Solar Atmospheric Neutrinos: A New Neutrino Floor for Dark Matter Searches

Kenny C. Y. Ng,1,2,3, John F. Beacom,2,3,4,† Annika H. G. Peter,2,3,4,‡ and Carsten Rott§

1Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
2Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210
3Department of Physics, Ohio State University, Columbus, OH 43210
4Department of Astronomy, Ohio State University, Columbus, OH 43210
5Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea

(Dated: 30 March 2017)

As is well known, dark matter direct detection experiments will ultimately be limited by a “neutrino floor,” due to the scattering of nuclei by MeV neutrinos from, e.g., nuclear fusion in the Sun. Here we point out the existence of a new “neutrino floor” that will similarly limit indirect detection with the Sun, due to high-energy neutrinos from cosmic-ray interactions with the solar atmosphere. We have two key findings. First, solar atmospheric neutrinos with energies below 10 MeV are absorbed in the Sun, and they may only be detected by Earth-based neutrino telescopes. Second, for neutrinos with energies above 10 MeV, which can be isolated by muon energy loss rate, solar atmospheric neutrinos should soon be detectable in IceCube. Discovery will help probe the complicated effects of solar magnetic fields on cosmic rays. These events will be backgrounds to WIMP scenarios with long-lived mediators, for which higher-energy neutrinos can escape from the Sun.

PACS numbers: 96.50.S-, 95.35.+d, 26.65.+t, 95.85.Ry

I. INTRODUCTION

Numerous astrophysical and cosmological observations show that most of the matter in the universe has no apparent electromagnetic interactions, and hence is called dark matter (DM) [1–3]. Identifying the particle nature of DM is important for understanding what lies beyond the standard models of cosmology and of particle physics.

Weakly Interacting Massive Particles (WIMPs) [4], which can be produced with the correct abundance as a thermal relic of the early universe [5, 6], are a popular DM candidate. WIMPs can be probed through annihilation signals seen by high-energy astrophysical observatories (indirect detection) [7, 8], production at colliders detected by missing energy [9, 10], and by the elastic scattering of nuclei in underground experiments (direct detection) [11–13].

As direct detection experiments improve in sensitivity, they will reach a “neutrino floor,” due to nuclear recoils induced by neutrinos from the Sun, cosmic supernovae, and Earth’s atmosphere [14–20]. This is an irreducible background, beyond which the sensitivity to DM scattering can improve at best with the square root of exposure. Importantly, current detectors are almost reaching this floor [21–24].

The scattering of DM with nuclei can also be probed by DM capture and annihilation in the Sun that leads to the production of high-energy neutrinos [25–28]. While for spin-independent (SI) scattering, the best sensitivity comes from direct detection experiments, for spin-dependent (SD) scattering, the sensitivity of solar DM searches can be better than that of direct detection experiments, depending on the annihilation channel. At present, the dominant background for solar DM searches is Earth atmospheric neutrinos (EAν). It is possible to improve the sensitivity faster than the square root of exposure by developing new detectors or analysis methods that can better leverage information on neutrino energies, directions, and flavors.

However, as neutrino telescopes become more sensitive, they too will face a “neutrino floor.” Cosmic-ray interactions with the Sun produce solar atmospheric neutrinos (SAν [29–32]). The SAν flux is an irreducible background for DM-induced neutrinos from the Sun. As discussed below, there are considerable uncertainties in predicting the SAν flux. Thus the SAν constitutes a hard floor; once their flux is detectable, the DM sensitivity cannot improve. If the SAν flux can be predicted well, or distinguished by the spectral shape, then the sensitivity will improve with the square root of exposure.

In this paper, we first consider SAν as a signal, interesting in its own right. We then consider SAν as a background to the solar DM search, and calculate the neutrino floor. (Some of our preliminary results were presented in conferences, e.g., Refs. [33]). In Sec. II, we review the SAν flux and calculate the detection prospects. In Sec. III, we review the neutrino flux from DM captured in the Sun and calculate the DM sensitivity floor caused by SAν. We also discuss the implications for non-minimal WIMP models. We aim for a precision of a factor of ~ 2, considering the uncertainties involved. We conclude in Sec. IV, where we also discuss how these uncertainties can be reduced.

* chun-yu.ng@weizmann.ac.il
† beacom.76@osu.edu
‡ apeter@physics.osu.edu
§ rott@skku.edu
II. SOLAR ATMOSPHERIC NEUTRINO FLUXES AND DETECTION

A. Solar Atmospheric Neutrino Flux

In this subsection, we review the $\text{SA}\nu$ flux calculation and define the model we use. We focus on muon neutrinos and their charged-current interactions, as the directionality provided by the final-state muons is crucial for detection and for background reduction, especially in the TeV range.

Cosmic rays entering the solar atmosphere undergo hadronic interactions and produce secondary neutrinos, similar to the production of $\text{EA}\nu$ \cite{34}. Because the thick-target limit is appropriate for incoming cosmic rays, the $\text{SA}\nu$ and $\text{EA}\nu$ are expected to have comparable intensity (flux per solid angle). However, there are some important differences.

If solar magnetic fields are ignored, then the most importance difference is at high neutrino energies. In Earth’s atmosphere, pions (kaons) above about 100 GeV (800 GeV) undergo significant hadronic scattering before decay \cite{34}, lowering the energy of their neutrinos and thus steepening their spectrum compared to the cosmic-ray spectrum. The Sun’s atmosphere is thinner, so this steepening does not occur until one to two orders of magnitude higher in energy \cite{29–32}. This difference makes the $\text{SA}\nu$ spectrum both higher and harder in the TeV range, which could help separate $\text{SA}\nu$ from $\text{EA}\nu$.

Magnetic fields are important at lower energies. Cosmic-ray propagation in the solar system is affected by solar magnetic fields carried by the solar wind, and magnetic fields near the solar surface can cause additional effects on cosmic-ray and charged secondary propagation. These effects were modeled by Seckel, Stanev, and Gaisser (SSG1991 \cite{30}). In their $\text{Nominal}$ model, magnetic effects strongly suppress the neutrino flux at low energies. In their $\text{Naive}$ model, where magnetic effects are ignored, the $\text{SA}\nu$ intensity is indeed comparable to the $\text{EA}\nu$ intensity near $\sim 1$ GeV. At sufficiently high energies, magnetic effects should be negligible. In the SSG1991 models, this transition occurs at about 300 GeV neutrino energy, though the value is theoretically quite uncertain. At lower energies, the spread between the SSG1991 models gives some indication of the uncertainty. The corresponding gamma-ray fluxes lie between these two extremes \cite{35–37}. We use the SSG1991 models up to 300 GeV.

At higher energies, the uncertainties are expected to be less, but can be non-negligible. For neutrino energies above 300 GeV, we use the model from Ingelman and Thunman (IT1996 \cite{32}). The IT1996 model assumes zero magnetic fields, and is consistent with the $\text{Naive}$ model of SSG1991 above $\sim 100$ GeV. We caution that it is not clear how much magnetic fields can affect the neutrino production at $\sim 1$ TeV, the most relevant energy range for $\text{SA}\nu$ detection, and we comment further in Sec. II C.
We take into account neutrino mixing. As shown in Refs. [38], there are both vacuum-mixing and matter effects. However, these effects are largely washed out after combining neutrino and antineutrinos, integrating over the production region, and using wide energy bins. The final muon neutrino flux is thus roughly a factor of $\sim 0.5$ less than that at production, similar to vacuum mixing alone, where $1 : 2 : 0$ transforms to nearly $1 : 1 : 1$. For simplicity, given the other large uncertainties, we simply reduce the total SA neutrino muon flux by this factor.

For the EA$\nu$ model, we use the all-sky averaged intensity from Ref. [39], and the parametric form in Ref. [40] to extrapolate to high energies, after matching the normalization. We ignore neutrino mixing for the EA$\nu$, which would reduce the flux by a factor of $2$ at low energies and would be negligible at high energies [41], where we are most interested. The EA$\nu$ intensity also changes with zenith angle [42], but is only a $\sim 50\%$ effect for the most important energies and directions considered here. We neglect this variation, in keeping with our precision goal of a factor of $\sim 2$.

Figure 1 shows the predicted SA$\nu$ flux after mixing, integrated over the angular size of the Sun. We have joined the SSG1991 and IT1996 fluxes at 300 GeV. We also show the EA$\nu$ flux for two cases. The first corresponds to the angular size of the Sun, with half angle $\theta_{\text{sun}} = 0.27^\circ$ and the second is the neutrino-muon separation angle $\theta_{\mu\mu} = 1^\circ$ $\sqrt{E_{\nu}/1\text{TeV}}$. As described above, in the same solid angle, the EA$\nu$ flux becomes smaller and steeper than the SA$\nu$ flux at high energies. For practical purposes, the background from the EA$\nu$ depends on the flux within $\theta_{\mu\mu}$. Taking into account the angular resolution for muons themselves would slightly increase the EA$\nu$ background. A key message of the figure is that the SA$\nu$ flux exceeds the EA$\nu$ background above a few TeV.

### B. Neutrino Detection

In this subsection, we discuss the detection of muon neutrinos from the Sun with neutrino telescopes. We adopt the “theorist’s” or ideal approach to estimate the best possible scenario. In a realistic case, background reduction and threshold effects reduce the signal efficiency, which are encoded in the effective areas provided by experimental collaborations. These effective areas are thus analysis-dependent, and could be improved. The ideal approach is necessary because we want to separate events by muon energy, which is not possible in the effective-area approach. We comment on the differences between the ideal and the realistic cases below.

As noted, we focus on muon neutrinos and the tracks they produce in charged-current interactions. We combine neutrinos and antineutrinos. The muon energy at birth, $E_{\mu}$, is related the neutrino energy, $E_{\nu}$, by $E_{\mu} = E_{\nu}(1 - y)$, where $y$ is the inelasticity parameter [43, 44]. For simplicity, we assume a fixed value of $y = 0.4$ throughout our energy range of interest. We neglect neutrino absorption in Earth, which becomes important only above $\sim 40\text{ TeV}$ for neutrinos that cross the diameter (and $\sim 1\text{ PeV}$ for neutrinos that travel from the Sun to IceCube [44]).

Muons can be produced inside the detector (starting events), or outside and then enter the detector after propagation (entering events). For starting events, the muon spectrum is

$$\frac{dN_{\text{sta}}}{dE_{\mu}} \approx \frac{N_{A}\rho VT}{1 - y} \left[ \frac{d\Phi}{dE_{\nu}} E_{\nu}^{\alpha}(E_{\nu}) \right]_{E_{\nu} = \frac{E_{\mu}}{1-y}},$$

where $d\Phi/dE_{\nu}$ is the neutrino flux, $\sigma$ is the interaction cross section [43, 44], $N_{A} = 6.02 \times 10^{23}$ is the Avogadro number, $\rho \simeq 1\text{ g cm}^{-3}$ is the density, $V$ is the fiducial volume of the detector, and $T$ is the effective exposure. This muon energy is its birth energy. In most cases, to reduce background from atmospheric muons, only upgoing events are considered. The effective exposure for the Sun is taken to be half the detector live time.

For entering muons, taking into account energy loss, the spectrum is [45, 46]

$$\frac{dN_{\text{ent}}}{dE_{\mu}} \approx \frac{N_{A}\rho AT}{\rho(\alpha + \beta E_{\mu})} \int_{E_{\nu}^{(1)}}^{E_{\nu}^{(2)}} dE_{\nu} \left[ \frac{d\Phi}{dE_{\nu}} E_{\nu}^{\alpha}(E_{\nu}) \right],$$

where $A$ is the geometric detector area, $\alpha = 2.0 \times 10^{-6}\text{ TeV cm}^{-2}\text{ g}^{-1}$, and $\beta = 4.2 \times 10^{-6}\text{ cm}^{-2}\text{ g}^{-1}$ [47, 48]. The muon energy is that when the muon enters the detector.

We consider two experimental setups, corresponding to Super-Kamiokande (Super-K) and IceCube. They cover the range of a small low-threshold detector and a large high-threshold detector, respectively. For Super-K, we use $V \approx 2 \times 10^{4}\text{ m}^{3}$ and approximate the geometric area to be $A \approx 780\text{ m}^{2}$. For IceCube, we use $V \approx 10^{7}\text{ m}^{3}$ and $A \approx 10^{6}\text{ m}^{2}$.

### C. Solar Atmospheric Neutrinos as Signal

In this subsection, we consider the SA$\nu$ as a signal. For this case, only an IceCube-sized detector is relevant. We then discuss the implications of detecting the Sun as a high-energy astrophysical neutrino source.

Figure 2 shows the muon spectrum of the SA$\nu$ signal compared to the EA$\nu$ background, following the procedure described above, with 10 years of IceCube live time. At low energies, the EA$\nu$ background is dominant. The background decreases rapidly, largely due to the decreasing neutrino-muon angle, and eventually falls below the SA$\nu$ flux. Therefore, detection of the SA$\nu$ signal critically depends on isolating high-energy events. Fortunately, this can be done with muons with energy $> 1\text{ TeV}$, above the minimum-ionizing regime, where the muon energy loss become radiative [49], which can be used to distinguish muons above 1 TeV, as demonstrated in Ref. [50]. We find the integrated number of events
above 1 TeV to be 4.5 and 4.1 for SAν and EAν, respectively. Above a slightly higher energy, the signal would decrease, but the background would decrease more. This suggests that IceCube and KM3NeT [51] are sensitive to the SAν signal.

If TeV muon events are detected from the Sun, we note that they can be distinguished from those from solar DM in standard WIMP scenarios. As described below, neutrinos above about 100 GeV produced in the solar core are absorbed as they leave the Sun. Therefore, if an excess of > 1 TeV muons is seen from the Sun, they are likely to be SAν events. As a result, we do not count these events when calculating the neutrino sensitivity floor for standard WIMPs. We comment on non-minimal DM scenarios below.

Given that SAν could potentially be detected as a signal, it is important to discuss the uncertainty of the SAν flux and the implications of a detection. Most of the inputs of the SAν flux calculation, such as the primary cosmic-ray flux, solar matter distribution, and neutrino mixing parameters, are well constrained. The most uncertain aspect of the SAν calculation is the effect of solar magnetic fields. Theoretically, the inclusion of their effects is challenging due to the complicated solar coronal and photospheric magnetic fields. From cosmic-ray shadow measurements, there is evidence that coronal fields [52] can affect the propagation of ∼ 10 TeV cosmic rays, which is the most relevant energy range for IceCube. Thus, the detection of the SAν could be used to determine the overall cosmic-ray interaction rate with the Sun, and therefore the magnetic field effects.

One can also study cosmic-ray interactions with the Sun through gamma-ray observations. Gamma rays are readily absorbed by the Sun. The no-magnetic-field scenario therefore corresponds to minimal gamma-ray production [53]. Observations with Fermi [35–37] show that the gamma-ray flux is much larger than the no-magnetic-field case, possibly up to 100 GeV. This suggests that magnetic fields are still affecting the cosmic-ray primaries up to at least 1 TeV. Above the energy where magnetic fields can be ignored, gamma-ray production is expected to be suppressed. As a result, even limits on the flux of TeV gamma rays from the Sun by HAWC [54] and LHAASO [55] would be an important clue. This, together with the detection of SAν by IceCube, would be important for normalizing cosmic-ray interaction rates with the Sun and disentangling magnetic-field effects.

Lastly, it is important to emphasize that the detection of the Sun as a high-energy neutrino point source would by itself an important milestone for neutrino astronomy, especially given that sources have yet to be identified for the IceCube events. The Sun is also conveniently observable for neutrino telescopes at both hemispheres, so it could in principle be a flux calibration source for successor experiments of IceCube and KM3NeT.

III. SOLAR DM SENSITIVITY FLOOR

A. Neutrinos from Solar WIMP DM

In this subsection, we review the calculation of neutrino flux from WIMP DM annihilation in the Sun. The process of DM capture and annihilation in the Sun is well studied [28, 57–59]. The time evolution of the DM number density \( N_\chi \) in the Sun is

\[
\frac{d}{dt} N_\chi = \Gamma_{\text{cap}} - C_{\text{ann}} N_\chi^2,
\]

where \( \Gamma_{\text{cap}} \) is the capture rate of DM in the Sun and \( C_{\text{ann}} \) is the annihilation coefficient. For typical parameters, equilibrium is easily achieved [28]. Hence, the annihilation rate, \( \Gamma_{\text{ann}} \), is related to the capture rate, \( \Gamma_{\text{ann}} = C_{\text{ann}} N_\chi^2 / 2 \approx \Gamma_{\text{cap}} / 2 \). The differential neutrino flux, \( d\Phi_\nu / dE \) is

\[
d\Phi = \frac{\Gamma_{\text{ann}}}{4\pi D_\odot^2} \frac{d\tilde{N}}{dE_\nu},
\]

where \( d\tilde{N}/dE \) is the neutrino spectrum per annihilation (with all mixing effects included) and \( D_\odot \approx 1.5 \times 10^8 \) km is the distance to the Sun.

The capture rate depends on the DM-nucleon cross section and the DM mass \( m_\chi \) and is largely independent of astrophysical uncertainties [59, 60]. We calculate the capture rates, and hence the annihilation rates, using DarkSUSY [61].

We obtain the neutrino spectrum per annihilation using WIMPSIM [56], which takes into account both neutrino absorption in the Sun and flavor evolution from production to the Earth [62, 63]. (The latter can be seen from the “wiggles” in the spectra.) We also ignore low-energy neutrinos from dark matter annihilation in the Sun [64, 65].

Figure 3 shows the total DM muon spectra for the \( \chi\chi \rightarrow \tau\tau \) channel as well as the SAν muon spectrum for IceCube and Super-K, respectively. We note that for high DM masses, the neutrino spectra \( \geq 1 \) TeV are identical. This is because neutrinos escaping from the core of the Sun reach an optical depth of unity around a few hundred GeV. Above that energy, the neutrino fluxes are exponentially suppressed, and hence have the same shape.

B. Indirect Detection Neutrino Floor

In this subsection, we consider SAν as a background to solar DM searches, and we calculate the corresponding sensitivity floor.

To estimate the neutrino sensitivity floor, we compare the number of SAν background events to the DM signal events by integrating the total (starting + entering)
muon spectrum,

\[ N = \int_{E_{\text{min}}}^{E_{\text{max}}} \left( \frac{dN^{\text{sta}}}{dE_{\mu}} + \frac{dN^{\text{ent}}}{dE_{\mu}} \right) \, . \]  \hspace{1cm} (5)

The energy range, \( E_{\text{min}} \) to \( E_{\text{max}} \), depends on the detector. For IceCube, we choose \( E_{\text{min}} \) and \( E_{\text{max}} \) to be 50 GeV and 1 TeV. The lower bound is chosen to roughly match the main IceCube selection in Ref. [66]. We assume events above 1 TeV can be identified and isolated by energy loss. They are not included here as standard WIMP DM cannot produce such neutrinos. (Including the high-energy neutrinos would cause only a modest difference in our results for the floor, because the SA\( \nu \) spectrum is falling.) For Super-K, \( E_{\text{min}} \) and \( E_{\text{max}} \) are chosen to be 1 GeV and 1 TeV. The precise choice of \( E_{\text{max}} \) does not change our result by much, due to the small number of events for both SA\( \nu \) and DM components. The choice of \( E_{\text{min}} \) does affect DM masses that are near the threshold. We consider only one energy bin as we assume neutrino telescopes have no energy information in this regime.

For energies below about 200 GeV, the uncertainty of SA\( \nu \) flux is estimated using the \textit{Naive} and \textit{Nominal} models from SSG1991. As mentioned above, the uncertainty at higher energies is not clear, given the complicated magnetic field effects on cosmic-ray interactions in the Sun. As can be seen from Fig. 3, the uncertainty in the SA\( \nu \) flux affects Super-K much more than IceCube. Integrating the \textit{Naive} and \textit{Nominal} SA\( \nu \) spectra, we obtain about 5—6 events/yr for IceCube and 0.008—0.007 events/yr for Super-K. Qualitatively, we can see that SA\( \nu \) events are not likely to be detectable in Super-K. This already shows that the neutrino sensitivity floor will not be reached by kiloton scale low-threshold detectors. For IceCube, however, even in the case when EA\( \nu \) backgrounds can be completely removed, the SA\( \nu \) events will ultimately limit the DM search.

To quantitatively calculate the neutrino floor, we find the DM flux that gives an equal number of events to the SA\( \nu \) background. For each DM mass and annihilation channel, this then defines a DM-nucleon cross section. The floor for Super-K is about 100 events/yr, and for IceCube, about 0.003—0.007 events/yr for SA\( \nu \). This is equivalent to assuming the SA\( \nu \) flux is falling.) For Super-K, \( E_{\text{min}} \) and \( E_{\text{max}} \) are chosen to be 1 GeV and 1 TeV. The precise choice of \( E_{\text{max}} \) does not change our result by much, due to the small number of events for both SA\( \nu \) and DM components. The choice of \( E_{\text{min}} \) does affect DM masses that are near the threshold. We consider only one energy bin as we assume neutrino telescopes have no energy information in this regime.

For energies below about 200 GeV, the uncertainty of SA\( \nu \) flux is estimated using the \textit{Naive} and \textit{Nominal} models from SSG1991. As mentioned above, the uncertainty at higher energies is not clear, given the complicated magnetic field effects on cosmic-ray interactions in the Sun. As can be seen from Fig. 3, the uncertainty in the SA\( \nu \) flux affects Super-K much more than IceCube. Integrating the \textit{Naive} and \textit{Nominal} SA\( \nu \) spectra, we obtain about 5—6 events/yr for IceCube and 0.008—0.007 events/yr for Super-K. Qualitatively, we can see that SA\( \nu \) events are not likely to be detectable in Super-K. This already shows that the neutrino sensitivity floor will not be reached by kiloton scale low-threshold detectors. For IceCube, however, even in the case when EA\( \nu \) backgrounds can be completely removed, the SA\( \nu \) events will ultimately limit the DM search.

To quantitatively calculate the neutrino floor, we find the DM flux that gives an equal number of events to the SA\( \nu \) background. For each DM mass and annihilation channel, this then defines a DM-nucleon cross section. The floor for Super-K is about 100 events/yr, and for IceCube, about 0.003—0.007 events/yr for SA\( \nu \). This is equivalent to assuming the SA\( \nu \) flux is falling.) For Super-K, \( E_{\text{min}} \) and \( E_{\text{max}} \) are chosen to be 1 GeV and 1 TeV. The precise choice of \( E_{\text{max}} \) does not change our result by much, due to the small number of events for both SA\( \nu \) and DM components. The choice of \( E_{\text{min}} \) does affect DM masses that are near the threshold. We consider only one energy bin as we assume neutrino telescopes have no energy information in this regime.

For energies below about 200 GeV, the uncertainty of SA\( \nu \) flux is estimated using the \textit{Naive} and \textit{Nominal} models from SSG1991. As mentioned above, the uncertainty at higher energies is not clear, given the complicated magnetic field effects on cosmic-ray interactions in the Sun. As can be seen from Fig. 3, the uncertainty in the SA\( \nu \) flux affects Super-K much more than IceCube. Integrating the \textit{Naive} and \textit{Nominal} SA\( \nu \) spectra, we obtain about 5—6 events/yr for IceCube and 0.008—0.007 events/yr for Super-K. Qualitatively, we can see that SA\( \nu \) events are not likely to be detectable in Super-K. This already shows that the neutrino sensitivity floor will not be reached by kiloton scale low-threshold detectors. For IceCube, however, even in the case when EA\( \nu \) backgrounds can be completely removed, the SA\( \nu \) events will ultimately limit the DM search.

To quantitatively calculate the neutrino floor, we find the DM flux that gives an equal number of events to the SA\( \nu \) background. For each DM mass and annihilation channel, this then defines a DM-nucleon cross section. This is equivalent to assuming the SA\( \nu \) events are totally indistinguishable from the DM annihilation events, or there is 100% uncertainty in the SA\( \nu \) flux. In principle, the expected number of of SA\( \nu \) events can be estimated with an accurate SA\( \nu \) model, or inferred from SA\( \nu \) observations at energies > TeV. However, given that there is likely appreciable uncertainty in the SA\( \nu \) flux, as suggested by gamma-ray data at \( \sim \) 100 GeV, the 100% uncertainty is reasonable and perhaps optimistic. Lastly, we also neglect the EA\( \nu \), as well as other backgrounds. Including these would increase the floor.

Figure 4 shows the neutrino sensitivity floor for the \( \tau\bar{\tau} \) and \( b\bar{b} \) channels, which represents hard and soft DM spectra, respectively. We only consider SD cross sections, as direct detection experiments are more efficient at probing the SI cross sections. The floor for Super-K is about two orders of magnitude below the current limit. Given the low event rate and the EA\( \nu \) background, it is unlikely that this floor will be reached. For IceCube, the situation
is more interesting, as the sensitivity floor is only about one order of magnitude below the current limit at high DM masses. With more exposure, and possibly improved analysis, the floor may be reachable.

To cross check, we also estimate the neutrino floor for IceCube with the realistic approach, using the effective area provided in Ref. [66], which is optimized for solar DM searches and covers roughly 30 – 3000 GeV neutrino energy. With this effective area, we find that both the SAν background and DM signal reduce by roughly a factor of 10, compared to the ideal case. The sensitivity floor obtained with our ideal approach and the realistic case agree to within a factor of 2. This is because the detector efficiency affects both the DM signal and SAν background by roughly the same factor.

In Figure 4, we also show the strongest direct detection limit currently available, from PICO-60 [68]. For the ττ channel, representative of cases with hard neutrino spectrum, the solar DM search is more sensitive in most of the mass range. For the b¯b case or a soft DM spectrum, direct detection experiments are already more sensitive, and are not far from the indirect detection neutrino floor. To be clear, direct detection sensitivity is not limited by the indirect detection neutrino floor.) In all cases, the solar DM search is complementary to direct detection, most notably due to their different dependence on the local DM velocity distribution [60].

It is also interesting to compare the neutrino floors between direct detection and indirect detection. We summarize the results for several representative experimental setups considered in Ref. [20]. For heavy targets, such as Ge and Xe, the direct detection floor is higher in general (even higher for Si), which is roughly $10^{-41}$ cm$^2$ at 10 GeV DM mass and $10^{-40}$ cm$^2$ at 1 TeV. This is expected, as heavy targets are more efficient at detecting the background MeV neutrinos through coherent scattering. In the case of light targets, such as CF$_4$ or C$_3$F$_8$, the direct detection neutrino floor is significantly lower, roughly $10^{-43}$ cm$^2$ at both 10 GeV and 1 TeV (even lower if energy information is utilized). This is lower than the indirect detection neutrino floor for solar DM searches. Hence, if this floor is reached in the future, a large direct detection experiment with light targets will be needed to reach small SD DM-nucleon cross sections. Alternatively, new analysis techniques will be needed to differentiate the SAν events from DM events, to lower the indirect detection neutrino floor.

### C. DM Models with Long-Lived Mediators

In this subsection, we briefly discuss a non-minimal DM scenario that modifies the discussion above. If DM annihilates first into a pair of long-lived dark mediators, the neutrinos produced through the delayed decay of those mediators can potentially freely escape the Sun [69, 70]. In this case, it is possible for TeV-scale DM to mimic the high-energy part of the SAν. Given that

![Figure 4](image-url)

**FIG. 4.** Left: The indirect detection neutrino sensitivity floors for SD DM cross section for Super-K and IceCube are shown in the bottom. We show the case for ττ channel, and the solid (dashed) line corresponds to the Naive (Nominal) case. We also show current indirect detection limits from Super-K [67] and IceCube [66]; the whitespace between them and the floors shows the remaining parameter space that can be probed by solar DM searches. For perspective, we also show the direct detection limits from PICO [68]. Right: Same as the left, but for b¯b channel.
the detection of the TeV SAν events are possibly imminent, the neutrino floor for high-mass DM with long-lived mediators may soon be reached.

To distinguish SAν from neutrinos in the long-lived mediator scenario, provided that the mediators decay outside the solar atmosphere, TeV gamma rays [70–72] or electrons (e±) [73–76] from the Sun may be the key. For the long-lived mediator scenario, the gamma-ray and electron flux can be comparable to the neutrino flux, and can be probed by sensitive ground-based (HAWC [54], LHAASO [55]) and space-borne (Fermi [77], AMS-02 [78], DAMPE [79], CALET [80], etc) detectors. However, in the case of cosmic-ray interactions with the Sun, the gamma-ray flux is hugely suppressed by the small angular size of the solar limb [53]. Therefore, multi-messenger GeV-TeV observations of the Sun are important in both understanding the cosmic-ray interactions and general DM searches.

IV. DISCUSSIONS AND CONCLUSIONS

We focus on neutrino-induced muon tracks due to their directionality. However, showers induced by electron and tau neutrinos are also powerful signatures for neutrino detection [81], as they have better neutrino energy resolution and have lower Earth atmospheric backgrounds. The energy information is important in improving the sensitivity of DM searches [58], and has been demonstrated at low energies in Super-K [67]. At the high-energy regime, this is also promising in the future with KM3NeT, which is expected to have better angular resolution with shower events. The neutrino flux from DM annihilations has a very different spectrum shape compared to SAν. As a result, if showers can achieve similar DM sensitivity as muons, they will be important for distinguishing the SAν background.

To conclude, in this work we consider the detection of SAν neutrinos and their implications for solar DM searches.

We show that in the multi-TeV regime, where muons can be isolated using their energy loss, SAν are detectable in IceCube and KM3NeT. This would help understand cosmic-ray interactions in the solar atmosphere. These events cannot be mimicked by standard WIMP scenarios due to neutrino absorption. However, DM with long-lived mediators could mimic these high-energy neutrinos. If these events are detected, TeV gamma rays or electrons could be important diagnostic tools.

For sub-TeV regime and considering IceCube, SAν events are indistinguishable with solar DM signals due to the lack of energy resolution. Therefore, SAν constitute a neutrino sensitivity floor, which is only about one order of magnitude below the current IceCube limit. To breach the floor would require an accurate model of SAν that includes magnetic-field effects, or new detector and analysis techniques that can better reconstruct neutrino energy and direction. Even then, the DM sensitivity can only improve with the square root of the exposure.

At lower energies and considering Super-K, the number of expected SAν events are much less than one and the neutrino floor is about two orders of magnitude below the current limit. Therefore, there is still a large discovery potential for low-threshold neutrino telescopes, provided that large detector mass and exposure are available, for example with Hyper-Kamiokande [82].

Comparing the sensitivity of SD cross section between solar DM searches and direct detection experiments, the latter are currently not as sensitive as solar DM annihilates to a hard neutrino spectrum, but opposite if the neutrino spectrum is soft. If the solar DM sensitivity floor is reached by neutrino telescopes, a large direct detection experiment with light targets may be able to reach one order of magnitude lower in cross section, until it is limited by MeV neutrino backgrounds.

Note added: During the final stage of this work, Ref. [83] appeared on arXiv. It provides an updated no-magnetic field SAν flux calculation and also points out the existence of the neutrino floor. Their SAν flux is consistent with the ones we use within a factor of 2 at ∼1 TeV. Their neutrino floors are higher than ours by about one order of magnitude, and the reason for the differences is unknown.

ACKNOWLEDGMENTS

We thank Rebecca Leane, Shirley Li, and Bei Zhou for helpful comments and discussions. KCYN is supported by a Croucher Fellowship and a Benoziyo Fellowship, and was partially supported by NSF Grant PHY-1404311 awarded to JFB. JFB is supported by NSF Grant PHY-1404311. KCYN and AHGP were supported by NASA grant NNX13AP49G awarded to AHGP and CR. CR acknowledges support from the Korea Neutrino Research Center which is established by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2009-0083526) and Basic Science Research Program NRF-2016R1D1A1B03931688.

[1] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rept. 267, 195 (1996), hep-ph/9506380.
[2] G. Bertone, D. Hooper, and J. Silk, Phys. Rept. 405, 279 (2005), hep-ph/0404175.
[3] L. E. Strigari, Phys. Rept. 531, 1 (2013), 1211.7090.
[4] G. Steigman and M. S. Turner, Nucl. Phys. B253, 375 (1985).
[71] B. Batell, M. Pospelov, A. Ritz, and Y. Shang, Phys. Rev. D81, 075004 (2010), 0910.1567.
[72] C. Arina, M. Backovic, J. Heisig, and M. Lucente, (2017), 1703.08087.
[73] P. Schuster, N. Toro, and I. Yavin, Phys. Rev. D81, 016002 (2010), 0910.1602.
[74] P. Schuster, N. Toro, N. Weiner, and I. Yavin, Phys. Rev. D82, 115012 (2010), 0910.1839.
[75] The Fermi LAT, M. Ajello et al., Phys. Rev. D84, 032007 (2011), 1107.4272.
[76] J. L. Feng, J. Smolinsky, and P. Tanedo, Phys. Rev. D93, 115036 (2016), 1602.01465.
[77] Fermi-LAT, S. Abdollahi et al., Phys. Rev. Lett. 118, 091103 (2017), 1703.01073.
[78] AMS Collaboration, M. Aguilar et al., Phys. Rev. Lett. 113, 121102 (2014).
[79] J. Chang, Chin. J. Spac. Sci. 34, 550 (2014).
[80] S. Torii, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 630, 55 (2011), Proceedings of the 2nd Roma International Conference on Astroparticle Physics (RICAP 2009).
[81] J. F. Beacom and J. Canda, JCAP 0411, 009 (2004), hep-ph/0409046.
[82] K. Abe et al., (2011), 1109.3262.
[83] C. A. Arguelles, G. de Wasseige, A. Fedynitch, and B. J. P. Jones, (2017), 1703.07798.