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The status and astrophysics results of the Baikal-GVD neutrino telescope

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The Baikal-GVD neutrino telescope is a cubic-kilometer scale neutrino detector being constructed in Lake Baikal. Presently the detector array consists of 14 sub-arrays (clusters), including in total 117 strings holding 4212 optical modules. The telescope's sensitive volume for high-energy cascade detection has reached 0.7 km^3. In this report we discuss status of the detector and present first physics results obtained using the data collected in 2018 – 2024. This includes a diffuse astrophysical neutrino flux measurement using cascade-like events, with a statistical significance exceeding 5σ, and first hints on the diffuse astrophysical flux in track-like events. We also discuss Baikal-GVD results on the Galactic neutrino flux, as well as searches for point-like neutrino sources.

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1. Introduction

The energy spectrum of cosmic ray (CR) nuclei extends to 10^{20} eV which suggests the existence of powerful distant particle accelerators. Hadronic interactions accompanying the production and propagation of high-energy CR lead to the neutrino production. Weakly interacting neutrino is not deflected or scattered on its way through the intergalactic medium and once detected points to its production site and provide the probe of energy scale in its vicinity constraining models of CR acceleration. The study of TeV - multi PeV neutrino flux is the main purpose of present generation of large-volume neutrino telescopes aiming for instrumented volume of 1 km^3. The existence of diffuse high-energy neutrino flux was discovered by the IceCube collaboration back in 2013 [1], presently it is established with significance well above 5σ. At the same time evidence for astrophysical neutrino sources is weaker. None of most significant IceCube candidates to neutrino sources like blazar TXS 0506+056, seyfert galaxy NGC 1068 or the Milky Way galaxy plane is established at 5σ significance level. Therefore the origins of cosmic neutrino flux remain largely unexplained. Our understanding of the cosmic neutrino will be boosted with new results from detectors presently in the commissioning stage like Baikal-GVD which is approaching 0.7 km^3 sensitive volume or KM3NeT being built in the Mediterranean sea.

After the winter expedition 2025 the Baikal-GVD neutrino telescope incorporates 14 independent clusters reaching the detector volume of 0.7 cubic kilometers. Being the largest neutrino telescope in the Northern Hemisphere, Baikal-GVD has started to contribute to cosmic neutrino study with the first independent observation of the diffuse astrophysical flux with the significance above 5σ or a strong hint of the galactic high-energy neutrino emission. The selection of these and other results are discussed in the present report.

2. The Baikal-GVD neutrino telescope

The large-volume Cherenkov neutrino telescope Baikal-GVD is located ~4 km from the shore in southern part of Lake Baikal. The lake depth at the telescope location is around 1366 m, water absorption length reaches 22 m. The telescope consists of independent detectors - clusters, each connected to the shore station via it's own independent optoelectric cable. Each cluster incorporates 8 or 9 strings each carrying 36 optical modules (OM) evenly distributed between depths of 750 and 1275 meters and instrumented with 10-inch high-quantum-efficiency PMT HAMAMATSU R7081-100 and various sensors. Lake Baikal freezes in winter and the thick ice cover in February - March allows to deploy new detector elements with the heavy machinery each year. After a challenging deployment campaign in Winter 2025, the detector incorporates 14 clusters (Fig.1) including in total 117 strings carrying 4212 OMs. The sensitive volume of the detector to the high-energy cascade detection is 0.7 km^3. In the next three years it is planned to further expand the detector to ~1km^3 sensitive volume instrumented with 6000 OMs.

High-energy neutrinos interacting near the detector via deep-inelastic scattering produce hadronic and/or electromagnetic cascades of charged particles which emit Cerenkov photons registered with OMs. Such cascades extend to meters and emit photon flux which can be detected in up to hundred meter radius and beyond, depending on cascade energy, producing point-like source signature in the detector. Such neutrino detection mode provides precise calorimetric-type neutrino

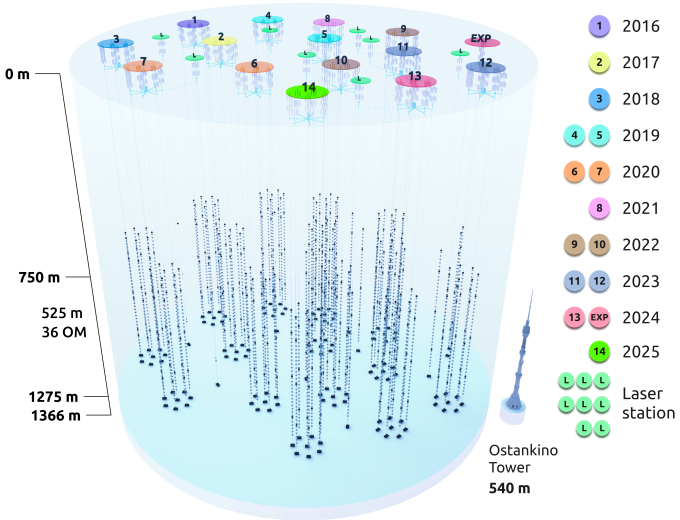

Figure 1: The Baikal-GVD neutrino telescope in the configuration deployed in February - March 2025.

energy measurement with resolution 10-20% and neutrino direction resolution of few degree. In case of ν_μ scattering via W-boson exchange muons are produced. Muon can traverse up to tens of kilometers depending on energy and leave track-like signature in the detector. For muon detection, the detectior sensitive volume is enhanced by the muon propagation range while the angular resolution can be as good as 0.2° and beyond thanks to large length of tracks.

3. Diffuse astrophysical neutrino flux studies

The dominating source of neutrino events detected by the large-volume neutrino telescope are atmospheric neutrinos, which are byproduct of interaction of cosmic rays with the Earth atmosphere producing soft neutrino spectrum with power ~ 3.6. The cosmic neutrino flux manifests itself as an excess over the atmospheric neutrino spectrum expectation becoming significant for neutrinos of tens of TeV energy and beyond depending on the detection channel. Atmospheric neutrino flux is dominated by ν_μ, with ν_e flux being tens of times less starting from hundreds of GeV neutrino energies. Keeping in mind good cascade energy resolution the cascade channel is an excellent tool for astrophysical diffuse flux searches and spectrum studies. Baikal-GVD has already reported an evidence of the diffuse astrophysical flux with total significance above 3σ using data taken at the construction phase in years from 2018 to 2022 [2]. Recently the analysis dataset was expanded with the data up to March 2024. The dedicated reconstruction algorithm [2] yielded a sample of 26795 cascades with reconstructed energy $E_{sh} > 10$ TeV, and hit multiplicity $N_{hit} > 11$ in the 6-year dataset. To suppress the background from atmspheric muons the analysis was restricted to upgoing events with reconstructed zenith angle $cos(\theta) < -0.25$. After applying additional cut on cascade energy $E_{sh} > 15$ and cuts to remove residual contribution from muon events [2], 18 cascade events were selected, with the most energetic cascade of reconstructed energy $E_{sh} \sim 135$ TeV. The expectation from atmospheric background is 2.8 events. The significance of the excess was

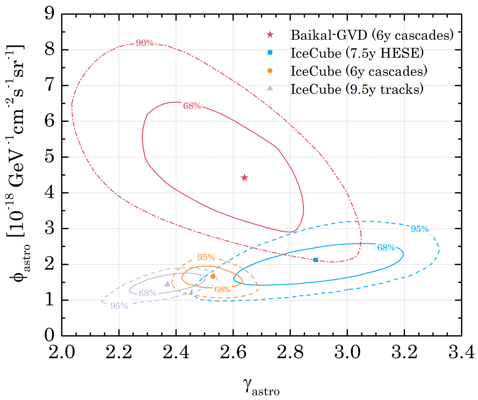

Figure 2: Result of the single power law spectrum fit in Baikal-GVD cascade channel compared to results of IceCube. Baikal-GVD results indicate in general larger flux normalisation.

estimated as 5.1σ taking into account systematic uncertainties which include uncertainty of the light absorption length, OM efficiency and atmospheric neutrino flux normalisation. The reconstructed cascade energy distribution was fitted with the sum of single power law for astrophysical spectrum and MC-based templates for background. For the standard parametrisation of astrophysical spectrum $F = \phi_0(E/100\ \text{TeV})^{-\gamma}$, where ϕ_0 — flux normalization, γ — spectral index, best fit values of $\gamma = 2.64^{+0.09}_{-0.11}$ and normalisation of $\phi_0 = 4.42\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ were obtained (Fig.2). The spectral index is in agreement with IceCube measurements while the normalisation of the flux in general exceeds most of IceCube fits although not contradicting the spectrum derived from HESE events.

An all-sky analysis of cascades is somewhat less sensitive to the diffuse flux due to overwhelming muon bundle background. Stricter cuts on the cascade energy, $E_{sh} > 70$ TeV, and hit multiplicity, $N_{hit} > 19$, were applied to minimize the background. Still the muon bundle contamination in the selected sample is expected at the level of 60%. The total of 27 events were selected in 6-year dataset while 15.7 events are expected from the background MC simulation. The respective significance of the excess is 2.73σ [3].

The largest energy cascade in the all-sky analysis is the downgoing event of 1.2 PeV energy, this observation was used to confront recent detection of neutrino candidate KM3-230213A with best-fit neutrino energy above 100 PeV by KM3NeT telescope [4]. The analysis was constrained to the energy range E>$10^{3.5}$ TeV. Given the livetime of the detector in cascade analysis corresponding to ~ 26.8 years in single-cluster operation equivalent and an effective area of the detector the limits on the total flux were set in the decade wide bins assuming E^{-1} spectrum. Baikal-GVD constraints are not in general in tension with the KM3NeT observation while the IceCube constraints are much tighter due to larger exposure and inclusion of the muon channel in the analysis [5]. More details on the analysis can be found in [6].

The track-like event detection channel is less sensitive to the diffuse neutrino flux due to large ν_μ background. Baikal-GVD data from April 2019 to March 2024 was processed with the track reconstruction, the total livetime of selected data corresponds to ~30 years of a single cluster operation. To minimize the background from atmospheric muon bundles, only upgoing events

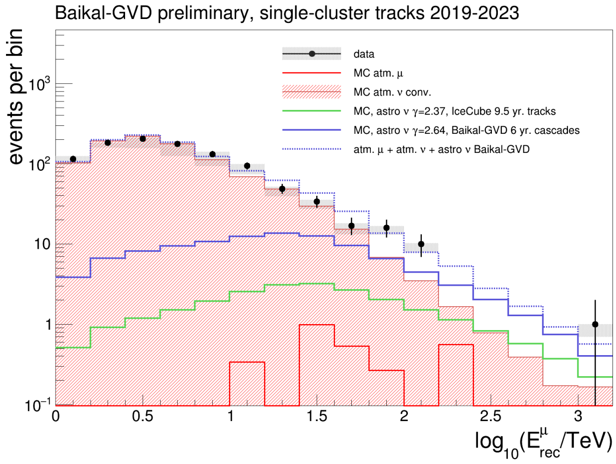

Figure 3: Distribution of the reconstructed muon energy of neutrino candidates in track-like channel compared to atmospheric neutrino flux expectation (red shaded histogram) and diffuse flux fits from IceCube and Baikal-GVD. Neutrino MC normalisation was scaled to match the normalisation in data for the atmospheric neutrino spectrum. The energy scale for MC was corrected to match the data by increasing the photoelectron yield in MC by 20%. Shaded area around the data points correspond to the muon energy scale uncertainty obtained by variation of photoelectron yield in MC by (-5%, +20%). Green histogram shows expectation from the IceCube fit with 9.5 years northern tracks [8]. Blue histogram shows expectation from Baikal-GVD upgoing cascade analysis discussed above [3]. Dashed curve shows sum of expectations from atmospheric muons, atmospheric neutrino and spectrum fit obtained in Baikal-GVD analysis [3].

were analysed. Boosted decision tree technique was used to suppress the background from residual misreconstructed muon bundle events and select the neutrino event candidates [7]. Possible excess of neutrino candidate rate in data at high energies was examined in a simple cut-based analysis optimised on MC simulation before unblinding the full dataset of 2019-2023 [7]. BDT and muon energy cuts were optimised for maximal sensitivity for flux with spectrum power $\gamma = 2.37$ derived in the IceCube spectrum measurement with 9.5 years of northern tracks [8]. The optimal energy cut was found as $E^{\mu}_{rec} > 45$ TeV, corresponding background MC expectations for the livetime of analysis are 23.5 events from atmospheric neutrino and 1.36 events from misreconstructed muon bundles. The reconstructed muon energy distribution for events passing the BDT cut in data and MC is shown at Fig.3. After applying the analysis cuts to data 38 events were selected. Preliminary significance estimate and flux limits were obtained using only statistical uncertainties. The P-value of an excess is 0.00847 and corresponding significance is $\sim 2.39\sigma$. The 90% CL flux limits obtained for $\gamma = 2.37$ [8] is $0.59 < \phi_0 < 3.95$ (10^{-18} GeV^{-1}cm^{-2}s^{-1}sr^{-1}). The observed excess favours the presence of the astrophysical neutrino flux component in Baikal-GVD track-like event data with the probability of 99.13% and relevant flux constraints do not contradict the IceCube track analysis [8].

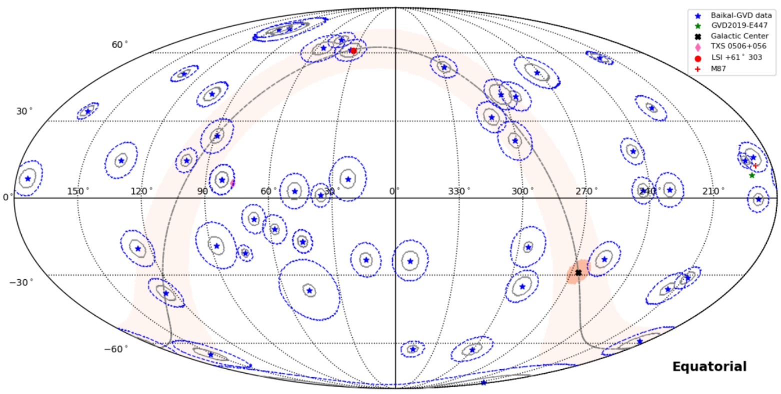

Figure 4: Map of Baikal-GVD events from all-sky cascade analysis in equatorial coordinates.

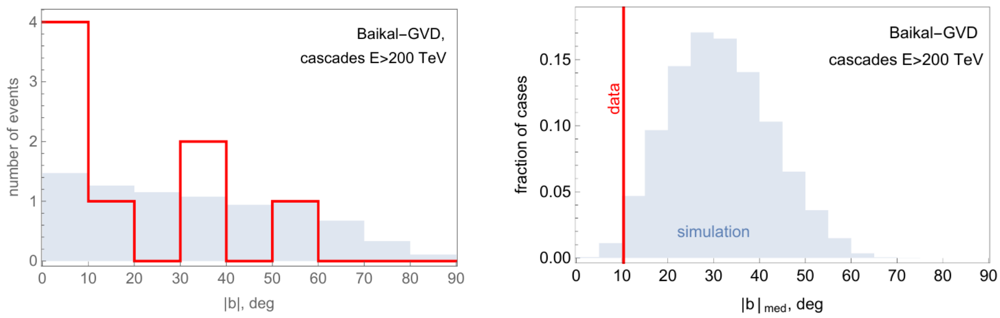

Figure 5: Distribution of absolute galactic lattitude, $|b|$, of cascades with energy E > 200 TeV (left). Distribution of $|b|_{med}$ test statistic (right). Plots are taken from [10].

4. Search for the neutrino emission from galactic plane

It is expected that a significant contribution to the overall astrophysical neutrino flux may come from our Milky Way galaxy. The galactic neutrino flux may include the diffuse component due to CR scattered in dense galactic medium or neutrinos produced in galactic neutrino high-energy sources. There is a solid evidence of PeV-scale CR production sites which could turn out to be neutrino sources in γ observations by imaging air Cerenkov telescopes and cosmic ray observatories such as e.g. the LHAASO observatory [9]. Pinpointing the high-energy neutrino emission from any of discovered galactic PeV-scale sources would signal on the hadronic origin of high-energy photon emission. An IceCube has reported an observation of diffuse neutrino flux from the galactic plane with 4.5σ significance in low-energy cascades [10]. Therefore the problem of the galactic neutrino flux study is very acute these days.

Located in the northern hemisphere Baikal-GVD is an excellent device to study the galactic plane and in particular galactic center with neutrinos. The map of events which have entered the diffuse all-sky cascade analysis (Fig.4) shows quite a few events in the 10° band around the galaxy plane. While the analysis of association of cascade events with point sources didn't lead to conclusive results [11] it may turn out that Baikal-GVD cascade data favours the diffuse emission from galactic plane. In very simple model-independent analysis inspired by [12] the degree of concentration of high-energy cascades around the galaxy plane has been quantified. The energy threshold for the analysis was chosen as $E_{sh} > 200$ TeV, respectively 8 candidate events have been selected, and their distribution in absolute galactic lattitude, $|b|$, has been examined. In total eight evens were selected, the distribution of events over the absolute galactic lattitude is shown at Fig.5 left panel. Four out of 8 events belong to 10° band around the galactic plane. The probability of such distribution was determined using the median absolute value of the galactic lattitude of the selected sample. Test statistic was determined for 10^5 artificial samples with randomised RA the resulting distribution of $|b|_{med}$ is shown at the Fig.5 right panel. The $|b|_{med}$ found in data equals to 10.4°. The probability of obtaining $|b|_{med}$ not larger than observed in data is 0.014, which corresponds to two-sided significance of 2.5σ. More details on the analysis can be found in [13]. In [14] the Baikal-GVD data have been combined with IceCube cascades and tracks applying similar selection E > 200 TeV. Combined data shows similar preference for galactic plane with the significance of 3.5σ. More data and inclusion of track-like events would improve understanding of the observed hint on the high-energy neutrino association with the galactic plane.

5. Point source search with tracks

The neutrino direction can be measured with sub-degree angular resolution using track-like events. Naturally they are the optimal tool to perform point source searches. A guided search for point-like neutrino sources has been conducted using the track-like event sample of April 2019 - March 2024. For this, upward-going tracks which pass a BDT-based quality cut which was optimized using MC simulations to provide the best sensitivity to an $E^{-}2$ neutrino spectrum were used. The analysis used a list of 112 astronomical objects, including the known neutrino emitters TXS 0506+056 and NGC 1068, the published direction to KM3-230213A, the Galactic center, some objects with claimed associations to IceCube and ANTARES neutrino events and hotspots, and a number of VHE gamma-ray emitters, as well as some X-ray selected Seyfert galaxies and some other notable galactic and extragalactic objects. In the present analysis all objects are assumed to be point-like. The search was conducted in a search cone of a radius of $\alpha = 2°$ around each object. In this simple cut-based analysis the number of events found in the search cone was compared to the estimated background level which was computed by data scrambling. No statistically significant excess has been found. The 90% C.L. upper limits were calculated under the assumption of a single power law neutrino flux with spectral indices $\gamma = 2; 2.5; 3.2$ (Fig.6). We note that this analysis does not include the reconstructed muon energy variable. The analysis sensitivity can be further improved by using a likelihood-based technique (instead of simple cuts) and incorporating the reconstructed energy in the analysis. More details on the analysis can be found in [7].

6. Conclusions

The Baikal-GVD neutrino telesope incorporates 14 full-scale clusters after the deployment campaign in February - March 2025. The detector includes 117 strings holding 4212 optical modules, enabling the sensitive volume for high-energy cascade detection ~0.7 cubic kilometers.

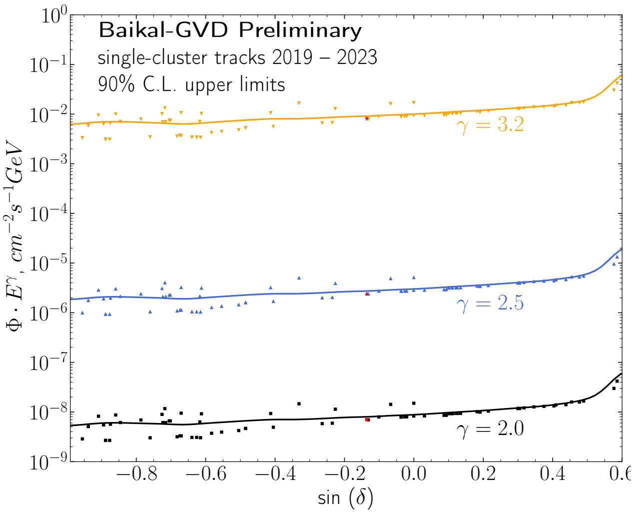

Figure 6: Point source flux limits obtained using track-like event sample from April 2019 to March 2024 for catalogue of 112 source candidates (see text).

Detector has been taking data since 2018 in incomplete configurations; the accumulated data sample allowed to produce first astrophysics results. The first independent evidence for the diffuse astrophysical neutrino flux at significance level of 5.1σ was obtained using the sample of cascade events from April 2018 to March 2024. The best -fit spectrum power is largely in agreement with IceCube results while the normalisation is in general larger than obtained in many of IceCube measurements. First hints on the diffuse astrophysical neutrino flux are also observed in a preliminary analysis of track-like events collected by Baikal-GVD between April 2019 and March 2024, with a statistical significance of 2.39σ.

Results on neutrino source searches start to appear. Analysis of high-energy cascades showed hint on concentration of cascades with E > 200 TeV near the galaxy plane. First point source search analysis in track-like event channel has been presented, so far without any statistically significant excesses.

In the next three years it is planned to expand Baikal-GVD to $\sim$ 1km^3 sensitive volume instrumented with a total of ~6000 OMs. More results are yet to come with inclusion of the data of April 2024 - March 2025, with improvement of analysis tools and of course with the new data from expanded detector configuration.

We note that this short report does not cover some of important activities such as e.g. Baikal-GVD multimessenger program [14] we kindly ask the reader to refer to respective section of proceedings of the Conference.

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