The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
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The beaming of subhalo accretion

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Abstract. We examine the infall pattern of subhaloes onto hosts in the context of the large-scale structure. We find that the infall pattern is essentially driven by the shear tensor of the ambient velocity field. Dark matter subhaloes are preferentially accreted along the principal axis of the shear tensor which corresponds to the direction of weakest collapse. We examine the dependence of this preferential infall on subhalo mass, host halo mass and redshift. Although strongest for the most massive hosts and the most massive subhaloes at high redshift, the preferential infall of subhaloes is effectively universal in the sense that its always aligned with the axis of weakest collapse of the velocity shear tensor. It is the same shear tensor that dictates the structure of the cosmic web and hence the shear field emerges as the key factor that governs the local anisotropic pattern of structure formation. Since the small (sub-Mpc) scale is strongly correlated with the mid-range ($\sim$ 10 Mpc) scale - a scale accessible by current surveys of peculiar velocities - it follows that findings presented here open a new window into the relation between the observed large scale structure unveiled by current surveys of peculiar velocities and the preferential infall direction of the Local Group. This may shed light on the unexpected alignments of dwarf galaxies seen in the Local Group.

1. Introduction

Zeldovich (1970) first introduced the concept of anisotropy in to the way we think about structure formation in cosmology. Numerical N-body simulations have been, arguably, the main driving force of research on structure formation (e.g. Springel *et al.* 2006, among others). Even a causal visual inspection of cosmological simulations reveals the anisotropic nature of the growth of structure, and evokes the "pancake" theory of Zeldovich and his school of thoght (Zeldovich *et al.* 1982; Doroshkevich *et al.* 1980). The analytical approach to galaxy formation, namely the cooling and fragmentation of gas in dark matter (DM) halos, relies even more heavily on the top-hat model and hence the assumption of spherical spherical symmetry was integrated into the fabric of the theory of galaxy formation (Rees & Ostriker 1977; White & Rees 1978). These studies envisaged galaxy formation proceeding from the heating of gas accreted onto DM halos to virial temperatures and subsequently cooling and fragmenting to form stars.

The notion of the cosmic web provides a very tempting framework for describing the anisotropic mass assembly of halos and galaxies. Subhaloes shape the the halo they inhabit (Faltenbacher *et al.* 2008; Hoffmann *et al.* 2014) and a number of studies have shown how the orientation of galactic spin is tied to large scale structure. Libeskind *et al.* (2013) found that halo spin aligns itself with the cosmic vortical field, while a number of related studies found weaker alignments with the "cosmic web". These numerical approaches have been complimented by a number of recent observational studies that have found similar trends in redshift surveys (e.g. Tempel *et al.* 2013).

In this work the LSS is defined using the eigenvectors of the velocity-shear field. Such a definition is "democratic" in the sense that each point in space has an equally well-defined

LSS irrespective of other environmental factors such as density. Using this definition we show that the accretion of subhaloes onto host haloes is universally reflective of the shear field.

2. Method

In order to examine the anisotropy of the angular infall pattern of subhaloes crossing the virial sphere of their host haloes, we use a DM-only N-body simulation of 1024^3 particles in a $64h^{-1}$ Mpc box. Such a simulation achieves a mass resolution of $1.89 \times 10^7 h^{-1}\mathrm{M}_\odot$ per particle and a spatial softening length of 1 h^{-1}kpc. A standard WMAP5 (Komatsu *et al.* 2009) ΛCDM cosmology is assumed: $\Omega_\Lambda = 0.72,\ \Omega_\mathrm{m} = 0.28,\ \sigma_8 = 0.817$ and $H_0 = 70$km/s/Mpc. The publicly available GADGET2 code is used and 190 snapshots (equally spaced in expansion factor) are stored from $z = 20$ to $z = 0$.

The velocity shear field is defined by the symmetric tensor: $\Sigma_{ij} = -\frac{1}{2H(z)}\left(\frac{\partial v_i}{\partial r_j} + \frac{\partial v_j}{\partial r_i}\right)$ where $i, j = x, y, z$. The $H(z)$ normalization is used to make the tensor dimensionless and the minus sign is introduced to make positive eigenvalues correspond to a converging flow. As dictated by convention, the eigenvalues are sorted in increasing order $(\lambda_1 > \lambda_2 > \lambda_3)$, and the associated eigenvectors are termed $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$.

In order to compute the shear tensor at each point in the simulation, the velocity field is gridded according to a Clouds-In-Cell (CIC) scheme. This is then smoothed with a gaussian kernel in Fourier space. The size of the CIC used here is 256^3, chosen such that every mesh cell contains at least one particle at $z = 0$ .The width of the gaussian smoothing we apply is adaptive and depends on the mass of the halo we wish to examine (see below).

Following Knollman *et al.* (2008) host halo mass is scaled by $M_\star(z)$, the mass of a typically collapsing object at a given redshift, namely $\widetilde{M} = M_\mathrm{halo}/M_\star$. $M_\star(z)$ is defined by requiring that the variance σ^2, of the linear over-density field within a sphere of radius $R(z) = (3M_\star(z)/4\pi\rho_\mathrm{crit})^{1/3}$, should equal to δ_c^2, the square of the critical density threshold for spherical collapse. $M_\star(z)$ is calculated using the cosmological parameters adopted here: at the present epoch $M_\star = 3.6 \times 10^{12} h^{-1} M_\odot$. At $z = 5$, $M_\star(z = 5) \approx 10^8 h^{-1} M_\odot$.

3. Results

The eigenvectors of the shear tensor, evaluated at the position of each host halo, provides the principal orthonormal vectors within which the anisotropy of mass aggregation onto halos can be naturally examined. Because the eigenvectors are orthonormal, they define an "eigen-frame". Each halo has its own eigen-frame, defined by the ambient shear field. Given that the eigenvectors are non directional lines, this corresponds to a single octant of the 3D cartesian coordinate system. The location of where subhaloes cross the halo virial radius ("entry points") is plotted in this eigen-frame. We stack the accretion events onto all host haloes at all redshifts. Fig. 1 shows the entry points in an Aitoff projection for all accretion events. Fig. 2 shows the entry points in an Aitoff projection for "major mergers" where the mass ratio of the accretion event is greater than 1:10.

In each of these figures we show the entry points in the eigenframe defined by the shear computed with three different smoothings that correspond to 4 (upper left), 8 (upper right) and 16 (bottom) virial radii. Host haloes are divided into four mass bins according to $\widetilde{M}$. Starting at "noon" and going clockwise, these are where $\widetilde{M} < 0.1$; $0.1 < \widetilde{M} < 1$; $1 < \widetilde{M} < 10$; and $10 < \widetilde{M}$. In order to quantify the statistical significance

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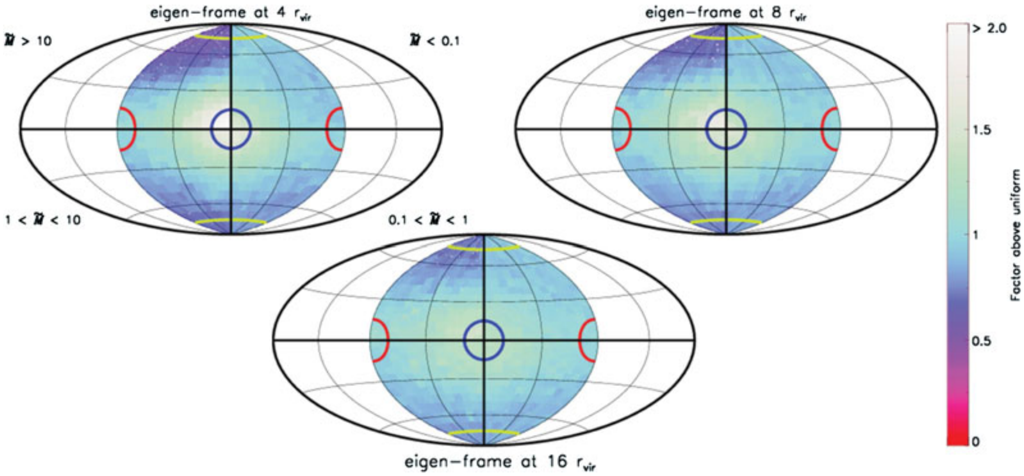

Figure 1. The location of subhalo entry points is shown in an Aitoff projection of the virial sphere. The density of subhalo entry points is shown for eigen-frames smoothed on 4 (upper left), 8 (upper right) and 16 (bottom) virial radii. Starting from "noon" and going clockwise, we show these entry points for accretion events occurring on to host haloes in four different mass ranges $\widetilde{M} < 0.1; 0.1 < \widetilde{M} < 1; 1 < \widetilde{M} < 10$ and $\widetilde{M} > 10$ and at all redshifts below z $\sim$ 5. $\widetilde{M}$ is a measure of the halo mass in units of the mass of a collapsing object at each redshift. The density of entry points is normalized to that expected from a uniform distribution, and contoured accordingly. The "north" and "south" pole correspond to $\mathbf{e}_1$; the two mid points on the horizontal axis at $\pm180°$ to correspond to $\mathbf{e}_2$, while the midpoint corresponds to $\mathbf{e}_1$. The yellow, red and blue circles define areas within 15 degrees of the eigen-frame axes, $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$, respectively.

The distribution of entry points is never consistent with uniform. Instead it universally (irrespective of host halo mass, scale on which the shear is computed or redshift) peaks close to $\mathbf{e}_3$: on large scales the shear tensor dictates the shape of cosmic web and on small scales it determines the infall pattern of satellites

of any anisotropy in the angular entry-point distribution, we divide the number of entry points in a given area on the virial sphere by that expected from a uniform distribution. The variance due to Poisson statistics of a uniform distribution of the same number of points, is small.

There is a strong tendency for the accretion to occur along $\mathbf{e}_3$. Regardless of the host halo mass, the merger ratio or the smoothing used, there is a statistically significant tendency for subhaloes to be accreted closer to $\mathbf{e}_3$ than to either other of the eigenvectors. Recall that $\mathbf{e}_3$ corresponds to the direction of slowest collapse. This is the main result of this paper: *subhaloes are preferentially accreted along the direction that corresponds to slowest collapse.* Note that this effect is greatest for the most massive host haloes and becomes progressively weaker as halo mass decreases. Also, as the gaussian smoothing kernel is increased the effect also weakens. This is expected: large smoothing kernels effectively homogenize the LSS, randomizing the principal direction of the shear tensor. Finally the tendency to be accreted along $\mathbf{e}_3$ is largest for "massive" subhaloes that are greater than 10% of their hosts. In the "best" case, where the smoothing is confined to $4r_{\rm vir}$, where only the most massive host haloes and the greatest merger events are considered, the mergers are more than 4 times as likely to come along $\mathbf{e}_3$, than expected from a uniform distribution.

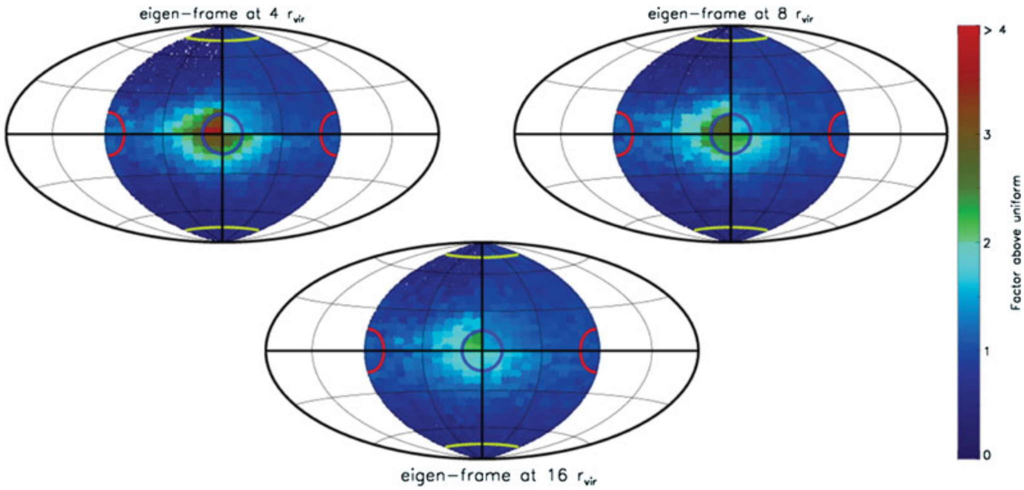

Figure 2. Same as Fig. 1 but only considering subhaloes whose mass is greater than 10% of their host.

By stacking our results in the manner shown, we have explicitly omitted any dependence of subhalo accretion on redshift or absolute halo mass. Below we examine how the funneling of accretion events changes with redshift and host halo mass.

In Fig. 3 we show the probability distribution of the cosine of the angle formed between the subhalo entry point ($\mathbf{r}_{\rm acc}$) and the eigenvectors of the shear $\mathbf{e}_1$ (black), $\mathbf{e}_2$ (green) and $\mathbf{e}_3$ (magenta), namely $\cos\theta = \mathbf{r}_{\rm acc} \cdot\ \mathbf{e}_i$, where $i = 1, 2, 3$. In what follows only this angle is considered. The probability distributions in Fig. 3 are valid for all redshifts but are split by mass (first column: $\widetilde{M} < 0.1$; second column: $0.1 < \widetilde{M} < 1$; third column: $1 < \widetilde{M} < 10$ and fourth column $\widetilde{M} > 10$). Additionally the eigenvectors are computed on three scales corresponding to smoothing of 4 (top), 8 (middle) and 16 (bottom row) times the halo's virial radius. Uniform distributions would be represented by a solid flat line at unity.

4. Summary and Discussion

It has long been realized that DM halos grow in an anisotropic fashion. This has often been claimed to be related to the cosmic web which constitutes the scaffolding for the building of halos and the galaxies within them. The accretion of matter onto halos generally proceeds in two modes: the accretion of clumps and the smooth accretion of diffuse material. In this paper, we have focused on the mergers of small halos with massive ones and analyzed their anisotropic infall pattern with respect to the eigen-frame of each individual host halo. The eigen-frame is defined by the three eigenvectors of the velocity shear tensor evaluated at the position of each halo. Our main finding is that, across a range of halo masses and redshifts, the infall direction of subhaloes is preferentially confined to the plane orthogonal to $\mathbf{e}_1$ (the direction of fastest collapse), within which it is aligned with $\mathbf{e}_3$ (the axis of slowest collapse).

Some of the main characteristics of the infall of subhalos onto more massive halos are listed here:

• Subhaloes tend to be accreted onto hosts from a specific direction with respect to the large scale structure.

• In the case of filaments, the $\mathbf{e}_3$ direction coincides with the "spine" of the filament (Tempel *et al.* 2014). Hence, the well known phenomenon of halos being fed by substructures funneled by filaments is recovered here.

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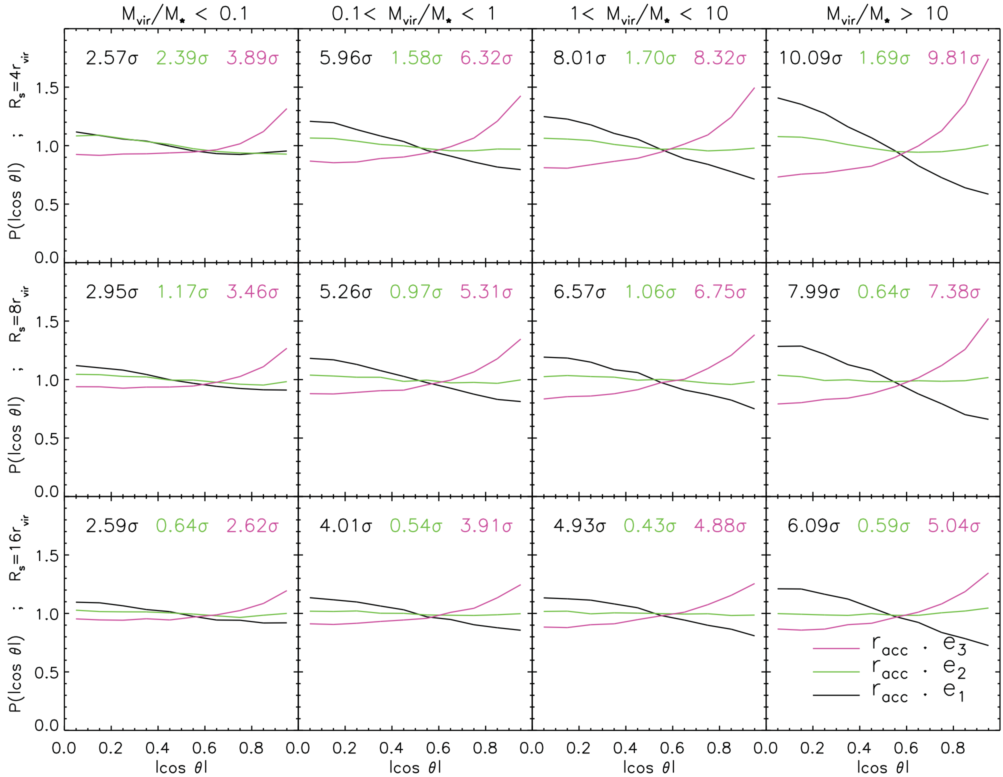

Figure 3. The anisotropic accretion shown in Fig. 1 is quantified by means of a probability distribution, $P(|\cos\theta|)$ of the cosine of the angle made between a subhalo's entry point ($\mathbf{r}_{\rm acc}$) and the eigenvectors $\mathbf{e}_1$ (black), $\mathbf{e}_2$ (green) and $\mathbf{e}_3$ (magenta). The top, middle and bottom rows show the probability distribution when the shear has been smoothed on 4, 8 and $16r_{\rm vir}$. The probability distributions are split according to value of $\widetilde{M}$, denoted on top of each column. The statistical significance of each probability distribution is characterized by the average offset between it and a random distribution in units of the Poisson error and is indicated by the corresponding colored number in each panel. Distributions that are consistent with random have values $< 1\sigma$.

• The strength of the beaming effect depends somewhat on the length scale used to compute the velocity-shear eigenframe: the smaller the scale, the stronger the beaming.

• More massive subhaloes are more anisotropically accreted onto host haloes than smaller subhaloes.

• Similarly, more massive host haloes accrete subhaloes more anisotropically than smaller ones.

• Accretion at high redshift is more anisotropic than accretion at low redshift, for all masses of hosts and subhaloes.

A somewhat naive reasoning might suggest that halos should be nourished along $\mathbf{e}_1$, the axis of the fastest collapse. However, this reasoning is flawed: halos grows by accreting material from their surrounding, and this occurs most rapidly in the direction of $\mathbf{e}_1$. It follows that at the time a given halo is inspected, the mere existence of that halo implies that much of the surrounding material has already been consumed by the halo along $\mathbf{e}_1$. This leaves the material along $\mathbf{e}_3$ as the main supply of fresh material that feeds the halo.

The beaming of subhalo accretion onto halos in a given bin of $\widetilde{M}$ (namely $M_{\rm vir}$ scaled by the redshift dependent $M_\star(z)$), narrows with increasing redshift (Fig. 4). In a scale-free universe, i.e. an Einstein-de Sitter cosmology with a power law power spectrum, the angular dependence of the accretion is expected to be completely epoch independent. This does not hold for the ΛCDM cosmology assumed here. As the universe evolves it becomes more dominated by the Λ term and consequently the role of gravity (via subhalo dynamics) diminishes with time. This is manifested in the accretion and merger rate: accretion onto halos decreases and the funneling of matter along $\mathbf{e}_3$ gets weaker.

Arguably, the most important ramification of this paper is that anisotropic nature of the mass growth of halos is dictated by the velocity shear tensor and not by cosmic web (Hoffman *et al.* 2012). That is to say, the anisotropic nature of subhalo accretion *does not* depend on the magnitude of the shear tensor's eigenvalues, nor does it depend on the "web environment". The beaming of subhaloes along $\mathbf{e}_3$ occurs equally in knots, filaments, sheets and voids. Rather, the shear tensor is the one that characterizes, shapes and dictates the directions of the cosmic web. This provides further support to earlier claims regarding the dominance of the shear tensor in shaping the large scale structure (Libeskind *et al.* 2012, 2013)

Libeskind, Hoffman & Gottlöber (2014) have recently shown that the principal directions of the shear tensor remain coherent over a wide range of redshifts and spatial scales. This opens interesting possibilities for relating the observed large scale velocity field with the properties of halos, and hence of galaxies and groups of galaxies. The work presented here, combined with observations of the local velocity field, will allow us to thus identify the direction along which most accretion onto the Local Group occurred. Such findings can have important implications on the peculiar geometric set up of dwarf galaxies in the local group.

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