Baikal-GVD: status and perspectives

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for the Baikal Collaboration
NUTEL2021, February 23, 2021

Baikal-GVD collaboration

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)

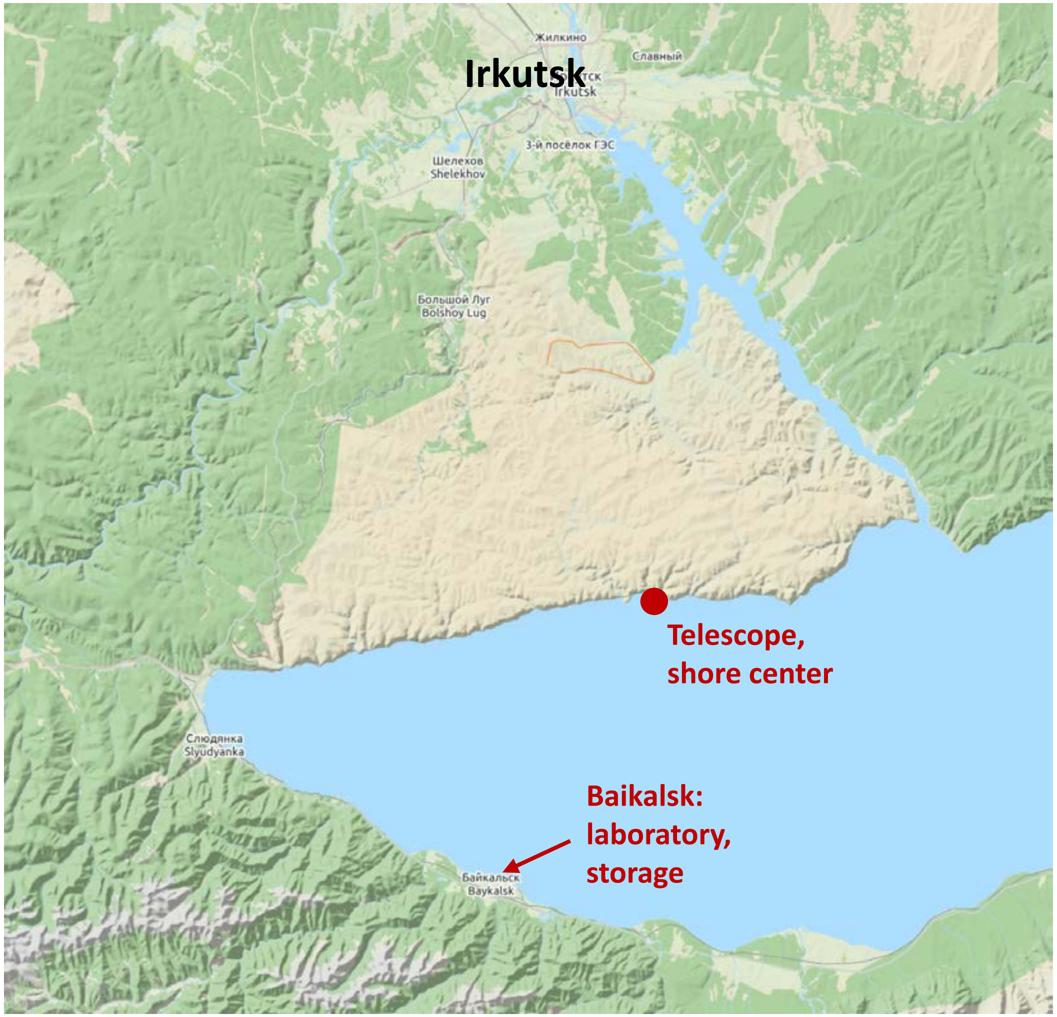
Baikal-GVD site

Railway stop “106 km” of
Circum-Baikal railway

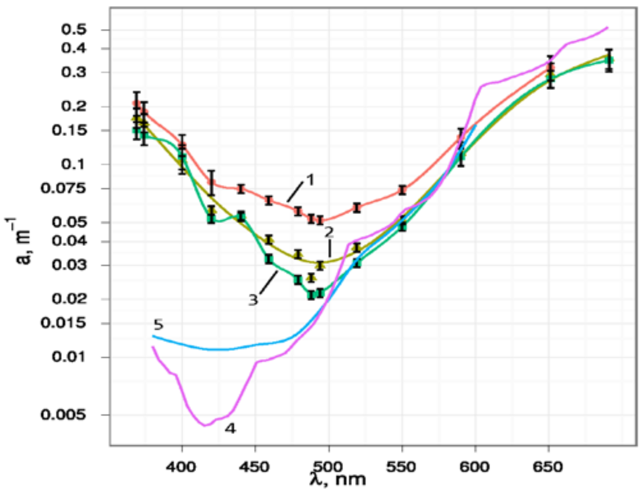
Telescope is located
3.6 km away from shore

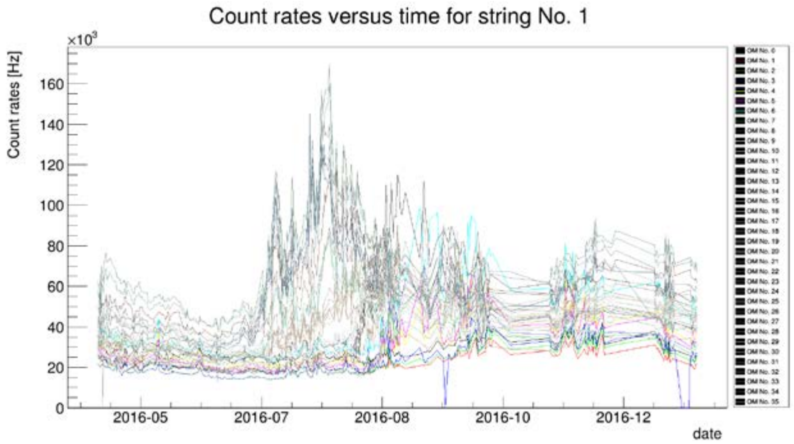
Constant lake depth:
•1366 - 1367 [m]

Stable ice cover for 6-8 weeks in
February - April
•Detector deployment
•Maintenance



Water properties



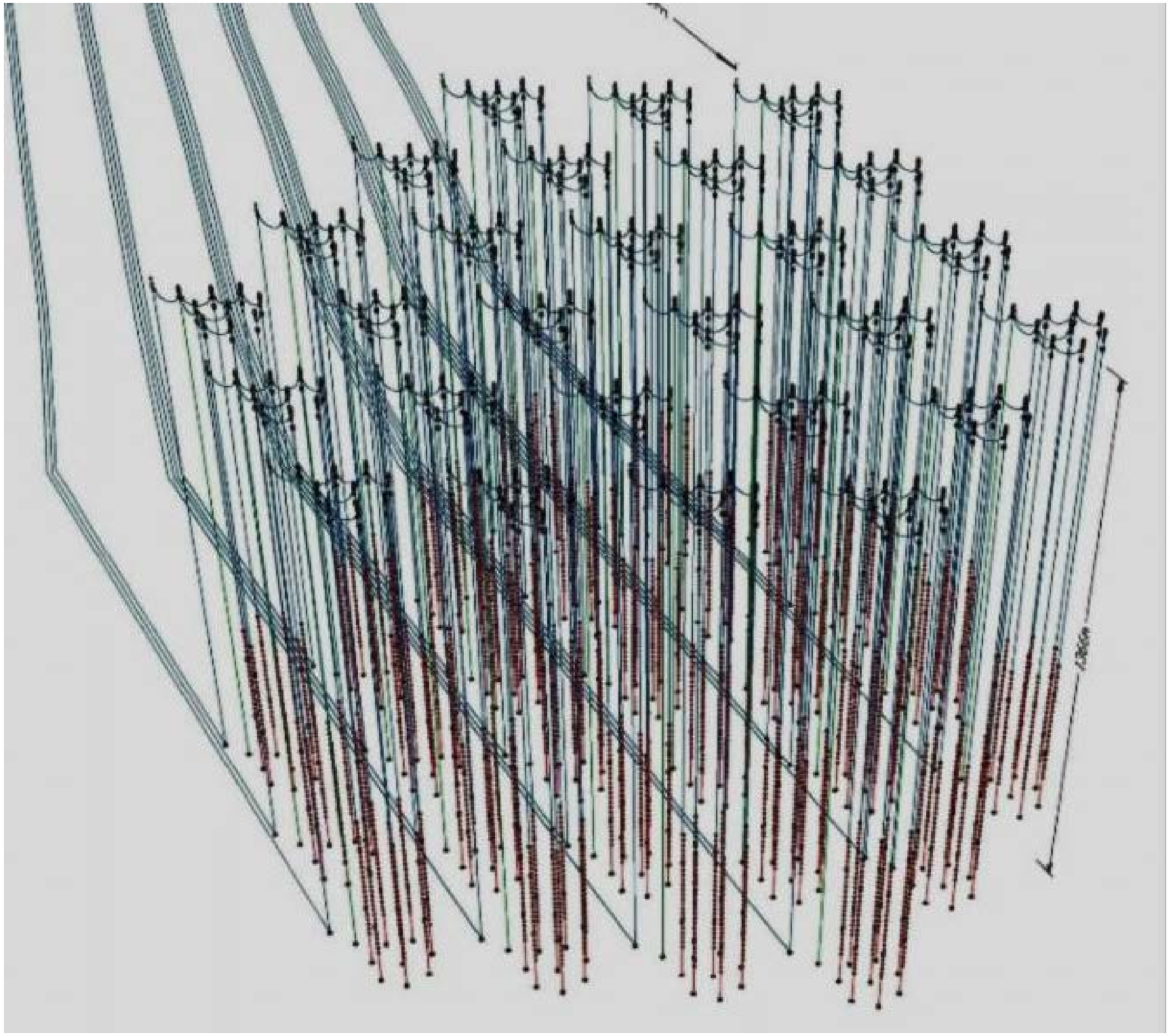


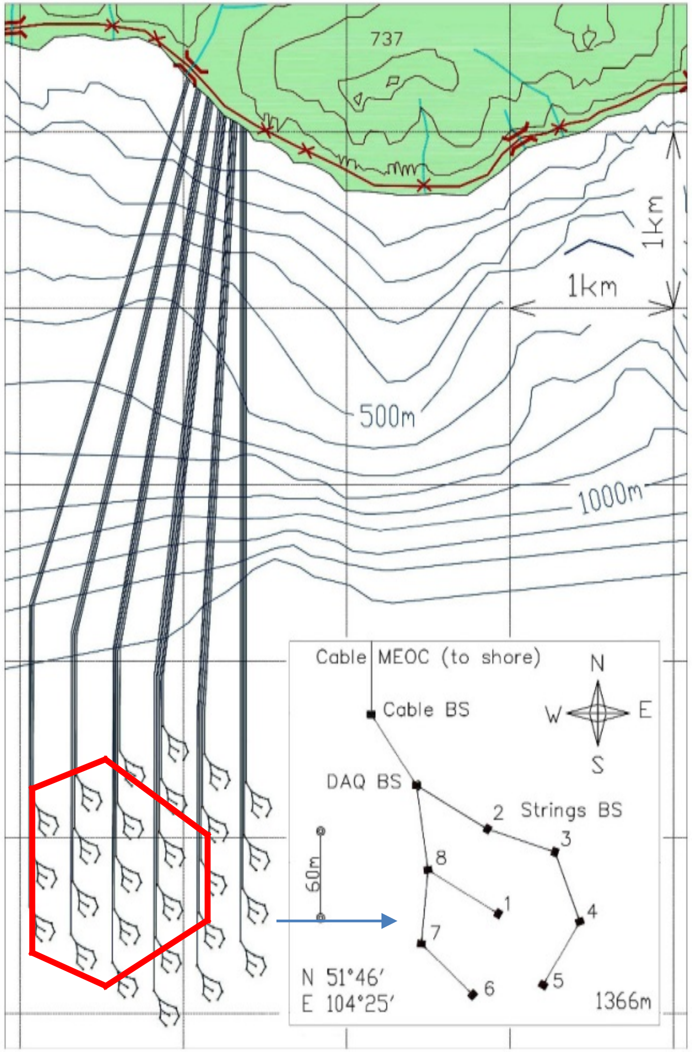
- **Absorption length: ~ 22-24 m**
- **Scattering length: L_s ~ 30-50 m**
  $L_{eff} = L_s/(1- \langle\cos\theta\rangle)$ ~ 300-500 m
- **Strongly anisotropic phase function: $\langle\cos\theta\rangle$ ~ 0.9**
- **Moderately low background in fresh water:**

  15 – 40 kHz (R7081HQE)
  absence of high luminosity bursts from biology and K^{40} background.

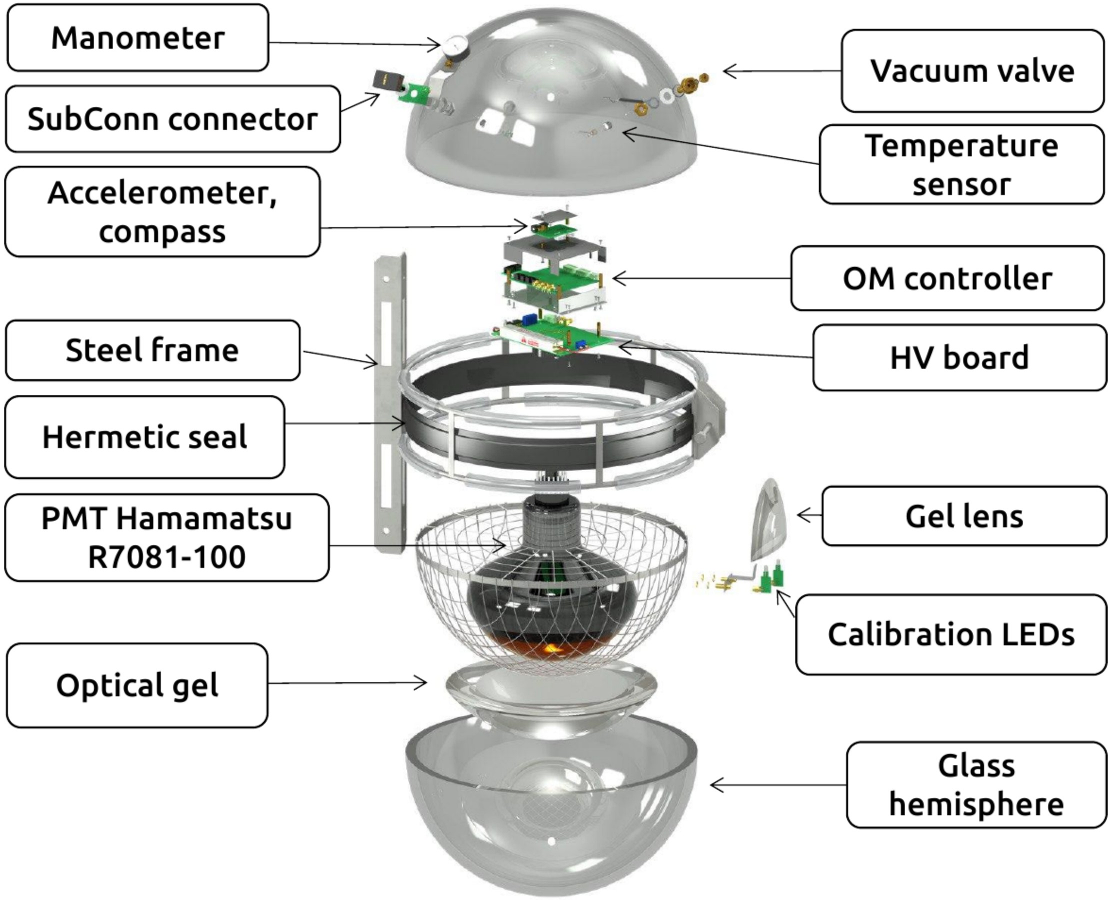
Gigaton Volume Detector at Lake Baikal

Baikal-GVD (Gigaton Volume Detector) is a cubic-kilometer scale underwater neutrino detector being constructed in Lake Baikal



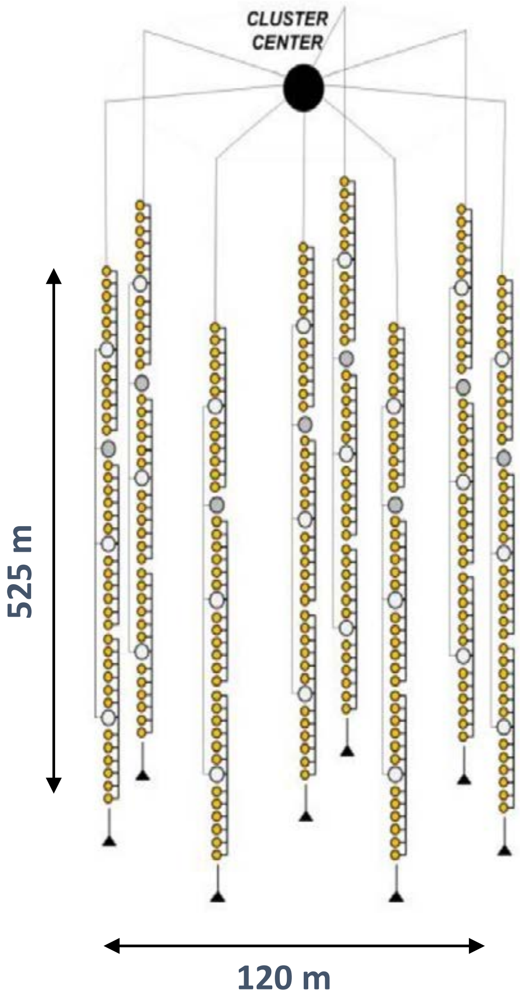


Baikal-GVD optical module



Baikal-GVD detector layout

CLUSTER:
8 strings

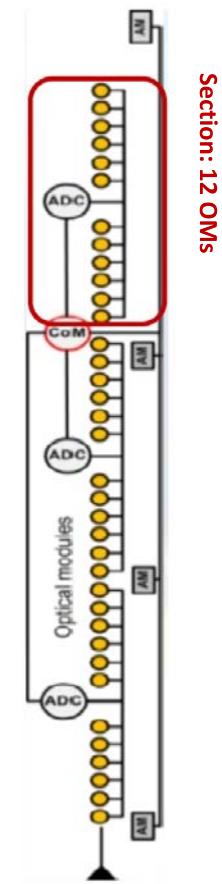


Cluster
- Consists of 8 strings
- 60 m step between strings
- Acts as independent detection unit
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger:

4.5 p.e. + 1.5 p.e. on adjacent OMs in 100 ns window

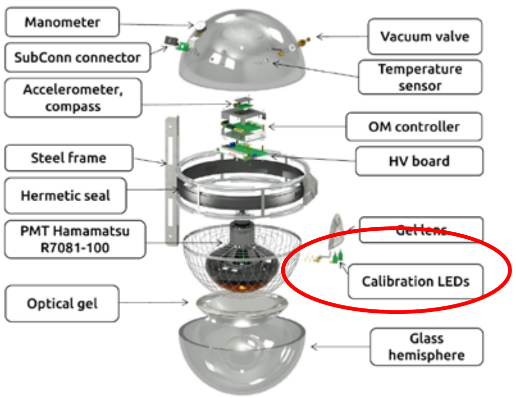
String
- 36 OMs, depths from 750 m to 1275 m
- 15 m step between OMs
- All OMs look downward
- Acoustic and LED calibration devices
- Anchored at the lake bottom

STRING

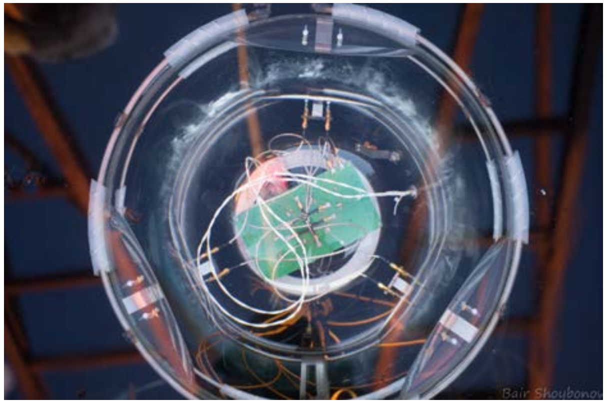


Calibration devices

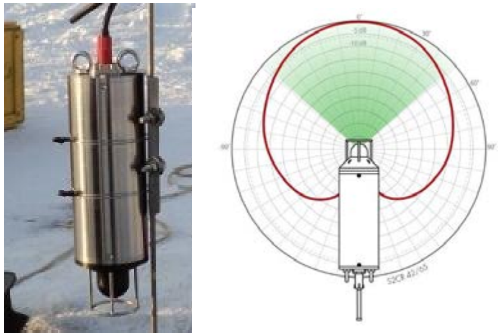
Calibration LEDs in each OM



LED beacons for time calibration

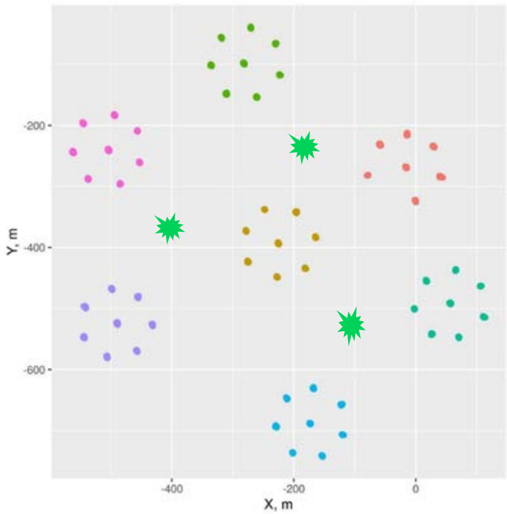


Hydrophones for acoustic positioning (4 per string, ~ 20 cm precision)



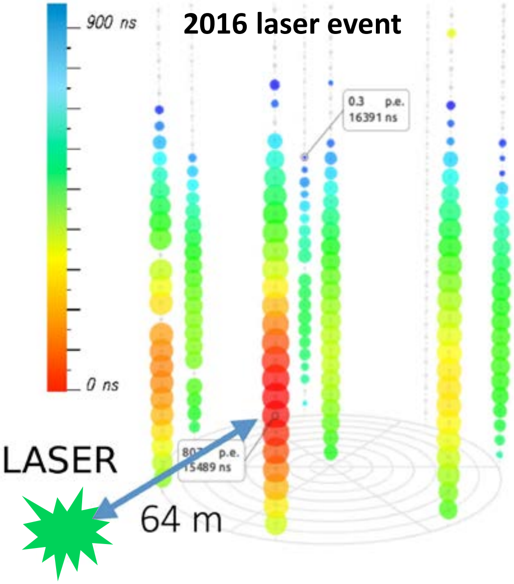
Laser 532 nm, 0.37 mJ, 1 ns

Baikal-GVD 2020 top view



- Cluster 1
- Cluster 2
- Cluster 3
- Cluster 4
- Cluster 5
- Cluster 6
- Cluster 7
- Tech. strings

with 1 or 2 lasers on each string



Acoustic positioning system

1. OM coordinates are acquired via an acoustic positioning system.

2. It consists of a network of acoustic modems (AMs) installed along GVD strings

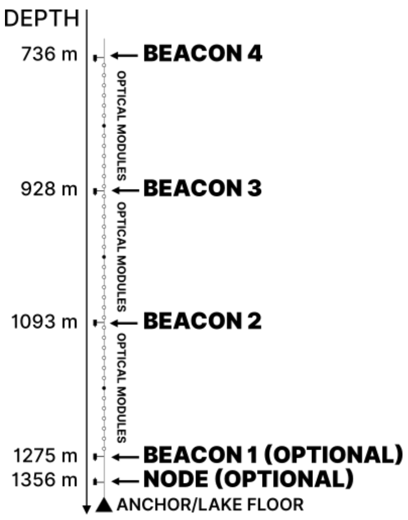
3. 4 AMs per string in a standard configuration.

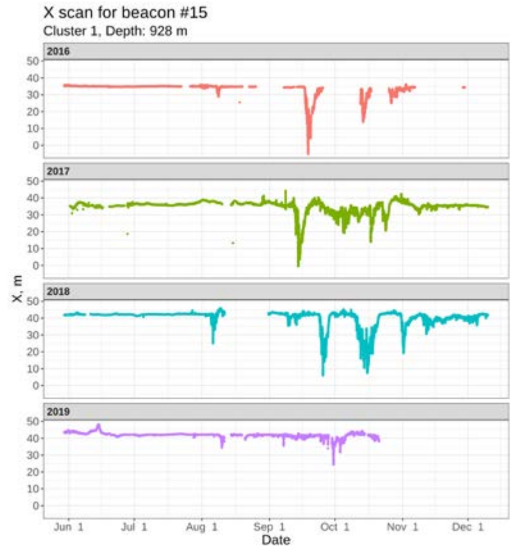
4. AM coordinates are regularly reconstructed via acoustic trilateration.

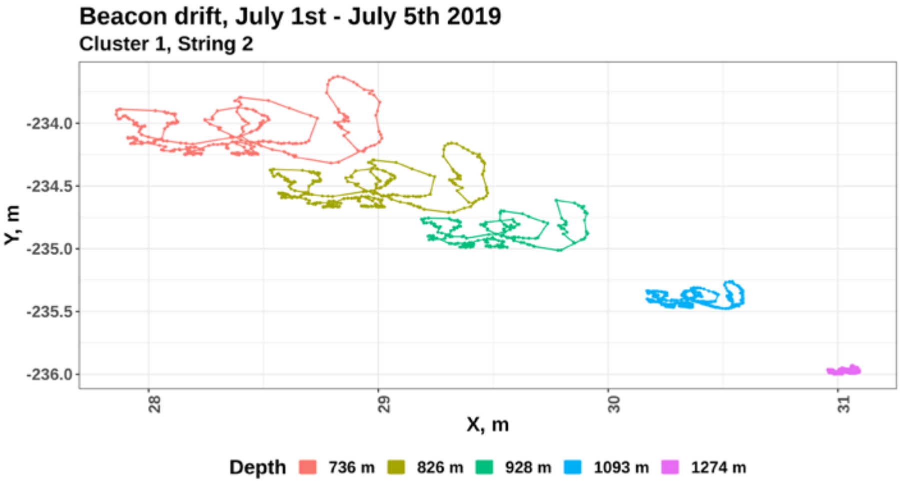
5. OM coordinates are obtained by interpolating AM coordinates.

6. OM coordinates error < 0.2m, as estimated via a calibration AM.

7. OM drift can reach tens of meters, depends on season and elevation.





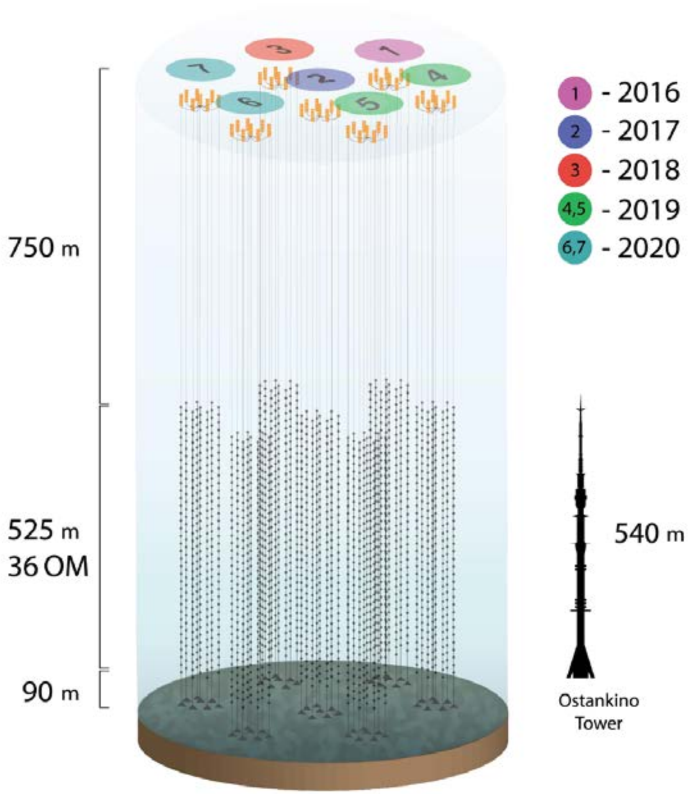


Winter expedition 2020

Despite harsh ice conditions this winter

two new clusters were deployed (576 OMs)

Baikal-GVD construction status and schedule

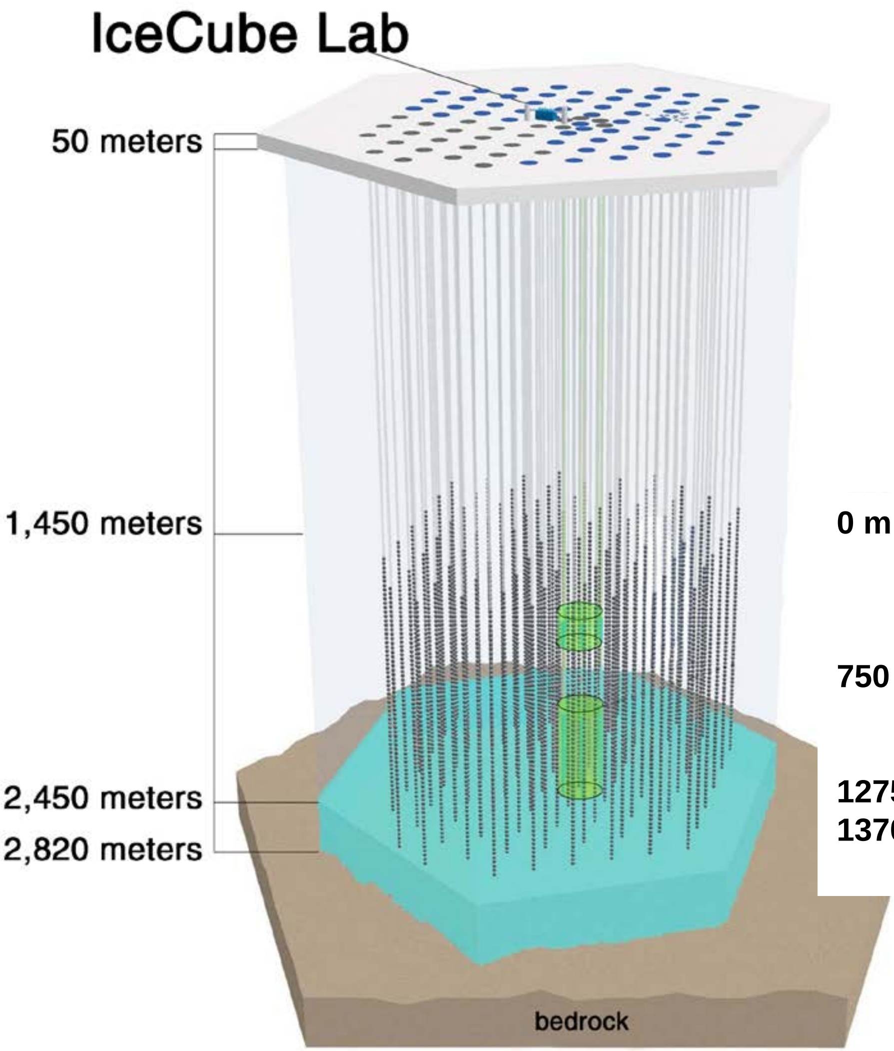


300 m step between clusters

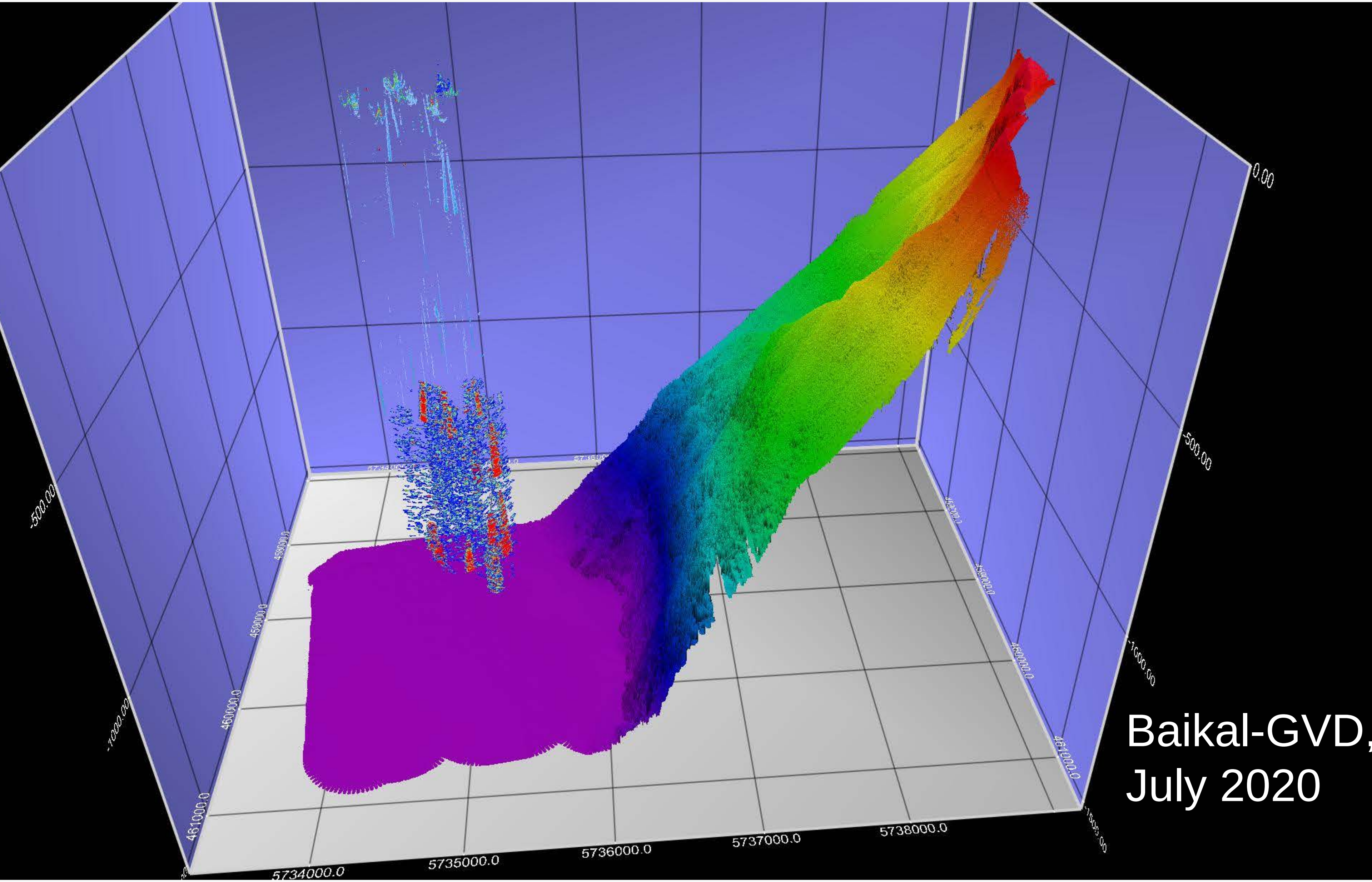
Deployment schedule

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

Effective volume 2020: 0.35 km^3

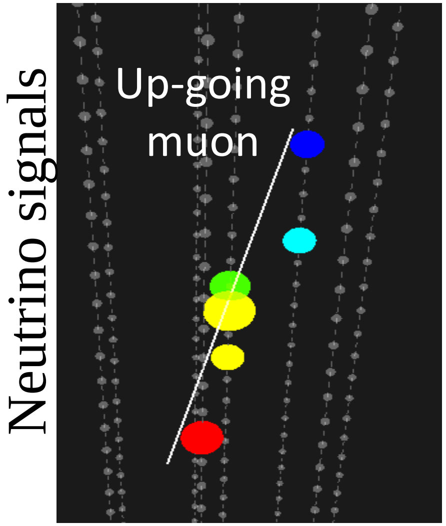

IceCube Lab
50 meters
1,450 meters
2,450 meters
2,820 meters
bedrock

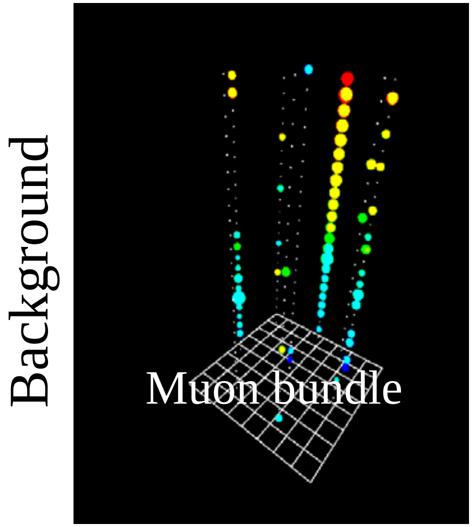

0 m
750 m
1275 m
1370 m
1 - 2016
2 - 2017
3 - 2018
4,5 - 2019
6,7 - 2020

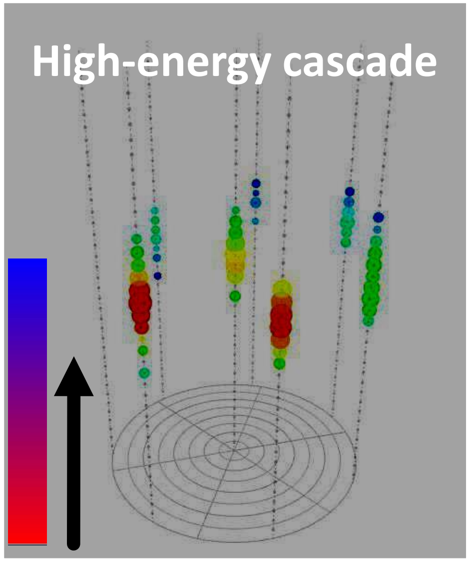


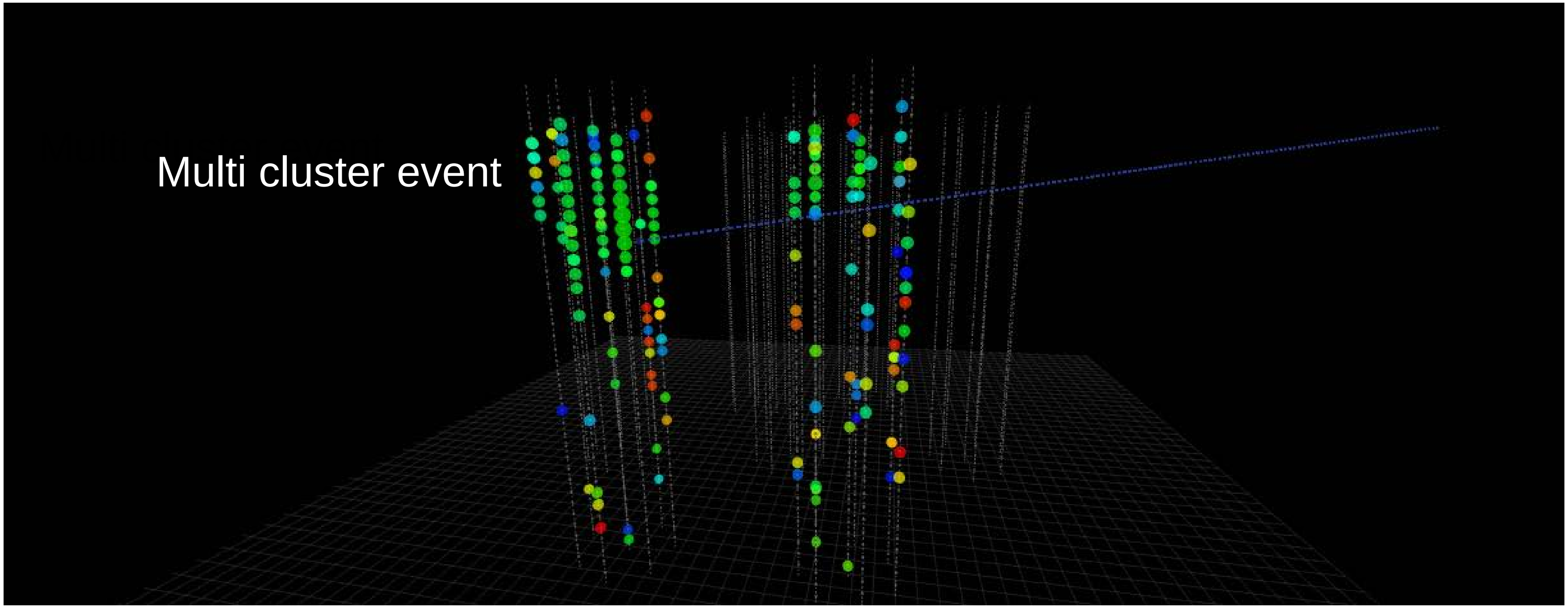
Baikal-GVD,
July 2020

Detector response









Preliminary resalts

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

Track analysis

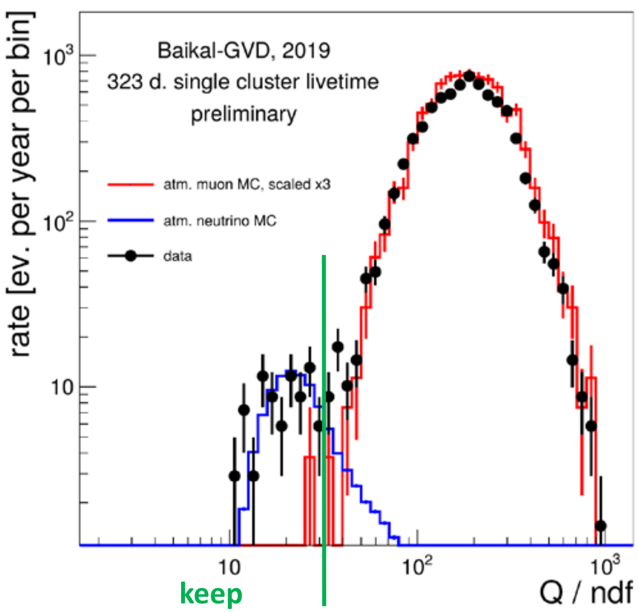
Fit track with quality function

$$Q = \chi^2(t) + f(q, r)$$

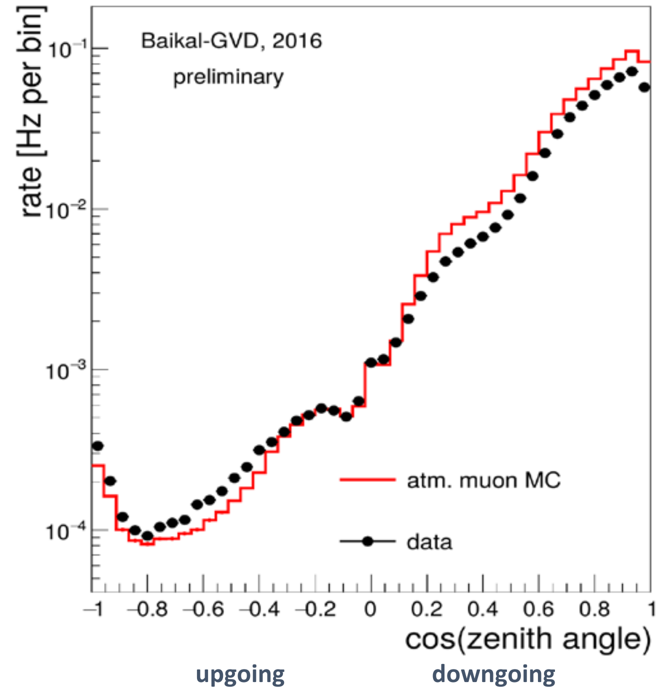
Neutrino selection:

- cut on zenith angle
- cut on fit quality

upgoing: θ_{zenith} > 120 deg.



event rate before quality cuts (dominated by muon bundles)

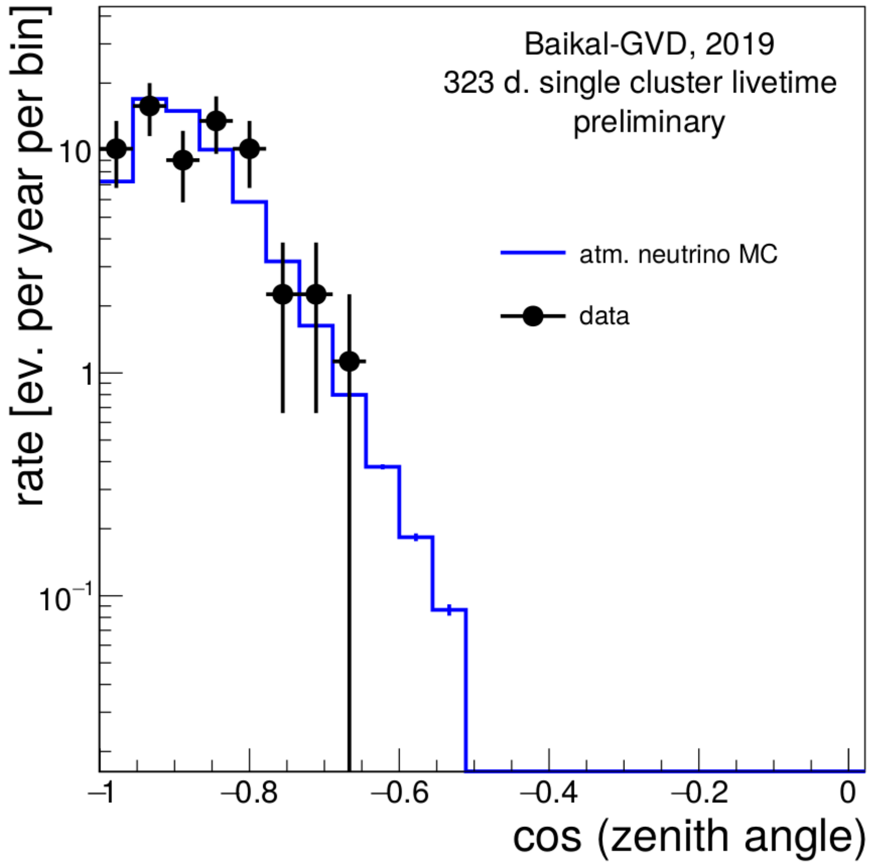


Fair agreement with MC predictions
Neutrino selection works as expected

A likelihood-based reconstruction is in development

Muon neutrino : single-cluster analysis

- Data taken between Apr 1 and Jun 30, 2019
- Live time: 323 days (single-cluster equivalent live time)



MC expected: 54.3
- atm. neutrino : 54.3
- atm. muon: < 1

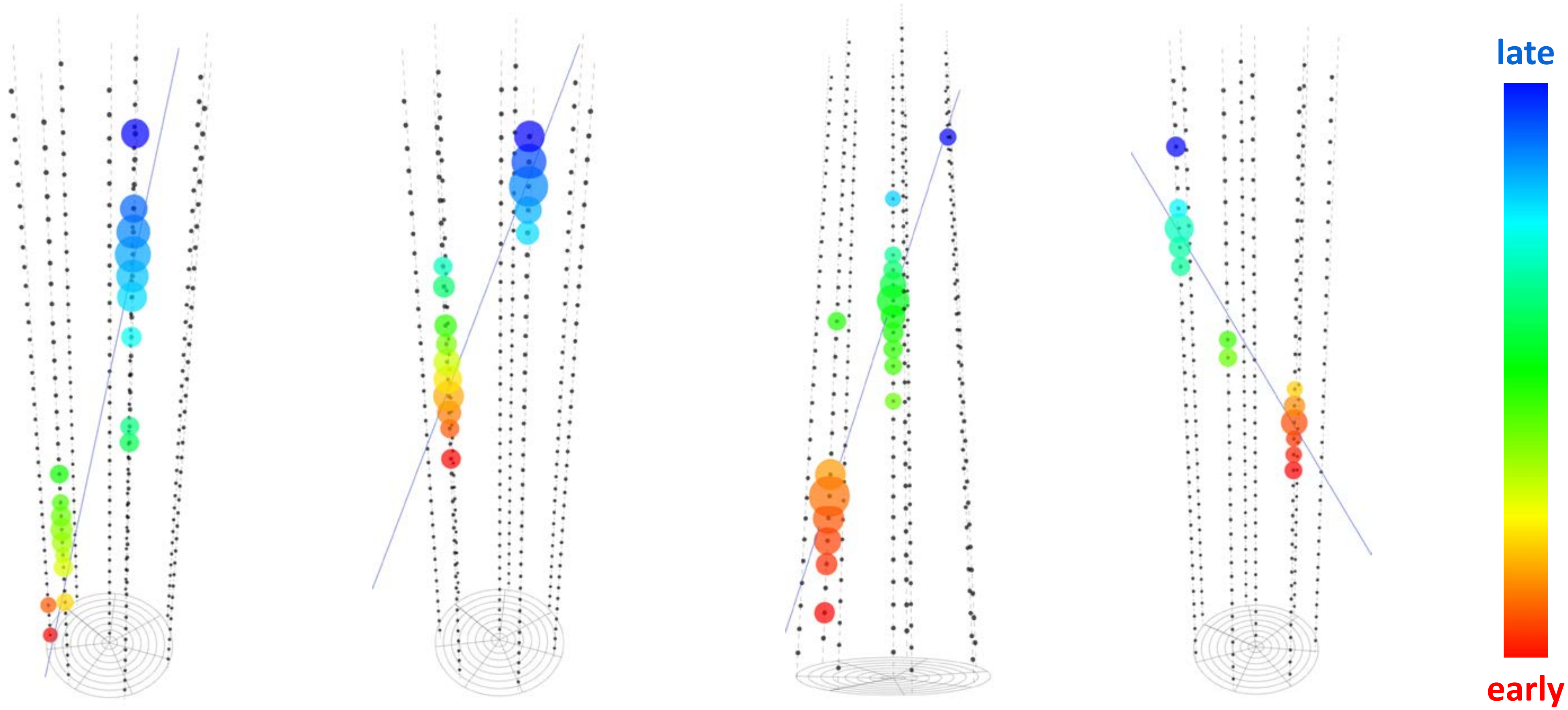
Observed: 57

Fair agreement with MC prediction for atmospheric neutrino

Angular resolution
~ 1° or better
(single cluster)

Multi-cluster analysis is in preparation

Muon neutrino candidates



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

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

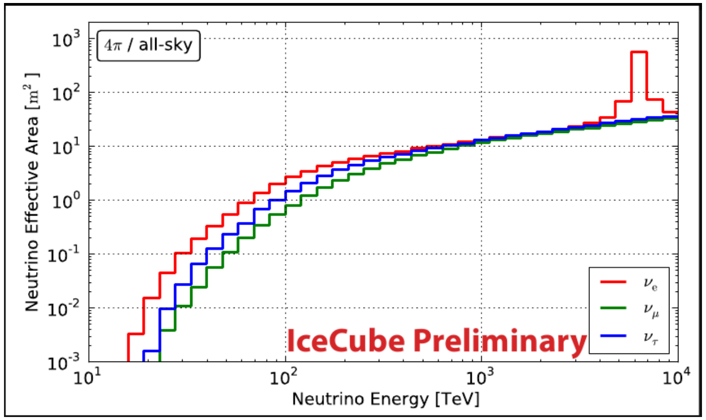
cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

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

Cascades detection with GVD Cluster

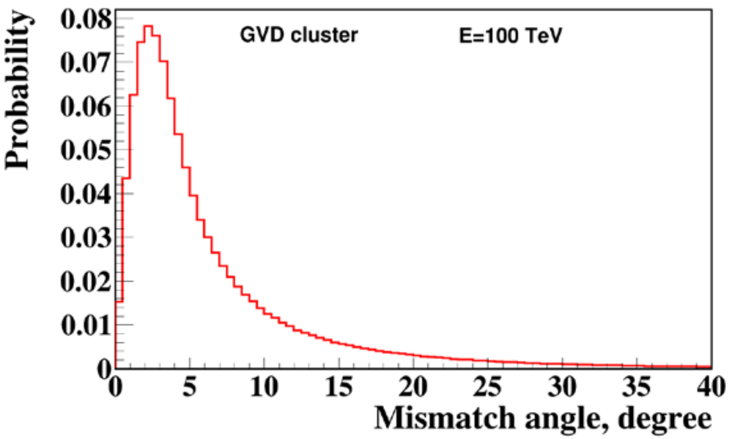
Neutrino Effective Area

IceCube HESE



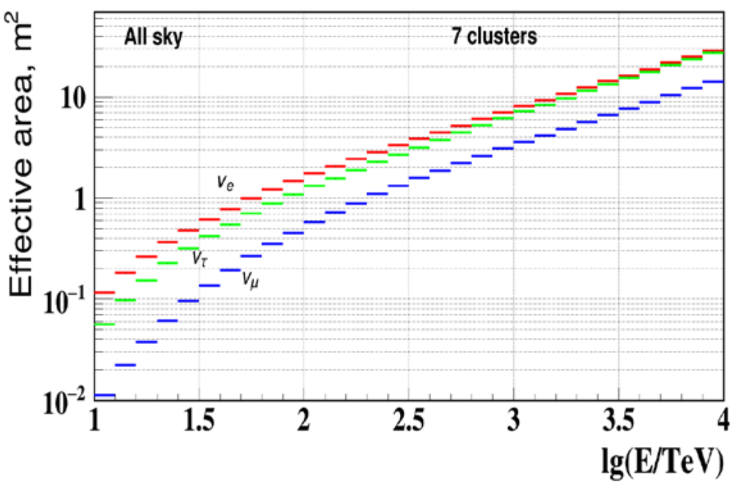
Directional resolution for cascades:
~ 2°- 4° - median value of mismatch angles

Distribution of mismatch angles



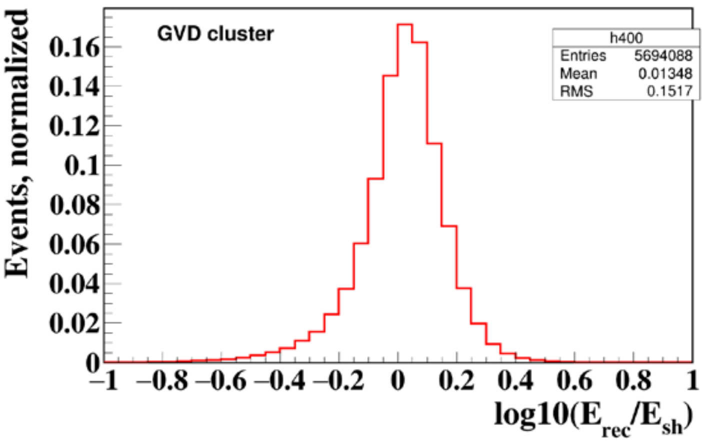
7 GVD Clusters

N_{hit} > 19 OMs

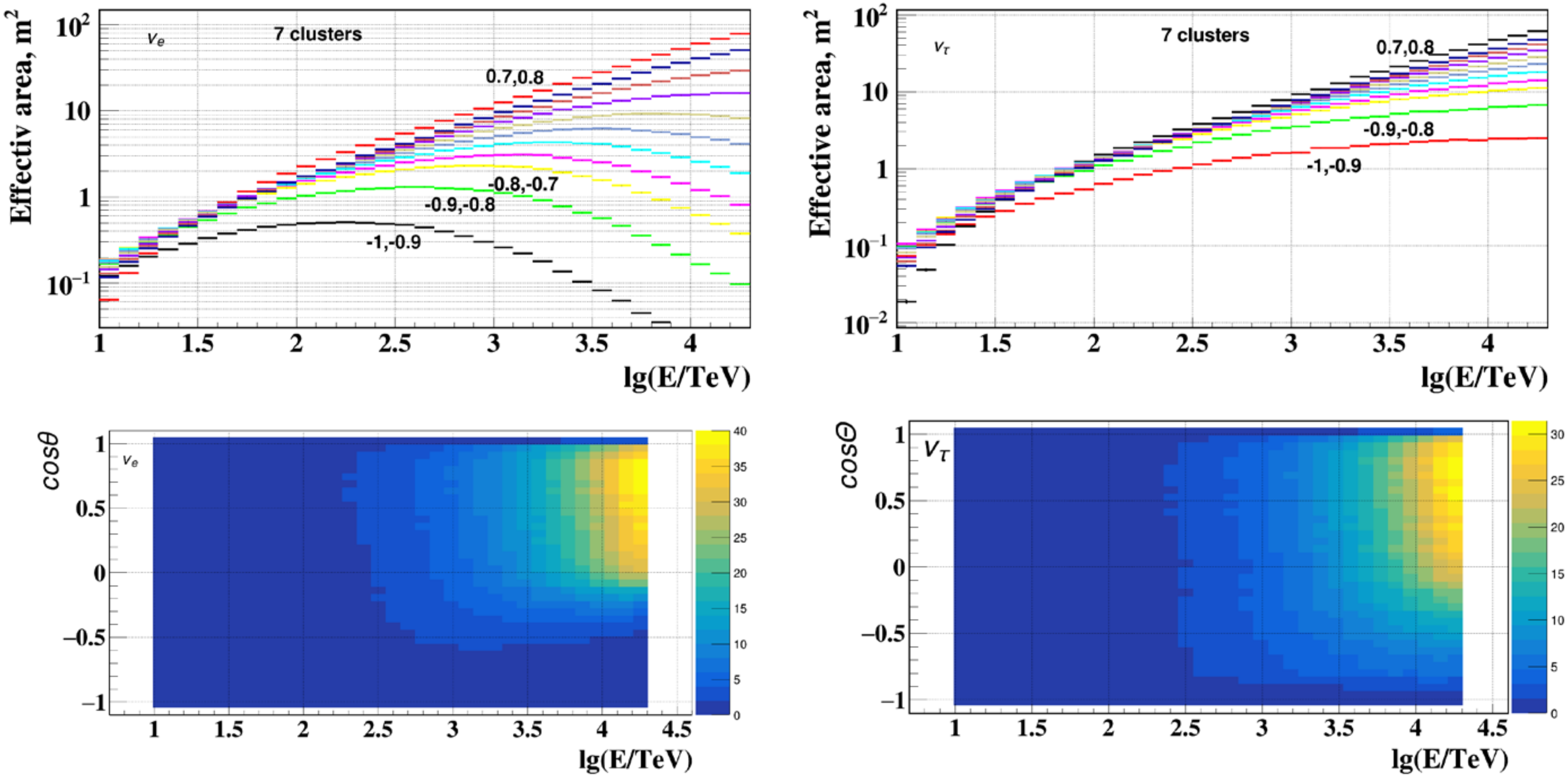


Energy resolution :

$\delta E/E$ ~ 10%-30%



Dependence of effective volume on zenith angle



Energy spectrum of astrophysical neutrinos measured by IceCube:

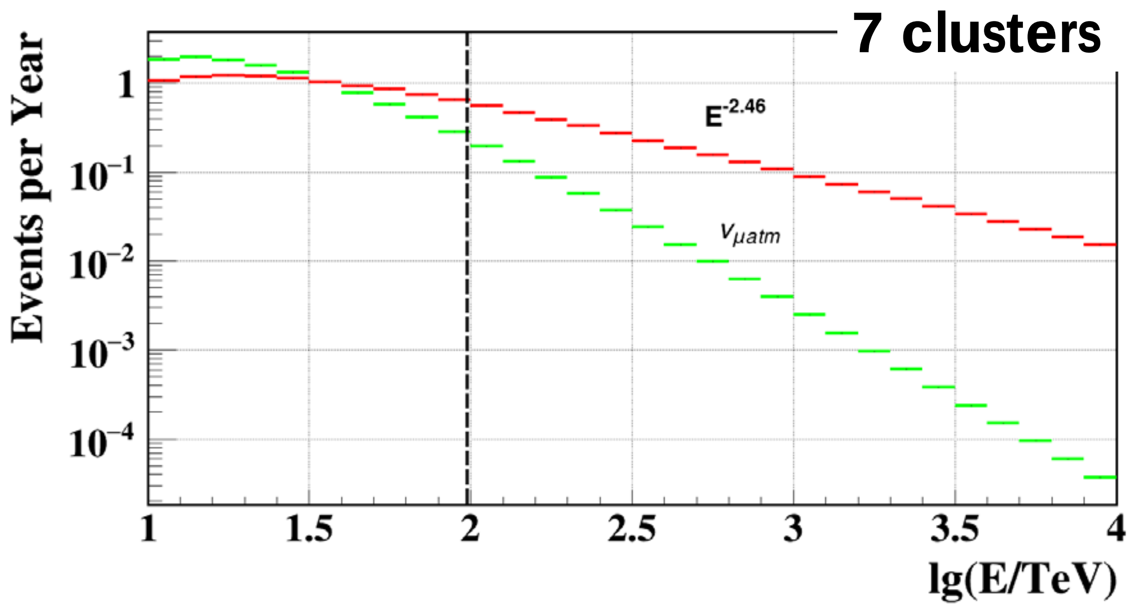
$4.1 \cdot 10^{-6}\ E^{-2.46}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

Expected number of detected events in 7 GVD Clusters from astrophysical neutrinos for 1 yr. observation

Event selection criteria (E_{sh} >100 TeV, N_{hit} >19):

~0.6 events/yr with 1 cluster

~ 3-4 events/yr with 7 clusters



Data sample

T = 3714 days (10.1 years) of one Cluster operation (2018, 2019, 2020)

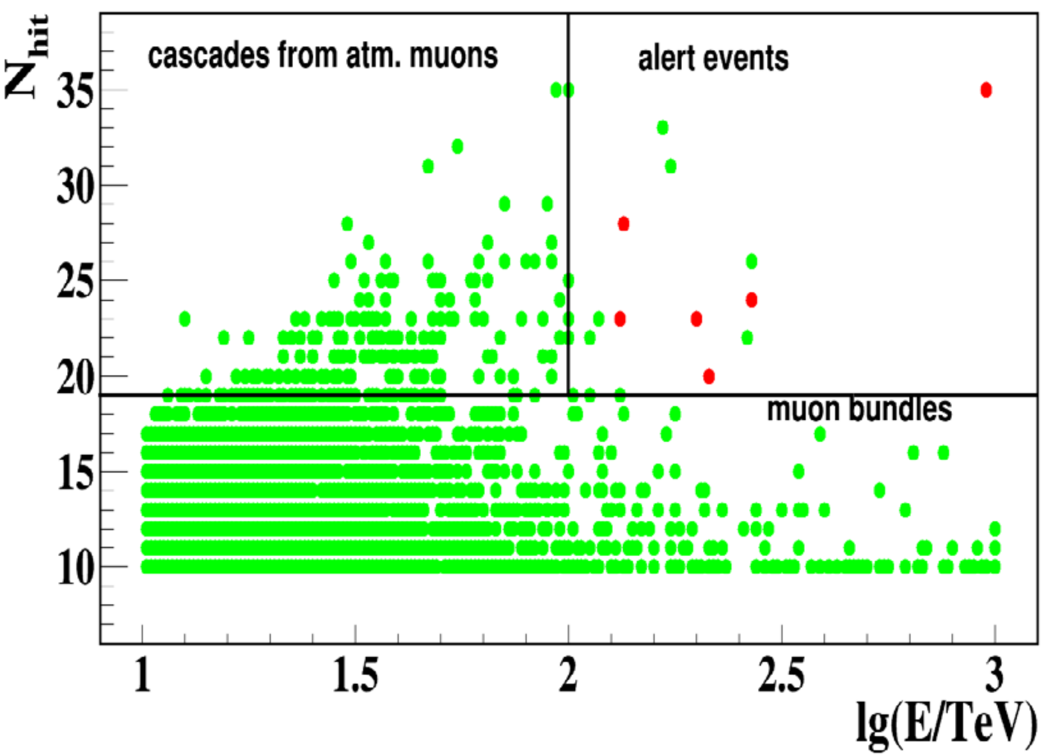
After reconstruction and all cuts applying, 9357 events have been selected with $N_{hit} > 9$ & $E > 10$ TeV

Trigger conditions for different studies

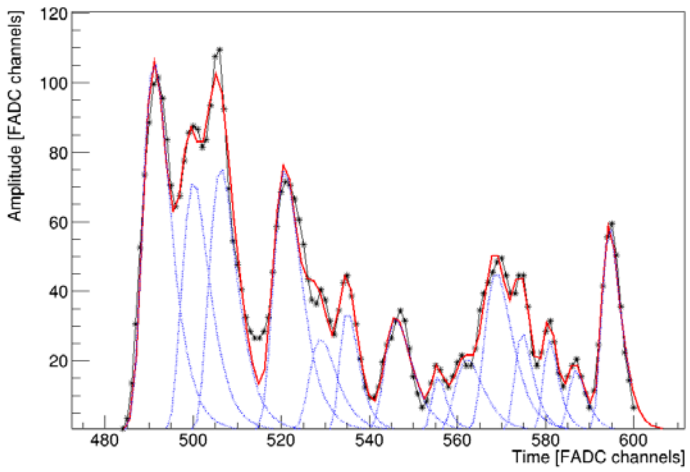
MM studies: $N_{hit} > 7$

Upward going neutrinos: $N_{hit} > 10$ & $\theta > 90°$

HE astrophys. neutrinos: $N_{hit} > 19$ & $E > 100$ TeV



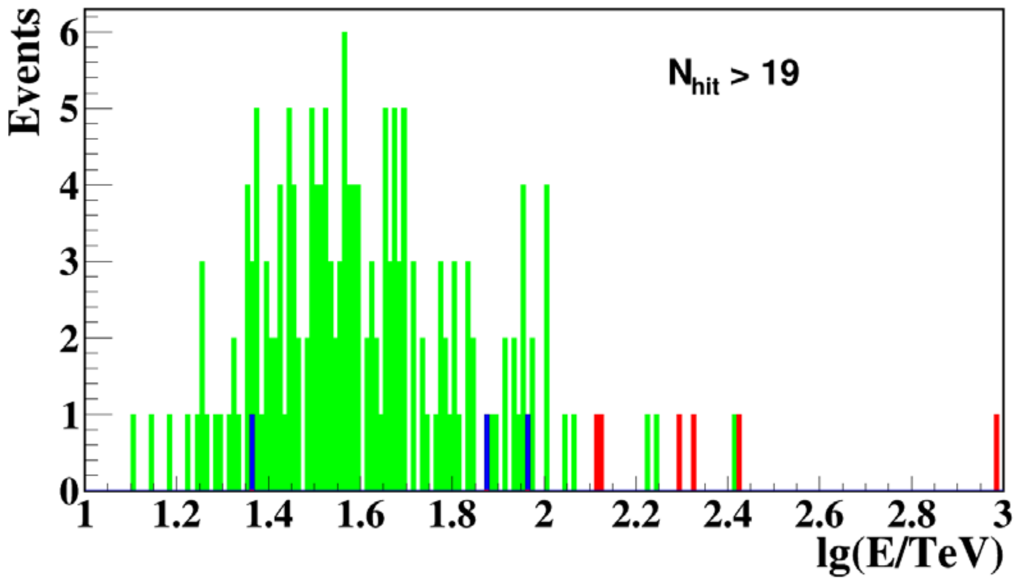
Wave form of multiple hit signal



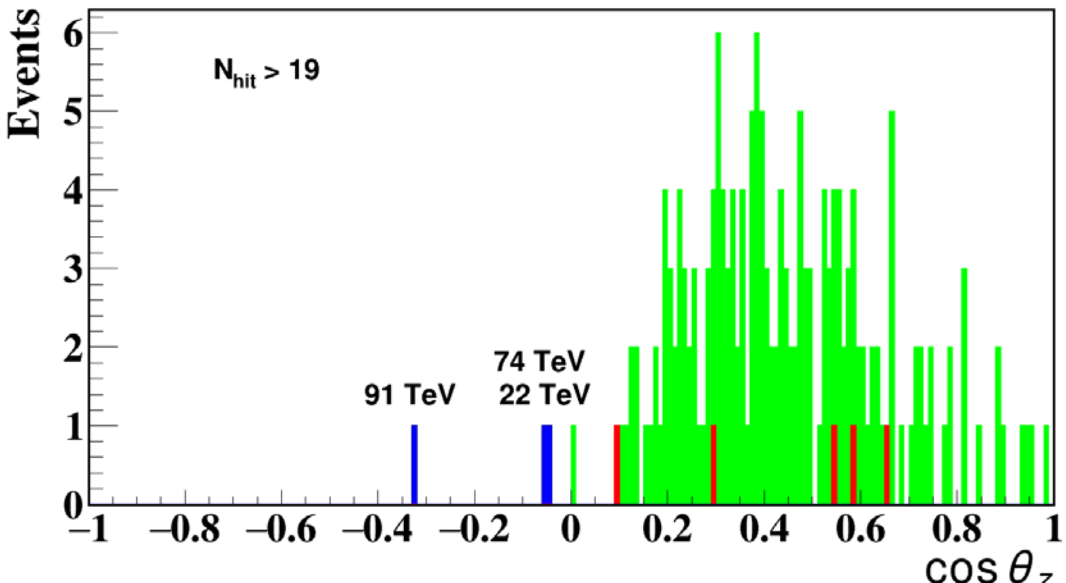
Hits separation for >20 ns time difference

High energy cascades (data)

Energy distribution



Cosine of zenith angle



Data from 2018 - 2020 ,
exposition: 3714 days

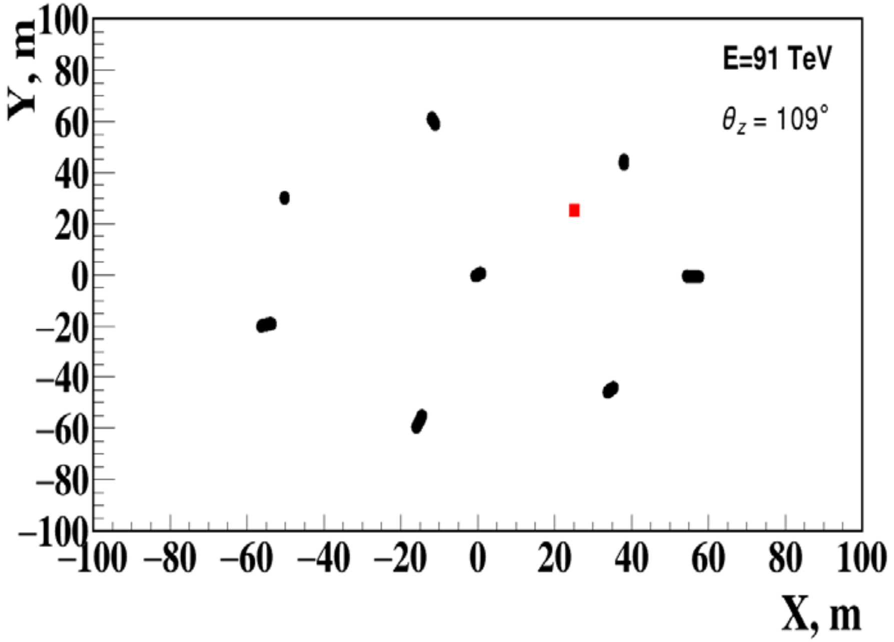
12 events with E > 100 TeV
and N_{hit} >19:
5-6 events – cascade events
7-6 events – cascade events
with muon pattern

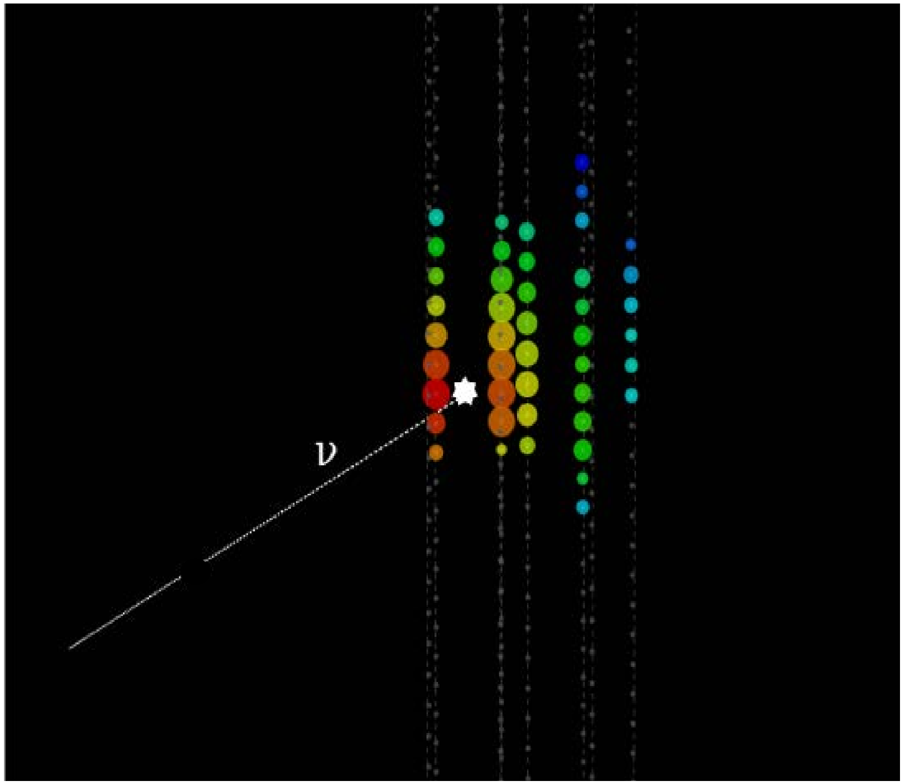
3 upgoing cascades: E ≈ 91 TeV
and E ≈ 74 TeV and 22 TeV

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

Preliminary

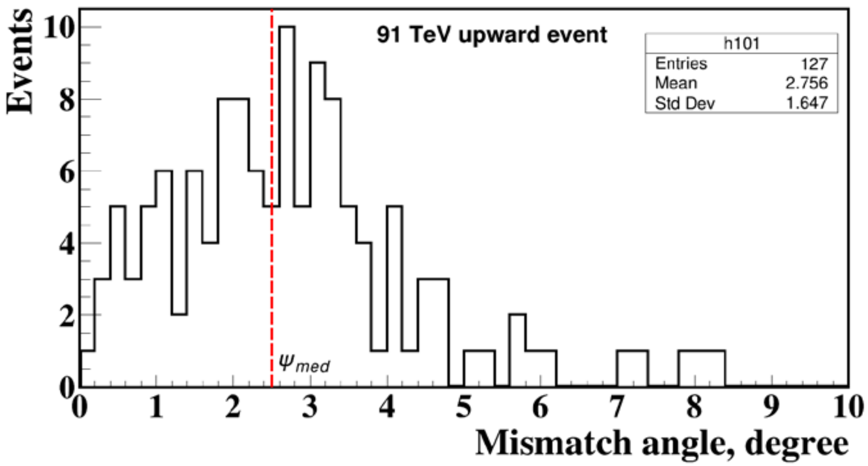
Contained event
Reconstructed energy E = (91 ± 11) TeV
Zenith angle $\theta_z = 109°$



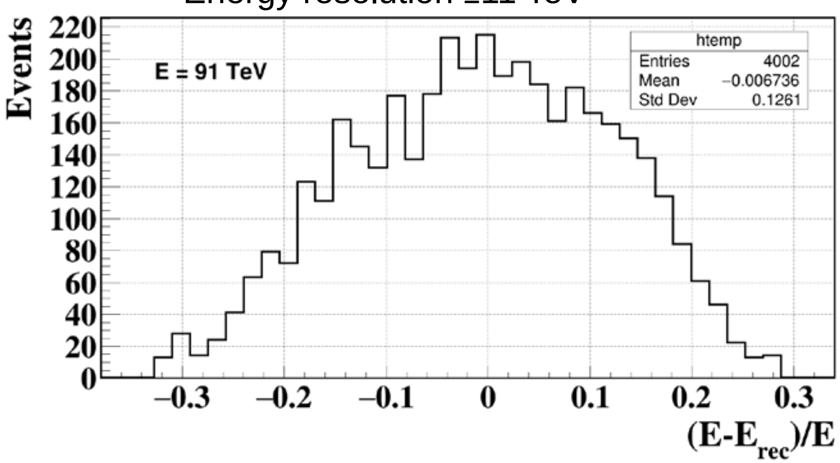


Preliminary

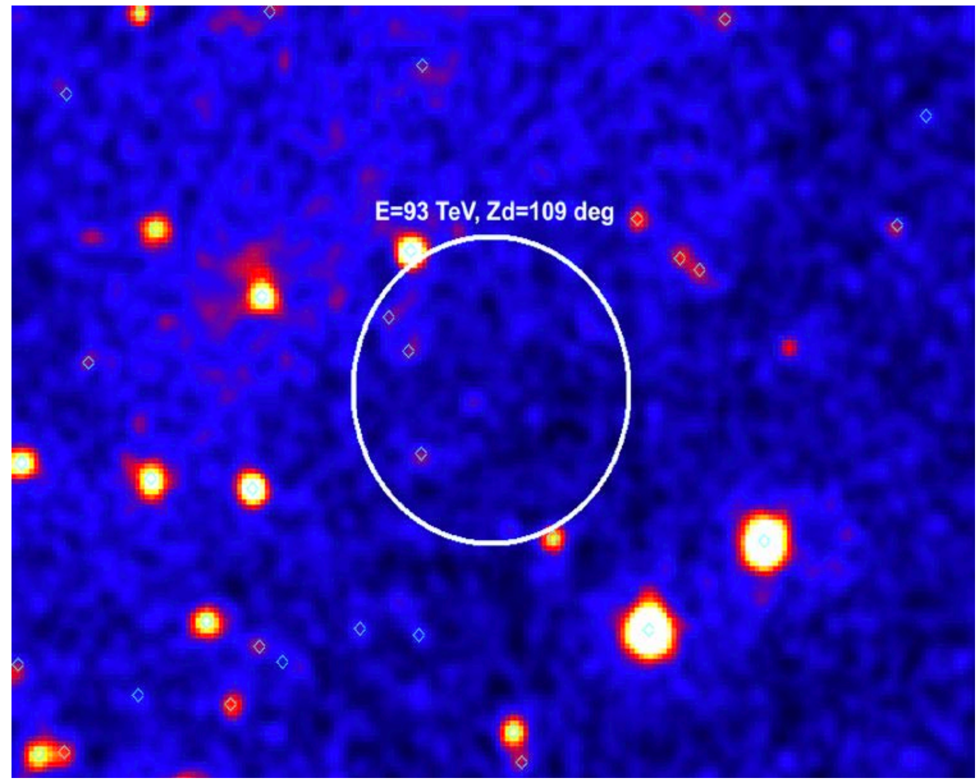
Angular resolution - $\psi_{med} = 2.5°$



Energy resolution ±11 TeV



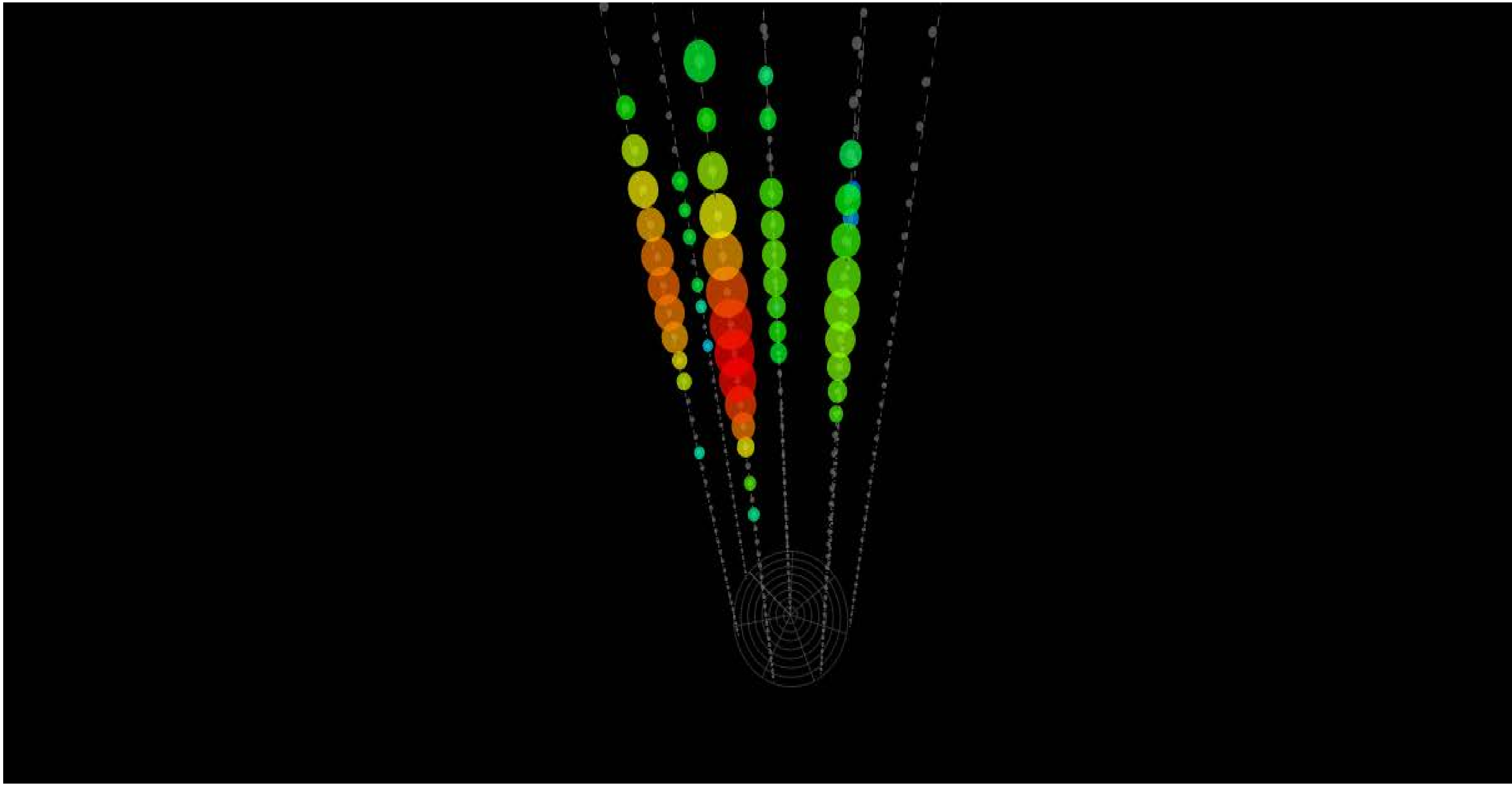
Sky map, 2° circle around event direction



First PeV_scale cascade!

Preliminary

Reconstructed energy E = 955 TeV (±20%);
distance from central string r = 91 m;
zenith angle = 61°

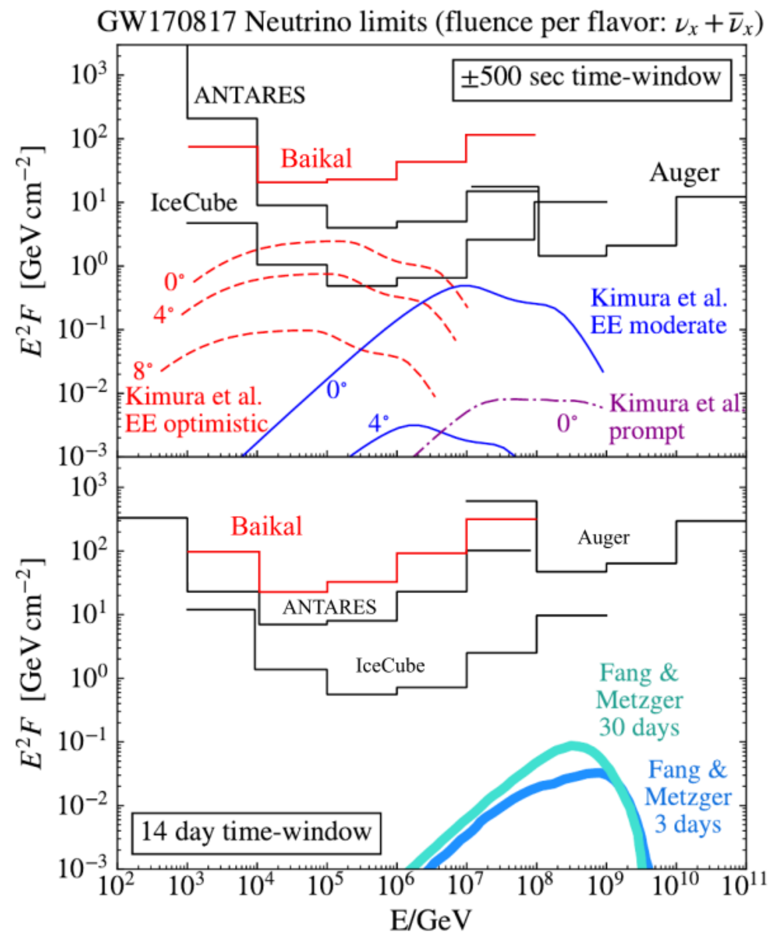


Baikal GVD: Multi-Messenger Studies

Upper limits on fluence of neutrinos associated with GW170817

No neutrino events associated with GW170817 have been observed Using cascade mode within ± 500 sec window and 14 days after the neutron star merger.

Assuming E^{-2} spectral behavior and equal fluence in all flavors upper limits at 90% c.l. have been derived on the neutrino fluence from GW170817 for each energy decade.



Baikal-GVD follows up of neutrino alerts

ANTARES (TAToO) $\mu_{\uparrow}$ since Dec 2018 <E> 7 TeV

ICECUBE (GCN) $\mu_{\uparrow}$ since Sept 2020 E> 100 TeV

search for {time,δ,α} correlations in single cluster

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in cascade mode
within 4.5° half-open cone towards sources over 4π-sky

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in track mode:
within 1.5° half-open cone towards sources in down hemisphere

ANTARES alerts

Between Dec 2018 and Jan 2020,
a total of 43 alerts have been analysed;
15 alerts came in 2020.

Following up alarm of trigger, we look for events on each cluster in time windows ±500 sec, ±1 hour and ±1day around alerts inside ½cones;

in cascade mode a full data sample of season 2018-2019 has been used for background estimates;

in tracks the first neutrino sample with 57 events in 2019 has been tested, while *softer quality cuts for muons selection were considering and under investigation now*.

No prompt coincidence in time and direction was found with ANTARES trigger.

Limits on energy fluence

Astronomy Letters, issue 2, 2021, in press

"High energy neutrino follow-up with Baikal-GVD", Avrorin A.D. et al.

CR&MM_2020/PosterCRMM_ICGVD_ALERTS_VDik.pdf

Alert	NN GCN	rank	E_ν ТэВ TeV	alt градусы deg.	N_{obs} ±12 часов ±12h	N_{bkg} в сутки	p-val значимости	$Fluence^{U.L.}$ ТэВ см$^{-2}$ TeV cm^{-2}
IC200911A	28411	Bronze	110.79	$23.2^{(\circ)}$	-	0.33	-	$1.43\text{x}10^{-3}$
IC200916A	28433	Bronze	110.48	$30.3^{(\circ)}$	-	0.29	-	$1.12\text{x}10^{-3}$
IC200921A	28468	Bronze	117.17	$-10.6^{(\circ)}$	-	0.36	-	$1.13\text{x}10^{-3}$
IC200926A	28504	Gold	670.50	$-28.2^{(\circ)}$	-	0.19	-	$1.14\text{x}10^{-3}$
IC200926B	28509	Bronze	121.42	$22.3^{(\circ)}$	1	0.39	0.32	$2.5\text{x}10^{-3}$
IC200929A	28532	Gold	182.89	$41.1^{(\circ)}$	1	0.35	0.29	$2.5\text{x}10^{-3}$
IC201007A	28575	Gold	682.65	$-32.5^{(\circ)}$	-	0.25	-	$1.12\text{x}10^{-3}$
IC201014A	28616	Bronze	146.93	$29.5^{(\circ)}$	1	0.44	0.36	$2.44\text{x}10^{-3}$
IC201021A	28715	Bronze	105.27	$47.1^{(\circ)}$	-	0.37	-	$1.37\text{x}10^{-3}$

9 IC alerts in Sept-Oct 2020

Spectrum E^{-2}

1 TeV—10 PeV

FC limits

Results:
p-val~ 0.2÷0.4 (~1σ)

Fluence U.L. at 90% c.l.
~1÷2 GeV cm^{-2}

Fiber optic data acquisition system for GVD

Development of fiber-optic DAQ is focused on GVD step 2.

The goal of upgrading the DAQ is to reduce the event registration threshold by increasing the data transfer speed and implementing a smart trigger system.

Basic principles:

- "One fiber per one string".
- "Common clock" for all sections of the cluster
- "Multi-trigger" operation mode

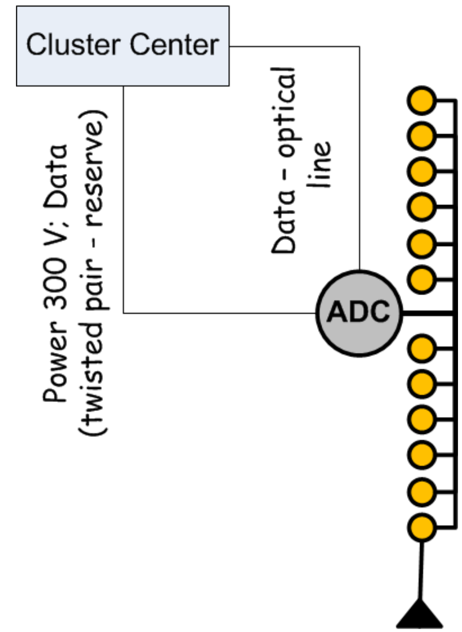
To meet these requirements:

- CWDM optical multiplexers are applied (up to 9 channels per one fiber)
- ADC/Master board was modernized on the basis of FPGA Xilinx Zynq. (extending the real-time processing capabilities of the section data).

Fiber optic experimental string

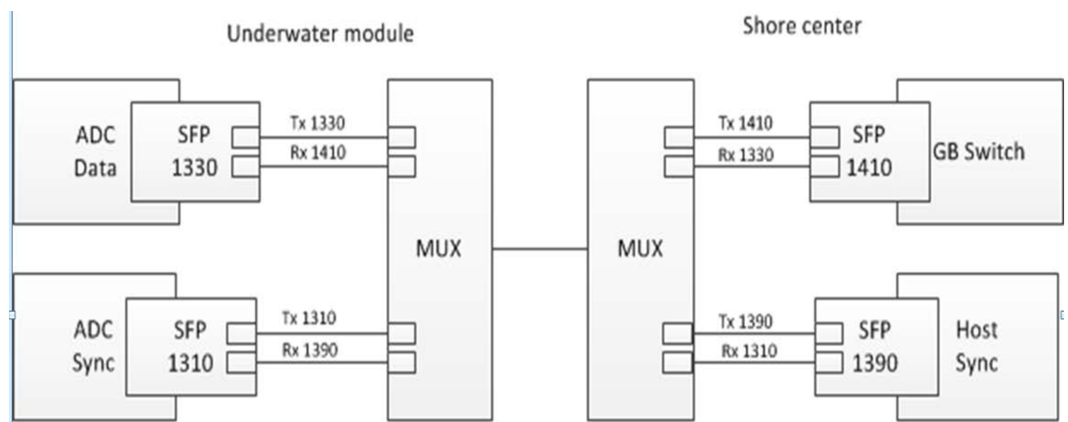
Experimental string is intended to in-situ tests of underwater fiber optic on the basis of CWDM

Basic element of the optical communication is CWDM multiplexor (MUX) that provided up to 9 physical line using different wavelengths.

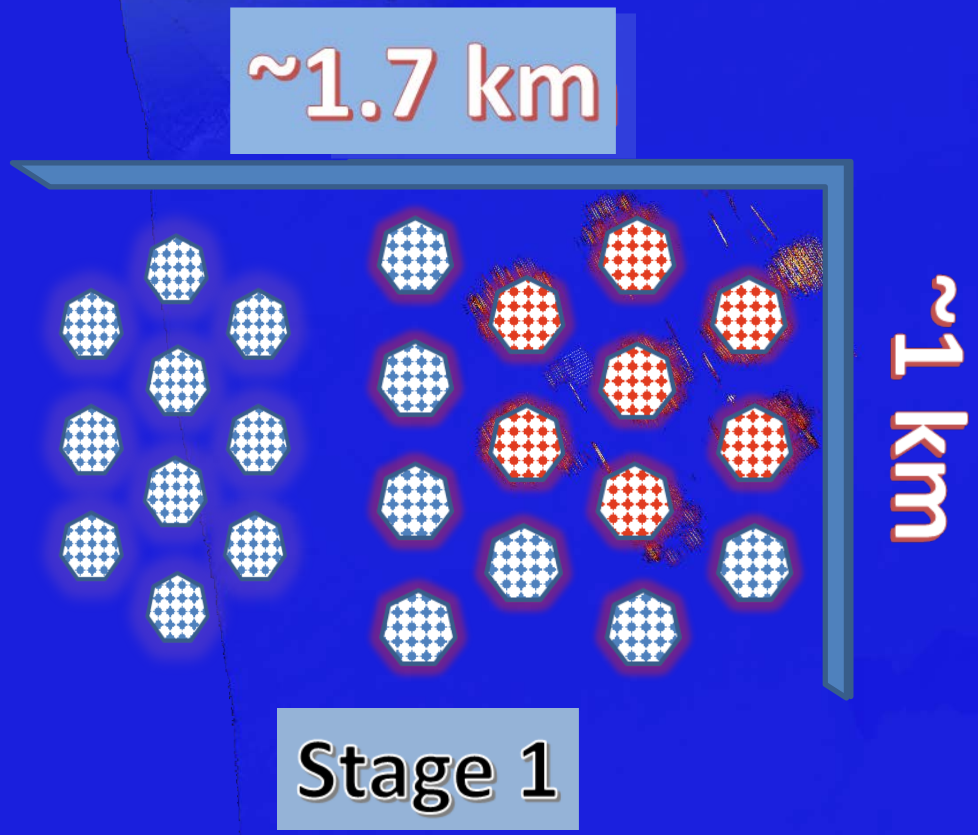


Exp. string comprises:
- New Master/ADC board (FPGA Zynq)
- 12 optical modules.

Mode of operation:
- Basic trigger: coincidences of two neighboring OMs;
- Monopol trigger.
- ADC and Sync data are transmitted via one optical fiber to the Shore Center



GVD 2020 and extention



Conclusion

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere: 0.35 km^3 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 astrophysics neutrino candidate events have been selected

Deployment rate – 2 clusters/year

GVD (1 km^3) in 2026