The distribution of satellite galaxies: the great pancake

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ABSTRACT
The 11 known satellite galaxies within 250 kpc of the Milky Way lie close to a great circle on the sky. We use high-resolution N-body simulations of galactic dark matter haloes to test if this remarkable property can be understood within the context of the cold dark matter (CDM) cosmology. We construct halo merger trees from the simulations and use a semi-analytic model to follow the formation of satellite galaxies. We find that in all six of our simulations, the 11 brightest satellites are indeed distributed along thin, disc-like structures analogous to that traced by the satellites of the Milky Way. This is in sharp contrast to the overall distributions of dark matter in the halo and of subhaloes within it, which, although triaxial, are not highly aspherical.

We find that the spatial distribution of satellites is significantly different from that of the most massive subhaloes but is similar to that of the subset of subhaloes that had the most massive progenitors at earlier times. The elongated disc-like structure delineated by the satellites has its long axis aligned with the major axis of the dark matter halo. We interpret our results as reflecting the preferential infall of satellites along the spines of a few filaments of the cosmic web.

Key words: cosmology: theory – dark matter – galaxies: haloes.

1 INTRODUCTION
In the cold dark matter (CDM) cosmology, structure builds up through fragments merging together in a roughly hierarchical way. High-resolution N-body simulations of the formation of dark matter haloes in the ΛCDM cosmology have demonstrated that the cores of tightly bound fragments often survive the merging process and remain as distinct substructures orbiting inside a parent halo (Klypin et al. 1999; Moore et al. 1999). The centre of the main halo and the accompanying substructures are naturally identified with the formation sites of central and satellite galaxies, respectively. The N-body simulations suggest that the mass functions of surviving substructures in galactic and cluster haloes are roughly self-similar. Yet, the luminosity function of galaxies in rich clusters has a very different shape from the luminosity function of satellites in smaller systems such as the Milky Way or the Local Group (Kauffmann et al. 1999; Moore et al. 1999).

The discrepancy between the small number of satellites around the Milky Way and the large number of surviving substructures, once regarded as a major challenge to the CDM cosmology, is now thought to be due to the astrophysical processes that regulate the cooling of gas in haloes and its subsequent transformation into stars. The increase in the entropy of the intergalactic medium brought about by the reionization of the gas at early times has been identified as a possible solution to the so-called ‘satellite problem’ (Kauffmann et al. 1993; Benson et al. 2002a; Bullock 2002; see also Stoehr et al. 2002). Reionization sharply reduces the efficiency of gas cooling in small haloes so that galaxies that formed prior to reionization are preferentially those that end up as satellites in systems like the Local Group. The detailed model calculated by Benson et al. (2002a), which includes the effects of early reionization as well as other forms of feedback, reproduces many observed properties of the satellite system of the Local Group, including the distribution function of circular velocity, the luminosity function and the colour distribution.

While the original satellite problem is no longer deemed a serious challenge, another related potential problem for the cosmological paradigm has recently been highlighted by Kroupa, Thies & Boily (2005). These authors argue that the strongly flattened spatial distribution of the 11 brightest dwarf satellites of the Milky Way, a feature known, but not understood, for many years (Kunkel & Demers 1976; Lynden-Bell 1976; Kunkel & Demers 1977; Lynden-Bell 1982; Majewski 1994), is inconsistent with the ΛCDM model. According
to Kroupa et al. (2005), CDM models predict a roughly isotropic distribution of satellites. They based this conclusion on the assumption that the spatial distribution of satellites resembles the spatial distribution of the halo dark matter, which indeed, as N-body simulations have demonstrated, is approximately (although not exactly) spherical (e.g. Frenk et al. 1988; Bullock 2002; Jing & Suto 2002).

In this paper, we demonstrate that the satellites of systems like the Local Group do not trace the distribution of halo mass. On the contrary, the satellites in our suite of high-resolution N-body simulations are generally arranged in highly flattened configurations that have similar properties to those of the Milky Way satellite system. This, at first sight surprising, result is a reflection of the anisotropic accretion of subhaloes, which generally stream into the main halo along the filaments of the cosmic web. The flattened structure in which the brightest Milky Way satellites lie traces a great circle on the sky and is approximately perpendicular to the Galactic plane (throughout this paper we use the terms ‘brightest’ and ‘most luminous’ satellite galaxies; strictly speaking these satellites were selected according to the mass of the stellar component). In our simulations, the satellite structures tend to be aligned with the major axis of the triaxial halo mass distribution, i.e. the longest axis of the halo is close to lying in the principal plane of the satellite distribution.

As this paper was nearing completion, two related papers appeared on http://xxx.lanl.gov/astro-ph. Both of them used high-resolution simulations of galaxy haloes similar to those that we have performed. Kang et al. (2005) identified ‘satellites’ in their four simulations with randomly chosen dark matter particles taken either from the halo as a whole or exclusively from substructures. They were able to find flattened satellite systems similar to that of the Milky Way in the former case but not in the latter. Zentner et al. (2005) found satellites in three N-body simulations of Milky Way type systems also in two different ways. In the first, they used the semi-analytic model of Kravtsov, Gnedin & Klypin (2004), which is based on similar principles as those applied by Benson et al. (2002a). In their second model, they identified satellites with the most massive subhaloes. Zentner et al. (2005) found that in both cases, the satellite systems had a planar distribution similar to that in the Milky Way and argued that the degree of central concentration of the satellite systems plays an important role in this result. They also showed that the population of subhaloes as a whole is anisotropic and preferentially aligned with the major axis of the triaxial halo.

Like Zentner et al. (2005), our study employs a semi-analytic model to follow the formation of the visible satellites. In this respect, both these studies are quite different from that of Kang et al. (2005) who based their conclusions purely on dark matter particles. Our model differs from that of Zentner et al. (2005) in several important respects. Our simulation codes and methods for identifying substructure are different. While they considered three haloes specifically chosen to lie on a filament, we used six simulations randomly chosen from a large cosmological volume. However, the biggest difference concerns the semi-analytic models used in the two studies. While both of them give a reasonable match to several observed properties of the satellites of the Milky Way, our semi-analytic model has been applied and tested much more extensively than that of Kravtsov et al. (2004). The model we use is based on the GALFORM code of Cole et al. (2000) as extended by Benson et al. (2002b). This model has been shown to give an acceptable account of many properties of the galaxy population as a whole, including the luminosity function in various passbands, from the UV to the far-infrared, and in various environments, distributions of colour, size and morphological type, etc. The model is also relatively successful at matching the properties of galaxies at high redshift, as discussed in Baugh et al. (2004). Finally, the two studies use somewhat different methods to quantify the distribution of Milky Way satellites and to compare the results with the observations. On the whole, the conclusions of the two studies are consistent although there remain some differences, as we discuss in Section 4.

The remainder of this paper is organized as follows: in Section 2, we outline the methods used; in Section 3.1, we present our results, which we interpret in Section 3.2; in Section 4, we discuss the implications of our findings.

### 2 SIMULATIONS AND GALAXY FORMATION MODEL

We have analysed six high-resolution N-body simulations of galactic-size dark matter haloes carried out with the GADGET code (Springel, Yoshida & White 2001a). The haloes, chosen to have a mass $\sim 10^{13} M_\odot$, were otherwise randomly selected from a large cosmological simulation of a cubic region of side 35.325 $h^{-1}$ Mpc in a flat ΛCDM universe (with $\Omega_m = 0.3, h = 0.7, \sigma_8 = 0.9$). The simulation was executed a second time adding ‘high-resolution’ (i.e. small mass) particles and appropriate small-scale power in the initial conditions, to a region surrounding the halo under consideration. These simulations have been studied extensively in previous papers (Power et al. 2003; Hayashi et al. 2004; Navarro et al. 2004a) and we refer the reader to those papers for specific details of how the simulations were carried out. Table 1 summarizes the important parameters of the simulations.

We identified bound substructures in the simulation using the algorithm SUBFIND (Springel et al. 2001b). First, ‘friends-of-friends’ groups (Davis et al. 1985) are found by linking together particles whose separation is less than 0.2 times the mean interparticle separation, corresponding roughly to particles within the virialized region of the halo. SUBFIND then identifies substructures within these haloes based on an excursion set approach, using the spatial and velocity information for each particle in order to define self-bound objects.

For each halo, we generate a complete merger history, identifying all progenitor and descendant haloes, as described in Helly et al. (2003). The semi-analytic galaxy formation model is calculated along each branch of the merger tree. This is based on the

### Table 1. Parameters for the six N-body halo simulations. For each halo (column 1): (2) shows the total number of particles in the simulation box; (3) the number of high-resolution particles in the simulation; (4) the virial radius of the halo in $h^{-1}$ kpc defined as the distance from the centre at which the mean interior density is 178$\rho_{crit}$; and (5) the number of particles inside the virial radius. In all cases, the simulation cube has a comoving length of 35.325 $h^{-1}$ Mpc and the mass of the high-resolution particles is $2.64 \times 10^9 h^{-1} M_\odot$.

|   | $N_{\text{tot}}$ (10$^6$) | $N_{\text{hr}}$ (10$^6$) | $R_{\text{vir}}$ ($h^{-1}$ kpc) | $N_{\text{vir}}$ (10$^6$) |
|---|-----------------|-----------------|-----------------|-----------------|
| gh1 | 14.6            | 12.9            | 110             | 1.07            |
| gh2 | 18.1            | 16.2            | 131             | 1.74            |
| gh3 | 18.0            | 16.2            | 170             | 3.73            |
| gh6 | 25.5            | 22.2            | 169             | 3.76            |
| gh7 | 19.2            | 17.3            | 156             | 2.99            |
| gh10 | 13.4            | 12.1            | 133             | 1.86            |
model described in detail in Cole et al. (2000) and Benson et al. (2002b). The model includes the following physical processes:

(i) the shock heating and virialization of gas within the gravitational potential well of each halo;
(ii) radiative cooling of gas onto a galactic disc;
(iii) the formation of stars from the cooled gas;
(iv) the effects of photoionization on the thermal state and cooling properties of the intergalactic medium;
(v) reheating and expulsion of cooled gas through feedback processes associated with stellar winds and supernovae explosions (see Benson et al. 2003b);
(vi) the evolution of the stellar populations;
(vii) the effects of dust absorption and radiation;
(viii) the chemical evolution of the stars and gas;
(ix) galaxy mergers (which, depending on the violence of the merger, may be accompanied by starbursts and the formation of a bulge: see Baugh et al. 2004); and
(x) the evolution of the size of the disc and bulge.

Our model differs from that of Cole et al. (2000) and Helly et al. (2003) in the way in which galaxy mergers are treated. In the current model, the positions of satellite galaxies and the time when they merge is determined by using information from SUBFIND. Central galaxies are placed on the most bound particle of the most massive subgroup in the halo. (SUBFIND identifies the background mass distribution of the halo as a separate subgroup, so this is generally a robust way to define the centre of the halo.) Satellite galaxies are placed on the descendant subhalo of the progenitor halo in which they formed. If the subhalo ceases to be identified by SUBFIND at some later output time, we continue to trace its constituent particles and place the galaxy at the centre of mass of this group of particles. A galaxy is considered to have merged on to the central galaxy if its distance from the central galaxy is less than the spatial extent of the set of particles it is associated with.

An overview of the results of our semi-analytic model as regards the evolution of the galaxy population as a whole may be found in Benson et al. (2003a) and Baugh et al. (2004), while results relevant to the satellites of the Milky Way may be found in Benson et al. (2002a).

3 RESULTS

We begin by quantifying the shapes of dark matter haloes in the simulations and subsystems within them. We then interpret the results in terms of the formation histories of the haloes and their subsystems.

3.1 The morphology of haloes and their subsystems

The semi-analytic model applied to the N-body simulations provides the position and internal properties of the central galaxy in each halo and its satellites. According to the semi-analytic model, three of the central galaxies are spirals and three are ellipticals. For the purpose of comparing with the analysis of Kroupa et al. (2005), we select the 11 most luminous satellites in each halo within a distance of 250 kpc from the central galaxy. We calculate the moment of inertia tensor of this satellite subsample, weighting each object equally, and obtain the principal axes of the distributions.

Fig. 1 shows three orthogonal projections along the principal axes of the satellite systems in our six simulations. Remarkably, the figure reveals that the loci of the 11 brightest satellites define a thin, disc-like structure around the central galaxy. As we show below, in most cases, the satellite structure is aligned with the major axis of its triaxial host dark matter halo.

The distribution of the luminous satellites differs significantly from the distribution of the dark matter substructures identified by SUBFIND. Fig. 2 is analogous to Fig. 1 but the points plotted now correspond to the most massive 1000 substructures found within 250 kpc of the central galaxy. The projections are along the principal axes of the inertia tensor of the substructure systems. It is evident that the distribution of substructures is much less anisotropic than that of the satellites in Fig. 1.

The eigenvalues of the diagonalized inertia tensor are proportional to the rms deviation of the $x$, $y$ and $z$ coordinates relative to
the principal axes. Denoting the major, intermediate and minor axes by $a$, $b$ and $c$ respectively ($a > b > c$), the flattening of the system may be quantified by the ratios $c/a$ and $b/a$. The early $N$-body simulations of Frenk et al. (1988) showed that CDM haloes are triaxial, and recent work indicates that $c/a = 0.7 \pm 0.17$ and $b/a > 0.7$ (Bullock 2002).

The axial ratios, found by diagonalizing the moment of inertia tensor, of the dark matter haloes and various subsystems of objects within them are plotted Fig. 3. Fig. 3(a) shows that our simulated haloes have axial ratios consistent with those found in previous simulations and tend to congregate near the top right of the panel corresponding to nearly spherical objects. This is also the region populated by the systems composed of the 1000 most massive subhaloes.

The axial ratios of the systems consisting of the 11 most luminous satellites are plotted in Fig. 3(b). The triangles correspond to our full semi-analytic model (shown in Fig. 1) and the squares to a variant in which the early reionization of the intergalactic medium is not included. The satellite systems in the two models have similar flattening because more than 80 per cent of the subhaloes that host the brightest satellites in the two cases are the same. However, as discussed by Benson et al. (2002a), neglecting the effects of reionization leads to an overprediction of the number of faint galaxies, including satellites in the Milky Way. Whether reionization is included or not, the satellites in our simulations cluster around the location of the Milky Way data marked by a cross in Fig. 3. This is the main result of our analysis: the flattening of the satellite system in our simulations is in excellent agreement with that of the Milky Way satellite system.

It is clear from Figs 3(a) and (b) that the brightest satellites inhabit a biased subset of subhaloes. To explore the origin of this bias, we select two subsets of subhaloes: the 11 most massive subhaloes at $z = 0$ and the 11 subhaloes that had the most massive progenitors prior to being incorporated within the virial radius of the main halo. The flattening of these two systems is compared in Fig. 3(c). The figure shows that the crucial factor in establishing a highly flattened system is not the final mass of the subhalo but the mass of the largest progenitor. It is the latter that correlates well with the final stellar mass or luminosity of the visible satellite, as shown in Fig. 4(a). Here, we plot the stellar mass of each satellite galaxy against the mass of its largest progenitor. This strong correlation is a result of the GALFORM model readily making the most luminous galaxies in the most massive progenitor haloes. In contrast, Fig. 4(b) shows there is no correlation between the stellar mass of each satellite and the mass of its host substructure. This is due to the subhaloes having been subjected to various amounts of tidal stripping.

Comparison of Figs 3(b) and (c) indicates that the flattening of the systems consisting of the 11 most luminous satellites and the 11 subhaloes that had the most massive progenitors are very similar. This is an important result because it demonstrates that our main conclusion regarding the compatibility of the Kroupa et al. (2005) data with the CDM cosmology does not depend on the details of our semi-analytic modelling of galaxy formation. So long as the brightest satellites form in those subhaloes with the most massive progenitors, our conclusions stand.

With only 11 satellites in our main samples, the possibility that estimates of the inertia moments might be unduly affected by the
presence of outliers is a concern. We investigate the sensitivity of our results to outliers by scaling all radial positions to a common value while keeping the angles of each radius vector fixed. The axial ratios of the rescaled data are compared to the original axial ratios of the 11 ‘reionization’ satellites in Fig. 3(d). Rescaling the satellite radial distances scatters the axial ratios somewhat but does not, on average, lower the overall flattening of the systems. As shown in the figure, rescaling the Milky Way data in the same way also has a small effect on the axial ratios.

Another concern is that the small number of satellites may introduce a bias in the axial ratio estimates. Indeed, our procedure would consistently give $c/a = 0$ for samples of three satellites (as they would lie on a plane), so it is important to check that the axial ratios of satellites shown in Fig. 3 are not driven by the size of the sample. We have compared the satellites with samples of the same size (11 objects) drawn from either the dark matter haloes or the 1000 subhalo sample. The dark matter particles were drawn at random from a smooth, triaxial Navarro, Frenk & White (NFW) distribution (Navarro, Frenk & White 1996, 1997) with axial ratios set equal to the mean of that of our dark matter haloes: $b/a = 0.86$, $c/a = 0.74$. The distribution of $c/a$ ratios thus obtained is fairly broad and biased; indeed, the average $c/a$ of 6000 random trials is $\sim 0.44$ with a dispersion of $\sim 0.12$. Similarly, for the parent sample of 1000 subhaloes we find that random samples of 11 objects give, for a total of 6000 trials (1000 per halo), a combined average $c/a$ of $\sim 0.41$, with similar dispersion, $\sim 0.12$.

Despite the sizeable dispersion, a Kolmogorov–Smirnoff (KS) test shows that the likelihood of obtaining the values of $c/a$ for the satellite systems shown in Fig. 3(b) by chance is quite small. This is shown in Table 2, where we list the probability that the $c/a$ axial ratio for the various samples of satellites shown in Fig. 3 is consistent with the shape of the distribution of dark matter or of the 1000 subhalo population. The probabilities are very low for our satellite galaxies sample (regardless of whether or not reionization is included), as well as for subhaloes with the most massive progenitors. On the other hand, samples of the 11 most massive subhaloes are seen to be fully consistent with either the dark matter or the 1000 subhalo sample as a whole.

Finally, we consider the connection between the highly anisotropic distribution of satellites and the orientation of their host dark matter halo. Consider the vector pointing along the major axis of the distribution (i.e. along $a_{\rm{DM}}$). Let $\theta$ denote the angle between this vector and a vector pointing along the major axis of the halo, $a_{\rm{DM}}$. For our six simulations, we find that $\cos(\theta) = 0.768, 0.979, 0.702, 0.747, 0.387$ and 0.942 for galaxy haloes gh1, gh2, gh3, gh6, gh7 and gh10, respectively. Thus, apart from gh7, there is a strong alignment between the major axis of the disc-like satellite systems and the major axis of the parent dark matter halo. In the Milky Way, the major axis of the satellite disc-like structure is perpendicular to the galactic disc. Thus, if our galaxy resides in a dark matter halo similar to those that we have simulated, then the disc must be aligned such that its normal vector points in the direction of the halo major axis.

### 3.2 Interpretation

The highly anisotropic distribution of satellite galaxies in Milky Way type systems is a somewhat surprising outcome of galaxy formation in a CDM universe. This is particularly so in view of the fact that the population of subhaloes as a whole is much less anisotropic and has axial ratios similar to those of the halo dark matter. The key to understanding the origin of the anisotropic satellite distribution lies in the connection between haloes and the cosmic web and, in particular, in the way in which satellites are accreted into the main halo. Fig. 5 illustrates the anisotropic nature of satellite accretion. The dots show a random 1 per cent of the dark matter particles that end up in the main halo at the final time. The circles mark the locations of the most massive progenitors of the 11 most luminous satellites at the final time. Rather than originating isotropically, those haloes destined to become bright visible satellites are accreted primarily along one or two of the cosmic web filaments.

This figure illustrates the highly anisotropic collapse typical of CDM structures on galactic scales. Careful inspection of the time evolution of the system shows that the collapse occurs first along 2D sheet-like structures, which subsequently wrap up into filamentary streams of dark matter (Navarro, Abadi & Steinmetz 2004b). By $z \sim 4.2$, these filamentary ‘highways’ along which protosatellite galaxies form are well established. The filaments are generally thicker than the locus of the largest protogalactic haloes, which tend to concentrate towards the central, densest parts of the filament in a near-1D configuration. As the most massive halo progenitors collapse to form the main galaxy, this alignment is largely preserved. Smaller haloes are more widely scattered across the thick filaments, reflecting their weaker clustering strength (Cole & Kaiser 1989;
Figure 5. The formation of a galactic halo and its satellites. The points show a random 1 per cent of the dark matter particles that end up in the main halo and the circles show the positions of the 11 most luminous satellites that end up within 250 kpc of the main galaxy by the present day. The scale of each plot is indicated by the line, which has a comoving length of 400 kpc. The initial collapse produces a 2D structure: a large pancake of dark matter.

Mo, Mao & White 1999). In addition, they are often accreted over a longer period and from a larger range of directions. Their distribution, now lacking a preferred orientation, ends up being much less anisotropic than that of the most massive haloes. Whether reionization is included or not, satellite galaxies in the semi-analytic model form preferentially in the subhaloes with the most massive progenitors and thus inherit their highly flattened configuration.

4 DISCUSSION AND CONCLUSIONS

We have shown that the, at first sight surprising, flattened distribution of satellites in the Milky Way is the natural outcome of the anisotropic accretion of matter along a small number of filaments, characteristic of halo formation in the CDM cosmology. Kroupa et al. (2005) reached the opposite conclusion, that the observed satellite distribution is incompatible with the CDM model, because they neglected the fact that the satellites do not trace the distribution of halo dark matter but form instead in the most massive haloes (prior to accretion) whose spatial distribution is biased.

Our results are not directly comparable to those of Kang et al. (2005) who also attempted to interpret the flattened distribution of Milky Way satellites with the aid of high-resolution $N$-body simulations. Kang et al. (2005) assumed that the satellites follow the dark matter distribution in the halo and did not consider the formation sites of satellites in detail. Zentner et al. (2005), on the other hand, implemented a semi-analytic model similar to ours in $N$-body simulations also similar to ours and those of Kang et al. (2005).

Our results are broadly consistent with those of Zentner et al. (2005). Unlike them, we did not choose haloes specifically lying along filaments but selected them at random from a large cosmological simulation. In the event, three of our haloes would, according to our semi-analytic model, host spiral galaxies and the other three elliptical galaxies. One difference between the two studies is that Zentner et al. (2005) found an acceptable match to the Milky Way satellite distribution both in their semi-analytic model and in a model in which the satellites are identified with the most massive subhaloes at the final time. We have shown that the distribution of the latter is not as flattened as the distribution of Milky Way satellites. The crucial factor is not the final mass of the halo, which is affected by tidal stripping, but the mass of the largest progenitor before it is accreted into the main halo. Indeed, if the satellites are identified with the haloes that had the largest progenitors, then their flattened distribution is very similar to that of the satellites identified by our semi-analytic model. Thus, our conclusions are independent of the details of our galaxy formation modelling.

As was also found by Knebe et al. (2004) and Zentner et al. (2005), the major axis of the flattened satellite distribution in our simulations points close to the direction of the major axis of the parent halo. This alignment reflects the preferential accretion of mass onto the halo along the dominant filament. An important consequence of this result is that, if the Milky Way resembles the systems we have simulated, then the Galactic disc should lie in the plane perpendicular to the major axis of the halo because the observed satellite system itself is perpendicular to the Galactic disc. This inference is consistent with the conclusion reached by Helmi (2004) from an analysis of the kinematics of the Sagittarius dwarf streams.

The satellite alignment that we have found in our simulations is almost certainly related to the ‘Holmberg effect’ (Holmberg 1969), the observation that the satellites of external galaxies within a projected radius of $r_p \approx 50$ kpc tend to lie preferentially in a cone along the minor axis of the galaxies, avoiding the equatorial regions. To test this observation requires a larger number of simulations than
those we have performed. Similarly, our current simulations are inadequate to test the extension of the Holmberg effect uncovered by Zaritsky et al. (1997) from a study of isolated spirals, which also revealed an excess of satellites along the minor axis of the galaxy, now out to projected distances of $r_p \sim 500$ kpc. A similar result was found by Sales & Lambas (2004) from a much larger sample of galaxies drawn from the 2-degree Field Galaxy Redshift Survey. They too found an anisotropic distribution for $r_p < 500$ kpc, but only for satellites moving with a velocity relative to their host of $\Delta v < 160$ km s$^{-1}$. In contrast, Brainerd (2005) found the opposite effect in a sample of satellites from the Sloan Digital Sky Survey, an alignment along the major axis at small radii ($r_p < 100$ kpc) and an isotropic distribution beyond.

Although our simulations are not large enough to study the distribution of satellites beyond the inner 250 kpc of the galactic centre, it seems likely that the anisotropic distribution of satellites will continue out to larger separations. We intend to study this problem in a larger set of simulations.

In summary, we have found that the flattened distribution of the Milky Way satellites, first noted by Lynden-Bell (1976) and most recently highlighted by Kroupa et al. (2005), turns out to have a simple explanation in the context of structure formation in the CDM model. It is merely a reflection of the intimate connection between galactic dark matter haloes and the cosmic web.

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