Нейтринный телескоп Baikal-GVD - первые результаты и ближайшие планы

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Neutrino telescope world map 2022

ANTARES
Deep water
0.02 km³
decommissioned in Feb 2022

KM3NeT
Deep water
1 + 0.006 km³
Construction

IceCube
Deep ice
1 km³
2011 –

IceCube-Gen2
Deep ice
~10 km³
2026+

Baikal/GVD
Deep water
~1 km³
half-complete

R&D projects not shown
Baikal-GVD collaboration (as of Feb 2022)

11 organisations from 6 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)
- Institute of Nuclear Physics (Almaty, the Republic of Kazakhstan)
Baikal-GVD site

- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance

- High water transparency
  - Absorption length: 22 m
  - Scattering length: 30 – 50 m ($L_{\text{eff}} \approx 480$ m)
- Moderately low optical background: 15–40 kHz (PMT R7081-100 ∅10”)

Sonar image
Baikal-GVD optical module

- Manometer
- SubConn connector
- Accelerometer, compass
- Steel frame
- Hermetic seal
- PMT Hamamatsu R7081-100
- Optical gel
- Vacuum valve
- Temperature sensor
- OM controller
- HV board
- Gel lens
- Calibration LEDs
- Glass hemisphere
GVD cluster

String

- 36 OMs, 15 m spacing, downward-looking

- 4 acoustic modems

- 4 electronics modules
  (3 section modules + 1 string module)

- Data network: shDSL 5.7 Mbit

- Depths from 750 m to 1275 m

Cluster

- 8 strings (288 OMs)
- 60 m spacing between strings
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger: 4 p.e. hit + 1.5 p.e. hit on adjacent OM in 100 ns window
- Inter-section synchronization by common trigger (~ 2 ns accuracy)
- Internal network: shDSL 5.7 Mbit
- Connection to shore: Ethernet / optic fiber
Экспедиция 2022

• Установлено:
  ✓ два новых кластера
    (16 гирлянд)
  ✓ 1 дополнительная межкластерная гирлянда
    (36 ОМ + лазер)
  ✓ 2 экспериментальные гирлянды
    на оптоволоконной технологии связи (активно 48 ОМ)
  ✓ 1 отдельная лазерная станция
• Проведён плановый ремонт ранее установленного оборудования
### Baikal-GVD construction status 2022 and schedule

#### Deployment schedule

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of clusters</th>
<th>Number of strings</th>
<th>Number of OMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>1</td>
<td>8</td>
<td>288</td>
</tr>
<tr>
<td>2017</td>
<td>2</td>
<td>16</td>
<td>576</td>
</tr>
<tr>
<td>2018</td>
<td>3</td>
<td>24</td>
<td>864</td>
</tr>
<tr>
<td>2019</td>
<td>5</td>
<td>40</td>
<td>1440</td>
</tr>
<tr>
<td>2020</td>
<td>7</td>
<td>56</td>
<td>2016</td>
</tr>
<tr>
<td>2021</td>
<td>8</td>
<td>64</td>
<td>2304</td>
</tr>
<tr>
<td><strong>2022</strong></td>
<td><strong>10</strong></td>
<td><strong>80 + 3</strong></td>
<td><strong>2880 + 84</strong></td>
</tr>
<tr>
<td>2023</td>
<td>12</td>
<td>96</td>
<td>3456</td>
</tr>
<tr>
<td>2024</td>
<td>14</td>
<td>112</td>
<td>4032</td>
</tr>
</tbody>
</table>

Effective volume 2022: 0.50 km³ (cascades E > 100 TeV)

- 10 clusters + 1 special string (laser+36 OM)
- + 2 experimental strings + 4 laser stations
Neutrino effective volume for tracks (one GVD cluster)

- Energy threshold ~ 200 GeV (higher than in ANTARES)
- Fully efficient at $E > 100$ TeV

$0.35 \text{ km}^3$

$\cos \theta < -0.5$

Expected performance for tracks

Angular resolution

Energy reconstruction

Improvements expected from likelihood-based reconstruction (under development)

energy resolution ~ factor 3 at $E \sim 100$ TeV
(±34% containment band)

G. Safronov @ ICRC 2021
Atmospheric muons with Baikal-GVD (single cluster)

Data taken between Apr 1 and Jun 30, 2019 with 5 clusters

~ 9 800 000 events reconstructed with at least 8 hits on at least 2 strings

Good agreement for \( \cos(\text{zenith}) > 0.2 \)

MC underpredicts the rate of misreconstructed events in the upgoing region by a factor of 3.5 (under study)

NB: most of these events are muon bundles (average multiplicity \( \sim 10 \))

Atmospheric neutrinos with Baikal-GVD (single cluster)

upgoing: $\theta > 120^\circ$

- MC expected: 43.6
  - atm. neutrino: 43.6
  - atm. muons: $< \sim 1$

Observed events: 44

Median energy of this sample $\approx$ 500 GeV

Track-like neutrino candidate events

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

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

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

cell 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
N_{strings} = 3
N_{hits} = 13
Multi-cluster track events

Example of a downgoing muon bundle event in real data

Work in progress!
Cascade analysis: effective area and rates

Analysis sensitive to all-flavour CC and NC interactions over the whole sky

Assumption for astrophysical neutrino energy spectrum (IceCube fit):
\[4.1 \times 10^{-6} E^{-2.46} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\]

Effective area for cascade detection

neutrino effective area for cascade detection

Expected number of cascade events per year

Effective volume for \(E > 100\) TeV \(\sim 0.35\) km\(^3\)

3–4 ev/yr with \(E_{\text{sh}} > 100\) TeV for 7 clusters
Cascade analysis performance

Directional resolution for cascades: 2°- 4° - median mismatch angle

Energy resolution: $\delta E/E \sim 10\%-30\%$
Cascade analysis : data and MC

Data from 2019-2020, livetime: 2915 days single-cluster equivalent

MC atmospheric muons - Corsika 7.74, Sybill 2.3c, protons, $E_p > 100$ TeV

One upgoing cascade: $E \approx 91$ TeV
Upward-going cascade

Upgoing (19° below horizon)  May 23, 2019

Cluster 1

GVD2019_1_114_N

E ~ 91 TeV

Contained event (50 m off central string)

Excellent candidate for a neutrino event of astrophysical origin

Sky plot of γ-ray sources

(credit: D.Semikoz, A.Neronov)

known sources in 3 degree circle:
PKS 0302-16 : unknown type of source
PMN J0301-1652 : unknown type of source

Preliminary
Improved cascade event selection

Search for early hits from muon track

Use it in event selection

This improves atmospheric muon rejection by an order of magnitude

After final cuts:

MC atm. muons : 4 events
MC astrophys. flux: 5 events
data (2019-2020) : 7 events
+3 events in 2018 data

> 50% purity expected for E > 100 TeV neutrino sample

See talks by Zh. Dzhilkibaev and Z. Bardačová @ ICRC 2021
Sky map with 10 Baikal-GVD cascade events

Legend

Background image: Fermi LAT

Green circles: Baikal-GVD events 2018 (50% and 90% C.L. regions)

White circles: Baikal-GVD events 2019-2020
Event doublet near Galactic plane

LSI +61 303 – γ- ray active microquasar

3.1° from GVD_2019_153_N and 7.4° from GVD_2018_656_N

Using PSFs of all 10 events the chance probability to observe such a doublet near LSI +61 303 was estimated: p-value = 0.007 or 2.7 σ (preliminary)
GVD follow up of ANTARES alerts

Following ANTARES upgoing $\mu$ alerts ($<E> = 7$ TeV)
Time windows: $\pm 500$ sec, $\pm 1$ hour and $\pm 1$ day
Both upgoing and downgoing cascades are looked for

Since Dec 2018, ~ 50 alerts have been analysed

3 potentially interesting events

<table>
<thead>
<tr>
<th>ANT alert</th>
<th>GVD cluster</th>
<th>T-T$_{\text{alert}}$, hours</th>
<th>Energy, TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7</td>
<td>3</td>
<td>+20.8</td>
<td>13.5</td>
</tr>
<tr>
<td>A7</td>
<td>3</td>
<td>-23.2</td>
<td>158</td>
</tr>
<tr>
<td>A7</td>
<td>2</td>
<td>-3.2</td>
<td>2.9</td>
</tr>
<tr>
<td>A15</td>
<td>2</td>
<td>+20.4</td>
<td>3.0</td>
</tr>
<tr>
<td>A15</td>
<td>3</td>
<td>-0.64</td>
<td>3.98</td>
</tr>
<tr>
<td>A16</td>
<td>2</td>
<td>-18.7</td>
<td>3.99</td>
</tr>
<tr>
<td>A16</td>
<td>4</td>
<td>-14.35</td>
<td>3.89</td>
</tr>
</tbody>
</table>

No prompt coincidence in time and direction was found

See talks by O. Suvorova and A. Garre @ ICRC 2021
GVD follow up of IceCube alerts

Since Sep 2020, following IC alerts (GCN / upgoing muons)

No statistically significant coincidence was found in this analysis, except possibly IceCube-211208A (see next slide)

90% upper limits derived for E-2 spectrum, equal fluence in all flavors, for E 1 TeV – 10 PeV and ±12 hr interval

http://dx.doi.org/10.1134/S1063773721020018

V.Y. Dik et al., JINST 16 (2021) C11008
https://doi.org/10.1088/1748-0221/16/11/C11008
Baikal-GVD follow up of IceCube-211208A / PKS 0735+17

Dec 8, 2021 20:02: IceCube “Astrotrack Bronze” neutrino event
Dec 9, 2021: MASTER reports optical activity of PKS 0735+17
   (slightly outside the 90% IceCube uncertainty region)
... PKS 0735+17 observed in HE gamma-rays (Fermi LAT), X-rays
   (Swift XRT) and radio
... ANTARES reports upper limits for PKS 0735+17 (no detection)
... KM3Net reports a neutrino with a background p-value = 0.14
... **Baikal-GVD** reports a downward-going (30° above horizon)
cascade-like event **4 hr after** the IceCube event from the direction
RA=119.44°, Dec=18.00°, that is **4.68° from PKS 0735+17** and 5.30°
from the best-fit direction of IceCube-211208A

Estimated energy = 43 TeV
PSF 50% (68%) containment radius = 5.5 deg (8.1 deg)
**Background estimate: 0.0044 events** in the 5.5 deg cone in 24 hr
(2.85 σ). Trail factors to be scrutinized

* PKS 0735+17 is a bright blazar very similar to TXS 0506+056

**Image by D.Semikoz & A.Neronov**
PKS 0735+17: a neutrino-emitting blazar?

N. Sahakyan et al., arXiv:2204.05060

A model with PeV protons interacting with an external UV photon field predicts $\sim 0.067$ muon and antimuon neutrinos over the observed 3-week flare.
Заключение

- **Baikal-GVD** – новый нейтринный телескоп в озере Байкал
  - Объём порядка 1 км³ (по завершении строительства)
  - Угловое разрешение лучше 1° (для треков)
  - Область зрения эффективно дополняет IceCube

- Обнаружены первые намеки на возможные новые астрофизические источники нейтрино

- Идет набор данных с 10 кластерами (~ 0.5 км³)
Backup slides
Neutrino effective area for tracks: one GVD cluster

![Graph showing the relationship between muon neutrino effective area and neutrino energy for a single Baikal-GVD cluster with different cuts.]
Cascade analysis angular resolution

Cascade angular resolution
for E~100 TeV: ~3 - 3.5 °
A 1 PeV cascade event (downgoing)  

Energy $E = 1200$ TeV ($\pm 30\%$)  
Distance from central string $r = 91$ m  
Zenith angle = 61°  

Fermi sources in 5° circle:  
RBS 1409 BL Lac $z=$unknown  
1ES 1421+582 $z=$unknown  
both with hard spectrum
### Selected events (2018-2020)

<table>
<thead>
<tr>
<th>Event ID</th>
<th>E, TeV</th>
<th>$\theta_z$, degree</th>
<th>$\varphi$, degree</th>
<th>R.A.</th>
<th>Dec</th>
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<tbody>
<tr>
<td>GVD2018_354_N</td>
<td>105</td>
<td>37</td>
<td>331</td>
<td>118.2</td>
<td>72.5</td>
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<tr>
<td>GVD2018_383_N</td>
<td>115</td>
<td>73</td>
<td>112</td>
<td>35.4</td>
<td>1.1</td>
</tr>
<tr>
<td>GVD2018_656_N</td>
<td>398</td>
<td>64</td>
<td>347</td>
<td>55.6</td>
<td>62.4</td>
</tr>
<tr>
<td>GVD2019_112_N</td>
<td>1200</td>
<td>61</td>
<td>329</td>
<td>217.7</td>
<td>57.6</td>
</tr>
<tr>
<td>GVD2019_114_N</td>
<td>91</td>
<td>109</td>
<td>92</td>
<td>45.1</td>
<td>-16.7</td>
</tr>
<tr>
<td>GVD2019_663_N</td>
<td>83</td>
<td>50</td>
<td>276</td>
<td>163.6</td>
<td>34.2</td>
</tr>
<tr>
<td>GVD2019_153_N</td>
<td>129</td>
<td>50</td>
<td>321</td>
<td>33.7</td>
<td>61.4</td>
</tr>
<tr>
<td>GVD2020_175_N</td>
<td>110</td>
<td>71</td>
<td>185</td>
<td>295.3</td>
<td>-18.9</td>
</tr>
<tr>
<td>GVD2020_332_N</td>
<td>74</td>
<td>92</td>
<td>9</td>
<td>223.0</td>
<td>35.4</td>
</tr>
<tr>
<td>GVD2020_399_N</td>
<td>246</td>
<td>57</td>
<td>49</td>
<td>131.9</td>
<td>50.2</td>
</tr>
</tbody>
</table>
Deployment
Water optical properties

Absorption cross section, m\(^{-1}\)

Scattering cross section, m\(^{-1}\)

\(\lambda\), nm

Baikal

AMANDA

ANTARES

BAIKAL(low)

BAIKAL(high)

ANTARES

350 400 450 500 550 600
Calibration devices

- **Section calibration**: 2 LEDs in each OM, 470 nm, $1 - 10^8$ ph., 5 ns
- **String calibration**: LED beacons in 12 OMs of the cluster
- **Cluster calibration**: 2 lasers per station, 532 nm, $10^{12} - 10^{15}$ ph., 1 ns

Calibration accuracy ~2 ns
Acoustic positioning

OM drift can reach tens of meters, depending on season and elevation
String geometry monitored with acoustic modems (4 AMs per string)
OM coordinates are obtained by interpolating AM coordinates, accuracy ~ 20 cm
Experimental string with optic fiber DAQ

Developing technological solutions for second stage of Baikal-GVD deployment (2024+)

Advantages:
- flexible trigger conditions
- Improved neutrino detection efficiency
- Improved timing accuracy

See poster by V. Aynutdinov @ ICRC 2021
Reconstructed energy for tracks

Example plot for a set of neutrino candidate events

- dE/dx energy estimator -
- Works for $E > 1$ TeV
- Largest measured energy in cut-based low-energy neutrino candidate sample:

$\theta = 165.5^\circ$
$N_{\text{strings}} = 3$
$N_{\text{hits}} = 10$

9.3 TeV

see talk by G. Safronov at ICRC 2021
Track reco : ongoing improvements

- Event selection with BDT
  → G. Safronov @ ICRC 2021

- Improved hit selection using clique search
  → A. Avrorin & B. Shaybonov @ ICRC 2021

- Likelihood fitter

- Machine learning techniques

- ...
Event types

Single-cluster tracks
- ✔ Low energy threshold
- ✔ Optimal sensitivity to nearly vertical tracks
- ✔ 90% of recorded track events

Multi-cluster tracks
- ✔ Moderately low energy threshold
- ✔ Optimal sensitivity to inclined tracks
- ✔ 10% of recorded track events

Single-cluster cascades
- ✔ High energy threshold
- ✔ Good energy resolution
- ✔ Relatively rare events

Multi-cluster cascades
- ✔ Very high energy threshold
- ✔ Excellent energy resolution
- ✔ Very rare events
Neutrino absorption in the Earth

doi:10.1038/nature24459