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Dark matter neutrino scattering in the galactic centre with IceCube

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Abstract: While there is evidence for the existence of dark matter, its properties have yet to be discovered. Simultaneously, the nature of high-energy astrophysical neutrinos detected by IceCube remains unresolved. If dark matter and neutrinos are coupled to each other, they may exhibit a non-zero elastic scattering cross section. Such an interaction between an isotropic extragalactic neutrino flux and dark matter would be concentrated in the Galactic Centre, where the dark matter column density is greatest. This scattering would attenuate the flux of high-energy neutrinos, which could be observed in IceCube. Using the seven-year Medium Energy Starting Events, we perform an unbinned likelihood analysis, searching for a signal based on a possible dark matter-neutrino interaction scenario. We search for a suppression of the high-energy astrophysical neutrino flux in the direction of the Galactic Centre, and compare these constraints to complementary low-energy information from large scale structure surveys and the cosmic microwave background.

Keywords: Neutrino detectors; Analysis and statistical methods; Simulation methods and programs

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Contents

1 Introduction

Over the last century the presence of dark matter (DM) has been implied by numerous observations of its gravitational effects, however, it has yet to be detected. Despite this lack of a signal, some information about DM can be gleaned by ruling out various theorized models and constraining parameters. These searches involve exploring possible interactions between DM and Standard Model particles and are typically directed towards areas where a large signal can be expected, in this case DM-neutrino scattering in the Galactic Centre. As most past searches for DM have considered interactions with quarks or electrons, DM-neutrino interactions are one of the least explored connections of DM with the Standard Model. DM-neutrino models are especially attractive for light DM, where annihilation into heavier products is forbidden and appears naturally in cases like the sterile neutrino. The elastic scattering of DM and neutrinos has been constrained for the Early Universe at low energies [1–3]. Limits on the DM-neutrino scattering have also been found for the high energies of IceCube, but have been hindered by a lack of observational data [4]. Searching for interactions at the high energies observed at IceCube is important as the scattering cross section scales with energy. This analysis considers a DM-neutrino scattering interaction that would be concentrated in the Galactic Centre and would lead to an energy dependent shadow in the astrophysical neutrino flux that could be observed by IceCube.

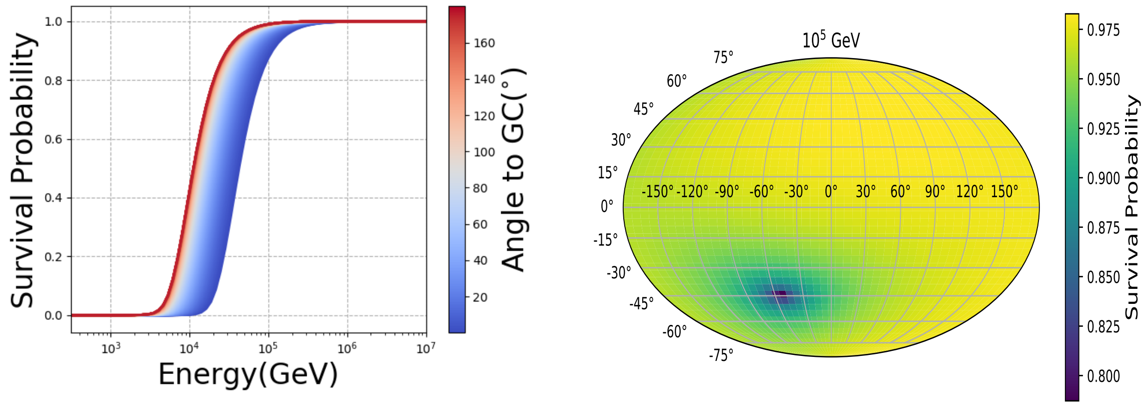
2 Dark matter-neutrino scattering

The main idea of this analysis is that extragalactic neutrinos travelling towards the Earth will scatter with the diffuse DM halo of the Milky Way. This will cause changes in the neutrino flux that are described by the cascade equation [5]:

$$\frac{d\Phi(E,\tau)}{d\tau} = -\sigma(E)\Phi(E,\tau) + \int_E^\infty d\tilde{E}\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\tau), \tag{2.1}$$

where Φ is the neutrino flux, $\tilde{E}$ is the incoming neutrino energy, E is the outgoing neutrino energy, τ is the DM column density, and σ is the scattering cross section given in [6]. The column density describes the amount of DM along the line of sight (l.o.s.) to the neutrino source:

$$\tau(\vec{x}) = \int_{l.o.s} n_\chi(\vec{x})dx. \tag{2.2}$$



(a) (b)

Figure 1. a) Survival probability for a neutrino flux across energy and angle to the Galactic Centre. Here $g = 1$, $m_\phi = 10\,\text{MeV}$, $m_\chi = 1\,\text{GeV}$. The low energy ($\leq 20\,\text{TeV}$) part of the neutrino flux is completely attenuated by DM-neutrino scatter, while the high energy ($\leq 500\,\text{TeV}$) is unaffected. b) Skymap of the survival probability for the astrophysical neutrino flux. This is for the scalar mediator-scalar DM scenario with $g = 1$, $m_\phi = 10\,\text{MeV}$, $m_\chi = 1\,\text{GeV}$ at $E_\nu = 1$ PeV.

where $n_\chi = \frac{\rho_\chi}{m_\chi}$ is for a Navarro-Frenk-White (NFW) profile [7]. The code that is used to solve the cascade equation is based on nuFATE [5].

Since the likelihood of a scattering interaction is proportional to the column density, a greater scattering effect should be expected at the Galactic Centre. This scattering effect would attenuate the neutrino flux as the neutrinos lose energy. Figure 1b shows the skymap of the flux survival probability where the astrophysical neutrino flux would be expected to be reduced at the Galactic Centre. This survival probability across energy and angle to the Galactic Centre is shown in figure 1a. For this specific example of a scalar DM and scalar mediator model there is a noticeable attenuation for energies below 1 PeV. There is also a gradient in attenuation where l.o.s angles closer to the Galactic Centre (smaller) lead to lower survival probability for any given energy.

3 Method

This analysis aimed to set sensitivities in searches for an energy dependent deficit in the isotropic extra-galactic neutrino flux at the Galactic Centre from DM neutrino elastic scattering. This is done using an unbinned likelihood analysis with simulated IceCube data that is sampled with a Markov Chain Monte Carlo (MCMC) algorithm. This involved determining an expected signal at IceCube by combining a DM and background hypothesis which is compared with a simulated dataset. The simulated dataset is constructed by randomly selecting events from the Monte Carlo expectation of the Medium Energy Starting Event-Cascade dataset. The likelihood of a DM hypothesis, $\vec{\theta}$, given the data, $\vec{x}$, and including nuisance parameters, $\vec{\eta}$ is:

$$\mathcal{L}(\vec{\theta},\vec{\eta};\vec{x}) = \frac{e^{-\lambda(\vec{\theta},\vec{\eta})}\lambda^k(\vec{\theta},\vec{\eta})}{k!}\prod_i^k f(\vec{x}_i,\vec{\theta},\vec{\eta}), \tag{3.1}$$

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where k is the number of observed events, λ is the number of expected events and f is the likelihood of individual events. The DM hypothesis is found with (2.1) for which the cross section includes the DM mass, mediator mass, and coupling strength. The nuisance parameters are included as the model for the neutrino background from astrophysical neutrinos, atmospheric neutrinos and atmospheric muons. The observable parameters at IceCube are energy, right ascension and the declination. The likelihood for each individual event, f, includes shape effects across the physical observables $\vec{x}$:

$$f(\vec{x}_i, \vec{\theta}, \vec{\eta}) = \sum_j K(\vec{x}_i - \vec{x}_j) \frac{d^2\Phi}{dE\, d\Omega}(x_j; \vec{\theta}, \vec{\eta}_j) \frac{L}{g(\vec{\eta}_j)}, \tag{3.2}$$

where K is the kernel density estimation function used to obtain a continuous probability density function of the expected events, $\frac{d^2\Phi}{dE d\Omega}$ is the neutrino flux from both the background and DM scattering signal, and $\frac{L}{g(\vec{\eta}_j)}$ is a weighting to account for the detector properties. This likelihood is then explored using `emcee` to constrain the upper limits on DM parameters and allow the nuisance parameters to be included as free parameters. `emcee` is an affine invariant Markov chain Monte Carlo ensemble sampler that allows high dimensional profile likelihoods to be efficiently explored [8].

4 Sensitivities

The case of a scalar DM and scalar mediator model was considered to determine sensitivities on the DM-neutrino interaction as observed at IceCube. The best-fit values from `emcee` are consistent with the null hypothesis indicating that a signal from DM-neutrino is not expected above a certain cross section. As such, sensitives for the upper limits that can be achieved with the MESE-C dataset can be obtained. The preference for low mass mediators, and higher mass DM (up to the neutrino energy) is found.

The maximum coupling constant that is allowed under the simulated dataset is plotted in figure 2a and compared to limits from cosmology. It can be seen that across a range of DM masses and for high mediator masses ($m_\phi \gtrsim 10^{-6}$), IceCube is more sensitive in constraining the maximum coupling for a DM-neutrino scattering scenario.

The cross section limits from IceCube can be plotted by marginalizing over the nuisance parameters and making the appropriate transformations on the prior space. The sensitivities obtained are shown in figure 2b, where the upper limit that is expected at IceCube is shown by the black line. The constraints on DM-electron and DM-nucleon scattering cross section from the SENSEI and XENON experiments are also shown by the yellow and blue regions respectively for a comparison [9].

This leads to sensitivities on the cross section $\sigma_{\nu-DM}$ at IceCube being set as:

$$\sigma_{\nu-DM} \lesssim 10^{-27} \left(\frac{m_\chi}{\text{GeV}}\right) \left(\frac{E_\nu}{\text{PeV}}\right)^{-2} \text{cm}^2, \tag{4.1}$$

where m_χ is the dark matter mass and E_ν is the neutrino energy. For this particular scalar DM-scalar mediator model these sensitivities mark the first limits that can be placed at high neutrino energies. The sensitivity of IceCube was found to be similar to that of cosmology, however, for high mediator masses, IceCube can provide stronger constraints on a possible DM-neutrino coupling.

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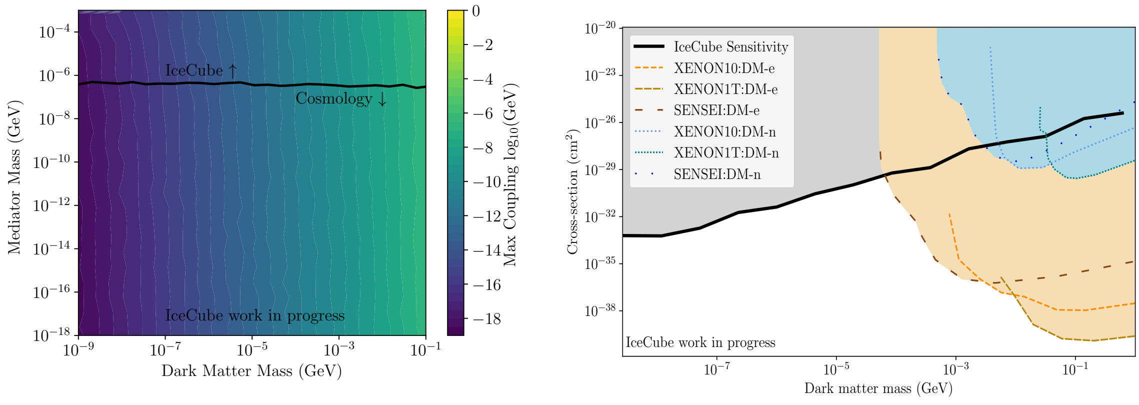

(a) (b)

Figure 2. a) The maximum coupling constant that is expected to be allowed by IceCube. Above the line constraints from IceCube are more stringent, while below the line those from cosmology dominate. b) The upper limit on the sensitivity for a neutrino-DM cross section is shown in black across DM mass. Also plotted are the DM-electron and DM-nucleon scattering cross section limits from SENSEI, XENON1T and XENON10 as presented in Ref: [9]. Since the cross section is energy dependent, this is plotted for a neutrino energy of 46 TeV.

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