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Origin of high-energy astrophysical neutrinos: new results and prospects

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Contents

Abstract. **High-energy neutrino astrophysics is developing intensively, and new and exciting results have been obtained in the last two years. Among them are the confirmation of the existence of a diffuse flux of astrophysical neutrinos by the new independent Baikal-GVD experiment, the discovery of neutrino emission in our Galaxy, new confirmations of the connection of some astrophysical neutrinos to blazars, and much more. This brief review, based on the author's presentation at the session of the RAS Physical Science Division, "Gamma quanta and neutrinos from space: what we can see now and what we need to see more," summarizes the results obtained since the publication of the review [*Phys. Usp.* 64 1261 (2021)] and can be considered a companion to it.**

Keywords: high-energy astrophysics, neutrino astrophysics, multi-messenger astronomy

1. Introduction

The study of astrophysical high-energy (TeV to PeV) neutrinos is presently at the stage of intensive development. The IceCube neutrino telescope, currently the largest, has amassed enough statistics to make conclusions about astrophysical sources of neutrinos, while Baikal-GVD and KM3NeT have quickly increased their volumes and have started to produce their first data. However, in view of the new results, questions about the origin of these neutrinos are more abundant than answers.

Here, we attempt to summarize numerous new (published after Ref. [1], that is, in 2022–2023) results in the field of high-energy neutrino astrophysics, as well as long-term plans for the field's development. A broader review of the subject, and of the results obtained up to and including 2021, can be found in [1]. A large part of the results mentioned in [1] are not discussed here, and references to them are not duplicated in order not to clutter up the present paper.

2. Experimental news

Let us first focus on significant advances in experiments that detect high-energy neutrinos. The results on astrophysical sources will be discussed in the following sections.

2.1 Baikal-GVD

Baikal-GVD, the largest neutrino telescope in the Northern Hemisphere, continues to increase its effective volume by gradually adding new clusters of optical modules (as of 2023, 12 clusters are operating, one of which is partially complete). Also, additional strings located in space between clusters were added to the configuration of the experiment. They should work to improve registration efficiency and the accuracy of determining neutrino parameters. In 2022, the first results of the experiment

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Table 1. Parameters of power-law fits (1) of the diffuse astrophysical neutrino spectrum from 2022–2023 analyses.

Analysis	Energies	Φ_0	γ
Baikal-GVD, upgoing cascades [2]	15 – 100 TeV	$3.04^{+1.52}_{-1.27}$	$2.58^{+0.27}_{-0.33}$
IceCube combined [3]	2.5 TeV – 6.3 PeV	$1.80^{+0.13}_{-0.16}$	2.52 ± 0.04
IceCube, starting tracks [4]	3 – 550 TeV	$1.68^{+0.19}_{-0.09}$	$2.58^{+0.10}_{-0.09}$

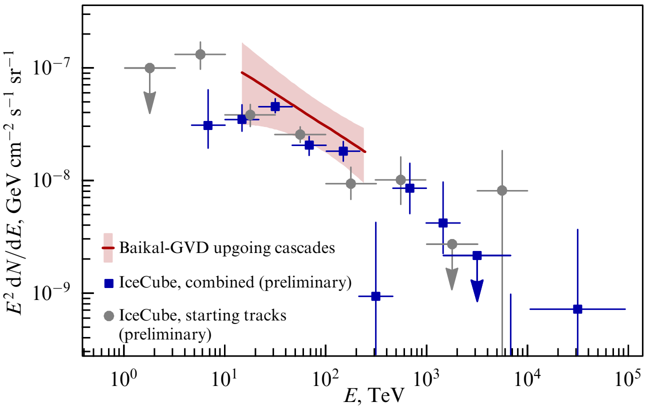

Figure 1. Spectra of diffuse astrophysical neutrinos (one flavor, the sum of neutrinos and antineutrinos), obtained in 2022–2023 analyses.

working in an incomplete configuration (2018–2021) were published.

A principal achievement, not only of the Baikal experiment but also of all of neutrino astronomy, was the confirmation of the very existence of high-energy astrophysical neutrinos. All previous studies of neutrinos were based on the results of one experiment, IceCube, which is not free, like any other, from systematic uncertainties. Based on the analysis of two samples of Baikal-GVD cascade neutrino events with the highest probability of an astrophysical origin, the hypothesis of the absence of astrophysical neutrino flux was rejected [2] with a statistical significance of 3.05σ. The first sample included 16 events with reconstructed energies above 70 TeV (the highest energy was 1200 TeV). For the second one, the lower energy limit of 15 TeV was used, but only events with arrival directions from below the horizon were selected, which significantly reduced the atmospheric background. Eleven such events were recorded, of which two had energies above 70 TeV and therefore were included in both samples. The below-horizon event with the highest energy, 225 TeV, arrived from a remarkable direction in the sky (see below in Section 3.1).

Recall that the standard parametrization of the spectrum of the isotropic diffuse flux of one-flavor neutrinos and antineutrinos with a power-law function is given by

$$\frac{\mathrm{d}F_{\nu+\bar{\nu}}}{\mathrm{d}E} = \Phi_0 \left(\frac{E_\nu}{100\ \mathrm{TeV}} \right)^{-\gamma} \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\,. \tag{1}$$

Traditionally, the analysis assumes equal fluxes of neutrinos of different flavors, so the total flux is obtained by multiplying Eqn (1) by three. Parameters Φ_0 and γ, obtained by Baikal-GVD, are given in Table 1, which can be considered a supplement to Table 3 of Ref. [1]. There, parameters obtained in two new IceCube analyses, discussed below, are also presented.

Figure 1 demonstrates that the spectrum obtained in the Baikal-GVD analysis agrees well with IceCube's results. This result is important, not only because it is obtained by a different team's independent analysis, but also because the two experiments differ significantly in sensitivity to different regions of the sky (Southern and Northern Hemispheres) and in methodology (ice and liquid water; see [1] for details).

2.2 Experiments in the Mediterranean Sea: ANTARES and KM3NeT

Another group of experiments detects neutrinos in the liquid water of the Mediterranean Sea. The ANTARES experiment completed its multi-year operation in 2022, when the working volume of its upcoming replacement, the large KM3NeT detector ARCA, exceeded the volume of ANTARES. Final publications based on the full ANTARES dataset are expected in the near future: some of the results are mentioned in Sections 3.1 and 4.1. Although KM3NeT already exceeds ANTARES by its volume, it is still small compared to IceCube and Baikal-GVD and has not yet reached sufficient exposure to detect the astrophysical diffuse neutrino flux. The experiment is increasing its working volume; at the end of 2022, it started to produce its first astrophysical results.

2.3 IceCube

The IceCube experiment has been in operation since 2008, and the main astrophysical results on high-energy neutrinos are still based on its data. In addition to increasing the data set, the IceCube team is working to improve the quality of event reconstruction and the accuracy of determining neutrino energies and arrival directions. The new reconstructions are expected to account for ice properties more precisely. Machine learning techniques have started to be applied for astrophysical analyses at the stage of reconstruction of individual IceCube events.

At the ICRC2023 conference, the IceCube experiment presented two new preliminary analyses of diffuse fluxes of astrophysical neutrinos (see Table 1 and Fig. 1). In particular, for the first time, a spectrum was constructed [3], which combines the information from different observing channels, including cascades and tracks, selected and processed in different ways. In contrast to previous analyses, the quality of the fit of the spectrum by a broken power-law function is slightly better than that by a single power law.

Another new spectrum [4] is based on the analysis of the tracks starting in the detector. This method of selection eliminates atmospheric muons efficiently, although, of course, it leaves atmospheric neutrinos in the sample. To isolate the latter contribution, statistical methods are used. This allows advancing to lower energies in the astrophysical flux estimation. Note some discrepancy with the combined spectrum at low energies (see Fig. 1). When the starting-track spectrum is fitted with a broken power law, it even produces a break in the opposite direction, although this effect is not statistically significant. The problem of disagreement of the spectra obtained in different analyses, discussed in detail in [1], retains its relevance.

Recently, several publicly available data sets related to the arrival directions of IceCube events have been released.

- *Catalog of alert and 'alert-like' track events, IceCat-1* [5]. Following the publication of its well-known result [6] related to the coincidence of a high-energy neutrino event with the gamma-ray flare of the blazar TXS 0506 + 056, IceCube revised criteria for selecting and reconstructing public alerts, which are issued to inform the world's observatories about high-probability astrophysical neutrinos. The first-generation alerts were published in 2016–2018, and new ones, starting in 2019. The catalog [5] presents some of these new alerts together with results of the reprocessing of earlier events with the same new procedure. Events which satisfy the new alert criteria were selected from the old data, so that a homogeneous sample of 275 events was obtained. An important innovation is the inclusion of a veto related to the triggering of a surface-mounted unit that allows certain events which have a high probability of being atmospheric to be excluded. The catalog includes events from May 2011 through December 2019 (the experiment has been running since 2008). It is presumed that information on newer events will be added to the online version of the catalog.
- *Updated arrival directions of high-energy starting events* (*HESE*) [7]. This is another reprocessing of the entire dataset using a new reconstruction procedure that should take into account the properties of ice in the IceCube detector volume in a more correct way. Best-fit arrival directions and their (irregularly shaped) uncertainty regions in the sky are given for 164 events.
- *Map of the Northern sky constructed from track events.* The numerical likelihood function used in the work on searching for neutrinos from the NGC 1068 galaxy ([8]; for details, see Section 3.2) was presented. As in previous similar papers, this function, defined on the celestial sphere, is related to the probability of detecting a local source of astrophysical neutrinos in this direction. It accounts both for the number of events coming from this direction and for their energies (the higher the energies, the higher the probability of an astrophysical neutrino origin).
- *Sky map of cascade events.* A similar likelihood function has also been published in connection with the observation of the neutrino emission from the Galactic plane ([9]; see Section 4.1). Cascade events were used for its construction.

Being openly accessible, these data can be utilized by researchers not affiliated with IceCube for new analyses and hypothesis testing (see, however, Sections 2.4 and 3.4).

2.4 New data, old challenges

The application of new, refined methods of statistical analysis of raw data and of reconstruction of track and cascade events leads to a significant reduction in statistical uncertainties of the arrival directions, and for cascades, also of the neutrino energy. With these developments, it is becoming more and more clear that the accuracy of reconstruction of neutrino properties is limited by systematic uncertainties. This manifests itself, in particular, in the differences among directions and energies obtained for the same events using different reconstructions (see, e.g., illustrations in [1]). For the IceCube experiment, one of the main sources of the uncertainty is the lack of knowledge of properties of the ice, that is, of the medium in which the detected signal is formed and propagates. Recently, IceCube publications started to present descriptions of how the systematic errors are taken into account in the data and to discuss approaches to reducing these uncertainties [10–12]. Presently, arrival directions of IceCube events with a high probability of an astrophysical origin are obtained using a simplified algorithm. For only one event [13] was the reconstruction performed under assumptions of different models of ice properties. Obtained for this particular event, the systematic error was translated, following certain rules [10], to all neutrino alerts. The use of this procedure was motivated by the fact that multiple repetitions of simulations with different assumptions about the ice properties, even for a small number of the most interesting events, required too much computer resources. Relatively recently, full simulations were performed for several events, and have predictably shown that the actual reconstruction uncertainty due to insufficient knowledge of ice properties may be either smaller or larger than that estimated with the simplified method [10]. The IceCube team is working on a solution to this problem [11].

Developing an efficient approach for estimating systematic uncertainties in the reconstruction of individual events remains a task for the future. Current published properties of IceCube events, including those in the catalog [5], were obtained in the simplified way described above. For practical purposes, additional systematic error can be accounted for by artificially increasing the statistical uncertainty [14, 15]. Thanks to the greater homogeneity of liquid water than of ice and to the relative technical simplicity of controlling its properties, systematic uncertainties are expected to be less significant for other detectors. However, the same challenges remain relevant for all instruments.

Issues related to modeling uncertainty become very serious in the context of the increasing use of machine-learning techniques for event reconstruction (for more details, see Section 3.4).

3. Extragalactic neutrinos

Most probably, a large part of astrophysical high-energy neutrinos come from extragalactic sources. New data and analyses confirm the origin of a significant fraction of high-energy astrophysical neutrinos in blazars (Section 3.1). At the same time, other extragalactic sources (Sections 3.2 and 3.3), as well as our Galaxy (Section 4), also contribute to the neutrino flux.

3.1 Neutrinos from blazars

Recall that blazars are powerful active galactic nuclei with relativistic jets directed at the observer. The radiation produced in the jet has a larger intensity for the observer because of the relativistic effects, and this puts blazars among the brightest sources of non-thermal radiation in the Universe. The most universal marker of a relativistic jet directed to the observer is provided by the synchrotron radiation of relativistic electrons at parsec scales, visible in the radio band with very-long baseline radio interferometry (VLBI). Not all blazars are gamma-ray sources, although among extragalactic sources of high-energy gamma rays, they constitute the dominant population.

3.1.1 Highest-energy neutrinos

New neutrino events: a direct test of the hypothesis. The statistical relationship between IceCube neutrino events and the population of blazars from the VLBI-selected sample was

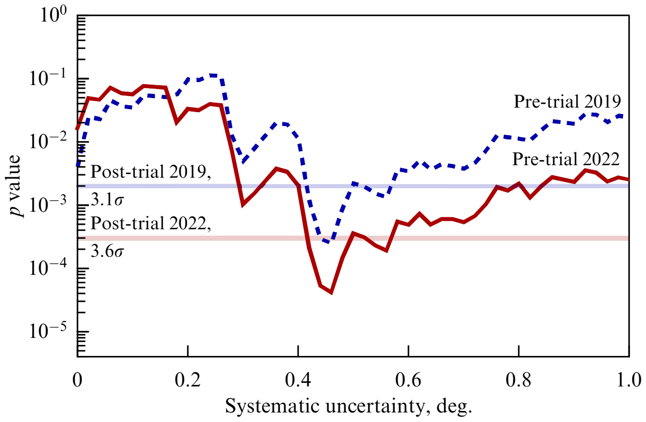

Figure 2. Probability of the null hypothesis of a random coincidence of high-energy neutrinos with radio blazars for data sets before 2019 [14] and before 2022 [16] for various estimated values of additional systematic error (pre-trial). Horizontal lines indicate significance obtained taking into account the choice of this value (post-trial).

found in Ref. [14] for events with energies above 200 TeV, the data on which were published up to and including 2019. The events collected in 2020–2022 have been analyzed by the same method in Ref. [14]. The same event selection criteria and the same procedure of the analysis, established in Ref. [16], were used. Fifteen new events have been added to the sample of 56 neutrinos used in [14]. The statistical significance of the association of neutrinos with energies above 200 TeV with blazars increased from 3.1σ to 3.6σ (Fig. 2). This result is a direct confirmation of the results of [14]; the proportion of new blazar associations [16] among neutrinos is consistent with that expected from [14].

Repeated neutrinos from the same blazars. The accumulation of IceCube statistics, as well as the start of new experiments Baikal-GVD and KM3NeT, resulted in observations of several neutrino events with the arrival directions coinciding with one and the same blazar. Let us focus on a few notable cases (Fig. 3).

PKS 1741-038. One of the most powerful radio blazars in the sky, it was highlighted [14] among the four most likely sources of neutrinos based on the coincidence with the IC110930 neutrino event[1] and on high flux density of the radio emission from a compact component. In 2022, from the same direction, another neutrino, IC220205, arrived that satisfied all the selection criteria used in [14, 16].

TXS 0506 + 056. The association of this blazar with event IC170922 (~ 290 TeV) started the history of observational associations between blazars and neutrinos [6]. Both this neutrino event and this blazar were included in the sample of Ref. [14]. At the end of 2022, the Baikal-GVD experiment reported in [17] a coincidence of the cascade event GVD210418CA with the same blazar. This is the event with the highest energy (225 ± 75 TeV) among the cascades coming from directions below the horizon, registered by Baikal-GVD in 2018–2021. The estimated probability of its astrophysical origin is 99.67%. Although the uncertainty of the arrival direction of this event (6.0°, 90% CL) is significantly larger than that of IceCube tracks, it is several times smaller than that of cascades in ice. This allows us to speak about the beginning of neutrino point-source astronomy in the cascade channel.

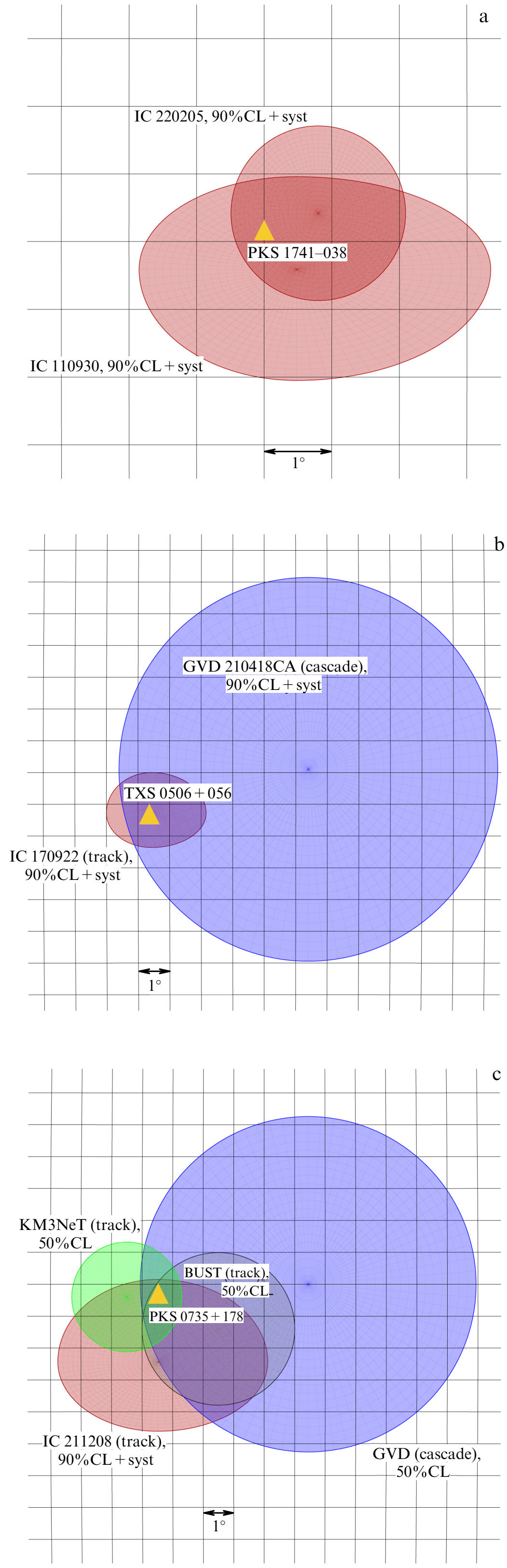

Figure 3. Arrival-direction error contours for neutrinos associated with blazars (a) PKS 1741–038, (b) TXS 0506+056, (c) PKS 0735+178 (see text).

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[1] Event identifiers indicate the experiment, IC — IceCube, GVD — Baikal-GVD, and the date of detection. For track events, only the most probable value of the neutrino energy is given, errors of determination of which are huge [1, 6].

PKS 0735 + 178. This source attracted attention after the IC211208 event (~ 171 TeV). Although the event did not meet the selection criteria established in [14] (the energy was below 200 TeV) and therefore has not been used in any statistical analysis, it coincided with a historical blazar flare, recorded in all bands, from radio to gamma rays. During the days of the December 2021 flare, neutrino events were recorded by all high-energy neutrino telescopes operating on Earth — in addition to IceCube, they are Baikal-GVD [18, 19], the Baksan Underground Scintillation Telescope (BUST) [20, 21], and KM3NeT [22]. Neutrinos from this blazar have been discussed, in particular, in [23–25]. It is worth noting that, although BUST has a small geometric volume and detects tracks of upgoing muons from neutrinos with an energy threshold of 1 GeV, i.e., orders of magnitude lower than those discussed here, its effective volume quickly grows with neutrino energy, and the registration of one event per flare in BUST is consistent with one IceCube event [21], assuming a steeply falling neutrino spectrum of the source.

Other samples of IceCube events or blazars. As was discussed in [1], statistically significant associations of high-energy neutrinos with blazars were also found in Ref. [26] that used selection criteria for events and blazars different from [14]. The sample of neutrino events from [26] (2009–2019) was again used in Ref. [27] to find associations with sources selected by fluxes in various bands, mostly blazars. The results of this study confirm the overall trend, including neutrino connection to flat-spectrum radio sources selected by the flux at 8 GHz. Unlike other studies, the most efficient selection criterion of blazars on the basis of VLBI data was not used here: the sample was selected from the CRATES catalog constructed on the basis of observations without the use of radio interferometry. About 4% to 42% of neutrinos in the sample [26] can be associated with CRATES selected blazars (90% CL interval), which is consistent with other estimates.

In 2023, the updated catalog of IceCube events having a high probability of astrophysical origin, IceCat-1, was published [5]. It contains events from 2011 through 2019, to which new reconstruction algorithms, currently used for alerts, were retroactively applied. Reconstructed arrival directions and energies of previously published events changed, in some cases significantly; many new events have also been added. Using this catalog for an analysis similar to [14], with direct application of the criteria from [14], results in a decrease [28] in the significance of associations between neutrinos and radio blazars compared to the original work (see discussion below in Section 3.4).

3.1.2 All observed neutrinos

Radio blazars as TeV to PeV neutrino sources. The relation between lower-energy neutrinos and radio blazars from the same VLBI-selected sample was established statistically [29] on the basis of the published likelihood-function map containing generalized information about the arrival directions of all IceCube track events for the first 7 years of work. It was demonstrated that about 25% of the flux of astrophysical muon neutrinos is associated with the population of blazars with a radio bright compact component. Separate events have been published for the 10-year dataset in another reconstruction. For this catalog, and using another analysis procedure, no directional correlations between neutrinos and blazars were found [30], so that the upper limit on the fraction of neutrinos from blazars was set at $< 30\%$. This is in agreement with [29]; see also the discussion in [31] and Section 3.4 below.

Therefore, statistical analyses indicate that neutrinos, both of the highest and of somewhat lower energies, are related to one and the same population of blazars. The number of blazars in the sample is large, and individual sources are quite different. To understand the mechanisms of neutrino production, it is important to identify whether neutrinos with a broad energy spectrum are born in the same blazars, or different source populations are responsible for different neutrino energy ranges. Some progress in addressing this issue comes from Ref. [32], which established a statistically significant (3.6σ) correlation between matching a high-energy neutrino from the sample [16] to a radio blazar and the presence of additional lower-energy neutrinos arriving from the same direction at the same time (± 1 day). It is likely that the same blazars can produce neutrinos of significantly different energies.

Analyses based on other samples. The relation between *all* events registered by large neutrino telescopes and blazars is being confirmed using other data. Specifically, the ANTARES collaboration obtained in [33] indications (2.2σ significance) of the presence of a spatial correlation of arrival directions of events registered during the operation period of the experiment, with the same catalog of radio blazars that was used in [14, 16, 29]. In addition to this, a search was also conducted for neutrino flares from the directions of these blazars. The most notable one was the excess of events from the blazar PKS 0242+1101 in 2013: a high-energy neutrino registered by IceCube came at the same time from the same direction, and the blazar experienced a powerful flare both in gamma rays (Fermi LAT) and in the radio band (OVRO).

Other selection criteria, primarily based on optical spectra, formed the basis of the BZCAT catalog of blazars used in [34, 35]. Although this sample is not complete by any criterion (in particular, sources are distributed unevenly across the sky), it is expected to have a very low level of contamination by non-blazar objects. Reference [34] considered track events from the Southern sky, i.e., those which, for IceCube, come from directions above the horizon. The likelihood function map based on 7 years of IceCube data was used — the same as was used in [29] for the Northern sky. The level of atmospheric muon contamination for events coming above the horizon is very high, so the maps for the Northern and Southern skies were constructed in different ways: for the Southern part, higher weight was given to the most energetic events, for which the probability of an astrophysical origin is higher. In [34], a rather involved method was applied in which ‘hot spots,’ that is, several directions with a high probability of the location of the neutrino source, were first identified in the Southern neutrino sky, and then those directions were tested for the presence of blazars. The association of neutrino ‘hot spots’ with blazars was established at a confidence level of 4.7σ. As for the Northern sky, the same authors used a different dataset [35], namely, the updated likelihood map published along with the result [8]. The same conclusion was reached but with a significance of 2.7σ. Note that using one and the same dataset for the Southern and Northern skies does not bring significant results for the latter [36] (see Section 3.4 for more details).

Theoretical implications. Production of neutrinos with energies ranging from TeV to PeV in the same sources, radio-bright blazars, is probably related to the interaction of protons, accelerated to energies about 20 times those of neutrinos, with X-ray photons (for more details, see [1]). The maximal probability of the birth of neutrinos with $\sim$ PeV energy corresponds to the interaction of protons with photons of ultraviolet light, but, for lower energies of neutrinos, hard X-ray photons are required. Thus, observational results suggest that neutrinos are born in those parts of blazars where photons with energies in a wide range are sufficiently abundant. On the other hand, the connection between neutrino detection and the flux of a compact radio source, monitored by VLBI, indicates that neutrinos are produced within a few parsecs from the central black holes of blazars.

Not many mechanisms have been described in the literature that satisfy these requirements, the most stringent of which is the presence of a sufficient amount of X-ray photons. Hard X-ray radiation from blazars is often associated with Compton scattering of relativistic electrons on the photons of their own synchrotron radiation, exactly the kind of radio emission that is responsible for the VLBI flux; so, it has been suggested [29] that the region of neutrino production coincides with the region where the compact radio emission comes from. Further development of this mechanism allowed constructing [37] a realistic two-zone model in which protons are accelerated near black holes but interact with Compton photons in the so-called millimeter blazar core, an area near the base of the jet that makes the main contribution to the VLBI flux in the millimeter band [38]. In such a mechanism, the neutrino flux from a single blazar turns out to be relatively small, which agrees well with the estimates of the number of high-energy neutrino sources and with the lack of correlations between neutrinos and high-energy gamma-ray emission from blazars, discussed in [1].

One of the predictions of models in this class is the large flux of hard X-ray emission of those blazars which are associated with neutrinos, in particular with those of the highest energies. This prediction has recently received observational confirmation [39].

3.2 Neutrinos from Seyfert galaxies

Another isolated individual neutrino source was associated with the M 77 galaxy, aka NGC 1068. This galaxy combines signs of nuclear activity (Seyfert type 2) and intense star formation. In [8], the IceCube collaboration rejects the hypothesis of the absence of neutrino association with this galaxy at a statistical significance of 4.2σ. Interpretation of this value is not straightforward because of the fact that, by itself, the significance of a neutrino hot spot in the direction close to NGC 1068 in a full-sky scan is [8] 2.0σ. The significance increases if the scan across the whole sky is replaced by a catalog of 110 'probable sources' compiled following rather arbitrary rules (for a more detailed discussion of this approach, see [1]). IceCube has been using such catalogs for some time, but it should be noted that the list has been significantly expanded when moving from the 2016 analysis [40] to the 2019 analysis [41]. In particular, in Ref. [41], NGC 1068 has been added to the list, along with 7 other galaxies with intense star formation, and in the very same paper, an excess of events from this direction in a full-sky scan was first detected. Since the events from 2011 to 2020 were used in [8], the use of the term 'a priori fixed catalog' in the context of the NGC 1068 source, included in 2019, is perhaps not fully justified.

Another unexpected difference between this and other sources, a very soft spectrum, is worth noting. It is well known that isolating the contribution of astrophysical neutrinos from the atmospheric background is possible only statistically and is based on the distributions in the zenith angle and, most importantly, the energy (see [1]). Most atmospheric events have a soft spectrum with the power-law index ≈ 3.7, while, for astrophysical neutrinos, one expects values of the index between about 2.0 and 2.7. In the analysis of events from NGC 1068, a value of the power-law index of 3.2 ± 0.2 was obtained [8], that is, the astrophysical origin of the neutrino excess is deduced mainly from the concentration of the neutrinos' arrival directions in a small region of the sky, not from their high energies.

Seyfert galaxies, as well as galaxies with intense star formation, are numerous, and the natural question arises about the contribution of other representatives of the same source classes to the neutrino flux. There are, for example, other similar nearby galaxies — are they neutrino sources? This question is explored in Ref. [42]. There, a list of nearby galaxies similar to NGC 1068 was constructed and their expected neutrino luminosities were estimated. Taking into account these luminosity estimates and positions in the sky, it was found that IceCube's current sensitivity should be sufficient to detect a neutrino signal only from two more galaxies (besides NGC 1068 itself), NGC 4151 and NGC 3079. The authors analyzed a 10-year public catalog [43] of IceCube events and found excesses of neutrinos from these sources with statistical significances of 3.0σ and 3.9σ, correspondingly. Note that, according to [42], both these sources also have a soft spectrum, though the values of power-law indices are not given in the paper.

3.3 Neutrinos from tidal disruption events

In the framework of an observational follow-up program triggered by IceCube neutrino alerts, a coincidence was found in [44] of a high-energy IceCube event with an optical flare, probably associated with the tidal destruction of a star by the gravitational field of a supermassive black hole in the center of one of the galaxies. Shortly afterward, another similar coincidence was found [45]. In both cases, a comparison of optical and infrared observations of the suspected source revealed a delay in the infrared flash that can be explained by the scattering of radiation on large amounts of dust. This motivated a statistical study [46] in which a catalog of similar events was constructed and a third match was found. The statistical significance of the coincidence of 3 of the 40 high-energy IceCube events included in the sample with flares associated with the accretion of matter on supermassive black holes is 3.6σ. In interpreting this quantitative result, it should be taken into account that two events which motivated the consideration of this sample were included in the calculation of the significance.

3.4 'Disappearing' correlations

As was noted above, changing the IceCube event reconstruction procedure often leads to a noticeable change in the key characteristics of the neutrinos, energies, and arrival directions. It can be seen that some of the interesting associations of neutrinos with potential astrophysical sources become less statistically significant when newly reprocessed samples of the same events are used. Let us focus on a few of these cases.

3.4.1 TXS 0506+056. Although active galactic nuclei were proposed as potential sources of high-energy neutrinos long before the discovery of the latter, the most serious attention to the possible connection between neutrinos and blazars was caused by the publication of two IceCube papers [6, 47] dedicated to the same source, a fairly ordinary blazar TXS 0506+056. Reference [6] announced the observation of a gamma-ray flare of this blazar a few days after detecting a high-energy neutrino from the direction of this source in September 2017. Reference [47], published simultaneously, discussed a neutrino flare in 2014 from the same direction, found in a subsequent analysis of old data. The statistical significance of the 2014 flare, according to [47], was 4.0σ before taking into account the penalty factors associated with the selection of analysis options, and 3.5σ after accounting for them. In the new reconstruction used by IceCube in 2023, changes in the characteristics of the same events led to a decrease in the first value to 3.3σ [48] (only events prior to October 2017 were used). This means that, taking into account the trial corrections, the flare described in [47] has a significance of 2.7σ in the new reconstruction. The best-fit neutrino flux of this possible flare has halved [48] compared to the original publication [47].

As for the coincidence of a high-energy event with the same blazar's gamma-ray flare, its statistical significance would also be diminished in the present-day analysis, though for a different reason: a large number of newer alert events did not result in the detection of any flare of a coincident source. Such an analysis, however, is not very easy to perform correctly due to the change in alert criteria after [6], mentioned in Section 2.3.

3.4.2 Blazar populations. A similar story develops with the effects found in analyses of blazar populations. As we noted in Section 3.1.1, the significance of associations between IceCube neutrinos with energies above 200 TeV and VLBI blazars decreases [28] when the new reconstruction [5] is used, compared to Ref. [14], which used the originally published arrival directions and energies. Here, one can also recall Ref. [30], where no significant correlation of the same blazars with lower-energy neutrinos was found in a newer IceCube reconstruction (see the discussions in [1, 31]).

A recent paper [36] is devoted entirely to comparing correlations of all IceCube neutrinos with blazar populations in the two datasets, the 7-year [40] and 10-year [43] ones. The authors of [36] use the method of hot spots in the sky map, applied in [34] to the likelihood map of the 7-year data set in the Southern sky. For the 10-year set of events, they built a similar map themselves [36]. The statistical significance of the result [34] has deteriorated from 4.7σ to 0.3σ with the transition to the reconstruction of Ref. [43]. The catalog of VLBI blazars used in [29] was also examined in the same way. It's interesting that it was found in [36] to correlate with 'hot spots' of the Southern sky at a significance level of 3.2σ (the original Ref. [29] used the Northern sky map and another method) — but only in the 7-year dataset. Use of the updated reconstruction [43] results in a dilution of this newly found effect as well.

3.4.3 Tidal disruption events. In Section 3.3, we discussed three IceCube events which coincided with episodes of intense accretion on supermassive black holes [46]. IceCube's recent work [12] utilizes a new catalog of neutrino events to test the association with tidal disruption events (TDEs) selected by criteria similar to [46]. Preliminary results indicate that there is no statistically significant correlation. It is noted that, for two out of three neutrinos previously associated with TDEs, the arrival directions changed in the new reconstruction in such a way that TDEs are now outside of the error contours, while the third event is no longer included in the sample at all.

3.4.4 Possible causes. For an external observer, it is difficult to judge why associations with astrophysical sources and their populations, significant in earlier analyses, consistently disappear when newer reconstructions for the same IceCube events are used. One potential explanation that is reached, for example, in [36], is that all of these sources do contribute to the neutrino flux, but their contributions are smaller than it seemed from the initial tests. This explanation is certainly possible, but it would look more natural when the effect weakens with new data, not with reprocessing of the same data by new algorithms. Indeed, in statistical analyses at the limit of the sensitivity, weak effects tend to open up as positive fluctuations, and therefore are often not visible in the next set of data.[2] But it is not easy to imagine — though, with a small probability, it is possible — that in a number of different analyses statistically significant results appeared due to the use of incorrect reconstruction, and an improvement in it led to their blurring.

One possible reason for the decrease in significance with the transition to newer reconstructions is the delicate balance of statistical and systematic uncertainties. Event reconstructions, developed in recent years, widely use machine learning techniques. This leads to a firmly proven significant reduction in statistical errors of determination of parameters of the particle that triggered the detector. At the same time, systematic uncertainties often give rise to serious, and difficult to control, problems. The point is that machine learning involves a training dataset with known characteristics on which, in fact, the algorithm learns to determine the characteristics of other events. In modern high-energy astroparticle physics, characterization of the primary particle is possible only indirectly, since, for energetic photons, neutrinos, and charged cosmic particles, only products of their interaction with the detector or the atmosphere is registered. Therefore, as training datasets, one has to use artificial sets of events based on Monte-Carlo simulations, which involve detailed modeling of the processes occurring in the detector, and thus require their perfect knowledge. In the case of IceCube, ideal knowledge of the optical properties of ice in the volume of a cubic kilometer is not yet possible, and therefore the training datasets are necessarily built using certain assumptions. If these assumptions are not fully correct, a new method may reduce statistical errors in determining the neutrino arrival direction, but the central value may be shifted due to the training dataset's non-ideality. In this case, simpler, but less model-dependent, analyses would win, like those used at the initial stages of the experiment's operation. It is difficult to understand, even for those directly involved in the data processing, to what extent this situation can take place in reality. It is clear that the final criterion for testing hypotheses about the origin of astrophysical neutrinos should be related to the analysis of data of independent experiments, primarily those using liquid water,

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[2] Just in the same way as positive fluctuations lead to unusual successes in sports and other human activities, which the person cannot repeat afterwards (see, e.g., [49]).

for which both statistical and systematic errors are considerably smaller [1] (see Section 5.2 below). So far, this work is just beginning [17, 33, 50].

4. Galactic neutrinos

Interactions of cosmic rays with matter in the Galactic disk result in neutrino production, and this process guarantees a certain flux of high-energy neutrinos from the disk of the Milky Way. In addition, individual Galactic objects in which cosmic rays are accelerated and interact with ambient matter are potential sources of Galactic neutrinos. Some contribution is also expected from interactions of cosmic particles leaving the Galaxy with circumgalactic gas. Possible sources of Galactic neutrinos and the history of their search are described in reviews [1, 51]. In 2022, this search succeeded.

4.1 Discovery of Milky Way neutrino emission

Reference [52] analyzed the distribution of arrival directions of IceCube events which had a high probability of astrophysical origin, energies above 200 TeV, and good quality of reconstruction, in the absolute value of the Galactic latitude, $|b|$. The median value of $|b|$ for a set of 71 events, selected according to the criteria established in previous analyses, is $|b|_{\text{med}} \approx 21°$. The expected value of $|b|_{\text{med}}$ for simulated sets of events distributed in the sky according to IceCube exposure is $\langle |b|_{\text{med}} \rangle \approx 36°$, and the probability of obtaining $|b|_{\text{med}} \leqslant 21°$ as a result of a random fluctuation is 4×10^{-5} (statistical significance of 4.1σ). This established the concentration of neutrino arrival directions from this sample into the Galactic plane. A similar analysis for all events from the catalog [43] demonstrated that the Galactic component is also observed at lower energies [52]. Making use of a single observable $|b|_{\text{med}}$ is the simplest, uncertainty-free way to search for the Galactic component of the neutrino flux, since it does not require any assumptions about specific sources or parameter tuning.

The ANTARES collaboration also studied in [53] the distribution of arrival directions of events and took advantage of the fact that, for this experiment, central regions of the Galaxy are observed below the horizon, which makes it possible to significantly reduce the atmospheric background from this direction. The traditional 'on–off' method was used, in which a narrow rectangle of $4° \times 60°$ in the center of the Galaxy was chosen as the signal ('on') area. The background was determined by the number of events in 'off' areas with the same observational conditions but in directions away from the Galactic center. An indication of an excess of events from the signal area with the statistical significance of 2.0σ was found. Both track and cascade events were used in the study, but the main contribution to the signal came from tracks: the number of neutrino tracks with energies above 1 TeV in the 'on' region was 21 with a background expectation of 11.7 ± 0.6, and the number of cascades was 13 with a background of 11.2 ± 0.9.

Finally, in 2023, a paper was published by the IceCube collaboration [9], which presented results of the search for a signal from the Galactic plane in the set of cascade events. The choice of the cascade channel was motivated by the high background for the tracks from the direction of the Galactic center, which, for IceCube, is always observed above the horizon. The search methodology used in this study was substantially different. In fact, it was not about finding an arbitrary signal from the Galaxy, but about testing three specific models of diffuse radiation associated with interactions of cosmic rays with gas in the disk. The first of the models was based on Fermi-LAT observations of diffuse gamma rays in the GeV range: it was assumed that this radiation is associated with decays of π^0 mesons, and neutrinos come from decays of $\pi^{\pm}$ mesons born in the same interactions. The distribution of arrival directions and the spectrum (power law with the 2.7 exponent) were extrapolated from the GeV range of the Fermi LAT to the TeV range of IceCube. The other two models, called $\text{KRA}\gamma_5$ and $\text{KRA}\gamma_{50}$, were obtained by modeling the propagation of cosmic particles in the Galaxy and their interactions with matter with the DRAGON code; the difference between the two is the energy of the assumed cosmic-ray spectral cutoff (5 or 50 TeV, respectively). For each of the three models, templates of the expected distribution of neutrinos in directions and energies were derived, taking into account the detection and selection procedures for IceCube events. Then, these expected distributions were compared with the help of the likelihood function with those actually observed. The null hypothesis of the absence of the neutrino flux from the Galactic plane was ruled out with a statistical significance of 4.71σ (π^0 template), 4.37σ ($\text{KRA}\gamma_5$ template), and 3.96σ ($\text{KRA}\gamma_{50}$ template). The final significance, taking into account these three trials, was 4.5σ.

The three independent results described above allow us to speak with confidence about the discovery of high-energy Galactic neutrinos: the Milky Way is now visible in the neutrino sky. However, as we will see below, reliable conclusions about the origin of these neutrinos are still far away. It would be of interest to verify the obtained results with the Baikal-GVD data. The first, so far little, published data on cascade events does not contradict the assumption of a Galactic component. Moreover, the arrival-direction error circles of 3 out of 11 Baikal-GVD events with energies above 100 TeV overlap, and this triplet is close to the Galactic plane [50]. This area of the sky is quite interesting; it contains, among other possible sources, one of a few Galactic binary systems observed in the gamma-ray band, LSI+61 303, as well as the point of the maximum of the likelihood function, used by IceCube to search for point sources in the Northern sky based on the 7-year track data [40]. In more recent analyses, the maximum of the likelihood shifted to the direction close to NGC 1068 (see Section 3.2).

4.2 Comparison of analyses

Figure 4 presents a sky map which shows the likelihood function used in the IceCube cascade analysis [9], arrival directions of IceCube track events from the sample used in [52], and Baikal-GVD cascade events [50]. One can observe some concentration of neutrinos toward the broad band near the Galactic plane in all cases. However, a direct comparison of the results of the different tests is hardly possible. Indeed, analyses [9, 52, 53] refer to different regions of the sky and different neutrino energies, and, most importantly, they use fundamentally different approaches (see Table 2). To compare the Galactic neutrino spectra obtained under different assumptions, one can use their generalized characteristic, the full-sky flux of neutrinos of Galactic origin, assessed on the basis of assumptions about its part in contributing to the detected flux. This is easiest to do when the flux is searched using a template, as was done in IceCube paper [9].

This recalculation for the ANTARES [53] result was presented in [54]. For study [52], it can be easily derived from the fraction of the diffuse neutrino flux attributable to

Table 2. 2022–2023 analyses in which high-energy neutrinos from our Galaxy were detected.

Analysis	Energies	Method	Significance
Kovalev et al. [52]	$\gtrsim 200$ TeV	Median $\lvert b\rvert$, tracks	4.1σ
ANTARES [53]	$\sim 1-100$ TeV	On/off, tracks and cascades	2.0σ
IceCube [9]	$\sim 1-100$ TeV	Distribution templates, cascades	4.5σ

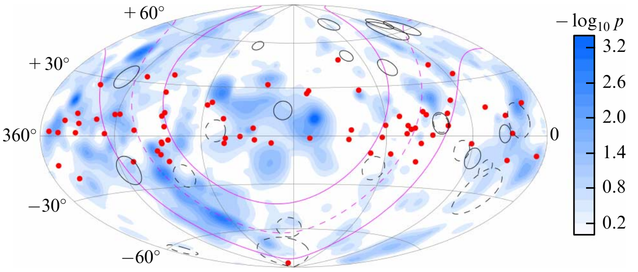

Figure 4. Sky map (equatorial coordinates, Hammer projection) with distribution of likelihood function constructed for IceCube cascade events [9]. Arrival directions of 71 IceCube tracks used in the analysis of Kovalev et al. [52] are shown as red dots. For arrival directions of Baikal-GVD cascade events from Ref. [50], 90% CL uncertainty contours are given (solid lines — sample of $E > 100$ TeV events, dashed lines — upgoing cascades; one event present in both samples and coinciding with TXS 0506+056 (see Section 3.1) is shown by a double contour). Dashed purple line is Galactic plane, and solid purple lines bound the band $|b| < 20°$.

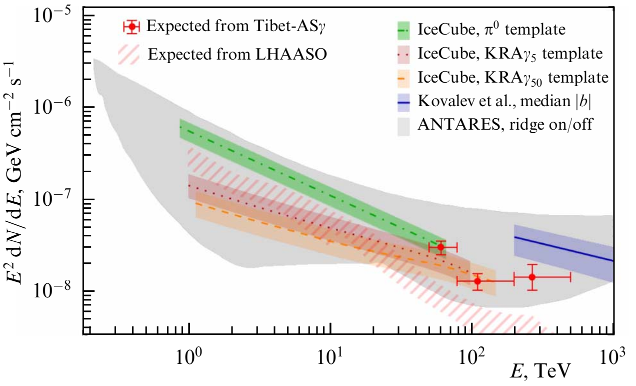

Figure 5. Estimated total, sky-integrated Galactic neutrino flux as a function of energy, according to results of Kovalev et al. [52], ANTARES [53, 54], and IceCube [9]. Hatched area and points with error bars represent neutrino spectra expected from measurements of Galactic diffuse gamma rays by LHAASO [55] and Tibet-ASγ [56], respectively (see Section 4.3).

the Milky Way, estimated in the paper. The results of comparing the spectra recalculated in this way are shown in Fig. 5. They indicate qualitative agreement of all three analyses, but do not allow for detailed quantitative comparisons without reference to specific data used to obtain them. We will return to this discussion in Section 4.4.

4.3 Galactic diffuse neutrino and gamma-ray emission above 100 TeV

Simultaneously with diffuse neutrino emission, photons of the same energy range should be produced in the Galactic disk. Unlike extragalactic radiation, this gamma radiation, with energies of about tens of TeV, is not strongly absorbed due to the e^+e^- pair production on background photons. Therefore, photons accompanying the neutrino emission from the Milky Way can be detected. They were indeed discovered by the Tibet-ASγ experiment [56] even earlier than Galactic neutrino emission was. In 2023, Galactic diffuse gamma rays were also detected by an independent experiment, LHAASO [55]. Overall, the results of the two experiments are qualitatively consistent with each other, though the flux measured by LHAASO is formally somewhat lower than that obtained by Tibet-ASγ. This may be related to particular details of accounting for the contribution of Galactic point sources by the two experiments, or to other systematic uncertainties

Although the fluxes, F_ν and F_γ, of neutrinos and photons born simultaneously in high-energy proton–proton interactions are roughly related by a simple law,

$$F_\nu(E_\nu) \approx 2F_\gamma\left(\frac{E_\nu}{2}\right)$$

(see discussion in [1]), a practical comparison of results of neutrino experiments with predictions based on this formula are not easy. The point again is that the analyses refer to different areas of the sky and to different energies, and are obtained by different methods. Some attempts at such a comparison were made in [52, 57–59]; they indicate good overall agreement between neutrino [9, 52, 53] and photon [55, 56] Milky Way diffuse fluxes, thereby indirectly confirming the origin of both in hadronic interactions. This is illustrated in Fig. 5, where we present, together with neutrino fluxes, their expectations from diffuse photon emission from the Galaxy measured by the two experiments, for which we used recalculations from Ref. [58].

4.4 Galactic neutrino angular distribution

To quantitatively understand the origin of Galactic neutrinos, the key issue is the spatial distribution of the neutrino sources. Here, at first glance, there seems to be some discrepancy between the results of different analyses. However, as we will see in a moment, this discrepancy is more apparent than real.

The angular distribution of diffuse Galactic emission in templates used by IceCube [9] is to a large extent determined by the distribution of matter in the disk of the Galaxy and therefore follows a narrow band in the sky (a few degrees wide, like the visible Milky Way). At the same time, a model-independent study [52] indicates an excess of events in a much wider band $|b| \lesssim 20°$. Note that the main result [52] does not use, nor directly predict, the width of the band, and this value appears only in the supplementary analysis, both for the main sample of events with energies above 200 TeV and at somewhat lower energies.

To understand the reasons for these different results, let us note the significant scatter in the normalizations of the Galactic diffuse neutrino spectra obtained by IceCube [9] using different templates (see Fig. 5). At low energies, where the main statistics are accumulated, the difference in fluxes, determined assuming different templates, reaches several standard deviations. The highest statistical significance is obtained for the template which uses extrapolation by three orders of magnitude without involving any quantitative physical model. The discrepancy in the results, obtained under different assumptions, may indicate that at least some of these assumptions are wrong. At the same time, due to poor angular resolution for IceCube cascade events, it is not possible to determine the shape of the Galactic neutrino signal in a reliable manner without the use of an *a priori* fixed template. Figure 4 qualitatively demonstrates that the excess of IceCube cascade events from the Galactic plane is possibly consistent with a wider distribution of arrival directions than the templates assume.

Any model of the origin of the diffuse neutrino flux from interactions of cosmic particles with matter in the Galactic disk makes use both of the distribution of this matter and of the spatially-dependent spectra of the cosmic radiation. While the gas distribution is fairly well known from observations, cosmic-ray concentration and spectra in remote regions of the disk can only be obtained indirectly. The reason for this is the complex motion of charged particles in magnetic fields, which in addition are poorly known themselves. To date, many models of the propagation of charged cosmic particles in the Galaxy are based on simplistic assumptions, one of the key ones being that the spectrum of Galactic cosmic rays recorded in the vicinity of the Earth is representative of the Galaxy. There are a number of indications that such an assumption does not hold (see, e.g., [60–63]). In particular, the presence of a nearby source of cosmic rays, combined with higher gas density in the so-called Local Bubble, can lead to an increased contribution of the nearby Galaxy region to the observed neutrino flux [60, 64]. Projected on the celestial sphere, this flux would come from higher Galactic latitudes than the main contribution of the disk, which may lead to broadening of the latitude distribution of Galactic neutrinos.

5. Prospects

The enormous background of non-astrophysical events, both atmospheric neutrinos and muons, together with large statistical and systematic uncertainties in the determination of neutrino parameters, remain the main factors limiting further development of neutrino astrophysics towards identifying and studying the sources of high-energy neutrinos. It is not surprising that the future of this field hinges on overcoming these two challenges.

5.1 Combating atmospheric backgrounds: high energies and high statistics

Since the atmospheric background is unavoidable, and each individual atmospheric neutrino is no different from an astrophysical one, advances in separating the astrophysical signal can only be linked to the increase in the number of detected events, which requires a large effective volume of the detector. On the one hand, higher statistics allows for more precise separation of the contribution of astrophysical neutrinos to the total observed flux, because ensembles of neutrinos of atmospheric and astrophysical origins have different distributions in energies, flavor composition, and arrival directions [1]. On the other hand, increasing the volume of the detector makes it possible to detect rare events with very high energies, for which the atmospheric background is low.

Among specific plans for the construction of new experiments, substantially larger than those currently in operation, is the IceCube-GEN2 project [65]. It is proposed to expand the existing IceCube detector (1 km^3) up to the instrumented volume of 7.9 km^3 (mainly due to the increase in area, because, at large depth, the optical properties of ice deteriorate considerably). The number of neutrino events, compared to IceCube, should increase, approximately, proportionally to the volume. Outside of the present detector, the distance between the strings of optical modules will be significantly increased.

In addition to IceCube-GEN2, projects for detectors with very large volumes include the TRIDENT [66] and HUNT [67] installations which are discussed below in Section 5.2.

For neutrinos with energies $\gtrsim 10^{17}$ eV, the atmospheric background is absent, and low fluxes become the main problem. The main hopes in this energy range are related to the detection of neutrinos by the radio emission of the cascade processes they cause (ARA [68], ARIANNA [69], RNO-G [70], GRAND [71] projects, etc.). Possible fluxes of astrophysical neutrinos of even higher energies are so small that, to record them, one needs a spacecraft observing large volumes of Earth's atmosphere (JEM-EUSO [72], POEMMA [73], etc.). Discussion of these energy ranges is beyond the scope of this paper.

5.2 Fight for accuracy: detectors in liquid water

The IceCube Upgrade project [74] (not to be confused with IceCube-GEN2) will soon be implemented at the South Pole. Among other things, it will include the installation of additional calibrating devices that will allow more precise control of optical properties of the ice, thus improving the accuracy of neutrino event reconstruction. However, ice properties vary within the operating volume, while calibration will only be carried out in a small part of it. The main prospects for refining the determination of neutrino properties are associated with the use of detectors in liquid water (see, e.g., a discussion in Ref. [1]).

Today, the largest liquid-water neutrino detector is Baikal-GVD [75], whose volume as of 2023 was about 0.6 km^3, and is increasing by about 0.1 km^3 every year. The data obtained from Baikal-GVD in an incomplete configuration have been used for astrophysical analyses since 2018 (see previous sections). Other $\sim$ 1-km^3 scale detectors include KM3NeT [76] (Mediterranean Sea), which began data collection in 2022, and the planned instruments P-ONE [77] (which will make use of the oceanological infrastructure off the Pacific coast of Canada; work is underway on the prototype) and NEON [78] (South China Sea, with a denser arrangement of optical modules than current telescopes). Also in the South China Sea, it is proposed to place the TRIDENT [66] experiment with a working volume of 8 km^3. Finally, the most far-reaching plans have been recently presented by a group of researchers associated with the above-mentioned LHAASO experiment: the HUNT [67] project is aimed at constructing a neutrino telescope with a working volume of up to 30 km^3. For the location of such a huge instrument, being considered are either a place far enough offshore in the South China Sea, or Lake Baikal, which is shallower, but has convenient infrastructure. Equipment tests at the first of these two sites were performed in 2022–2023, and at Baikal they are scheduled for 2024. The neutrino telescope at Lake Baikal became, more than 25 years ago, the first to detect [79, 80] a neutrino event with the method subsequently used to obtain all the results discussed in this paper (see also historical review [81]). Maybe in another 25 years, the facility will become the world's most ambitious neutrino detector with a working volume 30 times larger than that of the present-day IceCube.

We noted above that a significant limitation of astrophysical neutrino experiments is related to systematic uncertainties, which are different for each experiment. Therefore, the key reliability factor of neutrino astrophysics is the unification of the efforts of different experiments, which use different methods and have different sensitivities to the Northern and Southern skies. Since 2013, these efforts have been developed [82, 83] within the framework of the Global Neutrino Network[3] (GNN). Probably, the creation of focused thematic working groups, which would include representatives of different experiments, will allow us to advance much further in understanding astrophysical neutrino sources. A positive experience of the work of such groups is already seen in the field of ultra-high energy cosmic rays.

6. Conclusions

• High-energy neutrino astrophysics is entering a new stage of development with the start of cubic-kilometer scale experiments in liquid water: Baikal-GVD and KM3NeT. For the first time, the very existence of astrophysical neutrinos was confirmed independently of IceCube by the Baikal-GVD experiment.

• Results of various analyses, including those formally verifying previously formulated hypotheses with new data, confirm the origin of a significant part of astrophysical neutrinos in blazars. Due to systematic differences between approaches and datasets, the fraction of the neutrino flux associated with blazars is hard to determine precisely.

• There are strong indications that some of the neutrinos detected on Earth are born in other extragalactic sources, among which are Seyfert galaxies and centers of galaxies in which tidal disruption events occur.

• Neutrino emission from the Milky Way has been detected. Three independent analyses based on different data are qualitatively consistent with each other and with the observations of diffuse Galactic gamma rays. The discrepancies in the results of model-dependent quantitative analyses point to the possible need to revise models of cosmic-ray propagation in the Galactic disk.

• The statistical significance of a number of statements indicating point sources of neutrinos, including those related to the very first detected TXS 0506+056 source, is greatly reduced when using the same events re-processed with new IceCube reconstruction algorithms. This demonstrates the importance of understanding and correctly accounting for systematic uncertainties in the experiment.

• Plans for future neutrino telescopes are motivated by the desire to increase the exposure required to separate the astrophysical signal from the atmospheric background more precisely, and to use liquid water to reduce statistical and systematic uncertainties. The experiments of today's generation are combined in the Global Neutrino Network, where data sharing and collaborative analyses should help to eliminate a number of uncertainties in the conclusions already in the coming years.

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