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Abstract: Recent results from PAMELA and ATIC hint that $\mathcal{O}$(TeV) dark matter (DM) is annihilating, in our galactic neighborhood, mainly to leptons. The present annihilation rate is larger than at freeze-out, possibly due to a low-velocity enhancement. In this case the rate of neutrino emission from the Earth, due to DM annihilation, may be greatly enhanced while the rate from the Sun is unaltered. Neutrino telescopes may see these earthborn neutrinos. Combining with the data from direct detection experiments will yield valuable information about the DM sector.

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Approximately 20% of the matter-energy budget of the universe is due to Dark Matter (DM). The favored candidate for the DM particle is a thermal relic with annihilation cross section $\langle \sigma v \rangle \approx 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$, a weakly interacting DM (WIMP). Many experiments are underway to probe the DM, either directly through its interactions with Standard Model (SM) particles or indirectly through its annihilations to SM particles. Recently several indirect detection experiments have reported results which may be interpreted as due to DM annihilations, although they could also have an astrophysical origin [1].

The ATIC experiment has reported an excess of electron-positron flux around $300 - 800\,\mathrm{GeV}$ [2]. In addition PAMELA [3] is seeing an increase of the positron fraction around energies of $10 - 80\,\mathrm{GeV}$ and no corresponding excess in the antiproton fraction [4]. Taken together these suggest that $\mathcal{O}(1\,\mathrm{TeV})$ DM, annihilating preferentially to leptons, is being observed [5–7]. However, the annihilation cross section required to explain the excesses is substantially larger than $3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$ [8, 9]. The enhancement may be due to a boost factor, a nearby clump of DM or a low-velocity Sommerfeld effect (see also [10, 11] for an alternative explanation).

These results are exciting and surprising, not only are we possibly observing WIMP DM but maybe also a non-trivial DM sector, whose dynamics seems to imply an epoch-dependent annihilation cross section. Looking at the photon spectrum [12–16] and additional cosmic ray (CR) experiments [17–19] will test this emerging paradigm [7] and whether these excesses are actually due to DM. However, the photon and CR flux depends on the DM halo profile and the propagation model. We demonstrate here that the same DM sector dynamics may induce dramatic changes in the neutrino flux from the Earth which give a very different probe of the same microscopic phenomena. For a possible signal from galactic neutrinos see [20–22].

DM particles which accumulate in the Sun and Earth annihilate into SM particles, among which neutrinos can escape and be detected [23–27]. The flux depends on the capture and annihilation cross sections, unless the DM has already reached equilibrium which leads to a maximal flux, exclusively controlled by the capture rate. The effects which enhance the annihilation rate would, generically, not affect the capture rate. For instance, an ultra light particle with sizable coupling to the nuclei is required to Sommerfeld enhance the capture rate which is probably in conflict with various precision data. While the capture rate remains unaltered, a larger annihilation cross section will shorten the typical time for the DM to reach equilibrium. Our key observation is that since it is very probable that the Earth has not yet reached equilibrium for a relic annihilation cross section [28, 29], this effect would yield orders of magnitude enhancement in the neutrino flux from the core of the Earth. Moreover this flux will also be correlated with the DM direct search experiments [30, 31]. A combination of these data sets yields fairly clean information about the microscopic nature of the DM sector dynamics.

Neutrinos via DM annihilation. The competition between capture and annihilation of the DM leads to a present day DM annihilation rate [32]

$$\Gamma = \frac{1}{2} A N^2 = \frac{C}{2} \tanh^2 \left(t_\oplus \sqrt{CA} \right) , \tag{1}$$

where $t_\oplus \simeq 4.5 \times 10^9$ yrs is the age of the Earth, $A = \langle \sigma v \rangle / V_{\rm eff}$, $V_{\rm eff} = 5.7 \times 10^{22} {\rm cm}^3 \, ({\rm TeV}/m_\chi)^{3/2}$ is the effective volume of the Earth core [28] and C is the capture rate. For the Earth the capture rate is dominated by the spin independent (SI) elastic scattering (see [33] for the inelastic case) of the DM off various elements in the Earth [32],

$$C_\oplus \simeq 1.7 \times 10^5 {\rm s}^{-1} \frac{\rho^\chi_{0.3}}{(v^\chi_{270})^3} \left(\frac{\rm TeV}{m_\chi} \right)^2 \sum_i f_i \left(\frac{\sigma^{N_i}_{\rm SI}}{10^{-6}{\rm pb}} \right) , \tag{2}$$

where the sum is over the elements O, Si, Mg, S, Fe and Ni, only 3% of the Earth mass is neglected. The DM mass is denoted m_χ, $\rho^\chi_{0.3}$ and v^χ_{270} are the DM energy density and velocity in the halo in units of 0.3 GeV/cm^3 and 270 km/s respectively, while the factor f_i accounts for the mass fraction and distribution profile of the element i [32], whose cross section with DM is denoted $\sigma^{N_i}_{\rm SI}$. Direct detection experiments probe the SI cross section of DM scattering off protons, $\sigma^p_{\rm SI}$. To better than 1%, protons and neutrons contribute identically to the cross-section, such that $\sigma^N_{\rm SI} \approx N^4 \sigma^p_{\rm SI} \, (1 - 2m_N/m_\chi)$ for any nucleus of mass number N in the limit of $m_\chi \gg m_N$. Hence,

$$C_\oplus \simeq 9.6 \times 10^{11} {\rm s}^{-1} \frac{\rho^\chi_{0.3}}{(v^\chi_{270})^3} \left(\frac{\rm TeV}{m_\chi} \right)^2 \left(\frac{\sigma^p_{\rm SI}}{10^{-6}{\rm pb}} \right) . \tag{3}$$

The maximum rate of DM annihilation occurs after equilibrium is reached and is entirely determined by the capture rate, $\Gamma_{\rm eq} = C/2$. For times shorter than the equilibrium time $t_{\rm eq} = 1/\sqrt{CA}$ the abundance grows linearly with time and the annihilation rate is $\Gamma_{\rm neq} \sim \frac{1}{2} A C^2 t^2$. With a typical thermal relic annihilation cross section, $A_{\rm r} \simeq 5.3 \times 10^{-49} {\rm s}^{-1} \, (m_\chi/{\rm TeV})^{3/2}$, the Earth is far from equilibrium ($t_\oplus \ll t_{\rm eq}$) and not a good source of DM-neutrinos. However, if the observed electron/positron excesses are due to a low-velocity enhancement, R, the annihilation cross section can be far larger than that of the early universe, $A_\oplus = R A_{\rm r}$, bringing the Earth towards equilibrium today. The maximal enhancement in the rate is $\Gamma_{\rm eq}/\Gamma_{\rm neq} \sim (A_{\rm r} C_\oplus t^2_\oplus)^{-1}$ which can be several orders of magnitude and is obtained for $R \gtrsim (A_{\rm r} C_\oplus t^2_\oplus)^{-1}$. The escape velocity at the center of the Earth is approximately 15 km s^{-1} whilst DM in the halo has a Maxwell-Boltzmann distribution with $v_0 = 270$ km s^{-1}. The Sommerfeld enhancement grows as $\sim 1/v$ although this growth saturates at very low velocities [5], a further increase beyond $v = 270$ km s^{-1} may yield more non-trivial information about the DM sector. Thus, the enhancement may in fact be even larger than that for DM in the halo. It will be useful to define the critical capture rate for the Earth:

$$C^{\rm c}_\oplus = 1/A_{\rm r} t^2_\oplus \simeq 9.93 \times 10^{13} {\rm s}^{-1} \left(\frac{\rm TeV}{m_\chi} \right)^{3/2} , \tag{4}$$

above which the Earth would already have reached equilibrium and boosting the annihilation cross section will not result in an enhanced neutrino flux. Direct searches experiment such as CDMSII put an upper bound [30] on the SI elastic scattering cross section of 3.5×10^{-7}pb for $m_\chi = 1$ TeV. Thus, $C_\oplus \lesssim 10^{-2} C^{\rm c}_\oplus$ and the Earth is probably still far from equilibrium.

The capture rate (3) is derived assuming that the DM velocity distribution as encountered by the Earth is Gaussian. It is possible that in the solar system it differs from Gaussian [29, 34], particularly at the low velocities necessary for capture in the Earth and Sun. The DM abundance may also differ from the galactic halo density (see e.g. [29, 34–36] and refs. therein). Both direct and indirect detection experiments probe the same nuclear scattering cross section with different velocity sensitivity. Assuming a Gaussian distribution allows observations from direct and indirect experiments to be straightforwardly correlated. Furthermore, a future signal at direct detection experiments would directly probe the velocity distribution (through differential energy information) of the DM particles [31, 37, 38] at velocities of roughly $40 - 150\,\mathrm{km\,s^{-1}}$. Of particular importance are the Xe based experiments which have the lowest threshold, down to approximately three times the Earth escape velocity [38, 39].

Primary neutrinos. The muon flux at the surface of the Earth is given by:

$$\frac{d\Phi_\mu^{\mathrm{P}}}{dE_\mu} = \int_{E_\mu}^{\infty} dE_\nu \frac{d\Phi_\nu}{dE_\nu}\left[\frac{d\sigma_\nu^p(E_\nu,E_\mu)}{dE_\mu}\rho_p + (p\to n)\right] \times\ R_\mu(E_\mu) + (\nu\to\bar{\nu})\,, \tag{5}$$

with $\rho_{p,n}$ the number density of protons and neutrons in the medium, $5/9N_A\mathrm{cm}^{-3}$ and $4/9N_A\mathrm{cm}^{-3}$ for ice, where $N_A \simeq 6\times 10^{23}$ is Avogadro's number. $d\sigma_\nu^{p,n}/dE_\mu$ are the weak scattering cross sections of neutrinos on nucleons $\frac{d\sigma_\nu^{p,n}}{dE_\mu} = \frac{2m_pG_F^2}{\pi}\left(a_\nu^{p,n} + b_\nu^{p,n}\frac{E_\mu^2}{E_\nu^2}\right)$, where $a_\nu^{n,p} = 0.25, 0.15$, $b_\nu^{n,p} = 0.06, 0.04$ and $a_{\bar{\nu}}^{n,p} = b_\nu^{p,n}$, $b_{\bar{\nu}}^{n,p} = a_\nu^{p,n}$ [40]. $R_\mu(E_\mu)$, the muon range, defines the distance traveled by a muon until its energy drops below the energy threshold E_{th} of the detector, due to losses in the medium. Approximately, $R_\mu(E_\mu) = \frac{1}{\rho\beta}\log\left[\frac{\alpha+\beta E_\mu}{\alpha+\beta E_{\mathrm{th}}}\right]$, with ρ the density of the medium ($\simeq 1\,\mathrm{g\,cm^{-3}}$ for ice), $\alpha \simeq 2.0\,\mathrm{MeV\,cm^2g^{-1}}$ and $\beta \simeq 4.2\times 10^{-6}\mathrm{cm^2g^{-1}}$ for ice. For concreteness we focus here on IceCube [41], however as discussed below even AMANDA [42] and Super-K [43] are capable of constraining the annihilation signal. At IceCube, the energy threshold is about 50 GeV and for $E_\mu \sim$ TeV, R_μ is a few kilometers, longer than the detector.[1]

Since the DM is almost at rest, the muon neutrino flux at the surface of the Earth is monochromatic, $d\Phi_\nu/dE_\nu = \delta(E_\nu - m_\chi)B_{\bar{\nu}\nu}\Gamma/4\pi R_\oplus^2$, with $B_{\bar{\nu}\nu}$ the branching ratio of DM annihilating to neutrino pair and $R_\oplus \simeq 6.4\times 10^3\mathrm{km}$, the Earth radius. The resulting muon flux is:

$$\frac{d\Phi_\mu}{dE_\mu} = \frac{B_{\bar{\nu}\nu}\Gamma}{4\pi R_\oplus^2}\left[\frac{d\sigma_\nu^p(m_\chi,E_\mu)}{dE_\mu}\rho_p + (p\to n)\right] \times\ R_\mu(E_\mu)\Theta(m_\chi - E_\mu) + (\nu\to\bar{\nu}). \tag{6}$$

Combining this with the effective area [44] of the detector $A_{\mathrm{eff}}(E_\mu)$ gives the event rate in the detector, i.e. $dN/dE_\mu = A_{\mathrm{eff}}(E_\mu)d\Phi_\mu/dE_\mu$. This is shown for DM masses of 500 GeV and 1 TeV in figure 1, along with the background rate (discussed below) from atmospheric neutrinos.

Secondary neutrinos. Instead of direct production ν_μ may be produced from secondary decays of the annihilation products, and we concentrate here on charged lepton final states. Muons are stopped long before they decay [45] and are not a source of high energy neutrinos,

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[1] The higher density rock bed below IceCube stops a significant number of muons [54]. However, the production rate of muons is enhanced for the same reason and the effects cancel to leading order.

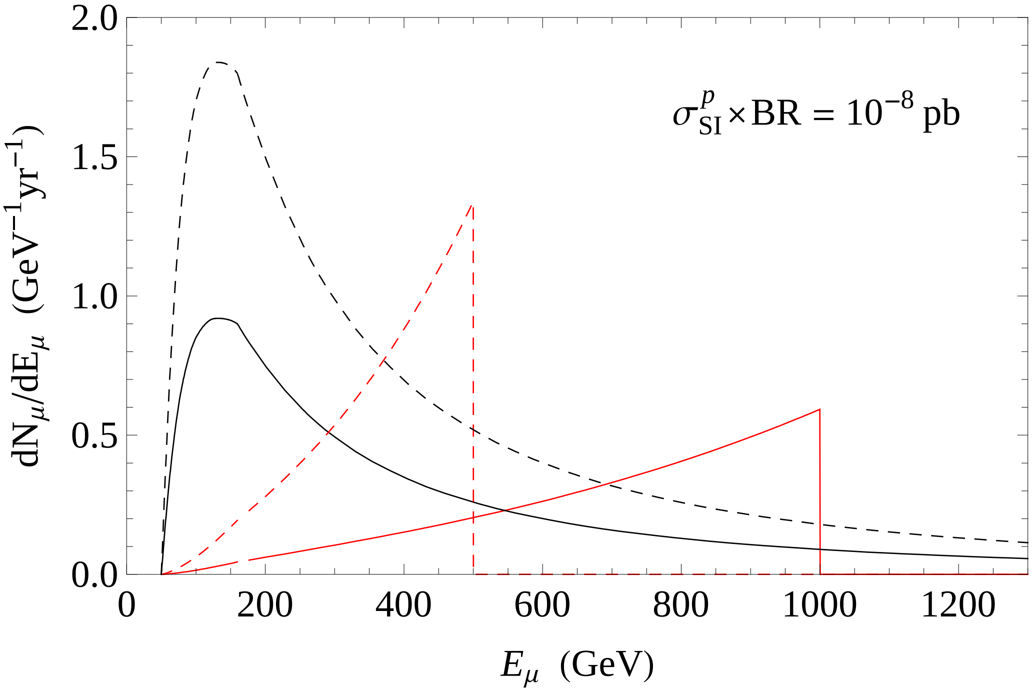

Figure 1. Muon rates from primary neutrinos (red) and atmospheric backgrounds (black) at IceCube. All plots show results for a 1 TeV (solid) and 500 GeV (dashed) DM, corresponding angular cuts have been placed on the background. The signal assumes the Earth has reached equilibrium.

whereas taus lose very little energy and will produce prompt neutrinos. When the DM annihilates preferentially to taus, which decay into neutrinos, the induced muon flux at the Earth surface, taking into account interactions with the material in the Earth, can be parametrized by the following analytic formula [46]:

$$\frac{d\Phi^{\rm S}_\mu}{dE_\mu} = B_{\bar\tau\tau}\Gamma\frac{p_1 m_\chi\, e^{-p_7 E_\mu}\left(1-e^{-p_5 m_\chi}\right)}{1+\exp\left[\frac{E_\mu - m_\chi(p_6+p_2\exp(-p_3 m_\chi))}{p_4 m_\chi}\right]}\,, \tag{7}$$

where m_χ is in GeV. $B_{\bar\tau\tau}$ is the branching ratio of DM annihilating into taus and $p_i \approx (2\times 10^{-22}/\mathrm{km}^2, 0.2, 5\times 10^{-3}, 0.1, 6\times 10^{-3}, 0.2, 10^{-3})$.

Backgrounds. The main source of background muon neutrinos comes from the shower of cosmic-rays interacting with the atmosphere. The anisotropic induced muon flux is then obtained from [40, 47]:

$$\frac{d^2\Phi^B_\mu}{dE_\mu d\cos\theta_z} = \int_{E_\mu}^{\infty} dE_\nu \frac{d^2\Phi_\nu}{dE_\nu d\cos\theta_z} R_\mu(E_\mu)R(\cos\theta_z)\times\left[\frac{d\sigma^p_\nu(E_\nu,E_\mu)}{dE_\mu}\rho_p + (p\to n)\right] + (\nu\to\bar\nu)\,, \tag{8}$$

where θ_z is the zenith angle and the differential fluxes of muon neutrinos and antineutrinos are estimated from tables found in [48]. The function $R(\cos\theta_z) = 0.70 - 0.48\cos\theta_z$ for $\theta_z > 85^\circ$ and 1 elsewhere, is the efficiency of IceCube for tracking up-going muons. The background can be substantially reduced by noting that the signal is collimated in a cone of half-angle $\Delta\theta = 1.8^\circ(\mathrm{TeV}/E_\nu)^{1/2}$ about $\theta_z = 180^\circ$, where E_ν is the energy of the incoming neutrino [32, 49]. For the Sun the background reduction is limited by the angular resolution of IceCube, $\Delta\theta = 0.5^\circ$, which we take about $\theta_z \simeq 66^\circ$. While the primary neutrino signal is monochromatic, $E_\nu = m_\chi$, the spectrum of secondary ν_μ is concentrated at low energy due to the slowdown of the DM annihilation products before they decay into neutrinos. This may result from either energy loss interactions or multiplicity of the primary decay products. Their typical energy is $E_\nu \sim E_{\mathrm{th}} = 50\,\mathrm{GeV}$, and $\Delta\theta \simeq 8^\circ$ which increases the relevant background by an order of magnitude compared to the primary case. Hence, the monochromatic neutrinos offer the best hope for a discovery at IceCube.

Earth & Sun detection. The reach of IceCube is shown in figure 2 for both primary and secondary neutrinos from the Earth.[2] We apply energy cuts for primary (secondary) signals of $250\,\mathrm{GeV} < E_\mu < m_\chi$ ($E_{\mathrm{th}} < E_\mu < 500\,\mathrm{GeV}$).[3] The capture rate for the Earth is plagued by large uncertainties and we use the estimate eq. (3). The latter assumes a Gaussian DM velocity distribution and may overestimate the capture rate by about an order of magnitude [29]. From these plots it is clear that DM that does not annihilate directly to neutrinos has very little hope of discovery at IceCube, even with a large Sommerfeld enhancement, and we concentrate on the primary neutrino case. The maximum neutrino flux is given by the red line and is well into the 5σ discovery region for most of the range that can be probed by direct detection. However, since $t_\oplus \ll t_{\mathrm{eq}}$ the expected rate is denoted by the black line. Enhancements of $\gtrsim 100$ are necessary for the ATIC/PAMELA results and may, depending on the details of the resonance structure [5, 50], be considerably larger for DM in the Earth. As shown in figure 2, we find that an order few (10^4) boost factor is required to get an observed signal for $\sigma^p_{\mathrm{SI}} \times \mathrm{BR}$ of order 2×10^{-7}pb (2×10^{-9}pb). Thus, by 2013 we will have probed most of the region where neutrinos from the Earth could be discovered. If direct detection experiments make an observation then we may have a correlated discovery in IceCube.

In the Sun's core the capture rate is dominated by the spin dependent (SD) elastic scattering of DM off hydrogen nuclei [32]:

$$C_\odot \simeq 3.57 \times 10^{18}\mathrm{s}^{-1}\,\frac{\rho^\chi_{0.3}}{(v^\chi_{270})^3}\left(\frac{\mathrm{TeV}}{m_\chi}\right)^2\left(\frac{\sigma^p_{\mathrm{SD}}}{10^{-6}\mathrm{pb}}\right), \tag{9}$$

and[4] $C^{\mathrm{c}}_\odot \simeq 3.23 \times 10^{17}\mathrm{s}^{-1}\,(\mathrm{TeV}/m_\chi)^{3/2}$. We emphasize again that there are significant astrophysics uncertainties on the DM density and its velocity distributions [49], and thus the actual capture rate (we use the value from [32] for concreteness; see also [51]). Furthermore, the SD scattering cross section of DM on proton is less constrained experimentally,

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[2] Above $\sim 300\,\mathrm{GeV}$ R_μ exceeds the detector size, L, then E_μ can only be extracted if the initial vertex is contained within IceCube [55]. The probablity for a contained vertex is $\sim L/(R_\mu + L)$. We have evaluated the resulting suppression for $m_\chi = 500$ (1000) GeV and find a reduction of the total event number of ~ 0.5 (0.4) which only slightly reduces the significance shown in figure 2.

[3] In the relevant parameter range the neutrino oscillations can be safely neglected.

[4] We use $V_{\mathrm{eff}} = 1.8 \times 10^{26}\mathrm{cm}^3\,(\mathrm{TeV}/m_\chi)^{3/2}$ for the effective volume of the core of the Sun [28].

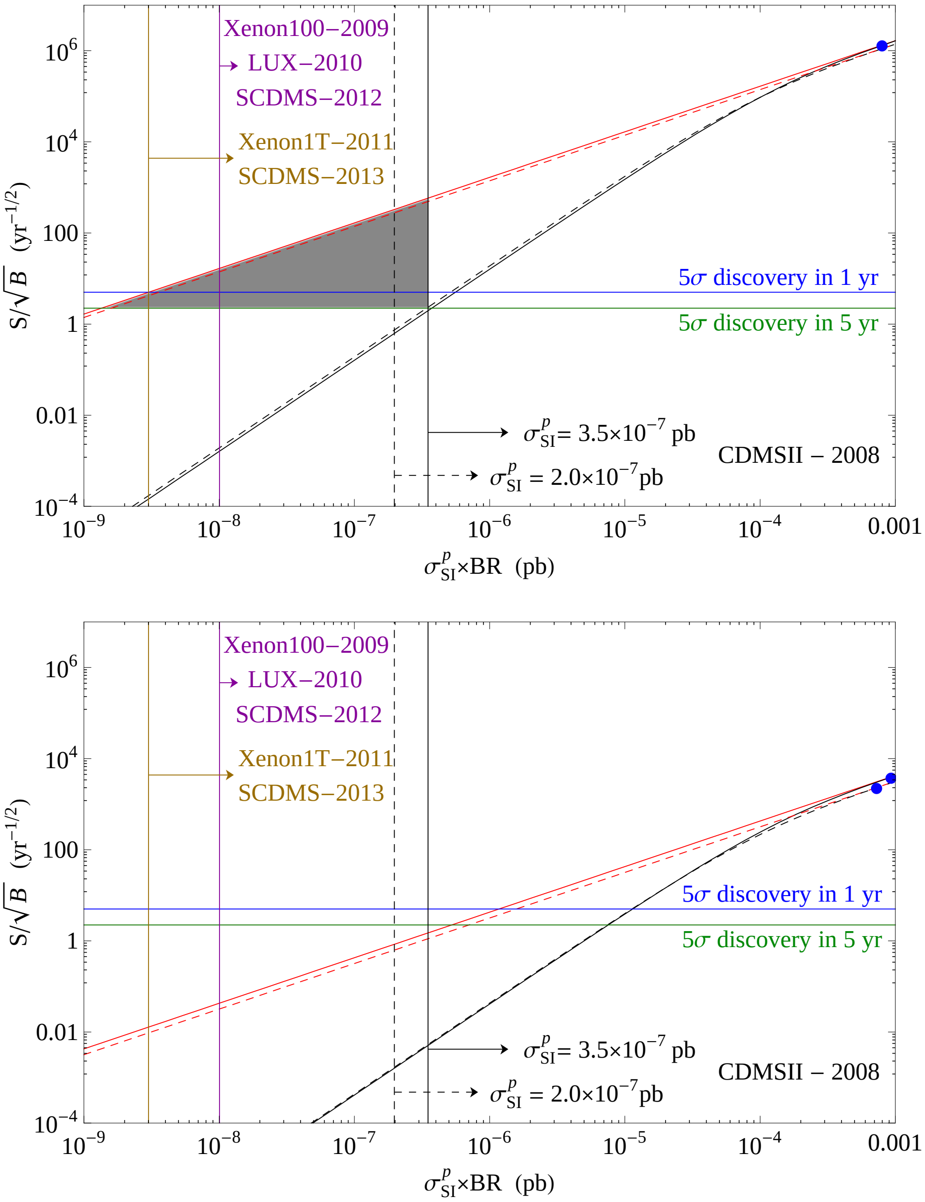

Figure 2. Statistical significance of a primary (top) and secondary (bottom) neutrino signals above the atmospheric background. BR denotes $B_{\bar{\nu}\nu}$ (primary) or $B_{\bar{\tau}\tau}$ (secondary). Upper curves (red) are equilibrium fluxes while lower ones (black) are naive fluxes for a 1 TeV (solid) and 500 GeV (dashed) DM. The blue dot corresponds to the critical capture rate, $C^{c}_{\oplus}$, see eq. (4). The vertical lines show the present and future upper bounds on $\sigma^p_{\rm SI}$ from direct detection. The horizontal lines show the discovery reach of IceCube.

the present bound being $\sigma^p_{\rm SD} \lesssim 0.8$pb (for $m_\chi \sim 1\,$TeV) from KIMS [52]. Thus, in this case, a future signal from the Sun, only from IceCube, would be harder to cleanly interpret. It is expected, generically, that the SD cross section is $3-4$ order of magnitude larger than the SI one. Thus, taking the above capture rates at face value we see that $C^{c}_{\odot} \ll C_{\odot}$ for

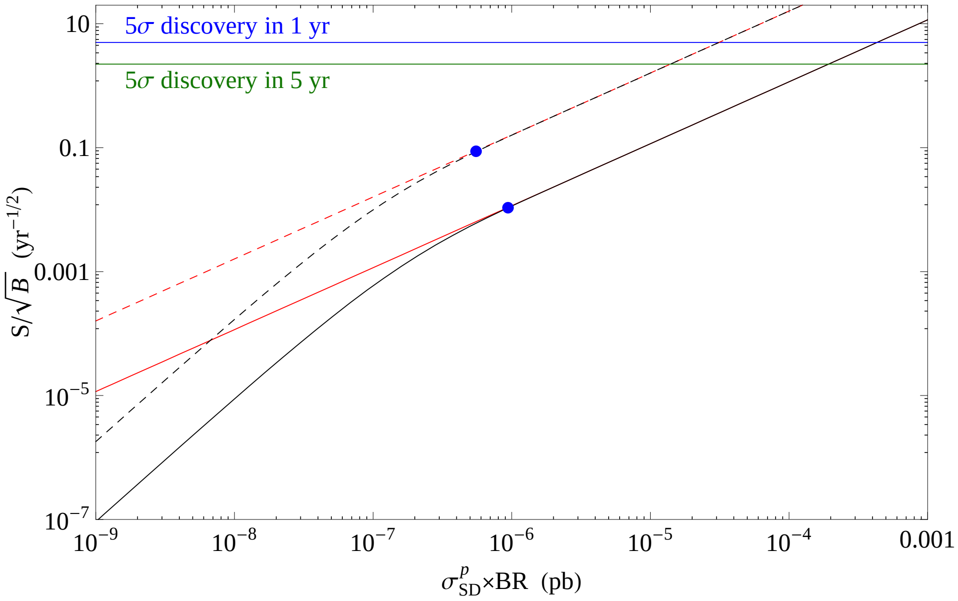

Figure 3. Statistical significance for primary neutrinos from the Sun as a function of SD scattering off protons. Since the capture rate in the Sun is more efficient than in the Earth it is most likely in equilibrium.

wide range of reasonable DM models. Consequently, it is likely that the Sun is now in equilibrium and its neutrino flux is already maximal, leaving no room for an enhancement of the annihilation rate, see figure 3.

Present experiments. AMANDA and Super-K place the strongest bounds on annihilation in the Earth. However, to the best of our knowledge, the analyses have only been done under the assumption of a neutralino WIMP, never model independently [42, 43]. In such scenarios neutrinos are only produced through secondary decays with a spectrum very different from our signal. As such we can not determine the efficiency of the experiments to detect primary neutrinos, to do so would require the collaborations to repeat their analyses. As an approximation we assume similar efficiency for primary and secondary neutrinos (probably an underestimate) and show in figure 4 the integrated upward-going muon flux for several choices of SI scattering cross section. We find AMANDA/Super-K cannot constrain secondary production but can potentially place strong constraints on the primary production. Hence, it is likely that current data rule out some of the presently viable parameter space and already limit the allowed enhancement.

Conclusions. Combining the information on the neutrino flux and the direct detection cross section yields a fairly robust measurement of the annihilation boost factor. The significance of the signal is greatly improved in cases where the annihilation channels involve primary neutrinos. A detailed study of a possible signal from primary and secondary Sun-born neutrinos may help to determine the primary branching ratio. In this case, lack of a related earthborn signal would indicate that a low velocity enhancement

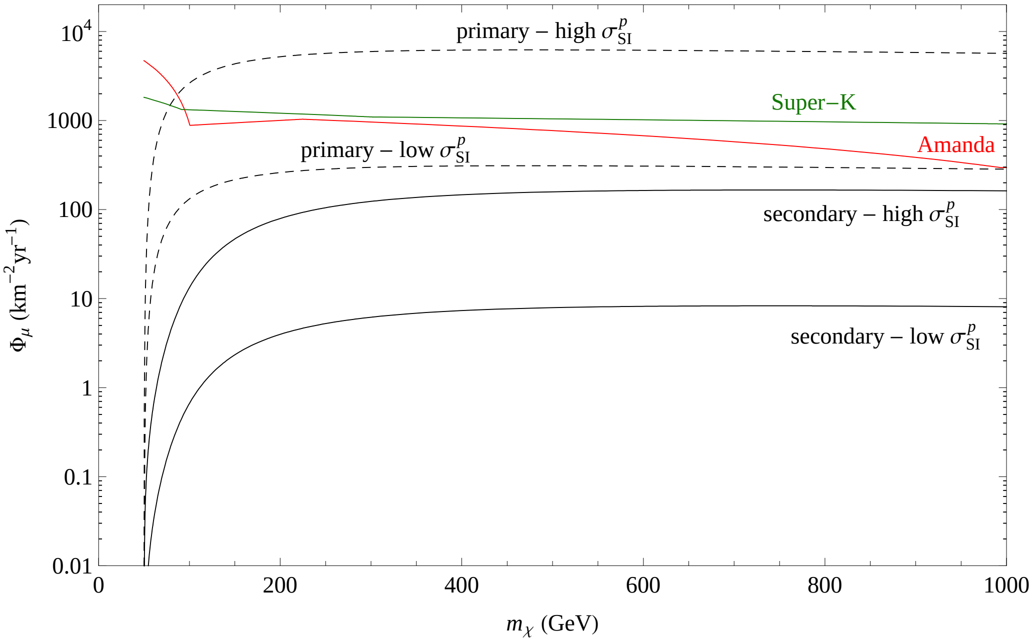

Figure 4. Comparison of AMANDA and Super-K bounds on secondary upward-going muon integrated flux with our secondary and primary signals. Estimated for high (low) SI cross section, $\sigma^p_{\rm SI} \times {\rm BR} = 2 \times 10^{-7}\,(1 \times 10^{-8})$ pb.

of the annihilation cross section is not the explanation for the ATIC/PAMELA excess. Instead, one would look for an astrophysics explanation. Note that such leptophilic DM [53] particles might have suppressed hadronic cross sections in typical models which could reduce the capture rate. In the ideal case where enough events are observed at IceCube a differential energy information could be extracted which may yield further insight into the DM sector, such as its mass and decay branching ratios.

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