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Recent results from the Baikal-GVD neutrino telescope

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Baikal-GVD is a large underwater neutrino detector currently under construction in Lake Baikal, Russia. With the detector volume already approaching 0.4 km^3 and a sub-degree angular resolution, Baikal-GVD is becoming one of the key players in neutrino astronomy. We review the current status of Baikal-GVD and recent results obtained with the partially complete instrument.

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1. Introduction

The Baikal Gigaton Volume Detector (Baikal-GVD) is a gigaton-scale underwater neutrino detector currently under construction in Lake Baikal, Russia [1]. Baikal-GVD has been devised for the study of astrophysical neutrinos with energies in the TeV–PeV range with a sensitivity similar to that of IceCube [2] and KM3NeT-ARCA [3] and with a complementary field of view. Simultaneous operation of Baikal-GVD with the other neutrino telescopes allows for continuous monitoring of transient phenomena over the full sky.

Baikal-GVD is a three-dimensional array of optical sensors, so-called "optical modules" (OMs). It is composed of multiple sub-arrays – clusters, each of which comprises 288 OMs. The OMs register the Cherenkov light from secondary charged particles produced by neutrino interactions. Events resulting from charged current (CC) interactions of muon (anti-)neutrinos tend to produce a spatially extended, track-like signature in the detector, while the CC interactions of the other neutrino flavors and neutral current (NC) interactions of all flavors are typically observed as nearly point-like events (cascade-like events). Both event types are used in physics data analyses.

Baikal-GVD has been actively under construction since 2015. As of July 2022, Baikal-GVD consists of 10 clusters, for a total detector volume of ≈ 0.4 km^3. The modular detector design allows for continuous acquisition of scientific data already with the partially constructed instrument. Using the Baikal-GVD data collected in 2016–2021, several data analyses have been performed. This includes an analysis of track-like events, which allowed for the validation of the sensitivity of Baikal-GVD to muon neutrinos, and an analysis of cascade-like events, which provided a first statistically significant detection of the astrophysical neutrino flux with Baikal-GVD. This paper provides a brief description of the Baikal-GVD project, its current construction status (Sect. 2) and presents some of the key results obtained with Baikal-GVD over the last few years (Sects. 3 and 4).

2. Baikal-GVD

Baikal-GVD is a km^3 water Cherenkov detector employing the fresh water of Lake Baikal for high energy neutrino detection. The detector site is located in the southern basin of Lake Baikal at 51° 46' N 104° 24' E, 3.6 km offshore. The lakebed at the site is flat at 1366–1367 m below the nominal surface level of the lake. The detector elements are arranged along vertical strings, each of which is anchored to the lakebed and kept taut by a buoy at the top (see Fig. 1). The basic sensory element of Baikal-GVD is the Optical Module (OM). The OM incorporates a 10-inch high-quantum-efficiency PMT (Hamamatsu R7081-100) packed together with a high voltage unit and other front-end electronics inside a pressure-resistant glass sphere. A standard Baikal-GVD string holds 36 OMs, with their photocathodes all oriented vertically downwards. The OMs are installed with 15 m vertical spacing, for a total instrumented string length of 525 m, starting 90 m above the lakebed. The strings are also equipped with hydrophones for acoustic positioning. The strings are grouped in clusters, with 8 strings per cluster, as shown in Fig. 1. The characteristic distance between the strings in a cluster is ≈ 60 m. Each cluster is connected to the shore station with its own electro-optical cable and can be operated independently. The clusters are arranged on the lakebed in a hexagonal pattern, with a 250–300 m distance between the cluster centers (Fig. 1). Additional

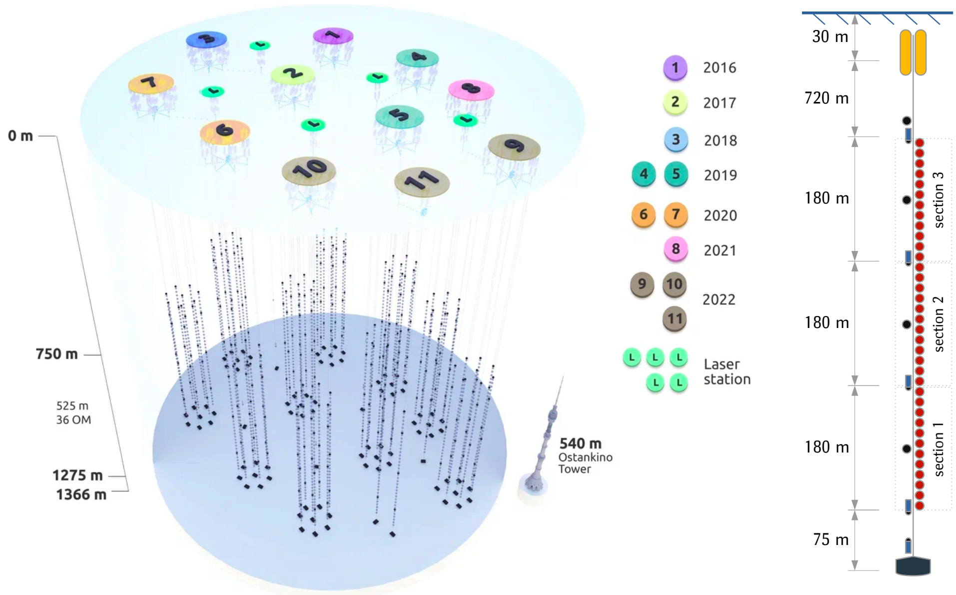

Figure 1: Left: Schematic view of the Baikal-GVD detector as of July 2022. The yearly progression of the detector deployment is shown in the legend. Right: The Baikal-GVD string layout. Red filled circles indicate the positions of the OMs. Black circles indicate the positions of various electronics modules.

strings equipped with high-power pulsed lasers are installed in-between the GVD clusters; these are used for detector calibration [4].

The light absorption length at the Baikal-GVD site reaches ≈ 24 m at a photon wavelength of 488 nm. The light scattering is relatively unimportant, with the effective light scattering length reaching ≈ 480 m at 475 nm [5, 6]. The sunlight does not affect the detector operation in any significant way, being absorbed in the overlying water layers. The lake is covered with thick ice (up to ≈ 1 m) from February to mid-April, providing a convenient solid platform for detector deployment and maintenance operations. For further details on the Baikal-GVD detector see [1, 7].

The first cluster of Baikal-GVD was deployed in 2016. Additional clusters were deployed each year since then (see Fig. 1). As of July 2022, the detector consists of 10 clusters, occupying a water volume of ≈ 0.4 km^3, and several additional strings dedicated for calibration and R&D studies. The construction plan for the next two years anticipates the deployment of four additional GVD clusters.

3. Analysis of track-like events

Track-like neutrino events play a central role in searches for point-like neutrino sources, owing to the high (sub-degree) angular resolution attainable for long muon tracks. The use of downward-going tracks for neutrino astronomy is however hindered by the overwhelming background of atmospheric muons. It is instrumental to understand the atmospheric muon and atmospheric neutrino backgrounds before proceeding to astrophysical neutrino searches. The analysis of track-like events in Baikal-GVD is subdivided to single-cluster analysis, for events triggered by only one Baikal-GVD cluster, and multi-cluster analysis, for events triggered by at least two clusters. Single-cluster events are much more numerous in Baikal-GVD than multi-cluster events, in part

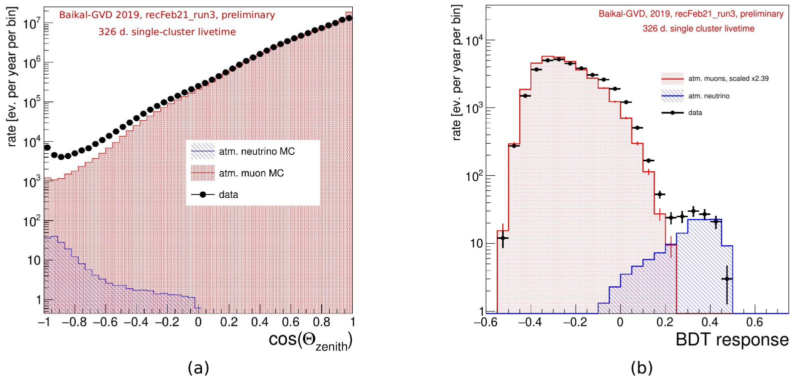

Figure 2: Results from a BDT-enhanced single-cluster analysis of track-like events using a spring 2019 Baikal-GVD dataset. Left: Zenith angle distribution of reconstructed tracks before quality cuts. The Baikal-GVD data (five clusters with a combined single-cluster equivalent livetime of 326 days) are shown by black points. The Monte Carlo (MC) predictions for atmospheric muons and atmospheric neutrinos are shown by red and blue filled histograms, respectively. Right: Output of the BDT classifier for the data, atmospheric muon bundles and atmospheric neutrino. The muon MC curve for this plot was re-scaled by 2.39 to match the normalization in the data. Figures reproduced from [8].

due to the lower energy threshold. Furthermore, the single-cluster analysis is most sensitive to nearly-vertical tracks, while the multi-cluster analysis provides coverage for the nearly horizontal directions. Thus the two analyses are complementary. At present, the single-cluster analysis is relatively more advanced. A simple cut-based analysis of a 2 months-long Baikal-GVD dataset collected in 2019 has demonstrated a reasonable level of control over the detector performance, with 9.8 million reconstructed downgoing events and 44 neutrino candidate events selected [7]. A new version of this analysis was presented in [8]. In this, an improved version of the same χ^2-based track reconstruction method was employed along with a neutrino selection method based on boosted decision trees (BDT), yielding 106 neutrino candidate events for the same 2 months-long dataset (see Figs. 2 and 3). This dataset is expected to be dominated by atmospheric neutrinos, with the median energy $\sim$ 500 GeV. For more details see [8]. Further data analysis improvements are in progress, aiming to enhance the sensitivity and angular resolution of the analysis, incorporate multi-cluster events, and optimize for the astrophysical neutrinos searches.

4. Analysis of cascade-like events

Cascade-like neutrino events play a key role in studies of the diffuse neutrino flux, large-scale neutrino sky anisotropies and large extended objects. This is thanks to the excellent energy resolution which can be achieved for these quasi point-like events, as well as the relatively low atmospheric ν_e and ν_τ backgrounds (compared to ν_μ). The effective volume of a Baikal-GVD cluster for cascade-like neutrino events with energy above 100 TeV is estimated as 0.05 km^3 [9]. This allows for the detection of the diffuse astrophysical neutrino flux already with the first few

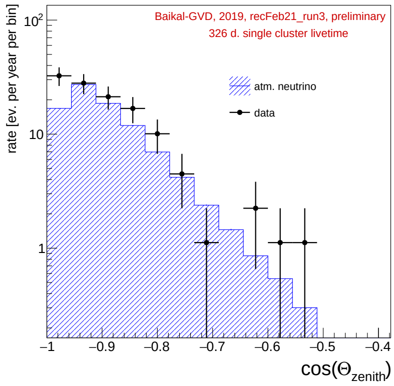

Figure 3: Zenith angle distribution of the selected neutrino candidate events obtained in the single-cluster analysis of track-like events of the spring 2019 Baikal-GVD dataset. Figure reproduced from [8].

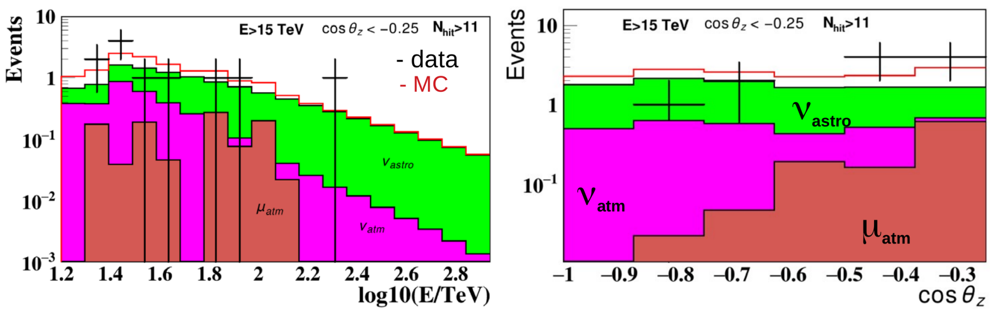

Figure 4: The reconstructed energy and zenith angle distributions of cascade-like events collected by Baikal-GVD in 2018–2021 (single-cluster analysis). The data are shown in black, with statistical error bars. The MC predictions for atmospheric muons, atmospheric neutrinos and diffuse astrophysical neutrinos (assuming the IceCube flux from [11]) are shown by colored histograms (not stacked). The sum of the three contributions (MC total) is shown by red line. Figure reproduced from [10].

years of data from the partially complete Baikal-GVD detector. Figure 4 shows the results of the analysis of upward-going cascade events collected from Baikal-GVD in 2018–2021 (5522 days of single-cluster equivalent lifetime). The MC prediction for atmospheric neutrinos and atmospheric muons in this analysis are, respectively, 3.0 and 0.95 events. The expected number of events due to the astrophysical neutrinos, computed using the IceCube flux parameters from [11], is 10 events. In data, 16 events were found. This rules out the null diffuse flux hypothesis with a statistical significance of 3.0 σ (p-value of 0.00268).

5. Conclusion

Baikal-GVD is a new TeV-PeV neutrino telescope under construction in Lake Baikal, Russia. As of July 2022, the detector consists of $\approx$ 3000 optical modules installed on 83 strings, for a total detector volume of $\approx$ 0.4 km^3. Thanks to the large detector size, as well as high transparency of the deep lake water and relatively low level of light scattering, Baikal-GVD is capable of providing a sub-degree angular resolution for track-like events. With the energy threshold of a few hundred GeV, the detector observes about one thousand of neutrino events per year. The analysis of cascade-like events provides a confirmation of the existence of a diffuse astrophysical neutrino flux, in agreement with the IceCube measurements.

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