Dark Matter Neutrino Scattering in the Galactic Centre with IceCube

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Motivation

The evidence for dark matter's (DM) gravitational effects are seen across a number of astronomical phenomena, from which it has been determined that DM composes about 26% of the Universe. Despite this abundance it has yet to be detected as a particle. From this lack of particle signal various theories can be ruled out and constrained. In this case DM-neutrino scattering is explored. 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. 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 at IceCube, but have been hindered by a lack of observational data [4]. This analysis considers a DM-neutrino scattering interaction that would be concentrated at the Galactic Centre and would lead to an energy dependent attenuation in the astrophysical neutrino flux that could be observed by IceCube.

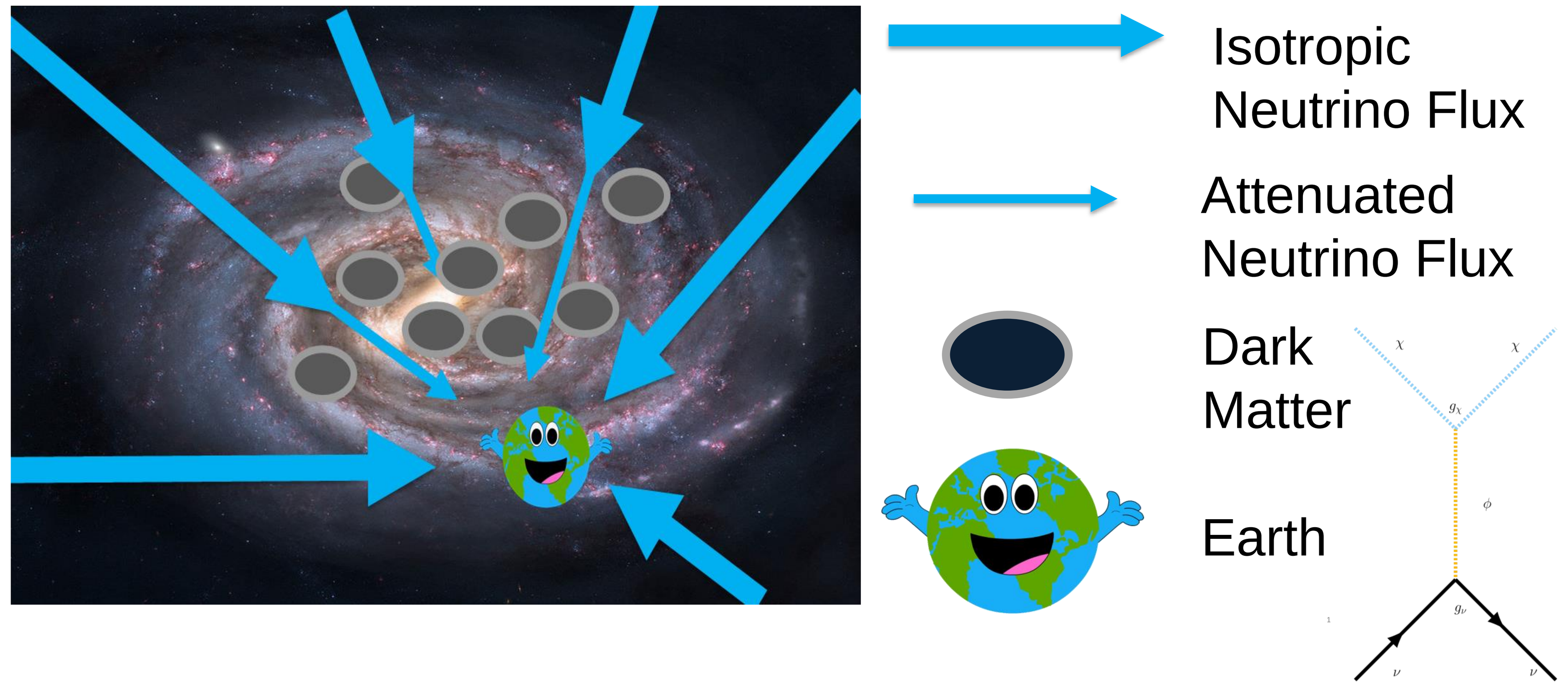

Figure 1: Graphical representation of analysis idea

The main idea, shown in Fig. 1, 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]:

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

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 of an NFW profile, and σ is the scattering cross section. The code that is used to solve the cascade equation is based on nuFATE [5].

Method

An unbinned likelihood method was used on simulated IceCube data that is sampled with a Markov Chain Monte Carlo (MCMC) algorithm. 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:

$$\mathcal{L}(\vec{\theta},\vec{\eta},\vec{x}) = \frac{e^{-\lambda(\vec{\theta},\vec{\eta})}\lambda^k(\vec{\theta},\vec{\eta})}{k!}\prod_i^k\sum_j K(\vec{x}_i-\vec{x}_j)\frac{d^2\Phi}{dEd\Omega}(\vec{\theta},\vec{\eta}_j,\vec{x}_j)\frac{L}{g(\vec{\eta}_j)}$$

where k is the number of observed events, and λ is the number of expected events. The DM hypothesis is found with the cascade equation for which the cross section includes the DM mass, mediator mass, and coupling strength [6]. 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, includes shape effects across the physical observables where $K(\vec{x}_i-\vec{x}_j)$ is the kernel density estimation function used to obtain a continuous probability density function of the expected events, $\frac{d^2\Phi}{dEd\Omega}$ is the neutrino flux from both the background and DM scattering, and $\frac{L}{g(\vec{\eta}_j)}$ is a weighting to account for the detector properties. This likelihood is then explored using `emcee` [7] to constrain the upper limits on DM parameters and allow the nuisance parameters to be included as free parameters.

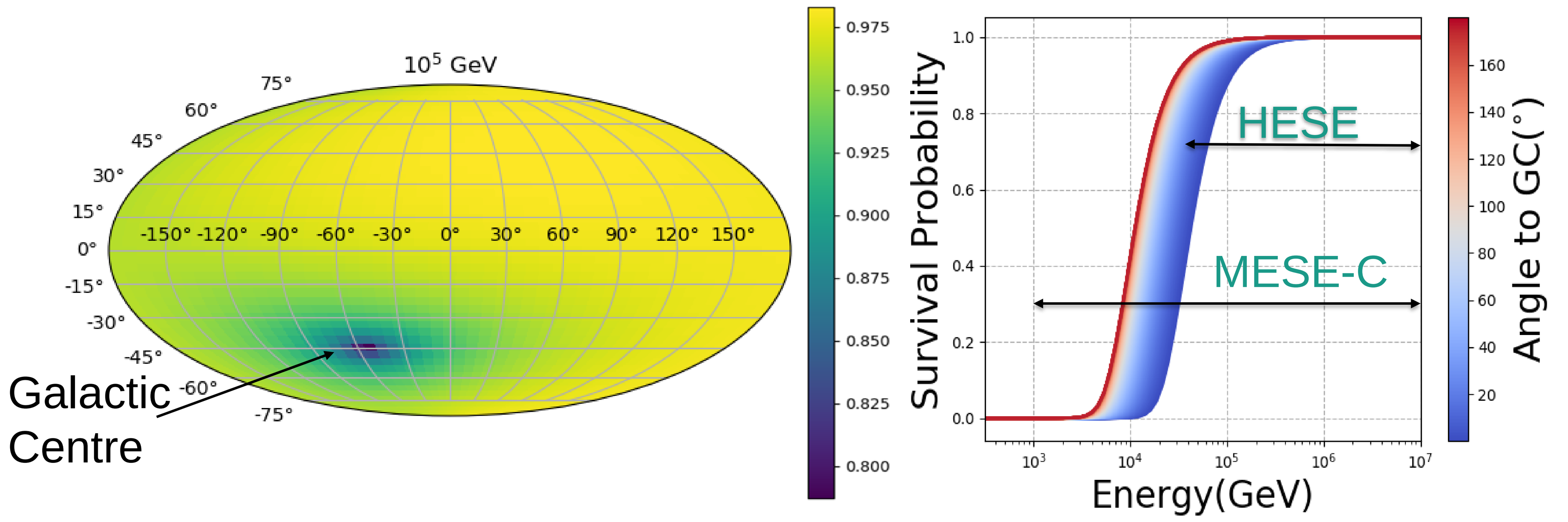

Figure 2: Skymap of survival probability of neutrino flux with reduction at Galactic Centre. There is a noticeable attenuation for energies below 1 PeV. There is also a gradient in attenuation.

References

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Sensitivities

The case of a scalar DM and scalar mediator model was considered to determine sensitivities on the neutrino DM 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 and shown in Fig 3a. A 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 Fig 3b and compared to limits from cosmology. It can be seen that across a range of DM masses and for high mediator masses, IceCube is more sensitive in constraining the maximum coupling for a DM-neutrino scattering scenario.

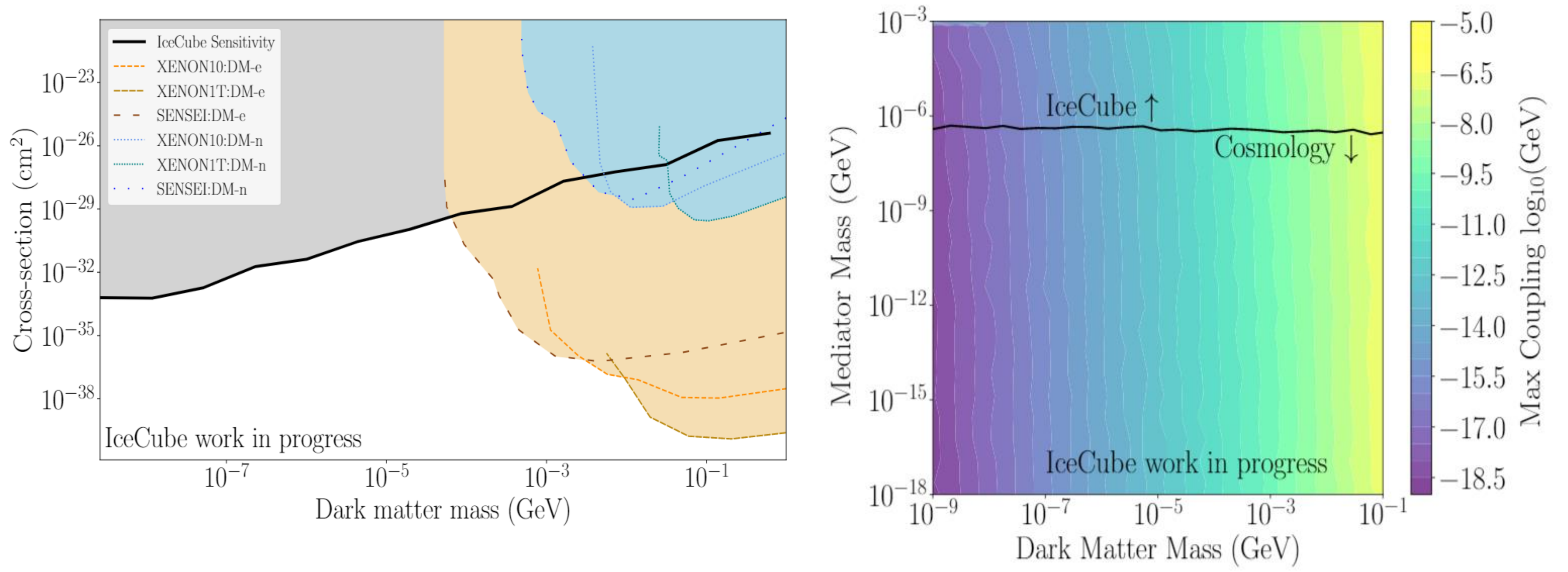

Figure 3: a) The maximum coupling constant that is expected by IceCube. Above the line constraints from IceCube are more stringent, while below the line those from cosmology dominate. b) The upper limit on the sensitivity for a neutrino-DM cross section is shown in black across DM mass. Also plotted are the DM-electron and DM-nucleon scattering cross section limits [8]. This is plotted for a neutrino energy of 46 TeV.

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

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

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.