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MOSCOW STATE UNIVERSITY

Neutrino Telescope in Lake Baikal: Recent Status and Future Perspectives

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on behalf of the Baikal-GVD collaboration

JINR, Dubna, Russia

Comenius University in Bratislava, Slovakia

Baikal-GVD Collaboration

Collaboration: 10 institutions, ~70 members

1. Institute for Nuclear Research, Moscow, Russia.
2. Joint Institute for Nuclear Research, Dubna, Russia.
3. Irkutsk State University, Irkutsk, Russia.
4. Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia.
5. Nizhny Novgorod State Technical University, Russia.
6. St. Petersburg State Marine University, Russia.
7. EvoLogics Gmbh., Berlin, Germany.
8. Institute of Experimental and Applied Physics, CTU in Prague, Czech Rep.
9. Comenius University, Bratislava, Slovakia.
10. Krakow Institute for Nuclear Research, Krakow, Poland

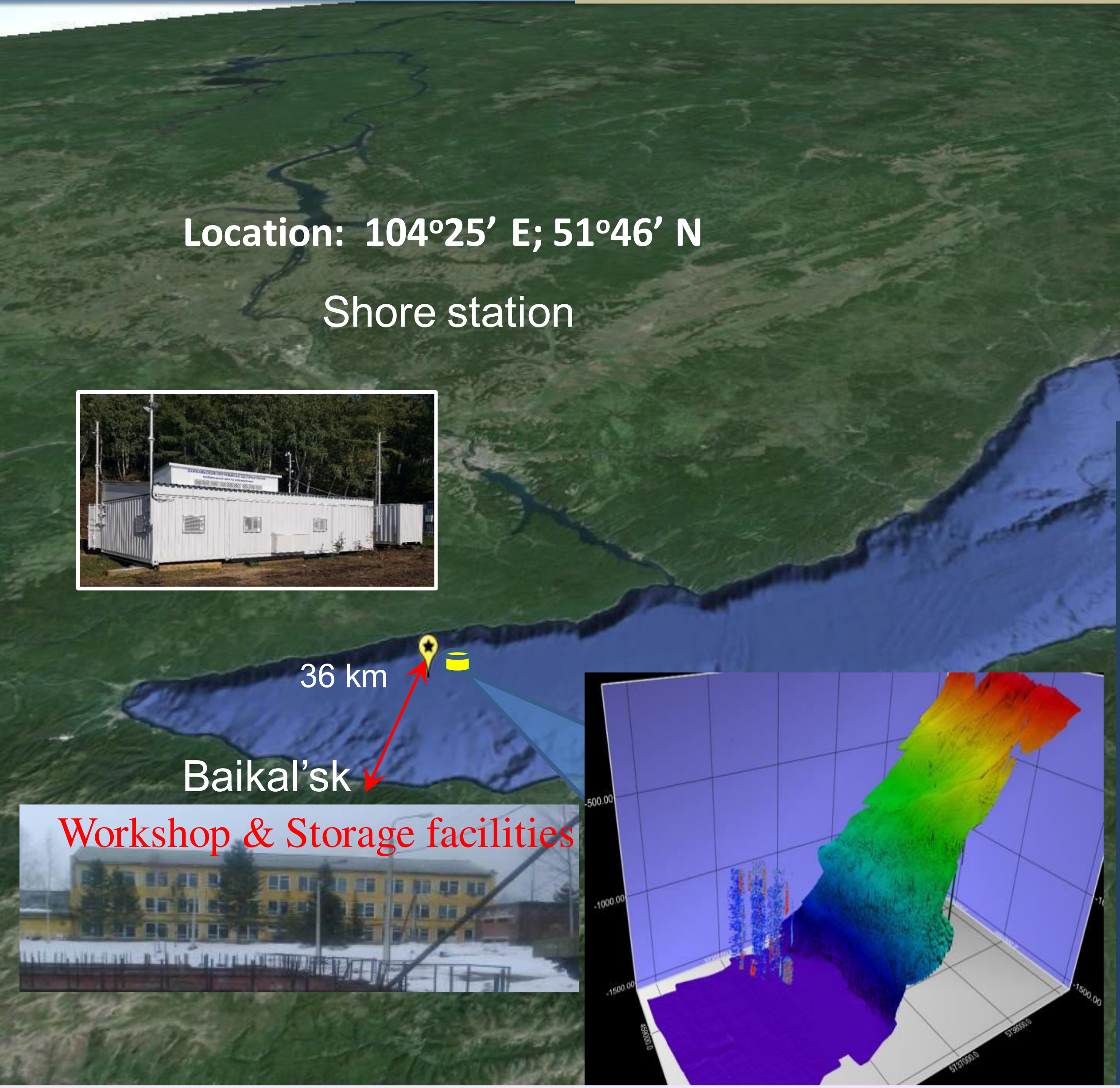
Baikal-GVD telescope
(under construction)

Objectives:
- 1 km^3-scale 3D-array of photo sensors
- flexible structure allowing an upgrade and/or a rearrangement of the main building blocks (clusters)
- high sensitivity and resolution of neutrino energy, direction, and flavour content

Physics Goals:
- Investigate Galactic and extragalactic neutrino "point sources" in energy range > 100 TeV
- Diffuse neutrino flux – energy spectrum, local, and global anisotropy, flavour content
- Sporadic cosmic sources (GRB, …)
- Dark matter and exotic particles search

a tool for multi-messenger astronomy

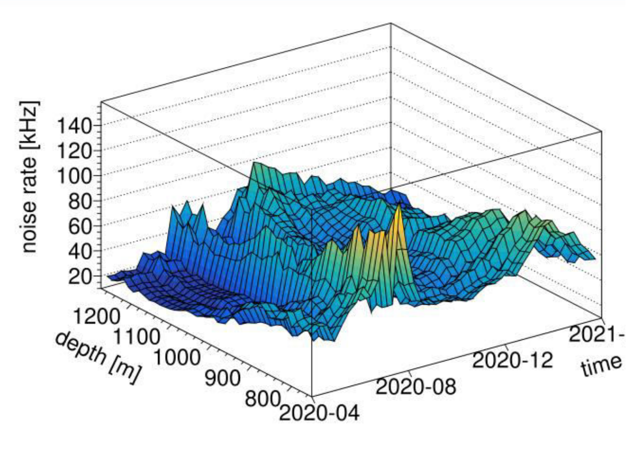
Baikal-GVD site

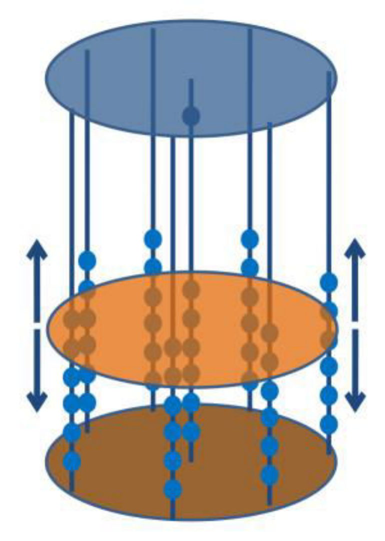


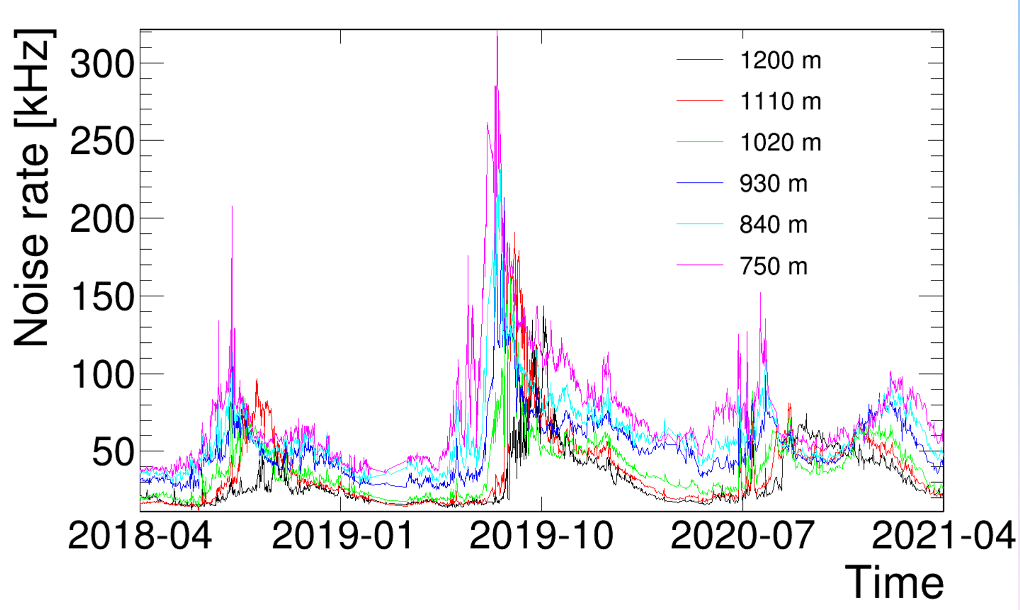
- Location ~ 3.6 km from shore
- Stable ice cover during Feb.-April: detector deployment and maintenance
- Baikal water properties:
  absorption length ~ 22-24 m
  scattering length ~ 30-50 m
  low background 15-60 kHz
  PMT R7081R7081-100 ∅10”
- Absence of high luminosity bursts from biology and K^{40} background
- The constant depth of the lake 1366-1367 m

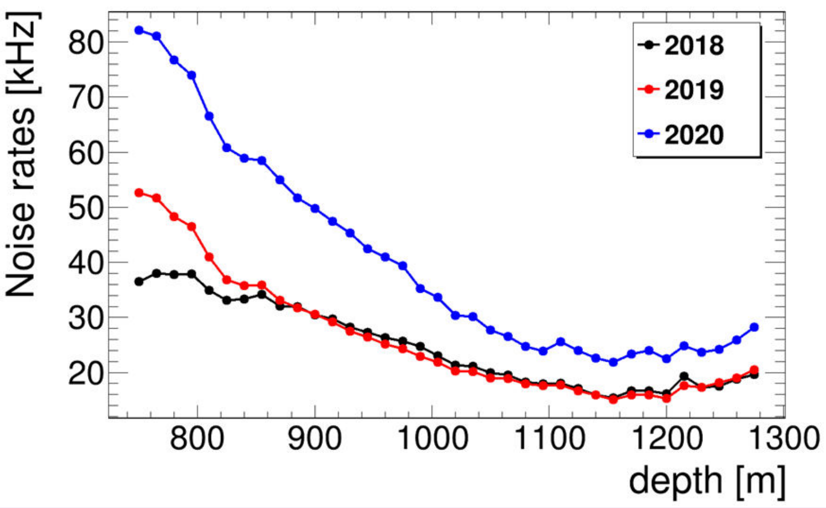
Baikal ambient light field

- The *increases* of the luminescence activity intermitting periods of relatively *stable* optical *background* in 2018-2021.
- The luminescent layer propagated upwards with the maximal speed of 28 m/day in Jan. 2021.



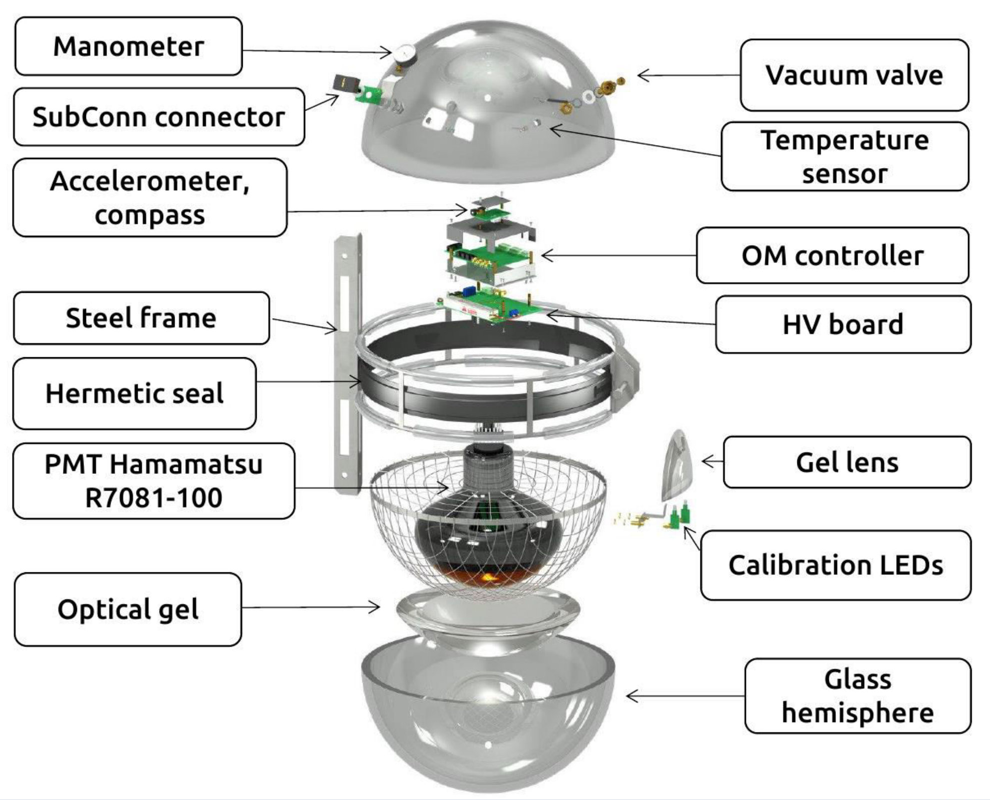




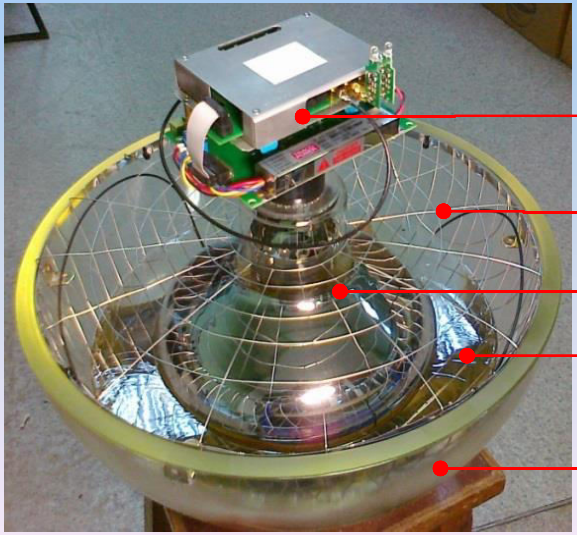


Baikal-GVD optical module

PMT Hamamatsu R7081-100
∅=10 inch
QE ≈ 35% @ 400nm
TTS ~ 3.5 ns
Gain ~10^7
Dark current ~8-12 kHz



Optical modules assemble
(JINR Dubna)



OM

Mu-metal cage

PMT

Optical gel

Pressure-resistant glass sphere VITROVEX (17”)

The new facility allows to produce and test up to 12 OM per day.

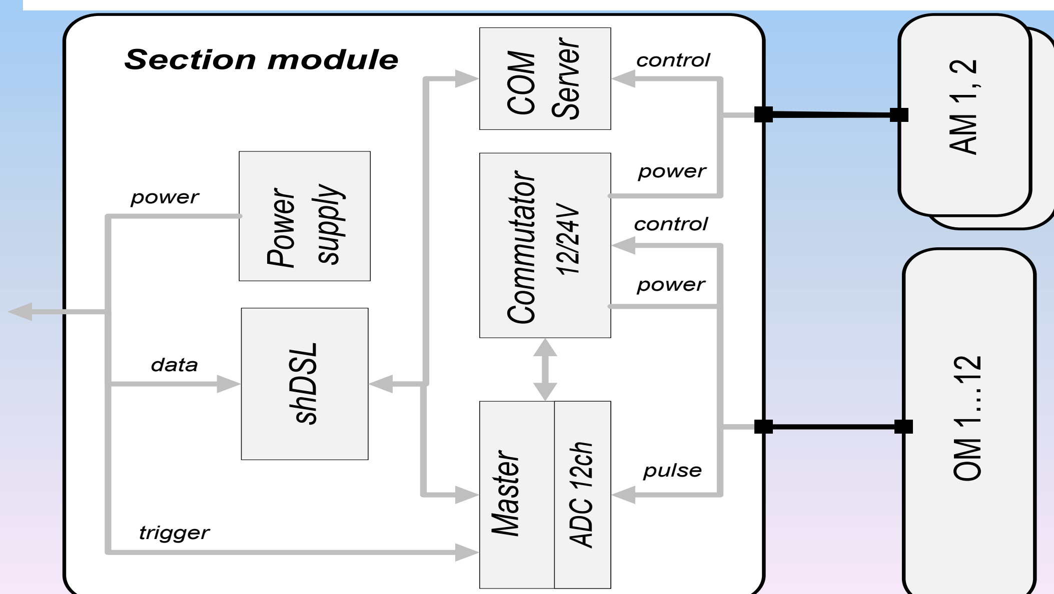
Baikal-GVD section of OMs

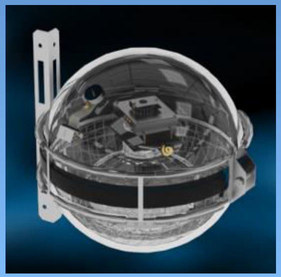
Section

- 12 OMs, 15 m spacing, all PMTs look downward.
- 2 acoustic modules (AM) of the positioning system.

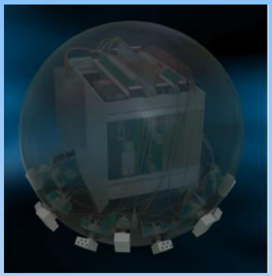
Section control module

- ADC12 ch, 200 MHz sampling;
- pulse form measuring.
- Trigger logic, events forming, data filtration.
- Data transmission: shDSL ethernet extender: 5.7 Mbit/s





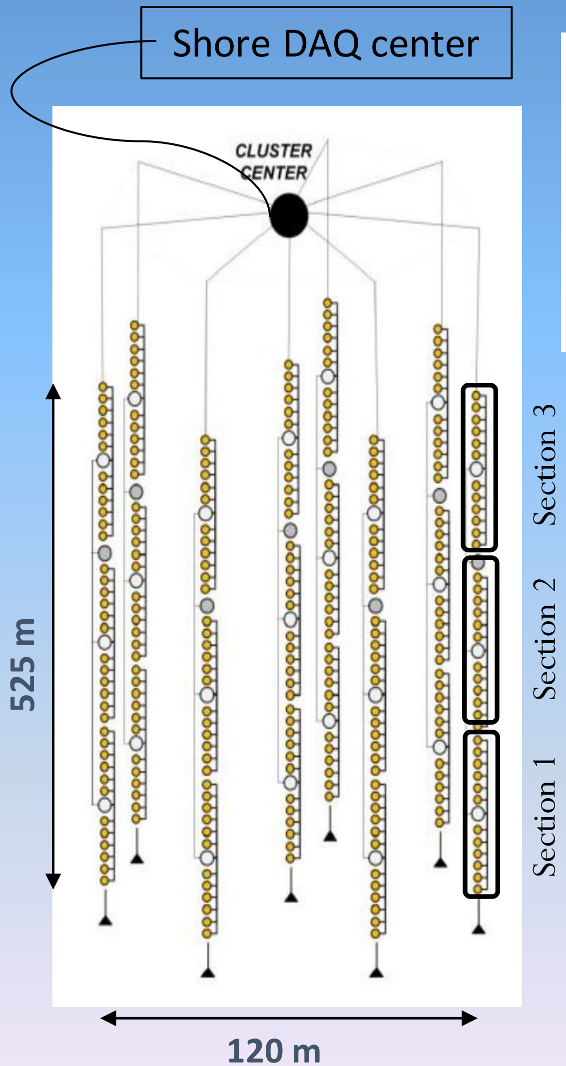
Optical module



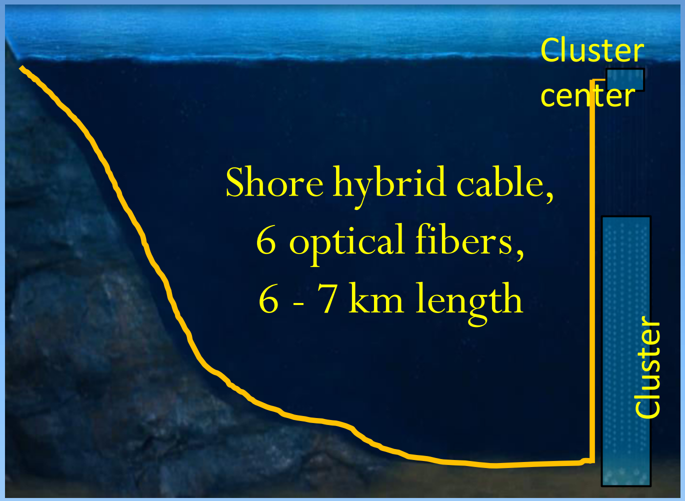
Section control module

Acoustic module

Baikal-GVD cluster



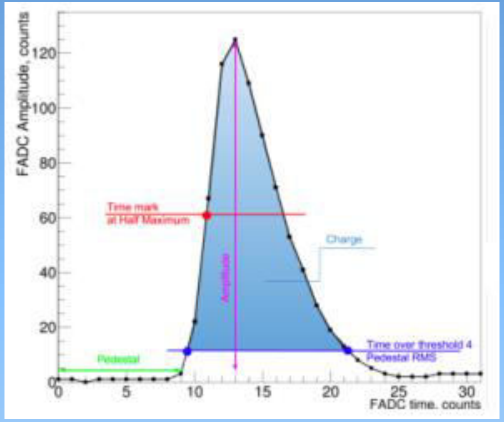
Cluster: 288 OMs
- 24 Sections on 8 strings,
- Cluster DAQ center
- Shore cable: 6 - 7 km
- Depths from 750 to 1275 m

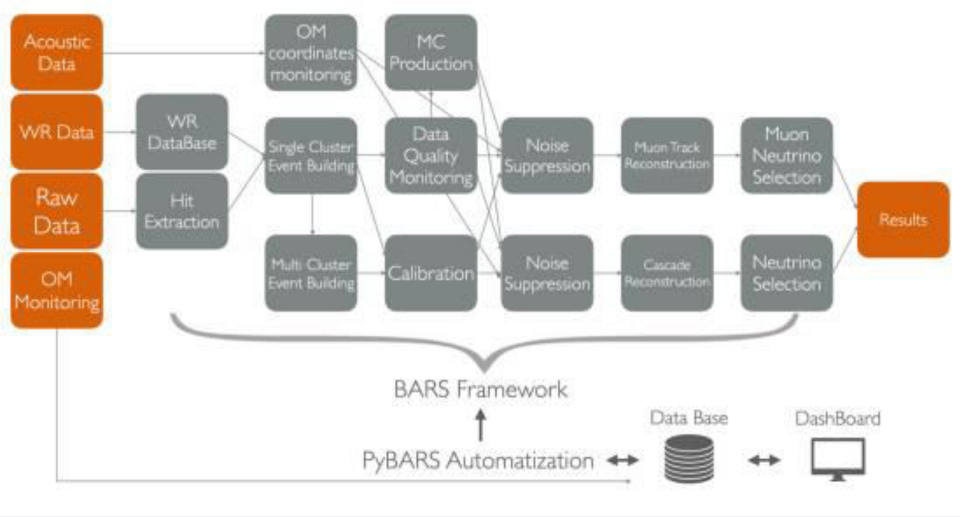


Cluster DAQ
- Trigger: 1.5 & 4 p.e. of adjacent optical modules.
- Maximum trigger rate: ~200 Hz.
- Data transferring: shDSL Ethernet extenders: 5.7 Mbit/s
- Inter-section synchronization by trigger: ~2 ns accuracy.

Automatic data processing

- 40 Gb/cluster/day send and stored at the shore centre
- 300 Mbit/s radio link over the lake to Baikal’sk
- Data send to JINR servers over the internet
- Data stored on EOS
- Recently (2021), completely automatic data processing (100s of cores) + alert production system

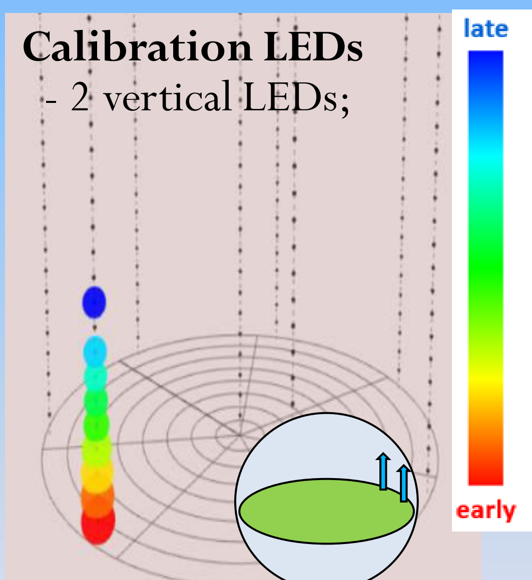


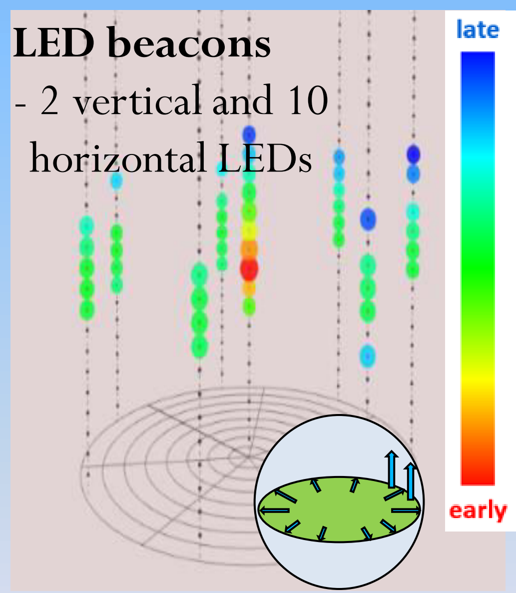


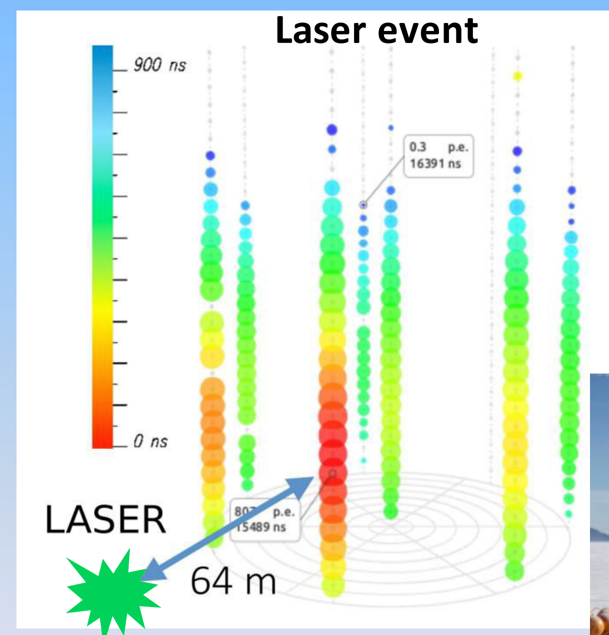
- Raw waveforms stored → possible reprocessing
- Pulse extractions
- White Rabbit synchronization of independent cluster data transfers
- Data Quality Monitoring

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 a cluster.
Cluster calibration: 2 Lasers per station, 532 nm, 10^{12} - 10^{15} ph., 1 ns.

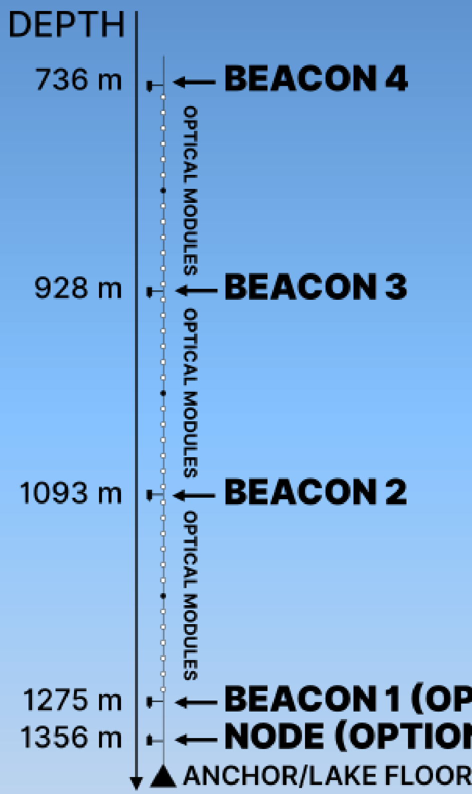


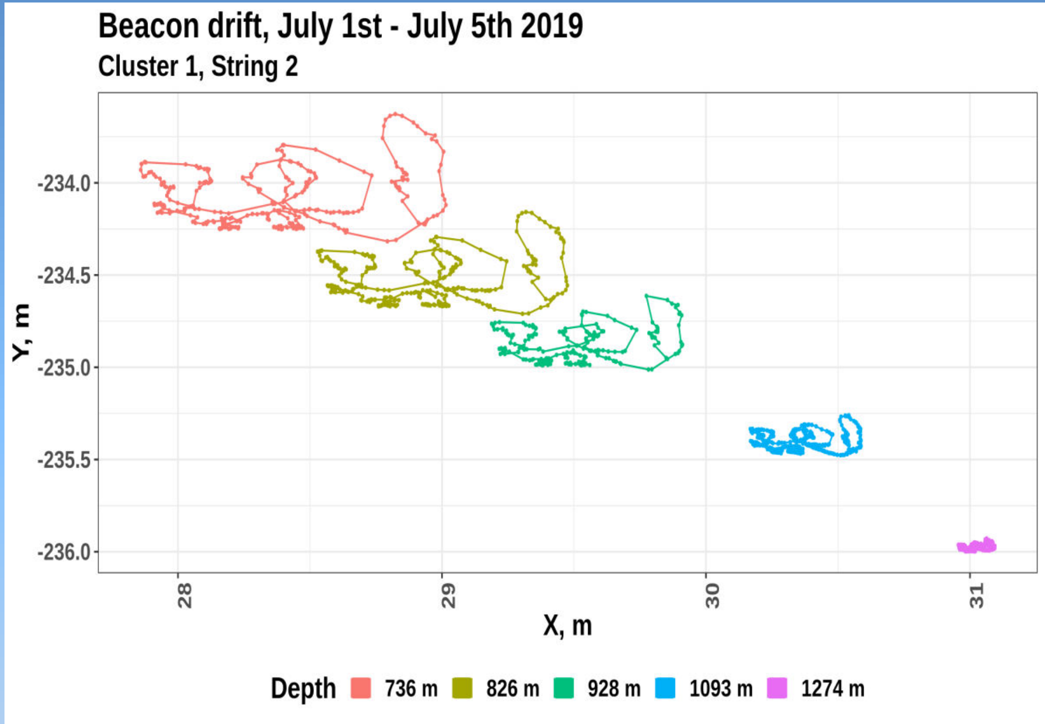




Calibration accuracy ~2 ns

Acoustic positioning system

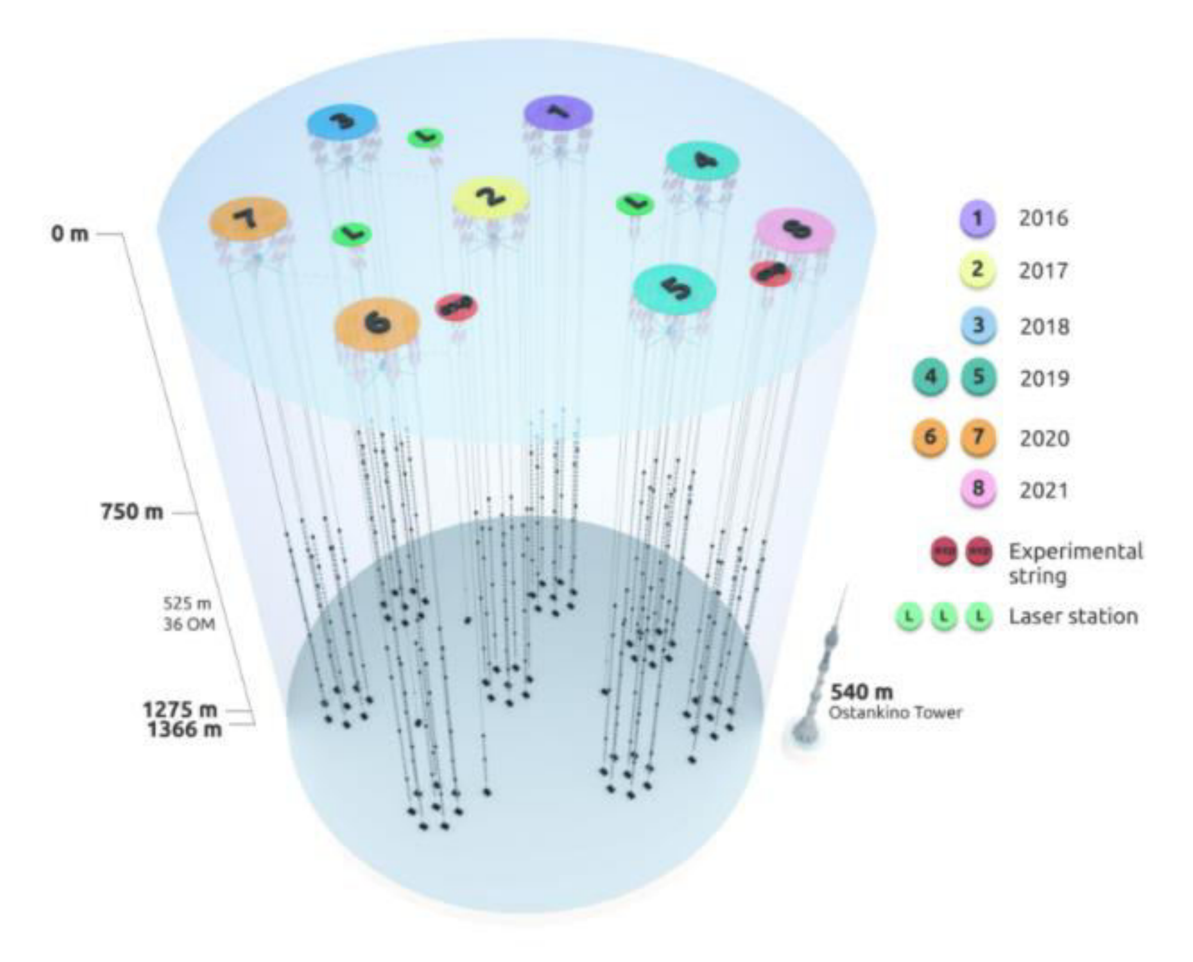




- OM drift can reach tens of meters, depending on season and elevation.
- OM coordinates are acquired via an acoustic positioning system.
- It consists of a network of acoustic modems (AMs) installed along strings
- 4 AMs per string in a standard configuration.
- OM coordinates are obtained by interpolating AM coordinates, error < 0.2 m

Baikal-GVD construction status and schedule

Status 2021: 8 clusters, 3 laser stations, 2 experimental strings



Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

Effective volume 2021: 0.40 km^3 (cascade mode)

Selected results

- Muons detection mode: atmospheric neutrinos
- Multi-messenger studies
- Cascades detection mode: HE cascades

Muons – track analysis

Present status: technique for neutrino events selecting and reconstructing is currently being developed.

Reconstruction: noise hit suppression and fit track with quality function:

$$Q(x, y, z, \theta, \phi) = \chi_t^2 + Q_r$$

Data sample: data taken between Apr 1 and Jun 30, 2019; 5 clusters.

Event selection: 8 hit OMs on at least two detector strings.

Neutrino selection cuts:

- Zenith angle >120°

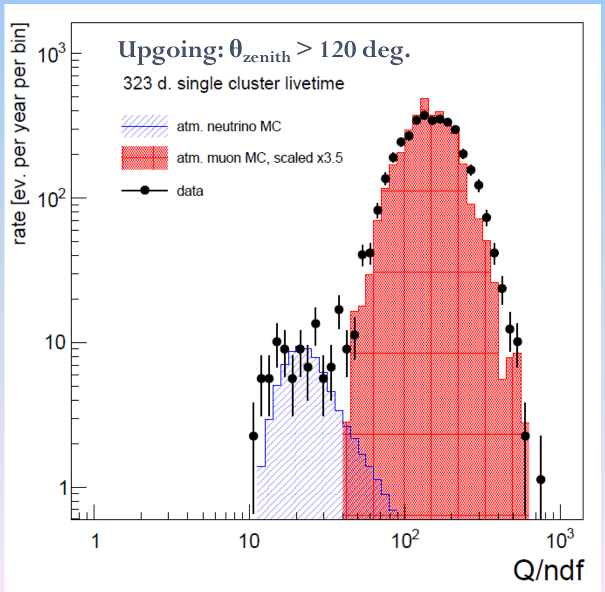
- Fit quality Q/ndf < 32

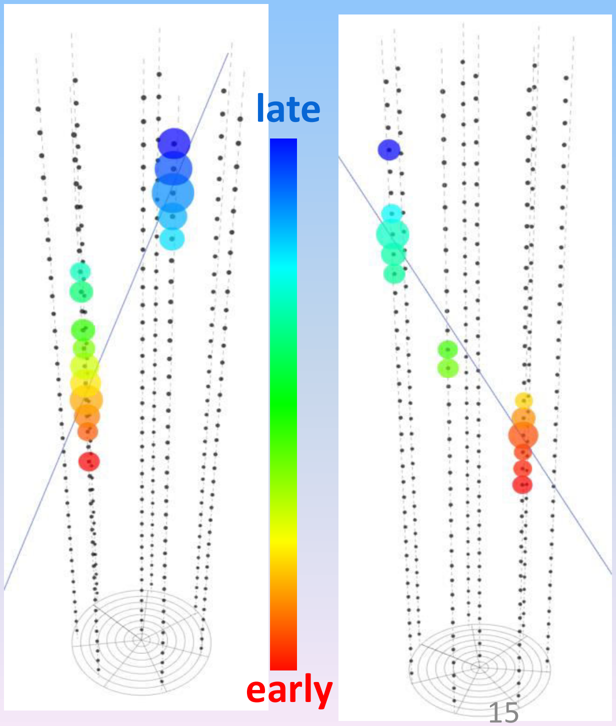
- Visible track length L >75 m

- Average distance to OMs < 18 m

- Charge of all hits > 18 p.e.

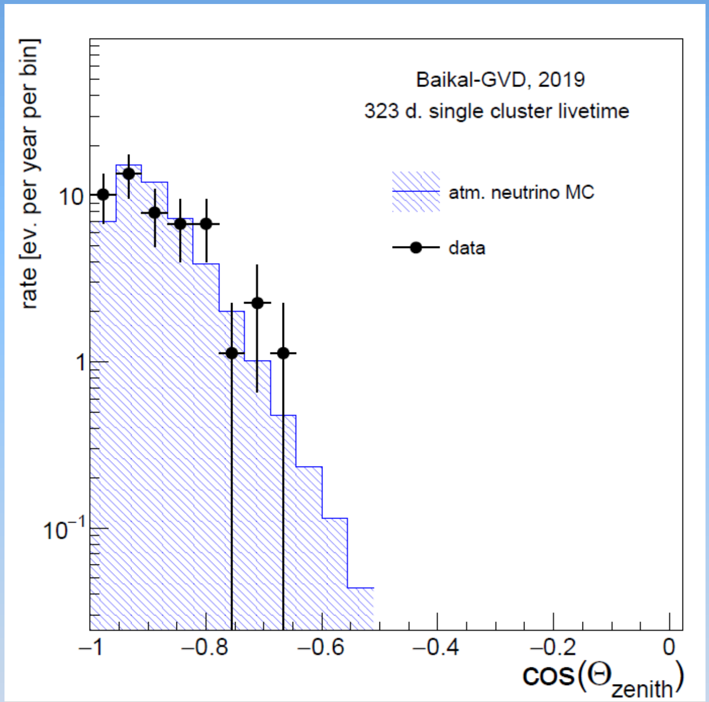
- Estimated zenith angle error < 2°

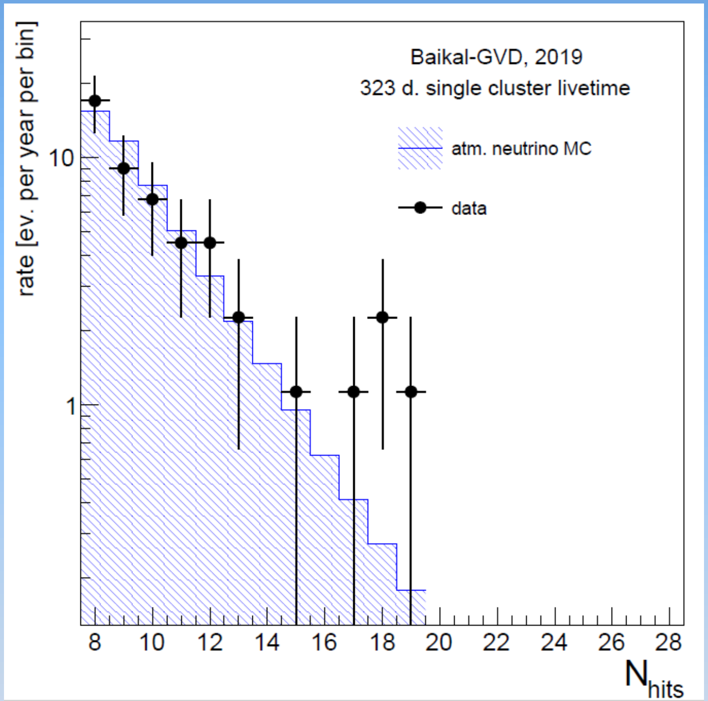




Muon neutrino: single-cluster analysis

- 9.8 million reconstructed events for the combined dataset from the 5 clusters.
- Single-cluster equivalent live time 323 days.





MC expected: 43.6 ±6.6 (stat.)
Observed: 44

Fair agreement with MC prediction for atmospheric neutrino

The median energy of the neutrino events 500 GeV.

Angular resolution: (single cluster) ~ 1° or better

Multi-messenger studies

BAIKAL-GVD 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 $\Delta T = \pm 1$ day and are under investigation with ANTARES.

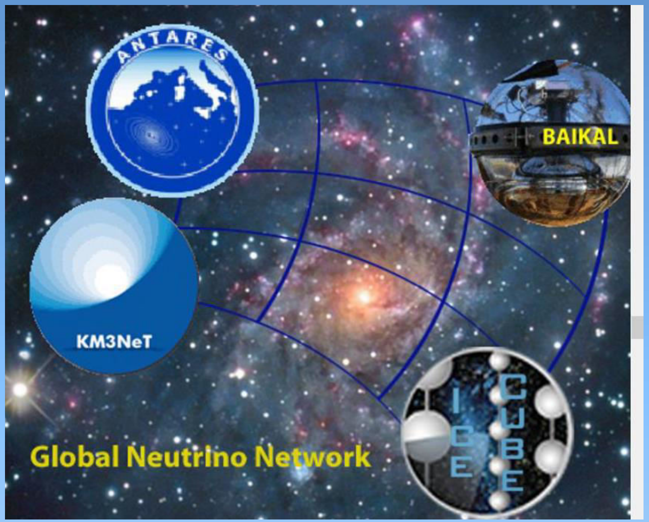
IceCube alerts

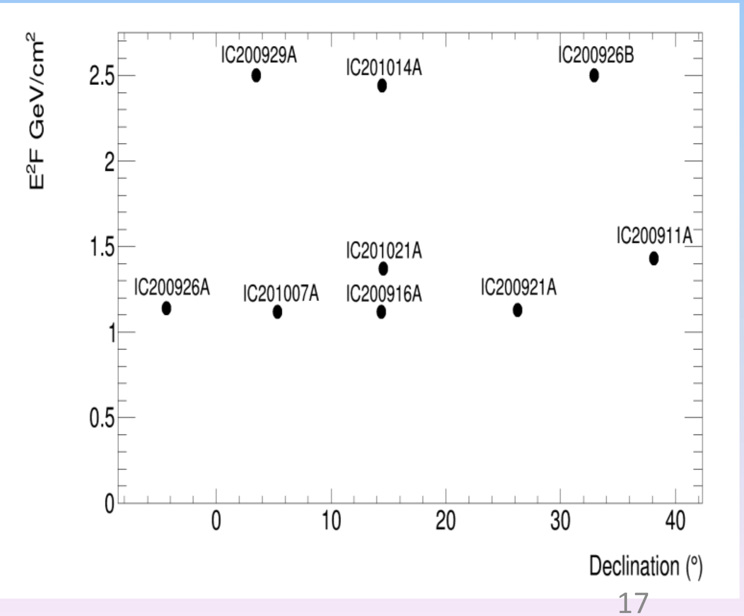
Starting Sept. 2020 Baikal-GVD follows **IC alerts (GCN) , 22** alerts.

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

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

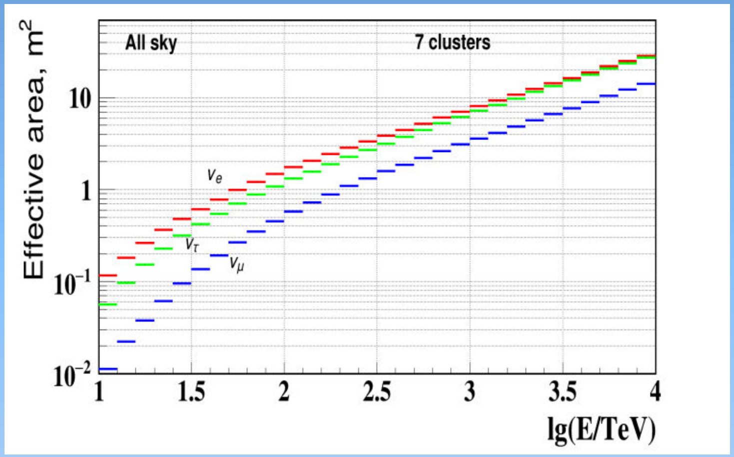
E^{-2} spectral behavior; equal fluence in all flavors.



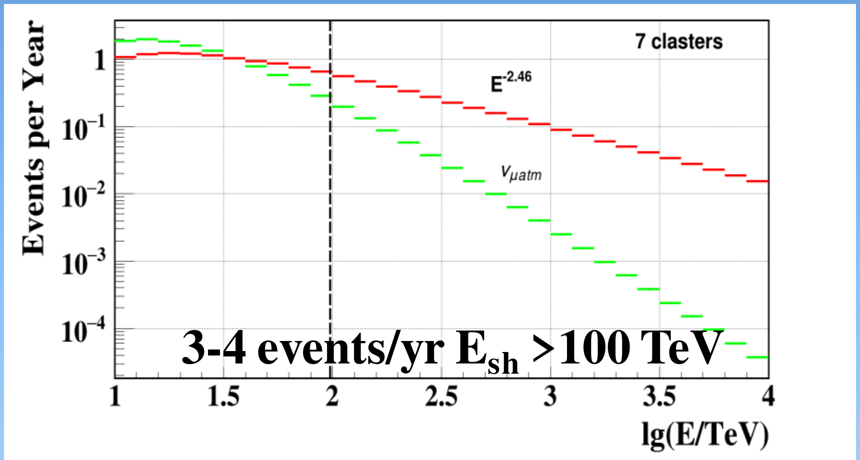


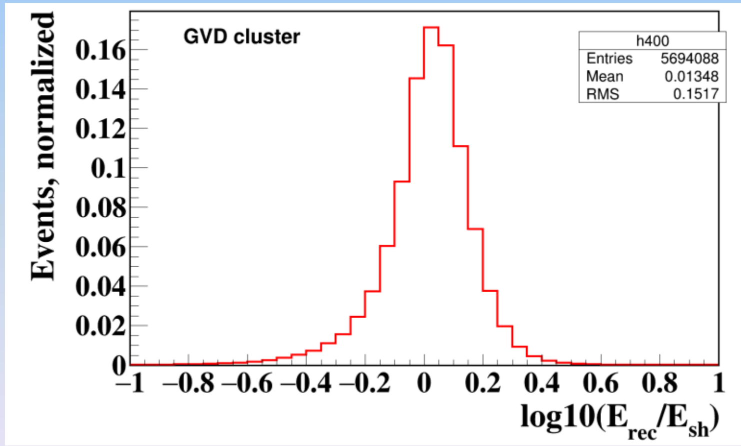
Cascades detection with Baikal-GVD

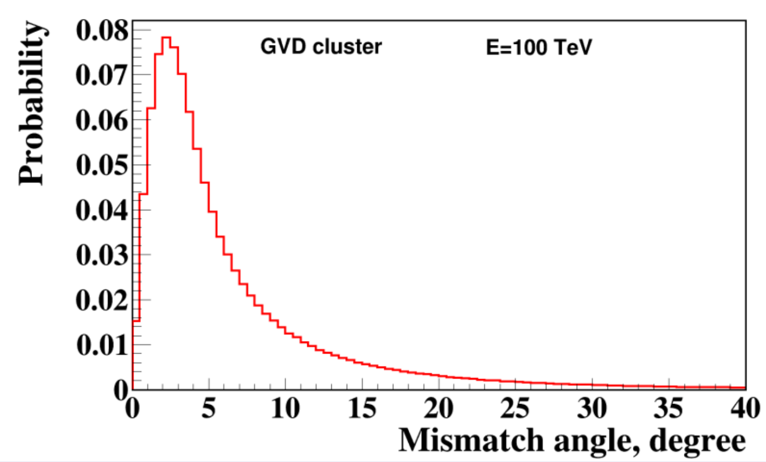
Neutrino effective area for 7 GVD clusters



Expected number of events in 7 GVD clusters from astrophysical neutrinos for 1 yr.







Energy resolution : $\delta E/E \sim$ 10%-30%

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

Preliminary!

High energy cascades (data and MC)

Data from 2019-2020 , **live-time: *2915* days** (in terms of one cluster)

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

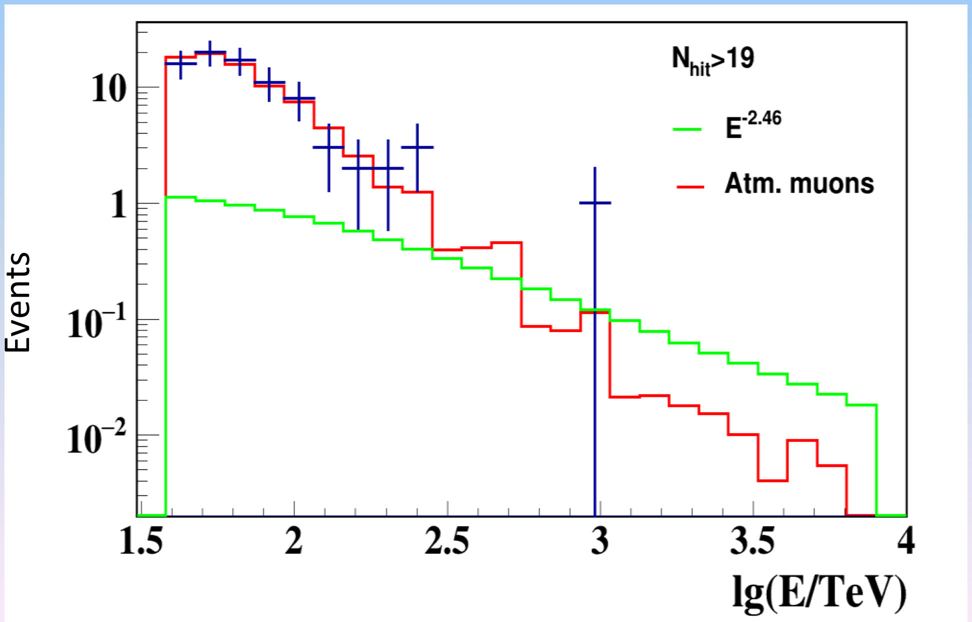
Thanks to Jakob van Santen for modification of DYNSTACK CORSIKA.

72 events with E > 40 TeV and N_{hit} > 19

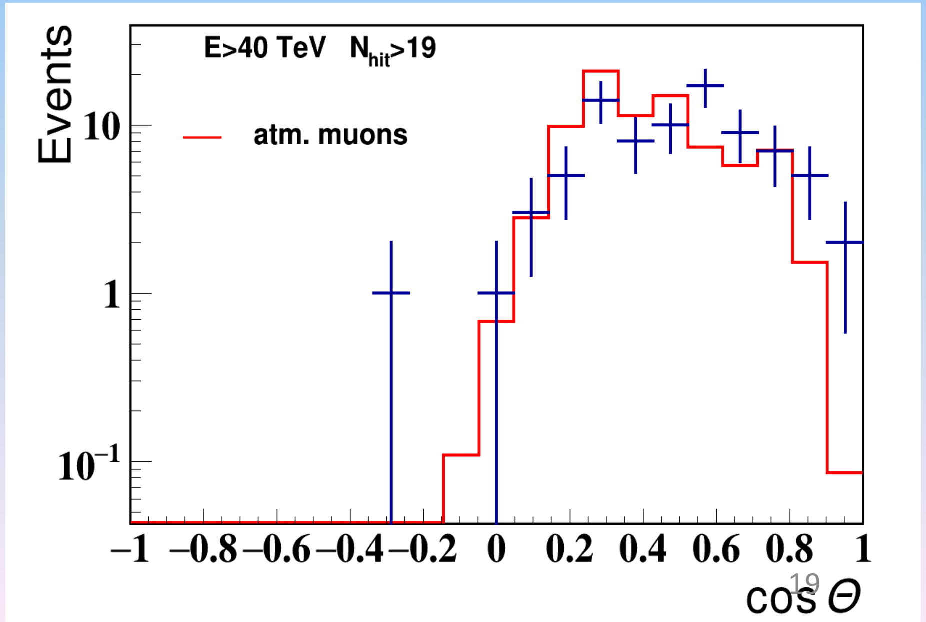
10 events with E > 100 TeV and N_{hit} >19:

One upgoing cascade: E ≈ 91 TeV

Energy distribution



Cosine of zenith angle



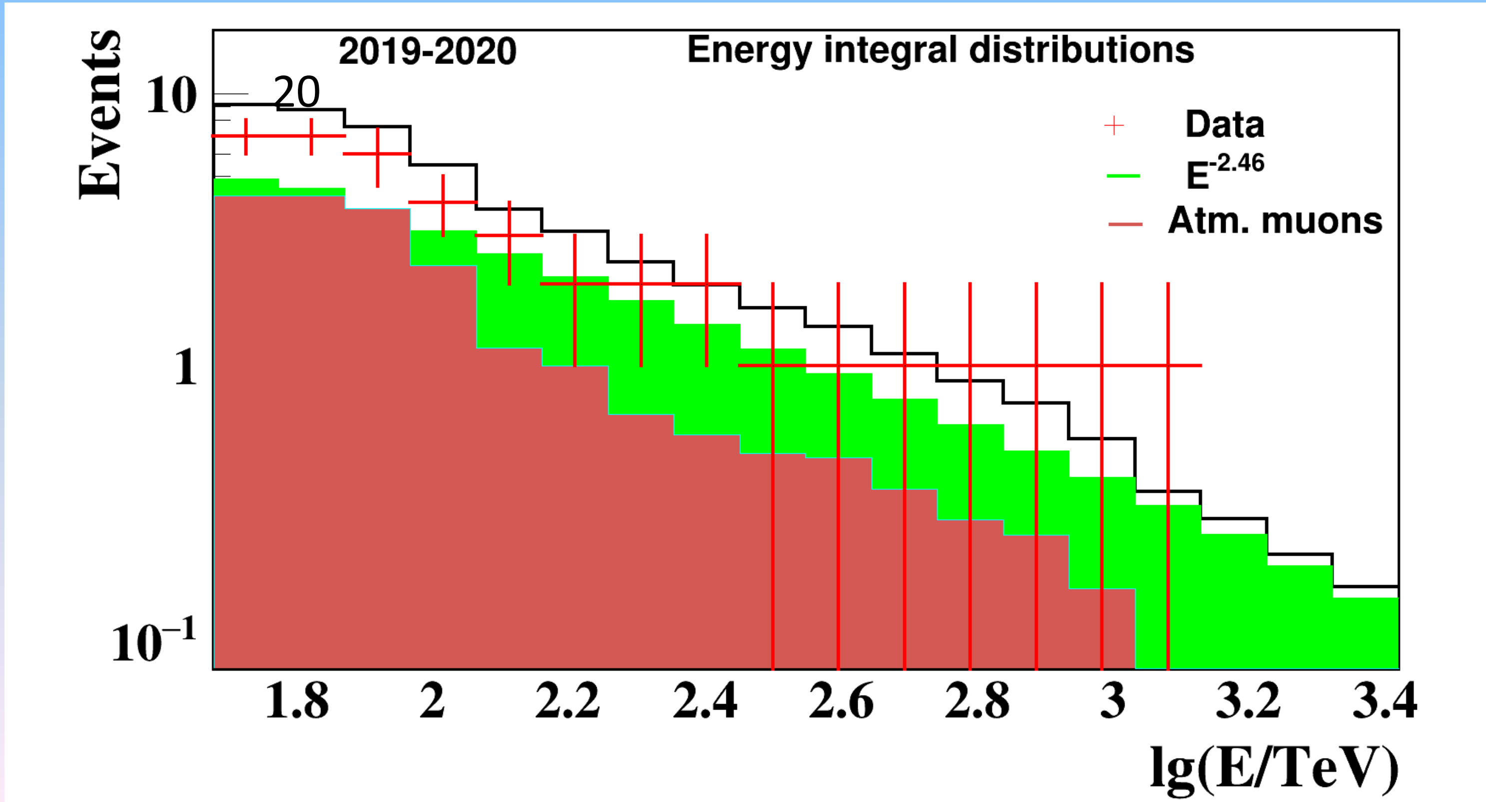
Preliminary!

Final selection requirements:

($N_{Type\_2} = 0$, $E_{rec} \geq 60$ TeV) or ($N_{Type\_2} = 1$, $E_{rec} \geq 100$ TeV)

7 data events have been selected.
4 events are expected from atm. muons
5 events are expected from $E^{-2.46}$ astrophys. flux with IC normalization

Cumulative distributions of data and events from atm. muons and astrophys. flux after final cuts



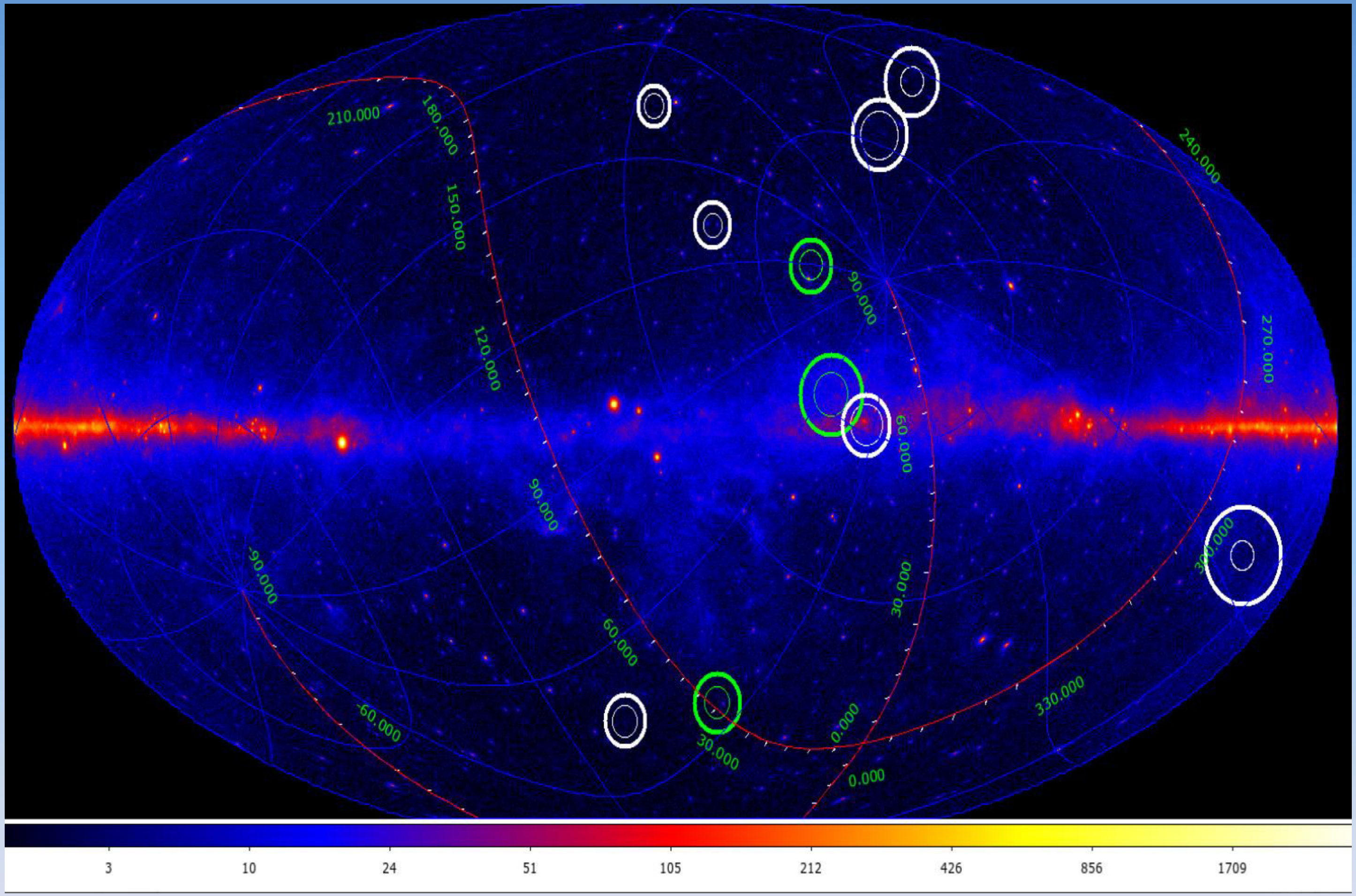
Preliminary!

Parameters of 10 selected events (2018-2020)

	E, TeV	θ_z, degree	φ, degree	R.A.	Dec
GVD2018_354_N	105	37	331	118.2	72.5
GVD2018_383_N	115	73	112	35.4	1.1
GVD2018_656_N	398	64	347	55.6	62.4
GVD2019_112_N	1200	61	329	217.7	57.6
GVD2019_114_N	91	109	92	45.1	-16.7
GVD2019_663_N	83	50	276	163.6	34.2
GVD2019_153_N	129	50	321	33.7	61.4
GVD2020_175_N	110	71	185	295.3	-18.9
GVD2020_332_N	74	92	9	223.0	35.4
GVD2020_399_N	246	57	49	131.9	50.2

Preliminary!

Sky map with 10 events

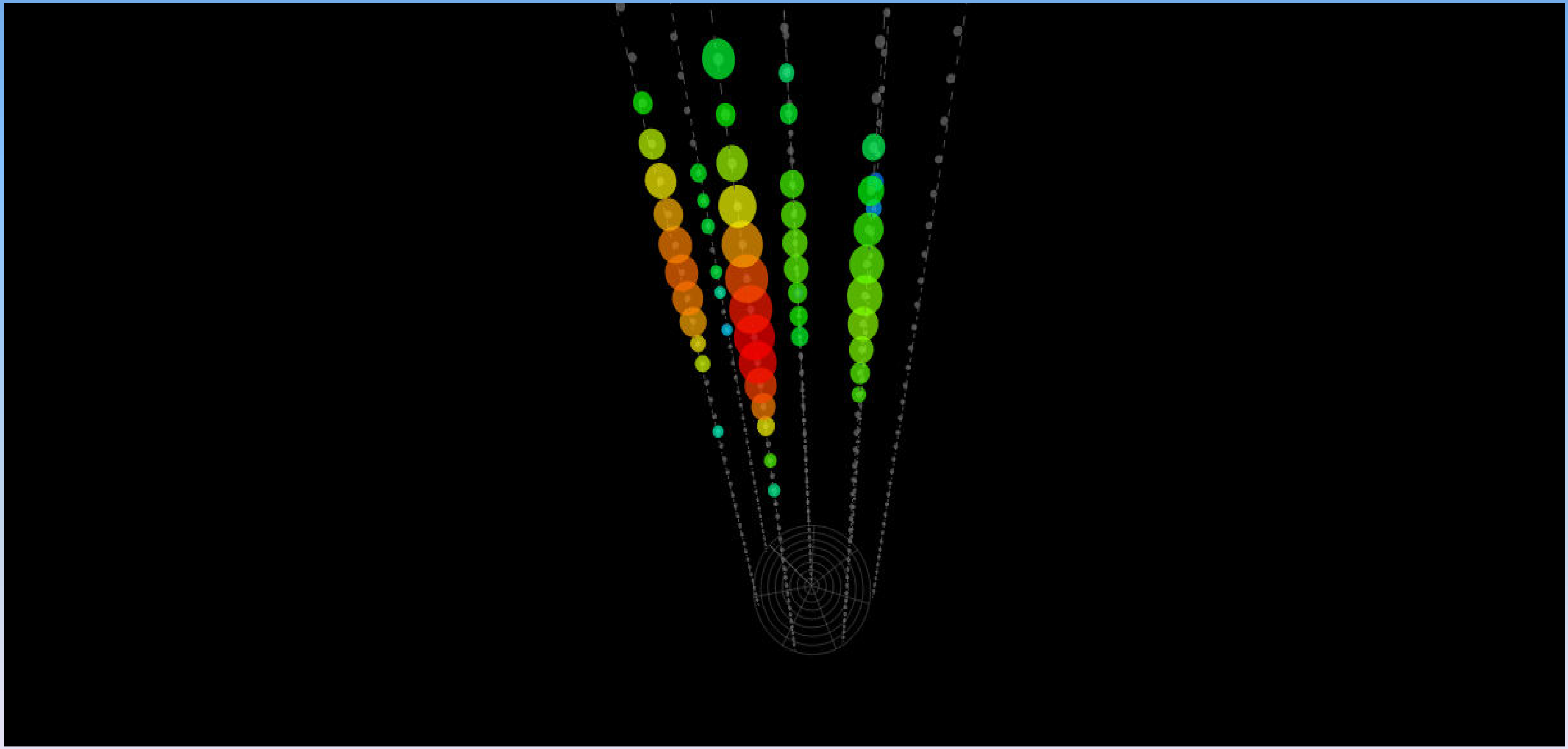


Small (large) circle stands for 68 % (95%) C.L.

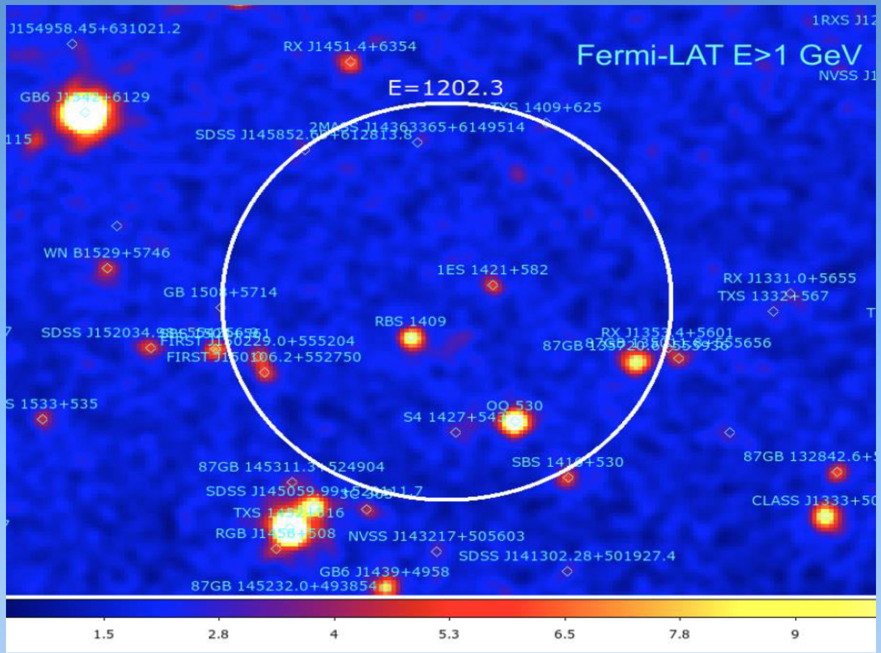
GVD_2019_112_N event

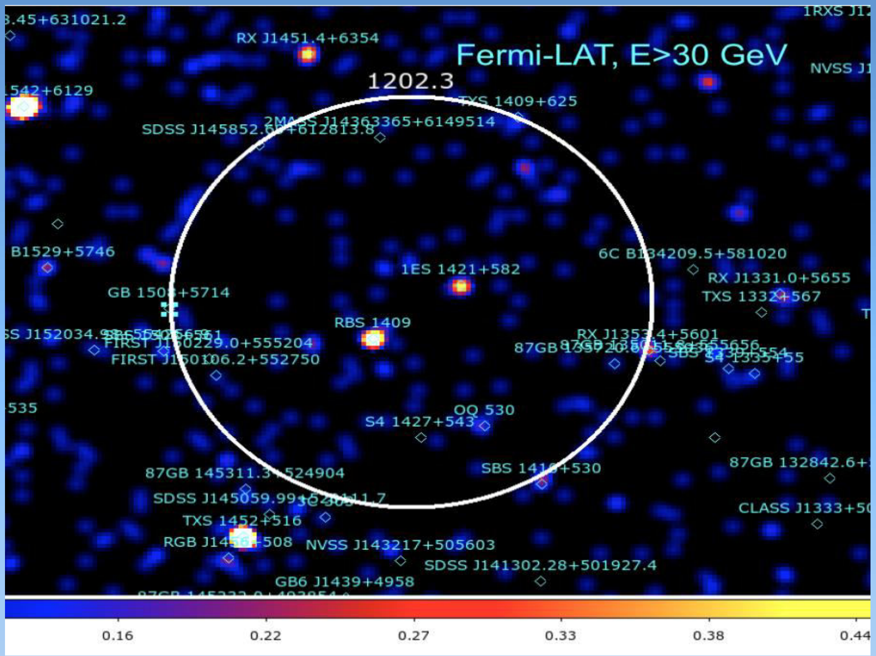
Preliminary!

- Energy E = 1 200 TeV (±30%)
- Distance from central string r = 91 m
- Zenith angle = 61°



Gamma sources nearby the event



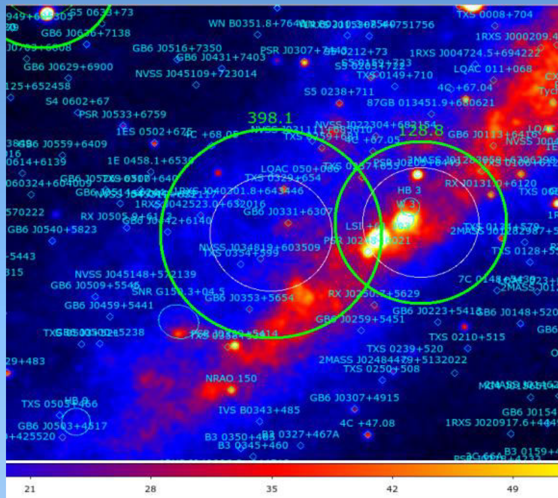


Fermi sources in 5° circle:
1ES 1421+582
RBS 1409
2MASS J14363365+6149514
OQ 530 = J1419+5423
brightest radio-blazar (1.1 Jy)
S4 1427+543
87GB 135720.6+555936
FIRST J150106.2+552750
FIRST J150229.0+555204

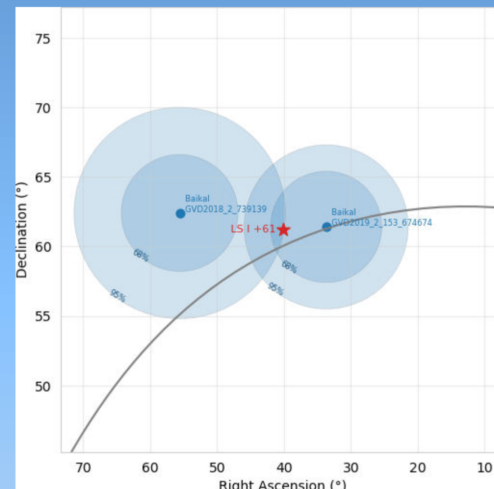
E> 30 GeV
RBS 1409 BL Lac z=unknown.
1ES 1421+582 z=unknown.
both with hard spectrum

Two close events at distance 10.3°: GVD_2018_656_N and GVD_2019_153_N

Sky map of Fermi sources



LSI +61 303 and the two events



LSI +61 303 – at 3.1° and 7.4° from GVD_2019_153_N and GVD_2018_656_N

LSI +61 303 – γ-ray active micro-quasar

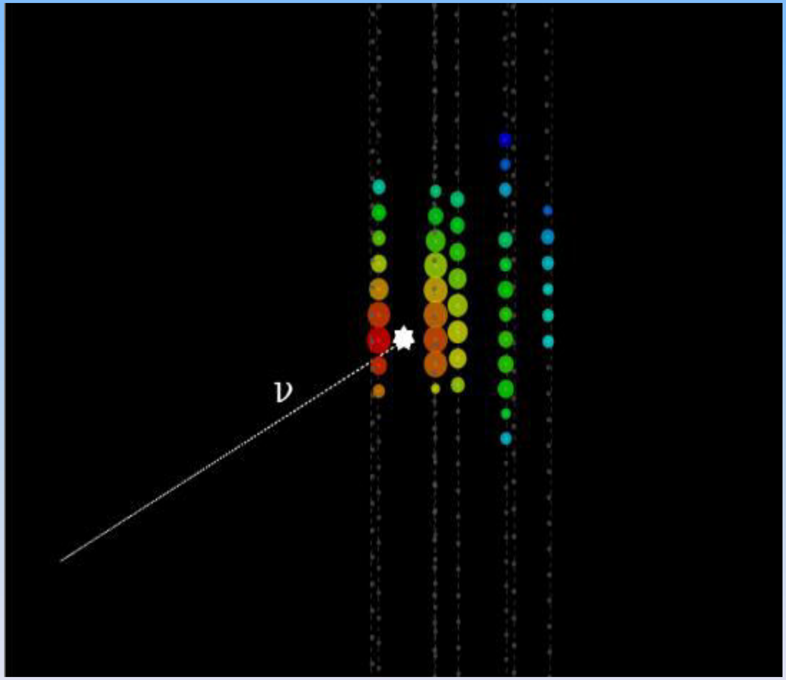
Using PSFs of all 10 events chance probability to observe such configuration was estimated:

p-value = 0.007 or 2.7 σ ! (conservative, preliminary!!!)

Preliminary!

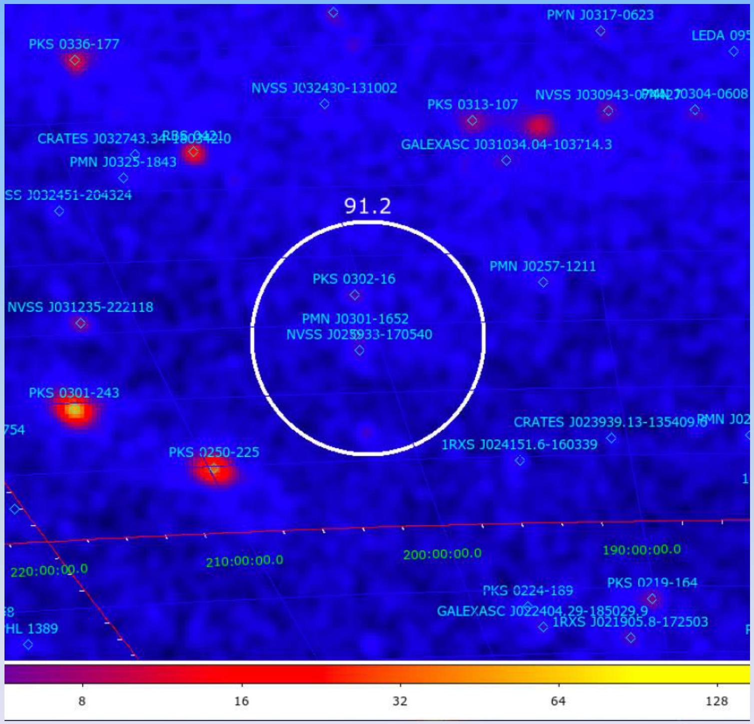
The first clear cascade event from the interaction of an upward moving electron- or a tau-neutrino at ~ 100 TeV

Contained event
Reconstructed energy E = (91 ± 11) TeV
Zenith angle $\theta_z = 109^\circ$



GVD2019_1_114_N

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

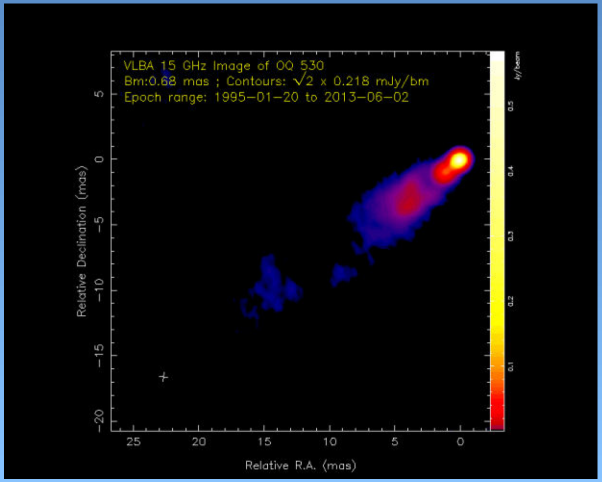


91.2 TeV (from below) no good known sources in 3°
PKS 0302-16 unknown type of source
PMN J0301-1652 unknown type of source

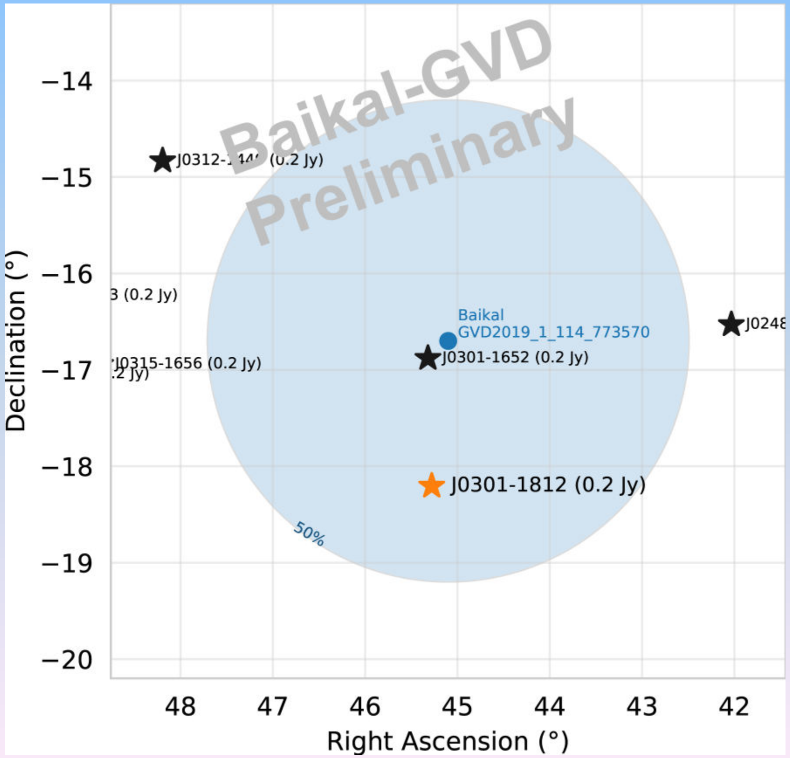
Radio-loud blazars – promising neutrino sources

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

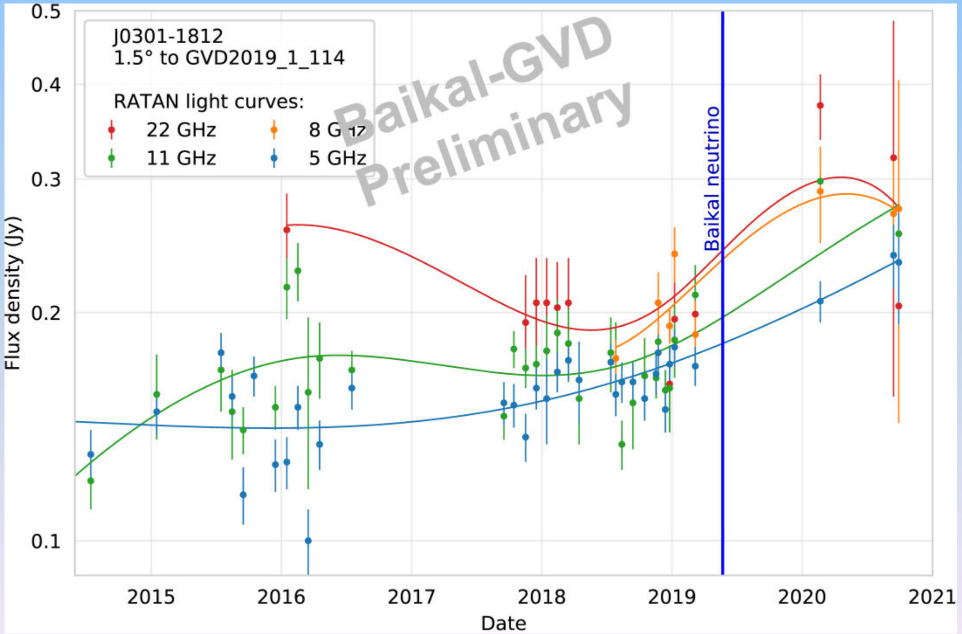
GVD2019_1_114_N
Radio blazar J0301-1812



Sky plot of radio-bright blazars nearby neutrino event

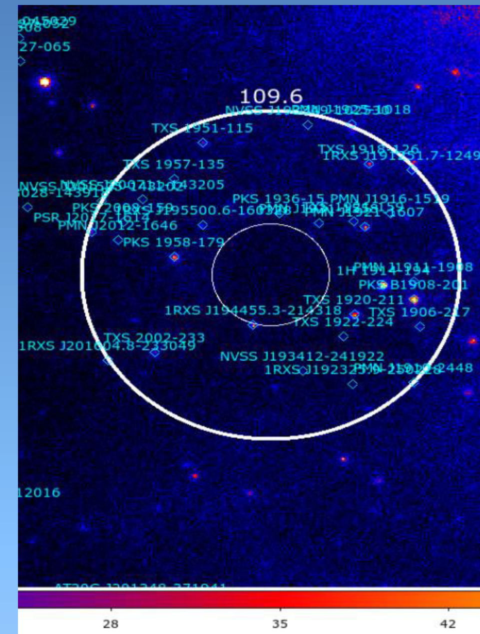


Light curves of J0301-1812 measured by RATAN-600

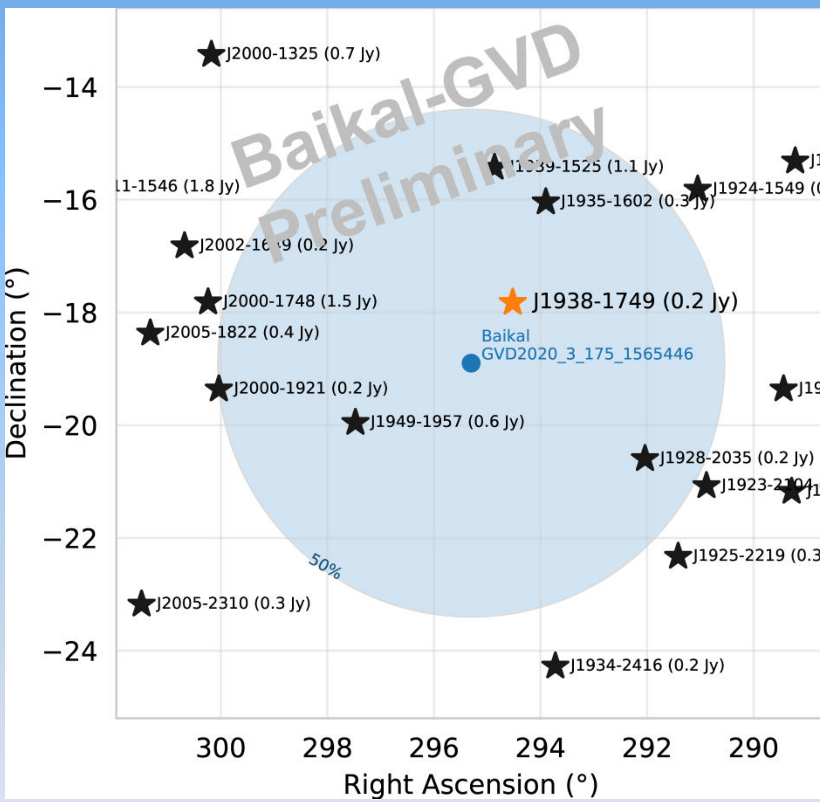


GVD2020_3_175_N

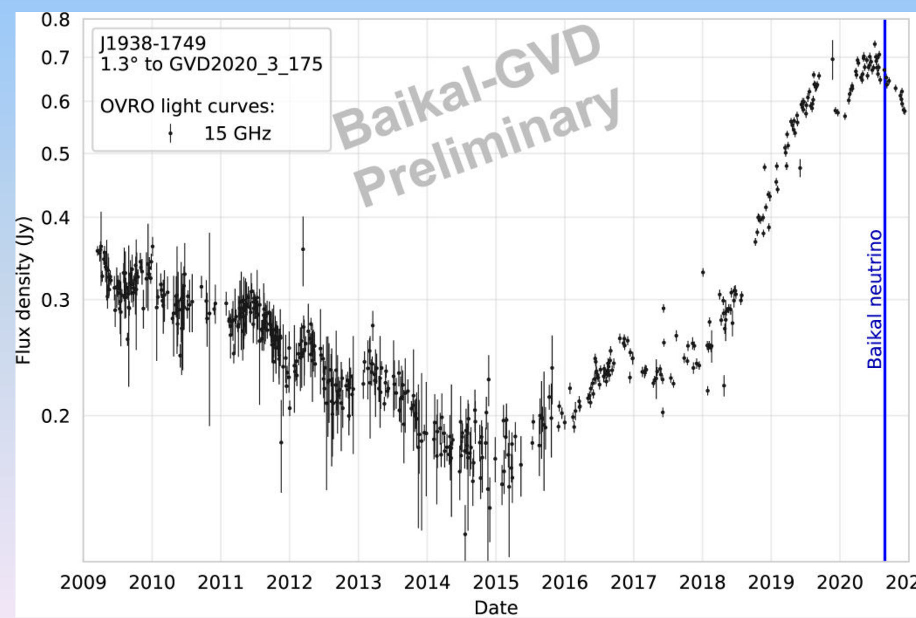
Radio blazar J1938-1749



Sky plot of radio-bright blazars nearby neutrino event



Light curves of J1938-1749 measured by OVRO



Acknowledgements

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Conclusions

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere: 0.4 km^3 and still growing.

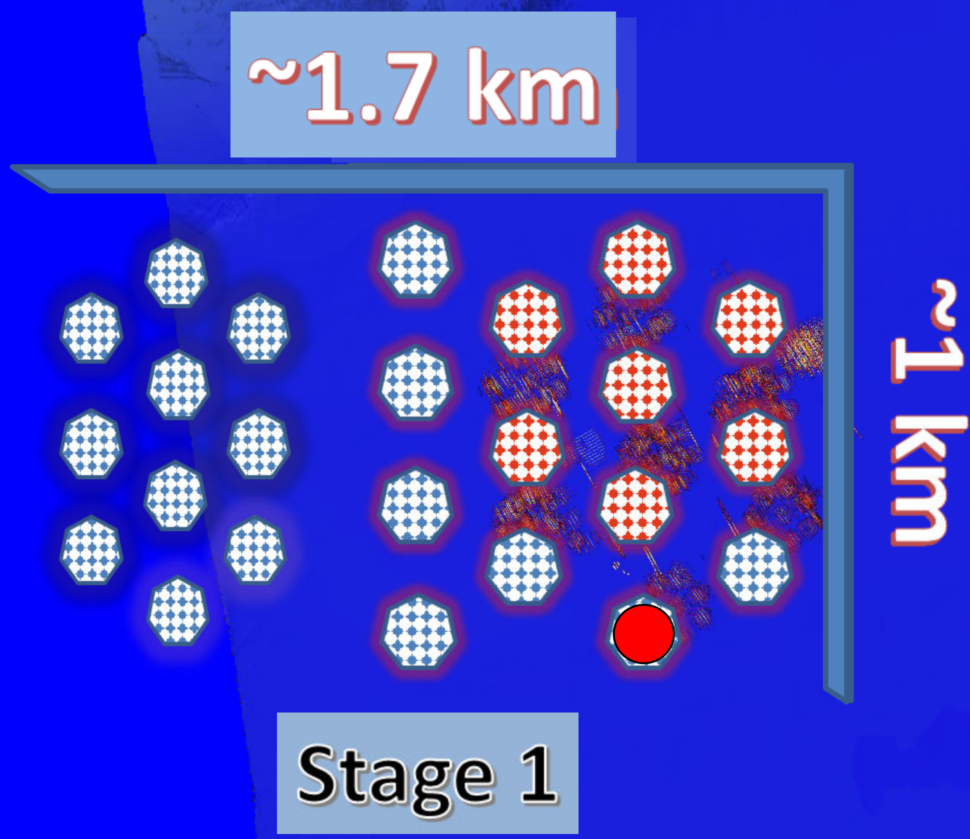
- Modular structure of the Baikal-GVD design allows a search for HE neutrinos and multi-messenger studies at the early phases of the array construction.

- Observations of atmospheric neutrinos by Baikal-GVD agree with expectations, first astrophysics neutrino candidate events have been selected.

Future plans

- Improvements in pulse extraction: Pulse fitting, Double Pulse identification, pulse separation
- Alerts: Shorten the time from a few hours to a few tens of minutes
- Multi-cluster track reconstruction, search for high-energy starting events
- Experimental strings with optical DAQ
- Increasing the effective volume about 2 clusters per winter expedition

GVD 2020 and extention



Thank you for your attention!

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