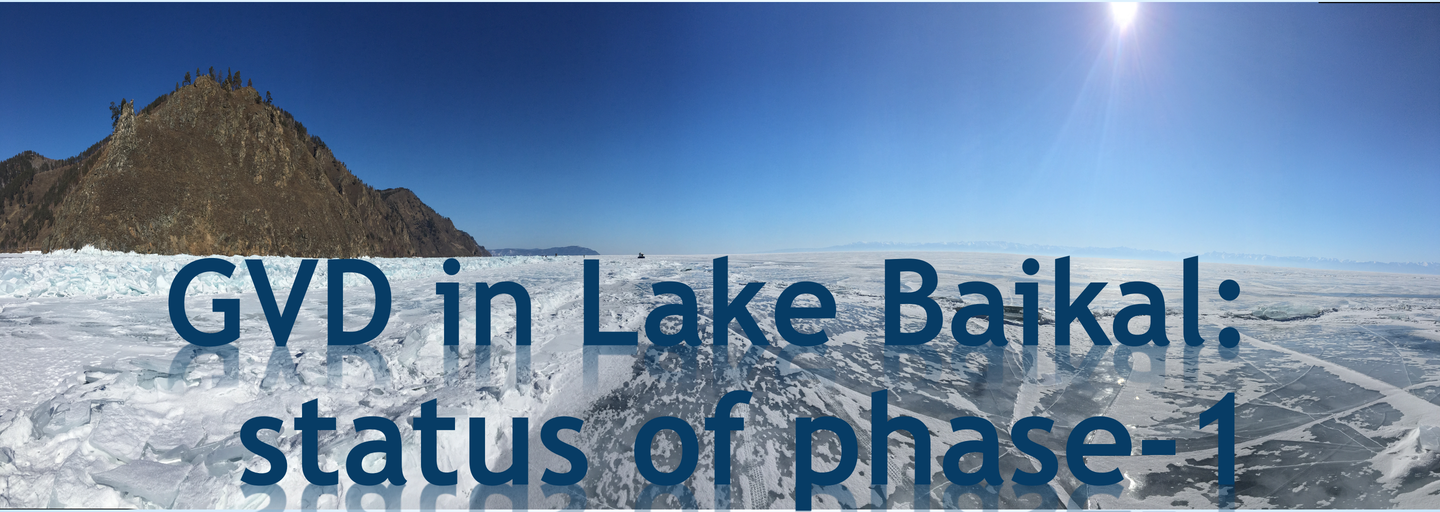
BAIKAL-GVD



GVD in Lake Baikal: status of phase-1

Olga Suvorova
Institute for Nuclear Research of RAS
on behalf of the Baikal collaboration

24 June 2019 – CPPM, Marseille

Baikal-GVD collaboration:
Gigaton Volume Detector in Lake Baikal

9 institutes, ~60 scientists

baikalweb.jinr.ru

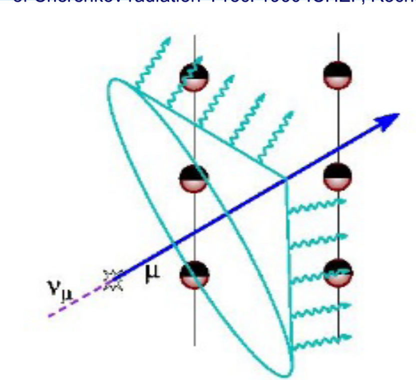
Motivation

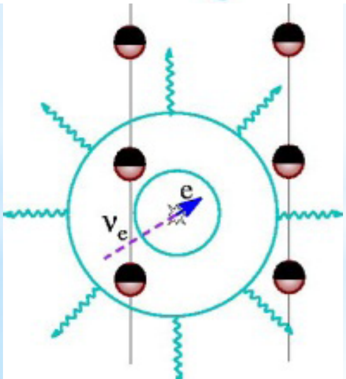
Neutrino detection: direction, energy, flavor

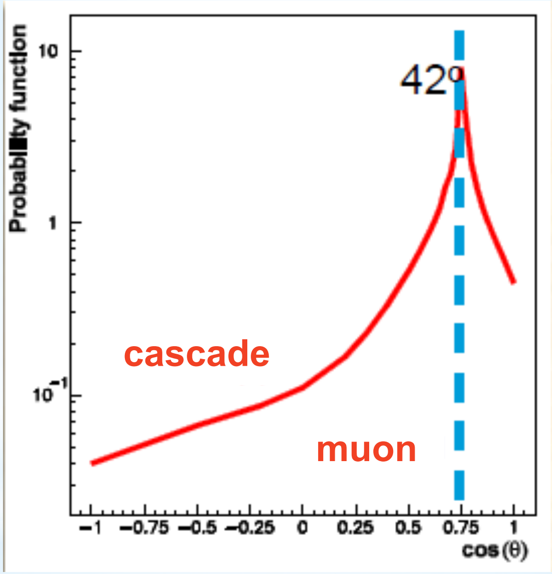
Detection principle

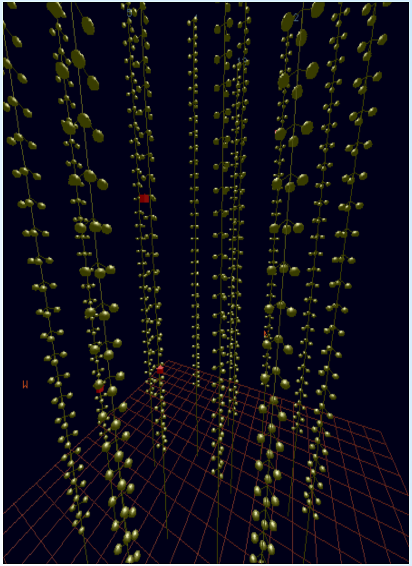
M.Markov, **1960**:
„We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation“ Proc. 1960 ICHEP, Rochester, p. 578.

$$\nu + N \rightarrow l + X$$





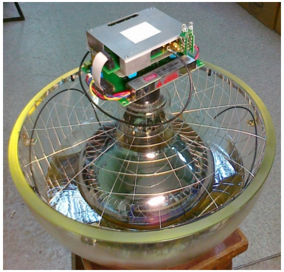
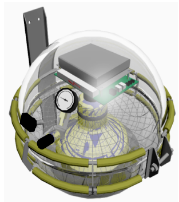
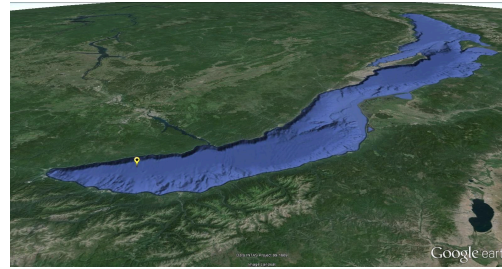




Arrival times & amplitudes,
PMTs arrangement and orientation

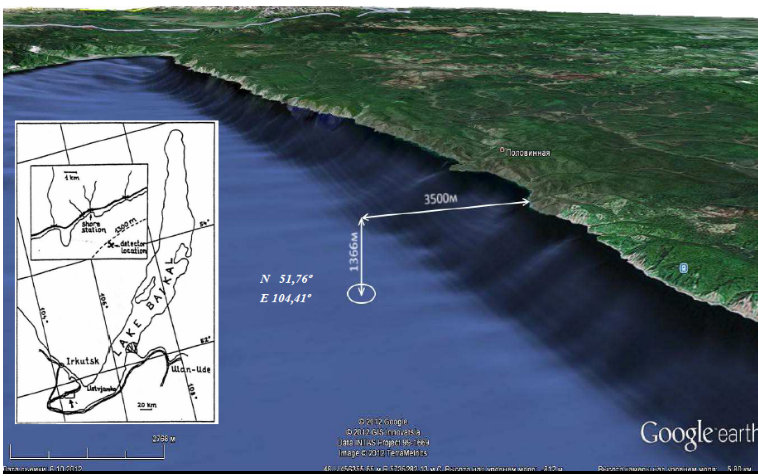
Environment properties

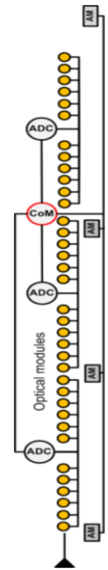
absorption, scattering, light background - K^{40}, bioluminescence…

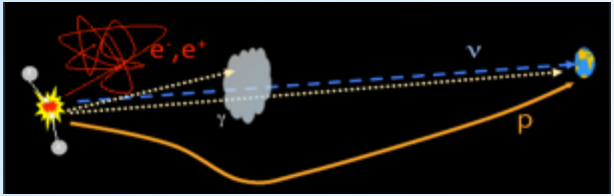
Optical module
PMT: R7081-100

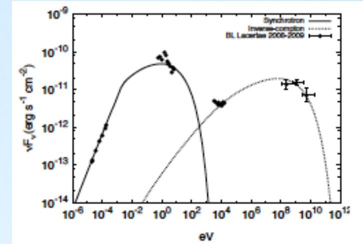
Baikal-GVD



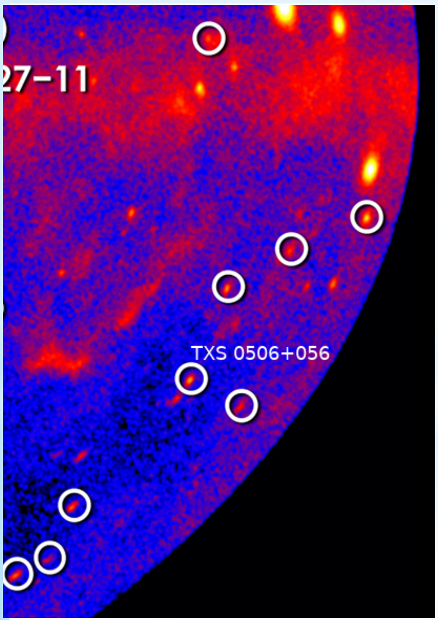



Why would we want to build a Gigaton Volume neutrino detector?



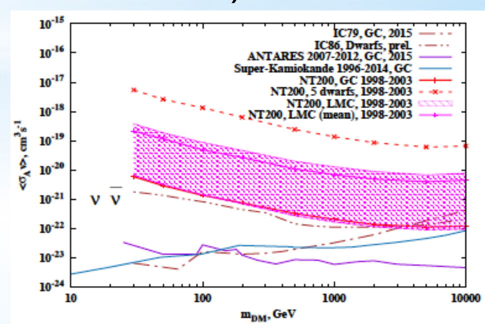


- Multi-messenger high energy astrophysics: EM radiation, GW, neutrinos, CR



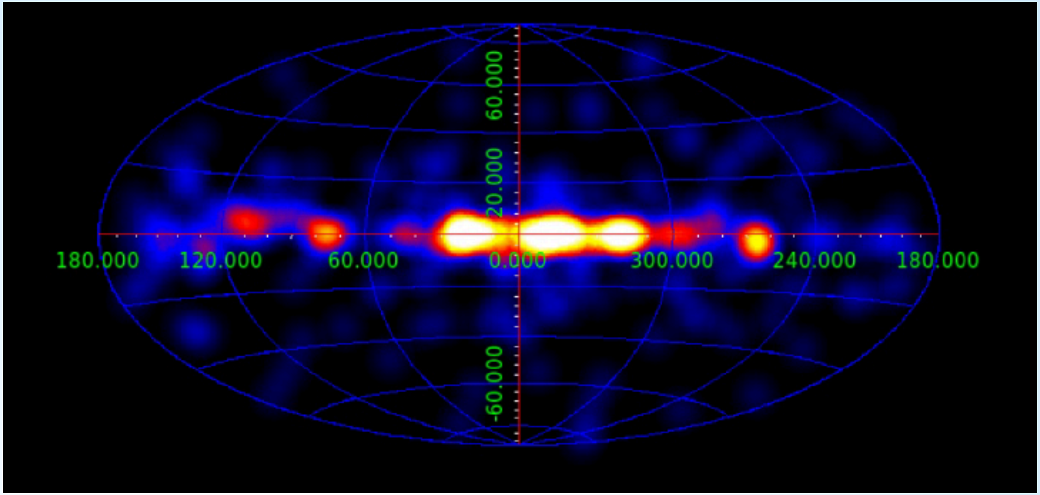
- The IC discovery of PeV events and latest claim on cosmic neutrinos; however TXS as alone neutrino source is not enough to understand why this blazar is a particular source
- Need a cubic kilometer detector in the Northern hemisphere (Baikal-GVD, KM3NeT)

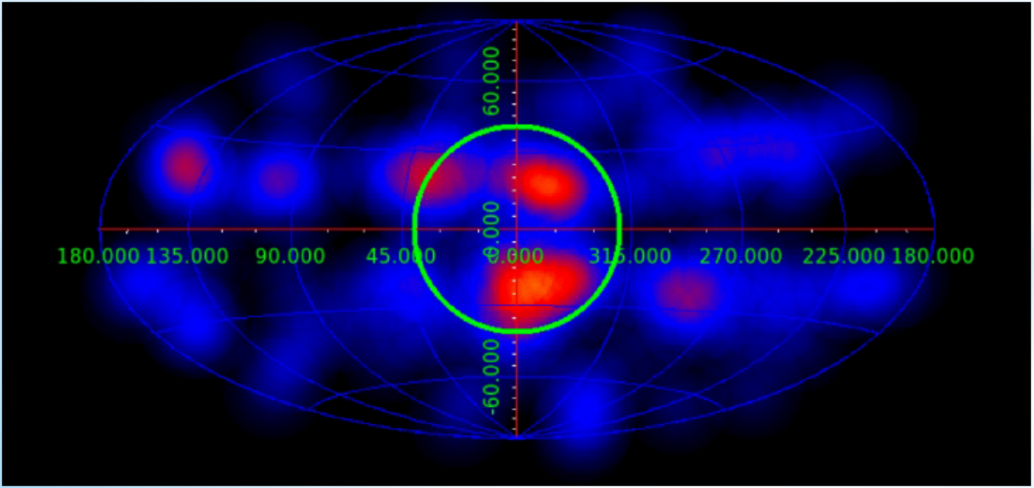
- dark matter



Sky map E_γ> 1 TeV for relative intensity: galactic and extragalactic

On base of FERMI-LAT catalogs

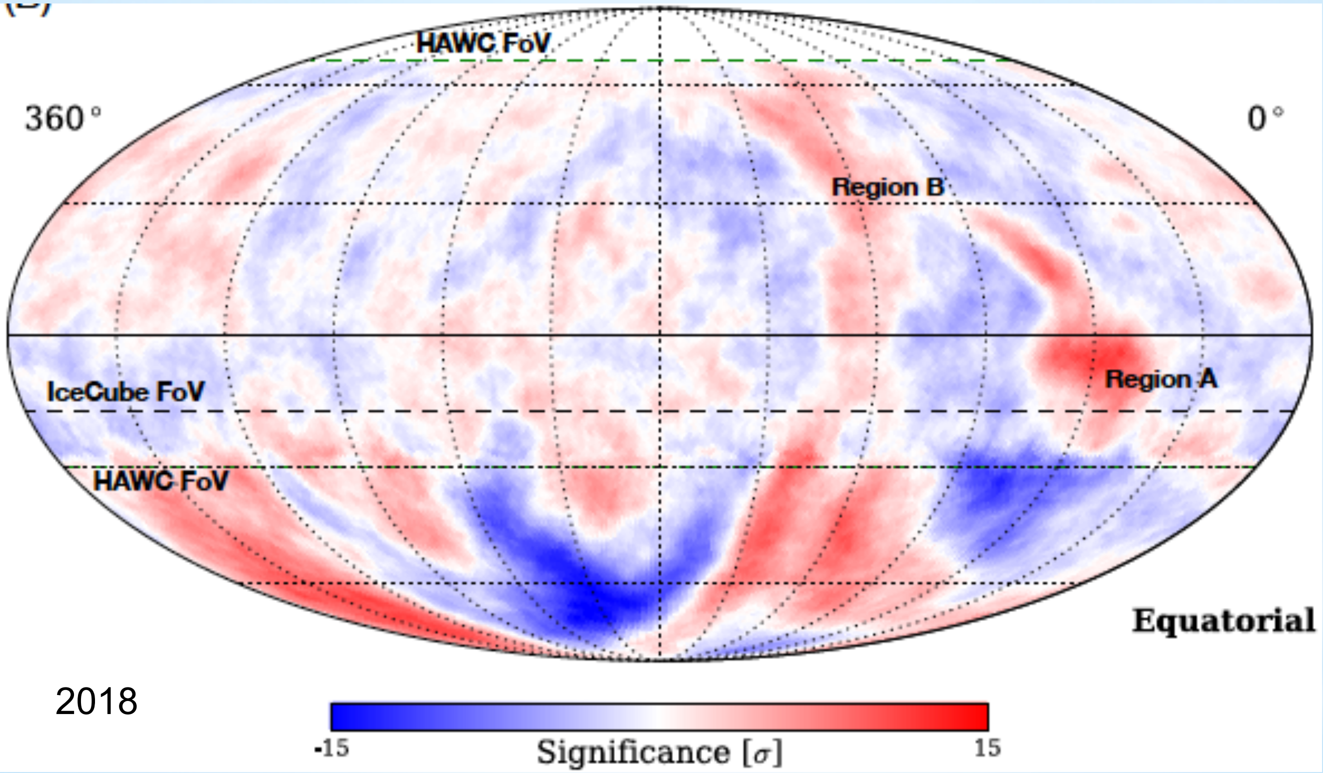




No galactic plan |b|>10°

Neronov, Semikoz, 2019

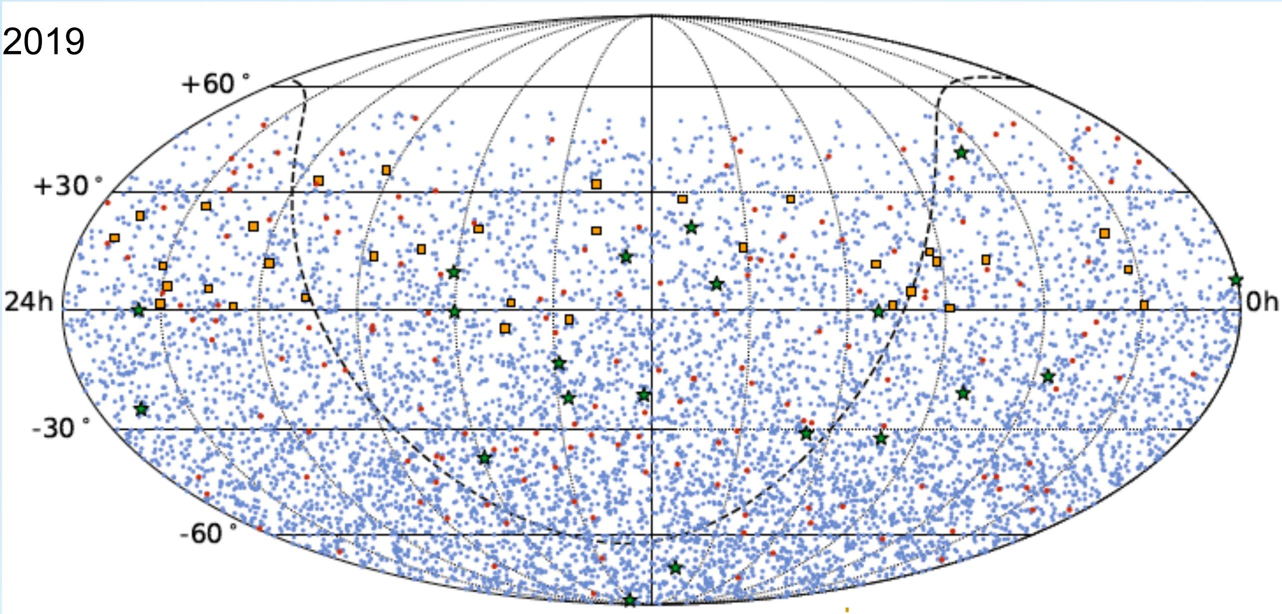
HAWC: CR sky map at 10 TeV



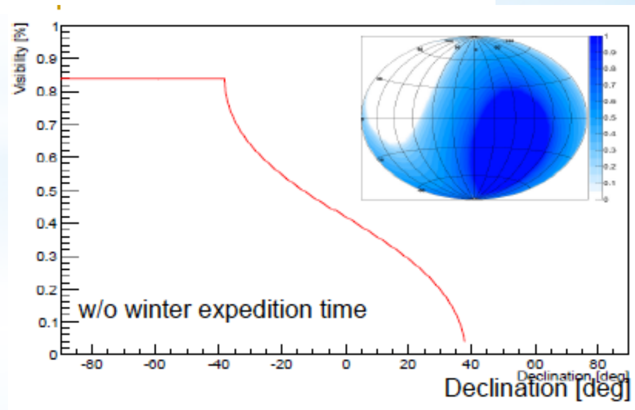
2018

Note: Baikal-GVD's FoV is about +40° on declination for upgoing muons

ANTARES follow-up IC events: HESE and Muons of TeVes range



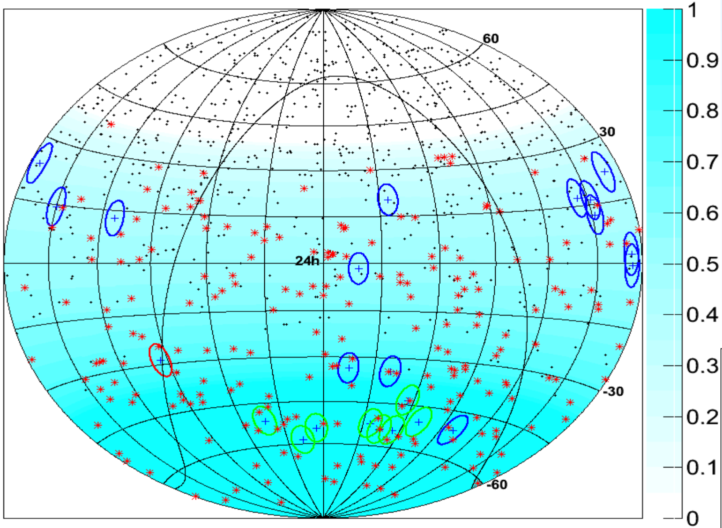
Baikal-GVD has almost the same visibility



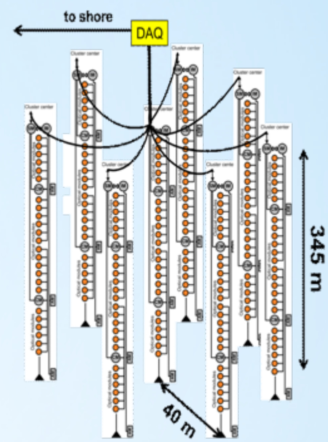
Baikal-GVD in search for TeVes neutrino, first step in 2015

results in: the only 1 cascade as candidate on Esh> 100 TeV

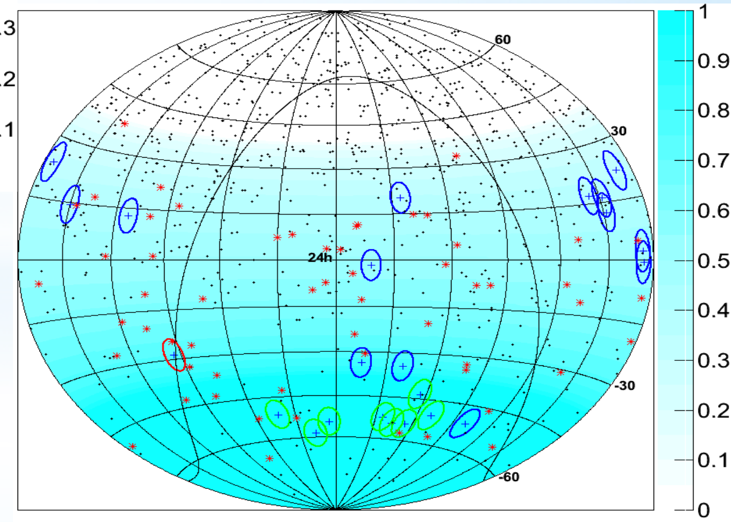
$E_{sh} \geq 1$ TeV, no cut on N_{hit}



«Dubna» 8 strings (192 OMs)



$E_{sh} \geq 100$ TeV, no cut on N_{hit}



Galactic Center

dSphs galaxies

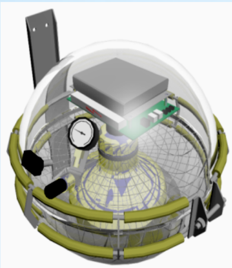
• All cascade candidates

★ Cascade candidates from bottom

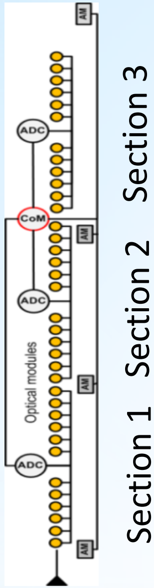
Baikal Gigaton Volume Detector (GVD)

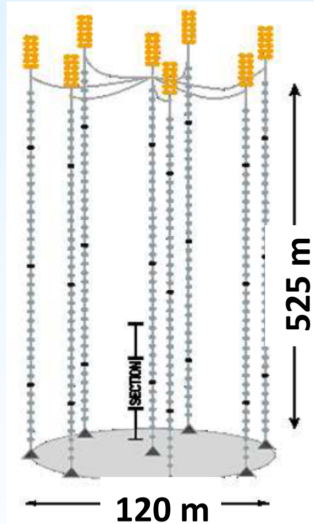
is targeting on VHE neutrinos from visible astrophysical sources in electromagnetics or gravitational waves either in DM phenomena through a gravitational field

Baikal-GVD: phase 1 (2020-2021)

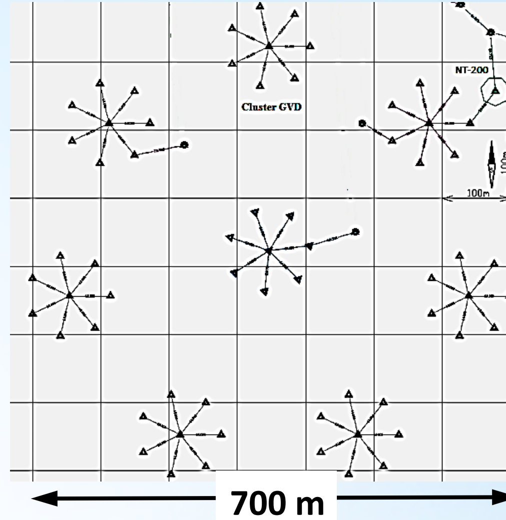


Optical module
PMT: R7081-100





Cluster: 8 strings



GVD-1: 8 clusters

GVD-1	
OMs	2304
Clusters (8 Strings)	8
Depths, m	750 – 1275
Eff. Volume	0.4 km^3

Directional resolution	Energy resolution
Cascades: 3.5° – 5.5°	δ(E/Esh) ~ 0.15
Muons: 0.25° - 0.5°	δ(lgE) ~ 0.4

South Baikal is covered with ice from February to April

Ice thikness ~ 60-90 см (some years up to 120 см);
This winter it is ~ 75 cm since the middle of January

Baikal-GVD place: current look

Baikal-GVD aims on search for astrophysical neutrinos

Basic approach in GVD construction:
* Flexible structure allowing an expand, upgrade and rearrange of the detection system and
* Simplicity of the basic detector elements

- **1370 m maximum depth**
- **Distance to shore ~4 km**
- **Absence of high luminosity 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**

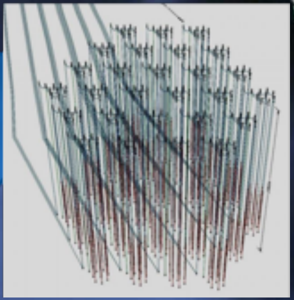
Половинная

3500м

1366м

N 51,76°

E 104,41°



3D array, 10^4 photodetectors

Eff. volume ~1.5 км^3

Data INTAS Project 99-1669

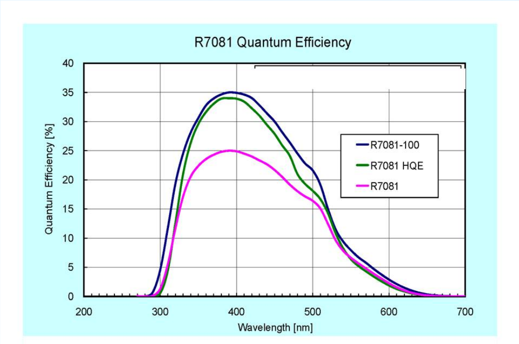
Image © 2012 TerraMetrics

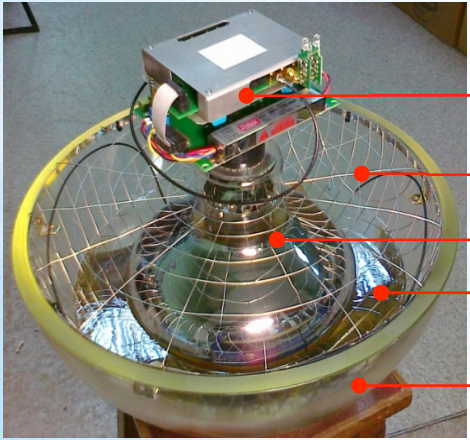
2768 м

Google earth

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")

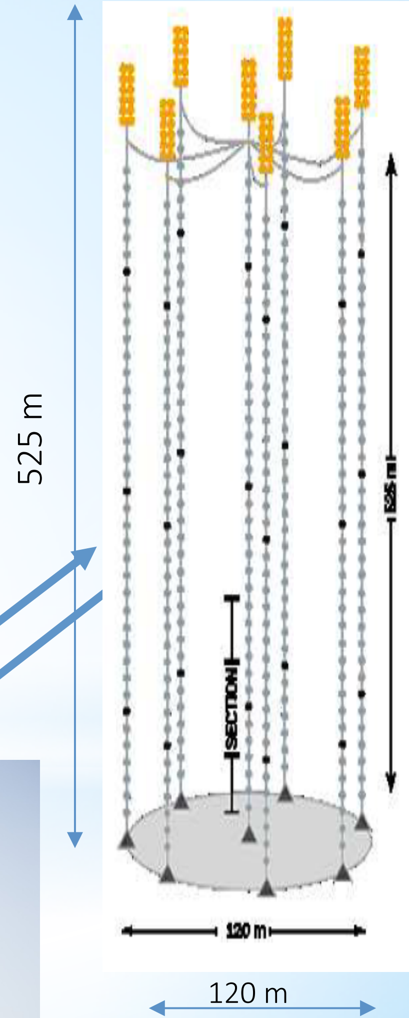
The Cluster of strings

- 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 calibration light beacons (matrix of LEDs)
  - Interstring time calibration

String is: 3 Sections of 12 OMs&ADC module

Sticker for an optical module

OM #329-19
PMT: MA1065
CC: 106W
1329-19
BAIKAL-GVD



Baikal-GVD status: April - June 2019

NEW:

2 clusters and 2 shore cables were mounted during expedition

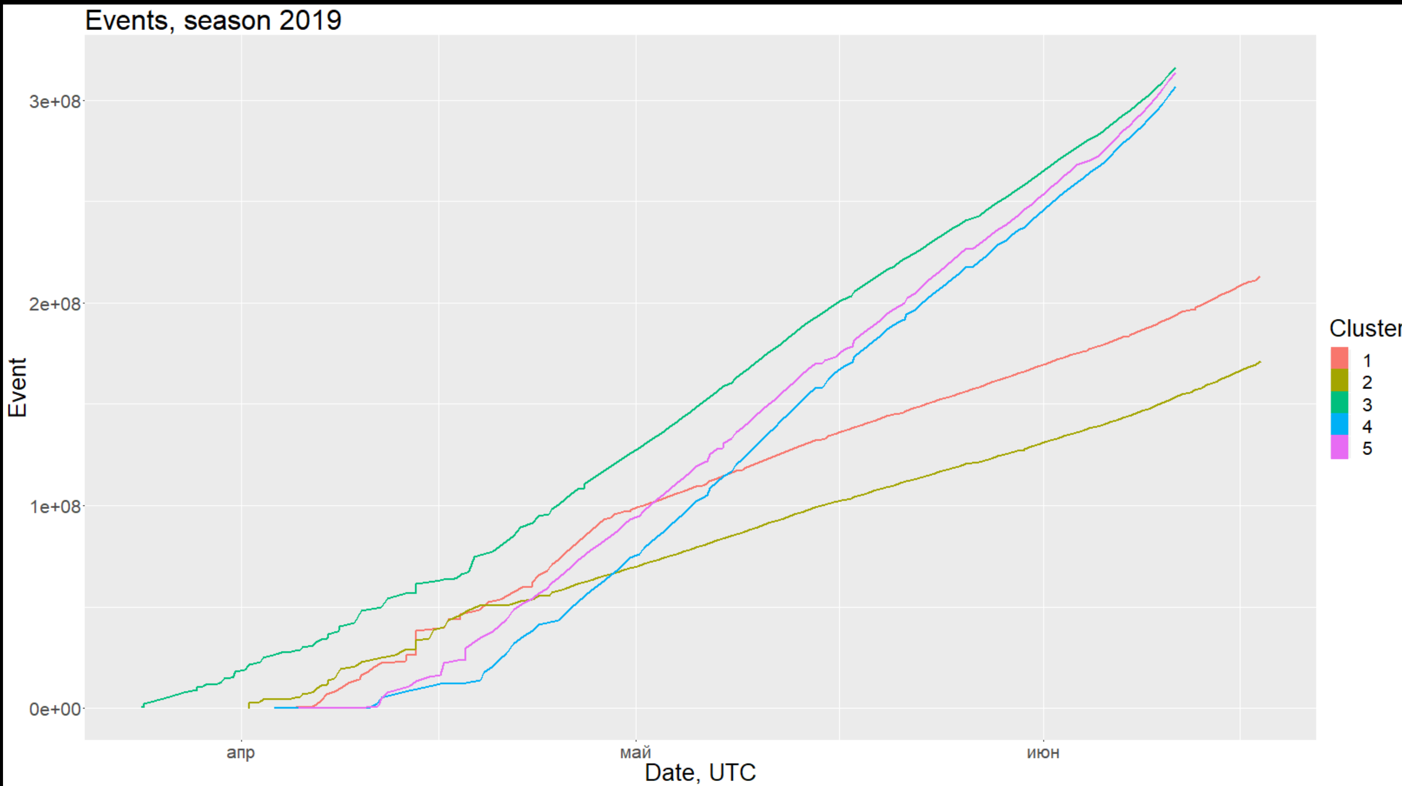
Total:	5 Clusters →	40 Strings →	120 Sections →	1440 OMs
"Old" faults:	0	0	1 (12 ch)	15
"New" faults:	0	0	0	2

Faulty channels

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
18	10	0	0	1

Unreliable channels: 3 ch. on Cluster 4.

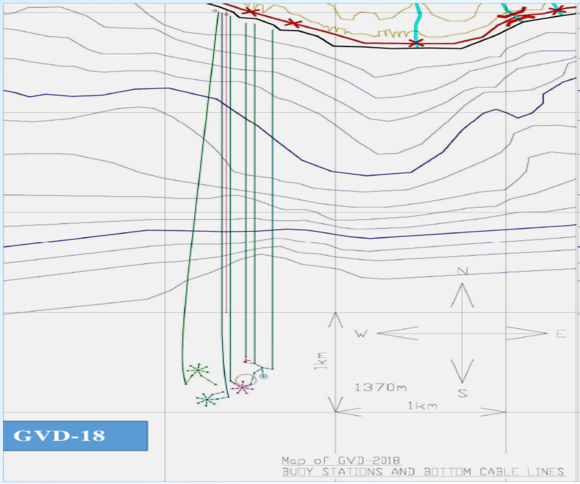
Five clusters since April 2019
All 5 clusters taking data

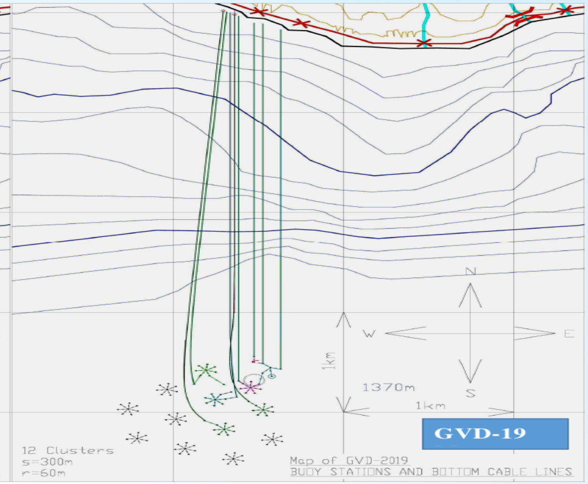


Apr **May** **June**

Baikal winter expedition 2019

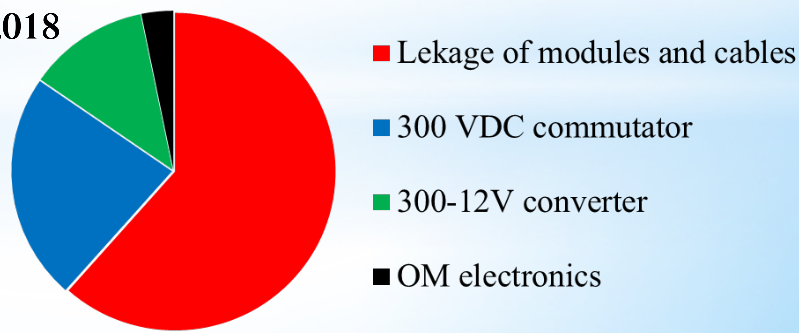
All connections are done on dry





Malfunctions analysis for season 2018

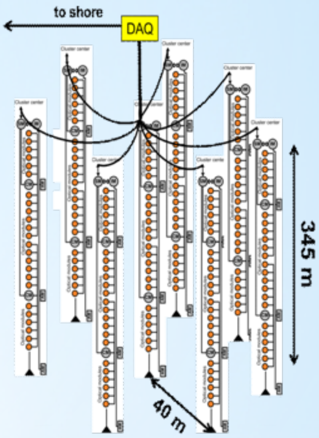
Leakage: 96ch, in all cases: small volume of water inside module.



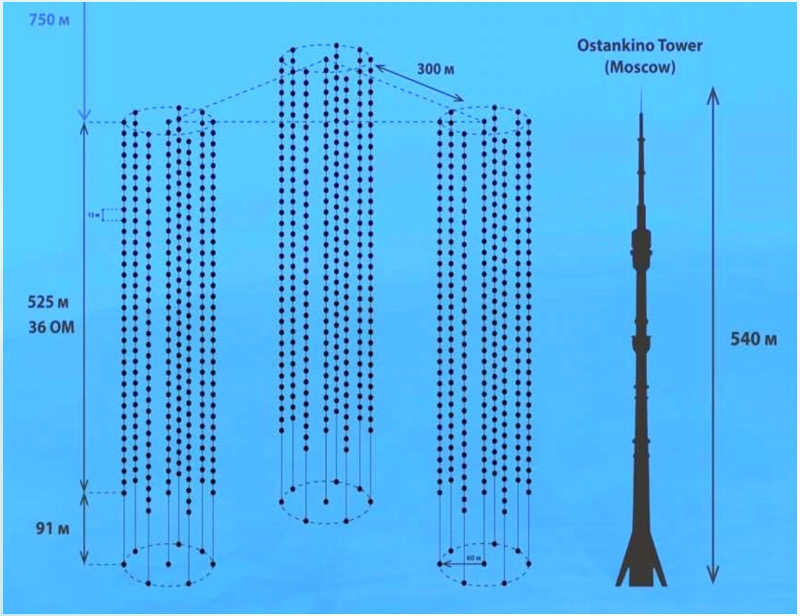
2018: 24 strings (864 OMs) – largest NT in the northern latitudes

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

2015: «Dubna»
8 strings (192 OMs)



2018: Data taken with three Baikal-GVD clusters

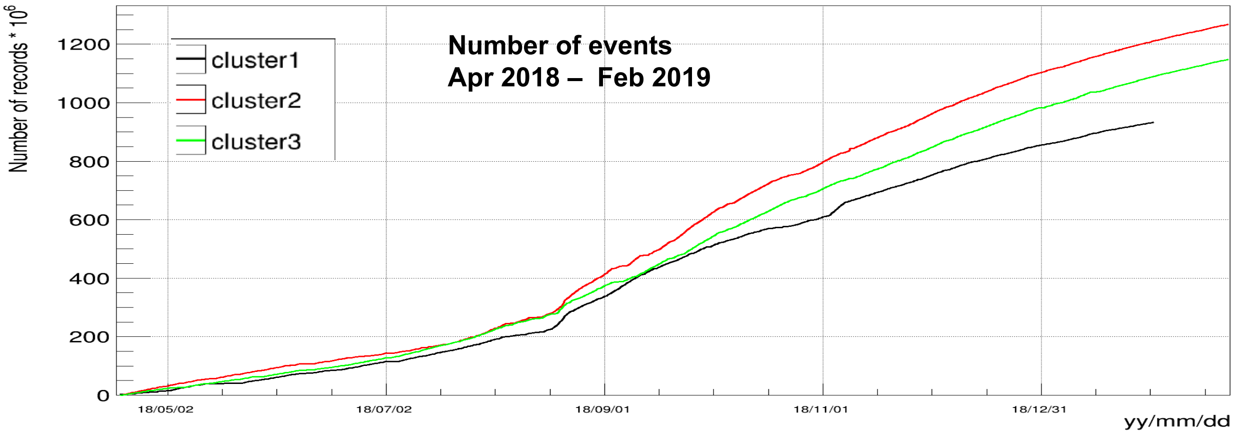


Status in 2018

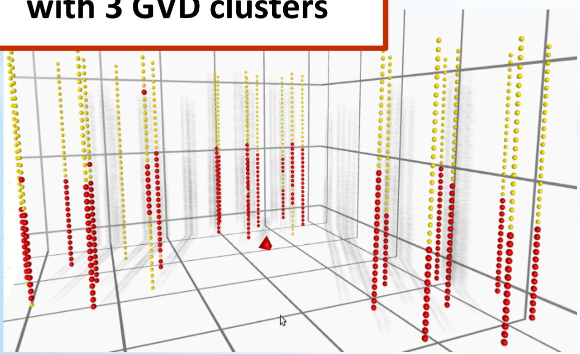
- Cluster 1 since 2016
- Cluster 2 since 2017
- Cluster 3 since 2018
- Powerful isotropic laser source

Operation of the Baikal-GVD in 2018

Detector was put into operation at 10 April 2018. After commissioning all sections of three clusters worked correctly.

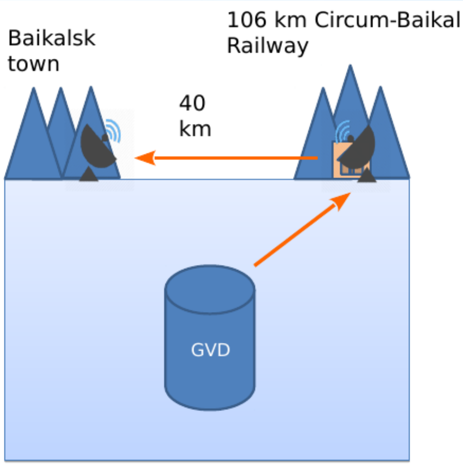


Laser flashes detection with 3 GVD clusters



Data transmition:

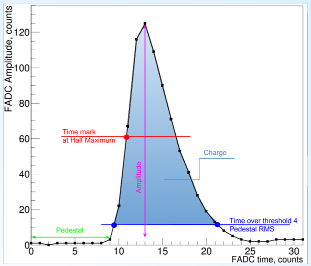
- 40 Gb per cluster per day to shore
- 5 Mb/s 40 km radio channel to Baikalsk
- Raw data transferred to storage Dubna facility through Internet

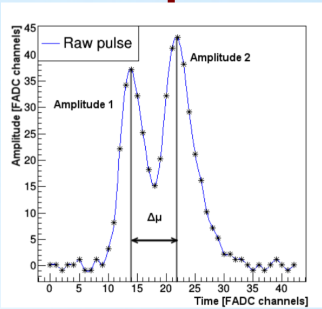


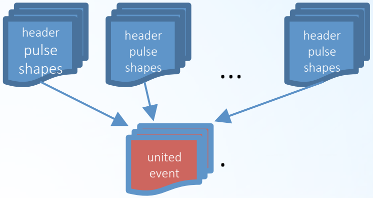
Data processing and analysis steps

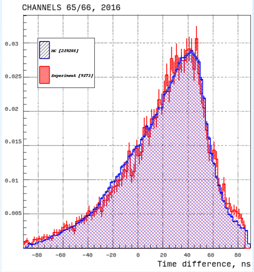
- Extraction of hit parameters from waveforms
- Joint events production
- Time and Amplitude calibration with light sources (laser source, LED matrixes, built-in OM LEDs) and atmospheric muons
- Geometry calibration with acoustic positioning system
- Data and Trigger quality monitoring

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



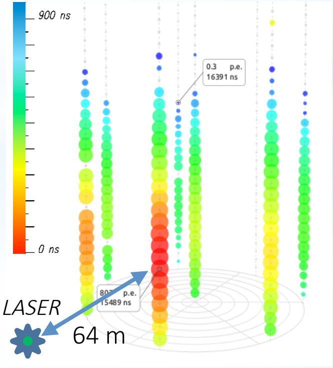


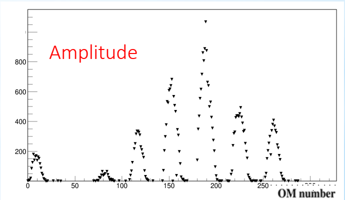


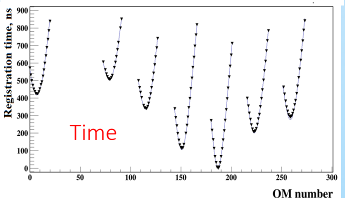


DQM @ level: OMs, section, cluster

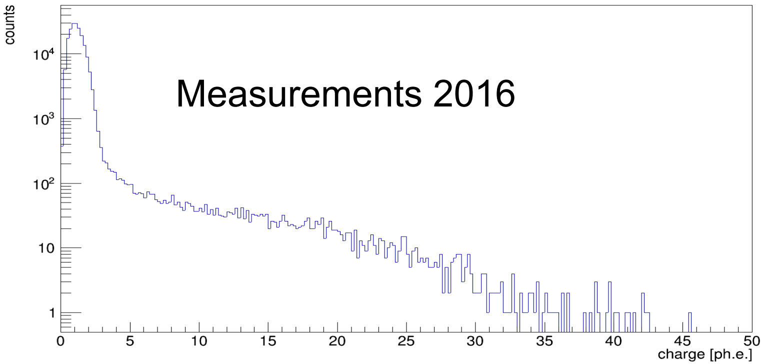
- ➔ Time difference between two neighbor events
- ➔ Events rate
- ➔ Average numbers of events per given time interval
- ➔ Triggers quality monitoring
- ➔ Charge distribution analyses:
  - 1 p.e. → amplitude calibration
  - High and low trigger thresholds
  - Full range analysis wrt baseline distributions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





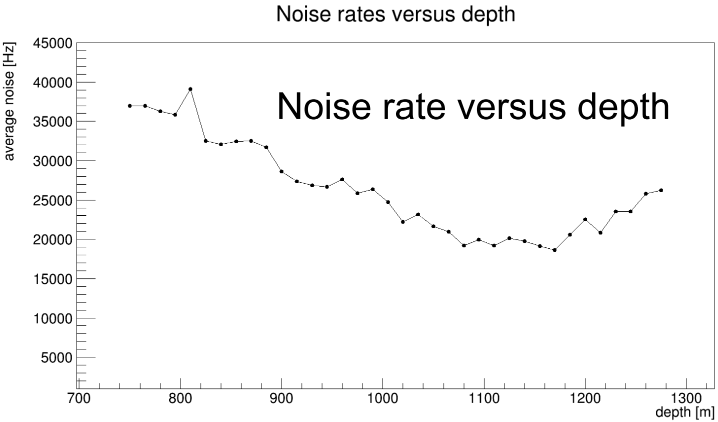


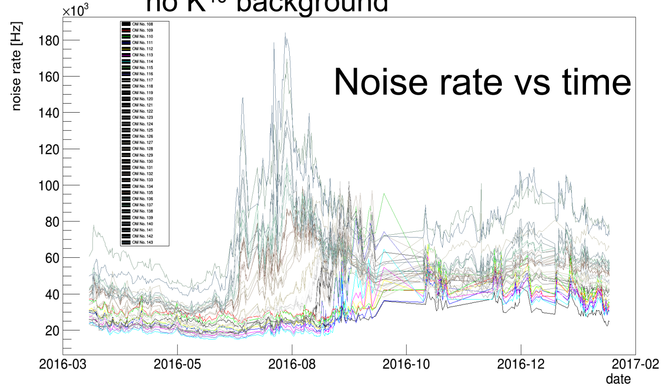
Baikal background light



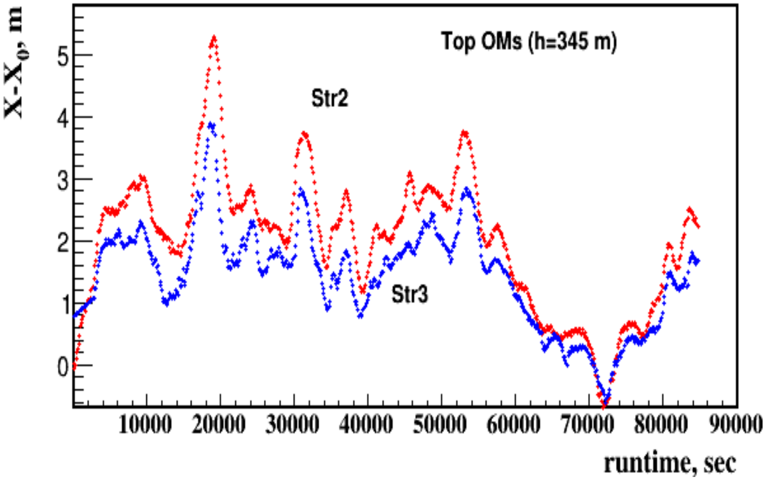
Baikal mainly emits in range of single ph.e.

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

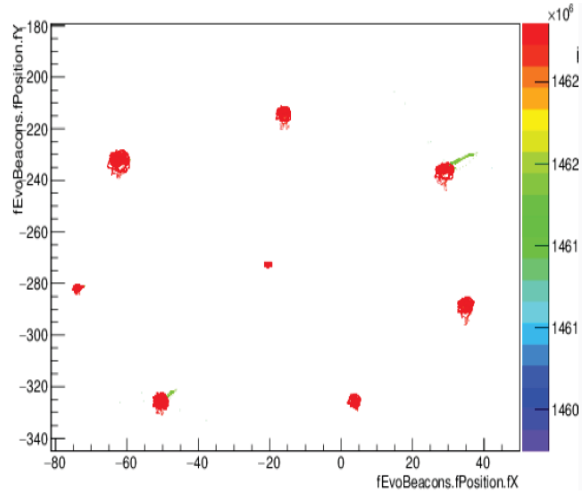


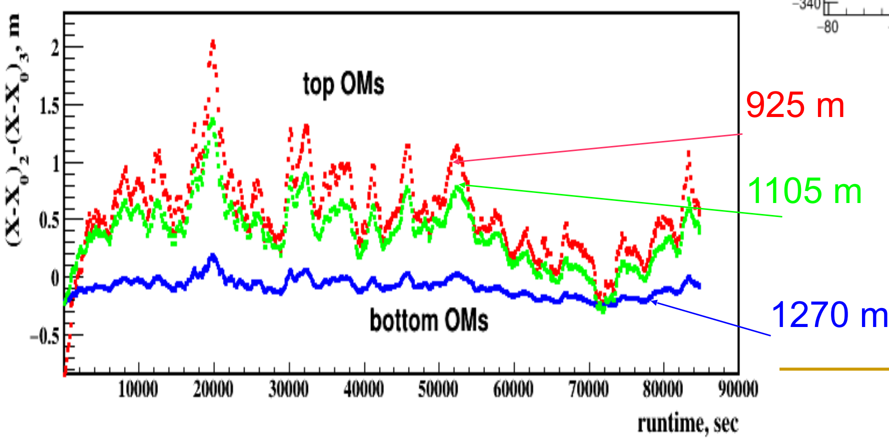


Performance of acoustic positioning system



Y-X node positions

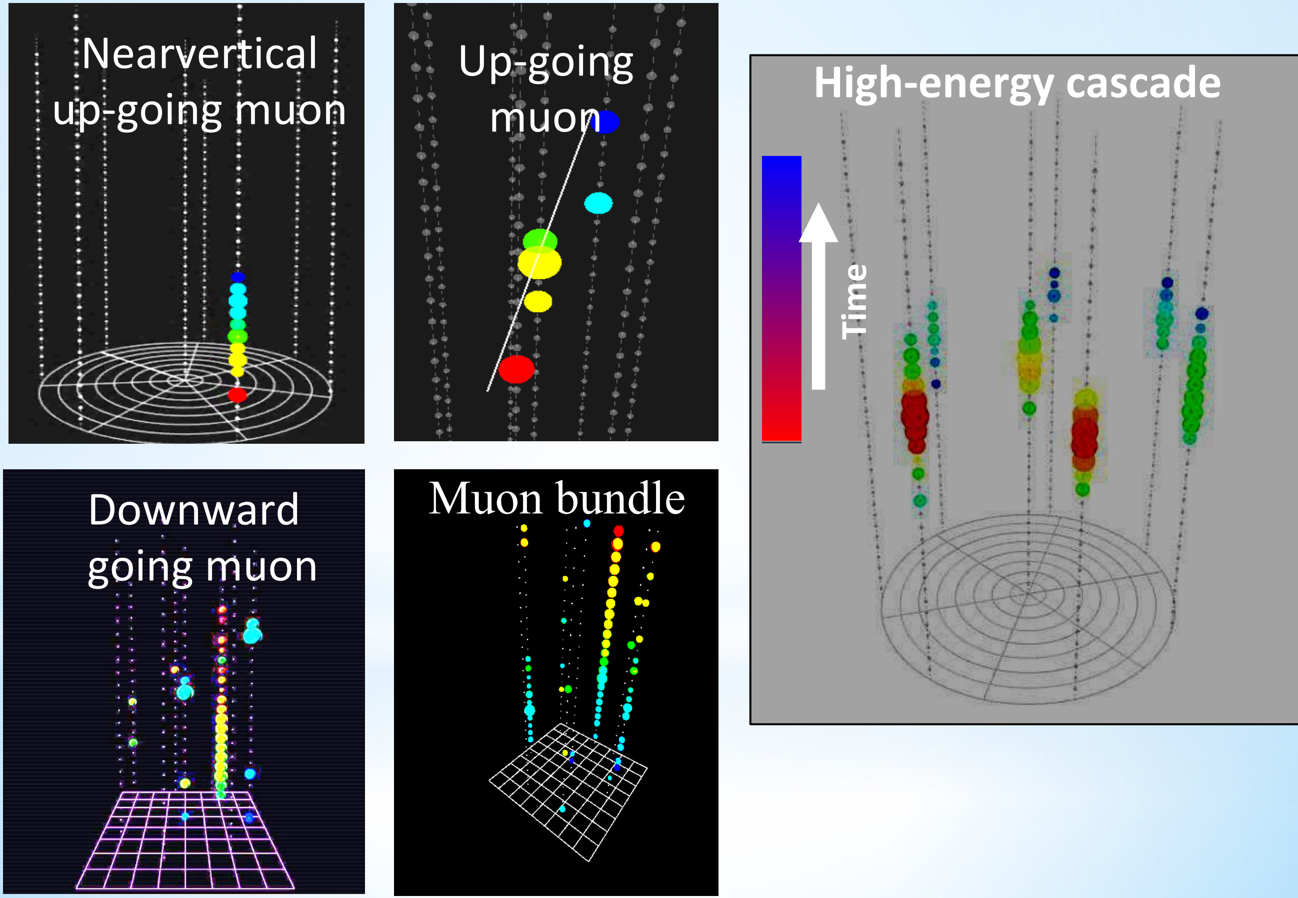




Detector response

Neutrino signals

Background

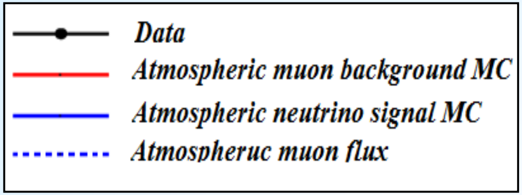


Search for muon neutrinos

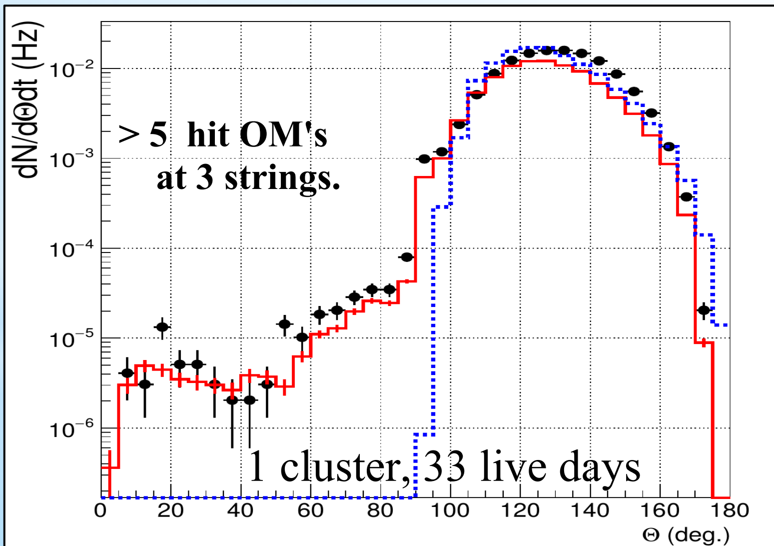
(analysis of 2016 data sample – ***first iteration***)

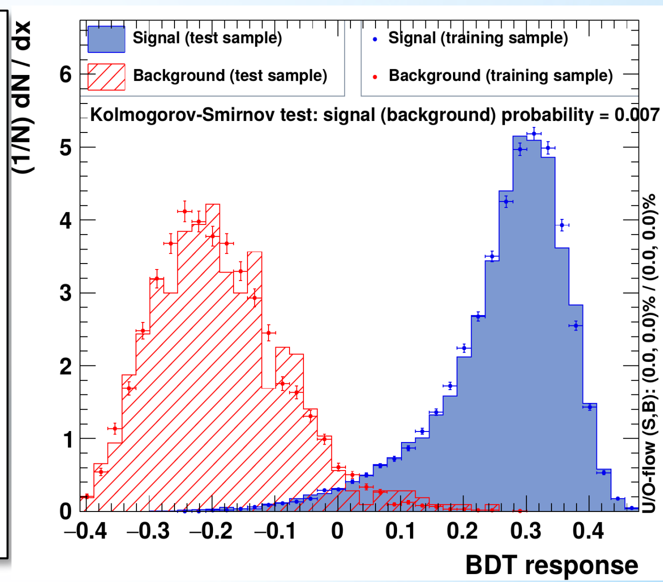
Muon neutrino are detected as a muon tracks from bottom hemisphere

After reconstruction



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





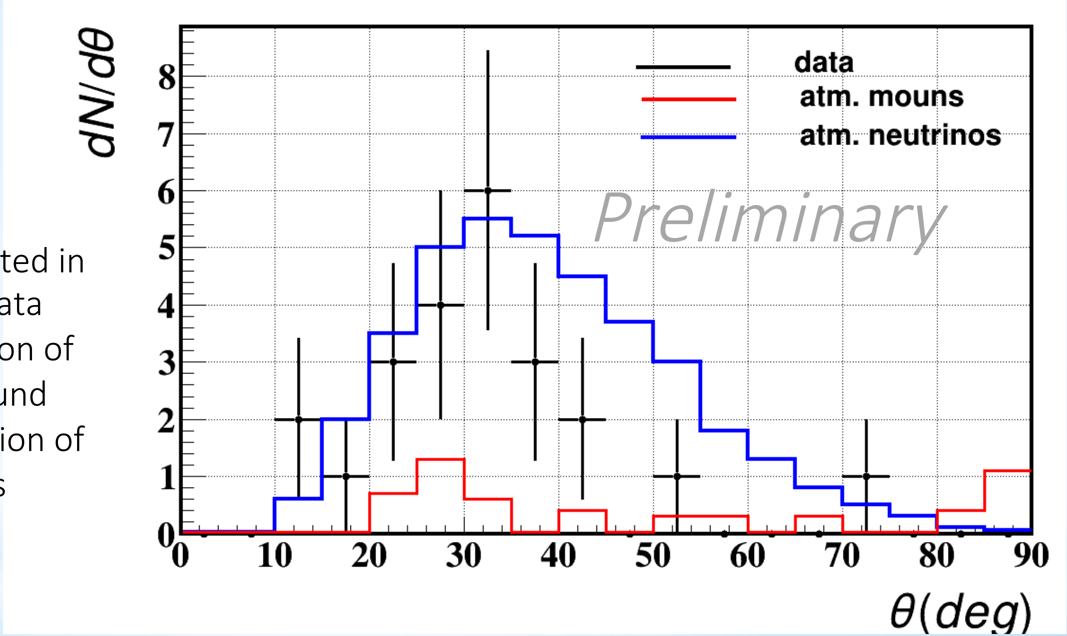
Zenith angle distributions of muons

First neutrinos selected

33 live days were used

Angular distribution for BDT > 0.2 cut

- 23 events were selected in the signal region in data
- ~ 3 events – estimation of atm. muons background
- ~36 events – estimation of signal atm. neutrinos



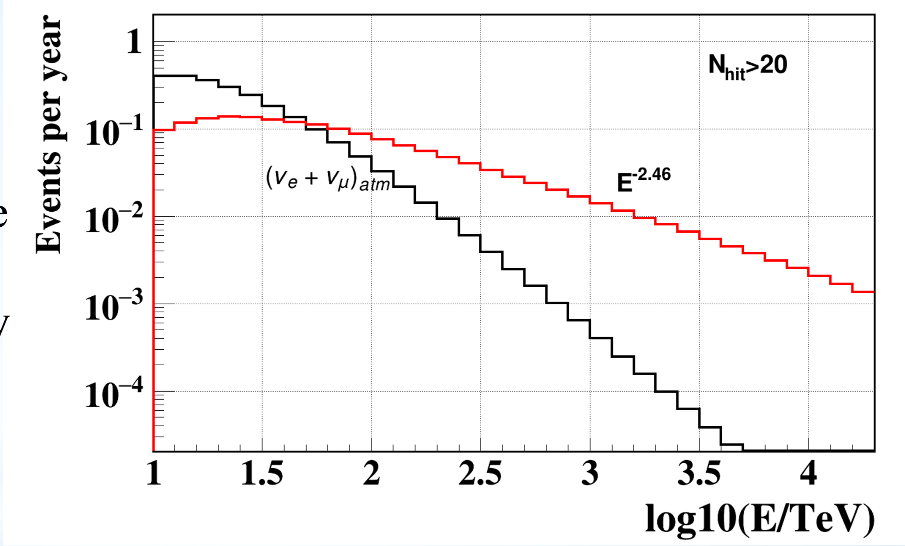
Search for cascades induced by astrophysical neutrinos

Directional resolution of cascades in water: 3°- 5°

Cascade selection:

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

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



About 0.6 events/year are expected for 1 GVD cluster

A search for cascades induced by astrophysical neutrinos

(analysis of 2016 data– ***first iteration***)

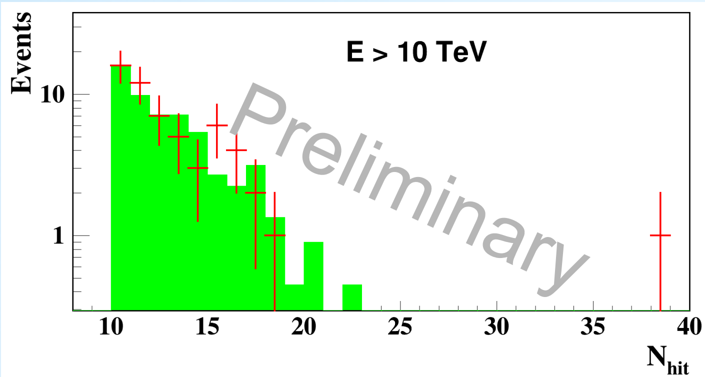
- Life time – 15 693 192 s = 182.0 days

- Total number of accumulated events – 6.86×10^8 events
  (thresholds: low/high = 1.5/4 ph.el. & Q >1.5 ph.el.)

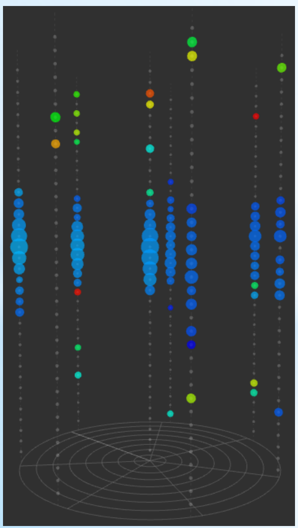
- After causality cuts – 3.27×10^8 events

  ($N_{hit} > 4$; $|t_i - t_j| < \Delta r_{ij}/v + \delta t$)

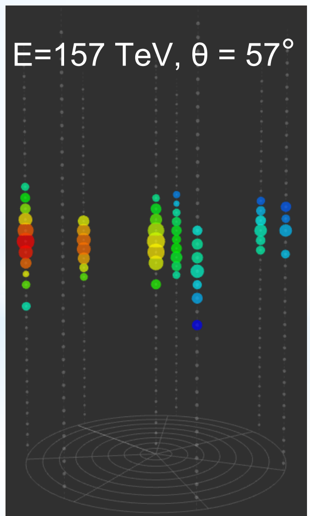
Cascade analysis with the first GVD cluster 2016



Cuts	Events	Rejection
Coordinates reconstruction & N_{hit} >9	577495	1
$\chi^2 < 4$	2405	1/240
Energy reconstruction		
$L_a < 20$	374	1/6.4
η > 0	159	1/2.4
E > 10 TeV	57	1/2.8
E > 100 TeV	5	1/11.4
Total rejection factor:		1/115499

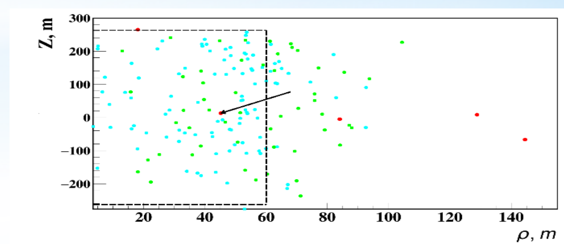


All hit OMs (93 hits)

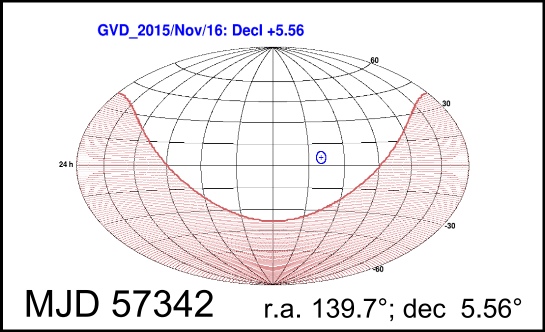


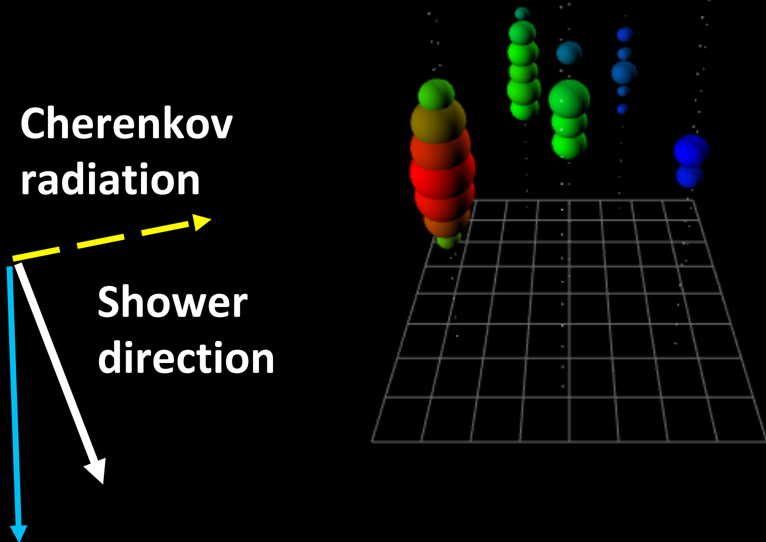
Selected hits for reconstruction (53 hits)

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



2015: E = 107 TeV, θ = 56.6°, φ_{loc} = 130°, ρ = 68 m, z = -59 m

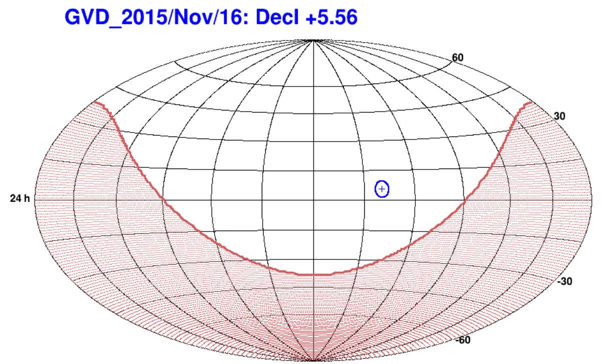


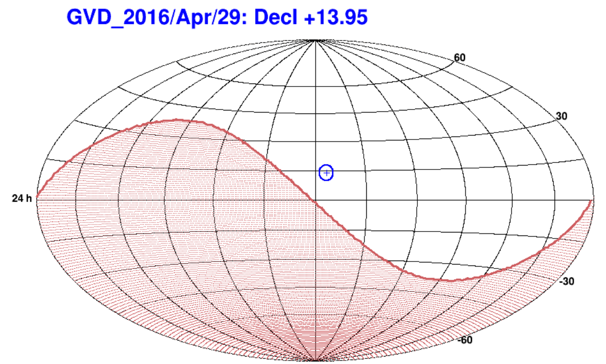


Skymap on two GVD cascade events with E>100 TeV

MJD 57342, E_{sh} 107 TeV

MJD 57507, E_{sh} 157 TeV

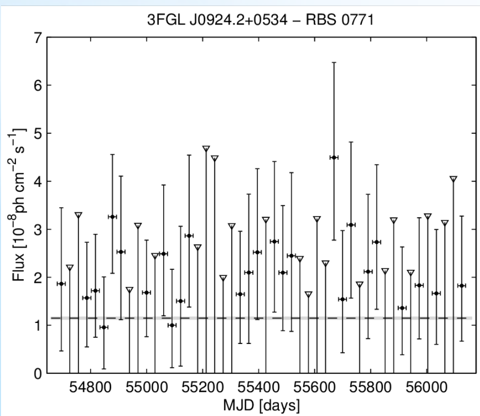


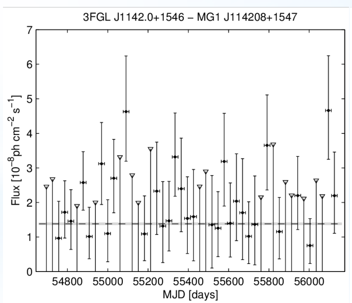


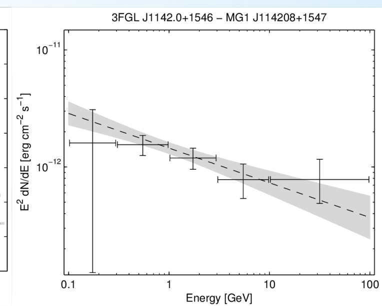
r.a. 139.7°; dec 5.56°

analysis in term p-val is in progress

r.a. 173.4°; dec 13.95°

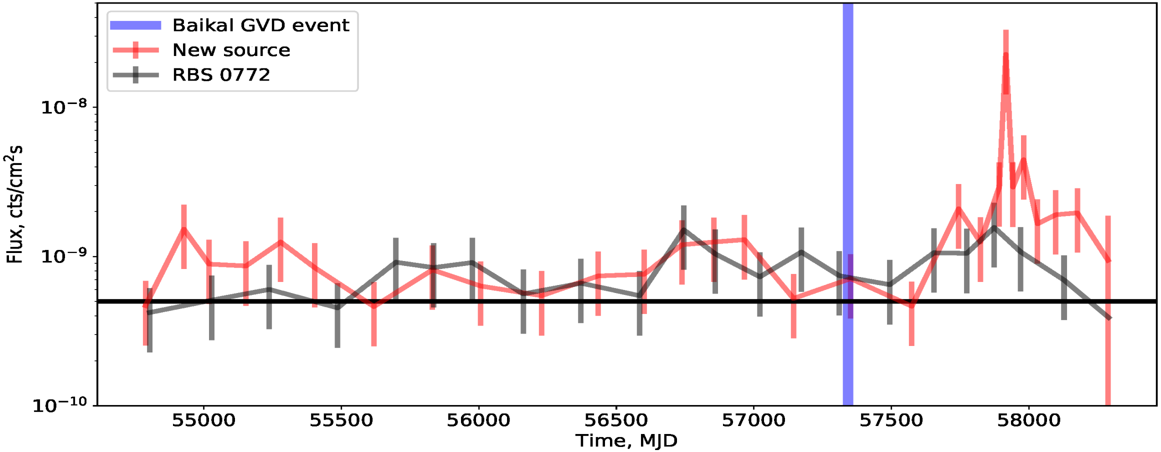


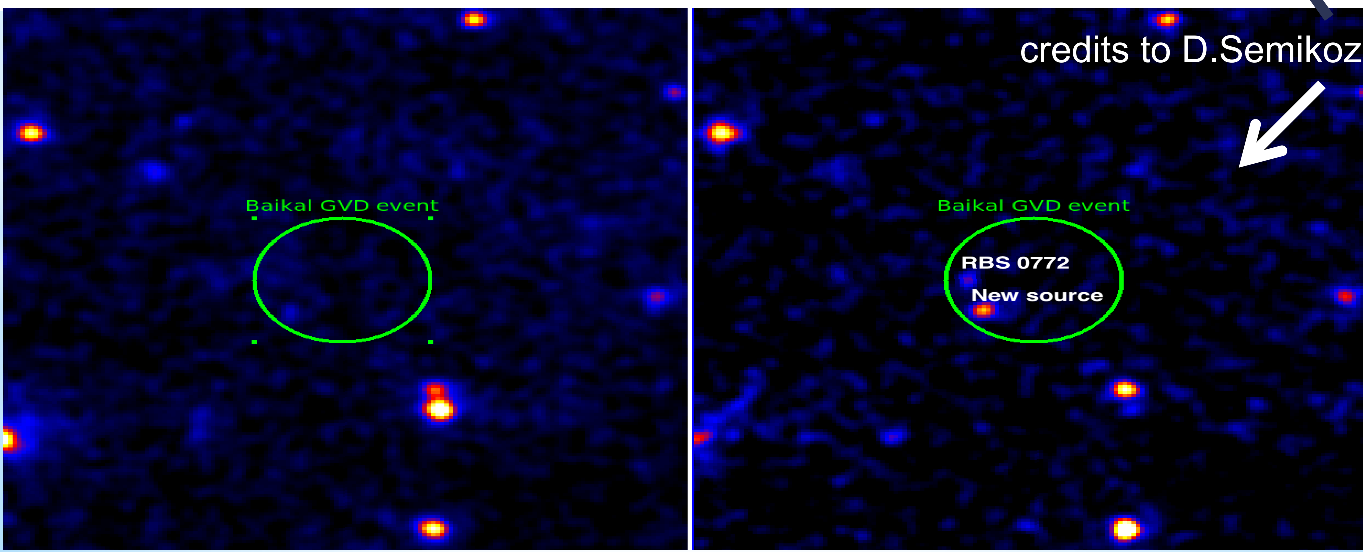




No TeV cat, MJD 54800-56008

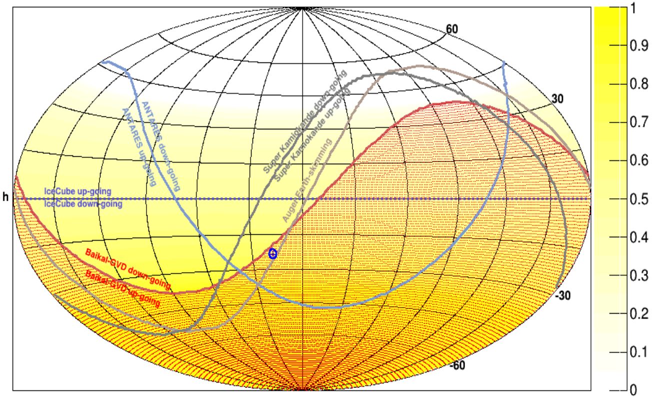
Follow-up 1st GVD_cascade MJD 57342 {RA 139.7°; Dec 5.56°}





2017: GVD horizon in time of 2 cosmic events

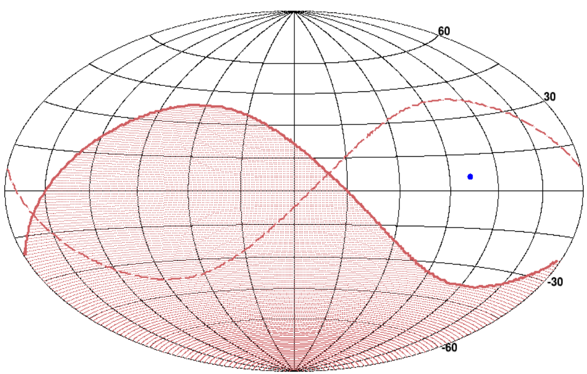
GW: 17.08.2017, (Advanced LIGO & Advanced VIRGO)
GRB170817A - 1.7 s delay (Fermi-GBM and INTEGRAL)



Cascade mode: search for events in two time-windows:
GW ± 500 sec (prompt emission): zenith angle θ = 93°.
GW +14 days (delayed emission); 74° < θ < 150°

Publ. in JETP Lett. 108 (2018) no.12, 787-790

IC170922A: TXS0506+056



IceCube on September 22, 2017: first evidence for the existence of an astrophysical source of high-energy neutrinos

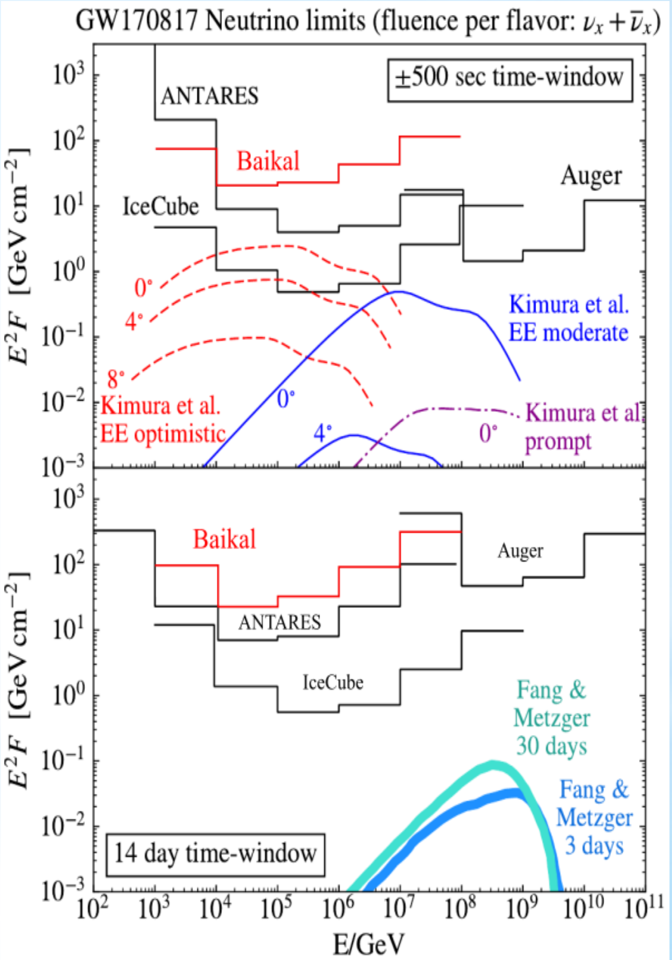
Cascade mode: preliminary analysis in search for time-direction coincidence

Upper limits on fluence of neutrinos associated with GW170817

No neutrino events associated with event GW170817A have been found in cascade search mode within the time window ± 500 seconds and 14 days after neutron stars merging.

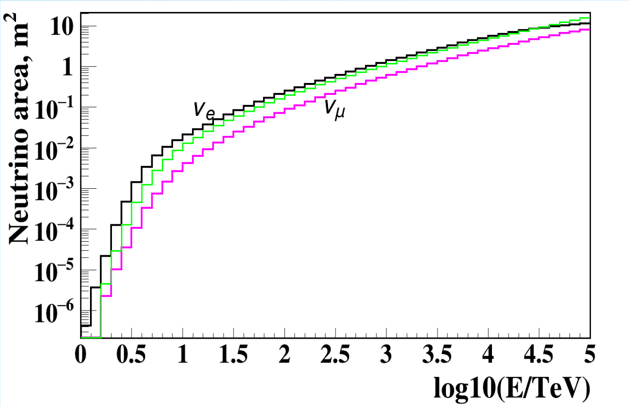
Assuming E^{-2} spectral behavior and equal fluence in all flavors, upper limits at 90% c.l. have been derived on the neutrino fluence from GW170817 for each energy decade.

Published in JETP Lett. 108 (2018) no.12, 787-790

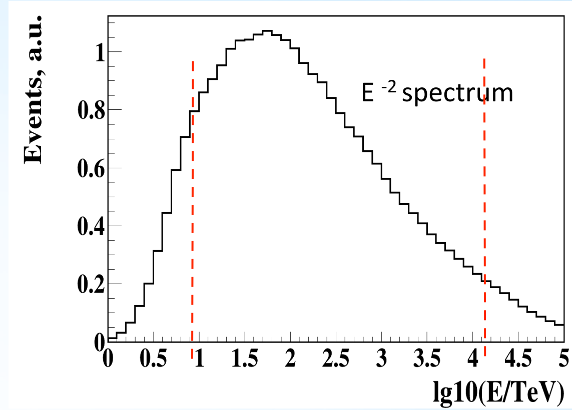


Search for neutrinos within GW ± 500s time-window and +14 days

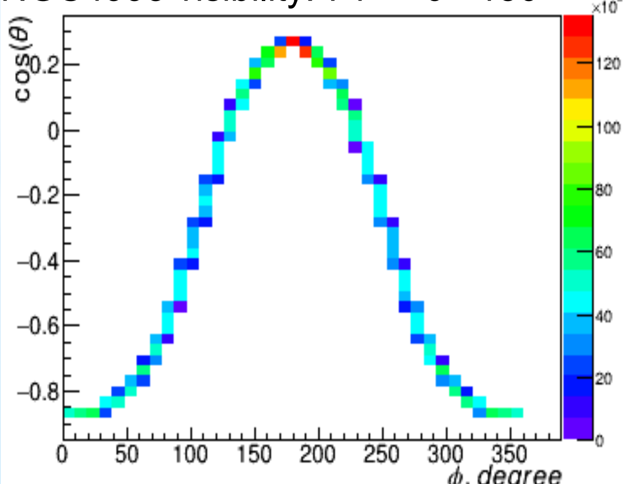
Neutrino effective area after all cuts



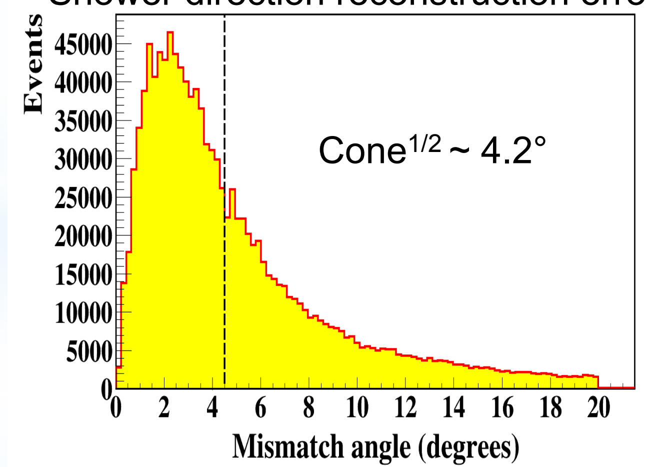
Expected energy distribution of events.
90 % of E^{-2} events within 5 TeV < E < 10 PeV



NGC4993 visibility: 74° < θ <150°



Shower direction reconstruction error

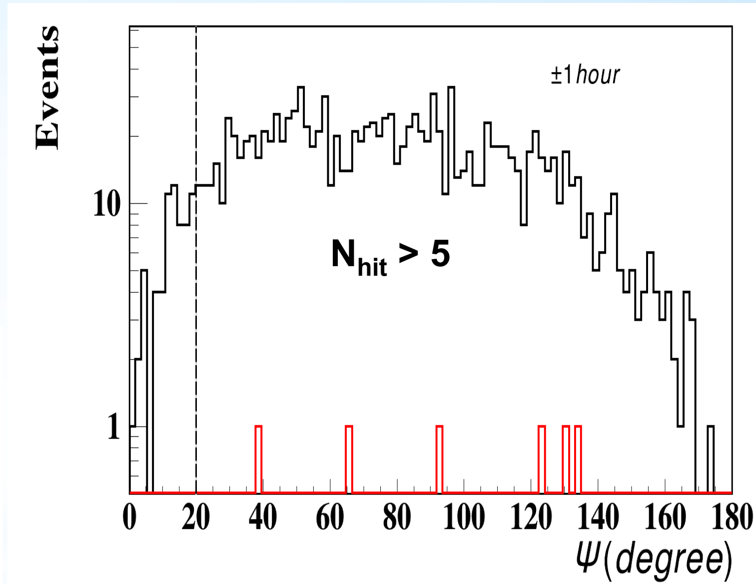


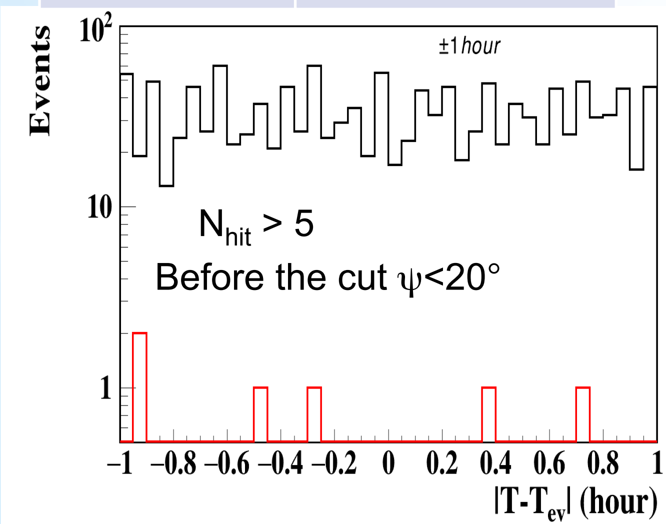
Search for neutrinos within ± 1 hour time-window around **IC170922A**

Events selection cuts

Cut	Events in ± 1 hour window
N_{hit} > 5 OM/3 Str.	1345
χ^2_t < 10	221
η > 0	11
L_a < 30	9
ψ < 20°	0

Angular distance around the direction of the source

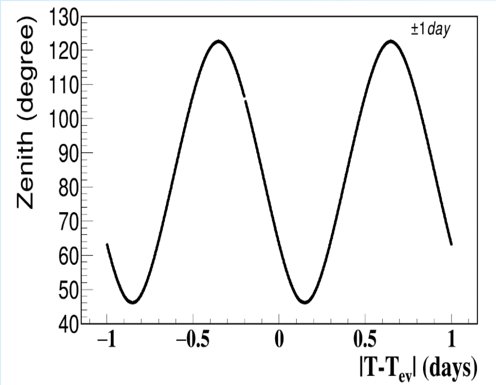




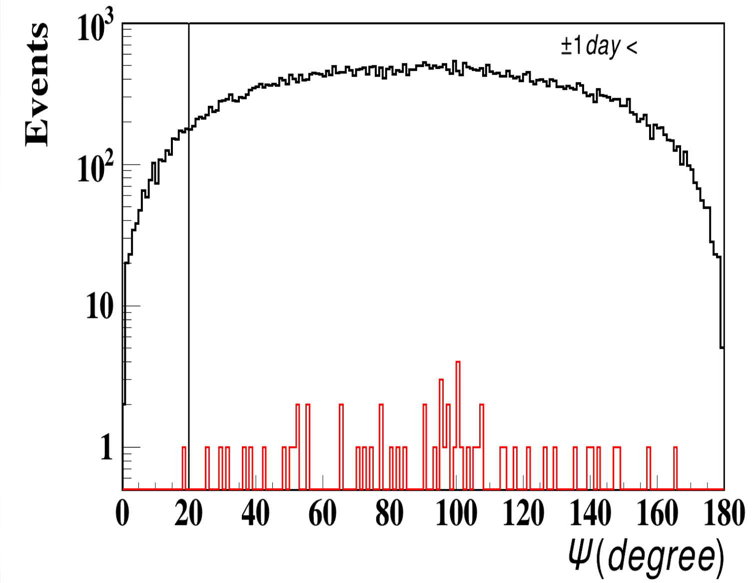
No neutrino candidate event was recorded within ± 1 hour time window around the IC170922A

Search for neutrinos within ± 1 day time-window around IC170922A

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



Angular distance around
the direction of the source



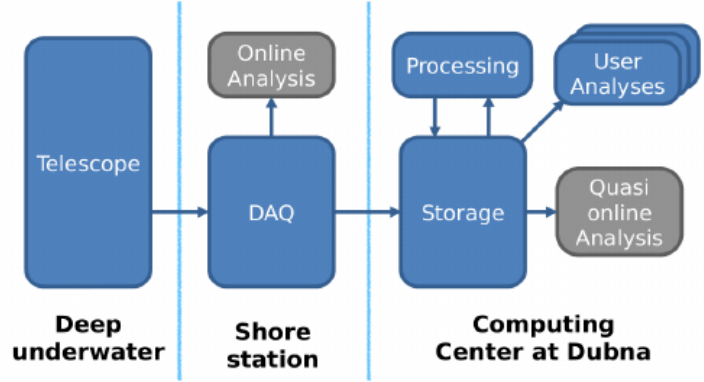
Events selection cuts

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°)

No neutrino events associated with IC170922A have been recorded

Online Analysis

- 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



are under development

Beginning of multimessenger program: follow-up neutrino

- MoU with ANTARES since November 2018

Current rate is 2-3 events per month, either true event or false one.

Then we look for

/ time-direction coincidences with ANTRARES trigger and follow-up data analysis of each cluster;

/ per cluster the search time-windows are from 10 sec, 1 hour and +/- 1 day;

/ search for coincidence in 6mks of two clusters within first +-10 sec or in +- 1hour around the trigger;

/ all candidates are tested by two modes of reconstruction: cascade (direction and energy estimate) and track (angles).

Follow-up 16 A-events, Dec-June

In season **2018-** 8;
in expedition time- 4;
in season **2019-** 4.

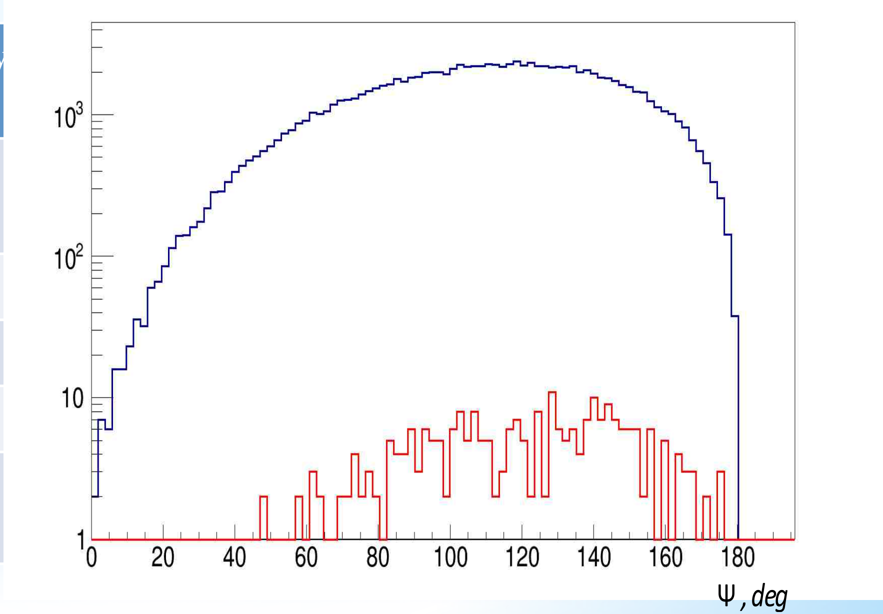
In categories:		Upward↑	Up_hrz↗	Dwn_hrz↘	Downward↓
• Rank 1:	2	1		1	
• Rank 2:	1	1			
• Rank 3:	13	8	2	1	2
• Rank 4:	0				

Example of reconstructed cascades in alert time

Alert_1 ±24h

- cut Nhit >7 OM/3str (blue)
- with all cuts (red)

Cut	Events in ±1 day window
N_{hit} > 7 OM/3str	106158
$\chi^2_t < 10$	12491
$\eta > 0$	368
$L_a < 20$	266
$\psi < 10°$	0



Similar to A2 and A5

As example of reconstructed cascades in alert time

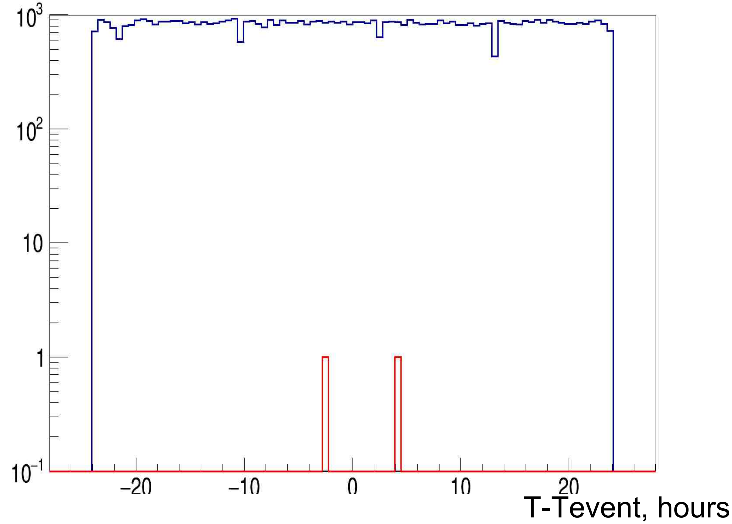
Alert_3 ±24h

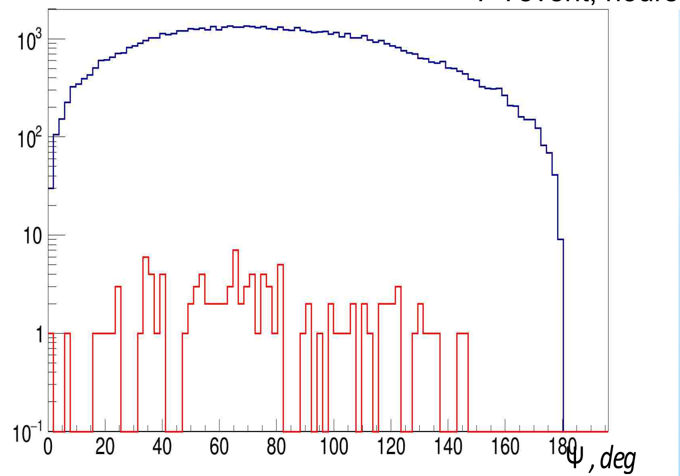
- cut Nhit >7 OM/3str (blue)
- with all cuts (red)

Cut	Events in ±1 day window
N_{hit} > 7 OM/3str	72255
$\chi^2_t < 10$	13022
$\eta > 0$	371
$L_a < 20$	259
$\psi < 10°$	2

After more accurate processing with angular step reduced from 7° to 1°: mismatch angles are found to be such 15.5° and 12.2°.

Similar to A4, A6 and A5





Alert_7 ±24h

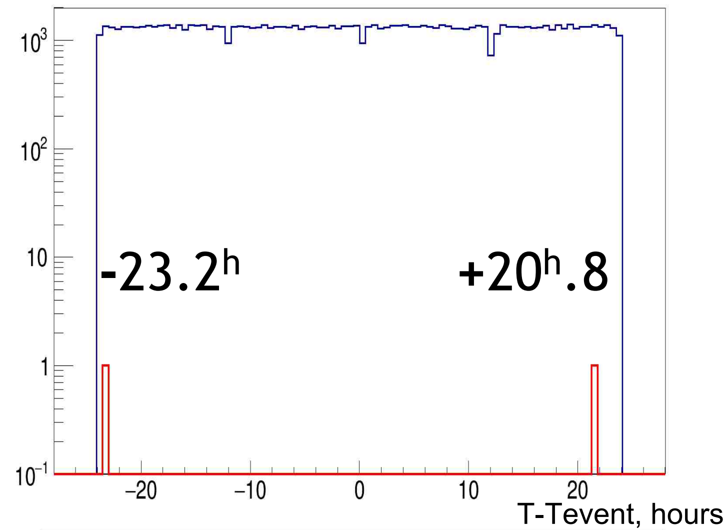
Cluster #3

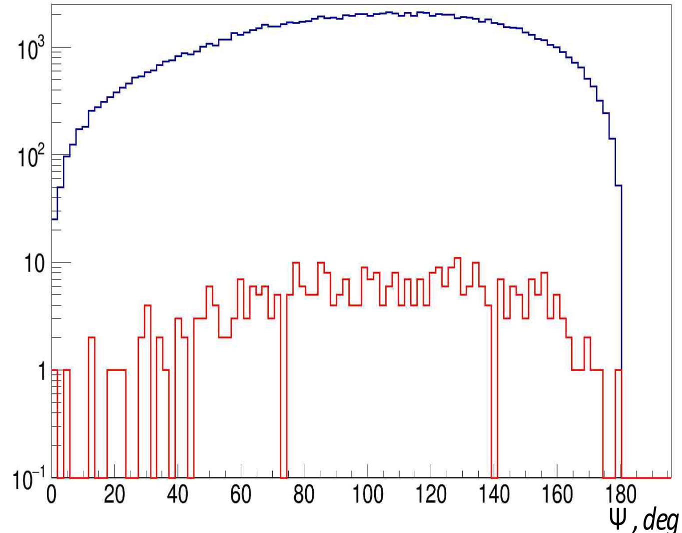
Cut	Events in ±1 day window
N_{hit} > 7 OM/3str	112970
χ^2_t < 10	13823
η > 0	520
L_a < 20	358
ψ < 10°	2

After more accurate processing with angular step reduced from 7° to 1°:

2 mismatch angles are 3°25' and 4°03'.

Reco E_{sh} are 13.5 and 158 TeV



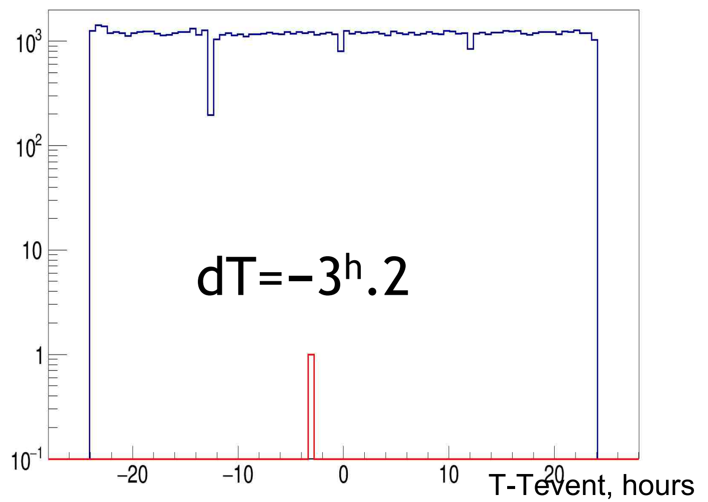


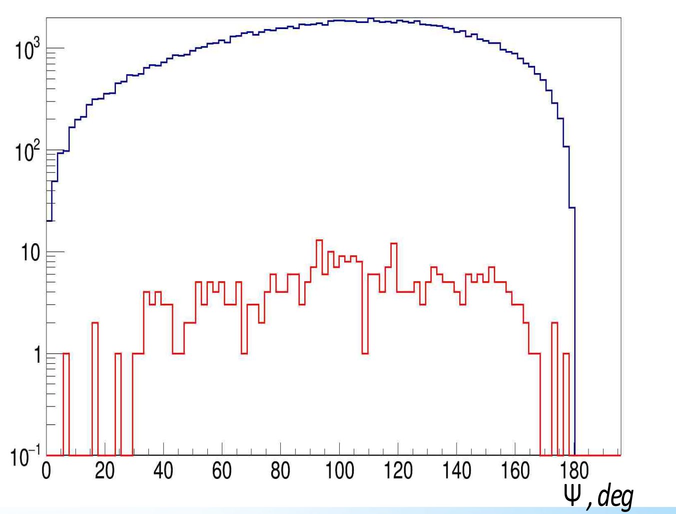
Alert_7 ±24h

Cluster #2

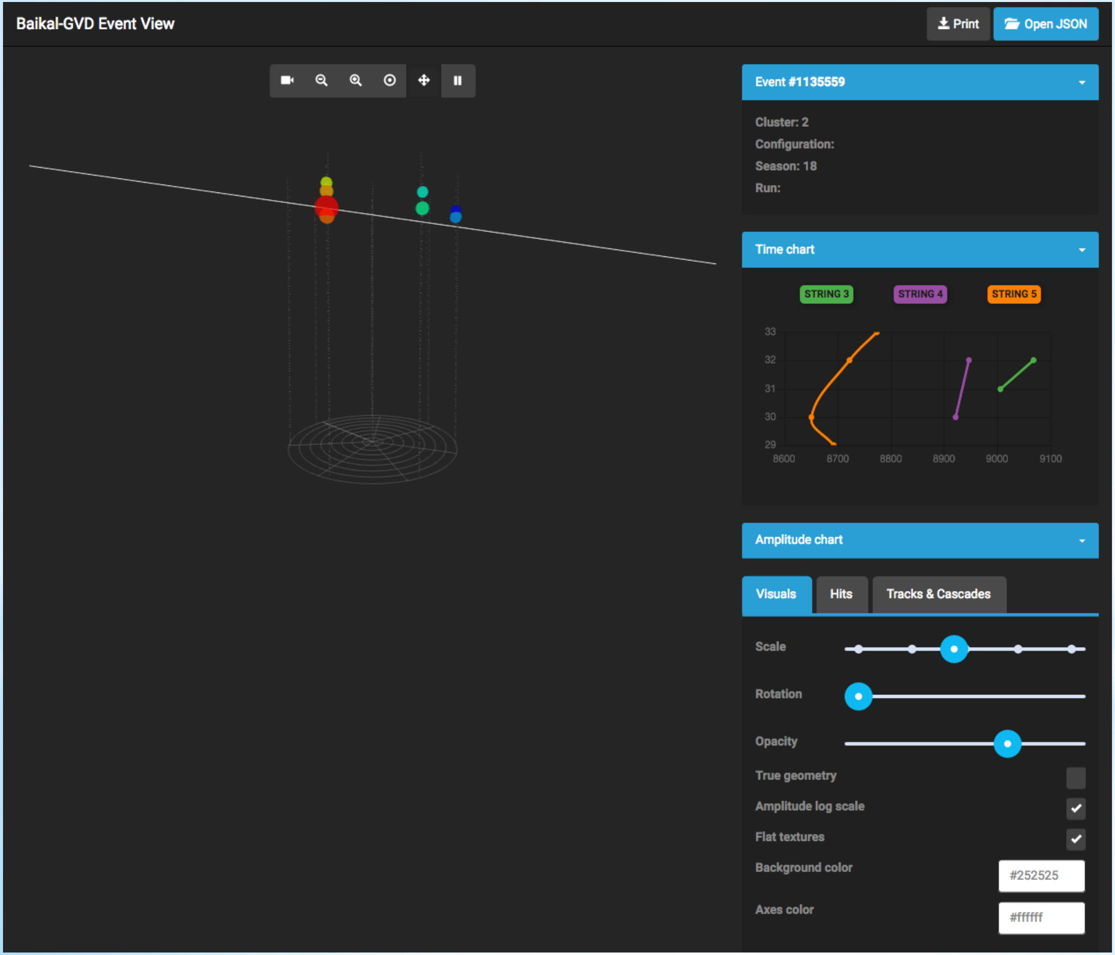
Cut	Events in ±1 day window
N_{hit} > 7 OM/3str	101287
χ^2_t < 10	11478
η > 0	464
L_a < 20	333
ψ < 10°	1

after more accurate processing with angular step reduced from 7° to 1°: mismatch angle is found to be 4°16'; reco E_{sh} is 2.9 TeV





Track-A7 near CascA7-1day_dT=+34s

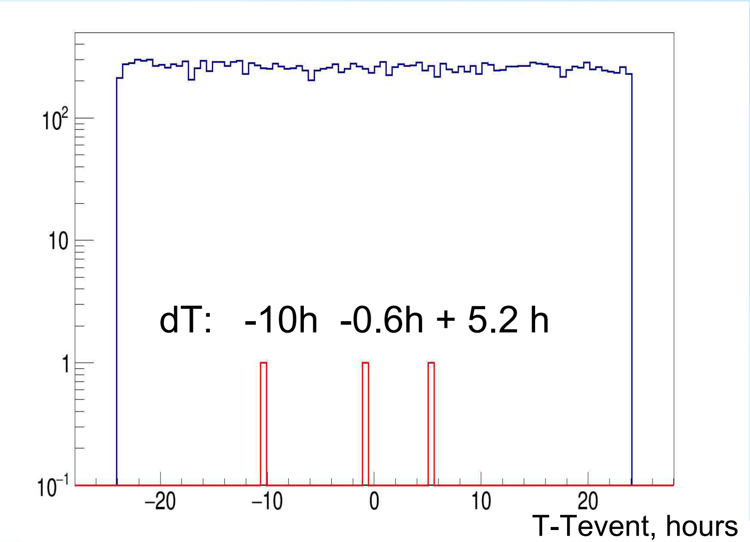


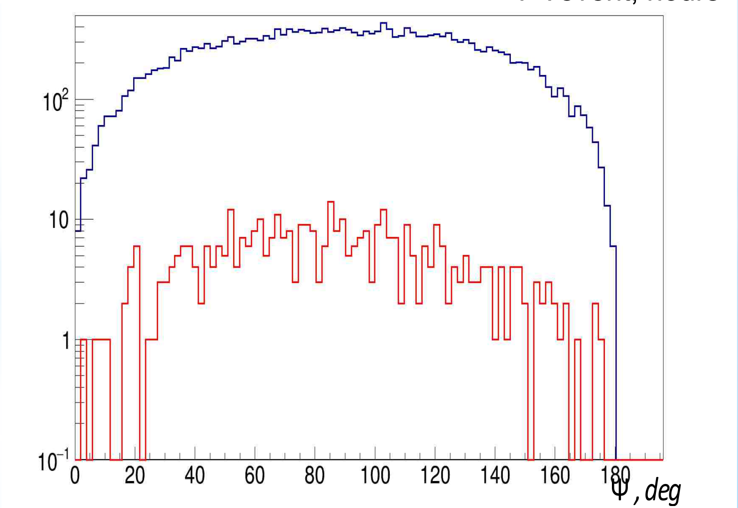
$\Psi_S = 7.6^\circ$

Alert_15 ±24h

Cut	Events in ±1 day window
N_{hit} > 7 OM/3str	22367
χ^2_t < 10	21690
η > 0	570
L_a < 20	395
ψ < 10°	3

Preliminary: 3 events with mismatch angles 3.7°; 5.9°; 9.6° and reco $E_{sh\ a}$ 3.9; 1000; 3.1 TeV.Detailed processing is incoming.





Muon tracks reco in alert time

Season 2018: only cl3 was finaly rested for AA

NN_alert	Up/Dwn	Closest_Time/ Psi	Tracks_±10s/ ±500s/Σrun	Cone_10 (1 run)/ Psi_closest (Time)
wd 1	Up	-0.65s / 146°	6(*)/ 30/ 1656	1 / 3.4°
th 2	Up	-4.34s / 60°	1/ 28/ 1601	3 / 5.8°
tu 3	Dwn	-13.2s / 97°	0/ 50/ 2107	4 / 6.0°
wd 4	Up_horizon	+2.0s / 27°	2/ 49/ 2764	4 / 3.0°
wd 5	Up	+11.6s / 40°	0/ 46/ 3617	2 / 3.2°
wd 6	Up_horizon	+35.5s / 73°	0/ 26 / 1191	5/ 0.96° (-1.46^h)
th 7	Dw_horizon	-18.6s/ 29°	0/16/ 1552	4/ 6.8°
su 8	Up	-7.6s/ 74.4°	1/28/ 1155	1/ 19.4°

Preliminary results:
yet not found coincidence with ANTARES alerts,
and further analysis is continued

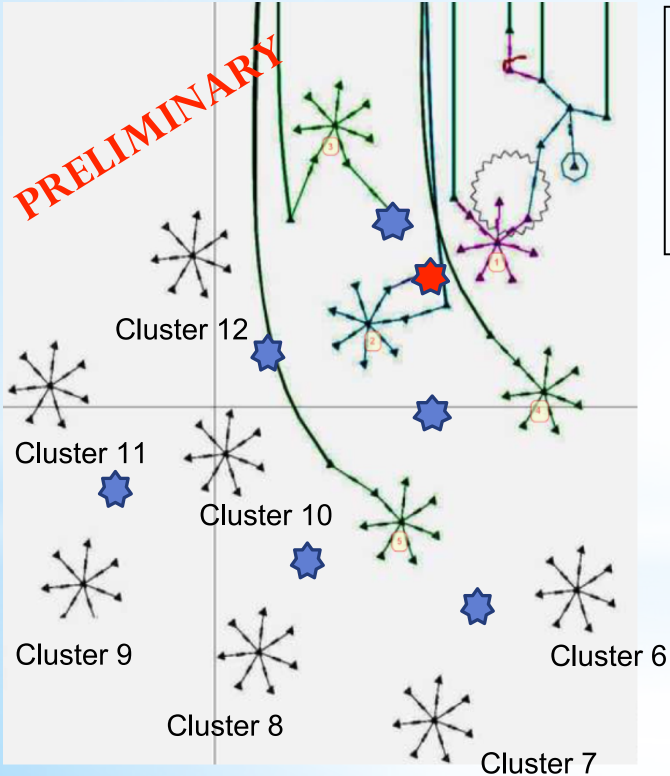
Timeline GVD-1 to reach 0.4 km^3

Year	2016	2017	2018	2019	2020	2021
Nb. of clusters	***1***	***2***	***3***	***5***	***7***	***9***
Nb. of OMs	***288***	***576***	***864***	***1440***	***2016***	***2592***

The sequence of clusters installation

Laser string

String for the tests of new electronics



A preliminary proposal for the sequence of the Clusters installation and position of the Laser/Technological strings is considered now

Summary

1. Currently, Baikal-GVD neutrino telescope is under construction in lake Baikal. Five clusters of Baikal-GVD were successfully commissioned in April 2019. The priority of Baikal collaboration is to install new two clusters in 2020.

2. During the year 2018 data were taken with the highest effective volume in the Northern hemisphere for high energy neutrino detection ~0.25 km^3.

3. The Baikal deep water optical activity is monitored in real time and is in analysis off line.

4. Modular structure of GVD design allows to search for HE neutrinos at the early phases of array construction. Two cascades events were found with energy higher 100 TeV with data samples of 2015 and 2016.

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

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


Thank you for your attention!