Baikal-GVD neutrino telescope: status and first results

Grigory Safronov
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for the Baikal-GVD collaboration
Introduction
Baikal-GVD neutrino telescope

Baikal-GVD (Gigaton Volume Detector) is a cubic-kilometer scale underwater neutrino detector being constructed in lake Baikal.

10 organisations from 5 countries, ~70 collaboration members

- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (Saint-Petersburg)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- EvoLogics (Berlin, Germany)
- Comenius University (Bratislava, Slovakia)
- Krakow Institute for Nuclear Research (Krakow, Poland)

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Neutrino telescope network

ANTARES
Deep water
0.01 km$^3$
2008 –

KM3NeT
Deep water
1 + 0.006 km$^3$
Construction

Baikal/GVD
Deep water
~1 km$^3$
Construction

IceCube
Deep ice
1 km$^3$
2011 –

IceCube-Gen2
Deep ice
~10 km$^3$
Projected, 1$^{st}$ phase imminent

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Purpose of the experiment

Main purpose of the Baikal-GVD experiment: study of astrophysical neutrino flux
- Detector is sensitive to $\nu$ of energies from $\sim 100$ GeV to multi-PeV

Natural and artificial neutrino sources

Astrophysical neutrino
- Essential ingredient of rapidly developing field of multi-messenger observations
- Direct propagation in interstellar and intergalactic medium
- Discovered by IceCube detector in 2013
- Mechanisms of generation largely remain unconstrained

Region of sensitivity of very large neutrino telescopes

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Neutrino detection principle

Sparse array of photodetectors in natural water (ice) reservoir

Cerenkov light from charged particle produced in neutrino interaction is detected

Neutrino event types:

Tracks (CC, $\nu_\mu$ $\nu_\tau$):
• Good angular resolution: $\sim$0.3° - 0.5°
• Poor energy resolution: 200-300%
• Increased sensitive volume due to muon propagation range

Cascades (CC $\nu_e$ $\nu_\tau$, NC):
• Moderate angular resolution 3°-10°
• Good energy resolution: 5-30%

Main background:

Events from bundles of atmospheric muons
Neutrino detection principle II

- Neutrino identification capabilities depend on the zenith angle and energy
- Enormous atmospheric muon background for downgoing events
- Upgoing atmospheric and cosmic neutrinos are well-identified
- Atmospheric neutrinos dominate until ~50-100 TeV
- Earth is opaque for $E_\nu > \sim 500$ TeV: horizontal events are of interest

Complimentary observation areas for different telescopes

p, He, ... atmospheric $\mu$

extraterrestrial $\nu$

p, He, ...

Baikal
South Pole
Mediterranean

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High energy neutrino astrophysics I

First observation of 4σ excess over atmospheric neutrino energy spectrum
IceCube 2013: [10.1126/science.1242856]

IceCube cascade events spectrum, 6yr. data (2020)
[Phys. Rev. Lett. 125, 121104 (2020)]

≥8σ IceCube diffuse flux significance
[Prog.Part.Nucl.Phys.102,73-88(2018)]

ANTARES 12 years significance of excess: 1.8σ
[P. Coyle, ICRC2021]

Spectral index of astrophysical neutrino events:
2.3 - 2.9 depending on analysis
High energy neutrino astrophysics II

No 5σ discovery level evidence of high-energy neutrino sources so far

Evidence of neutrino from the direction of TXS 0506+056 blazar [3.6σ]

[10.1126/science.aat1378]

10 year time integrated IceCube point source search: Galaxy NGC 1048: 2.8σ post trial significance

[Phys. Rev. Lett. 124, 051103 (2020)]

ANTARES 13 years point source search: Radio-bright blazar J0242+1101: 2.4σ post trial

[PoS(ICRC2021)1161]

4.1σ evidence for neutrino emission from radio-bright blazars, selected with Very-Long-Baseline Interferometry observations


The Sun and 1987A Supernovae burst remain to be the only ones confirmed extraterrestrial sources of neutrino

Need to extend the high-energy neutrino sample!
Multi-messenger astronomy

Tidal disruption events (TDE)

Black hole consumes a star

IceCube neutrinos spatially consistent with TDEs:

IC191001A → AT2019dsg
IC200530A → AT2019fdr

[Grigory Safronov for Baikal-GVD]

Neutron star merger

GW170817 - neutron star merger, first gravitational waves detection associated with γ/optical/radio signal

[Phys. Rev. Lett. 119, 161101]
[JETP Letters, v.108, issue 12]

limits on the neutrino flux

Neutrino: constraints on the hadronic acceleration processes in the source

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Baikal-GVD detector
Baikal-GVD experiment site

- Platform “106 km” of Circum-Baikal railway
- Telescope is located 3.6 km away from shore
- Constant lake depth: 1366 - 1367 [m]

- Water transparency:
  - Absorption length: 22 m
  - Scattering length: 30-50 m
- Stable ice cover over 6-8 weeks in February - April: detector deployment and maintenance

Irkutsk

Telescope, shore center

Baikalsk: laboratory, storage

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## Detector construction status

### Deployment schedule

<table>
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<th>Year</th>
<th>Total number of clusters</th>
<th>Total number of strings</th>
<th>Number of OMs</th>
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<tr>
<td>2024</td>
<td>14</td>
<td>112</td>
<td>4032</td>
</tr>
</tbody>
</table>

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Baikal-GVD optical module

Telescope sensitive element: optical module (OM), 2304 OMs are deployed

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Baikal-GVD cluster

Cluster - independent detection unit, consists of 8 strings

String
- 36 OMs, depths from 750 to 1275 m
- Readout is organised in 3 sections, 12 OMs each
- Acoustic and LED calibration devices
- Anchored at the lake bottom

Cluster center is located at 30m depth
- Trigger electronics
- High voltage distribution
- Data transmission electronics

Trigger
- Cluster center reads out and sends event (5 μs window) to the shore center if the trigger condition is met
- Trigger condition: ~4.5 and ~1.5 [p.e.] signal on adjacent OMs within one section and 100 ns window
Acoustic positioning system

Water currents cause up to 50 m deviations of top OM from median location with the average velocity of 0.5 cm/s

System of acoustic beacons at each string:
- Time of acoustic signal propagation between beacons is measured each 1 - 6 minutes
- Each OM position is reconstructed online for each measurement
- **OM positioning precision < 20 cm**
Time calibration systems

Time scales for each of OMs must be synchronous

Interchannel intrasection calibration:
• OM calibration LEDs

Intersection calibration:
• LED beacons, up to 100m light propagation

Intercluster calibration, water properties monitoring
• 3 technological strings carrying 5 dedicated lasers
• Isotropic flashes 532 nm (green)
• 0.37 mJ: \(10^{15}\) photons, length 1ns

Time calibration precision ~ 2ns
Data stream

Data is transferred from Shore center to JINR

- Shore center → Baikalsk: 300 Mbit/s radiochannel
- Baikalsk → JINR: Ethernet
- Compressed data volume ~40GB per day
- Delay due to shore → JINR data transfer: < 1 min.
- At JINR data is stored using EOS service
Event reconstruction is run on JINR computing cluster in the automatic regime
• c++ BARS framework wrapped in a set of python steering scripts
• Single-cluster and multi-cluster event building
• Data quality monitoring (DQM)
• Reconstruction of muons and cascades
• Production of quasi-real-time neutrino event alerts

Presently single-cluster dataset is being reconstructed while multi-cluster reconstruction is in development

[Pos(ICRC2021)1040]
**Shore center:** High voltage and low voltage monitoring, event rates, detector occupancies, OM sensor data at web-based dashboard, detector geometry monitoring, thunderstorm alarm

**JINR:** A posteriori data quality monitoring (DQM) within BARS framework, databases
- **DQM:** Uniformity of event rate, hot channels, charge distributions, charge calibration
- **Dashboard:** web-based interface to JINR databases containing OM sensor data, detector geometry data, HV and LV data, run info, data processing status
Reconstruction and results
Event reconstruction: muons

A set of PMT impulses in 5 µs window at each OM is considered for event reconstruction.

Time and charge information is used to reject random impulses from PMT dark current and lake water chemiluminescence.

Track coordinates and direction are estimated using cleaned collection of impulses: fit with $Q = \chi^2(t)$
- Angular resolution $\sim 0.5^\circ$ at $E_\mu \sim 100$ TeV for sufficient track length.

Large variety of track quality variables is estimated e.g. time residuals, fit errors, track likelihood, etc.

These variables are further used in the neutrino selection.

Muon energy is estimated using average energy loss $dE/dX$ as a proxy
- $\sim$ Corrected sum charge divided by track length
- Factor 3 resolution at 100 TeV

Muon neutrino selection

Neutrino signal region: upgoing and nearly-horizontal muons
Single-cluster analysis: $\theta_{\text{zenith}} > 120^\circ$

Misreconstructed atmospheric muon background exceeds signal by the factor $10^2 - 10^4$

Background suppression is a challenge

Two methods for low-energy neutrino selection were developed
• Cut-based (cuts on set of 13 variables)
• Machine learning: boosted-decision tree (BDT) classifier (15 input variables)

High-energy neutrino selection is in development
First muon neutrino candidate sample

First set of muon neutrino candidates based on data from April-June 2019

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, $<E_{\nu}> \sim 500$ GeV
- Runs from April 1st until June 30th
- Total single cluster exposition 323 days
- Total number of events selected: 44 neutrino candidates
- Results are compared to atmospheric neutrino simulation

**MC expected:** 43.6
- atm. neutrino : 43.6
- atm. muon: 0

**Observed:** 44

Excellent agreement of MC expectation and data

Single upgoing muon angular resolution for single-cluster analysis $\sim 1^\circ$

[arXiv:2106.06288, submitted to EPJC]

An effort to extend analysis to the full dataset and high energies is ongoing
Muon neutrino candidates

cluster 3, run 122
evt. 1549343
$\theta_{\text{zenith}} = 169.78^\circ$
$N_{\text{strings}} = 3$
$N_{\text{hits}} = 19$

cluster 1, run 157
evt. 1414137
$\theta_{\text{zenith}} = 161.78^\circ$
$N_{\text{strings}} = 2$
$N_{\text{hits}} = 15$

cluster 4, run 99
evt. 438088
$\theta_{\text{zenith}} = 162.22^\circ$
$N_{\text{strings}} = 3$
$N_{\text{hits}} = 18$

cluster 5, run 162
evt. 1939721
$\theta_{\text{zenith}} = 148.07^\circ$
$N_{\text{strings}} = 3$
$N_{\text{hits}} = 13$

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High energy cascade reconstruction

Cascades reconstruction
- Time $\chi^2$ fit for the position reconstruction
- Likelihood minimisation for direction and energy

Angular resolution: 3-3.5° depending on energy

Energy resolution: $\delta E/E \sim 10\%-30\%

~0.4-0.6 astrophysical neutrino per year for one cluster are expected
  - In assumption of astrophysical neutrino spectrum $\sim E^{-2.46}$ (IceCube fit)

More details on cascade reconstruction and selection: [Pos(ICRC2021)1144]
High energy cascade events I

10 high-energy cascade events were selected in 2018-2020 data

Estimated energy from 74 TeV up to 1.2 PeV!

FERMI γ-ray maps are produced by D. Semikoz and A. Neronov

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High energy cascade events II

Two close events at distance 10.3°: GVD_2018_656_N and GVD_2019_153_N

**LSI + 61 303** - γ-ray active microquasar

- 3.1° from GVD_2019_153_N
- 7.4° from GVD_2018_656_N
PeV cascade
Reconstructed energy: 1.2 PeV
Zenith angle: 61°

Two sources with hard $\gamma$ spectrum within 5° circle:
- BL Lac RBS 1409
- 1 ES 1421+582

High energy cascade events III

$E_\gamma > 1$ GeV
$E_\gamma > 30$ GeV

E = 30 GeV
RBS 1409 BL Lac unknown
1 ES 1421+582 unknown
Both with hard spectrum

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High energy cascade events IV

The first clear cascade event from the interaction of an upward moving neutrino at 100 TeV

Upgoing cascade:
Contained event
Reconstructed energy
E=(91.2±11) TeV
Zenith angle: 109°

No good known sources in 3° circle
Multi-messenger program in cascade channel

- Follow-up for neutron star merger event **GW170817**: [JETP Letters, v.108, issue 12]
- Follow-up for tidal disruption events **AT2019dsg** and **AT2019fdr** is in development
- Radio-burst from magnetar **SGR 1935+2154** on 28/04/20
  - IceCube neutrino time-integrated flux (fluence) limit: 5.2*10^-2 GeV*cm^-2
  - ANTARES fluence limit: 14 GeV*cm^-2
  - Baikal-GVD fluence limit: 2 GeV*cm^-2 [Pos(ICRC2021)946]

Radio-bright blazars near high-energy cascade events (in collaboration with A. Plavin, Y. Kovalev, S. Troitsky)

**GVD2020_3_175_1565446** → **J1938-1749**

**GVD2020_1_114_773570** → **J0301-1652**
Neutrino alert program

BAIKAL alerts
Since Sept 2020: data processing with a delay of several hours. Nearest plans: HE alerts processing with delay less than tens of minutes.

ANTARES alerts
Since the end of Dec 2018 Baikal-GVD follows ANTARES alerts. Processed 48 alerts, among which 3 possible coincidences were found in cascade mode within 5° and dT ±1 day and are under investigation with ANTARES.

ICECUBE alerts
Starting Sept 2020 Baikal-GVD follows IC alerts (GCN), 22 alerts.
Upper limits at 90% c.l. on the neutrino fluence: \( \sim 1\pm 2 \text{ GeV cm}^{-2} \) for energy range 1TeV– 10PeV. \( E^{-2} \) spectral behavior; equal fluence in all flavors

[Astronomy Letters 47(2):94-104 (2021)]
Summary

• Since April 2021 Baikal-GVD detector includes 8 clusters (over 2300 optical modules)
• Detector positioning and calibration methods are developed
• Automatic data processing and monitoring framework is commissioned
• A set of 44 muon neutrino candidates was selected in 323 days single cluster livetime in 2019, excellent agreement with MC expectation is obtained
• A set of 10 high-energy cascade events was selected in 2018-2020 data
• Multi-messenger studies using cascade events are in progress
• Baikal-GVD receives and analyses ANTARES and IceCube neutrino alerts. Baikal-GVD alerts are generated with few hours delay, improvement to tens of minutes is imminent
BACKUP
Brief history of Baikal project

1980: Start of experiments at “106 km” site

1993: NT36 - 3 strings, 36 optical modules (OM)

1996: NT96 - 4 strings, 96 OM

1998: NT200 - 8 strings, 196 OM

2004-2005: NT200+ - three additional strings, 12 OM each


2016: First full-scale cluster of Baikal-GVD deployed

2021: Baikal-GVD operates 8 clusters, 2304 OM

One of the first ever underwater neutrino events, NT96, 1997
Lake water transparency:
- Absorption length: 22m
- Scattering length: 30-50m

PMT noise due to water chemiluminiscence
- “Quiet period”: 20 - 50 kHz
- High noise period: up to ~200kHz on top channels

Realistic noise MC simulation
- Noise rate
- PMT charge deposition ditributions