Status of Baikal-GVD experiment

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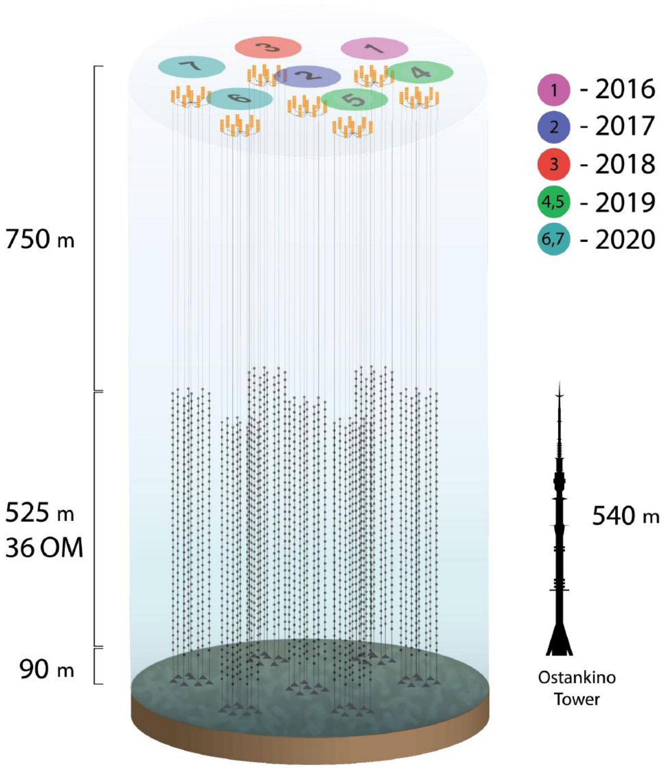
for the Baikal-GVD collaboration

Introduction

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

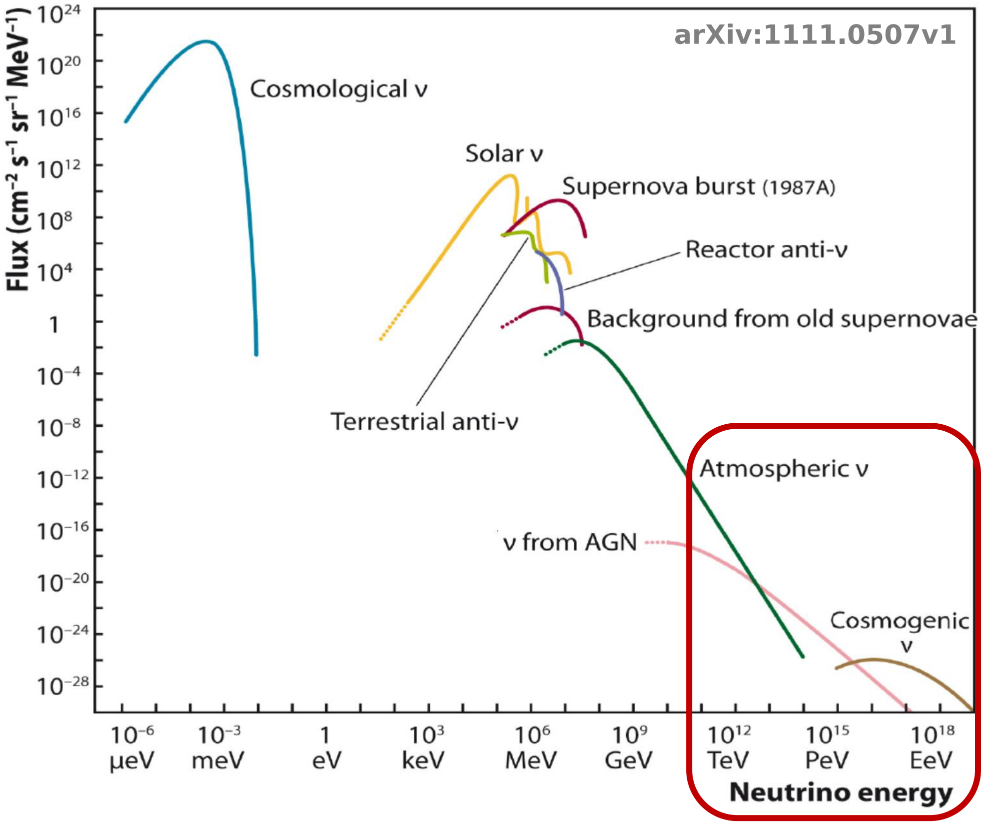
10 organisations from 5 countries, ~70 collaboration members



- 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 astrophysics

Natural and artificial neutrino sources

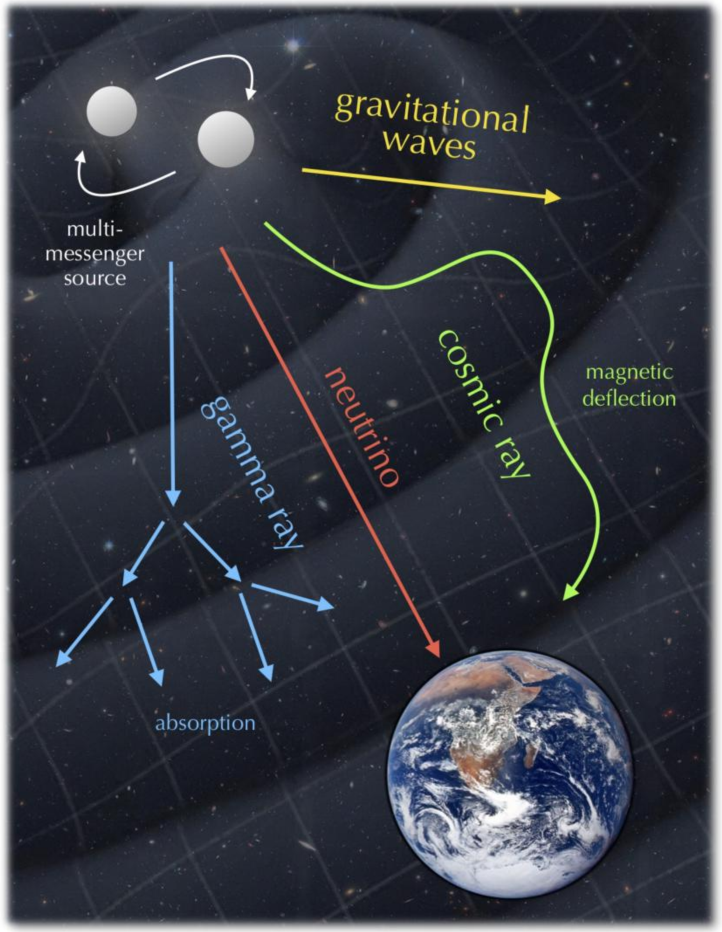


Region of sensitivity of very large neutrino telescopes

Main purpose of the Baikal-GVD experiment is the study of astrophysical neutrino flux

Astrophysical neutrino

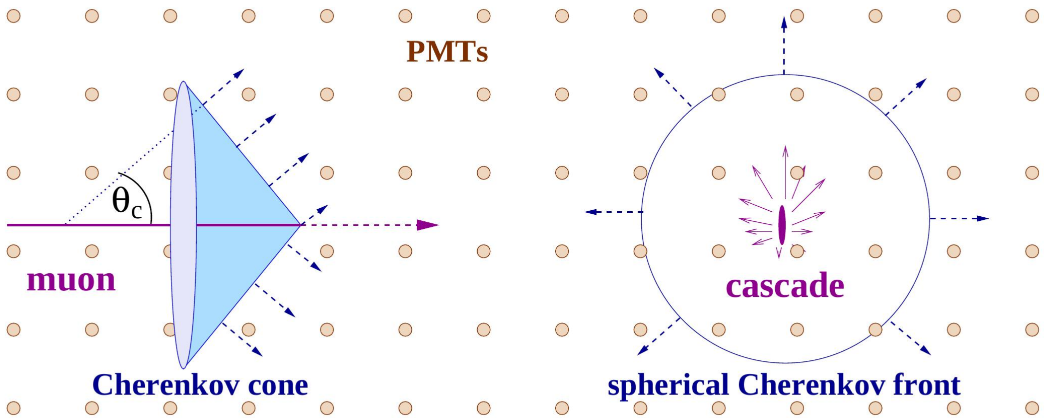
- Direct propagation in interstellar and intergalactic medium
- Discovered by IceCube in 2013
- Mechanisms of generation largely remain unconstrained
- Essential ingredient of rapidly developing field of multi-messenger observations



Neutrino detection

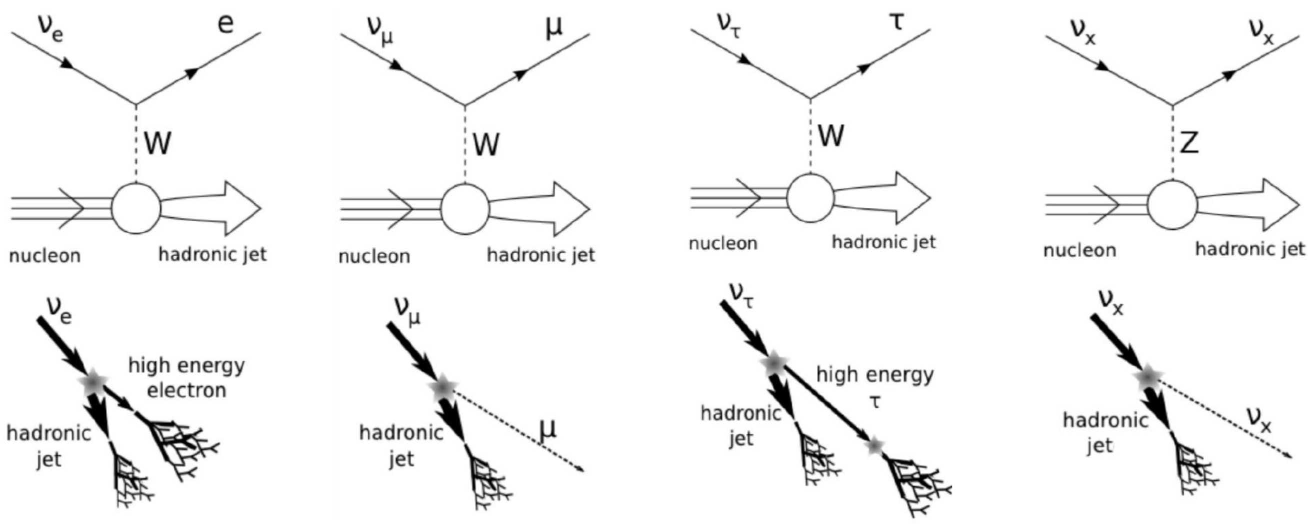
Moisey Markov: “We propose to install detectors deep in a lake or in the sea and determine the direction of charged particles with the help of Cherenkov radiation”
ICHEP 1960, Rochester

arXiv:1111.0507v1



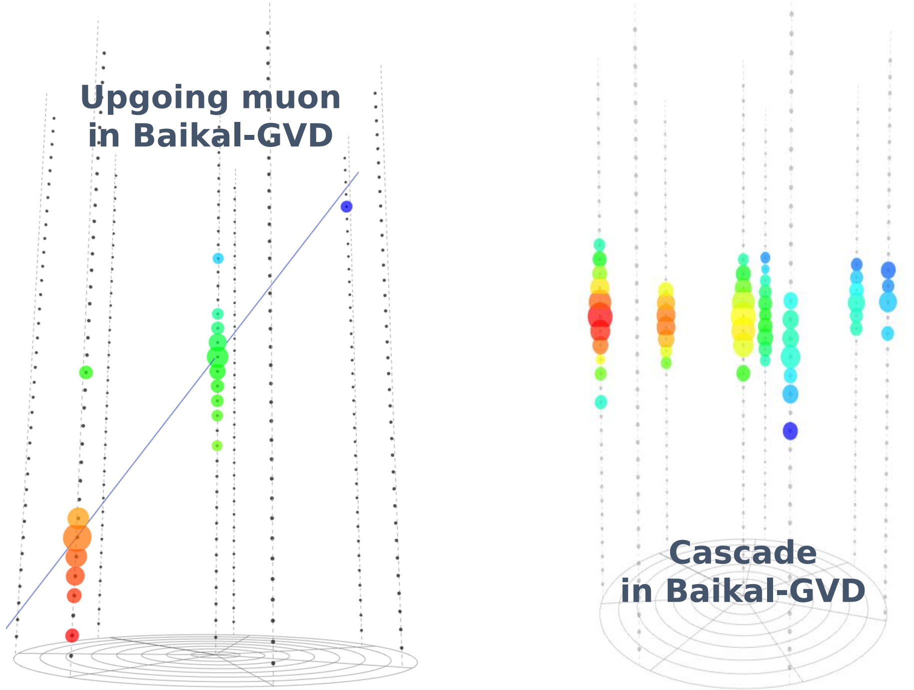
Charged current interactions:

Neutral current:

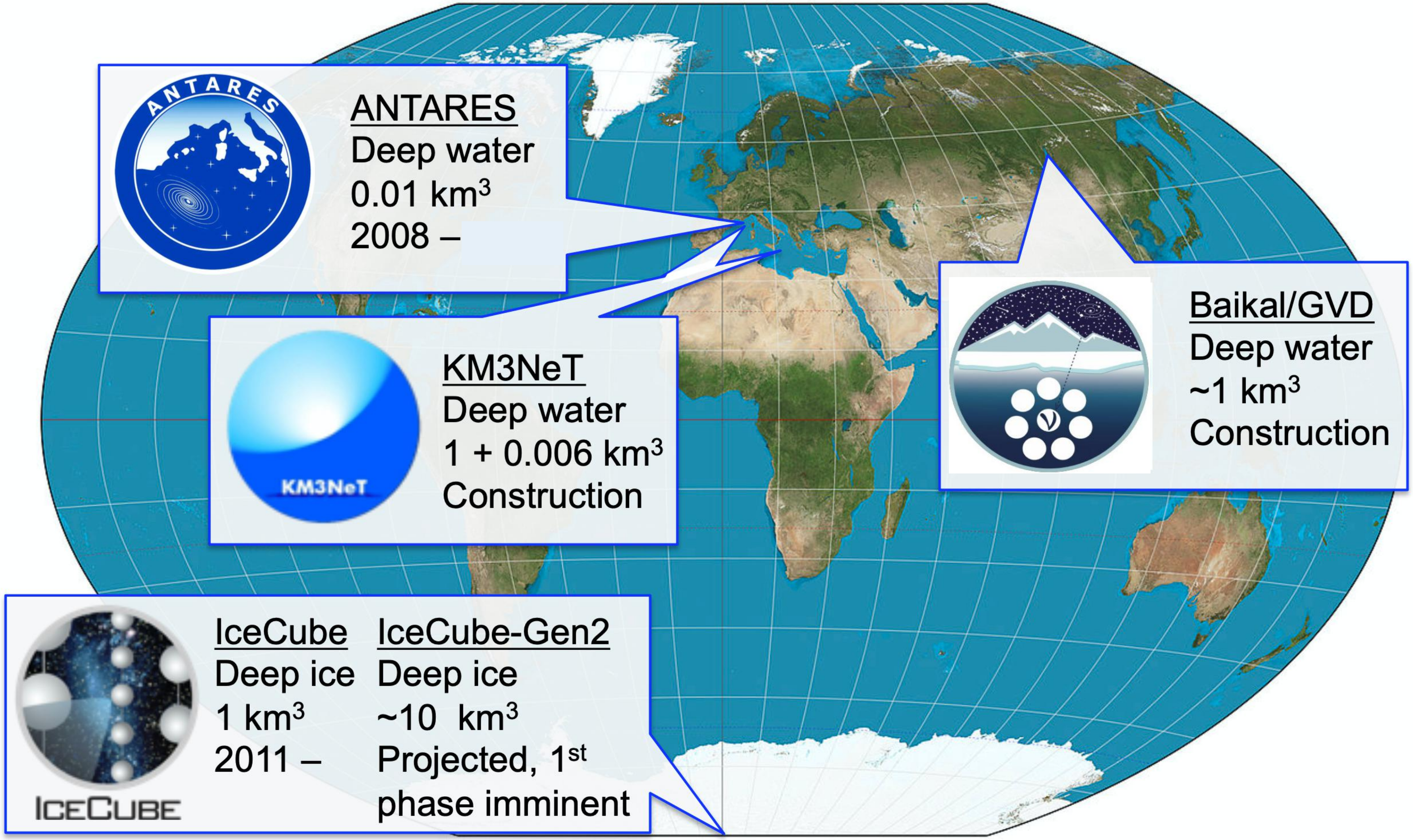


cascade | **muon + cascade** | **double cascade (82%) muon + cascade (18%)** | **cascade**

credit: J. Tiffenberg, NUSKY 11



Neutrino telescope network



Experiment site

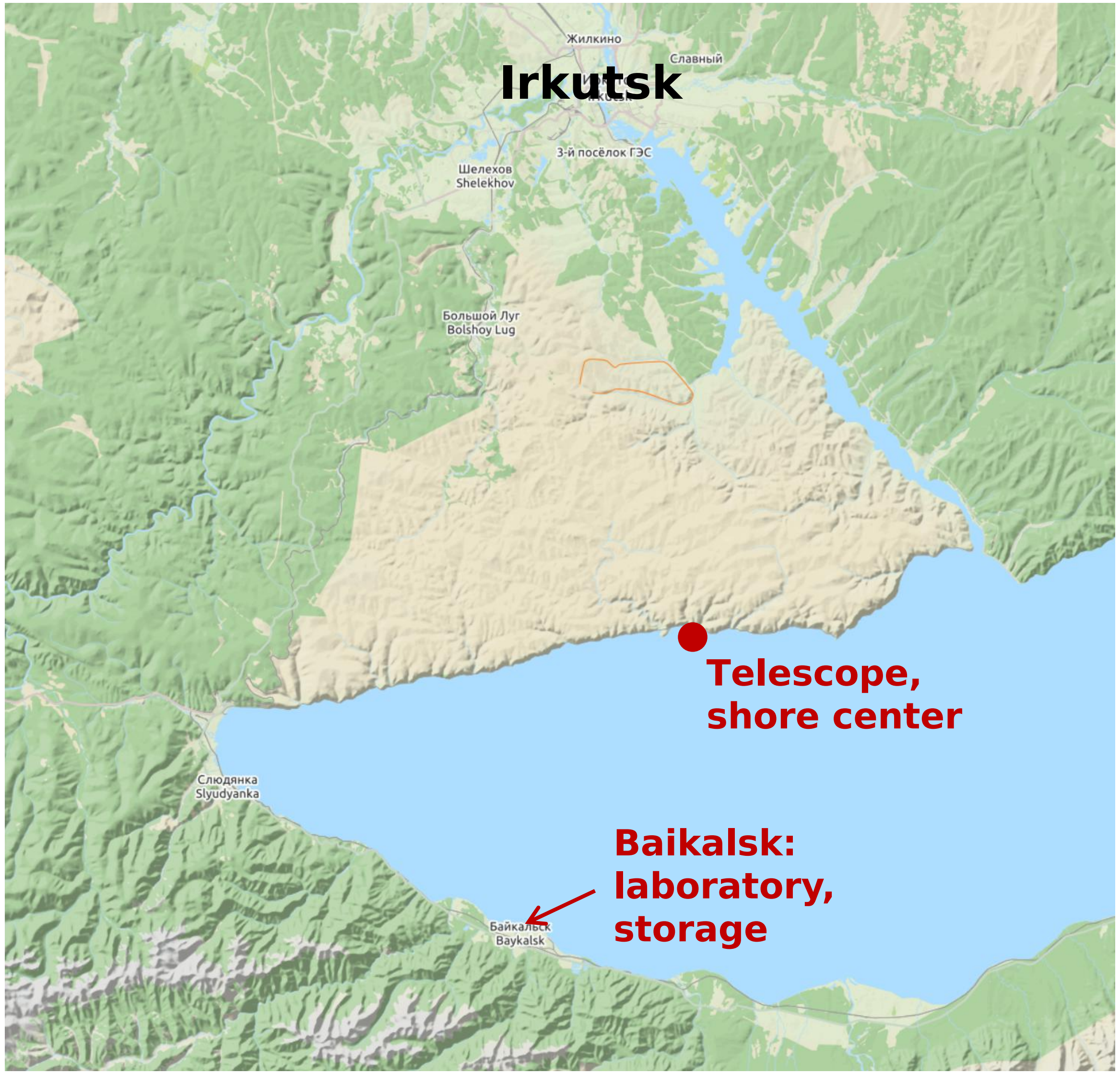
Platform “106 km” of
Circum-Baikal railway

Telescope is located
3.6 km away from shore

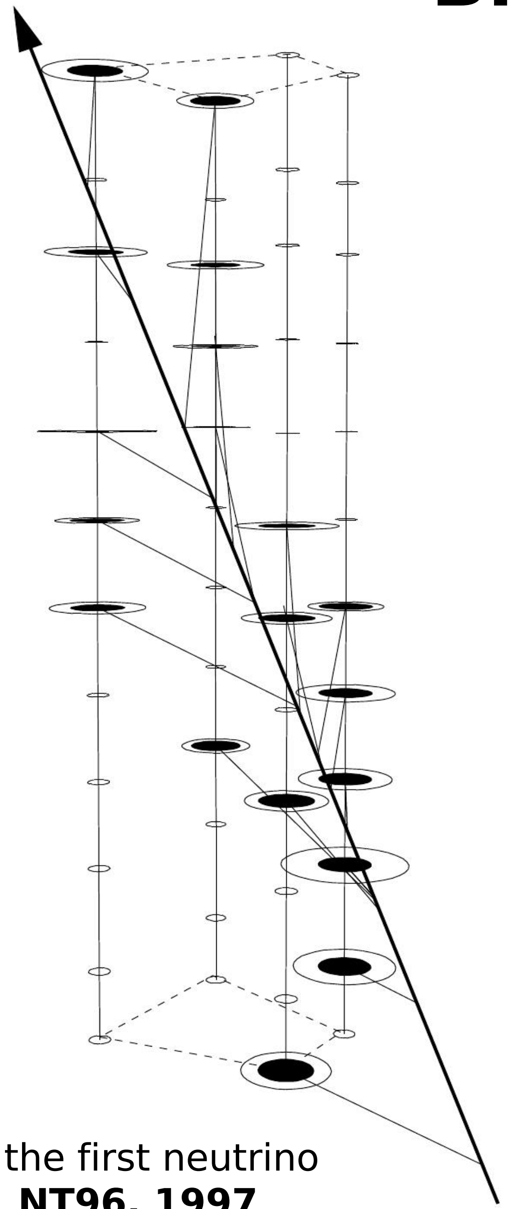
Constant lake depth:
- 1366 - 1367 [m]

Water transparency:
- Absorption length: 22 m
- Scattering length: 30 - 50 m

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



Brief history of Baikal project



One of the first 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

2020: Baikal-GVD operates 7 clusters, 2016 OM

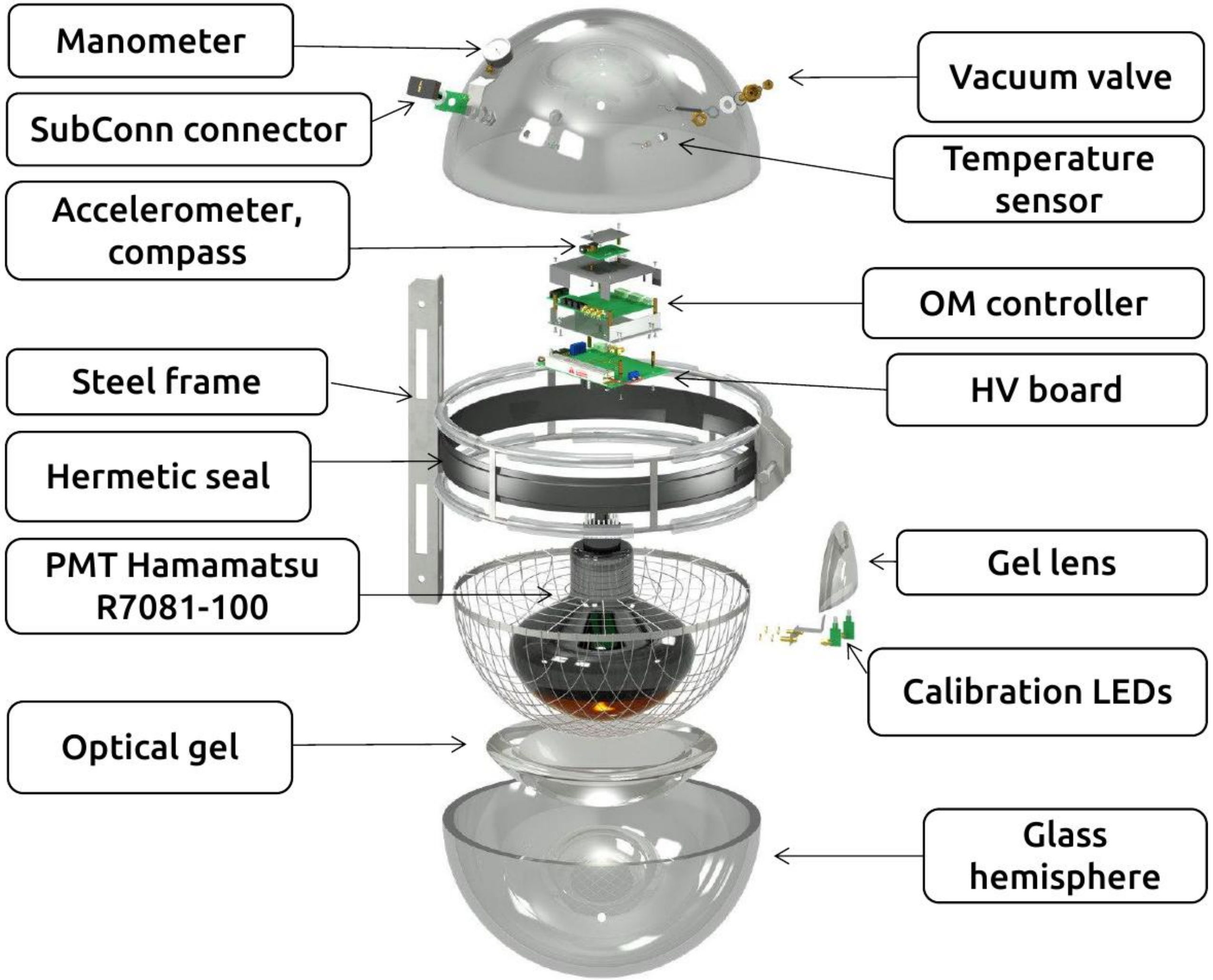
Winter expedition

Despite harsh ice conditions this winter (2019-2020),

two new clusters were deployed (596 OMs)

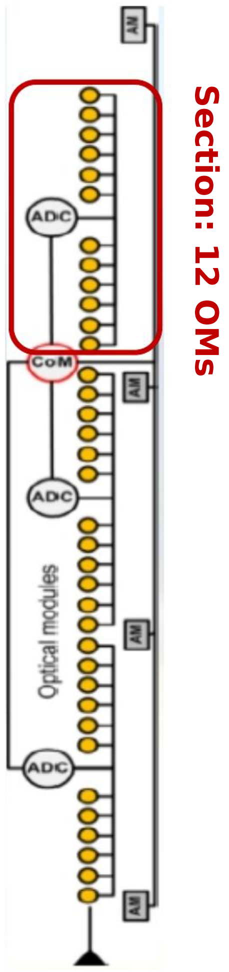
Baikal-GVD optical module

Telescope sensitive element: optical module (OM), **2016 OMs are deployed**



Baikal-GVD cluster

STRING:
3 sections



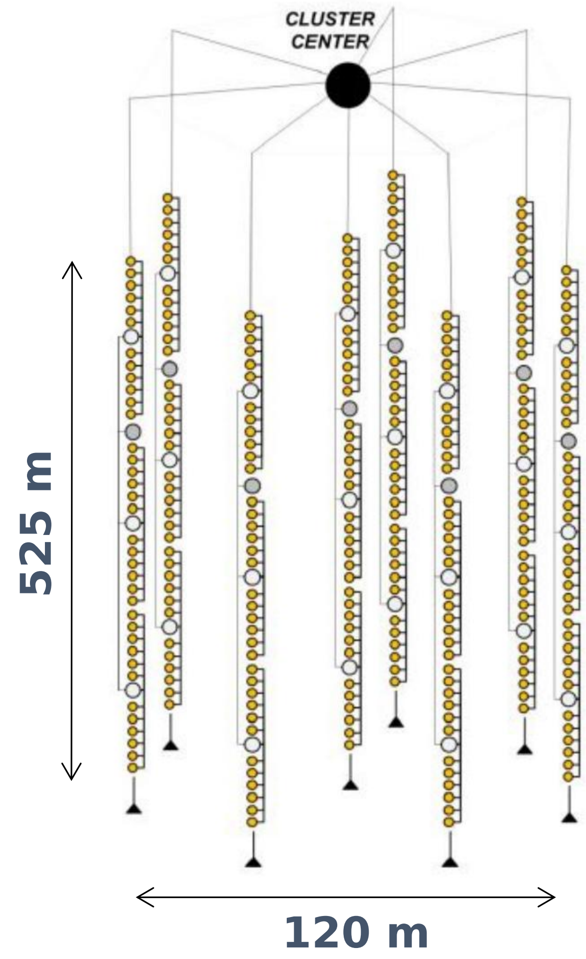
Cluster - independent detection unit, consists of 8 strings

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

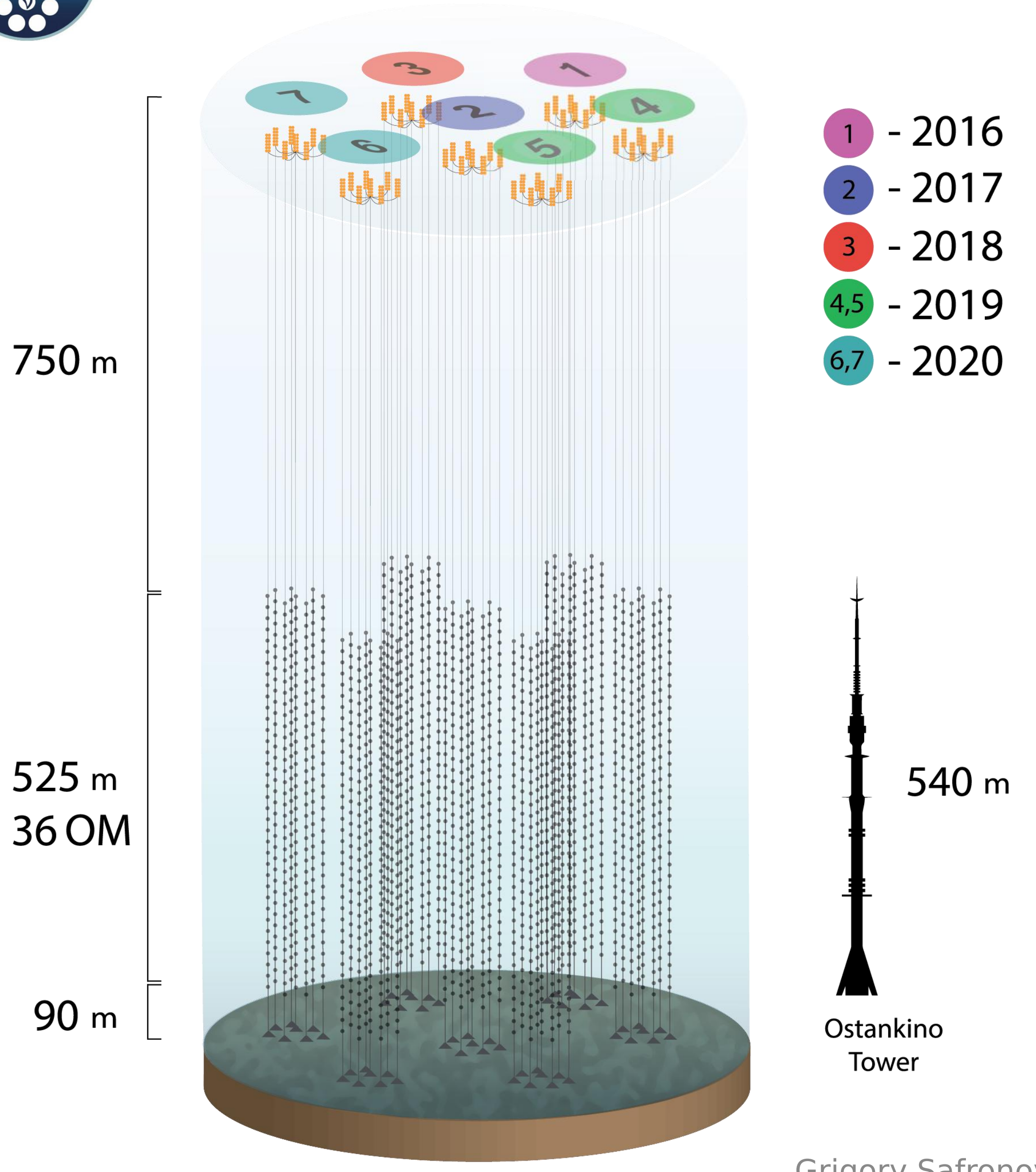
Cluster center is located at 30m depth
- Trigger electronics
- High voltage distribution
- Data transmission electronics

Trigger
- Cluster center reads out and sends event to the shore 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



Detector construction status

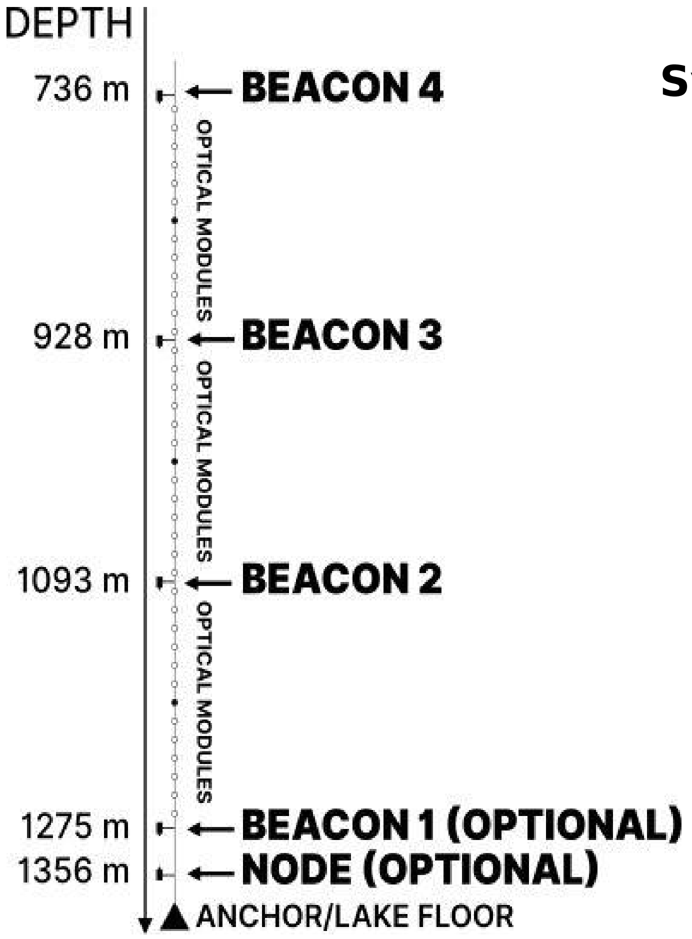


Deployment schedule

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	9	72	2592
2022	11	88	3168
2023	13	104	3744
2024	15	120	4320

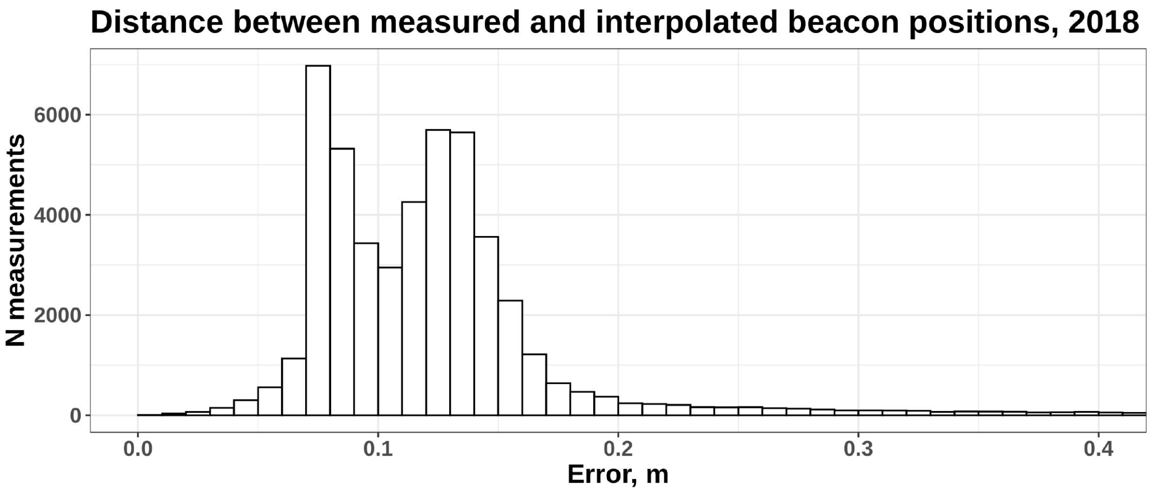
Acoustic positioning system

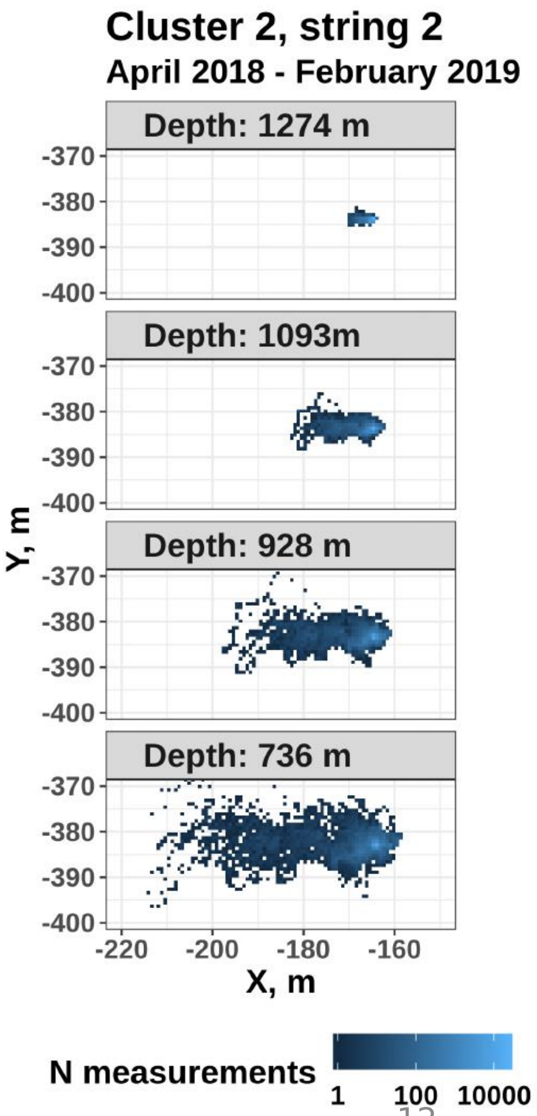
Water currents cause up to 50 m deviations of top OM from median location with the average velocity of 0.5 cm/s



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**





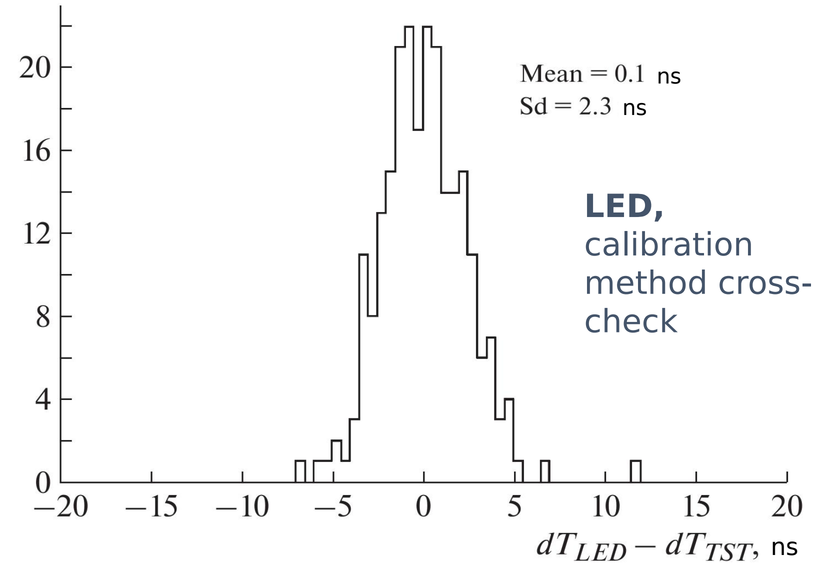
Time calibration

Precise PMT pulse timing is crucial for event reconstruction

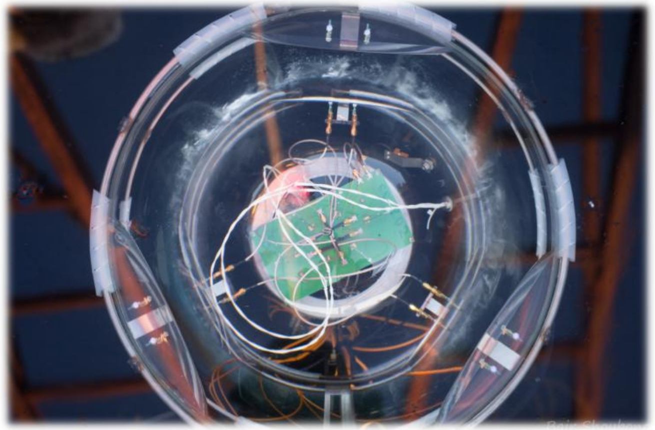
Interchannel intrasection calibration:
- OM calibration LEDs

Intersection calibration:
- LED matrices, up to 100m light propagation

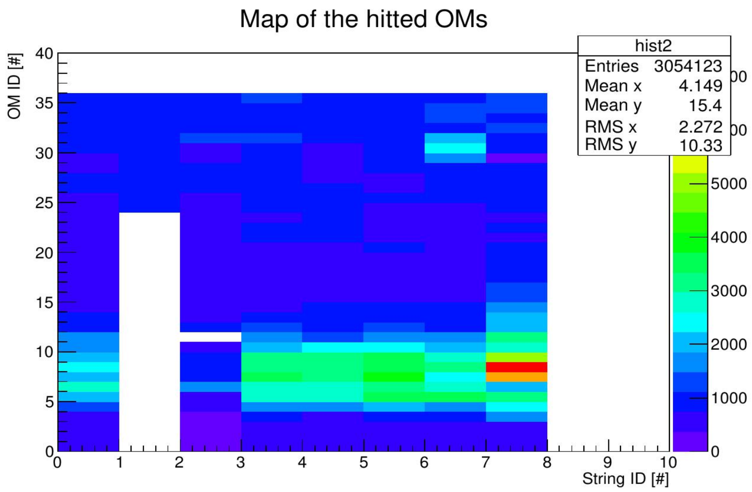
Calibration precision ~ 2 ns



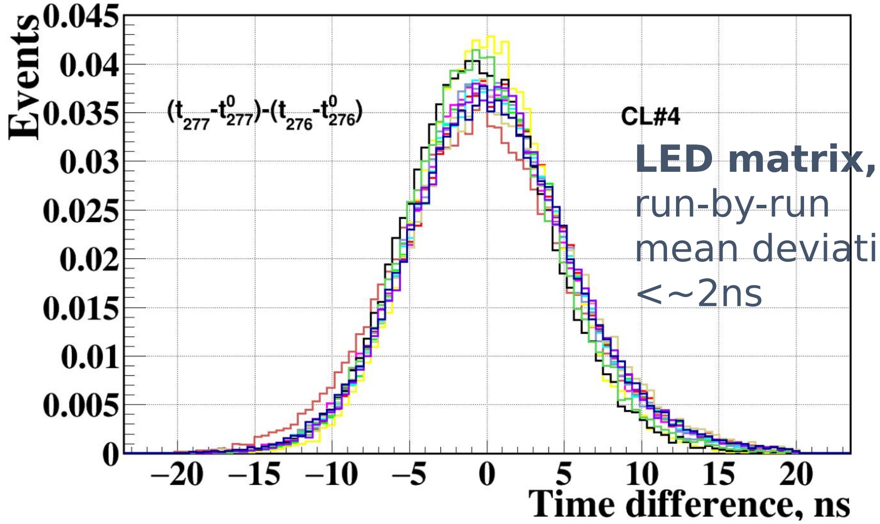
LED, calibration method cross-check



LED matrix module



matrix run occupancy



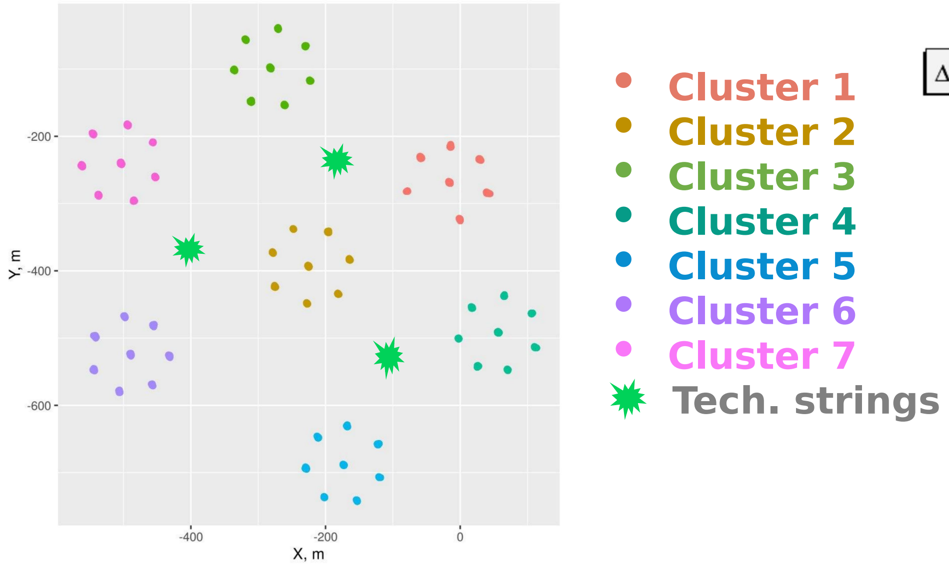
LED matrix, run-by-run mean deviation <~2ns

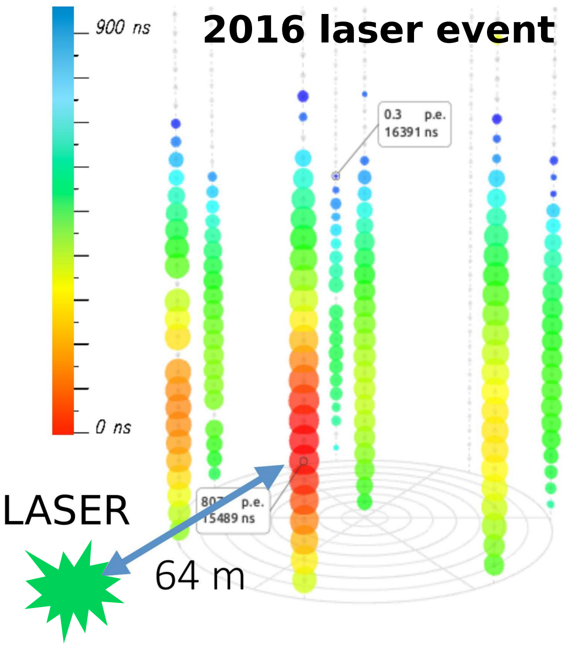
Laser system

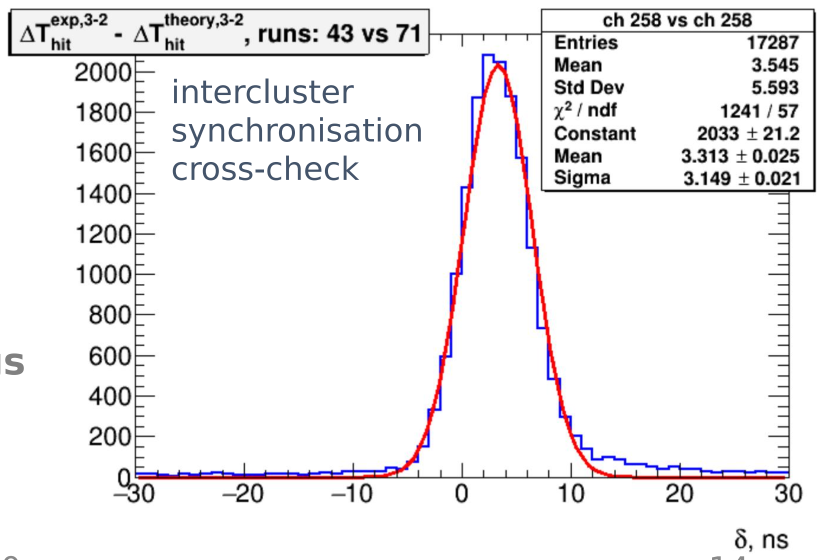
Intercluster calibration,
water properties monitoring

- 3 technological strings carrying 5 dedicated lasers
- Isotropic flashes 532nm (green)
- 0.37 mJ: 10^{15} photons, length 1ns

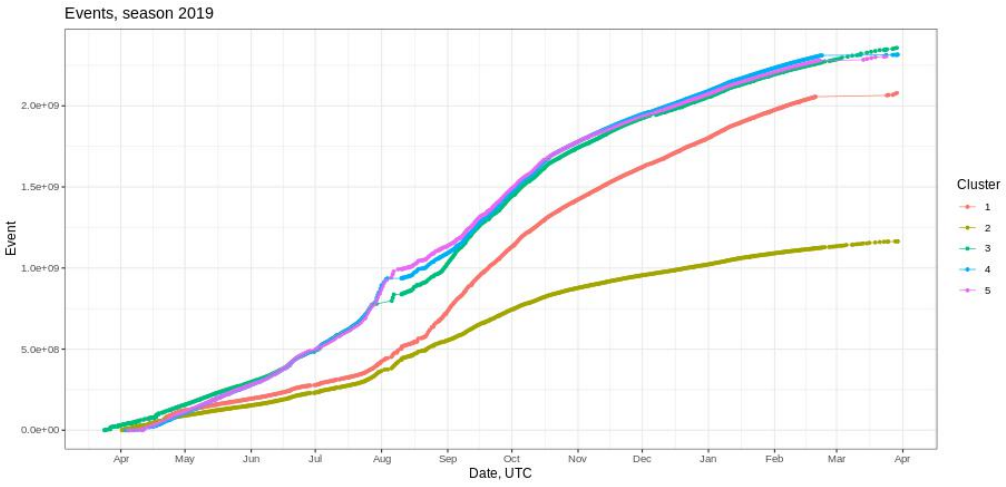
Baikal-GVD 2020 top view



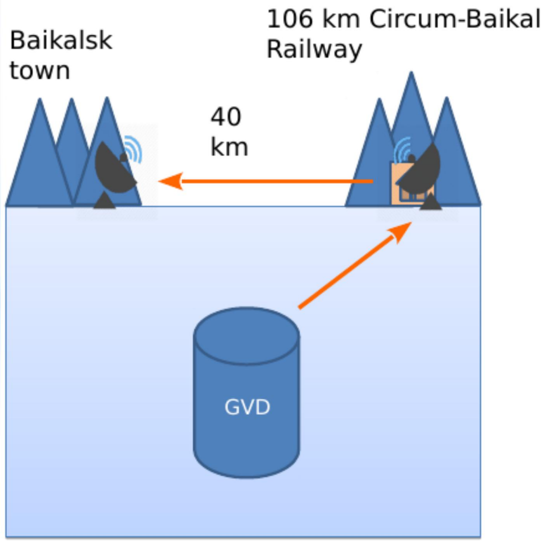


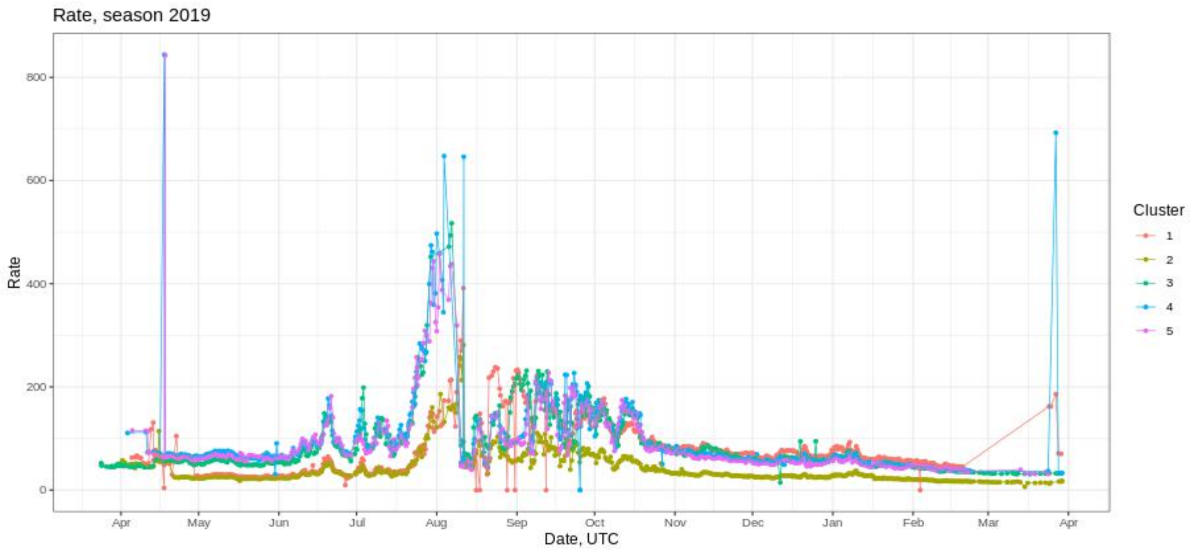


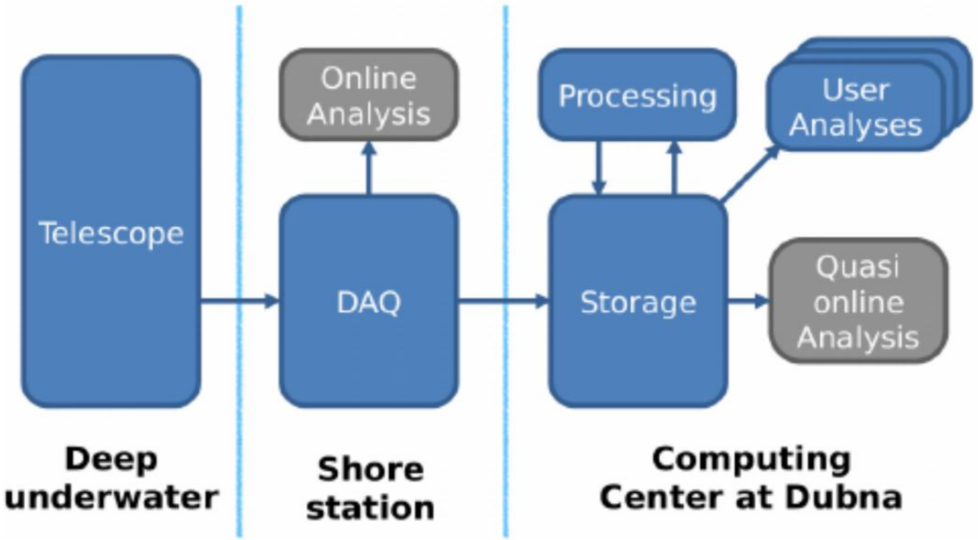
Data processing



- 40 Gb per cluster per day to the shore center
- Radiochannel 250 Mb/s to Baikalsk
- Data is transferred to JINR over the internet
- Automatic data processing at JINR
- User analyses at JINR

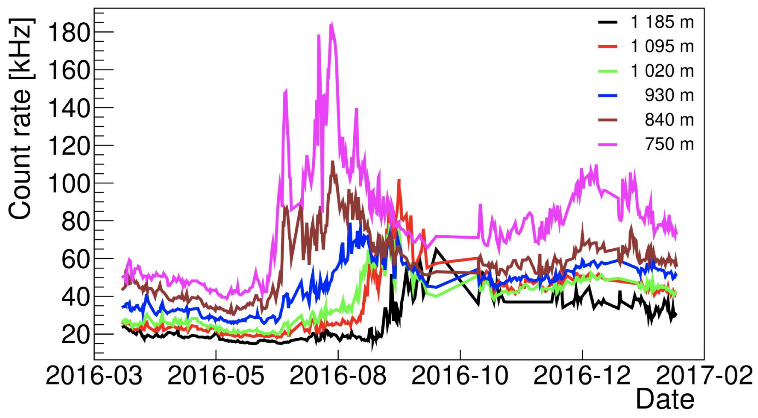






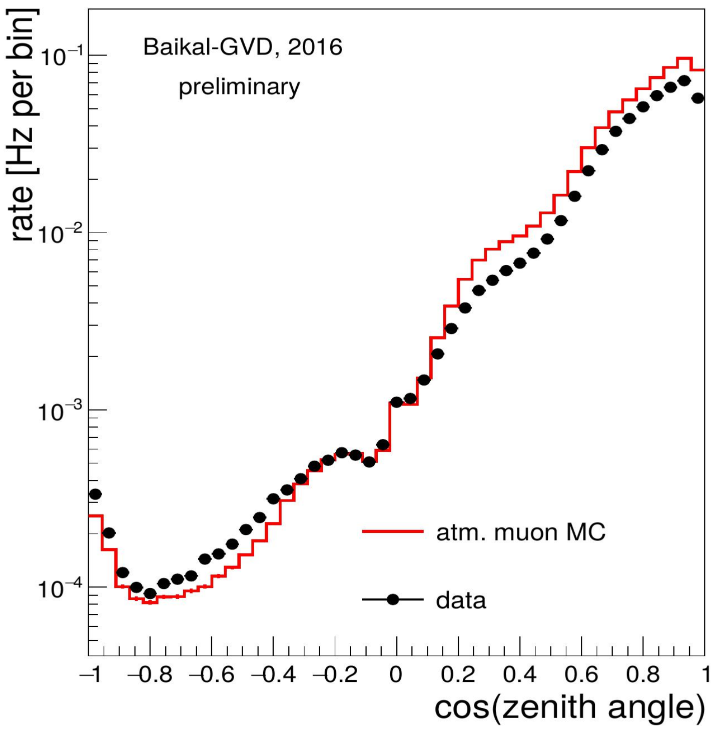
Muon reconstruction

OM noise rate



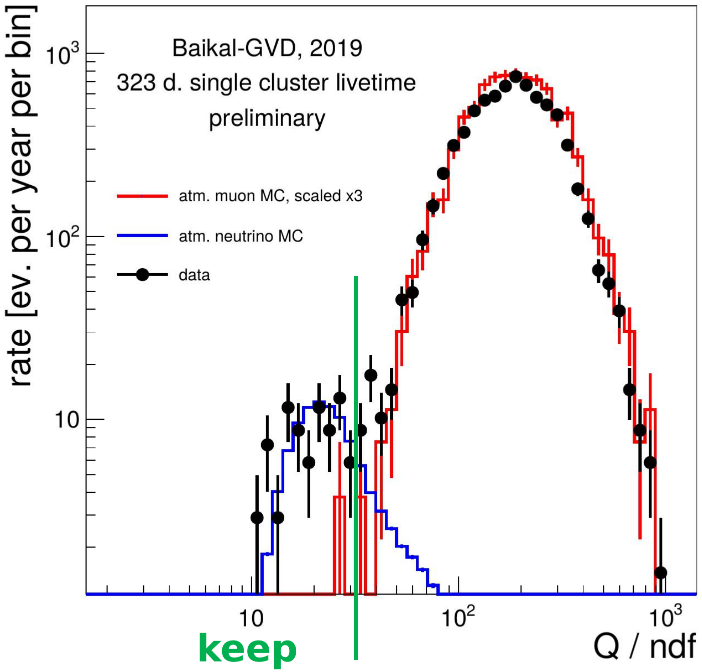
Baikal water biogenic noise, dark current
- 20-60 kHz per OM
  in quiet period (before July)

muon rate



upgoing **downgoing**

upgoing: θ_{zenith} > 120 deg.



Muon reconstruction
- Hit finding: select signal hits, reject noise
- Track fitting: fit the track with quality function: $Q = \chi^2(t) + f(q, r)$

Muon neutrino selection
- Signal region: upgoing muons
- Misreconstructed atmospheric muon background exceeds signal by factor 10^5 - 10^6
- Set of cuts was developed on dedicated MC samples with realistic detector simulation
- Most powerful cut: [Q/ndf] variable

Muon neutrino sample

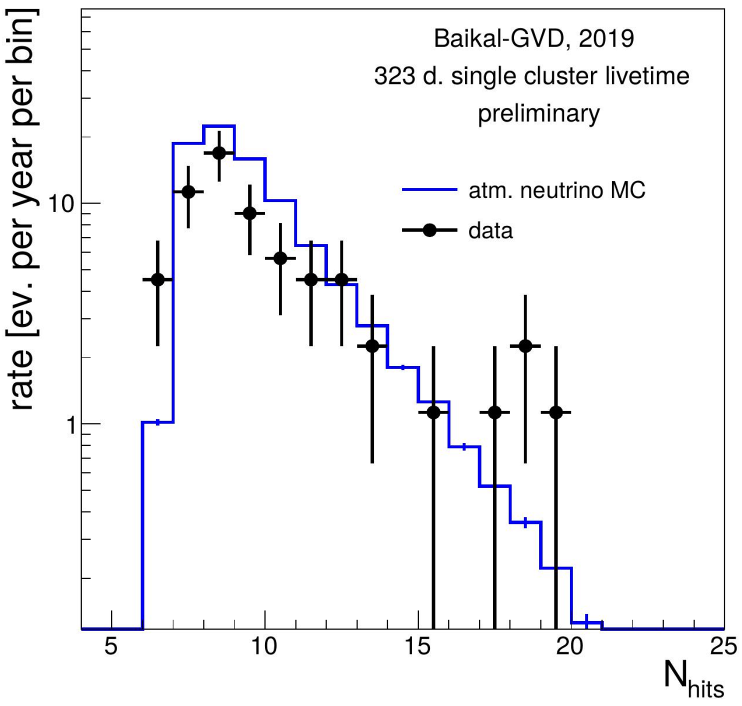
We present set of muon neutrino candidates based on quiet period in 2019

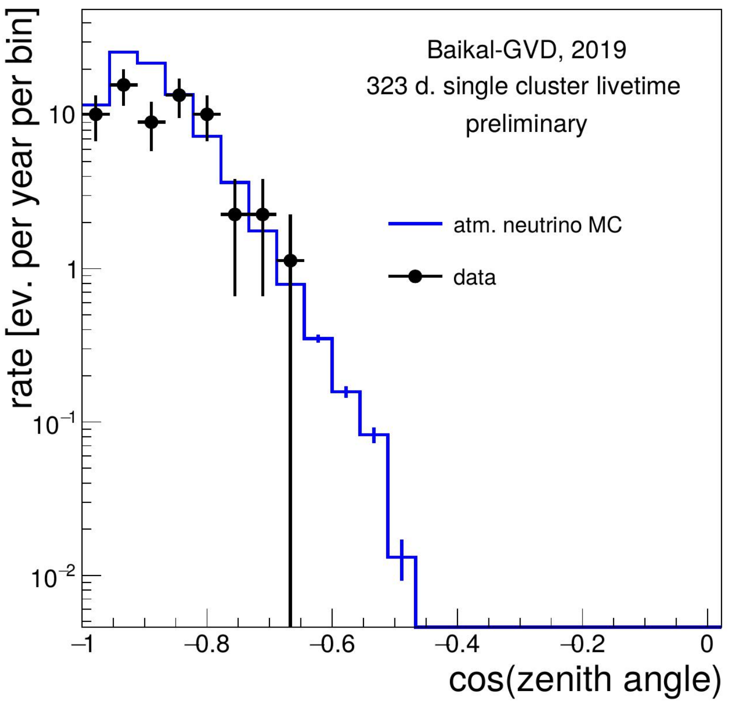
- Runs from April 1st until June 30th
- Total single cluster exposition 323 days
- Total number of events selected: 57 neutrino candidates
- Results are compared to atmospheric neutrino simulation

MC expected: 77.2

- atm. neutrino :77.2
- atm. muon: 0

Observed: 57

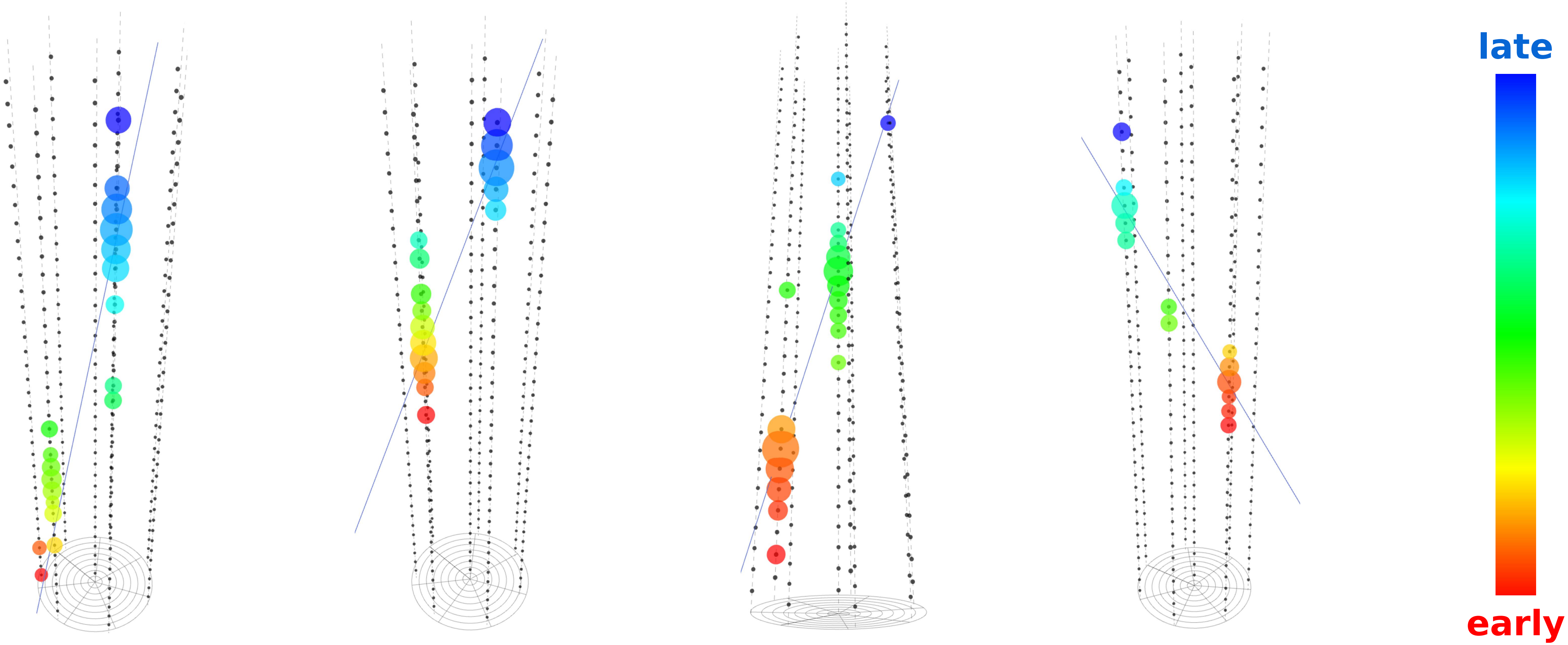




Fair agreement of MC expectation and data

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

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

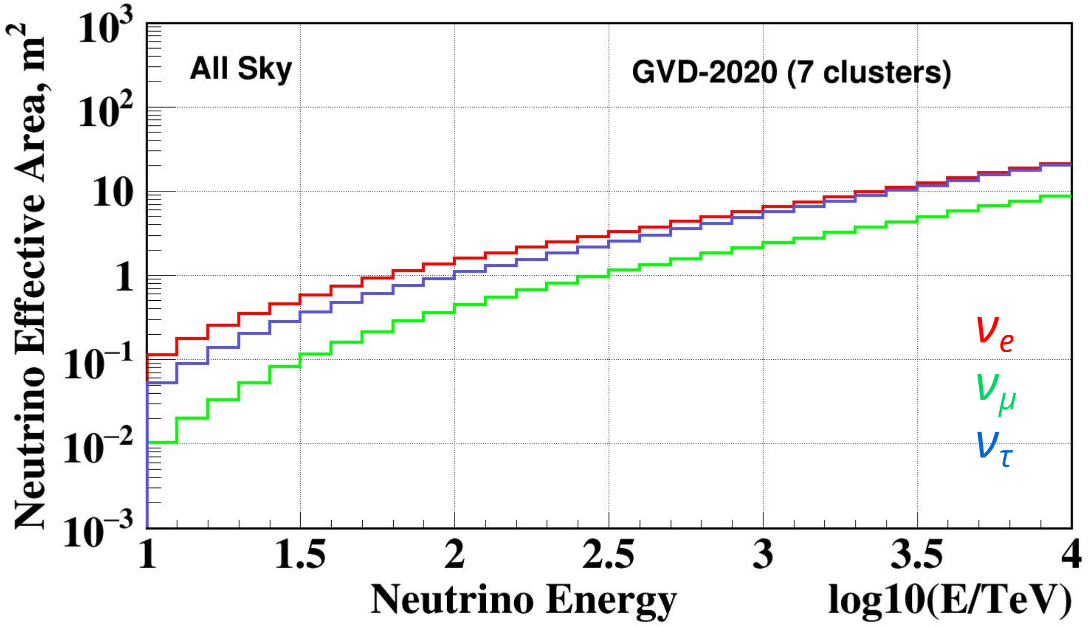
cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

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

High energy cascades I

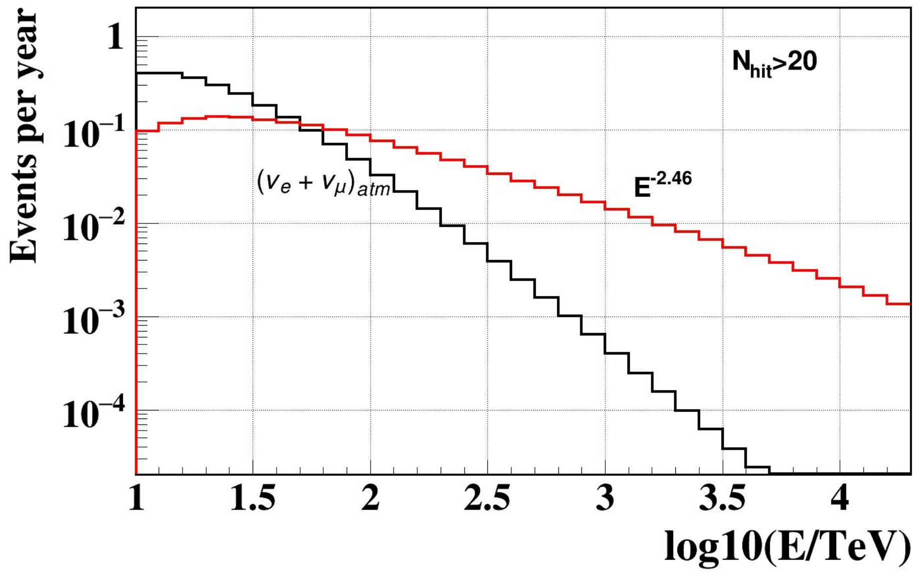
Effective volume for > 100 TeV cascade detection has reached **0.35 km³**
[IceCube HESE events volume: 0.4 km³]

neutrino effective area for cascade detection



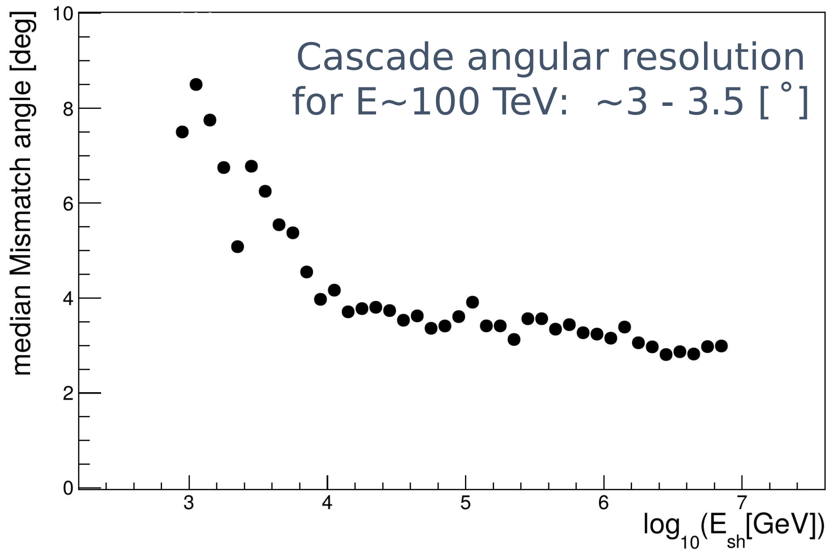
Assumption for astrophysical neutrino energy spectrum (IceCube fit):
$4.1 \cdot 10^{-6} E^{-2.46}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

Expected number of cascade events per year per Baikal-GVD cluster:



- 0.6 cascade events with E>100 ТэВ and N_{hit} > 20 are expected per year per cluster
- **4.2 events per year for 7 clusters**

High energy cascades II

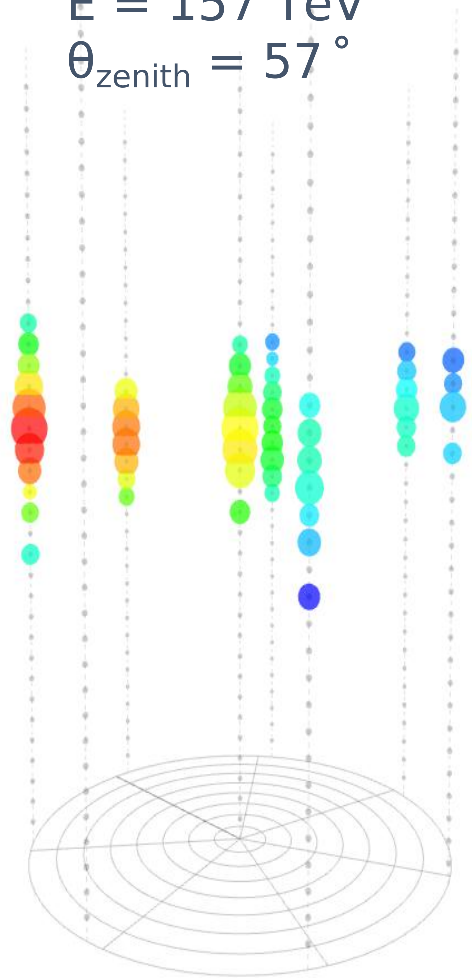


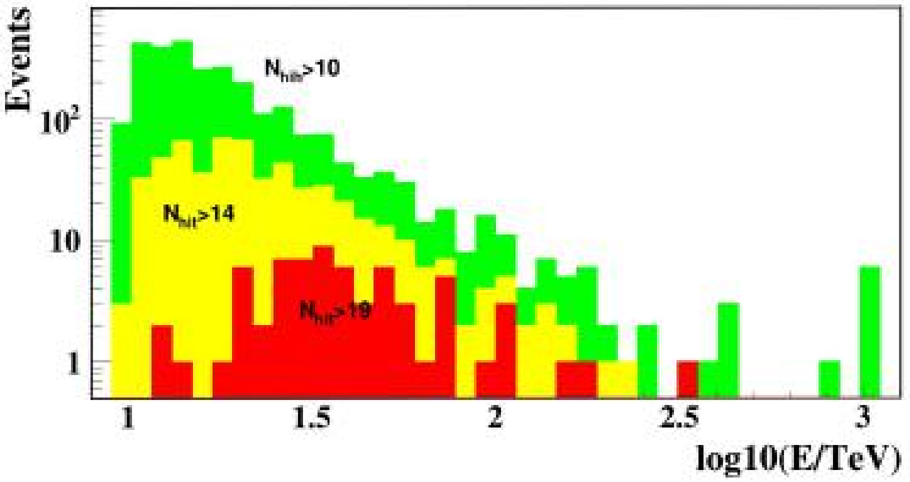
2016, 2018 and 2019 (4 months) data were processed,
full exposition: 1364 days

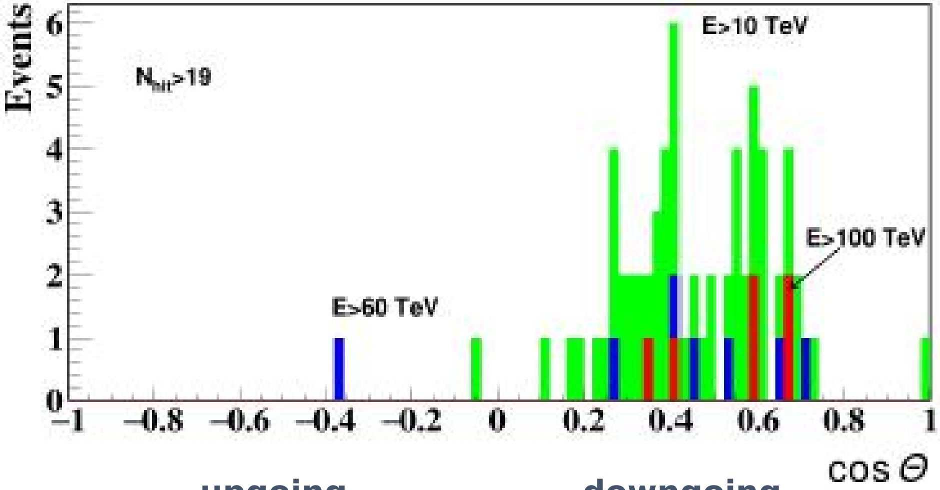
7 candidates with E > 100 TeV and number of hits >19

An upgoing cascade with E = 71 ТэВ was found

53 fired OMs
E = 157 TeV
θ_{zenith} = 57˚



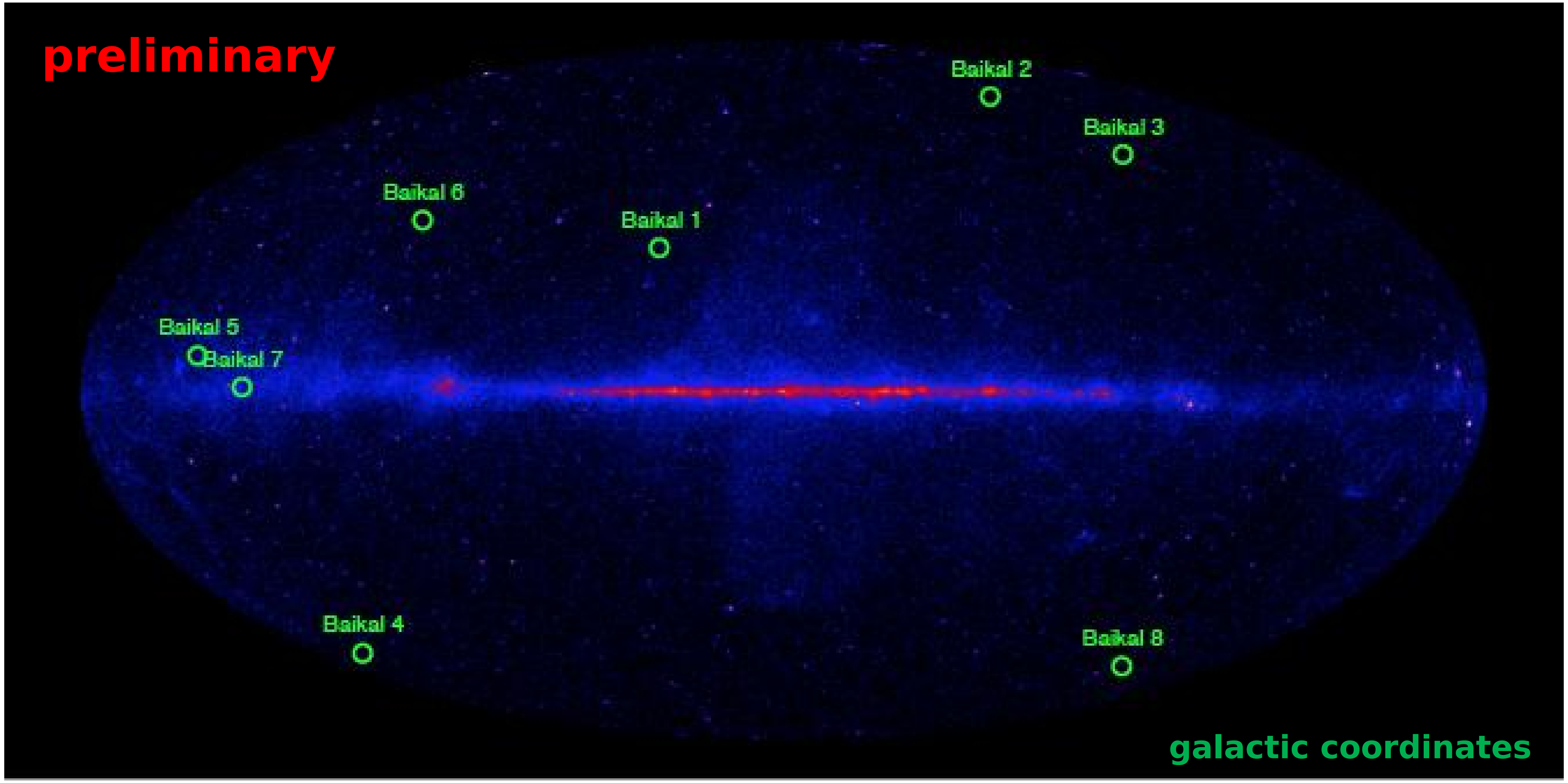




upgoing downgoing

High energy cascades III

Map of cascade alert events



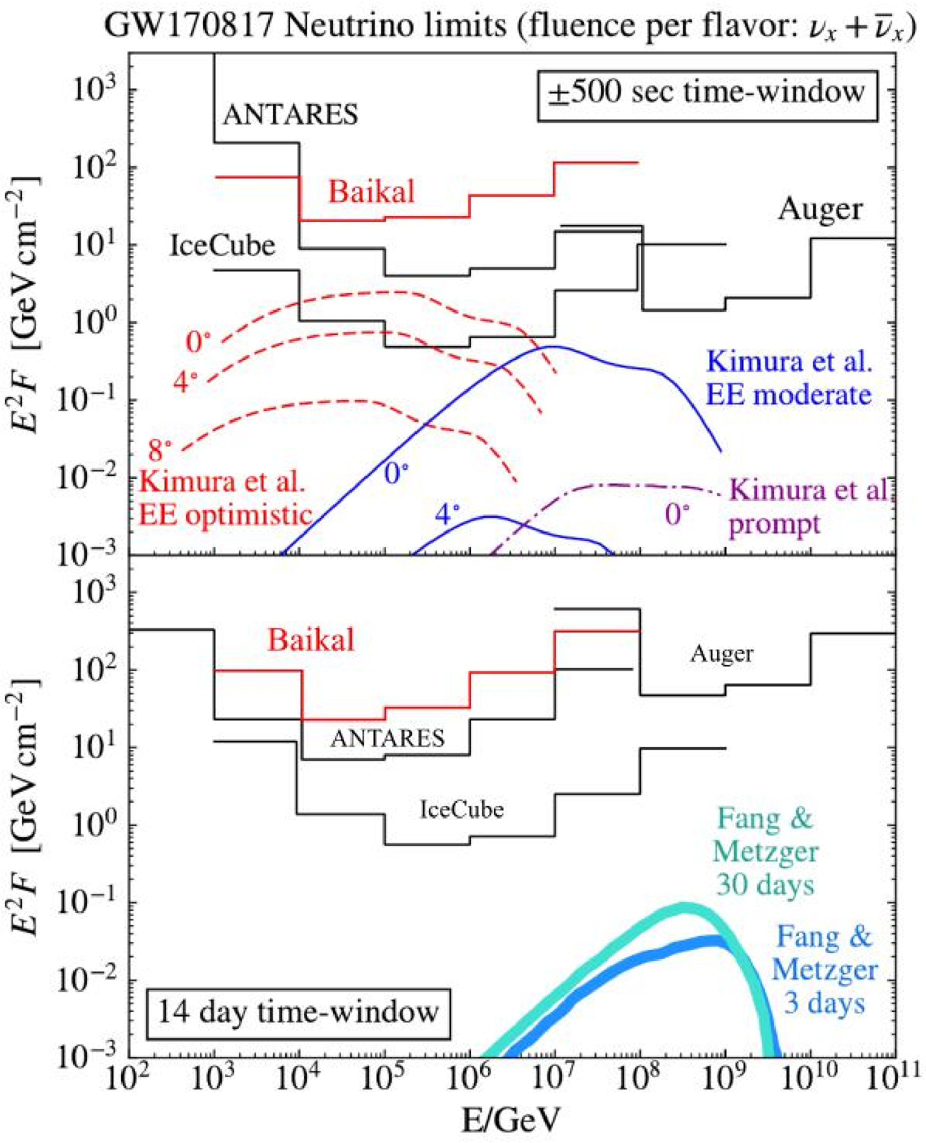
4FGL, map of sources E_γ > 10 GeV (*D.Semikoz, A.Neronov*)

Multi-messenger studies

GW170817 - neutron star merger, first gravitational waves detection associated with gamma/optical/radio signal
[Phys. Rev. Lett. 119, 161101]

Search for neutrino events in cascade mode
- no events within ± 500 sec window
- no events in 14 days window after the merger

Upper limits on the neutrino flux at 90% CL have been derived assuming E^{-2} spectral behavior and equal flavor flux
[JETP Letters, v.108, issue 12, arXiv:1810.10966]



Summary

- Since April 2020 Baikal-GVD detector includes 7 clusters (over 2000 optical modules)

- Accurate detector positioning and calibration methods are developed

- Muon reconstruction techniques are developed and results are in fair agreement with MC expectations

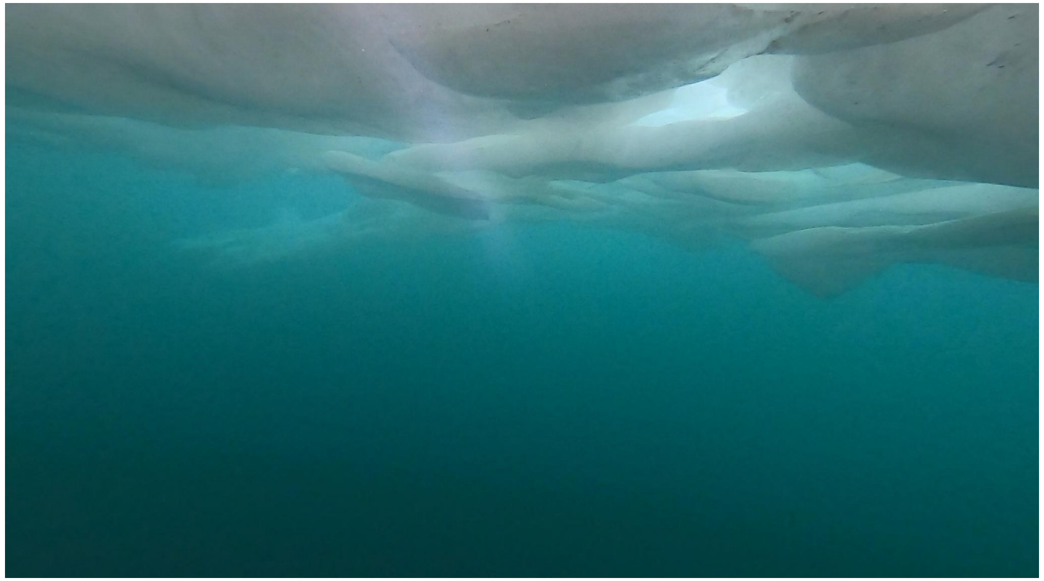
- A set of 57 muon neutrino candidates was selected in 323 days single cluster livetime in 2019

- A set of 8 high-energy cascade alert events was selected in 1364 days of single cluster livetime in 2016, 2018 and 2019

- Work in progress: multi - cluster analyses

Backup

Expedition 2020



Baikal-GVD – status 20 Nov 2019

Total: 5 Clusters → 40 Strings → 120 Sections → 1440 OMs

Faulty channels: "Counts = 0 "

Cluster 1
Str 4 Sec 3 Ch 1-12
Str 5 Sec 1 Ch 12
Str 6 Sec 2 Ch 1-12
Str 6 Sec 3 Ch 8-12
Str 7 Sec 1 Ch 11

Cluster 2
Str 1 Sec 3 Ch 12
Str 5 Sec 2 Ch 7-12
Str 7 Sec 1 Ch 1-6,11
Str 8 Sec 1 Ch 11,12
Str 8 Sec 2 Ch 3,7

Cluster 3

Cluster 4
Str 4 Sec 1 Ch 1-12
Str 5 Sec 3 Ch12

Cluster 5
Str 1 Sec 3 Ch 3,4, 9-12
Str 3 Sec 3 Ch 7;
Str 5 Sec 3 Ch 12;
Str 8 Sec 1 Ch 1
PM Comm 300 VDC

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Total
27 May 2019	18	10	0	0	1	29 (2.0%)
20 Nov 2019	31	18	0	13	9	71 (4.9%)

3