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Heavy Dark Matter Annihilation search with IceCube tracks

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Dwarf Spheroidal galaxies (dSphs) are suspected dark matter dense astrophysical objects within our galactic neighborhood. DSphs are otherwise faint high-energy neutrino sources which makes them ideal dark matter targets. An early IceCube dark matter search toward dSphs was performed with an incomplete detector with 59 strings and 339.8 days of live time. This updated analysis is performed on IceCube's full 86 strings with 10.4 years of data from the Northern Hemisphere. We study a dark matter mass range not well explored ranging from hundreds of GeV to 100 PeV in dark matter mass. We present the current IceCube sensitivity and preliminary limits on the velocity-weighted cross-section of annihilating dark matter. We report that our data is consistent with the neutrino background.

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1. Introduction

Dark Matter (DM) continues to be an elusive problem in astrophysics, particle physics and cosmology. Current cosmological models are most consistent with a universe which today is dominated by dark energy (Λ) and cold DM (CDM) Often this is referred to as the Λ**CDM** model, which fits to observations, e.g. the Cosmic Microwave Background (CMB). According to CMB observations with the Planck satellite, DM accounts for 26.8% of the universe's energy composition, whereas baryonic matter accounts for 4.9% [1–3].

This work presents an indirect search for DM via the neutrino sector. Neutrinos provide a powerful opportunity to probe regions previously inaccessible as neutrinos do not strongly interact with baryonic matter. In this work, we present a DM search towards dwarf spheroidal galaxies (dSphs) with the IceCube Neutrino Observatory. The selection of dSphs as the source class comes from their high DM content with diminished neutrino background from conventional channels, e.g. cosmic ray collisions in the dSph medium. This work focusses on dSphs in the Northern Hemisphere.

2. The IceCube Neutrino Observatory

The IceCube Neutrino Observatory, located at the South Pole, has been operating for more than a decade. The in-ice array consists of 86 strings which support 5160 optical modules embedded in glacial ice at the South Pole. The IceCube detector is sensitive to elusive, high-energy neutrinos across the entire sky. It detects these neutrinos from Cherenkov radiation emitted from secondary, relativistic charged particles traversing the ice after a neutrino collision in the vicinity of the ice in the detector. For the purposes of this study, we focus on muon-track data which can sample a wide neutrino energy range from 1 GeV to 100's PeV [4].

3. Analysis

In this study, we show that IceCube is sensitive to annihilating DM with masses above 1 TeV. Additionally, IceCube's sensitivity is comparable to that of gamma-ray observatories in spectral models that produce hard neutrino features where $E_\nu \approx m_\chi$. We present a DM annihilation search using the Northern Sky muon track dataset. The search will be towards dSphs as they have little high energy neutrino contributions from baryonic processes. Additionally, dSphs are observed to have large DM to baryonic matter ratios, thus are strong search targets. The extension of these sources are smaller than the angular resolution of the detector, so the selected sources are treated as point sources for IceCube. DM masses from 500 GeV to 100 PeV and several DM annihilation channels are explored in this study; however only two annihilation channels are provided in these proceedings.

The last IceCube search for DM annihilation within dwarf galaxies was performed in 2013 [5]. IceCube is estimated to have a high sensitivity to hard neutrino DM spectra [6]. Much has changed in IceCube since this previous DM annihilation search, such as additional strings (previously 59 versus presently 86), more sophisticated analysis methods, and more accurate theoretical event modeling.

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The expected differential neutrino flux from DM-DM annihilation to standard model particles, $d\Phi_\nu/dE_\nu$, over solid angle, Ω is described by the equation.

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN_\nu}{dE_\nu}\int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r,\theta'), \tag{1}$$

where ρ_χ is the dark matter density in the dSph, Here dN_ν/dE_ν is the simulated neutrino spectra for DM annihilates into SM particles, m_χ is the DM mass, $\langle\sigma v\rangle$is the velocity-weighted cross-section if DM annihilates into SM particles. We account for the influence of neutrino oscillations for this analysis in Section 3.1.

3.1 Neutrino Spectra from DM Annihilation

Neutrino spectra from heavy DM annihilation were modeled using `HDMSpectra` [7] at neutrino production and then using χarov [8] for their propagation to Earth. `HDMSpectra` improves on previous results by including electroweak or gluon radiative corrections and higher-order loop corrections from the W and Z bosons (e.g. triple gauge boson couplings like WWZ and $WW\gamma$). These corrections are especially important for accurately estimating the neutrino flux.

We use the χarov software to propagate the neutrinos from the source to Earth. The propagation distances are large compared to the oscillation baseline, so we take the averages of the flavor transition probabilities [8] to estimate the incident neutrino fluxes:

$$P(\nu_\alpha \to \nu_\beta) \approx \begin{bmatrix} 0.55 & 0.18 & 0.27 \\ 0.18 & 0.44 & 0.38 \\ 0.27 & 0.38 & 0.35 \end{bmatrix}. \tag{2}$$

IceCube's muon-track data have limited sensitivity to ν_e which mostly produce spherical Cherenkov-light features, so-called cascades, instead of tracks. Therefore, the expected flavor contribution to signal neutrinos, n_s is dominated by ν_μ and also ν_τ [4] at the highest energies. We therefore model the expected composite neutrino spectrum as the sum of these two flavors.

Several channels in our broader study include a 'line' feature where there is a significant fraction of neutrinos with $E_\nu \approx M_\chi$. The line is much narrower than IceCube's energy uncertainty. Therefore, before performing a fit, the estimated neutrino flux is convolved with a Gaussian kernel of width $0.05 \times M_\chi$. The composite neutrino spectra after all particle physics considerations are show in Fig. 1 for $\chi\chi \to \tau^+\tau^-$and $\nu_\mu\bar{\nu}_\mu$.

For the calculation of the line-of-sight (l.o.s.) integral, so-called "J-Factor", we adopt the Geringer-Sameth's ($\mathcal{GS}$) model [9] to estimate the dark matter distribution around the center of the dSphs. These models are based on a Zhao DM density profile [10]. We treat these sources as point-like in this analysis. A summary of the sources studied here are provided in Table 1.

4. Likelihood Methods

We use a maximum likelihood method previously used in IceCube point-source searches [11]. The likelihood function is defined as:

$$L(n_s) = \prod_{i=1}^{N}\left[\frac{n_s}{N}S_i + \left(1 - \frac{n_s}{N}\right)B_i\right], \tag{3}$$

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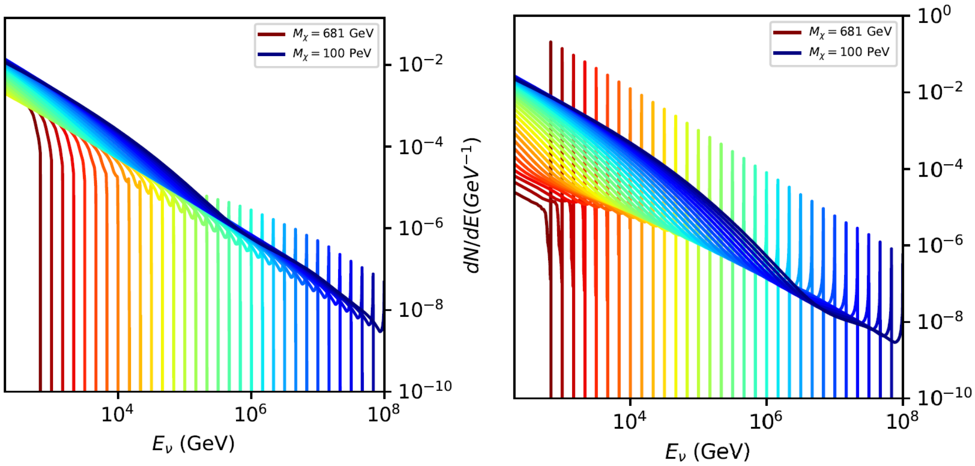

Figure 1: Composite neutrino spectra for $\chi\chi \rightarrow \tau^+\tau^-$ (left) and $\nu_\mu\bar{\nu}_\mu$ (right). Spectra are shown as dN/dE versus E_ν. Redder lines are spectra for lower DM mass annihilation. Bluer lines are higher mass. The displayed neutrinos energies correspond to the energy range of IceCube's sensitivity. The DM masses used for the spectra range from 681 GeV to 100 PeV.

where i is an event index, S and B are the signal probability distribution function (PDF) and background PDF respectively. For a joint analysis where multiple sources likelihoods are "stacked", the likelihood is expanded to:

$$L(n_s) = \prod_{i=1}^{N_{\mathrm{sources}}} L_i(n_s), \tag{4}$$

where L_i is the likelihood, Eq. (3), from the i-th source in the stacked analysis. The test statistic (TS) is computed with the maximum log-likelihood ratio test,

$$\mathrm{TS}_{\mathrm{max}} = -2\ln\left(\frac{\mathcal{L}_0}{\mathcal{L}^{\mathrm{max}}}\right), \tag{5}$$

where $\mathcal{L}_0$ corresponds to the background hypothesis, $n_s = 0$.

5. Results and Conclusions

We show the 90% sensitivities defined as the minimum number of expected signal events (n_s) required to have $\mathrm{TS}_{\mathrm{max}}$ larger than the median of the background simulations in 90% of cases. We compute n_s from the equation

$$n_s = T_{\mathrm{live}} \int_0^{\Delta\Omega} d\Omega \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} dE_\nu A_{\mathrm{eff}}(\hat{n}, E_\nu) \frac{d\Phi_\nu}{d\Omega dE_\nu}(\hat{n}, E_\nu), \tag{6}$$

to extract the sensitivity on the DM matter velocity-weighted annihilation cross-section, $\langle\sigma v\rangle$. The quantity T_{live} is the detector live time, A_{eff} is the effective area of the detector, and E_{min} (E_{max}) are the minimum (maximum) energy of the expected neutrino spectrum.

The sensitivities are calculated for each source individually as if they were the only source and as a stack, based on 1000 simulation trials. Fig. 2 shows the sensitivities for the DM annihilation to

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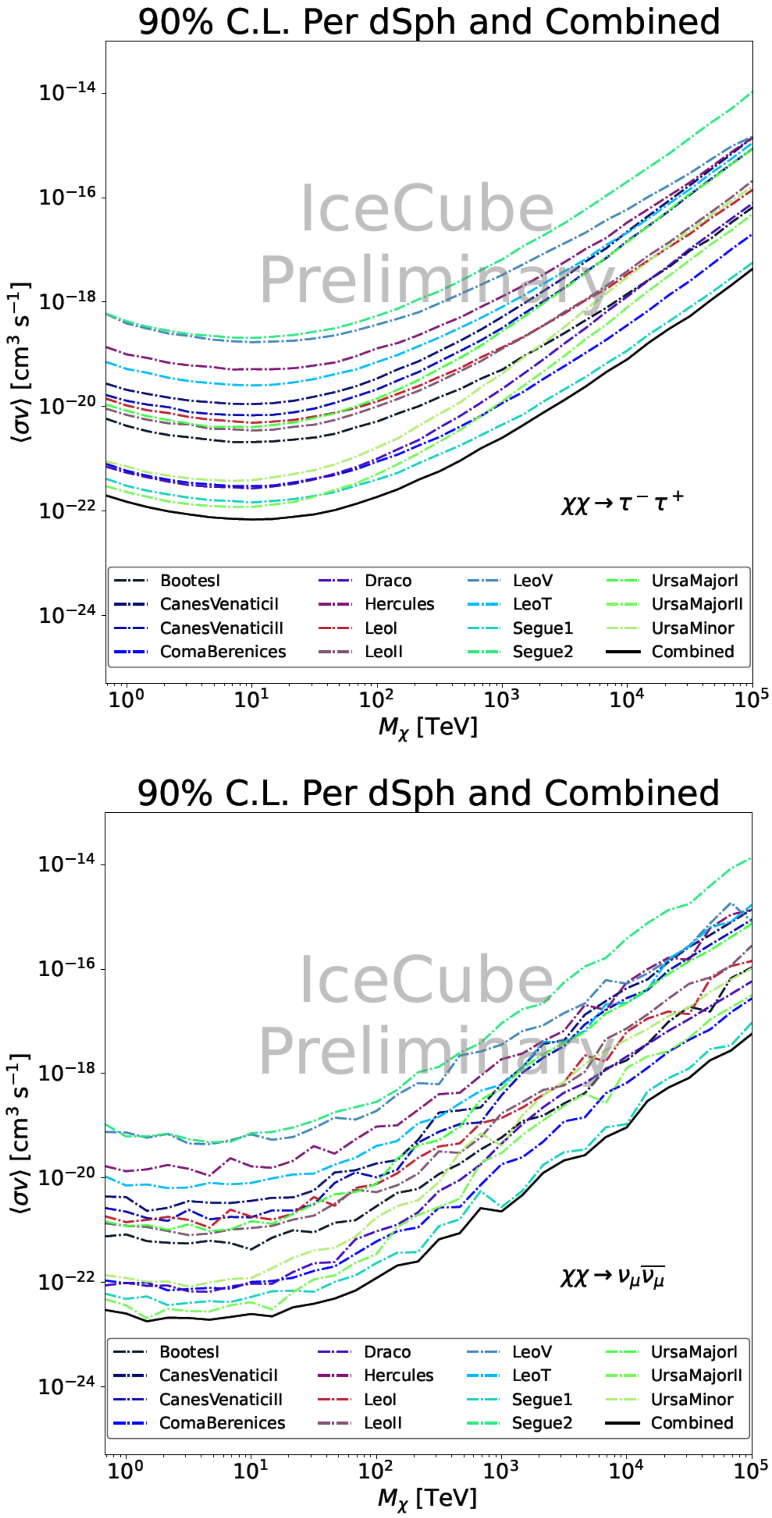

Figure 2: Per source sensitivity of $\langle\sigma v\rangle$ versus M_χ for $\chi\chi \rightarrow \tau^+\tau^-$ (top) and $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$ (bottom) from 15 dwarf galaxies and the combined sensitivity using data from all sources. Colored, dashed lines are sensitivities from individual dwarves. Solid white line is the combined sensitivity.

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Table 1: Table of dwarf galaxies investigated in this study, showing their heliocentric distances (column 2) and their longitude and latitude in galactic coordinates (column 3) for the dwarves. The final columns shows the J-factors of each source measured by Geringer-Sameth and their $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ ($\mathcal{GS}$ set) [9] are the mean J-factor values for a source extension that is truncated at the outermost observed star.

Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$
Segue I	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$
Segue II	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$

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τ leptons and ν_μ. Figs. 3 and 4 compare the stacked sensitivities to limits from studies performed by other observatories and past IceCube analyses, respectively.

This study expands significantly on the previous IceCube dSph DM [5] search via the following changes. Particle physics predictions have been revised and show greater expected neutrino contributions to the DM spectra. More dSphs have been identified and their DM density more precisely modeled. Finally, IceCube has significantly improved its track and event reconstruction while accumulating more than 10 years of data. These factors have greatly improved IceCube's sensitivity to DM annihilation from dSphs. Finally, for the first time, IceCube presents an analysis that set limits on PeV DM annihilation from dSph.

When compared to previous IceCube publications of dSphs [5] (see Fig. 4), we see an order of magnitude improvement in our sensitivity. When considering a more conventional channel like τ leptons (see Fig. 3), IceCube's heavy DM sensitivity is comparable to gamma-ray observatories.

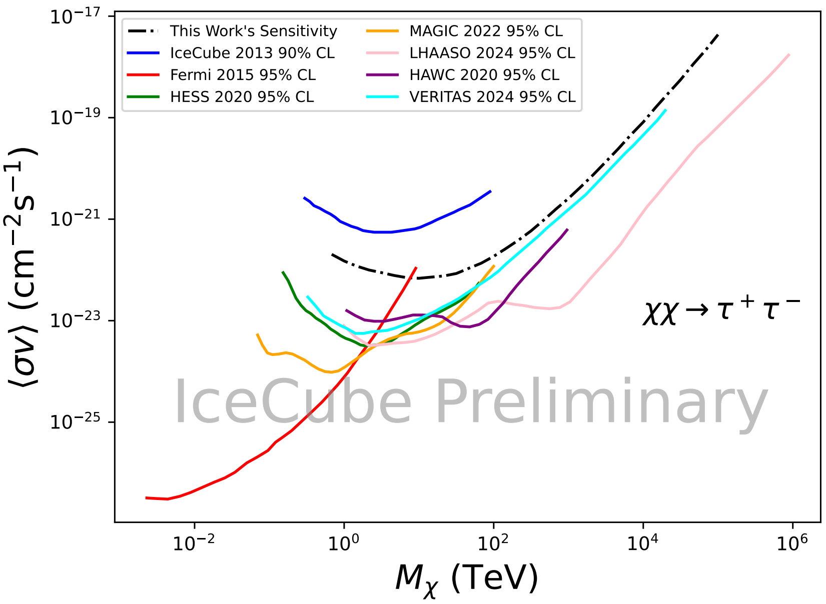

Figure 3: IceCube sensitivity for $\chi\chi \rightarrow \tau^+\tau^-$ from 15 dwarf spheroidal galaxies compared to other astrophysics observatories. Solid, colored lines are limits from other observatories. The dashed black line is this work's sensitivity. Previous limits are shown for IceCube [5], Fermi-*LAT* [12], H.E.S.S. [13], LHAASO [14], MAGIC [15], HAWC [16], and VERITAS [17].

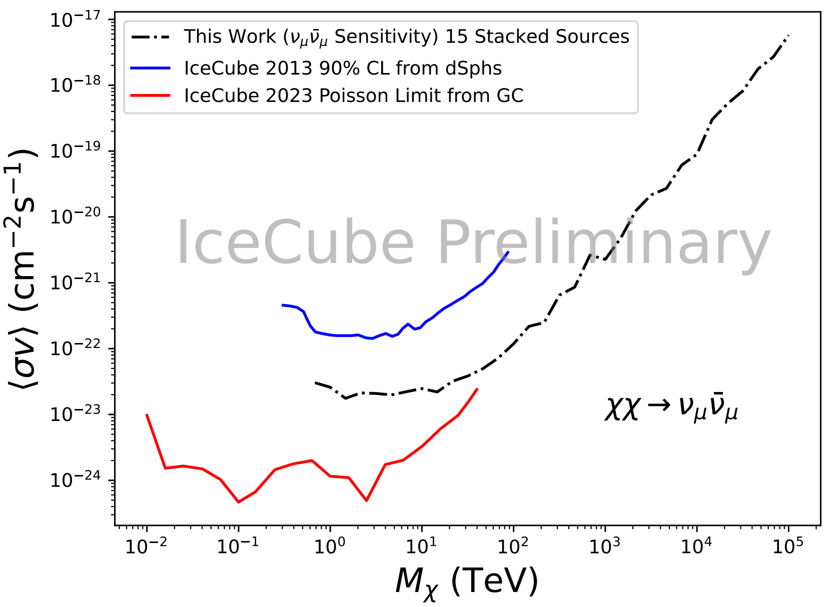

Figure 4: IceCube sensitivity for $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$ from 15 dwarf spheroidal galaxies compared to past IceCube analyses from dwarves [5] and the galactic center [18]

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