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*Proceeding Paper*

# Searches for Dark Matter in the Sun with the IceCube Neutrino Telescope †

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**Abstract:** The IceCube detector is particularly sensitive to high-energy neutrinos due to its size and photosensor spacing. In this review we present results from the search for dark matter in the sun and earth, including a search for dark matter that annihilates into a metastable mediator that subsequently decays into standard model particles and a search for solar atmospheric neutrinos that present a significant background to solar dark matter searches. We present the results from different searches for dark matter in the sun and the earth in this proceeding paper.

**Keywords:** dark matter; sun; secluded dark matter

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## 1. Introduction

The IceCube Neutrino Observatory [1], located at the geographic south pole, is the world's largest neutrino telescope in terms of instrumented volume. It consists of a Cherenkov detector of one cubic kilometre volume using ultra-pure ice instrumented with sensors at depths between 1.45 and 2.45 km and a square kilometre air-shower detector at the surface of the ice [2]. The primary objectives of the detector are the measurement of high-energy astrophysical neutrino fluxes and determining the sources of these fluxes [3].

Though the primary scientific goals of the detector are to measure high-energy astrophysical neutrinos and to identify their sources, a range of dark matter (DM) searches is also being conducted [4,5] with IceCube data.

Among the wide variety of candidate models for the particle nature of DM [6] are so-called weakly interacting massive particles (WIMPs), where the DM particle interacts with standard model particles on a scale of weak interaction. This model gives rise to a flux of standard model particles, such as neutrinos, as the result of the decays or annihilations of WIMPs. It also leads to the accumulation of DM in massive objects such as the sun or the earth by WIMPs losing momentum when scattering inside the object and then becoming gravitationally trapped. The WIMPs accumulated in the sun or earth decay with the number of accumulated WIMPs $N$ following the Boltzmann equation

$$\frac{dN}{dt} = C_C - C_A N^2 - C_E N, \tag{1}$$

with the capture rate $C_C$ and the annihilation factor $C_A$. The evaporation term $C_E N$ can be neglected for WIMP masses above a few GeV. When solving the Boltzmann equation the annihilation rate $\Gamma_A$ becomes

$$\Gamma_A = \frac{C_C}{2} \tanh \frac{t^2}{\tau^2} \tag{2}$$

with the timescale

$$\tau = \frac{1}{\sqrt{C_C C_A}}. \tag{3}$$

In celestial objects with an age beyond this timescale an equilibrium forms between annihilation and accumulation [7], while the sun fulfils this requirement in the range where the limits of neutrino annihilation rate experiments lie, but the earth does not. In this case a thermally averaged annihilation cross-section $\langle \sigma_A vs. \rangle$ has to be assumed to calculate the sensitivities or limits on the spin-dependent and -independent scattering cross-sections $\sigma_{SD}$ and $\sigma_{SI}$, respectively.

## 2. Dark Matter Search in the Earth

Using eight years of data collected with the IceCube detector captured between 2011 and 2018, a search for DM in the earth was conducted. The analysis used signal neutrino spectra calculated with the WimpSim package [8]. Annihilations into W-bosons, tauons and bottom quarks were considered.

### *2.1. Method*

The analysis employs a dedicated event selection to reduce background from muons from cosmic ray air showers. The event selection uses boosted decision trees (BDTs) to generate a score between $-1$ for background-like events and 1 for signal-like events.

The analysis employs an effective likelihood [9], considering a generalized Poisson likelihood, which accounts for uncertainties on the underlying distributions.

### *2.2. Sensitivities*

Sensitivities for this analysis were calculated assuming a thermal cross-section of $\langle \sigma_A vs. \rangle = 3 \times 10^{-26}$ cm$^3$ s to ensure a fair comparison to other experiments. All sensitivities were calculated at a 90% confidence level and can be seen in Figure 1. This new analysis shows improvements compared with previous iterations [10] of the analysis which only used zenith distributions.

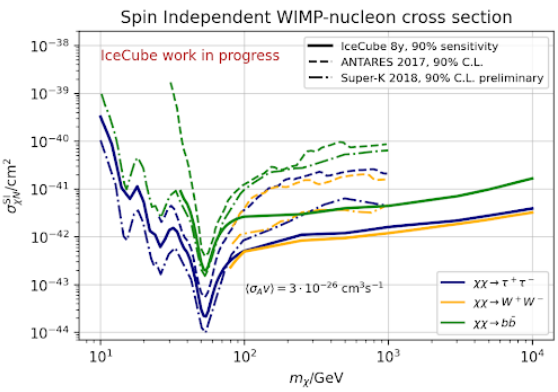


**Figure 1.** Sensitivities at a 90% confidence level [11] compared to the latest results from ANTARES [12] and SuperKamiokande [13].

## 3. Solar Atmospheric Neutrinos

Solar atmospheric neutrinos are produced in the solar atmosphere from the interaction between cosmic rays and solar atmosphere, similar to how neutrinos are produced by cosmic ray interactions with the earth's atmosphere. The expected spectrum of these neutrinos is similar to DM signal spectra for DM searches towards the sun, and thereby present a background for these analyses [14].

### *3.1. Data Sample*

Gamma-ray data collected during past solar cycles by FermiLAT suggests an anti-correlation between the solar activity and high-energy gamma-ray flux from the sun [15]. The most recent analysis using IceCube data [16] includes data from 2009 to 2020, covering the most recent solar minimum that started in 2017.

### *3.2. Model and Sensitivities*

The analysis uses a model for the solar atmospheric neutrino spectrum from J. Edsjö [17]. To calculate the differential limits in Figure 2, the energy range was split into separate half-decadal bins, calculating the sensitivity for each. A model-independent power-law flux with $\gamma = 3$ was used here.

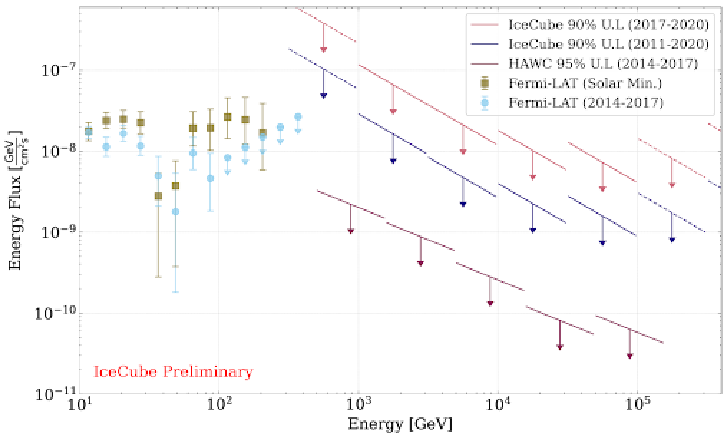


**Figure 2.** Differential sensitivity for a power-law flux with $\gamma = 3.0$ [16]. Bins contributing to the 90% central sensitivity range have solid lines. Results from HAWC [18] and FERMI-LAT [15] are also shown.

## **4. Solar Dark Matter**

### *4.1. Method*

For the most recent analysis in the search for DM in the sun [19], spectra were calculated with the $\chi$aro$\nu$ package [20]. $\chi$aro$\nu$ uses the $\nu$SQuIDS software to propagate neutrinos taken from some initial calculation to the detector. The initial standard model spectra can either be taken from PYTHIA [21] calculations or from a more recent calculation by Bauer, Rodd and Webber (BRW) [22]. The BRW calculation improves on PYTHIA by including additional electroweak corrections, allowing particles to emit weak gauge bosons at lower energies similar to photons emission. This causes spectra for hadronic WIMP annihilation and decay channels to harden when the radiated bosons produce hard neutrinos.

At low energy the OscNext selection is used. The OscNext selection includes eight years of data collected between 2011 and 2019. The high-energy selection uses nine years of data collected between 2011 and 2020 with an improved angular and energy resolution.

At medium energy the event selection is designed to increase the coverage of the analysis in the energy range where a larger flux of solar atmospheric neutrinos are expected (100 GeV).

At higher energy a newer IceCube dataset of muon tracks is employed, using nine years of 86-string data from 2011 to 2020.

### *4.2. Sensitivity*

The three selections are constructed to be non-overlapping, so that for this analysis a binned likelihood that combines all three selections can be employed. The sensitivities derived with this likelihood are shown in Figure 3, and compared to the limits obtained from previous solar WIMP analyses.

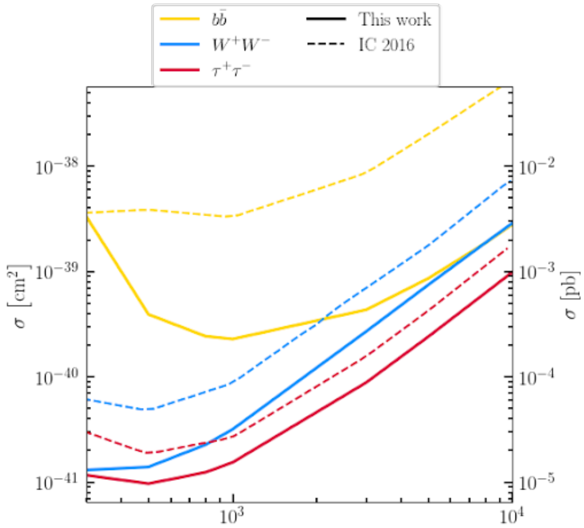


**Figure 3.** The sensitivities of the most recent searches for DM in the sun with five and nine years of data [19].

## 5. Secluded Dark Matter

Secluded DM (SDM) is a model type for particle DM, where the DM particles produce a pair of metastable mediator particles in annihilations that decay after lifetimes that can exceed several seconds into a pair of standard model particles. Scenarios with such mediators innately occur in many models of supersymmetric DM [23] or a dark Higgs particle [24]. The mediator in these models is itself not a standard model particle and has no significant direct interactions with standard model particles.

Regular DM models yield signal fluxes from the sun that are heavily attenuated by the dense solar plasma. However, for SDM this attenuation is avoided when the decay length of the mediator exceeds the radius of the sun. In these cases the neutrino signal is generated in mediator decays occurring outside the solar plasma, and thus there is no opportunity for neutrinos to interact with the solar plasma.

### *Limits*

The analysis has not found any significant indication of SDM in the sun. Consequently, limits on spin-dependent scattering cross-sections were set. The various DM mass cases are strongly correlated and the likelihood thus finds no signal events in most cases (Figure 4).

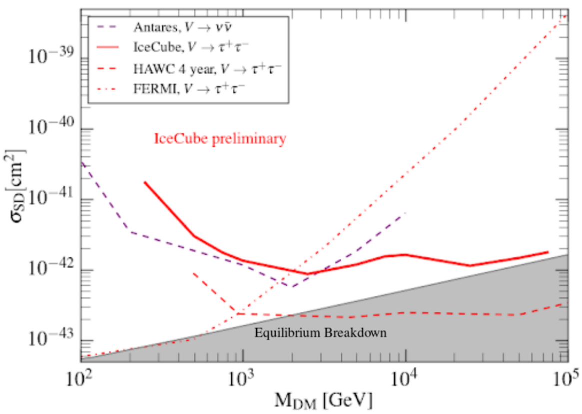


**Figure 4.** The limits on the spin-dependent DM–nucleon scattering in comparison [25] with other experiments [18,26,27]. The results for the $\tau^+\tau^-$ channel are shown in comparison with other experiments. In this plot a mediator mass of 100 GeV and a mediator decay length of one solar radius was assumed.

## 6. Conclusions

Using data from the IceCube experiment some of the strongest limits and best sensitivities among the indirect searches for DM in the earth and sun with neutrino experiments were produced. Updates to these analyses, such as the SDM analysis, are promising improvements on the results through the inclusion of new data and better methods and simulations.

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