we refer to it as an alignment with the halo major axis or the LSS.

3. RESULTS

3.1. Accretion along Halo Major Axis and the LSS

Observations of galaxy distributions have found that satellite galaxies are aligned with the major axes of their host galaxies, and this alignment is dependent on the mass/color of the hosts (e.g., Yang et al. 2006). Due to the fact that the observed signal is weak compared to that from $N$-body simulations (e.g., Kang et al. 2007), satellite galaxies’ alignments can be explained if the central galaxy roughly follows the shape of the dark matter halo and the tracing becomes stronger with halo mass (e.g., Dong et al. 2014). Such an explanation implies that the observed alignment can be purely ascribed to the nonlinear evolution inside dark matter halos.

In the first part of this section we study whether such an alignment between the positions of subhalos and halo major axis (or $e_3$ of the LSS) can be seen at the time of accretion, and investigate which kind of alignment is stronger ($\theta_\text{MA}$ or $\theta_\text{e3}$). Before discussing our results, we first check how the shape of dark matter halos is correlated with the tidal field around them. In Figure 2 we plot the average angle between the major axis of
the halo and $e_3$, the slowest collapse direction of the mass on large scales. In the left panel, we show the dependence of the alignment on smoothing length at given redshift, and in the right panel we show the redshift evolution for a fixed smoothing length. Note that here the halo mass is scaled by the characteristic mass ($M_*$) of halo collapsing at different redshifts. By scaling the halo mass with $M_*$ we are actually studying the peak of the density field (with given height) with its surrounding LSS, which has a more physical meaning (Hahn et al. 2007a; Trowland et al. 2013).

Figure 2 shows that the major axis of the dark matter halo is well aligned with its LSS ($e_1$), and the alignment increases with halo mass. The left panel shows that at given redshift, the alignment is stronger for a smaller smoothing length (1 Mpc$/h$), indicating that the mass distribution on a large scale is better described by this smoothing length. The right panel shows that at a given smoothing length, the alignment is evolving with redshift, and is stronger at low redshift due to the nonlinear evolution. The universal alignment of halo major axis with the orientation of the density field ($e_1$) agrees well with the results published so far (e.g., Forero-Romero et al. 2014, and references therein). The results clearly show that when a halo collapses its internal mass will be strongly compressed along the fast collapse direction where the mass overdensity is highest, so the particles will more likely move along the least compressed direction $e_3$. Such a scenario well captures the spirit of Zel’dovich theory and is a manifestation of the correlation between halo shape (density peak) and the orientation of the density field on a large scale (Bond et al. 1996; van de Weygaert & Bertschinger 1996; Lee & Pen 2000; Porciani et al. 2002; Rossi 2013; Libeskind et al. 2014).

Now we investigate the primordial anisotropy of subhalos at the time of accretion. As found in observations, the alignment of satellites is stronger in massive host halos. For this reason, we investigate whether the primordial anisotropy is also dependent on the mass of host halos. We select host halos at $z = 0$ with a wide range of mass from $10^{10} M_\odot$ to $10^{14} M_\odot$, and trace their subhalos back to the accretion times. For each accretion event, we can get the angle between the infalling position of a subhalo (halo $h$) and the major axis of the host halo, $\cos(\theta_{MA})$, and the angle with the $e_3$ direction, $\cos(\theta_e)$. Their distributions are shown in Figure 3, and different panels are for host halos with different virial mass at $z = 0$. The black solid lines are distributions of $|\cos(\theta_{MA})|$ and red dashed lines are for $|\cos(\theta_e)|$.

Some interesting results can be seen from Figure 3. First, the infalling subhalos have a tendency to align with halo major axes, and the alignment increases with host halo mass. However, the alignment with $e_3$ is different and, more importantly, it is not universal. In massive halos (lower right panel), the alignment is even stronger than with the halo major axis, but it is anti-aligned in low-mass host halos (upper left panels), where subhalos are accreted perpendicularly to $e_3$. So, the accretion in low-mass halos is preferentially along the fast collapse direction. This has important implications in explaining why the spin of low-mass halos is aligned with the filament. We will show the results in detail in Section 3.2.

The Zel’dovich theory predicts that structure formation proceeds subsequently along the three eigenvectors of LSS, i.e., it first collapses along $e_1$ to form a sheet, and then the second collapse happens along $e_2$ to form a filament. A halo will form if the matter along the filament ($e_3$) continues to collapse. In
this scenario, the accretion of a growing halo is expected to be along the recently collapsed direction ($e_3$). Although the Zel’dovich approximation is only valid on a linear scale in Lagrangian space, it remains valid to describe the feature in the Eulerian nonlinear regime, as we see in the lower panels. Only on very small scales does the accretion depart from the predictions of the Zel’dovich theory (upper left panels). On small scales, the mass accretion is more random, and is slightly aligned with the halo major axis, implying that mass accretion is more likely determined by the local halo potential. The departure of anisotropic accretion from the Zel’dovich prediction has been realized for a long time (e.g., Icke 1973; Silk & White 1978; Eisenstein & Loeb 1996). Bond & Myers (1996) provided a comprehensive description of the nonlinear anisotropic collapse of ellipsoids, which matches the simulation results better than the Zel’dovich theory.

Our results about subhalo accretion with $e_3$ marginally agree with the recent results of Libeskind et al. (2014) and Shi et al. (2015), who have also studied the accretion of subhalos with respect to the LSS. Libeskind et al. (2014) found that subhalos are predominantly accreted along the $e_3$ direction, and this effect increases with both the subhalo and host halo masses. As we will see in the next section, they obtained a positive alignment because their bins of host halo mass are wider, and thus the anti-alignment from low-mass halos is immersed in the positive alignment signal from high-mass halos. Shi et al. (2015) use a method similar to ours to define the LSS, and they also found that subhalos are accreted along the $e_3$ direction. However, their analysis is only for massive halos ($>10^{12} M_\odot$), where their results are consistent with ours. It is not clear what are the results for subhalo accretion in the low-mass halos in Shi et al. (2015).

In Figure 4 we compare the current alignment of subhalos (using subhalos’ positions and the host halo major axes at $z=0$) with that at infall. The black solid lines are the same as in Figure 3, and the red dashed ones show the current alignment in different host halos. It is seen that the $z=0$ alignment is stronger in massive halos, which is consistent with what the data suggest. In general, the current alignment of subhalos with their hosts is larger than the alignment at the time of accretion. A stronger evolution is more obvious in halos with mass around $10^{12} M_\odot$. However, observed galaxies often live in halos with mass larger than $10^{12} M_\odot$ (Yang et al. 2006), and the observed alignment of galaxies is much weaker, even compared with the primordial alignment (black solid lines). So, it is still difficult to quantify how much of the observed

![Figure 3. Alignment of subhalos with the halo major axis and the $e_3$ direction of the LSS at their time of infall (see text for details). Different panels are for the final host halos at $z=0$ with different mass. The alignment with the halo shape (black solid lines) is universal and increases with halo mass. The alignment with $e_3$ (red dashed lines) is stronger in massive halos, but it is reversed for low-mass halos, where it is perpendicular to $e_3$.](image-url)
In Figure 3 the distribution of accretion angle is a pure number counting, and not weighted by the mass of subhalos. In Figure 5 we plot the cumulative fraction of mass accreted along the $e_3$ direction (left panel) and along the major axes of halos (right panel). Note that in our analysis the minimum halo mass counts only 20 particles, so we neglect the smooth mass.

In Figure 4 the current alignment of subhalos with the halo major axis at $z = 0$ (red dashed lines), and the alignment at accretion (black solid lines). It is found that the current alignment with the halo major axis is higher than that in the past, indicating a nonlinear evolution effect that is more obvious in intermediate halo masses.

Figure 4. Current alignment of subhalos with the halo major axis at $z = 0$ (red dashed lines), and the alignment at accretion (black solid lines). It is found that the current alignment with the halo major axis is higher than that in the past, indicating a nonlinear evolution effect that is more obvious in intermediate halo masses.

Figure 5. Cumulative fraction of accreted mass in subhalos with a given alignment angle. The left panel is for alignment with $e_3$ and the right panel is for alignment with halo major axis. A higher fraction of mass is accreted along $e_3$ in massive halos, and it becomes almost isotropic in low-mass halos.
accretion and consider only the resolved mass in subhalos. It is seen that in massive halos (>10^{14} M_\odot), the net mass accretion is along the major axis of the host or along e_3, and the latter is slightly stronger. For example, more than 50% of the resolved mass is accreted with \theta < 30^\circ. For low-mass host halos, the mass accretion is close to being isotropic.

3.2. Dependence on Accretion Mass and Redshift

Above we have shown the overall accretion of subhalos along the halo major axis and e_3 of the LSS. However, in that analysis we fix the mass of host halos at z = 0 and study the accretion of their progenitors at high redshift. We do that to understand the primordial alignment of accreted subhalos and to compare with their current alignment in the z = 0 hosts. In this case, the main progenitors and the accreted subhalo mass are all evolved with redshift. In this part, we do not fix the z = 0 host, but study the alignment for fixed host halo mass at different redshifts. In this way, we can quantify the mass dependence and compare with the recent study by Libeskind et al. (2014).

In Figure 6 we show the alignment along the host halo major axis (left panel) and the e_3 direction (right panel). The left panel shows that the alignment with halo major axis increases with host halo mass, and it is stronger for halos at high redshift. Note that here we do not scale the halo mass by the characteristic mass of halo collapsing (M_\ast), as we did in Figure 2. So for given halo mass, the density contrast is higher at high redshift. Note that for massive halos the alignment from the simulation of the 200 Mpc/h box is systematically lower than that from the small box simulation, and this is due to some low-mass subhalos that have not been resolved in the large-box simulation. Basically, our results agree with previous studies (e.g., Benson 2005; Wang et al. 2005; Shi et al. 2015), which state that the alignment with the halo major axis is stronger for massive halos. It is also seen that the alignment is universal, i.e., that subhalos are always accreted along the major axis, although it is close to being isotropic for low-mass halos.

The results in the right panel are more interesting. First, the accretion with e_3 of the LSS is stronger than the alignment with the halo major axis shown in the left panel, and it also increases with host halo mass and redshift. Moreover, such dependences on halo mass and accretion time are much stronger than the alignment with the halo major axis. Second, it is seen that the alignment with e_3 is not universal. For low-mass halos, the accretion is actually perpendicular to e_3, and the transitional mass of the alignment is around 3 \times 10^{10} M_\odot/h at z = 0, and it decreases to 5 \times 10^9 M_\odot/h at z = 2.

Libeskind et al. (2014) also studied the alignment of subhalos with the e_3 axis of the LSS around host halos. However, their approaches are different from ours. First, they use the velocity shear to define the LSS, whereas we use the density field (see Forero-Romero et al. 2014 for discussion and comparison between the classifications of the LSS based on density and on velocity field). Second, the alignment of subhalos in their analysis is measured when subhalos cross a few virial radii (∼ 4–16 R_\vir) of the host halo. Although the approaches are quite different, we get similar dependences on host halo mass and redshift compared with their results. The main difference is that they found that the accretion is always along e_3, while we find that for very low-mass halos, the accretion of subhalos is perpendicular to e_3. Regardless of the different approaches, there are two possible additional reasons for the difference with our results. First, in Libeskind et al. (2014) they combine the signal for host halo mass normalized by the characteristic mass, M_\ast, of halo collapse. At z = 0, M_\ast is about ∼3 \times 10^{12} M_\odot. They found that for all halos with m < 0.1 M_\ast the accretion is along e_3. For a rough comparison, if we also combine the accretion signal for halos with M_\host < 0.1 M_\ast at z = 0, we also find that the alignment is along e_3. Second, the smoothing length in Libeskind et al. is not constant for all halos, but is related to the virial radius of each halo. As we see in Figure 2, using a small smoothing length produces a stronger alignment between the halo major axis and the orientation of the surrounding density field, and thus it is expected that the alignment with the LSS is close to the alignment with the halo major axis and is more universal.

4. CONCLUSION AND DISCUSSION

In this paper, we use N-body simulations to study the anisotropy of subhalo accretion with respect to the halo shape...
decreases with increasing redshift. We have obtained these main results:

1. The major axis of the dark matter halo is well aligned with the least compressed direction, $e_3$, of the LSS around the halo, in agreement with the expectation from the Zel’dovich theory.

2. Subhalos are accreted along the major axis of the host halo, and the alignment increases with host halo mass and redshift (being stronger at high redshift). Most importantly, this alignment is universal (positive) across all halo masses.

3. The accretion of subhalos along $e_3$ is not universal. In massive host halos, the accretion is aligned with $e_3$, while in low-mass host halos, the accretion of subhalos is perpendicular to $e_3$. The transitional mass for this flip is lower at high redshifts.

Our results show that there is a primordial anisotropy of subhalos at accretion, and the degree of alignment is stronger than the observed alignment of satellites galaxies at $z = 0$. Thus, it is still difficult to conclude how much of the observed signal of galaxies is from the primordial alignment or from the evolution effect inside dark matter halos. In any case, a misalignment between central galaxies and host halos is needed in order to explain the observed degree of alignment between satellites and the shape of central galaxies (e.g., Dong et al. 2014).

Our result about the accretion along the $e_3$ direction has important implications for the correlation between the halo spin and the LSS. Previous studies using $N$-body simulations (e.g., Zhang et al. 2015 and references therein) have reached convergent conclusions that the relation between halo spin and the LSS is not universal. The spin of massive halos is parallel to $e_3$, while the spin of low-mass halos is perpendicular to $e_3$. The characteristic mass for the flip of this correlation decreases with increasing redshift (e.g., Trowland et al. 2013). Some studies (Codis et al. 2012, 2015; Aragón-Calvo & Yang 2014; Welker et al. 2014) pointed out that this is due to the disparity in the merger history of halos with different mass. They speculated that for massive halos, their subhalos are accreted along the filament, and for low-mass halos, their subhalos are accreted perpendicular to the filament. Under the assumption that the orbital angular momentum of accreted subhalos is transferred into the host halo spin, it is natural to expect a non-universality of the halo spin with filaments. However, such a speculation for the disparity in mass accretion is not clearly shown in their analysis. Our results, for the first time, show that the accretion along $e_3$ is really not universal, and the redshift dependence also agrees with the results from simulations.

In deriving the above non-universality of the alignment between subhalo accretion angle and the orientation of the LSS ($e_3$), we use a constant smoothing length for all halos (although it evolves with reshift). Most previous results (see Forero-Romero et al. 2014 for references) used a constant smoothing length (ranging between 0.5 and 2 Mpc, well covered by our choice of smoothing length), and most of them (if not all) reached agreement on the non-universality of the halo spin--LSS correlation. This implies that by using a constant smoothing length for all halo masses, the non-universality of the accretion angle of subhalos must be in place so as to explain the simulation results. Our results do support this implication.

Nevertheless, our choice of smoothing length means that we are actually looking at the mass accretion pattern on a fixed scale at given redshift. Aragón-Calvo et al. (2007b) used a multi-scale morphology filter on the density field, and they also found that the halo spin--LSS correlation has a mass dependence. This implies that the anisotropic accretion of subhalos could depend on both mass and redshift, and it calls for a more complete study on subhalo accretion using different smoothing lengths.

In addition to the subhalo accretion anisotropy, to further understand in detail the correlation between halo spin and LSS, one needs to study the formation history of the halo spin in different environments of the LSS, in order to identify which kind of mergers contribute to the final correlation. Such an analysis should make use of the velocity and spin information from $N$-body simulations. Also, one has to understand why the correlation between subhalo accretion and $e_3$ of LSS is different for high- and low-mass halos. We will investigate these issues in a future paper.

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