PROCEEDINGS OF SCIENCE

Implications of non-galactic dark matter for sub-GeV direct detection searches

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A fraction of the dark matter in the solar neighborhood might be composed of non-galactic particles with speeds larger than the escape velocity of the Milky Way. The non-galactic dark matter flux would enhance the sensitivity of direct detection experiments, due to the larger momentum transfer to the target. In this contribution, we first summarize our current knowledge of the dark matter distribution outside the Milky Way, we then review the modelling of the non-galactic dark matter flux at the Solar System, and we finally assess its impact on sub-GeV direct detection experiments searching for both nuclear and electron recoils.

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1. Introduction: Dark matter in the local universe

Astronomical data suggests the existence of diffuse dark matter components homogeneously distributed between clusters and superclusters of galaxies, aside from the localized galactic dark matter halos, [1]. Estimations of the mean matter density using all-sky catalogs within the local universe are systematically lower than the cosmological value measured by Planck. In the region within 11 Mpc from us, where the Virgo Supercluster and the Local Group are embedded, the matter density is estimated to be Ω_m=0.17 [2], while the cosmological measurement is significantly larger Ω_m=0.315 [3]. This difference could be explained if a fraction of the dark matter is dispersed outside the virial regions of galaxy groups and clusters [4]. These diffuse components, such as cosmic filaments and walls, are predicted in cosmological large scale simulations [5] and can be searched with weak gravitational lensing [6].

The question that we aim to answer in [7] is whether the diffuse dark matter components of the Local Group and the Virgo Supercluster could have a sizable impact on direct detection experiments searching for light dark matter. Similar analyses have been performed focusing on nuclear recoils induced by dark matter particles with masses in the GeV scale, [8][9][10][11]. Here, we concentrate instead on sub-GeV dark matter particles, for which modifications in the high velocity tail of their distributions are expected to cause a larger impact in direct detection experiments, both for nuclear and electron recoils. In what follows, we briefly describe our modelling of the non-galactic dark matter flux at the Solar System and present upper limits on the dark matter nucleon/electron cross section when considering both the galactic and the non-galactic dark matter components.

2. The non-galactic dark matter flux at the Solar System

The penetration of the dark matter particles from the Local Group envelope in the Milky Way was modelled in [8]. Using semianalytical methods and kinematical parameters of the system Milky Way-M31 from [12], the authors find that the non-galactic particles amount to $\sim$ 12% of the total local density of dark matter in the solar neighbourhood, with velocities close to the escape velocity of the Milky Way ($v_{\rm LG} \sim 600$ km/s) and a very narrow and isotropic velocity distribution, effectively assembling the form of a dark matter stream. Therefore, the contribution from the Local Group to the dark matter flux at the location of the Solar System can be written as:

$$\mathscr{F}_{\rm LG}(\vec{v}) = \frac{\rho_{\rm LG}^{\rm loc}}{m_{\rm DM}} v \delta^3(\vec{v} - \vec{v}_{\rm LG}), \tag{1}$$

where $\rho_{\rm LG} = 0.037$ GeV/cm^3. The Virgo Supercluster dark matter particles could also contribute to the dark matter flux in the Solar System. Measurements estimate the average density of the diffuse component to be close to the cosmological average value ($\sim 10^{-6}$ GeV/cm^3) [4]. However, the gravitational focusing due to the Local Group can enhance the value of the density at the Solar Sytem to $\rho_{\rm VS} = 10^{-5}$ GeV/cm^3. Regarding the velocity of the Virgo Supercluster dark matter particles, our current knowledge is very limited. We assume that they have a velocity dispersion comparable to that of the observable members of the supercluster, which yields speeds of $v_{\rm VS} \sim 1000$ km/s.

The contribution from the Virgo Supercluster to the dark matter flux at the location of the Solar System can then be written as:

$$\mathscr{F}_{\rm VS}(\vec{v}) = \frac{\rho_{\rm VS}^{\rm loc}}{m_{\rm DM}} v \delta^3(\vec{v} - \vec{v}_{\rm VS}). \tag{2}$$

Consequently, we model the total dark matter flux at the position of the Solar System as the normalized sum of three contributions:

$$\mathscr{F}(\vec{v}) = \mathscr{F}_{\rm SHM}(\vec{v}) + \mathscr{F}_{\rm LG}(\vec{v}) + \mathscr{F}_{\rm VS}(\vec{v}), \tag{3}$$

where $\mathscr{F}_{\rm SHM}(\vec{v})$ is the galactic dark matter flux given by the Standard Halo Model (SHM), but where we take the local density of the galactic particles to be (88%) of the total local density, for which we adopt the usual value $\rho^{loc} = 0.3$ GeV.

3. Results: Upper limits on the dark matter nucleon/electron cross section

In this section, we present upper limits on the dark matter nucleon/electron cross section from various experiments, when considering the total dark matter flux at the Solar System. We refer to [7] for details on the calculation of the scattering rates and the derivation of upper limits. Here, we concentrate on the implications of our results for sub-GeV focused direct detection searches.

We show in Figure 1 the upper limits on the dark matter-nucleon spin independent (left panel) or spin-dependent (right panel) scattering cross section as a function of the dark matter mass from the non-observation of dark matter induced nuclear recoils at the CRESST-III, CDMSlite [13], XENON1T and PICO60 experiments. The potential impact of the dark matter from the Local Group envelope for the search of light dark matter is apparent from the Figure. For sub-GeV dark matter, this contribution can enhance the recoil rate at the CRESST experiment by at least a factor of ~ 2. As the dark matter mass decreases, the enhancement becomes more and more important, and even allows to probe masses for which the galactic dark matter would not induce detectable recoils.

In Figure 2, we show the 90% C.L upper limits on the dark matter-electron scattering cross section at fixed momentum transfer $q = \alpha m_e$ from XENON10 and XENON100 data, including both the galactic and the non-galactic dark matter components, for a heavy mediator (left panel) and for an ultralight mediator (right panel). For $m_{\rm DM} = 50 - 1000$ MeV, dark matter from the Local Group envelope enhances the reach of the XENON100 experiment by at least one order of magnitude, compared to the expectations of the SHM. For $m_{\rm DM} = 30 - 50$ MeV, close to the kinematical threshold of the XENON100 experiment, the enhancement is even more significant. Further, the non-galactic dark matter components allow to probe the mass region $m_{\rm DM} = 13 - 30$ MeV, for which dark matter particles from the host halo do not induce detectable recoils. For the XENON10 experiment the conclusions are analogous, although in this case the enhancement is more modest. We also show in the Figure values of parameters expected from theoretical models for a heavy or an ultralight mediator, respectively. For the heavy mediator case, the thick purple band corresponds to the values that can account for the observed dark matter abundance if dark matter is a complex scalar, via freeze-out and with no initial asymmetry [14]. Fermionic dark matter reproduces the correct thermal abundance via freeze-out with an initial asymmetry for values of $\bar{\sigma}_{\rm DM-e}$ above the purple line. The region below this curve is excluded by Planck, due to energy injections from the annihilation of the symmetric dark matter component [3]. Finally, the dotted purple line represents sensitivity targets for ELDER dark matter particles [15], and points above this line correspond to SIMP dark matter models with the same hidden-photon mediator as for the freeze-out case [16][17]. For the ultralight mediator case, the purple shaded region shows the values favored by the freeze-in mechanism [14]. Clearly, the non-galactic components significantly improve the discovery potential of experiments. Furthermore, as can be seen in the Figure, considering the non-galactic components allows to test the freeze-out mechanism for a complex scalar dark matter particle with no initial asymmetry for m_{DM} in the range 8 – 50 MeV. For dark matter masses above 50 MeV the constraints of XENON1T are already broadly in tension with the freeze-out band, and the non-galactic components would help to test this region of the parameter space [18]. For a few dark matter masses below 8 MeV, constraints from the SENSEI [19] collaboration might also be in tension with the freeze-out mechanism when considering the non-galactic components.

4. Conclusions

In this contribution, we have discussed our current knowledge of the dark matter in the local universe in some detail, motivating the existence of diffuse dark matter components in groups and clusters of galaxies. Then, we have formulated a simplified model for the non-galactic dark matter flux in the solar neighbourhood, arising from the diffuse components of the Local Group and the Virgo Supercluster. Finally, we have presented upper limits in the dark matter nucleon/electron cross section from various experiments focusing on sub-GeV dark matter, when considering both the non-galactic and the galactic components. We have extended the results presented in [7], including the analysis of CDMSlite data and by confronting our upper limits with additional dark matter production mechanisms.

The implications of non-galactic dark matter for sub-GeV direct detection experiments can be summarized as:

- For nuclear recoils, the non-galactic components enhance the detection rate of dark matter particles in the mass range of 0.2 – 10 GeV by a factor of $\sim 2 - 10^3$ with respect to the SHM-only upper limit, for both spin-independent and spin-dependent interactions. Further, the dark matter mass range that experiments are able to probe is extended to lower values. Also, the non-galactic dark matter components would leave a characteristic signature in the recoil spectrum in the form of step-like features, which could be discerned from the smooth spectrum expected from recoils induced by dark matter particles from the host halo or from the irreducible neutrino background.

- For electron recoils, we find that the enhancement is appreciable over a larger range of recoil energies, and not only close to the kinematical threshold of the experiments. For interactions mediated by a heavy hidden photon or an ultralight mediator, the sensitivity of experiments is enhanced by a factor of $\sim 2 - 10^2$. When considering the non-galactic components, the reach of current experiments allows to test the freeze-out mechanism for a complex scalar and a fermionic dark matter particle, for a wide range of sub-GeV dark matter masses.

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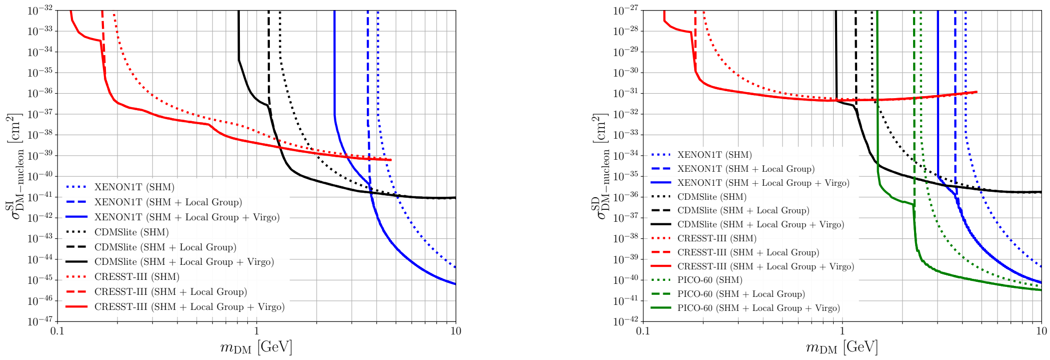

Figure 1: Upper limits at the 90%C.L. on the spin-independent (left panel) and spin-dependent(right panel) dark matter-nucleon cross-section from the null search results from the XENON1T (blue), CDMSlite (black) [13], CRESST-III (red) and PICO-60 (green) experiments, assuming equal coupling to protons and neutrons. The dotted line indicates the upper limit derived under the assumption that only galactic dark matter, described by the Standard Halo Model, contributes to the dark matter flux at the Solar System. The dashed lines show the impact of including in the flux also the non-galactic dark matter component from the Local Group and the solid lines show the impact of including also the diffuse component ofthe Virgo Supercluster.

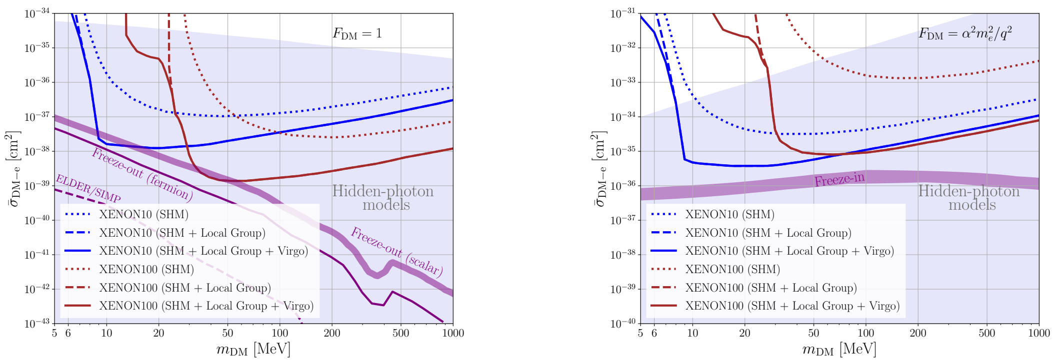

Figure 2: Upper limits at the 90% C.L. on the dark matter-electron cross-section from the null search results from the XENON10 (blue) and XENON100 (brown) experiments, assuming an interaction mediated by a heavy hidden photon (left panel) or an ultralight hidden photon (right panel). The dotted line indicates the upper limit derived under the assumption that only galactic dark matter, described by the Standard Halo Model, contributes to the dark matter flux at the Solar System. The dashed lines show the impact of including in the flux also the non-galactic dark matter component from the Local Group and the solid lines show the impact of including also the diffuse component of the Virgo Supercluster. We also show in the shaded lavender region the values of parameters expected from hidden-photon models, and in purple upper limits and regions favoured by different production mechanisms (see main text for details).

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We remark that the non-galactic phase space distribution in the Local Group envelope is still poorly known, both observationally and from zoom-in dark matter simulations, due to the presence of M31 near the Milky Way. Therefore, the limits on the cross-section derived in this work should be taken with a grain of salt. Still, we point out that our modelling of the non-galactic dark matter flux relies only on two assumptions: that the envelope mass is comparable to the masses of the Local Group member galaxies, and that the angular momentum distribution of the envelope dark matter particles resembles a Gaussian. The first assumption is favored by observations, and the second one is in agreement with N-Body simulations. We hope that future astronomical data could help to constrain these sources of uncertainties. A more refined modelling of the dark matter envelope of the Local Group and the Virgo Supercluster will lead to a more robust assessment of the impact of these two contributions in direct dark matter searches. A proper understanding of the non-galactic components to the dark matter flux may prove to be crucial for the correct interpretation of the experimental data.

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References

[1] I.D. Karachentsev, *Missing dark matter in the local universe*, *Astrophysical Bulletin* **67** (2012) 123–134.

[2] I.D. Karachentsev and K.N. Telikova, *Stellar and dark matter density in the local universe*, *Astronomische Nachrichten* **339** (2018) 615–622.

[3] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini et al., *Planck 2018 results*, *Astronomy Astrophysics* **641** (2020) A6.

[4] D. Makarov and I. Karachentsev, *Galaxy groups and clouds in the Local ($z \sim 0.01$) universe*, *Mon. Not. Roy. Astron. Soc.* **412** (2011) 2498 [1011.6277].

[5] M. Cautun, R. van de Weygaert, B.J.T. Jones and C.S. Frenk, *Evolution of the cosmic web*, *Monthly Notices of the Royal Astronomical Society* **441** (2014) 2923–2973.

[6] S. Miyazaki, M. Oguri, T. Hamana, M. Shirasaki, M. Koike, Y. Komiyama et al., *A large sample of shear-selected clusters from the hyper suprime-cam subaru strategic program s16a wide field mass maps*, *Publications of the Astronomical Society of Japan* **70** (2017) .

[7] G. Herrera and A. Ibarra, *Direct detection of non-galactic light dark matter*, *Physics Letters B* **820** (2021) 136551.

[8] A. Baushev, *Extragalactic dark matter and direct detection experiments*, *Astrophys. J.* **771** (2013) 117 [1208.0392].

[9] K. Freese, P. Gondolo and L. Stodolsky, *On the direct detection of extragalactic WIMPs*, *Phys. Rev. D* **64** (2001) 123502 [astro-ph/0106480].

[10] G. Besla, A. Peter and N. Garavito-Camargo, *The highest-speed local dark matter particles come from the large magellanic cloud*, *Journal of Cosmology and Astroparticle Physics* **2019** (2019) 013–013.

[11] P.S. Behroozi, A. Loeb and R.H. Wechsler, *Unbound particles in dark matter halos*, *Journal of Cosmology and Astroparticle Physics* **2013** (2013) 019–019.

[12] T.J. Cox and A. Loeb, *The Collision Between The Milky Way And Andromeda*, *Mon. Not. Roy. Astron. Soc.* **386** (2008) 461 [0705.1170].

[13] R. Agnese, A. Anderson, T. Aralis, T. Aramaki, I. Arnquist, W. Baker et al., *Low-mass dark matter search with cdmslite*, *Physical Review D* **97** (2018) .

[14] R. Essig, T. Volansky and T.-T. Yu, *New Constraints and Prospects for sub-GeV Dark Matter Scattering off Electrons in Xenon*, *Phys. Rev. D* **96** (2017) 043017 [1703.00910].

[15] E. Kuflik, M. Perelstein, N.R.-L. Lorier and Y.-D. Tsai, *Elastically decoupling dark matter*, *Physical Review Letters* **116** (2016) .

[16] Y. Hochberg, E. Kuflik, T. Volansky and J.G. Wacker, *Mechanism for thermal relic dark matter of strongly interacting massive particles*, *Physical Review Letters* **113** (2014) .

[17] D. Baxter, Y. Kahn and G. Krnjaic, *Electron Ionization via Dark Matter-Electron Scattering and the Migdal Effect*, *Phys. Rev. D* **101** (2020) 076014 [1908.00012].

[18] XENON collaboration, *Light Dark Matter Search with Ionization Signals in XENON1T*, *Phys. Rev. Lett.* **123** (2019) 251801 [1907.11485].

[19] L. Barak, I.M. Bloch, M. Cababie, G. Cancelo, L. Chaplinsky, F. Chierchie et al., *Sensei: Direct-detection results on sub-gev dark matter from a new skipper ccd*, *Physical Review Letters* **125** (2020) .