Neutrino Floor in Leptophilic $U(1)$ Models: Modification in $U(1)_{L\mu-L\tau}$

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In this work, we investigate the beyond standard model (BSM) impact of leptophilic $U(1)$ models, namely $U(1)_{L\mu-L\tau}$, $U(1)_{L\nu-L\tau}$ and $U(1)_{L\mu-L\tau}$ on coherent elastic neutrino-nucleus scattering (CE$\nu$NS) and hence its effect on dark matter (DM) direct detection experiments. Imposing the latest relevant experimental constraints on these models, we obtain $\mathcal{O}(50\%)$ enhancement for case of $U(1)_{L\mu-L\tau}$ in a region $m'_{Z} \approx 20$ MeV. Subsequently, we observe that the enhancement seen in CE$\nu$NS is roughly getting translated to enhancement by a factor of 2.7 (for Germanium based detectors) and 1.8 (for Xenon based detectors) in the neutrino scattering event rate which eventually enhances the neutrino floor by same amount. This enhancement is more prominent in the region with DM masses less than 10 GeV. The model parameter space that leads to this enhancement, can simultaneously explain both anomalous magnetic moment of muon ($\mathcal{g}_-^2 \mu$) and observed DM relic density, in a modified scenario. Enhancement of neutrino floor requires increased number of DM-nucleon scattering events in the future DM direct detection experiments, to establish themselves to be DM signal events. In absence of any DM signal, those experiments can directly be used to measure the neutrino rate, quantifying the BSM effects.

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I. INTRODUCTION AND MOTIVATION

The majority of the matter present in our Universe is in the form of a non-luminous matter called dark matter (DM). Its presence is well motivated through astro-physical observations like galactic rotational curves and gravitational lensing etc. Particle candidates of DM are well motivated by WIMP (weakly interacting massive particle) miracle, where we expected a DM at TeV scale with interaction strength typical to have correct DM relic density. Such DM candidates were incorporated in beyond standard model (BSM) theories in numerous ways; Inert Higgs Doublet, Right handed neutrino and Super-symmetry are few of them to be named. But till date, no conclusive observational evidence of the presence of such a particle is found either in the LHC, specifically designed to probe the TeV scale physics, or in the DM direct and indirect detection experiments. The search for the DM particles are on through different DM direct and detection experiments, albeit with a renewed vigor directed to find DM particles at a lower mass scale.

DM direct detection relies on the measurement of its recoil energies due to the DM scattering with detector material. While direct detection experiments like Xenon1T[1], PandaX[2], LUX [3] etc are yet to find evidence of the DM, one silicon based CDMS-II [4] detector reported three dark matter scattering events, which are in a conflict with null observation from other experiments. The possibility of these three events coming from fluctuation of the standard background to the DM signal is significantly low (∼5.4%) [4]. However, if presence of beyond the SM physics can substantially modify the known background then a stronger argument can be made in favor of null results from other direct detection experiments.

Being neutral and weakly interacting, similar to how the DM candidates also interact, neutrino recoil can mimic the DM signal. Therefore, the neutrino events can pose as significant background to the DM events, aided by their relative prevalence in the nature, i.e. the high flux rate of the solar neutrinos. Direct detection experiments involve signals with nuclear recoil energies upto 100 KeV. With this scale of nuclear recoil, the momentum transfer is sufficiently small so that scattering amplitudes from individual nucleons can coherently add up to provide the ν-nuclear scattering, enhanced proportionally to total number of nucleons. This type of scattering, as observed in recent COHERENT[5] experiment, is known as coherent elastic neutrino nucleus scattering (CEνNS). With increasing sensitivity and exposure of the direct detection experiments, DM exclusion plots are excluding more of the parameter space and approaching the parameter region where it will become difficult to differentiate (with 90 % C.L.) DM-nucleus scattering events from the neutrino-nucleus ones. This region in the $a_\nu^0 - m_{DM}$ plane, where the neutrino background remains indistinguishable from possible DM signals is termed Neutrino Floor. Any significant enhancement in the neutrino floor can raise the background in DM direct detection experiments and can therefore lead to fake positive DM signal events. Even in the absence of DM signal detection, DM experiments still can be used to directly probe the different neutrino flux induced events, once the experiments become sensitive to neutrino floor deciphering the DM signal events. Even in the absence of DM signal detection, DM experiments still can be used to directly probe the different neutrino flux induced events, once the experiments become sensitive to neutrino floor deciphering the DM signal events. Even in the absence of DM signal detection, DM experiments still can be used to directly probe the different neutrino flux induced events, once the experiments become sensitive to neutrino floor deciphering the DM signal events. Even in the absence of DM signal detection, DM experiments still can be used to directly probe the different neutrino flux induced events, once the experiments become sensitive to neutrino floor deciphering the DM signal events. Even in the absence of DM signal detection, DM experiments still can be used to directly probe the different neutrino flux induced events, once the experiments become sensitive to neutrino floor deciphering the DM signal events. Even in the absence of DM signal detection, DM experiments still can be used to directly probe the different neutrino flux induced events, once the experiments become sensitive to neutrino floor deciphering the DM signal events.

In this work, we investigate a set of leptophilic models, $U(1)_{L_\mu - L_\tau}$, $U(1)_{L_e - L_\tau}$, and $U(1)_{L_\mu - L_\tau}$, where neutrino quark couplings arise only at one loop level and, due to this suppression, are therefore expected to modify the neutrino-nucleus recoil rate and the neutrino floor minimally. Still, a provision of a very light $Z'$ is still there in these models, as this suppression can lead to relaxed constraints from proton beam dump and hadronic colliders. Further, due to absence of $Z'$ boson couplings to the $e^+e^-$ in the case of $U(1)_{L_e - L_\tau}$ model, electron beam dump experiments put no constraints on low $Z'$ mass region of the parameter space, which is also central to presence of a light DM with observed relic density. These $U(1)$ models are also well motivated by results from DM indirect detection experiments (i.e. DAMPE [7] and AMS02 [8] etc ), along with the possible explanation of $e^+e^-$ excess observed in cosmic rays through DM annihilation to leptons via $Z'$. In this parameter region of $U(1)_{L_\mu - L_\tau}$, there is an extra contribution through $Z' - \gamma$ in the CEνNS process, paving way to its significant enhancement compared to the SM value, aided by the lightness of the $Z'$ boson. This can potentially lead to excess amount of neutrino recoils, preferably in the low recoil energy domain. This increment can essentially lead to an enhancement in the neutrino events background present in DM direct detection experiments, which translates to more DM-nucleon cross section region being not viable to distinguish DM events from neutrino events, therefore, resulting in an upliftment of the neutrino floor.

Any new interactions which can modify CEνNS can also potentially alter the neutrino floor profile. Effective operators inducing Non Standard Interactions (NSI) [9] between neutrinos and quark have been studied in this connection. Vector and Scalar current NSIs show significant enhancements, especially for scalar where augmentation of $\mathcal{O}(20\%)$ can be seen in neutrino floor. Simplified models involving new mediators also have been studied in this context [10]. Amplification by several orders in case of scalar mediators and by a factor of 2 in case of vector mediator was seen in neutrino floor in DM mass less than 10 GeV. Studies also exist where $Z'$ boson arising in $U(1)_X$ models such as B-L and B-L$(3)$[10], can induce direct tree level coupling between neutrinos and quarks can modify the neutrino floor.
Plan of the paper is as follows. In the section II, we briefly discuss the model details and Lagrangian interaction terms of $U(1)_{L_\mu - L_\tau}, U(1)_{L_\mu - L_e}$, and $U(1)_{L_\tau - L_e}$ models. Constraints on the parameter space in these models are also briefly discussed. In section III, we investigate the modification of CE/NS rate together the combined experimental constraints in the models. Next we study the change in CE/NS event rate induced by incoming neutrino flux for the case $U(1)_{L_\mu - L_\tau}$, compared to the SM, which can appear as a background to DM signal in direct detection experiments. We choose Germanium and Xenon based detectors for their ability to scan different parameter regions of dark matter mass. In the section IV, we study the modification of neutrino floor and investigate its impact in future dark matter experiments. Finally, in section V we summarize, along with a discussion of results.

II. MODEL

In this article we have considered the minimal $U(1)_X$ extensions to standard model which could lead to significant non standard interaction between neutrino and nucleus which can serve as background to direct detection of dark matter. Minimal standard model with three generation gives rise to four independent global $U(1)$ symmetries, electron-lepton number $(U(1)_{L_e})$, muon-lepton number $(U(1)_{L_\mu})$, tau-lepton number $(U(1)_{L_\tau})$ and baryon number $(U(1)_B)$. out of which, three combinations, namely $(U(1)_{L_\mu - L_e}), (U(1)_{L_\mu - L_\tau})$, and $(U(1)_{L_\tau - L_e})$ are free of gauge anomaly [11–13] without extending the SM with extra particles. $U(1)_{B-L}$ is also anomaly free with introduction of right-handed Neutrinos [6] and leads to modification of Neutrino floor, but we will refrain from discussing it here as it has already been discussed in [10]. In what follows we will denote $U(1)_{L_\mu - L_\tau} \equiv U(1)_{\mu - \tau}$.

In $U(1)_{\mu - \tau}$ models, the additional $U(1)$ symmetry can be spontaneously broken by introduction of a new scalar $S$, which leads to the $Z'$ boson obtaining a finite mass via a non-trivial coupling to $S$ [14]. With new these new particles we can write the additional terms beside the SM as,

$$L_{\text{new}} = -\frac{1}{4} Z^\mu_\nu Z^\nu_\mu + \sum_l \tilde{l}_j^\mu (-g_{i-j} Y_l^i Z'_\mu) l + (D_\mu S)^\dagger (D^\mu S) + \mu^2 S^\dagger S + \lambda_S (S^\dagger S)^2 + \lambda_{SH} (S^\dagger S) H^\dagger H$$

(1)

here $S$ is the new scalar where $\mu^2$ and $\lambda_S$ are co-efficients of bilinear and quartic self interactions respectively, which couples with SM Higgs $H$ via quartic coupling $\lambda_{SH}$ . $Z'$ boson couples with leptons $l$ through $Y_l^i = L_i - L_j$ for respective $U(1)_{\mu - \tau}$ model, highlighted by the interaction term,

$$L_i - L_f = -g_{i-j}(\tilde{l}_i^\gamma \gamma l_i - \tilde{l}_j^\gamma \gamma l_j + \bar{\nu}_i \gamma^\mu L\nu_i - \bar{\nu}_j \gamma^\mu L\nu_j)Z'_\mu .$$

(2)

The presence of an extra gauge boson $Z'$ in the leptophobic $U(1)$ models can potentially act as a new mediator and open up new annihilation channels in the dark matter scenario, when the dark matter couples to the $Z'$. When a DM candidate couples to $Z'$, then resultant DM annihilations to leptons can be interpreted as observed and expected electron (positron) excess in the DM indirect detection experiments. A vector like fermion dark matter [14–17] is highlighted by the interaction term,

$$\delta_{ij} = \frac{1}{(2\pi)^2}[\log^{-1} K^2 + g^{\prime\mu\nu} l^2] \int_0^1 dx \left( \frac{x(x-1)l^2 + m_i^2}{x(x-1)l^2 + m_j^2} \right) x(1-x)$$

(3)

through the feynman diagram [17, 20] shown in figure 1a. Similarly neutrino-nuclear interactions mediated by figure 1b will serve as the chief BSM background to dark matter Direct-detection in considered models. A scalar DM [21] candidate can also be introduced where the gauge anomaly is taken care of by other new particles.
Following different constraints discussed in the Ref. [6], the limits on $U(1)_{\mu-e}$, $U(1)_{\mu-\tau}$ and $U(1)_{\mu-\gamma}$ models are presented here. The major constraints on these models come from various beam dump experiments [22–24]. In the electron beam dump experiments like E137, E141 (SLAC), E774 (Fermilab) etc where electron beam falls on detector material and the dielectric state final state cross section is measured. The electron production through light $Z'$ boson is possible in the models $U(1)_{\mu-\tau}$, $U(1)_{\mu-\nu}$ where the light boson decays to electron only through loop effects, the constraints from the electron beam dump experiments become less stringent. For the leptophilic models like these, due to absence of direct quark interaction, cannot be constrained by the proton beam dump experiments. Borexino[25] and TEXONO[26] experiments measure the cross sections of the processes where neutrinos scatter off the electron i.e. the $\nu_\tau - e$ process. These processes will be significantly modified where the light $Z'$ couples to the electron along with different neutrinos, while for the $U(1)_{\mu-\gamma}$, these interaction only happen through a $Z - Z'$ mixing, and therefore constraints are less stringent. In the neutrino trident production process like $\nu_\mu Z \to \nu_\mu \mu^+ \mu^-$ which is measured in the neutrino experiments like CCFR, Charm-II [27], nuTEV etc can provide not so suppressed contributions through the light $Z'$ for the $U(1)$ models having direct $\mu$ couplings i.e. $U(1)_{\mu-\tau}, U(1)_{\mu-\nu}$, while the constraint will be way weaker for $U(1)_{\mu-\gamma}$. Presence of new leptonic forces [28] can contribute to matter effects for neutrino oscillations. Due to this effect Super-K provides additional constraints for $U(1)_{\mu-e}$, $U(1)_{\mu-\tau}$, while $U(1)_{\mu-\gamma}$ remains insensitive. COHERENT experiment currently only has preliminary CEνNS measurement which does not put stringent constraints.

III. NEUTRINO-NUCLEUS INTERACTION RATE

In context of DM direct detection experiments, incident neutrinos with energies upto tens of MeV can coherently interact with the nucleus of detecting material producing nuclear recoils, which are hard to differentiate against DM nuclear interactions. Due to the weak nature of neutrino interactions, the detectors are impossible to shield against them. Even without the detection of DM candidates, with increased exposure time and incident flux, experiments can detect coherent neutrino nucleus scattering [5] and provide us with the opportunity to probe new neutrino physics.

In the process of coherent neutrino-nucleus scattering (CEνNS) introduced in Ref. [29], for small momentum transfer i.e. $qR \leq 1$, where $q$ and $R$ are momentum transfer and radius of the target nucleus respectively, the incident neutrino can scatter with the entire nucleus coherently. In general CEνNS can lead to nuclear recoils upto a few KeVs, which in the case of $Xe^{131}$ target is translated to incident neutrino energies upto $\approx 50$ MeV. While, in the Standard Model, the interaction is mediated by $Z^0$ boson, with the presence of light $Z'$ boson in $U(1)_{\mu-\gamma}$ model, CEνNS is further augmented by $Z' - Z^0/\gamma$ mixing. In the regime when nuclear recoil energies are at most few hundred KeVs, the dominant CEνNS due to extra $Z'$ boson will be mediated by $Z' - \gamma$ as shown in Fig. 1b.

Taking into account the effects of the mixing, the total neutrino-nucleus differential scattering cross-section in $U(1)_{\mu-\gamma}$ can be written as

$$
\frac{d\sigma_{\gamma,j}}{dE_{\gamma}} = \frac{d\sigma_{SM}}{dE_{\gamma}} - m_N G_f Q_{\nu N i-j} Q_{\nu N} \left(1 - \frac{E_r m_N}{2E_{\gamma}^2} \right) F^2(E_{\gamma}) \frac{1}{\sqrt{2\pi} (2E_r m_N + m_{Z'}^2)} \left(1 - \frac{E_r m_N}{2E_{\gamma}^2} \right) F^2(E_{\gamma}),
$$

(4)

where as the SM counterpart for the neutrino-nucleus scattering process is given by,

$$
\frac{d\sigma_{SM}}{dE_{\gamma}} = G_f^2 m_N^2 Q^2_{\nu N} \left(1 - \frac{E_{\gamma} m_N}{2E_{\gamma}^2} \right) F^2(E_{\gamma}).
$$

(5)
Here $G_F$ is the Fermi constant, $Q_{eN} = N - (1 - 4 \sin^2 \theta_W) Z$ is effective weak hyper-charge in the SM for the target nucleus with $N$ neutrons and $Z$ protons and $F(E_r)$ is the Helm form factor given in Ref. [30], that exhibits the loss of coherence above recoil energies of $\approx 10$ KeV. The effective weak interaction vertex in the neutrino part for the BSM case of $U(1)_{i-j}$ model can be written as,

$$ Q_{\nu N i-j} = g_{i-j}^2 \frac{2 \alpha_{EM}}{m_N} \delta_{ij} Z $$

where $g_{i-j}$ is coupling given in Eq. 2, $\alpha_{EM}$ is the fine structure constant and $\delta_{ij}$ is the loop factor.

To discern the beyond standard model effect of these models, we define a ratio,

$$ \frac{\sigma_{i-j}}{\sigma_{SM}} = \frac{\int_{E_r}^{E_r^{max}} \frac{d\sigma_{i-j}}{dE_r} dE_r}{\int_{E_r}^{E_r^{max}} \frac{d\sigma_{SM}}{dE_r} dE_r}, $$

where $E_r^{max} \approx \frac{2(E_\nu)^2}{m_N}$, when we assume energy transfer to be almost full. This quantity measures the ratio of neutrino-nucleus scattering cross-section of $U(1)_{i-j}$ to that of the SM. With the assumption that the incident neutrino beam comprises of $\nu_e, \nu_\mu$, the $U(1)_{e-\mu}$ model gets contributions from both leading to destructive interference in the CE$\nu$NS, where as $U(1)_{e-\tau}$, and $U(1)_{\mu-\tau}$ get contributions from the $\nu_e$ and $\nu_\mu$ respectively, as in the latter case $\nu_e$ does not couple to $Z'$ of the model.

FIG. 2: We show parameter regions disallowed (shaded) by experiments [6] in $g_{i-j}$ vs $m_{Z'}$ (GeV) planes for $U(1)_{e-\mu}$, $U(1)_{e-\tau}$ and $U(1)_{\mu-\tau}$ models. Green scatter points are measures of $\frac{\sigma_{i-j}}{\sigma_{SM}}$ as specified in each case for Ge$^{68}$.
In Fig. 2 we check the BSM significance of $U(1)_{i-j}$ models by computing the ratio $(R_{i-j} = \frac{g_{i-j}}{m_{Z'}})$ defined in Eq. 7 in the parameter region allowed by experiments discussed in the Ref. [6]. The shaded regions in the $g_{i-j} vs m_{Z'}$ plane in the Fig. 2a and Fig. 2b represent the parameter space ruled out from combined constraints from different experiments, respectively for the $U(1)_{\mu}$ and $U(1)_{e-\tau}$ models. The green dots are combinations of $(g_{i-j}, m_{Z'})$ such that $R_{i-j} \geq 1.05$ in each case. In Fig. 2c and Fig. 2d, green dots signify the combination of $(g_{i-j}, m_{Z'})$ such that $R_{i-j} \geq 1.05$ and $R_{i-j} \geq 1.5$ respectively for $U(1)_{e-\tau}$ model each. For the case of $U(1)_{e-\mu}$ and $U(1)_{e-\tau}$ models, it is observed that the points with 5% enhancement in the CEνNS lie in the shaded region, leading us to decipher that even 5% increment is not possible due to the BSM effects within the allowed parameter space. On the other hand, for the $U(1)_{\mu-\tau}$ model, CEνNS enhancement of as high as 50% can be achieved in the allowed region. This peculiarity can be attributed to relaxation of constraints from experiments involving $\nu_e$ and electron, more specifically due to absence of constraints from electron beam dump experiments. This happens in the case of $U(1)_{\mu-\tau}$, as $Z'$ does not have tree level couplings with $\nu_e, e^\pm$ in the model. Therefore, we plan to dig deeper only into the $U(1)_{\mu-\tau}$ model in following discussion.

As discussed previously, CEνNS can lead to measurable nuclear recoils in detectors. A regular neutrino flux would lead to detection of scattering events over a time depending on luminosity of incident neutrinos and strength of the interaction. The neutrino-nucleus event rate equation which determines the neutrino matter interaction, can be written as \[ \frac{dR_{\nu e-N}}{dE_r} = \frac{\epsilon}{m_N} \int_{E_{\nu}^\text{min}}^{E_{\nu}} dE_{\nu} \left( P(\nu_\alpha \to \nu_\beta, E_\nu) \frac{d\sigma(E_\nu, E_r, \nu_\beta)}{dE_r} \right) E_{\nu} \]

where $\epsilon$ is the exposure of the experiment measured in units of mass \times time. $E_{\nu}^\text{min}$ is minimum incident neutrino energy required to produce a detectable recoil for a material nucleus of mass $m_N$ with energy $E_r$, which in the limit of $m_N \gg E_\nu$ can be written as,

\[ E_{\nu}^\text{min} = \sqrt{\frac{m_N E_r}{2}} \]

Here, $\frac{d\sigma(E_\nu, E_r, \nu_\beta)}{dE_r}$ is $\beta$ flavor dependent neutrino-nucleus differential scattering cross-section and $\frac{d\phi_{\nu_\alpha}}{dE_\nu}$ is the incoming neutrino flux of flavor $\alpha$. The fluxes used in this analysis involve fluxes from solar, atmospheric, diffuse supernova neutrinos, which can be found in Refs. [32, 33] and have been redrawn in Fig. 3. Apart from the continuous sources, electron capture on Be$^7$ leads to two mono-energetic neutrino lines at 384.3 KeV and 861.3 KeV and have been taken into account. $P(\nu_\alpha \to \nu_\beta, E_\nu)$ is the transition probability of $\nu_\alpha \to \nu_\beta$ in the incident flux. Electron neutrinos emitted from different layers of solar core can undergo flavor oscillations in the inter-lying medium, therefore leading to finite probability of incident solar neutrinos to be of different flavor when they reach earth. It was shown in Refs. [34, 35] that survival probability of neutrinos with particular flavor remain very close to each other for two or three flavor neutrino oscillation. Therefore, we use the neutrino survival probabilities for two flavor neutrino oscillation

\[ R_{\nu e-N} = \frac{\epsilon}{m_N} \int_{E_{\nu}^\text{min}}^{E_{\nu}} dE_{\nu} \left( P(\nu_\alpha \to \nu_\beta, E_\nu) \frac{d\sigma(E_\nu, E_r, \nu_\beta)}{dE_r} \right) E_{\nu} \]

\[ E_{\nu}^\text{min} = \sqrt{\frac{m_N E_r}{2}} \]
FIG. 4: Event rate for neutrino-nucleus scattering with change of recoil energy. Blue line is the event rate for SM whereas red line is for $U(1)_{\mu-\tau}$. Left panel is for Ge$^{68}$ and right for Xe$^{131}$. Benchmark model parameter space for these plots: $Z'$ mass 19 MeV and coupling $g_{\mu-\tau} = 8 \times 10^{-4}$.

model studied in Ref. [35] to calculate $P(\nu_e \rightarrow \nu_\mu, E_\nu)$ which is used to compute neutrino-nucleus rate equations and afterwards, the neutrino floor, for $U(1)_{\mu-\tau}$.

Using the rate Eq. 8, we show in Fig. 4, dependence of neutrino-nucleus scattering rate on recoil energy, with an exposure of 1 ton year. The contours represent the number of CE$\nu$NS events per KeV of nuclear recoil energy in one ton detector of given material, counted over a year. The incident neutrino flux rate is the most drastically changing function in the integrand, leading the profile of contours to mimic it. As can be seen in Fig. 3, the total neutrino flux rate experiences a big drop with increase in incident neutrino energy. In comparison to the solar neutrino flux, very little is contributed by the atmospheric and DSNB neutrino sources which contribute beyond $E_\nu \sim 20$ MeV. Similar profile is seen in event rate contours in Fig. 4. The bulges appearing in the event rate contours can be attributed to switching off of individual neutrino flux sources in the total flux. As an example, the first two bulges seen at 0.003 and 0.023 KeV recoil energies in the case of Germanium nuclei can be sourced to PP spectrum and Be$^{7}$ 861 KeV line. In the left panel 4a, the event rate for SM is shown along with the event rate for $U(1)_{\mu-\tau}$ model for Ge based detectors. Similarly, event rates for both the models are shown in the right panel 4b for Xenon based detectors. Enhancement by factor around 2.8 can be seen in the case of Germanium and by a factor of 1.8 for Xenon for recoil energies of sub-KeV regime. Beyond 1 KeV the enhancement diminishes rapidly as momentum transfer increases beyond the chosen $m_{Z'}$.

IV. NEUTRINO FLOOR

In the context of DM direct detection experiment, neutrino floor represents the neutrino background to the DM signal events. The projection of background CE$\nu$NS events in terms of signal DM parameter space is enshrined through the neutrino floor. Neutrino floor is defined as the minimum value of DM-nucleon scattering cross-section, below which nuclear recoil due to DM will remain indistinguishable from the those recoils due to neutrinos. The cross section on the neutrino floor will be set such that for each DM mass, the ratio of 2.3 DM signal events (90% C.L.)[33] to one neutrino background event is maintained. This can lead us to establish a boundary in DM-nucleon scattering cross-section above which there is certainty ( at 90% C.L.) that the observed events, if any, are indeed the DM signal events, i.e. they are coming from DM-nucleon interactions.

Following the Refs. [36, 37] investigating local DM, it is becoming increasingly certain that DM also permeates our immediate galactic vicinity. Recent constraints [38] estimate the local DM density $\rho_{DM} \simeq 0.3 - 0.4$ GeV/cm$^3$. When the DM particle passes through the matter, it can interact with constituents of the atom. These interactions can lead to elastic or inelastic scattering with electrons and elastic scattering with nucleus, depending on the scale of momentum transfer and nature of DM interactions with matter. If the DM matter interactions take place inside a detector then they can be detected by measuring recoiling energy of nucleus or electron. For DM of mass greater than few hundred MeVs, DM-nucleus scattering plays a more important role in detection of DM [39]. The differential
DM-nucleus scattering event rate is given by [40].

\[
\frac{dR_{DM-N}}{dE_r} = \epsilon \frac{\rho_{DM} \sigma^0_{n} A^2}{2 m_{DM} \mu_{n}^2} F^2(E_r) \int_{v_{min}} f(v) dv
\]

(10)

Here \( \epsilon \) is the exposure of the detector given in units of MT (mass \times time), \( m_{DM} \) is the DM mass, \( \mu_{n} \) is DM-nucleon reduced mass, \( A \) is the mass number of target nuclei, \( \sigma^0_{n} \) is the DM-nucleon scattering cross-section at zero momentum transfer. \( F(E_r) \) is the Helmholtz form factor. The Maxwell-Boltzmann distribution function, \( f(v) \) is assumed to describe the velocity distribution of DM in Earth frame and \( v_{min} = \sqrt{m_N E_r / 2 \mu_{n}^2} \) where \( \mu_{N} \) is DM-nucleus reduced mass. The Integral in Eq. 10 can be calculated analytically as [30]

\[
\int_{v_{min}} f(v) dv = \frac{1}{v_0 \eta_E} \left[ \text{erf}(\eta_+) - \text{erf}(\eta_-) \right] - \frac{1}{\pi v_0 \eta_E} (\eta_+ - \eta_-) \epsilon \eta_{esc}^2
\]

(11)

Here \( \eta_E = \frac{v_E}{v_0}, \eta_{esc} = \frac{v_{esc}}{v_0} \) and \( \eta_k = \min \left( \frac{v_{min}}{v_0} \pm \eta_E, \frac{v_{esc}}{v_0} \right) \) where \( v_0 \) is local galactic rotational velocity, \( v_E \) velocity of Earth with respect to galactic center, \( v_{esc} \) escape velocity of DM from galaxy. We have used values \( v_0 = 220 \text{ km/s}, \) \( v_E = 232 \text{ km/s} \) and \( v_{esc} = 544 \text{ km/s} \) in above calculations.

To construct the neutrino floor, first the exposure required to produce one neutrino event needs to be evaluated. That is done following Eq. 8 and then setting \( \frac{\int_{E_{th}}^{E_{max}} d\phi_{\nu}}{dE_r} dE_r = 1 \). In this integral, the minimum recoil energy is taken as the threshold energy \( E_{th} \) and maximum nuclear recoil energy, \( E_{max} \) is chosen to be 100 KeV. To put it in an alternate way, the mass of the detector (M) times the time for which the experiment is run (T) is computed for a given threshold energy such that it gives us exactly \( n_{\nu} \) counts for neutrino scattering events. The exposure is expressed as,

\[
\epsilon_{\nu} = \frac{n_{\nu}}{T} \left( \int_{E_{th}}^{E_{max}} \frac{1}{m_N} \int_{E_{min}}^{E_{max}} \frac{d\phi_{\nu}}{dE_r} P(\nu_\alpha \rightarrow \nu_\beta, E_\nu) \frac{d\sigma(\nu_\beta, E_r, \nu_\beta)}{dE_r} dE_\nu \right)^{-1},
\]

(12)

where \( n_{\nu} = 1 \) can be set for one neutrino-nucleus scattering event.

Next, we use the computed exposure in the dark matter side. The DM-nucleus event rate in Eq. 10 is integrated through \( \int_{E_{th}}^{E_{max}} \frac{dR_{DM-N}}{dE_r} dE_r = 2.3 \) to produce 2.3 DM scattering events, with the same exposure which was required for single neutrino scattering event. That equation can be solved for DM-nucleon scattering cross-section \( \sigma^0_{n} \), using the same threshold for recoil energy lower limit. This can be recapitulated in form of the master equation.

![FIG. 5: Black dashed line signify neutrino floor in case of SM with Germanium detector, which is constructed by taking lower limit of \( \sigma^0_{n} \) with varying threshold in logarithmic steps from 0.001 to 100 KeV with exposure to attain one neutrino scattering event each. As an example we also show colored \( \sigma^0_{n} \) contours for threshold energies \( 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2} \) KeV highlighting how neutrino floor is spanned.](image)
that translates to the required DM-nucleon scattering cross-section,

\[
\sigma_n^0 = \frac{2.3}{1} \left( \int_{E_{\text{th}}^{\text{max}}} E_{\nu}^{-\frac{1}{2}} \frac{dE_{\nu}}{dE_{\nu}} \bigg|_{\nu_{\alpha} \to \nu_{\beta}} P(\nu_{\alpha} \to \nu_{\beta}, E_{\nu}) \frac{d\sigma(E_{\nu}, E_{\tau}, \nu_{\beta})}{dE_{\nu}} \right) \times \frac{(\rho_{DM} A^2)}{(2 m_{DM} p_n^2)} \int_{E_{\text{th}}^{\text{min}}}^{E_{\text{th}}^{\text{max}}} F^2(E_{\nu}) \int_{v_{\text{min}}}^{v} \frac{f(v)}{v} dv \right)^{-1} \tag{13}
\]

Here \(E_{th}^{max}\) is the maximum recoil energy of DM with mass \(m_{DM}\) can produce in a given nuclei. It is written as,

\[
2 m_{DM} \left( \frac{m_N m_{DM}}{(m_N + m_{DM})} \right) v_{esc}^2.
\]

![Graphs showing DM-Nucleon cross-sections](image)

**FIG. 6:** Neutrino floor projected in the \(\sigma_n^0\) vs \(m_{DM}\) plane. Comparison of the neutrino floor for the SM (presented by the blue line) and that for \(U(1)_{\mu - e}\) (presented by the red line). For different detector materials, \(Ge^{128}\) (top panel) and \(Xe^{131}\) (bottom panel), dashed and dotted lines respectively show current and future DM-nucleon direct detection exclusion plots. Benchmark chosen for these plots: \(Z'\) mass 19 MeV and coupling \(g_{\mu - e} = 0.0008\).

Using the expression in Eq. 13, a number of curves for \(\sigma_n^0\) (DM-nucleon scattering cross-section) as a function of DM mass are generated with varying threshold energy in logarithmic steps from 0.001 KeV to 100 KeV. The exposure is kept so that it can generate one neutrino scattering event in each case i.e \(n_\nu = 1\). Then the lowest cross-section among different \(E_{th}\) plots are taken for each DM mass to draw a line in the DM-nucleon cross-section \(\sigma_n^0\) versus \(m_{DM}\) plane. This curve will put a lower limit on DM-Nucleon cross-section above which we can be certain (at 90% C.L.) that the measured events will occur due to DM-nucleon scattering i.e. they are DM signal events. In Fig.5, we have shown how different threshold energy plots are used to obtain the neutrino floor. When the recoil energy in the DM-nucleon scattering events are smaller than the threshold energy, \(E_{th}\), they do not register as recoil events in the detector. If it is assumed that all DM follow same velocity distribution, a lighter DM produces lower recoils.
Therefore, with a higher threshold energy, lighter DM recoils remain unnoticed, leading to less sensitivity of the $\sigma_n^0$ curves to lighter DM.

With the methodology discussed above, we show in Fig. 6, theoretically estimated neutrino floor curves along with current and future sensitivity of different DM direct detection experiments on the $\sigma_n^0 - m_{DM}$ plane. Solid lines signify the contours such that for each DM mass, above that cross section, DM scattering events can be differentiated from the neutrino scattering events at 90% confidence level (i.e. 2.3 DM events per one neutrino event). Plots in the top show, for Germanium based DM direct detection experiments, two neutrino floor being drawn for the SM and $U(1)_{\mu-\tau}$ models, where significant enhancement of the neutrino floor is observed for the BSM case. In top right panel, we zoom in to show $\sigma_n^0$ versus $m_{DM}$ contours for Germanium, with $m_{DM}$ being limited to a range 0.2 to 10 GeV, focusing on the enhancement in $U(1)_{\mu-\tau}$. Almost a consistent enhancement by a factor of 2.7 in the neutrino floor is observed for low mass range less than 7 GeV. In this DM mass region, the limit on $\sigma_n^0$ is sensitive to the threshold energies below 1 KeV. With that $E_{th}$, lower limit of recoil energies hover around 1 KeV or less. As shown in Fig. 4, lower recoil energy contributions are higher and therefore dominant in the $E_r$ integral which lead to a lower $E_{th}$ being translated to lower $E_r$ in our case. For $E_r$ values less than 1 KeV, the neutrino-nucleon interaction rate gets enhanced by an factor of 2.7 which eventually translates to an increase of neutrino floor in the sub-10 GeV $m_{DM}$ region by the same factor. Exclusion plots for Germanium based experiments include direct detection reach from projected SuperCDMS HV [41] experiment, that from CDMSlite [42] (SuperCDMS LT) experiments shown in top row plots of Fig. 6 through dashed lines of different colors.

Bottom panels show graphs for Xenon based experiments, where moderate enhancement of the neutrino floor is observed for the BSM case, by a factor of 1.82 in the neutrino floor for lower mass region. Different dashed lines show DM-nucleon direct detection exclusion plots from projected XENONnT [1] experiment, and that from the XENON1T experiment, presented in different colors. In bottom right panel, we again show $\sigma_n^0$ versus $m_{DM}$ contours for Xenon, with $m_{DM}$ varying in the range 5 to 30 GeV, highlighting the enhancement. DM mass going beyond 7 GeV, the neutrino floor starts to show diminishing enhancement. This can be attributed to decreasing augmentation in $U(1)_{\mu-\tau}$ CE/NS event rate with respect to the SM at higher recoil energies. As discussed earlier, neutrino floor is spanned by taking the lower limit on DM exclusion plots drawn using Eq. 13 by varying threshold energy. The DM mass range of 7 - 15 GeV in the neutrino floor is spanned by varying threshold recoil energies from 1 to 10 KeV, which shows not so significant enhancement in CE/NS rate, as can be seen in Fig. 4.

It is worthwhile to note that future projection of the exclusion plots from SuperCDMS HV [41] and XENONnT [1] experiments have an overlap with the modified neutrino floor in the $U(1)_{\mu-\tau}$ model. The enhancement in the neutrino floor will enable to observe neutrino signal events in these detectors, even in the absence of any DM signal. These events due to the overlap could have been erroneously attributed to DM-nucleon scattering, which are CE/NS events in reality. Any future signal in that range should be probed with more vigor and from alternative experiments to ascertain the presence of DM. If DM is not present, then the signal can lead to observable BSM effects in neutrino sector, which inadvertently shows up in the DM experiments.

V. SUMMARY AND CONCLUSION

In this article, we have studied the new physics contribution from leptophilic $U(1)_{e-\mu}, U(1)_{e-\tau}$ and $U(1)_{\mu-\tau}$ models to the CE/NS, eventually leading to an enhancement to the neutrino floor, which is soon going to become sensitive to the future DM direct detection experiments. We have included the latest combined constraints from electron beam dump experiments, neutrino scattering experiments and astrophysical constraints etc., on these models, to find out relatively relaxed constraints on the $U(1)_{\mu-\tau}$ model. The enhancement in the CE/NS process for these models are confronted with combined experimental constraints on the $m_{Z'} - g_{\mu-j}$ plane. We were able to achieve 50% and more enhancement in CE/NS for the case of $U(1)_{\mu-\tau}$ model compared to that of the SM, in the allowed parameter space with $Z'$ mass hovering in the range 10-50 MeV. Due to tighter electron beam dump constraints on the $U(1)_{e-\mu}$ and $U(1)_{e-\tau}$ models, we could not manage any sizable (≥5%) enhancement. For $m_{Z'}, g_{\mu-\tau}$ values showing the maximum augmentation in the allowed region for $U(1)_{\mu-\tau}$ model we pick a benchmark point $m_{Z'} = 19\text{MeV}, g_{\mu-\tau} = 8 \times 10^{-4}$. We have shown contours of neutrino-nucleus scattering event rate with its variation with nuclear recoil to pin down the rate enhancement compared against SM. For that benchmark point, neutrino-nucleus rate amplification by factors of 2.8 and 1.8 were seen for the cases of Germanium and Xenon respectively, at nuclear recoil energies around 0.01 KeV, which diminishes at higher recoil energies. This enhancement is an combination of increase of neutrino-nucleus scattering rate for $U(1)_{\mu-\tau}$, further weighted by the neutrino flux. Finally for the neutrino floor, first the exposure required to produce one neutrino-nucleus scattering events for a given threshold energy in the DM direct detection detectors, is obtained. The the same exposure is used to investigate the contribution of $U(1)_{\mu-\tau}$ model in the contours depicting values of DM-nucleon scattering cross-section ($\sigma_n^0$) for DM masses ($m_{DM}$) above which we can be certain at 90% confidence level (2.3 DM events per 1 neutrino scattering event), that measured events are coming from the
DM scattering with detecting material rather than neutrino scattering. Enhancement by a factor 2.8 and 1.82 in the neutrino floor were respectively seen for Germanium and Xenon based experiments, in the lighter DM region with $m_{DM} < 10$ GeV.

In conclusion we find that $U(1)_{\mu-\tau}$ provides significant modification in the CE$\nu$NS floor. This enhancement is especially significant for low mass (less than 10 GeV) dark matter. From the context of DM extension to $U(1)_{\mu-\tau}$ model, the enhancement is noteworthy as the parameter space which leads to the maximum enhancement, can also explain anomalous magnetic moment of muon and relic density of dark matter simultaneously. Therefore, it can be worthwhile to probe the parameter region in neutrino scattering experiments, like COHERENT experiment, to get a clear picture of the impact the model has in BSM neutrino physics. Further, DM direct detection experiments can reach the enhanced neutrino floor according to the future projections which may ultimately enable us to probe the hitherto unknown neutrino flux in the DM experiments.

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APPENDIX

1. Tables: Results

| $E_r$ (KeV) | $\frac{dR^{SM}_{\nu-N}}{dE_r}$ (Ton Year KeV)$^{-1}$ | $\frac{dR^{SM}_{\nu-N}}{dE_r}$ (Ton Year KeV)$^{-1}$ | $\frac{dR^{SM}_{\nu-N}}{dE_r}$ (Ton Year KeV)$^{-1}$ |
|------------|---------------------------------|---------------------------------|---------------------------------|
| 0.001      | 1.95644×10$^{6}$                | 5.1514×10$^{6}$                | 2.63                            |
| 0.005      | 2.76×10$^{5}$                   | 7.34×10$^{5}$                  | 2.65                            |
| 0.01       | 2.01×10$^{5}$                   | 5.34×10$^{5}$                  | 2.65                            |
| 0.05       | 3918.8                          | 10525.8                        | 2.68                            |
| 0.1        | 258.2                           | 800.8                          | 3.10                            |
| 0.5        | 151.8                           | 428.7                          | 2.82                            |
| 1.0        | 83.3                            | 212.3                          | 2.54                            |
| 5.0        | 0.18                            | 0.31                           | 1.67                            |
| 10.0       | 2.9×10$^{-4}$                   | 3.9×10$^{-4}$                  | 1.34                            |

TABLE I: Neutrino nucleus event rate versus recoil energy table showing the comparison between $U(1)_{\mu-\tau}$ and SM for Germanium nuclei. Benchmark chosen: $Z'$ mass 19 MeV and coupling $g_{\mu-\tau} = 8.0 \times 10^{-4}$. 

\[ E_r (\text{KeV}) \quad \frac{dR^{SM}_{\nu N}}{dE_r} (\text{Ton Year KeV}^{-1}) \quad \frac{dR^{\mu - \nu}_{\mu N}}{dE_r} (\text{Ton Year KeV}^{-1}) \quad \frac{dR^{\mu - N}_{\mu N}}{dE_r} (\text{Ton Year KeV}^{-1}) \]

\begin{tabular}{|c|c|c|}
\hline
0.001 & 6.746\times10^6 & 1.241\times10^7 & 1.84 \\
0.005 & 1.866\times10^6 & 2.377\times10^6 & 1.84 \\
0.01 & 4.48\times10^5 & 8.28\times10^6 & 1.84 \\
0.05 & 1613 & 3360 & 2.08 \\
0.1 & 1401 & 2837 & 2.04 \\
0.5 & 528 & 965 & 1.82 \\
1.0 & 159 & 263.3 & 1.64 \\
5.0 & 0.0016 & 0.0019 & 1.20 \\
10.0 & 5.43\times10^{-4} & 5.99\times10^{-4} & 1.10 \\
\hline
\end{tabular}

TABLE II: Neutrino nucleus event rate versus recoil energy table showing the comparison between \( U(1)_{\mu - \tau} \) model and SM for Xenon nuclei. Benchmark chosen: \( Z' \) mass 19 MeV and coupling \( g_{\mu - \tau} = 8.0 \times 10^{-4} \).

\[ m_{DM} (\text{GeV}) \quad \text{SM Neutrino floor (cm}^2) \quad U(1)_{\mu - \tau} \text{ Neutrino floor (cm}^2) \quad \text{Enhancement} \]

\begin{tabular}{|c|c|c|c|}
\hline
0.5 & 2.37\times10^{-43} & 6.30\times10^{-43} & 2.65 \\
1.0 & 5.30\times10^{-44} & 1.42\times10^{-43} & 2.67 \\
5.0 & 7.11\times10^{-45} & 1.90\times10^{-44} & 2.67 \\
10 & 2.16\times10^{-47} & 2.87\times10^{-47} & 1.32 \\
50 & 3.90\times10^{-49} & 4.36\times10^{-49} & 1.11 \\
100 & 4.08\times10^{-49} & 4.53\times10^{-49} & 1.11 \\
500 & 1.23\times10^{-48} & 1.33\times10^{-48} & 1.08 \\
1000 & 2.31\times10^{-48} & 2.48\times10^{-48} & 1.07 \\
\hline
\end{tabular}

TABLE III: Neutrino floor versus dark matter mass table highlighting modification of neutrino floor for \( U(1)_{\mu - \tau} \) with respect to SM for Germanium nuclei. Benchmark chosen: \( Z' \) mass 19 MeV and coupling \( g_{\mu - \tau} = 8.0 \times 10^{-4} \).

\[ m_{DM} (\text{GeV}) \quad \text{SM Neutrino floor (cm}^2) \quad U(1)_{\mu - \tau} \text{ Neutrino floor (cm}^2) \quad \text{Enhancement} \]

\begin{tabular}{|c|c|c|c|}
\hline
0.5 & 3.92\times10^{-43} & 7.27\times10^{-43} & 1.85 \\
1.0 & 8.67\times10^{-44} & 1.62\times10^{-43} & 1.86 \\
5.0 & 1.10\times10^{-44} & 2.06\times10^{-44} & 1.87 \\
10 & 1.51\times10^{-47} & 1.78\times10^{-47} & 1.17 \\
50 & 3.41\times10^{-49} & 3.66\times10^{-49} & 1.11 \\
100 & 4.03\times10^{-49} & 4.25\times10^{-49} & 1.07 \\
500 & 6.83\times10^{-48} & 6.89\times10^{-48} & 1.01 \\
1000 & 1.04\times10^{-48} & 1.05\times10^{-48} & 1.01 \\
\hline
\end{tabular}

TABLE IV: Neutrino floor versus dark matter mass table highlighting modification of neutrino floor for \( U_{\mu - \tau} \) with respect to SM for Xenon nuclei. Benchmark chosen: \( Z' \) mass 19 MeV and coupling \( g_{\mu - \tau} = 8.0 \times 10^{-4} \).

2. \( Z' - \gamma \) mixing in \( U_{i-j} \) model

In the \( U(1)_{i-j} \) models, contribution to CEνNS due to extra \( Z' \) boson are mediated by \( Z' - Z/\gamma \) mixing as shown in Fig. 1a. The loop contribution driven mixing element is given by,

\[
\mu^{2e} \int \frac{d^d k}{(2\pi)^d} \frac{2tr[\gamma^\mu(\not{l} + m_l)\gamma^\nu(\not{k} + m_l)]}{[(l + k)^2 - m_l^2][(k^2 - m_l^2)]} 
\]

(14)
Using Feynman parametrization

\[\frac{1}{[(l + k)^2 - m_i^2] [k^2 - m_j^2]} = \int dx \frac{1}{x ((l + k)^2 - m_i^2) - (1 - x) (k^2 - m_j^2)} \]

Using Feynman parametrization

\[\frac{1}{(l + k)^2 - m_i^2} \frac{1}{k^2 - m_j^2} = \int dx \frac{1}{x ((l + k)^2 - m_i^2) - (1 - x) (k^2 - m_j^2)} \]

Putting back 16 and 15 in 14

\[\mu^2 \int_0^1 dx \int \frac{d^dk}{(2\pi)^d} \frac{4 \left[ l^\mu k^\nu - g^\mu\nu (l, k) + 2k^\mu k^\nu - g^\mu\nu (k^2) + m^2_ig^\mu\nu \right]}{(k^2 - \Delta)^2} \]

shifting \( k \rightarrow k' - tx \) and substituting \( \Delta = x(x - 1)l^2 + m_j^2 \), we have

\[\mu^2 \int_0^1 dx \int \frac{d^dk}{(2\pi)^d} \frac{4 \left[ (x - x^2)(-2l^\nu l^\mu + g^\nu\mu l^2) + \frac{2}{3} - 1 \right] g^\mu\nu k^2 + m^2_ig^\mu\nu}{(k^2 - \Delta)^2} \]

Under the rotation \( k^0 \rightarrow ik_E \) and \( k^i \rightarrow k^i \)

\[i\mu^2 \int_0^1 dx \int \frac{d^dk_E}{(2\pi)^d} \frac{4 \left[ (x - x^2)(-2l^\nu l^\mu + g^\nu\mu l^2) - \frac{2}{3} - 1 \right] g^\mu\nu k^2 + m^2_ig^\mu\nu}{(k_E^2 + \Delta)^2} \]

using the simplification

\[\frac{d^dk_E}{(2\pi)^d} = \frac{k_{E,d-1}^d}{(2\pi)^d} d\Omega_d \]

\[\int_0^\infty dy \frac{y^b}{(y^2 + \Delta)^b} = \Delta^{\frac{b+1}{2}} - b \Gamma\left(\frac{b+1}{2}\right) \Gamma(b - \frac{b+1}{2}) \frac{2\Gamma(b)}{2\Gamma(b)} \]

where, \( \int \Omega_d = \frac{2\pi^{\frac{d}{2}}}{\Gamma(\frac{d}{2})} \)

Integral in 19 in \( \overline{MS} \) scheme is solved as

\[\frac{1}{(2\pi)^2} \left[ -l^\mu l^\nu + g^\mu\nu l^2 \right] \int_0^1 dx \left( -\frac{2}{\epsilon} + \log \frac{x(x - 1)l^2 + m_j^2}{4\pi\mu^4} + \gamma_E \right) x(1 - x) \]

In \( U(1)_{i-j} \) model the infinite terms cancel between two lepton flavors and we have

\[\frac{1}{(2\pi)^2} \left[ -l^\mu l^\nu + g^\mu\nu l^2 \right] \int_0^1 dx \left( \log \frac{x(x - 1)l^2 + m_j^2}{x(x - 1)l^2 + m_j^2} \right) x(1 - x) \]
based on elastic nuclear recoil. Astropart. Phys., 6:87–112, 1996. doi:10.1016/S0927-6505(96)00047-3

[31] M.C. Gonzalez-Garcia, Michele Maltoni, Yuber F. Perez-Gonzalez, and Renata Zukanovich Funchal. Neutrino Discovery Limit of Dark Matter Direct Detection Experiments in the Presence of Non-Standard Interactions. JHEP, 07:019, 2018. doi:10.1007/JHEP07(2018)019

[32] Louis E. Strigari. Neutrino Coherent Scattering Rates at Direct Dark Matter Detectors. New J. Phys., 11:105011, 2009. doi:10.1088/1367-2630/11/10/105011

[33] J. Billard, L. Strigari, and E. Figueroa-Feliciano. Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments. Phys. Rev., D89(2):023524, 2014. doi:10.1103/PhysRevD.89.023524

[34] P. Hernandez. Neutrino physics. In High-energy physics. Proceedings, 5th CERN-Latin-American School, Recinto Quirama, Colombia, March 15-28, 2009, 2010.

[35] IlÃãngdio Lopes and Sylvaine Turck-ChiÃée. Solar neutrino physics oscillations: Sensitivity to the electronic density in the Sun’s core. Astrophys. J., 765:14, 2013. doi:10.1088/0004-637X/765/1/14

[36] J. I. Read. The Local Dark Matter Density. J. Phys., G41:063101, 2014. doi:10.1088/0954-3899/41/6/063101

[37] Miguel Pato, Fabio Iocco, and Gianfranco Bertone. Dynamical constraints on the dark matter distribution in the Milky Way. JCAP, 1512(12):001, 2015. doi:10.1088/1475-7516/2015/12/001

[38] Pablo F. de Salas. Dark matter local density determination based on recent observations. In 16th International Conference on Topics in Astroparticle and Underground Physics (TAUP 2019) Toyama, Japan, September 9-13, 2019, 2019.

[39] Jason Wyenberg and Ian M. Shoemaker. Mapping the neutrino floor for direct detection experiments based on dark matter-electron scattering. Phys. Rev. D, 97(11):115026, 2018. doi:10.1103/PhysRevD.97.115026

[40] Teresa MarrodÃãngUndagoitia and Ludwig Rauch. Dark matter direct-detection experiments. J. Phys., G43(1):013001, 2016. doi:10.1088/0954-3899/43/1/013001

[41] R. Agnese et al. Projected Sensitivity of the SuperCDMS SNOLAB experiment. Phys. Rev., D95(8):082002, 2017. doi:10.1103/PhysRevD.95.082002

[42] R. Agnese et al. Low-mass dark matter search with CDMSlite. Phys. Rev., D97(2):022002, 2018. doi:10.1103/PhysRevD.97.022002