Neutrinos in the Multi-Messenger Era

November 29th - December 2nd, 2022
Louvain-la-Neuve, Belgium

A decade of neutrino searchers in lake

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for the Baikal-GVD Collaboration

A decade of neutrino searchers in lake

2010 – Technical Design Report “Baikal-GVD” – km^3 scale NT in Lake Baikal

2011 – 2014 Preparatory Phase (cable to shore, pilot detectors, first strings)

2015 – Demonstration cluster Dubna – 192 OMs at 8 reduced strings

2016 – First baseline cluster (288 OMs), start data taking

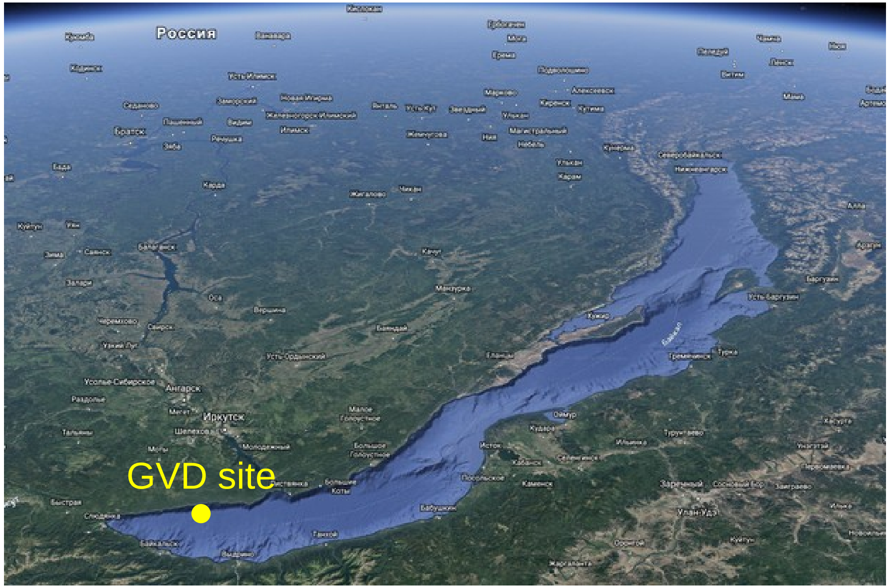
2022 – 10 clusters in operation (2880 + 36 OMs)

2017 – Start multi-messenger studies (GW170817)

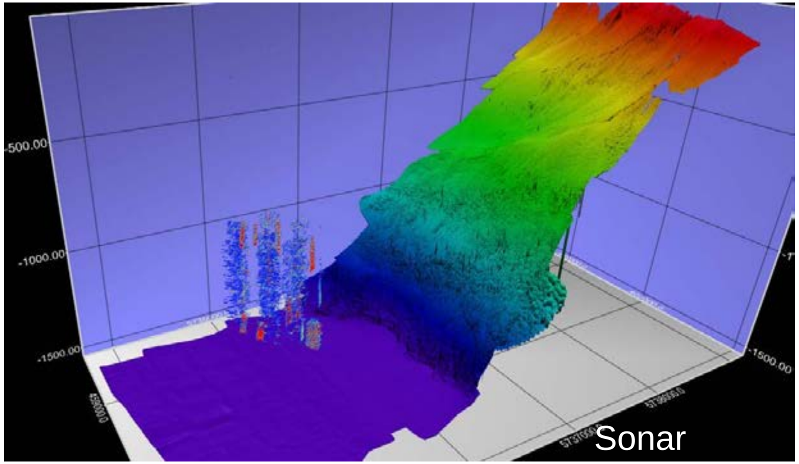
2018-2021 – First astrophysical neutrino candidates (cascades), first atmospheric muon neutrinos

2022 – confirmation of the IC diffuse astrophysical flux at 3σ significance level, based on an analysis of 2018-2021 data

Baikal-GVD site

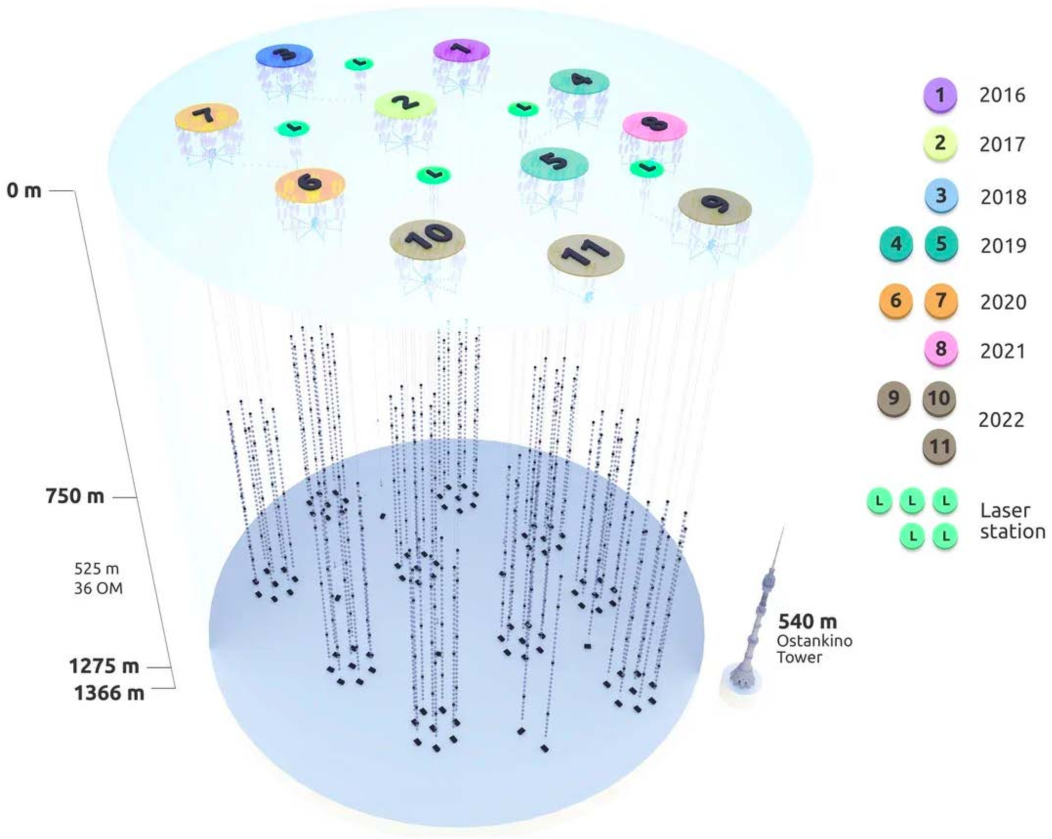


- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance



- High water transparency
  - ✓ Absorption length: 22 m ±5%
  - ✓ Scattering length: 60 – 80 m (λ ≈ 480-500 nm)
- Moderately low optical background: 15–40 kHz (PMT R7081-100 Ø10”)

Baikal-GVD construction status 2022 and schedule

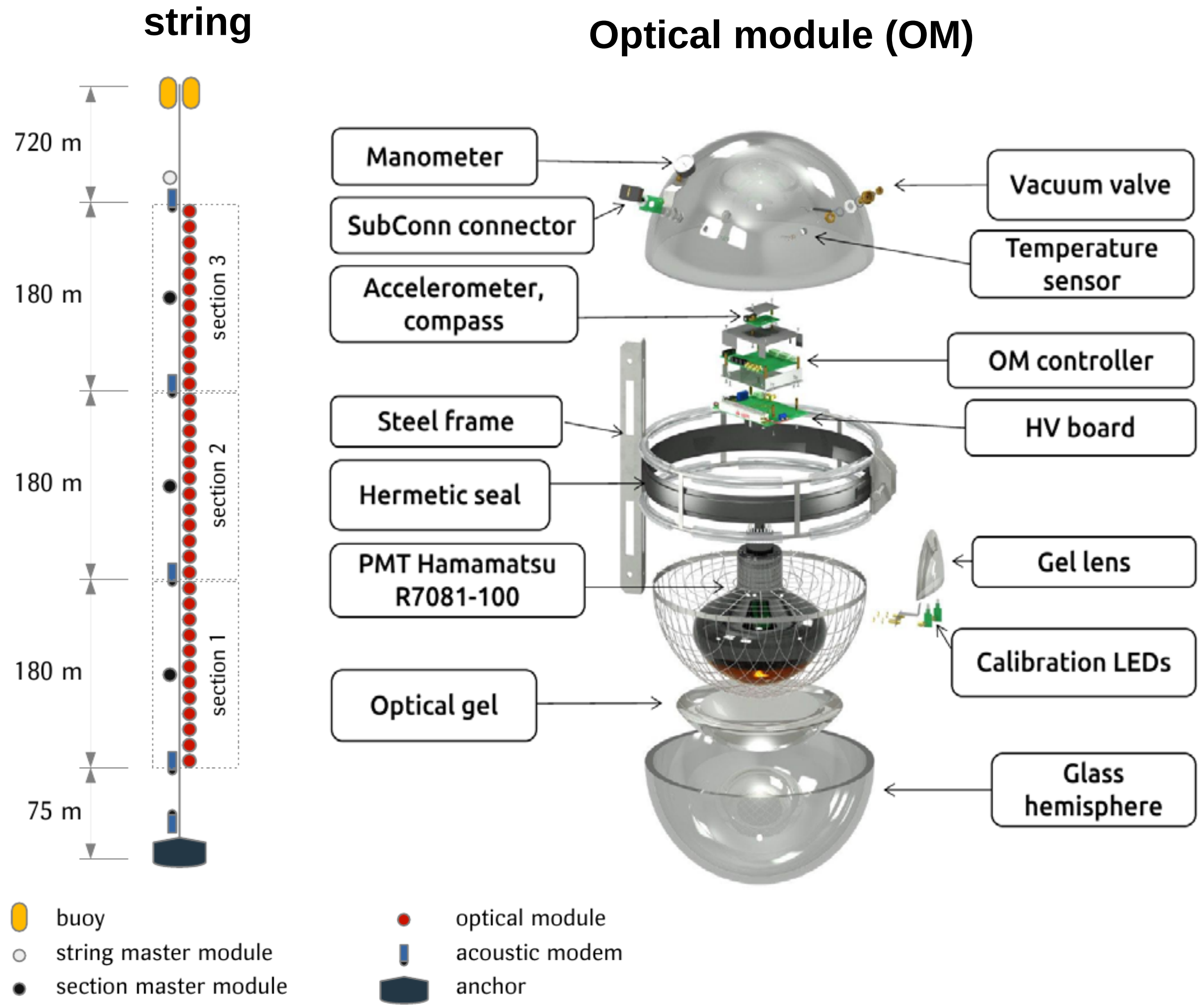


10 clusters + 1 special string (laser+36 OM)
+ 2 experimental strings + 4 laser stations

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**	**80 + 3**	**2880 + 84**
2023	12	96	3456
2024	14	112	4032

Detector components



Each string carries 36 OMs

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

Time calibration systems

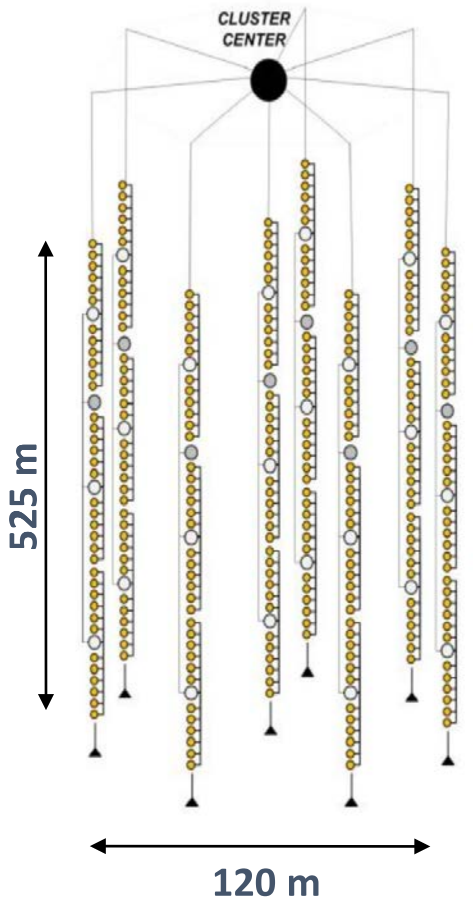
- LED photodiodes in each OM
- LED beacons at each string
- Isotropic lasers between clusters
- Calibration precision ~2 ns

Geometry calibration system

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

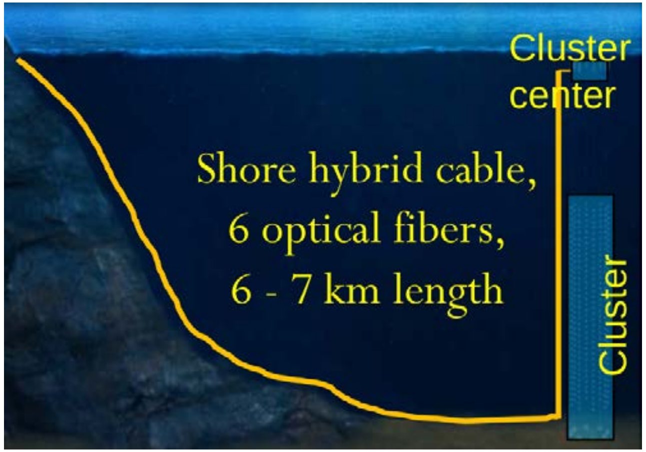
GVD cluster

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



Data stream

Baikal shore center

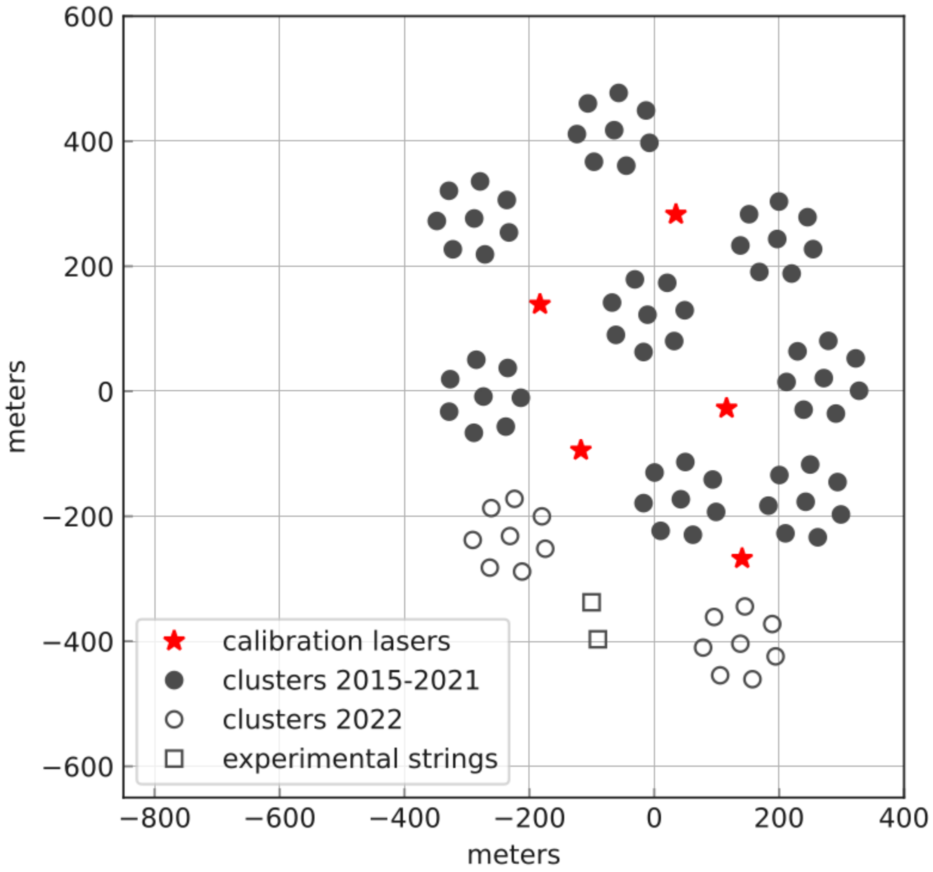
- Power distrubution
- Data readout hardware
- Data-taking management (shifter)
- Data quality control
- Fast reconstruction and alert production (to be deployed)

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 tranfer: < 1 min.
- At JINR data is stored using EOS service

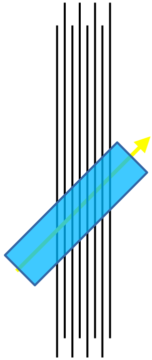
Expedition 2022

- Installed equipment:
- Two new clusters (16 strings)
- 2 “experimental” strings using fiber optic technology for data transmission
- 1 additional inter-cluster string (36 OM + laser)
- 1 laser station
- + scheduled maintenance of previously installed equipment



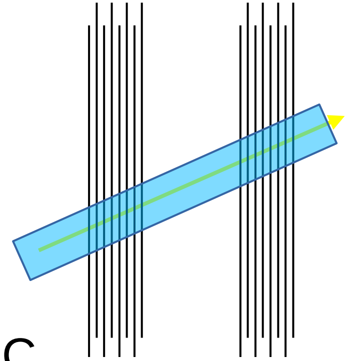
Event types

Single-cluster tracks



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

Multi-cluster tracks

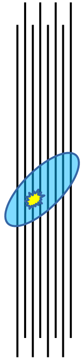


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- 10% of recorded track events

ν_μ CC

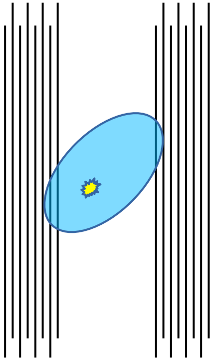
NC, ν_e ν_τ CC

Single-cluster cascades



- High energy threshold
- Good energy resolution
- Relatively rare events

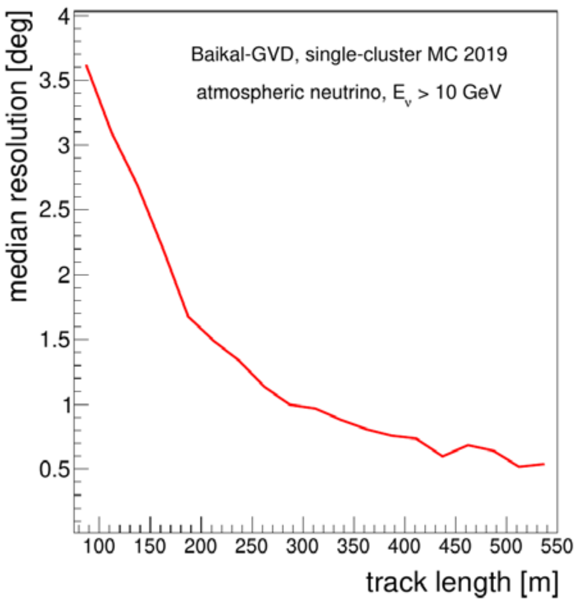
Multi-cluster cascades



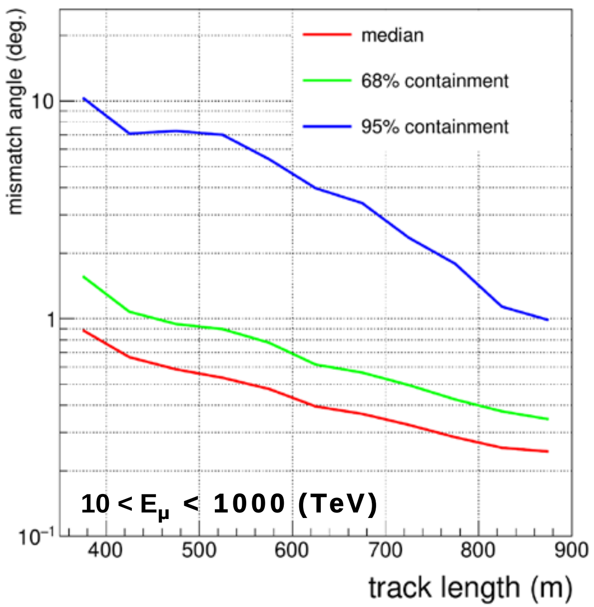
- Very high energy threshold
- Excellent energy resolution
- Very rare events

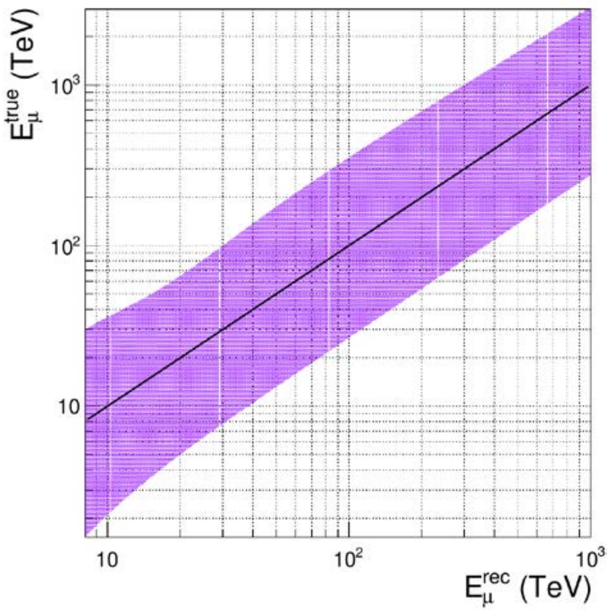
Muon track reconstruction precision

Single-cluster reconstruction



Multi-cluster reconstruction





Better than 0.5° resolution for tacks with length > ~500 m

Multi-cluster event reconstruction allows to reach the best angular precision

Factor 3 - 3.5 energy resolution in 8 TeV - 1 PeV range

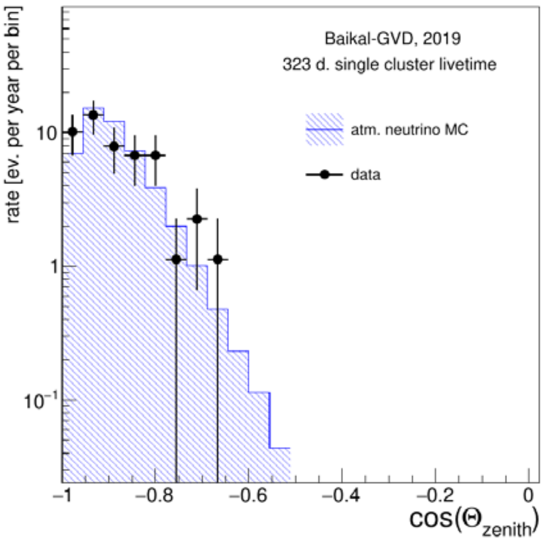
First neutrino candidate event sample

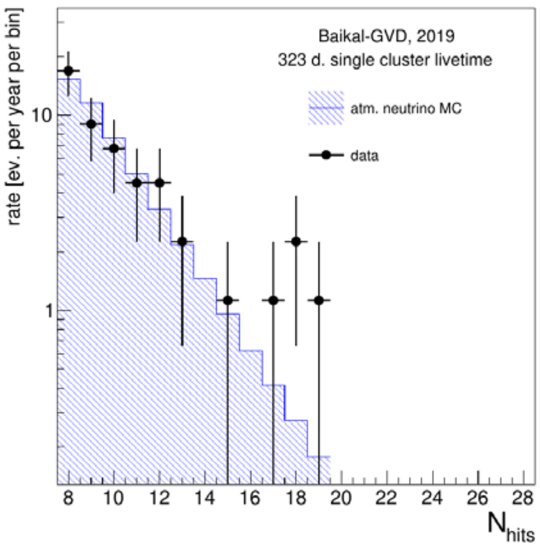
First set of single-cluster muon neutrino candidates based on 2019 data

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, <E_ν> ~ 500 GeV
- Runs from April 1st until June 30th
- Results are compared to atmospheric neutrino simulation

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

Observed: 44





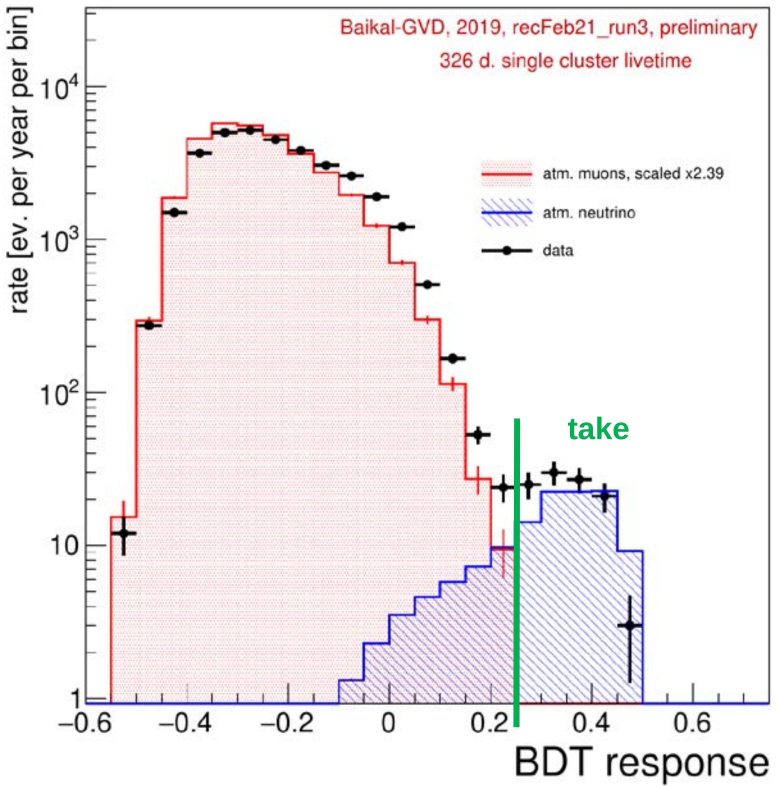
Excellent agreement of MC expectation and data

Single upgoing muon angular resolution for single-cluster analysis ~ 1°

[Eur. Phys. J. C 81, 1025 (2021), arXiv:2106.06288]

Track-like events analysis progress

Upgoing events: $\theta_{zenith} > 120°$



Track-like reconstruction and neutrino selection techniques are being refined

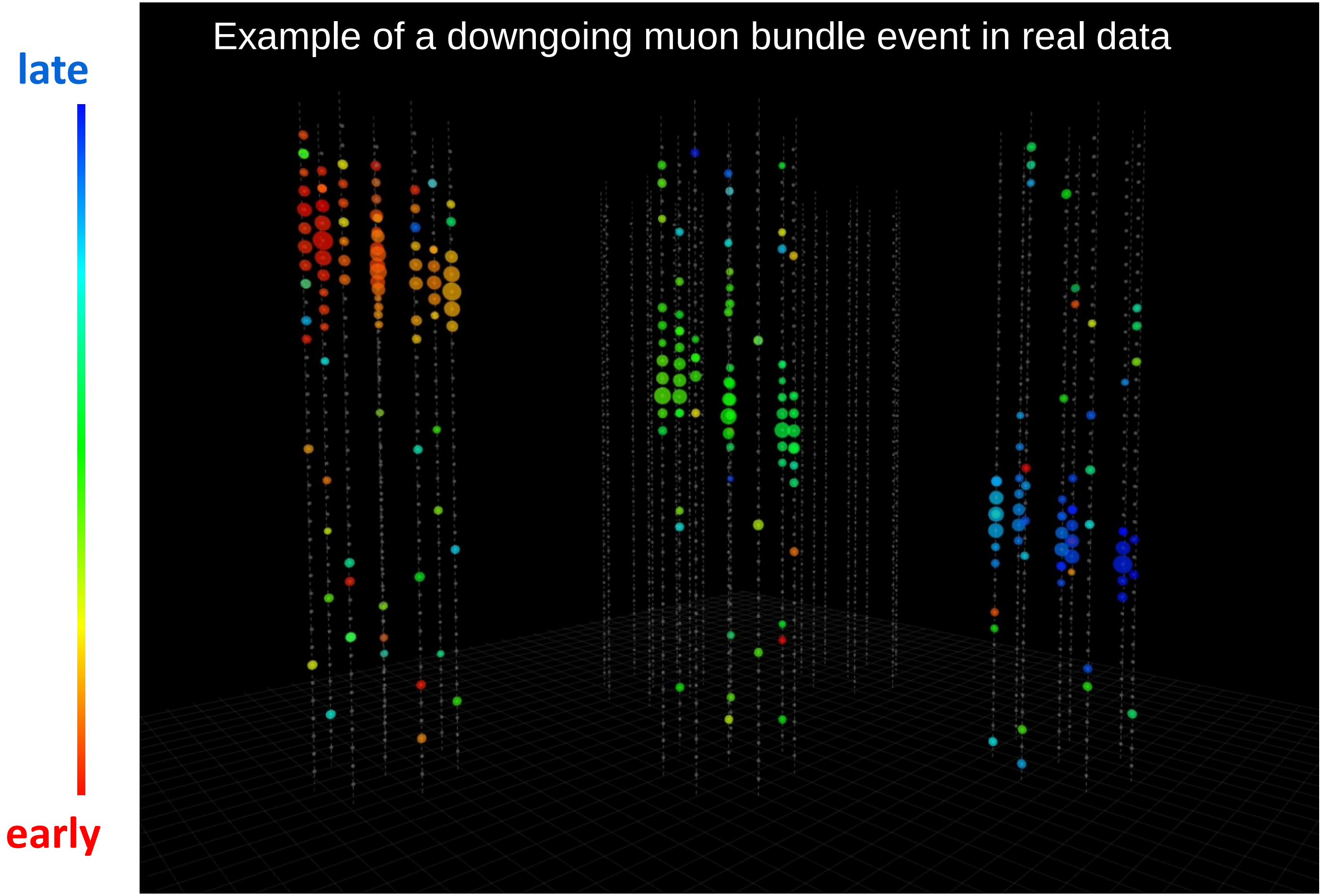
An improvement in sensitivity by a factor of 2 with recent developments
[PoS(ICRC2021)1063, PoS(ICRC2021)1080]

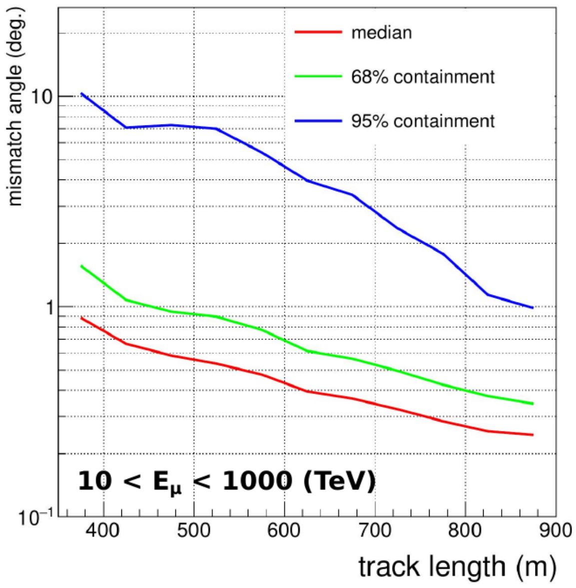
- Improvement in noise suppression techniques
- More efficient neutrino selection using boosted decision trees (BDT)

MC expected: 81.2
Observed events: 106

Machine learning application for Baikal water noise suppression: [arXiv:2210.04653]

Multi-cluster track events





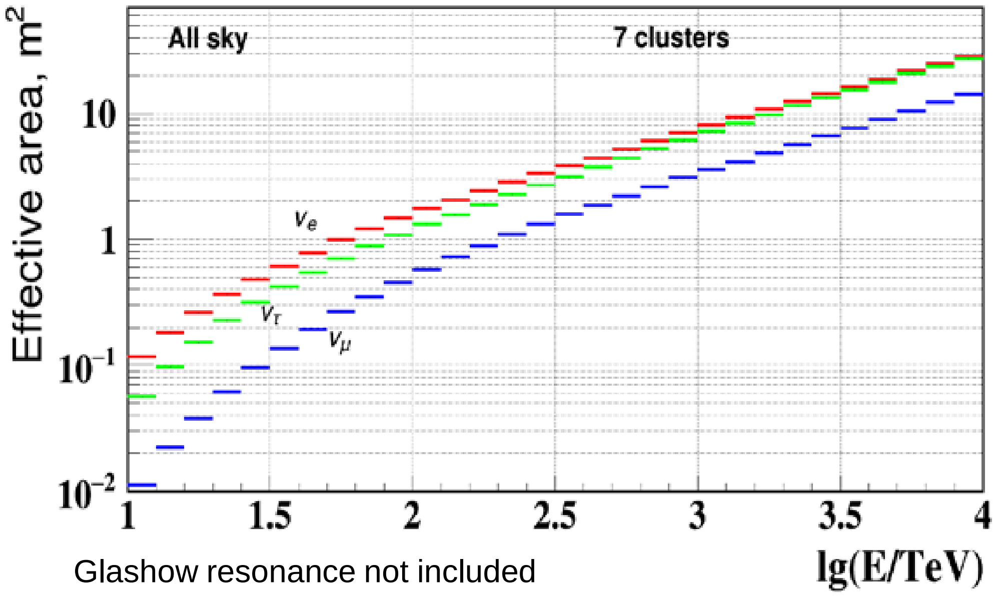
Median energy ~ 4 TeV

Work in progress !

Cascade analysis : effective area and rates

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

neutrino effective area for cascade detection

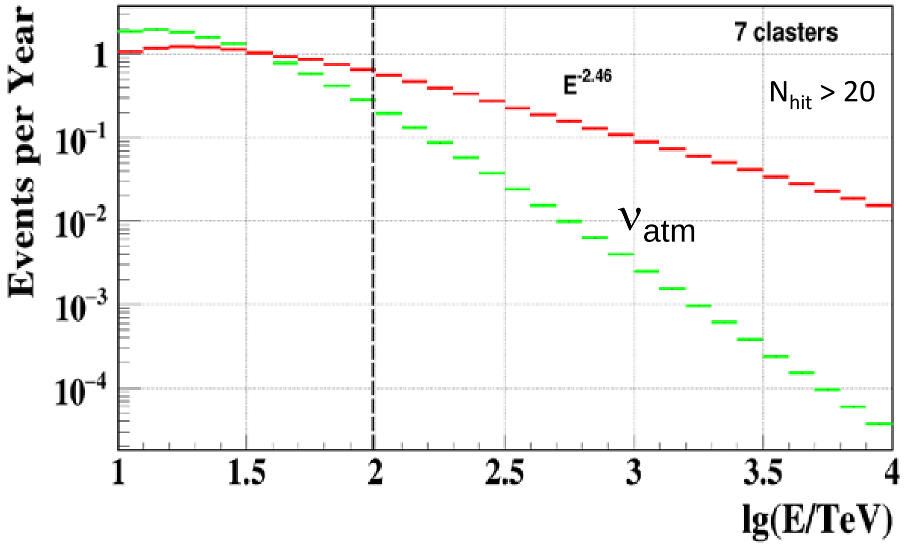


Glashow resonance not included

Assumption for astrophysical neutrino energy spectrum (IceCube fit):

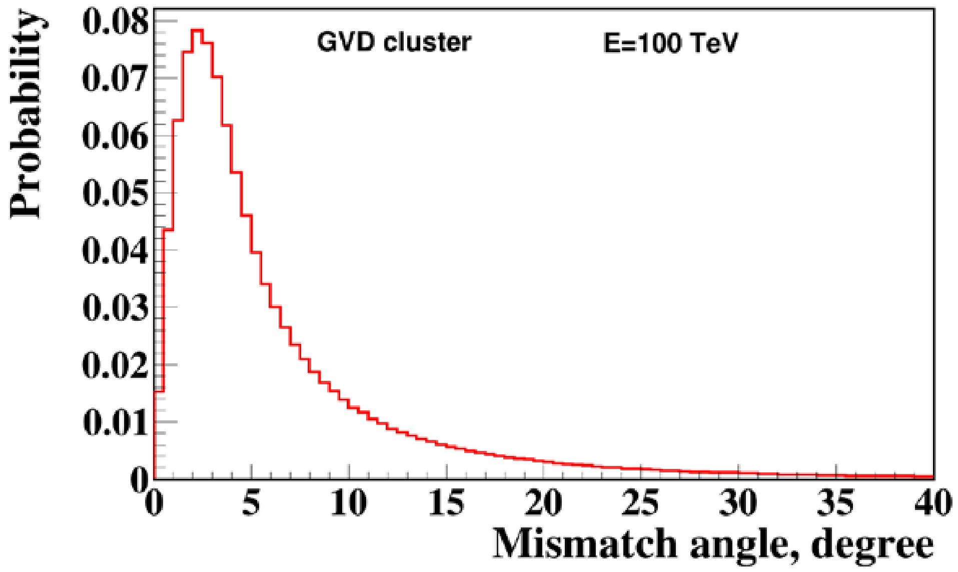
$4.1\cdot10^{-6}\ E^{-2.46}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

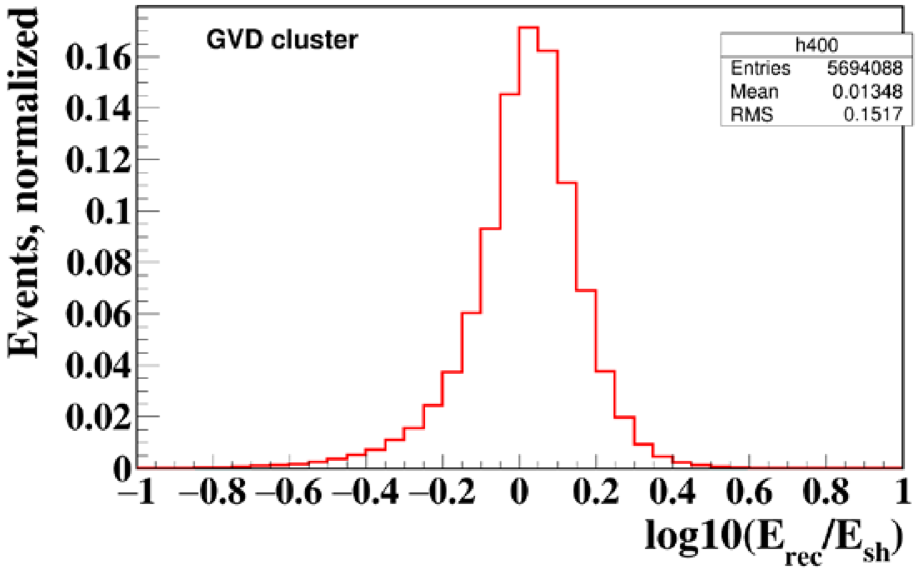
Expected number of cascade events per year



- 3–4 ev/yr with E_{sh} >100 TeV for 7 clusters

Cascade analysis performance





Directional resolution for cascades:
median mismatch angle ~ 2°÷4°

Energy resolution : δE/E ~ 10÷30%

A search for astrophysical diffuse neutrino flux

Data from 2018-2021, livetime: 5522 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 *arXiv:2211.09447*

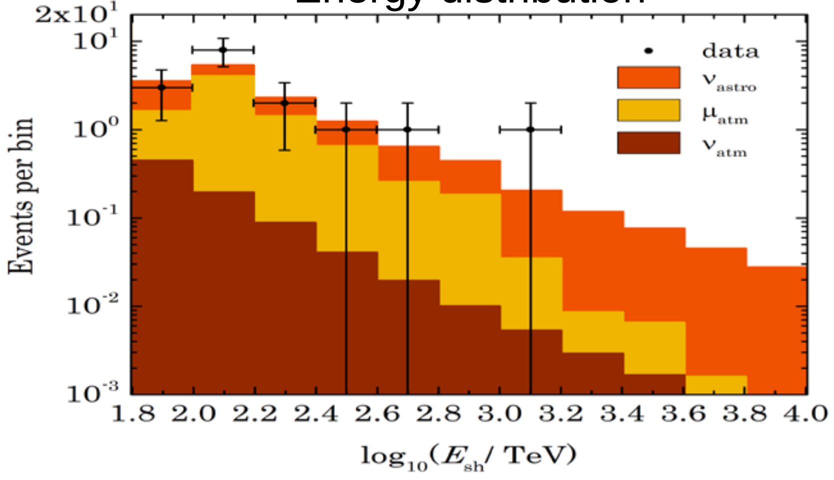
Additional selection requirements:
(N_{hit_μ} = 0, E_{rec} ≥ 70 TeV) or
(N_{hit_μ} = 1, E_{rec} ≥ 100 TeV)
N_{hit_μ} is number of hits in time interval where hits from muons are expected

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

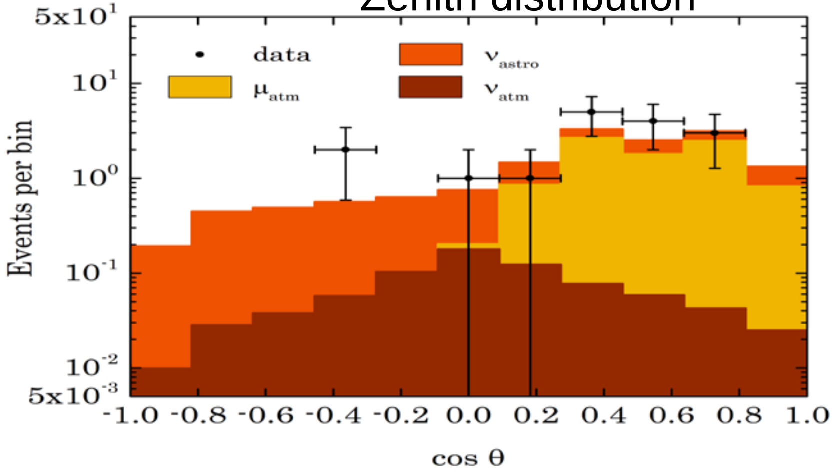
Found in real data: 16 events

Probability for the background-only hypothesis (stat.+sys.)
P-value = 0.026 (2.22 σ)

Energy distribution



Zenith distribution



Search for upward moving events *arXiv:2211.09447*

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

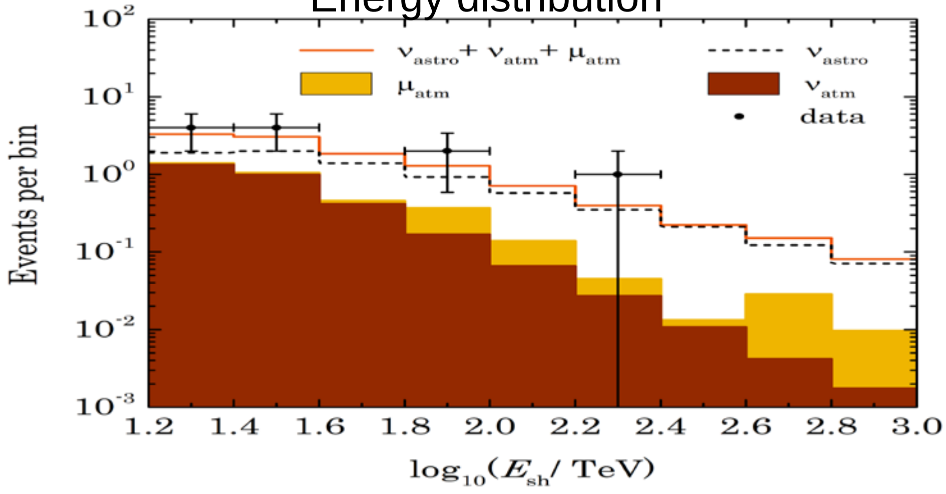
6.3 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

Found in data: 11 events

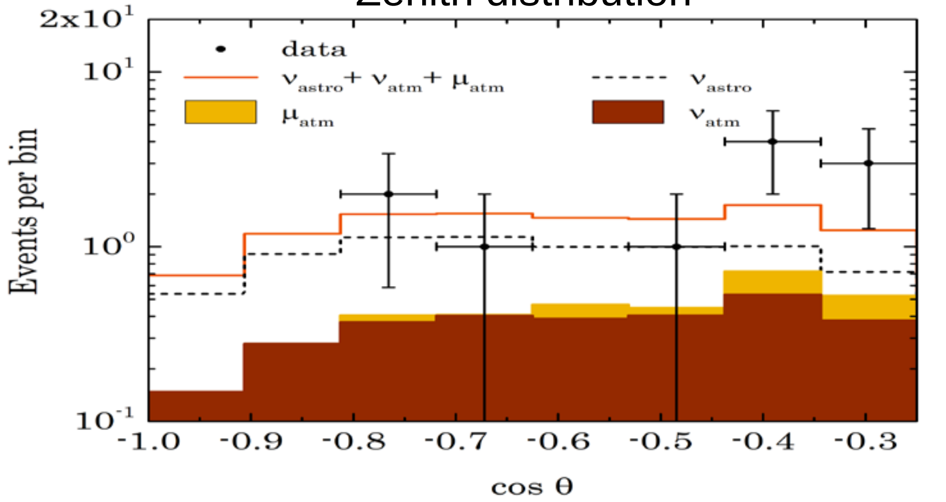
Probability for the background-only hypothesis (stat.+sys.)

P-value = 0.0024 (3.05σ)

Energy distribution



Zenith distribution



Single pawer-low model of isotropic astrophysical flux:
(ν_e: ν_μ : ν_τ=1:1:1)

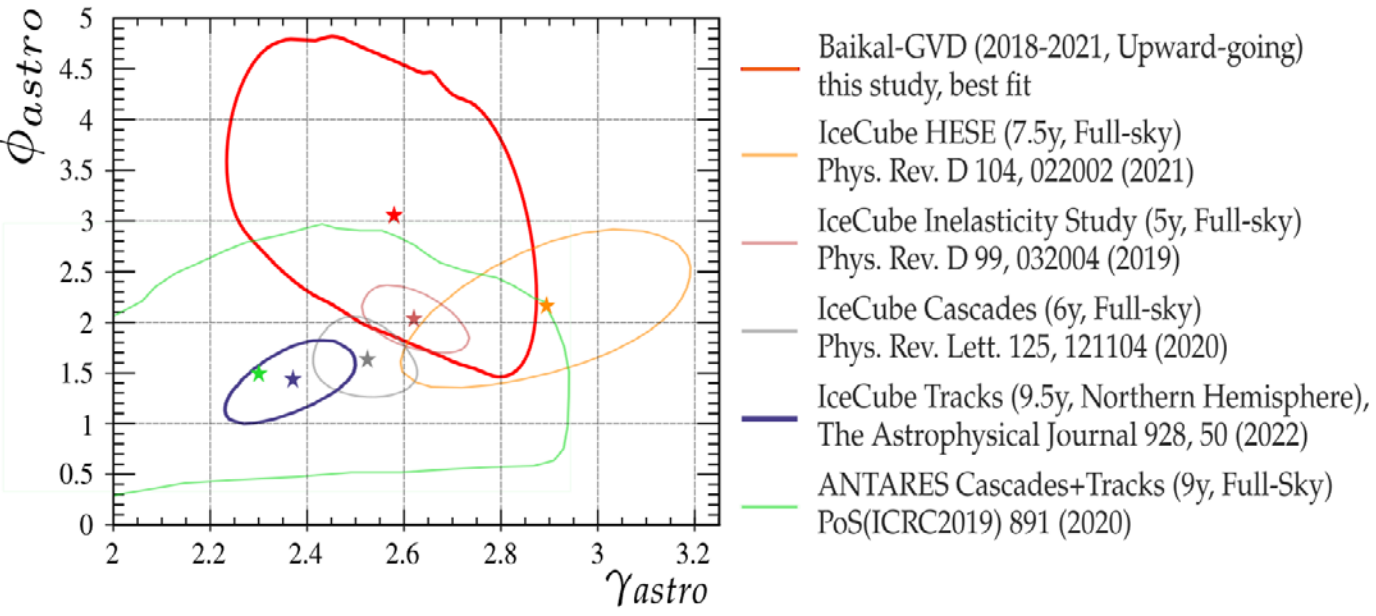
$$\Phi^{\nu+\bar{\nu}} = 3 \times 10^{-18}\, \varphi_{astro} \left(\frac{E}{10^5}\right)^{-\gamma_{astro}} (GeV\ cm^2\ s\ sr)^{-1}$$

Baikal-GVD best fit parameters:

spectral index $\gamma_{astro} = 2.58$

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

68% C.L. contours



arXiv:2211.09447

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

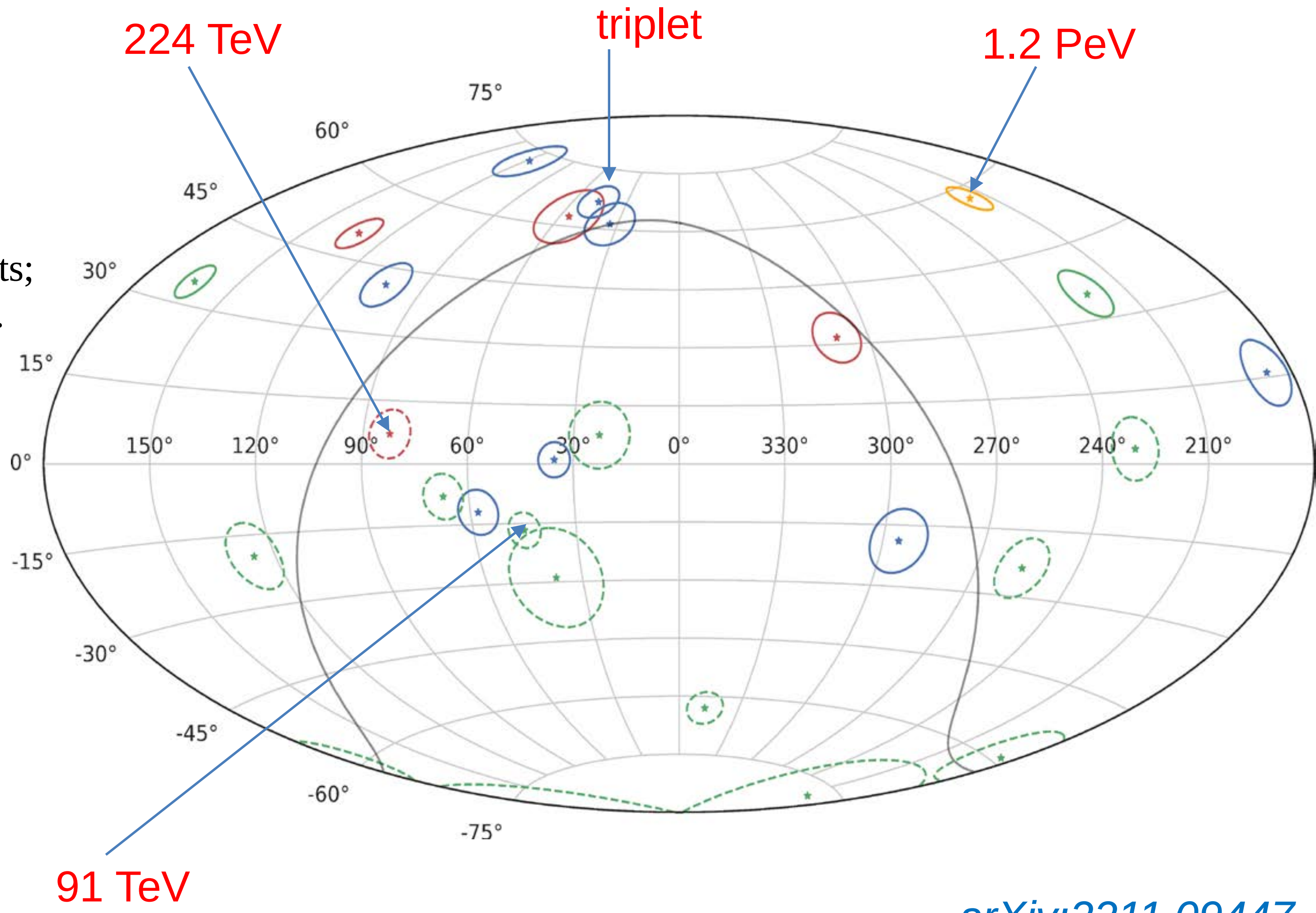
The best-fit positions and 90% angular uncertainty regions:

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

Colour represents event energy:

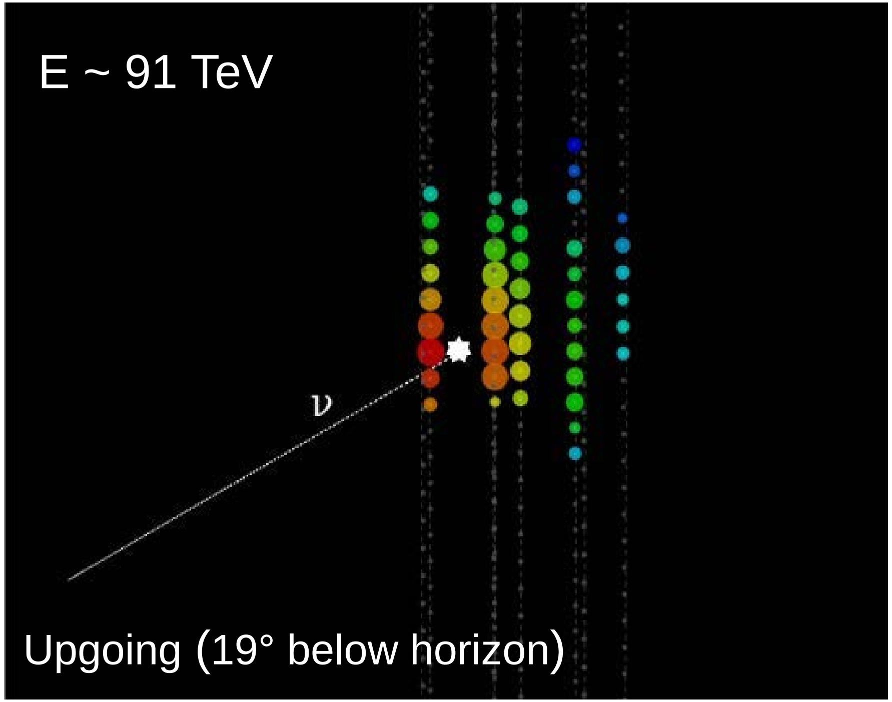
green – E < 100 TeV,
blue – 100TeV < E < 200 TeV,
red – 200 TeV < E < 1000 TeV,
orange – E > 1 PeV.

The Galactic plane is indicated as a grey curve.



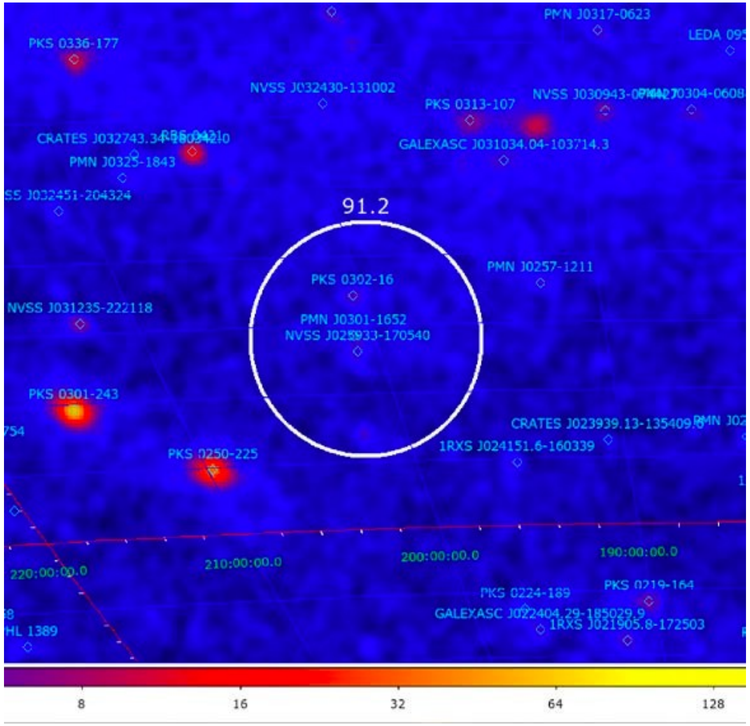
arXiv:2211.09447

Upward-going cascade GVD190523CA



Contained event (50 m off central string).
Excellent candidate for a neutrino event of astrophysical origin.
Signalness = 93.4%

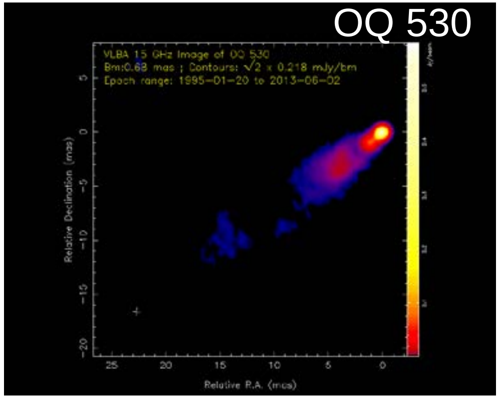
Sky plot of γ-ray sources
(credit: D.Semikoz, A.Neronov)



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

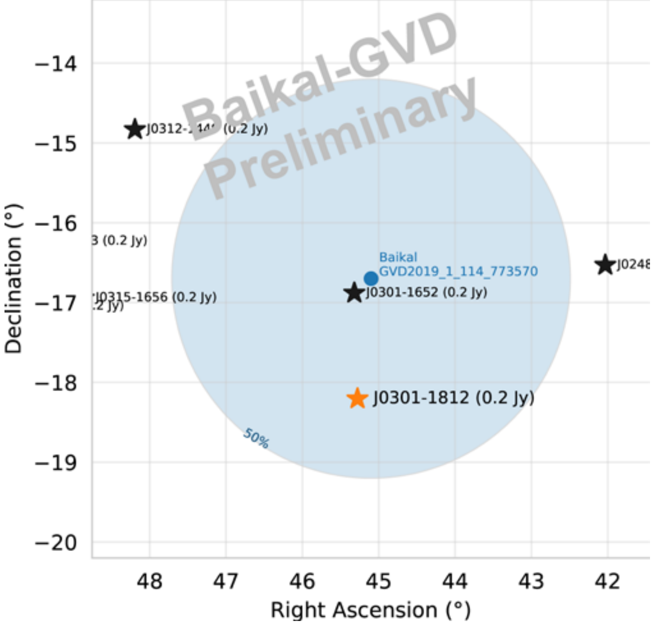
Radio-loud blazars – promising neutrino sources

A. Plavin et al., ApJ 894, 101 (2020)
A. Plavin et al., ApJ 908, 157 (2021)

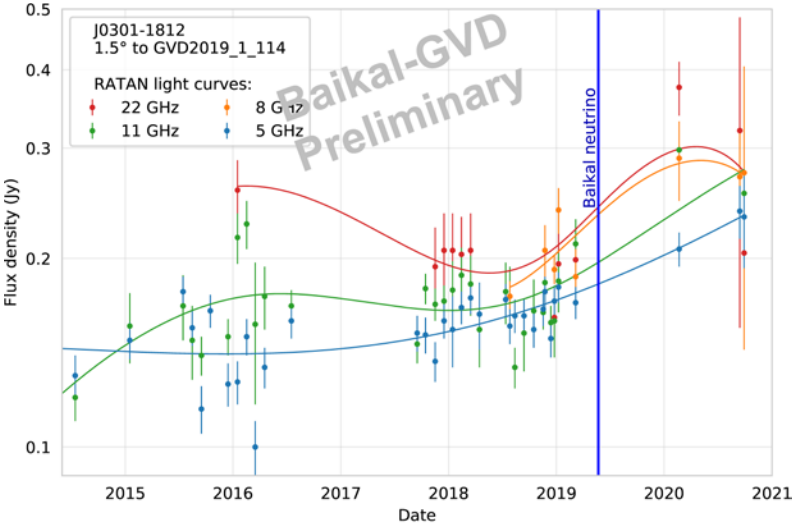


GVD190523CA
Radio blazar J0301-1812

Sky plot of radio-bright blazars nearby neutrino event



Light curves of J0301-1812 measured by RATAN-600



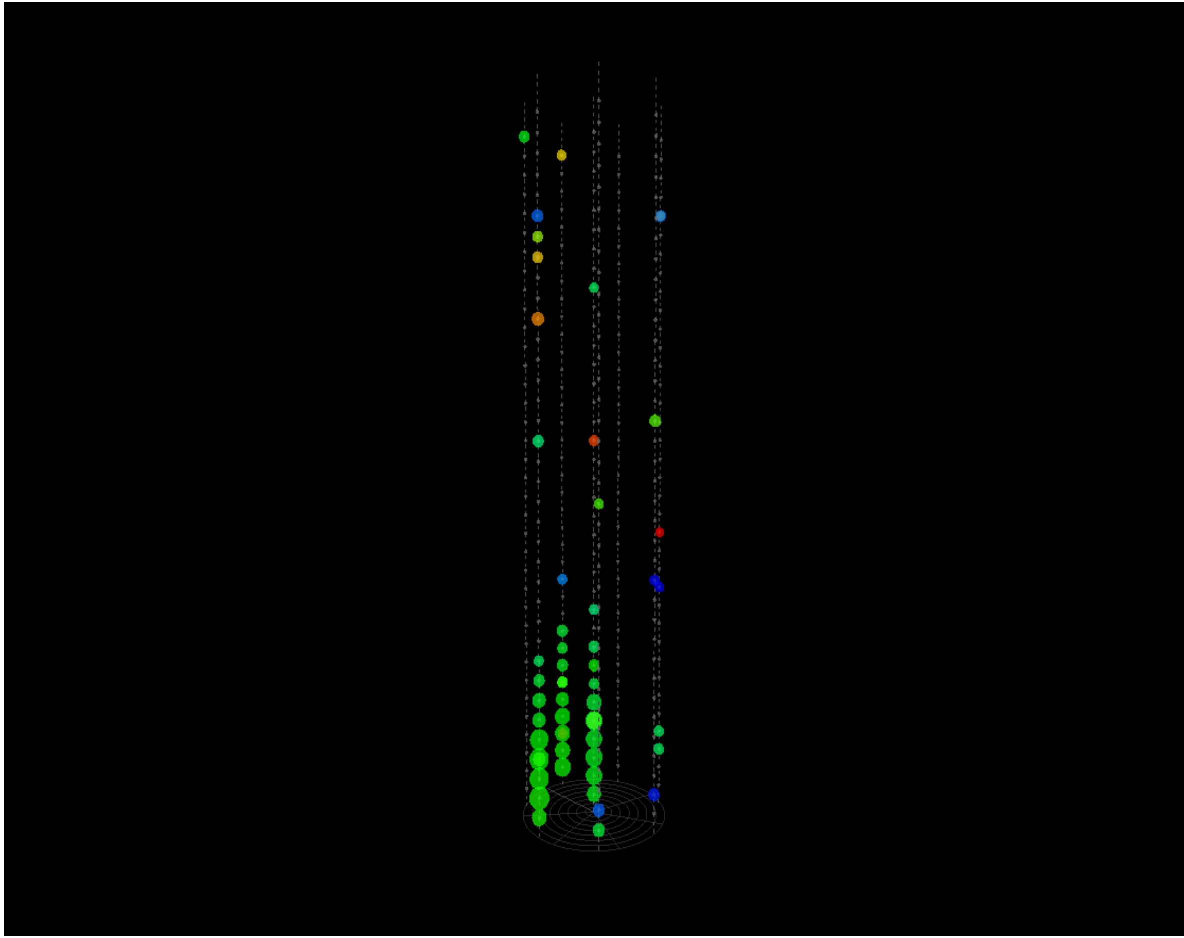
Upward-going cascade GVD210418CA

MJD = 59322.94855324
Energy E = 224 TeV (±30%)
Distance from central string r = 70 m
Zenith angle = 115°
RA = 82.4°, Dec = 7.1°

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

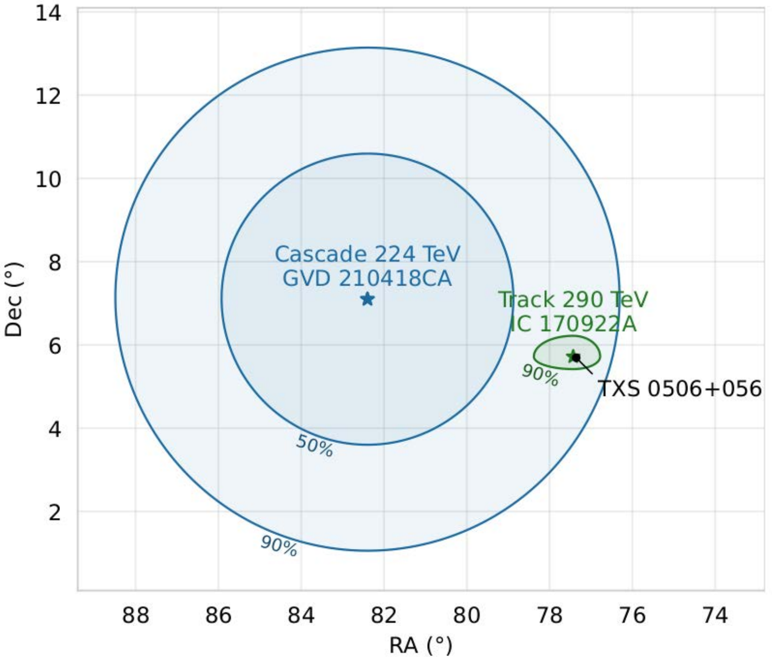
P-value = 0.0033 (2.93σ)

Signalness: 97.1%



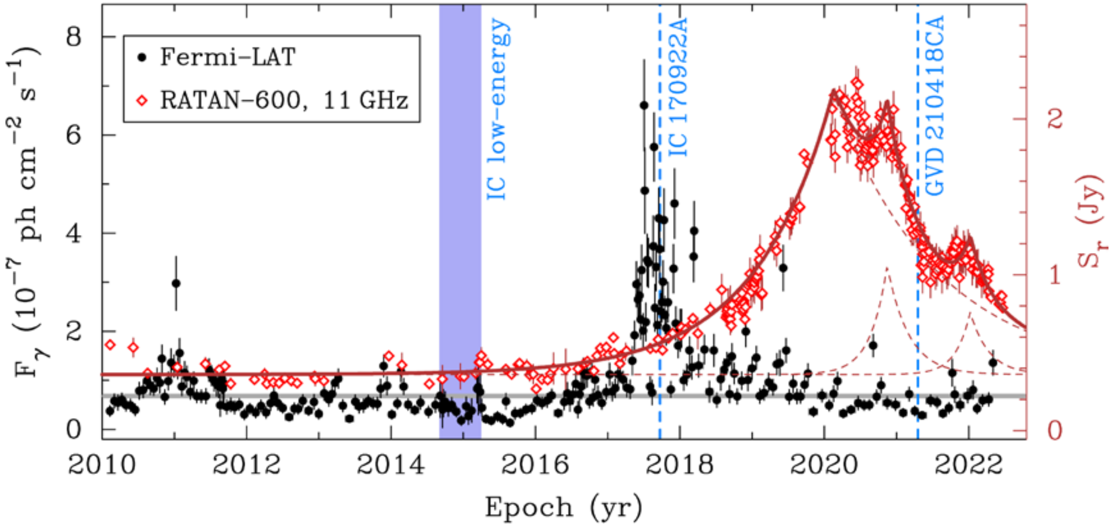
A high energy neutrino from the direction of TXS 0506+056

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.

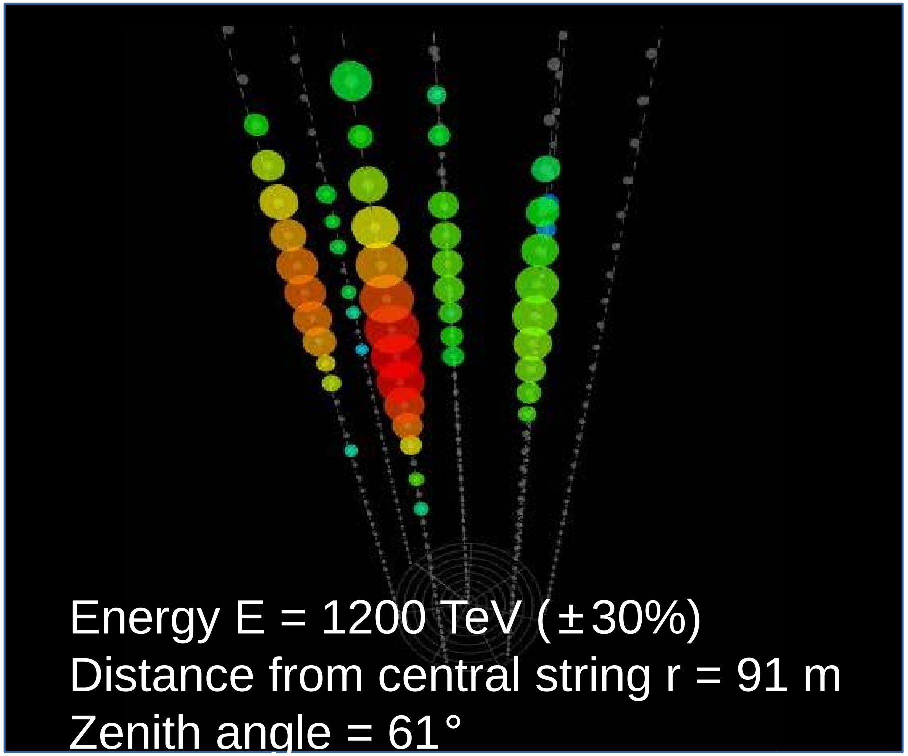


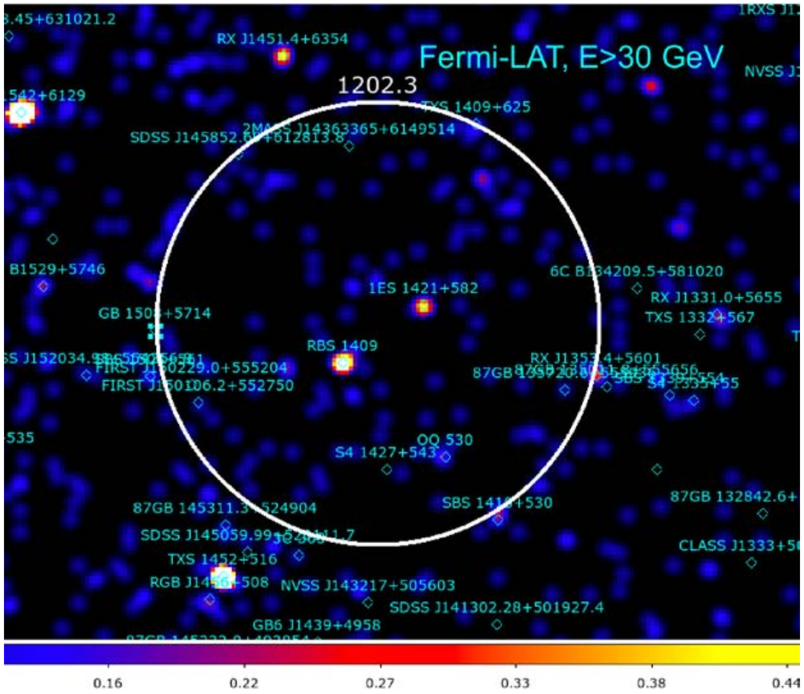
Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

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

arXiv:2210.01650

A 1 PeV cascade event (downgoing) GVD190517CA





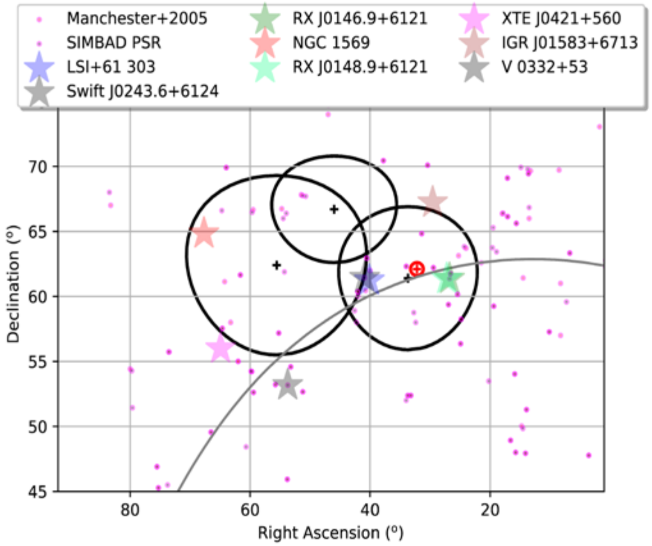
Probability for the background-only hypothesis (stat.+sys.)

P-value = 0.0054 (2.78σ)

Signalness 96.6%

Fermi sources in 5° circle:
RBS 1409 BL Lac z=unknown
1ES 1421+582 z=unknown
both with hard spectrum

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))

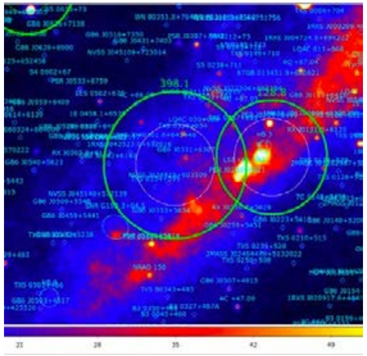
Stars - Several close high-mass X-ray binaries.

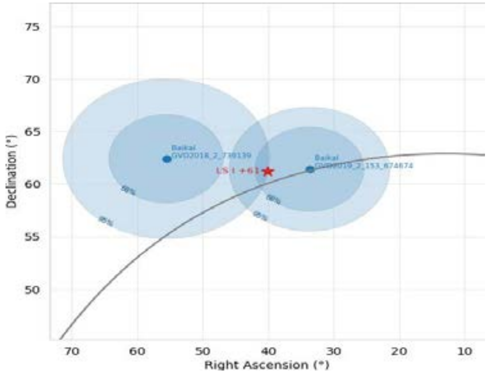
Dots - Galactic pulsars (Manchester et al. 2005, SIMBAD Astronomical Database)

★ 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”]

GVD follow up of ANTARES alerts

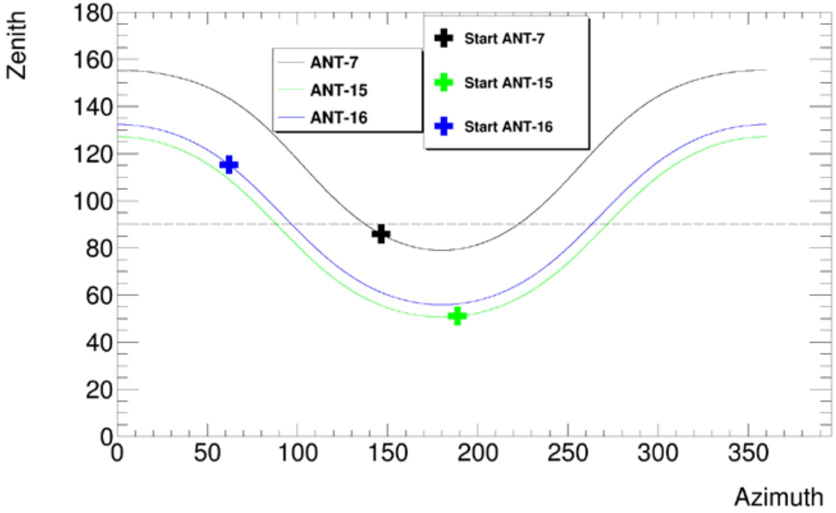
Following ANTARES upgoing μ alerts (<E> = 7 TeV)
Time windows: ±500 sec, ±1 hour and ±1 day
Both upgoing and downgoing cascades are looked for

Since Dec 2018, 60 alerts have been analysed

3 potentially interesting events

ANT alert	GVD cluster	$T-T_{alert}$, hours	Energy, TeV
A7	3	+20.8	13.5
A7	3	-23.2	**158**
A7	2	-3.2	2.9
A15	2	+20.4	3.0
A15	3	-0.64	3.98
A16	2	-18.7	3.99
A16	4	-14.35	3.89

Source visibility



No prompt coincidence in time and direction was found

O. Suvorova et al. @ Neutrino 2022
O. Suvorova and A.Garre @ ICRC 2021

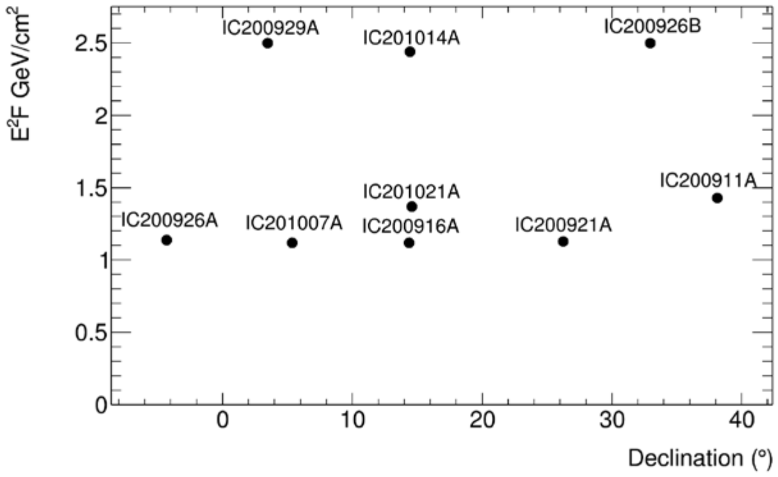
GVD follow up of IceCube alerts

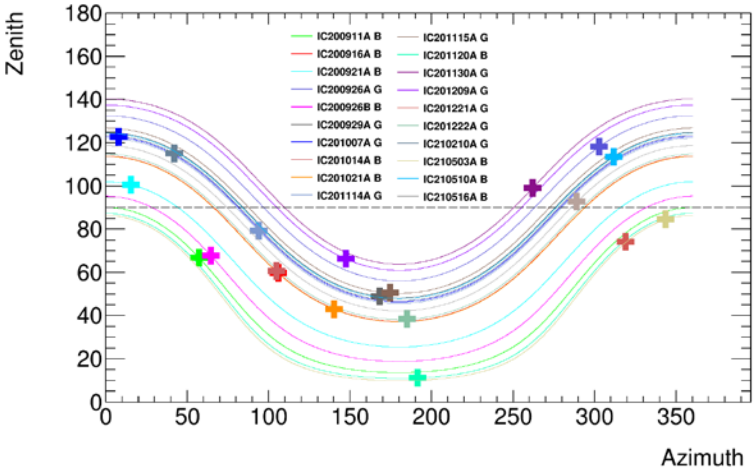
Since Sep 2020, following IC alerts (GCN / upgoing muons)

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

Baikal-GVD upper limits





A.D. Avrorin et al., Astronomy Letters, Vol.47, N 2, 114 (2021)
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 in vicinity of bright blazar PKS 0735+17

Active state of PKS 0735+17 reported in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio

Baikal-GVD found a downward-going (30° above horizon) **cascade-like event 4 hr after** the IceCube event
5.3° from the best-fit direction of IceCube-211208A
4.7° from PKS 0735+17

E ≈ 43 TeV
PSF 50% (68%) containment radius = 5.5 deg (8.1 deg)

Pre-trial p-value = 0.0044 (2.85 σ) [24 hr, 5.5 deg cone]

Trial factor ~ 40 (total number of IceCube alerts analyzed)

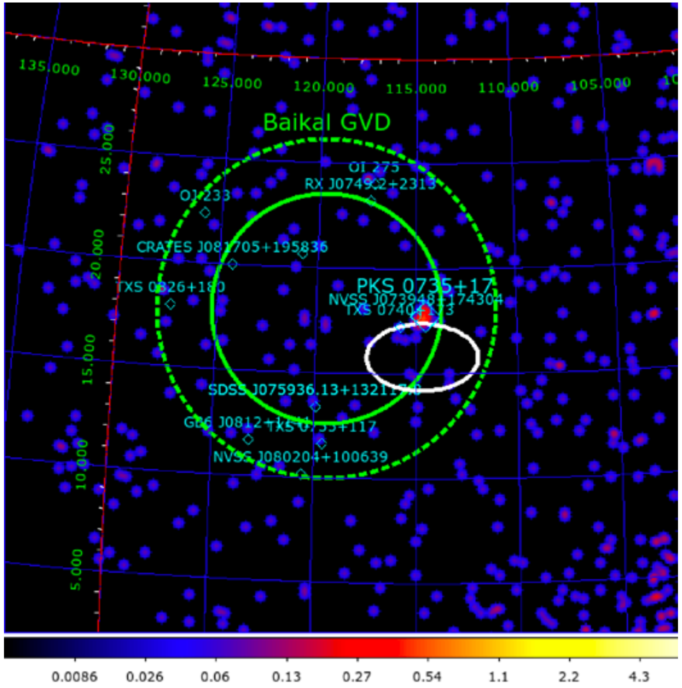


Image by D.Semikoz & A.Neronov

ATeL 15112

Also see N. Sahakyan et al., arXiv:2204.05060

Conclusion

- Baikal-GVD is a new 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
- Hints of possible new neutrino sources are accumulating