Baikal-GVD: status and perspectives

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for the Baikal Collaboration
ICRC2021, Berlin, July 12, 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

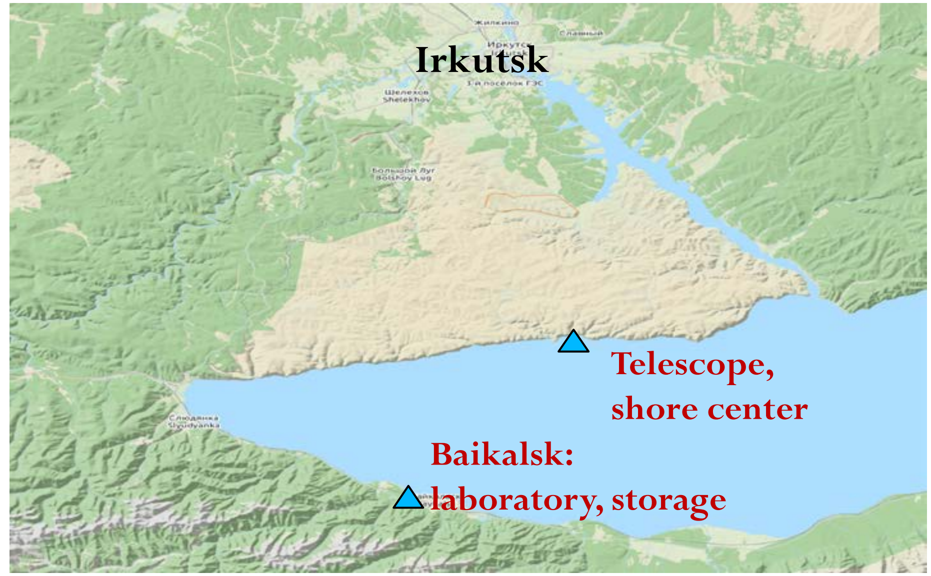
Telescope is located
~4 km away from shore

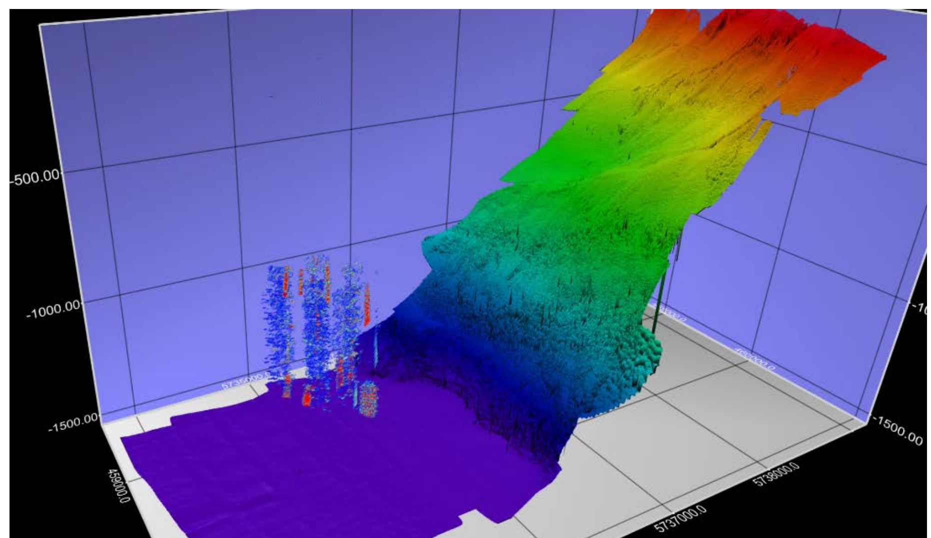
Stable ice cover for 6-8 weeks in February – April: detector deployment and maintenance.

Baikal water :
Absorption length: ~ 22-24 m
Scattering length: ~ 30-50 m

Moderately low background
15–40 kHz: PMT R7081-100 ∅10"

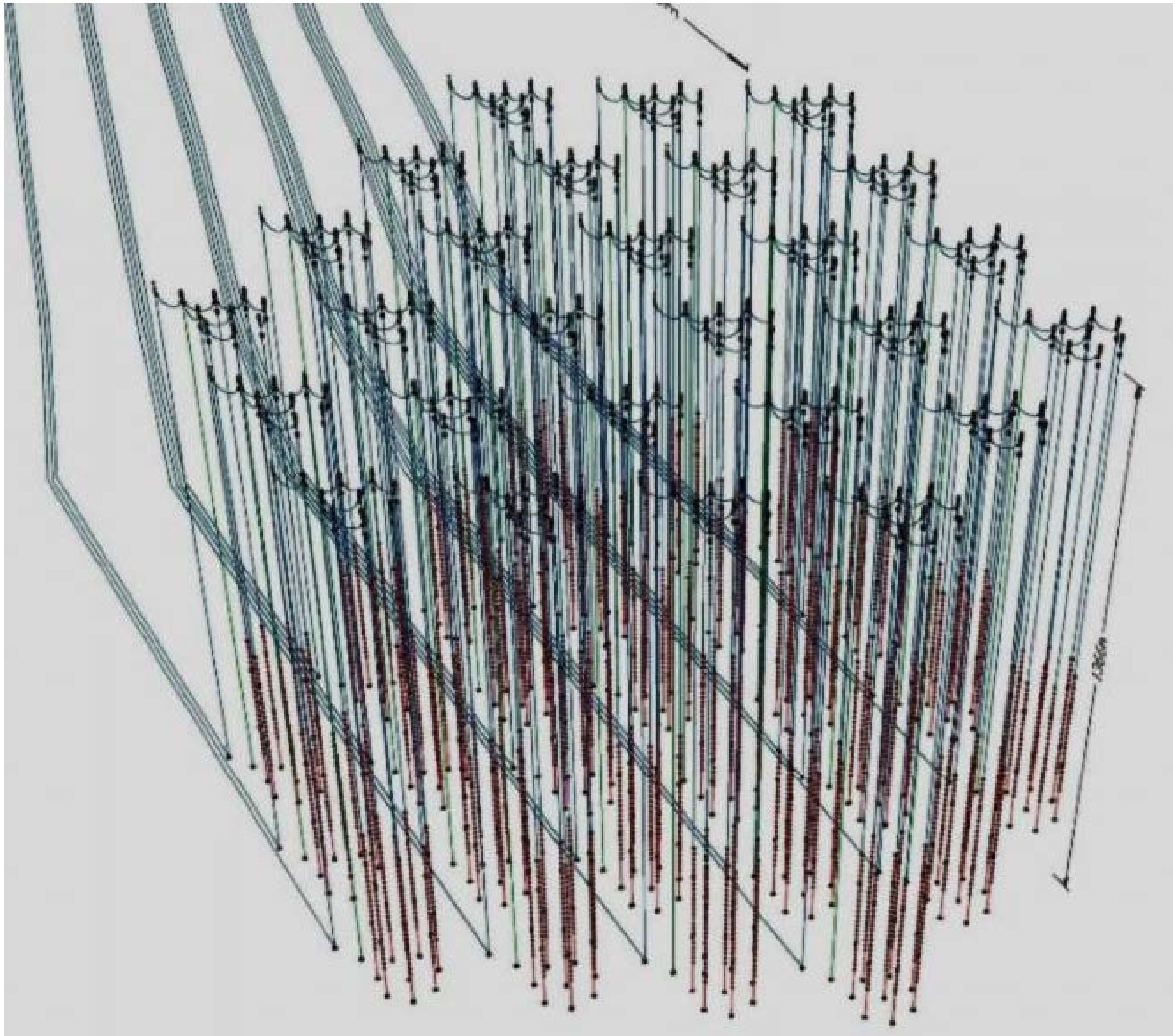
The constant depth of the lake (1366-1367 m)

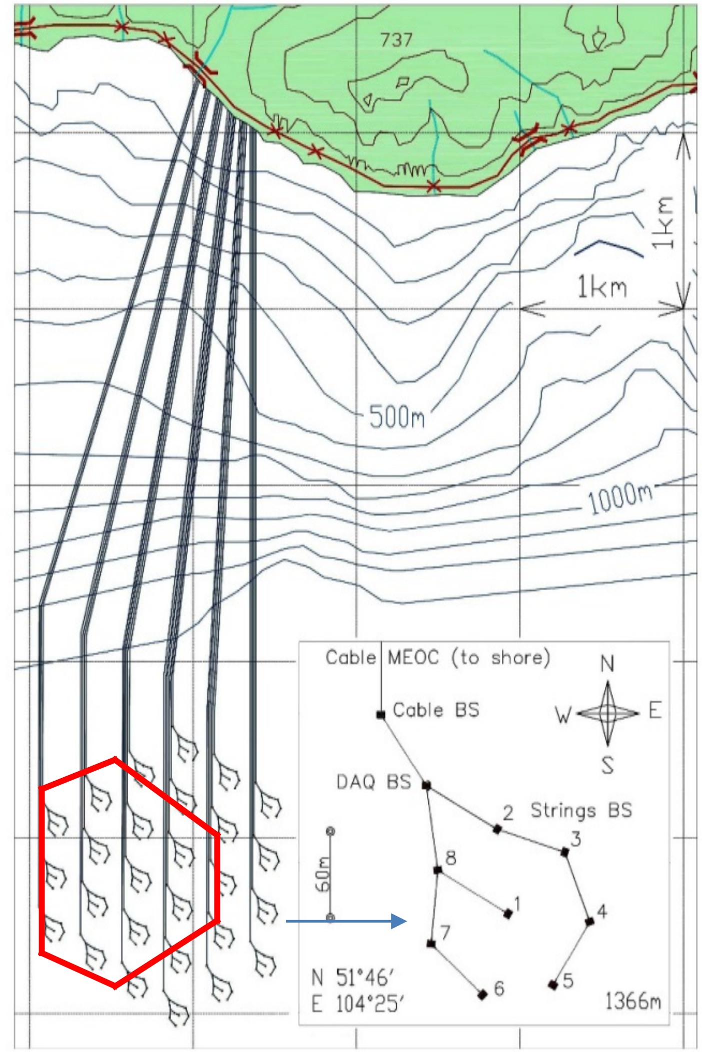




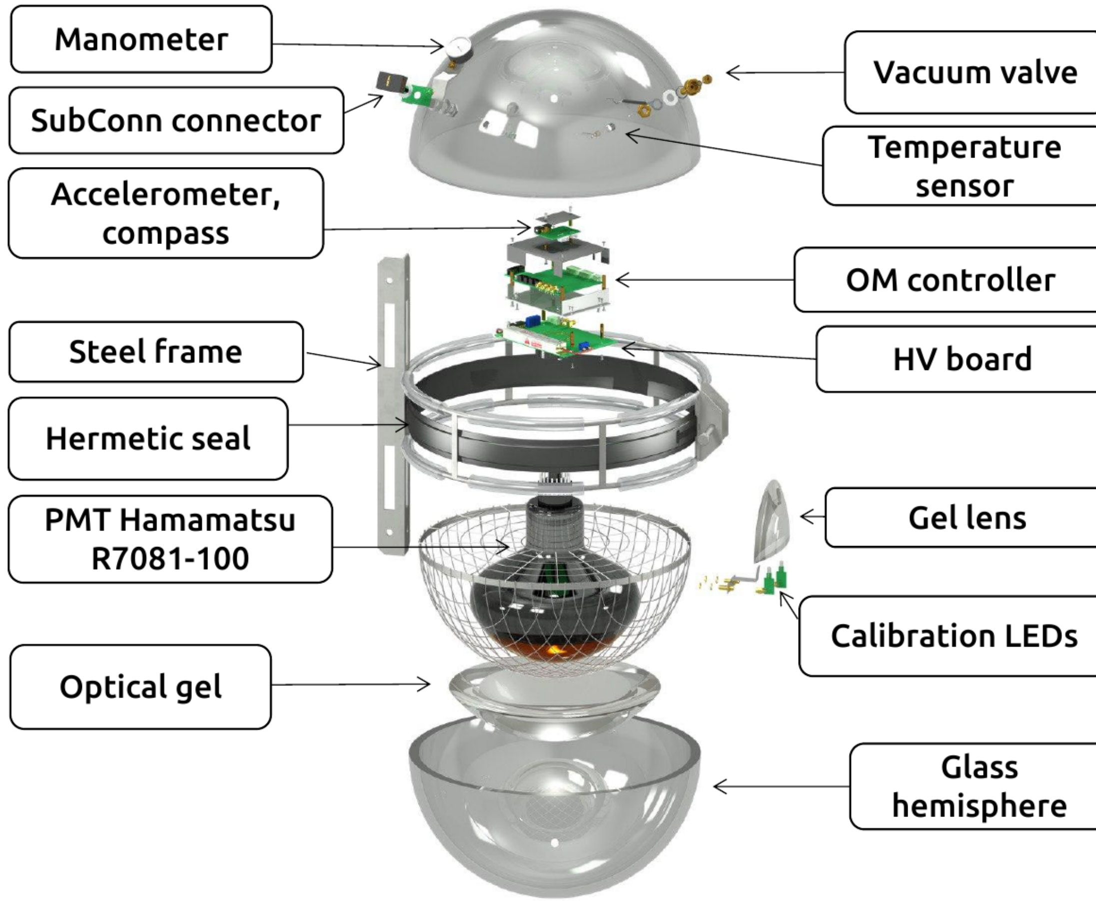
Gigaton Volume Detector at Lake Baikal

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





Baikal-GVD optical module



Section of OMs

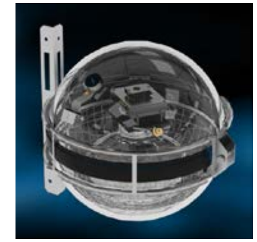
Section

- 12 OMs, 15 m spacing, All PMTs look downward.
- 2 acoustic modules (AM) of the positioning system.

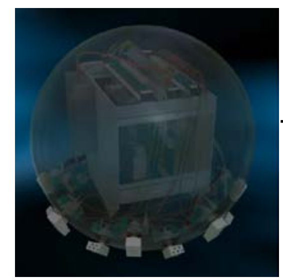
Section control module

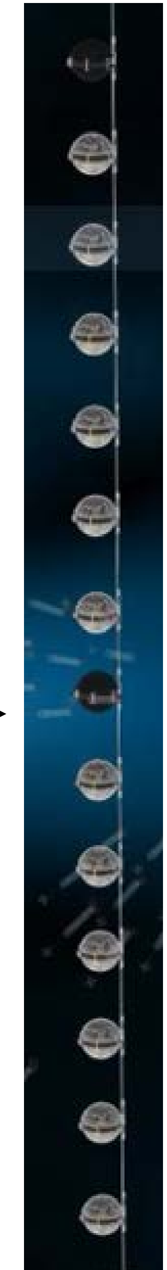
- ADC12 ch, 200 MHz sampling; pulse form measuring.
- Trigger logic, events forming, data filtration.
- Data transmission: shDSL ethernet extender: 5.7 Mbit

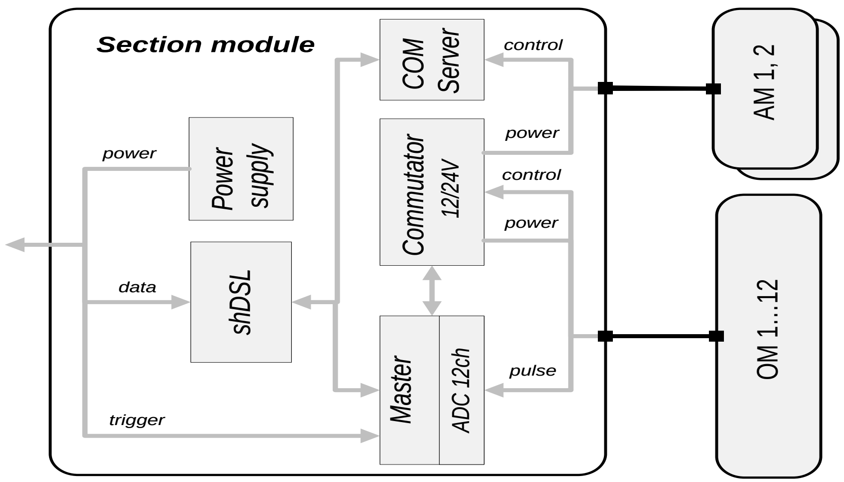
O[tical module

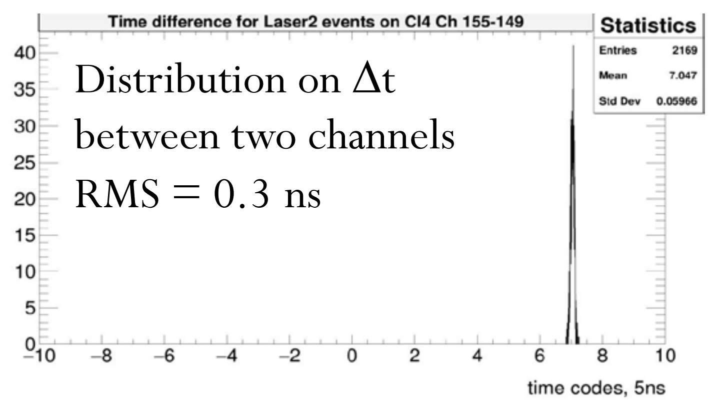


Section control module



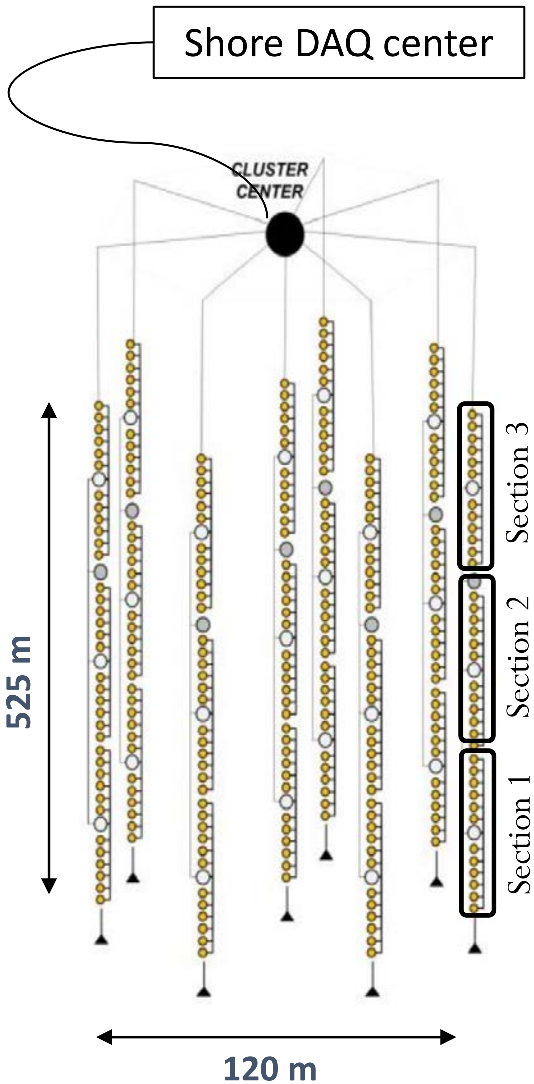






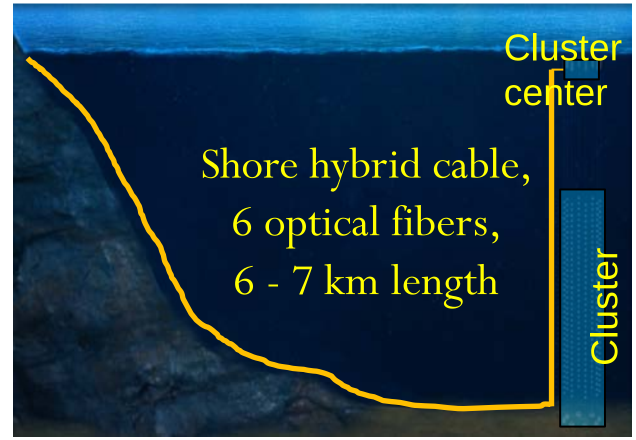
Pulse form interpolation provides accuracy of the pulse time estimation ~0.3 ns.

Cluster



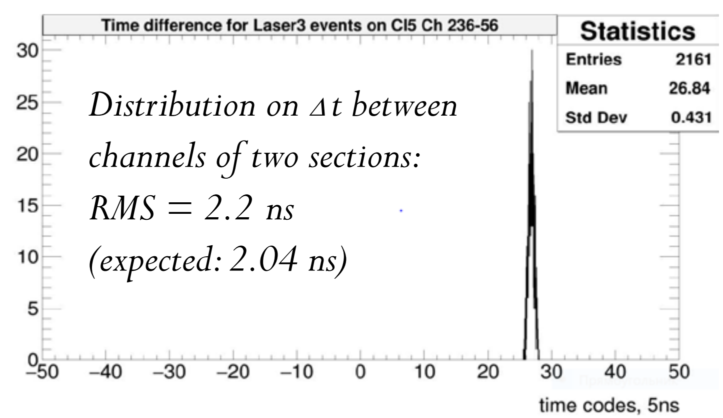
Cluster: 288 OMs

- 24 Sections on 8 strings,
- Cluster DAQ center
- Shore cable: 6 - 7 km
- Depths from 750 to 1275 m



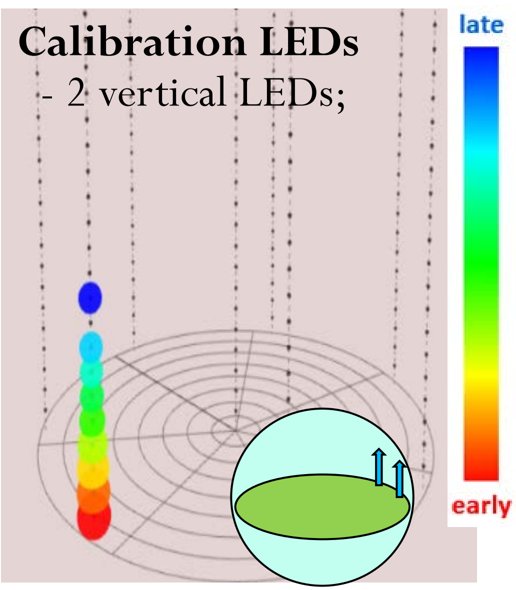
Cluster DAQ

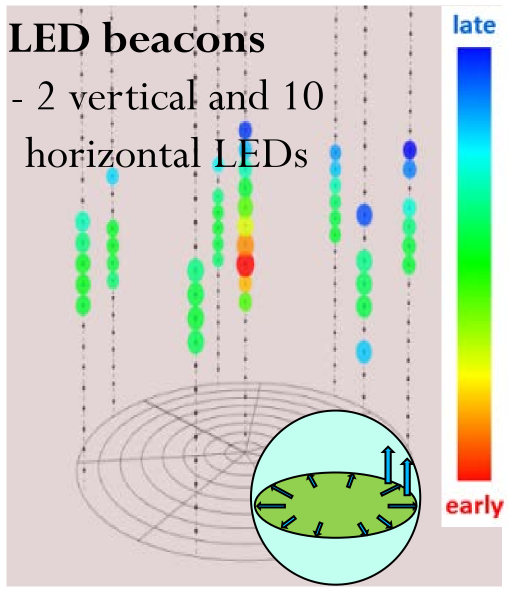
- Trigger: 1.5 & 4 pe of adjacent channels.
- Maximum trigger rate: ~200 Hz.
- Data transferring: shDSL Ethernet extenders: 5.7 Mbit.
- Inter-section synchronization by common trigger: ~2 ns accuracy.

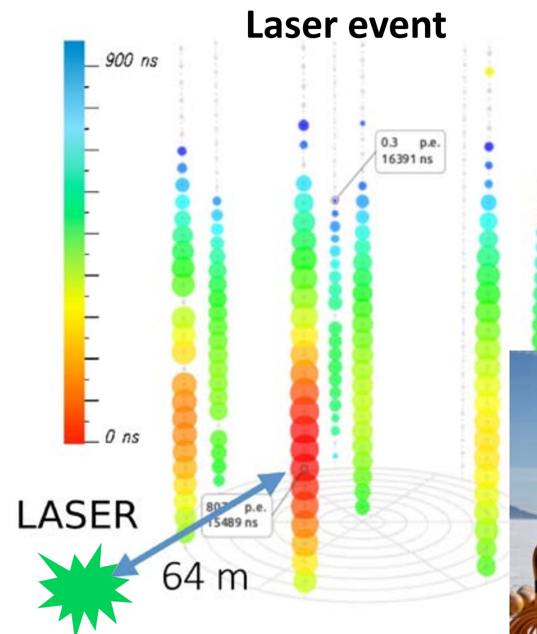


Calibration devices

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

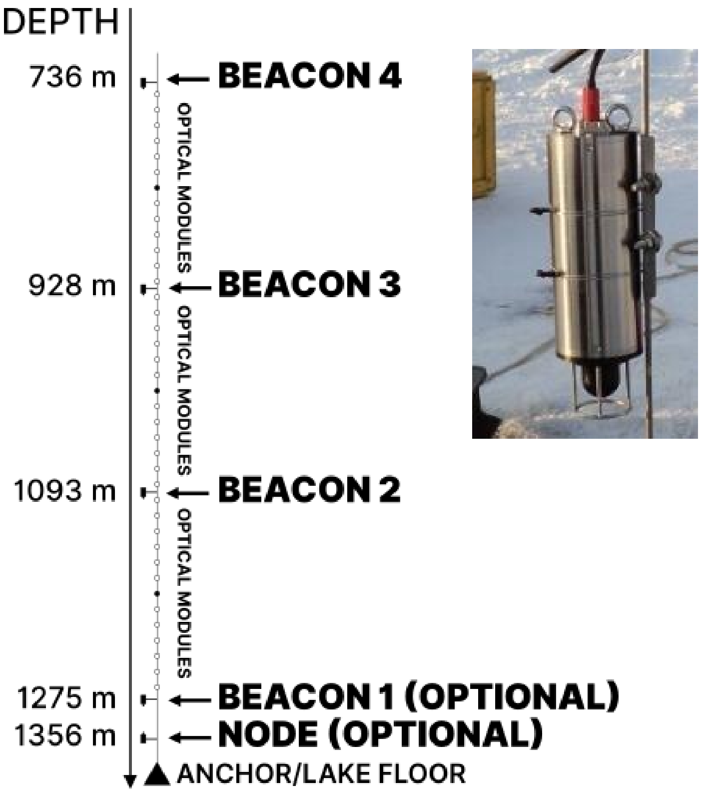


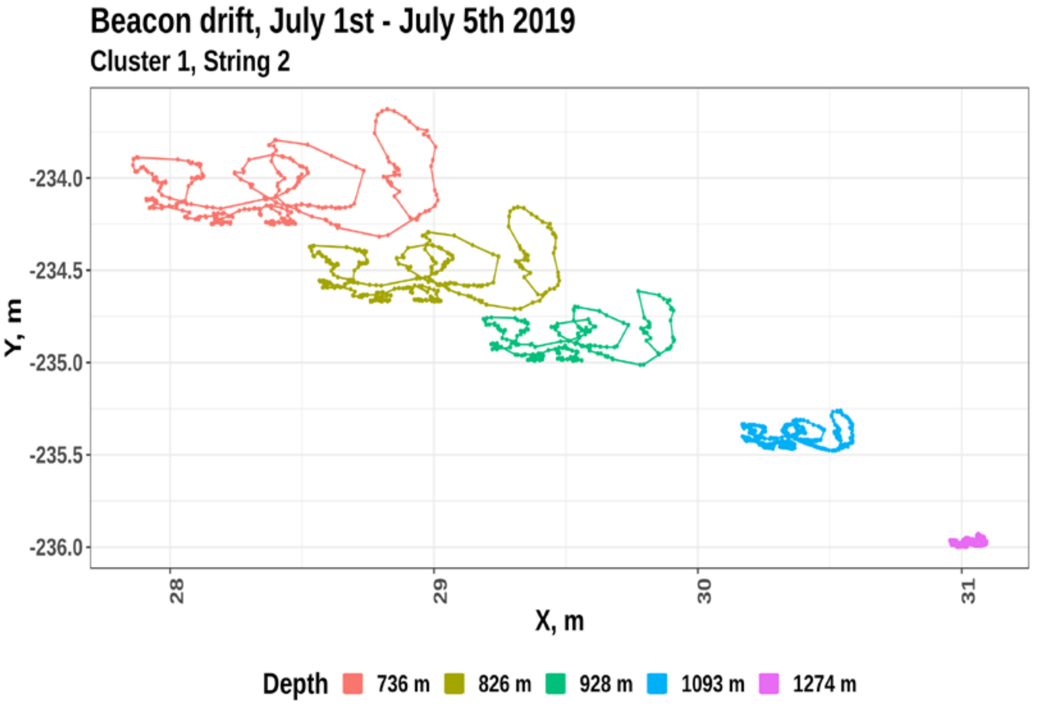




Calibration accuracy ~2 ns

Acoustic positioning system





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

OM coordinates are acquired via an acoustic positioning system.

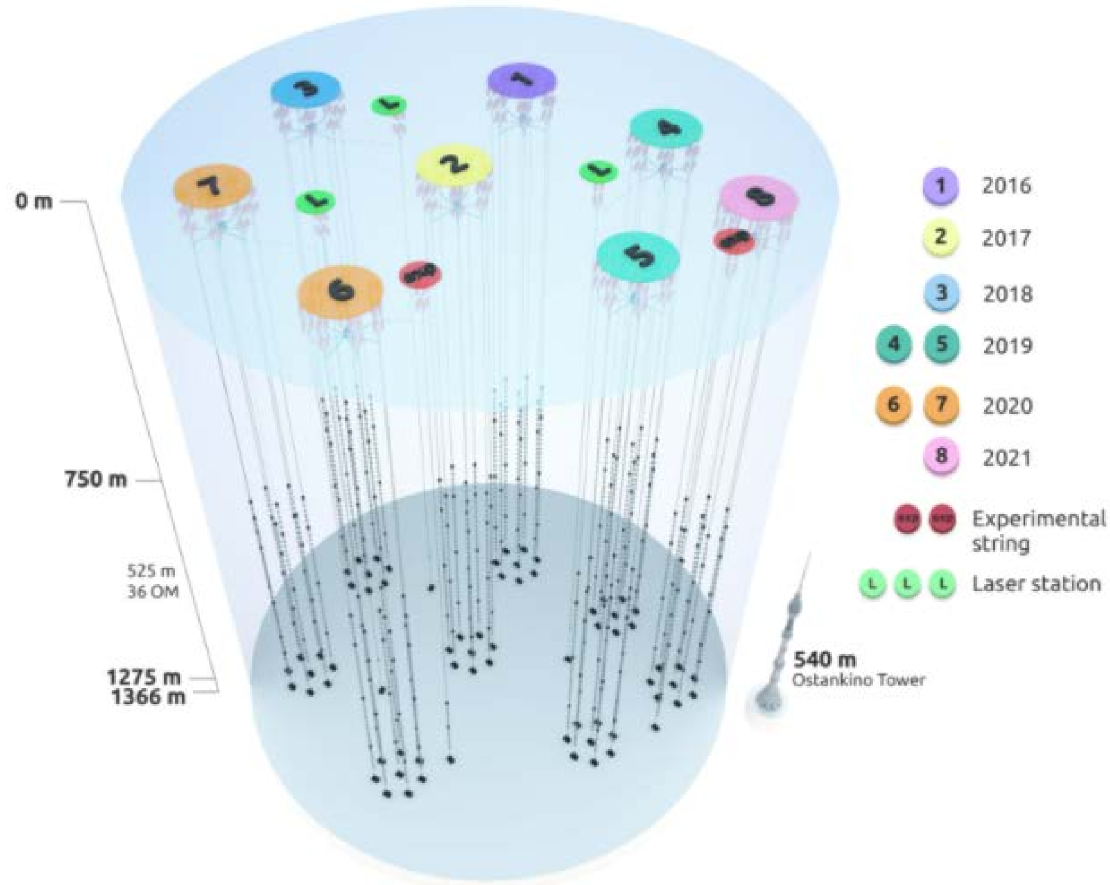
It consists of a network of acoustic modems (AMs) installed along GVD strings

4 AMs per string in a standard configuration.

OM coordinates are obtained by interpolating AM coordinates, error < 0.2m,

Baikal-GVD construction status and schedule

Status 2021: 8 clusters, 3 laser stations, experimental



Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

Effective volume 2021: 0.40 km^3 (cascade mode)

Selected results

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

Track analysis

(talk ID1449 by D.Zaborov)

Present status: technique for neutrino events selecting and reconstructing is currently being developed.

Reconstruction: noise hit suppression and fit track with quality function:

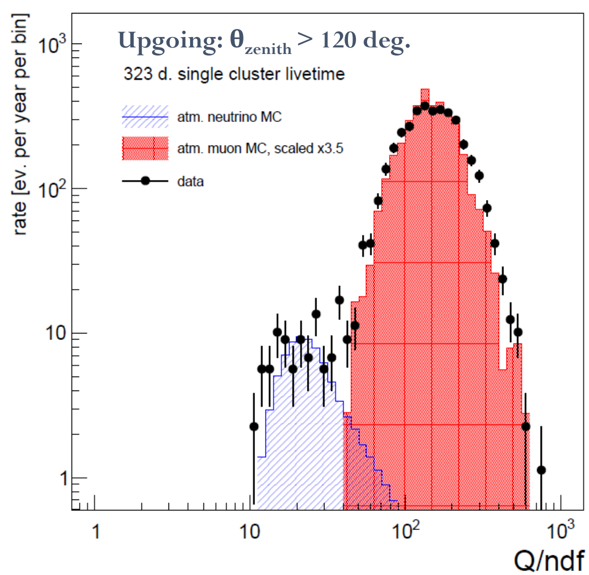
$$Q(x, y, z, \theta, \phi) = \chi_t^2 + Q_r$$

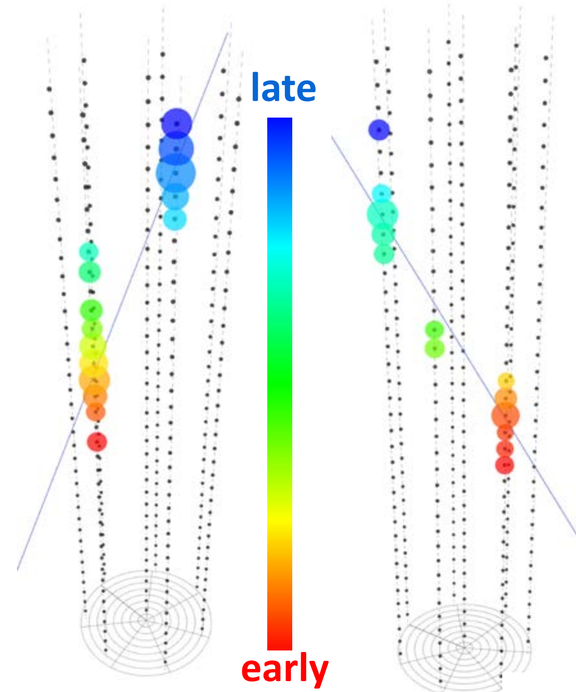
Data sample: data taken between Apr 1 and Jun 30, 2019; 5 clusters.

Event selection: 8 hit OMs on at least two detector strings;

Neutrino selection cuts:

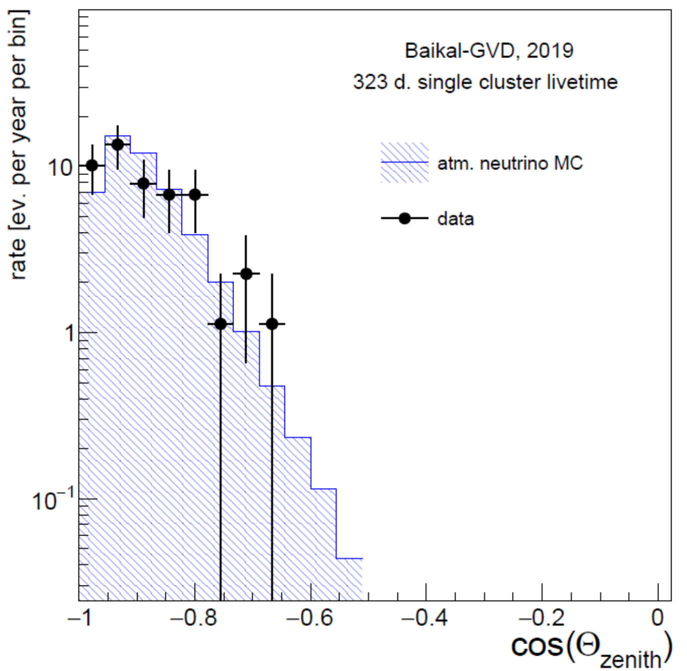
- ***Zenith angle >120°***
- ***Fit quality Q/ndf < 32***
- *Visible track length L >75 m*
- *Average distance to OMs < 18 m*
- *Charge of all hits > 18 pe*
- *Estimated zenith angle error < 2°*

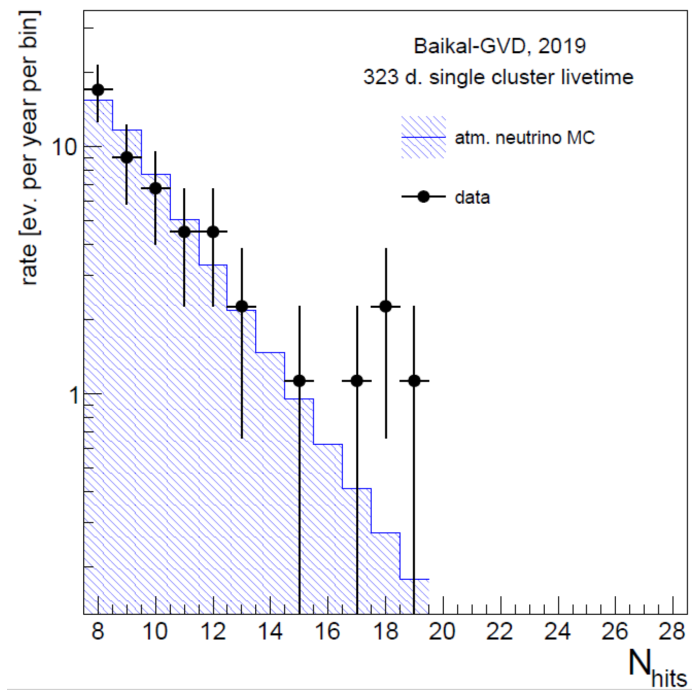




Muon neutrino : single-cluster analysis

- 9.8 million reconstructed events for the combined dataset from the 5 clusters.
- Single-cluster equivalent live time 323 days.





MC expected: 43.6 ±6.6 (stat.)
Observed: 44

Fair agreement with MC prediction for atmospheric neutrino

The median energy of the neutrino events 500 GeV.

Angular resolution: (single cluster) ~ 1° or better

Multimessenger studies (talk ID946 by O.Suvorova)

BAIKAL alerts

Since Sept 2020: data processing with a delay of several hours. Nearest plans: HE alerts processing with delay less than tens of minutes.

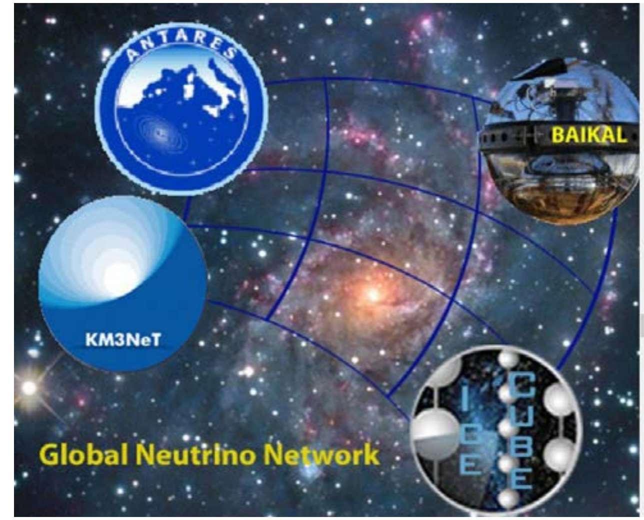
ANTARES alerts

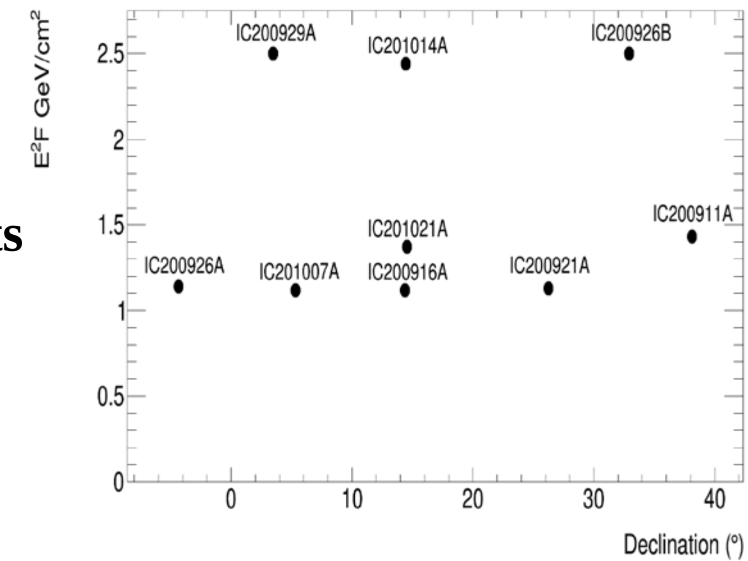
Since the end of Dec 2018 Baikal-GVD follows ANTARES alerts. Processed 48 alerts, among which 3 possible coincidences were found in cascade mode within 5° and dT ±1 day and are under investigation with ANTARES.

ICECUBE alerts

Starting Sept 2020 Baikal-GVD follows **IC alerts (GCN) , 22** alerts.

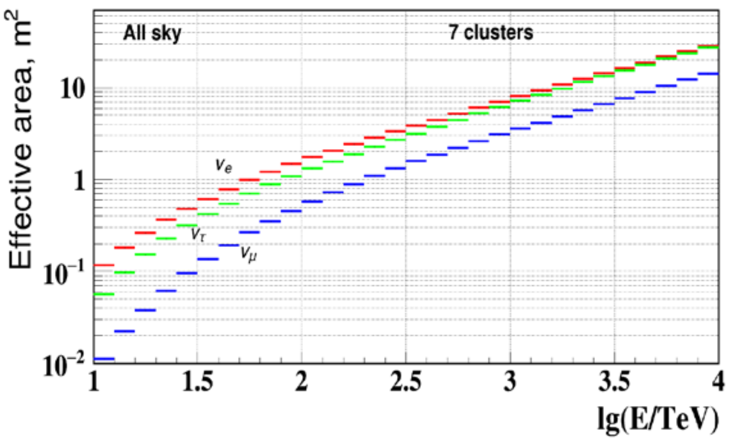
Upper limits at 90% c.l. on the neutrino fluence: ~1÷2 GeV cm^{-2} for energy range 1TeV– 10PeV. E^{-2} spectral behavior; equal fluence in all flavors



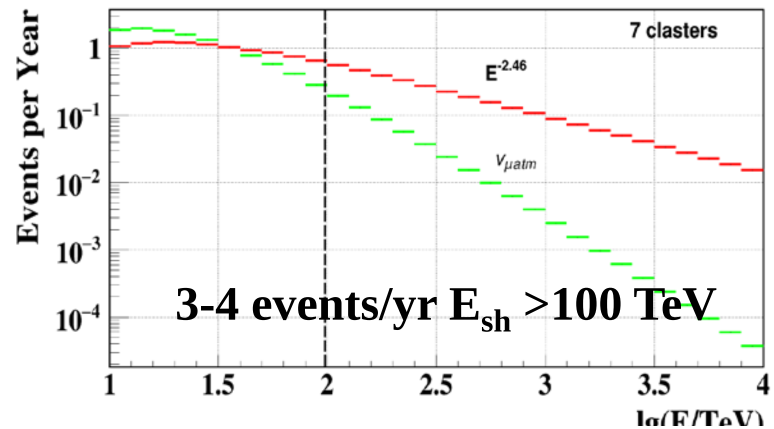


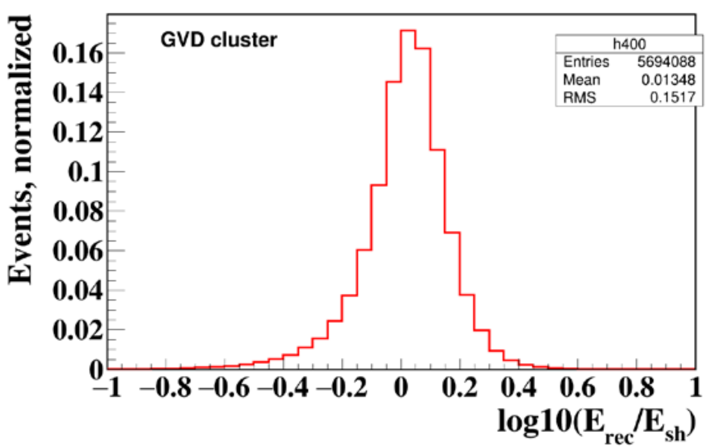
Cascades detection with GVD Cluster

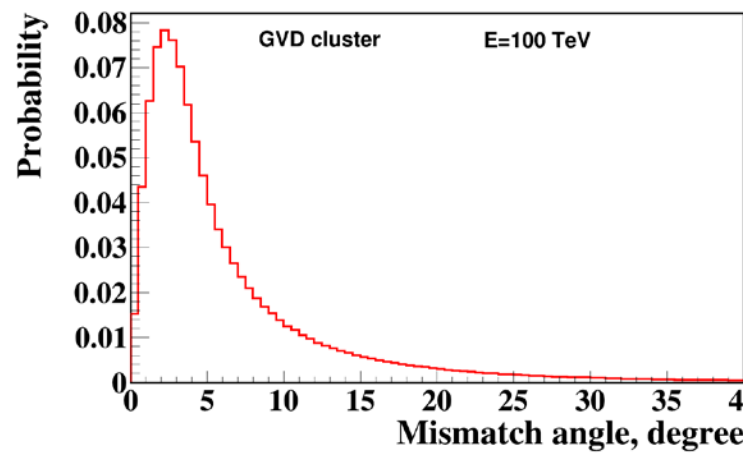
Neutrino Effective Area for 7 GVD Clusters



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







Energy resolution : $\delta E/E \sim$ 10%-30%

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

High energy cascades (data and MC)

Preliminary!

Data from 2019-2020 , **livetime: *2915* days** (in terms of one cluster)

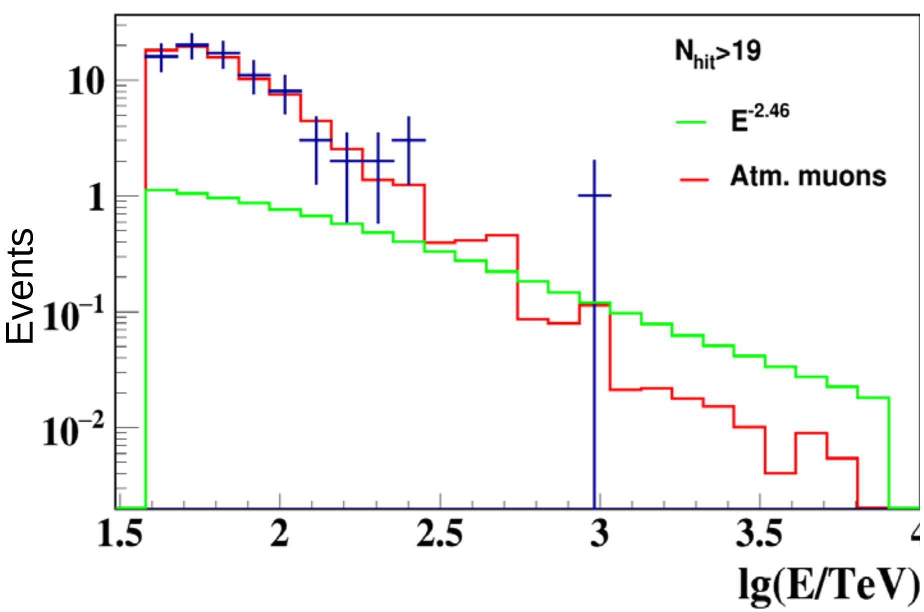
MC atmospheric muons - Corsika 7.74, Sybill 2.3c, protons, E_p>100 TeV

Thanks to Jakob van Santen for modification of DYNSTACK CORSIKA.

72 events with E > 40 TeV and N_{hit} > 19

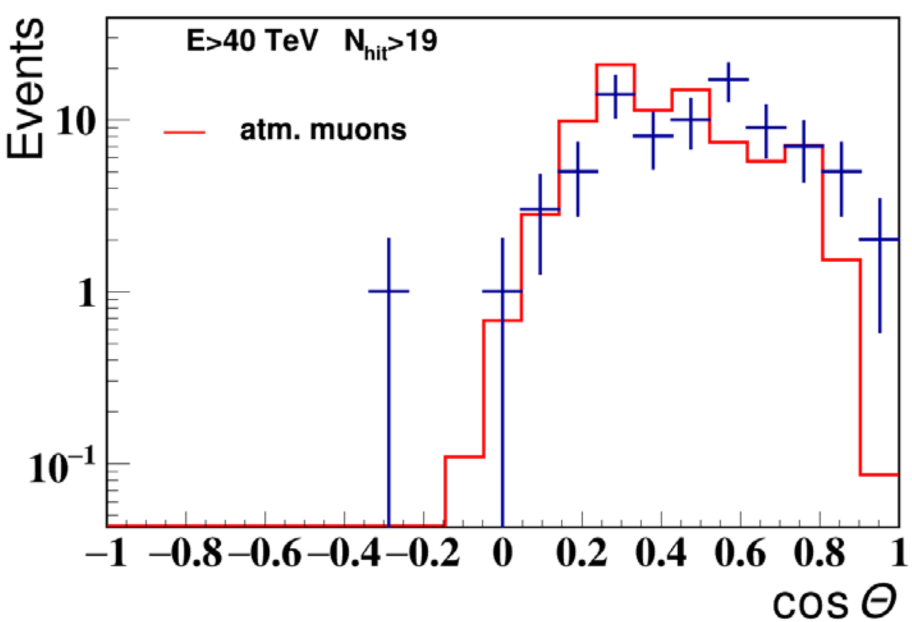
10 events with E > 100 TeV and N_{hit} >19:

Energy distribution



One upgoing cascade: E ≈ 91 TeV

Cosine of zenith angle

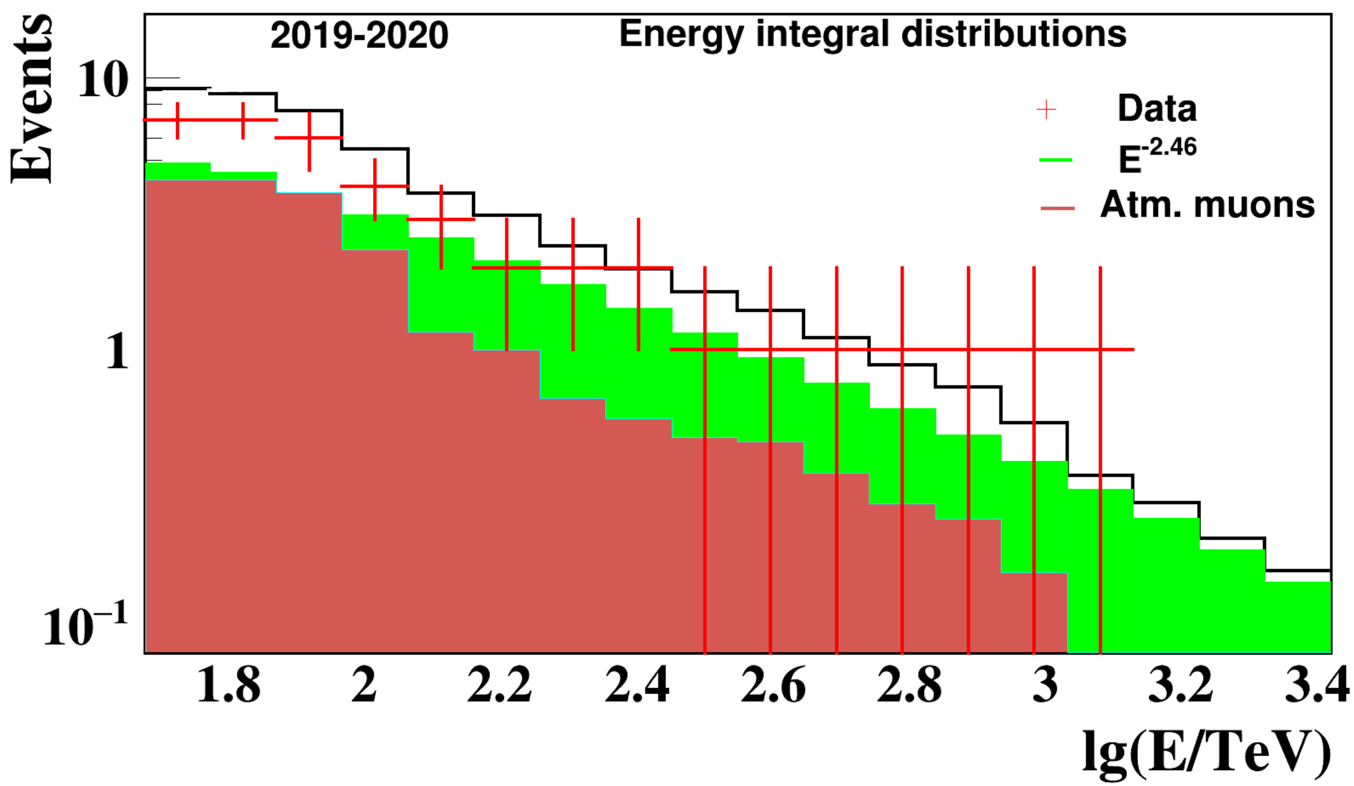


Final selection requirements:

($N_{Type\_2} = 0$, $E_{rec} \geq 60$ TeV) or ($N_{Type\_2} = 1$, $E_{rec} \geq 100$ TeV)

7 data events have been selected.
4 events are expected from atm. muons
5 events are expected from $E^{-2.46}$ astrophys. flux with IC normalization

Cumulative distributions of data and events from atm. muons and astrophys. flux after final cuts



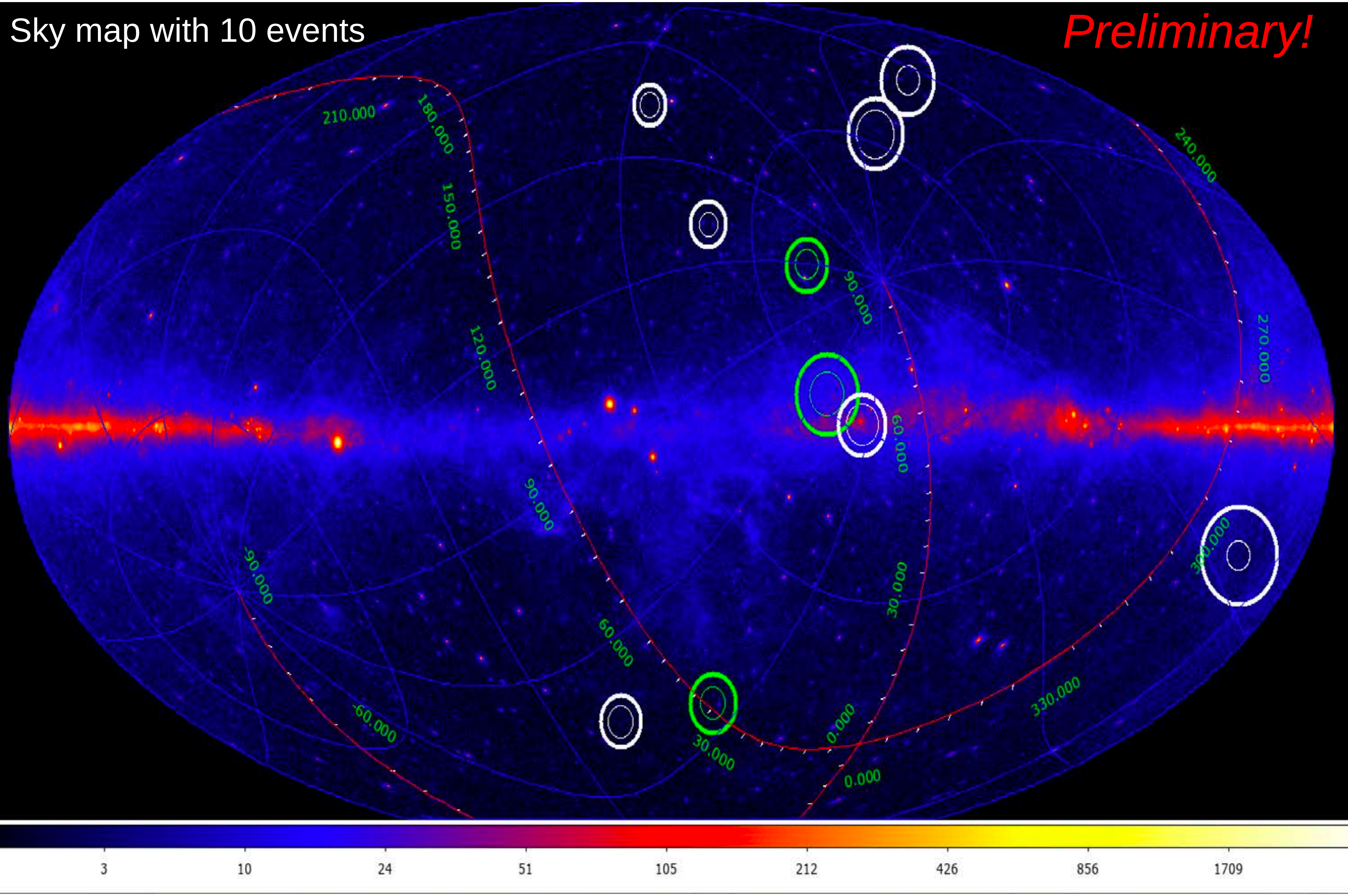
Preliminary!

Parameters of 10 selected events (2018-2020)

	E, TeV	θ_z, degree	φ, degree	R.A.	Dec
GVD2018_354_N	105	37	331	118.2	72.5
GVD2018_383_N	115	73	112	35.4	1.1
GVD2018_656_N	398	64	347	55.6	62.4
GVD2019_112_N	1200	61	329	217.7	57.6
GVD2019_114_N	91	109	92	45.1	-16.7
GVD2019_663_N	83	50	276	163.6	34.2
GVD2019_153_N	129	50	321	33.7	61.4
GVD2020_175_N	110	71	185	295.3	-18.9
GVD2020_332_N	74	92	9	223.0	35.4
GVD2020_399_N	246	57	49	131.9	50.2

Sky map with 10 events

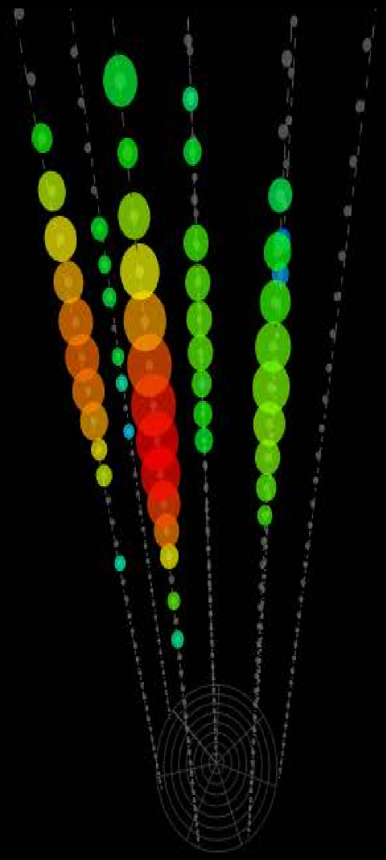
Preliminary!

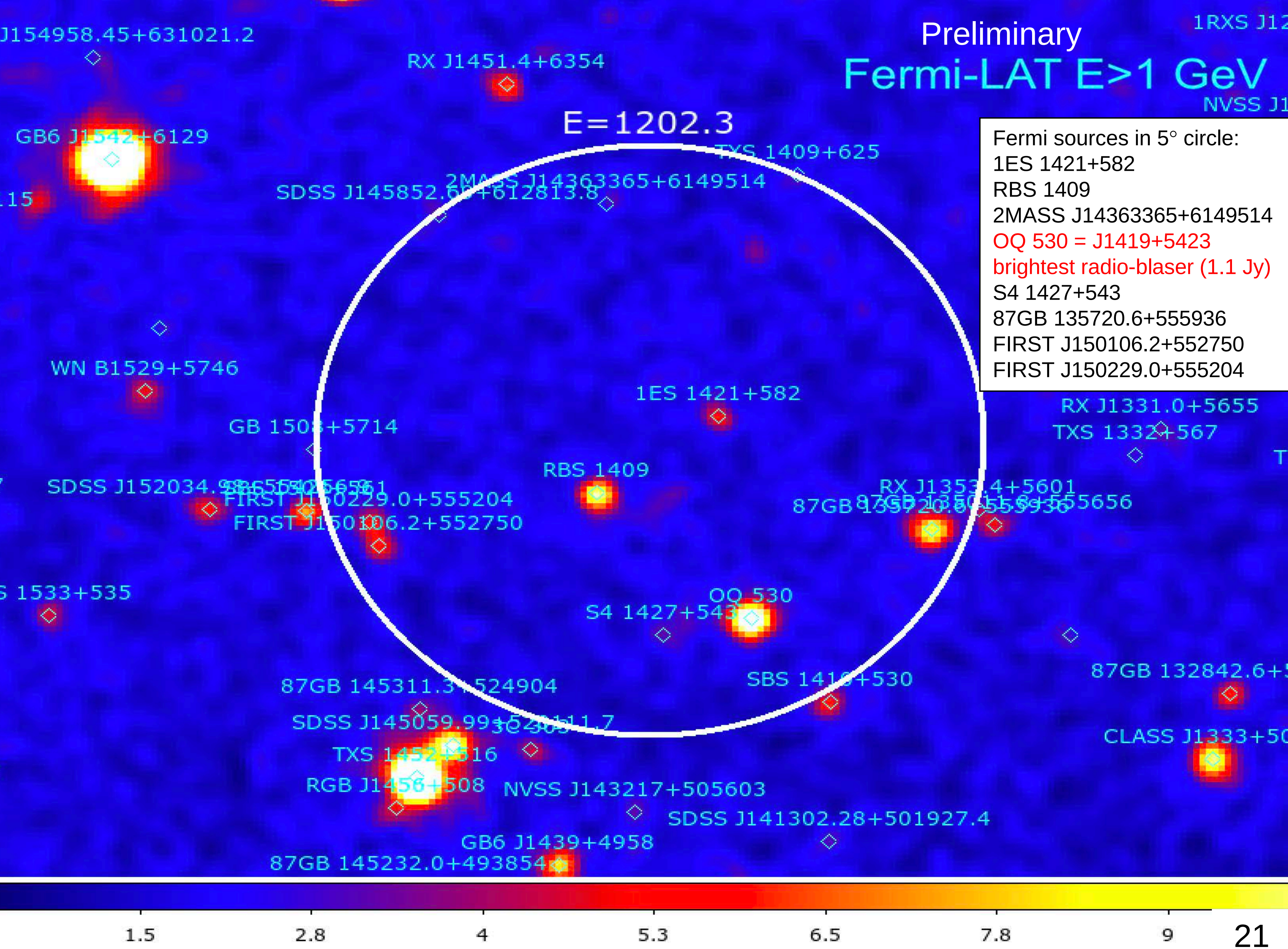


GVD_2019_112_N

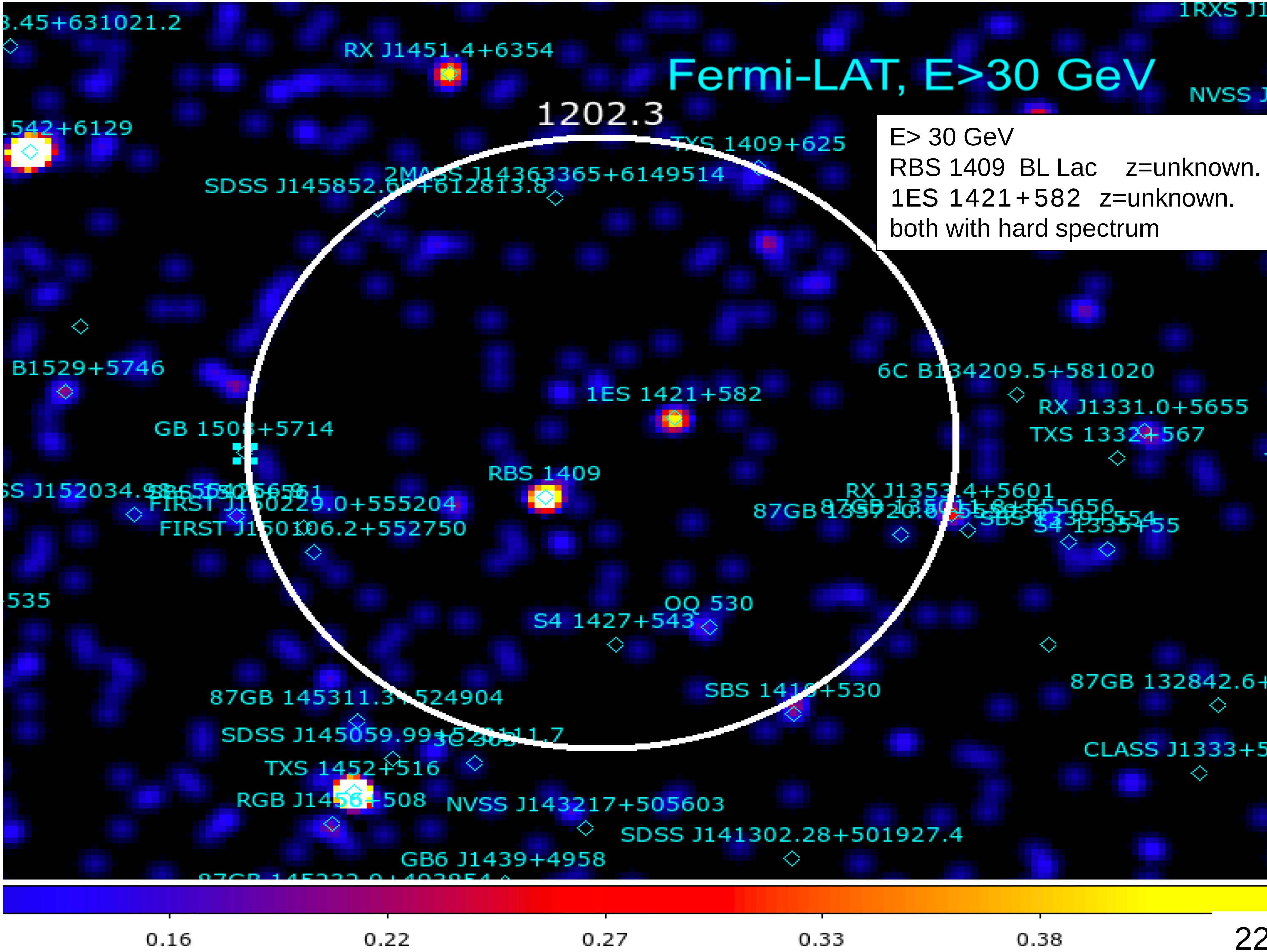
Preliminary

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





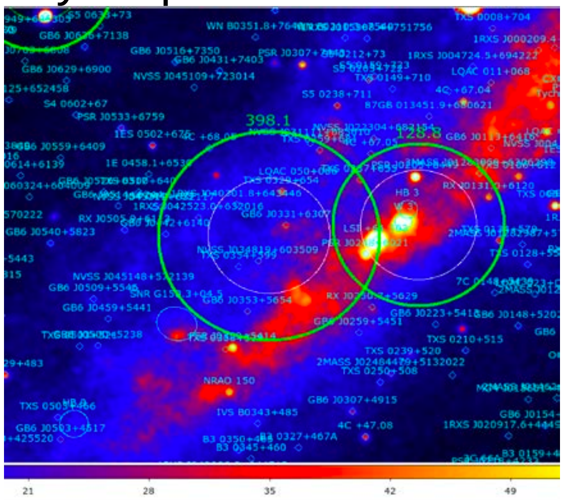
Fermi sources in 5° circle:
1ES 1421+582
RBS 1409
2MASS J14363365+6149514
OQ 530 = J1419+5423
brightest radio-blaser (1.1 Jy)
S4 1427+543
87GB 135720.6+555936
FIRST J150106.2+552750
FIRST J150229.0+555204


Fermi-LAT, E>30 GeV
1202.3
E> 30 GeV
RBS 1409 BL Lac z=unknown.
1ES 1421+582 z=unknown.
both with hard spectrum
RX J1451.4+6354
TXS 1409+625
2MASS J14363365+6149514
SDSS J145852.6 +612813.8
B1529+5746
1ES 1421+582
6C B134209.5+581020
RX J1331.0+5655
TXS 1332+567
RBS 1409
FIRST J150229.0+555204
FIRST J150106.2+552750
RX J1353.4+5601
OQ 530
S4 1427+543
SBS 1410+530
87GB 145311.3+524904
87GB 132842.6+
CLASS J1333+50
TXS 1452+516
RGB J1456+508
NVSS J143217+505603
SDSS J141302.28+501927.4
GB6 J1439+4958
0.16
0.22
0.27
0.33
0.38

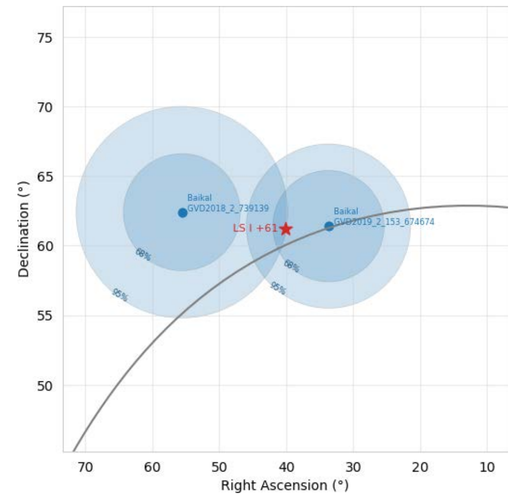
Preliminary!

Two close events at distance 10.3°: GVD_2018_656_N & GVD_2019_153_N

Sky map of Fermi sources



LSI +61 303 and two events



LSI +61 303 – at 3.1° and 7.4° from GVD_2019_153_N and GVD_2018_656_N

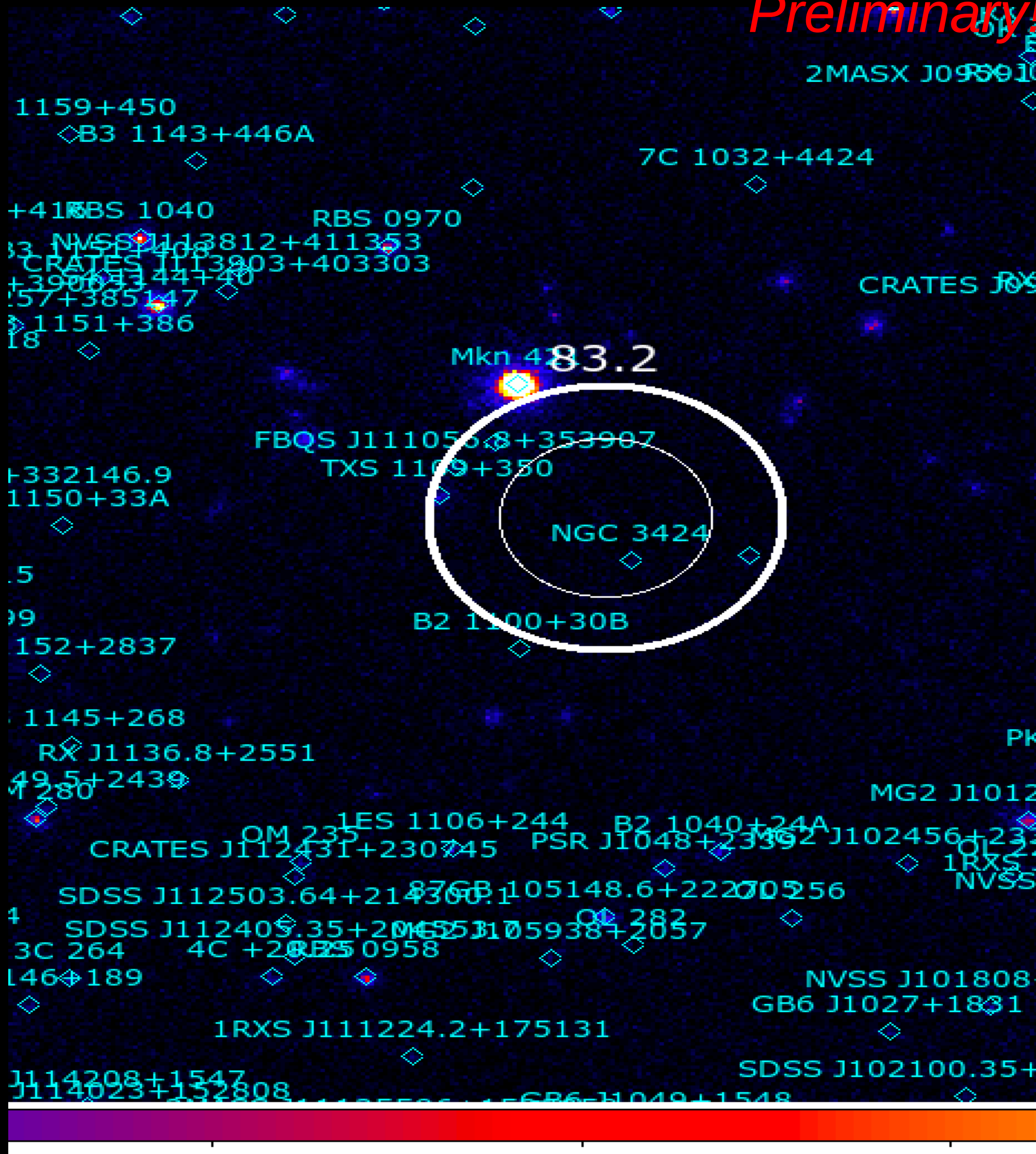
LSI +61 303 – γ-ray active microquasar

Using PSFs of all 10 events chance probability to observe such configuration was estimated:

p-value = 0.007 or 2.7 σ ! (conservative, preliminary!!!)

GVD_2019_663

Mrk 421
brightest source

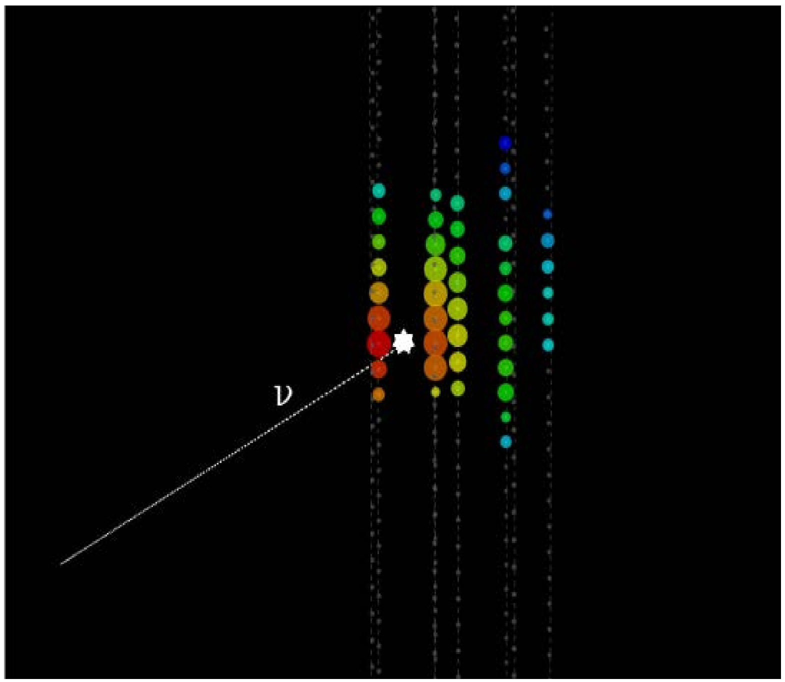


GVD2019_1_114_N

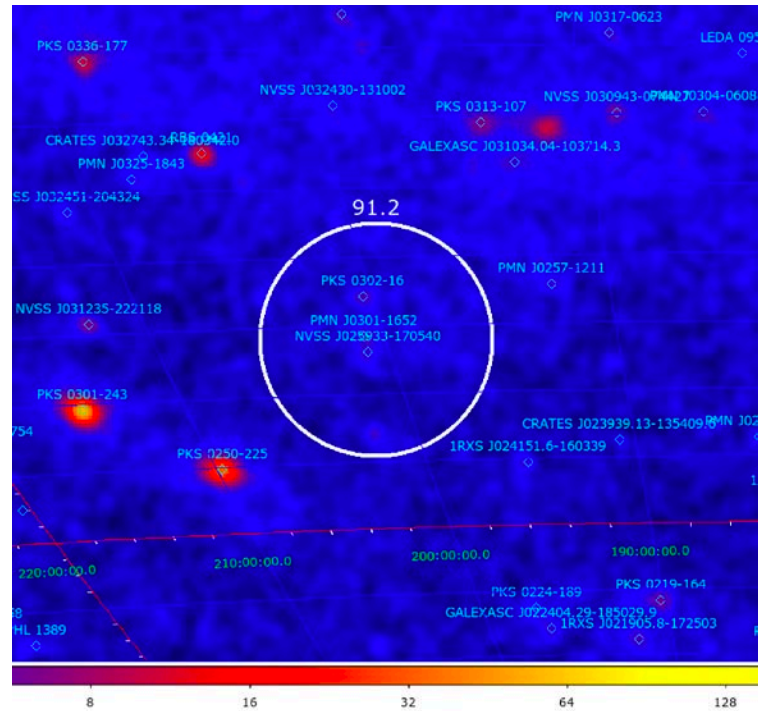
Preliminary

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

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



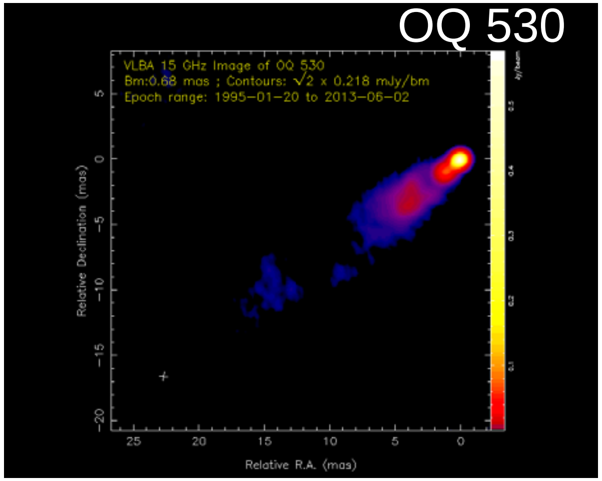
Sky plot of γ-ray sources
(D.Semikoz, A.Neronov)



91.2 ТэВ (from below) no good known sources in 3 degrees
PKS 0302-16 unknown type of source
PMN J0301-1652 unknown type of source

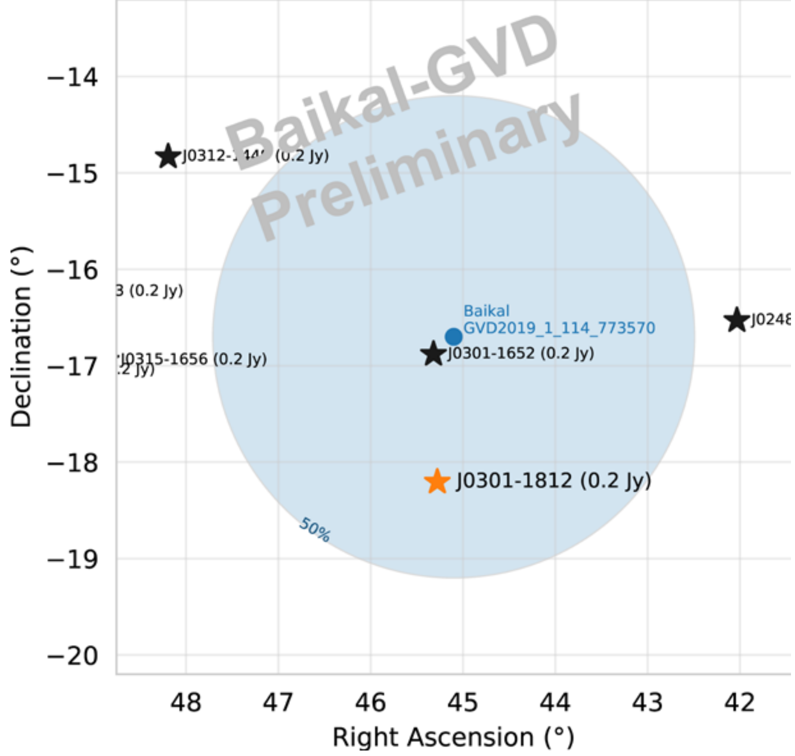
Radio-loud blazars – promising neutrino sources

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

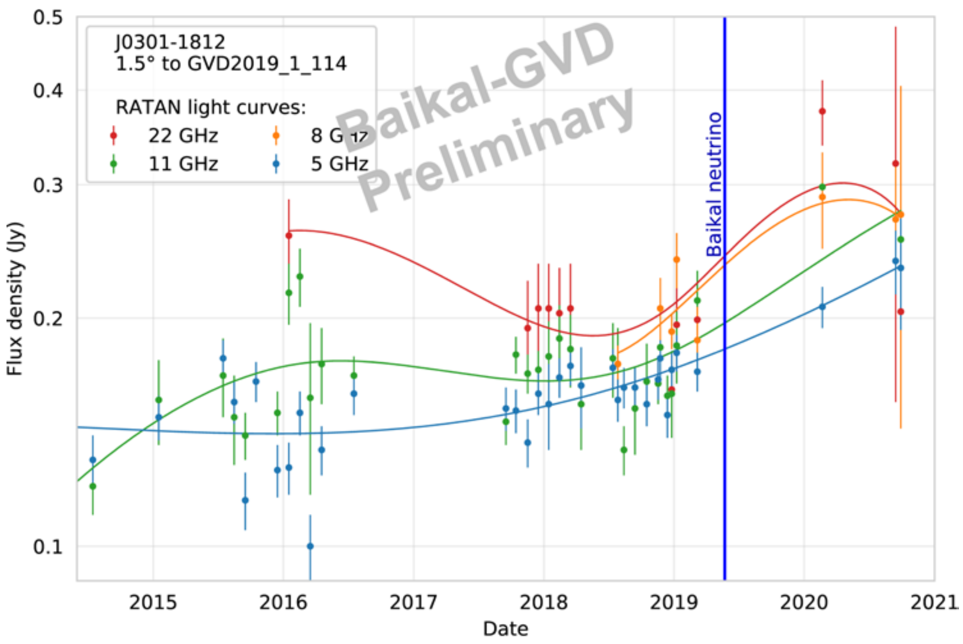


GVD2019_1_114_N
Radio blazar J0301-1812

Sky plot of radio-bright blazars nearby neutrino event

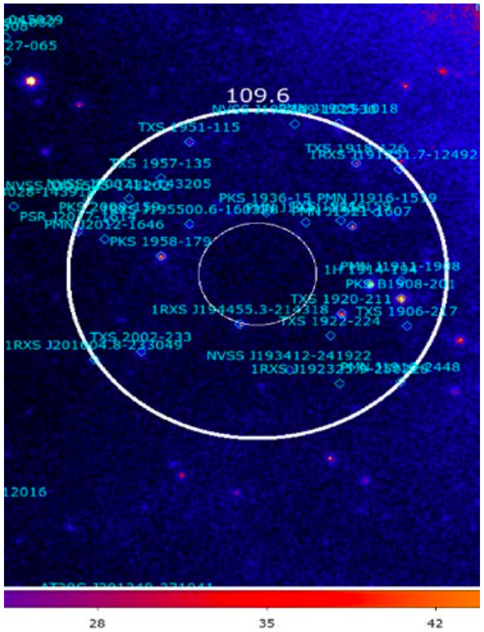


Light curves of J0301-1812 measured by RATAN-600

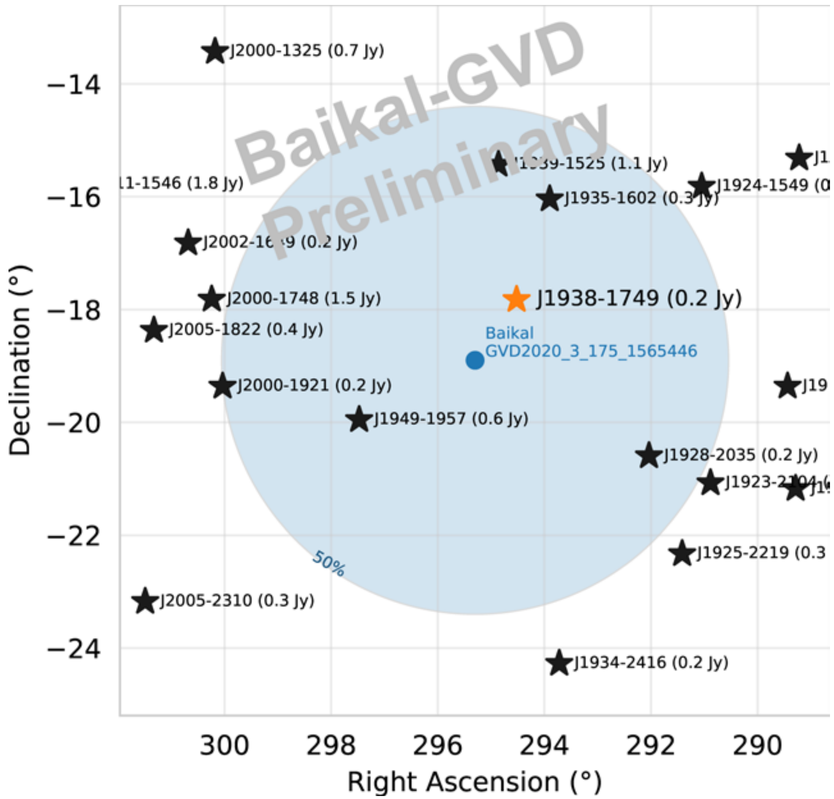


GVD2020_3_175_N

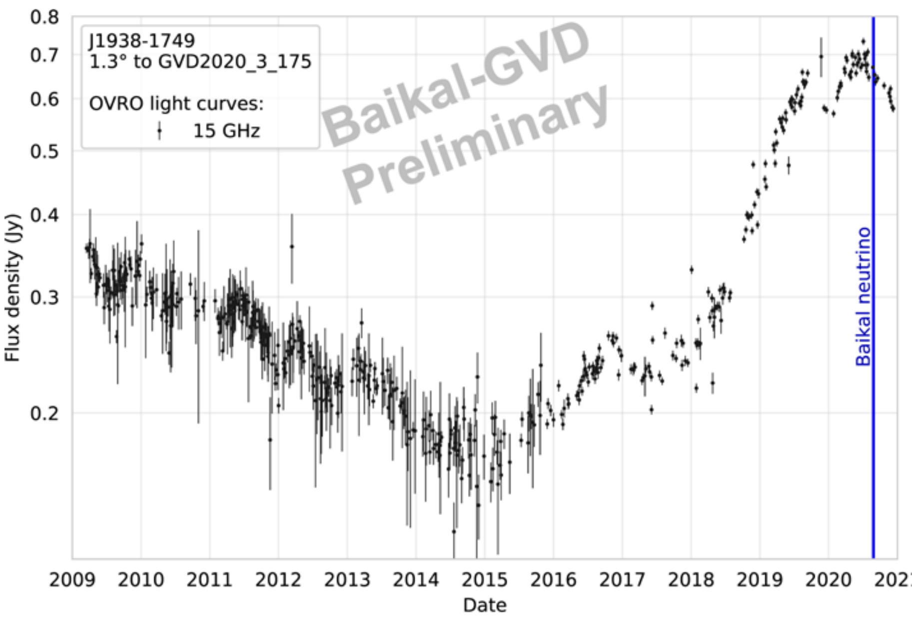
Radio blazar J1938-1749



Sky plot of radio-bright blazars nearby neutrino event



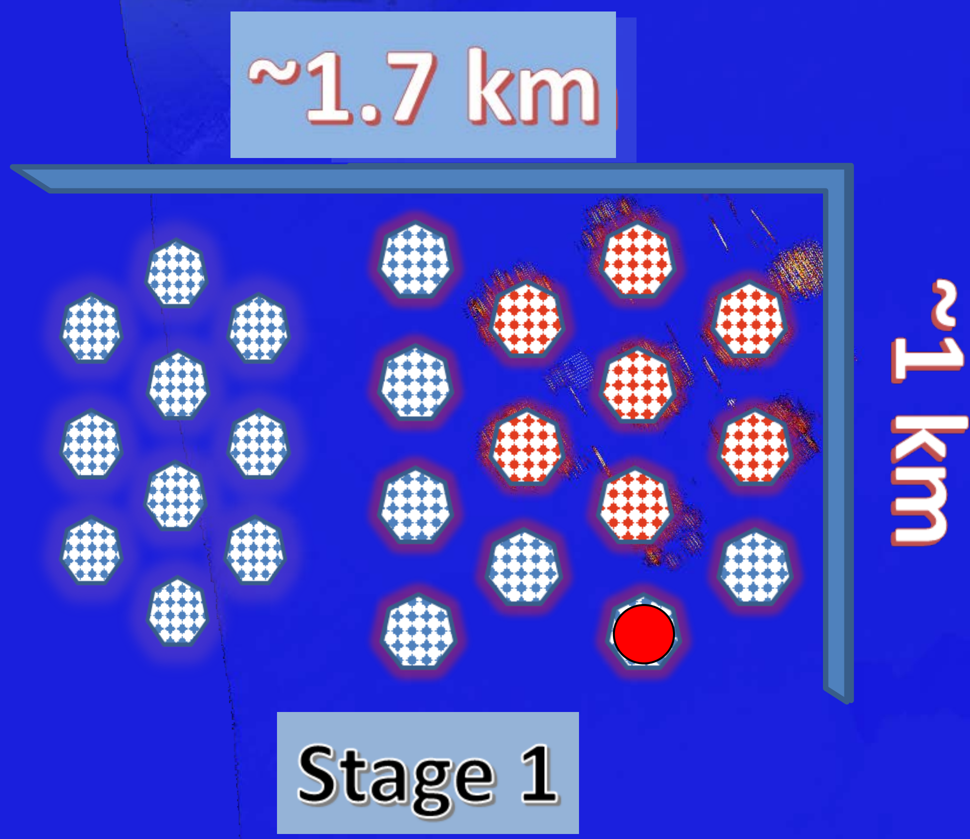
Light curves of J1938-1749 measured by OVRO



ACKNOWLEDGMENTS

We thank Y. Kovalev, A. Neronov, A. Plavin, D. Semikoz and S. Troitsky who perform comparing of our results with astrophysical data.

GVD 2020 and extention



Conclusion

- Baikal-GVD is now the largest neutrino telescope in the Northern Hemisphere: 0.4 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