Baikal-GVD neutrino telescope: status and first results

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Introduction

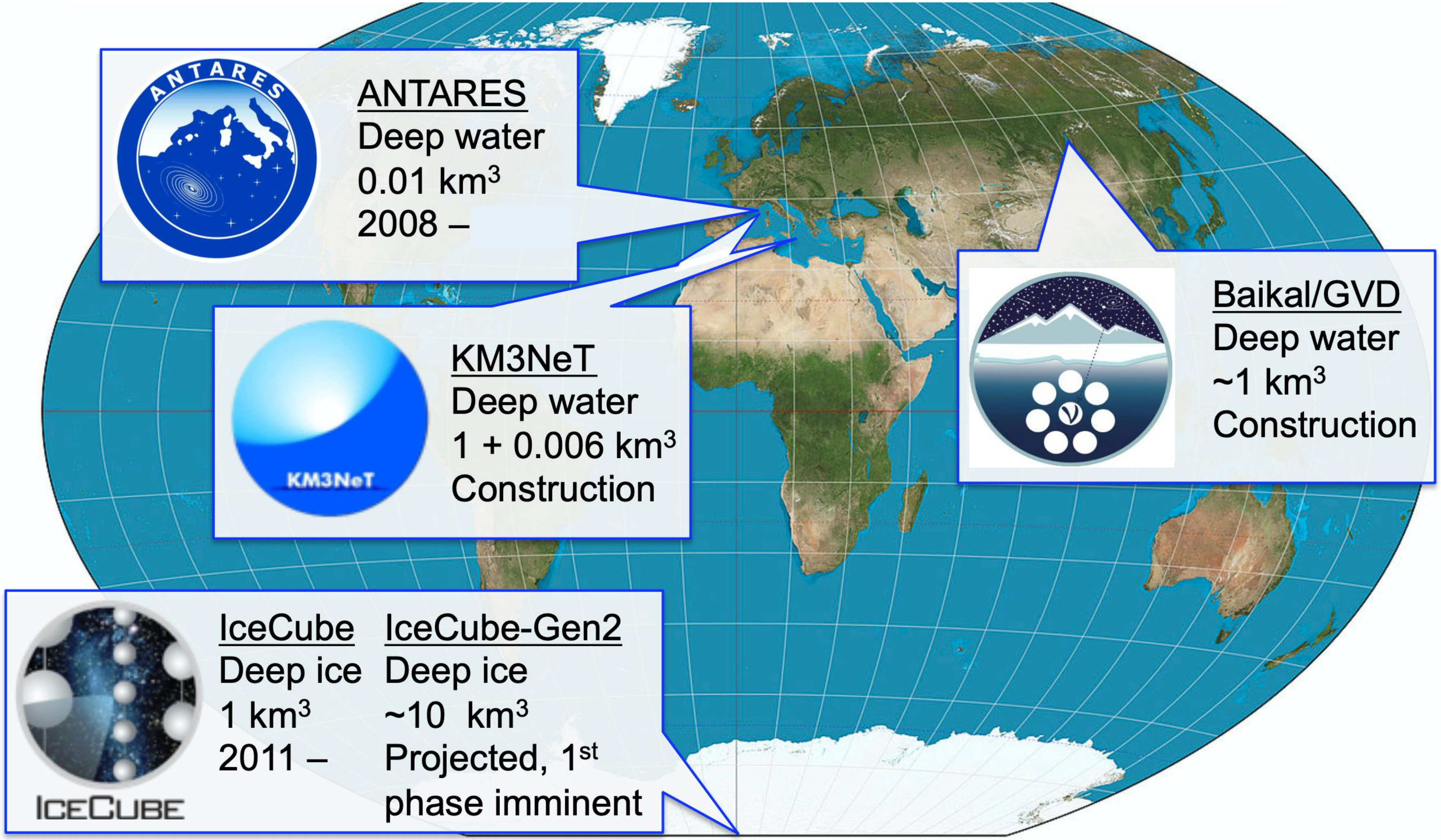
Baikal-GVD neutrino telescope

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 Institue for Nuclear Research (Krakow, Poland)

Neutrino telescope network

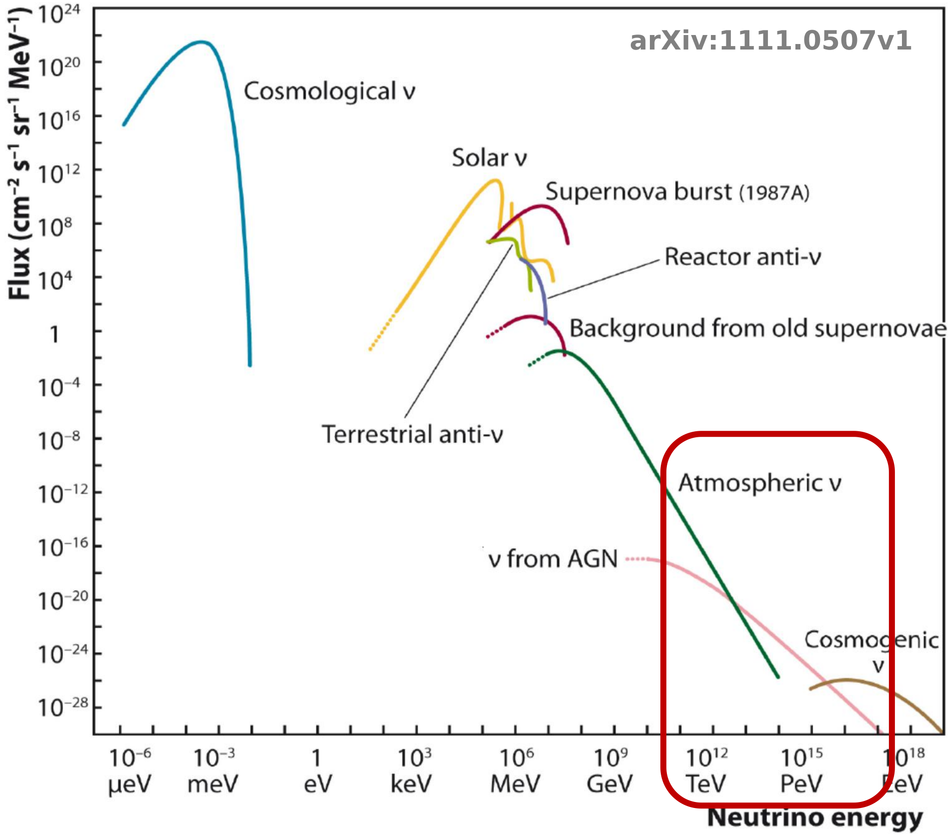


Purpose of the experiment

Main purpose of the Baikal-GVD experiment: study of astropysical neutrino flux

- Detector is sensitive to ν of energies from ~100 GeV to multi-PeV

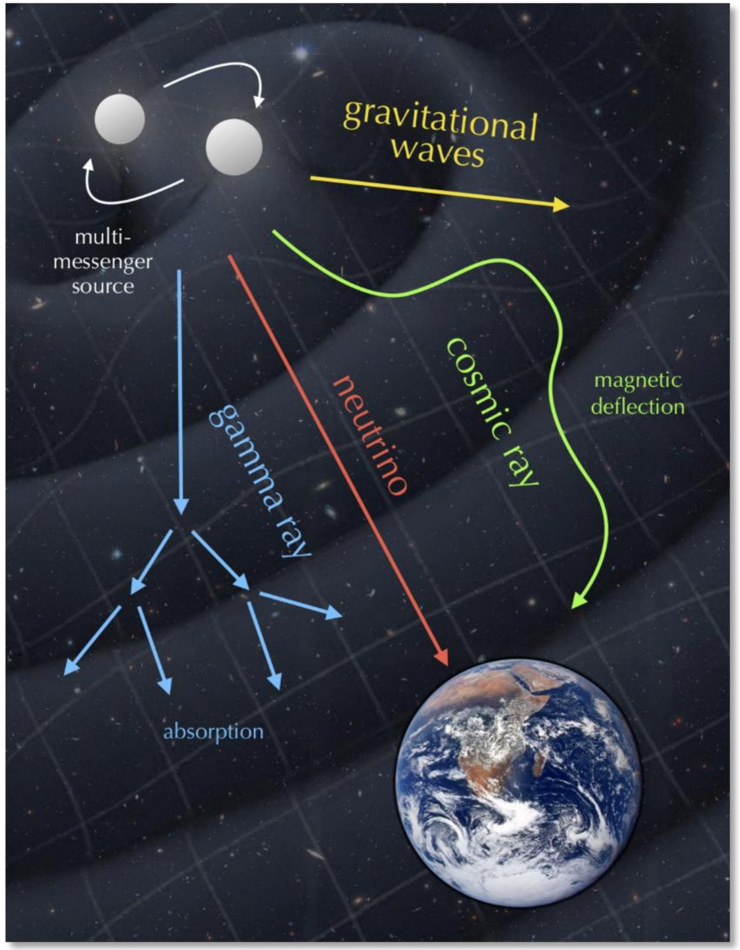
Natural and artificial neutrino sources



Region of sensitivity of very large neutrino telescopes

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



Neutrino detection principle I

Sparse array of photodetectors in natural water (ice) reservoir

Cerenkov light from charged particle produced in neutrino interaction is detected

Neutrino event types:

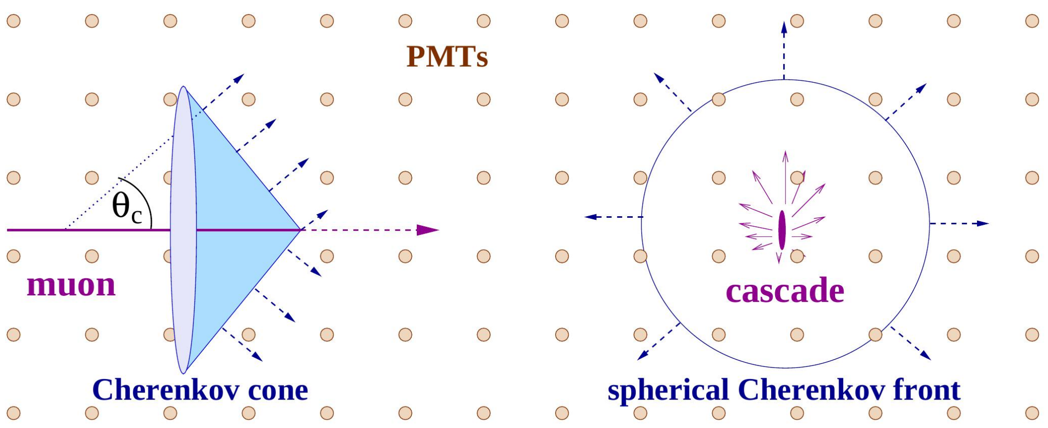
Tracks (CC, ν_μ ν_τ):
- Good angular resolution: ~0.3° - 0.5°
- Poor energy resolution: 200-300%
- Increased sensitive volume due to muon proagation range

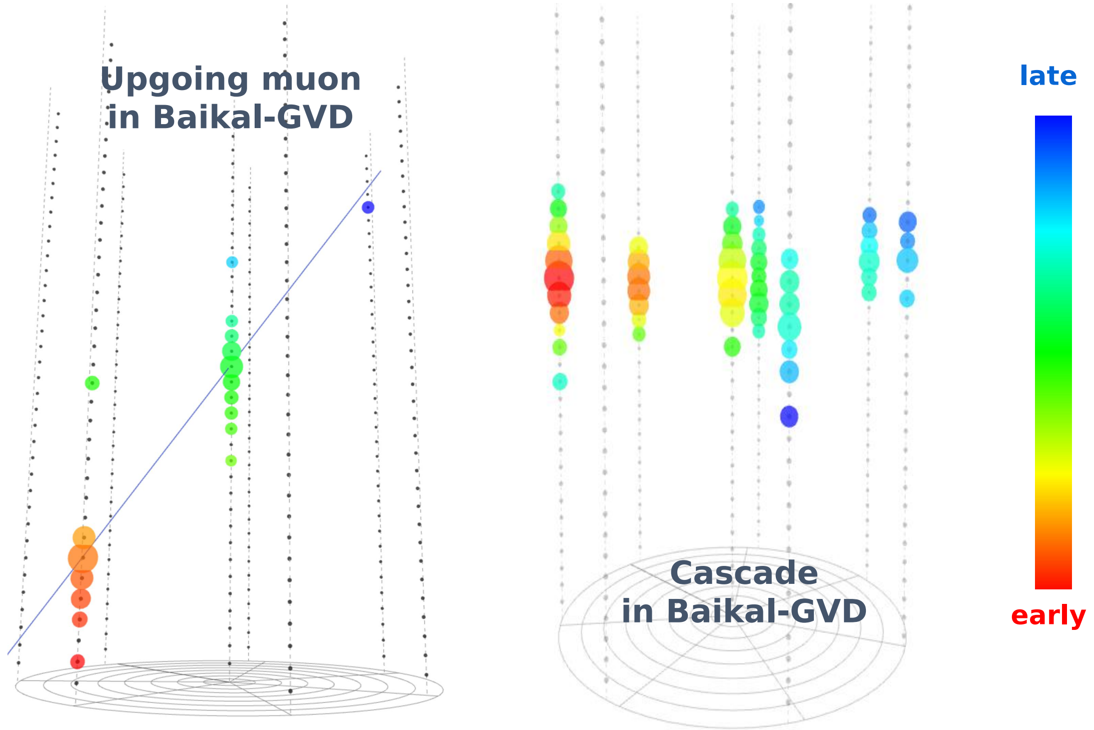
Cascades (CC ν_e ν_τ, NC):
- Moderate angular resolution 3°-10°
- Good energy resolution: 5-30%

Main background:

Events from bundles of atmospheric muons

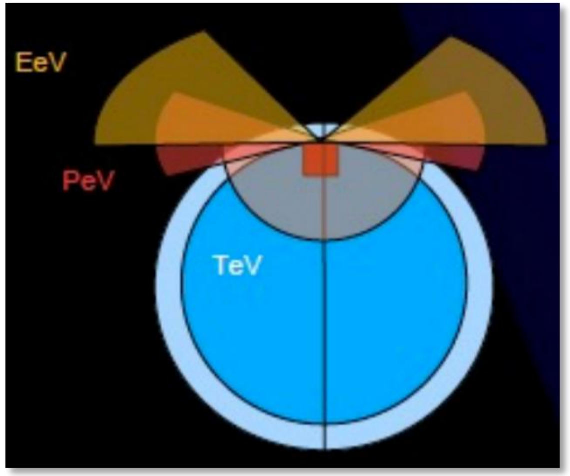
arXiv:1111.0507v1

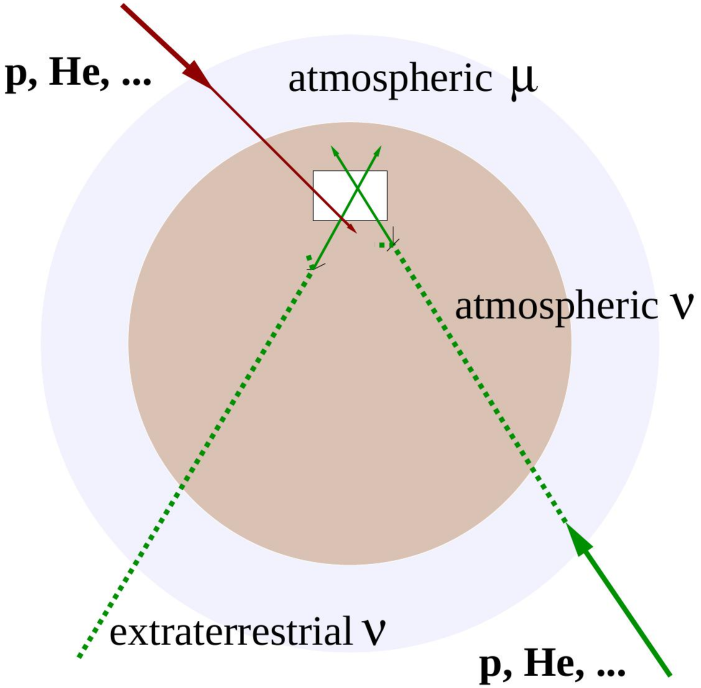




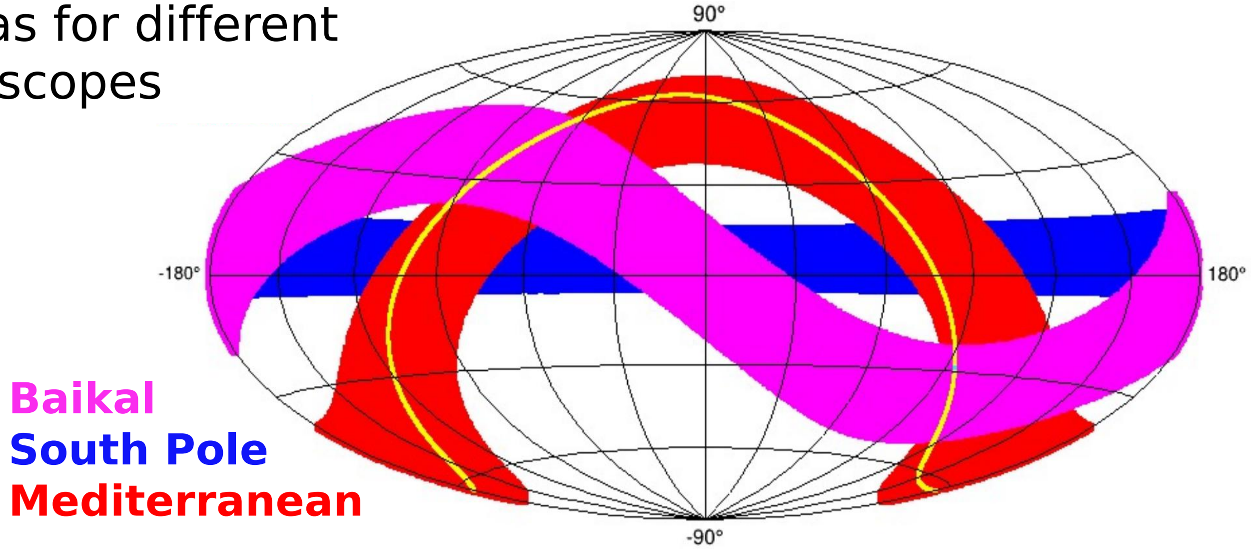
Neutrino detection principle II

- 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 neutrino dominate until ~50-100 TeV
- Earth is opaque for E_ν > ~ 500 TeV: horisontal events are of interest





Complimentary observation areas for different telescopes

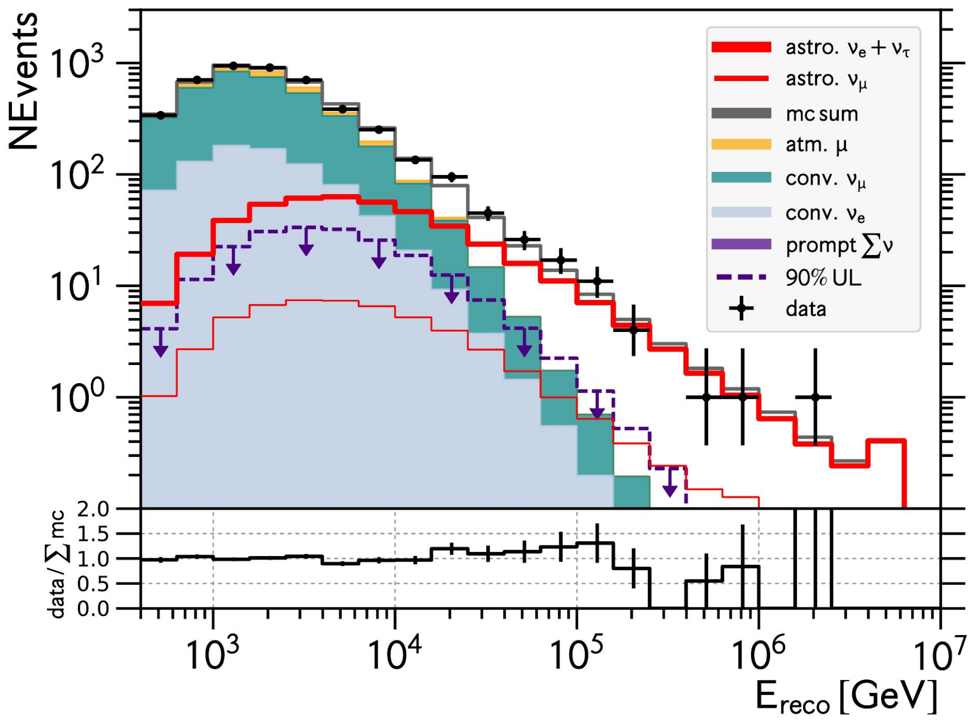


P. Coyle, ICRC2021

High energy neutrino astrophysics I

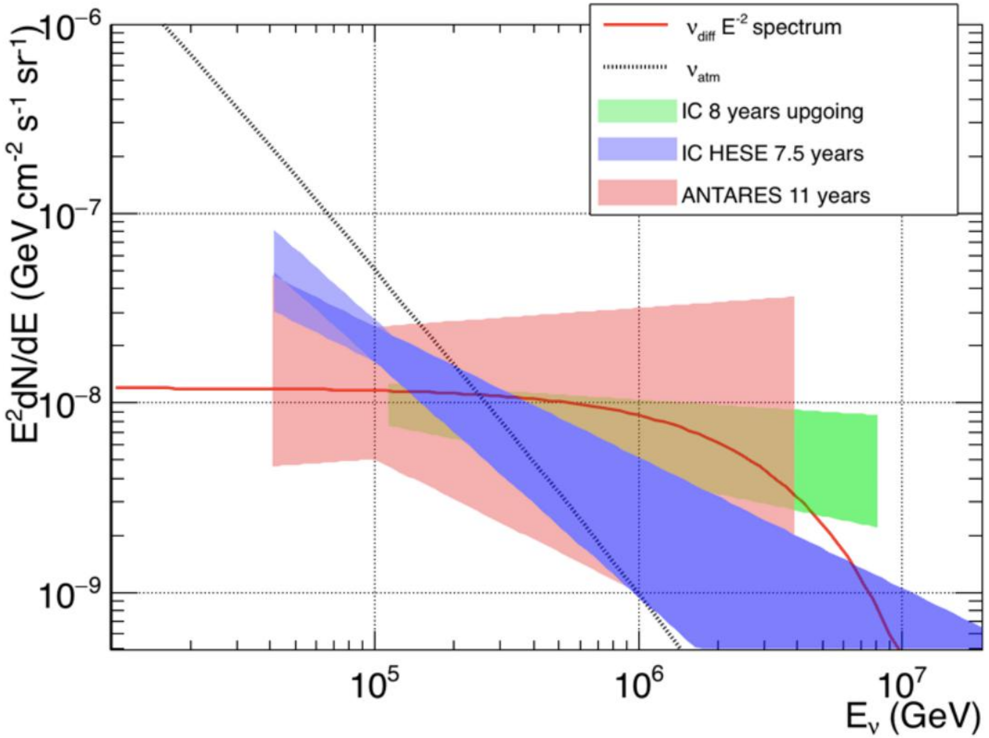
First observation of 4σ excess over atmospheric neutrino energy spectrum
IceCube 2013: [10.1126/science.1242856]

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]



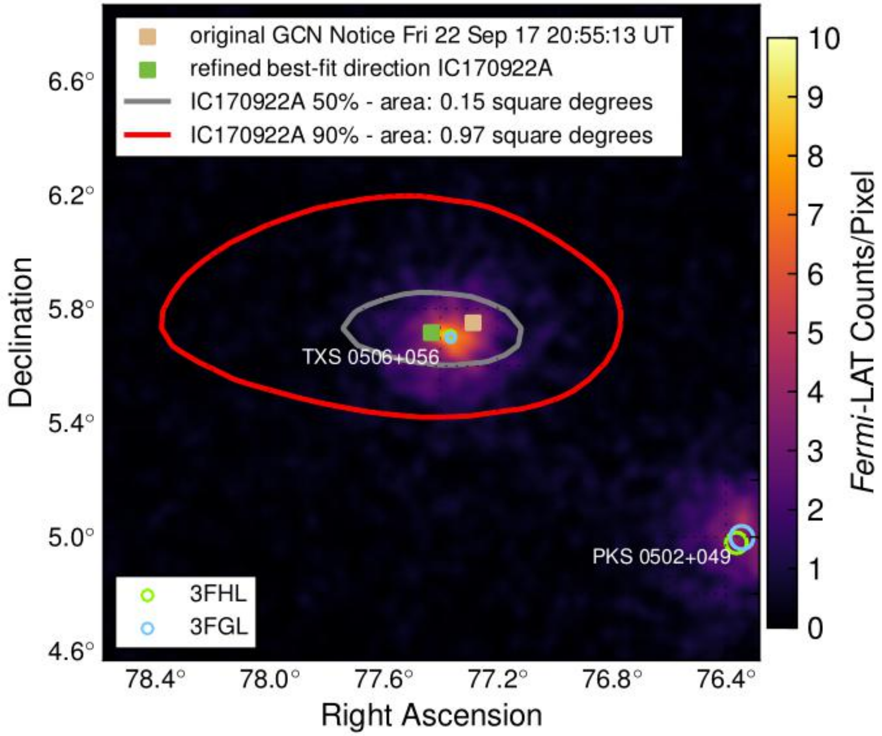
Spectral index of astrophysical neutrino events: 2.3 - 2.9 depending on analysis

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]



IceCube alert followed by FERMI γ-telescope

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
[A. Plavin et. al., ApJ 908 157 (2021)]

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!

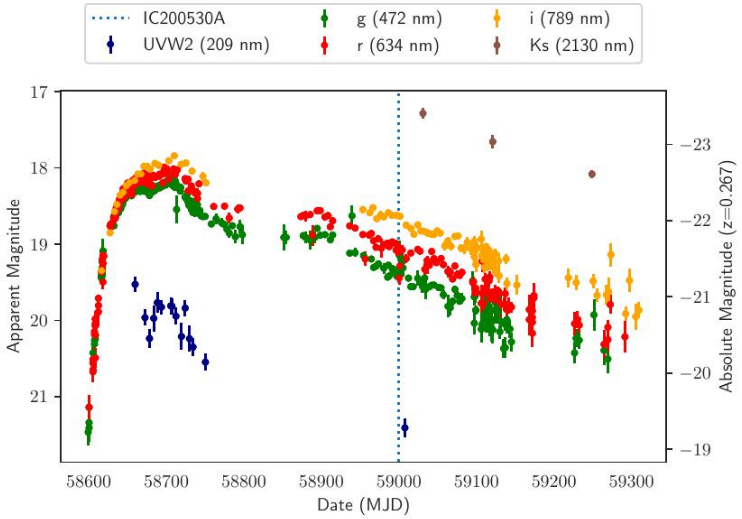
Multi-messenger astronomy

Tidal disruption events (TDE)

Black hole consumes a star

IceCube neutrinos spatially consistent with TDEs:

IC191001A → AT2019dsg
IC200530A → AT2019fdr
[R. Stein et. al., ICRC2021]

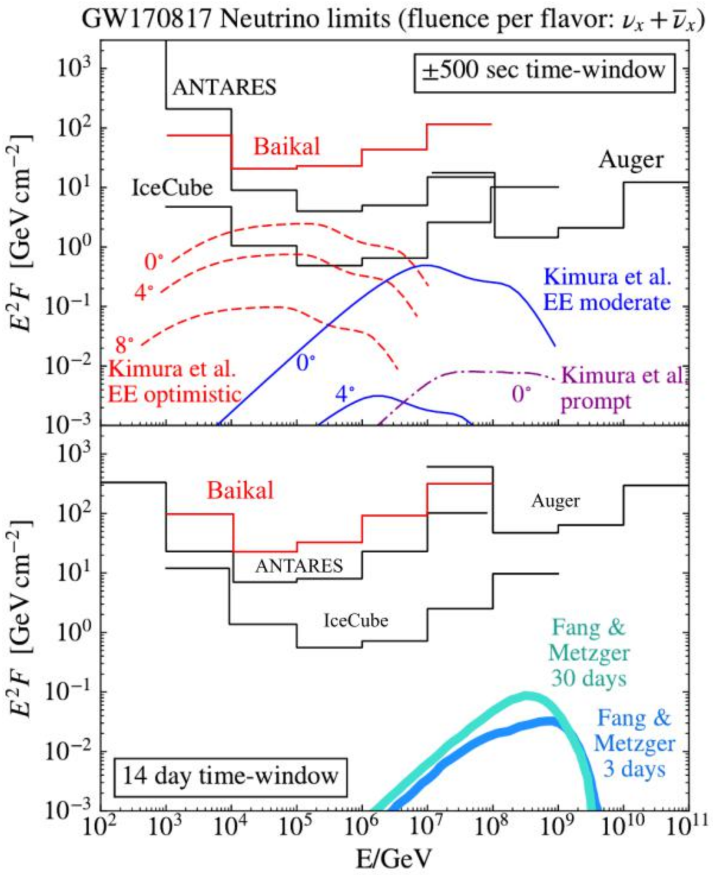


IC200530A

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

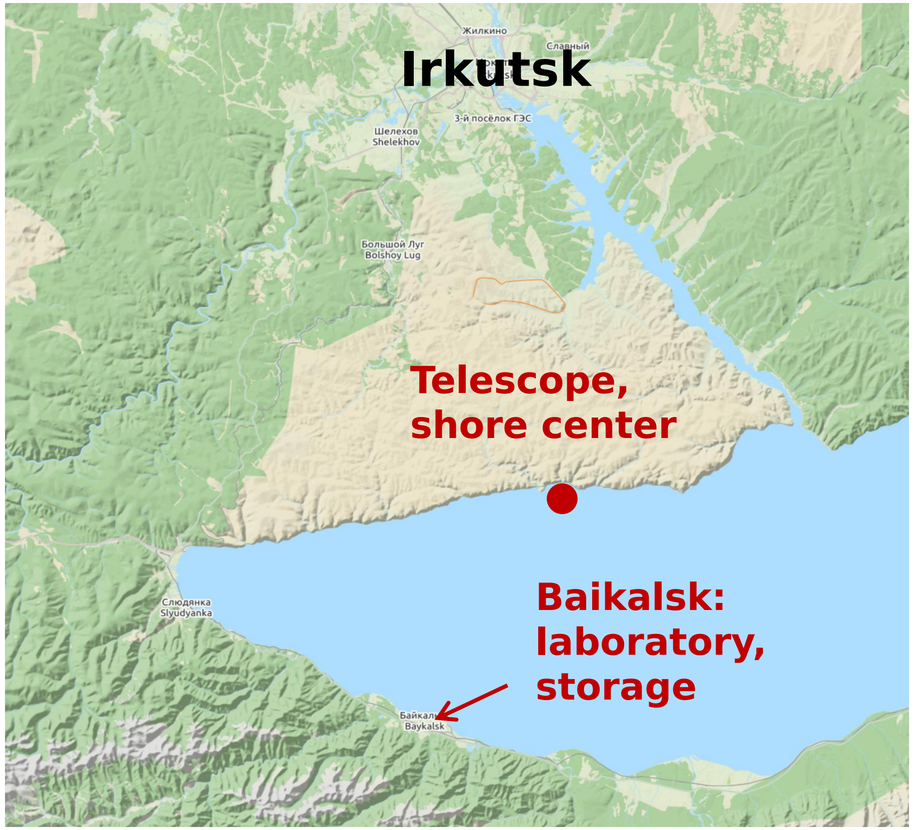
Neutrino: constraints on the hadronic acceleration processes in the source

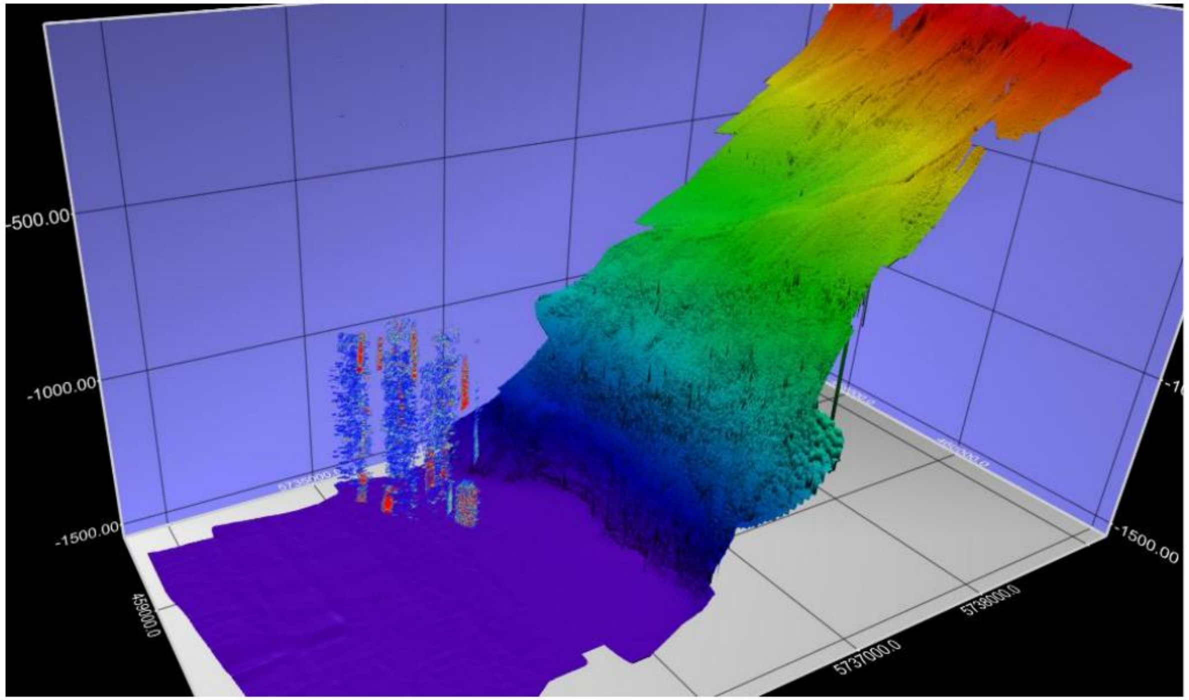
Baikal-GVD detector

Baikal-GVD experiment site

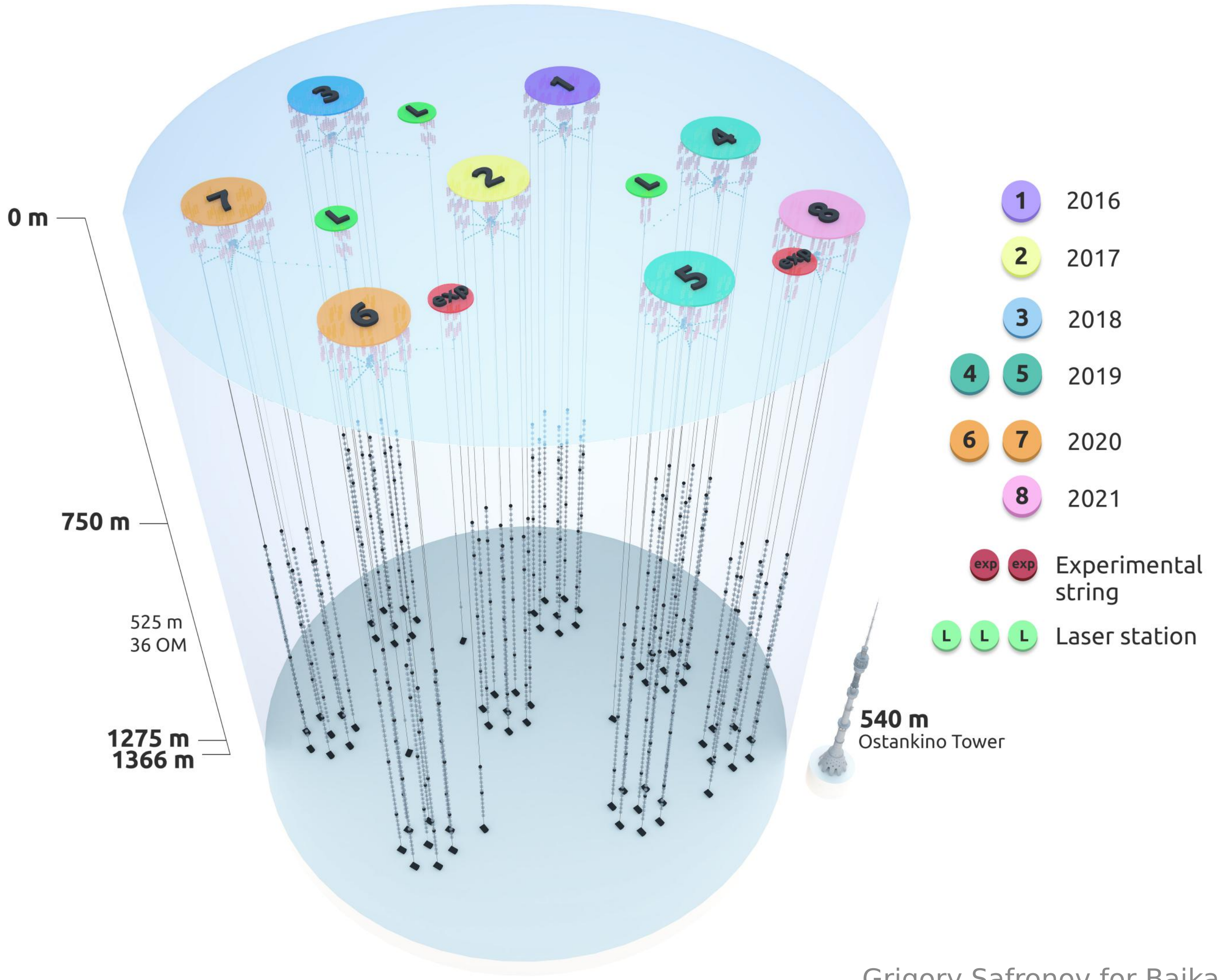
- Platform “106 km” of Circum-Baikal railway
- Telescope is located 3.6 km away from shore
- Constant lake depth: 1366 - 1367 [m]

- 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





Detector construction status



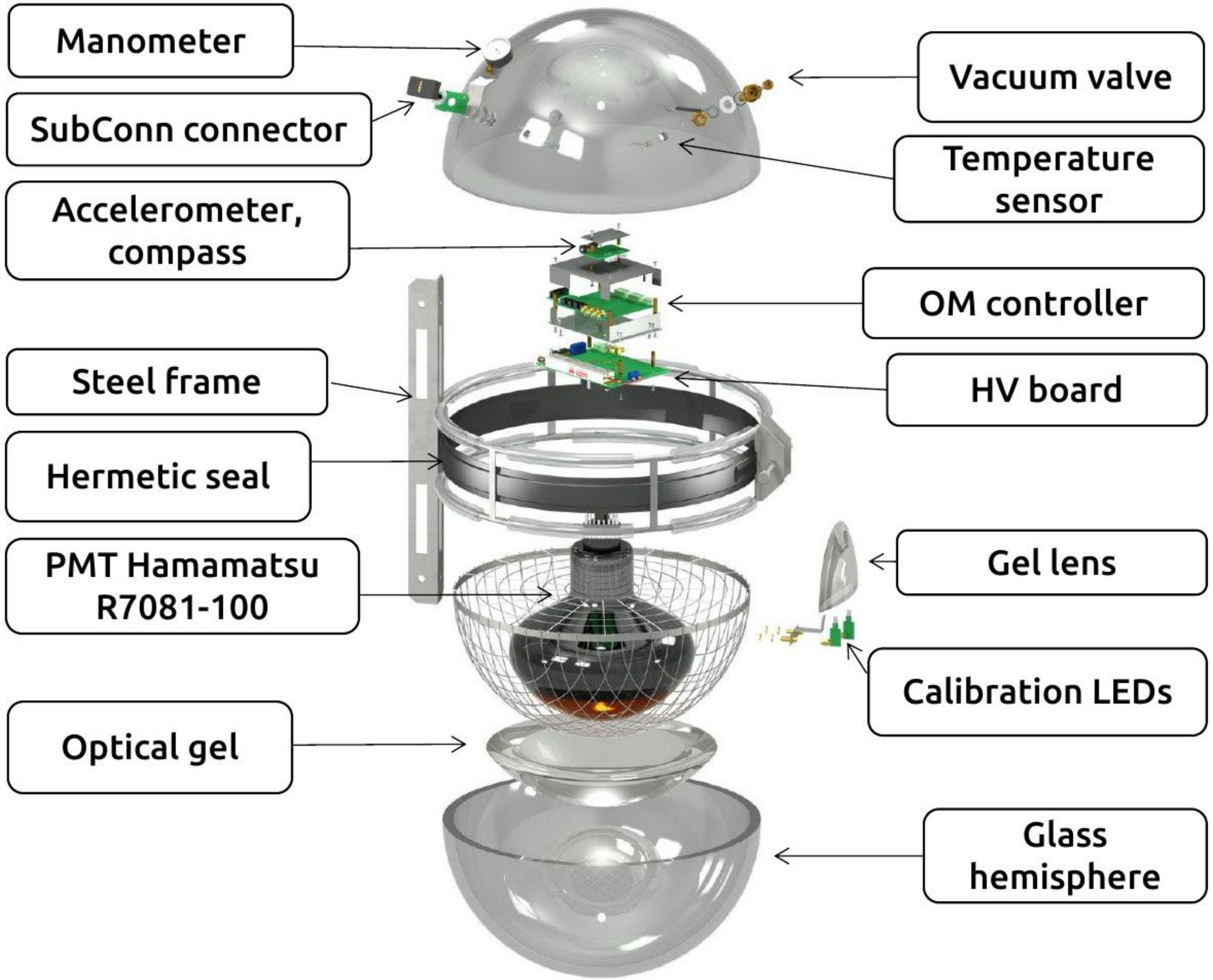
Deployment schedule

Year	Total number of clusters	Total 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	2880
2023	12	96	3456
2024	14	112	4032

Winter expedition

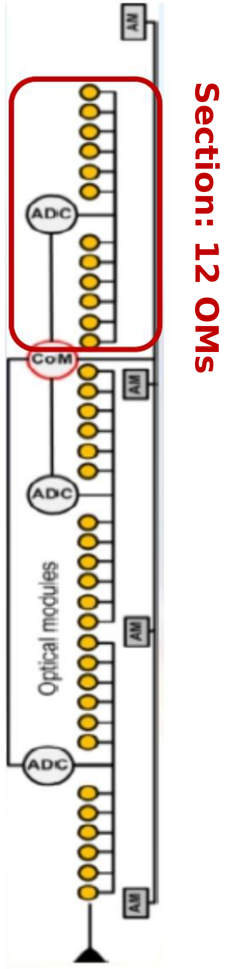
Baikal-GVD optical module

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



Baikal-GVD cluster

STRING:
3 sections



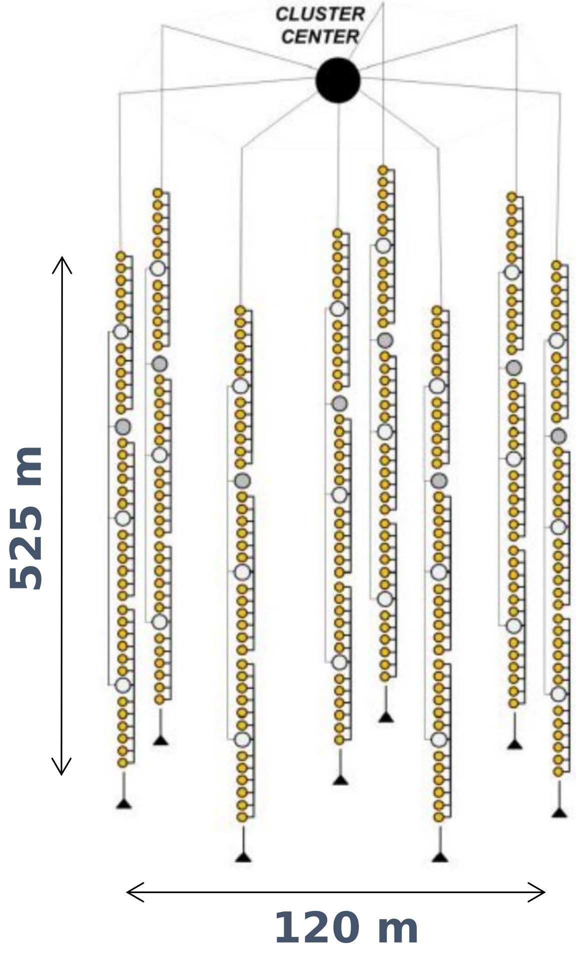
Cluster - independent detection unit, consists of 8 strings

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

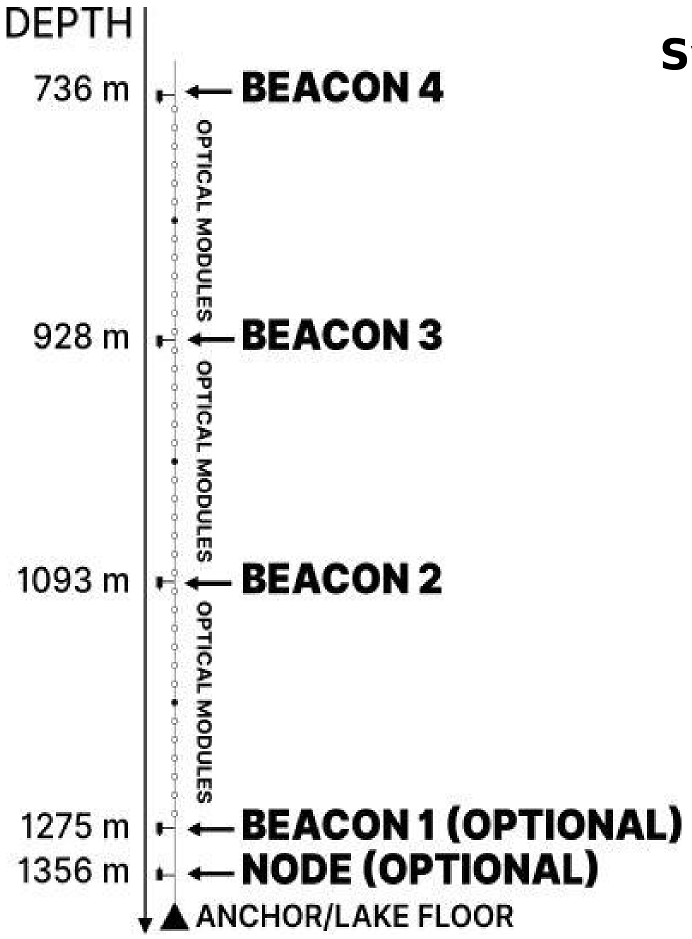
Trigger
- Cluster center reads out and sends event (5 μs window) to the shore center if the trigger condition is met
- Trigger condition: ~4.5 and ~1.5 [p.e.] signal on adjacent OMs within one section and 100 ns window

CLUSTER:
8 strings



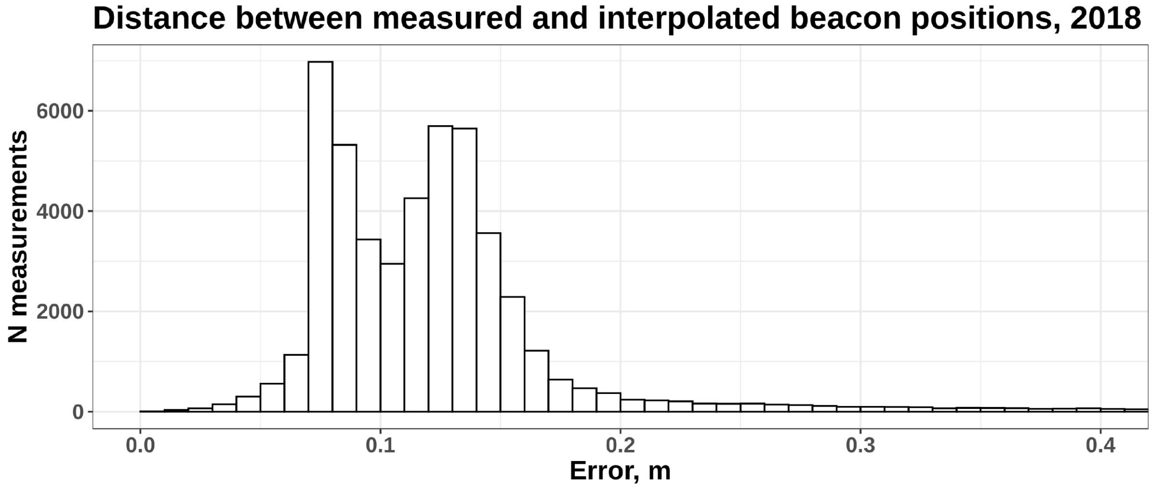
Acoustic positioning system

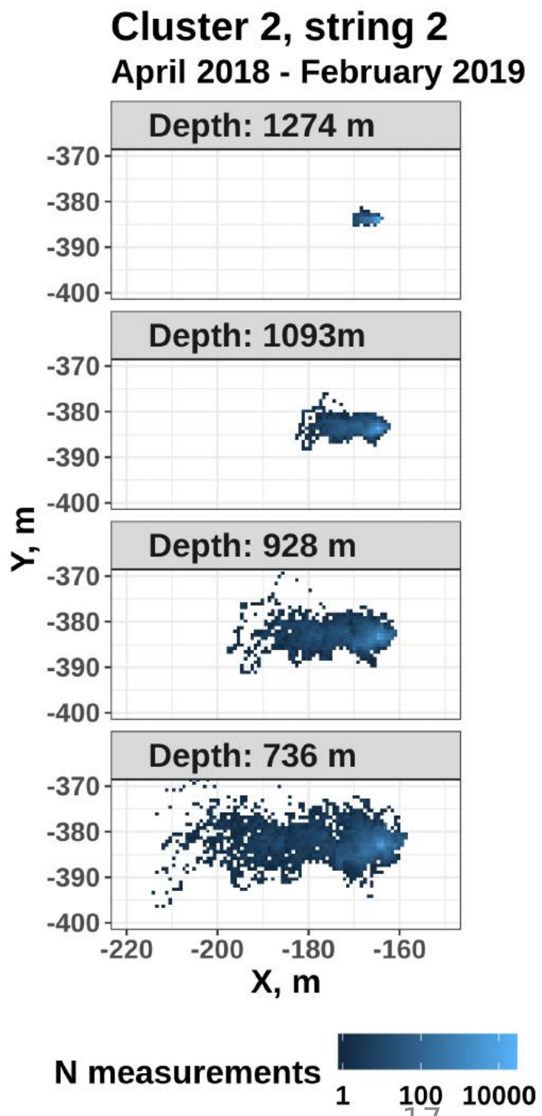
Water currents cause up to 50 m deviations of top OM from median location with the average velocity of 0.5 cm/s



System of acoustic beacons at each string:

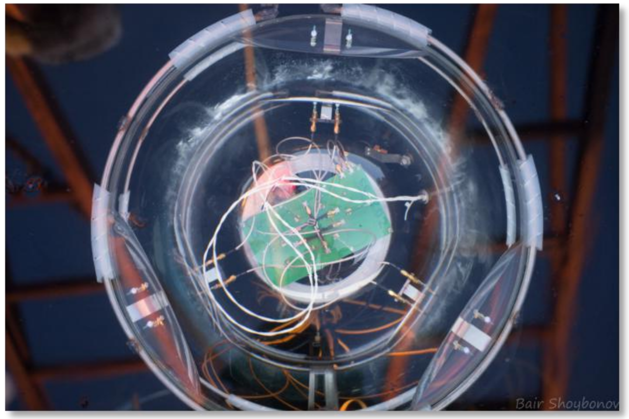
- Time of acoustic signal propagation between beacons is measured each 1 - 6 minutes
- Each OM position is reconstructed online for each measurement
- **OM positioning precision < 20 cm**

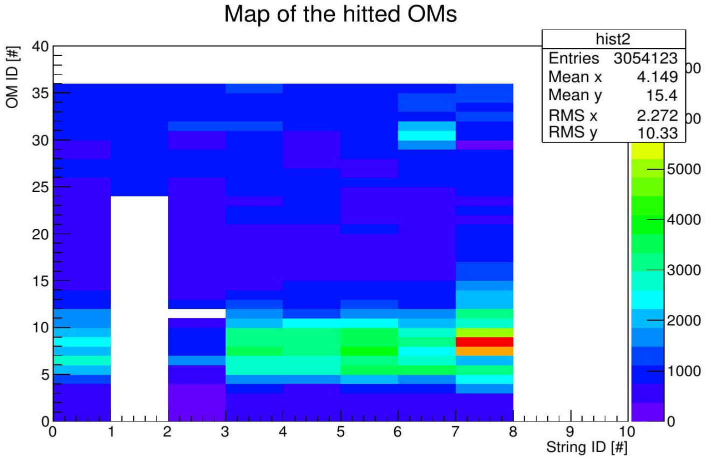




Time calibration systems

LED beacon





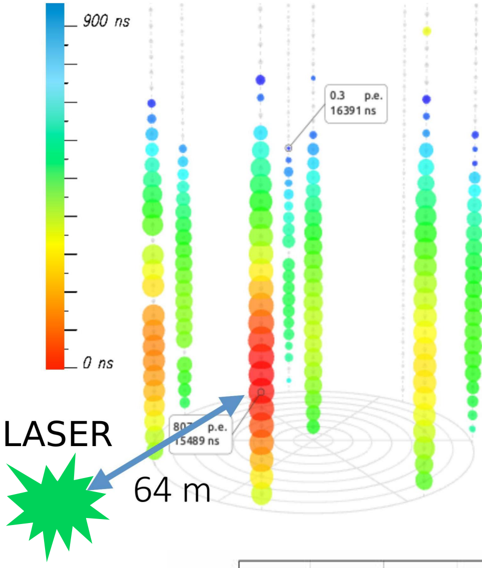
Time scales for each of OMs must be synchronous

Interchannel intrasection calibration:

- OM calibration LEDs

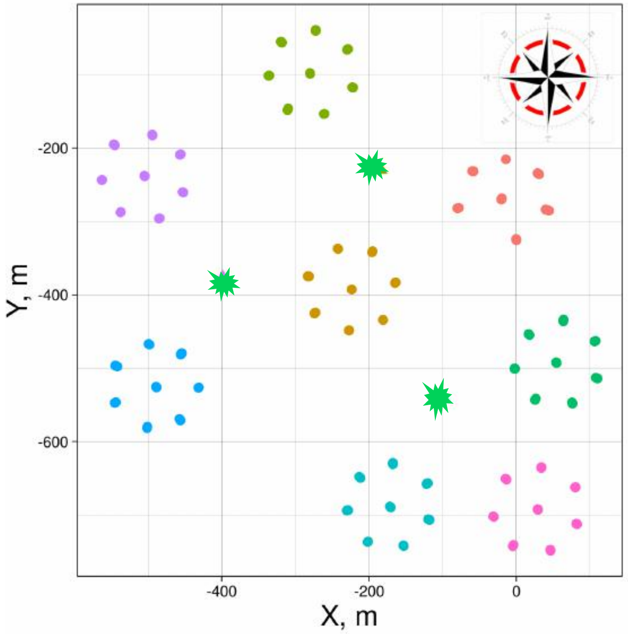
Intersection calibration:

- 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



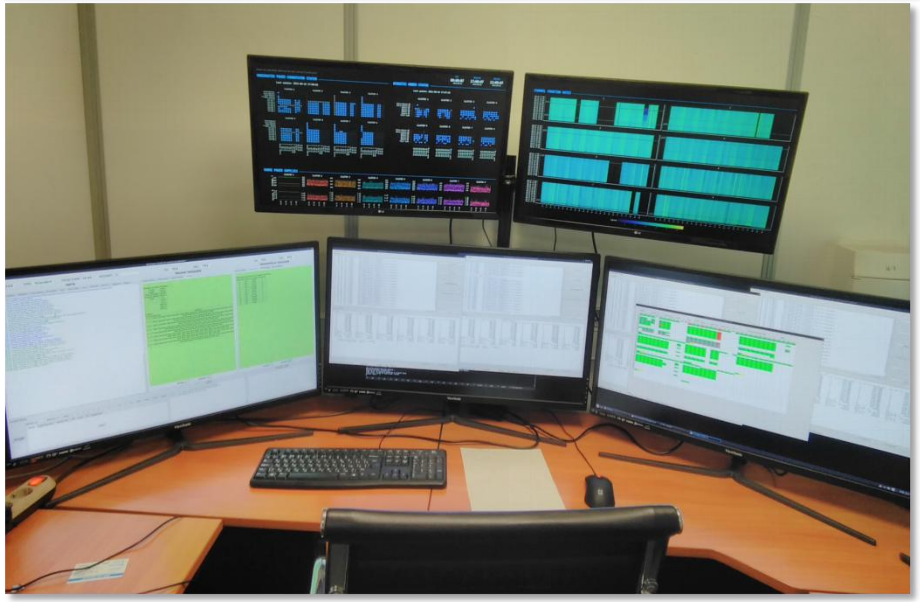
Time calibration precision ~ 2ns

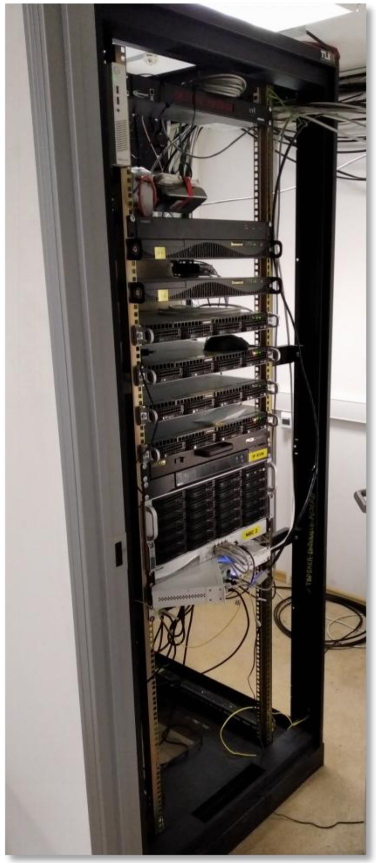
Data stream

Data is transferred from Shore center to JINR

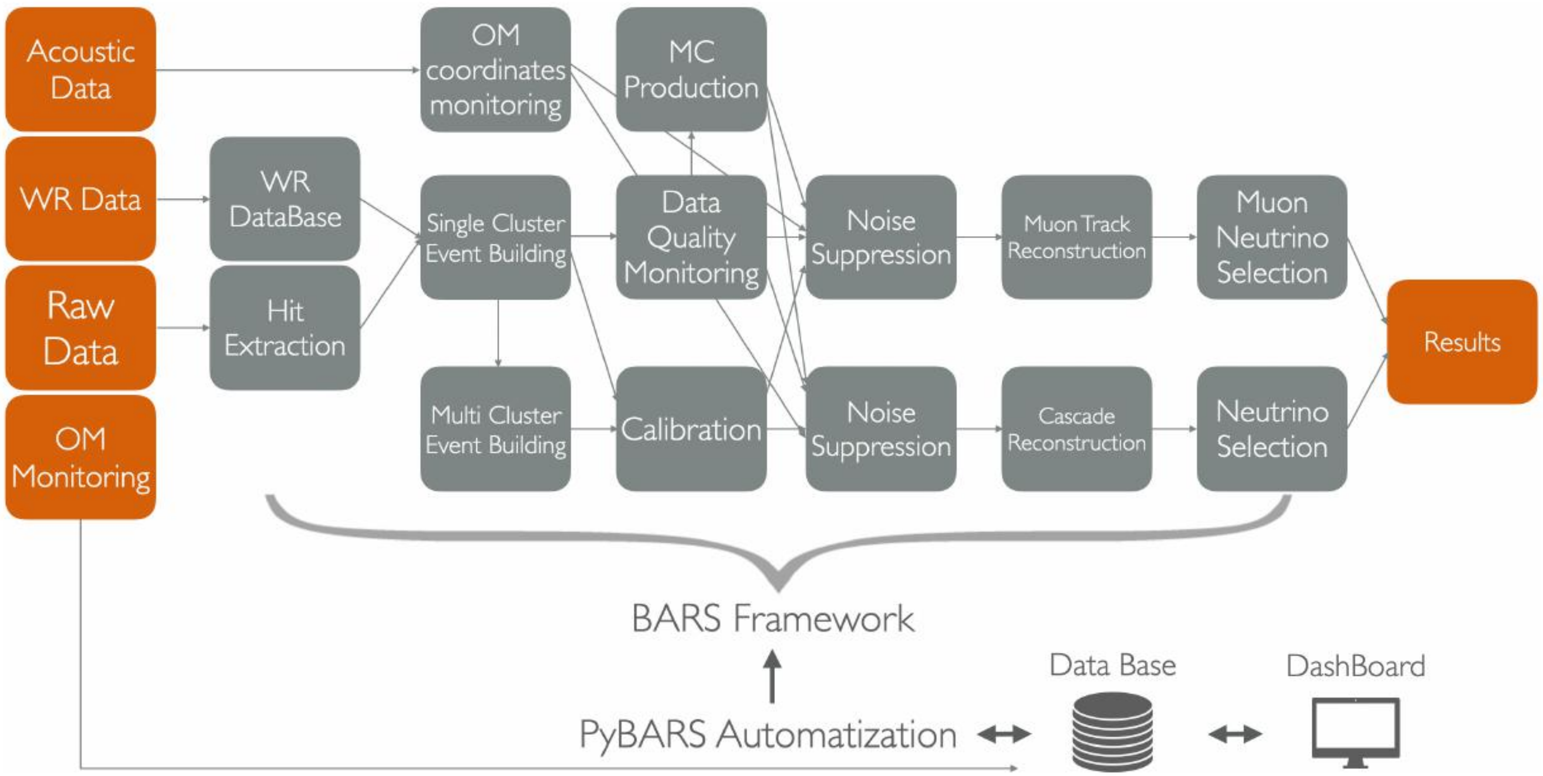
- Shore center → Baikalsk: 300 Mbit/s radiochannel
- Baikalsk → JINR: Ethernet
- Compressed data volume ~40GB per day
- Delay due to shore → JINR data tranfer: < 1 min.
- At JINR data is stored using EOS service

Baikal shore center





Event reconstruction



[Pos(ICRC2021)1040]

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

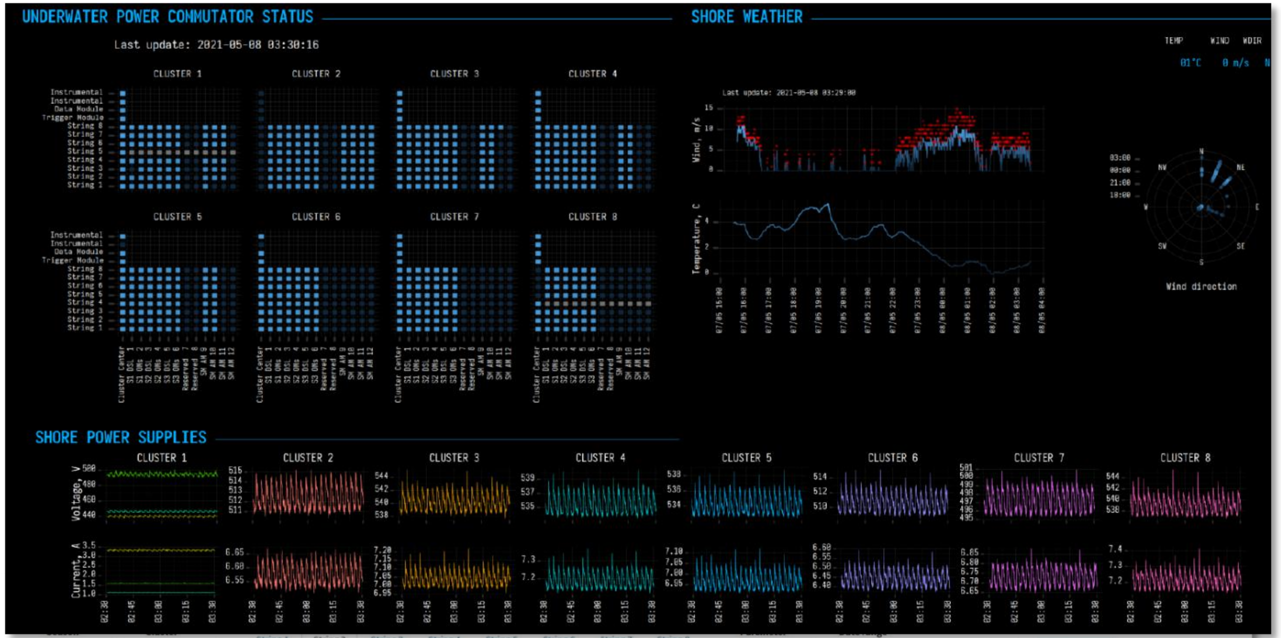
Presently single-cluster dataset is being reconstructed while multi-cluster reconstruction is in development

Detector and data monitoring

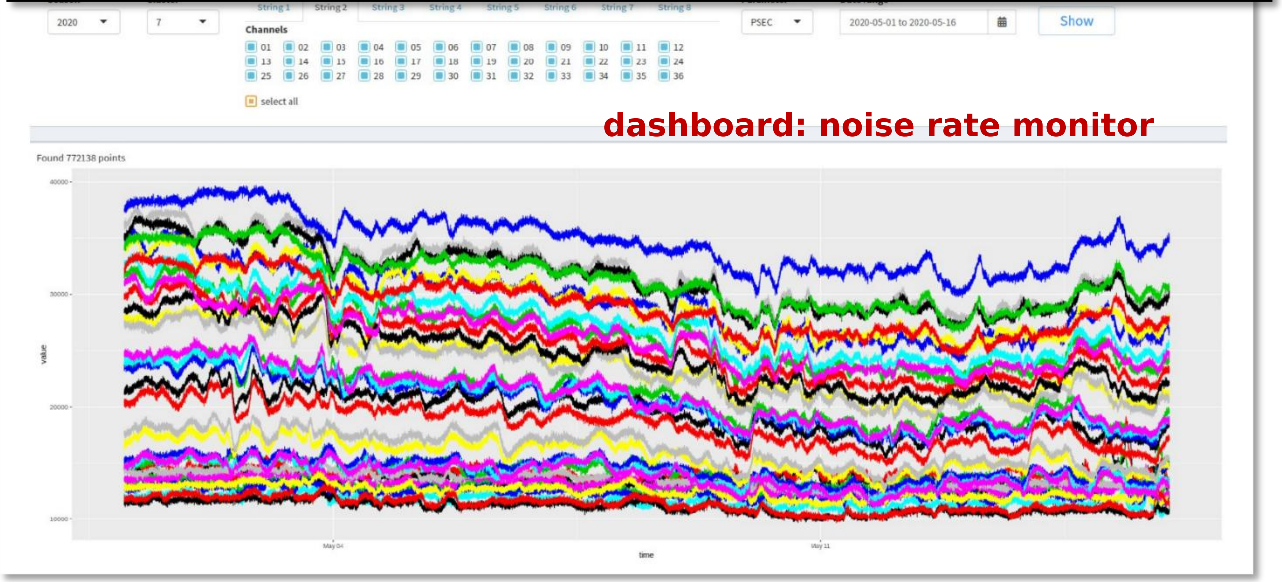
Shore center: High voltage and low voltage monitoring, event rates, detector occupancies, OM sensor data at web-based dashboard, detector geometry monitoring, thunderstorm alarm

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



shifter power monitoring



dashboard: noise rate monitor

Reconstruction and results

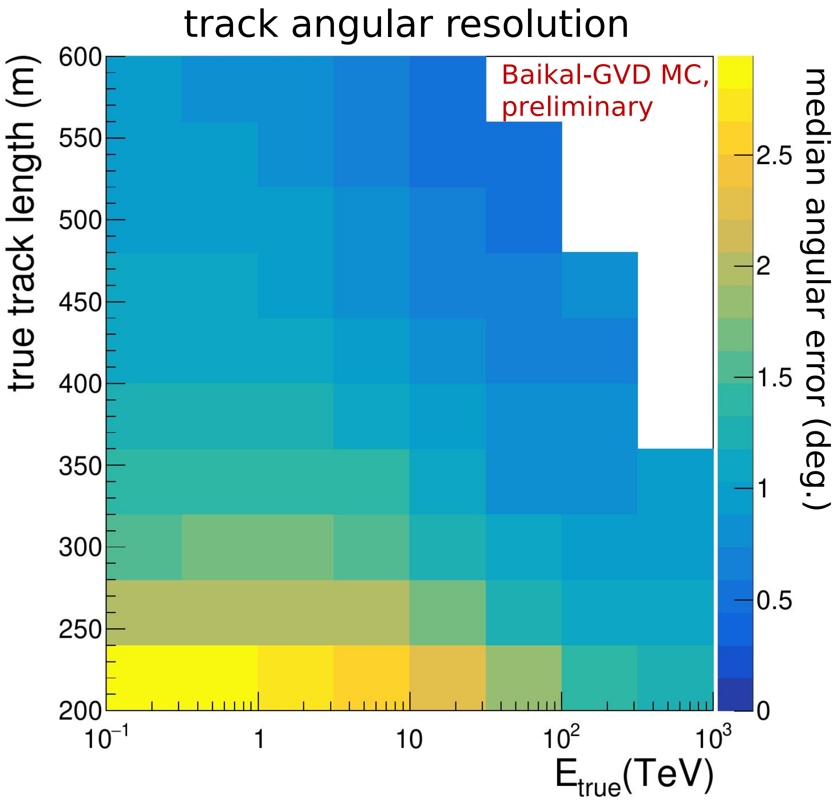
Event reconstruction: muons

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 chemiluminiscense

Track coordinates and direction are estimated using cleaned collection of impulses: fit with $Q = \chi^2(t)$

- Angular resolution ~0.5° at E_μ ~ 100 TeV for sufficient track length



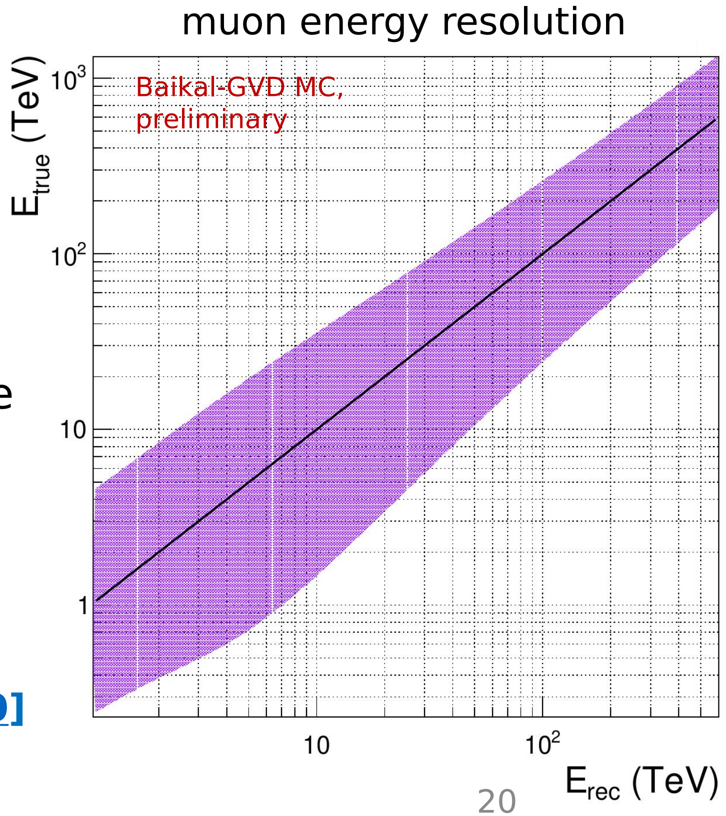
Large variety of track quality variables is estimated e.g. time residuals, fit errors, track likelihood, etc.

These variables are further used in the neutrino selection

Muon energy is estimated using average energy loss dE/dX as a proxy

- ~ Corrected sum charge divided by track length
- Factor 3 resolution at 100 TeV

[PoS(ICRC2021)1063, PoS(ICRC2021)1080]

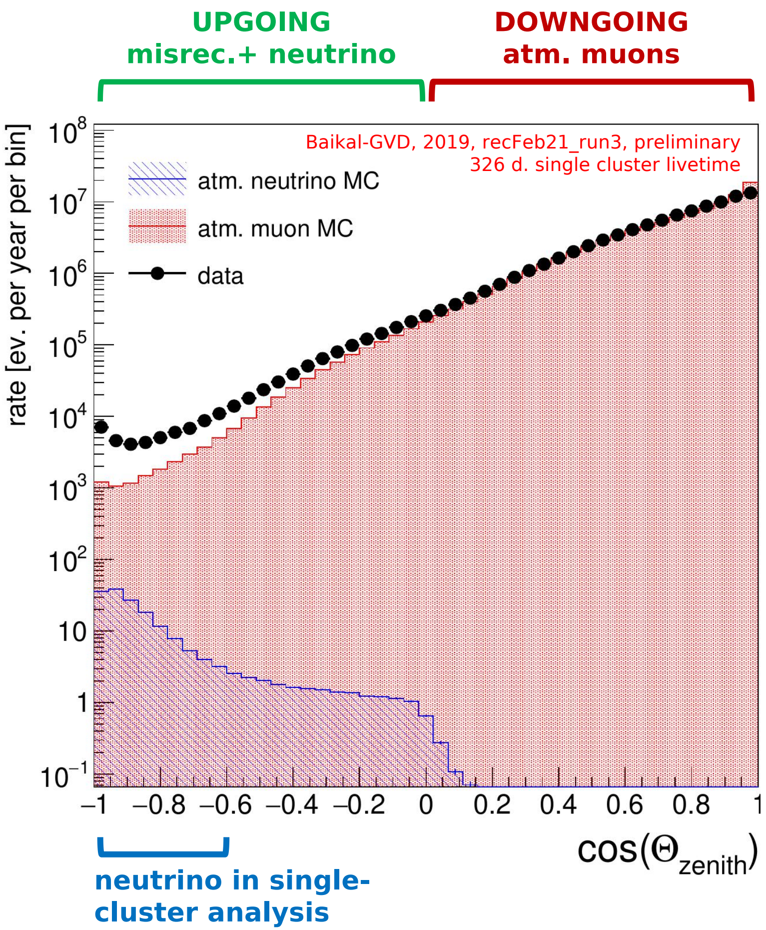


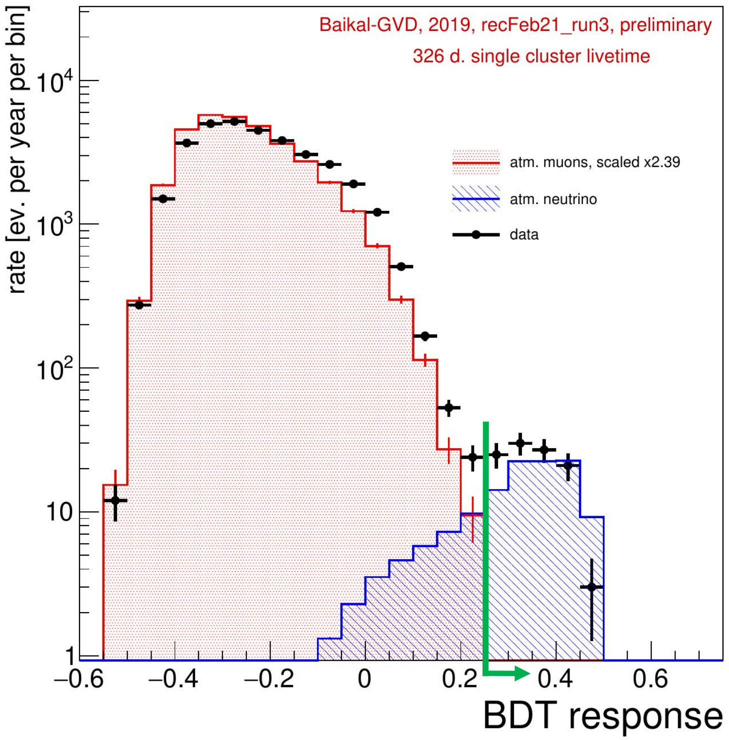
Muon neutrino selection

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

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

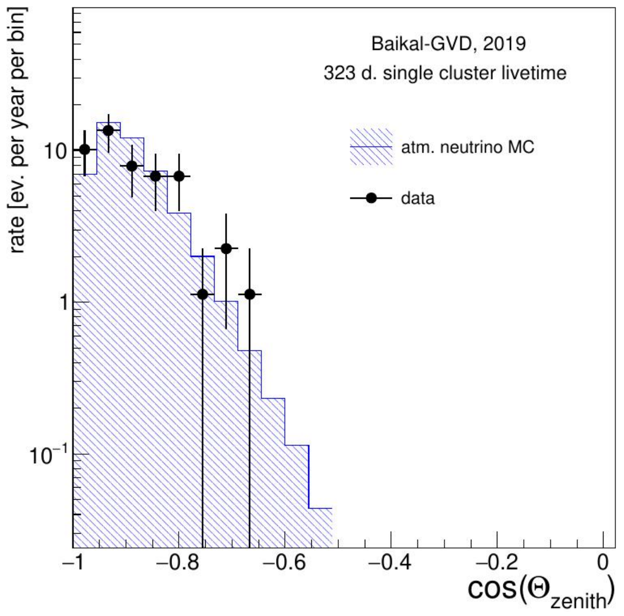
First muon neutrino candidate sample

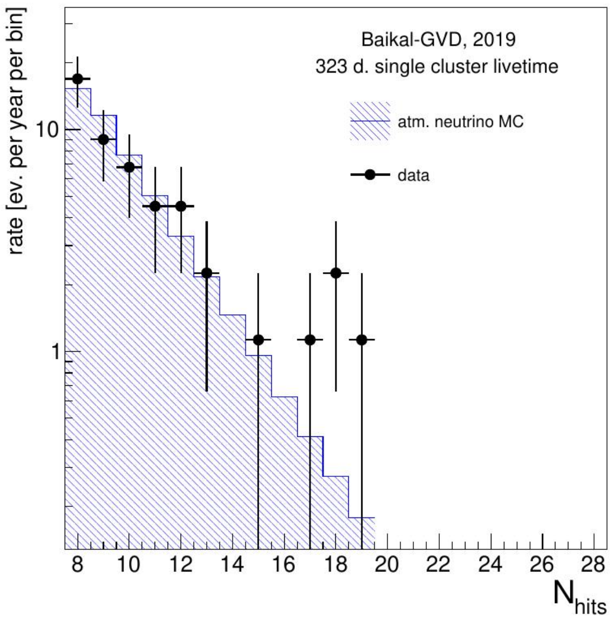
First set of muon neutrino candidates based on data from April-June 2019

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, $\langle E_\nu \rangle \sim 500$ 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





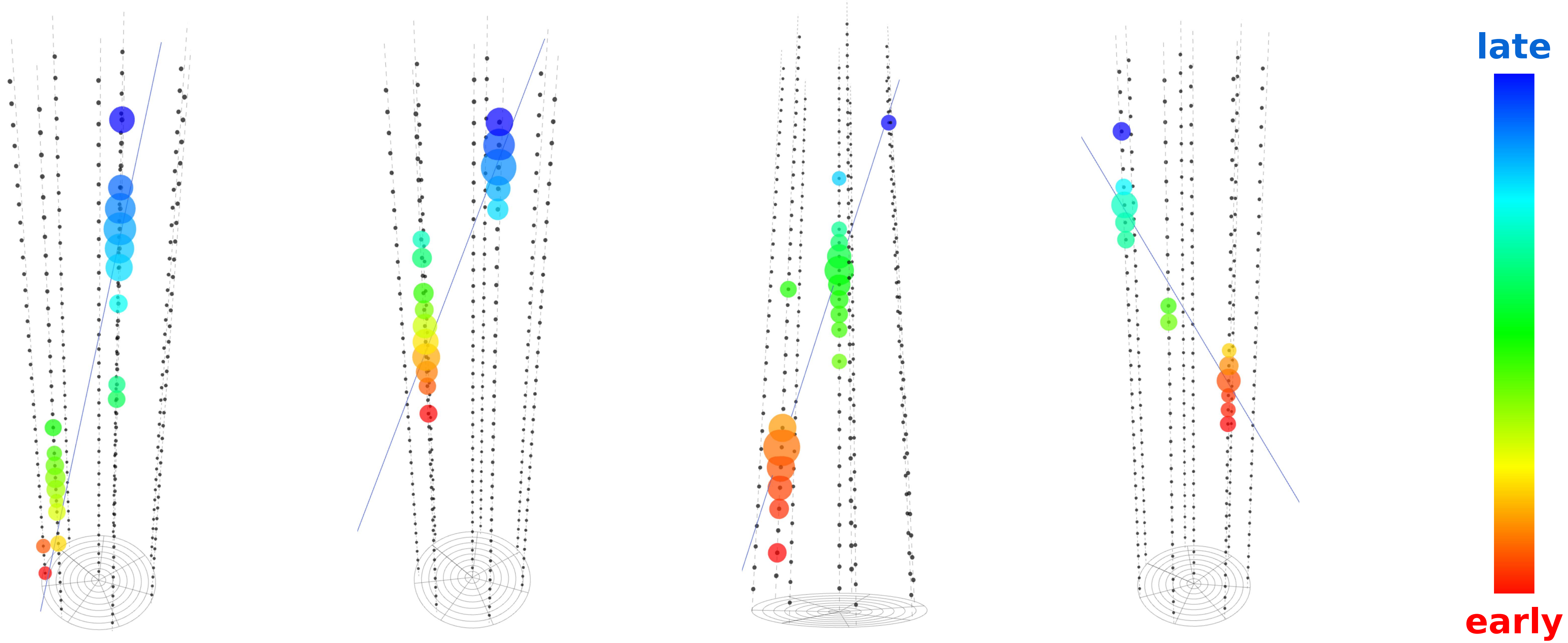
Excellent agreement of MC expectation and data

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

[arXiv:2106.06288, submitted to EPJC]

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

Muon neutrino candidates



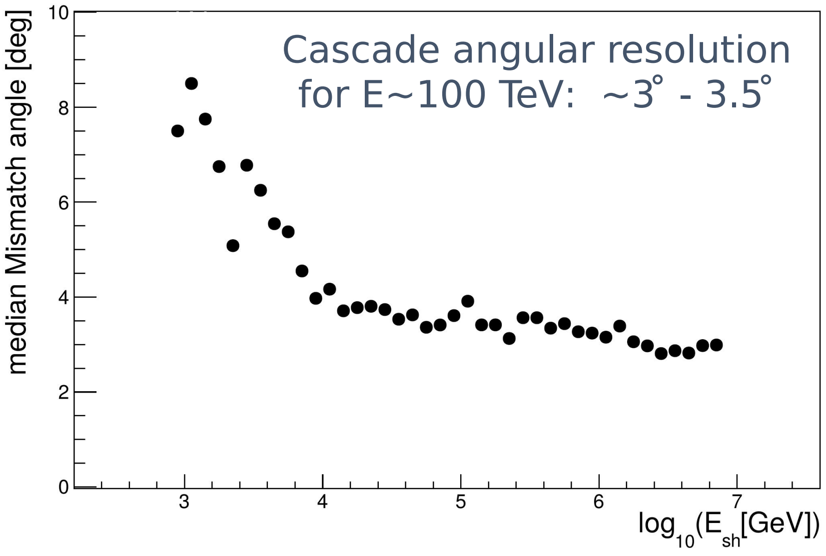
cluster 3, run 122
evt. 1549343
$\theta_{zenith} = 169.78°$
$N_{strings} = 3$
$N_{hits} = 19$

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

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

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

High energy cascade reconstruction

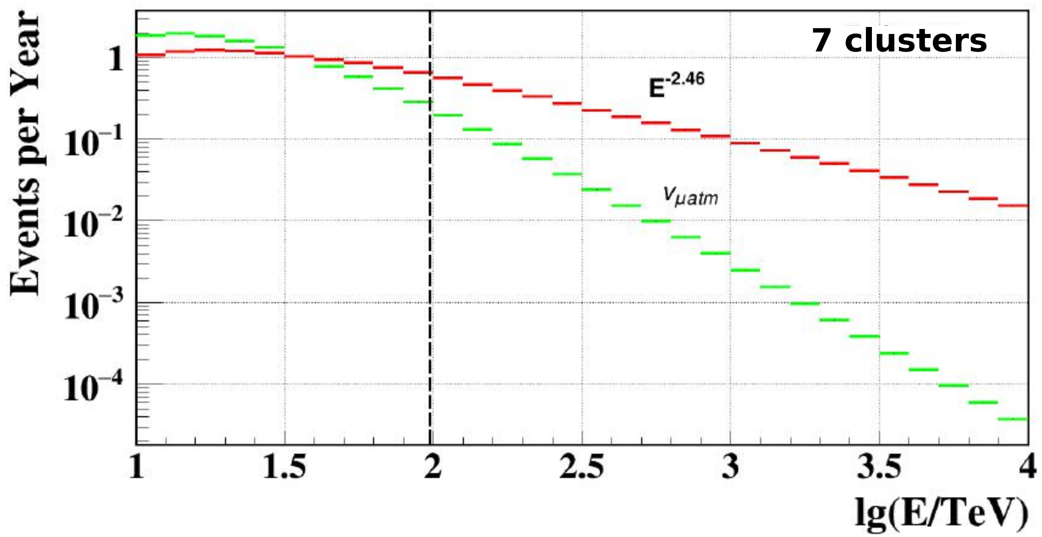


Cascades reconstruction

- Time χ^2 fit for the position reconstruction
- Likelihood minimisation for direction and energy

Angular resolution: 3-3.5° depending on energy

Energy resolution: **δE/E ~ 10%-30%**



~0.4-0.6 astrophysical neutrino per year for one cluster are expected

- In assumption of astrophysical neutrino spectrum ~$E^{-2.46}$ (IceCube fit)

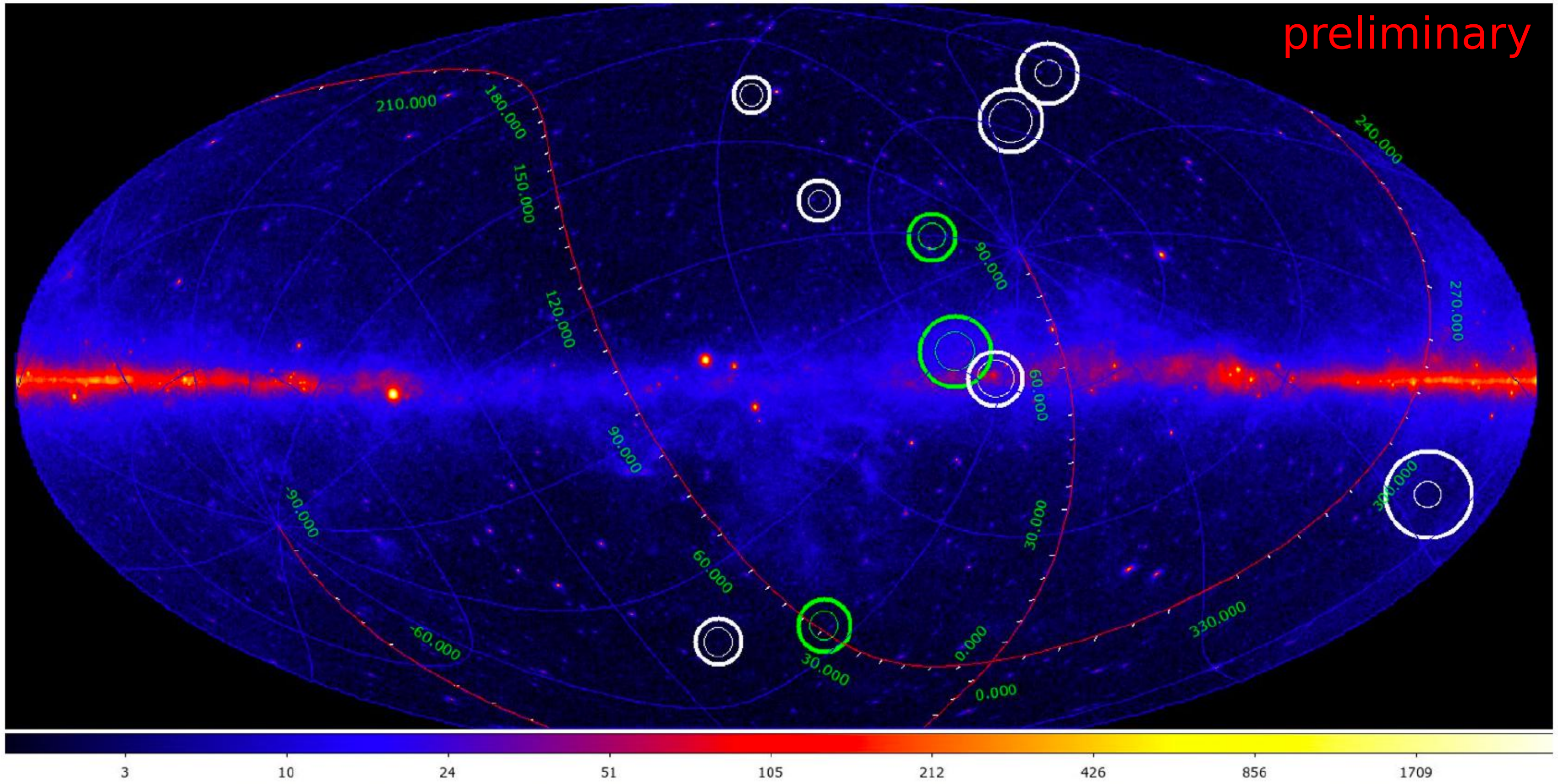
More details on cascade reconstruction and selection: **[Pos(ICRC2021)1144]**

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!

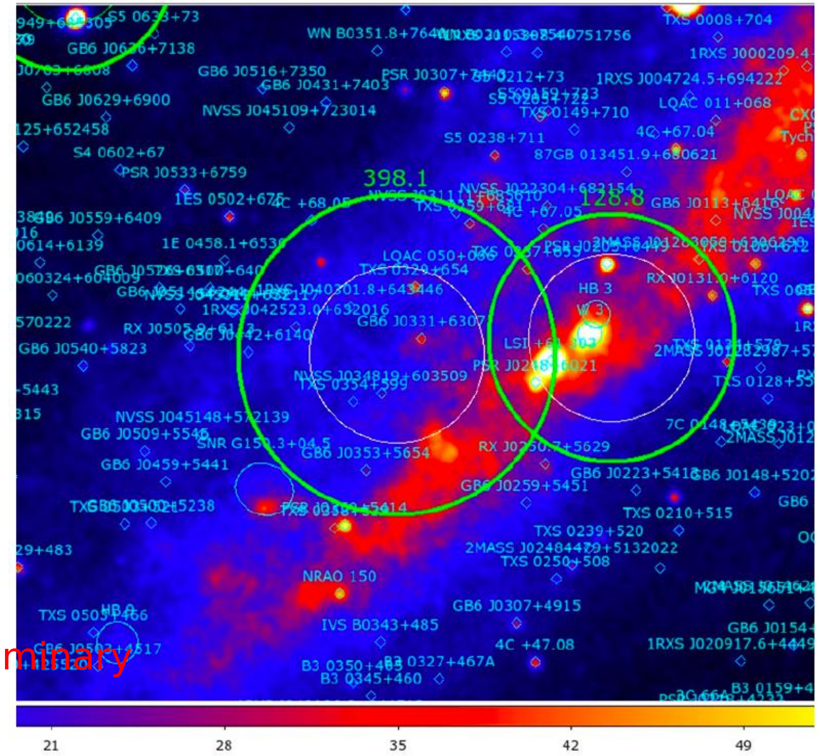
galactic plane

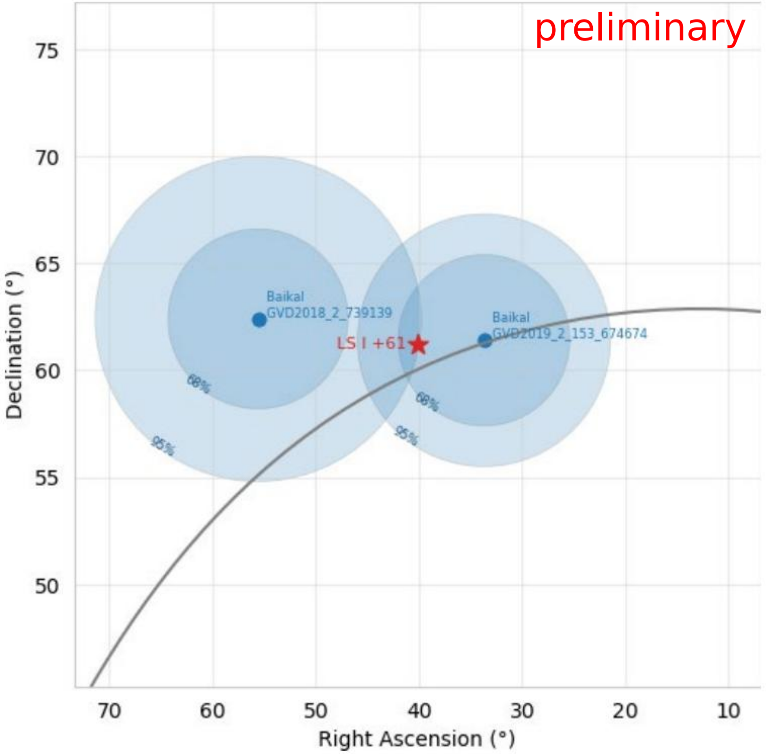


FERMI γ-ray maps are produced by D. Semikoz and A. Neronov

High energy cascade events II

Two close events at distance 10.3°: GVD_2018_656_N and GVD_2019_153_N



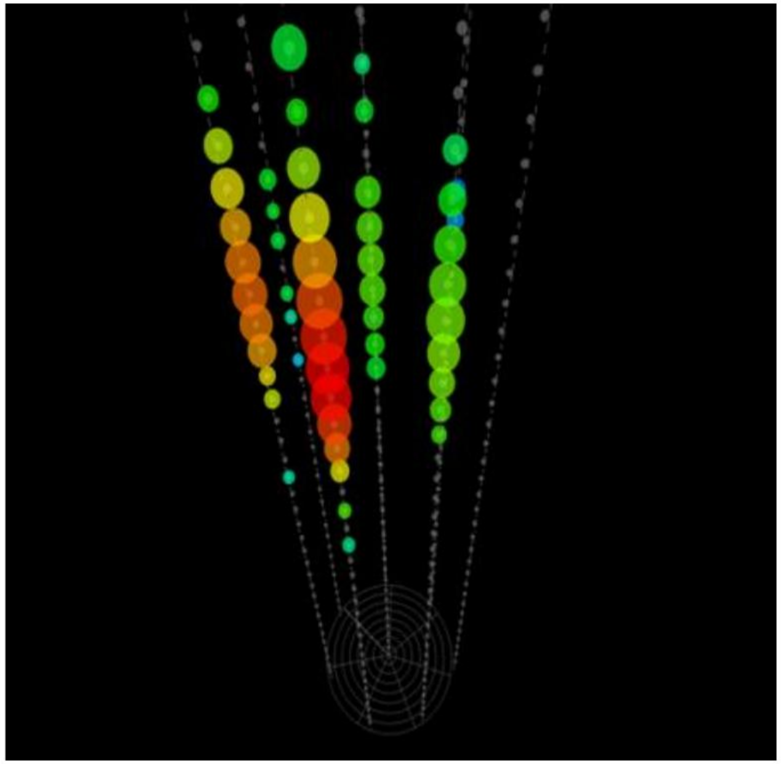


LSI + 61 303 - γ-ray active miscroquasar

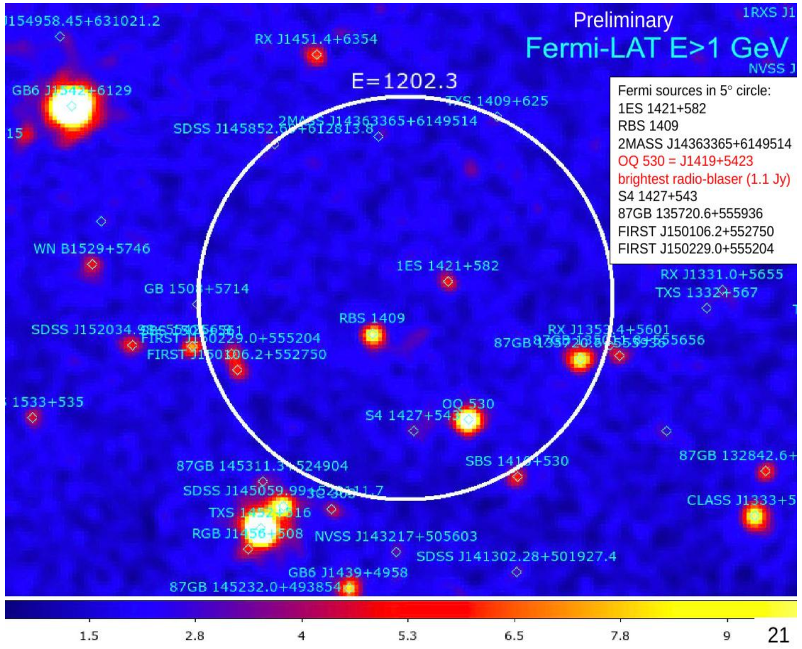
- 3.1° from GVD_2019_153_N
- 7.4° from GVD_2018_656_N

High energy cascade events III

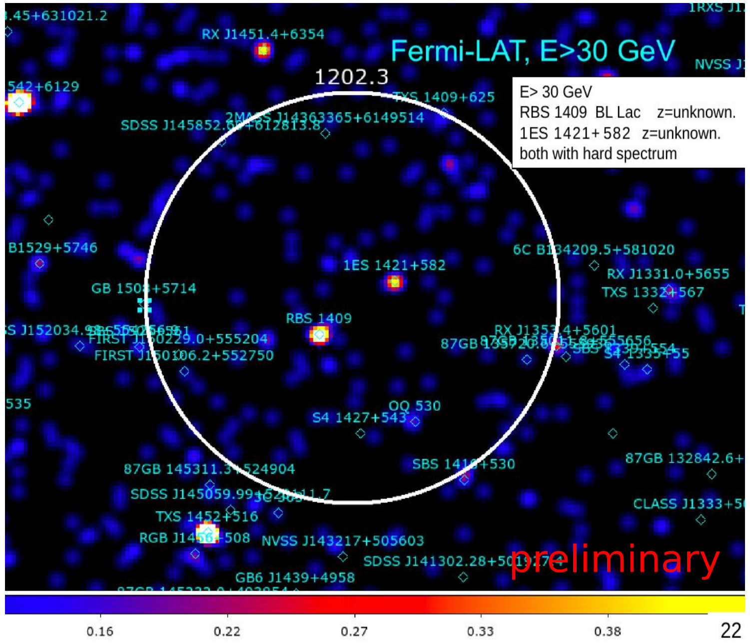
PeV cascade
Reconstructed energy: 1.2 PeV
Zenith angle: 61°



$E_{\gamma} > 1$ GeV



$E_{\gamma} > 30$ GeV

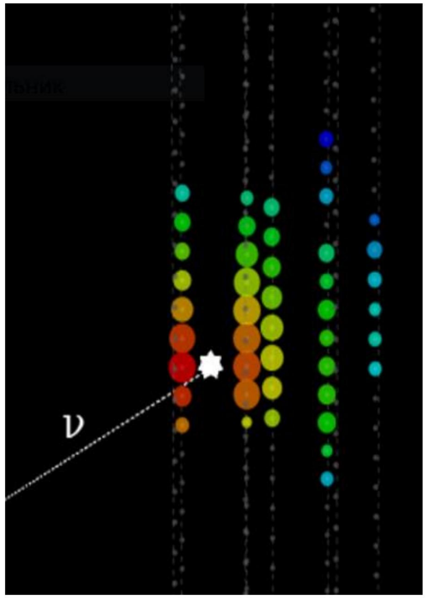


Two sources with hard γ spectrum within 5° circle:

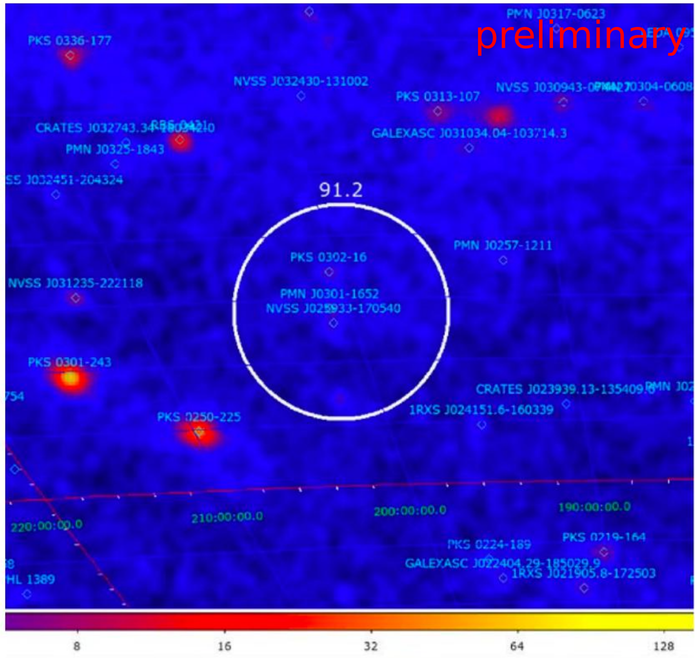
- BL Lac RBS 1409
- 1 ES 1421+582

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°



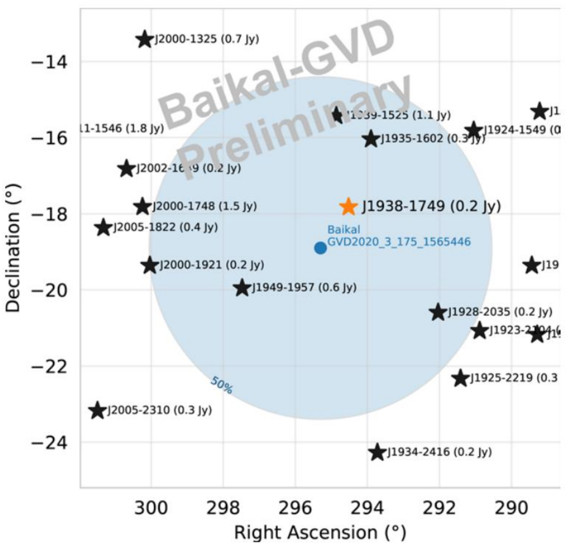
No good known sources in 3° circle

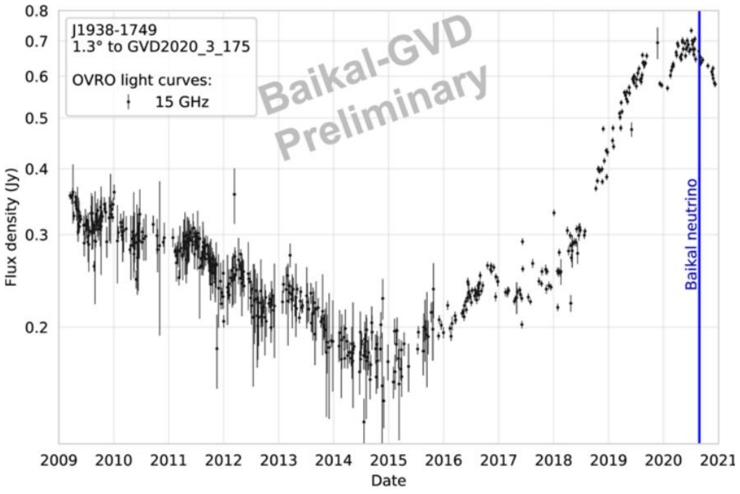
Multi-messenger program in cascade channel

- 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]**

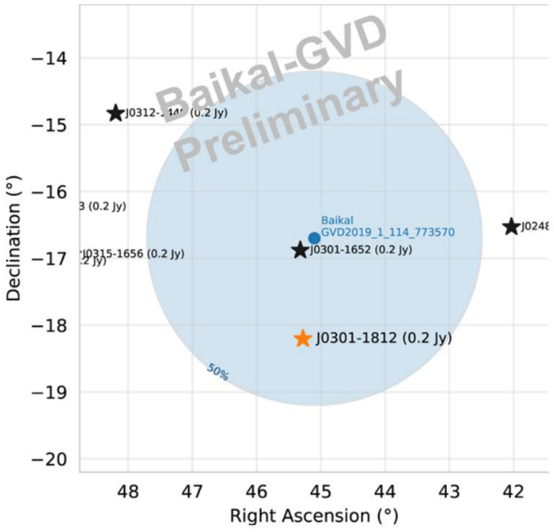
Radio-bright blazars near high-energy cascade events (in collaboration with A. Plavin, Y. Kovalev, S. Troitsky)

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.

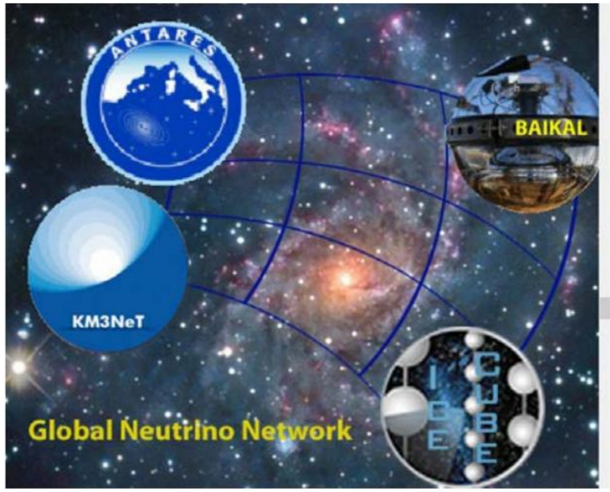
ICECUBE alerts

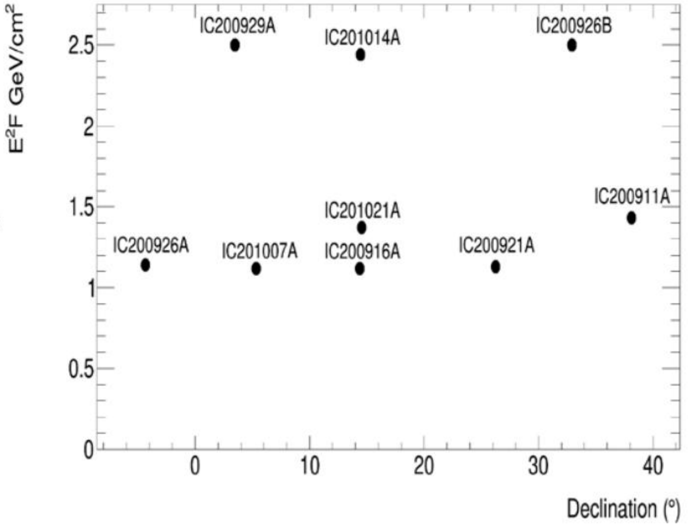
Starting Sept 2020 Baikal-GVD follows **IC alerts (GCN) , 22** alerts.

Upper limits at 90% c.l. on the neutrino fluence:

~1÷2 GeV cm^{-2} for energy range 1TeV– 10PeV.

E^{-2} spectral behavior; equal fluence in all flavors





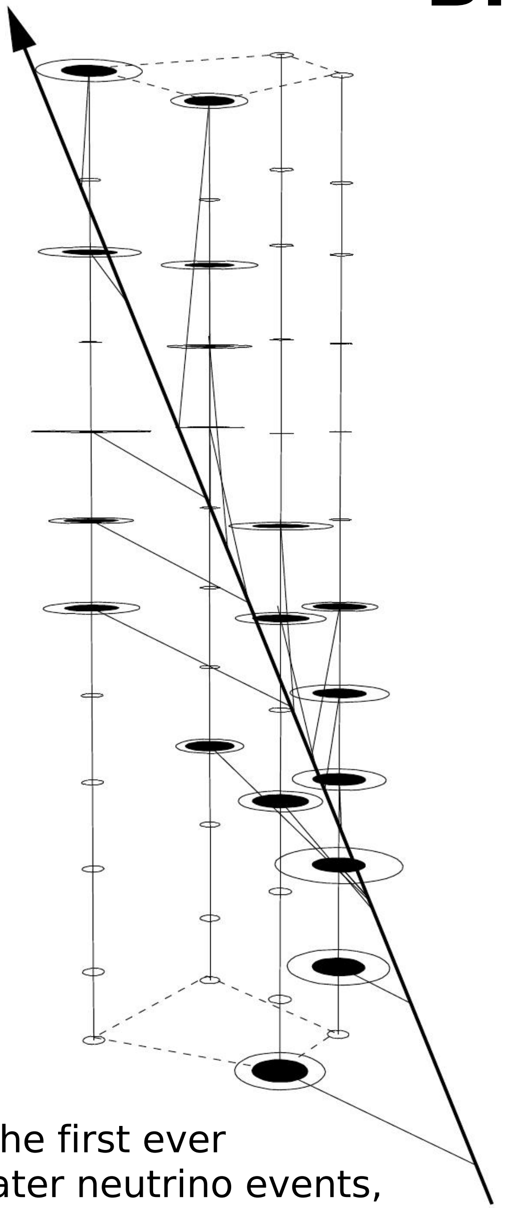
[Astronomy Letters 47(2):94-104 (2021)]

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



One of the first ever underwater neutrino events, **NT96, 1997**
[arXiv:astro-ph/9705244]

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

2015: Start of Baikal-GVD construction. Demonstration cluster “Dubna”, 8 strings, 192 OM

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

2021: Baikal-GVD operates 8 clusters, 2304 OM

Baikal water properties

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

season 2019, cluster 2