PAPER • **OPEN ACCESS**

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To cite this article: Matthias Danninger 2017 *J. Phys.: Conf. Ser.* **888** 012039

Review of indirect detection of dark matter with neutrinos

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Abstract. Dark Matter could be detected indirectly through the observation of neutrinos produced in dark matter self-annihilations or decays. Searches for such neutrino signals have resulted in stringent constraints on the dark matter self-annihilation cross section and the scattering cross section with matter. In recent years these searches have made significant progress in sensitivity through new search methodologies, new detection channels, and through the availability of rich datasets from neutrino telescopes and detectors, like IceCube, ANTARES, Super-Kamiokande, etc. We review recent experimental results and put them in context with respect to other direct and indirect dark matter searches. We also discuss prospects for discoveries at current and next generation neutrino detectors.

1. Introduction

While the presence of dark matter (DM) in the Universe has been inferred through astrophysical and cosmological observational evidence, very little is known about the nature of DM and its particle properties. Overall, the experimental evidence points to DM as being massive (interacts gravitationally), dark (no electromagnetic interactions at rates comparable to ordinary matter), of non-baryonic nature, cold (influences structure formation), and stable on a Cosmological time scale (see Ref. [1] for a review). One of the most promising and experimentally accessible candidates for DM are so-called Weakly Interacting Massive Particles (WIMPs) [1], predicted in extensions of the SM. DM properties like the particle mass, the lifetime, the self-annihilation cross section into Standard Model (SM) particles, and the interaction cross-section with nucleons are only weakly constrained by astronomical and cosmological observations.

Neutrino telescopes can be used to probe all of these DM properties indirectly where we aim to detect primary or secondary particles created in DM annihilations, such as neutrinos. The number of DM annihilations is proportional to the square of the DM density. As a result, the most promising search targets are regions with an expected high density of DM and low, well understood, astrophysical background. Ordered in increasing distance from the Earth itself, such target candidates are the Earth, the Sun, the Galactic Center, galactic halo regions, DM dominated dwarf galaxies, and nearby galaxy clusters.

This review is structured in the following way. A brief review of experiments and analysis search strategies are discussed first, followed by a review of recent results. Prospects for the detection of DM with neutrinos and a discussion of an improved event-level likelihood formalism for including neutrino telescope data in global fits to new physics are discussed before concluding.

Table 1. Rough comparison of neutrino telescope characteristics relevant for DM searches. The median angular resolution ($\overline{\Theta}$) is quoted for different representative neutrino energies (E_ν), where applicable. More details in Refs. [6, 8] (IceCube), [5, 9] (ANTARES), [4, 10] (Super-K), and [11] (Baksan). Table adapted from [12].

	E_ν-range (GeV)	Instrumented volume (ton)	$\overline{\Theta}$ (°) at E_ν 25 / 100 / 1000 GeV
IceCube	$\gtrsim 10^*$	∼1 Gton	13 / 3.2 / 1.3
ANTARES	$\gtrsim 10$	∼20 Mton	6 / 3.5 / 1.6
Super-K	$\gtrsim 0.1$	∼50 kton	1-1.4†
Baksan	$\gtrsim 1^\dagger$	∼3 kton	1.5† (tracks > 7 m)

* Threshold corresponds to DeepCore events for this analysis. [8]
† Values are given at muon level (E_μ); $\overline{\Theta}$ dominated by kin. scattering angle.

2. Experiments and novel analysis techniques

To detect high-energy neutrinos in statistically significant numbers, a combination of large detectors and long observation times is needed. Neutrino telescopes combine large volumes with a nearly 100% duty cycle making them ideal to search for neutrinos from DM annihilations. The Baksan underground scintillator telescope [2] uses muon counters, whereas water or ice Cherenkov detectors, like IceCube [3], Super-Kamiokande [4] (Super-K), and ANTARES [5], detect Cherenkov light radiated by charged particles that are produced in interactions with nuclei inside or close-by the detector. An order-of-magnitude comparison of detector characteristics relevant for DM searches is given in Table 1.

Significant improvements in analysis methods and event selection strategies have been achieved by all experiments for most of the recent results increasing the sensitivity to signals from DM annihilations by sometimes orders in magnitude. Datasets are commonly split into different topological event categories [6, 10] targeting a wide range of DM masses. Such event categories are classified by contained, partially contained, and through-going events. Improved stringent atmospheric muon veto techniques allow down-going event selections, enabling searches for DM signatures within the Galactic Center for detectors like IceCube [6, 7]. Extending statistical analysis techniques to also include event-level energy information within the signal region leads to an improvement in limits especially at high DM masses [13, 14]. Such energy estimators are based on the reconstruction of charged-particle energies and topologies from the observed Cherenkov light yield. Furthermore, particle identification allows to include electron neutrino event samples in the analysis, doubling the expected signal flux. Such an extension of the current searches to include the electron channel is even more rewarding as the atmospheric neutrino background in this channel is generally much lower (approx. factor 3).

3. Limits on the dark matter annihilation cross section

In regions in the Universe with an expected high density of DM, such particles could self-annihilate and produce a flux of neutrinos detectable at Earth. The differential flux depends on the annihilation cross section of the WIMPs as

$$\frac{\mathrm{d}\phi_\nu}{\mathrm{d}E} = \frac{\langle\sigma_\mathrm{A} v\rangle}{2}\frac{1}{4\pi m_\chi^2} J_a(\Psi)\frac{\mathrm{d}N_\nu}{\mathrm{d}E}, \tag{1}$$

where $\langle\sigma_\mathrm{A} v\rangle$ is the product of the self-annihilation cross section and the WIMP velocity, averaged over the velocity distribution of the annihilating particles, m_χ is the WIMP mass, $\frac{\mathrm{d}N_\nu}{\mathrm{d}E}$ is the neutrino energy spectrum per annihilation and $J_a(\Psi)$ is the integral of the squared DM density

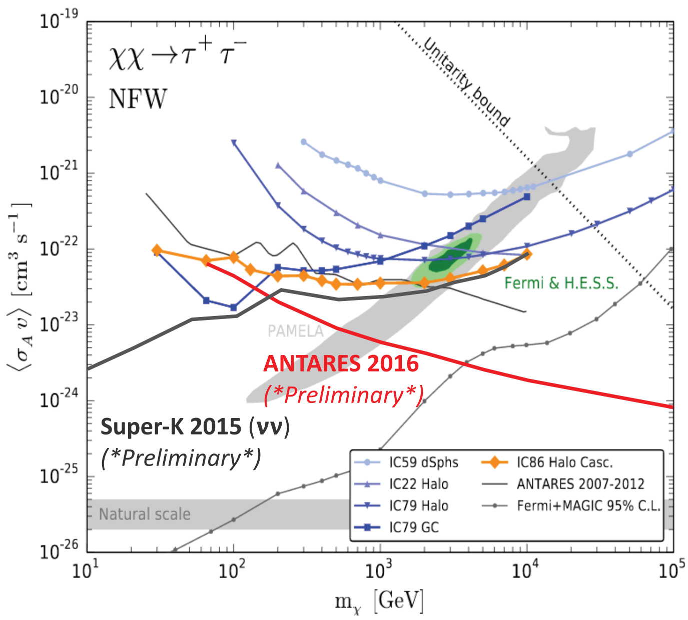

Figure 1. Comparison of upper limits on $\langle\sigma_{\rm A} v\rangle$ as a function of the WIMP mass for the annihilation into $\tau^+\tau^-$. Figure is adapted from [16]. Various IceCube searches [16] are compared with preliminary results from Antares [14] and Super-K [17] (annihilation channel into $\nu\bar{\nu}$ is shown). Also shown are the latest upper limits from gamma-ray searches obtained from the combination of FermiLat and Magic results [18]. The three shaded areas indicate allowed regions if the $e^+ + e^-$ flux excess seen by FermiLat, H.E.S.S. and the positron excess seen by PAMELA would be interpreted as originating from DM annihilations.

along the line of sight. The expected signal is particularly sensitive to the adopted DM density profile, which determines the term $J_a(\Psi)$, reflecting the number of expected neutrinos in a given direction that have been produced in DM annihilations inside a cone with axis oriented in that direction. To this day, all results are consistent with the expected background from atmospheric muons and neutrinos. The upper 90% confidence level (C.L.) limits on the annihilation cross section as a function of the DM mass are reported for different annihilation channels and selected choices of the DM halo profile.

Figure 1 shows current limits using the Navarro-Frenk-White (NFW) [15] cusped profile for a DM annihilation channel into $\tau^+\tau^-$. Limits from IceCube show searches with different detector configurations and targeting different signal regions (Galactic center, Galactic Halo, and dwarf galaxies) [16]. For IceCube, the Galactic center is always seen above the horizon. Thus, dedicated veto techniques against atmospheric muons are required to make the southern hemisphere accessible. In contrast, the Galactic center is 60% of the time of the year below the Horizon for Antares resulting in significantly stronger limits at higher WIMP masses [14]. Results from the Super-K Collaboration can be found in Ref. [17] and are extending current limits from neutrinos down to WIMP masses as low as 1 GeV (Note, the DM annihilation channel into $\nu\bar{\nu}$ is shown in this instance).

3.1. Heavy Dark Matter Decays

DM is not required to be absolutely stable, and thus it may decay into neutrinos, with an associated lifetime $\tau_{\rm DM}$, could give rise to a neutrino signal both from the Galactic DM halo and from extragalactic DM. The decay into monochromatic ν-lines is of particular interest and public IceCube data has been used to set the strongest current bounds on neutrino signals from DM decays in the TeV to PeV DM particle mass range with limits on $\tau_{\rm DM}$ ranging between 10^{28} and 10^{29} s [19]. Considering foreseen improvements in both neutrino and gamma-ray data, these searches open up exciting possibilities for future searches from decaying DM particles [19].

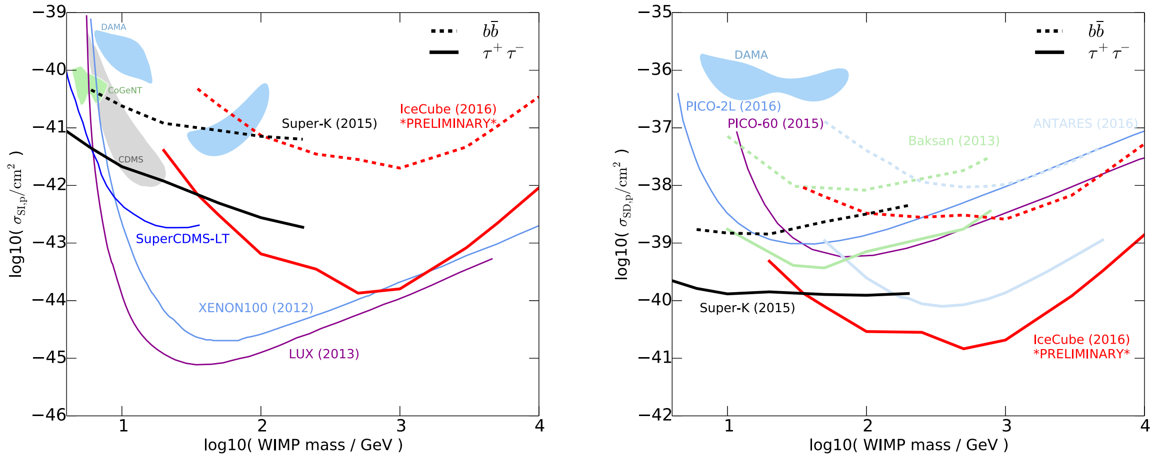

Figure 2. 90% C.L. upper limits on $\sigma_{\rm SI}$ (left) and $\sigma_{\rm SD}$ (right) of DM particles with protons. Shown are limits form IceCube [23], Super-K [10], Antares [24], Baksan [11], and direct detection experiments [25, 26, 27, 28, 29].

4. Limits on the dark matter scattering cross section

WIMPs from the Milky Way DM halo could be gravitationally captured by the Sun and accumulate in its centre [20, 21, 22]. WIMP capture is initiated by an elastic scattering process in which a WIMP could loose enough energy to fall below the escape velocity of the Sun, and hence becomes gravitationally bound to it. In subsequent scatters the WIMP can loose more energy and eventually sink to the center of the gravitational well and thermalize. As a result of the continuous DM capture by the Sun, we could find ourselves in the vicinity of a very dense DM accumulation that exceeds the average local DM density by orders of magnitude. The model-dependent WIMP interaction cross section is composed of the spin-independent component (SI) and the spin-dependent component (SD) of the interaction cross section with nucleons (σ). As the Sun is primarily a proton target, it could capture DM very effectively via SD scattering, where contributions from heavier elements can be ignored. This is different for capture via SI scattering, where it is important to sum over all elements in the Sun, owing to $\sigma_{\rm SI} \sim {\rm A}^2$, where A is the atomic mass number. As a result, the SI cross-section depends on detailed information on the solar abundance of elements. The final states in a DM annihilation are model specific, and, depending on the theory, a mix of various final states can be produced. Neutrinos that can escape the Sun and give raise to an observable WIMP signal can be produced directly in the annihilation or through decays of annihilation products. Two end points of the spectrum are chosen to approximately bracket the range of all models in Fig. 2: the soft $b\bar{b}$ and hard $\tau^+\tau^-$ channels (each with 100% branching).

The neutrinos produced as part of the DM annihilation process in the Sun could be observable at Earth and can be searched for as a point-like source in neutrino telescopes. No excess above the background-only expectation has been reported by the experiments. From the upper limit on the number of signal events, a limit on the annihilation rate in the Sun can be derived, which in turn can be used to set a limit on the WIMP capture rate in the Sun. Assuming equilibrium between WIMP capture and annihilation in the Sun, the capture rate is then directly proportional to the WIMP-proton scattering cross sections $\sigma_{\rm SI}$ and $\sigma_{\rm SD}$. By assuming that the capture is dominated either by SD or SI scattering, it is possible to derive the limit on $\sigma_{\rm SI}$ and $\sigma_{\rm SD}$ at the 90% C.L., respectively (Fig. 2).

Remarkably, searches for high-energy neutrinos from the Sun are currently the most sensitive

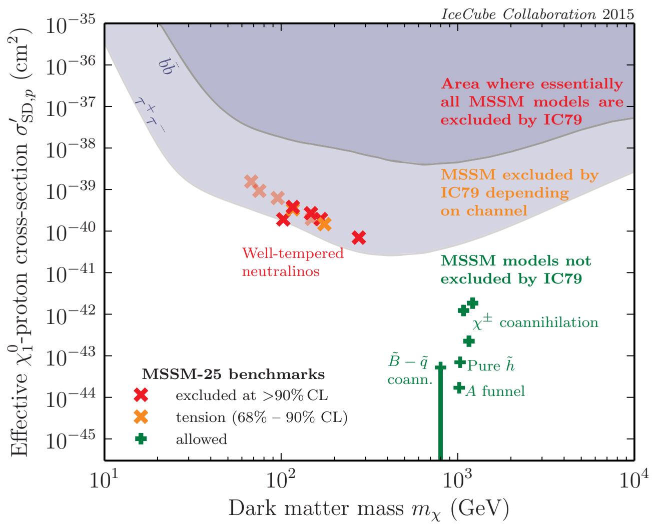

Figure 3. Implications of the IceCube analysis for benchmark models in the MSSM-25. Models shown with solid red crosses are excluded, faded red symbols are excluded by both IceCube and LUX bounds [27], solid orange crosses indicate models in tension with IceCube data at more than 1σ, and green plus symbols indicate models not constrained by IceCube. Benchmarks are from the MSSM-25 and MSSM-19 scans of Refs. [39, 40], and correspond to models allowed by LHC, relic density and other direct and indirect constraints. Shaded regions are indicative only; these assume pure SD scattering and annihilation to the canonical 'hard' and 'soft' channels. Figure taken from [13].

means of probing the SD interactions between protons and most models of DM. Results from Super-K are most stringent for very low DM masses down to 4 GeV, whereas limits from IceCube become dominant for DM masses above 50 GeV owing to the larger instrumented detector volume. These results are complementary to direct detection efforts, but significantly weaker for σ_{SI}. Limits from neutrino telescopes depend only weakly on astrophysical assumptions, e.g. the WIMP velocity distributions, and nuclear form-factor uncertainties [12]. These results are also complementary to searches for DM at colliders like the Large Hadron Collider (LHC) that are often searches for missing energy signals, relying on the detection of an accompanying particle or hadronic jet signature [30, 31]. These searches depend strongly on the choice of the underlying effective theory and mediator masses, leading to weaker limits if the mediator is light. Alternatively, concrete simplified DM models may be assumed to allow an interpretation of collider searches together with direct and indirect limits (see Refs. [32, 33] for more details).

5. Future prospects and conclusions

Searches for DM annihilation signals from the Sun using high energy neutrinos is a discovery channel for DM, and currently provide the most stringent σ_{SD} limits for scattering on protons for most models. The sensitivity will continue to improve with existing detectors in the coming years. Exciting prospects for DM searches also exist at next-generation neutrino telescopes such as PINGU [34], ORCA [35], and Hyper-Kamiokande [36]. The lowered energy threshold of these experiments will allow current searches to extend their reach to test WIMP masses that are below the current respective detection thresholds. In this context, DM scenarios motivated by DAMA's annual modulation signal [37] will be testable independently of direct detection experiments.

Most searches for high-energy neutrinos from the Sun take a semi-model-independent approach, assuming that capture and annihilation have reached equilibrium in the Sun, and that DM annihilates exclusively into a single final state. These assumptions are expressly violated in many concrete models for the identity of DM [13]. Resulting limits are often difficult to meaningfully connect to theoretical predictions. Ref. [13] describes a formalism applicable to all neutrino telescope experiments that allows event-level neutrino telescope data to be used to constrain DM models with mixed annihilation final states, thereby allowing such searches to be properly included in global fits to theories beyond the SM. We therefore want to encourage Collaborations to publish data in such a format to further facilitate such global fit efforts. Figure 3 shows the impacts of such an analysis using IceCube data for selected benchmark models in the minimal supersymmetric standard model (MSSM) [13].

Gamma-ray telescopes are much more competitive for annihilation DM signals from the Galactic Center, galactic halo regions, or DM dominated dwarf galaxies for low DM masses (below ∼1 TeV). Inversely, for high DM masses searches for high energy neutrinos are more competitive than gamma-rays. This yields exciting prospects and new search opportunities for the ARCA [35] and IceCube Gen2 [38] high energy extensions in the near future.

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