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Search for Extended Sources of Neutrino Emission in the Galactic Plane with IceCube

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Abstract

The Galactic plane, harboring a diffuse neutrino flux, is a particularly interesting target in which to study potential cosmic-ray acceleration sites. Recent gamma-ray observations by HAWC and LHAASO have presented evidence for multiple Galactic sources that exhibit a spatially extended morphology and have energy spectra continuing beyond 100 TeV. A fraction of such emission could be produced by interactions of accelerated hadronic cosmic rays, resulting in an excess of high-energy neutrinos clustered near these regions. Using 10 years of IceCube data comprising track-like events that originate from charged-current muon neutrino interactions, we perform a dedicated search for extended neutrino sources in the Galaxy. We find no evidence for time-integrated neutrino emission from the potential extended sources studied in the Galactic plane. The most significant location, at 2.6σ post-trials, is a 1°.7 sized region coincident with the unidentified TeV gamma-ray source 3HWC J1951+266. We provide strong constraints on hadronic emission from several regions in the galaxy.

Unified Astronomy Thesaurus concepts: Neutrino astronomy (1100)

1. Introduction

The search for the sources of cosmic rays is a key area of research in multimessenger astronomy. Cosmic rays up to PeV energies are thought to originate in acceleration sites within the Milky Way known as PeVatrons (Blasi 2013; Gabici et al. 2019; Bose et al. 2022). The accelerated cosmic-ray protons interact with the surrounding matter to produce pions, which decay into neutrinos and gamma rays. However, gamma rays may also be produced by leptonic cosmic rays via inverse Compton scattering and/or bremsstrahlung processes. The detection of neutrinos from a Galactic source would provide definitive evidence for hadronic acceleration therein. The IceCube Neutrino Observatory has been observing a diffuse flux of TeV–PeV energy neutrinos of largely unknown origin (Aartsen et al. 2020a). While the two most promising candidate sources of astrophysical neutrinos to date are extragalactic (Aartsen et al. 2018a, 2018b; Abbasi et al. 2022a) the near-isotropic flux may contain a small Galactic component as well (Aartsen et al. 2017a; Denton et al. 2017). A more recent IceCube analysis has also reported diffuse neutrino emission from the Galactic plane, compatible with the expectation from cosmic-ray interactions with the interstellar medium (Abbasi et al. 2023a).

The Galactic plane has been extensively surveyed in gamma rays at multi-TeV energies (Ward & VERITAS Collaboration 2010; Archer et al. 2016; Abdalla et al. 2018, 2021; MAGIC Collaboration et al. 2020). The High Altitude Water Cherenkov (HAWC) Observatory and the Large High Altitude Air Shower Observatory (LHAASO) have detected several sources that emit photons at more than 100 TeV (Albert et al. 2020a; Abeysekara et al. 2020; Cao et al. 2021). At such high energies—in the so-called Klein–Nishina regime—gamma-ray emission via inverse Compton scattering is increasingly suppressed (Klein & Nishina 1929), which means the aforementioned >100 TeV emission could be a signature of hadronic interactions. Some of these sources exhibit a spatial extent up to $\sim 2^{\circ}$. A number of the aforementioned sources have been found in close proximity of pulsars with high spin-down luminosity, hinting toward a leptonic origin of the gamma-ray emission (Albert et al. 2021a; Sudoh et al. 2021; Hooper & Linden 2022). In many cases, the gamma-ray data are not enough to distinguish between hadronic acceleration followed by pion decay, and leptonic interactions at the source (Sudoh & Beacom 2023a, 2023b). That is why a comprehensive search for neutrino emission in the Galaxy is required. Moreover, diffuse gamma rays with energies between 100 TeV and 1 PeV have also been reported by the Tibet air-shower array (Tibet ASγ Collaboration et al. 2021) and LHAASO (Cao et al. 2023), further hinting toward the presence of undetected sources that may be accompanied by neutrinos.

Previous works using IceCube data have analyzed several supernova remnants, pulsar wind nebulae, and unidentified objects detected in TeV gamma rays as point sources (Aartsen et al. 2019, 2020a, 2020b), and have constrained neutrino emission from the 12 ultrahigh-energy sources observed by LHAASO (Abbasi et al. 2023b). In this work, we adopt a more extensive, model-independent approach to search for extended sources of neutrino emission in the Galactic plane. The last search for extended sources with IceCube only used one year of complete detector configuration (Aartsen et al. 2014a). This work is an improvement on previous IceCube searches in the Galactic plane in several ways. First, we test for the presence of neutrino sources of multiple possible angular sizes using nine years of data. Second, we select a catalog of special extended regions of interest (ROIs) in the Galactic plane that emit >50 TeV gamma rays, and test for neutrino emission. We also account for any possible contamination from diffuse emission in the Galactic plane. The paper is structured as follows. Section 2 briefly reviews the detector and data sample used in the search. Section 3 describes details of the analysis and provides the results of the various searches conducted. Section 4 concludes.

2. The IceCube Neutrino Observatory and Data

The IceCube Neutrino Observatory is designed to detect cosmic neutrinos, most effectively above a few TeV in energy, via the Cherenkov radiation produced as a result of neutrino interactions in ice. The individual detector units, known as digital optical modules, are embedded in Antarctic ice on 86 strings, forming a hexagonal array spanning a cubic kilometer of ice. Details about the detector and signal reconstruction can be found in Abbasi et al. (2009, 2010) and Aartsen et al. (2014b).

Charged-current muon neutrino interactions produce muons that deposit energy in the detector in the form of tracks, which can be reconstructed with a directional accuracy of less than 1° above 1 TeV. We use a data sample consisting of muon tracks collected between 2011 May and 2020 May, with a total livetime of 3184 days. The sample has been used and validated in several searches for point sources with IceCube (Aartsen et al. 2020a; Abbasi et al. 2022b, 2022c, 2023b). The main background for astrophysical neutrinos in this data sample are track-like events from atmospheric neutrinos and muons produced during the interaction of cosmic rays with the atmosphere.

In addition to track-like events, IceCube also detects showers or "cascades" produced by neutral-current and (electron/tau neutrinos') charged-current interactions. The direction of neutrino-induced cascades can be reconstructed with limited accuracy and has a typical angular uncertainty of $\sim 15°$. While this work primarily uses tracks due to their superior sensitivity, we use cascades as a statistically independent data set to perform certain cross-checks (Section 3.2).

3. Analysis

We use the unbinned maximum likelihood method to search for time-integrated excess neutrino emission above background from a given region in the sky as described in Braun et al. (2008). The likelihood is formed by a product of probability densities over all events in the data,

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left[\frac{n_s}{N} \mathcal{S}_i + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right] \tag{1}$$

where the fitted parameters are the number of signal events, n_s, and the spectral index, γ. N is the total number of events in the data set, $\mathcal{S}_i$ is the signal probability density function (PDF), and $\mathcal{B}_i$ is the background PDF. The signal and the background PDFs contain a spatial term and an energy term. The computation of the PDFs is discussed in detail in Aartsen et al. (2017b). Here we describe the two modifications that are used in this analysis to focus on extended sources.

First, the spatial term in the signal PDF functionally depends on the extent of the source. The probability that the ith event came from an extended source at $\boldsymbol{x}_s$ is modeled by a 2D Gaussian given by

$$S_i = \frac{1}{2\pi(\sigma_i^2 + \sigma_s^2)} \exp\left(-\frac{|\boldsymbol{x}_i - \boldsymbol{x}_s|^2}{2(\sigma_i^2 + \sigma_s^2)} \right), \tag{2}$$

where $\boldsymbol{x}_i = (\alpha_i, \delta_i)$ is the ith event direction in R.A. and decl., σ_i is the angular uncertainty of the ith event, and σ_s is the source extent.

The second modification is applied during the computation of B_i to account for any signal contamination in the background. The background PDF at a given decl. is calculated by randomizing the events in R.A. Since the process uses actual data it may result in an overestimation of the background in the presence of a nearby source. The signal events from the source would be scrambled into the background. In order to avoid this contamination, we mask all regions that are potential sources of neutrino emission, before randomizing the R.A. of events. In this way, potential signal events are not included in the estimation of the background. An overall correction factor is applied to the background density to account for the fraction of sky that is masked during the calculation.

In this work, we mask out a disk of radius 1°.5 centered on the two known candidate sources of neutrinos: TXS 0506+056 and NGC 1068 (Aartsen et al. 2018a; Abbasi et al. 2022a). To account for any diffuse emission from the Galaxy, we mask all events that have a Galactic latitude $|b| \leqslant 5°$. The size is chosen based on the locations of Galactic TeV gamma-ray sources detected by HAWC and LHAASO, which are all within 5° of the Galactic plane (Albert et al. 2020a; Cao et al. 2021). We note that for the source extents considered in this work ($\leqslant 2°$), this analysis is sensitive to $\mathcal{O}(1\%)$ of the nominal Galactic diffuse flux measured in Abbasi et al. (2023a). For source extents $<5°$, the inclusion of a model of Galactic plane emission in the background PDF has a negligible impact on the sensitivity.

Following the estimation of background, we maximize the likelihood in Equation (1) to determine the best-fit parameters, n_s and γ, for a source with a fixed extent at a given location. In this work, we test for four different source extents: 0°.5, 1°.0, 1°.5, and 2°.0. The different locations searched are described below.

3.1. The Galactic Plane Scan

The first search consists of a largely model-independent scan of every location in the Galactic plane in the range $-5° \leqslant b \leqslant 5°$, making no assumptions about the detailed morphology or spectral slope of the underlying emission. The cut in Galactic latitude is based on the measurements of diffuse TeV gamma-ray emission from the plane (Tibet ASγ Collaboration et al. 2021; Cao et al. 2023). We bin the sky into equal-area HEALpix pixels with the mean spacing between pixels set to 0°.115 (Górski et al. 2005). At each pixel location, we fit for a neutrino source of a fixed extent and a spectrum described by a simple power law with spectral index γ. The total number of signal events from the source and γ are the free parameters of the fit, which determine the differential flux at 1 TeV (reference energy). For each location, we have four sets of fits corresponding to the four source extents. The test statistic for a fit is given by

$$\mathrm{TS} = 2\log\left(\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}(n_s = 0)}\right), \tag{3}$$

where $\hat{n}_s$ and $\hat{\gamma}$ are the best-fit values of the free parameters. For each fit, a local or pre-trials p-value is determined by comparing the observed TS with a TS distribution from an ensemble of background-only trials. Since a very large number of locations are tested multiple times for possible neutrino emission, a further "trials correction" factor for the lowest p-value is calculated by simulating the whole search 5000 times on background-only data.

No significant emission from a source with an extent between 0°.5 and 2° is observed at any location in the Galactic plane. Figure 1 shows the local p-value map of the Galactic plane assuming a source extent of 2°. The upper limits on the flux for the location with the lowest p-value are shown in Table 1.

3.2. The Catalog Search

The second search focuses on neutrino emission from known extended sources of TeV gamma-ray emission. A targeted catalog search has the advantage of using multimessenger information to pin down potential sources, resulting in a reduced trials factor compared to the all-sky search. For this analysis, we select a catalog of sources that exhibit an extended morphology as observed by TeV gamma-ray observatories (Wakely & Horan 2008). The sources that pass this criterion are labeled in Figure 1. In some cases, two or more reported sources are possibly associated and are less than 0°.5 apart from each other. We group these sources into an ROI and choose a location equidistant from all sources as the central location of

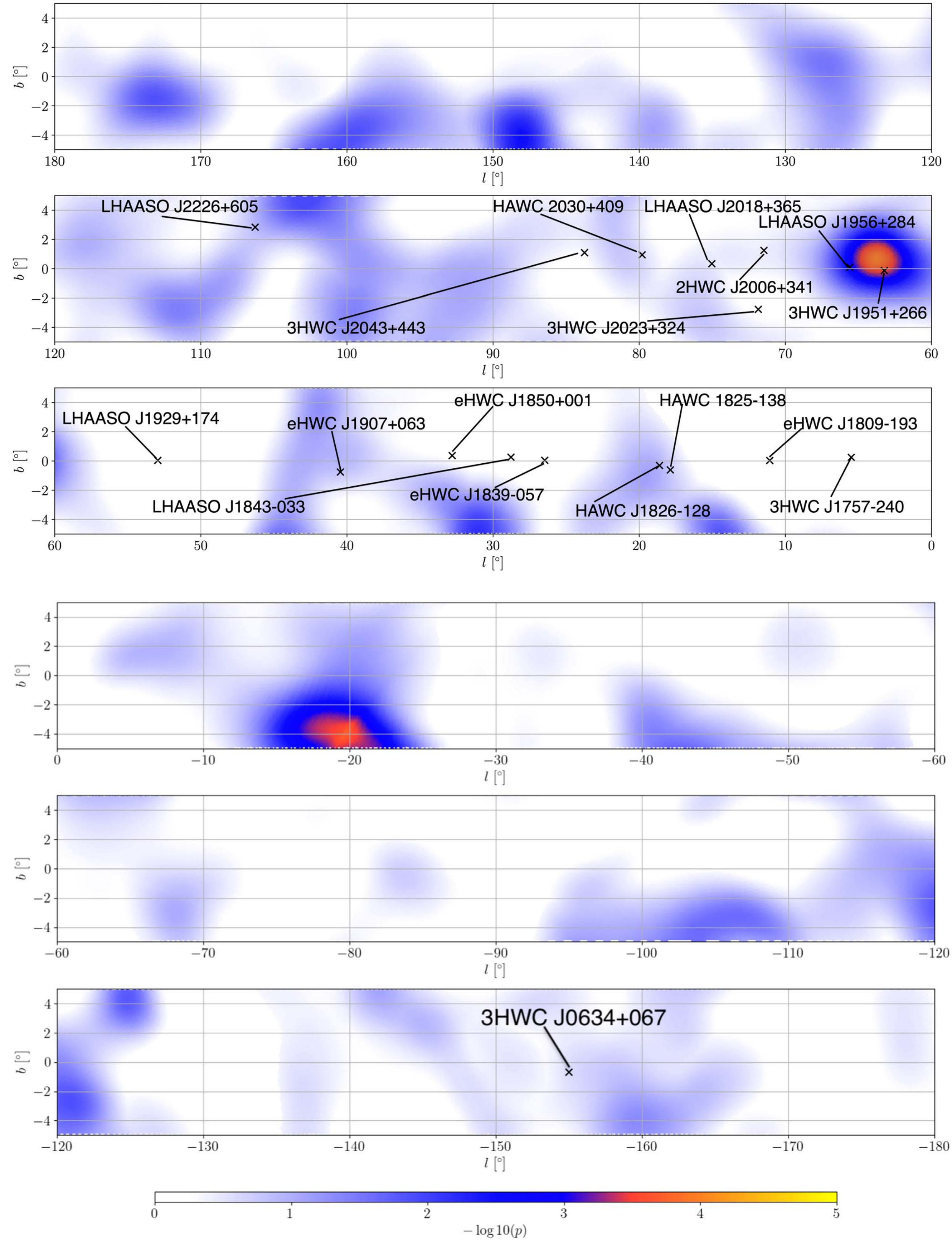

Figure 1. Local (pre-trials corrected) *p*-value map in Galactic coordinates for a 2°.0 source extent. The ROI locations used in the catalog search are labeled (see text for details).

Table 1
Summary of Results for the Hottest Spot in Each Scan along the Galactic Plane for Different Extents

σ (deg)	R.A. (deg)	Decl. (deg)	l (deg)	b (deg)	$\hat{n}_s$	$\hat{\gamma}$	$\phi_{90\%}$ (TeV^{-1} cm^{-2} s^{-1})
0.5	296.98	27.45	63.53	1.00	80.3	3.10	5.13×10^{-11}
1.0	296.98	27.45	63.53	1.00	111.4	3.00	6.29×10^{-11}
1.5	297.42	27.53	63.80	0.71	150.5	3.03	6.61×10^{-11}
2.0	297.42	27.53	63.80	0.71	182.3	3.09	1.04×10^{-10}

Note. The coordinates of the hottest spot, the best-fit number of signal events ($\hat{n}_s$), the spectral index ($\hat{\gamma}$), and the 90% confidence limit (CL) upper-limit flux at 1 TeV are given for each search.

Table 2
Locations of the ROIs and the Possible Sources Therein that are Used in the Catalog Search

Region of Interest	R.A. (deg)	Decl. (deg)	l (deg)	b (deg)	Possible Sources and Associated Extent
ROI-1	95.32	38.21	175.44	10.97	3HWC J0621+382 (0°.5) (Albert et al. 2020a)
ROI-2	95.47	37.92	175.76	10.95	LHAASO J0621+3755 (0°.4) (Aharonian et al. 2021)
ROI-3	98.66	6.73	205.03	−0.65	3HWC J0634+067 (0°.5) (Albert et al. 2020a)
ROI-4	269.3	−24.09	5.49	0.25	3HWC J1757-240 (1°.0) (Albert et al. 2020a)
ROI-5	272.46	−19.34	11.07	0.03	eHWC J1809-193 (0°.34) (Abeysekara et al. 2020)
ROI-6	276.42	−13.66	17.87	−0.61	HAWC J1825-138 (0°.47) Albert et al. 2021b LHAASO J1825-1326 (0°.3) (Cao et al. 2021)
ROI-7	276.5	−12.86	18.61	−0.31	HAWC J1826-128 (0°.2) (Albert et al. 2021b)
ROI-8	279.86	−5.73	26.47	0.05	eHWC J1839-057 (0°.34) Abeysekara et al. (2020) LHAASO J1839-0545 (0°.3) (Cao et al. 2021)
ROI-9	280.73	−3.58	28.78	0.26	eHWC J1842-035 (0°.39) (Abeysekara et al. 2020) LHAASO J1843-0338 (0°.3) (Cao et al. 2021)
ROI-10	282.47	0.05	32.80	0.37	eHWC J1850+001 (0°.37) (Abeysekara et al. 2020) LHAASO J1849-0003 (0°.3) Cao et al. (2021)
ROI-11	286.98	6.34	40.45	−0.76	eHWC J1907+063 (0°.67) (Abeysekara et al. 2020) LHAASO J1908+0621 (0°.3) (Cao et al. 2021)
ROI-12	292.25	17.75	52.94	0.04	LHAASO J1929+1745 (0°.3) (Cao et al. 2021)
ROI-13	297.9	26.61	63.23	−0.1	3HWC J1951+266 (0°.5) (Albert et al. 2020a)
ROI-14	299.05	28.75	65.58	0.10	LHAASO J1956+2845 (0°.3) (Cao et al. 2021)
ROI-15	301.55	34.35	71.46	1.25	2HWC J2006+341 (0°.72) (Albert et al. 2020b)
ROI-16	304.90	36.82	75.03	0.34	eHWC J2019+368 (0°.3) (Abeysekara et al. 2020) LHAASO J2018+3651 (0°.3) Cao et al. (2021) TASG J2019+368 (0°.28) (Amenomori et al. 2021)
ROI-17	305.81	32.44	71.85	−2.77	3HWC J2023+324 (1°.0) (Albert et al. 2020a)
ROI-18	307.81	41.07	79.80	0.95	eHWC J2030+412 (0°.18) (Abeysekara et al. 2020) LHAASO J2032+4102 (0°.3) (Cao et al. 2021) HAWC J2030+409 (2°.13) (Abeysekara et al. 2021)
ROI-19	310.89	44.3	83.74	1.10	3HWC J2043+443 (0°.5) (Albert et al. 2020a)
ROI-20	336.75	60.95	106.28	2.84	LHAASO J2226+6057 (0°.3) (Cao et al. 2021)

the ROI. Isolated sources are labeled as individual ROIs. This procedure gives us a catalog of 20 ROIs to search for neutrino emission with an extent between 0°.5 and 2°.0. Table 2 lists the ROI locations and the corresponding sources.

For each ROI, we fit for n_s and γ for extents 0°.5, 1°.0, 1°.5, and 2°.0 as described above. No significant extended emission is observed in any of the ROIs, resulting in constraints on the total neutrino flux from each region. Table 3 provides the 90%

Table 3
Catalog Search Results in Order of Most Constraining to Least Constraining

Region of Interest	Gamma-Ray Source Name	ϕ_ν from pp Collisions ($\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$)	$\phi_{90\%}$ at 50 TeV ($\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$)	$\phi_{90\%}/\phi_\nu$
ROI-18	HAWC J2030+409	3.88×10^{-16}	1.78×10^{-16}	0.459
ROI-11	eHWC J1907+063	4.95×10^{-16}	2.39×10^{-16}	0.482
ROI-16	eHWC J2019+368	3.82×10^{-16}	1.85×10^{-16}	0.485
ROI-9	eHWC J1842-035	3.04×10^{-16}	1.64×10^{-16}	0.540
ROI-7	HAWC J1826-128	5.54×10^{-14}	3.70×10^{-14}	0.668
ROI-8	eHWC J1839-057	3.04×10^{-16}	2.82×10^{-16}	0.928
ROI-18	eHWC J2030+412	1.82×10^{-16}	1.78×10^{-16}	0.978
ROI-10	eHWC J1850+001	2.23×10^{-16}	2.25×10^{-16}	1.01
ROI-16	TASG J2019+368	1.79×10^{-16}	1.85×10^{-16}	1.04
ROI-2	LHAASO J0621+3755	4.28×10^{-17}	5.79×10^{-17}	1.35
ROI-11	LHAASO J1908+0621	1.66×10^{-16}	2.39×10^{-16}	1.44
ROI-9	LHAASO J1843-0338	8.91×10^{-17}	1.64×10^{-16}	1.84
ROI-1	3HWC J0621+382	2.93×10^{-17}	5.64×10^{-17}	1.92
ROI-6	HAWC J1825-138	1.80×10^{-14}	3.87×10^{-14}	2.16
ROI-19	3HWC J2043+443	3.95×10^{-17}	9.08×10^{-17}	2.30
ROI-10	LHAASO J1849-0003	9.03×10^{-17}	2.25×10^{-16}	2.49
ROI-20	LHAASO J2226+6057	1.28×10^{-16}	3.44×10^{-16}	2.69
ROI-18	LHAASO J2032+4102	6.59×10^{-17}	1.78×10^{-16}	2.70
ROI-16	LHAASO J2018+3651	6.10×10^{-17}	1.85×10^{-16}	3.03
ROI-17	3HWC J2023+324	2.10×10^{-17}	6.62×10^{-17}	3.15
ROI-8	LHAASO J1839-0545	8.54×10^{-17}	2.82×10^{-16}	3.30
ROI-12	LHAASO J1929+1745	4.64×10^{-17}	1.71×10^{-16}	3.69
ROI-3	3HWC J0634+067	4.30×10^{-17}	2.12×10^{-16}	4.92
ROI-14	LHAASO J1956+2845	5.00×10^{-17}	6.36×10^{-16}	12.7
ROI-13	3HWC J1951+266	3.20×10^{-17}	6.20×10^{-16}	19.4
ROI-5	eHWC J1809-193	4.86×10^{-16}	2.17×10^{-14}	44.7
ROI-6	LHAASO J1825-1326	4.36×10^{-16}	3.87×10^{-14}	88.9
ROI-15	2HWC J2006+341	8.37×10^{-19}	2.35×10^{-16}	280
ROI-4	3HWC J1757-240	8.41×10^{-17}	9.93×10^{-14}	1.18×10^3

Note. For each ROI, we show the expected neutrino flux at 50 TeV assuming hadronic origins of the associated gamma-ray emission, the 90% CL limits assuming $\gamma = 3.0$, and the ratio of the upper limit to the expected neutrino emission.

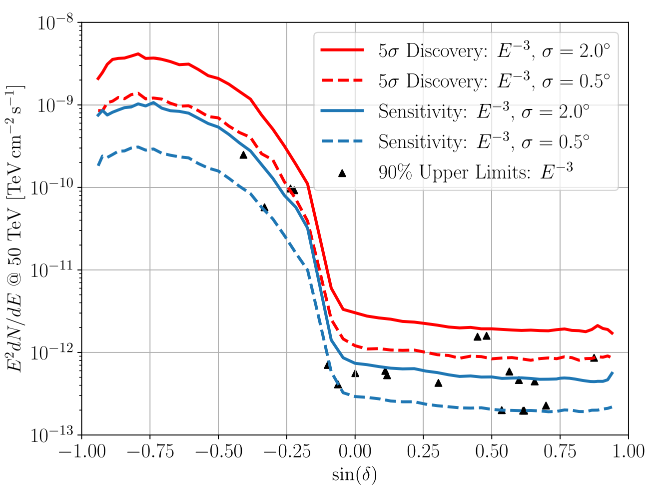

Figure 2. The 90% CL limits on the neutrino flux at 50 TeV from the ROIs in the catalog search, assuming a spectral index of 3. The solid red and blue lines show the 5σ discovery potential and sensitivity for a source with $\sigma_s = 2°.0$. The dashed red and blue lines show the 5σ discovery potential and sensitivity for a source with an extent of 0°.5. See text for the definitions of the ROIs.

upper limits on the differential neutrino flux from each ROI at a reference energy of 50 TeV. See the Appendix for detailed fit results. For each ROI, we provide the upper limit corresponding to the extent that gives the smallest p-value during the various fits, for $\gamma = 3$.

We also compare our constraints to the expected muon neutrino flux, $\phi_\nu(E_\nu)$, from the sources within each ROI. Following the methods in Ahlers & Murase (2014), we calculate $\phi_\nu(E_\nu)$ under the assumption that all of the observed gamma-ray flux, $\phi_\gamma(E_\gamma)$, from a given source is produced in pp collisions, and is therefore accompanied by neutrinos. We only consider pp interactions here, since those are expected to dominate over pγ interaction in the Galactic plane region (Murase et al. 2013; Ahlers & Murase 2014). $\phi_\nu(E_\nu)$ is then given by $\phi_\nu(E_\nu) = 2^{1-\gamma}\phi_\gamma(E_\gamma)$, where γ is the common spectral index of the neutrino and gamma-ray emission, and the neutrino energy E_ν is half the gamma-ray energy, E_γ (Ahlers & Murase 2014).

The ROIs considered in this work include notable PeVatron candidates. For instance, we obtain the strongest limits in terms of constraining the hadronic emission from ROI-18, with $\phi_{90\%}/\phi_\nu \sim 0.5$, where ϕ_ν is the predicted neutrino flux assuming all gamma rays are hadronic. This ROI is part of the Cygnus region and includes HAWC J2030+409, LHAASO J2032+4102, and eHWC J2030+412 (Abeysekara et al. 2021; Amenomori et al. 2021). ROI-20 is co-located with LHAASO J2226+6057, which is 0°.14 away from the supernova remnant G106.3+02.7 (also associated with HAWC J2227+610) (Albert et al. 2020c), which is another proposed hadronic accelerator (Fang et al. 2022). In this region, our most conservative upper limit is a factor of ~2.7 above the hadronic

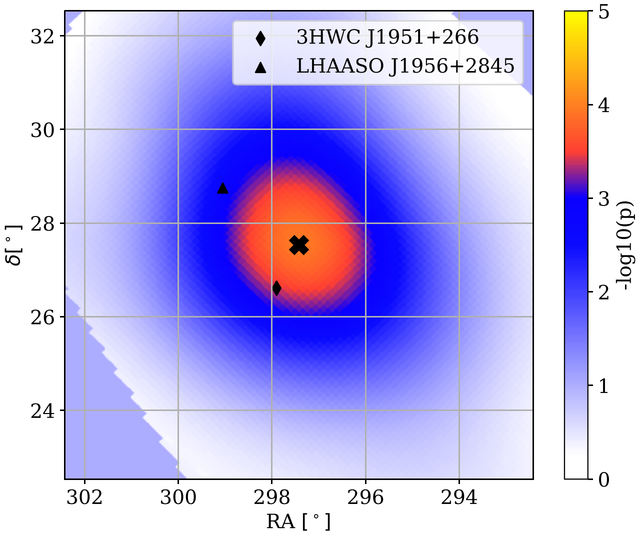

Figure 3. The region of the Galactic plane with the lowest p-values in the general scan as well as the catalog search. The general hotspot is marked with a cross. Sources corresponding to ROI-13 (3HWC J1951+266) and ROI-14 (LHAASO J1956+2845) from the catalog search are also labeled. The map shows pre-trials corrected p-values only.

scenario, implying the need for improved sensitivity to detect neutrinos from this potential cosmic-ray accelerator.

Figure 2 shows the upper limits on the flux from each ROI for the extent with the highest TS assuming $\gamma = 3$. Also shown are the sensitivity and discovery potential as a function of source decl.

3.3. The Most Significant Region

The highest TS in the catalog search is obtained for ROI-13 at the location of 3HWC J1951+266 for an extent of 1°.5, with a best-fit flux of 5.2×10^{-13} TeV cm^{-2} s^{-1} at 100 TeV and $\gamma = 3.03$. For this ROI, we perform a scan across a finer grid of extents to determine the source extent that best describes the potential neutrino signal. The local significance is further corrected for multiple testing (including the 20 ROIs and several extents) by performing all the tests on 5000 simulations and constructing a background-only p-value distribution. The global (or trials-corrected) p-value is then given by the probability of obtaining a particular local p-value of ROI-13 in the aforementioned distribution. We obtain the lowest p-value for an extent of 1°.7 at a global significance of 2.6σ. The hottest spot in the Galactic plane scan is located 1°.02 away from ROI-13 and 1°.88 away from ROI-14. Figure 3 shows the most significant locations in both the catalog search and the general scan for an extent of 1°.5. Following this result, we also study the location of the hotspot using an independent data set of neutrino-induced cascades and find the best-fit flux and spectral index to be consistent with the tracks' results. However, the result is not significant enough to qualify as evidence for emission.

4. Conclusions

We perform a targeted search for spatially extended neutrino emission in the Milky Way utilizing 10 years of neutrino track-like events in IceCube. We focus on potential source extents between 0°.5 and 2°.0 in a general scan across the Galactic plane and a catalog search with extended regions of TeV gamma-ray sources. The most significant location is a 1°.7 region centered on the unidentified source 3HWC J1951+266 and is found to be inconsistent with the background-only hypothesis at 2.6σ after trials correction. We emphasize that this is still below our threshold for evidence of significant emission. Our analysis also places constraints on neutrino emission from a number of regions hypothesized to contain PeVatron candidates including the Cygnus cocoon and the Boomerang supernova remnant.

We encourage further multiwavelength campaigns across the Galactic plane in light of these new constraints. Such studies would complement IceCube observations in helping understand the emission mechanisms underlying various regions in the plane. Furthermore, a large fraction of the Galactic plane lies in the Southern sky, where IceCube has limited sensitivity to individual sources, and TeV gamma-ray surveys have limited coverage. In the coming years, more data with IceCube, as well as a number of near-future and planned observatories like KM3Net (Aiello et al. 2019), IceCube Gen-2 (Aartsen et al. 2021), P-ONE (Agostini et al. 2020), and Baikal-GVD (Suvorova et al. 2021), will be able to probe the Galactic plane for PeVatrons in detail with better coverage and improved angular resolution.

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Appendix

Here we provide additional detailed results of the fits. Table 4 reports the summary of various fits for ROI-13. Table 5 reports the fit results and upper limits for all ROIs. Figure 4 shows the upper limits for all ROIs and the sensitivity of the analysis for two different assumed spectral indices.

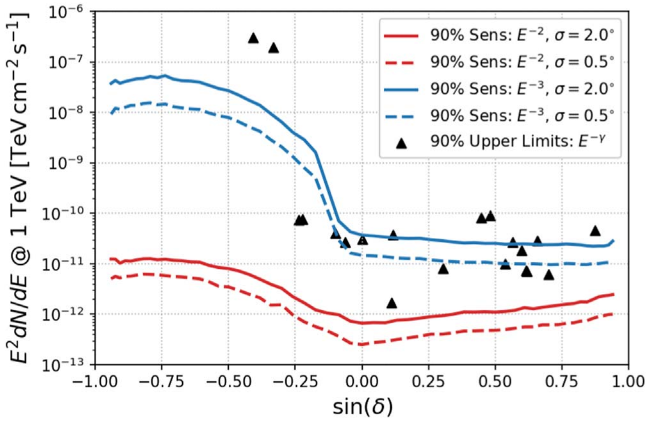

Figure 4. The 90% upper-limit fluxes at a pivot energy of 1 TeV for the source extents with the smallest pre-trial p-value for each ROI, shown as the black triangles. The upper limits are compared to the 90% CL sensitivity curves with $\sigma_s = 0°.5$ (dashed lines) and $\sigma_s = 2°.0$ (solid lines) at $\gamma = 2.0$ (red lines) and $\gamma = 3.0$ (blue lines).

Table 4
Results for Each Source Extent Evaluated at the Location of ROI-13: (R.A., decl.) = (297°.9, 26°.61) (top)

Extent (deg)	$\hat{n}_s$	$\hat{\gamma}$	$p_{\rm pre}$ ($\sigma_{\rm pre}$)
1°.0	99.33	3.03	3.87×10^{-4} (3.36σ)
1°.1	108.27	3.03	3.80×10^{-4} (3.37σ)
1°.2	116.95	3.04	2.67×10^{-4} (3.46σ)
1°.3	125.43	3.05	2.07×10^{-4} (3.53σ)
1°.4	133.63	3.06	2.07×10^{-4} (3.53σ)
1°.5	141.52	3.07	1.40×10^{-4} (3.63σ)
1°.6	149.03	3.08	1.73×10^{-4} (3.58σ)
1°.7	156.12	3.10	1.27×10^{-4} (3.66σ)
1°.8	163.06	3.12	2.27×10^{-4} (3.51σ)
1°.9	169.44	3.13	1.67×10^{-4} (3.59σ)
2°.0	175.29	3.14	2.53×10^{-4} (3.48σ)
Extent (deg)	**$\hat{n}_s$**	**$\hat{\gamma}$**	**$p_{\rm post}$ ($\sigma_{\rm post}$)**
1°.7	156.12	3.10	4.50×10^{-3} (2.61σ)

Note. The observed number of signal events, $\hat{n}_s$, and the spectral index, $\hat{\gamma}$, are also reported. A post-trial p-value was obtained for the hottest extent of 1°.7 by taking into account all 20 ROI locations and 16 possible extents in the finer scan, ranging from 0°.5 to 2°.0 in steps of 0°.1.

Table 5
The 90% Upper-limit Fluxes at a Pivot Energy of 50 TeV for the Source Extents with the Smallest Pre-trial p-value for Each ROI

Region of Interest	Extent (deg)	$\hat{n}_s$	$\hat{\gamma}$	$\phi_{90\%}$ at 50 TeV (TeV^{-1} cm^{-2} s^{-1})
ROI-1	0°.5	0.0	3.00	5.64×10^{-17}
ROI-2	0°.5	0.0	3.00	5.79×10^{-17}
ROI-3	0°.5	32.9	3.56	3.39×10^{-17}
ROI-4	1°.0	14.1	3.54	2.92×10^{-13}
ROI-5	0°.5	0.0	3.75	8.19×10^{-14}
ROI-6	1°.5	7.0	2.39	6.54×10^{-15}
ROI-7	1°.5	9.2	2.40	6.48×10^{-15}
ROI-8	0°.5	9.3	3.08	2.34×10^{-16}
ROI-9	0°.5	0.6	4.00	4.30×10^{-18}
ROI-10	2°.0	18.9	3.07	1.82×10^{-16}
ROI-11	0°.5	7.8	2.14	3.90×10^{-16}
ROI-12	0°.5	18.6	2.54	3.87×10^{-16}
ROI-13	1°.5	141.5	3.07	4.91×10^{-16}
ROI-14	2°.0	149.5	3.18	3.59×10^{-16}
ROI-15	2°.0	31.2	4.00	4.23×10^{-18}
ROI-16	0°.5	24.7	2.83	2.76×10^{-16}
ROI-17	0°.5	1.9	3.21	3.51×10^{-17}
ROI-18	0°.5	30.6	3.52	2.93×10^{-17}
ROI-19	0°.5	6.5	2.63	2.05×10^{-16}
ROI-20	2°.0	85.0	3.38	8.11×10^{-17}

Note. The associated extent, fitted number of signal events, $\hat{n}_s$, and the fitted spectral index, $\hat{\gamma}$ are shown.

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