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Probing the Galactic Neutrino Flux at Neutrino Energies above 200 TeV with the Baikal Gigaton Volume Detector

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Abstract

Recent observations of the Galactic component of the high-energy neutrino flux, together with the detection of the diffuse Galactic gamma-ray emission up to sub-PeV energies, open new possibilities to study the acceleration and propagation of cosmic rays in the Milky Way. At the same time, both large nonastrophysical backgrounds at TeV energies and the scarcity of neutrino events in the sub-PeV band currently limit these analyses. Here, we use the sample of cascade events with estimated neutrino energies above 200 TeV, detected by the partially deployed Baikal Gigaton Volume Detector (GVD) in 6 yr of operation, to test the continuation of the Galactic neutrino spectrum to sub-PeV energies. We find that the distribution of the arrival directions of Baikal-GVD cascades above 200 TeV in the sky suggests an excess of neutrinos from low Galactic latitudes with the chance probability of 1.4×10^{-2}. We also find the excess above 200 TeV in the most recent IceCube public data sets, both of cascades and tracks. The chance probability of the excess in the combined IceCube and Baikal-GVD analysis is 3.4×10^{-4}. The flux of Galactic neutrinos above 200 TeV challenges often-used templates for neutrino search based on cosmic-ray simulations.

Unified Astronomy Thesaurus concepts: Galactic cosmic rays (567); High energy astrophysics (739); Neutrino astronomy (1100)

1. Introduction

The origin of cosmic rays with energies between $\sim 10^{12}$ and $\sim 10^{20}$ eV was puzzling for decades. The observation of high-energy astrophysical neutrinos by the IceCube experiment (M. G. Aartsen et al. 2013; R. U. Abbasi et al. 2021), recently confirmed by the Baikal Gigaton Volume Detector (GVD; V. A. Allakhverdyan et al. 2023a), has opened a new view on this old question. Indeed, these neutrinos are most probably born, together with photons, in interactions of energetic cosmic rays with matter and radiation. Unlike charged cosmic rays, neutrinos are not deflected by cosmic magnetic fields and thus point back to the place where they were produced. Unlike photons, neutrinos are not absorbed or scattered and thus reach the observer from distant or opaque sources. Despite complications related to the large atmospheric background and to the relatively low precision of the reconstruction of individual events, high-energy neutrino astronomy has

[17] Deceased.

developed into an important new branch of astrophysics, see, e.g., S. Troitsky (2021, 2024) for reviews.

Of particular interest is the neutrino radiation coming from our Galaxy, which is expected (C.-Y. Chen et al. 2015; A. Neronov & D. Semikoz 2016a; A. Palladino & F. Vissani 2016; A. Palladino et al. 2016) to supplement the extragalactic contribution. Despite numerous early attempts (A. Neronov et al. 2014; S. Troitsky 2015; A. Neronov & D. Semikoz 2016b; P. B. Denton et al. 2017; A. Albert et al. 2018; M. G. Aartsen et al. 2019), the existence of the Galactic neutrino flux has been established only recently, in three independent data sets (Y. Y. Kovalev et al. 2022; R. Abbasi et al. 2023a; A. Albert et al. 2023). The three results, obtained with different techniques and testing different parts of the Milky Way, demonstrate overall order-of-magnitude consistency with each other, as well as with the inference from observations of diffuse gamma rays by Tibet-ASγ (M. Amenomori et al. 2021) and LHAASO (Z. Cao et al. 2023), see, e.g., Figure 5 of S. Troitsky (2024) and discussion therein. However, considerable differences in best-fit normalizations are present even between different templates used by R. Abbasi et al. (2023a) for the search of the Galactic plane signal with IceCube cascade events. Moreover, a model-independent analysis of published IceCube tracks demonstrates (Y. Y. Kovalev et al. 2022) a significant Galactic excess at neutrino energies above 200 TeV, which does not match predictions of the templates both in the spectrum and in the spatial distribution of the signal. Studies of these tensions open up the possibility to improve contemporary models of the Galactic cosmic rays.

With a current instrumented volume of $\sim 0.6\,\mathrm{km}^3$ (and growing) and having better angular resolution thanks to the liquid water with respect to ice, Baikal-GVD is properly suited for studies of the Galactic neutrino signal at the highest neutrino energies. Here, we report on the observation of the Milky Way with Baikal-GVD cascade events above 200 TeV, consistent with Y. Y. Kovalev et al. (2022). We also consider new publicly available sets of IceCube cascade and track events above 200 TeV and find that the Galactic signal in these data is consistent with our results.

In Section 2, we briefly describe Baikal-GVD and its updated cascade data set. Section 3 describes the analysis of the data set and its results. In Section 4, we compare the Baikal-GVD Milky Way results with those obtained from IceCube data and discuss the astrophysical implications of our observation. Section 5 presents our brief conclusions.

2. Data

Baikal-GVD is the largest neutrino telescope currently operating in the Northern Hemisphere (latitude 51°.5N). Like other water Cerenkov instruments, it may detect neutrino-induced events as cascades and tracks, with very different sensitivities and analysis procedures. Details of the experiment, event selection, and analysis can be found, e.g., in V. A. Allakhverdyan et al. (2021, 2023a, 2024) and A. V. Avrorin et al. (2022), and we do not repeat them here.

The high-energy cascade sample was described by V. A. Allakhverdyan et al. (2023a). It contains events with reconstructed energies $E \geqslant 70$ TeV and the expected probability of their astrophysical origin $>50\%$, estimated from simulations. Compared to V. A. Allakhverdyan et al. (2023a), we add two more years of data collection. The telescope consists of clusters of optical modules, currently 13, with each cluster operated as an independent unit. Since the telescope is growing, with new clusters added every spring, these 2 yr almost doubled the exposure, which corresponds to $\approx$26.8 yr of one-cluster operation from spring 2018 to spring 2024.

Table 1
List of Baikal-GVD Cascades with Reconstructed Neutrino Energies $E \geqslant 200$ TeV, Observed in 2018–2023 Observational Seasons

Event ID	E (TeV)	l (deg)	b (deg)	r_{50} (deg)	r_{90} (deg)
GVD190517CA	1200	99.9	54.9	2.0	3.0
GVD210117CA	246	168.8	38.8	1.6	3.6
GVD210409CA	263	73.3	−6.1	3.3	6.3
GVD210418CA	224	196.8	−14.6	3.0	5.8
GVD221112CA	380	61.0	−4.7	2.9	7.7
GVD230518CA	214	199.0	4.7	2.3	4.7
GVD231006CA	245	76.9	5.3	2.3	5.1
GVD230611CA	479	15.2	36.2	2.6	5.2

Note. Presented are energies E, Galactic coordinates (l, b), and 50% CL and 90% CL accuracies of the determination of the arrival direction, r_{50} and r_{90}, respectively.

Following the previous study (Y. Y. Kovalev et al. 2022), we consider events with $E \geqslant 200$ TeV. Table 1 presents the list of eight events used in this analysis. In agreement with simulations, only one of these events comes from below the horizon, because the Earth becomes opaque for neutrinos of sub-PeV energies. Monte Carlo simulations indicate that about 64% of the events passing the selection criteria and having $E \geqslant 200$ TeV are expected to have astrophysical origins.

3. Search for Galactic Neutrinos

In the present study, we adopt the model-independent approach used by Y. Y. Kovalev et al. (2022). It does not rely on any assumptions about the origin and properties of the Galactic signal and tests only the excess of events from the Galactic plane. We introduce a single nonparametric test statistic, the median of the absolute value of the Galactic latitude, $|b|_{\rm med}$, calculated over the events sample. Following Y. Y. Kovalev et al. (2022), we use the events with best-fit reconstructed energies $E \geqslant 200$ TeV. The second selection cut of Y. Y. Kovalev et al. (2022), the area of the track direction error region in the sky, is irrelevant for the cascade events studied here. Therefore, the present study represents a direct test of the observation of Y. Y. Kovalev et al. (2022) with completely independent data.

To search for the possible excess of events from the Galactic plane, which would decrease $|b|_{\rm med}$, we compare the observed value of $|b|_{\rm med}$ with that expected for a distribution of arrival directions having no Galactic excess. This distribution is not isotropic because of the contributions of both atmospheric and extragalactic events, and further correction because of the nonuniform energy-dependent experimental exposure. However, for a continuously operating installation like Baikal-GVD, the Earth's rotation makes this distribution independent from the R.A. Therefore, reshuffling the R.A. values of observed events provides for a robust data-driven way to generate random sets of arrival directions, used multiple times in the analysis of data of various neutrino telescopes, see, e.g., V. A. Allakhverdyan et al. (2023b), R. Abbasi et al. (2023b), and A. Albert et al. (2024). In this way, we generate 10^5

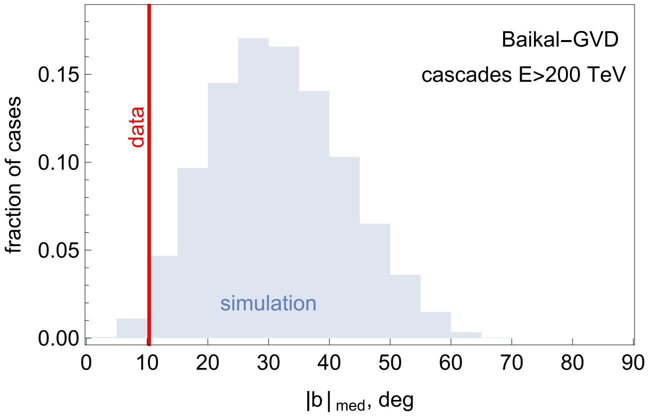

Figure 1. Distribution (shaded histogram) of the median $|b|_{\mathrm{med}}$ in simulated sets of Baikal-GVD cascades with $E \geqslant 200$ TeV. The observed value of $|b|_{\mathrm{med}}$ is shown by the vertical red line.

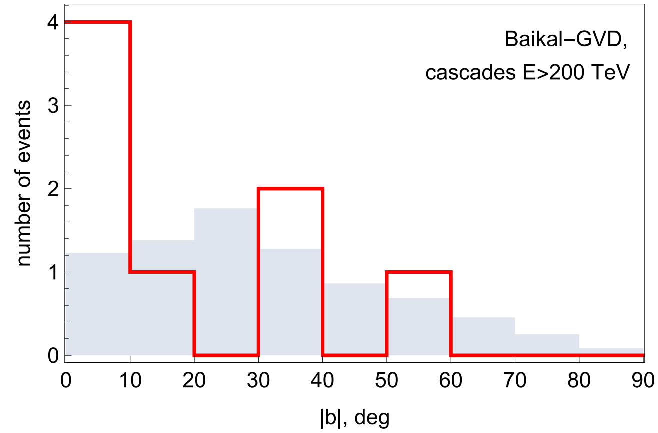

Figure 2. Observed (red line) and expected (shaded histogram) distribution of $|b|$ for Baikal-GVD cascades with $E \geqslant 200$ TeV.

artificial sets of eight events each and calculate $|b|_{\mathrm{med}}$ for each of them.

For the real data set, $|b|_{\mathrm{med}} = 10^{\circ}\!.4$, while the value expected from simulations is $\langle |b|_{\mathrm{med}} \rangle = 31^{\circ}\!.4$, which indicates the presence of the Galactic excess in the data, see Figure 1. To assess the significance of the excess, we estimate the fraction of realizations of simulated data sets for which the value of $|b|_{\mathrm{med}}$ does not exceed the observed one. This gives the p-value of the rejection of the hypothesis of the absence of the Galactic excess, $p = 1.4 \times 10^{-2}$, see Figure 1. Note that the study does not have any trials, therefore this value should be treated as the posttrial one. It is customary to illustrate the rejection p-values with corresponding significances for two-sided Gaussian distribution. Hereafter we quote these significances, keeping in mind that only p-values are meaningful for non-Gaussian statistics. The rejection of the absence of the Galactic excess with Baikal-GVD cascades would correspond to 2.5σ in this interpretation.

Given the size of the event sample, it would be difficult to measure the spectrum, and even the normalization, of the Galactic neutrino flux. For a very rough estimate, we examine the distribution of observed and simulated events in $|b|$, see Figure 2, and make use of the Poisson distribution to find the excess number of events with $|b| < 10^{\circ}$ to be $n_{\mathrm{MW}} = 2.8^{+3.2}_{-1.2}$. We compare it with the total expected number of astrophysical events in the sample, $n_{\mathrm{astro}} = 5.1$, and estimate the Galactic neutrino flux as the fraction of the total full-sky astrophysical neutrino flux measured by Baikal-GVD with cascades (V. A. Allakhverdyan et al. 2023a),

$$F_{\mathrm{MW}} = \frac{n_{\mathrm{MW}}}{n_{\mathrm{astro}}} \xi F_{\mathrm{astro}} = 4\pi 10^{-18} \phi_{\mathrm{MW}} \left(\frac{E}{100 \quad \mathrm{TeV}} \right)^{-\gamma},$$

with $\phi_{\mathrm{MW}} = 1.6^{+2.0}_{-0.9}$ GeV^{-1} cm^{-2} s^{-1} and $\gamma = 2.58^{+0.27}_{-0.33}$ (like in V. A. Allakhverdyan et al. 2023a, this is the total flux of neutrinos and antineutrinos per flavor, assuming flavor equipartition).

Here we introduced the coefficient ξ related to the difference in the exposures for $|b| < 10^{\circ}$ and isotropic astrophysical neutrinos, which have different distributions in the zenith angles. Unlike for the main analysis in terms of $|b|_{\mathrm{med}}$, here we use Monte Carlo (MC) simulations (V. A. Allakhverdyan et al. 2023a) of the atmospheric and astrophysical neutrinos to determine both ξ and the expected distribution in $|b|$ of non-Galactic events. We have verified that reshuffling the R.A. of real events gives quantitatively similar results, which are consistent with the MC-based estimates within the statistical uncertainties due to the limited number of events available for reshuffling.

4. Discussion

4.1. Comparison with IceCube Data at $E \geqslant 200$ TeV

Y. Y. Kovalev et al. (2022) studied a compilation of publicly available data on IceCube tracks with estimated energies $E \geqslant 200$ TeV and found a statistically significant excess from events from low Galactic latitudes. The present study confirms this result with the Baikal-GVD data. However, new IceCube sets of both cascades and tracks have recently become available for the public, and we use them to search for the Galactic neutrino component above 200 TeV by exactly the same method.

There are 12 high-energy starting cascade events (HESEs) with $E \geqslant 200$ TeV reported by R. Abbasi et al. (2023c) and IceCube Collaboration (2023a). Note that the astrophysical purity of the HESE data set at these energies, $\sim$95%, is higher than that for the Baikal-GVD set we use here, $\sim$64%, because of different selection cuts. At the same time, the total exposure of Baikal-GVD is 20.9 m^2 yr for this data set, while that of the IceCube HESE sample we use ($E \geqslant 200$ TeV) may be estimated as 176 m^2 yr based on the effective area (R. U. Abbasi et al. 2021) and the exposure time of 12 yr. Note that the HESE sample includes four starting tracks in addition to the 12 cascades we use here. The total numbers of events in both sets, 16 in HESE (expected 22.8) and eight in Baikal-GVD cascades (expected 8.3), agrees with the experiments' exposures at a 5% confidence level (CL) and 45% CL, respectively.[18]

Applying the procedure described in Section 3 to the IceCube HESE data set, we find a similar Galactic excess because the observed $|b|_{\mathrm{med}} = 12^{\circ}\!.4$, while the expected $\langle |b|_{\mathrm{med}} \rangle = 31^{\circ}\!.9$. The p-value for this excess $p = 8.7 \times 10^{-3}$ (2.6σ).

The recent public uniform compilation of high-energy IceCube track events is presented in the ICECAT catalog (R. Abbasi et al. 2023d; IceCube Collaboration 2023b),

[18] For the estimates in this paragraph, the best-fit power-law fluxes obtained from the HESE (R. U. Abbasi et al. 2021) and Baikal-GVD (V. A. Allakhverdyan et al. 2023a) samples are used.

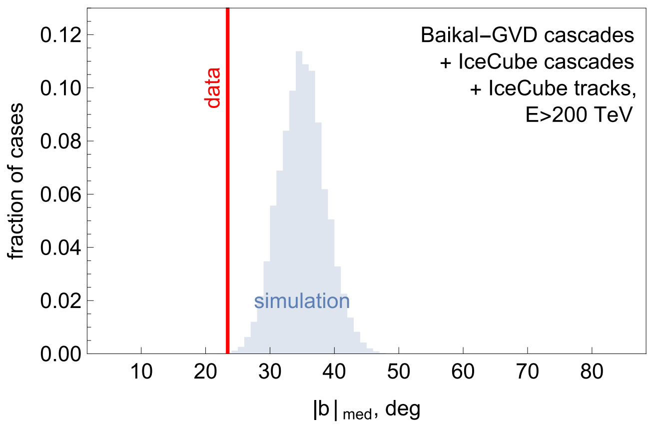

Figure 3. Distribution (shaded histogram) of the median $|b|_{\rm med}$ in simulated combined sets of Baikal-GVD cascades, IceCube cascades, and IceCube tracks with $E \geqslant 200$ TeV. The observed value of $|b|_{\rm med}$ is shown by the vertical red line.

Table 2
Results (This Work) of the Search for the Galactic Component of the Neutrino Flux above 200 TeV (see the Text for Details)

Sample	$\|b\|_{\rm med}$ Observed (deg)	$\langle\|b\|_{\rm med}\rangle$ Expected (deg)	p
Baikal-GVD cascades	10.4	31.4	1.4×10^{-2} (2.5σ)
IceCube cascades	12.4	31.9	8.7×10^{-3} (2.6σ)
Combined	12.4	31.5	1.7×10^{-3} (3.1σ)
IceCube tracks	24.7	36.0	1.8×10^{-3} (3.1σ)
All combined	23.4	35.0	3.4×10^{-4} (3.6σ)

recently updated to its version 2. Making use of the same cuts defined by Y. Y. Kovalev et al. (2022), that is, requiring the best-fit $E \geqslant 200$ TeV and the 90% CL area of uncertainty in the track direction below 10 deg^2, we are left with 67 events, with the average astrophysical purity of this sample ∼65%. This sample is not independent from that of Y. Y. Kovalev et al. (2022), having a considerable overlap, though the energies and directions reported in ICECAT were obtained with a different reconstruction procedure. Not surprisingly, this sample also demonstrates the Galactic excess, with the observed $|b|_{\rm med} = 24^\circ\!.7$, expected $\langle|b|_{\rm med}\rangle = 36^\circ\!.0$, and $p = 1.8 \times 10^{-3}$ (3.1σ).

We see that all three data sets, Baikal-GVD cascades, IceCube cascades, and IceCube tracks (all above 200 TeV), demonstrate the excess of events close to the Galactic plane, also visible in the sky map, see Section 4.2. We also perform a combined analysis of all three samples in the same manner, resulting in $p = 3.4 \times 10^{-4}$ (3.6σ), see Figure 3. For convenience, we collect the results of the three analyses performed here, and of their combination, in Table 2.

In each set, we estimate the fraction of events from the Milky Way in the total astrophysical neutrino flux above 200 TeV as described in Section 3 for cascades, $|b| < 10^\circ$, and in Y. Y. Kovalev et al. (2022) for tracks, $|b| < 20^\circ$. Making use of these fractions and the total fluxes measured in different analyses, we obtain rough estimates of the full-sky Milky Way neutrino flux at energies between 200 TeV and 1 PeV. Here, we use the astrophysical flux of V. A. Allakhverdyan et al. (2023a) for Baikal-GVD cascades, of R. U. Abbasi et al. (2021) for IceCube HESE events, of M. G. Aartsen et al. (2020) for lower-energy cascades, and of C. Haack & C. Wiebusch (2018) for IceCube tracks.[19] The flux estimates obtained in this way are collected in Table 3. One can see that our results for Baikal-GVD cascades, IceCube cascades, and IceCube tracks are in good agreement, given the uncertainties. Note that the statistical uncertainties in these flux estimates are large because of the low number of events associated with the Milky Way. We consider the results of the model-independent $|b_{\rm med}|$ test, see Table 2, as the main results of our study.

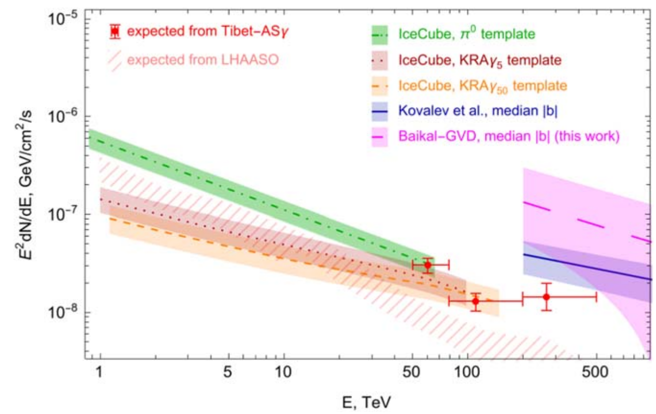

Figure 4. Estimated full-sky spectra of Galactic neutrinos (per one flavor of neutrino plus antineutrino) obtained in the present and in some of preceding studies, together with those expected from observations of diffuse Galactic gamma rays. See the plot legend for notations and S. Troitsky (2024) for details and further references.

Table 3
Integral Fluxes (in Units of 10^{-13} cm^{-2} s^{-1}) of Galactic Neutrinos with 200 TeV $< E <$ 1 PeV and the Galactic Fractions in the Total Astrophysical Flux (per Flavor) of Neutrinos at These Energies, Obtained in Different Analyses

Analysis	Flux	Fraction
Predicted by templates		
KRAγ_5	0.34	…
KRAγ_{50}	0.78	…
π^0	0.077	…
Templates normalized to IceCube (R. Abbasi et al. 2023a)		
KRAγ_5	$0.19^{+0.06}_{-0.05}$	$0.044^{+0.016}_{-0.014}$
KRAγ_{50}	$0.29^{+0.10}_{-0.09}$	$0.067^{+0.026}_{-0.024}$
π^0	$0.37^{+0.09}_{-0.08}$	$0.086^{+0.026}_{-0.025}$
Estimated by Y. Y. Kovalev et al. (2022)		
IceCube tracks	1.3 ± 0.5	0.28 ± 0.09
Estimated in the present work		
Baikal-GVD cascades	$3.9^{+5.0}_{-2.7}$	$0.52^{+0.60}_{-0.21}$
IceCube cascades	$1.0^{+1.2}_{-0.6}$	$0.26^{+0.30}_{-0.12}$
IceCube tracks	$0.9^{+0.7}_{-0.5}$	$0.22^{+0.15}_{-0.10}$

4.2. Implications

In Table 3, we also present the Galactic neutrino fluxes between 200 TeV and 1 PeV predicted in three spectral templates (M. Ackermann et al. 2012; D. Gaggero et al.

[19] Energies of ICECAT events were estimated (IceCube Collaboration 2023b) assuming this older spectrum.

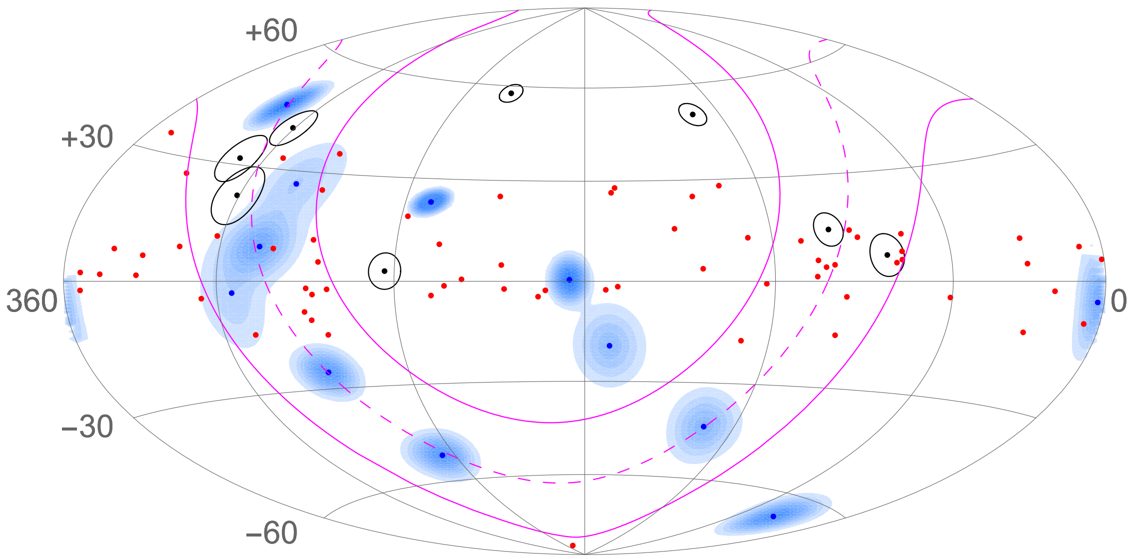

Figure 5. Arrival directions of Baikal-GVD (black projected circles of r_{90} radius) and IceCube (shading presenting the likelihood of the direction) cascade events, as well as IceCube track events (red dots) with $E \geqslant 200$ TeV in the sky map in equatorial coordinates. The dashed magenta line represents the Galactic plane, and two full magenta lines limit the zone $|b| < 20°$.

2015) assumed in IceCube studies (R. Abbasi et al. 2023a). The normalizations of the template spectra have been kept free by R. Abbasi et al. (2023a), and, in addition, we estimate the Galactic fluxes and fractions for the best-fit normalizations of the three templates. One can see a dramatic difference between the template predictions and our model-independent results above 200 TeV: previously used spectral templates underpredict the Galactic neutrino flux at these energies.

One of the strongly motivated mechanisms for the production of Galactic neutrinos assumes interaction of energetic cosmic rays with ambient matter, which are saturated by pi-meson production. While decays of charged $\pi^{\pm}$ give birth to the neutrinos, their neutral counterparts π^{0} decay to energetic photons, so the fluxes of the two messengers become related, see, e.g., S. Troitsky (2021) and references therein. Unlike from extragalactic sources, these photons reach us from the Milky Way with modest to no attenuation. Diffuse fluxes of such very energetic Galactic gamma rays have been observed by the Tibet-ASγ (M. Amenomori et al. 2021) and LHAASO (Z. Cao et al. 2023) experiments.

Figure 4 presents the observed Galactic neutrino flux from Baikal-GVD cascades, estimated in the present work, together with expectations from Tibet-ASγ and LHAASO observations (see K. Fang & K. Murase 2023 and S. Troitsky 2024 for details), in the assumption of the common origin of both neutrinos and photons in the proton collisions. The difference between two experiments in the gamma-ray fluxes at high energies may be related to different masks imposed to cut point sources of high-energy emission. In this case, the fact that the Milky Way neutrino emission better fits the expectations from Tibet-ASγ than those from LHAASO might indicate that the Galactic neutrino emission above 200 TeV comes, at least partially, from individual sources, Galactic PeVatrons. Indeed, the sky map of the neutrino events studied here, Figure 5, suggests some clustering of cascade events toward the Cygnus region, which also manifest itself in gamma rays (M. Amenomori et al. 2021). Moreover, recently LHAASO detected significant gamma-ray flux in a $\sim 6°$ size halo Cygnus region with gamma rays up to to PeV energies distributed across this region (Z. Cao et al. 2024). ICECAT has very low exposure toward this region at high energies, so it is hardly possible to test this concentration with IceCube tracks.

5. Conclusions

By analyzing cascade events with estimated neutrino energies above 200 TeV, observed by Baikal-GVD during 6 yr of operation, we find the concentration of events toward the Galactic plane, indicating the presence of a large Galactic component in the high-energy astrophysical neutrino flux, with the p-value of the absence of the Galactic component of $p = 1.4 \times 10^{-2}$ obtained in a nonparametric, model-independent approach. The estimated Galactic neutrino flux above 200 TeV matches the one obtained by Y. Y. Kovalev et al. (2022) for IceCube tracks in the same energy range. We test that the similar results hold for the most recent publicly available IceCube samples of both cascades and tracks, with the p-value of 3.4×10^{-4} obtained in the combined analysis of the three samples by the same method.

The Galactic neutrino flux agrees with the expectations from the gamma-ray diffuse Milky Way emission observed by Tibet-ASγ, though a direct comparison requires model-dependent assumptions. The neutrino flux is somewhat higher than similar expectations from LHAASO observations. This may indicate that the neutrino emission is not purely diffuse, and some part of it comes from localized, pointlike or extended, sources, masked in the LHAASO analysis. The Cygnus region, seen in the neutrino sky map, may host some of them (A. M. Bykov et al. 2021; R. Abbasi et al. 2022; W. Li et al. 2024; A. Neronov et al. 2024).

The Galactic neutrino component at very high energies is so prominent that it is clearly detected despite low statistics. The fraction of Galactic events in the total astrophysical flux above 200 TeV reaches several tens of percents, which is in disagreement with the assumptions of many model-dependent analyses, including that of R. Abbasi et al. (2023a). Together with the distribution of observed arrival directions in the sky, which suggested (Y. Y. Kovalev et al. 2022) a wider Milky Way in neutrinos than predicted by models, this observation challenges contemporary scenarios of cosmic-ray acceleration and propagation in the Galaxy. As has been previously pointed out by Y. Y. Kovalev et al. (2022) and S. Troitsky (2024), explaining this shape may require significant contribution of neutrinos from the local origin to the total flux, see K. J. Andersen et al. (2018), A. Neronov et al. (2018), and G. Giacinti & D. Semikoz (2023).

Baikal-GVD continues to collect data, gradually increasing its instrumented volume. The upcoming Baikal-GVD data sets, including track-like events, as well as data from the other neutrino telescopes, promise exciting prospects to test the intriguing observations presented here.

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References

Aartsen, M. G., Abbasi, R., Abdou, Y., et al. 2013, Sci, 342, 1242856
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2019, ApJ, 886, 12
Aartsen, M. G., Ackermann, M., Adams, J., et al. 2020, PhRvL, 125, 121104
Abbasi, R., Ackermann, M., Adams, J., et al. 2022, ApJL, 930, L24
Abbasi, R., Ackermann, M., Adams, J., et al. 2023a, Sci, 380, adc9818
Abbasi, R., Ackermann, M., Adams, J., et al. 2023b, ApJ, 954, 75
Abbasi, R., Ackermann, M., Adams, J., et al. 2023c, ICRC (Nagoya), 38, 1030
Abbasi, R., Ackermann, M., Adams, J., et al. 2023d, ApJS, 269, 25
Abbasi, R. U., Ackermann, M., Adams, J., et al. 2021, PhRvD, 104, 022002
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2012, ApJ, 750, 3
Albert, A., André, M., Anghinolfi, M., et al. 2018, ApJL, 868, L20
Albert, A., Alves, S., André, M., et al. 2023, PhLB, 841, 137951
Albert, A., Alves, S., André, M., et al. 2024, ApJ, 964, 3
Allakhverdyan, V. A., Avrorin, A. D., Avrorin, A. V., et al. 2021, EPJC, 81, 1025
Allakhverdyan, V. A., Avrorin, A. D., Avrorin, A. V., et al. 2023a, PhRvD, 107, 042005
Allakhverdyan, V. A., Avrorin, A. D., Avrorin, A. V., et al. 2024, MNRAS, 527, 8784
Allakhverdyan, V. A., Avrorin, A. D., Avrorin, A. V., et al. 2023b, MNRAS, 526, 942
Amenomori, M., Bao, Y. W., Bi, X. J., et al. 2021, PhRvL, 126, 141101
Andersen, K. J., Kachelrieß, M., & Semikoz, D. V. 2018, ApJL, 861, L19
Avrorin, A. V., Avrorin, A. D., Ayinutdinov, V. M., et al. 2022, JETP, 134, 399
Bykov, A. M., Petrov, A. E., Kalyashova, M. E., & Troitsky, S. V. 2021, ApJL, 921, L10
Cao, Z., Aharonian, F., An, Q., et al. 2023, PhRvL, 131, 151001
Cao, Z., Aharonian, F., An, Q., et al. 2024, SciBu, 69, 449
Chen, C.-Y., Bhupal Dev, P. S., & Soni, A. 2015, PhRvD, 92, 073001
Denton, P. B., Marfatia, D., & Weiler, T. J. 2017, JCAP, 2017, 033
Fang, K., & Murase, K. 2023, ApJL, 957, L6
Gaggero, D., Grasso, D., Marinelli, A., Urbano, A., & Valli, M. 2015, ApJL, 815, L25
Giacinti, G., & Semikoz, D. 2023, arXiv:2305.10251
Haack, C., & Wiebusch, C. 2018, ICRC (Busan), 35, 1005
IceCube Collaboration 2023a, IceCube HESE 12-year Data Release, v2, Harvard Dataverse, doi:10.7910/DVN/PZNO2T
IceCube Collaboration 2023b, ICECAT-1: IceCube Event Catalog of Alert Tracks, v4, Harvard Dataverse, doi:10.7910/DVN/SCRUCD
Kovalev, Y. Y., Plavin, A. V., & Troitsky, S. V. 2022, ApJL, 940, L41
Li, W., Huang, T.-Q., Xu, D., & He, H. 2024, ApJ, 969, 6
Neronov, A., Kachelrieß, M., & Semikoz, D. V. 2018, PhRvD, 98, 023004
Neronov, A., & Semikoz, D. 2016a, PhRvD, 93, 123002
Neronov, A., & Semikoz, D. 2016b, APh, 75, 60
Neronov, A., Semikoz, D., & Savchenko, D. 2024, PhRvD, 110, 043024
Neronov, A., Semikoz, D. V., & Tchernin, C. 2014, PhRvD, 89, 103002
Palladino, A., Spurio, M., & Vissani, F. 2016, JCAP, 12, 045
Palladino, A., & Vissani, F. 2016, ApJ, 826, 185
Troitsky, S. 2015, JETPL, 102, 785
Troitsky, S. 2021, PhyU, 64, 1261
Troitsky, S. 2024, Phys.-Usp., 194, 371