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Light dark matter detection prospects at neutrino experiments

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We consider the prospects for the detection of relatively light dark matter through direct annihilation to neutrinos. We specifically focus on the detection possibilities of water Cherenkov and liquid scintillator neutrino detection devices. We find, in particular, that liquid scintillator detectors may potentially provide excellent detection prospects for dark matter in the 4–10 GeV mass range. These experiments can provide excellent corroborative checks of the DAMA/LIBRA annual modulation signal, but may yield results for low mass dark matter in any case. We identify important tests of the ratio of electron to muon neutrino events (and neutrino versus antineutrino events), which discriminate against background atmospheric neutrinos. In addition, the fraction of events which arise from muon neutrinos or antineutrinos (R_μ and $R_{\bar{\mu}}$) can potentially yield information about the branching fractions of hypothetical dark matter annihilations into different neutrino flavors. These results apply to neutrinos from secondary and tertiary decays as well, but will suffer from decreased detectability.

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I. INTRODUCTION

One of the key experimental approaches to the detection of dark matter is through indirect detection experiments. The idea is that, in some region of elevated dark matter density (for example, the core of the Sun or the Earth, or the Galactic center), dark matter particles annihilate with each other to produce standard model (SM) particles which can be detected with experiments on Earth or in orbit around Earth. The focus is therefore on stable standard model particles, such as p^+-p^- pairs, e^+-e^- pairs, photons or neutrinos.

One possibility is that the stable particles listed above can be produced directly through dark matter annihilation (i.e, through the process $XX \to p^+p^-, e^+e^-, \gamma\gamma, \nu\bar{\nu}$). The other possibility is that dark matter particles annihilate to some other standard model particles, which in turn decay by showering off the stable particles listed above. Either scenario has interesting distinguishing features. The advantage of indirect production of stable SM particles is that it is universal; SM particles produced through DM annihilation will shower off at least some set of p, e, γ, ν (often all of them) as they decay. The direct annihilation of dark matter particles to stable SM particles will, on the other hand, be suppressed by the branching fraction to that particular final state (which may be quite small). The advantage of direct production of stable SM states, however, is that the SM particle is produced with an energy equal to the dark matter mass. This can potentially result in a sharp peak in the energy spectrum, as opposed to the broad spectrum expected of indirect production.

Note that we are talking about "indirect detection" herein, in the sense of the neutrinos resulting from annihilations, as opposed to the large number of "direct detection" experiments which aim at detecting the recoil of an elastic scattering in a laboratory detector. This recoil typically in the KeV kinetic energy range tells little about the nature of the weakly interacting massive particle (WIMP), and is hard to differentiate from background processes. Hence it seems that all possible methods of detection will be needed to definitively discern the existence and nature of dark matter.

One of the main theoretical candidates for dark matter has been neutralino WIMPs, and some search strategies and analyses have been optimized with this in mind. However, a series of dark matter experiments has presented hints of data which might suggest a dark matter candidate [1]. A unifying feature of these hints is that they are not easily explained by neutralino WIMPs. On the other hand, a variety of theoretical models have also arisen in recent years which can provide reasonable dark matter candidates which are not neutralino WIMPs, and at a wide range of masses and couplings [2,3]. It is thus worthwhile to revisit some of the underexplored regions of parameter space.

Our focus in this paper is on the detection of dark matter annihilation directly to neutrinos. This particular pathway has not been subject to great study, partly because neutralino WIMPs are Majorana fermions, and thus have highly suppressed annihilations to neutrinos [4]. But for more general dark matter candidates, such direct annihilations might have a significant branching fraction. Moreover, recent focus on leptophilic hidden sectors [5] highlight the possibility of dark matter which annihilates primarily to leptons, in which case direct annihilation to neutrinos may have a significant branching fraction. Furthermore, an advantage of direct annihilation to neutrinos over direct annihilation to e^+e^- pairs is that the neutrinos do not interact significantly, implying that, unlike the case with charged SM particles, they will still provide a sharp peak in the energy spectrum at an Earth-based detector. Another interesting feature of neutrino signatures for dark matter annihilation in the solar core is that the signal is largely independent of astrophysics uncertainties. The reason is that, for almost all models, the Sun's dark matter density is in equilibrium, meaning that the annihilation rate is directly related to the rate at which the Sun captures dark matter. This is in turn determined by the dark matter mass and the dark matter–nucleon scattering cross section, with fewer of the uncertainties which plague other indirect detection signatures.

The main thrust of a study of direct annihilation to neutrinos must necessarily be focused on the low dark matter mass range, specifically $m_X \sim 4$–10 GeV. For smaller dark matter mass, dark matter evaporation from the Sun becomes significant [6,7], and it is difficult to get significant bounds on the dark matter–nucleon scattering cross section. For masses larger than ~10 GeV, bounds on the dark matter– nucleon-spin-independent-scattering cross section from direct detection experiments already are so tight that it appears unlikely that significant improvement can arise from neutrino experiments. Moreover, heavier dark matter will produce more energetic neutrinos through direct annihilation; the muons produced by weak interaction of these neutrinos will also be more energetic, and much less likely to be fully contained within the detector (an important caveat is that higher energy electron neutrinos may still be fully contained, and provide a probe of spin-dependent scattering for heavier dark matter).

Yet this narrow mass region is in itself already significant, as dark matter in this mass range could potentially explain the hints seen at the DAMA experiment [8–12] (though see also [13]). This range of light dark matter has been the subject of much recent theoretical and phenomenological interest [3,14–16] and there has already been significant interest in the possibility of investigating this range with the Super-Kamiokande experiment [7,17–19]. Hence it is worth seeing what can be done to improve sensitivity to dark matter in this mass range.

In Sec. II we will review the types of neutrino detection experiments which are relevant for this discussion, in particular, water Cherenkov and liquid scintillator detectors. In Sec. III we will review the possibility of using liquid scintillator detectors to provide directionality information on incoming neutrinos, which allows for much greater sensitivity to dark matter annihilations in the Sun. In Sec. IV we will discuss the relationship between observed electron neutrinos and muon neutrinos, and the implications for dark matter annihilation. In Sec. V we will exhibit the types of bounds which current and future neutrino experiments can obtain for light dark matter which annihilates directly to neutrinos. We conclude with a discussion of our results in Sec. VI.

II. DETECTOR OVERVIEW

Clearly to make progress in indirect dark matter sensing via neutrinos, we need ever larger instruments, and instruments with better resolution for the presently considered monoenergetic neutrinos from dark matter. The present largest water Cherenkov detector, Super-Kamiokande (SK) [20], has a fiducial volume of 22 500 m^3. There are several proposals for larger instruments, such as Hyper-Kamiokande, UNO, Memphys, and possible instruments at the proposed Deep Underground Science and Engineering Laboratory in the Homestake mine. All of these are in the class of 20–50 times larger in mass than SK.

For Cherenkov instruments, neutrino signals for the energy range from a few tens of MeV upwards are dominated by neutrinos generated by cosmic rays striking the atmosphere. At energies of the order of 1 to a few GeV the ratio of muon neutrinos to electron neutrinos is roughly equal, as it would have been 2:1 except half the muon neutrinos have equilibrated with tau neutrinos through oscillations (and at terrestrial distances the electron neutrinos of these energies have not oscillated much at all). The quasielastic neutrino interaction dominates at these low energies, and well developed algorithms distinguish between electron and muon events with 99% efficiency. The energies of individual events are measured to a few percent and angles to several degrees. There is an inherent coupling between vertex resolution and energy and angle in these ring measuring detectors, which prevents reaching the better resolutions one might expect due to hundreds or even thousands of phototube hits.

Liquid scintillation detectors, of which KamLAND is the largest in existence with a 600 ton fiducial mass, have far greater light production per unit energy deposition (for example, 250 photoelectrons/MeV at KamLAND versus 10 photoelectrons/MeV at SK). Borexino, at 100 tons, also contributes. These will soon be joined by SNO+, a 1 kt liquid scintillator detector in Canada. Other detectors are under discussion and proposal: the portable deep ocean 10 kt Hanohano instrument, the 50 kt LENA instrument (in a mine cavity in Europe), and potential detectors in Homestake. These instruments have been designed largely for detecting geoneutrinos and reactor neutrinos.

For liquid scintillation detectors, the advantage of greater light production (compared to the highly directional Cherenkov radiation) is offset by the uniformity of radiation of the scintillation light. This has been thought, until recently, to obviate the use of liquid scintillation detectors for directional information or for neutrino flavor identification. As suggested in [21] it may be possible to employ the times of the first hits at each photomultiplier tube to define a "Fermat surface" which can be back-projected in a type of tomography to make good reconstruction of simple particle topologies (as from atmospheric neutrino events and nucleon decay), including strong flavor identification. The simple Monte Carlo program results referred to indicate at this time resolutions in angle and energy perhaps 10 times smaller than for SK (and presumably also for future water Cherenkov detectors). We do not wish to make potentially controversial claims herein, but only to note the importance of such sensitivity to dark matter detection, as we discuss below. We will thus take the water Cherenkov resolution as 3% in muon energy and 3 degrees in angle, scaling with the square root of energy in GeV on an event by event basis [20]. The optimistic case for scintillators we take as 10 times better in each parameter. The real world is probably somewhere in between.

III. DIRECTIONALITY AND DETERMINING NEUTRINO ENERGY

Water Cherenkov detectors determine the direction of a muon or an electron event record via fitting of "Cherenkov rings" to the photomultiplier tube hits (employing both time and amplitude). The liquid scintillation detectors can utilize the Fermat surface to do the same, except that the light from near the beginning of the track and near the end of the track gives point source signatures that well define the track vertex and end point.

For neutrinos coming from the Sun (or Earth center or Galactic center), we know (assume) the incoming neutrino direction, calculable at the detector at any moment. Measuring the relativistic muon momentum relative to this direction yields the neutrino energy:

$$E_\nu \approx \frac{m_N E_\mu}{m_N - E_\mu(1-\cos\theta)}. \tag{1}$$

Given estimates of measurement uncertainties, plus the angular distribution expected, the neutrino energy (and hence dark matter mass) resolution of water Cherenkov detectors in the 4–10 GeV range will be ~3%–20%, depending on the angle of the muon with respect to the Sun. An average estimate of the energy resolution is 10% for water Cherenkov detectors, and up to 1% for optimistic future liquid scintillation detectors.

IV. IMPORTANCE OF THE OBSERVED FLAVOR RATIO

Note that most discussions have focused upon muon neutrino detection. However, electron neutrinos are very useful here since they are fully contained more readily in the detectors (hence larger effective target volumes, particularly at energies extending to around 100 GeV, compared to a few GeV for containing muon events). No matter what the source annihilation neutrino fraction, neutrino mixing will deliver a mixed beam at our detectors. The technology for discriminating electron events from muon events in the energy range of around 1 GeV is very well developed and gives separations to order of a percent crossover, which for our case here would seem to be more than adequate.

Detection of dark matter muon neutrinos requires consistent detection of electron neutrinos and vice versa due to inescapable neutrino oscillations. There are two important regimes to note: neutrino oscillations within the Sun and neutrino oscillations in the vacuum. Neutrinos produced by dark matter annihilation in the Sun are produced at the core, which is effectively a point source. As these neutrinos pass through the Sun, electron neutrinos will scatter off background electrons through W-boson mediated interactions, while other neutrinos will not. This interaction will significantly modify neutrino oscillation within the Sun [22]. These effects have been calculated in detail in the adiabatic approximation in [23] (note that neutrinos and antineutrinos will have different matter-induced oscillations). Neutrinos leaving the Sun will subsequently exhibit vacuum oscillation as they travel to the Earth. In the case of a pure ν_e source emerging from the Sun, the ratios after the flight time for mixing will be $e/\mu/\tau = 5/2/2$, and for a pure ν_μ source they will be $4/7/7$. For the equal production of ν_e and ν_μ with little ν_τ (for example, due to low mass of the dark matter), we should see the ratios at Earth as $14/11/11$ [24].

In all these cases the τ appearance will be slight and difficult to resolve, so we will have to rely upon μ to e ratios to untangle the dark matter physics. Presently conceived detectors cannot distinguish between ν_e and $\bar{\nu}_e$ at these energies (perhaps later a liquid argon instrument with a magnetic field can do this). But these detectors can distinguish, statistically, between ν_μ and $\bar{\nu}_\mu$ due to stopped muon decay (μ^- generally get absorbed on nuclei and μ^+ decay, detectably). In the case of a magnetized iron detector such as the proposed INO, the sign of the $\mu^\pm$ charge can be measured directly by the curvature of the muon track. Though the ν_μ and the $\nu_{\bar{\mu}}$ have different cross sections in the slightly isospin asymmetric target material (oil or water) and the y distributions are different, the event ratios should be predictable to a few percent. Moreover these rates will be somewhat different for dark matter neutrinos and the background atmospheric neutrinos, providing another signature for dark matter neutrinos. Thus, the observables we use for this flavor analysis are $R_\mu \equiv \frac{N_\mu}{(1/2)(N_\mu + N_{\bar{\mu}} + N_{e,\bar{e}})}$ and $R_{\bar{\mu}} \equiv \frac{N_{\bar{\mu}}}{(1/2)(N_\mu + N_{\bar{\mu}} + N_{e,\bar{e}})}$, which are the ratios of the number of muon (or antimuon, respectively) events to the total number of $\mu^\mp$, $e^\mp$ neutrino events.

We assume that lepton flavor is conserved in dark matter annihilation. If one further assumes tribimaximal mixing (which is quite consistent with experimental data), and $\theta_{13} = 0$, then the oscillation matrix (through both the Sun and vacuum) is entirely determined by the w_e, the fraction of (anti)neutrinos produced at the Sun's core by dark matter annihilation which are of the electron type [23]. In particular, one then finds that $\frac{1}{3}$ of all neutrinos arriving at Earth (after vacuum and matter-induced oscillations) are of the μ type, while the fraction of antineutrinos of the μ type arriving at Earth is given by $\frac{1}{12}(5 - 3w_e)$. Since we have two observables and one parameter, we find two independent determinations of w_e

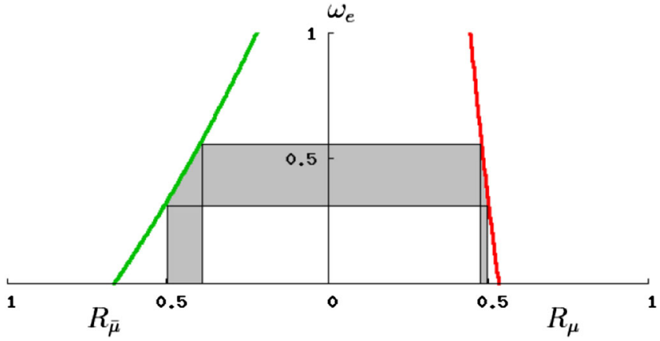

FIG. 1 (color online). The electron neutrino fraction produced from dark matter annihilation, as a function of R_μ and $R_{\bar{\mu}}$. The shaded region corresponds to values of w_e and R_μ consistent with $R_{\bar{\mu}} = 0.44 \pm 0.04$. Note that only the regions $\frac{4}{9} \le R_\mu \le \frac{8}{15}$ and $\frac{2}{9} \le R_{\bar{\mu}} \le \frac{2}{3}$ are consistent with dark matter annihilation in the Sun with tribimaximal mixing and $\theta_{13} = 0$.

(see Fig. 1):

$$w_e = \frac{5}{3}\left(\frac{2 - 3R_{\bar{\mu}}}{2 + R_{\bar{\mu}}}\right) = \frac{8}{3R_\mu} - 5. \tag{2}$$

As we see from the figure, the constraint $0 \le w_e \le 1$ imposes two independent consistency conditions on the muon fraction observables. An inconsistency in the measurement of either would falsify the ansatz of flavor-conserving dark matter annihilation, with tribimaximal mixing and $\theta_{13} = 0$. For the ansatz $\theta_{13} \neq 0$, a similar analysis may be performed along the lines of [23]; this analysis is more complicated and beyond the scope of this work.

Note that range of R_μ consistent with the above ansatz is quite narrow; to make a measurement of R_μ of greater precision would require an unrealistic number of events. But the range of $R_{\bar{\mu}}$ consistent with this ansatz is larger, and with perhaps 500 total ν, $\bar{\nu}$ events one might conceivably obtain a measurement of $R_{\bar{\mu}}$ with 10% accuracy within this range.

V. DARK MATTER BOUNDS FROM NEUTRINOS

Dark matter accumulates in the core of the Sun due to elastic capture scattering from solar nuclei. If a dark matter particle loses enough energy to nuclear recoil, its velocity will fall below the escape velocity. Dark matter is then gravitationally captured by the Sun, and eventually settles at the core. The capture rate, Γ_C, is thus largely determined by the dark matter–nucleon scattering cross section and the dark matter number density.

In particular, we find

$$\Gamma_C \sim \left(\frac{\sigma_{X-N}}{m_X}\right)\left(2 \times 10^{29}\,\frac{\text{GeV}}{\text{pb s}}\right). \tag{3}$$

The coefficient [7,18] is accurate up to $\mathcal{O}(1)$ factors related to the composition and motion of the Sun, the halo density, etc., but it will be sufficient for our purposes.

It was shown in [7,25,26] that for the range of dark matter masses of interest, the Sun is in equilibrium (a similar result has been shown for the case where dark matter primarily interacts with electrons at tree-level [27]). This implies that $\Gamma_C = 2\Gamma_A$, where Γ_A is the total dark matter annihilation rate. In the case of the direct annihilation (which we assume here), $\Gamma_{\nu_\mu,\bar{\nu}_\mu} = \frac{2}{3}B_\nu\Gamma_A$, where B_ν is the branching fraction to all neutrino species (the factor of $\frac{1}{3}$ is a rough assumption from neutrino oscillation; the actual value depends on the initial flavor ratios as discussed above). It is this neutrino production rate which we can bound with limits from neutrino experiments.

We are interested here in the event rate for fully contained muons (i.e., muons which are created by a neutrino weak interaction within the detector and which stop within the detector). These are of interest, because it is only for fully contained events that we can measure the total energy of the neutrino, which exhibits a peak in the energy spectrum.

We define N as the number of events needed for a discovery of dark matter after a run time T. This corresponds to a solar neutrino production rate due to dark matter of

$$\Gamma_{\nu_\mu,\bar{\nu}_\mu} = \frac{N}{T}\,\frac{4\pi(1.5 \times 10^{11}\ \text{m})^2}{\sigma_{\text{FC}}^{\text{eff}}}, \tag{4}$$

where $\sigma_{\text{FC}}^{\text{eff}}$ is the effective cross section for the detector to produce fully contained muon events. This effective cross section is given by

$$\sigma_{\text{FC}}^{\text{eff}} = \sigma_{\nu-N} \times \frac{\rho}{m_N} \times \text{eff volume}, \tag{5}$$

where ρ is the density of the detector and the effective volume is the approximate volume of the detector which can yield fully contained muons for the given neutrino energy (this effective volume is dependent on the detector geometry). Here, $\sigma_{\nu-N}$ is the neutrino(antineutrino)-nucleon scattering cross section.

For the energy range of interest, $M_W \gg E_\nu > m_N$, where m_N is the mass of a nucleon. In this case, the (anti)neutrino–nucleon scattering cross section can be approximated as [28–30]

$$\begin{aligned}
\sigma_{\nu n} &= 8.81 \times 10^{-3}\ \text{pb}\,(E_\nu/\text{GeV}),\\
\sigma_{\nu p} &= 4.51 \times 10^{-3}\ \text{pb}\,(E_\nu/\text{GeV}),\\
\sigma_{\bar{\nu} n} &= 2.5 \times 10^{-3}\ \text{pb}\,(E_\nu/\text{GeV}),\\
\sigma_{\bar{\nu} p} &= 3.99 \times 10^{-3}\ \text{pb}\,(E_\nu/\text{GeV}).
\end{aligned} \tag{6}$$

One should also include the small contribution from resonant, coherent and diffractive processes, but this approximation will be sufficient for our purposes.

For specificity, we can use Super-Kamiokande as an example (see also [17]). We find there that

$$\sigma_{\rm FC}^{\rm eff} \sim (1.4\times 10^{-8})\left(\frac{E_\nu}{\rm GeV}\right)({\rm meter})^2 \times \left(\frac{\rho}{\rm g/cm^3}\right) \times \text{vol factor}, \quad (7)$$

where "vol factor" is the factor by which the effective volume of the detector in question for fully contained events at the given energy exceeds the fiducial volume of SK. This gives us a detection limit

$$\sigma_{XN} \simeq \left(\frac{1.2\times 10^{-3}\ {\rm pb}}{\text{vol factor}}\right)\left(\frac{\rho}{\rm g/cm^3}\right)^{-1}\left(\frac{3}{\sum_F B_F\langle Nz\rangle_F}\right) \times \left(\frac{N_{\rm events}}{N_{\rm live\ days}}\right), \quad (8)$$

where $z = \frac{E_\nu}{m_X}$. Note that one achieves the same bound for fully contained electrons arising from electron neutrinos interacting with the detector.

A. Limits for a liquid scintillator detector

We are now ready to put the pieces together to obtain a basic analysis of the detection prospects for dark matter at a liquid scintillator neutrino detector via the annihilation process $XX \to \nu\bar{\nu}$ in the Sun's core.

The key point here is that a liquid scintillator can be expected to provide a high resolution measurement of the full neutrino energy for interactions which produce a fully contained muon. Of course, there are efficiencies which depend on the details of the scattering process (such as whether it is best characterized as quasielastic, resonant or deep-inelastic) and the details of the detector.

Dark matter annihilation in the Sun produces neutrinos which arrive at Earth from a known direction, varying with time. However, scattering within the detector will produce leptons in a cone around the direction to the Sun, with rms half-angle $\theta \sim 20^\circ\sqrt{10\ {\rm GeV}/E_\nu}$ [28]. The background to this signal would be fully contained muons arising from interactions of atmospheric neutrinos with the detector. The Super-Kamiokande Collaboration reports [20] that, for $E_{\nu_\mu} \gtrsim 4$ GeV, it expects less than 20 fully contained muon events (in the cone of the Sun) per GeV neutrino energy bin per 1000 live days running time due to atmospheric neutrinos (the rate falls to 2 events per GeV per 1000 live days at $E_{\nu_\mu} \sim 10$ GeV). Using the fiducial volume of Super-Kamiokande ($V = 22\,500\ {\rm m}^3$) and a $N_{\rm live\ days} = 3000$ run time as a guide, we would thus expect $\lesssim 1$ fully contained muon background event per energy bin (assuming a 1% energy resolution). We are thus in the limit of small statistics; a detection of 10 fully contained muon events in the cone of the Sun, with total energy in the same bin, should be sufficient to detect dark matter annihilation in the Sun with m_X given by the measured neutrino energy.

Furthermore, for direct annihilation to neutrinos, we have $E_\nu = m_X$, so we may take $\langle Nz\rangle = 1$. We thus find

$$\sigma_{XN} \simeq 1.2\times 10^{-3}\ {\rm pb} \times \left(\frac{\rho}{\rm g/cm^3}\right)^{-1}\left(\frac{3}{B_\nu}\right)\left(\frac{N_{\rm events}}{N_{\rm live\ days}}\right) \times \left(\frac{22\,500\ {\rm m}^3}{V}\right), \quad (9)$$

and our bound is largely independent of m_X. Choosing $\rho = 1\ {\rm g/cm^3}$, $N = 10$, $N_{\rm live\ days} = 3000$, $V = 22\,500\ {\rm m}^3$ and $B_\nu = 1$ yields the discovery potential plotted in Fig. 2. Note that this bound is based only on detection prospects from ν_μ, $\bar{\nu}_\mu$. A similar bound would result if one only studied the ν_e, $\bar{\nu}_e$ signal. A combined analysis of both signals will improve detection prospects by approximately a factor of 2. But a more detailed analysis would be required to account for varying efficiencies for each of the two signals, and is beyond the scope of this paper.

It is worth noting that neutrino detectors will produce similar bounds on the spin-dependent-dark-matter–proton scattering cross section, due to capture from hydrogen.

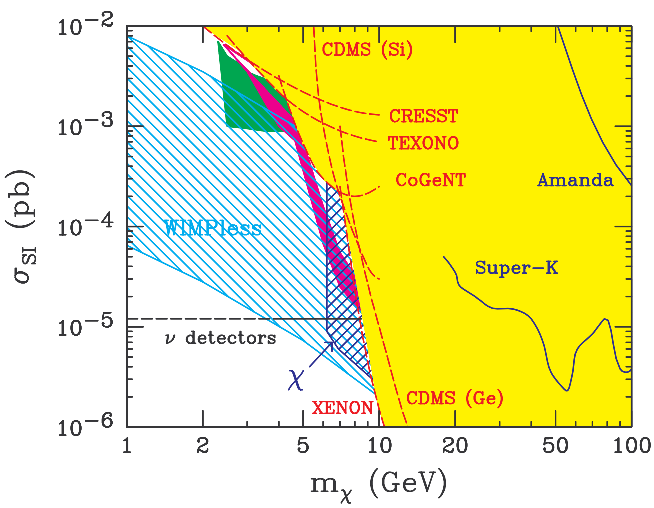

FIG. 2 (color online). Bounds on spin-independent X-nucleon scattering as a function of dark matter mass m_X. The dark (magenta) shaded region is DAMA-favored given channeling and no streams [10], and the medium (green) shaded region is DAMA-favored at 3σ given streams but no channeling [8]. The light (yellow) shaded region is excluded by the direct detection experiments indicated [32]. The dark blue cross-hatched region is the prediction for the neutralino models considered in Ref. [16], and the light blue slashed region is the parameter space of a class of WIMPless models considered in [3,18]. The indicated blue solid lines are the published limits from SK [17] and AMANDA [33] (assuming annihilation to $b\bar{b}$). The indicated black solid line is the detection threshold for liquid scintillator neutrino detectors of $\rho = 1\ {\rm g/cm^3}$ with $22\,500\ {\rm m}^3$ fiducial volume running for 3000 live days, assuming annihilation only to neutrinos and detection only of ν_μ. The black dashed line indicates the sensitivity of liquid scintillator neutrino detectors if WIMP evaporation effects are ignored.

This is of interest because direct detection bounds on spin-dependent-dark-matter–nucleon scattering cross sections are much weaker than in the spin-independent case. It might thus be worthwhile to extend this analysis to dark matter masses greater than 10 GeV, where the sensitivity found in this analysis may beat current spin-dependent bounds (remember, the bound from direct annihilation is largely independent of the dark matter mass).

However, we are still limited by the fact that we need fully contained leptons. For $m_X > 10$ GeV, even a detector significantly larger than SK will still see few fully contained muons. However, the electrons produced from ν_e interactions will be fully contained. An analysis of these fully contained electron events may potentially allow one to extend the analysis described here to $m_X \gg 10$ GeV in the case of spin-dependent scattering. Assuming similar energy and angular resolution for electrons and muons, we have estimated the detection prospects for the type of detector described above in Fig. 3. However, a more accurate bound requires a detailed treatment of the scintillator's response to the electron showers. A more detailed analysis of neutrino detector bounds from electron events seems to be a very promising avenue for further investigation.

B. Limits for a water Cherenkov detector

For a water Cherenkov detector, the main difference in detection prospects will be in the energy (mass) resolution and in the number of events N needed for detection. The

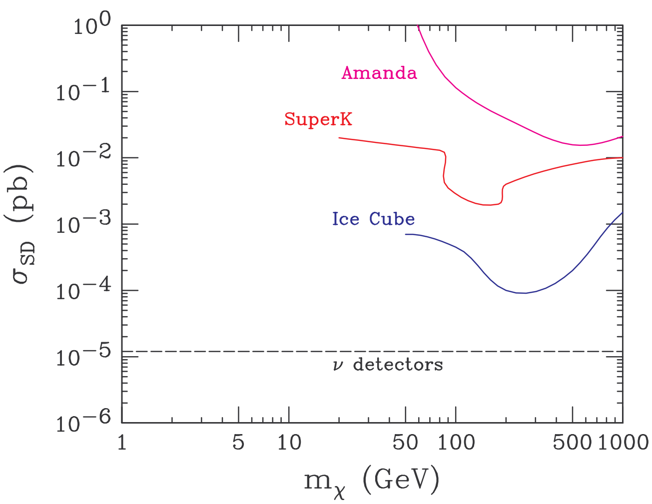

FIG. 3 (color online). Bounds on spin-dependent X-proton scattering as a function of dark matter mass m_X. The indicated red line is the published limit from SK [17] and the magenta line is the published limit from AMANDA [33] (assuming annihilation to $b\bar{b}$, and the analysis of 2001–2003 data). The blue line is the projected limit from IceCube-80 + DeepCore[33] (assuming 1800 live days). The dashed black line is the detection threshold for liquid scintillator neutrino detectors of $\rho = 1$ g/cm^3 with 22 500 m^3 fiducial volume running for 3000 live days, assuming annihilation only to neutrinos and detection only of ν_e.

measurement of the energy and angle of the muon will yield as sharp a peak in reconstructed neutrino energy distribution. But the neutrino energy resolution we expect is only $\sim 10\%$. So for neutrino energies ~ 10 GeV we still expect to be in the limit of small statistics, and the previous bounds hold. But for $E_\nu \sim 4$ GeV, one would expect close to 40 atmospheric neutrino events per energy bin (assuming 10% energy resolution) [20]. In this regime, demanding $\text{signal}/\sqrt{\text{background}} = 5$ for the discovery of an excess over known background should require about 30 events.[1] The sensitivity of a water Cherenkov detector would thus be about a factor of 3 worse (for a run time of 3000 live days and a volume of 22 500 m^3).

The important point for us is to note the scaling of our limit with detector volume and with run time. For the cases where small statistics are relevant, we found that our detection limit scaled inversely with both volume and run time. But when background becomes significant, our sensitivity will scale as $\text{signal}/\sqrt{\text{background}} \propto \sqrt{\text{volume} \times \text{time}}$. Our detection bound will thus scale as $(\text{volume} \times \text{time})^{-(1/2)}$. One should note that the limits obtained here for both liquid scintillator and water Cherenkov detectors are dependent on $\mathcal{O}(1)$ factors related to both astrophysics and the particle physics of the Sun and the detector response.

C. Other dark matter annihilation modes

Having done the case of leptophilic neutrino annihilations, we are in a position to generalize these results for more general decays into various combinations of decay products, as discussed earlier. One may think of the leptophilic case as the Green's function, which must be swept over the decay spectra for other types on annihilation products. Detectability of dark matter suffers as the signal to noise gets worse, naturally. But the issues of flavor ratios remain, for each energy. So, while the signal to noise will take a beating, the information on the dark matter decays will increase, if resolvable, potentially revealing whether the neutrinos are primary, secondary or even tertiary decay products. Clearly some work is needed in this area, which we have not yet completed.

VI. CONCLUSIONS

We have investigated the prospects for liquid-scintillator-type and water-Cherenkov-type neutrino detectors to discover dark matter through the $XX \to \nu\bar{\nu}$ annihilation process in the core of the Sun. We have found that the high energy resolution available at a liquid scintillator detector, combined with its ability to resolve the directionality of muons, would give a liquid scintillator detector excellent detection prospects in the 4–10 GeV range. Although a

[1] The uncertainty in the measurement of the excess is determined by $\sqrt{\text{signal} + \text{background}}$.

water Cherenkov detector will also have very good prospects in this range, its (presumably) lesser energy and track angle resolution give an advantage to liquid-scintillator-type detectors (assuming early calculations for these detectors are indeed realizable). In any event, we have pointed out that the coupled detection of both muon and electron neutrinos from annihilations will yield important and unique information of the dark matter branching fractions. We have identified a parametrization of the ratios of muon and antimuon events to the total which can reveal the source $\nu_{e,\bar{e}}$ fraction in dark matter annihilations, yielding perhaps the first detailed measurement of the structure of dark matter interactions.

This light dark matter range is of particular interest, since it is a mass range which can potentially explain the DAMA result. Indeed, there has been much recent interest in leptophilic dark matter candidates, for which the annihilation channel to neutrinos can be significant. For this possibility, low threshold neutrino experiments should provide the best bounds on the dark matter–nucleon scattering cross section. For heavier dark matter, it is possible that an analysis of fully contained electron events can yield significant detection prospects. Interestingly, it has been recently argued that neutrino probes of dark matter can also reveal information about local dark matter density fluctuations in the regions through which the Sun has traversed in the past [31]. It seems that dark matter detection at neutrino detectors may have a very bright future.

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