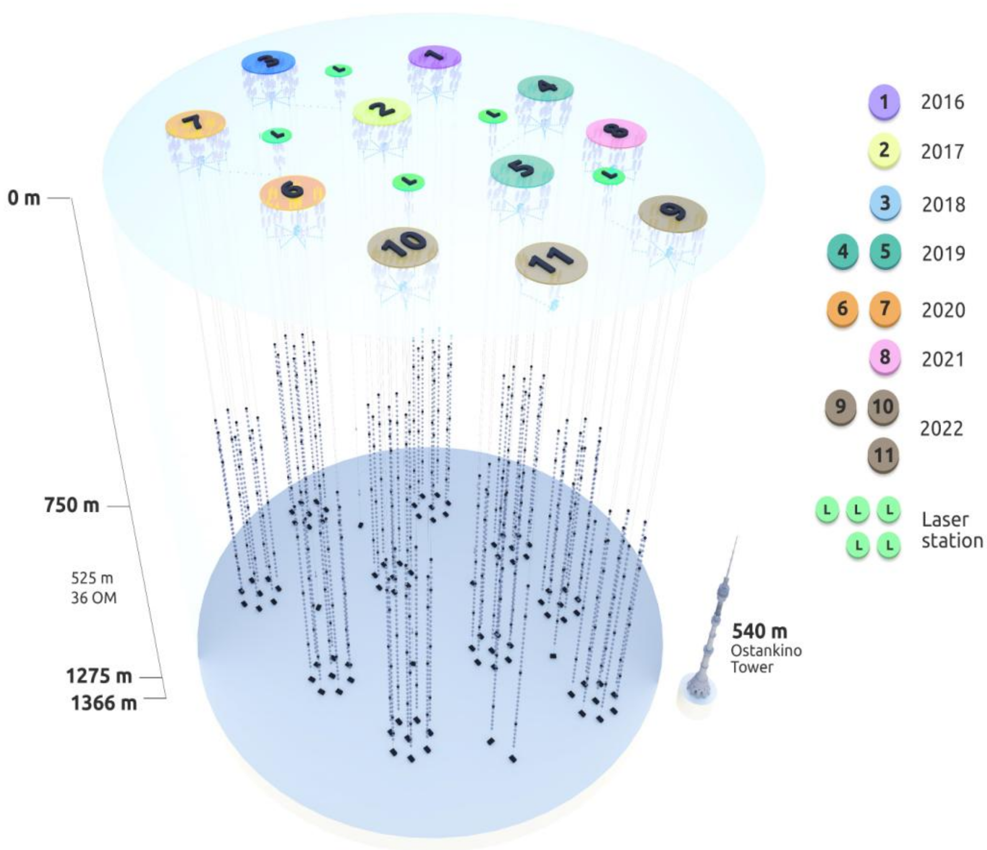
37 Всероссийская конференция по космическим лучам

Байкальский глубоководный нейтринный эксперимент: статус и перспективы

Ж.-А. Джилкибаев
Коллаборация Baikal-GVD
Июнь 27 – Июль 1, 2022, Москва

Baikal-GVD construction status and schedule

Status 2022: 10 clusters, 5 laser stations, 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
2025	16	4608
2026	18	5184

Section of OMs

Section

• 12 OMs, 15 m spacing, All PMTs look downward.

• 2 acoustic modules (AM) of the positioning system.

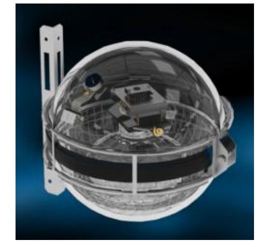
Section control module

• ADC 12 ch, 200 MHz sampling; pulse form measuring.

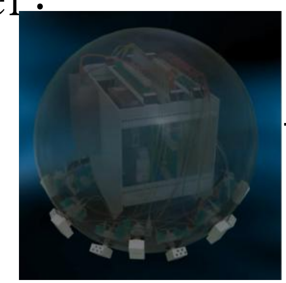
• Trigger logic, events forming, data filtration.

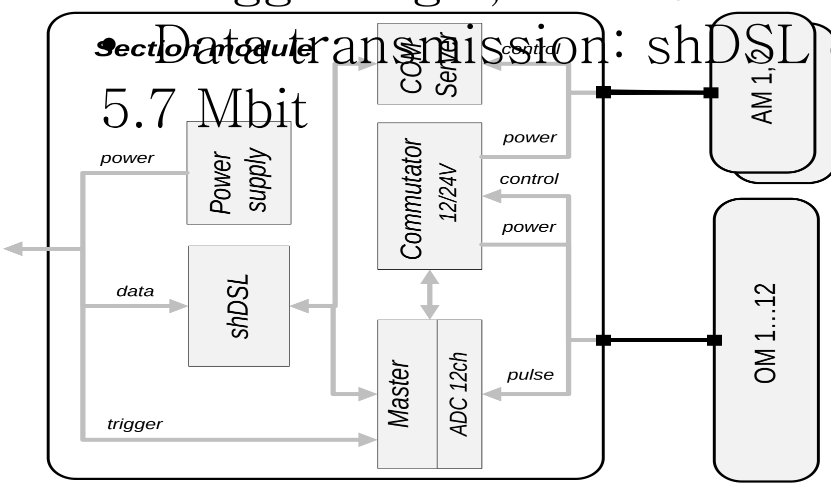
• Data transmission: shDSL ethernet extender: 5.7 Mbit

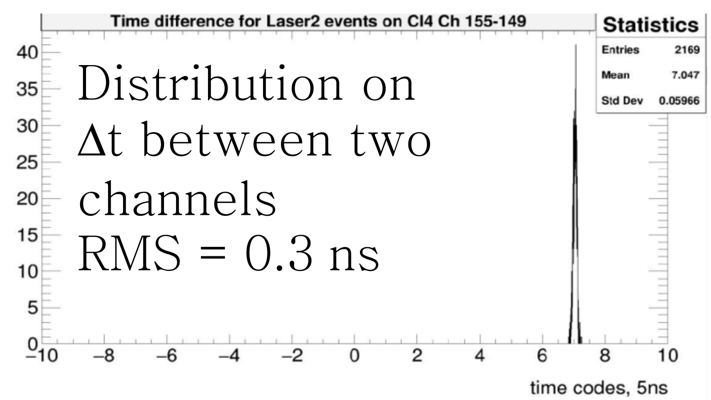
O[tical module



Section control module



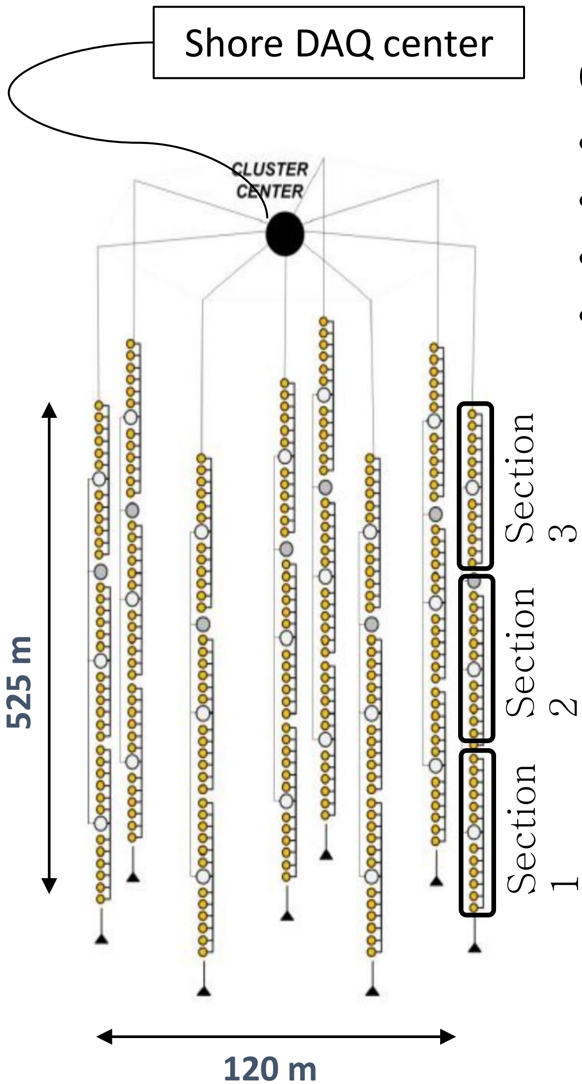




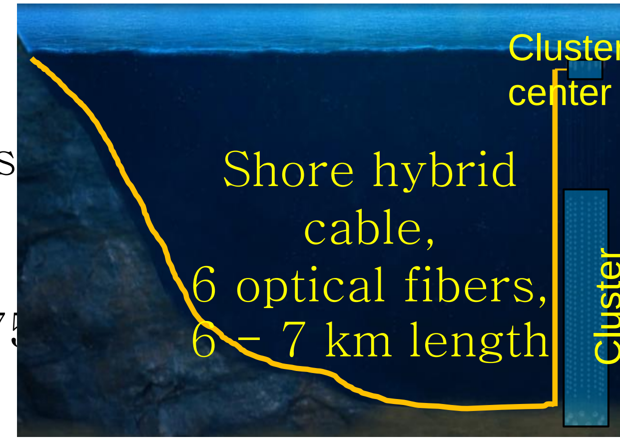
Distribution on Δt between two channels
RMS = 0.3 ns

Pulse form interpolation provides accuracy of the pulse time estimation ~0.3 ns.

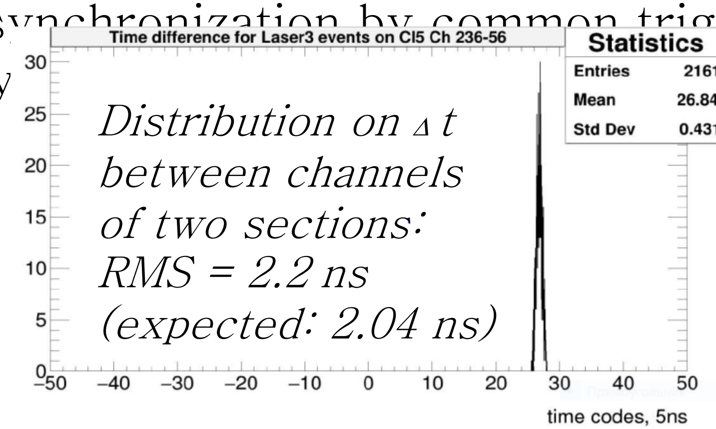
Cluster



Cluster: 288 OMs
- 24 Sections on 8 strings
- Cluster DAQ center
- Shore cable: 6 – 7 km
- Depths from 750 to 127



Cluster DAQ
- Trigger: 1.5 & 4 pe of adjacent channels.
- Maximum trigger rate: ~200 Hz.
- Data transferring: shDSL Ethernet extenders: 5.7 Mbit.
- Inter-section synchronization by common trigger: ~2 ns accuracy



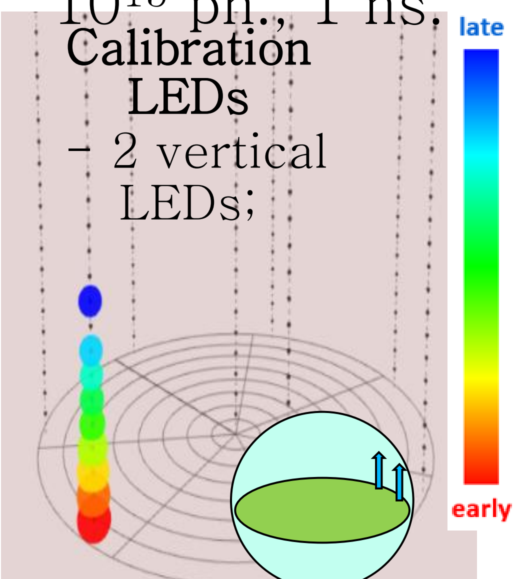
Calibration, control and monitoring systems

- Time calibration of measuring channels
- Acoustic positioning system
- Water properties monitoring
- Deep water light background monitoring
- Data quality monitoring
- Detector parameters monitoring
- Data transmission and processing

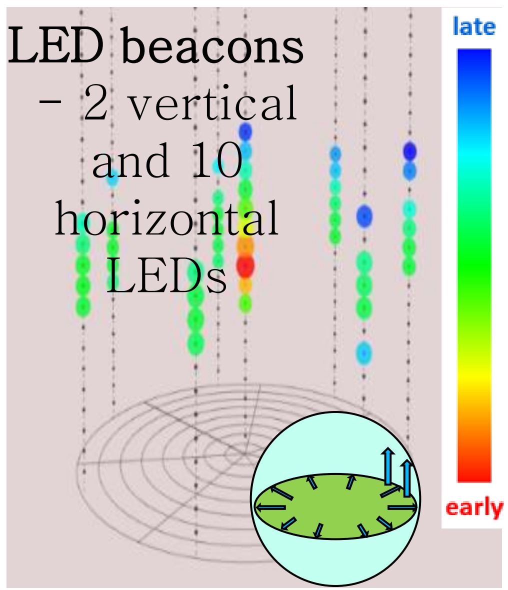
Time calibration of measuring channels

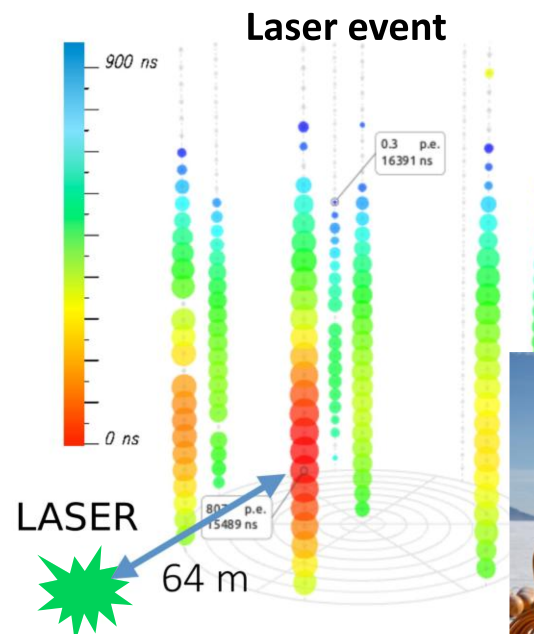
Section calibration: 2 LEDs in each OM, 470 nm, 1 – 10^8 ph., 5 ns.
String calibration: LED beacons in 12 OMs of the cluster.
Cluster calibration: 2 Lasers per station, 532 nm, 10^{12} – 10^{15} ph., 1 ns.

Calibration LEDs
– 2 vertical LEDs;



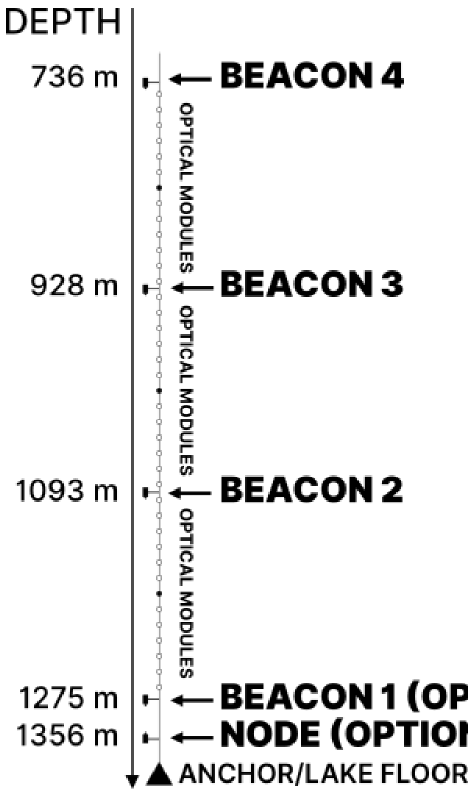
LED beacons
– 2 vertical and 10 horizontal LEDs

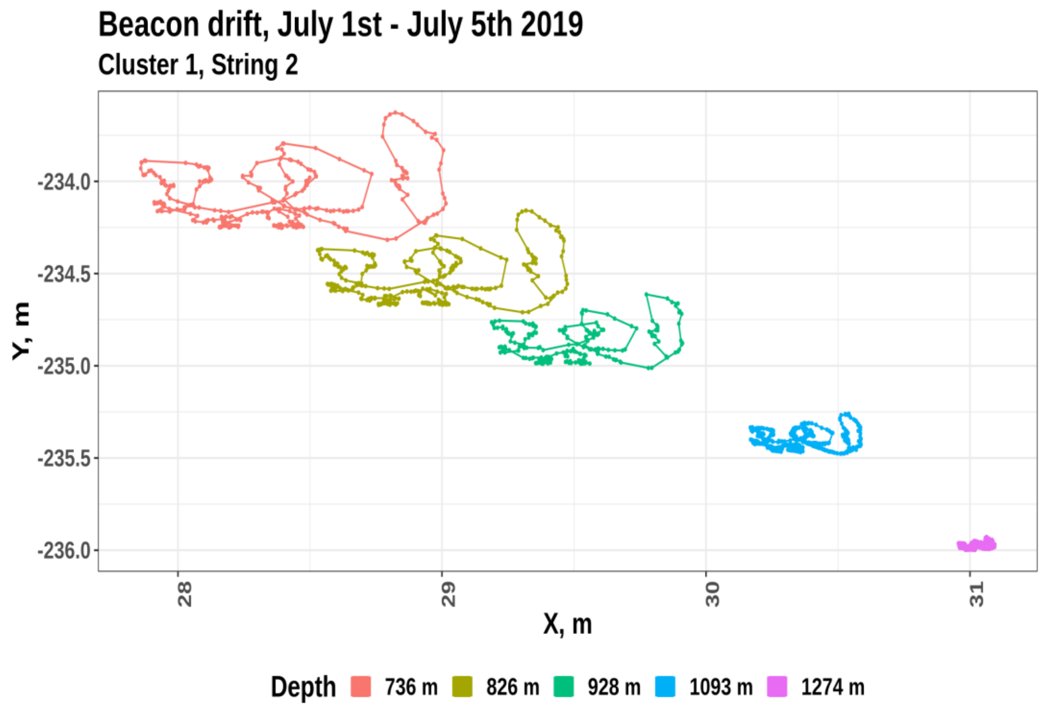




Calibration accuracy ~2 ns

Acoustic positioning system



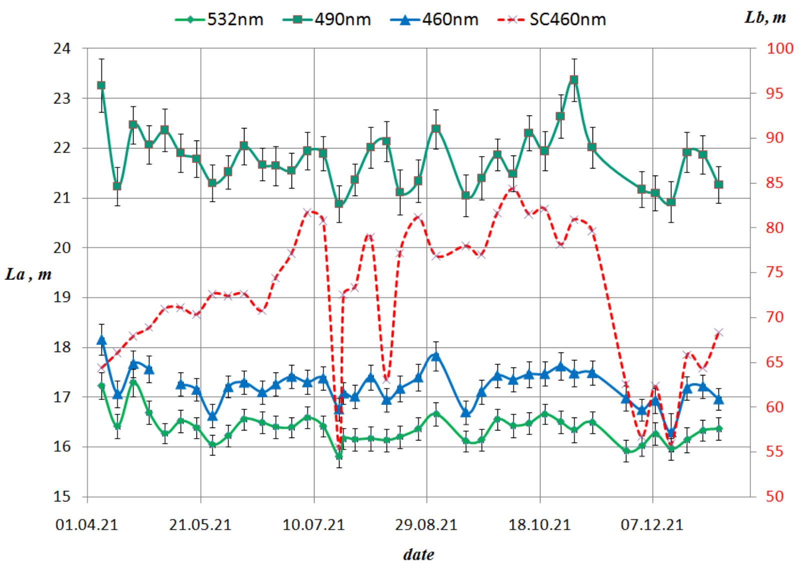


OM drift can reach tens of meters, depends on season and elevation.
OM coordinates are acquired via an acoustic positioning system.
It consists of a network of acoustic modems (AMs) installed along GVD strings
4 AMs per string in a standard configuration

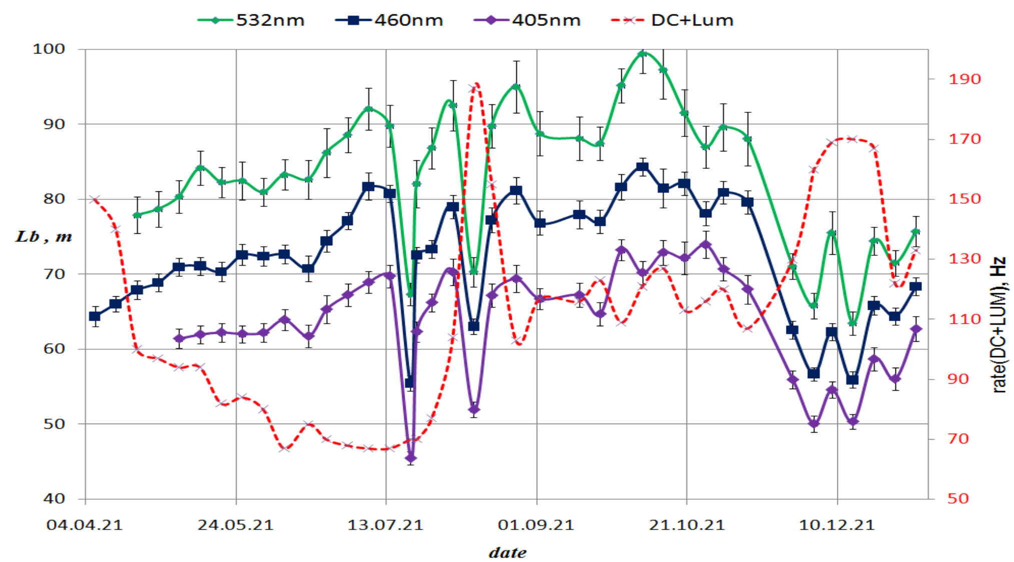
Monitoring of water properties

BAIKAL5D - device

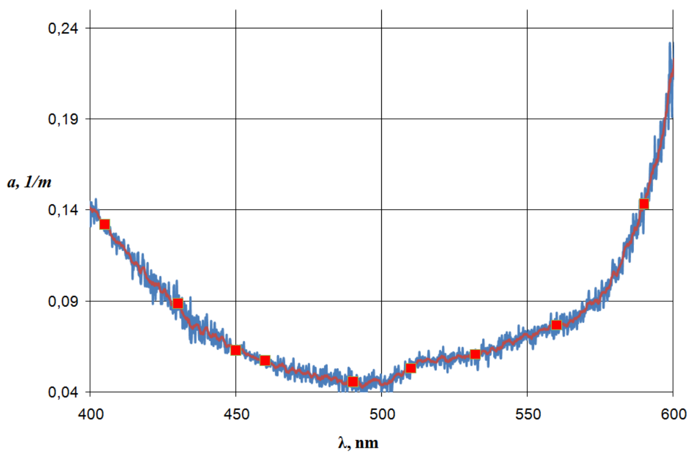
Absorption length



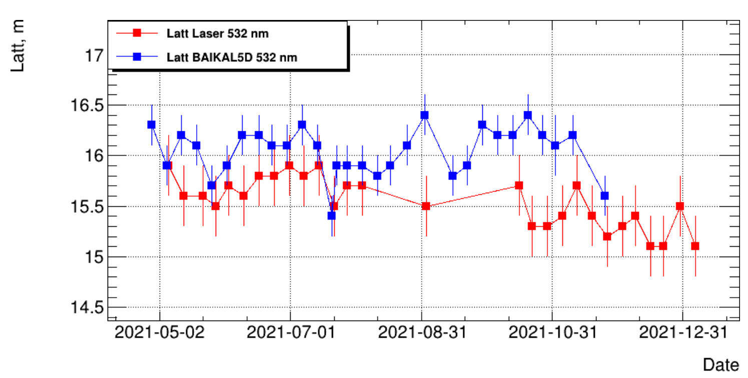
Scattering length



Spectral dependence of absorption length

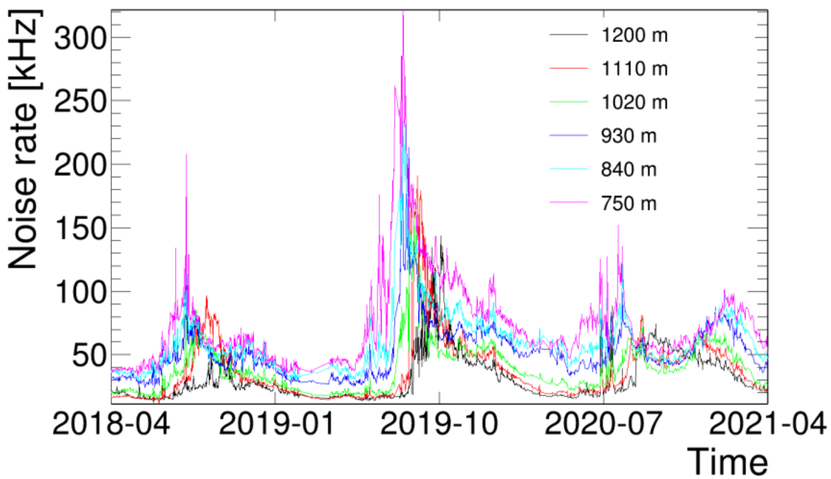


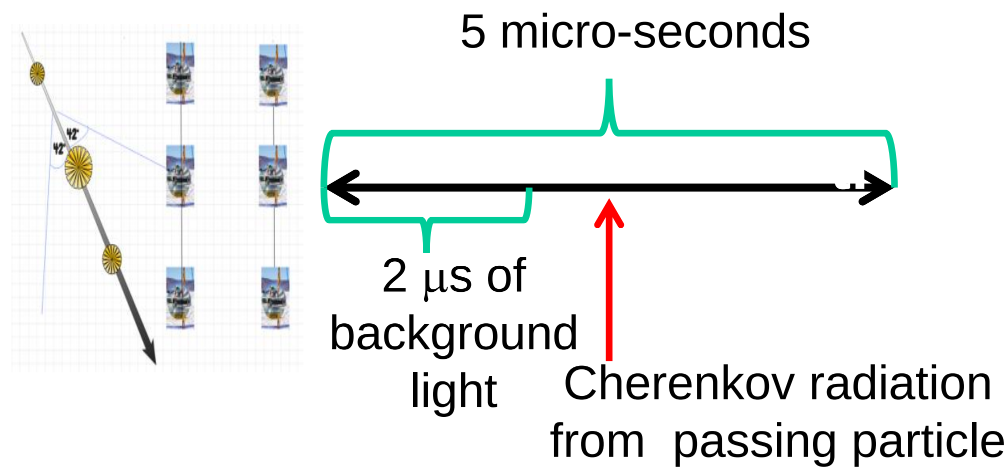
Laser measurements vs. BAIKAL5D



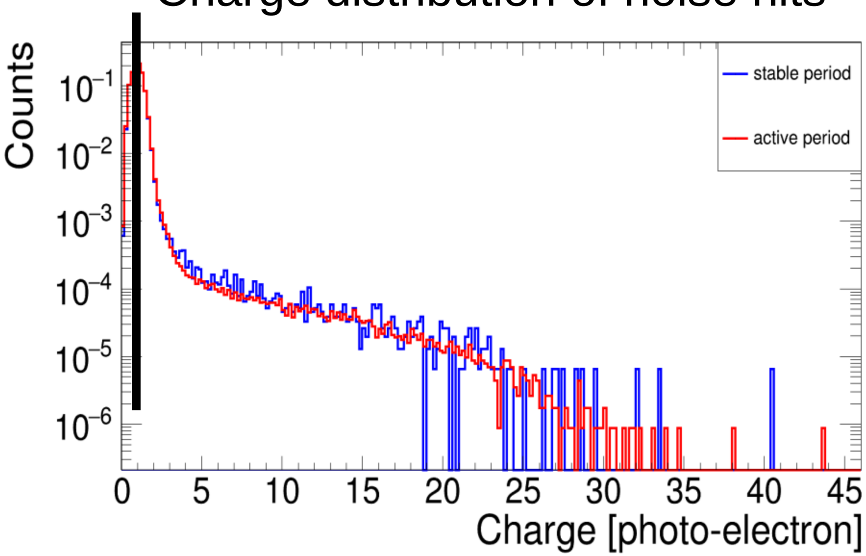
Monitoring of water light background

Temporal behavior of noise rate
at different depth

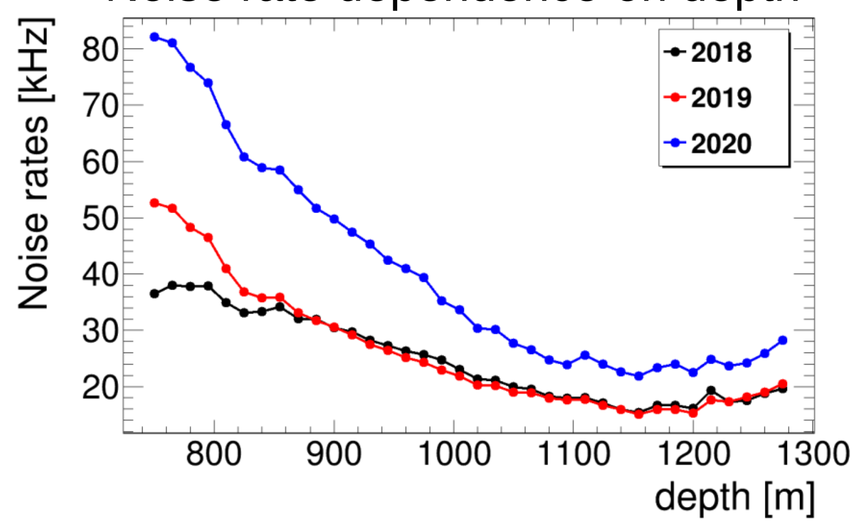




Charge distribution of noise hits

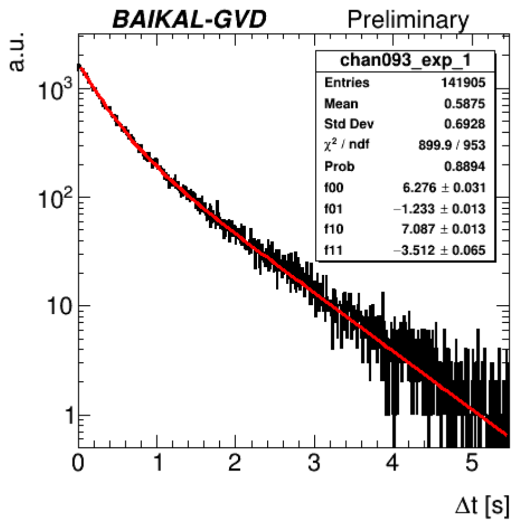


Noise rate dependence on depth

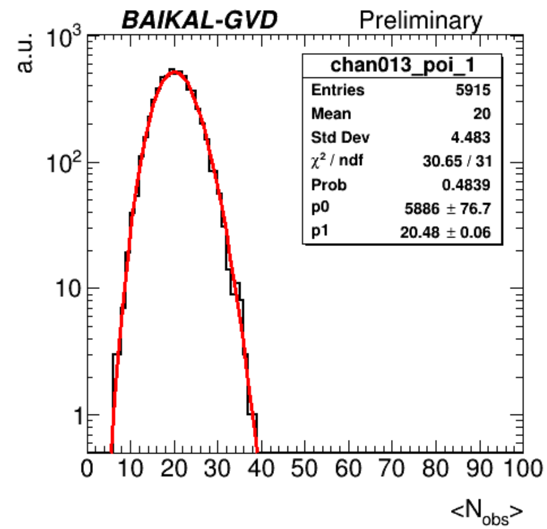


Data quality monitoring

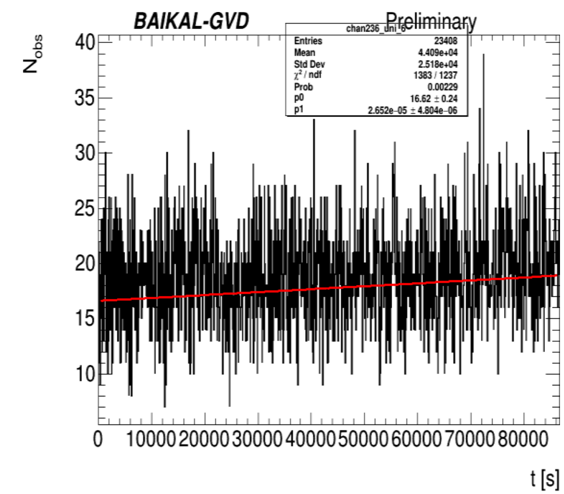
Time difference



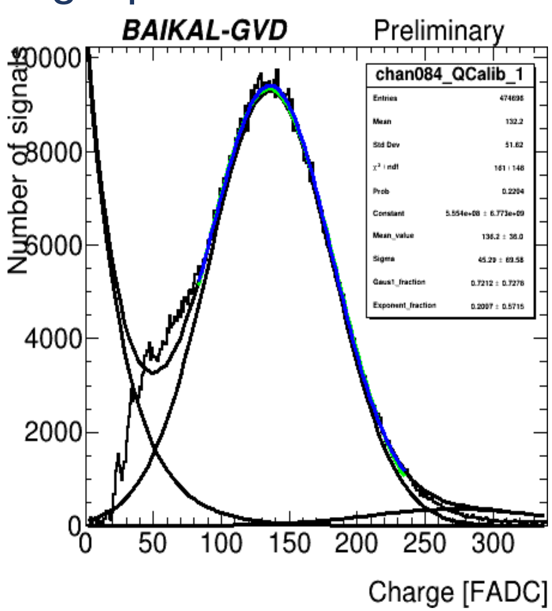
Poisson distribution



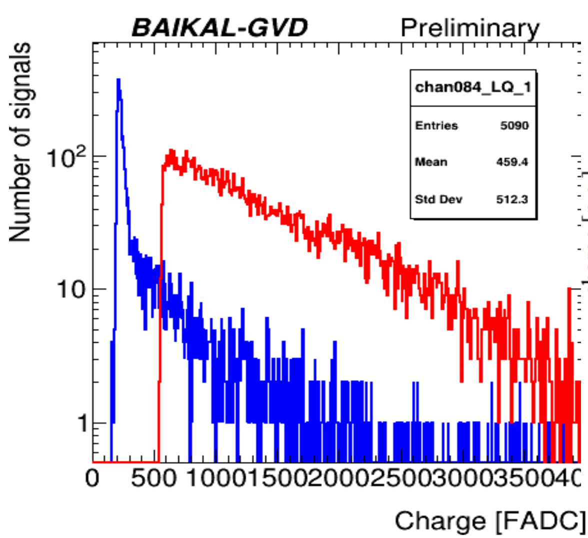
Uniformity

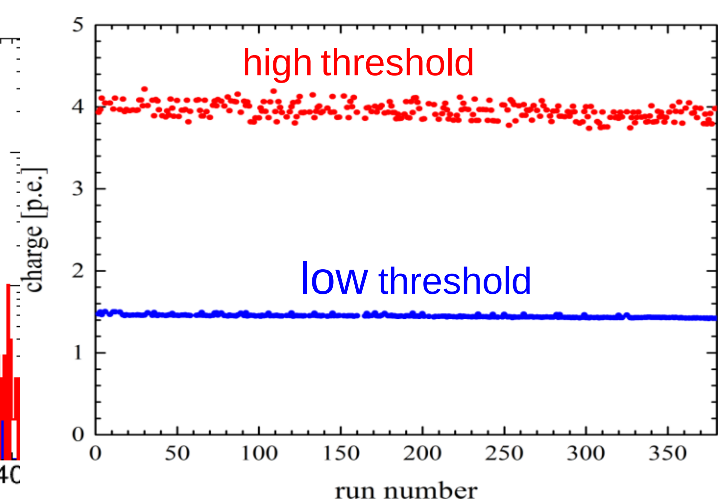


Single photo-electron distribution



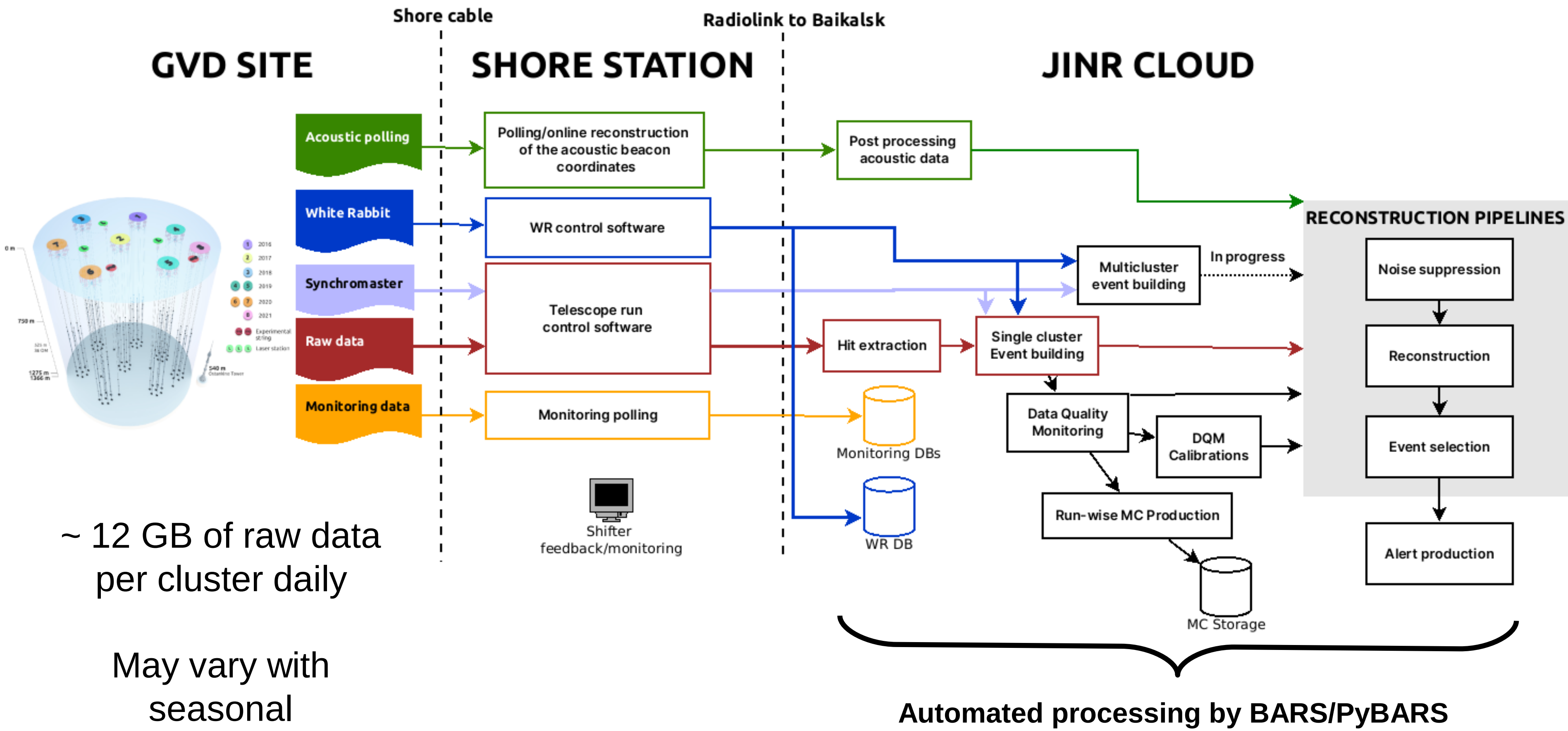
Trigger thresholds are extracted and monitored





Data transmission and processing

1.1 DATA FLOW



~ 12 GB of raw data per cluster daily

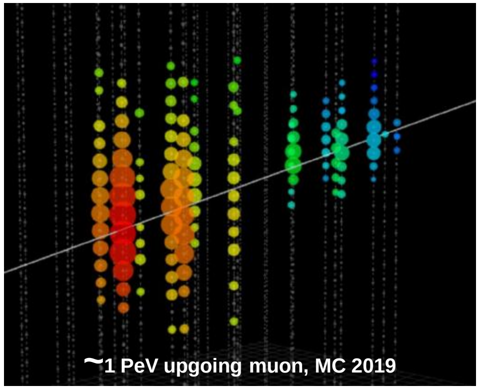
May vary with seasonal noise variations

Selected results

- Muons detection mode: atmospheric neutrinos
- Multimessenger studies
- Cascades detection mode: HE cascades

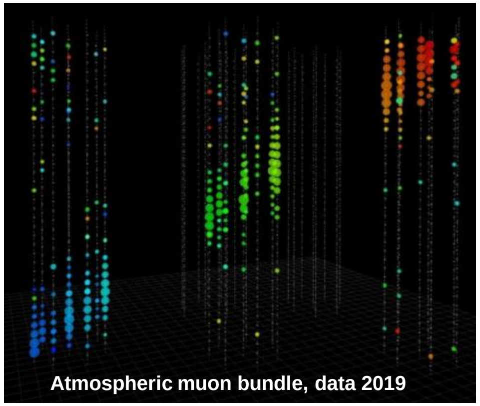
Track analysis

Two analysis modes: single-cluster and multi-cluster



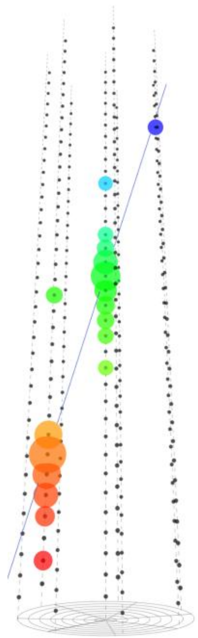
Single-cluster:

- Nominal trigger, each cluster is considered as isolated detector
- Presently limited to $\theta_Z > 120°$
- First set of neutrino candidates was published
- Work is ongoing on extending of the dataset



Multi-cluster:

- Coincidence of single-cluster triggers, dedicated dataset
- Active work is ongoing on neutrino selection methods



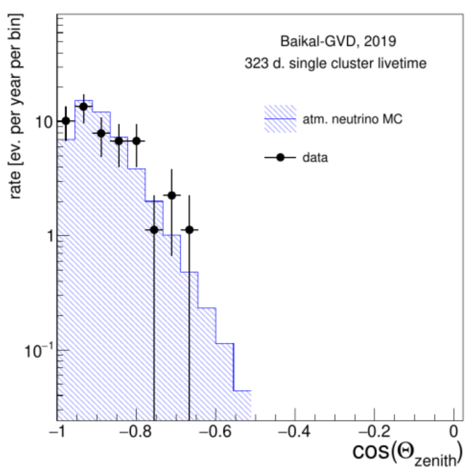
season 2019
cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

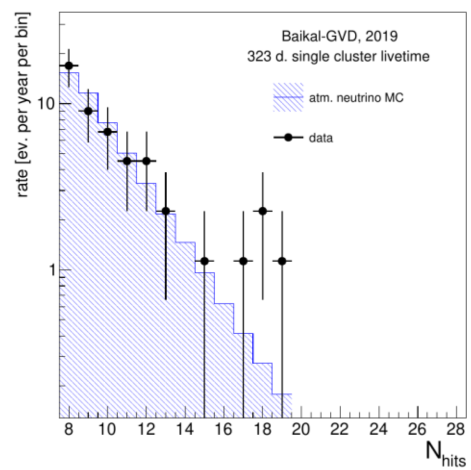
Single-cluster muon neutrino candidates

- Cut-based analysis optimized for low-energy (atmospheric) neutrino, <E_ν> ~ 500 GeV
- Applied to runs **from April 1st until June 30th 2019**
- Single-cluster exposition 323 days

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°

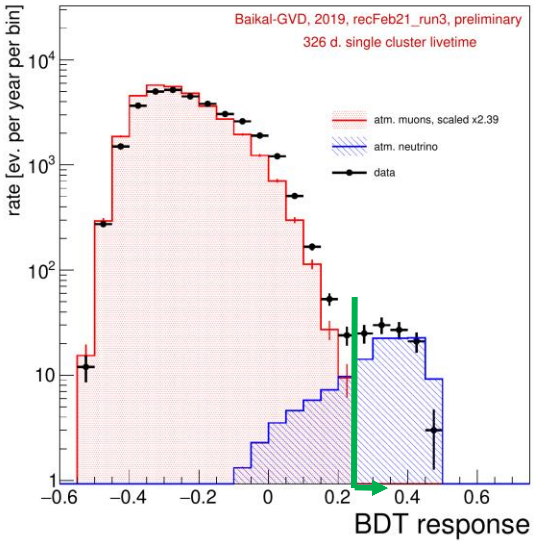
[Eur. Phys. J. C 81 (2021) 1025]

Single-cluster muon neutrino candidates

Sensitivity of analysis was improved with new reconstruction and neutrino selection methods

Event reconstruction:

- Hit finder: efficient hit-finding algorithm [PoS-ICRC2021-1063]
- Track fit: $\chi^2(t)$ - based fitter
- Energy estimation based on dE/dX proxy
- Neutrino selection based on BDT



A sample of 106 neutrino candidate events was obtained for 326 days of single-cluster livetime

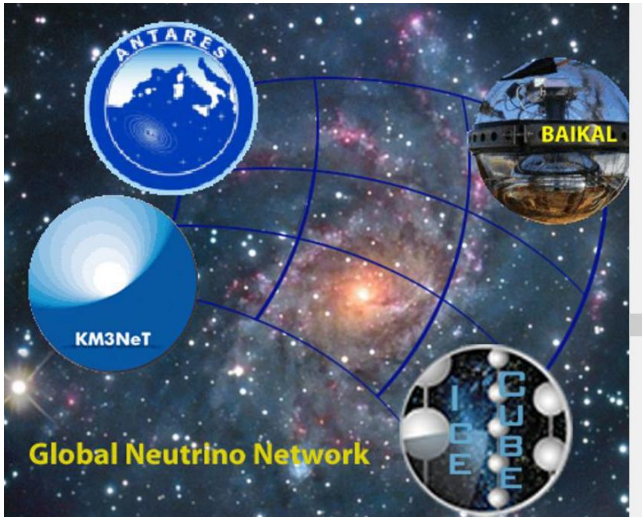
- Factor ~2 improvement with respect to previous analysis
- An MC expectation: 81.2 events ⇒ possible ~30% contamination with background in data

An effort to extend single-cluster analysis to the full dataset is ongoing

Multimessenger studies

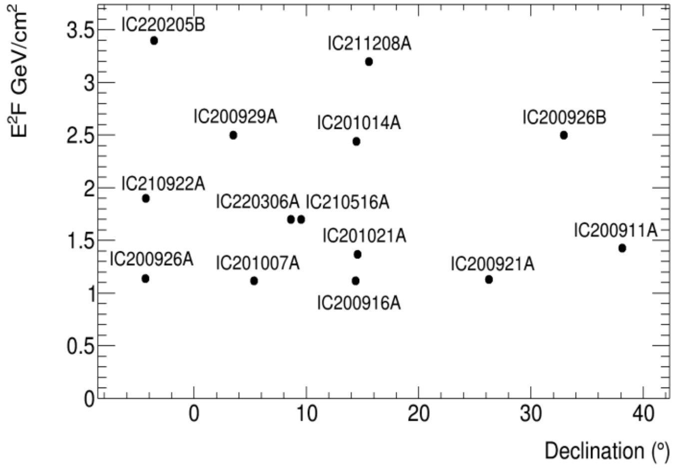
BAIKAL alerts

Since Sept 2020: data processing with a delay of several hours. Currently, fast regime of HE alerts processing takes less that 3 minutes.



ANTARES alerts

Since the end of Dec 2018 Baikal-GVD follows ANTARES alerts. Processed 60 alerts, among which 3 possible coincidences were found in cascade mode within 5° and dT ±1 day. Joint GVD-ANTARES analysis has been done and published.



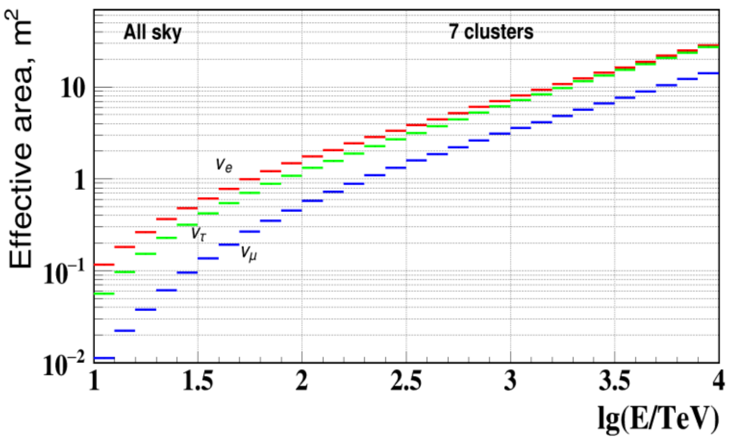
ICECUBE alerts

Starting Sept 2020 Baikal-GVD follows **IC alerts (GCN) 45** alerts.

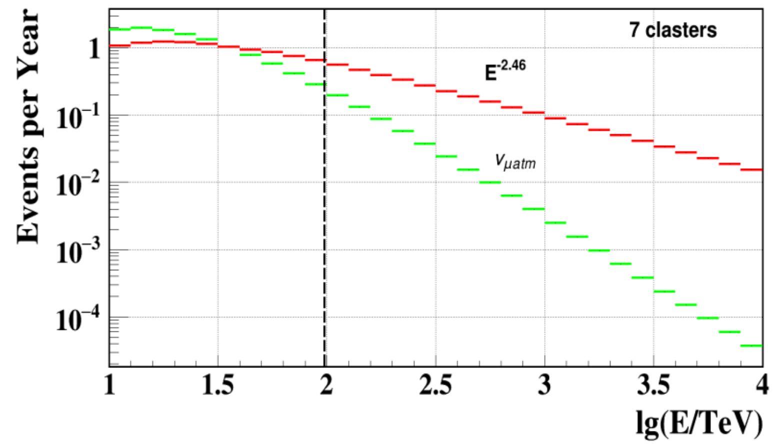
Upper limits at 90% c.l. on the neutrino fluence: ~1÷2 GeV cm^{-2} for energy range 1TeV– 10PeV. E^{-2} spectral behavior; equal fluence in all flavors

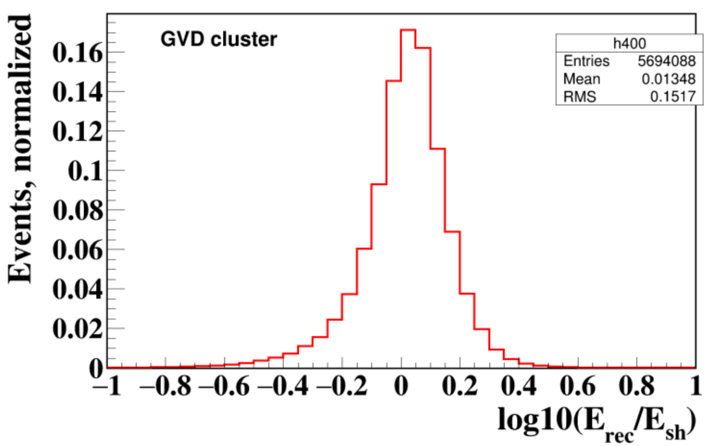
Cascades detection with GVD Cluster

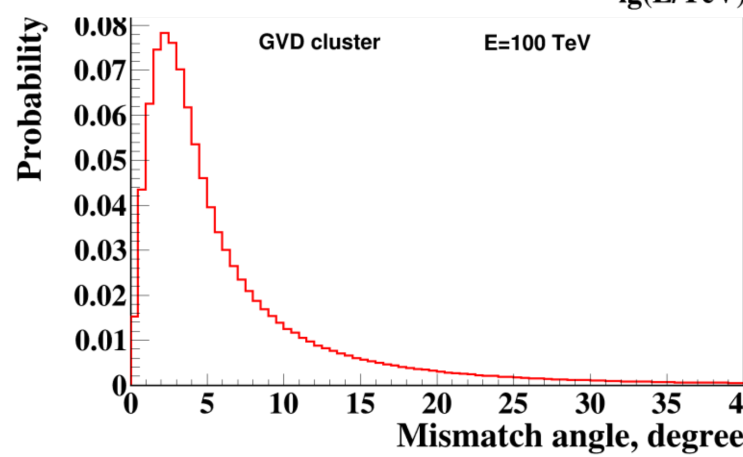
Neutrino Effective Area for 7 GVD Clusters



Expected number of events in 7 GVD Clusters from astrophysical







Energy resolution： δE/E ~ 10%-30%

Directional resolution for cascades:
2°– 4° – median value of

Preliminary!

High energy cascades (data and MC)

Data from 2018-2021 , **livetime: *5522* days** (in terms of one cluster)

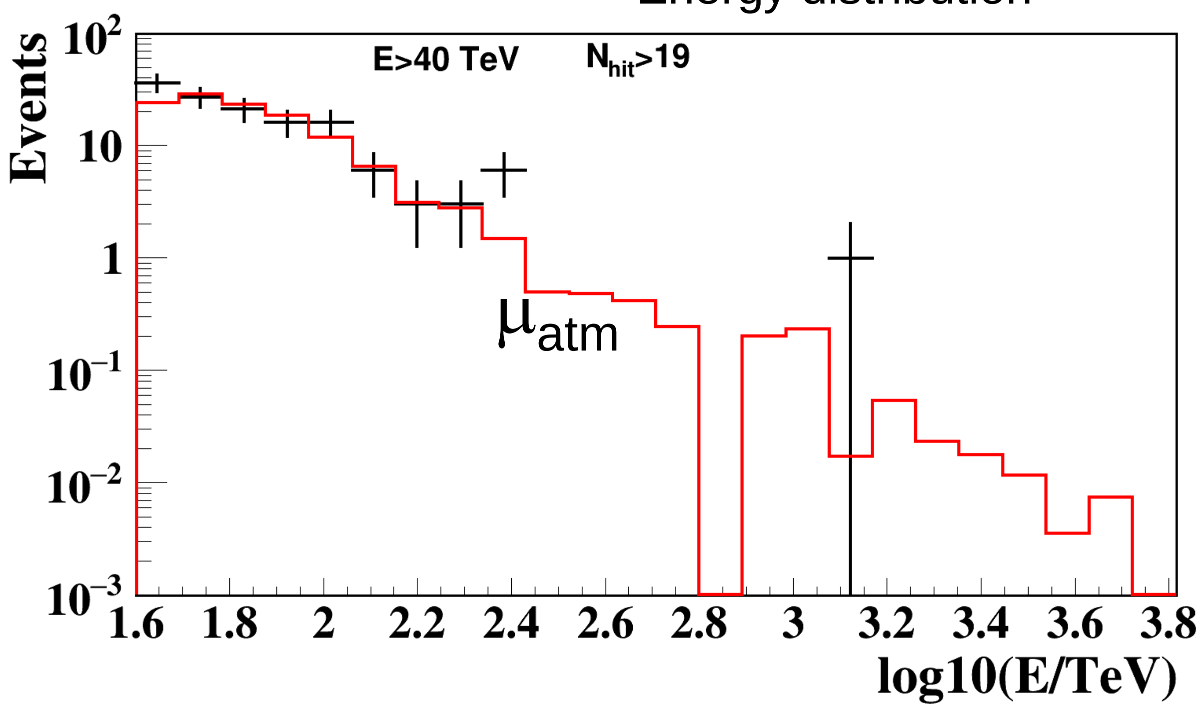
MC atmospheric muons - Corsika 7.74, Sybill 2.3c, protons, E_p>100 TeV
MC atmospheric neutrinos – L.Volkova (1980)
Benchmark astrophysical flux – IC $E^{-2.46}$

Standard cascades selection:

[JETP, 134 (2022) 399]

135 events with E > 40 TeV and N_{hit} > 19
23 events with E > 100 TeV and N_{hit} >19:

Energy distribution



All sky search for HE cascades

Preliminary!

Additional selection requirements

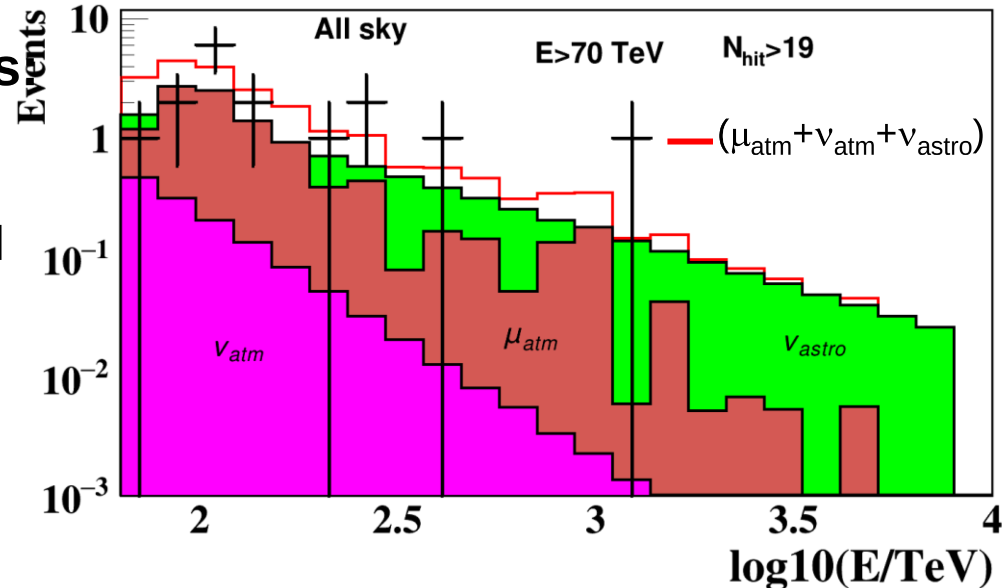
(N_{Type_2} = 0, $E_{rec} \geq$ 70 TeV) or
(N_{Type_2} = 1, $E_{rec} \geq$ 100 TeV),
(N_{Type_2} – number of hits in time interval where hits from muons are expected)

16 data events have been selected
8.7 events from atm. muons
0.8 events from atm. neutrinos
7.8 events are expected from IC $E^{-2.46}$ astrophysical flux

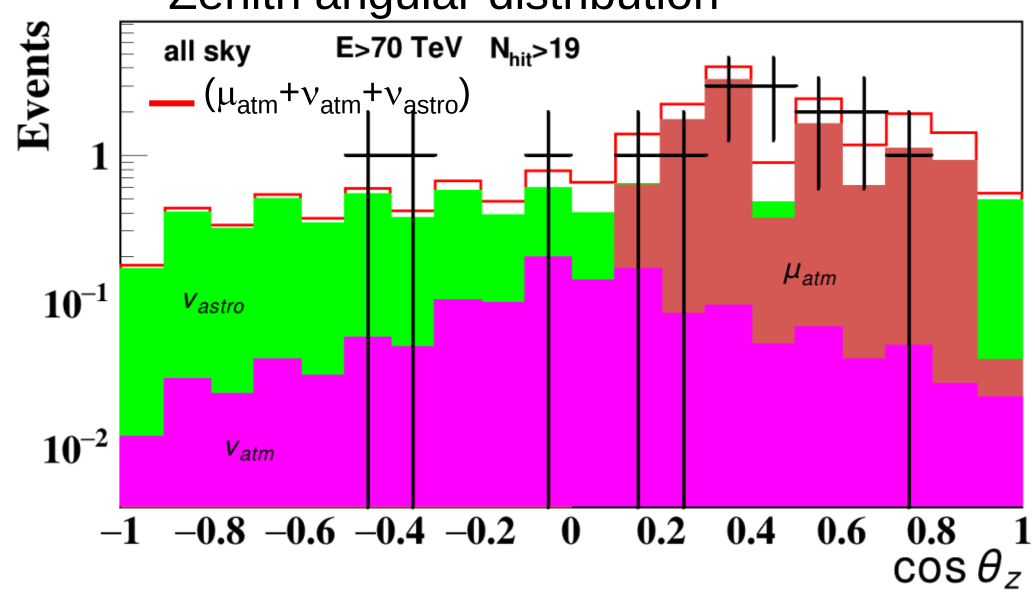
Probability for the background-only hypothesis (stat. errors only):

P-value=0.033 or 2.13σ

Energy distribution



Zenith angular distribution



Search for upward moving events *Preliminary!*

Additional selection requirements

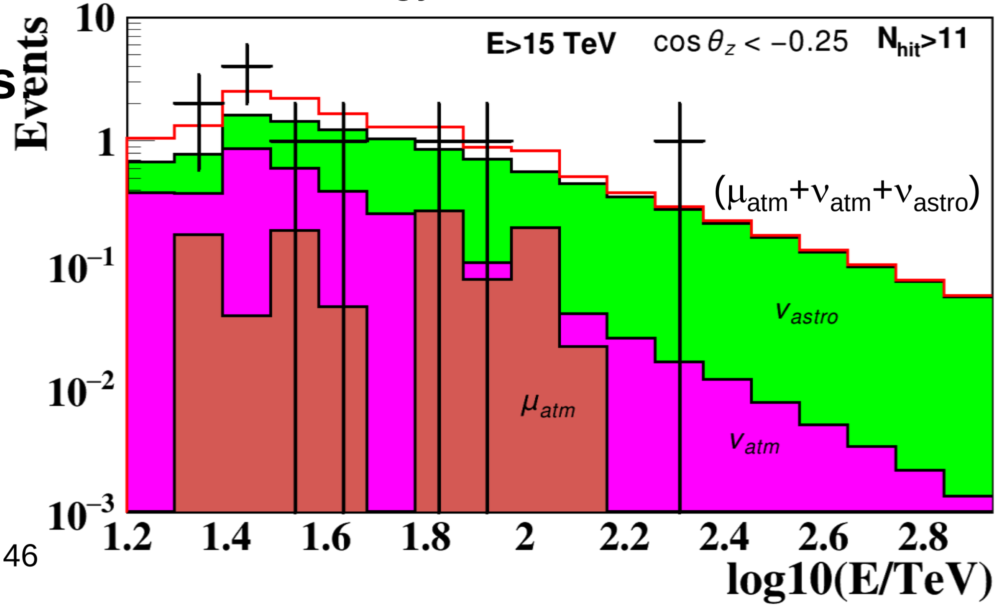
E > 15 TeV & N_{hit} >11 & $\cos\theta_z$ < -0.25

11 - data events have been selected
0.95 - events from atm. muons
3 - events from atm. neutrinos
10.3 - events are expected from IC $E^{-2.46}$ astrophysical flux

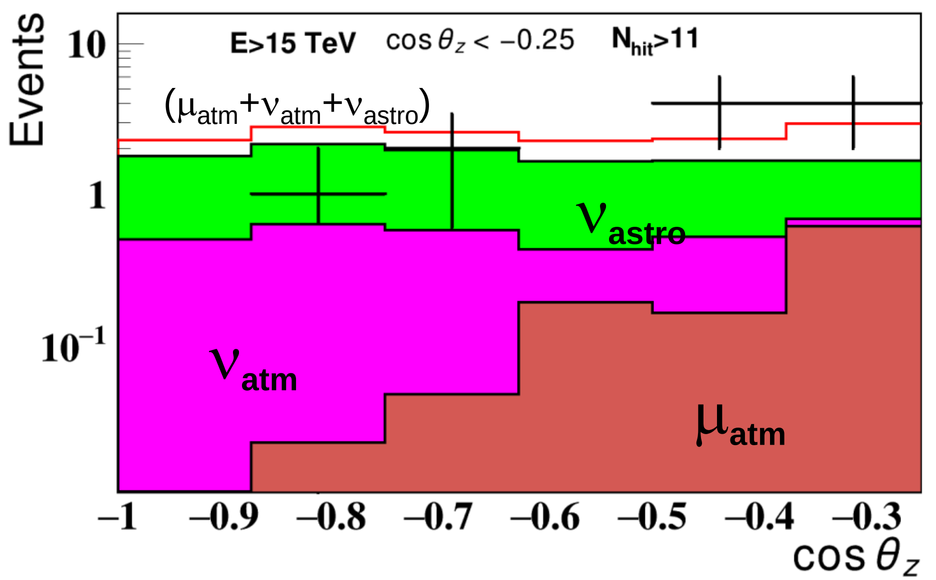
Probability for the background-only hypothesis (stat. errors only):

P-value = 0.00268 (3σ)

Energy distribution



Zenith angular distribution



Preliminary!

Combined analysis of upward moving events and downward moving HE cascades

25 data events have been selected

9.7 events are expected from atm. muons

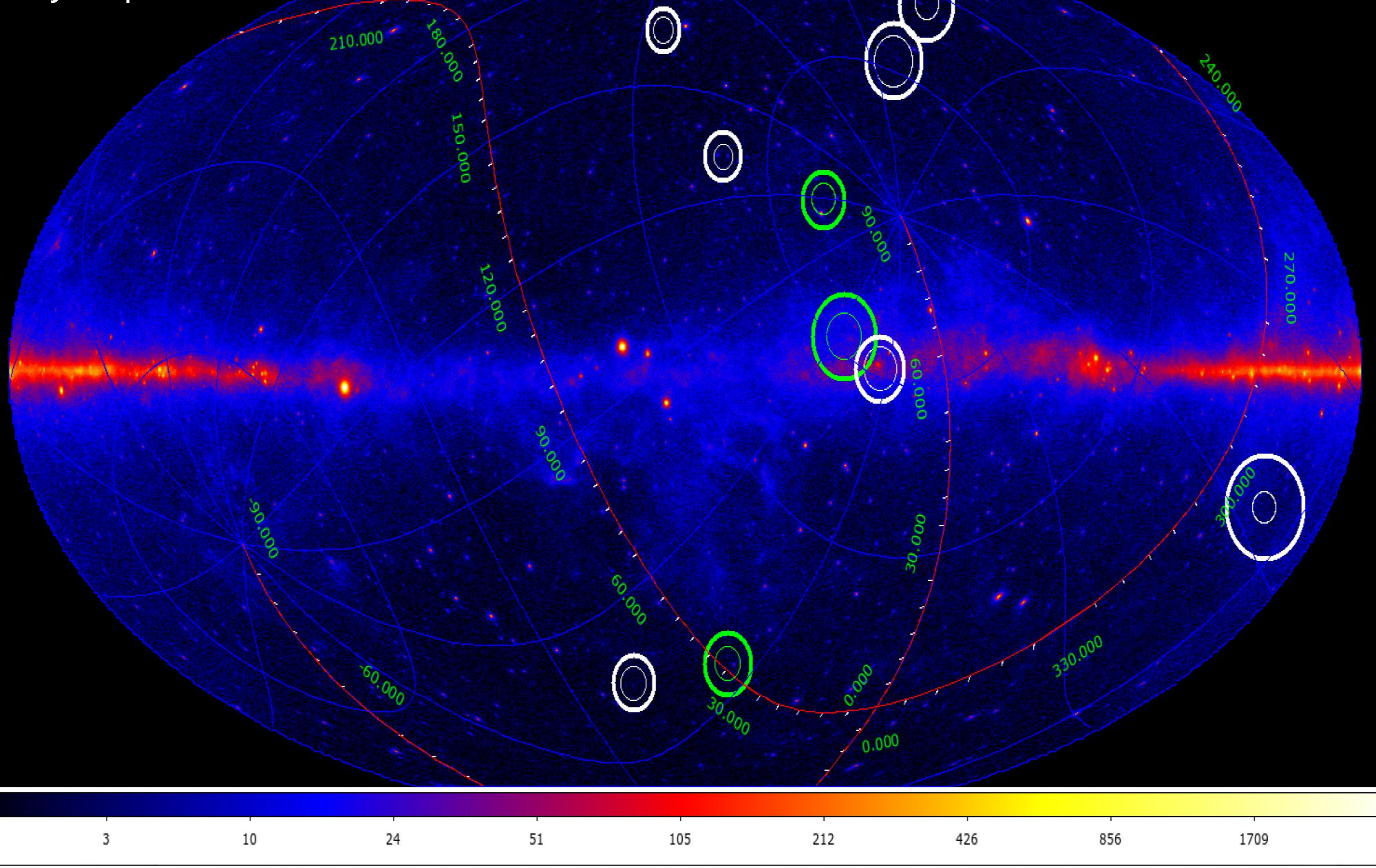
3.4 events are expected from atm. neutrinos

16 events are expected from IC $E^{-2.46}$ diffuse astrophysical neutrino flux

P-value = 0.0022 (3σ)

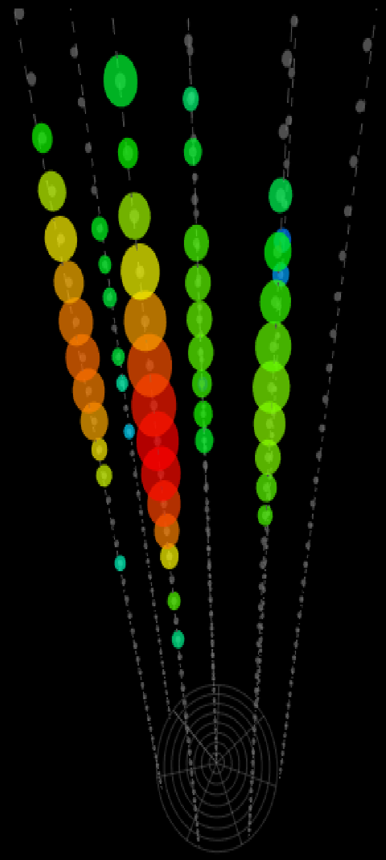
Baikal-GVD confirms IceCube observation of astrophysical diffuse neutrino flux at 3σ level !

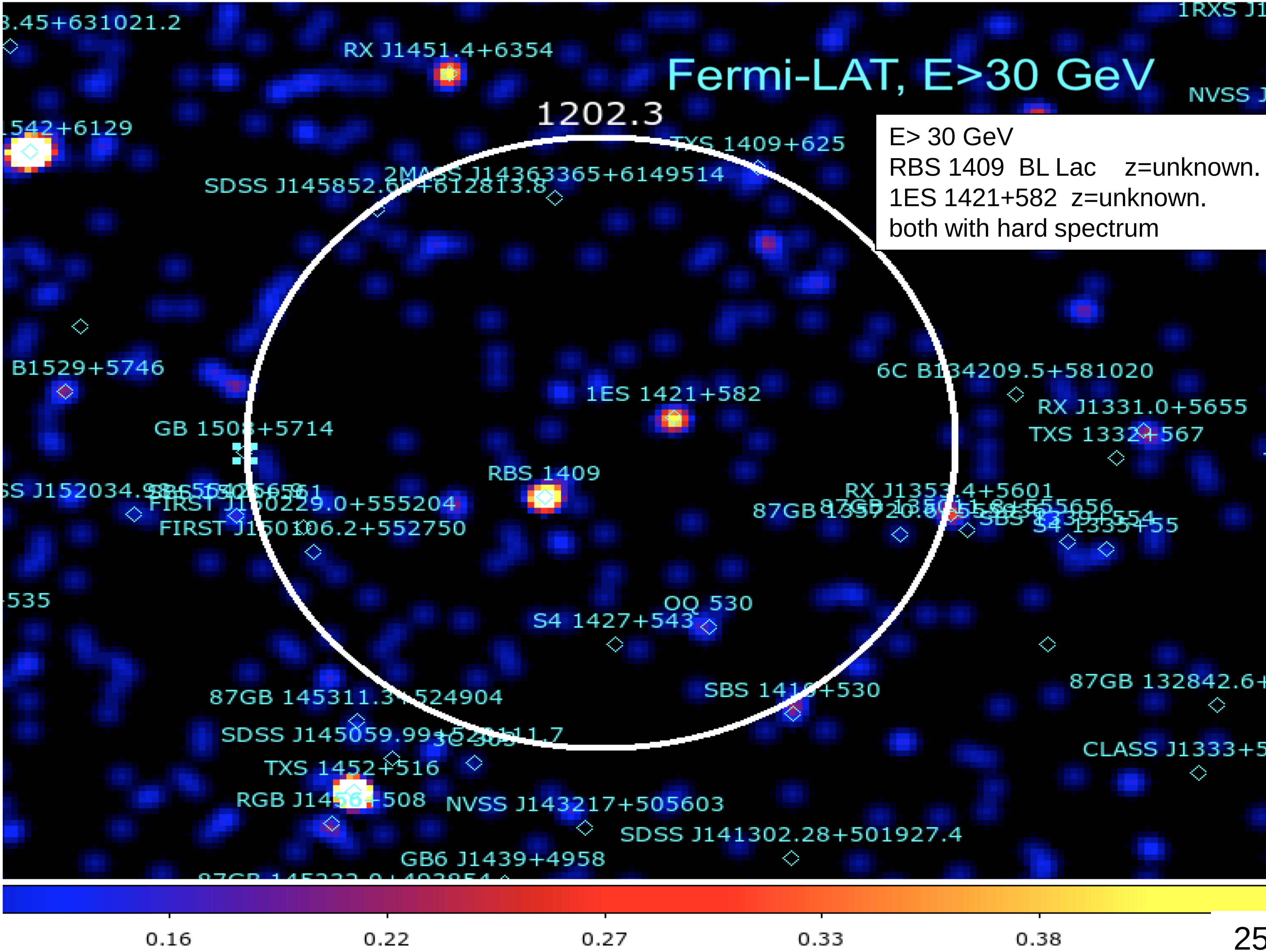
Sky map with 10 events 2018-2020



GVD_2019_112_N

Energy E = 1200 TeV (±30%);
distance from central string r = 91 m;
Zenith angle = 61°



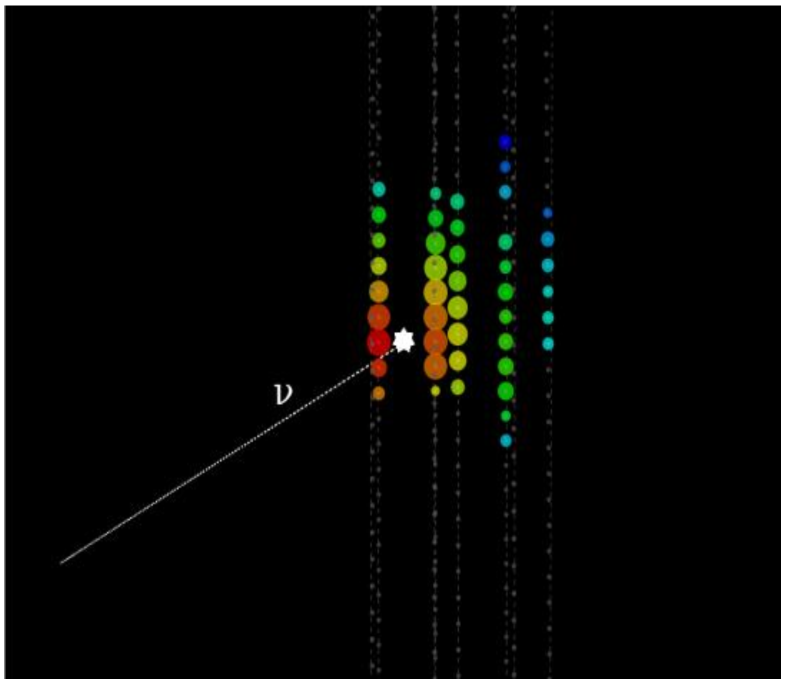


E> 30 GeV
RBS 1409 BL Lac z=unknown.
1ES 1421+582 z=unknown.
both with hard spectrum

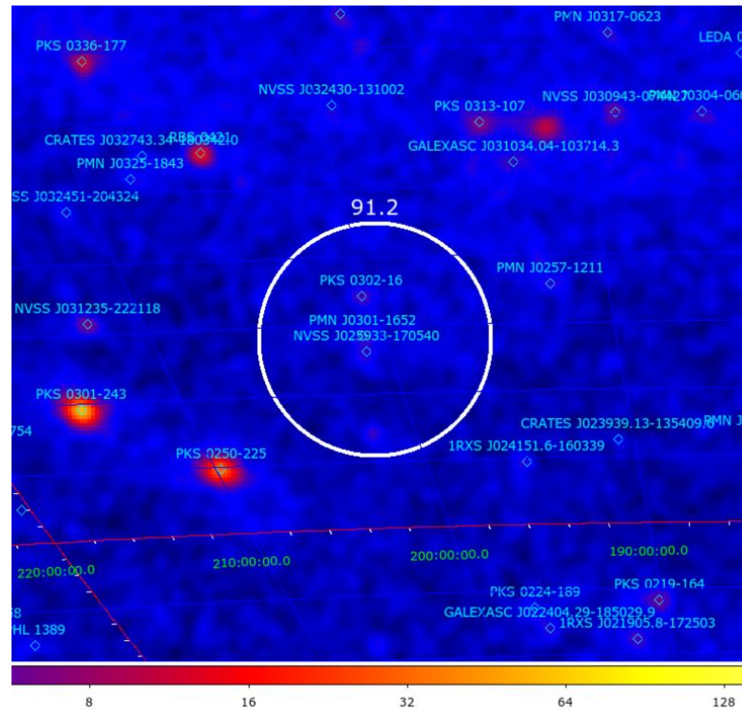
GVD2019_1_114_N

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

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



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

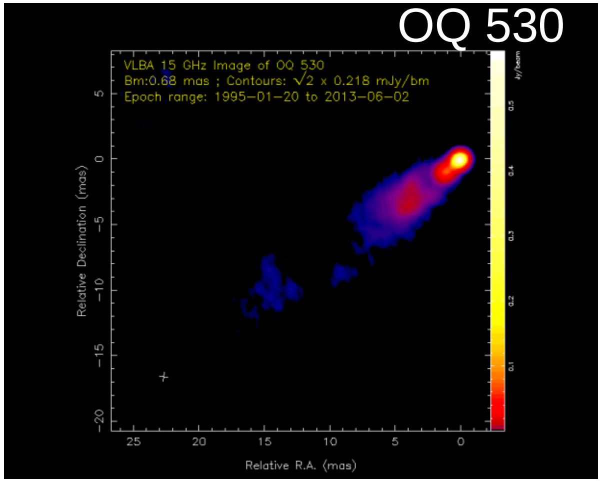


No good known sources in 3 degrees
PKS 0302-16 unknown type of source
PMN J0301-1652 unknown type of source

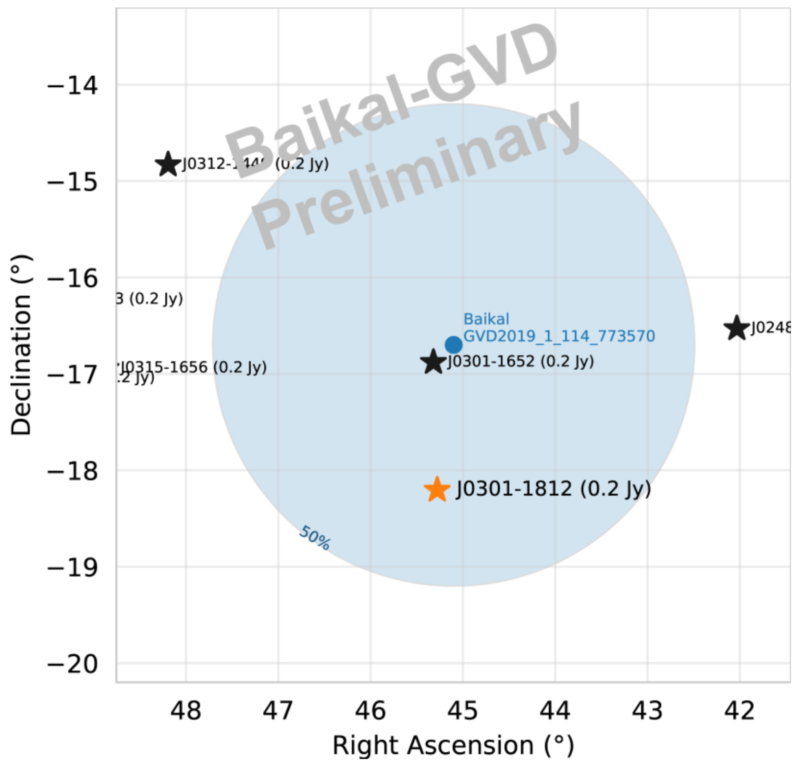
Radio-loud blazars – promising neutrino sources

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

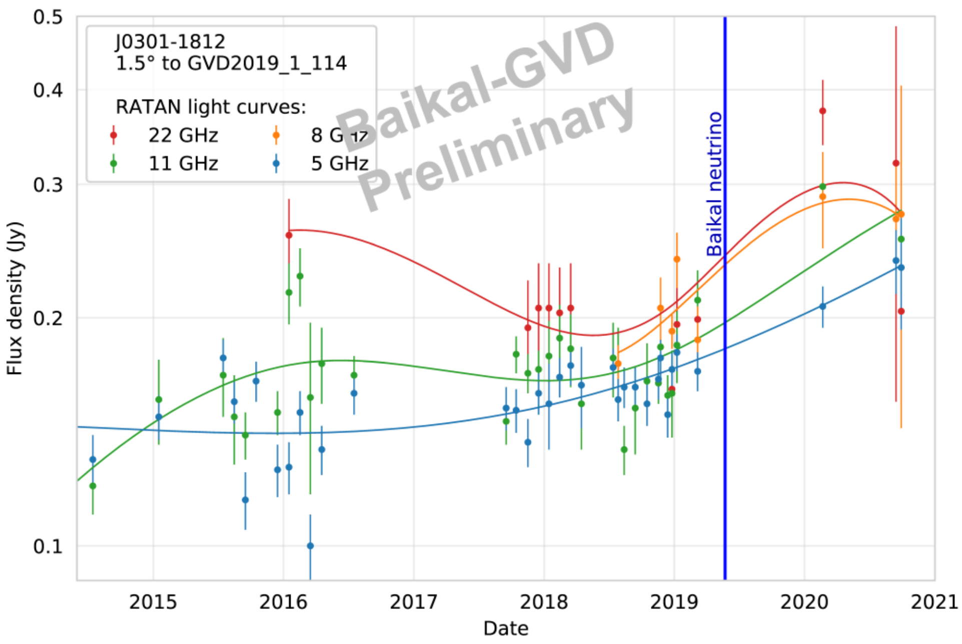
GVD2019_1_114_N
Radio blazar J0301-1812



Sky plot of radio-bright blazars nearby neutrino event

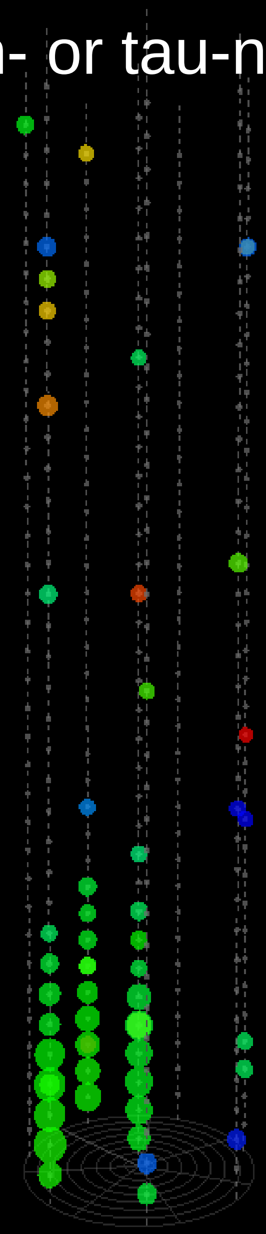


Light curves of J0301-1812 measured by RATAN-600



The second clear cascade event from the interaction of an upward moving electron- or tau-neutrino at the 200 TeV

GVD_2021_20_N



Energy E = 224 TeV (±30%);
distance from central string
r = 70 m;
Zenith angle = 115°

Conclusion

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere and growing

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

- Observations of atmospheric neutrinos by Baikal-GVD agree with expectations

- First 25 astrophysics neutrino candidate events have been selected - Baikal-GVD confirms IceCube observation of astrophysical diffuse neutrino flux at 3σ level

OUTLOOK

- 2025/2026 – ~ 1km^3 GVD with total of 16-18 clusters

- 2022-2024 – “Conceptual Design Report” for next generation neutrino telescope in Lake Baikal


Deployment rate – 2 clusters/year
GVD (1 km^3) in 2026