

Possible high-energy neutrino emission from dark matter annihilation in the disrupting dwarf galaxy Boötes III

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We report the first search for high-energy neutrino emissions from dark matter (DM) annihilation in stellar-stream cores. Motivated by a recent gamma-ray study that proposed these cores as a new class of indirect DM targets, we analyze three stream cores in the Northern Hemisphere using the public ten-year tracklike neutrino data released by IceCube. Under the $\chi\chi \rightarrow \nu\bar{\nu}$ annihilation hypothesis, the most significant excess among the three targets is found at the position of the nearby dwarf galaxy Boötes III, the core of the Styx stream, with the DM mass of $m_\chi \simeq 10\text{--}31$ TeV. The excess has a posttrial significance of 3.1σ . Considering the existing IceCube dwarf-galaxy limit for the same channel, we obtain a limit on the J-factor J_{ann} , $\log_{10}(J_{\text{ann}}/\text{GeV}^2 \text{ cm}^{-5}) \gtrsim 19.1^{+0.3}_{-0.6}$. This limit is broadly consistent with empirical estimates of J_{ann} for Boötes III. The results provide the first candidate target with a possible high-energy neutrino signal associated with DM annihilation. This neutrino excess and the general existence of DM-induced neutrino signals from other similar sources will be confirmed with the near-future large high-energy neutrino detectors, thus enabling us to probe the nature of DM particles.

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I. INTRODUCTION

A wide range of astrophysical and cosmological observations require a dominant dark matter (DM) component, whose fundamental nature remains unknown [1]. Weakly interacting massive particles (WIMPs), predicted in many extensions of the Standard Model (SM), are among the most widely studied DM candidates [2]. Their possible annihilation or decay into SM particles has motivated extensive indirect searches for secondary messengers such as gamma rays, cosmic rays, and neutrinos [3]. High-energy (HE) neutrinos are one of promising messengers for searches for DM-induced emissions [4]; unlike charged cosmic rays, they are not deflected by magnetic fields, and they are much less attenuated than gamma-rays at high energies or in dense environments.

The IceCube Neutrino Observatory at the South Pole [5] has opened a new window on the TeV-PeV universe by detecting HE neutrinos of astrophysical origin [6]. Identifying the sources of these neutrinos, however, remains a challenge. To date, only a limited number of associations have been established. These include the blazar TXS 0506 + 056,

associated with the 2017 neutrino alert at $\sim 3\sigma$ significance level [7] and an earlier neutrino flare with significance of 3.5σ [8], the nearby Seyfert galaxies NGC 1068 and NGC 4151, reported with significances of 4.2σ and $\sim 3\sigma$, respectively [9–11], and diffuse neutrino emission from the Galactic plane at the 4.5σ level [12]. The origin of a large fraction of the astrophysical neutrino flux remains to be investigated. Previous studies have investigated DM-induced neutrinos from a variety of potential targets, including the Galactic center [13–16], the Galactic halo [17], the Sun [18–21] and the Earth [22,23], galaxy clusters [24], and dwarf galaxies [24–27]. However, no potential neutrino signal attributable to DM annihilation has been found from any of these targets.

More recently, Ref. [28] proposed stellar streams originating from dwarf galaxies as a new class of targets for indirect DM searches. Dwarf galaxies are expected to be highly DM dominated [29,30]. Although stellar streams can lose most of their original DM halos through tidal stripping, a significant amount of DM may still remain in their cores [31,32]. Annihilation within these cores could therefore produce detectable gamma-ray or neutrino emissions. Reference [28] has performed a search for gamma-ray emissions from these stream cores by analyzing the data from the Large Area Telescope (LAT) onboard *Fermi*, but has not found significant signals. In this work, we perform the first search for neutrino emissions from DM annihilation in dwarf-galaxy stream cores by using IceCube's public ten-year tracklike dataset.

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The targets are from the *golden* sample of Ref. [28], which consists of eight reliable dwarf-galaxy origin streams chosen according to DM-motivated criteria. By further requiring the stream cores with declinations between -3° and 81° , where the IceCube has favorable sensitivity for tracklike events [9], we are left with three stream-core targets: LMS-1, PS1-D, and Styx. For LMS-1 and PS1-D, we adopt the core positions from Ref. [28], where the stream midpoints were used as the assumed core locations in the absence of an identified progenitor or core counterpart. The core of the Styx stream is observationally associated with the disrupting dwarf galaxy Boötes III [33–35]. We refer to this target as Boötes III hereafter.

From analyzing IceCube’s neutrino dataset, we find a neutrino excess with a posttrial significance of 3.1σ at the position of Boötes III. This dwarf galaxy, at R.A. = 209.3° and Dec. = 26.8° (J2000), has a distance of $d \simeq 46.5$ kpc. It was first identified as a diffuse stellar overdensity nearly coincident with the Styx stellar stream and was suggested to be the progenitor of Styx in the final stages of tidal disruption [33]. Spectroscopic observations identified candidate Boötes III members with a systemic velocity of $V_{\text{helio}} = 197.5 \pm 3.8 \text{ km s}^{-1}$ and a velocity dispersion of $14.0 \pm 3.2 \text{ km s}^{-1}$, supporting the interpretation of Boötes III as the transitional system between a bound dwarf galaxy and an unbound stellar stream [34]. Gaia proper-motion measurements further showed that this dwarf galaxy is dynamically associated with Styx and follows a highly eccentric orbit, with a recent pericentric passage within ~ 12 kpc of the Galactic center [35].

II. ICECUBE DATA ANALYSIS AND RESULTS

The public IceCube ten-year dataset contains all-sky tracklike events recorded between April 2008 and July 2018 [36]. There were ~ 1.1 million events in the dataset, dominated by those of the atmospheric backgrounds. Tracklike events arise primarily from charged-current interactions of ν_μ ($\bar{\nu}_\mu$) with nucleons and provide an angular resolution of $\lesssim 1^\circ$ [37]. Thus, they are the IceCube events of the best class for point-source searches. We use an unbinned maximum-likelihood method [38] in our search for neutrino emissions from DM annihilation in the three targets, and details for the data analysis are provided in the Appendix.

The differential neutrino flux from DM annihilation is given by

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} \times J_{\text{ann}}, \quad (1)$$

where $\langle\sigma v\rangle$ is the velocity-averaged annihilation cross section, m_χ is the DM mass, and J_{ann} is the so-called astrophysical J -factor, determined by the DM density profile of a target [39]. The term dN_ν/dE_ν denotes the neutrino spectrum per annihilation for the annihilation

TABLE I. Information for the three stream-core targets and likelihood analysis results, where R.A. and Dec. stand for Right Ascension and Declination respectively. The TS provides the maximum values obtained in the scan over m_χ under the $\chi\chi \rightarrow \nu\bar{\nu}$ annihilation hypothesis (Note that for LMS-1 and PS1-D, the stream midpoints are adopted as the core positions [28].).

Target	R.A. [deg]	Dec. [deg]	Distance [kpc]	n_s	TS
LMS-1	231.9	27.8	18.1	7	2.1
PS1-D	139.7	0.8	22.9	0	0.0
Boötes III/Styx	209.3	26.8	46.5	17	12.2

channel considered. We focus on the most direct channel $\chi\chi \rightarrow \nu\bar{\nu}$ [4]. Note that this is an average neutrino channel, i.e., assuming $\nu\bar{\nu} = \frac{1}{3}(\nu_e\bar{\nu}_e + \nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau)$. We obtain annihilation spectra for m_χ from 1 TeV to 1 PeV using HDMSpectra [40], which include both the continuum and line components. After accounting for neutrino oscillations following Ref. [27], the resulting $\nu_\mu\bar{\nu}_\mu$ spectra at the Earth are used as signal templates in the likelihood analysis (see Fig. 6 in Appendix as an example). The test statistic (TS) used to evaluate the presence of a signal is defined as $\text{TS} = 2 \log \Lambda(n_s, m_\chi)$, where $\log \Lambda$ is the log-likelihood ratio with respect to the background-only hypothesis and n_s is the number of signal events for a given m_χ (see Appendix).

The results from the likelihood analysis of the IceCube data for the three stream cores are given in Table I. The corresponding TS profiles obtained from scanning over m_χ are displayed in the left panel of Fig. 1. The largest and only significant excess is at the position of Boötes III, with $\text{TS} = 12.2$ at $m_\chi \simeq 26.5$ TeV. The corresponding best-fit signal number is $n_s = 17_{-7}^{+8}$, where the uncertainty is at a 68% confidence level (CL) obtained from the one-dimensional likelihood scan [41]. The steplike structure of the TS profile in Fig. 1 arises from the binning of the publicly available IceCube detector response [36], which limits the precision of the DM mass determination. We therefore estimate the DM mass, which lies approximately in the range of $m_\chi \simeq 10\text{--}31$ TeV at a 68% CL for Boötes III.

To estimate the significance of the excess at Boötes III, we generate 10^6 background-only pseudoexperiments and repeat the full scan over m_χ in each trial. This procedure accounts for the look-elsewhere effect associated with the DM-mass scan [42]. The resulting background-only TS distribution is shown in Fig. 2. The p -value is estimated as the fraction of pseudoexperiments whose maximum TS values exceed that obtained from the real data. From the TS distribution, a pretrial p -value p_{pre} is found to $p_{\text{pre}} \simeq 3.2 \times 10^{-4}$, which corresponds to a significance of 3.4σ . There is a trial factor arising from the search from the number of targets $n_t = 3$, the posttrial p -value $p_{\text{post}} = 1 - (1 - p_{\text{pre}})^3 \simeq 9.5 \times 10^{-4}$, which corresponds to a significance of 3.1σ .

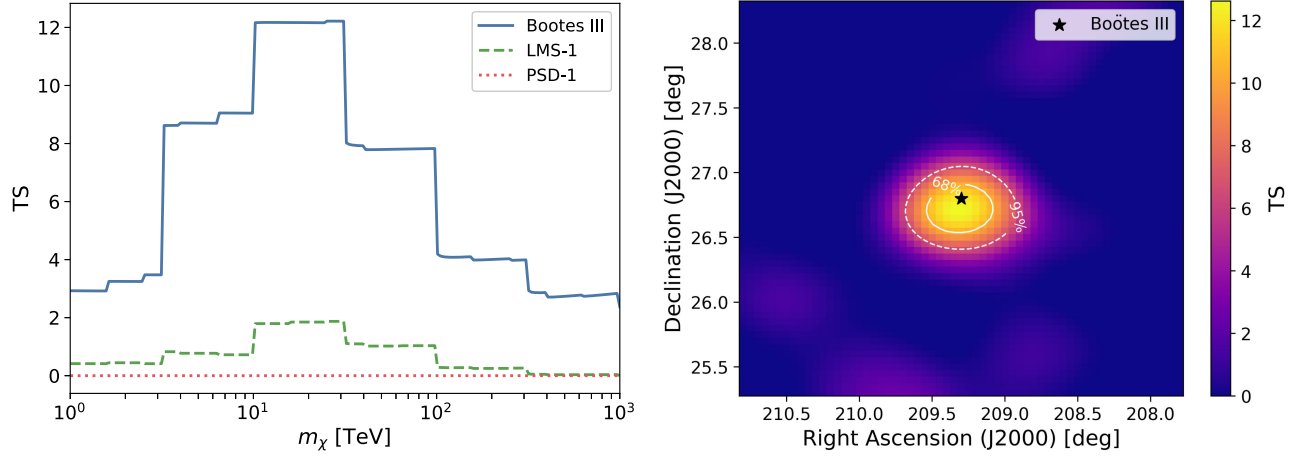


FIG. 1. Left: TS values obtained from scanning the DM mass m_χ from 1 TeV to 1 PeV for the three selected stream-core targets (LMS-1, dashed line; PS1-D, dotted line; Boötes III, solid line). The largest TS peak at the best-fit value $m_\chi = 26.5$ TeV is found for Boötes III. Right: $3^\circ \times 3^\circ$ TS map centered at the position of Boötes III (marked with a black star), where the DM mass is fixed at the best-fit value. The white solid and dashed contours show the 68% and 95% uncertainty regions of the neutrino excess spot, respectively. Boötes III lies within the 68% contour, only 0.1° from the TS maximum's location.

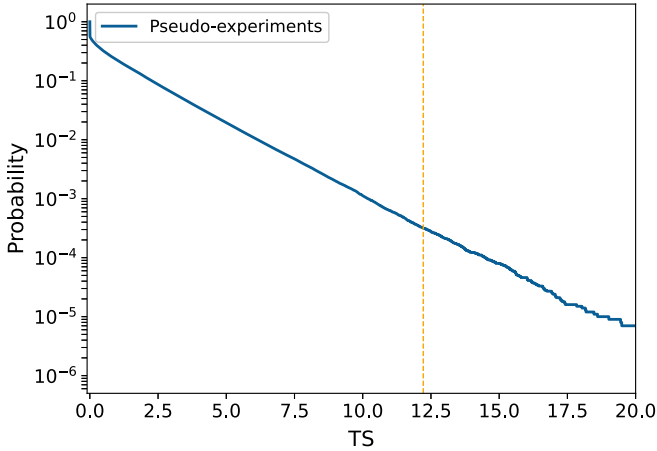


FIG. 2. TS distribution obtained from 10^6 background-only pseudoexperiments. The orange dashed line indicates the TS observed at the position of Boötes III in the real data.

We further constructed a TS map by scanning a $3^\circ \times 3^\circ$ region around Boötes III with a bin size of 0.05° (the right panel of Fig. 1). The maximum $TS = 12.6$, found at R.A. = 209.3° and Dec. = 26.7° (J2000), only 0.1° away from the position of Boötes III. The 68% and 95% uncertainty regions for the neutrino excess spot are estimated using Wilks's theorem with two degrees of freedom [43]. Boötes III lies within the 68% uncertainty region.

III. DISCUSSION

By analyzing the public ten-year tracklike neutrino data released by IceCube, we conduct the search for HE neutrino emissions from DM annihilation in three stellar-stream cores in the Northern Hemisphere; this type of the

sources were recently proposed as possible sites of DM annihilation and tested with *Fermi*-LAT gamma-ray observations [28]. We find a neutrino excess spatially coincident with the disrupting dwarf galaxy Boötes III, the core of the Styx stream. Under the DM annihilation signal hypothesis in channel $\chi\chi \rightarrow \nu\bar{\nu}$, the excess reaches a posttrial detection significance of 3.1σ . Although the significance is relatively low and the analysis relies on the certain hypothesis, the result provides the first candidate target with a possible HE neutrino signal associated with DM annihilation.

Considering the DM annihilation as the origin of the neutrino excess, we explore the corresponding particle parameter space. Since Boötes III is a disrupting dwarf galaxy in transition between a bound dwarf system and an unbound stellar stream, its J-factor J_{ann} is substantially more uncertain than that of a dwarf galaxy in dynamic equilibrium. We do not attempt to determine $\langle\sigma v\rangle$ and J_{ann} separately, but instead we scan the two-dimensional likelihood in the plane of m_χ and $\langle\sigma v\rangle J_{\text{ann}}$, to which the neutrino flux is directly proportional (see also Ref. [44]). The resulting allowed parameter space is shown in Fig. 3, in which the 68%, 95%, and 99.7% confidence regions are given, estimated from using Wilks's theorem with two degrees of freedom. As a reference, IceCube has reported a 90% CL upper limit on the annihilation cross section for the $\chi\chi \rightarrow \nu\bar{\nu}$ channel from dwarf-galaxy searches, with $\langle\sigma v\rangle \simeq 5 \times 10^{-22} \text{ cm}^3 \text{ s}^{-1}$ at $m_\chi \simeq 26.5$ TeV (see Fig. 3 of Ref. [27]). Taking this upper-limit value, the excess we find would require $\log_{10}(J_{\text{ann}}/\text{GeV}^2 \text{ cm}^{-5}) \gtrsim 19.1^{+0.3}_{-0.6}$, where the uncertainty corresponds to the 95% confidence interval. Based on the photometric scaling relations, $\log_{10}(J_{\text{ann}}/\text{GeV}^2 \text{ cm}^{-5}) = 18.65 \pm 0.60$ was estimated for Boötes III [45], although this estimate is subject to large systematic uncertainties due to the disrupted nature of

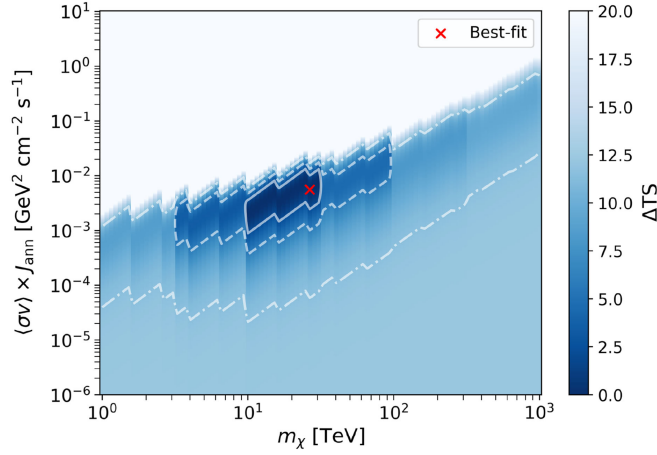


FIG. 3. Two-dimensional likelihood scan in the $m_\chi - \langle \sigma v \rangle J_{\text{ann}}$ plane for the Boötes III neutrino excess. The red cross marks the best-fit point. The white solid, dashed, and dash-dotted contours show the 68%, 95%, and 99.7% confidence regions, respectively, obtained using Wilks's theorem with two degrees of freedom.

Boötes III. We note that the two values are consistent with each other within the uncertainties.

There are several reasons in favor of the excess detection toward Boötes III. First, it is a well-defined target in the sample as the core of Styx. For comparison, the progenitors or compact cores have not been clearly identified for LMS-1 and PS1-D, possibly because either they are nearly completely dissolved or the surviving remnants have not been located. Second, its distance ($d \simeq 46.5$ kpc) places Boötes III among the relatively nearby dwarf-galaxy systems used in indirect DM searches. In the sample of Ref. [45], it lies within approximately the nearest 30% of the targets. Third, it benefits from its Northern-sky position in the IceCube observations, since the downgoing atmospheric muons are suppressed in the tracklike data. Finally, under the $\chi\chi \rightarrow \nu\bar{\nu}$ annihilation hypothesis, the expected neutrino spectrum is relatively hard (see Fig. 6 in Appendix). Such a spectrum is easier to be distinguished from the atmospheric background, which is dominated by lower-energy events, and to be detected in IceCube point-source searches [37].

Except the DM annihilation in dwarf galaxies and their tidal remnants, no strong HE processes, such as particle acceleration, are expected to occur in them. In order to check the possibility that an unrelated HE source in coincidence with the direction of Boötes III, we have searched for possible counterpart candidates. Within the 95% uncertainty region of the neutrino excess spot, no known types of HE neutrino sources, such as hard x-ray active galactic nuclei [9–11,46] and gamma-ray blazars [7,8], are found, where the Swift/BAT all-sky hard x-ray survey catalog [47] and the Fermi-LAT source catalog [48] are considered.

Future neutrino data will be essential for testing whether the neutrino excess persists and for extending the search to additional stream cores. More than half of targets in the

initial stream-core sample we choose lie in the Southern sky, where the IceCube does not have its optimal sensitivity. Current and next-generation neutrino observatories in the Northern Hemisphere or at midlatitudes, including KM3NeT [49], Baikal-GVD [50], TRIDENT [51], HUNT [52], and NEON [53], will provide sensitive coverage for the Southern-sky targets. Improved dynamical modeling of the Boötes III system is also needed to determine whether a sufficiently dense DM remnant can survive in the stream core and to reduce the uncertainty on the J factor.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

APPENDIX: ICECUBE DATA ANALYSIS

The public IceCube ten-year point-source dataset [36] has been widely used in previous searches for neutrino emissions [10,37,41,54–56]. We grouped the data into five event samples corresponding to different detector configurations: IC40, IC59, IC79, IC86_I, and IC86_II–VII [37]. An unbinned maximum-likelihood method was used to test for a signal from the DM annihilation [38]. The likelihood function $\mathcal{L}$ is written as

$$\mathcal{L} = \prod_k \prod_{i=1}^{N_k} \left(\frac{n_s^k}{N_k} S_i^k + \frac{N_k - n_s^k}{N_k} B_i^k \right), \quad (\text{A1})$$

where N_k and n_s^k are the total number of events and the number of signal events in sample k , respectively. The quantities S_i^k and B_i^k are the signal and background probability density functions (PDFs) for the i th event in sample k .

The signal PDF is divided into the spatial and energy components

$$S_i^k = \mathcal{S}_S^k(\vec{x}_i, \sigma_i | \vec{x}_s) \mathcal{E}_S^k(E_i | \delta_s, p_s), \quad (\text{A2})$$

where $\mathcal{S}_S^k$ describes the detector's point-spread function (PSF) for a source at position $\vec{x}_s$. We approximated this term by a two-dimensional Gauss [57],

$$\mathcal{S}_S^k(\vec{x}_i, \sigma_i | \vec{x}_s) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{\psi_i^2}{2\sigma_i^2}\right) \frac{\psi_i}{\sin(\psi_i)}, \quad (\text{A3})$$

where ψ_i is the angular separation between the reconstructed direction $\vec{x}_i$ for event i and the source position $\vec{x}_s$, and σ_i is the angular uncertainty of the event.

The term $\mathcal{E}_S^k$ is the signal energy PDF, which gives the probability density for observing a signal event with reconstructed energy E_i from a source at declination δ_s . It is written as [57]

$$\mathcal{E}_S^k(E_i|\delta_s, p_s) = \frac{\int \Phi_\nu(E_\nu, p_s) A_{\text{eff}}^k(E_\nu, \delta_s) \mathcal{M}_k(E_i|E_\nu, \delta_s) dE_\nu}{\int \Phi_\nu(E_\nu, p_s) A_{\text{eff}}^k(E_\nu, \delta_s) dE_\nu}, \quad (\text{A4})$$

where p_s denotes the parameter of the assumed source spectrum $\Phi_\nu(E_\nu, p_s)$. For example, for neutrino energy E_ν of a power-law spectrum, $\Phi_\nu \propto E_\nu^{-\gamma}$ and $p_s = \gamma$. The quantities A_{eff}^k and $\mathcal{M}_k$ are the effective area and smearing matrix of the detector for sample k , respectively, provided in the public IceCube data release.

The background PDF is also factorized into spatial and energy components,

$$B_i^k = S_B^k(\delta_i) \mathcal{E}_B^k(E_i, \delta_i) = \frac{1}{2\pi} P_B^k(\delta_i) \mathcal{E}_B^k(E_i, \delta_i). \quad (\text{A5})$$

The background spatial term depends only on the event declination δ_i [i.e., the PDF $P_B^k(\delta_i)$], because the background distribution is uniform in right ascension for IceCube. The background energy PDF describes the reconstructed energy distribution of background events and is derived directly from the data. We estimate the background PDFs using bins of $\Delta \sin \delta_\mu = 0.02$ in reconstructed declination and $\Delta \log_{10} E_\mu = 0.1$ in reconstructed energy [57]. Figure 4 shows the binned spatial PDFs and Fig. 5 shows the binned energy PDF from the IC86_II–VII sample as an example.

The relative signal weight of sample k is given by

$$w_k = \frac{t_k \int \Phi_\nu(E_\nu, p_s) A_{\text{eff}}^k(E_\nu, \delta_s) dE_\nu}{\sum_{k'} t_{k'} \int \Phi_\nu(E_\nu, p_s) A_{\text{eff}}^{k'}(E_\nu, \delta_s) dE_\nu}, \quad (\text{A6})$$

where t_k is the detector livetime for sample k , and k' represents data samples other than k . The expected number of signal events in sample k is written as $n_s^k = n_s w_k$, where n_s is the total number of signal events.

The log-likelihood ratio with respect to the background-only hypothesis ($n_s = 0$) is

$$\begin{aligned} \log \Lambda(n_s, p_s) &= \log \frac{\mathcal{L}(n_s, p_s)}{\mathcal{L}(n_s = 0)} \\ &= \sum_k \sum_{i=1}^{N_k} \log \left[1 + \frac{n_s w_k}{N_k} \left(\frac{S_i^k}{B_i^k} - 1 \right) \right]. \end{aligned} \quad (\text{A7})$$

The test statistic (TS) is defined as

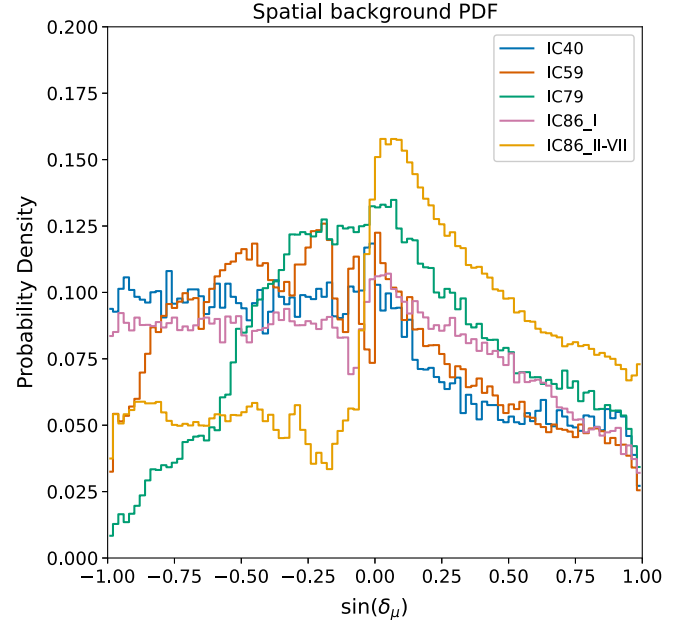


FIG. 4. Binned spatial background PDFs for five IceCube data samples used in the likelihood analysis (same as Ref. [57]).

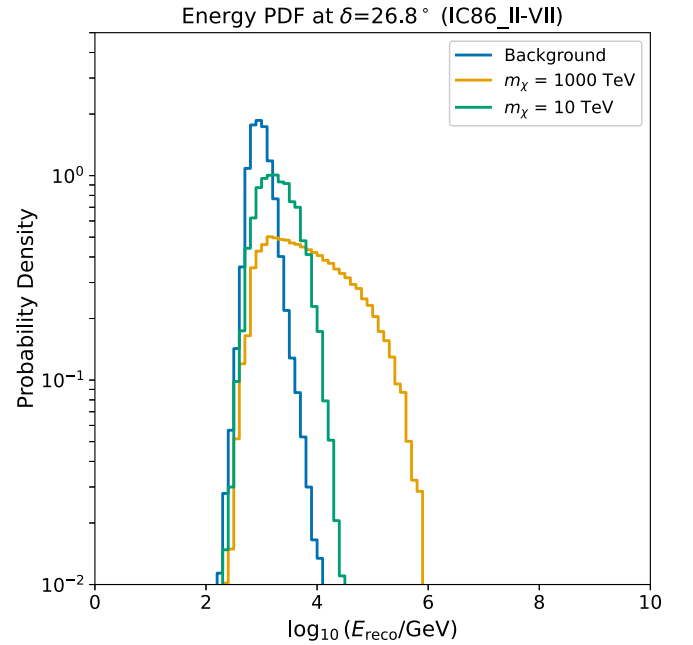


FIG. 5. Comparison of the background and signal energy PDFs at the Boötes III declination ($\delta_s = 26.8^\circ$), for which the IC86_II–VII sample is taken as an example. The blue curve denotes the background energy PDF, and the green and orange curves denote the signal energy PDFs for $m_\chi = 10$ TeV and $m_\chi = 1000$ TeV, respectively.

$$\text{TS} = 2 \log \Lambda(n_s, p_s). \quad (\text{A8})$$

The best-fit values n_s and p_s are obtained by maximizing the likelihood ratio.

We validated our analysis framework by testing the data analysis for the active galaxy NGC 1068, which has been reported as an HE neutrino source by the IceCube Collaboration [9,37]. In this validation, we assumed a power-law neutrino energy spectrum, $\Phi_\nu \propto E^{-\gamma}$. Our analysis gave $n_s = 52^{+16}_{-14}$, $\gamma = 3.2^{+0.4}_{-0.3}$, and flux at 1 TeV $\Phi_{1 \text{ TeV}} = 3.2^{+1.0}_{-1.0} \times 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ (all uncertainties are at 68% CL), consistent with those from the previous ten-year IceCube point-source analysis [37].

For our DM annihilation search, the source spectrum Φ_ν was replaced by the flux model in Eq. (1) of the main text, for which $\Phi_\nu \propto \frac{dN_\nu}{dE_\nu}$ for a given m_χ . We obtained the DM annihilation spectral templates dN_ν/dE_ν for the $\chi\chi \rightarrow \nu\bar{\nu}$ channel for m_χ from 1 TeV to 1 PeV at 100 logarithmically spaced mass points, using HDMSpectra [40]. Examples of the annihilation spectra for the $\nu_\mu\bar{\nu}_\mu$ flavor at the Earth after considering neutrino oscillations are shown in Fig. 6. The likelihood analysis was then performed for each m_χ template and for each target source.

We estimated the significance of the neutrino excess by performing Monte Carlo simulations of background-only pseudoexperiments. The pseudodata were generated by randomizing right-ascension value of each event uniformly in the range $[0, 2\pi)$ while keeping other parameters (declination, reconstructed energy, angular uncertainty, and data sample) unchanged. This procedure exploits the approximate uniformity of the IceCube background in right ascension. For each pseudoexperiment, we repeated the same analysis procedure as applied to the real data, including the scan over m_χ . Therefore, the look-elsewhere effect associated with the choice of the DM mass [42] was taken

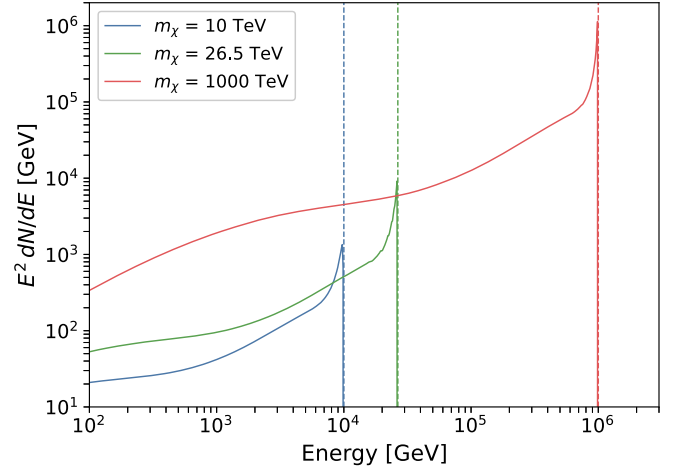


FIG. 6. Oscillated $\nu_\mu\bar{\nu}_\mu$ spectra at the Earth for the $\chi\chi \rightarrow \nu\bar{\nu}$ channel, generated with HDMSpectra. The curves show $E^2 dN/dE$ for $m_\chi = 10, 26.5$, and 1000 TeV . The vertical dashed lines mark the corresponding DM masses, where the linelike neutrino component is located. Both continuum and line components are included in the analysis.

into account. We generated 10^6 background-only pseudoexperiments. The p -value was estimated as the fraction of pseudoexperiments whose maximum TS values exceeded the value obtained from the real data. The observed maximum TS for Boötes III was $\text{TS} = 12.2$, estimated to have $p_{\text{pre}} \simeq 3.2 \times 10^{-4}$ (corresponding to a significance of 3.4σ). After applying a trials factor of three for the number of the stream cores tested in this work, the posttrial p -value is $p_{\text{post}} \simeq 9.5 \times 10^{-4}$ (corresponding to 3.1σ).

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