Neutrinos from the Sun can discover dark matter-electron scattering

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(Dated: August 25, 2023)

We probe dark matter-electron scattering using high-energy neutrino observations from the Sun. Dark matter (DM) interacting with electrons can get captured inside the Sun. These captured DM may annihilate to produce different Standard Model (SM) particles. Neutrinos produced from these SM states can be observed in IceCube and DeepCore. Although there is no excess of neutrinos from the Solar direction, we find that the current data-sets of IceCube and DeepCore set the strongest constraint on DM-electron scattering cross section in the DM mass range 10 GeV to 10^5 GeV. Our work implies that future observations of the Sun by neutrino telescopes have the potential to discover DM-electron interaction.

INTRODUCTION

Have we searched for all possible ways in which new physics can manifest itself in our existing data-sets? This is an important question to consider in beyond the SM searches. The effects of new physics may be present in existing data-sets, but we will be able to find them only if we use the right observables to interpret the data-sets. The above-mentioned strategy may be a discovery probe of new physics. We show that using an existing IceCube data-set, we can set the strongest constraint on DM-electron scattering cross sections. This implies that by utilizing similar near-future data-sets, it is possible to discover non-gravitational interactions of DM.

DM is a ubiquitous component of the Universe: this is an inescapable conclusion from various cosmological and astrophysical observations [1–4]. These observations imply the presence of DM via its gravitational interactions. In spite of this large body of evidences, we neither know the DM candidate nor its non-gravitational interactions with various SM particles [5–12]. Since new physics can be present in a variety of different ways, it is important to search for all different couplings of DM with SM particles. In this work, we focus on DM-electron scattering for leptophilic DM [13–62].

The search for DM-electron couplings has made rapid progress over the last decade. Various techniques have probed large regions of DM-electron coupling parameter space [63–86]. These searches motivate us to ask: is there an observable which can discover DM-electron scattering cross-section beyond what has already been probed? In this work, we obtain the most stringent constraint on DM-electron scattering cross-section, σ_e, for a wide range of DM masses using current IceCube data-sets.

The Sun, as the nearest star to the Earth, is an interesting target for DM. The Sun has been moving through the Milky Way DM halo over its lifetime ($\gtrsim$ Gyr). If there is an interaction between DM and SM states, then a fraction of local DM particles gets captured within the Sun, for DM masses above ~ 5 GeV. There are large number of electrons inside the Sun, which would facilitate DM capture through electron scattering. These DM particles may annihilate into different SM particles (whose decay, hadronization, electroweak correction (EW) etc. produce neutrinos)[1] including neutrinos. Neutrinos are the only SM particles which can escape from the Sun, and can be detected in Earth-based neutrino telescopes. Using exist-

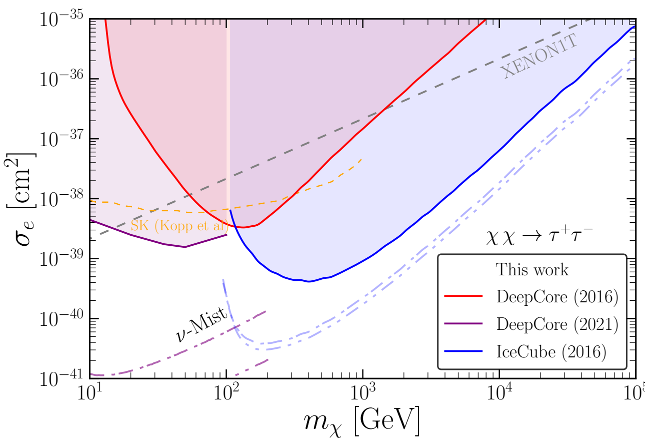

FIG. 1. Excluded region of DM-electron scattering cross section, σ_e, for DM annihilating to $\tau^+\tau^-$. The purple, red, and blue shaded regions are excluded by DeepCore (2021), DeepCore (2016), and IceCube (2016) data respectively. The XENON1T and SK bounds are shown by the dashed grey and orange lines respectively. Along the dot-dashed, double dot-dashed light blue (purple) lines, DM induced neutrino events would be equal to the same of two different models for Solar atmospheric neutrino background (SAν) events in IceCube (DeepCore).

[1] Unless specified, we do not distinguish between neutrinos and anti-neutrinos in this work.

ing results of IceCube and DeepCore, we set the strongest limits on σ_e for DM mass range $\sim 10\,\text{GeV}-100\,\text{TeV}$.

In Fig. 1, we show our derived limits for the σ_e as a function of the DM mass. Here we assume the DM particles, captured within the Sun, annihilate to $\tau^+\tau^-$. The solid blue, red and purple lines show the bounds derived in this work using IceCube and DeepCore data-sets from Refs. [87, 88]. Our framework probes new regions of parameter space in the DM mass range $\sim$ 10 GeV-100 TeV. This suggests Solar observations using neutrino telescopes can discover DM-electron interactions in near future. The dot-dashed and double dot-dashed lines represent "ν-Mist" which we will discuss later.

DM CAPTURE IN THE SUN

While the Sun is traversing the Milky-Way halo, DM particles can get gravitationally attracted towards the Sun's potential. Further non-gravitational interactions may lead to scattering between DM and Solar constituents. After scattering, if the final velocity of the DM particle is less than the Solar escape velocity, then it gets trapped inside the Sun. Furthermore, these captured DM particles can thermalize within the Sun due to further scattering with electrons and be concentrated within $\sim 1\%$ of the Solar radius [27, 45, 89, 90]. These captured DM can annihilate to produce primary and secondary neutrinos which can be detected by various neutrino telescopes. We adopt the model-independent approach of considering a non-zero DM-electron cross-section leading to DM capture inside the Sun (see Refs. [90–140] for similar study with DM-nucleon scattering).

In the weak σ_e limit, capture rate of DM particles having mass m_χ [45]

$$C_\odot = \int_0^{R_\odot} 4\pi r^2 dr \int_0^\infty du_\chi \left(\frac{\rho_\chi}{m_\chi}\right) \frac{f_{v_\odot}(u_\chi)}{u_\chi} w(r) \int_0^{v_e(r)} R_e^-(w \to v)\, dv, \tag{1}$$

where $R_\odot$ is the Solar radius and $\rho_\chi = 0.3$ GeV/cm^3 is the local DM density. Here $f_{v_\odot}(u_\chi)$ is the DM velocity distribution in the Solar rest frame. DM velocities at asymptotic and r distance are u_χ and $w(r) = \sqrt{u_\chi^2 + v_e^2(r)}$ respectively with escape velocity $v_e(r)$. The integrand in Eq. (1), $R_e^-(w \to v)$ is the differential scattering rate for DM particles with velocity w scattering to a final velocity v, such that $v < w$. The form of $R_e^-(w \to v)$ for velocity independent scattering is [45]

$$R_e^-(w \to v) = \frac{2}{\sqrt{\pi}} \frac{\mu_+^2}{\mu} \frac{v}{w} n(r)\, \sigma_e \left[\chi(-\alpha_-, \alpha_+) + \chi(-\beta_-, \beta_+) e^{\frac{\mu(w^2-v^2)}{u_e(r)^2}} \right], \tag{2}$$

where,

$$\mu = \frac{m_\chi}{m_e},\ \mu_\pm = \frac{\mu \pm 1}{2},\ \chi(a,b) = \int_a^b e^{-y^2}\, dy \tag{3}$$

$$\alpha_\pm = \frac{\mu_+ v \pm \mu_- w}{u_e(r)},\ \beta_\pm = \frac{\mu_- v \pm \mu_+ w}{u_e(r)}, u_e(r) = \sqrt{\frac{2\,T_\odot(r)}{m_e}}$$

with $n(r)$, $T_\odot(r)$ being the number density and temperature of Solar electrons as a function of. Here we are using AGSS09 Solar model for our analysis [141]. Some types of DM-electron interactions generate DM-nuclear scattering in the loop level, which would give additional contribution in the capture rate. However, for some of the interactions, as has been shown in Refs. [27, 55] (but, see also [62]) DM-electron scattering would be the dominant process for DM capture. A detailed study of this assuming all possible spins and interactions of DM is beyond the scope of our article.

In our mass and cross section range of interest the capture rate is

$$C_\odot \approx 3.04 \times 10^{18} \left(\frac{10^3\text{GeV}}{m_\chi}\right)^2 \left(\frac{\sigma_e}{10^{-40}\,\text{cm}^2}\right)\ \text{s}^{-1} \tag{4}$$

NEUTRINO FLUX

Captured DM inside the Sun may annihilate into different SM final states. There is an interplay between the rate at which DM gets captured and annihilated away. Under equilibrium condition between the capture and annihilation rate (true for the DM regions that we are probing), the latter is

$$\Gamma_{\text{ann}} \equiv \frac{C_\odot}{2}\,. \tag{5}$$

Note that DM evaporation is ineffective in our mass range of interest ($\gtrsim$ 10 GeV) [142]. We have also neglected the effect of model dependent DM self-interaction. The equilibrium time scale depends on the DM mass, DM-electron scattering, and DM annihilation cross-sections. In the supplementary material (see Fig. 5), we show the regions where the equilibrium is achieved in thermally averaged DM annihilation cross-sections and DM-electron scattering cross section plane for various choices of DM masses.

Only primary and secondary neutrinos of energies $\lesssim$ 500 GeV (due to neutrino attenuation, discussed later) will emerge out of the Sun without substantial attenuation. The differential neutrino energy flux at earth is

$$E_\nu^2 \frac{d\phi_\nu}{dE_\nu} = \frac{\Gamma_{\text{ann}}}{4\,\pi\, D_\odot^2} \times E_\nu^2 \frac{dN_\nu}{dE_\nu}, \tag{6}$$

where $D_\odot$ is the Earth-Sun distance.[2] The neutrino spectrum is denoted by dN_ν/dE_ν per DM annihilation. The

[2] Time variation of $D_\odot$ effects our results insignificantly. We have

Sun's center is a dense environment, some particles (like muons) will interact before decay, and others (like top-quark, tau) will decay before interaction. Therefore neutrino spectra at the center of the Sun will be different from the typical Galactic halo environment spectrum. We have utilized the results from the publicly available code, χaroν [143] (see also [134, 144–146]), which includes these effects along with other important effects like EW corrections [147] (for DM masses $> 500\,\mathrm{GeV}$).

The propagation media of neutrinos from the Solar center to the detector include the Sun, the vacuum, Earth's atmosphere, and the Earth rock (negligible impact for this work). The primary propagation effects are trapping of neutrinos and tau regeneration in the Solar medium, and neutrino oscillation. Electron and muon neutrinos, once produced near the center of the Sun, mainly interact through charged current (CC) interactions and produce corresponding charged leptons. These charged leptons thermalize within the Sun and thus essentially remove electron and muon neutrinos above the transparency energy (energy above which neutrinos can escape the Sun). Tau leptons, produced from interactions of tau neutrinos, are so short-lived that they will decay before scattering [143, 148]. Their decay products include tau neutrinos with energies less than ($\sim$ 20% reduction) that of initial tau neutrinos. For initial tau neutrinos with energies above the corresponding transparency energy, this process will continue until the final tau neutrino reaches energy below the transparency energy. Finally, one needs to consider the effect of neutrino oscillation. We have incorporated all these effects using `nuSQuIDS` [149]. The obtained differential neutrino spectra from `nuSQuIDS` is then used in Eq. (6) to calculate the differential neutrino flux at the detector.

ANALYSIS

Neutrinos produced from DM capture through DM-electron scattering will have observable signatures in terrestrial neutrino telescopes like IceCube, Super-Kamiokande (SK), etc. Current data do not show excess events from the Solar direction. We have analyzed current IceCube and DeepCore data-set to constrain σ_e. In our neutrino energy range of interest, neutrino detection topologies include cascades and tracks. Cascades are produced by neutral current (NC) interactions of all neutrino flavors and by CC interactions of electron and tau neutrinos. CC interactions of muon neutrinos produce muons which produce track-like signatures.

IceCube & DeepCore (2016) [87]: In this analysis, IceCube utilizes austral winter data from May 2011 to May 2014. During this period, muon-neutrinos from the Solar direction will produce up-going muon tracks. This facilitates differentiating the signal from the large down-going atmospheric muon background. The directionality of the up-going track-like events serves as a proxy for the direction of neutrinos. Atmospheric neutrinos from the Solar direction are an irreducible background to this search. This analysis only focuses on (anti-)muon tracks produced by interactions of muon (anti-)neutrinos. For neutrinos with energies $\gtrsim 100\,\mathrm{GeV}$ (from DM annihilations), the full instrumented volume of IceCube contributes to the Solar DM annihilation sensitivity, whereas DeepCore is sensitive only to neutrinos with energies $\lesssim 100\,\mathrm{GeV}$.

In [87] event rates are given with respect to the cosine of the Solar opening angle ($\theta_{\rm Sun}$), the angle subtended by reconstructed (anti-)muon with respect to the Solar direction. The differential event rate as a function of $\theta_{\rm Sun}$ is

$$\frac{dN_{\theta_{\rm Sun}}}{d\cos(\theta_{\rm Sun})} = 2\ T \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} A_{\rm eff}(E_\nu)\frac{d\phi_\nu}{dE_\nu} \frac{1}{\sqrt{2\pi}\sigma_\theta} e^{-\frac{(\cos(\theta_{\rm Sun})-1)^2}{2\sigma_\theta^2}} dE_\nu, \quad (7)$$

where $T = 532$ days, and factor 2 is there since cosine is an even function of $\theta_{\rm Sun}$. The energy dependent effective area ($A_{\rm eff}(E_\nu)$), lower and upper limit of the integration $E_\nu^{\rm min}$ and $E_\nu^{\rm max}$ are adopted from Ref. [87]. The dispersion (σ_θ) also depends on energy through

$$\sigma_\theta = \left|\frac{\sqrt{2}\,(1-\cos[\Delta\theta(E_\nu)])}{2\,\mathrm{InverseErf}(0.5)}\right|, \quad (8)$$

where energy dependency of median angular resolution $\Delta\theta(E_\nu)$ is extracted from Ref. [87]. InverseErf is the inverse error function. Since this analysis is done with track-like signatures only muon neutrinos and muon anti-neutrinos contribute to the differential flux given in Eq. (7).

Assuming DM is annihilating to $\tau^+\tau^-$, we show the IceCube event rate with the blue solid line in Fig. 2 for $m_\chi = 1\,\mathrm{TeV}$ and $\sigma_e = 10^{-37}\,\mathrm{cm}^2$ (this choice is consistent with other experiments). The black dots represent observed data points and the red solid line with the shaded band depict the background atmospheric neutrino events and its uncertainty. Clearly the chosen DM parameter space is already ruled out by the current IceCube observation, showing the power of our technique.

Numerically we obtain the constraint on DM parameter space by performing a χ^2 analysis. The χ^2 estimator is given by

$$\chi^2 = \sum_{i=1}^{7}\left(N^i_{\rm data} - N^i_{\rm bkg} - N^i_{\theta_{\rm Sun}}\right)^2/(\sigma^i_{\rm bkg})^2\,, \quad (9)$$

fixed it to 1st of May, since IceCube data are taken during austral winter.

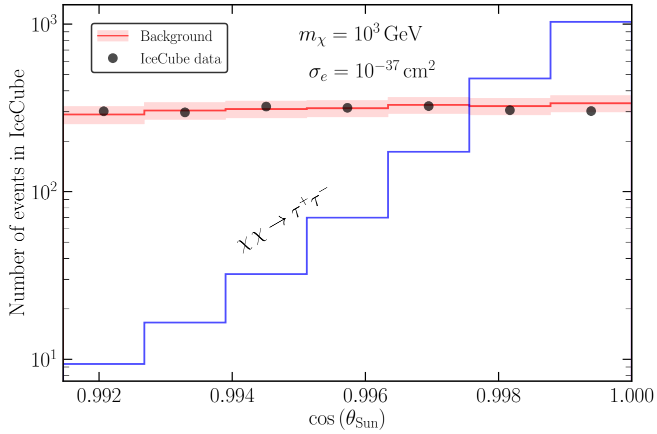

FIG. 2. Number of events against the $\cos(\theta_{\mathrm{Sun}})$ for captured DM annihilating to $\tau^+\tau^-$ with $\sigma_e = 10^{-37}\,\mathrm{cm}^2$ and $m_\chi = 10^3\,\mathrm{GeV}$ is shown by blue solid line. Black dots, red solid line, and the shaded region show the data, expected atmospheric neutrino events, and 2σ uncertainty in the background events respectively. The calculation and the data-set are from IceCube (2016) analysis.

where N^i_{data}, N^i_{bkg}, and $N^i_{\theta_{\mathrm{Sun}}}$ are the observed data (black points in Fig. 2), atmospheric neutrino events (red solid line in Fig. 2), and signal events (by integrating Eq. (7) for each bin) respectively. The uncertainty in the prediction of background is denoted by σ^i_{bkg}. In our analysis the minimum value of χ^2 (χ^2_{min}) is achieved in absence of the signal. For a fixed DM mass, we iterate over σ_e until $\chi^2 - \chi^2_{\mathrm{min}} \approx 2.71$. This sets 95% confidence level constraint on DM-electron scattering cross section. We performed the same analysis to obtain the constraint from the DeepCore (2016) data-set.

DeepCore (2021) [88]: Unlike the analysis mentioned above, in this case, IceCube collaboration has focused only on 6.75 years of DeepCore data. DeepCore has lower energy threshold and can detect both track and cascade-like signatures. The median angular resolutions for neutrino of energies 10 GeV and 200 GeV are $\sim 35^\circ$ and $\lesssim 5^\circ$ respectively. Given that the Sun has $\sim 0.5^\circ$ angular diameter in the sky, therefore an analysis like the previous one is difficult to perform. Rather, we compared the annihilation rate, given in Eq. (5), with the same of Ref. [88] for each of the considered channels to obtain our results.

RESULTS AND DISCUSSION

For captured DM annihilation to $\tau^+\tau^-$, our results are shown in Fig. 1. The region above the grey dashed line is excluded by lab-based direct detection (DD) experiment, obtained from $1/m_\chi$ extrapolated XENON1T S2-only limit [65]. The solid blue, red, and purple lines show the limits that we derive using IceCube (2016), DeepCore (2016), and DeepCore (2021) data respectively. We also display previously obtained SK constraint [27] by the dashed orange line. It is clear that our constraints are stronger than the previous limits for DM mass range $\in [10,\, 10^5]$ GeV.[3]

IceCube loses sensitivity below DM masses ~ 200 GeV, as the neutrinos produced from such DM remain below the detector's threshold. Similarly DeepCore (2016) analysis is sensitive to DM masses $\gtrsim 20$ GeV. However, for DeepCore (2021) data, better event reconstruction [88, 152] and use of high-efficiency digital optical modules facilitate the detection of neutrinos with energies $\gtrsim 5$ GeV. Thus the DeepCore (2021) limit extends up to DM mass ~ 10 GeV. Our bounds weaken above DM mass ~ 300 GeV owing to the combined effect of neutrino attenuation inside the Sun and fall of capture rate with the increment of DM mass. In a realistic particle physics model, DM may not annihilate to a particular final state with 100% branching ratio (as considered in this work). However, even if DM annihilation branching ratio to $\tau^+\tau^-$ or $\nu\bar{\nu}$ is $\sim 10\%$, our bound will be strongest in large regions of the parameter space. In passing we point out that our framework would also be useful to probe strong DM-electron scattering cross-section to which underground DD experiments are blind. A detailed study of that including multiple scattering is left for future work. The region below the dot-dashed and double dot-dashed light purple and blue lines indicate "ν-Mist", where DM induced neutrino events will be the same or less than that of the SAν [153–155]. We calculate this following the method presented in Ref. [154].[4] The dashed and dot-dashed lines correspond to two different models of SAν. In this region of the parameter space, with sufficient exposure it would be possible to differentiate DM induced neutrino events from SAν by doing a spectrum analysis.

In the supplementary material, we present our results for the final states e^+e^- and $\nu\bar{\nu} \equiv \frac{1}{3}(\nu_e\bar{\nu}_e + \nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau)$. For the e^+e^- channel, (see Fig. 3) the only source of producing neutrinos is the EW correction; thus, we only get limits for DM masses above 500 GeV (below this DM mass χ`aro`ν does not include the small EW correction), and the obtained bound is competitive with the XENON1T DD bound. For the $\nu\bar{\nu}$ final state, (see Fig. 4) our constraints are much stronger than DD and SK bounds in most of the parameter space. This indicates the exciting prospect of discovering DM-electron scattering in future neutrino telescopes like

[3] We do not extend our limit above DM mass 100 TeV to respect the partial wave unitarity bound [150, 151].

[4] In some regions of this parameter space, the DM capture rate would not be in equilibrium for typical annihilation rates, thus we use the full solution [103] to obtain the DM induced neutrino flux.

Hyper-Kamiokande [156], KM3NeT [157], PINGU [158], Baikal-GVD [159], IceCube Gen2 facility [160], etc.

CONCLUSIONS

Low threshold DD experiments are most sensitive to DM-electron scattering for DM masses $\sim 10-100\,\mathrm{MeV}$, but their sensitivity decreases for DM masses $\gtrsim 1\,\mathrm{GeV}$ due to the decrement in the DM flux. In this paper, we studied a novel strategy to probe DM-electron scattering in the DM mass range $10-10^5\mathrm{GeV}$. In our framework, DM gets captured inside the Sun through DM-electron scattering. The captured DM annihilates to produce different SM final states. Primary and secondary neutrinos produced from these SM states can escape the Sun and be detected in IceCube.

We have analyzed IceCube (2016), DeepCore (2016), and DeepCore (2021) data to probe the above scenario. In the absence of any signal, we found the strongest constraint in large regions of DM parameter space. IceCube (2016) data provide the strongest constraint for DM-electron scattering in the DM mass range $200-10^5$ GeV. DeepCore data give the strongest bounds in the mass range of $\sim 10-100\,\mathrm{GeV}$. DM annihilation final states which produces copious amounts of neutrinos (e.g., $\tau^+\tau^-$ and $\nu\bar{\nu}$), leads to a stronger bound than neutrino-poor final state (e.g., e^+e^-). For $\tau^+\tau^-$ and $\nu\bar{\nu}$ final state, our bounds are stronger than the previous bounds in large regions of the parameter space. This suggests that upcoming neutrino telescopes (like Hyper-K, KM3NeT, etc.) would possibly be able to discover the signature of DM-electron scattering. We have only focused on velocity-independent DM-electron scattering cross section, bounds on velocity-dependent cross section would be considered elsewhere.

Acknowledgments – We thank Carlos Arguelles, Debajit Bose, Celine Boehm, Dibya S. Chattopadhyay, Raghuveer Garani, Joachim Kopp, Subhendra Mohanty, Toby Opferkuch, Nirmal Raj, Tirtha S Ray, Tracy Slatyer, and Juri Smirnov for comments and discussions. TNM would like to acknowledge the financial support from the Department of Atomic Energy, Government of India, for the Regional Centre for Accelerator-based Particle Physics (RECAPP), Harish Chandra Research Institute. AKS acknowledges the Ministry of Human Resource Development, Government of India, for financial support via the Prime Ministers' Research Fellowship (PMRF). SM acknowledges the Department of Science and Technology (DST), Government of India, for financial support via the Kishore Vaigyanik Protsahan Yojana (KVPY: now discontinued and merged with the INSPIRE fellowship). RL acknowledges financial support from the Infosys foundation (Bangalore), institute start-up funds, and the Department of Science and Technology (Govt. of India) for the grant SRG/2022/001125.

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[1] PLANCK collaboration, N. Aghanim et al., *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641** (2020) A6, [1807.06209].

[2] A. M. Green, *Dark Matter in Astrophysics/Cosmology*, in *Les Houches summer school on Dark Matter*, 9, 2021. 2109.05854.

[3] G. Bertone, D. Hooper and J. Silk, *Particle dark matter: Evidence, candidates and constraints*, Phys. Rept. **405** (2005) 279–390, [hep-ph/0404175].

[4] L. E. Strigari, *Galactic Searches for Dark Matter*, Phys. Rept. **531** (2013) 1–88, [1211.7090].

[5] O. Buchmueller, C. Doglioni and L. T. Wang, *Search for dark matter at colliders*, Nature Phys. **13** (2017) 217–223, [1912.12739].

[6] M. Ahlers, K. Helbing and C. Pérez de los Heros, *Probing Particle Physics with IceCube*, Eur. Phys. J. C **78** (2018) 924, [1806.05696].

[7] G. Krnjaic et al., *Snowmass 2021 Rare & Precision Frontier (RF6): Dark Matter Production at Intensity-Frontier Experiments*, 2207.00597.

[8] B. Batell, N. Blinov, C. Hearty and R. McGehee, *Exploring Dark Sector Portals with High Intensity Experiments*, in *2022 Snowmass Summer Study*, 7, 2022. 2207.06905.

[9] C. Pérez de los Heros, *Status, Challenges and Directions in Indirect Dark Matter Searches*, Symmetry **12** (2020) 1648, [2008.11561].

[10] T. R. Slatyer, *Les Houches Lectures on Indirect Detection of Dark Matter*, 2109.02696.

[11] J. Cooley, *Dark Matter direct detection of classical WIMPs*, 2110.02359.

[12] Y. Kahn and T. Lin, *Searches for light dark matter using condensed matter systems*, Rept. Prog. Phys. **85** (2022) 066901, [2108.03239].

[13] L. M. Krauss, S. Nasri and M. Trodden, *A Model for neutrino masses and dark matter*, Phys. Rev. D **67** (2003) 085002, [hep-ph/0210389].

[14] E. A. Baltz and L. Bergstrom, *Detection of leptonic dark matter*, Phys. Rev. D **67** (2003) 043516, [hep-ph/0211325].

[15] E. Ma, *Verifiable radiative seesaw mechanism of neutrino mass and dark matter*, Phys. Rev. D **73** (2006) 077301, [hep-ph/0601225].

[16] T. Hambye, K. Kannike, E. Ma and M. Raidal, *Emanations of Dark Matter: Muon Anomalous Magnetic Moment, Radiative Neutrino Mass, and Novel Leptogenesis at the TeV Scale*, Phys. Rev. D **75** (2007) 095003, [hep-ph/0609228].

[17] R. Bernabei et al., *Investigating electron interacting dark matter*, Phys. Rev. D **77** (2008) 023506, [0712.0562].

[18] M. Cirelli, M. Kadastik, M. Raidal and A. Strumia, *Model-independent implications of the e+-, anti-proton*

cosmic ray spectra on properties of Dark Matter, Nucl. Phys. B **813** (2009) 1–21, [0809.2409].

[19] C.-R. Chen and F. Takahashi, *Cosmic rays from Leptonic Dark Matter*, JCAP **02** (2009) 004, [0810.4110].

[20] X.-J. Bi, P.-H. Gu, T. Li and X. Zhang, *ATIC and PAMELA Results on Cosmic e+- Excesses and Neutrino Masses*, JHEP **04** (2009) 103, [0901.0176].

[21] Q.-H. Cao, E. Ma and G. Shaughnessy, *Dark Matter: The Leptonic Connection*, Phys. Lett. B **673** (2009) 152–155, [0901.1334].

[22] H.-S. Goh, L. J. Hall and P. Kumar, *The Leptonic Higgs as a Messenger of Dark Matter*, JHEP **05** (2009) 097, [0902.0814].

[23] X.-J. Bi, X.-G. He and Q. Yuan, *Parameters in a class of leptophilic models from PAMELA, ATIC and FERMI*, Phys. Lett. B **678** (2009) 168–173, [0903.0122].

[24] A. Ibarra, A. Ringwald, D. Tran and C. Weniger, *Cosmic Rays from Leptophilic Dark Matter Decay via Kinetic Mixing*, JCAP **08** (2009) 017, [0903.3625].

[25] H. Davoudiasl, *Dark Matter with Time-Varying Leptophilic Couplings*, Phys. Rev. D **80** (2009) 043502, [0904.3103].

[26] A. Dedes, I. Giomataris, K. Suxho and J. D. Vergados, *Searching for Secluded Dark Matter via Direct Detection of Recoiling Nuclei as well as Low Energy Electrons*, Nucl. Phys. B **826** (2010) 148–173, [0907.0758].

[27] J. Kopp, V. Niro, T. Schwetz and J. Zupan, *DAMA/LIBRA and leptonically interacting Dark Matter*, Phys. Rev. D **80** (2009) 083502, [0907.3159].

[28] T. Cohen and K. M. Zurek, *Leptophilic Dark Matter from the Lepton Asymmetry*, Phys. Rev. Lett. **104** (2010) 101301, [0909.2035].

[29] E. J. Chun, J.-C. Park and S. Scopel, *Dirac gaugino as leptophilic dark matter*, JCAP **02** (2010) 015, [0911.5273].

[30] W. Chao, *Pure Leptonic Gauge Symmetry, Neutrino Masses and Dark Matter*, Phys. Lett. B **695** (2011) 157–161, [1005.1024].

[31] N. Haba, Y. Kajiyama, S. Matsumoto, H. Okada and K. Yoshioka, *Universally Leptophilic Dark Matter From Non-Abelian Discrete Symmetry*, Phys. Lett. B **695** (2011) 476–481, [1008.4777].

[32] P. Ko and Y. Omura, *Supersymmetric U(1)B x U(1)L model with leptophilic and leptophobic cold dark matters*, Phys. Lett. B **701** (2011) 363–366, [1012.4679].

[33] C. D. Carone and R. Primulando, *A Froggatt-Nielsen Model for Leptophilic Scalar Dark Matter Decay*, Phys. Rev. D **84** (2011) 035002, [1105.4635].

[34] D. Schmidt, T. Schwetz and T. Toma, *Direct Detection of Leptophilic Dark Matter in a Model with Radiative Neutrino Masses*, Phys. Rev. D **85** (2012) 073009, [1201.0906].

[35] M. Das and S. Mohanty, *Leptophilic dark matter in gauged $L_\mu - L_\tau$ extension of MSSM*, Phys. Rev. D **89** (2014) 025004, [1306.4505].

[36] P. S. B. Dev, D. K. Ghosh, N. Okada and I. Saha, *Neutrino Mass and Dark Matter in light of recent AMS-02 results*, Phys. Rev. D **89** (2014) 095001, [1307.6204].

[37] J. Kopp, L. Michaels and J. Smirnov, *Loopy Constraints on Leptophilic Dark Matter and Internal Bremsstrahlung*, JCAP **04** (2014) 022, [1401.6457].

[38] S. Chang, R. Edezhath, J. Hutchinson and M. Luty, *Leptophilic Effective WIMPs*, Phys. Rev. D **90** (2014) 015011, [1402.7358].

[39] P. Agrawal, Z. Chacko and C. B. Verhaaren, *Leptophilic Dark Matter and the Anomalous Magnetic Moment of the Muon*, JHEP **08** (2014) 147, [1402.7369].

[40] N. F. Bell, Y. Cai, R. K. Leane and A. D. Medina, *Leptophilic dark matter with Z' interactions*, Phys. Rev. D **90** (2014) 035027, [1407.3001].

[41] A. Freitas and S. Westhoff, *Leptophilic Dark Matter in Lepton Interactions at LEP and ILC*, JHEP **10** (2014) 116, [1408.1959].

[42] Q.-H. Cao, C.-R. Chen and T. Gong, *Leptophilic dark matter confronts AMS-02 cosmic-ray positron flux*, Chin. J. Phys. **55** (2017) 10–15, [1409.7317].

[43] S. M. Boucenna, M. Chianese, G. Mangano, G. Miele, S. Morisi, O. Pisanti et al., *Decaying Leptophilic Dark Matter at IceCube*, JCAP **12** (2015) 055, [1507.01000].

[44] B.-Q. Lu and H.-S. Zong, *Leptophilic dark matter in Galactic Center excess*, Phys. Rev. D **93** (2016) 083504.

[45] R. Garani and S. Palomares-Ruiz, *Dark matter in the Sun: scattering off electrons vs nucleons*, JCAP **05** (2017) 007, [1702.02768].

[46] G. H. Duan, L. Feng, F. Wang, L. Wu, J. M. Yang and R. Zheng, *Simplified TeV leptophilic dark matter in light of DAMPE data*, JHEP **02** (2018) 107, [1711.11012].

[47] G. H. Duan, X.-G. He, L. Wu and J. M. Yang, *Leptophilic dark matter in gauged $U(1)_{L_e - L_\mu}$ model in light of DAMPE cosmic ray $e^+ + e^-$ excess*, Eur. Phys. J. C **78** (2018) 323, [1711.11563].

[48] W. Chao, H.-K. Guo, H.-L. Li and J. Shu, *Electron Flavored Dark Matter*, Phys. Lett. B **782** (2018) 517–522, [1712.00037].

[49] T. Li, N. Okada and Q. Shafi, *Scalar dark matter, Type II Seesaw and the DAMPE cosmic ray $e^+ + e^-$ excess*, Phys. Lett. B **779** (2018) 130–135, [1712.00869].

[50] K. Ghorbani and P. H. Ghorbani, *DAMPE electron-positron excess in leptophilic Z' model*, JHEP **05** (2018) 125, [1712.01239].

[51] Y. Sui and Y. Zhang, *Prospects of type-II seesaw models at future colliders in light of the DAMPE e^+e^- excess*, Phys. Rev. D **97** (2018) 095002, [1712.03642].

[52] Z.-L. Han, W. Wang and R. Ding, *Radiative Seesaw Model and DAMPE Excess from Leptophilic Gauge Symmetry*, Eur. Phys. J. C **78** (2018) 216, [1712.05722].

[53] E. Madge and P. Schwaller, *Leptophilic dark matter from gauged lepton number: Phenomenology and gravitational wave signatures*, JHEP **02** (2019) 048, [1809.09110].

[54] S. Junius, L. Lopez-Honorez and A. Mariotti, *A feeble window on leptophilic dark matter*, JHEP **07** (2019) 136, [1904.07513].

[55] N. F. Bell, G. Busoni and S. Robles, *Capture of Leptophilic Dark Matter in Neutron Stars*, JCAP **06** (2019) 054, [1904.09803].

[56] S. Yaser Ayazi and A. Mohamadnejad, *DAMPE excess from leptophilic vector dark matter: a*

model-independent approach, J. Phys. G **47** (2020) 095003, [1909.10729].

[57] A. Joglekar, N. Raj, P. Tanedo and H.-B. Yu, *Relativistic capture of dark matter by electrons in neutron stars*, Phys. Lett. **B** (2020) 135767, [1911.13293].

[58] S. Ghosh, A. Dutta Banik, E. J. Chun and D. Majumdar, *Leptophilic-portal dark matter in the light of AMS-02 positron excess*, Phys. Rev. D **104** (2021) 075016, [2003.07675].

[59] S. Chakraborti and R. Islam, *Implications of dark sector mixing on leptophilic scalar dark matter*, JHEP **03** (2021) 032, [2007.13719].

[60] N. F. Bell, G. Busoni, S. Robles and M. Virgato, *Improved Treatment of Dark Matter Capture in Neutron Stars II: Leptonic Targets*, JCAP **03** (2021) 086, [2010.13257].

[61] S.-I. Horigome, T. Katayose, S. Matsumoto and I. Saha, *Leptophilic fermion WIMP: Role of future lepton colliders*, Phys. Rev. D **104** (2021) 055001, [2102.08645].

[62] R. Garani, F. Gasparotto, P. Mastrolia, H. J. Munch, S. Palomares-Ruiz and A. Primo, *Two-photon exchange in leptophilic dark matter scenarios*, JHEP **12** (2021) 212, [2105.12116].

[63] R. Essig, J. Mardon and T. Volansky, *Direct Detection of Sub-GeV Dark Matter*, Phys. Rev. D **85** (2012) 076007, [1108.5383].

[64] R. Essig, M. Fernandez-Serra, J. Mardon, A. Soto, T. Volansky and T.-T. Yu, *Direct Detection of sub-GeV Dark Matter with Semiconductor Targets*, JHEP **05** (2016) 046, [1509.01598].

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

[66] SuperCDMS collaboration, R. Agnese et al., *First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector*, Phys. Rev. Lett. **121** (2018) 051301, [1804.10697].

[67] DarkSide collaboration, P. Agnes et al., *Constraints on Sub-GeV Dark-Matter–Electron Scattering from the DarkSide-50 Experiment*, Phys. Rev. Lett. **121** (2018) 111303, [1802.06998].

[68] DarkSide-50 collaboration, P. Agnes et al., *Search for dark matter particle interactions with electron final states with DarkSide-50*, 2207.11968.

[69] DAMIC collaboration, A. Aguilar-Arevalo et al., *Constraints on Light Dark Matter Particles Interacting with Electrons from DAMIC at SNOLAB*, Phys. Rev. Lett. **123** (2019) 181802, [1907.12628].

[70] EDELWEISS collaboration, Q. Arnaud et al., *First germanium-based constraints on sub-MeV Dark Matter with the EDELWEISS experiment*, Phys. Rev. Lett. **125** (2020) 141301, [2003.01046].

[71] SENSEI collaboration, M. Crisler, R. Essig, J. Estrada, G. Fernandez, J. Tiffenberg, M. Sofo haro et al., *SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run*, Phys. Rev. Lett. **121** (2018) 061803, [1804.00088].

[72] SENSEI collaboration, L. Barak et al., *SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD*, Phys. Rev. Lett. **125** (2020) 171802, [2004.11378].

[73] T. N. Maity, T. S. Ray and S. Sarkar, *Halo uncertainties in electron recoil events at direct detection experiments*, Eur. Phys. J. C **81** (2021) 1005, [2011.12896].

[74] PandaX-II collaboration, C. Cheng et al., *Search for Light Dark Matter-Electron Scatterings in the PandaX-II Experiment*, Phys. Rev. Lett. **126** (2021) 211803, [2101.07479].

[75] T. N. Maity and R. Laha, *Dark matter substructures affect dark matter-electron scattering in xenon-based direct detection experiments*, JHEP **02** (2023) 200, [2208.14471].

[76] S. Bhowmick, D. Ghosh and D. Sachdeva, *Blazar boosted Dark Matter – direct detection constraints on $\sigma_{e\chi}$: Role of energy dependent cross sections*, 2301.00209.

[77] D. Bardhan, S. Bhowmick, D. Ghosh, A. Guha and D. Sachdeva, *Bounds on boosted dark matter from direct detection: The role of energy-dependent cross sections*, Phys. Rev. D **107** (2023) 015010, [2208.09405].

[78] DAMIC-M collaboration, I. Arnquist et al., *First Constraints from DAMIC-M on Sub-GeV Dark-Matter Particles Interacting with Electrons*, 2302.02372.

[79] D. Wadekar and G. R. Farrar, *Gas-rich dwarf galaxies as a new probe of dark matter interactions with ordinary matter*, Phys. Rev. D **103** (2021) 123028, [1903.12190].

[80] Y. Ali-Haïmoud, *Testing dark matter interactions with CMB spectral distortions*, Phys. Rev. D **103** (2021) 043541, [2101.04070].

[81] D. V. Nguyen, D. Sarnaaik, K. K. Boddy, E. O. Nadler and V. Gluscevic, *Observational constraints on dark matter scattering with electrons*, Phys. Rev. D **104** (2021) 103521, [2107.12380].

[82] M. A. Buen-Abad, R. Essig, D. McKeen and Y.-M. Zhong, *Cosmological constraints on dark matter interactions with ordinary matter*, Phys. Rept. **961** (2022) 1–35, [2107.12377].

[83] C. Giovanetti, M. Lisanti, H. Liu and J. T. Ruderman, *Joint Cosmic Microwave Background and Big Bang Nucleosynthesis Constraints on Light Dark Sectors with Dark Radiation*, Phys. Rev. Lett. **129** (2022) 021302, [2109.03246].

[84] D. Bose, T. N. Maity and T. S. Ray, *Solar constraints on captured electrophilic dark matter*, Phys. Rev. D **105** (2022) 123013, [2112.08286].

[85] N. Bellomo, K. V. Berghaus and K. K. Boddy, *Dark matter freeze-in produces large post-inflationary isocurvature*, 2210.15691.

[86] S. Chatterjee and R. Laha, *Explorations of pseudo-Dirac dark matter having keV splittings and interacting via transition electric and magnetic dipole moments*, Phys. Rev. D **107** (2023) 083036, [2202.13339].

[87] IceCube collaboration, M. G. Aartsen et al., *Search for annihilating dark matter in the Sun with 3 years of IceCube data*, Eur. Phys. J. C **77** (2017) 146, [1612.05949].

[88] IceCube collaboration, R. Abbasi et al., *Search for GeV-scale dark matter annihilation in the Sun with IceCube DeepCore*, Phys. Rev. D **105** (2022) 062004, [2111.09970].

[89] P. Baratella, M. Cirelli, A. Hektor, J. Pata, M. Piibeleht and A. Strumia, *PPPC 4 DMν: a Poor*

Particle Physicist Cookbook for Neutrinos from Dark Matter annihilations in the Sun, *JCAP* **03** (2014) 053, [1312.6408].

[90] A. R. Zentner, *High-Energy Neutrinos From Dark Matter Particle Self-Capture Within the Sun*, *Phys. Rev. D* **80** (2009) 063501, [0907.3448].

[91] J. Silk, K. A. Olive and M. Srednicki, *The Photino, the Sun and High-Energy Neutrinos*, *Phys. Rev. Lett.* **55** (1985) 257–259.

[92] L. M. Krauss, K. Freese, W. Press and D. Spergel, *Cold dark matter candidates and the solar neutrino problem*, *Astrophys. J.* **299** (1985) 1001.

[93] M. Srednicki, K. A. Olive and J. Silk, *High-Energy Neutrinos from the Sun and Cold Dark Matter*, *Nucl. Phys. B* **279** (1987) 804–823.

[94] K.-W. Ng, K. A. Olive and M. Srednicki, *Dark Matter Induced Neutrinos From the Sun: Theory Versus Experiment*, *Phys. Lett. B* **188** (1987) 138.

[95] S. Ritz and D. Seckel, *Detailed Neutrino Spectra From Cold Dark Matter Annihilations in the Sun*, *Nucl. Phys. B* **304** (1988) 877–908.

[96] K. A. Olive and M. Srednicki, *Solar Neutrino Searches and Cold Dark Matter*, *Phys. Lett. B* **205** (1988) 553.

[97] Super-Kamiokande collaboration, S. Desai et al., *Search for dark matter WIMPs using upward through-going muons in Super-Kamiokande*, *Phys. Rev. D* **70** (2004) 083523, [hep-ex/0404025].

[98] M. Cirelli, N. Fornengo, T. Montaruli, I. A. Sokalski, A. Strumia and F. Vissani, *Spectra of neutrinos from dark matter annihilations*, *Nucl. Phys. B* **727** (2005) 99–138, [hep-ph/0506298].

[99] O. Mena, S. Palomares-Ruiz and S. Pascoli, *Reconstructing WIMP properties with neutrino detectors*, *Phys. Lett. B* **664** (2008) 92–96, [0706.3909].

[100] C. Savage, G. Gelmini, P. Gondolo and K. Freese, *Compatibility of DAMA/LIBRA dark matter detection with other searches*, *JCAP* **04** (2009) 010, [0808.3607].

[101] D. Hooper, F. Petriello, K. M. Zurek and M. Kamionkowski, *The New DAMA Dark-Matter Window and Energetic-Neutrino Searches*, *Phys. Rev. D* **79** (2009) 015010, [0808.2464].

[102] P. Agrawal, E. M. Dolle and C. A. Krenke, *Signals of Inert Doublet Dark Matter in Neutrino Telescopes*, *Phys. Rev. D* **79** (2009) 015015, [0811.1798].

[103] A. H. G. Peter, *Dark matter in the solar system II: WIMP annihilation rates in the Sun*, *Phys. Rev. D* **79** (2009) 103532, [0902.1347].

[104] S. M. Koushiappas and M. Kamionkowski, *Galactic Substructure and Energetic Neutrinos from the Sun and the Earth*, *Phys. Rev. Lett.* **103** (2009) 121301, [0907.4778].

[105] V. Niro, A. Bottino, N. Fornengo and S. Scopel, *Investigating light neutralinos at neutrino telescopes*, *Phys. Rev. D* **80** (2009) 095019, [0909.2348].

[106] J. Ellis, K. A. Olive, C. Savage and V. C. Spanos, *Neutrino Fluxes from CMSSM LSP Annihilations in the Sun*, *Phys. Rev. D* **81** (2010) 085004, [0912.3137].

[107] V. Barger, Y. Gao and D. Marfatia, *Dark matter at DeepCore and IceCube*, *Phys. Rev. D* **83** (2011) 055012, [1101.4410].

[108] IceCube collaboration, R. Abbasi et al., *Multi-year search for dark matter annihilations in the Sun with the AMANDA-II and IceCube detectors*, *Phys. Rev. D* **85** (2012) 042002, [1112.1840].

[109] N. F. Bell, A. J. Brennan and T. D. Jacques, *Neutrino signals from electroweak bremsstrahlung in solar WIMP annihilation*, *JCAP* **10** (2012) 045, [1206.2977].

[110] N. Bernal, J. Martín-Albo and S. Palomares-Ruiz, *A novel way of constraining WIMPs annihilations in the Sun: MeV neutrinos*, *JCAP* **08** (2013) 011, [1208.0834].

[111] H. Silverwood, P. Scott, M. Danninger, C. Savage, J. Edsjö, J. Adams et al., *Sensitivity of IceCube-DeepCore to neutralino dark matter in the MSSM-25*, *JCAP* **03** (2013) 027, [1210.0844].

[112] IceCube collaboration, M. G. Aartsen et al., *Search for dark matter annihilations in the Sun with the 79-string IceCube detector*, *Phys. Rev. Lett.* **110** (2013) 131302, [1212.4097].

[113] A. Ibarra, M. Totzauer and S. Wild, *High-energy neutrino signals from the Sun in dark matter scenarios with internal bremsstrahlung*, *JCAP* **12** (2013) 043, [1311.1418].

[114] K. Choi, C. Rott and Y. Itow, *Impact of the dark matter velocity distribution on capture rates in the Sun*, *JCAP* **05** (2014) 049, [1312.0273].

[115] R. Allahverdi, S. S. Campbell, B. Dutta and Y. Gao, *Dark matter indirect detection signals and the nature of neutrinos in the supersymmetric $U(1)_{B-L}$ extension of the standard model*, *Phys. Rev. D* **90** (2014) 073002, [1405.6253].

[116] J. Kumar and P. Sandick, *Searching for Dark Matter Annihilation to Monoenergetic Neutrinos with Liquid Scintillation Detectors*, *JCAP* **06** (2015) 035, [1502.02091].

[117] R. Catena, *Dark matter signals at neutrino telescopes in effective theories*, *JCAP* **04** (2015) 052, [1503.04109].

[118] Super-Kamiokande collaboration, K. Choi et al., *Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande*, *Phys. Rev. Lett.* **114** (2015) 141301, [1503.04858].

[119] ANTARES collaboration, S. Adrian-Martinez et al., *Search of Dark Matter Annihilation in the Galactic Centre using the ANTARES Neutrino Telescope*, *JCAP* **10** (2015) 068, [1505.04866].

[120] R. Allahverdi, B. Dutta, D. K. Ghosh, B. Knockel and I. Saha, *Distinguishing Neutrino Mass Hierarchies using Dark Matter Annihilation Signals at IceCube*, *JCAP* **12** (2015) 003, [1506.08285].

[121] M. Danninger and C. Rott, *Solar WIMPs unravelled: Experiments, astrophysical uncertainties, and interactive tools*, *Phys. Dark Univ.* **5-6** (2014) 35–44, [1509.08230].

[122] C. Rott, S. In, J. Kumar and D. Yaylali, *Dark Matter Searches for Monoenergetic Neutrinos Arising from Stopped Meson Decay in the Sun*, *JCAP* **11** (2015) 039, [1510.00170].

[123] J. L. Feng, J. Smolinsky and P. Tanedo, *Detecting dark matter through dark photons from the Sun: Charged particle signatures*, *Phys. Rev. D* **93** (2016) 115036, [1602.01465].

[124] J. Lopes and I. Lopes, *New Limits on Thermally annihilating Dark Matter from Neutrino Telescopes*, *Astrophys. J.* **827** (2016) 130, [1607.08672].

[125] R. Catena and A. Widmark, *WIMP capture by the Sun*

in the effective theory of dark matter self-interactions, *JCAP* **12** (2016) 016, [1609.04825].
[126] S. Baum, L. Visinelli, K. Freese and P. Stengel, *Dark matter capture, subdominant WIMPs, and neutrino observatories*, *Phys. Rev. D* **95** (2017) 043007, [1611.09665].
[127] R. Allahverdi, Y. Gao, B. Knockel and S. Shalgar, *Indirect Signals from Solar Dark Matter Annihilation to Long-lived Right-handed Neutrinos*, *Phys. Rev. D* **95** (2017) 075001, [1612.03110].
[128] J. Smolinsky and P. Tanedo, *Dark Photons from Captured Inelastic Dark Matter Annihilation: Charged Particle Signatures*, *Phys. Rev. D* **95** (2017) 075015, [1701.03168].
[129] A. Widmark, *Thermalization time scales for WIMP capture by the Sun in effective theories*, *JCAP* **05** (2017) 046, [1703.06878].
[130] N. Fornengo, A. Masiero, F. S. Queiroz and C. E. Yaguna, *On the Role of Neutrinos Telescopes in the Search for Dark Matter Annihilations in the Sun*, *JCAP* **12** (2017) 012, [1710.02155].
[131] S. V. Demidov, *Non-standard interactions and neutrinos from dark matter annihilation in the Sun*, *JCAP* **02** (2018) 001, [1711.00911].
[132] HAWC collaboration, A. Albert et al., *Constraints on Spin-Dependent Dark Matter Scattering with Long-Lived Mediators from TeV Observations of the Sun with HAWC*, *Phys. Rev. D* **98** (2018) 123012, [1808.05624].
[133] C. Rott, D. Jeong, J. Kumar and D. Yaylali, *Neutrino Topology Reconstruction at DUNE and Applications to Searches for Dark Matter Annihilation in the Sun*, *JCAP* **07** (2019) 006, [1903.04175].
[134] C. Niblaeus, A. Beniwal and J. Edsjo, *Neutrinos and gamma rays from long-lived mediator decays in the Sun*, *JCAP* **11** (2019) 011, [1903.11363].
[135] A. Nuñez Castiñeyra, E. Nezri and V. Bertin, *Dark matter capture by the Sun: revisiting velocity distribution uncertainties*, *JCAP* **12** (2019) 043, [1906.11674].
[136] A. Brenner, A. Ibarra and A. Rappelt, *Conservative constraints on the effective theory of dark matter-nucleon interactions from IceCube: the impact of operator interference*, *JCAP* **07** (2021) 012, [2011.02929].
[137] J. F. Acevedo, J. Bramante, A. Goodman, J. Kopp and T. Opferkuch, *Dark Matter, Destroyer of Worlds: Neutrino, Thermal, and Existential Signatures from Black Holes in the Sun and Earth*, *JCAP* **04** (2021) 026, [2012.09176].
[138] N. F. Bell, J. B. Dent and I. W. Sanderson, *Solar gamma ray constraints on dark matter annihilation to secluded mediators*, *Phys. Rev. D* **104** (2021) 023024, [2103.16794].
[139] N. F. Bell, M. J. Dolan and S. Robles, *Searching for dark matter in the Sun using Hyper-Kamiokande*, *JCAP* **11** (2021) 004, [2107.04216].
[140] M. Zakeri and Y.-F. Zhou, *Constraining time dependent dark matter signals from the Sun*, *JCAP* **04** (2022) 026, [2109.11662].
[141] N. Vinyoles, A. M. Serenelli, F. L. Villante, S. Basu, J. Bergström, M. C. Gonzalez-Garcia et al., *A new Generation of Standard Solar Models*, *Astrophys. J.* **835** (2017) 202, [1611.09867].
[142] R. Garani and S. Palomares-Ruiz, *Evaporation of dark matter from celestial bodies*, *JCAP* **05** (2022) 042, [2104.12757].
[143] Q. Liu, J. Lazar, C. A. Argüelles and A. Kheirandish, *$\chi aro\nu$: a tool for neutrino flux generation from WIMPs*, *JCAP* **10** (2020) 043, [2007.15010].
[144] M. Blennow, J. Edsjo and T. Ohlsson, *Neutrinos from WIMP annihilations using a full three-flavor Monte Carlo*, *JCAP* **01** (2008) 021, [0709.3898].
[145] P. Gondolo, J. Edsjo, P. Ullio, L. Bergstrom, M. Schelke and E. A. Baltz, *DarkSUSY: Computing supersymmetric dark matter properties numerically*, *JCAP* **07** (2004) 008, [astro-ph/0406204].
[146] T. Bringmann, J. Edsjö, P. Gondolo, P. Ullio and L. Bergström, *DarkSUSY 6 : An Advanced Tool to Compute Dark Matter Properties Numerically*, *JCAP* **07** (2018) 033, [1802.03399].
[147] C. W. Bauer, N. L. Rodd and B. R. Webber, *Dark matter spectra from the electroweak to the Planck scale*, *JHEP* **06** (2021) 121, [2007.15001].
[148] I. F. M. Albuquerque, L. Hui and E. W. Kolb, *High-energy neutrinos from superheavy dark matter annihilation*, *Phys. Rev. D* **64** (2001) 083504, [hep-ph/0009017].
[149] C. A. Argüelles, J. Salvado and C. N. Weaver, *nuSQuIDS: A toolbox for neutrino propagation*, *Comput. Phys. Commun.* **277** (2022) 108346, [2112.13804].
[150] K. Griest and M. Kamionkowski, *Unitarity Limits on the Mass and Radius of Dark Matter Particles*, *Phys. Rev. Lett.* **64** (1990) 615.
[151] I. M. Shoemaker and L. Vecchi, *Unitarity and Monojet Bounds on Models for DAMA, CoGeNT, and CRESST-II*, *Phys. Rev. D* **86** (2012) 015023, [1112.5457].
[152] IceCube collaboration, M. G. Aartsen et al., *Measurement of Atmospheric Neutrino Oscillations at 6–56 GeV with IceCube DeepCore*, *Phys. Rev. Lett.* **120** (2018) 071801, [1707.07081].
[153] C. A. Argüelles, G. de Wasseige, A. Fedynitch and B. J. P. Jones, *Solar Atmospheric Neutrinos and the Sensitivity Floor for Solar Dark Matter Annihilation Searches*, *JCAP* **07** (2017) 024, [1703.07798].
[154] K. C. Y. Ng, J. F. Beacom, A. H. G. Peter and C. Rott, *Solar Atmospheric Neutrinos: A New Neutrino Floor for Dark Matter Searches*, *Phys. Rev. D* **96** (2017) 103006, [1703.10280].
[155] J. Edsjo, J. Elevant, R. Enberg and C. Niblaeus, *Neutrinos from cosmic ray interactions in the Sun*, *JCAP* **06** (2017) 033, [1704.02892].
[156] Hyper-Kamiokande collaboration, K. Abe et al., *Hyper-Kamiokande Design Report*, 1805.04163.
[157] KM3Net collaboration, S. Adrian-Martinez et al., *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001, [1601.07459].
[158] IceCube-Gen2 collaboration, K. Clark, *Status of the PINGU detector*, *PoS* **ICRC2015** (2016) 1174.
[159] Baikal-GVD collaboration, A. A. D. et al., *Baikal-GVD: status and first results*, *PoS* **ICHEP2020** (2021) 606, [2012.03373].
[160] IceCube-Gen2 collaboration, B. Clark, *The IceCube-Gen2 Neutrino Observatory*, *JINST* **16** (2021) C10007, [2108.05292].

Supplementary Material
Neutrinos from the Sun can discover dark matter-electron scattering

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Other final states: Here we present our limits for other considered DM annihilation final states. For e^+e^- final state, the limit is presented above DM mass 500 GeV since EW bremsstrahlung is the only source of producing neutrinos and our bound is competitive to the extrapolated XENON1T bound, as shown in Fig. 3. For $\nu\bar{\nu}$ final state our bounds are stronger than the previously obtained bounds in DM matter mass range $10 - 10^5$ GeV, as depicted in Fig. 4. The steep rise in DeepCore (2016) bound (red solid line in Fig. 4) from DM mass 130 GeV to 140 GeV is due to absence of the angular resolution beyond neutrino energy ~ 139 GeV in Ref. [87] and thus missing peak of the spectrum for rest of the DM masses $\gtrsim 140$ GeV.

Equilibrium time: In Fig. 5, we present the contours where captured DM equilibrium time scale is equal to Solar age. The teal, dark blue, orange color lines are for DM masses 10 GeV, 100 GeV, and 900 GeV respectively. Above these lines (indicated by the arrows) captured DM equilibrium time scale would be less than the Solar age. We also show bounds obtained with captured DM annihilation to $\nu\bar{\nu}$ in this work for aforesaid DM masses by the star, dagger, and diamond for typical choice of thermal relic cross section. Clearly even for a smaller choice of thermally averaged annihilation cross section, DM would also equilibrate inside the Sun for the achieved DM-electron scattering cross section.

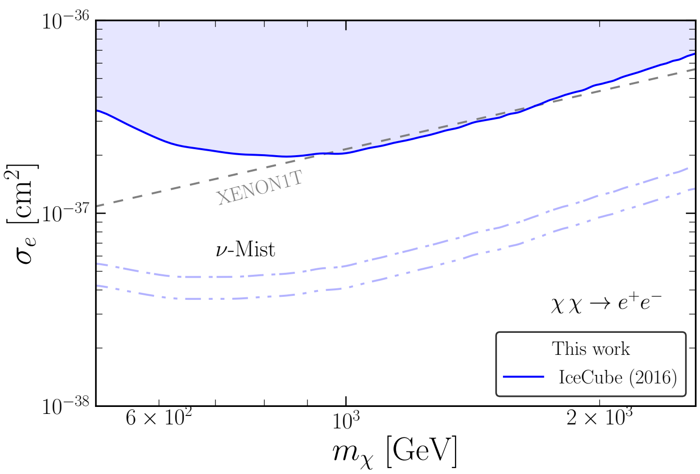

FIG. 3. Excluded region of the DM-electron scattering cross section. Other relevant details are same as Fig. 1 but for e^+e^- final state.

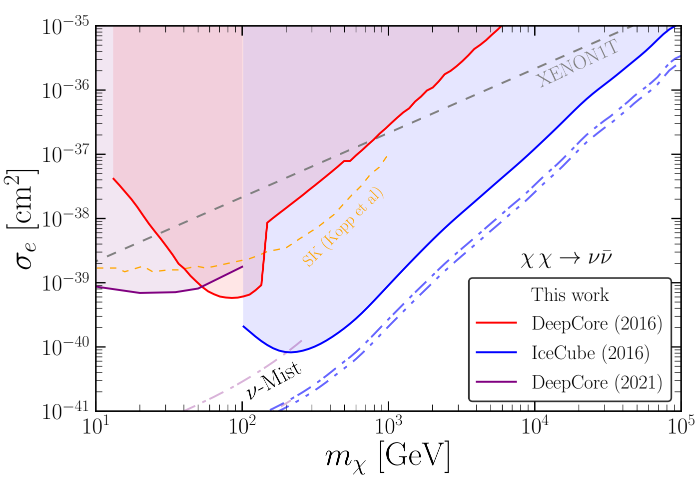

FIG. 4. Excluded region of the DM-electron scattering cross section. Other relevant details are same as Fig. 1 but for $\nu\bar{\nu}$ final state.

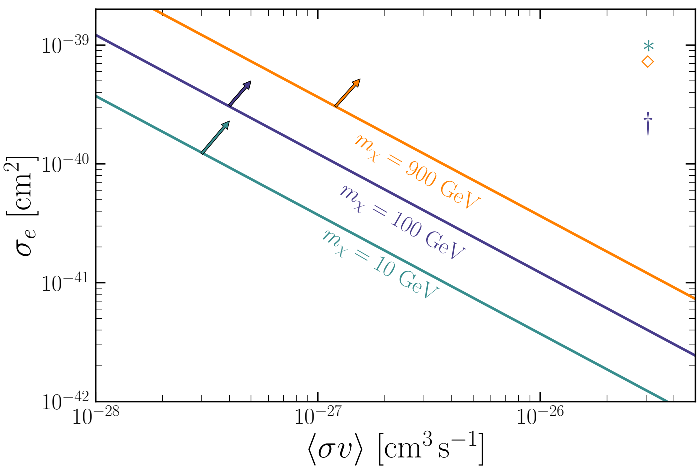

FIG. 5. The different colored solid lines indicate the contours above (on) which captured DM equilibrium time scale will be greater than (equal to) the Solar age for different DM masses, as mentioned in the figure. For completeness we have also shown our bounds assuming annihilation cross-section $\langle\sigma v\rangle = 3\times10^{-26}\text{cm}^3\text{s}^{-1}$ to $\nu\bar{\nu}$ by the star, dagger, and diamond for DM masses 10 GeV, 100 GeV, and 900 GeV respectively.