Fedor Šimkovic
Comenius University and JINR Dubna
on behalf of the Baikal Collaboration

Neutrino telescope in Lake Baikal: Present and Future

Outline

I. *Introduction*

Baikal-GVD Collaboration, location of telescope

II. *The Construction and Functioning of the Baikal-GVD Detector*

status and outlook of the construction, acoustic positioning system, laser operation, background light, data processing of events

III. *(Preliminary) results from the Baikal-GVD*

sample of muon tracks and cascade events, search for muon ν's, cascades induced by astrophysical ν's, ν's related to GW170817A and related to IC170922A

IV. *Conclusion and Outlook*

BAIKAL-GVD

Baikal-GVD Collaboration

Collaboration: 9 institutions, 50 members

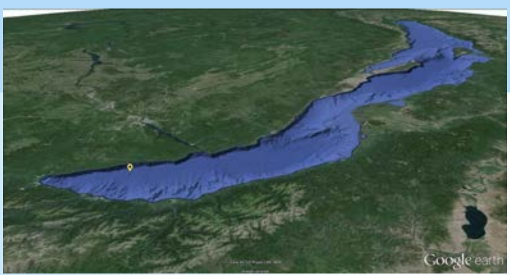
1. Institute for Nuclear Research, Moscow, Russia.
2. Joint Institute for Nuclear Research, Dubna, Russia.
3. Irkutsk State University, Irkutsk, Russia.
4. Skobeltsyn Institute of Nuclear Physics MSU, Moscow, Russia.
5. Nizhny Novgorod State Technical University, Russia.
6. St. Petersburg State Marine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

Associated members:

10. Krakow Institute for Nuclear Research, Poland

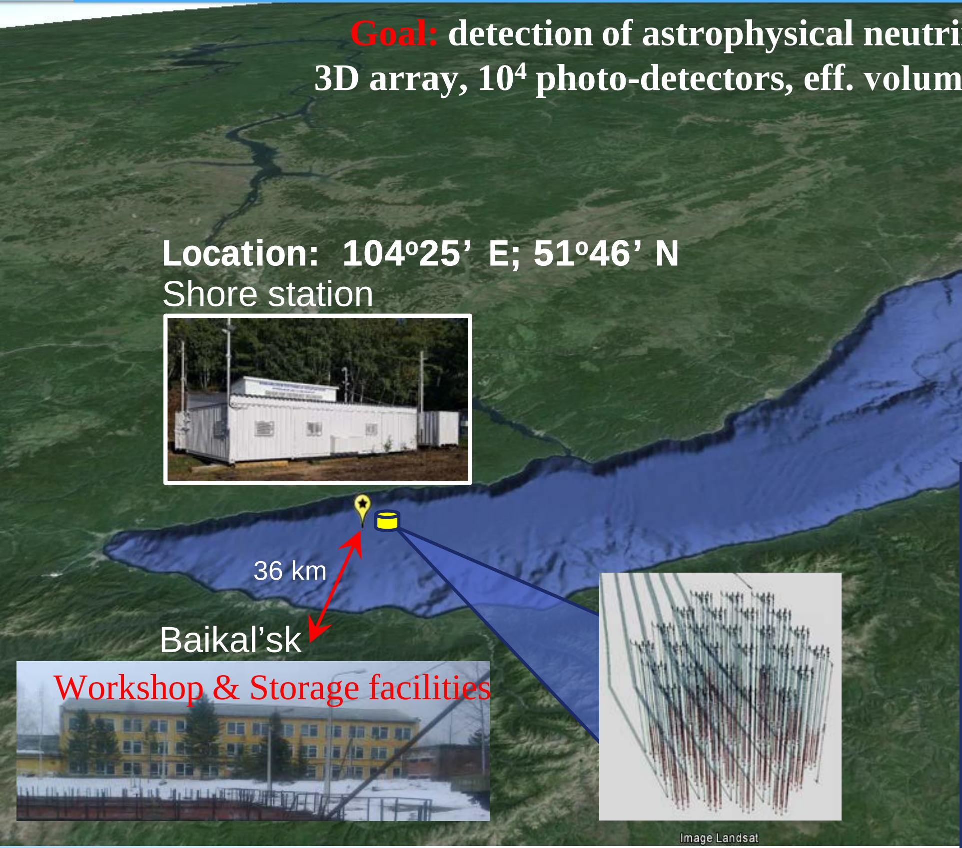
…

…



Location of the Baikal-GVD neutrino telescope

Goal: detection of astrophysical neutrinos with 3D array, 10^4 photo-detectors, eff. volume ~1.5 км^3



Location: 104º25' E; 51º46' N

Shore station

Workshop & Storage facilities

- **1370 m maximum depth**
- **Distance to shore ~4 km**
- **Absence of high luminosity bursts from biology and K^{40} background**
- **Water properties:**
  - **Abs. length: 22 ± 2 m**
  - **Scatt. length: L_s ~ 30-50 m**
  - **L_s /(1- <cosθ>) ~ 300-500 m**
- **Strongly anisotropic phase function: <cosθ> ~ 0.9**
- **Possibility to deploy the detector from the ice of the lake**

Baikal-GVD telescope
(under construction)

Objectives:

- 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

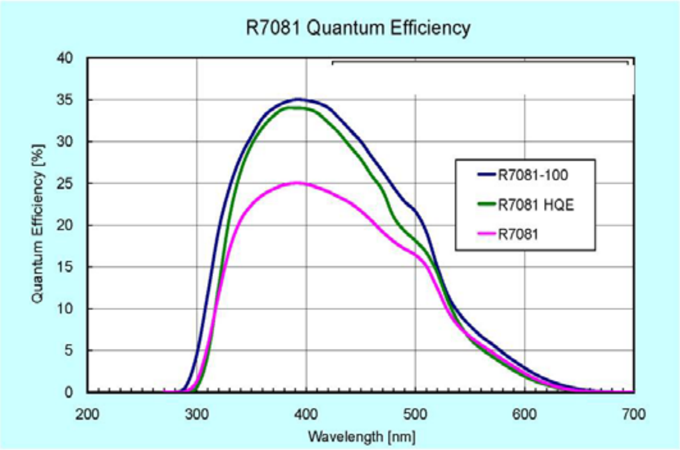
Physics Goals:

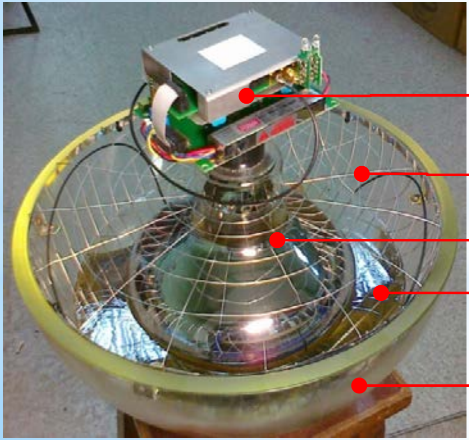
- Investigate Galactic and extragalactic neutrino "point sources" in energy range > 100 TeV
- Diffuse neutrino flux – energy spectrum, local, and global anisotropy, flavour content
- Sporadic cosmic sources (GRB, …)
- Dark matter and exotic particles search

a tool for multimessenger astronomy

The Optical Module

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





OM electronics
Mu-metal cage
PMT
Optical gel
Pressure-resistant glass sphere
VITROVEX (17”)

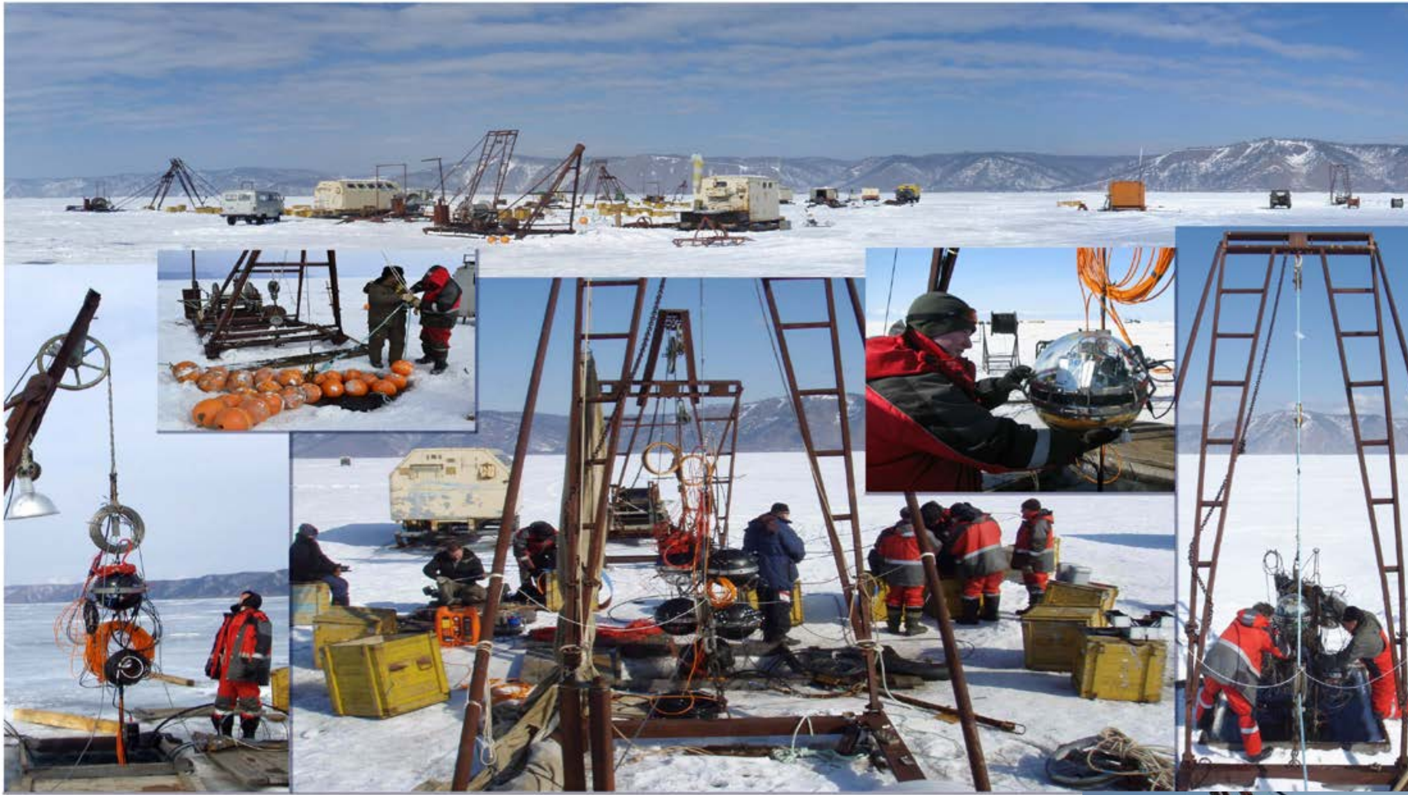
Optical modules assemble (JINR Dubna)

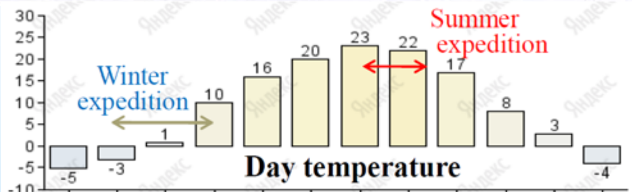
In 2018 production rate (including testing) was up to 6 OM/day

The optical modules production facility

The new facility allows to produce and test up to 12 OM per day. In 2019 we need to produce and send to the site 600 OM up to end of February

Winter expeditions at Lake Baikal



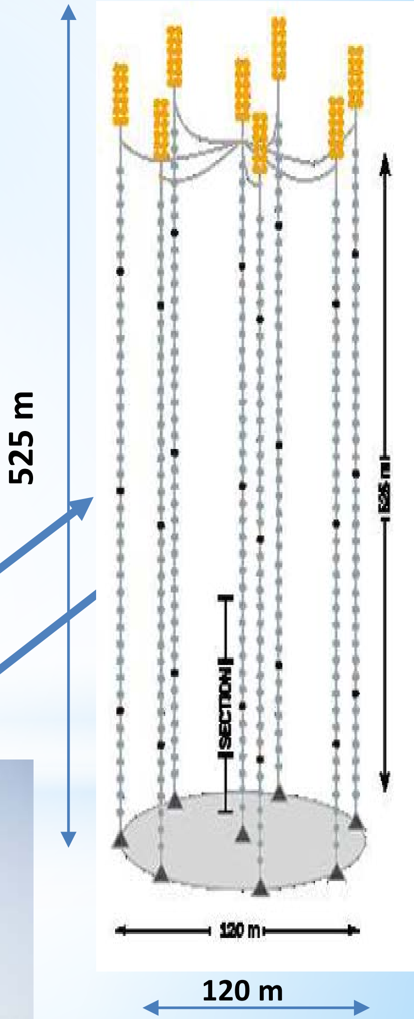


The Cluster of Strings

- **288 OMs at 8 strings**
  - **36 OMs per string, 15 m spacing**
  - **depth 750 - 1275 m**
  - **60 m between strings**
- **Cluster DAQ center (30 m below surface)**
  - **Trigger, power, data transfer systems of the cluster**
- **Electro-optical cable to shore**
- **Acoustic positioning system (4 beacons on each string)**
- **3-9 calibration light sources (matrix of LEDs)**
  - **Inter-string time calibration**

String is: 3 Sections of 12 OMs&ADC module

Sticker for an optical module



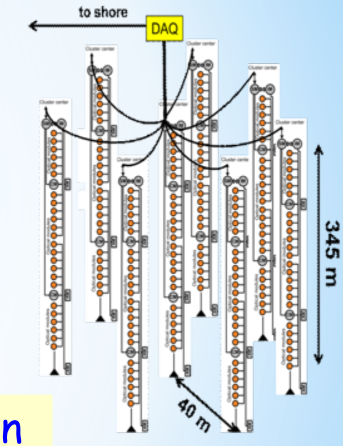
Status 2018: three Baikal GVD clusters

24 strings (864 OMs)

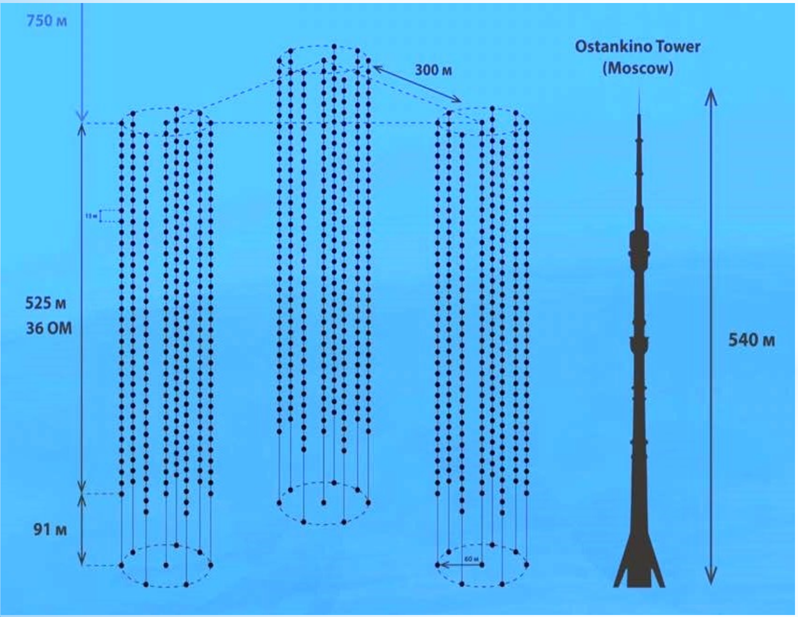
largest NT in the northern latitudes

2015: «Dubna»

8 strings (192 OMs)



Configuration	2015	2016	2017	2018
The number of OMs	192	288	576	864
Geometric sizes, m	∅80×345	∅120×525	2×∅120×525	3×∅120×525
Eff. Vol	0.03 km^3	0.05 km^3	0.1 km^3	0.15 km^3

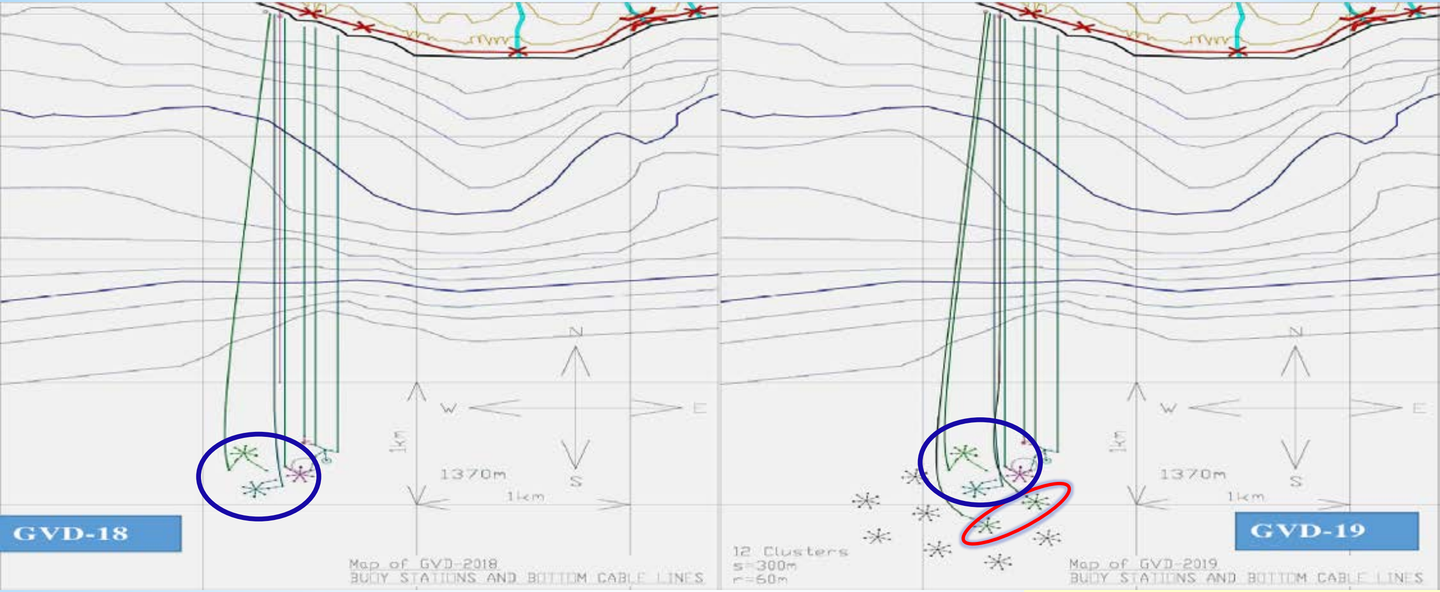


Data taken with three Baikal-GVD clusters

- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

Effective vol.
0.25 km^3 = ¼ km^3

Five Baikal-GVD clusters since April 2019
(2 clusters and 2 shore cables added)

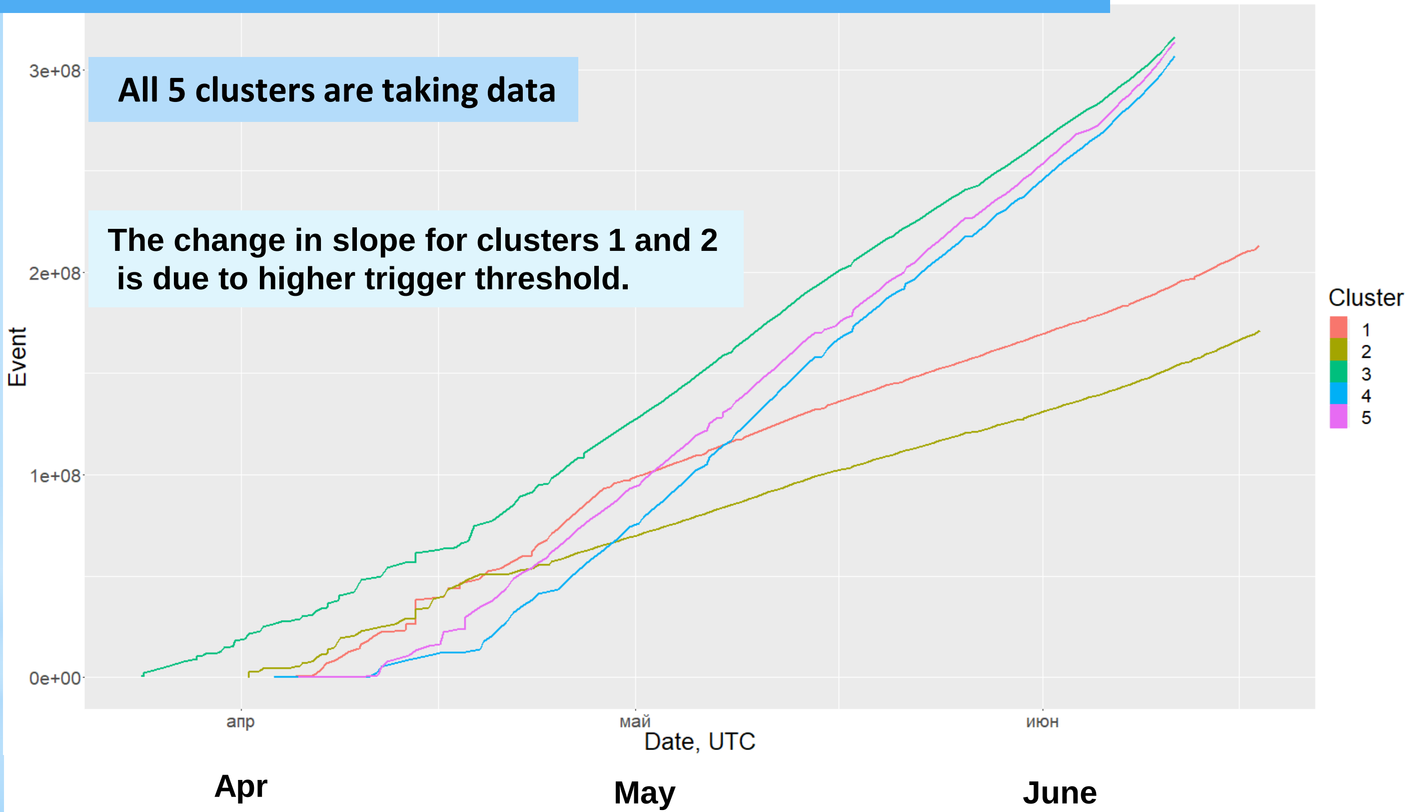


Configuration	2016	2017	2018	2019
The number of OMs	288 (8str×36)	576	864	1 440
Eff. Vol. (E > 100TeV)	0.05 km^3	0.1 km^3	0.15 km^3	0.25 km^3

~ 600 m

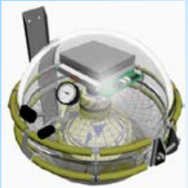
Baikal-GVD Detector allows to register already 2 to 3 events per year from astrophysical ν's with energies above 100 TeV

The event accumulation rate of the five clusters from April till June 2019



Their DAQ (already optimized for the last 3 clusters) was challenged by the high data rates. About 1.5 10^9 events have been recorded, with a data taking efficiency of 90% for single clusters and almost 100% with at least one cluster taking data.

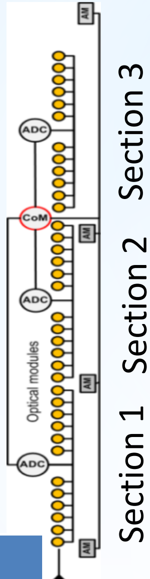
Baikal-GVD: Phase 1 (completion in 2021)

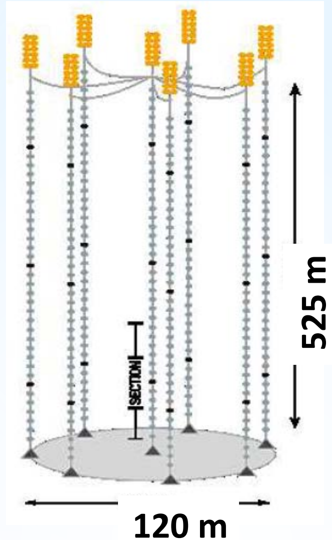


Optical module

PMT: R7081-100

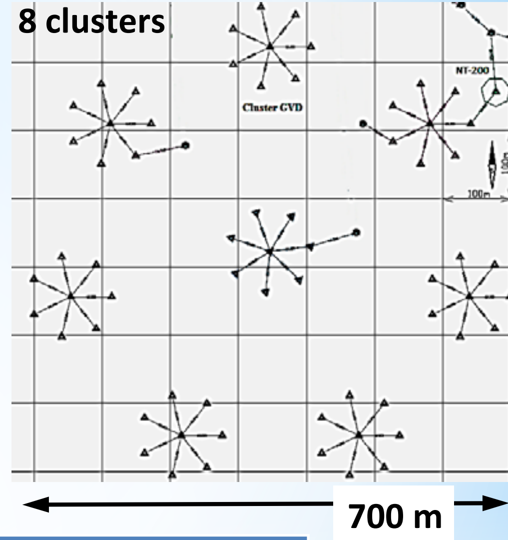
GVD-1	
OMs	**2304**
Clusters (8 Strings)	**8 (9)**
Depths [m]	**750 – 1275**
Eff. Vol. [km^3]	**0.4 (0.45)**





Cluster:

8 strings



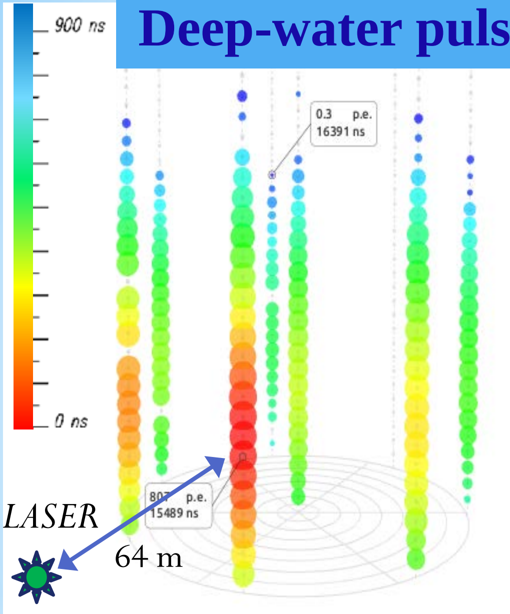
Directional resolution
Cascades: 3.5° – 5.5°
Muons: 0.25° - 0.5°

Energy resolution
δ(E/Esh) ~ 0.15
δ(lgE) ~ 0.4

Year	2016	2017	2018	2019	2020	2021
No. of clusters No. of OMs	***1*** ***288***	***2*** ***576***	***3*** ***864***	***5*** ***1440***	***7*** ***2016***	***9*** ***2592***

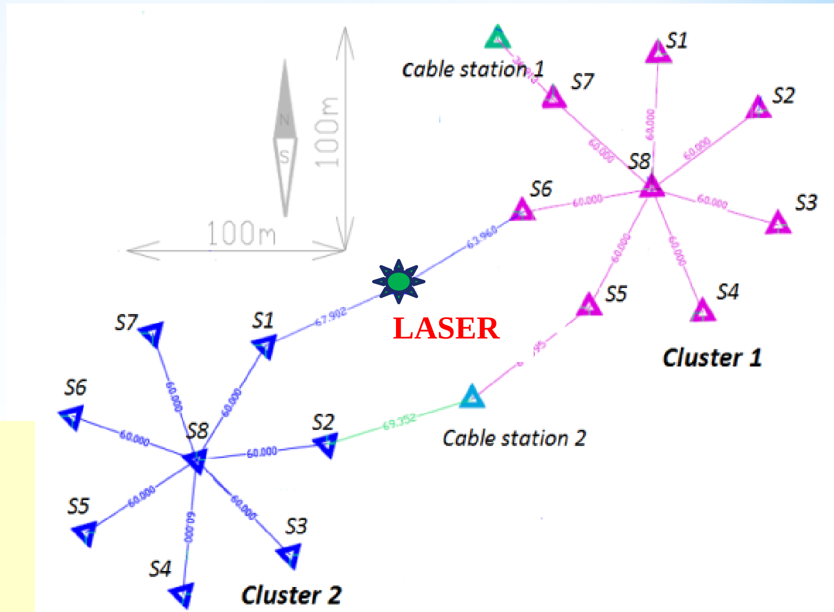
A possible extension of Phase 1 to Phase 2 with construction of additional 14 clusters will depend on the performance and physical output of the Baikal GVD detector in 2021.

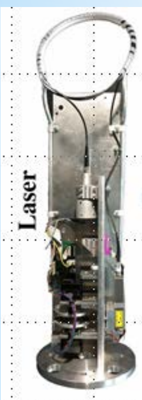
Deep-water pulsed laser



Purposes: inter-cluster time calibration, precision of the OMs positioning, Cascade emulation

! see poster: PS3-103



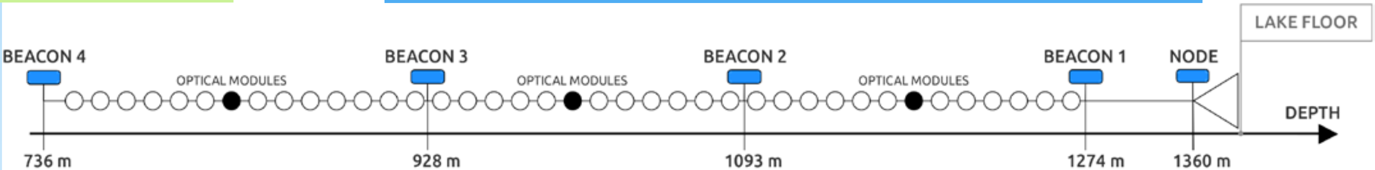


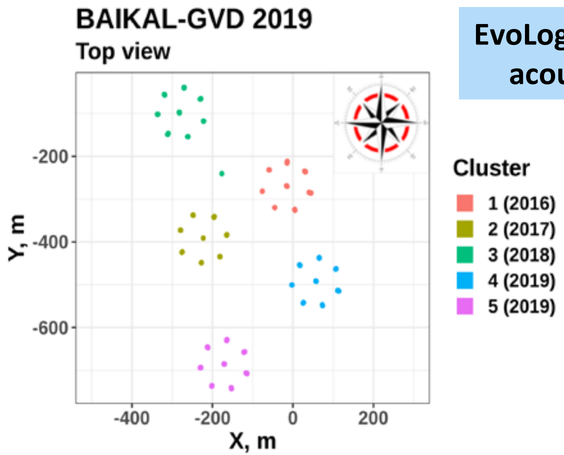
Wavelength:
532 nm
Pulse energy:
0.37 mJ
($\sim 10^{15}$ photons)
Flash duration:
~1 ns

Depth: ~1200 m
Distance to the nearest strings:
64 m: Cluster 1, 68 m: Cluster 2

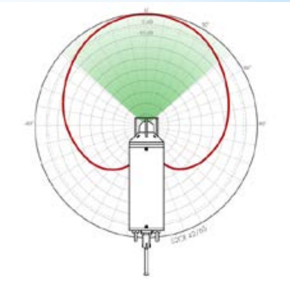
! see poster:
PS3-129:

Hydro-acoustic positioning system
(APS coordinate measurements)





EvoLogics S2C R42/65 acoustic modem

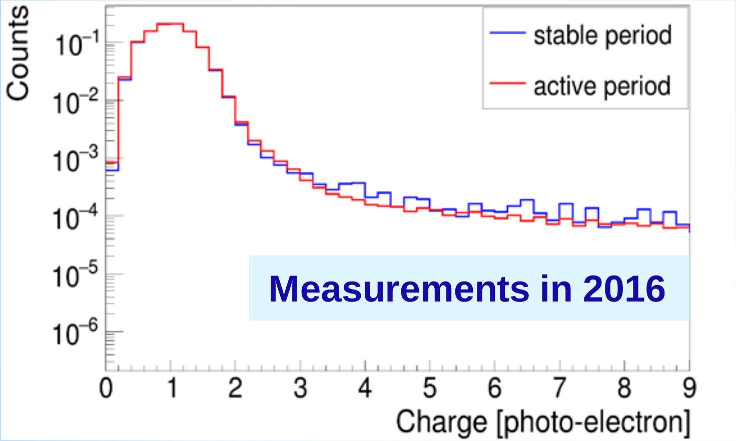


- 4 acoustic modems (AMs) on each string.
- 1 AM (node) is fixed to the anchor, the rest (beacons) are mobile.

APS allows positioning optical modules with an average accuracy of 12 cm (the photocathode diameter is 25 cm), which is equivalent to a sub nanosecond time calibration. Over a season the most mobile OMs can drift beyond 50 meters from their median positions with the average speed of 0.5 cm/s and top speed of 3 cm/s. OM coordinates within a cluster and between clusters are highly correlated.

Background light at Baikal-GVD detector

! see poster: **PS3-101**

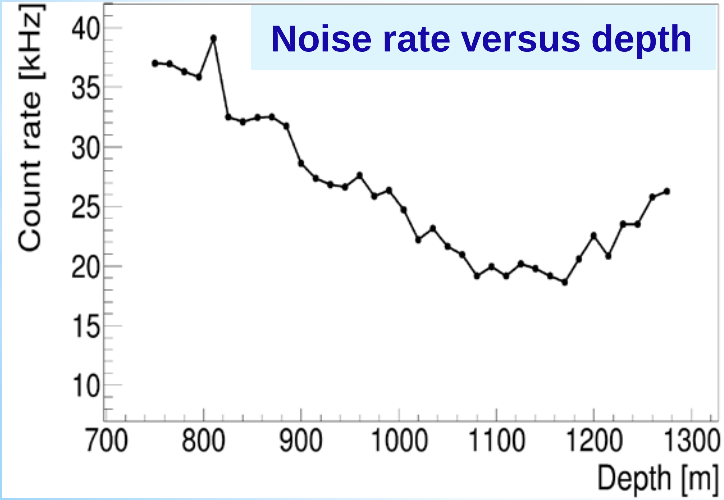


Measurements in 2016

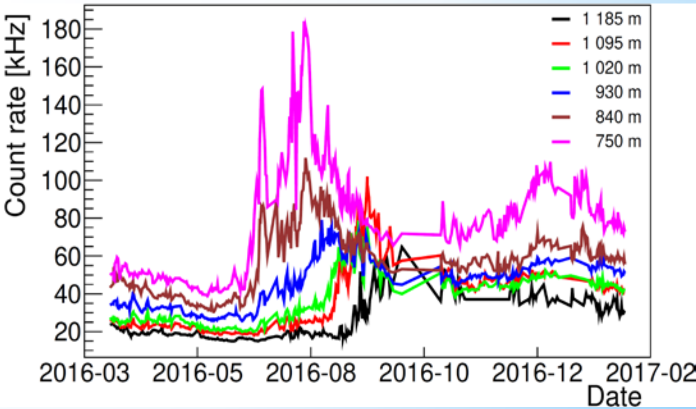
Lake Baikal mainly emits in range of a single ph.e.

Moderately low background
20 – 60 kHz,
no high luminosity bursts from biology,
no K^{40} background

Noise rate versus depth



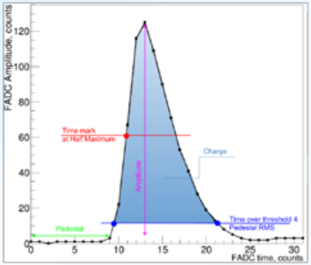
Noise rate vs time

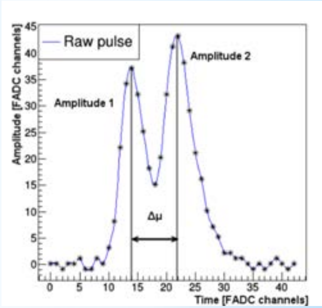


! see poster:
PS3-100

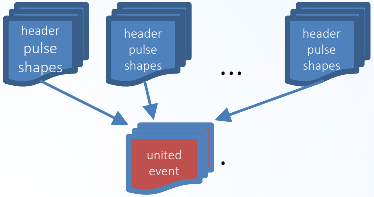
Data processing and analysis steps

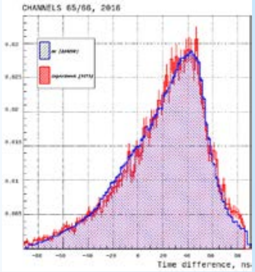
- Extraction of hit parameters from wave forms
- Joint events production
- Time and Amplitude calibration with light sources (laser source, LED matrixes, built-in OM LEDs) and atmospheric muons
- Geometry calibration with acoustic positioning system
- Data and Trigger quality monitoring





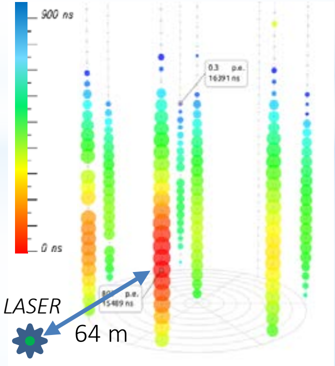
→ Telescope response: $Q_i, T_i, \vec{R}_i, i = 1,..,N_{hit}$

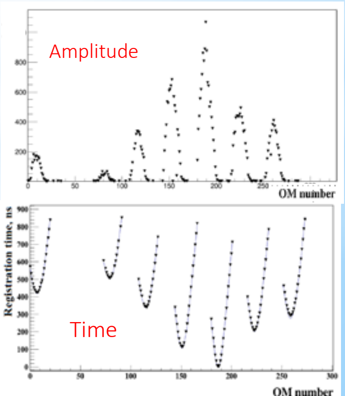




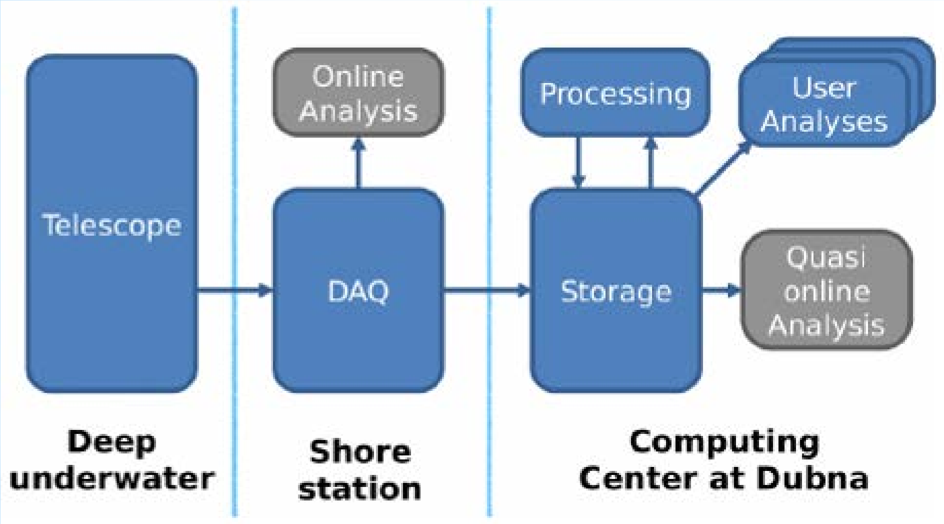
DQM @ level: OMs, section, cluster

- ➔ Time difference between two neighbor events
- ➔ Events rate
- ➔ Average numbers of events per given time interval
- ➔ Triggers quality monitoring
- ➔ Charge distribution analyses:
  - 1 p.e. → amplitude calibration
  - High and low trigger thresholds
  - Full range analysis wrt baseline distributions
  - Sensitivity-wise monitoring





Online analysis and alert system
are under development



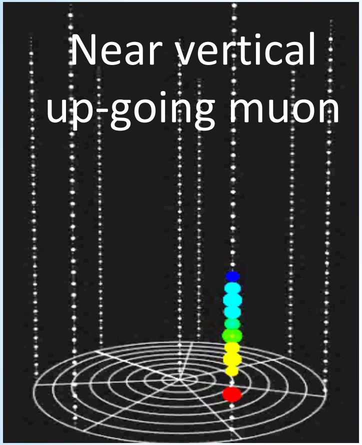
- 40 GB per cluster per day to shore
- 5 Mb/s by radio channel to 40 km away Baikalsk
- raw data transferred to storage Dubna facility through a high-bandwidth internet

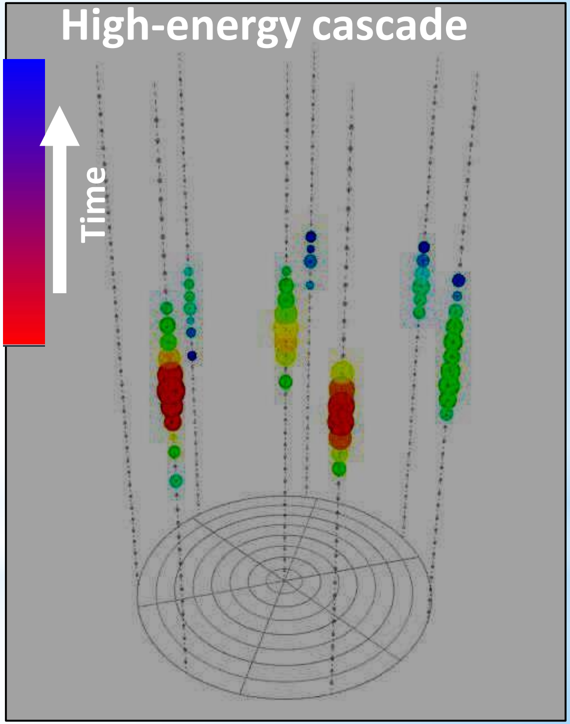
- Real time data stream that is available through TCP socket on the shore

- Latest raw data file (6 min. of exposition) that is available in Dubna CC after few minutes

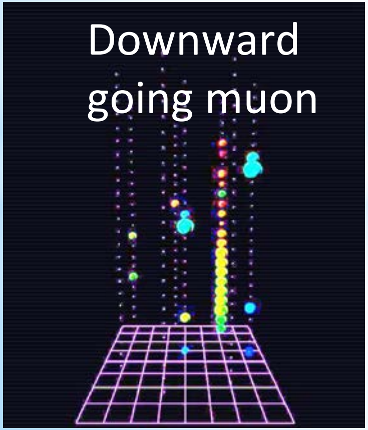
Typical Baikal-GVD Detector Responses

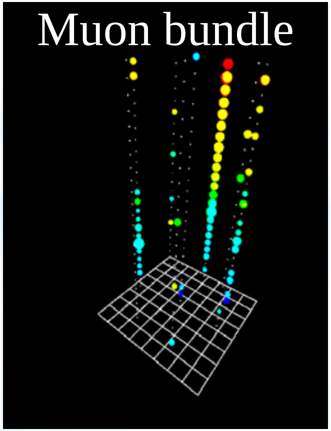
Neutrino signals





Background

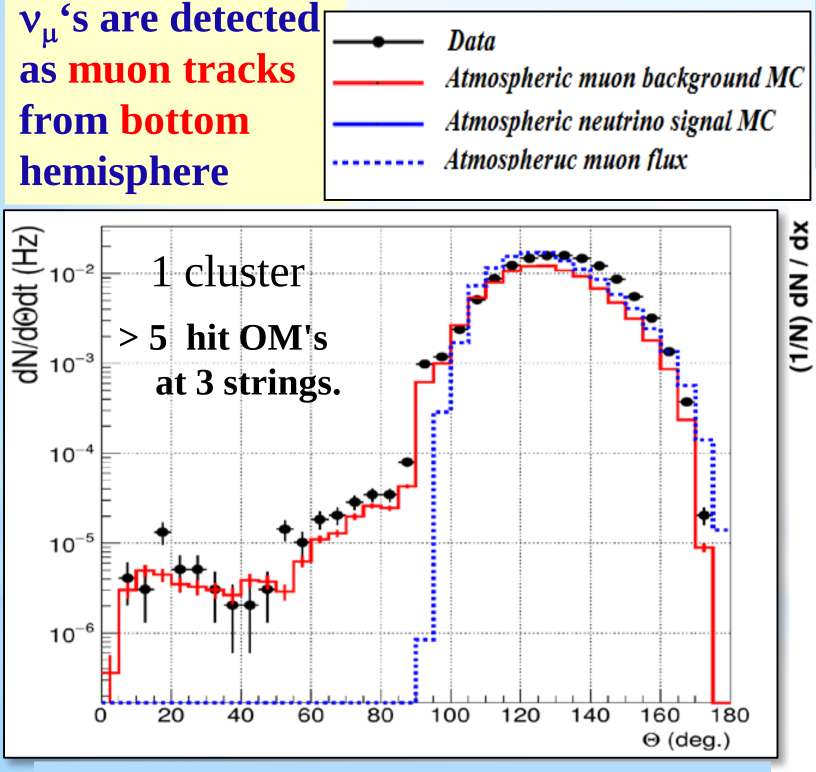




! see talk
NU11b
Lukáš Fajt

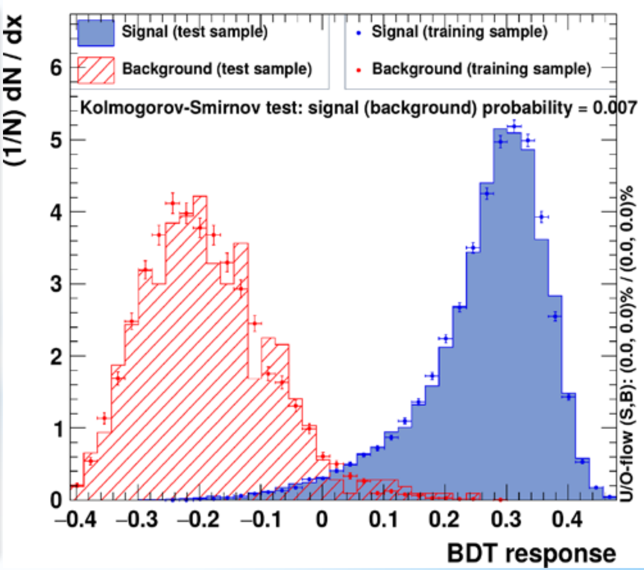
Search for muon neutrinos
(analysis of 2016 data sample – *first iteration*)

ν_μ's are detected as muon tracks from bottom hemisphere



Zenith angle distributions of muons

After track reconstruction and cuts on quality variables have been done, Boosted decision tree (BDT in TMVA) was used (>0.2)



see ICRC2019 proceedings

! see talk of NU4f Rastislav Dvornický

Search for *cascades induced* by astrophysical ν's

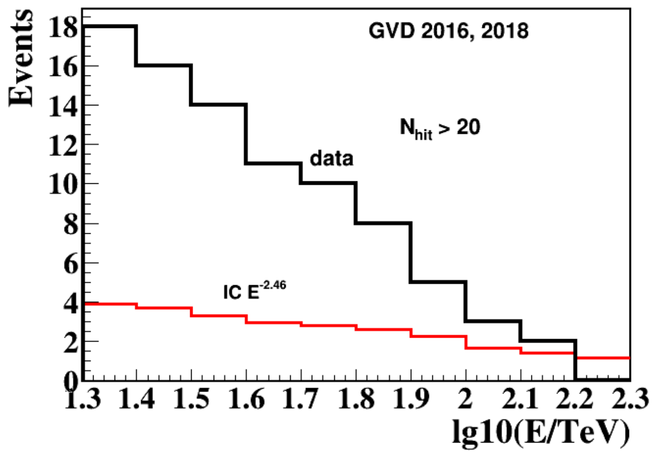
(For 1 year exposition 0.6 events are expected in one GVD cluster from astrophysical neutrino flux)

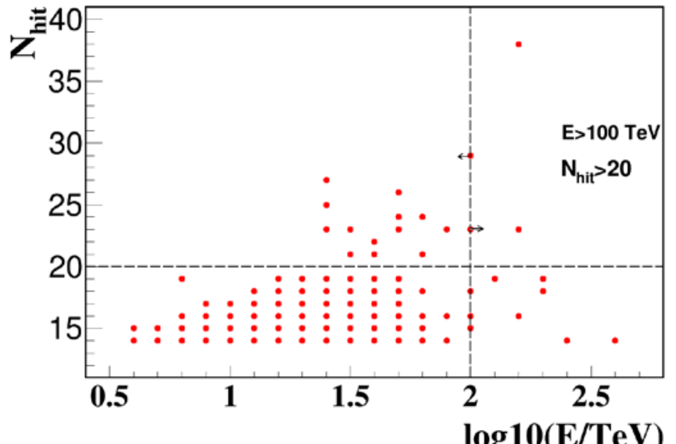
Cascade selection:

- **Causality cuts** (noise rejection)
- **Reconstruction of cascade** position direction and energy and cuts on quality parameters
- $N_{hit} > 20$

For 2016, 2018 data (2.4 year×cluster) the number of selected cascade events:

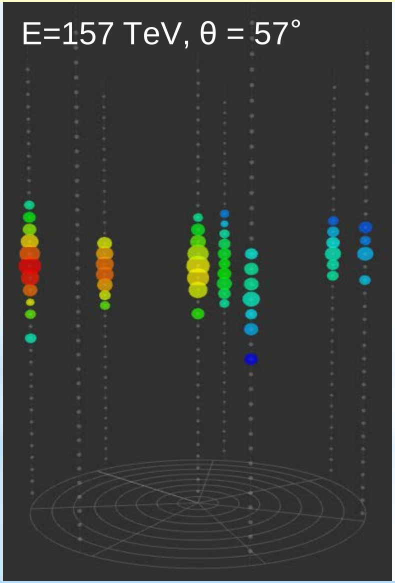
$N_{hit} > 13$	& E > 1 TeV:	417 events
$N_{hit} > 20$	& E > 1 TeV:	18 events
$N_{hit} > 20$	& E > 100 TeV:	3 events





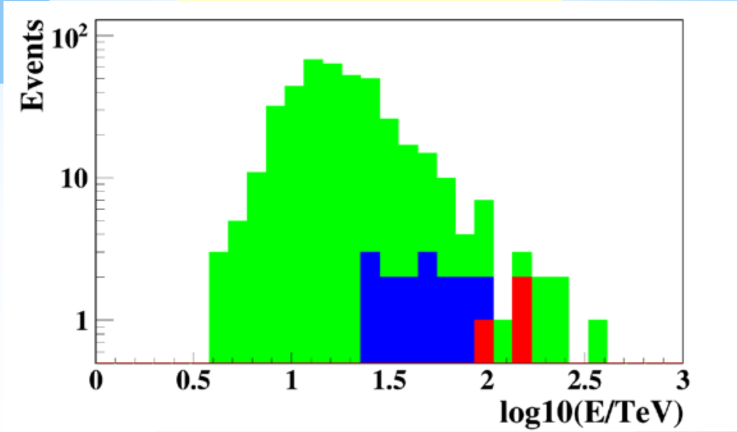
In Green - 417 events (N_{hit} >13, E>1 TeV)
In Blue - 18 events (N_{hit} >20)
In Red - 3 events (N_{hit} >20, E >100 TeV)
(1.4 events are expected for 872 life days from astrophysical flux)

Selected hits for reconstruction (53 hits)

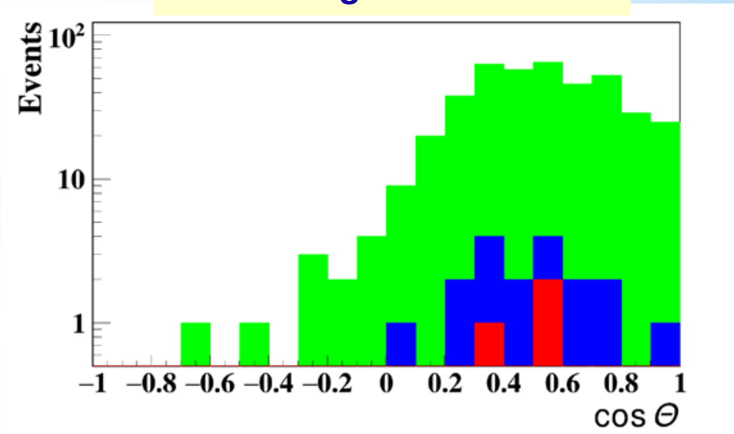


E=157 TeV, θ = 57°, φ_{loc} = 249°, x=-25m, y=-37m, z=11m, ρ=44m

Energy distribution



Zenith angle distribution



Search for ν's related to GW170817A

Binary neutrons stars merged in NGC4993 galaxy

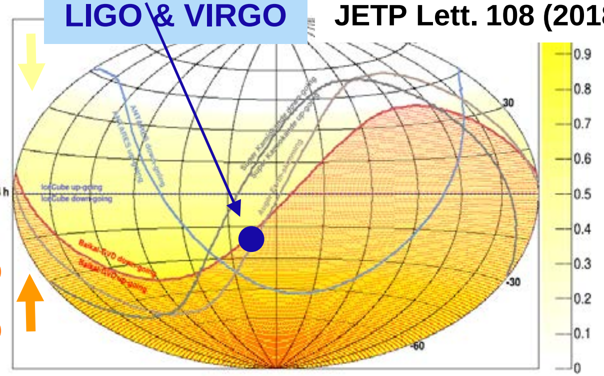
Cascade search mode

- **prompt emission:** GW ± 500 sec zenith angle θ = 93°
- **delayed emission:** GW +14 days 74° < θ < 150°

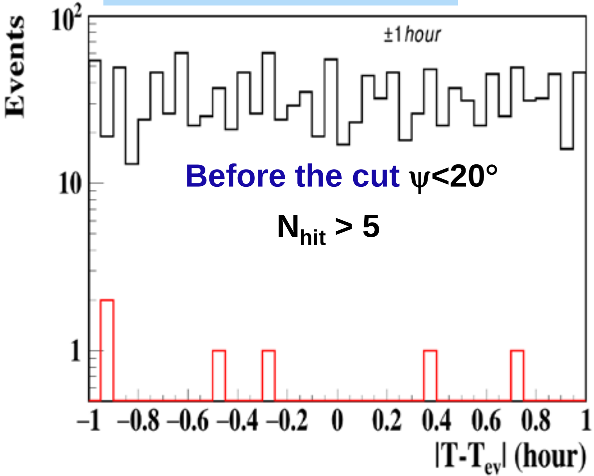
E^{-2} spectral behavior assumed

LIGO & VIRGO

JETP Lett. 108 (2018) 787-790

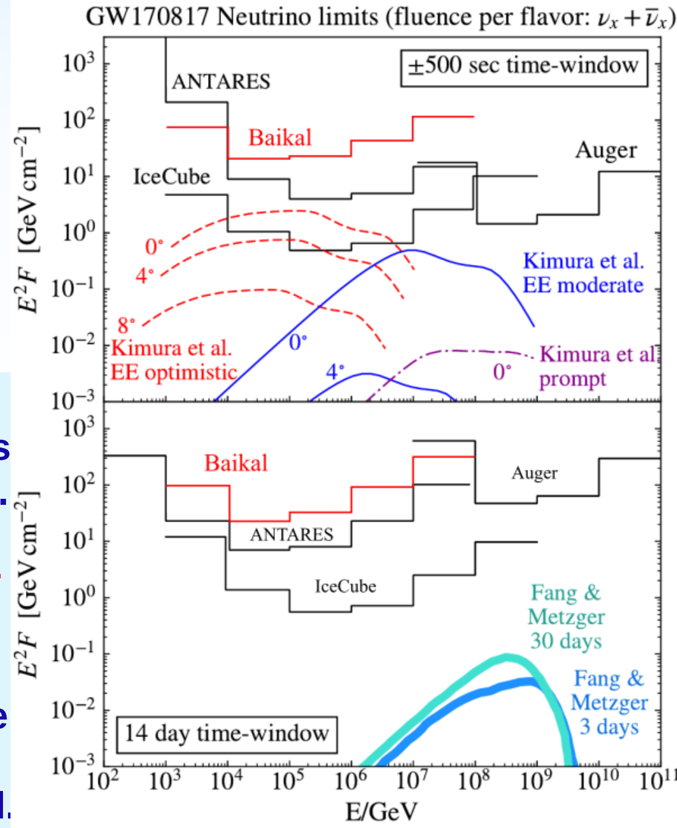


Events selection cuts

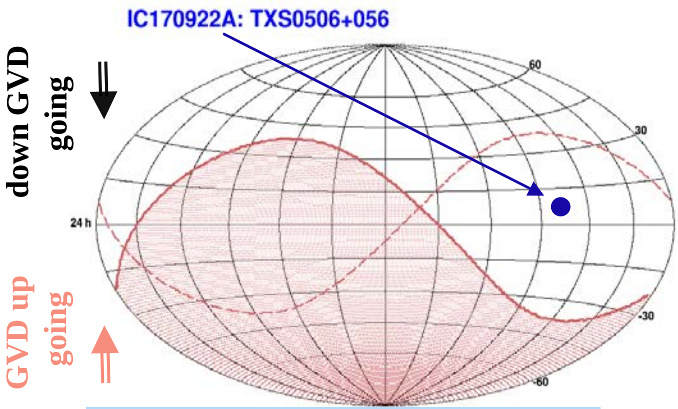


No ν events found.

Upper limits on ν fluence at 90% c.l.



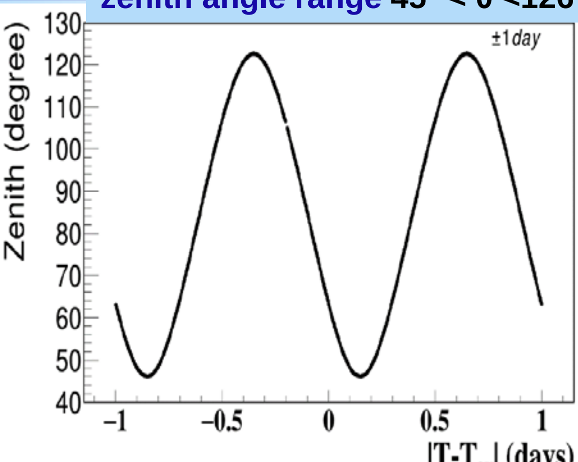
Cascades search for ν's related to IC170922A
(within ± 1 day time-window)



IceCube on 22.09. 2017: first evidence for the existence of an astrophysical source of high-energy ‘s (γ-ray blazar TXS 0506+056)

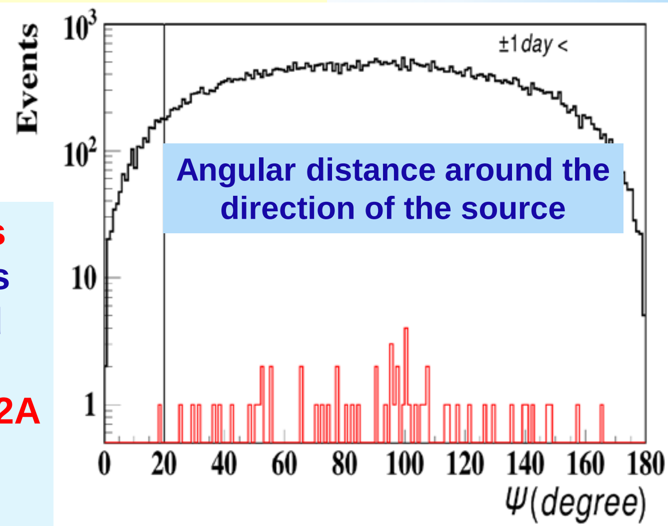
Cut	Events in ±1 day window
N_{hit} > 7 OM/3 Str.	56822
χ^2_t < 6	1717
η > 0	68
L_a < 30	58
ψ < 20°	1 (ψ = 18°)

Source direction at GVD site zenith angle range 45° < θ <126°



No ν ‘s events related to IC170922A were found

Angular distance around the direction of the source



Summary and Outlook

- Currently, Baikal-GVD neutrino telescope is under construction in Lake Baikal. Five clusters of the Baikal-GVD have been successfully commissioned in April 2019 and an effective volume of 0.25 km^3 was reached. The priority for the Baikal Collaboration in 2020 is to install next two clusters.

- During the year 2018, the Baikal-GVD data were taken with the highest effective volume for high energy neutrino detection in the Northern hemisphere: ~0.15 km^3.

- Modular structure of GVD design allows to search for HE neutrinos at the early phases of array construction. First cascades events were found with energy higher 100 TeV with data samples since 2015 year.

- Data recorded by GVD in 2017 were used in search for neutrino events associated with gravitational wave GW170817 and IC170922A events.

- Development of Baikal-GVD alert system for multi-messenger studies is in progress

Posters of Baikal-GVD Collab.

Rastislav Dvornický and Lukáš Fajt

- **PS1-13:** **The Baikal-GVD neutrino telescope: First results of multi-messenger studies**
- **PS3-100:** **Data Quality Monitoring system in the Baikal-GVD experiment**
- **PS3-101:** **The optical noise monitoring systems of the Lake Baikal environment for the Baikal-GVD telescope**
- **PS3-102:** **The inter-cluster time synchronization systems within the Baikal-GVD detector**
- **PS3-103:** **The Baikal-GVD detector calibrations**
- **PS3-129:** **Spatial positioning system of the Baikal-GVD underwater components**

Thank you for your attention!

BAIKAL-GVD