Overview of the Baikal-GVD neutrino telescope: 2024 status

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Abstract. A review of the Baikal-GVD neutrino telescope status after the winter 2024 deployment campaign that results in 4 104 optical modules installed on 114 vertical strings is presented. The results of analysis of Baikal-GVD data collected in 2018-2023 show the presence of cosmic neutrino flux in high-energy cascade channel consistent with observations by the IceCube neutrino telescope. Track-like events analysis results in identification of first high-energy muon neutrino candidates.

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1 Introduction

The construction of large volume neutrino telescopes installed in ice or under water both in the Southern (IceCube) and Northern (Baikal-GVD and KM3NeT) Hemispheres allowed the registration of high-energy neutrinos of astrophysical origin. Yet, the astrophysical sources of the most energetic particles in the Universe remain unknown. Neutrinos are not deflected either by intergalactic magnetic fields or influenced by the cosmic microwave background radiation. This property makes them perfect tool for identification of distant high-energy particle sources. First report on a detection of a diffuse neutrino flux has been done by the IceCube neutrino observatory located at South Pole [1]. Until recent, first hints of sources established with radio, optical, x-ray and gamma-astronomy observations to high-energy neutrino have been obtained [2, 3].

A recent progress on the construction of the Baikal-GVD neutrino telescope is reported. Developments in track-like and cascade-like event analyses are presented. Difuse neutrino flux results obtained in cascade channel are shown.

2 Baikal-GVD experiment 2024 status

Baikal-GVD is a water Cherenkov neutrino telescope being constructed in the southern part of Lake Baikal since 2016 [4]. The detector location is approximately 3.6 km offshore at 51° 46'N and 104° 24'E coordinates, where lakebed is nearly flat at a constant depth of 1 366 meters. The layout of the telescope has been established for optimal measurement of astrophysical neutrinos in the TeV-PeV energy range. There are two main neutrino event classes, namely tracks and cascades. Events resulting from charged current (CC) interactions of muon (anti-)neutrinos possess a track-like topology, while the CC interactions of the other neutrino flavors and neutral current (NC) interactions of all flavors typically mimic nearly point-like events labeled as cascades. The Baikal-GVD telescope is formed as a 3-dimensional array of photo-sensors - optical modules (OMs). Each OM comprises a 10-inch high-quantum-efficiency photo-multiplier tube (Hamamatsu R7081-100 PMT) oriented

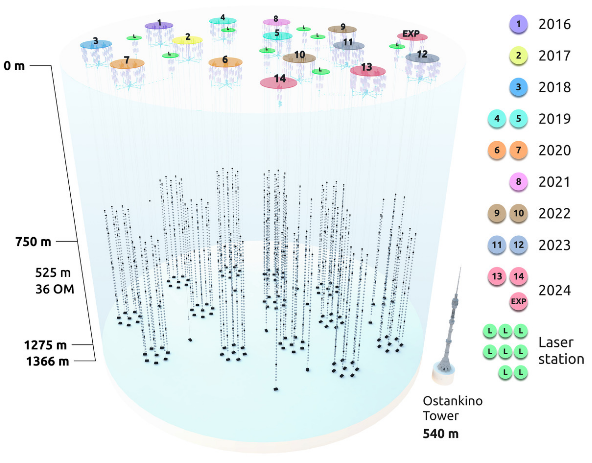

Figure 1. Schematic view of the Baikal-GVD neutrino telescope. The legend shows annual progress in the deployment of the detector since the operation start - year 2016.

downwards and electronics for the measurement of pressure, humidity, tilt, etc. The optical modules are attached to load-carrying cables, anchored to the bottom of the lake and kept straight by a system of buoys at the top, forming vertical strings, each with 36 OMs positioned with 15 m vertical spacing. Baikal-GVD section is the basic element of the detector readout consisting of 12 OMs on one string and a control module (CM). The CM controls the OM status, converts the analog signals of the PMT into the digital form by a 12-channel ADC with a sampling frequency of 200 MHz, and forms local triggers of the section. Each OM is connected by a 92 m long copper cable to the CM. The standard trigger condition requires a registration of two pulses on two neighboring OMs within the same section in a 100 ns time window with integrated charges exceeding given thresholds. The string control module (SM) controls the 3 sections of the string, acoustic beacons for acoustic monitoring of the PMT positions. Each OM includes an LED which is used for calibration of the OMs located above it. Additionally, some OMs incorporate brighter light sources, LED beacons, which are used primarily for inter-string time calibration [5, 6]. Completely functionally independent unit of the Baikal-GVD detector is a cluster that consists of 7 peripheral strings surrounding a central one at a 60 m distance. Once the trigger condition is fulfilled for any CMs on these strings, a 5 μs event time frame is read out from all the CMs of the cluster and send to the shore station by a dedicated electro-optical cable. The clusters are arranged on the lakebed in a hexagonal pattern, with a distance of 300 m approximately between the cluster centers. Timeline of the deployment that started in 2016 with cluster number one is shown in Fig.(1).

The special additional inter-cluster strings (ICS) equipped with high-power pulsed lasers (green strings labeled with L in Fig.(1)) dedicated for the inter-cluster time calibration and the light propagation studies are being installed since 2022. There are eight such strings deployed until recent. They are placed approximately in the geometric centers of each three clusters of the detector. Each of these strings hold the acoustic modems (providing the positioning of the ICS) and one or two laser beacons with tunable intensity providing inter-cluster time calibration and charge calibration of the OMs (see [7]). Four of these inter-cluster strings are also equipped with a full set of 36 OMs. Studies performed on Monte Carlo (MC) simulations yield that for cascades with an energy higher than 100 TeV the addition of inter-cluster strings leads to an increase in the number of events equal to 24% for the distance between clusters being 250 m. In result, the installation of additional ICS is the most effective way to increase the Baikal-GVD telescope sensitivity of cascade-like neutrino events. As of January 2025, Baikal-GVD includes 4 104 OMs on 114 strings.

3 Developments in the track-like events analysis

Track-like events topology in the Baikal-GVD detector is created by muons originating in charged current (CC) interactions of muon (anti-)neutrinos and tau (anti-)neutrino CC interactions, in case when tau decays into a muon. Reconstruction of a muon track in the detector represents a consecutive two step process. In the first step, registered pulses originating in emission of Cherenkov light by muon are selected while the background pulses are excluded (see [8]). The track direction, energy, and some quality paramaters (e.g. fit convergence, value of minimisation function) are obtained by means of algorithm based on the directional causality criterion and fast causally-connected pulse subset search algorithm [9] as the second step of the reconstruction procedure. The directional resolution ranges from $\sim 1.5^\circ$ for short tracks to below 0.5° for long nearly vertical tracks. A selection of 44 neutrino candidate events from data collected in April–June 2019 has been achieved by a hit finding algorithm for muon reconstruction (see [10]). The neutrino candidate event rate roughly agrees with the MC expectation for atmospheric neutrino flux (Fig.(2) left and middle). An application of this selection to the full year 2019 dataset results in finding a promising event of an

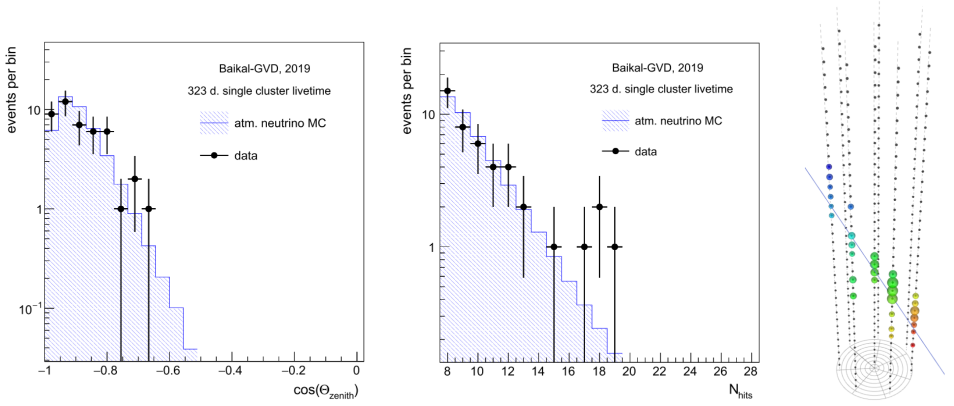

Figure 2. A sample of upgoing track-like neutrino events as a result of the analysis from the 2019 data [10]. Left panel: Zenith angle distribution. Middle panel: Distribution of number of hits used in the reconstruction. The black points are the Baikal-GVD data. Blue filled area stands for the MC prediction for atmospheric neutrinos. Right panel: Visualization of a 100 TeV upgoing muon neutrino candidate selected by the current analysis. Estimated signalness > 90 % indicates high probability of astrophysical origin of this event.

upgoing muon with median estimate of energy corresponding to 103.4 TeV. The value of reconstructed zenith angle θ is 153.4° and the visible track length is 332.4 m (see Fig.(2)). By considering atmospheric muon bundles, atmospheric neutrino including prompt neutrino contribution, and by using astrophysical neutrino spectrum index γ_{astro} ~-2.36, the estimation of probability (signalness) of this event being of astrophysical origin is larger than 90%.

4 Cascade events in Baikal-GVD

The key role in the search for high-energy astrophysical neutrinos is a reliable reconstruction of high-energy neutrino induced cascades. An improvement is achieved by setting cuts on quality variables by means of Monte Carlo simulations according to the data sample accumulated in 2016 – 2017, e.g. pulses with charge Q higher than 1.5 p.e. are considered only. A criterium of selecting events with a large multiplicity of hit OMs $N_{hit} > 7$ at least on three strings supports further improvement. High-energy cascade energy, direction, and vertex reconstruction is a two step process [11]. In the first step, vertex coordinates $\vec{r}_{sh}$ are found by minimization of χ_t^2 function with use of time information of pulses on OMs. At this procedure level cascade is treated as a point-like souce of light. The obtained cascade vertex coordinates serve as input for the second step which reconstructs the cascade energy and direction by use of the maximum-likelihood method. The achieved precision of energy and direction of the cascade varies typically between 10% – 30% and 2° – 4°, respectively. Data analysis described in our previous studies [12] was used in search of astrophysical neutrinos in data collected by Baikal-GVD during the 2018–2021 observing seasons. The result is a set of 11 upward-going high-energy cascade events with cuts on OM hit multiplicity $N_{hit} > 11$, reconstructed energy $E_{sh} > 15$ TeV, and reconstructed zenith angle $\cos\theta <$ -0.25. These are considered as astrophysical neutrino candidates. Based on this dataset, characterization of

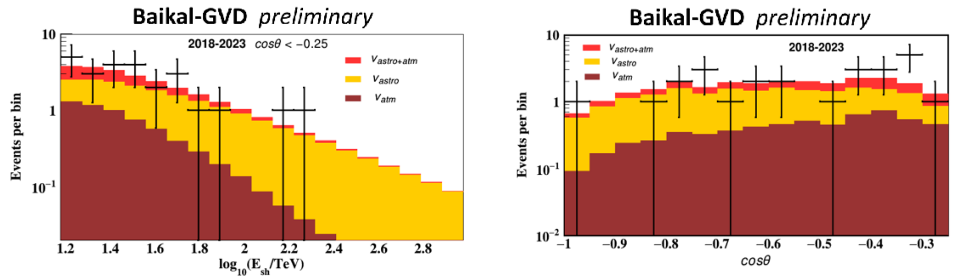

Figure 3. Left panel: Reconstructed cascade energy distributions of the dataset consisting of 25 selected events. The best-fit distribution of astrophysical neutrinos (yellow), expected distributions from atmospheric neutrinos (brown) and the sum of the expected signal and background distributions (orange) based on the 11 events dataset are also shown. Right panel: The same for the reconstructed zenith angle distribution.

the diffuse neutrino flux under the assumption of single power law model

$$\Phi_{astro}^{\nu+\bar{\nu}} = 3 \times 10^{-18} \Phi_0 \left(\frac{E_\nu}{E_0} \right)^{-\gamma_{astro}} [\mathrm{GeV^{-1} cm^{-2} s^{-1} sr^{-1}}] \tag{1}$$

with $E_0 = 100$ TeV, one neutrino/anti-neutrino flavor flux normalization Φ_0, and a spectral index γ_{astro} was performed. By means of a binned likelihood approach, the achieved Baikal-GVD results of the best fit parameters are found to be $\Phi_0 = 3.04^{+1.52}_{-1.21}$ and $\gamma_{astro} = 2.58^{+0.27}_{-0.33}$ (see [13]).

By keeping the same cuts ($N_{hit} > 11$, $E_{sh} > 15$ TeV, and $\cos\theta <$ -0.25), the search for cascade events in Baikal-GVD data collected during the 2018–2023 (up to March 2024) data taking periods results in a set of 25 upward-going high-energy cascade events. The energy and zenith angle distributions of these 25 events along with MC predictions (based on the 11 events dataset) are shown in Fig.(3). The background-only hypothesis is excluded at the level of 5.54 σ (see [14]). This is a strong confirmation of the diffuse astrophysical neutrino flux measured by the Baikal-GVD neutrino telescope, which is consistent with measurements of IceCube and ANTARES (all-neutrino flavor). Search for single power law best fit parameters (see Eq.(1)) with the new data set having two times higher statistics is in progress.

The discrete stochastic processes along the muon track represent the main background in search for neutrino induced cascade events. A selection technique that reliably distinguishes between the neutrino-induced cascades and the cascade-like background events (mainly from atmospheric muon bundles) is recently under development. This technique represents an additional step in the cascade selection algorithm described in [15]. In more detail, several variables were selected for the training and testing of a Boosted Decision Tree within the TMVA package of the CERN ROOT framework that significantly help to reduce the background (see [15]).

An identification of the double cascade event among the cascade-like events implies a very high chance for the registration of astrophysical neutrino. The double cascade reconstruction algorithm is divided into two consecutive steps. Firstly, a selection of pulses that originate from cascades is perfomed with suppression of noise pulses that are excluded as a background. Secondly, the signal pulses are categorized into two groups, with the first group of pulses associated to the cascade created in the ν_τ interaction vertex and the second one that is associated to the pulses from τ-lepton decay cascade. Further, vertices coordinates, direction, and energies of both cascades are obtained by means of minimization the χ^2 function with use of time information of pulses on OMs and the maximum-likelihood method. Detailed description and evaluation of the performance of the algorithm for search of double cascade events is presented in [16].

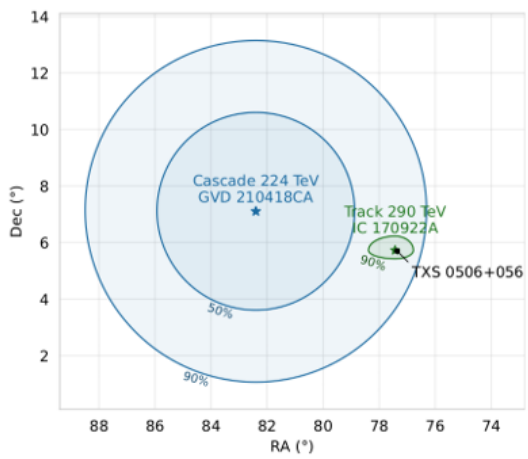

Figure 4. Equatorial coordinates of TXS 0506+056 blazar, high-energy (290 TeV) IceCube event IC 170922A with 90% confidence region, and the highest energy (224 TeV) upward-going Baikal-GVD event GVD 210418CA with 50% and 90% confidence region are shown.

One of the strongest neutrino candidate source in extragalactic sky at E > 200 TeV, TXS 0506+056, was discovered by the IceCube observatory [2]. We note that the arrival direction of an upward-going neutrino candidate event (GVD210418CA, E=224±75 TeV) with the highest energy registered among upward neutrino candidate events detected by the Baikal-GVD telescope is consistent with TXS 0506+056 blazar (see Fig.(4)). The signalness of this event is estimated to be 97.1%. This neutrino source lies within a 90% confidence region of the GVD210418CA direction [17].

5 Conclusion

The progress in the construction of the Baikal-GVD neutrino telescope that now comprises 4 104 optical modules on 114 vertical strings has been reported. Low-energy neutrino event rate in track-like channel is in a fair agreement with the MC expectation for atmospheric neutrino flux. A track-like event that is most likely of astropysical origin has been selected. The analysis of Baikal-GVD cascade-like events confirms the existence of the astrophysical diffuse neutrino flux at the level of 5.54 σ.

6 Acknowledgements

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