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Dark matter searches in the Galactic Center with IceCube-DeepCore and IceCube-Upgrade

The IceCube Collaboration

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The nature of Dark Matter is one of the important unresolved questions in fundamental physics. It is assumed in many Beyond Standard Model theories that dark matter candidates can have weak coupling to Standard Model (SM) particles. In heavy cosmological objects, like galaxies, the Sun, or the Earth, dark matter can be gravitationally accumulated in high abundance. Then, the DM can decay or annihilate into the anomalous flux of SM particles detectable by various detector types. In this contribution, I will present a recent search for neutrino signals from GeV-scale Dark Matter in the Galactic Center with the IceCube-DeepCore. I will also discuss the prospect of such a search with the IceCube-Upgrade, an upcoming extension of the IceCube Neutrino Observatory to enhance performance in the GeV energy range.

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39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

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1. Introduction

Multiple compelling evidences support the existence of dark matter (DM) [1], a non-luminous component that constitutes approximately 22% of the total energy density of the universe [2]. Despite decades of dedicated effort, the fundamental nature of dark matter remains one of the most pressing open questions in modern physics.

One leading hypothesis is that dark matter consists of particles that, in addition to gravitational interactions, can weakly interact with Standard Model (SM) particles. This idea is motivated by numerous Beyond Standard Model (BSM) theories that predict a wide range of DM candidates, including Weakly Interacting Massive Particles (WIMPs) which are typically considered in the GeV–TeV mass range [3]. If DM particles can annihilate or decay into SM particles, they could produce detectable secondary particles such as neutrinos, photons, or cosmic rays. Such a search strategy is referred to as indirect detection of DM [4]. These searches often target regions with a high concentration of dark matter, such as massive astrophysical objects.

Among all potential targets, the Galactic Center (GC) is particularly promising due to its proximity to the Earth and high dark matter density. The GC also hosts the long-standing *GeV-excess* observed in gamma rays by Fermi-LAT [5]. The origin of this excess remains controversial: it may be explained by dark matter annihilation at GeV-scale masses or by unresolved astrophysical point sources, such as a population of sub-threshold millisecond pulsars [6]. Observations from other cosmic messengers, such as neutrinos, can provide independent and complementary insights into this puzzle.

In this contribution, we present a search for GeV-scale dark matter using 9.3 years of data from IceCube-DeepCore [7], a densely instrumented sub-array of the IceCube Neutrino Observatory [8] optimized for low-energy neutrino detection down to a few GeV. This analysis employs a state-of-the-art event selection benefited from multiple improvements in detector calibration, event simulation, and reconstruction techniques.

We also discuss the prospects of future searches with the upcoming IceCube-Upgrade [9], a next-generation extension of the IceCube array focused on the GeV energy range, scheduled to begin deployment in the summer of 2025.

2. IceCube-DeepCore and IceCube-Upgrade

The IceCube Neutrino Observatory is a large-volume Cherenkov detector located at the geographic South Pole, where it is embedded deep within Antarctic ice [8]. It comprises a three-dimensional array of photomultiplier tubes (PMTs) designed to detect Cherenkov light generated by secondary charged particles from neutrino interactions. The DeepCore sub-detector [7], situated in the clearest ice near the bottom center of the array, features a denser sensor configuration and upgraded PMTs with enhanced quantum efficiency. The design enables sensitivity to neutrino energies down to approximately 10 GeV.

This work adopts a recently refined DeepCore dataset, incorporating advanced calibration and improved simulation to enhance the purity of selected neutrino events. For observations in the northern sky, atmospheric muon backgrounds are naturally filtered by Earth. In contrast, for the southern sky, where the Galactic Center resides, the outer IceCube array functions as an active veto system, selecting events that originate within DeepCore based on initial light deposition. Further technical details on the dataset are provided in Ref. [10].

The forthcoming IceCube-Upgrade [9], scheduled for deployment during the 2025–2026 Antarctic summer season, will leverage the existing detector with seven new strings densely instrumented within the current DeepCore volume. The Upgrade is optimized for improved performance in the few-GeV energy range, and it will significantly enhance our understanding of the optical properties of the surrounding glacial ice, benefiting the performance of the entire detector. The analysis presented here is based on the latest simulation of the Upgrade, incorporating novel methods for raw data processing, event reconstruction, and background rejection [11].

3. Dark matter signal from Galactic Center

The differential flux of neutrinos from DM annihilation or decay in the Galactic Center can be expressed as a function of neutrino energy E_ν and opening angle Ψ between neutrino direction and GC.

$$
\begin{aligned}
\frac{\mathrm{d}\phi_\nu^{\mathrm{ann.}}}{\mathrm{d}E_\nu}(E_\nu, \Psi) &= \frac{1}{4\pi}\frac{\langle\sigma\upsilon\rangle}{2m_{\mathrm{DM}}^2}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_\Omega\int_{\mathrm{l.o.s}}\rho^2\left(r(l,\Psi)\right)\mathrm{d}l\;\mathrm{d}\Omega\;, \\
\frac{\mathrm{d}\phi_\nu^{\mathrm{dec.}}}{\mathrm{d}E_\nu}(E_\nu, \Psi) &= \frac{1}{4\pi}\frac{1}{m_{\mathrm{DM}}\tau}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_\Omega\int_{\mathrm{l.o.s}}\rho\left(r(l,\Psi)\right)\mathrm{d}l\;\mathrm{d}\Omega\;, \qquad (1)
\end{aligned}
$$

where $\langle\sigma\upsilon\rangle$ is the thermally averaged annihilation cross-section, τ the decay lifetime, and m_{DM} the dark matter mass. $\mathrm{d}N_\nu/\mathrm{d}E_\nu$ is the neutrino spectrum produced for each annihilation of decay. The last integrals are called J-factor and D-factor for the case of annihilation and decay correspondingly.

The energy dependence of the resulting neutrino flux is governed by the differential neutrino spectrum $\mathrm{d}N_\nu/\mathrm{d}E_\nu$, under the assumption of a 100% branching ratio into individual primary channels: W^+W^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, and the three neutrino-antineutrino pairs: $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, and $\nu_\tau\bar{\nu}_\tau$. When dark matter particles annihilate or decay directly into neutrinos, the resulting spectrum exhibits a distinctive *neutrino line* signature i.e. a monochromatic peak located at $E_\nu = m_{\mathrm{DM}}$ in the case of annihilation and at $E_\nu = m_{\mathrm{DM}}/2$ for decay. Such a spectrum is distinctive from the usual power-law spectra of astrophysical backgrounds.

In this work, the spectra are generated using the χaroν framework [12], which incorporates PYTHIA-based event simulations along with state-of-the-art electroweak corrections [13]. Neutrino flavors at the Earth are treated under the assumption of averaged-oscillation due to very long-baseline propagation.

The J(D)-factor quantifies the astrophysical contribution to the dark matter signal and is defined as the line-of-sight (l.o.s) integral of the dark matter density profile ρ over a given solid angle Ω. The DM density ρ is assumed to be spherically symmetric and thus can be expressed as a function of distance r from the GC.

The precise form of the dark matter density profile remains uncertain, with an ongoing debate over whether the Galactic halo has a central *cusp* with increased abundance toward GC or a flat *core* [14]. To capture this uncertainty, this analysis adopts two benchmark parameterizations: the Navarro-Frenk-White (NFW) profile, representing a cuspy distribution, and the Burkert profile,

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which exhibits a core-like structure. The parameters specific to the Milky Way halo are taken from Ref. [15]. J(D)-factors as a function of the opening angle Ψ are then calculated using the CLUMPY code [16].

4. Analysis method

This analysis utilizes a binned Poisson likelihood framework based on two observables: the reconstructed neutrino energy (E_{reco}) and the reconstructed opening angle of neutrino direction from the Galactic Center (Ψ_{reco}). The likelihood function is defined as the product of Poisson probabilities across all bins, comparing the observed event count n_i^{obs} with the predicted number μ_i:

$$\mathcal{L}_{\text{Poisson}}(\xi) = \prod_{i=min}^{max} \text{Poisson}(n_i^{\text{obs}}, \mu_i)\,, \tag{2}$$

where the predicted bin content is expressed as $\mu_i = n_{\text{obs}}^{\text{tot}} f(i, \xi)$. Here, $n_{\text{obs}}^{\text{tot}}$ is the total number of observed events and $f(i, \xi)$ denotes the model-predicted fraction of events in bin i:

$$f(i\,;\,\xi) = \xi\,\mathcal{S}_i \,+\, (1-\xi)\mathcal{B}_i\,. \tag{3}$$

In this expression, $\mathcal{S}_i$ and $\mathcal{B}_i$ are the probability density functions (PDFs) for the signal and background respectively. ξ is the signal fraction and the parameter of interest in this analysis.

The signal PDF is derived from Monte Carlo simulations, using a response matrix that encapsulates the detector's full response chain including neutrino interaction, triggering, event selection, and reconstruction with respect to the true neutrino properties (e.g., flavor, energy, and incoming direction). This matrix is used to transform the theoretical flux in Eq. (1) into an expected event distribution in the observable space.

For the analysis with DeepCore, the background PDF is constructed using a data-driven scrambling technique. The background is evaluated as the average over 100 data samples in which each event is randomly reassigned a right ascension value. This method relies on the high duty cycle of IceCube (>98%) and Earth's rotation which result in the uniform distribution of atmospheric muon and neutrino backgrounds in right ascension. However, if a real signal is present, it may bias the background estimation. To correct for this potential contamination, the background can be recalculated as:

$$\mathcal{B}_i = \frac{1}{1-\xi}(\mathcal{B}_i^{\text{scr}} - \xi\mathcal{S}_i^{\text{scr}})\,, \tag{4}$$

where $\mathcal{S}_i^{\text{scr}}$ denotes the right ascension scrambled signal PDF and $\mathcal{B}_i^{\text{scr}}$ denote the background obtained from scrambled datasets. The resulting likelihood is referred to as the *signal-subtraction likelihood*.

For the IceCube-Upgrade sensitivity study, the background PDF is instead derived from MC simulations by reweighting MC events according to atmospheric flux models for muons and neutrinos. Thus, the normal Poisson likelihood is adopted for the Upgrade sensitivities.

Fig. 1 illustrates an example of the signal and background PDFs for the analysis observables in the case of the DM search with DeepCore. As depicted in the figure, the signal distribution exhibits a clear enhancement in the direction of the Galactic Center, enabling its potential discrimination from the more isotropic background.

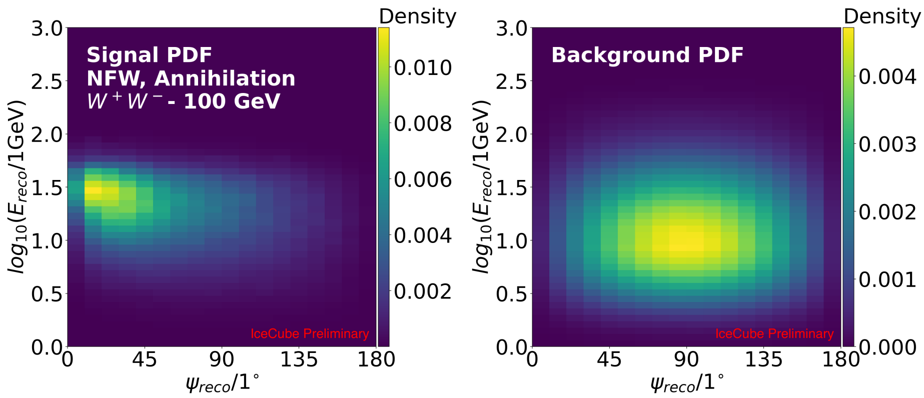

Figure 1: Two-dimensional PDFs as a function of reconstructed energy (E_{reco}) and reconstructed opening angle to the Galactic Center (ψ_{reco}) in DeepCore analysis. *Left*: signal PDF of dark matter with mass 100 GeV annihilating into $W^{+}W^{-}$ assuming NFW profile. *Right*: background PDF from right ascension scrambled data.

A test statistic is then constructed from the log-likelihood ratio to assess the significance of a potential signal or to set upper limits in the case of its absence. Further methodological details can be found in Ref. [17].

5. Results

5.1 Results from IceCube-DeepCore

The search for neutrino signal from dark matter in the Galactic Center is performed with 9.3 years of IceCube-DeepCore data. Across all tested dark matter scenarios - including combinations of annihilation and decay, NFW and Burkert halo profiles, a range of dark matter masses, and the considered primary channels - no statistically significant excess over the background expectation is observed. The most significance is found for dark matter annihilation into $b\bar{b}$ with a mass of approximately 201.6 GeV, assuming an NFW profile. This scenario yields a local significance of 2.47 σ, which is reduced to a post-trial significance of 1.08 σ after accounting for the look-elsewhere effect of testing multiple DM hypotheses.

In Fig. 2, we illustrate the compatibility of the observed data with both the background-only and best-fit signal hypotheses. The comparison is shown as the ratio of the data and the best-fit model to the null hypothesis, projected separately onto the angular distance from the Galactic Center (left panel) and reconstructed energy (right panel). The figure reveals that the observed excess arises predominantly from the directional distribution, rather than the energy spectrum. This is largely due to the background being estimated via right ascension (RA) scrambling, a method that effectively reduces the energy projection of signal-related features. Nevertheless, including the energy observable remains essential for enhancing the upper limit set, particularly for scenarios involving neutrino line signals, as demonstrated in Ref. [18].

Since the observed data are consistent with the background-only hypothesis, upper limits at the 90% confidence level are derived on the thermally averaged dark matter self-annihilation cross-

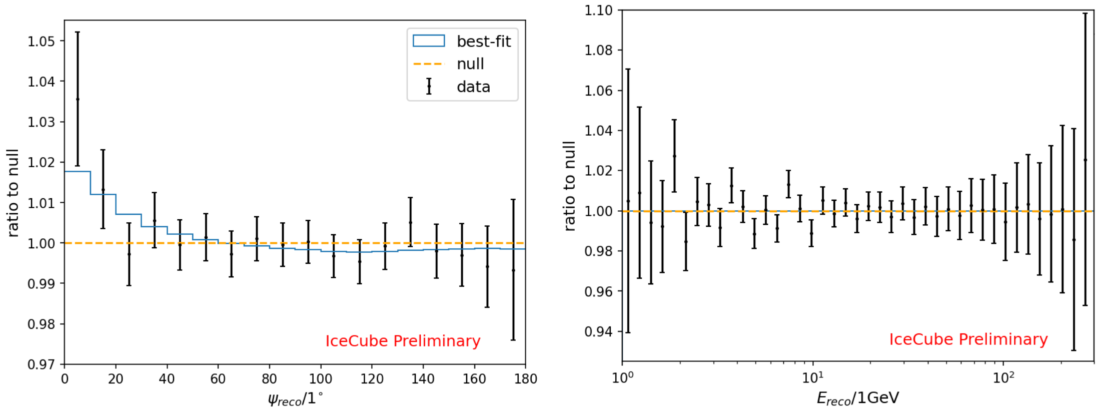

Figure 2: Ratio of the observed event distribution and the best-fit signal hypothesis to the background-only (null) hypothesis, shown as a function of reconstructed angular distance from the Galactic Center (left) and reconstructed energy (right). Statistical uncertainties on the data are indicated by the error bars.

section, as well as lower limits on the dark matter lifetime, for all considered annihilation and decay channels under both the NFW and Burkert halo profiles.

Fig. 3 presents representative results for the case of dark matter annihilation into $\nu_e\bar{\nu}_e$ and $\tau^+\tau^-$ primary channels, assuming an NFW density profile. The derived limits are compared to those from previous IceCube analyses and other leading experiments. Notably, the current analysis achieves substantial improvements, reaching up to an order of magnitude stronger limits around a dark matter mass of approximately 10 GeV. In the mass range from several tens of GeV up to 100 GeV, the resulting constraints represent the most stringent bounds from any neutrino telescope to date and set world-leading limits on the neutrino line signal.

5.2 Prospect with IceCube-Upgrade

Fig. 4 shows the projected sensitivity of the IceCube Upgrade to dark matter annihilation signals originating from the Galactic Center, under the assumption of a Navarro-Frenk-White (NFW) halo profile. Within just three years of data collection, the Upgrade is expected to reach sensitivity levels comparable to those achieved by the 9.3-year DeepCore dataset presented. Remarkably, for dark matter masses below 20 GeV, the Upgrade is projected to improve upon existing limits by approximately an order of magnitude. For neutrino line channels, the anticipated sensitivity reaches thermally averaged annihilation cross sections on the order of $\sim 10^{-25}\mathrm{cm}^3\mathrm{s}^{-1}$, setting world-leading constraints across the mass range of 3 to 500 GeV.

6. Conclusions

IceCube-DeepCore has established world-leading constraints on neutrino line signatures and currently provides the most stringent limits among neutrino telescopes for GeV-scale dark matter, serving as a competitive complement to other detection strategies. These achievements have been made possible through significant advancements in detector calibration, simulation, and event reconstruction. The forthcoming IceCube-Upgrade will further enhance the detector's capabilities,

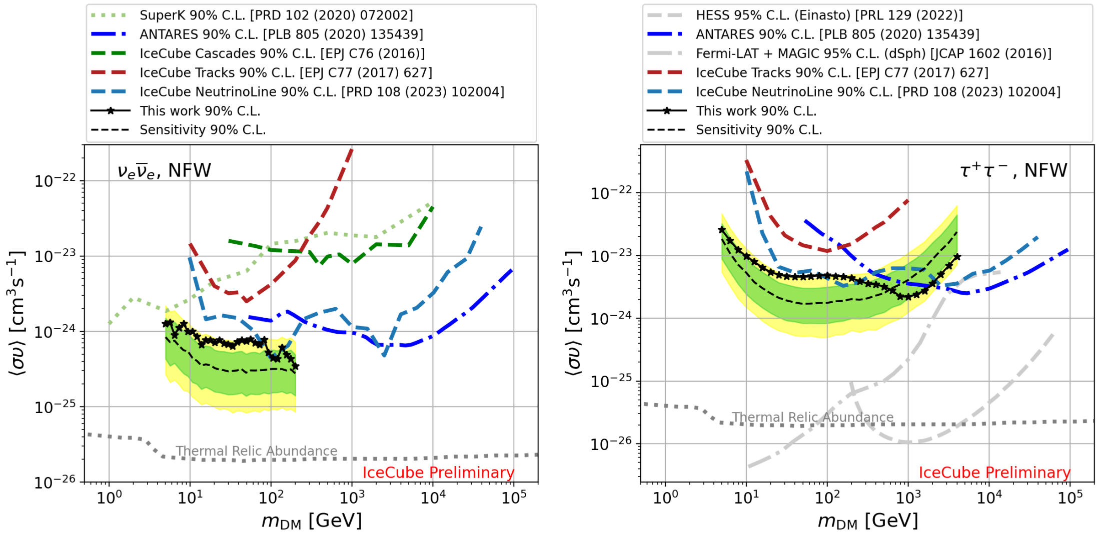

Figure 3: IceCube-DeepCore sensitivity and 90% confidence level upper limits on the thermally averaged self-annihilation cross-section for dark matter annihilating into $\nu_e\bar{\nu}_e$ channel (left) and $\tau\bar{\tau}$ channel (right), shown in comparison with previous IceCube results [18–20] and limits from other experiments [21–24]. The dashed black curve indicates the median expected sensitivity, while the green and yellow bands correspond to the 1σ and 2σ statistical fluctuations, respectively. The grey dotted line denotes the thermal relic cross-section as calculated in Ref. [25]

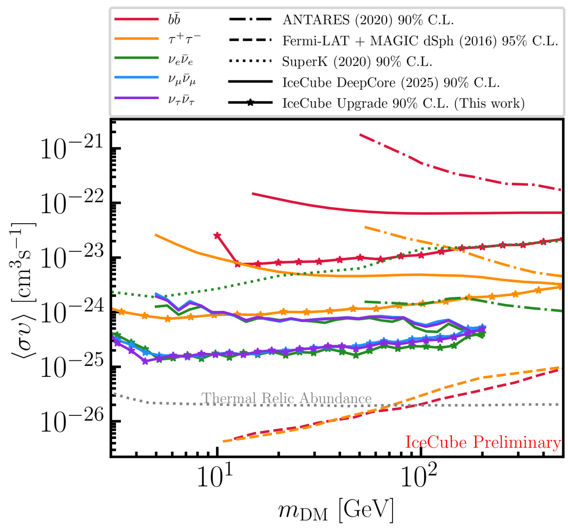

Figure 4: Projected sensitivity of IceCube-Upgrade assuming 3 years of data taking on the thermally averaged self-annihilation cross-section for dark matter annihilation in the Galactic Center in comparison with current IceCube-DeepCore results and limits from other experiments [21, 22, 24]. The grey dotted line denotes the thermal relic cross-section as calculated in Ref. [25]

offering improved sensitivity to dark matter signals and expanding the scientific reach of the IceCube Observatory.

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Acknowledgments

The authors gratefully acknowledge the support from the following agencies and institutions: USA – U.S. National Science Foundation-Office of Polar Programs, U.S. National Science Foundation-Physics Division, U.S. National Science Foundation-EPSCoR, U.S. National Science Foundation-Office of Advanced Cyberinfrastructure, Wisconsin Alumni Research Foundation, Center for High Throughput Computing (CHTC) at the University of Wisconsin–Madison, Open Science Grid (OSG), Partnership to Advance Throughput Computing (PATh), Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS), Frontera and Ranch computing project at the Texas Advanced Computing Center, U.S. Department of Energy-National Energy Research Scientific Computing Center, Particle astrophysics research computing center at the University of Maryland, Institute for Cyber-Enabled Research at Michigan State University, Astroparticle physics computational facility at Marquette University, NVIDIA Corporation, and Google Cloud Platform; Belgium – Funds for Scientific Research (FRS-FNRS and FWO), FWO Odysseus and Big Science programmes, and Belgian Federal Science Policy Office (Belspo); Germany – Bundesministerium für Forschung, Technologie und Raumfahrt (BMFTR), Deutsche Forschungsgemeinschaft (DFG), Helmholtz Alliance for Astroparticle Physics (HAP), Initiative and Networking Fund of the Helmholtz Association, Deutsches Elektronen Synchrotron (DESY), and High Performance Computing cluster of the RWTH Aachen; Sweden – Swedish Research Council, Swedish Polar Research Secretariat, Swedish National Infrastructure for Computing (SNIC), and Knut and Alice Wallenberg Foundation; European Union – EGI Advanced Computing for research; Australia – Australian Research Council; Canada – Natural Sciences and Engineering Research Council of Canada, Calcul Québec, Compute Ontario, Canada Foundation for Innovation, WestGrid, and Digital Research Alliance of Canada; Denmark – Villum Fonden, Carlsberg Foundation, and European Commission; New Zealand – Marsden Fund; Japan – Japan Society for Promotion of Science (JSPS) and Institute for Global Prominent Research (IGPR) of Chiba University; Korea – National Research Foundation of Korea (NRF); Switzerland – Swiss National Science Foundation (SNSF).