The Local Dark Matter Distribution from Hydrodynamic Simulations

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We investigate the predictions of the EAGLE and APOSTLE hydrodynamic simulations for dark matter direct detection searches. We extract the dark matter density and velocity distribution at the Solar position for a set of simulated galaxies which satisfy Milky Way observational constraints, and use them to analyze current direct detection data. We find that the local dark matter density of the Milky Way-like galaxies fall in the range of $0.41 - 0.73$ GeV/cm^3, and their dark matter velocity distributions fit well a Maxwellian distribution with peak speed in the range of $223 - 289$ km/s.

1 Introduction

The uncertainties in the dark matter (DM) distribution in our Galaxy leads to large uncertainties in the interpretation of results from direct DM experiments. Direct DM searches aim at measuring the small recoil energy of a target nucleus in the detector after the collision with a DM particle arriving from the Milky Way (MW) halo. The DM density and velocity distribution in the Solar neighborhood are key astrophysical inputs in the calculation of direct detection event rates.

In the Standard Halo Model (SHM), which is the most commonly adopted halo model in the analysis of direct detection data, the DM halo is spherical and isothermal with an isotropic Maxwell-Botzmann velocity distribution. The fiducial value of the local DM density is 0.3 GeV/cm^3, and the peak speed of the local velocity distribution is assumed to be equal to the local circular speed of 220 or 230 km/s. Since many of the assumptions of the SHM are not valid, in this work which is based on [1], we extract the local DM distribution of MW-like

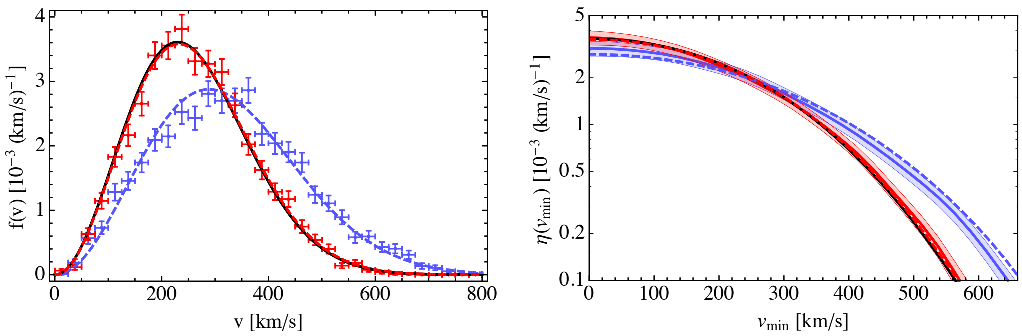

Figure 1: Left: DM speed distributions (mean and 1σ Poisson errors) in the Galactic rest frame for two MW-like haloes with speed distributions closest to (red) and farthest from (blue) the SHM Maxwellian (solid black line). Right: Time averaged halo integrals as a function of $v_{\rm min}$ for the same two galaxies shown in the left panel, obtained from the mean velocity distributions (solid colour lines) and the velocity distributions at $\pm 1\sigma$ from the mean (shaded bands). In the left and right panels, the best fit Maxwellian speed distributions and their corresponding halo integrals are shown by dashed lines with matching colours for each galaxy, respectively.

galaxies from the EAGLE [2, 3] and APOSTLE [4, 5] high resolution hydrodynamic simulations which include both DM and baryons, and study their implications for DM direct detection. From the full set of galaxies in the simulations, we select 14 MW-like galaxies using a set of criteria based on the observed MW kinematical data.

2 Dark matter density and velocity distribution

The event rate in direct detection experiments depends on the local DM density, ρ_χ, and the DM velocity distribution in the detector rest frame, $f_{\rm det}(\mathbf{v}, t)$. For the case of spin-independent elastic scattering, the differential event rate can be written as,

$$\frac{dR}{dE_R} = \frac{\rho_\chi A^2 \sigma_{\rm SI}}{2 m_\chi \mu_{\chi p}^2} F^2(E_R)\, \eta(v_{\rm min}, t),$$

where E_R is the recoil energy of the nucleus with mass number A after the scattering with a DM particle with mass m_χ, $\sigma_{\rm SI}$ is the spin-independent DM-nucleon scattering cross section, $\mu_{\chi p}$ is the reduced mass of the DM–nucleon system, and $F(E_R)$ is a form factor. The minimum speed required for the DM particle to deposit a recoil energy E_R in the detector is $v_{\rm min} = \sqrt{m_A E_R/(2\mu_{\chi A}^2)}$, where m_A is the nucleus mass, and $\mu_{\chi A}$ is the reduced mass of the DM and nucleus. $\eta(v_{\rm min}, t)$ is the *halo integral*, which together with ρ_χ contain the astrophysics dependence of the recoil rate,

$$\eta(v_{\rm min}, t) \equiv \int_{v > v_{\rm mim}} d^3v\, \frac{f_{\rm det}(\mathbf{v}, t)}{v}\,.$$

To determine the DM density and velocity distribution of the simulated MW-like galaxies at the Solar position, we consider a torus aligned with the stellar disc, with a galactocentric

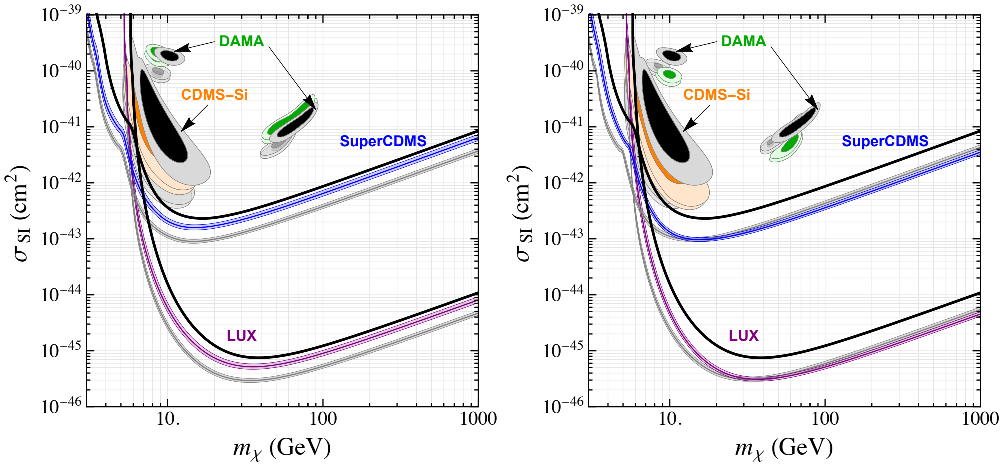

Figure 2: The DAMA (at 90% CL and 3σ) and CDMS-Si (at 68% and 90% CL) preferred regions, and the LUX and SuperCDMS (at 90% CL) exclusion limits in the $m_\chi - \sigma_{\rm SI}$ plane for two MW-like galaxies with smallest (shown in colour) and largest (shown in gray) local DM density (left panel), and two galaxies with speed distributions closest to (shown in colour) and farthest from (shown in gray) the SHM Maxwellian (right panel). For each galaxy, the shaded exclusion band and the two adjacent allowed regions of the same colour are obtained from the upper and lower 1σ limits of the halo integral. The black exclusion limits and allowed regions correspond to the SHM Maxwellian.

radius in the range of $7 - 9$ kpc, and a height of $|z| < 1$ kpc with respect to the galactic plane. For the 14 simulated MW-like galaxies, we find the average DM density in the torus is in the range of $0.41 - 0.73$ GeV/cm^3.

The local DM speed distribution in the Galactic rest frame is shown in the left panel of Fig. 1 for two MW-like galaxies with speed distributions closest to and farthest from the SHM Maxwellian (with a peak speed of 230 km/s). We fit a Maxwellian speed distribution with a free peak speed (shown in dashed) to the DM speed distributions of the simulated galaxies, and find the best fit peak speed in the range of $223 - 289$ km/s. The right panel of Fig. 1 shows the time-averaged halo integrals for the same MW-like galaxies shown in the left panel. The halo integrals obtained from the best fit Maxwellian speed distributions fall within the 1σ uncertainty band of the halo integrals of the simulated MW-like galaxies.

3 Implications for dark matter direct detection

To perform an analysis of direct detection data, we use the local DM density and velocity distribution of our selected MW-like galaxies. We investigate how the exclusion limits set by the LUX [6] and SuperCDMS [7] experiments, and the preferred regions set by the DAMA [8] and CDMS-Si [9] experiments vary in the DM mass and spin-independent cross section plane. The left panel of Fig. 2 shows the exclusion limits and allowed regions for the four direct detection experiments obtained using the DM distribution of two MW-like galaxies with the smallest and largest local DM density. To show the effect of the velocity distribution on the preferred regions and exclusion limits, in the right panel of Fig. 2, we show the results for the two haloes with velocity distribution closest to and farthest from the SHM Maxwellian. The shaded exclusion bands and the two adjacent preferred regions of the same colour are obtained from the upper and lower 1σ uncertainty limits of the halo integral. The exclusion limits and allowed regions shown in black are obtained assuming a local DM density of 0.3 GeV/cm^3, and the SHM Maxwellian velocity distribution with peak speed of 230 km/s.

As can be seen from Fig. 2, the largest shift in the exclusion limits and preferred regions for the simulated MW-like galaxies compared to the SHM is due to the variation of the local DM densities of the simulated MW-like galaxies. The effect of the velocity distribution is only important at lower DM masses, where the experiments probe larger $v_{\rm min}$ values, and are therefore sensitive to the high velocity tail of the DM velocity distribution.

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