

Baikal-GVD: status and prospects

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Abstract. Baikal-GVD is a next generation, kilometer-scale neutrino telescope under construction in Lake Baikal. It is designed to detect astrophysical neutrino fluxes at energies from a few TeV up to 100 PeV. GVD is formed by multi-megaton subarrays (clusters). The array construction started in 2015 by deployment of a reduced-size demonstration cluster named "Dubna". The first cluster in its baseline configuration was deployed in 2016, the second in 2017 and the third in 2018. The full-scale GVD will be an array of ~10.000 light sensors with an instrumented volume about of 2 cubic km. The first phase (GVD-1) is planned to be completed by 2020-2021. It will comprise 8 clusters with 2304 light sensors in total. We describe the design of Baikal-GVD and present selected results obtained in 2015 – 2017.

1 Introduction

The deep underwater neutrino telescope Baikal Gigaton Volume Detector (Baikal-GVD) is currently under construction in Lake Baikal [1]. Baikal-GVD is formed by a three-dimensional lattice of optical modules (OMs) arranged at vertical load-carrying cables to form strings. The telescope has a modular structure and consists of functionally independent clusters - sub-arrays comprising a total of 288 OMs each and connected to shore by individual electro-optical cables. The first, reduced size cluster named "Dubna" has been deployed in Lake Baikal and was operated during 2015. In April 2016, this array has been upgraded

to the baseline configuration of a GVD-cluster, which comprises 288 optical modules attached at 8 strings at depths from 750 m to 1275 m. In 2017 and 2018 the second and the third GVD-clusters were deployed, increasing the total number of operating optical modules to 864 OMs. During Phase-1 of Baikal-GVD implementation an array consisting of eight clusters will be deployed by 2020-2021. Since each GVD-cluster represents a multi-megaton scale Cherenkov detector, studies of neutrinos of different origin are allowed with early stages of construction.

2 Detector

The detector instruments the deep water of Lake Baikal with optical modules – pressure resistant glass spheres equipped with photomultiplier tubes (PMT) Hamamatsu R7081-100 with photocathode diameter of 10” and a quantum efficiency of ~35% [2]. The PMTs record the Cherenkov radiation from secondary particles produced in interactions of high-energy neutrinos inside or near the instrumented volume. From the arrival times of light at the PMTs and from the amount of light, direction and energy of the incoming neutrinos are derived. Baikal-GVD in it’s 2018 design consists of three clusters – each of them with 288 optical modules (see Figure 1). A cluster comprises eight vertical strings attached to the lake floor: seven side strings on a radius of 60 m around a central one. Each string carries 36 OMs, arranged at depths between 735 and 1260 meters (525 m instrumented length). The vertical spacing between the OMs along a string is 15 m. The OMs on each string are functionally combined in 3 sections. A section comprises 12 OMs with data processing and communication electronics and forms a detection unit (DU) of the array. All analogue signals from the PMTs are digitized, processed in the sections and sent to shore if certain trigger conditions (e.g. a minimum number of fired PMTs) are fulfilled [3].

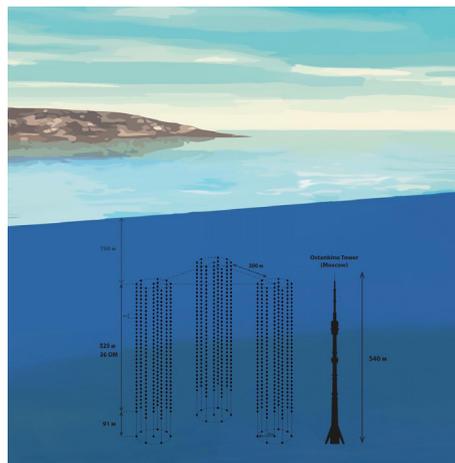


Figure 1. Artist’s view of GVD-2018, compared to the Moscow television tower.

The clusters are connected to shore (~3.5 km distance) via a network of cables for electrical power and high-bandwidth data communication. The shore station provides power, detector control and readout, computing resources and a high-bandwidth internet connection to the data repositories. The overall design allows for a flexible and cost-effective implementation of Baikal-GVD. The large detection volume, combined with high angular and energy resolution and moderate background conditions in the fresh lake water allows for efficient

study of cosmic neutrinos, muons from charged cosmic rays and search for exotic particles. It is also an attractive platform for environmental studies.

3 Selected results

3.1 Search for muon neutrinos

A search for upward moving muon neutrinos was performed with the data collected by the first cluster of the telescope in 2016. A set of 70 runs in which the detector demonstrated stable behaviour was chosen. The total exposition time of the analysed sample is close to 33 days. Precise measurements of optical module positions, timing and amplitude calibrations were available for the whole year 2016 and were applied for the present analysis.

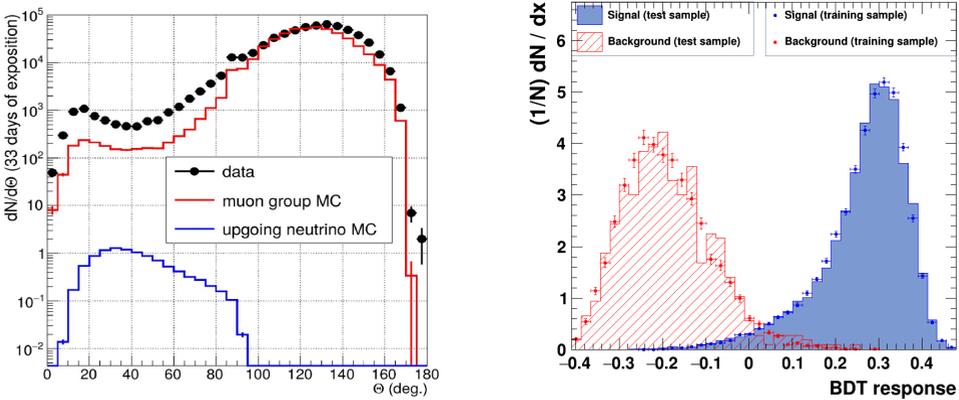


Figure 2. Left: Angular distributions of atmospheric muons accumulated over 33 days of exposition and compared to normalised Monte Carlo for atmospheric muons. The figure also shows the angular distribution for muons from upward moving atmospheric neutrinos. Right: Distribution of BDT discriminant value for signal (blue) and background (red) samples.

Reconstruction of muons is performed in two stages. The collection of PMT signals in each event includes noise pulses due to PMT dark current and light background from the lake water. Such pulses appear with 20-100 kHz per OM depending on season and depth. These pulses are rejected with the noise suppression procedure. Pulses are combined by the causality requirement: $|t_i - t_j| \leq \frac{\Delta R_{ij}}{c_w} + t_s$, where t_i, t_j are pulse times, ΔR_{ij} is distance between modules, c_w is the speed of light in water and $t_s = 10$ ns. A simple track position and direction estimation is done for each causally-connected group. OM hits which do not obey model of muon propagation and direct Cherenkov light emission are excluded in a gradually tightening set of cuts on hit residuals. The set of hits selected with this procedure has a noise contamination at the level of 1-2% depending on the elevation of the muon track. Selected set of pulses is used for the track fit under the assumption of direct Cherenkov emission from the muon track. The resulting median resolution of the procedure as measured in the up-going neutrino Monte Carlo sample is at the level of 1 degree.

Figure 2 (left panel) shows the reconstructed angular distribution in data compared to the prediction of Monte Carlo simulation of the detector response to atmospheric muons. Good agreement in shape of the distributions is achieved although the muon rate in data is

1.5 times larger than in MC. Muon bundles misreconstructed as up-going muons constitute a large background to the up-going neutrino search.

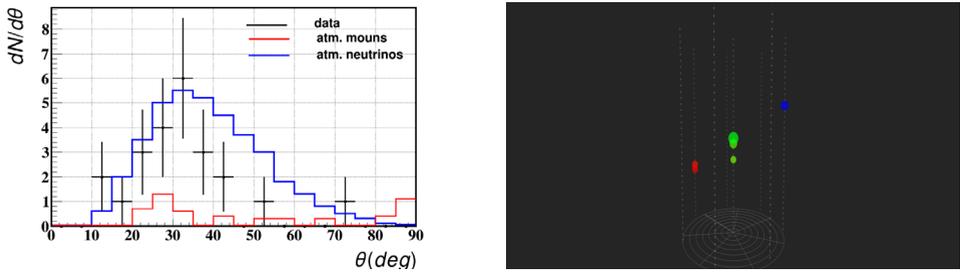


Figure 3. Left: Angular distributions of selected neutrino events, as well as expectations from atmospheric muons and neutrinos. Right: Event view of upward moving neutrino observed in this analysis. Each sphere represents an OM. Colors represent the arrival times of the photons where red indicates early and blue late times. The size of the spheres is a measure for the recorded number of photoelectrons.

A procedure based on a boosted decision tree (BDT) as implemented in the TMVA framework [4] was developed for the selection of neutrino events. A set of quality variables was reconstructed for each event and used for the BDT discriminant. The BDT was trained on events reconstructed as up-going in MC samples of atmospheric up-going neutrinos (signal) and atmospheric muons (background). Good signal/background discrimination was achieved for a BDT value of 0.2 (Figure 2, right panel). The BDT value was calculated for the data events and events with a BDT value > 0.2 were selected. In total 23 neutrino candidate events were found (Figure 3, left panel) while 42 events are expected from up-going neutrino MC. The number of expected background events is about 6. In Figure 3 (right) event view of one upward moving neutrino observed in the present analysis is shown.

3.2 Cascade detection by GVD

IceCube discovered a diffuse flux of high-energy astrophysical neutrinos in 2013 [5]. The data sample of their high-energy starting event analysis (HESE, 7.5 year sample) comprises 103 events, 77 of which are identified as cascades and 26 as track events [6]. These results demonstrate the importance of the cascade mode of neutrino detection with neutrino telescopes. The Baikal Collaboration has a long-term experience to search for a diffuse neutrino flux with the NT200 array using the cascade mode [7, 8]. Baikal-GVD has the potential to record astrophysical neutrinos with flux values measured by IceCube [9] even at early phases of construction. A search for high-energy neutrinos with Baikal-GVD is based on the selection of cascade events generated by neutrino interactions in the sensitive volume of the array [10]. Here we discuss the first preliminary results obtained by the analysis of data accumulated with Baikal-GVD in 2015-2016.

To search for high-energy neutrino flux of astrophysical origin, the data collected from 24 October till 17 December 2015 have been used. A data sample of triggered 4.4×10^8 events has been accumulated, which corresponds to 41.64 live days. Causality cuts and the requirement of $N \geq 3$ hit OMs leave about 1.8×10^7 events for the following analysis. After applying an iterative procedure of cascade vertex reconstruction for hits with charge higher 1.5 ph.e.l., followed by the rejection of hits contradicting the cascade hypothesis on each iteration stage, 316,229 events survived. After cascade energy reconstruction and event quality cuts, 12,931

cascade-like events survive. A total of 1192 events from final sample were reconstructed with energies above 100 TeV. The multiplicity distribution of hit OMs for these events is shown in Figure 4 (left). Also shown are the expected event distributions from an astrophysical flux with an $E^{-2.46}$ spectrum and the IceCube normalization, as well as the expected distributions from atmospheric muons and atmospheric neutrinos. The statistics of the generated atmospheric muon sample corresponds to 72 live days data taking.

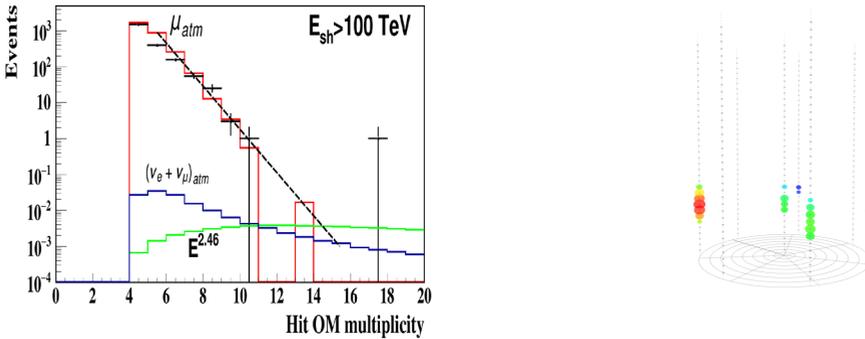


Figure 4. Left: Multiplicity distribution of hit OMs for experimental events with reconstructed energy $E_{rec} > 100$ TeV (dots). Also shown are the distributions of events expected from astrophysical neutrinos with an $E^{-2.46}$ spectrum and background events from atmospheric muons and neutrinos. Right: The event observed in October 2015.

All but one experimental events have multiplicities less than 10 hit OMs and are consistent with the expected number of background events from atmospheric muons. One event with 17 hit OMs was reconstructed as downward moving cascade. For a more precise reconstruction of cascade parameters, this event was reanalysed including hits with charges lower 1.5 ph.e.. 24 hits are consistent with a cascade hypothesis and the following cascade parameters: cascade energy $E = 107$ TeV, zenith angle $\theta = 56.6^\circ$ and azimuthal angle $\phi = 130.5^\circ$ ¹, distance from the array axis $\rho = 67.7$ m. The event is shown in Figure 4 (right panel).

The search for cascades from astrophysical neutrinos has been continued with data collected between April 2016 and January 2017, which corresponds to an effective livetime of 182 days. A data sample of 3.3×10^8 events was selected after applying causality cuts and the requirement of $N \geq 3$ hit OMs with hit charges ≥ 1.5 ph.e. on ≥ 3 strings.

At the next stage of the analysis the cascade reconstruction procedure and a set of quality cuts have been applied to data. In Table 1 the number of surviving events and the efficiency of applied cuts are shown. Here χ^2_ν - value of the minimizing function after cascade vertex reconstruction, L_A - log likelihood after energy reconstruction, η - variable which depends on probabilities of hit OMs to be hit and non-hit OMs not to be hit. Positive values of η are expected for cascades. Hit multiplicity distributions of events after cuts from Table 1 are shown in Figure 5 (left). In the right panel of Figure 5 the hit multiplicity of events with $E_{sh} > 10$ TeV and expected distribution of background events from atmospheric muons are shown. Finally, 57 events with reconstructed energies $E_{sh} > 10$ TeV and 5 events with $E_{sh} > 100$ TeV have been selected. Four of five events with energies higher than 100 TeV have hit multiplicities consistent with the expected distribution of background events from

¹The reconstructed directional vector $\vec{\Omega}(\theta, \phi)$ is opposite to the direction of the cascade development axis in water and represents the coordinates of a potential neutrino source on the celestial sphere in the array coordinate system.

Table 1. Efficiency of applied cuts

Cuts	Events	Rejection factor
After cascade vertex reconstruction		
$N_{hit} \geq 10$	577495	1
$\chi^2_t < 4$	2405	1/240
After cascade energy and direction reconstruction		
$L_A < 20$	374	1/6.4
$\eta > 0$	159	1/2.4
$E_{sh} > 10 \text{ TeV}$	57	1/2.8
$E_{sh} > 100 \text{ TeV}$	5	1/11.4
Total rejection factor:		1/115499

atmospheric muons. One event with 38 hit OMs was reconstructed as downward moving

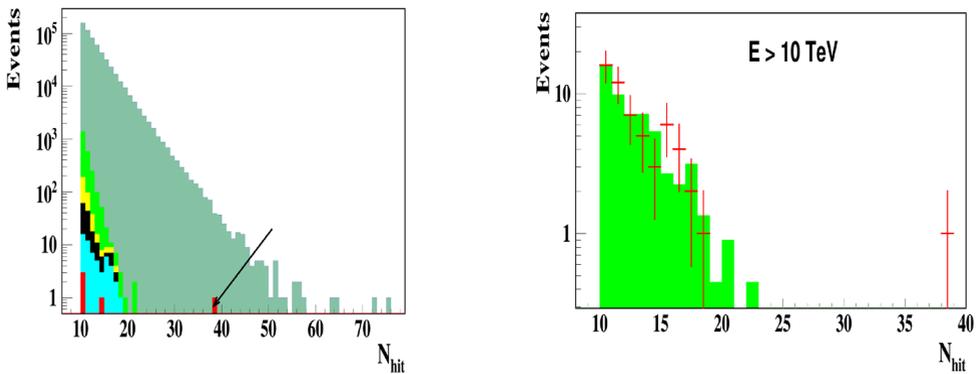


Figure 5. Left: Multiplicity distributions of hit OMs after cuts explained in Table 1. Right: The same for data (points) and atmospheric muons (histogram) with reconstructed energies $E_{sh} > 10 \text{ TeV}$.

contained cascade. For more precise reconstruction of cascade parameters, this event was reanalysed including hits with charges lower 1.5 ph.e.. 53 hits are consistent with a cascade hypothesis and the following parameters: energy $E = 154.9 \text{ TeV}$, zenith angle $\theta = 57.3^\circ$ and azimuthal angle $\phi = 249.4^\circ$, distance from the array axis $\rho = 44.7 \text{ m}$. The event is shown in Figure 6. In the left and right panels hit OMs before and after noise hit rejection are shown, respectively.

The two clear high-energy cascade events have been selected from data recorded during 2015-2016. Coordinates of the potential sources of these events are the following: right ascension (RA) 229.5° and declination (Dec) 5.6° for the first (2015) event, and right ascension (RA) 173.4° and declination (Dec) 13.9° for the second (2016) event in equatorial coordinates.

3.3 Search for high-energy neutrinos associated with GW170817

On August 17, 2017, a gravitational wave signal, GW170817, from a binary neutron star merger has been recorded by the Advanced LIGO and Advanced Virgo observatories [11]. A short GRB (GRB170817A), associated with GW170817, was detected by Fermi-GBM and INTEGRAL. Optical observations allowed the precise localization of the merger in the



Figure 6. The event observed in April 2016: left - all hit OMs, right - hits which survive all cuts.

galaxy NGC 4993 at a distance of ~ 40 Mpc. High-energy neutrino signals associated with the merger were searched for by the ANTARES and IceCube neutrino telescopes in muon and cascade modes and the Pierre Auger Observatory [12] and Super-Kamiokande [13]. Two different time windows were used for the searches. First, a ± 500 s time window around the merger was used to search for neutrinos associated with prompt and extended gamma-ray emission [14, 15]. Second, a 14-day time window following the GW detection, to cover predictions of longer-lived emission processes [16, 17]. No significant neutrino signal was observed by the neutrino telescopes.

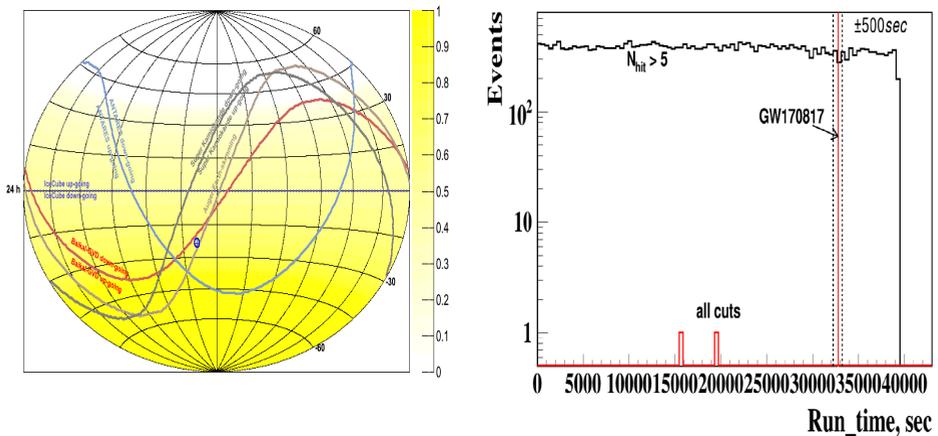


Figure 7. Left: Localizations of NGC 4993 and horizons separating down-going and up-going neutrino directions for IceCube, ANTARES, SuperKamiokande and Baikal-GVD at the time of the GW event in equatorial coordinates. The zenith angle of the source at the detection time of the merger was 73.8° for ANTARES, 66.6° for IceCube, 108° for SK and 93.3° for Baikal-GVD. Right: Temporal distribution of events during the data taking run containing the ± 500 s time window around the GW event. The black histogram represents events with hit OMs $N_{hit} > 5$, and the red histogram represents events surviving all selection cuts used for the neutrino search within ± 500 s time window around the GW event.

Here we discuss preliminary results of a search for high-energy neutrinos in coincidence with GW170817/GRB170817A using the cascade mode of neutrino detection. Two GVD-clusters have been operated during 2017. The zenith angle of NGC 4993 at the detection time of GW170817 was 93.3° for Baikal-GVD (see, Figure 7, left panel). Since background events from atmospheric muons and neutrinos can be drastically suppressed by requiring time and space coincidence with the GW signal, relatively weak cuts can be used for neutrino selection. For the search for neutrino events within ± 500 s window around the GW event, 731 events were selected, which comprise >5 hit OMs at >2 hit strings. After applying cascade reconstruction procedures and dedicated quality cuts, two events were selected. Finally, requiring directional coincidence with NGC 4993 $\psi < 20^\circ$ no neutrino candidates survive. The median angular error is 4.5° with this set of relaxed cuts and the expected number of atmospheric background events is about 5×10^{-2} during the coincident time window. Shown in Figure 7 (right panel) are temporal distributions of events fulfilling the additional selection requirement (black histogram) as well as events surviving all cuts (red histogram) during the 39347 s long data taking run, which contains the ± 500 s time window around GW170817.

The search over 14 days used a more stringent cut on the number of hit OMs - $N_{hit} > 7$. No events spatially coincident with GRB170817A were found. Given the non-detection of neutrino events associated with GW170817, upper limits on the neutrino fluence have been derived (see Figure 8).

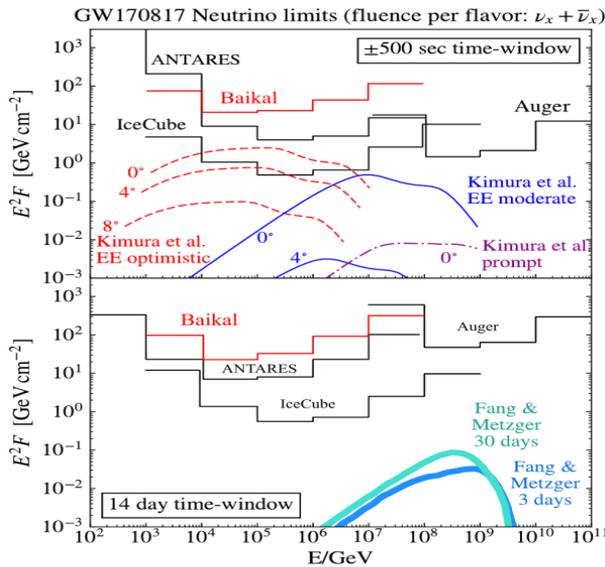


Figure 8. Upper limits (at 90 % confidence level) on the neutrino spectral fluence from GW170817 during a ± 500 s window centered on the GW trigger time (top panel), and a 14-day window following the GW trigger (bottom panel). For each experiment, limits are calculated separately for each energy decade, assuming a spectral fluence $F(E) = F_{up} \times [E/GeV]^{-2}$ in that decade only. Also shown are predictions by neutrino emission models (see [12] for details).

4 Conclusion

The ultimate goal of the Baikal-GVD project is the construction of a km^3 -scale neutrino telescope with implementation of about ten thousand light sensors. The array construction started by deployment of reduced-size demonstration cluster named "Dubna" in 2015, which comprises 192 optical modules. The first cluster in its baseline configuration was deployed in 2016 and the second one in 2017. After deployment of the third GVD-cluster in April 2018 Baikal-GVD comprises the total of 864 OMs arranged at 24 strings and becomes, at present, the largest underwater neutrino telescope. The modular structure of Baikal-GVD design allows studies of neutrinos of different origin with early stages of construction. Analysis of data

collected in 2015-2017 allows for extraction of a sample of upward through-going muons as clear neutrino candidates and the identification of the first two promising high-energy cascade events - candidates for events from astrophysical neutrinos. The search for neutrinos associated with GW170817 with Baikal-GVD allows to derive upper limits on the neutrino spectral fluence from this source. The commissioning of the first stage of the Baikal neutrino telescope GVD-1 with an effective volume 0.4 km^3 is envisaged for 2020-2021.

This work was supported by the Russian Foundation for Basic Research (Grants 16-29-13032, 17-02-01237).

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