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Indirect Dark Matter Searches with IceCube

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Abstract. I review results from searches for neutrinos from annihilating or decaying dark matter with the IceCube Neutrino Observatory, using data from the fully deployed detector and new event selection algorithms. So far, no signal has been observed and limits have been put on the dark matter lifetime, spin-dependent interaction cross section of dark matter and nucleons, as well as the velocity-averaged dark matter annihilation cross section. We present competitive limits on the annihilation of Galactic halo dark matter with mass between 10 GeV and 300 TeV, which are rather insensitive to the halo density profile. The limits on the spin-dependent scattering cross section from IceCube searches for dark matter annihilations in the Sun set the strongest such bounds for dark matter of mass above 100 GeV. IceCube has searched for halo dark matter decays and set stringent limits on the life time of particles with mass above 10 TeV.

1. Introduction

The first suggestions of dark matter existence were made to explain velocity dispersion of galaxy clusters and the flat rotation curves of spiral galaxies [1, 2], and further evidence has since accumulated including gravitational lensing effects and structure formation studies. Dark matter is believed to constitute approximately 25% of the energy density in the universe.

Dark matter is inferred through its gravitational interactions only, no other type of interaction between dark matter and Standard Model particles has been detected yet. A standard hypothesis is that dark matter is a Weakly Interacting Massive Particle [3]. Such a dark matter candidate could produce standard model particles through decay or self-annihilation, and the IceCube Neutrino Observatory (IceCube) is sensitive to neutrinos produced either directly in the decay/annihilation or resulting from the subsequent decay of other produced particles.

The IceCube detector is located in the deep, dark, and clear ice at the South Pole, and consists of 5160 photosensors on 86 vertical strings covering a cubic kilometer of ice [4]. IceCube detects Cherenkov light from charged particles moving superluminally through the ice, such as those produced by neutrinos interacting with the ice. By observing the elongated muon tracks from charged current interactions of muon neutrinos, a good resolution on the direction is achieved. By observing the events from all other interactions, where only a ‘cascade’ is present, a good measure of the neutrino energy is possible. Given the very large size of the detector, many analyses use the outermost layers of IceCube to detect and reject incoming atmospheric muons, greatly enhancing the sensitivity of the searches.

With IceCube, the direction and energy of the neutrino can be determined sufficiently well to search for neutrinos produced in dark matter self-annihilations or decays by targeting regions where dark matter is expected to be concentrated. In this talk an overview of multiple IceCube analyses is given, covering searches for dark matter self-annihilation in the Galactic halo and in

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the Sun, as well as searches for dark matter decay in the halo. No signal of neutrinos has so far been observed. The following sections will discuss these analyses and provide information on the event selection, the analysis carried out, and the resulting limits from IceCube.

2. Dark matter self-annihilation in the Galactic halo

The distribution of dark matter in the Milky Way is assumed to be spherically symmetric, however the exact density profile is not yet known. In these searches we consider both the Navarro-Frenk-White (NFW) [5] and Burkert [6] halo density profiles. We use the parameter values for these halo density profiles determined in [7]. Given a model for the dark matter density in the galactic halo, we can determine the amount of dark matter along any line of sight [8]. Using `PYTHIA8` [9] we can determine the energy spectrum of the neutrinos, $\mathrm{d}N/\mathrm{d}E$, produced from the annihilation of a dark matter particle of mass m into pairs of quarks, leptons, bosons or directly to neutrinos. The neutrino flux Φ from dark matter annihilations depends on the velocity-averaged product of its self-annihilation cross section and velocity, $\langle\sigma_A v\rangle$, as follows:

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = \frac{\langle\sigma_A v\rangle}{4\pi \cdot 2m^2}\frac{\mathrm{d}N}{\mathrm{d}E}\int \rho^2(r(l,\Psi))\mathrm{d}l, \qquad (1)$$

where $\rho(r)$ is the dark matter density of the halo as a function of distance to the center of our Galaxy, with the integral calculated along the line of sight l for an opening angle of Ψ.

In the analyses the most likely value for $\langle\sigma_A v\rangle$ is calculated by comparing the event distribution in direction and energy of the experimental data to a combination of the targeted signal determined from weighting simulated neutrino events to follow Eq.(1), and the background (expected to be isotropic in right ascension) determined from experimental data randomized in time. Due to the extended nature of the dark matter halo a possible signal will affect the background expectation, and therefore we subtract it off from the background template in order to arrive at an unbiased estimation of $\langle\sigma_A v\rangle$.

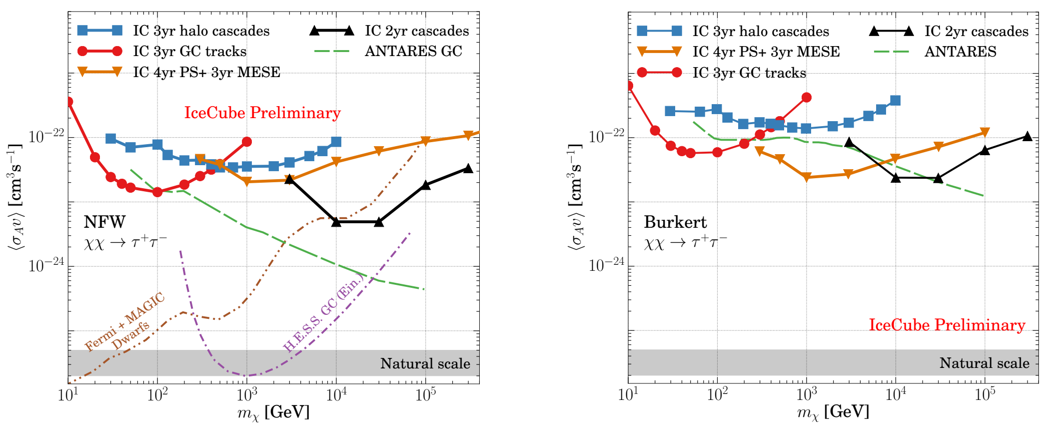
The three results from IceCube searches cover dark matter masses from 10 GeV to 300 TeV, by combining multiple event selections (some of which were developed for other searches):

- **Low energy tracks from the galactic center (IC 3yr GC tracks)**: This event selection focuses on dark matter mass around 100 GeV, but goes down as low as 10 GeV (and up to 1 TeV), exploiting the pointing of the tracks to distinguish the signal from the background. In order to study the events with energies close to the detector threshold, a dedicated low energy reconstruction was implemented. The sample is mostly neutrinos originating within 10^0 of the Galactic center, hence most of the events enter IceCube from above. So a veto around DeepCore (the more densely instrumented, innermost part of IceCube) is used to reject atmospheric muons, and select only tracks starting within IceCube (which are more likely to be from neutrino interactions). Details of the analysis with this event selection are described in [10], and the result is indicated in red in figure 1.
- **High energy tracks from the Galactic halo (IC 4yr PS + 3yr MESE)**: The events are composed of 4 years of data with a selection of tracks from all directions designed for Point Source (PS) searches in IceCube [11, 12, 13]. In addition, 3 years of the Medium Energy Starting Events (MESE) data [14] was also added to extend the selection to higher neutrino energies and to strengthen the sensitivity to the southern hemisphere. However, the event sample is mostly sensitive to the northern hemisphere and the outer halo of dark matter in the Milky Way. More information on the analysis of these events can be found in [15], and the result is plotted in orange on figure 1.
- **High energy cascades from the galactic halo (IC 2yr cascades)**: This selection of events is designed to do an unfolding analysis of the neutrino spectrum [16], and achieve a high signal to background ratio using 2 years of data by using a progressively larger fiducial

volume with increasingly higher neutrino energies. Even though the directional resolution is reduced for cascades, the extended nature of the Galactic halo compensate to some extent, and with this selection it is possible to get a good sensitivity above a dark matter mass of 300 TeV (in contrast to the first IceCube dark matter search using cascades which was looking at relatively lower energies [17]). More information on the analysis of these events can also be found in [15], and the result is plotted in black on figure 1.

Maximum likelihood ratio analyses are carried out on each of the event selections using the directional information and energy of the neutrinos (though the energy is only relevant in the two latter analyses covering dark matter masses above 10 TeV). The observed neutrino flux is consistent with the background-only hypothesis, and therefore limits on $\langle \sigma_A v \rangle$ at 90% confidence are extracted according to the prescription by Feldman and Cousins [18].

In figure 1 the resulting limits are shown for self-annihilation to a pair of taus. In figure 1 (a) the NFW halo density profile is assumed and the results are compared to the limits from the ANTARES Neutrino Telescope, as well as gamma-ray experiments. IceCube sets competitive limits on $\langle \sigma_A v \rangle$ from neutrino observations, which are leading results for dark matter mass below 100 GeV. ANTARES is located in the northern hemisphere and can therefore benefit from additional shielding from atmospheric muons by the Earth when looking in the direction of the Galactic Center, where most of the dark matter is concentrated assuming the NFW profile. However, we do not know the actual dark matter distribution in the halo of our Galaxy which introduces a large uncertainty in the extracted limits on $\langle \sigma_A v \rangle$. Changing to the cored Burkert profile, the strongest limits on $\langle \sigma_A v \rangle$ are actually provided by IceCube (shown in figure 1 (b)). IceCube is less model dependent due to the fact that it looks for neutrinos from the whole Galactic halo than just relying on neutrinos from its Centre. This is illustrated especially well with the IC 4yr PS + 3yr MESE analysis, which mainly probes the outer halo of the Milky Way.



(a) (b)

Figure 1: Upper limits on $\langle \sigma_A v \rangle$ versus dark matter mass, for the annihilation channel $\chi\chi \to \tau^+\tau^-$, assuming either the NFW halo profile in (a) or the Burkert halo profile in (b). The three searches from the Galactic halo are compared to the previous results of the IceCube 3yr halo cascades search [17] and results from ANTARES [19]. In addition, upper limits are shown from gamma-ray searches towards the Galactic center (assuming Einasto profile) by H.E.S.S. [20] and from the dwarf galaxy Segue 1 (Dwarfs) by FermiLAT+MAGIC [21]. Indicated is the value of $\langle \sigma v \rangle$ needed for dark matter to be a thermal relic (natural scale) [22]

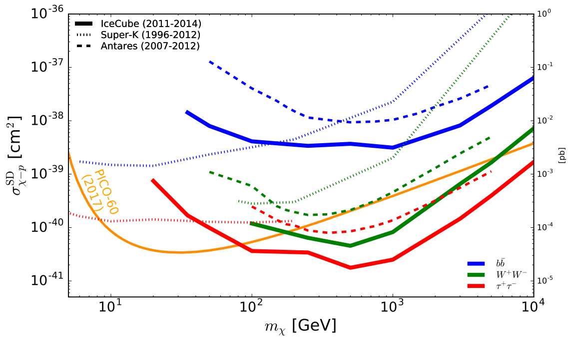


Figure 2: IceCube limits on $\sigma_{\rm SD}$ versus dark matter mass for neutrinos produced via different dark matter self-annihilation channels, compared with results from ANTARES [30] and Super-Kamiokande [31]. Upper limits are also shown from the direct detection experiment PICO-60 [32]

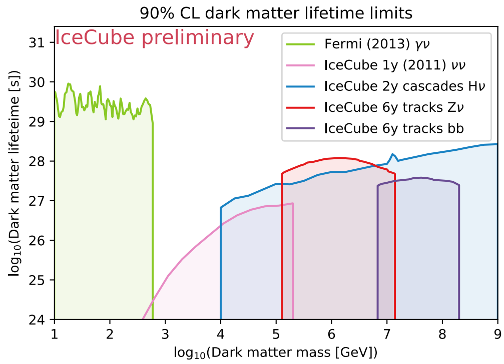


Figure 3: Limits on the lifetime of dark matter assuming the Burkert halo profile compared to the previous IceCube limit for decay into neutrinos only [37] and the γ-ray search by Fermi [38].

3. Dark matter self-annihilation in the Sun

As the Sun moves around in the Galactic halo, it will capture dark matter which can subsequently self-annihilate, producing high energy neutrinos that escape the Sun unscattered [23, 24, 25]. Given the Sun's size and age, the capture and annihilation rates come into equilibrium [24] and hence a measure of the annihilation rate translates to a value for the dark matter nucleon cross section [26]. With the Sun made up of mainly hydrogen and helium the capture rate is driven by the spin-dependent cross section between dark matter and the nucleons, $\sigma_{\rm SD}$.

The targeted signal is estimated using flux calculations from `DarkSUSY` [27] and `WIMPSim` [28], and is compared to the isotropic background in a likelihood analysis (similar to the one used in the analyses of the Galactic halo), to estimate the most likely value of $\sigma_{\rm SD}$.

With 3 years of IceCube data, the analysis only use days with the Sun below the horizon, as that results in a more powerful rejection of the atmospheric muon background. This result in 522 days of livetime with events selected for low background and well reconstructed events. Details on the analysis are published in [29]. The experimental data is consistent with the background-only hypothesis, and in figure 2 the resulting 90% confidence limits on $\sigma_{\rm SD}$ are presented (using the Feldman and Cousins method [18]). The solid lines are the results from IceCube, for different annihilation channels in different colors, illustrating that above 100 GeV, IceCube provides the best limits on $\sigma_{\rm SD}$ from neutrino observation. Assuming a 100% branching ratio into a pair of taus, IceCube also provide the best limits comparable to those from direct dark matter detection experiments.

4. Dark matter decay in the Galactic halo

IceCube has detected a flux of high energy astrophysical neutrinos [33], which could originate from decays of long-lived heavy dark matter particles. The target signal is now dark matter decays in the halo of our Galaxy (Burkert halo density profile using parameter values from [7]) and an isotropic extra-galactic component with a red-shifted energy spectrum. The background is estimated from simulation of three components; atmospheric neutrinos, muons and an isotropic astrophysical component following a single power law.

Two independent searches are carried out, exploiting two different event selections. One analysis uses the 2 years sample of contained cascades [16] (referred to previously as '2yr cascades'). The other analysis uses 6 years of neutrino tracks from the northern hemisphere (described in [34]). Details on the analyses can be found in [35]. The analyses use a maximum likelihood ratio method to determine the most likely value of the dark matter mass and lifetime, as well as the flux normalization and power law index of the diffuse astrophysical neutrinos.

The fits in both analyses imply a non-zero contribution from dark matter, though they are still consistent with the background-only hypothesis. For the cascade analysis, the Feldman and Cousins method [18] is used while for the tracks analysis, the Neyman approach [36] was implemented to calculate the lower limits on the dark matter lifetime (shown in figure 3).

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