Baikal-GVD neutrino telescope: recent status

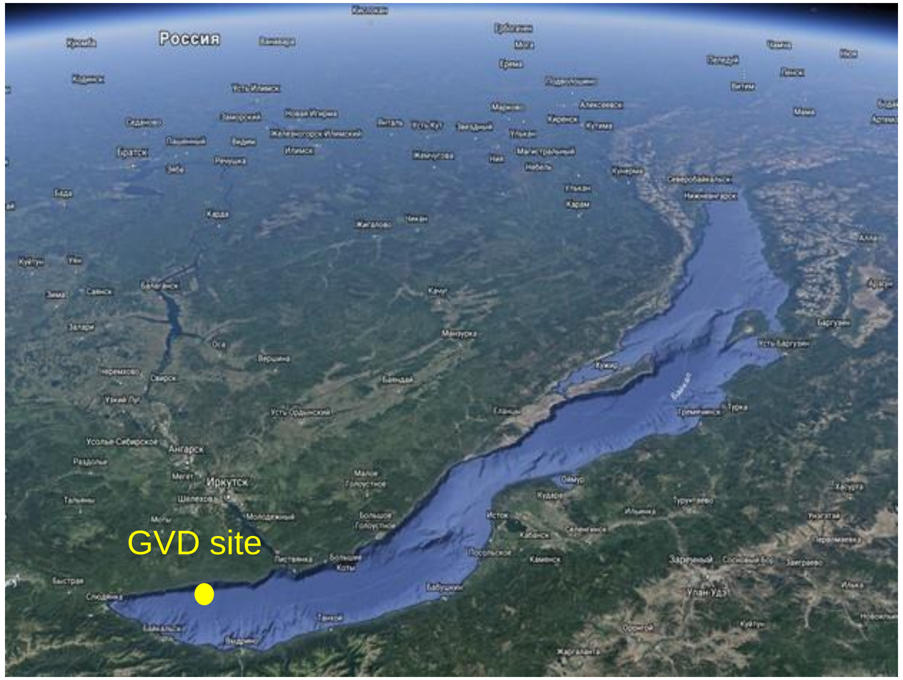
Rastislav Dvornický
for the Baikal-GVD collaboration

Comenius University in Bratislava, Slovakia
dvornicky@fmph.uniba.sk

UNIVERZITA KOMENSKÉHO V BRATISLAVE

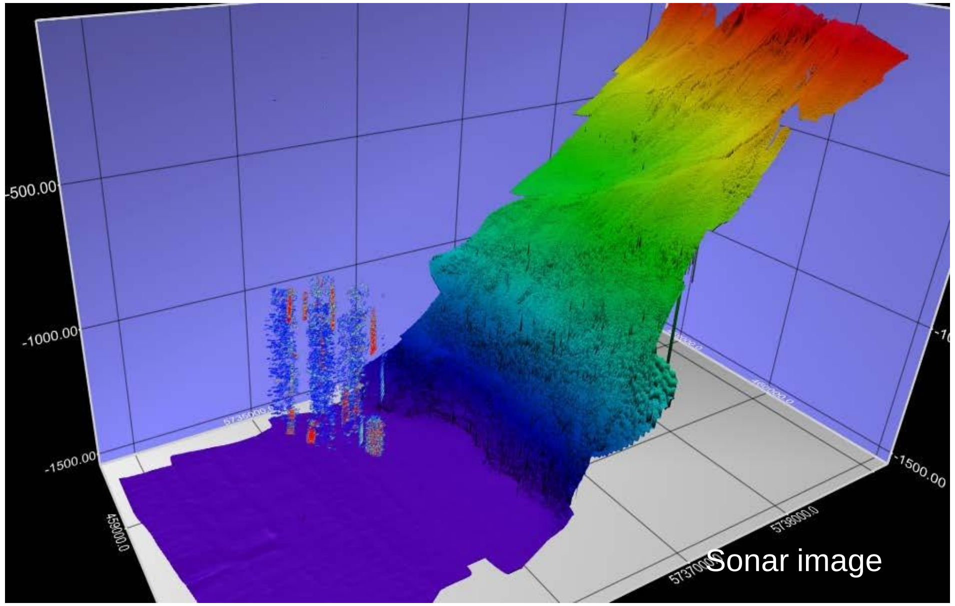
BAIKAL-GVD

Baikal-GVD site



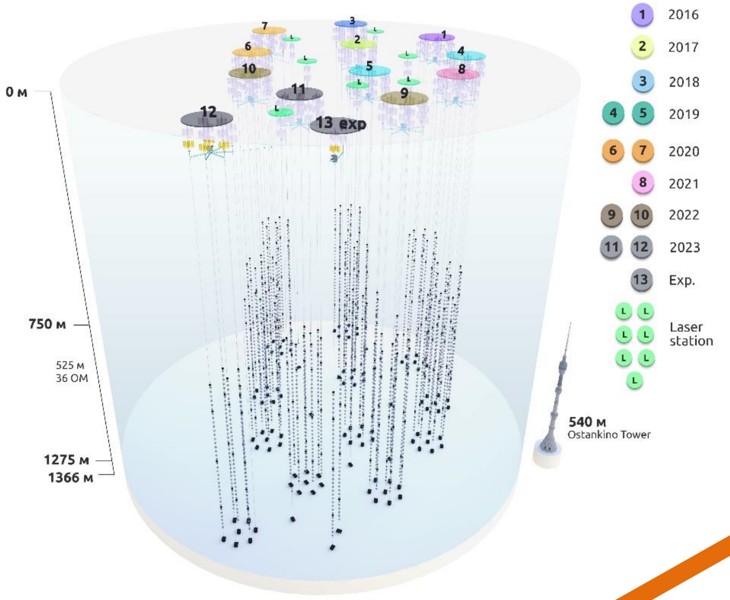
- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance

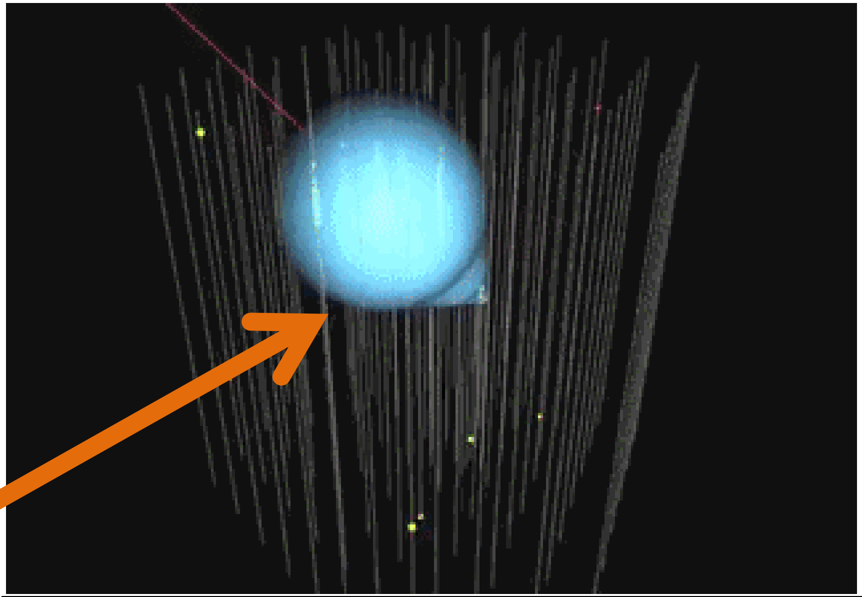
- High water transparency
  - ✓ Absorption length: 22 m ±5%
  - ✓ Scattering length: 60 – 80 m ($\lambda \approx$ 480-500 nm)
- Moderately low optical background: 15–60 kHz (PMT R7081-100 Ø10”)

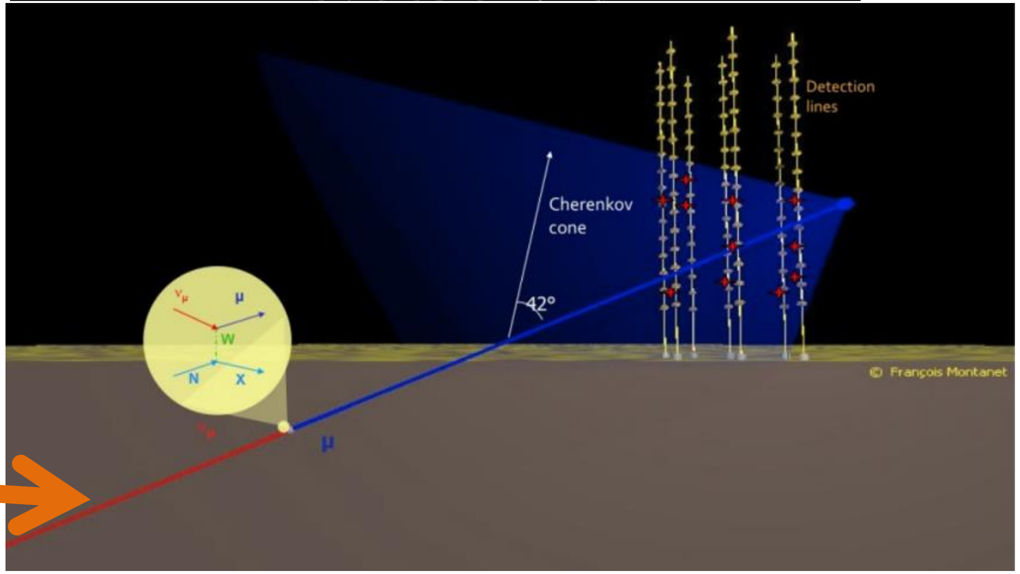


Sonar image

Detection principle



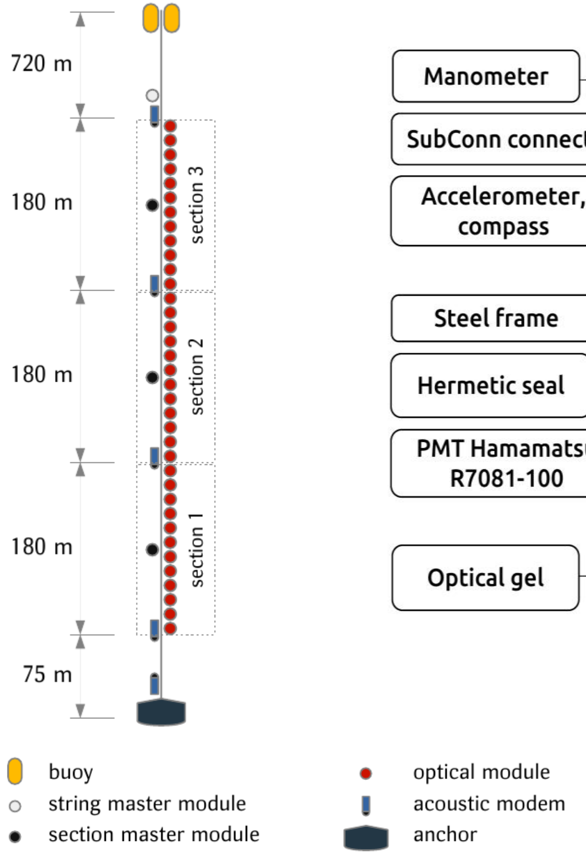




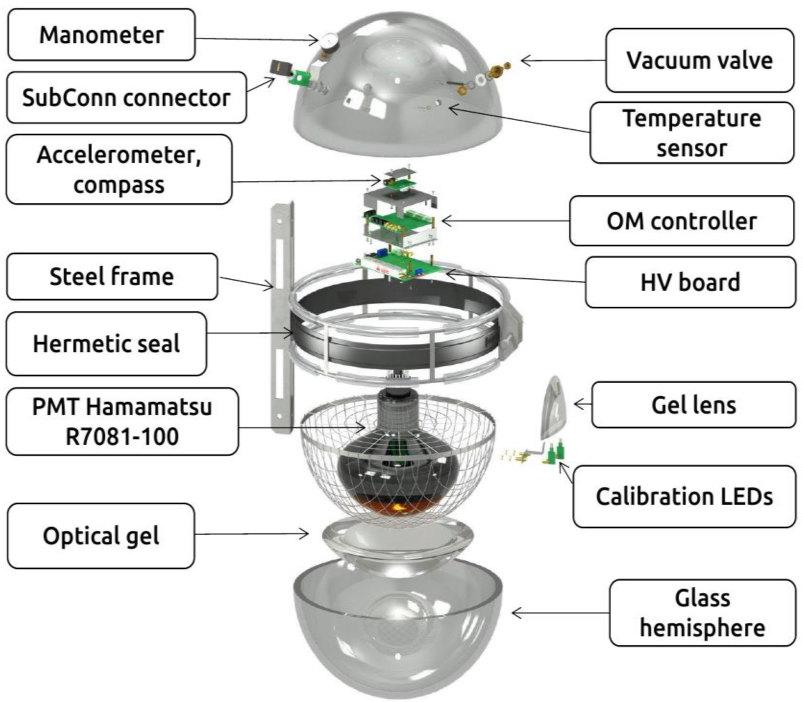
$$\nu_l + N \to \begin{cases} e^- + X \to cascades \\ \tau^- + X \to cascades \\ \mu^- + X \to track \end{cases}$$

Detector components

string



Optical module (OM)



Each string carries 36 OMs

- 10-inch high Q eff. PMT
- 15 m vertical step
- OM facing the lake bottom

Time calibration systems

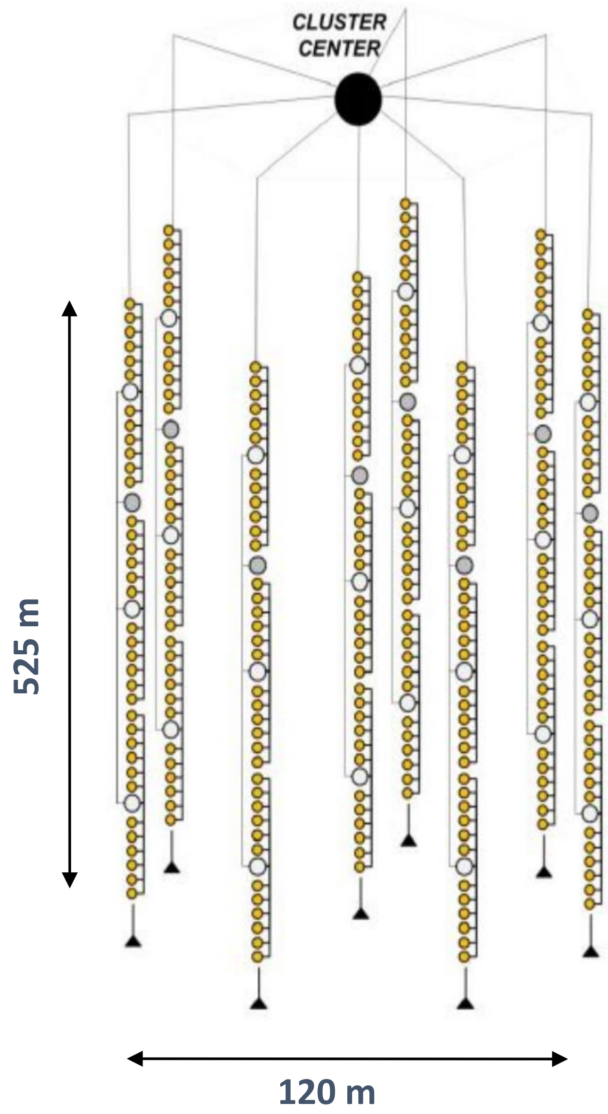
- LED photodiodes in each OM
- LED beacons at each string
- Isotropic lasers between clusters
- Calibration precision ~2 ns

Geometry calibration system

- Acoustic modems on each string
- Acoustic polling each 1-6 minutes
- OM positioning precision ~ 20cm

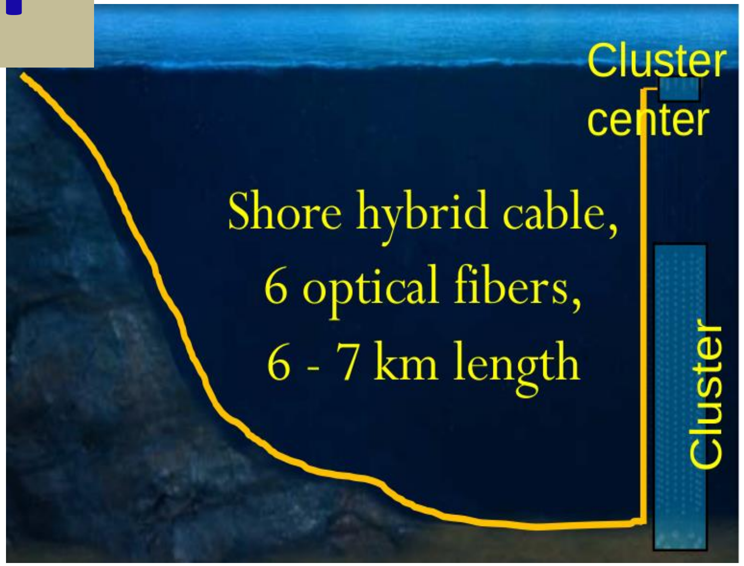
Baikal-GVD cluster

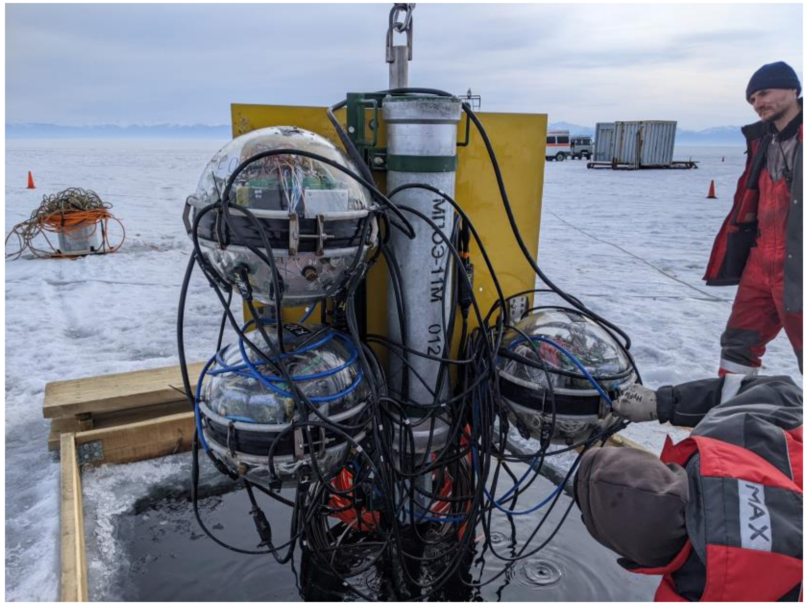
Cluster:
8 strings



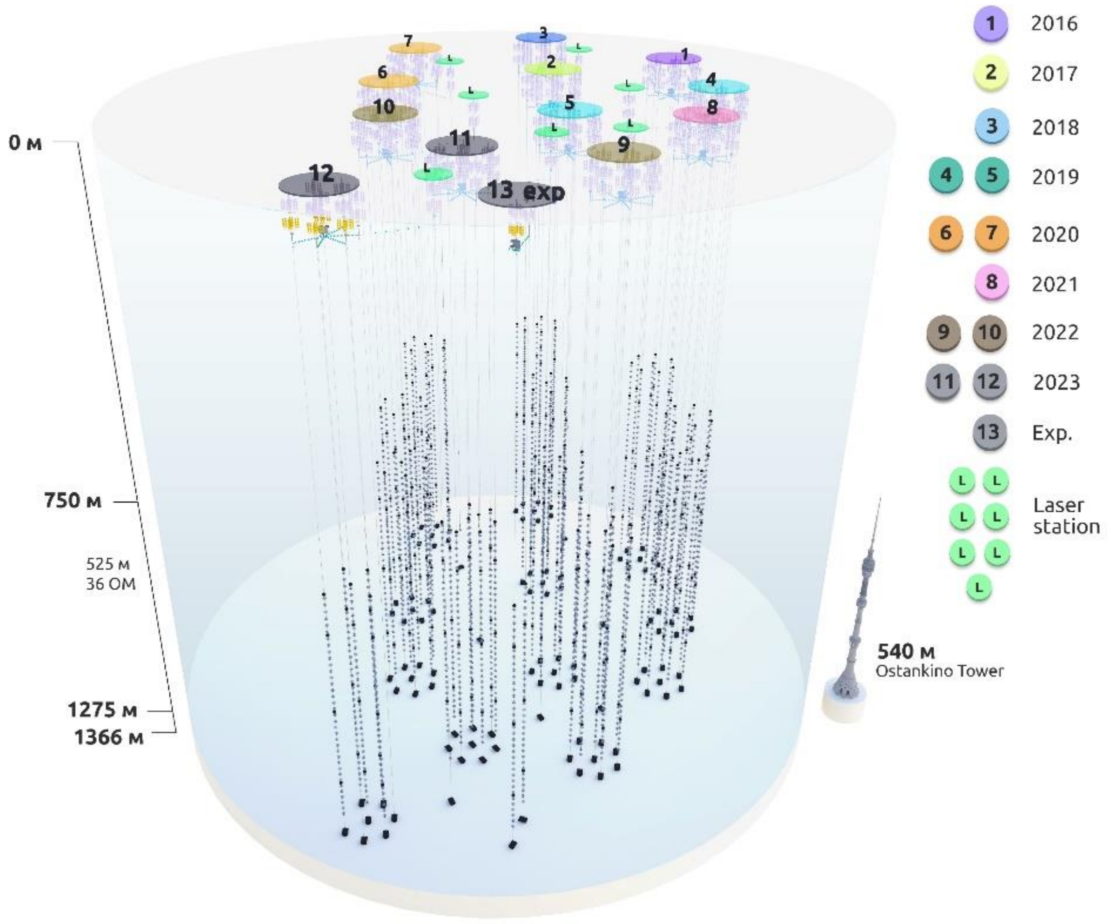
Cluster

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





Baikal-GVD construction status 2023

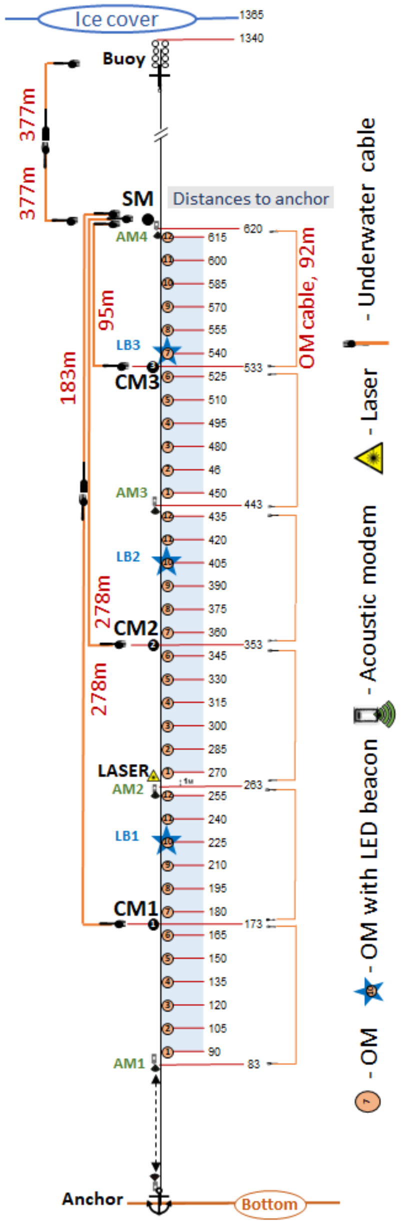


12 clusters, 3 special strings (laser+36 OM),
2 experimental strings, 7 laser stations

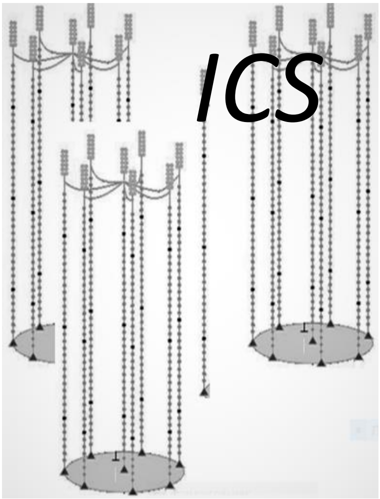
Deployment schedule

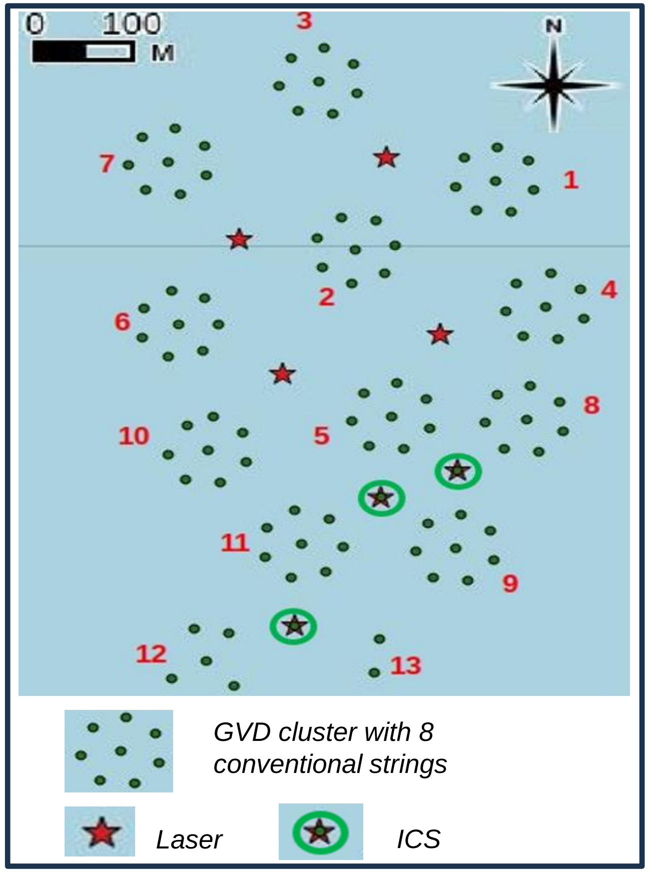
Year	Number of clusters	Number of strings	Number of OMs
2016	1	8	288
2017	2	16	576
2018	3	24	864
2019	5	40	1440
2020	7	56	2016
2021	8	64	2304
2022	10	81	2916
2023	**12**	**96**	**3456**

Inter-cluster string



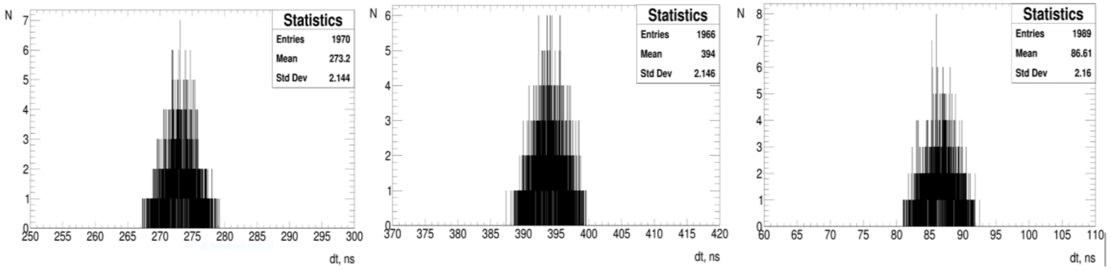
- The most effective way to increase the Baikal-GVD telescope sensitivity of cascade-like neutrino events is to install additional inter-cluster strings (ICS) in the geometric centers of each triplet of the Baikal-GVD clusters.
- 36 OMs, 3 sections, 4 acoustic beacons, laser, and LED matrix
- The ICS is installed as a 9th string of one of the clusters



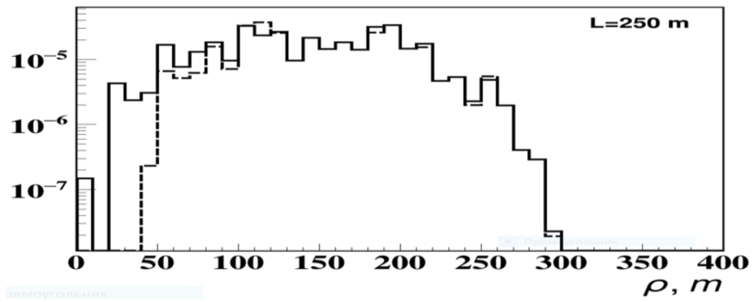


Inter-cluster string

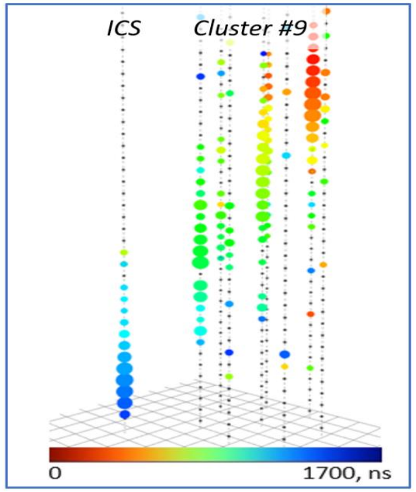
- The accuracy of the ICS time calibration relatively surrounded clusters using ICS LED beacons was about 2.5 ns.
- The accuracy of the synchronization of the ICS with the surrounding clusters was 2.1 – 2.2 ns
- An increase of events in cascade mode by 10% and 24% for E > 1 TeV and 100 TeV (MC).
- Data acquisition system, deep-sea cable infrastructure, and power supply system of the GVD cluster can be easily adapted to serve 9 strings instead of 8.



Distribution of events on the delay of the response times of pairs of synchronized channels, measured between ICS and clusters 5, 8, and 9.

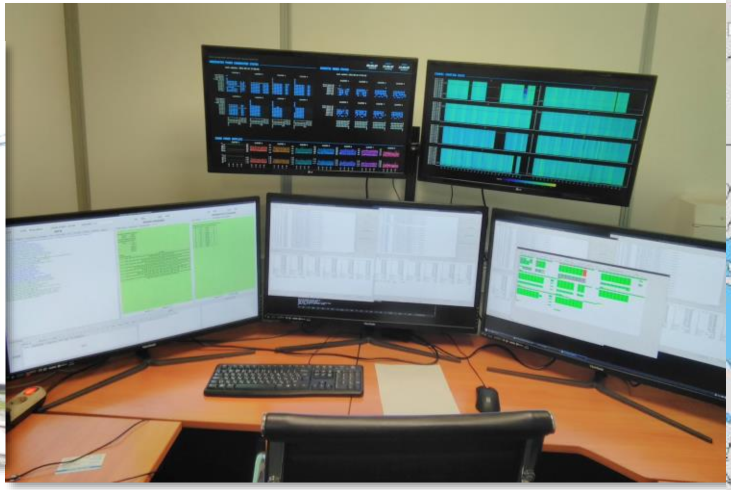


Distribution of events on the distance ρ to the geometric center of three clusters with (solid line) and without (dashed line) ICS.



An example of muon bundle detection jointly by GVD cluster and ICS.

Data stream

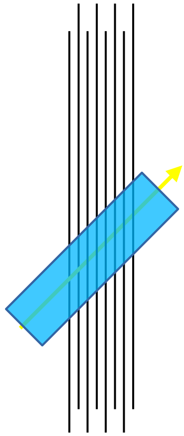


Baikal shore center
- Power distribution
- Data readout hardware
- Data-taking management (shifter)
- Data quality control
- Fast reconstruction and alert production (to be deployed)

Data is transferred from Shore center to JINR
- Shore center → Baikalsk: 300 Mbit/s radiochannel
- Baikalsk → JINR: Ethernet
- Compressed data sample ~40GB per day
- Delay due to shore → JINR data transfer: < 1 min.
- At JINR data is stored using EOS service

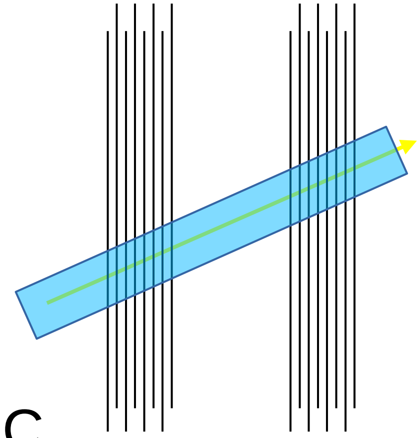
Event types

Single-cluster tracks



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

Multi-cluster tracks

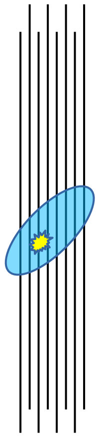


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- 10% of recorded track events

ν_μ CC

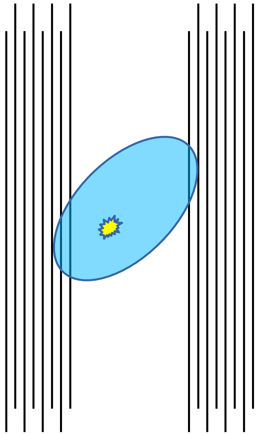
NC, ν_e ν_τ CC

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

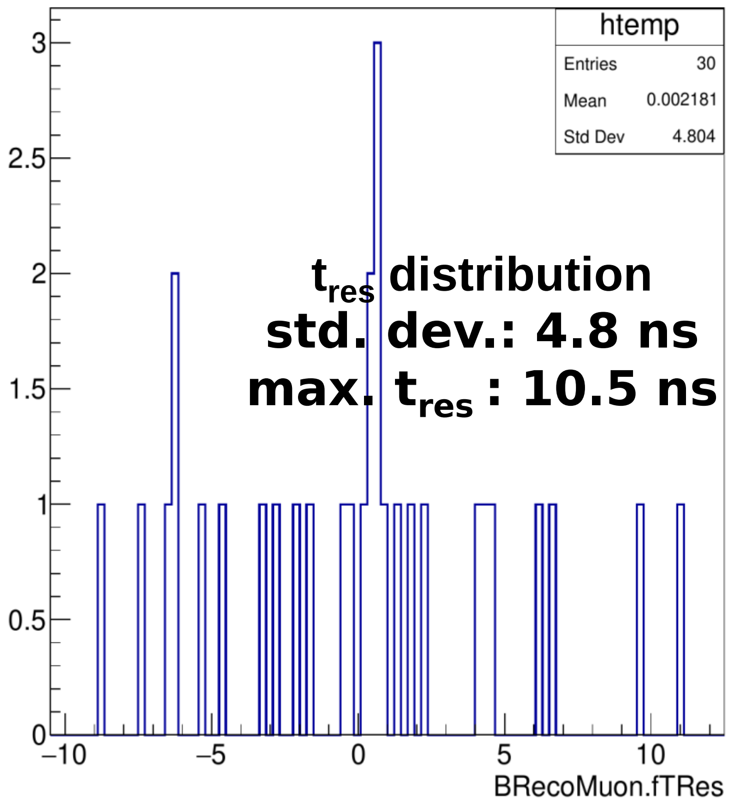
Single-cluster HE neutrino event

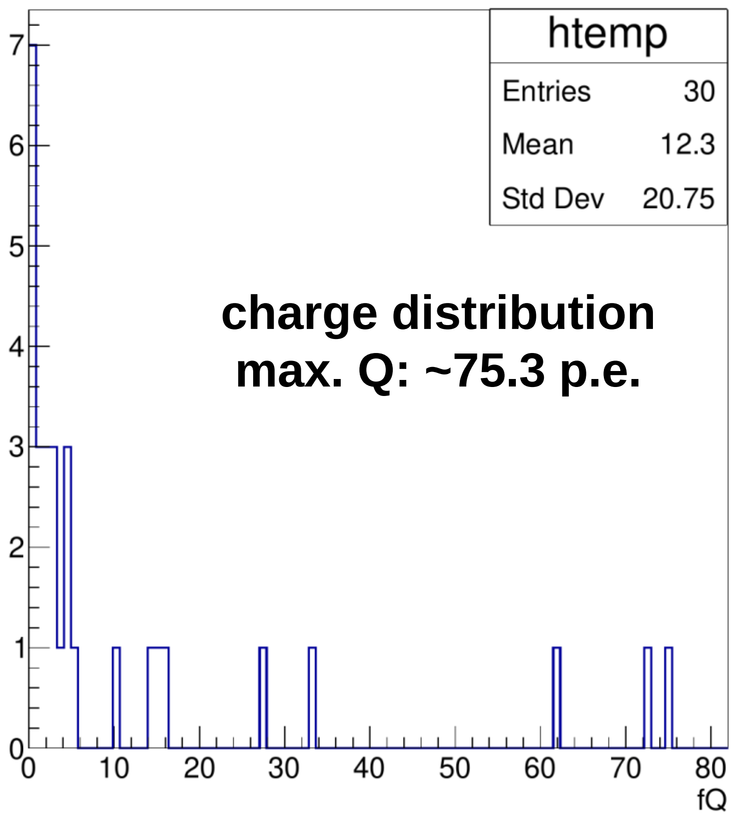
The most spectacular event selected in single-cluster analysis

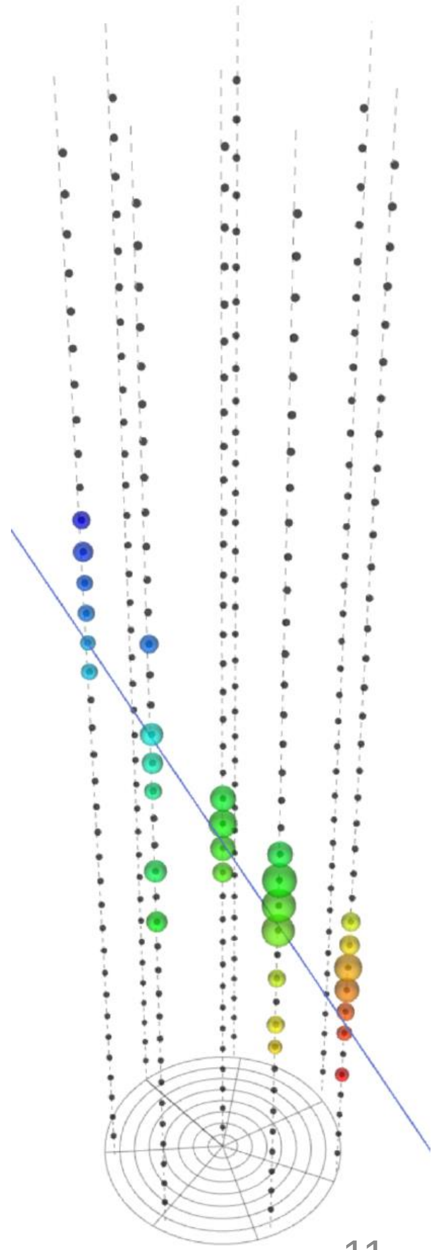
Cluster 3, run 590
$\theta_z = 153.4°$
$N_{hits}=30$

E = 103.4 (24.9<E<266.3) (TeV)
Z_{dist} = 332.4 m
L_{path} = 339.3 m

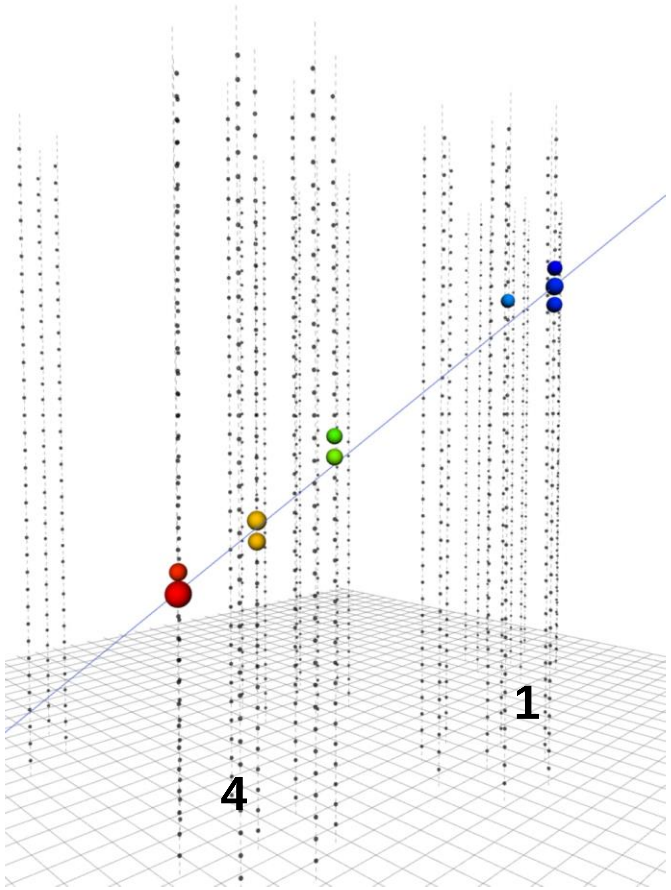
Angular resolution:
$\delta\psi$=0.45° (50%)
Signalness: $N_{astro}/(N_{astro}+N_{atm})$:
S>0.88

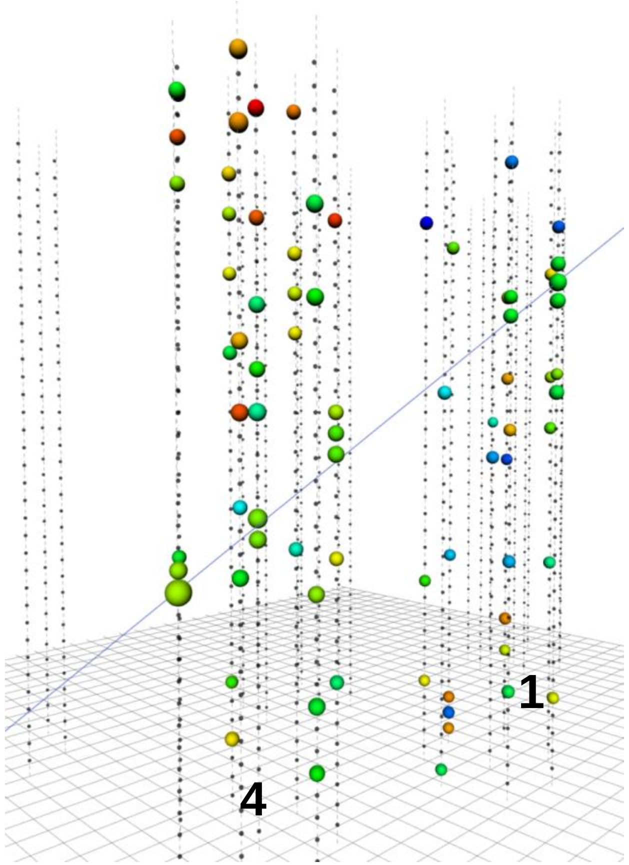






First multi-cluster neutrino





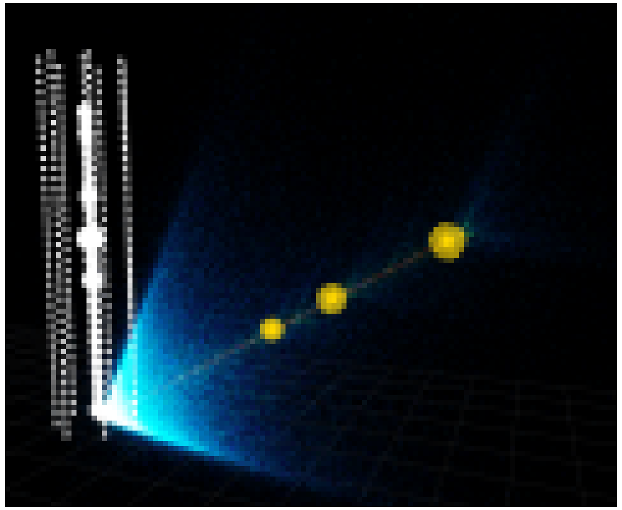
MCL run 1497
Clusters 1 & 4

fNHits	10
fSourceZenithRec	125.6
fZDist	399 m
fPathLength	361 m
fEnergyRec	< 1TeV

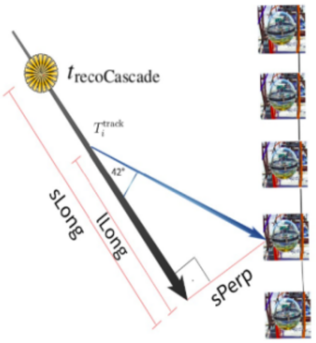
Work in progress

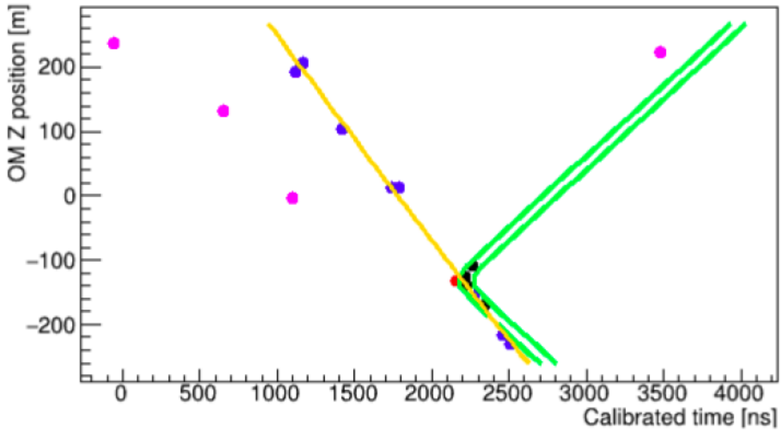
Development of algorithm to distunguish cascades from muons

- Muons produce cascade-like events along their tracks
- Distinguish from neutrino induced cascades
- Development of selection methods based on various established variables
- Use of BDT and convolutional neural networks (work in progress)



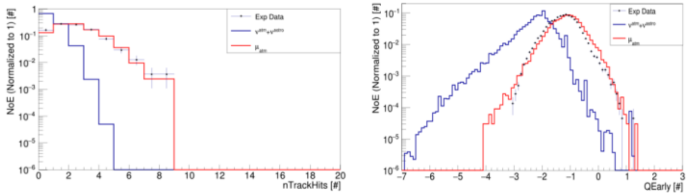
$$T_i = t_{\mathrm{recoCascade}} + (\mathrm{sLong} - \mathrm{lLong})\frac{1}{c} + \sqrt{\mathrm{sPerp}^2 + \mathrm{lLong}^2}\frac{1}{c_{\mathrm{water}}}$$





noise hits, track hits, cascade hits, reconstructed cascade,

expected cascade hits time,expected track hits time



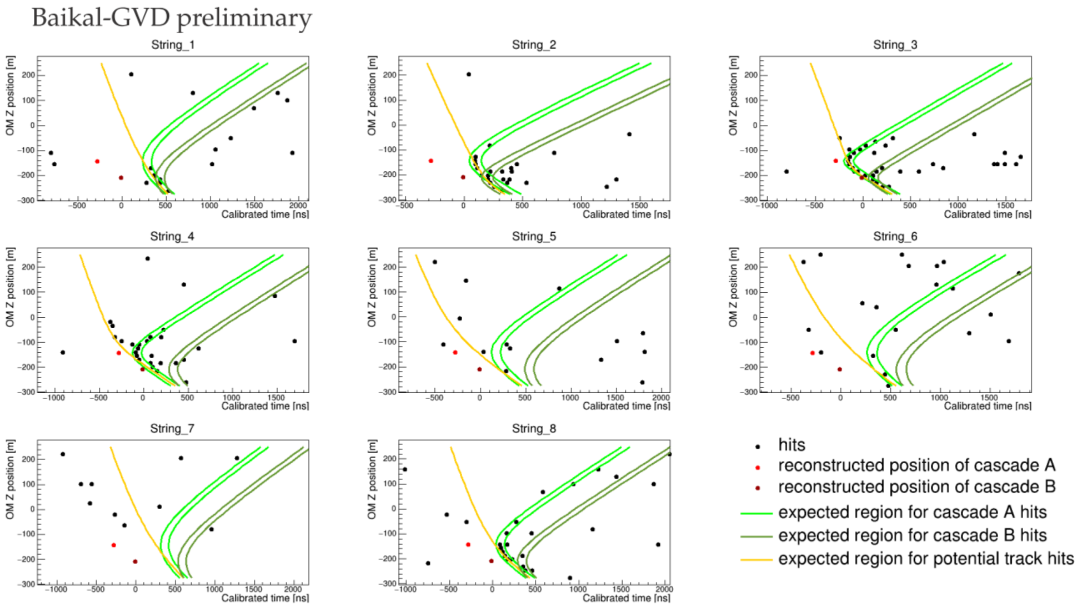
- **Experimental Data:** Upgoing cascade-like contained event (#1) from experimental data with energy 83.3 TeV reconstructed in Cluster 1

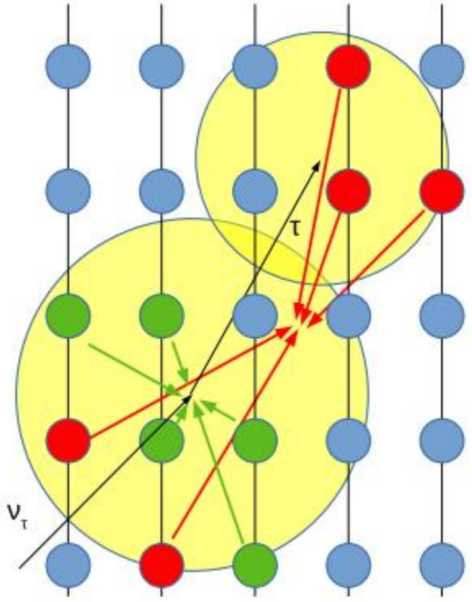
Cl	E_{rec} [TeV]	θ [°]	ϕ [°]	ρ [m]	Q [p.e.]	nHits	nRecoHits	nTrackHits
1	83.3	70.9	4.96	47.65	1665.01	106	44	1

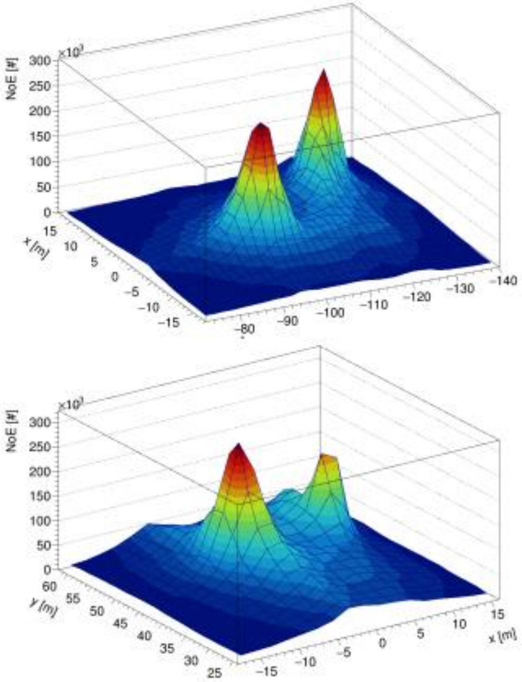
PoS(ICRC2023)986

Development of double cascades selection techniques

- Tau neutrino detection via double cascade pattern (search for astrophysical neutrinos)
- The goal to assign pulses to one cascade – their true origin
- Use of singe cascade reconstruction steps to estimate their poistions, energy, chi^2, and log-likelihood, …







PoS(ICRC2023)1016

Cascade analysis: search for diffuse neutrino flux

Data from 2018-2021, live-time: 4928 days single-cluster equivalent

- All-sky search for HE cascades:

  threshold of E > 100 TeV allows to observe events from upper hemisphere

- Search for upward moving events:

  lower energy threshold (E>15 TeV) due to low atmospheric background for cascade detection channel

All-sky search for HE cascades

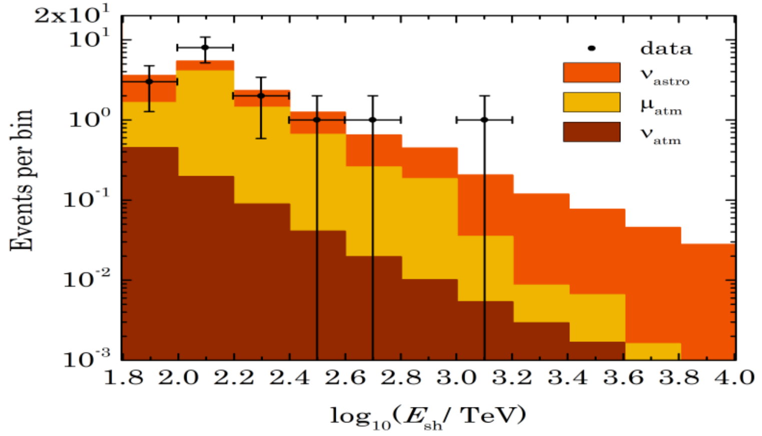
Phys.Rev. D 107, 042005 (2023)

Additional selection requirements:
(N_{hit_μ} = 0, E_{rec} ≥ 70 TeV) or
(N_{hit_μ} = 1, E_{rec} ≥ 100 TeV)
N_{hit_μ} is number of hits in time interval where hits from muons are expected

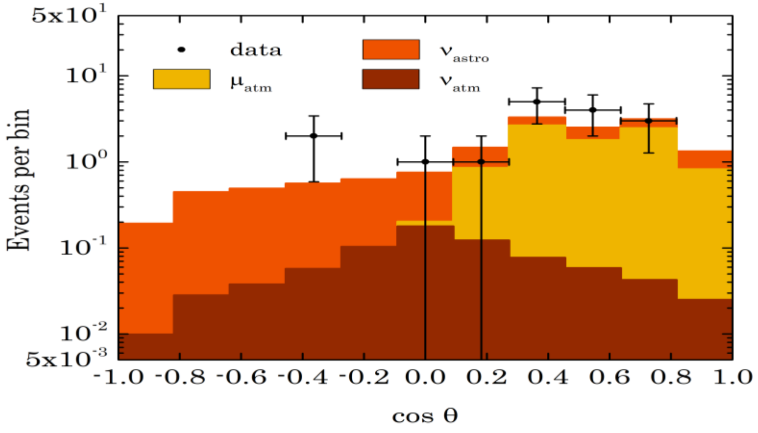
Expected:
7.4 events from atm. muons
0.8 events from atm. neutrinos
5.8 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

Found in real data: 16 events
Probability for the background-only hypothesis (stat.+sys.)
P-value = 0.026 (2.22 σ)

Energy distribution



Zenith distribution



Search for upward moving events

Phys.Rev. D 107, 042005 (2023)

Additional selection requirements:

E > 15 TeV & N_{hit} >11 & $\cos\theta < -0.25$

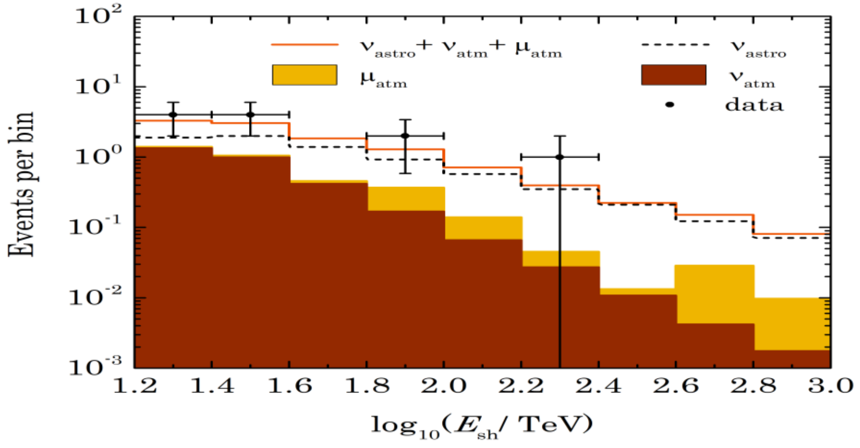
Expected:
0.5 events from atm. muons
2.7 events from atm. neutrinos
6.3 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

Found in data: 11 events

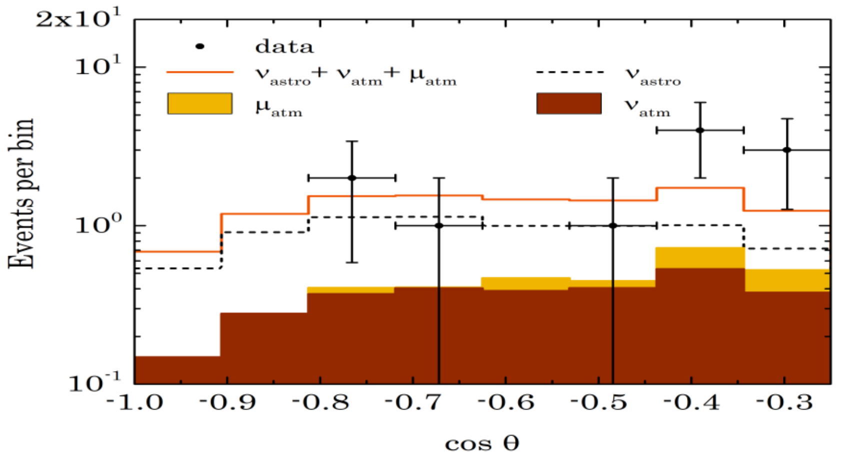
Probability for the background-only hypothesis (stat.+sys.)

P-value = 0.0024 (3.05σ)

Energy distribution



Zenith distribution



Single power-low model of isotropic astrophysical flux:
($\nu_e : \nu_\mu : \nu_\tau$=1:1:1)

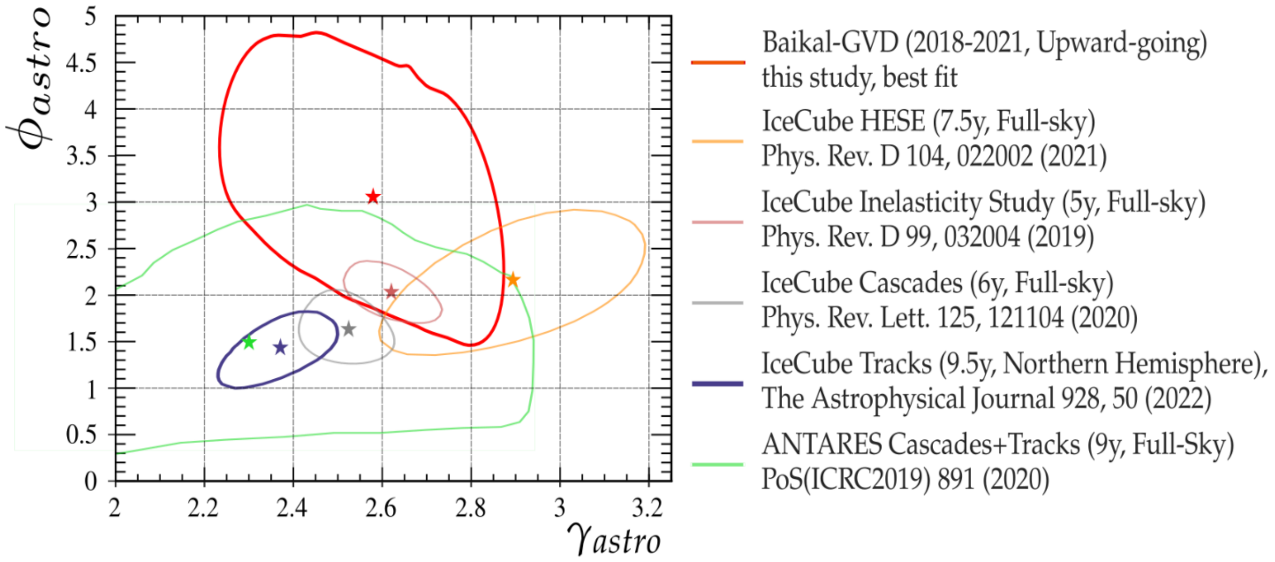
$$\Phi^{\nu+\bar{\nu}} = 3 \times 10^{-18}\, \varphi_{astro} \left(\frac{E}{10^5}\right)^{-\gamma_{astro}} \quad (GeV\ cm^2\ s\ sr)^{-1}$$

Baikal-GVD best fit parameters:

spectral index $\gamma_{astro} = 2.58$

One flavor normalization $\varphi_{astro} = 3.04$

68% C.L. contours



Phys.Rev. D 107, 042005 (2023)

The Baikal-GVD high-energy cascade sky map (in equatorial coordinates)

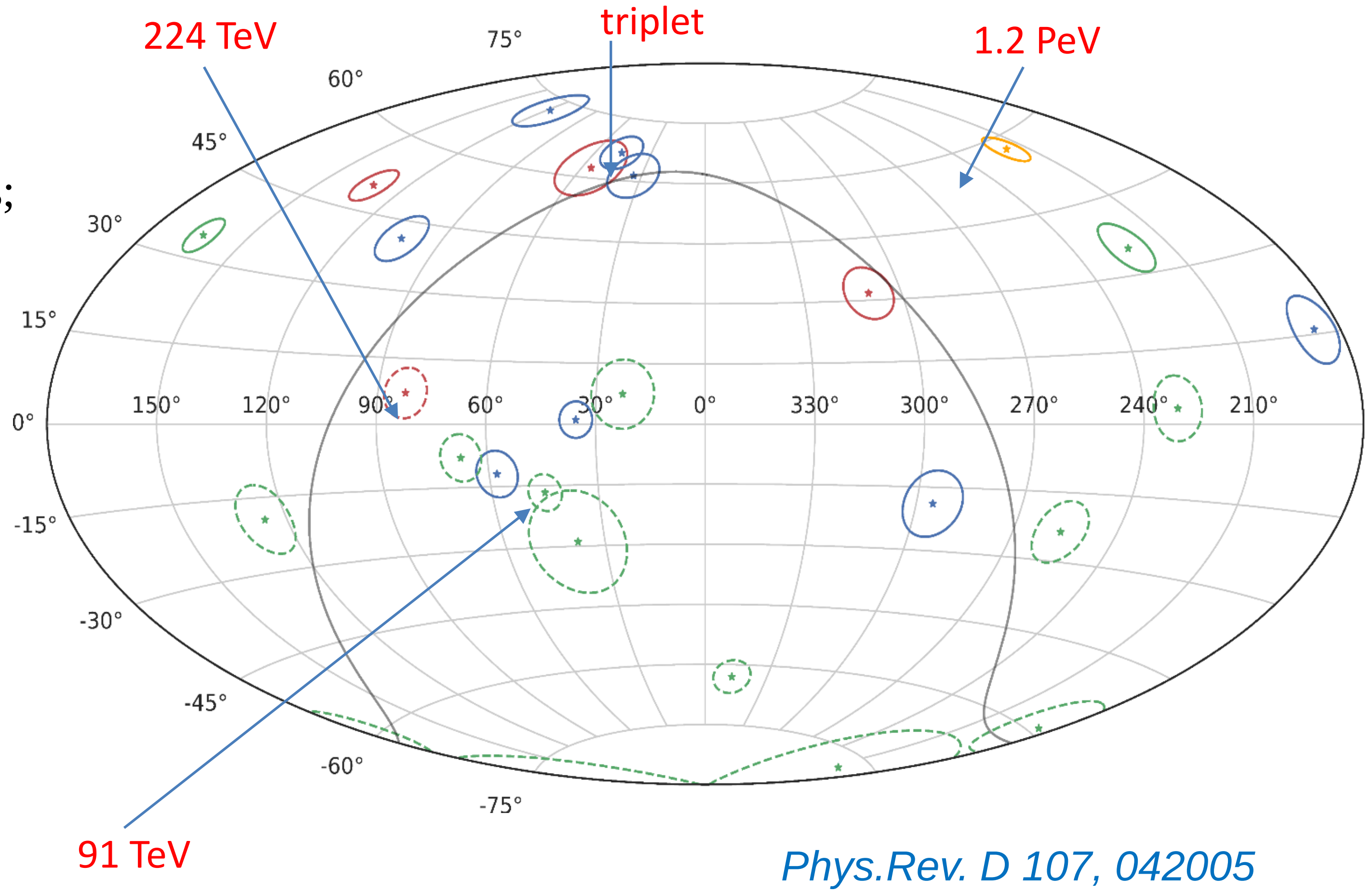
The best-fit positions and 90% angular uncertainty regions:

dashed circles - under-horizon events;
solid circles - above horizon events.

Colour represents event energy:

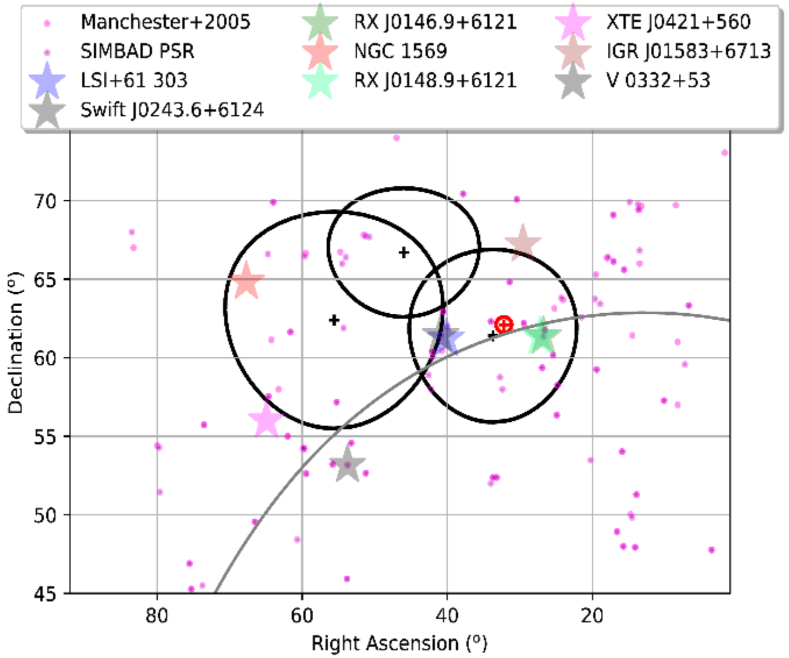
green – E < 100 TeV,
blue – 100TeV < E < 200 TeV,
red – 200 TeV < E < 1000 TeV,
orange – E > 1 PeV.

The Galactic plane is indicated as a grey curve.



Phys.Rev. D 107, 042005

Event triplet near Galactic plane



Three events (GVD190216CA, GVD190604CA and GVD210716CA) close to the Galactic plane (grey line) and their corresponding 90% errors (black).

The red plus and circle – IC hotspot and 0.5° uncertainty at 90% level (Aartsen & et al. ApJ, 835,151 (2017))

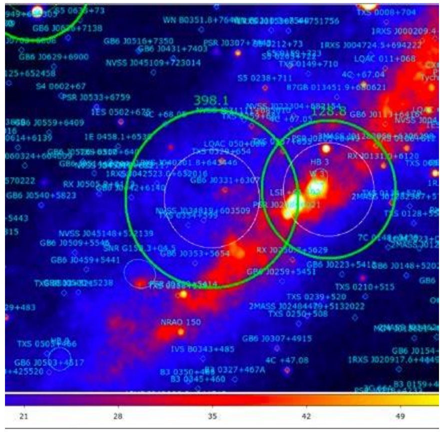
Stars - Several close high-mass X-ray binaries.

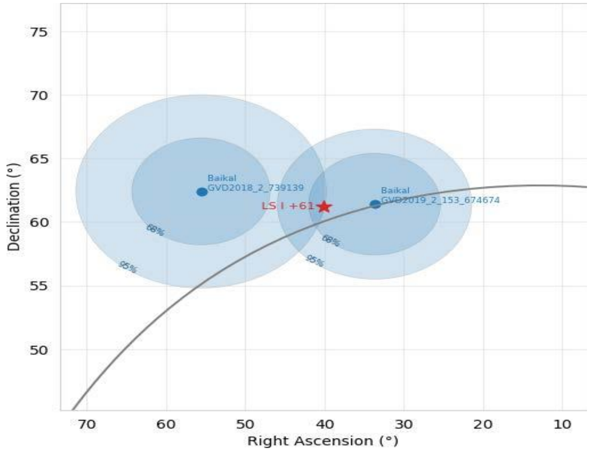
Dots - Galactic pulsars (Manchester et al. 2005, SIMBAD Astronomical Database)

★ LSI +61° 303 γ-ray active binary system

★ Swift J0243.6+6124 s the only discovered pulsating ultraluminous X-ray source (PULX) in the Galaxy.

LSI +61 303 and the two Baikal-GVD events

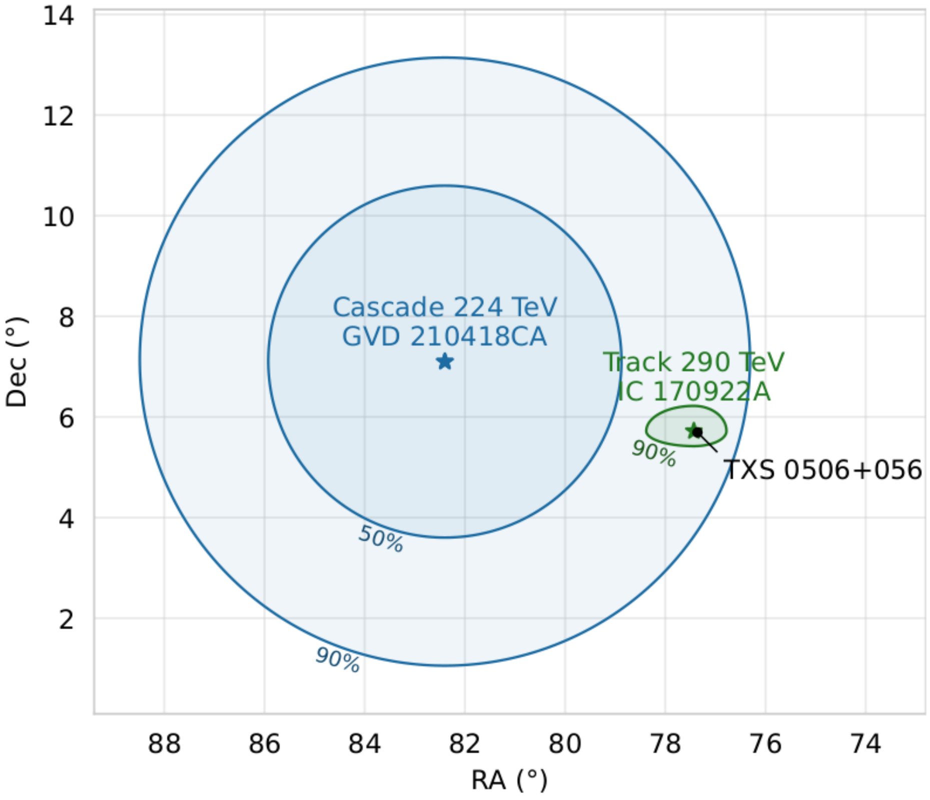




LSI +61 303 – γ-ray microquasar 3.1° from GVD190604CA and 7.4° from GVD190216CA (both are down-going events). Using the PSFs of all 16 HE-events, the chance probability to observe such a doublet near LSI +61 303 was estimated as 0.0187 (2.35σ) [not corrected for the “look elsewhere effect”]

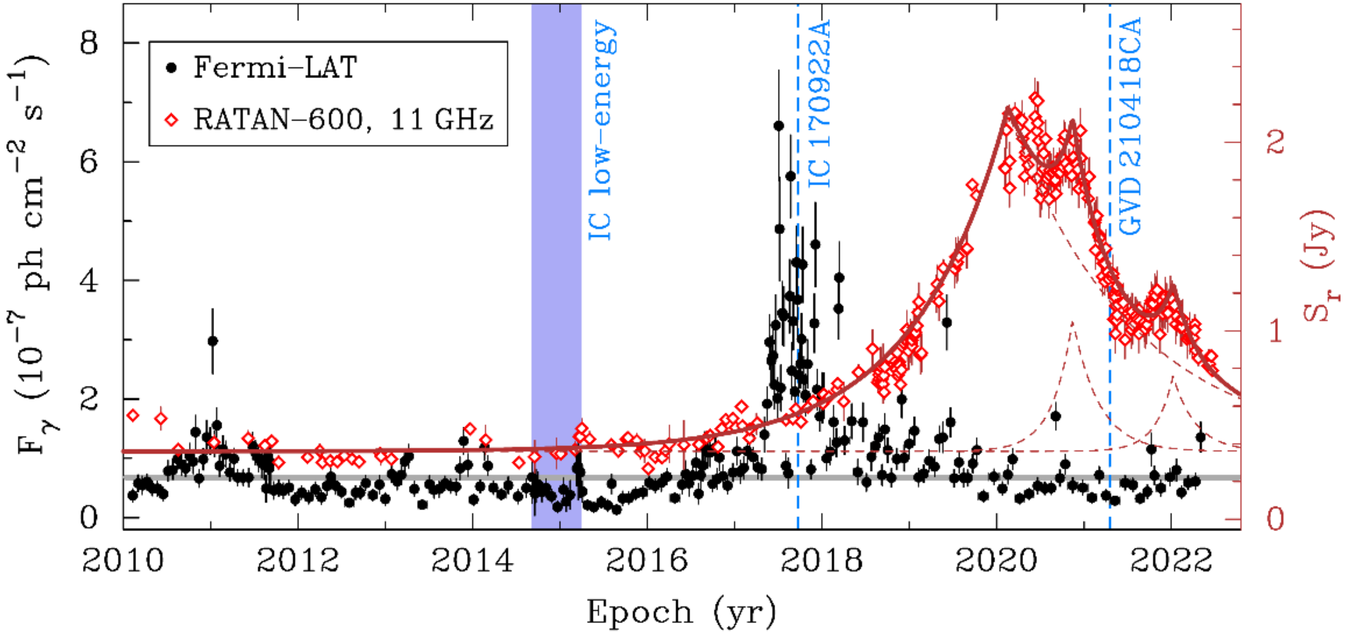
A high energy neutrino from the direction of TXS 0506+056

GVD210418CA (97% signalness) lies within 90% error circle from TXS 0506+056



The chance probability for such an association to occur randomly due to the background is p = 0.0074

Radio and gamma-ray light curves of TXS 0506+056.



Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

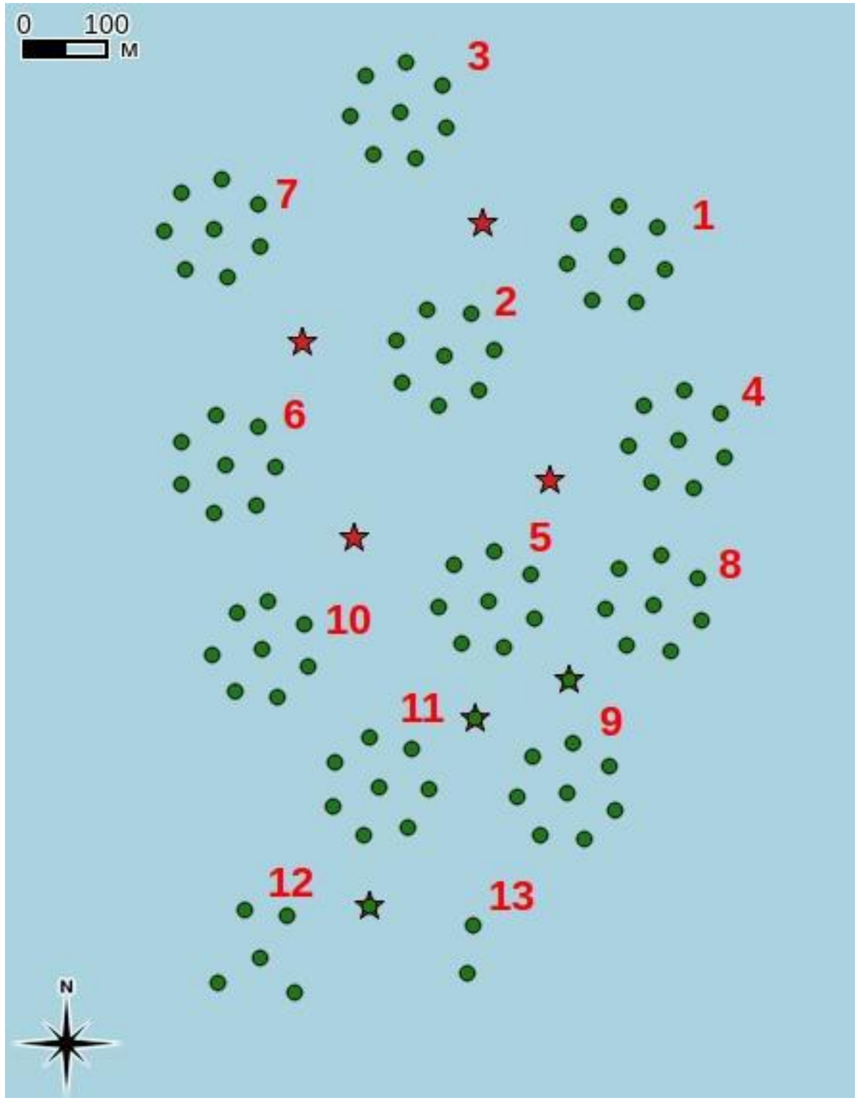
- IC event registered during γ flare and radio activity
- Baikal-GVD event during radio activity
- Probability of IC non-observation: 11%

arXiv:2210.01650

Configuration 2023

The nearest future:

- ✓ 2027/28 – 1 km^3 (20 clusters, ~6000 OMs)
- ✓ Additional inter-cluster strings (36 OM + laser)
- ✓ Introduce fiber optic technology for data transmission (cluster №13)
- ✓ Project of 10 km^3 detector



Conclusion

- Baikal-GVD is a neutrino telescope under construction in Lake Baikal
  - Volume already approaching 0.5 km^3
  - Sky coverage complementary to IceCube
- The IceCube's diffuse neutrino flux is confirmed by Baikal-GVD with a 3σ significance
- Multi-cluster track events
- Deployment of inter-cluster strings
- Hints of possible new neutrino sources are arising


Thank you for your attention!