

Dark Matter Annihilation to Neutrinos: Current Limits and Future Prospects

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Neutrinos can escape dense environments, otherwise opaque to photons, and travel cosmic distances unscathed by background radiation or magnetic fields. While ideal cosmic messengers, they present a unique opportunity to test physics beyond the Standard Model, especially dark matter. Moreover, there is a distinct possibility that the neutrino sector is the principal portal through which the dark matter interacts with the Standard Model. In this talk, we will discuss new opportunities offered by high-energy neutrinos and provide new model-independent limits on dark matter annihilation into neutrinos based on measurements of neutrinos. We present the most up-to-date and comprehensive results on dark matter annihilation into neutrinos using the most recently available data from neutrino telescopes, with measurements spanning a wide energy range. Finally, we will present the projections for next-generation of neutrino experiments.

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1. Introduction

Weakly interacting massive particles (WIMPs) are the primary candidates for particle dark matter (DM). The WIMP hypothesis yields a thermally average cross-section rate, $\langle\sigma v\rangle \simeq 3 \times 10^{-26} \text{ cm}^3/\text{s}$, which can explain the observed relic abundance after the freeze-out and is independent of the annihilation products. Meanwhile, thermal production of WIMPs in the early Universe implies possible ongoing annihilation of DM to Standard Model (SM) particles. This possibility has facilitated the indirect search for dark matter.

In this study, we focus on the direct annihilation of DM to neutrinos. This presents the most invisible channel for DM annihilation search. The distinct possibility that neutrinos might be the principal portal to the dark sector facilitates this assumption. Such possibility is motivated by the *scotogenic* models where neutrinos' mass is achieved via interaction with DM, see *e.g.* [1]. Furthermore, the upper limit on the DM annihilation cross-section to neutrinos serves as an upper bound on DM annihilation to SM particles, as the latter is larger [2].

In general, DM could annihilate to all SM particles. Annihilation to most SM particles results in the production of gamma rays and neutrinos. Today, the most constraining limits on DM annihilation cross-section are obtained from the absence of signal in multiwavelength observations, especially from the Milky Way and its satellite galaxies. However, there is a distinct possibility for DM directly annihilating to neutrinos which makes indirect search via neutrinos important. Moreover, neutrinos, contrary to photons, can arrive from the edge of the Universe with negligible attenuation or obscuring. As such, we can search for heavy DM with neutrinos, which is not viable with electromagnetic radiation.

The global spectrum of neutrinos spans a wide range of energy, from relic cosmic neutrino background with energies of eV to long-sought neutrinos produced in the interaction of ultra-high-energy cosmic rays with the CMB with energies exceeding 10^{18} eV. Figure 1 shows the spectrum of neutrinos from the sky from low to high energies. The figure is a mixture of observations and predictions. For energies, $\gtrsim 0.1 \text{ MeV}$, there exist an interrupted flux of neutrinos from the sky. An extraordinary amount of data has been collected in this range for measuring neutrino fluxes which can be utilized to search for DM annihilation to neutrinos. In this proceeding, we summarize our recent work [3] on the compendium of constraints on DM annihilation to neutrinos. We present new limits whilst we provide previously reported constraints in a consistent way but adjusting the underlying assumptions with a unique set of DM parameters. We demonstrate that neutrino telescopes are closing in on the parameter space of DM annihilation. While for the low-mass regime, the limits are already approaching the relic density values, the current and upcoming neutrino telescopes aiming at very high energies are opening a new avenue for the indirect search of DM.

2. Neutrino flux from dark matter annihilation

In direct DM annihilation to neutrino-antineutrino pairs, a neutrino will carry energies equal to the DM mass. That is, $E_\nu = m_\chi$. The energy spectrum of neutrinos is therefore

$$\frac{dN_\nu}{dE_\nu} = 2\delta\left(1 - \frac{E_\nu}{m_\chi}\right) \frac{m_\chi}{E_\nu^2}, \quad (1)$$

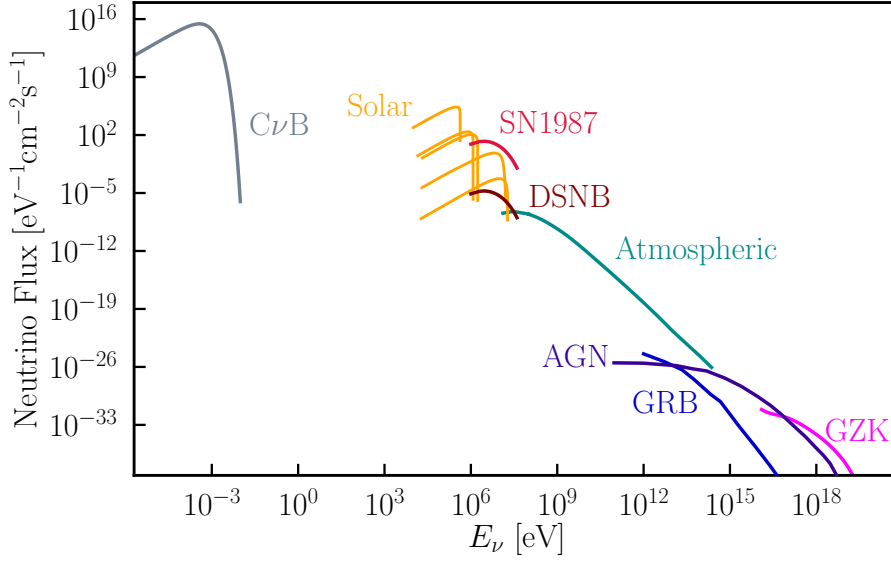


Figure 1: The cosmic-neutrino spectrum. Sources are the Big Bang (CνB), the Sun, supernovae (SN), atmospheric neutrinos, active galactic nuclei (AGN) galaxies, and GZK neutrinos.

at the site where annihilation is occurring. There are two main contributions to the neutrino flux: Galactic and extragalactic. The former contribution comes from DM annihilation to neutrinos in the Milky Way and the DM halo surrounding it. This contribution provides an anisotropic neutrino emission that peaks around the center of the Galaxy. The extragalactic signal includes neutrino emission from structures beyond the Milky Way and is an integral over all redshifts. The resulting neutrino emission is therefore isotropic.

Assuming equal flavor composition, the Galactic contribution to the neutrino flux per flavor is given by

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi} \frac{\sigma\nu}{\kappa m_\chi^2} \frac{1}{3} \frac{dN_\nu}{dE_\nu} J(\Omega), \quad (2)$$

where $\kappa = 2(4)$ for Majorana (Dirac) DM. In this study, we set $\kappa = 2$ (Majorana DM). m_χ is the DM mass and $J(\Omega)$ is a three-dimensional integral over the target solid angle in the sky, $d\Omega$, and the distance dx along the line of sight (l.o.s.) of the DM density ρ_χ , namely

$$J \equiv \int d\Omega \int_{\text{l.o.s.}} \rho_\chi^2(x) dx. \quad (3)$$

We use a generalized NFW profile to describe the DM halo, given by

$$\rho_\chi(r) = \rho_s \frac{2^{3-\gamma}}{\left(\frac{r}{r_s}\right)^\gamma \left(1 + \frac{r}{r_s}\right)^{3-\gamma}}. \quad (4)$$

We use DM halo parameters compatible with the best-fit values of [4]. When calculating the J -factor, we take into account the effective coverage of the neutrino detectors. Some experiments, such as IceCube, have an all-sky coverage. However, experiments like ANITA and GRAND only access certain parts of the sky. For these experiments, we recompute the J -factor by adapting their

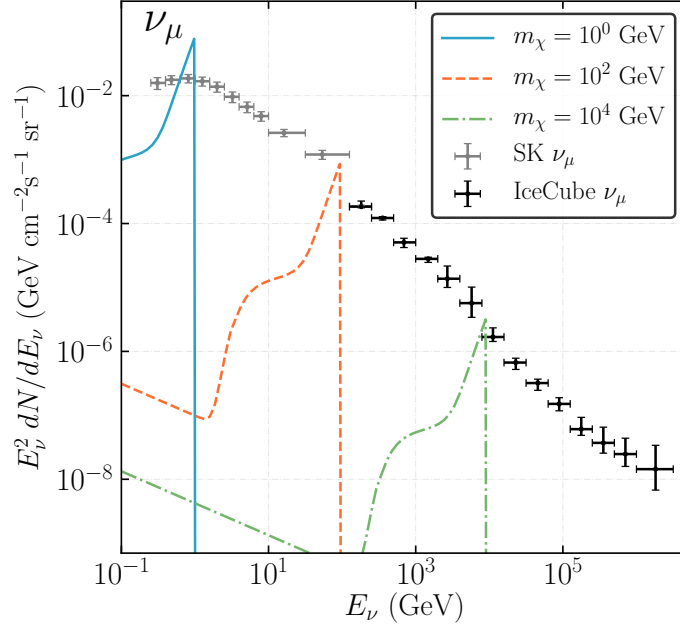


Figure 2: An Example of neutrino fluxes produced by DM annihilation overlayed on the observed neutrino flux measurement. Expected flux of neutrinos from extragalactic DM annihilation as a function of energy, shown for several DM masses. Here, the extragalactic DM annihilation fluxes are compared to the unfolded muon neutrino atmospheric fluxes from both Super-Kamiokande [5] and IceCube [6, 7].

respective sensitivity, and from local coordinates to Galactic coordinates and integrate over the accessible region of the sky for each experiment in Galactic coordinates.

The isotropic extragalactic contribution has two components: flux from the non-collapsed distribution of DM and contribution from overdensities in galactic halos across the Universe. The expected neutrino flux, therefore, is given by

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi} \frac{\Omega_{DM}^2 \rho_c^2 \sigma_\nu}{km_\chi^2} \frac{1}{3} \int_0^{z_{up}} dz \frac{(1+G(z))(1+z)^3}{H(z)} \frac{dN_{\nu+\bar{\nu}}(E')}{dE'} \quad (5)$$

where $dN_\nu(E')/dE$ is the neutrino energy spectrum at the Earth, where E' (E) is the energy at the source (detector). The source production spectrum in Eq. 1 is modified with the redshift as

$$\frac{dN_{\nu+\bar{\nu}}(E')}{dE'} = 2 \frac{m_\chi}{E'^2} \delta\left(\frac{m_\chi}{E'} - 1\right) = \frac{2}{E} \delta\left[z - \left(\frac{m_\chi}{E} - 1\right)\right]. \quad (6)$$

In Eq. 5, the first part of the factor $1+G(z)$ in the integrand represents the isotropic background DM contribution, while $G(z)$ is the halo boost factor at redshift z , which accounts for the enhancement to the annihilation rate in DM clusters, as well as their evolution with redshift.

In Fig. 2, we showcase the neutrino spectrum of DM annihilation to neutrino-antineutrino pairs from cosmological sources. We overlay the measured muon neutrino flux in Super Kamiokande (SK) and IceCube. Fluxes are computed using the value of the cross-section corresponding to the 90% C.L. limit derived in this work.

3. Upper Limits on Dark Matter Annihilation to Neutrinos

So far, no observation has found a signal from DM annihilation leading to constraints on the annihilation of DM to neutrinos in a variety of experiments, each aiming at a specific range of energies. These measurements include the observed solar, atmospheric, and astrophysical neutrino fluxes, as well as upper limits on the diffuse supernova background and GZK neutrinos. We utilize the reported neutrino flux to deduce the upper limit on the DM annihilation cross-section rate. In order to find the upper limit on $\langle\sigma v\rangle$, we estimate the expected signal and background. We estimate the signal flux from Eqs. 2 and 5. The background in each energy range depends on the origin of the flux and characteristics of particle detection in each detector. The upper limits provided here also depend largely on the systematics that govern the neutrino detection in each range or detection technique.

In order to find the upper limit, we perform a likelihood analysis that incorporates this information where possible. In Fig. 3, we present the upper limits on DM annihilation cross-section from sub-GeV DM to superheavy DM with m_χ exceeding PeVs. The lines marked with a heart show the limits obtained in our study. The rest of the lines are compiled from measurements of experimental collaboration or independent groups. In order to make a uniform comparison, when possible, we have re-scaled the J -factor for the limits or the sensitivities of the experiments.

At $m_\chi \sim \text{MeV}$, limits obtained from upper limits from Borexino [8] and KAMLAND [9] constrain the DM cross-section rate better than $10^{-21} \text{ cm}^3/\text{s}$. At slightly higher energies, SK dominates the upper limit, especially the upper limits found from the search for diffuse supernova background [10] is strong and touches the thermal relic line. We also show the limit from [11] that limits DM cross-section for masses below GeV. Around GeV mass, the dominant neutrino spectrum at Earth is the atmospheric neutrinos, produced by very high-energy cosmic-ray interaction. SK and IceCube provide a precise measurement of this flux. Here, we estimated the upper limits from SK measurement at lower energies as well as the limits reported by the SK [12, 13] and IceCube [14] Collaborations. Above 100 GeV, ANTARES presents the most constraining limit until $m_\chi \sim 10^5 \text{ GeV}$ [15]. We show the limits obtained from IceCube high-energy neutrino flux measurement [16] in the same energy range, which extends to $m_\chi \sim 10 \text{ PeV}$. The strongest limits are from analyses that incorporate both energy and direction for the neutrinos.

At the highest energies, in Fig. 3, we show the limit from IceCube EHE analysis [17]. The limit is deduced from the upper limit on the cosmogenic neutrino flux in 9 years of IceCube data. These limits assume 100% of the dark matter is composed of a given Majorana particle. If instead only a fraction, f , is considered, these results should be multiplied by $1/f^2$. In the case of Dirac DM, limits would be scaled up by a factor of two.

In addition to the upper limits from the current neutrino experiments, we provide the prospects for studying DM annihilation to neutrinos from future neutrino experiments. At low energies, DUNE and Hyper Kamiokande are going to establish a strong measurement of the annihilation cross-section, narrowing down the allowed parameter space. At higher energies, utilizing atmospheric and IceCube astrophysical neutrinos, the sensitivity would be improved the development detector in the Mediterranean, KM3NeT, and in Lake Baikal, Baikal GVD. Neutrino telescopes' reach to ultra-high-energies is going to be enhanced by the development and commissioning of P-One, IceCube Gen-2, and GRAND. These planned neutrino telescopes will establish a survey of DM annihilation

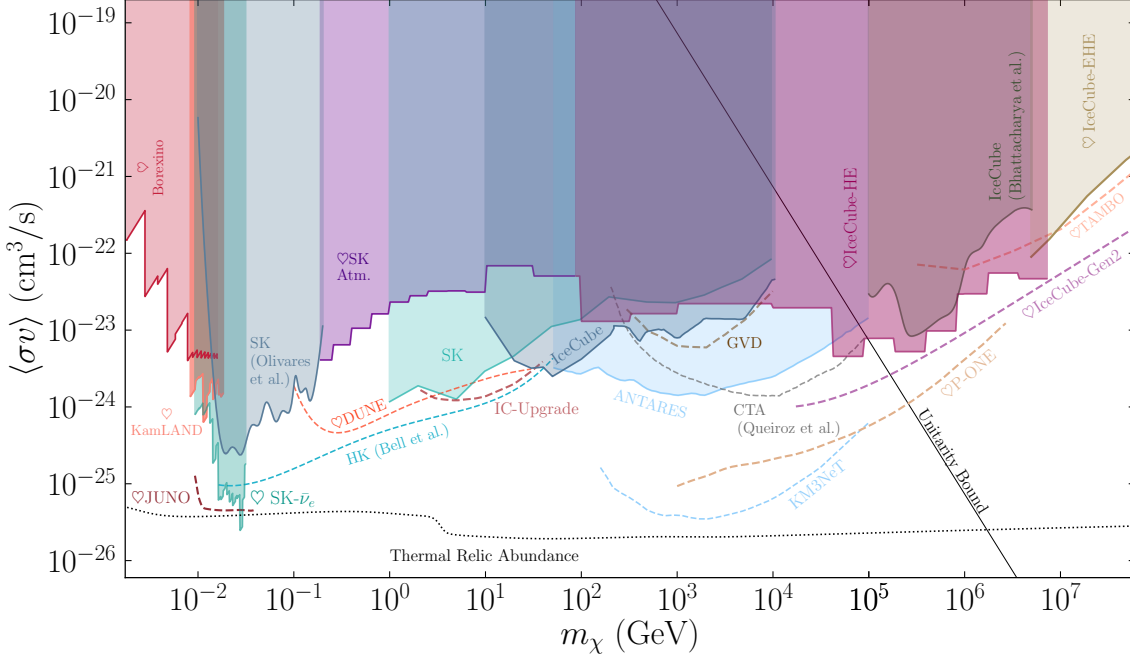


Figure 3: The landscape of DM annihilation into neutrinos up to 10^8 GeV. We show new limits, as well as previously published limits. Solid and dashed lines represent 90% C.L. limits and sensitivities, respectively. Projected sensitivities assume 5 years of data taking for neutrino experiments and 100 hours of observation for CTA. The dotted line corresponds to the value required to explain the observed abundance via thermal freeze-out. The straight diagonal line, labeled as “Unitarity Bound,” gives the maximum allowed cross section for a non-composite DM particle. These results assume 100% of the dark matter is composed of a given Majorana particle. See Fig. 4 for constraints and projections up to 10^{11} GeV.

for very heavy DM and surpass the region that is constrained by the Unitarity of the cross-section.

Figure 4 presents a close up of the limits for heavy DM with $m_\chi > \text{TeV}$. In addition to the limit from IceCube-EHE analysis, we also show the upper limit from Auger cosmogenic neutrino search [18]. Future neutrino telescopes aiming at measuring neutrino flux beyond PeV energies, such as IceCube Gen-2, GRAND, and RNO-G are going to further improve sensitivity for superheavy DM searches.

The limits we present here are for the s-wave, where DM annihilation cross-section is not velocity dependent. For p- and d-wave limits, see [3].

4. Summary and Outlook

Thanks to the experimental advances in neutrino detection, we are able to obtain a comprehensive set of limits on DM annihilation directly to neutrino-antineutrino pairs, for a DM mass range spanning 15 orders of magnitude; from 10^{-3} GeV to 10^{12} GeV. This energy range is remarkably covered by a variety of neutrino experiments searching for neutrinos from supernova background, sun, atmosphere, and the sources of IceCube high-energy neutrinos. In this landscape, the strongest limits are obtained from SK, ANTARES, and IceCube. Naturally, analyses that utilize the arrival direction of neutrinos, in addition to their energy, are more sensitive.

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