The local dark matter distribution from hydrodynamic simulations


DOI
10.3204/DESY-PROC-2009-03/Bozorgnia_Nassim

Publication date
2017

Document Version
Final published version

Published in
Proceedings of the 12th Patras Workshop on Axions, WIMPs and WISPs, PATRAS 2016

License
CC BY

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
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-Boltzmann 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
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, \( \rho_\chi \), and the DM velocity distribution in the detector rest frame, \( f_{\text{det}}(v, t) \). For the case of spin-independent elastic scattering, the differential event rate can be written as,

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

where \( E_R \) is the recoil energy of the nucleus with mass number \( A \) after the scattering with a DM particle with mass \( m_\chi \), \( \sigma_{\text{SI}} \) 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 \( v_{\text{min}} = \sqrt{m_A E_R/(2 \mu_{\chi A}^2)} \), where \( m_A \) is the nucleus mass, and \( \mu_{\chi A} \) is the reduced mass of the DM and nucleus. \( \eta(v_{\text{min}}, t) \) is the halo integral, which together with \( \rho_\chi \) contain the astrophysics dependence of the recoil rate,

\[
\eta(v_{\text{min}}, t) \equiv \int_{v > v_{\text{min}}} d^3v \frac{f_{\text{det}}(v, t)}{v}.
\]

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...
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 $1\sigma$ 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 Patras 2016
one page of the document contains the following content:

**The Local Dark Matter Distribution from Hydrodynamic Simulations**

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/cm³, 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 \( v_{\text{min}} \) values, and are therefore sensitive to the high velocity tail of the DM velocity distribution.

### 4 Acknowledgments

N.B. acknowledges support from the European Research Council through the ERC starting grant WIMPs Kairos. This work was supported by the Science and Technology Facilities Council (grant number ST/F001166/1); Interuniversity Attraction Poles Programme initiated by the Belgian Science Policy Office (AP P7/08 CHARM). This work used the DiRAC Data Centric system at Durham University, operated by the Institute for Computational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). This equipment was funded by BIS National E-infrastructure capital grant ST/K00042X/1, STFC capital grant ST/H008519/1, and STFC DiRAC Operations grant ST/K003267/1 and Durham University. DiRAC is part of the National E-Infrastructure. We acknowledge PRACE for awarding us access to the Curie machine based in France at TGCC, CEA, Bruyères-le-Châtel.

### References


