Baikal-GVD: status and perspectives

Zh.-A. Dzhilkibaev, INR (Moscow), for the Baikal Collaboration
NUTEL2021, February 23, 2021
Baikal-GVD collaboration

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)
Baikal-GVD site

Railway stop “106 km” of Circum-Baikal railway

Telescope is located 3.6 km away from shore

Constant lake depth:
• 1366 - 1367 [m]

Stable ice cover for 6-8 weeks in February - April
• Detector deployment
• Maintenance
Water properties

- **Absorption length**: $\sim 22-24$ m

- **Scattering length**: $L_s \sim 30-50$ m  
  $L_{\text{eff}} = \frac{L_s}{1 - \langle \cos \theta \rangle} \sim 300-500$ m

- **Strongly anisotropic phase function**: $\langle \cos \theta \rangle \sim 0.9$

- **Moderately low background in fresh water**:  
  15 – 40 kHz (R7081HQE)  
  absence of high luminosity bursts from biology and $K^{40}$ background.
Gigaton Volume Detector at Lake Baikal

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

**Cluster**
- Consists of 8 strings
- 60 m step between strings
- Acts as independent detection unit
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger:
  4.5 p.e. + 1.5 p.e. on adjacent OMs in 100 ns window

**String**
- 36 OMs, depths from 750 m to 1275 m
- 15 m step between OMs
- All OMs look downward
- Acoustic and LED calibration devices
- Anchored at the lake bottom
Calibration devices

**Calibration LEDs in each OM**

- Manometer
- SubConn connector
- Accelerometer, compass
- Steel Frame
- Hermetic seal
- PMT Hamamatsu R7081-100
- OM controller
- HV board
- Glass hemisphere
- Vacuum valve
- Temperature sensor
- OM

**LED beacons for time calibration**

- Laser 532 nm, 0.37 mJ, 1 ns

**Baikal-GVD 2020 top view**

- Cluster 1
- Cluster 2
- Cluster 3
- Cluster 4
- Cluster 5
- Cluster 6
- Cluster 7
- Tech. strings with 1 or 2 lasers on each string

**Hydrophones for acoustic positioning**

- (4 per string, ~ 20 cm precision)

**2016 laser event**

- LASER 64 m

- 0.3 p.e.
- 16391 ns
- 900 ns
1. OM coordinates are acquired via an acoustic positioning system.

2. It consists of a network of acoustic modems (AMs) installed along GVD strings.

3. 4 AMs per string in a standard configuration.

4. AM coordinates are regularly reconstructed via acoustic trilateration.

5. OM coordinates are obtained by interpolating AM coordinates.

6. OM coordinates error < 0.2m, as estimated via a calibration AM.

7. OM drift can reach tens of meters, depends on season and elevation.
Winter expedition 2020

Despite harsh ice conditions this winter, two new clusters were deployed (576 OMs).
### Baikal-GVD construction status and schedule

#### Deployment schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Total number of clusters</th>
<th>Total number of strings</th>
<th>Number of OMs</th>
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<tbody>
<tr>
<td>2016</td>
<td>1</td>
<td>8</td>
<td>288</td>
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<td>2017</td>
<td>2</td>
<td>16</td>
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<td>2018</td>
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<td>2019</td>
<td>5</td>
<td>40</td>
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<td>2022</td>
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<td>80</td>
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<tr>
<td>2023</td>
<td>12</td>
<td>96</td>
<td>3456</td>
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<tr>
<td>2024</td>
<td>14</td>
<td>112</td>
<td>4032</td>
</tr>
</tbody>
</table>

Effective volume 2020: $0.35 \text{ km}^3$
Detector response

Neutrino signals

Up-going muon

Background

Muon bundle

High-energy cascade

Multi cluster event
Preliminary results

- Muons detection mode: atmospheric neutrinos
- Cascades detection mode: HE cascades
- Multimessenger studies
Track analysis

Fit track with quality function

\[ Q = \chi^2(t) + f(q, r) \]

Neutrino selection:
- cut on zenith angle
- cut on fit quality

Upgoing: \[ \theta_{\text{zenith}} > 120 \text{ deg.} \]

Neutrino selection works as expected

Fair agreement with MC predictions

A likelihood-based reconstruction is in development
Muon neutrino: single-cluster analysis

- Data taken between Apr 1 and Jun 30, 2019
- Live time: 323 days (single-cluster equivalent live time)

MC expected: 54.3
- atm. neutrino: 54.3
- atm. muon: < 1

Observed: 57

Fair agreement with MC prediction for atmospheric neutrino

Angular resolution
~ 1° or better
(single cluster)

Multi-cluster analysis is in preparation
Muon neutrino candidates

cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
N_{strings} = 3
N_{strings} = 19

cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
N_{strings} = 2
N_{strings} = 15

cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
N_{strings} = 3
N_{hits} = 18

cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
N_{strings} = 3
N_{hits} = 13
Cascades detection with GVD Cluster

Neutrino Effective Area

IceCube HESE

Directional resolution for cascades:
~ 2° - 4° - median value of mismatch angles

Distribution of mismatch angles

Energy resolution:
δE/E ~ 10%-30%

7 GVD Clusters
N hit > 19 OMs

Energy resolution:
δE/E ~ 10%-30%
Dependence of effective volume on zenith angle
Energy spectrum of astrophysical neutrinos measured by IceCube:

$4.1 \cdot 10^{-6} \ E^{-2.46} \ \text{GeV}^{-1} \ \text{cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1}$

Event selection criteria ($E_{\text{sh}} > 100 \ \text{TeV}, \ N_{\text{hit}} > 19)$:

~0.6 events/yr with 1 cluster
~3-4 events/yr with 7 clusters

Expected number of detected events in 7 GVD Clusters from astrophysical neutrinos for 1 yr. observation
After reconstruction and all cuts applying, 9357 events have been selected with $N_{\text{hit}} > 9$ & $E > 10$ TeV.

$T = 3714$ days (10.1 years) of one Cluster operation (2018, 2019, 2020)

Data sample

Wave form of multiple hit signal

Hits separation for >20 ns time difference

Trigger conditions for different studies

- MM studies: $N_{\text{hit}} > 7$
- Upward going neutrinos: $N_{\text{hit}} > 10$ & $\theta > 90^\circ$
- HE astrophys. neutrinos: $N_{\text{hit}} > 19$ & $E > 100$ TeV
High energy cascades (data)

Energy distribution

Data from 2018 - 2020, exposition: **3714 days**

12 events with \( E > 100 \text{ TeV} \)
and \( N_{hit} > 19 \):
5-6 events – cascade events
7-6 events – cascade events
   with muon pattern

3 upgoing cascades: \( E \approx 91 \text{ TeV} \)
and \( E \approx 74 \text{ TeV} \) and \( 22 \text{ TeV} \)
The first clear cascade event from the interaction of an upward moving electron- or tau-neutrino at the 100 TeV

Contained event
Reconstructed energy $E = (91 \pm 11) \text{ TeV}$
Zenith angle $\theta_z = 109^\circ$

Preliminary
Angular resolution - $\psi_{med} = 2.5^\circ$

Energy resolution $\pm 11$ TeV

Sky map, $2^\circ$ circle around event direction
First PeV_scale cascade!

Reconstructed energy $E = 955 \text{ TeV (±20\%)}$;
distance from central string $r = 91 \text{ m}$;
zenith angle $= 61^\circ$
Upper limits on fluence of neutrinos associated with GW170817

No neutrino events associated with GW170817 have been observed using cascade mode within $\pm 500$ sec window and 14 days after the neutron star merger.

Assuming $E^{-2}$ spectral behavior and equal fluence in all flavors, upper limits at 90% c.l. have been derived on the neutrino fluence from GW170817 for each energy decade.
Baikal-GVD follows up of neutrino alerts

ANTARES (TAToO) \( \mu \uparrow \) since Dec 2018 \( \langle E \rangle \ 7 \text{ TeV} \)

ICECUBE (GCN) \( \mu \uparrow \) since Sept 2020 \( E > 100 \text{ TeV} \)

## search for \{\text{time,} \delta, \alpha\} correlations in single cluster

in cascade mode
within 4.5° half-open cone towards sources over 4\pi-sky

in track mode:
within 1.5° half-open cone towards sources in down hemisphere
Following up alarm of trigger, we look for events on each cluster in time windows ±500 sec, ±1 hour and ±1 day around alerts inside ½ cones; in cascade mode a full data sample of season 2018-2019 has been used for background estimates; in tracks the first neutrino sample with 57 events in 2019 has been tested, while softer quality cuts for muons selection were considering and under investigation now.

No prompt coincidence in time and direction was found with ANTARES trigger.
## Limits on energy fluence

“High energy neutrino follow-up with Baikal-GVD”, Avrorin A.D. et al.

### CR&MM_2020/PosterCRMM_ICGVD_ALERTS_VDik.pdf

<table>
<thead>
<tr>
<th>Alert</th>
<th>NN</th>
<th>rank</th>
<th>$E_\nu$ (TeV)</th>
<th>alt (deg.)</th>
<th>N_{obs}</th>
<th>N_{bkg}</th>
<th>p-val</th>
<th>Fluence U.L. (TeV cm$^{-2}$)</th>
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<td>28411</td>
<td>Bronze</td>
<td>110.79</td>
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</tr>
</tbody>
</table>

9 IC alerts in Sept-Oct 2020

Spectrum $E^{-2}$

1 TeV—10 PeV

FC limits

**Results:**

- $p$-val $\sim 0.2 \div 0.4$ ($\sim 1\sigma$)

- Fluence U.L. at 90% c.l. $\sim 1 \div 2$ GeV cm$^{-2}$
Fiber optic data acquisition system for GVD

Development of fiber-optic DAQ is focused on GVD step 2.

The goal of upgrading the DAQ is to reduce the event registration threshold by increasing the data transfer speed and implementing a smart trigger system.

Basic principles:
- “One fiber per one string”.
- “Common clock” for all sections of the cluster
- “Multi-trigger” operation mode

To meet these requirements:
- CWDM optical multiplexers are applied (up to 9 channels per one fiber)
- ADC/Master board was modernized on the basis of FPGA Xilinx Zynq. 
  (extending the real-time processing capabilities of the section data).
Fiber optic experimental string

Experimental string is intended to in-situ tests of underwater fiber optic on the basis of CWDM

Basic element of the optical communication is CWDM multiplexor (MUX) that provided up to 9 physical line using different wavelengths.

**Exp. string comprises:**
- New Master/ADC board (FPGA Zynq)
- 12 optical modules.

**Mode of operation:**
- Basic trigger: coincidences of two neighboring OMs;
- Monopol trigger.
- ADC and Sync data are transmitted via one optical fiber to the Shore Center
GVD 2020 and extension

~1.7 km

Stage 1

~1 km
Conclusion

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere: 0.35 km$^3$ and growing

- Modular structure of GVD design allows a search for HE neutrinos and multimessenger studies at the early phases of array construction.

- Observations of atmospheric neutrinos by Baikal-GVD agree with expectations; first astrophysics neutrino candidate events have been selected
Deployment rate – 2 clusters/year

GVD (1 km³) in 2026