On the Direct Detection of Dark Matter Annihilation

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We investigate the direct detection phenomenology of a class of dark matter (DM) models in which DM does not directly interact with nuclei, but rather the products of its annihilation do. When these annihilation products are very light compared to the DM mass, the scattering in direct detection experiments is controlled by relativistic kinematics. This results in a distinctive recoil spectrum, a non-standard and or even absent annual modulation, and the ability to probe DM masses as low as a ~10 MeV. We use current LUX data to show that experimental sensitivity to thermal relic annihilation cross sections has already been reached in a class of models. Moreover, the compatibility of dark matter direct detection experiments can be compared directly in $E_{\text{min}}$ space without making assumptions about DM astrophysics. Lastly, when DM has direct couplings to nuclei, the limit from annihilation to relativistic particles in the Sun can be stronger than that of conventional non-relativistic direct detection by more than three orders of magnitude for masses in a 2-8 GeV window.

INTRODUCTION

While very little is known about Dark Matter (DM), it’s cosmological abundance is experimentally quite well-determined: $\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$ [1]. One framework for understanding the relic abundance of Dark Matter (DM) is thermal freeze-out [2]. Number-changing interactions in the early universe, $XX \leftrightarrow (\text{SM}) \text{SM}$ keep DM in thermal equilibrium with the SM bath, until the rate of these annihilation processes drops below the rate of Hubble expansion. After this point the abundance of DM is essentially fixed, with a value scaling as $\Omega_{\text{DM}} \propto 1/\langle \sigma_{\text{ann}} v_{\text{rel}} \rangle$ in the absence of a particle/antiparticle asymmetry. This scenario is attractive in that it provides a well-defined framework for the relic abundance that can be tested in a variety of ways, including direct detection [3].

In this paper we investigate a modification of this scenario in which the abundance of DM, X, is set by the annihilation process $XX \leftrightarrow YY$ with Y a state in the dark sector (or a SM neutrino) that possesses interactions with hadrons. Since Y interacts with nuclei, it can scatter and produce a detectable nuclear recoil at direct detection experiments. The resulting phenomenology at direct detection of this class of models is distinctive, owing to the fact that (1) the scattering partner of the nucleus is relativistic, rendering the kinematics of scattering completely different and (2) it is the flux of the scattering partner Y that determines the rate of events at a detector rather than X. Both of these features have novel consequences. The former fact gives traditional direct detection experiments sensitivity down to 10 MeV masses, while the latter fact yields distinctive possibilities for annual modulation.

While loop processes will always engender scattering of X on nuclei at direct detection, we will focus on DM masses less than ~GeV such that the non-relativistic scattering of X does not produce detectable nuclear recoils above a detector’s typically $O(\text{keV})$ threshold. A similar scenario has recently been investigated in [4] with a focus on the Cherenkov signals at Super-Kamiokande and IceCube. Our focus is on sub-GeV DM.

In this paper we use current LUX [6] limits to demonstrate that direct detection experiments are sensitive to thermal relic annihilation cross sections for galactic center annihilation of DM in a window of DM masses from 10 MeV to 1 GeV. Direct detection has historically been marred by multiple conflicting data sets. It is therefore of great utility to have the ability to compare experiments as directly as possible. We illustrate how current and future direct detection data can be easily analyzed for compatibility in this framework by mapping results to $E_{\text{min}}$-space.

ANNIHILATING DM IN THE GALACTIC CENTER

In the present paper we illustrate the prospects for detecting relativistic annihilation products from DM at direct detection experiments. Two possible sources are annihilation within the Galactic Center and the Sun. A key difference between these two sources is that the latter relies on a stable balance between the accretion and evaporation rates of DM interacting with nucleons inside the Sun.

For simplicity consider “2-to-2” annihilation, $XX \rightarrow YY$. Then the differential rate (per unit detector mass) at a direct detection experiment is,

$$\frac{dR}{dE_R} = \frac{\Phi_Y}{m_N} \int_{E_{\text{min}}(E_R)}^{E_{\text{max}}(E_R)} dE_Y \frac{dN}{dE_Y} \left( \frac{d\sigma_{YN}}{dE_R} \right),$$

where $\Phi_Y$ is the local flux of Y’s, $E_{\text{min}}(E_R) = \sqrt{m_N E_R/2}$ and $dN/dE_Y = 2\delta (E_Y - m_X)$.

For simplicity, we begin by adopting a contact interaction between Y and a quark $q$ of the form $\mathcal{O}_{qY} = G_Y (\bar{Y} \gamma_q Y) (\bar{q} \gamma^\mu q)$ where $G_Y$ is the effective coupling.
dark matter annihilation cross section, \(H_{\text{SM}}\rightarrow L\), relativistic DM of June 2012 thermal relic

![Graph showing limits on \(\sigma_{\text{ann}}\) vs. dark matter mass, \(m_X\).](image)

FIG. 1. : LUX Limits on \(\sigma_{\text{ann}}\), for which \(G_Y = G_F = 1.2 \times 10^{-5} \text{ GeV}^{-2}\), and a model in which DM annihilates to sterile neutrinos that interact with a baryonic \(Z'\) gauge boson with quark/dark matter couplings, \(g_q\) and \(g_X\). In the shaded gray band we vary the couplings from \(g_q = 0.02\) (monojet limit from CDF [7]) and \(g_X = 0.1\) to \(g_X = g_q = 9 \times 10^{-3}\).

By analogy with neutrino-nucleus elastic scattering the differential cross section is [10],

\[
\frac{d\sigma_{YN}}{dE_R} = \frac{G_F^2}{2\pi} A^2 m_N F^2(E_R) \left[ 1 - \left( \frac{E_{\text{min}}}{E_Y} \right)^2 \right]. \tag{2}
\]

The flux of \(Y\) particles from DM annihilation in the Galactic Center is estimated as [4], \(\Phi_Y = 1.6 \times 10^{-2} \text{ cm}^{-2} \text{ s}^{-1} \left( \frac{\sigma_{X\rightarrow Y\gamma} v_{Y\gamma} V_{Y\gamma}}{5 \times 10^{-8} \text{ cm}^3 \text{s}^{-1}} \right) \left( \frac{20 \text{ MeV}}{m_X} \right)^{1/2} \).

Given this flux, once a model of \(Y\)-nucleus interactions is adopted the only remaining parameter to determine is the annihilation cross section.\(^2\) First let us take a minimal choice by relying on the remaining SM to furnish the interactions of \(Y\) with the nucleus. This immediately singles out the neutrinos as the only SM possibility for \(Y\). The elastic, spin-independent scattering of SM neutrinos with nuclei can be computed using Eq. [2] with the replacement, \(G_Y A^2 \rightarrow G_F (N/2)^2\), where \(N\) is the number of neutrons and \(G_F\) is the Fermi constant. We see in Fig. [1] that with present LUX data, the resulting sensitivity to the annihilation cross section is quite weak, being many orders of magnitude away from thermal relic sensitivity for all DM masses.

On the other hand, DM could well annihilate to non-SM particles that have larger than electroweak-size interactions. Since we are interested in direct detection phenomenology, we focus on a model in which DM annihilates into new light states \(\nu_b\) that share interactions with nuclei. “Baryonic neutrino” models of this type have been studied before [8–11], though with a focus on their emission from the Sun.

For illustration, we will make use of a simplified model of quark-\(\nu_b\) interactions via the exchange of a light vector

\[\mathcal{L} \supset V^\mu (g_{\nu_b} g_{\gamma} q + g_X \bar{\nu}_b \gamma \nu_b)\], \tag{3}

where the couplings \(g_q\) and \(g_X\) describe the coupling of SM quarks and \(\nu_b\) to the vector \(V^\mu\). Interactions of this type arise in models of gauged baryon number [8–10] [12] [13], gauged \(U(1)_{B-L}\) [11] [14], and kinetic mixing [11], though it is only in the first case that couplings to leptons are absent. A detailed exploration of the allowed parameter space of Eq. [3] is beyond the scope of this work, but see [11] for a discussion of this. As a benchmark scenario we fix \(m_{\nu_b} = 50 \text{ MeV}\) and \(g_X = 0.1\) and \(g_q = 0.02\). The value of \(g_q\) is chosen to be just at the boundary of the monojet limits set by CDF data [12].

With this benchmark, the \(V^\mu\) mass is sufficiently heavy for the interaction to be considered contact-like at direct detection energies, with the the coupling \(G_Y = (g_X g_q)/m_{\nu_b}^2\). We see in Fig. [1] that models of this type are already being probed by direct detection and can in particular exclude thermal relics in the 10 MeV - 1 GeV window. In obtaining this limit we have ignored attenuation and stopping effects and assumed that the incident \(\nu_b\) flux is undisturbed as it travels to the underground detector [15][22]. Going beyond both the contact interaction assumption and including stopping effects are both interesting effects that we plan to return to in the future.

It is important to observe that annihilation of DM to relativistic states from the galactic center predicts no sizeable annual modulation since: (1) solar system speeds are so small compared to the speed of the annihilation products, (2) and the distance to the galactic center over the course of a year does not vary appreciably. In the case of annihilation from the Sun however, the annual modulation is known to peak in January due to the eccentricity of the Earth’s orbit. Thus solar neutrino signals in direct detection experiments predict a nearly maximally “wrong” phase with respect to the expectation from non-relativistic DM of June 2nd [23]. This expectation can be violated however when the annihilation product \(Y\) experiences flavor oscillations on \(O(\text{AU})\) length scales as in

\(^1\) Note that in [10] it was estimated that the inelastic scattering cross section is a small at low-energies compared to the elastic cross section, \(\sigma(\text{elastic})/\sigma(\text{inelastic}) \sim A^2/(E_Y^3 R_N^2)\), where \(R_N \sim (10 \text{ MeV})^{-1}\). Thus for a Xenon target nucleus, inelastic scattering is sub-dominant for \(E_Y \lesssim \text{GeV}\). Given our focus on sub-GeV DM we will ignore inelastic processes in this paper.

\(^2\) We are implicitly assuming here that \(Y\) does appreciably contribute to the DM density, but is stable enough to survive transit from the Galactic Center to the Earth. This can be accomplished with either long but finite lifetimes for \(Y\) or by arranging for the relic abundance of \(Y\) to be much less than the total DM abundance.
for example \cite{8,10} though this requires very small mass-splittings, $\Delta m^2 \sim 10^{-10}$ eV$^2$.

**DIRECT DETECTION IN $E_{\text{min}}$-SPACE**

Direct detection involves a unique combination of particle physics, nuclear physics, and astrophysics. The kinematics of scattering in the non-relativistic case are controlled by the minimum DM particle velocity, $v_{\text{min}}(E_R) = \sqrt{m_N E_R/2 \mu_{X N}^2}$, required to produce a nuclear recoil of energy $E_R$. In the absence of unknown form factors, all experimental data can be mapped into $v_{\text{min}}$-space at each DM mass and compared without specifying the nature of the astrophysical distribution or density of DM \cite{24,25}. These “halo-independent” methods have received significant attention \cite{26,41}. We generalize these methods to cover relativistic scattering as well, where the “halo-independence” here comes from the absence of specific assumptions regarding the local DM density, density profile, velocity distribution, and annihilation source.

As can be seen from Eq. (1) and the form of $E_{\text{min}}(E_R)$, the relativistic scattering case allows a comparison of data which is independent of the DM mass. Thus using Eq. (1) we can divide out the nucleus-specific quantities, $\hat{g}(E_{\text{min}}) \equiv 2\mu_n^2 (A^2 F^2(E_R))^{-1} dR/dE_R$, to immediately obtain the result in Fig. 2. Conservative limits are derived as in \cite{25} by assuming a step function form for $\hat{g}$. The form of $E_{\text{min}}(E_R)$ has the interesting effect of strongly suppressing the sensitivity of experiments employing heavy target nuclei. It is also interesting to observe that LUX \cite{6} and a relativistic DM interpretation of DAMA \cite{22} and CDMS-Si \cite{43} data are fully compatible, though essentially ruled out by the recent SuperCDMS data \cite{44}. Thus, for example an interpretation of the DAMA and/or CDMS-Si data in terms of the baryonic neutrino model of Pospelov is in strong tension with recent exclusions from SuperCDMS. Clearly, allowing for isospin-violation in order to suppress the sensitivity from Germanium-scattering would result in the positive signals seen by CDMS-Si and DAMA and the null results of LUX and SuperCDMS to be fully compatible. Allowing for some inelastic down-scattering may also ease the tension between the datasets.

One source of relativistic scattering at direct detection has already been proposed: the oscillation of solar neutrinos into new BSM states with O(AU) oscillation lengths and large interactions with nuclei \cite{8,9}. Since the model adopted in \cite{8,9} is gauged baryon number, the result of Fig. 2 is directly applicable, demonstrating that SuperCDMS has now excluded this novel interpretation.
DM ANNIHILATION FROM THE SUN

For solar annihilation to dominate over the contribution from the Galactic Center, the Sun must contain a large quantity of captured DM. In a symmetric DM context, solar annihilation fluxes are roughly \( \Phi \approx \frac{C_A N_X}{4 \pi R^2} \). Adopting the assumption that only annihilation and nuclear capture play a role we can specify a model of scattering of the \( Y \) states on nuclei and then derive bounds on the DM-nucleus cross section. This works only in the regime where evaporation of DM out of the Sun is negligible, such that the equilibrium abundance of DM is, \( N_{eq} \approx \sqrt{C_{XN}/C_A} \). We again adopt the model of DM annihilating to new neutrinos that interact with a new gauge boson kinetically mixed with the SM photon, \( g_X = g_0 \), and \( m_V = 50 \text{ MeV} \). This yields the result shown in Fig. 3. At low DM mass the limit cannot be trusted, as sufficiently light DM is prone to evaporation from collisions with solar nuclei. Parameter space in the shaded region of Fig. 3 is not testable to due rapid evaporation of DM from the solar interior. We note that in models where DM experiences significant self-interaction the abundance of DM in the Sun can be much larger, which can strengthen the limit in Inv. 3 significantly. We leave for future work the extension of the framework considered here to an asymmetric DM scenario (see e.g. [3] and [5]).

DISCUSSION AND SUMMARY-

In summary, this work has investigated the sensitivity of direct detection searches to dark matter annihilation. Thermal relic dark matter sets a natural scale for the thermally averaged DM annihilation cross section around \( \langle \sigma_{ann} v_{rel} \rangle \sim 6 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} \). This scale can be searched for in CMB, gamma-ray, and even neutrino data. Both CMB and gamma-ray data have breached thermal relic sensitivity for light DM masses.

Though these constraints have sizable astrophysical uncertainties, they may indicate that light DM requires non-SM modes of annihilation. Here we have studied models in which DM annihilates to a light, non-SM state that can scatter elastically on nuclei and deposit a detectable recoil energy. Though more decoupled from the SM than traditional WIMPs, we have shown that models of this type are testable at traditional direct detection experiments. We have furthermore demonstrated that in this class of indirect annihilation searches, all astrophysical uncertainties can be “integrated out” and experimental sensitivities can be directly compared.

This work could be extended to include electronic scattering at direct detection, though the reduction in the Cherenkov threshold for electrons implies that Super-K limits extend to much lower masses for leptophilic models. The most similar studies to our own which have been recently carried out assumed that DM interacts with the SM through a kinetically mixed photon, implying couplings both hadronic and electronic couplings. In this case, large volume detectors like Super-Kamiokande and IceCube yield very strong limits. In contrast, we are interested in a complementary portion of the parameter space compared to [1] in that we have focused on hadronic models where: (1) the annihilation products are nearly massless compared to nuclear recoil energies and (2) light DM masses which are near or below Cherenkov threshold and thus difficult to probe at Super-K.

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[10] M. Pospelov, Neutrino Physics with Dark Matter Experiments and the Signature of New Baryonic Neutral Currents, Phys.Rev. D84 (2011) 085008, arXiv:1103.3261.

[11] R. Hamik, J. Kopp, and P. A. Machado, Exploring neutrino Signals in Dark Matter Detectors, JCAP 1207 (2012) 026, arXiv:1202.6073.

[12] M. L. Graesser, I. M. Shoemaker, and L. Vecchi, A Dark Force for Baryons, arXiv:1107.2666.

[13] S. Tulin, New weakly-coupled forces hidden in low-energy QCD, Phys.Rev. D89 (2014) 114008, arXiv:1404.4370.

[14] A. E. Nelson and J. Walsh, Short Baseline Neutrino Oscillations and a New Light Gauge Boson, Phys.Rev. D77 (2008) 033001, arXiv:0711.1363.

[15] J. Collar and I. Avignone, F.T., The Effect of elastic scattering in the Earth on cold dark matter experiments, Phys.Rev. D47 (1993) 5238–5246.

[16] F. Hasenbalg, D. Abriola, F. Avignone, J. Collar, D. Di Gregorio, et al., Cold dark matter identification: Diurnal modulation revisited, Phys.Rev. D55 (1997) 7350–7355, astro-ph/9702165.

[17] G. Zaharijas and G. R. Farrar, A Window in the dark matter exclusion limits, Phys.Rev. D72 (2005) 083502, astro-ph/040651.

[18] G. D. Mack, J. F. Beacom, and G. Bertone, Towards Closing the Window on Strongly Interacting Dark Matter: Far-Reaching Constraints from Earth’s Heat Flow, Phys.Rev. D76 (2007) 043523, arXiv:0705.4298.

[19] R. Foot, Implications of the DAMA and CRESST experiments for mirror matter type dark matter, Phys.Rev. D69 (2004) 036001, hep-ph/0308254.

[20] J. M. Cline, Z. Liu, and W. Xue, Millicharged Atomic Dark Matter, Phys.Rev. D85 (2012) 101302, arXiv:1201.4858.

[21] K. Sigurdson, M. Doran, A. Kurylov, R. R. Caldwell, and M. Kamionkowski, Dark-matter electric and magnetic dipole moments, Phys.Rev. D70 (2004) 083501, astro-ph/0406355.

[22] C. Kouvaris and I. M. Shoemaker, Daily Modulation as a Smoking Gun of Dark Matter with Significant Stopping, arXiv:1405.1729.

[23] J. H. Davis, Fitting the annual modulation in DAMA with neutrons from muons and neutrinos, Phys.Rev.Lett. 113 (2014) 081302, arXiv:1407.1052.

[24] P. J. Fox, G. D. Kribs, and T. M. Tait, Interpreting Dark Matter Direct Detection Independently of the Local Velocity and Density Distribution, Phys.Rev. D83 (2011) 034007, arXiv:1011.1910.

[25] P. J. Fox, J. Liu, and N. Weiner, Integrating Out Astrophysical Uncertainties, Phys.Rev. D83 (2011) 103514, arXiv:1011.1915.

[26] M. T. Frandsen, F. Kahlhoefer, C. McCabe, S. Sarkar, and K. Schmidt-Hoberg, Resolving astrophysical uncertainties in dark matter direct detection, JCAP 1201 (2012) 024, arXiv:1111.0292.

[27] P. Gondolo and G. B. Gelmini, Halo independent comparison of direct dark matter detection data, JCAP 1212 (2012) 015, arXiv:1202.6359.

[28] M. T. Frandsen, F. Kahlhoefer, C. McCabe, S. Sarkar, and K. Schmidt-Hoberg, The unbearable lightness of being: CDMS versus XENON, JCAP 1307 (2013) 023, arXiv:1304.6066.

[29] E. Del Nobile, G. B. Gelmini, P. Gondolo, and J.-H. Huh, Halo-independent analysis of direct detection data for light WIMPs, JCAP 1310 (2013) 026, arXiv:1304.6183.

[30] N. Bozorgnia, J. Herrero-Garcia, T. Schwetz, and J. Zupan, Halo-independent methods for inelastic dark matter scattering, JCAP 1307 (2013) 049, arXiv:1305.3575.

[31] E. Del Nobile, G. B. Gelmini, P. Gondolo, and J.-H. Huh, Generalized Halo Independent Comparison of Direct Dark Matter Detection Data, JCAP 1310 (2013) 048, arXiv:1306.5273.

[32] E. Del Nobile, G. B. Gelmini, P. Gondolo, and J.-H. Huh, Update on Light WIMP Limits: LUX, lite and Light, JCAP 1403 (2014) 014, arXiv:1311.4247.

[33] P. J. Fox, G. Jung, P. Sorensen, and N. Weiner, Dark Matter in Light of LUX, Phys.Rev. D89 (2014) 103526, arXiv:1401.0216.

[34] E. Del Nobile, G. B. Gelmini, P. Gondolo, and J.-H. Huh, Direct detection of Light Anapole and Magnetic Dipole DM, JCAP 1406 (2014) 002, arXiv:1401.4508.

[35] B. Feldstein and F. Kahlhoefer, A new halo-independent approach to dark matter direct detection analysis, JCAP 1408 (2014) 005, arXiv:1403.4608.

[36] P. J. Fox, Y. Kahn, and M. McCullough, Taking Halo-Independent Dark Matter Methods Out of the Bin, arXiv:1403.6830.

[37] G. B. Gelmini, A. Georgescu, and J.-H. Huh, Direct detection of light Ge-phobic” exothermic dark matter, JCAP 1407 (2014) 028, arXiv:1404.7484.

[38] S. Scopel and K. Yoon, A systematic halo-independent analysis of direct detection data within the framework of Inelastic Dark Matter, JCAP 1408 (2014) 060, arXiv:1405.0364.

[39] J. F. Cherry, M. T. Frandsen, and I. M. Shoemaker, Halo Independent Direct Detection of Momentum-Dependent Dark Matter, JCAP 1410 (2014), no. 10 022, arXiv:1405.1420.

[40] B. Feldstein and F. Kahlhoefer, Quantifying (dis)agreement between direct detection experiments in a halo-independent way, arXiv:1409.5446.

[41] N. Bozorgnia and T. Schwetz, What is the probability that direct detection experiments have observed Dark Matter?, arXiv:1410.6160.

[42] DAMA Collaboration, LIBRA Collaboration Collaboration, R. Bernabei et al., New results from DAMA/LIBRA, Eur.Phys.J. C67 (2010) 39–49, arXiv:1002.1029.

[43] CDMS Collaboration Collaboration, R. Agnese et al., Silicon Detector Dark Matter Results from the Final Exposure of CDMS II, Phys.Rev.Lett. (2013) arXiv:1304.4279.

[44] SuperCDMS Collaboration Collaboration, R. Agnese et al., Search for Low-Mass WIMPs with SuperCDMS, Phys.Rev.Lett. 112 (2014) 241302, arXiv:1402.7137.

[45] A. Gould, Resonant Enhancements in WIMP Capture by the Earth, Astrophys.J. 321 (1987) 571.

[46] A. Gould, EVAPORATION OF WIMPs WITH ARBITRARY CROSS-SECTIONS, Astrophys. J. (1989).

[47] G. Busoni, A. De Simone, and W.-C. Huang, On the Minimum Dark Matter Mass Testable by Neutrinos from the Sun, JCAP 1307 (2013) 010, arXiv:1305.1817.
[48] A. R. Zentner, High-Energy Neutrinos From Dark Matter Particle Self-Capture Within the Sun, Phys.Rev. D80 (2009) 063501, [arXiv:0907.3448].
[49] M. T. Frandsen and S. Sarkar, Asymmetric dark matter and the Sun, Phys.Rev.Lett. 105 (2010) 011301, [arXiv:1003.4505].
[50] J. Fan, A. Katz, and J. Shelton, Direct and indirect detection of dissipative dark matter, JCAP 1406 (2014) 059, [arXiv:1312.1336].
[51] C.-S. Chen, F.-F. Lee, G.-L. Lin, and Y.-H. Lin, Probing Dark Matter Self-Interaction in the Sun with IceCube-PINGU, JCAP 1410 (2014), no. 10 049, [arXiv:1408.5471].
[52] M. L. Graesser, I. M. Shoemaker, and L. Vecchi, Asymmetric WIMP dark matter, JHEP 1110 (2011) 110, [arXiv:1103.2771].
[53] T. Lin, H.-B. Yu, and K. M. Zurek, On Symmetric and Asymmetric Light Dark Matter, Phys.Rev. D85 (2012) 063503, [arXiv:1111.0293].
[54] N. F. Bell, S. Horiuchi, and I. M. Shoemaker, Annihilating Asymmetric Dark Matter, [arXiv:1408.5142].
[55] M. S. Madhavacheril, N. Sehgal, and T. R. Slatyer, Current Dark Matter Annihilation Constraints from CMB and Low-Redshift Data, Phys.Rev. D89 (2014) 103508, [arXiv:1310.3815].
[56] Fermi-LAT Collaboration Collaboration, M. Ackermann et al., Dark matter constraints from observations of 25 Milky Way satellite galaxies with the Fermi Large Area Telescope, Phys.Rev. D89 (2014), no. 4 042001, [arXiv:1310.0828].
[57] IceCube Collaboration Collaboration, M. Aartsen et al., IceCube Search for Dark Matter Annihilation in nearby Galaxies and Galaxy Clusters, Phys.Rev. D88 (2013), no. 12 122001, [arXiv:1307.3473].
[58] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, First Direct Detection Limits on sub-GeV Dark Matter from XENON10, Phys.Rev.Lett. 109 (2012) 021301, [arXiv:1206.2644].