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On the Phase-Space Structure of the Milky Way Dark-Matter Halo

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Abstract. We analyse a high resolution simulation of the formation of a cluster's dark-matter halo in a Λ CDM cosmology (Springel et al. 2001). The resolution achieved allows us to map the phase-space structure in detail, and characterize its evolution and degree of lumpiness. When scaling down the cluster halo to a Milky-Way size halo, we probe the substructure expected in the solar neighbourhood. Here we specifically address the relevance of such substructure for direct detection experiments aimed at determining the nature of dark-matter.

1. Introduction

Over the last twenty years a theory has emerged for the formation of structure in the Universe (Peebles 1974; White & Rees 1978). The hierarchical paradigm has allowed astronomers to make very definite predictions on the properties of galaxies today and about their evolution from high redshift. Direct comparisons to observations have shown that this model is quite successful in reproducing both the local and distant Universe. However, it relies on a basic *assumption*: that most of the matter in the Universe is dark, in the form of some yet to be identified weakly interacting elementary particles.

Thus the crucial test of this paradigm consists in the determination of the nature of dark-matter through direct detection experiments. Among the most promising candidates from the particle physics perspective are axions and neutralinos. The idea behind most detection experiments is to determine the count rate over recoil energy above a given (detector) background level. The experimental situation has been improving rapidly over the past years, as the relevant regions of parameter space for the different dark-matter candidates are starting to be probed (Bergström 2000). In all experiments, the count rate is strongly dependent on the velocity distribution of the incident particles. In most cases, an isotropic Maxwellian distribution has been assumed (e.g. Freese, Frieman & Gould 1988), although there are other examples in the recent literature, discussing multivariate Gaussian distributions (e.g. Green 2000). Attempts at understanding the effect of substructure on the velocity distribution of dark-matter particles have also been made (e.g. Hogan 2001). However, most of these works did not assume realistic distributions of matter in the Solar neighbourhood, as we shall demonstrate in the next section.

The simulations we analyse here were generated by zooming in on, and re-simulating with higher resolution, a particular cluster and its surroundings

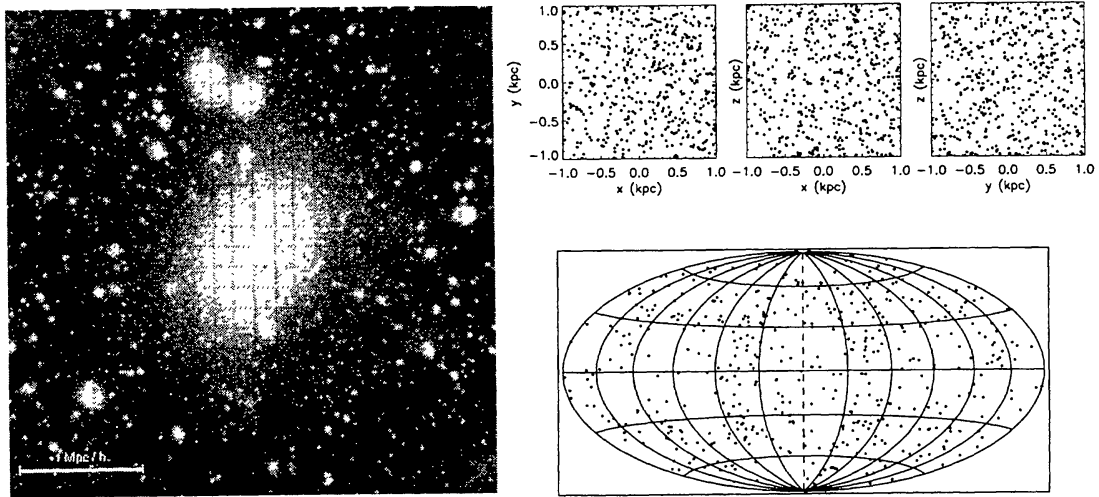


Figure 1. The left panel shows the projected mass distribution of the simulated halo out to the virial radius. The top panels on the right show the spatial distribution of particles inside a 2 kpc on a side volume located at 8 kpc from the halo centre, i.e. this volume is centered on the “Sun”. The bottom panel shows their distribution in the sky.

formed in a cosmological Λ CDM simulation, with parameters $\Omega_0 = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$ and $\sigma_8 = 0.9$. The cluster selected for resimulation is the second most massive cluster in the parent simulation and has a virial mass of $8.4 \times 10^{14} h^{-1} M_\odot$ (see the left panel of Figure 1). The highest resolution resimulation of the cluster region has 6.6×10^7 particles. We scale the cluster to a “Milky Way” halo by requiring that the maximum circular velocity is 220 km/s, which yields a scaling factor $\gamma = v_c^{cl}/v_c^{MW} \sim 9.18$.

2. The phase-space structure in the Solar neighbourhood

2.1. Spatial distribution

One of the critical issues in understanding the outcome of the various dark-matter experiments consists in understanding the expected signal: Is the distribution of particles in the vicinity of the Sun smooth or is it dominated by a just a few streams or even bound lumps (e.g. Moore et al. 2001)? In Figure 1 we plot the positions of all particles inside a cubic volume of 2 kpc on a side, located at the position of the “Sun”. The spatial distribution of particles inside this representative volume is extremely smooth. This is mostly due to the fact that the material that ends up in the inner galaxy mostly comes from a few very massive halos which have rapidly mixed.

2.2. Kinematics

In Figure 2 we show the velocities of particles located in a box of 4 kpc on a side in the vicinity of the Sun. Their velocity distribution is relatively smooth, and appears to be quite consistent with a Gaussian (see left panel Figure 3), at least to the “naked eye”. However if we focus on the highest energy particles

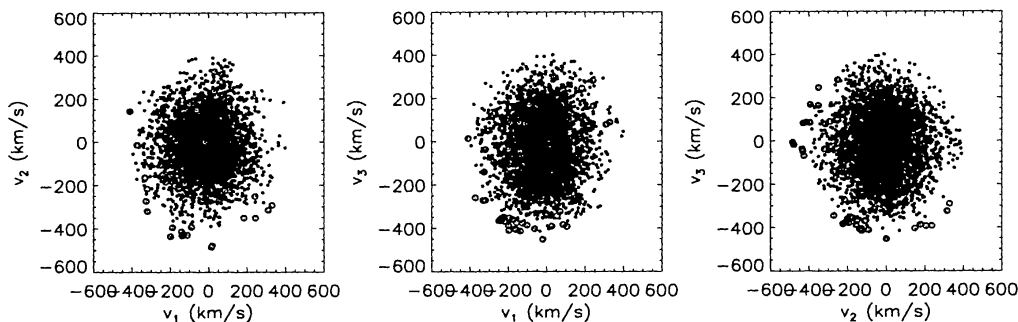


Figure 2. Velocities of particles located in a box of 4 kpc on a side at the “Solar” radius. There are 4362 particles in this volume, and highlighted are the 1% fastest. The velocity dispersions along the principal axes are (111.2, 120.1, 141.4) km/s. The lump with $v \sim (-250, -200, -400)$ km/s corresponds to a halo of $1.94 \times 10^{10} M_{\odot}$ identified at $z = 2.4$, and accreted at $z = 1$, or 8.2 Gyr ago.

this seems no longer to be the case, as shown by the particles highlighted in grey. The 1% fastest moving particles are strongly clumped, and their velocity distribution is highly anisotropic.

To quantify the substructure present in this volume we compute the correlation function ξ in velocity space, defined as $\xi = \frac{\langle DD \rangle}{\langle RR \rangle} - 1$, where $\langle DD \rangle$ is the number of pairs of particles in our simulation with velocities in a given velocity range (or bin), and $\langle RR \rangle$ is defined analogously for the same number of random points, which we draw from a trivariate Gaussian distribution determined from the data in the principal axes velocity frame, and is the average over ten such realizations. The right panel in Figure 3 shows that there is an excess of particles with similar velocities (i.e. below 100 km/s) with respect to what would be expected for a random multivariate Gaussian distribution. However, if we focus on the fastest moving particles, the excess of particles is very noticeable, particularly at small velocity differences, indicative of the presence of streams, as clearly visible in Fig. 2.

3. Conclusions

A dark-matter halo formed in a Λ CDM cosmology is not a smooth entity. Not only do dark-matter halos contain a large number of dark satellites, they also have large amounts of substructure in the form of streams. By scaling a cluster halo down to a galaxy halo simply by the ratio of their maximum circular velocities (equivalent to scaling their mass ratio to the third power), we predict that the Galactic dark-matter halo in the “Solar neighbourhood” should be smoothly distributed in space, but clumped in at least a few hundred kinematically cold streams (Helmi, White & Springel 2001). These streams have their origin in the different halos that merged to form the dark halo of the galaxy.

Our results indicate that direct detection experiments may quite safely assume a multivariate Gaussian to represent the motions of the dark-matter particles. However, experiments which are only sensitive to the highest energy (i.e.

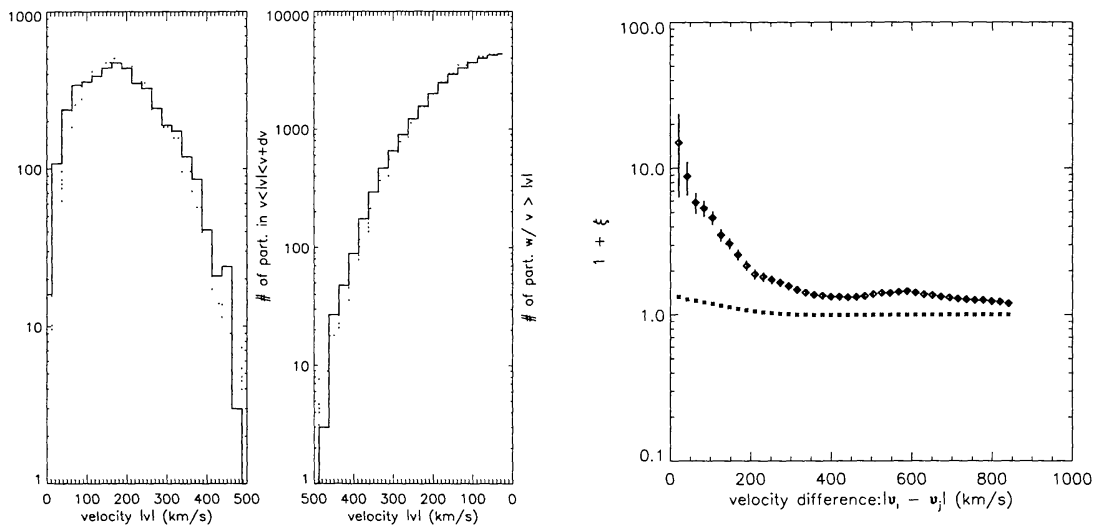


Figure 3. For the same box as in Figure 2 we plot the differential (left) and the cumulative (centre) velocity distributions. The dotted histograms correspond to a multivariate Gaussian. On the right, we plot the “correlation function” ξ as the number of neighbours with velocity differences in a given range compared to what is expected for random deviates drawn from a multivariate Gaussian. Asterisks correspond to ξ over all the particles in the box, whereas diamonds to the 1% fastest moving particles.

fastest moving) dark-matter particles will be subject to the presence of a few dominating streams, and an excess of particles with similar energies should then be expected in comparison with a smooth Gaussian distribution. If direct detection experiments are also sensitive to the direction of motion of the incident dark-matter particles, the signal expected for the fastest moving particles is also highly anisotropic, and could be eventually be used, not just to determine the nature of the dark-matter, but also to recover at least partially the merging history of our galaxy.

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