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Neutrinos from dark matter captured in neutron star distribution near the galactic center

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Due to abundant dark matter and stellar-rich environments, the galactic center is the optimal location to probe for signatures of captured dark matter annihilation. In this work, we have studied the dark matter capture in the galactic center neutron star distribution and analyzed the neutrinos coming from the annihilation of captured dark matter through long-lived mediators in an idealized gigaton neutrino detector like IceCube/KM3NeT. We report projected limits on the dark matter-nucleon scattering cross-section that are orders of magnitude below the current limits in the TeV-PeV mass scales.

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1. Introduction

The existence of dark matter (DM) in our universe has been indicated by several cosmological and astrophysical observations, though the exact microscopic nature of the DM remains an enigma. Consideration of a particulate DM candidate which shares some non-gravitational interaction with the standard model (SM) states opens up the possibility to detect the DM signal in ground-based direct detection and collider experiments. However, the null results in such experiments have pushed us to explore the DM in various exotic locations of our universe. One such possibility is to look for DM signatures that are trapped within a celestial body owing to its interactions with the SM constituents. The neutron stars (NS) are the ideal targets to probe the DM scattering with the SM particles due to the high density. In this work, we have studied the capture of DM particles by a population of neutron stars around the galactic center that hosts the densest distribution of DM and stellar population in our galaxy [1]. These captured DM particles can dominantly annihilate through long-lived mediators that can emerge from the stellar interior and decay within the interstellar medium to produce gamma-ray or neutrino signatures [2–5]. These neutrinos may be detected at terrestrial detectors like IceCube [6] or KM3NeT [7]. We demonstrate that within this framework, the sensitivities of these experiments are orders of magnitude stronger than the existing limits on the DM-nucleon scattering cross-section in the TeV-PeV mass range.

2. Dark Matter Capture

As a celestial body is roaming through the halo of DM, the DM particles get focused to the celestial object due to its gravitational potential and the DM particles can scatter with the SM constituents multiple times before losing sufficient energy to be trapped within the stellar environment. At a distance r from the galactic center, the rate of capture of DM particles after S times scattering within a NS is given by [8],

$$C_{\rm NS}(r) = \sum_{\rm S} C_{\rm S} = \sum_{\rm S} \pi\, R^2\, p_{\rm S}(\tau) \left(\frac{\rho_\chi(r)}{m_\chi}\right) \int_0^{u_{\rm esc}} \frac{f(u_\chi)\, du_\chi}{u_\chi} \left(u_\chi^2 + v_{\rm esc}^2\right) g_{\rm S}(u_\chi), \qquad (1)$$

where R is the radius of the NS, $\rho_\chi(r)$, m_χ and $p_S(\tau)$ are the DM density, mass and probability of S times scattering of the DM particles and τ is the optical depth. u_χ, $f(u_\chi)$ and $g_S(u_\chi)$ are the DM halo velocity, velocity distribution and the probability of capture respectively. The total rate of DM capture due to NS distribution can be expressed as,

$$C_{\rm tot} = 4\,\pi \int_{r_1}^{r_2} r^2\, n_{\rm NS}(r)\, C_{\rm NS}(r)\, dr, \qquad (2)$$

where $n_{\rm NS}(r)$ is the density of neutron stars at the galactic center adopted from [9]. We have utilized the typical NS of mass $M = 1.5\, M_\odot$ and radius $R = 10\,{\rm km}$. We have considered a region $r = 0.1 - 10\,{\rm pc}$ and utilised different DM density profiles tabulated in [1].

3. Neutrino Flux

The accumulated DM particles can annihilate or evaporate from the NS interior. However, the evaporation is numerically insignificant for the considered DM mass range. Considering the equilibrium scenario, the muon neutrino flux reaching the Earth due to the dominant annihilation of the DM particles into long-lived mediators is given by,

$$E_\nu^2 \frac{d\phi_{\nu_\mu}}{dE_\nu} = \frac{\Gamma_{\rm ann}}{4\,\pi\,D^2} \times {\rm Br}(Y \to {\rm SM}\,\bar{\rm SM}) \times \left(\frac{1}{3} E_\nu^2 \frac{dN_\nu}{dE_\nu}\right) \times \left(e^{-\frac{R}{\eta c \tau_Y}} - e^{-\frac{D}{\eta c \tau_Y}}\right), \tag{3}$$

where D is the distance of the galactic center, $\Gamma_{\rm ann}$ is the annihilation rate, ${\rm Br}(Y \to {\rm SM}\,\bar{\rm SM})$ is the branching ratio of mediator (Y) decay to SM states and the neutrino spectrum dN_ν/dE_ν is adopted from [10]. η, τ_Y are the boost parameter, lifetime of the mediator (Y) which are adjusted in such a way so that the mediator can escape from the NS.

4. Results

In order to study the reach of a gigaton neutrino detector in this scenario we consider the muon track-like events generated from the incoming muon flux at the detector due its better angular resolution than the cascade events. The primary sources of background for this neutrino search are the atmospheric and astrophysical neutrino backgrounds. We have not considered the atmospheric muon background as it can be avoided by applying some veto to the detector. For KM3NeT, the detector remains ~ 37% of the time below the horizon for the galactic center and for IceCube we need to use a small inner region of the detector to reject the muon backgrounds.

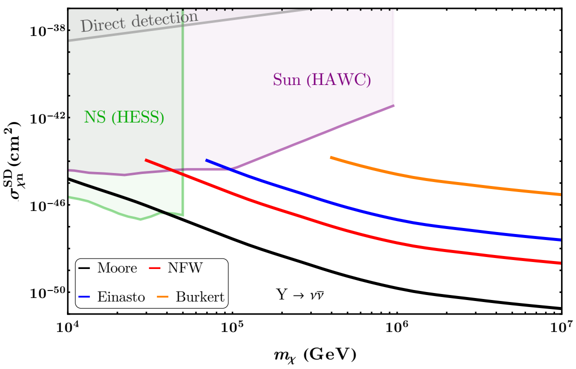

Figure 1: Sensitivities of SD DM-nucleon scattering cross-sections for neutrino channel due to captured DM annihilation in a galactic NS population for different DM density profiles.

We have estimated the sensitivity by comparing the signal events with the background events generated from considering both the atmospheric and astrophysical backgrounds in the energy bins $[\max(E_{\rm thres}, m_\chi/5), m_\chi]$ which is greater than the energy resolution of the considered detectors [11]. In Fig. 1, the projected limits on the spin-dependent (SD) DM-nucleon scattering cross-section is shown for the mediator decay to neutrinos for different DM density profiles. The projected exclusion plots for spin-independent scattering with all the other decay channels of the mediator are cataloged in [1]. In Fig. 1, the direct detection limits are obtained from PICO-60 results [12] and the other limits are described in [3, 4].

5. Conclusion

If the DM particles share some non-gravitational interaction with the SM particles, then the scattering with the SM constituents of the NS can lead to their capture inside the star. We have considered the DM capture in the distribution of NS at the galactic center and the subsequent annihilation of the accumulated DM particles through long-lived mediators that can emerge from the NS environment and decay to SM states within the interstellar medium. The produced neutrinos can be probed in gigaton detectors on the Earth. Within the aforementioned paradigm, the projected sensitivity of the neutrino detectors extends orders of magnitude further into the DM-nucleon scattering cross-section than the existing limits for TeV-PeV mass scales.

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