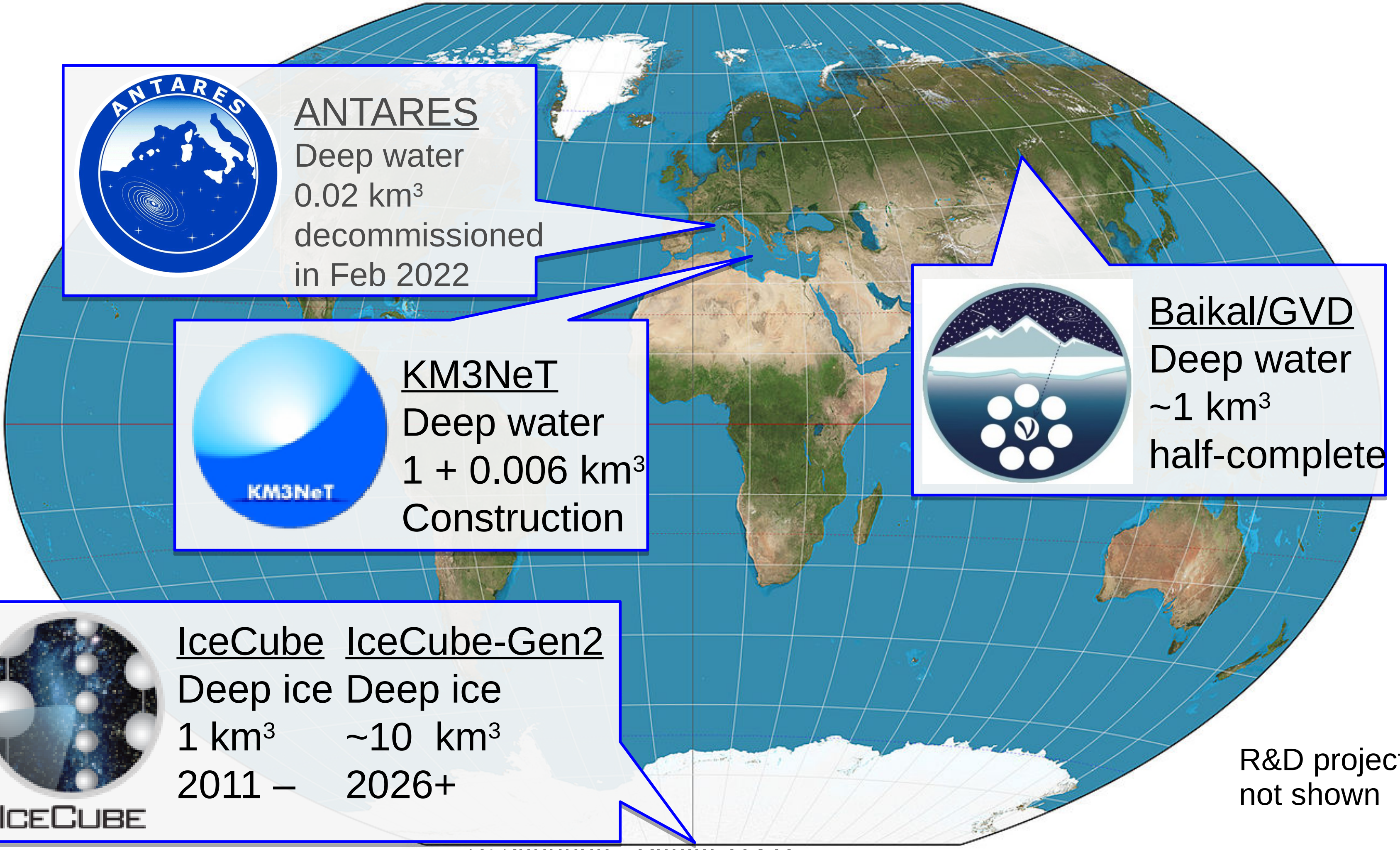
Черенковские Чтения
19 апреля 2022

Нейтринный телескоп Baikal-GVD - первые результаты и ближайшие планы

Дмитрий Заборов

(ИЯИ РАН)

Neutrino telescope world map 2022



ANTARES
Deep water
0.02 km^3
decommissioned
in Feb 2022

KM3NeT
Deep water
1 + 0.006 km^3
Construction

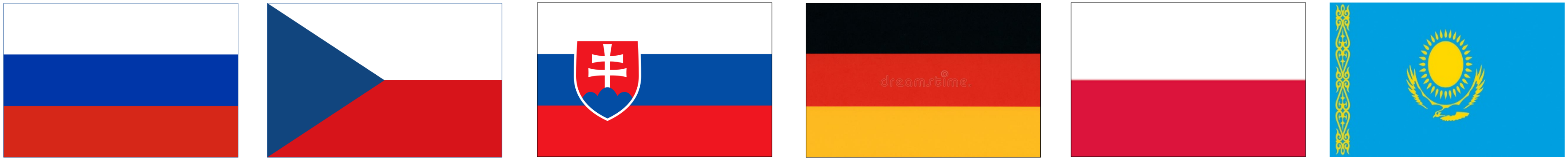
Baikal/GVD
Deep water
~1 km^3
half-complete

IceCube	IceCube-Gen2
Deep ice	Deep ice
1 km^3	~10 km^3
2011 –	2026+

R&D projects
not shown

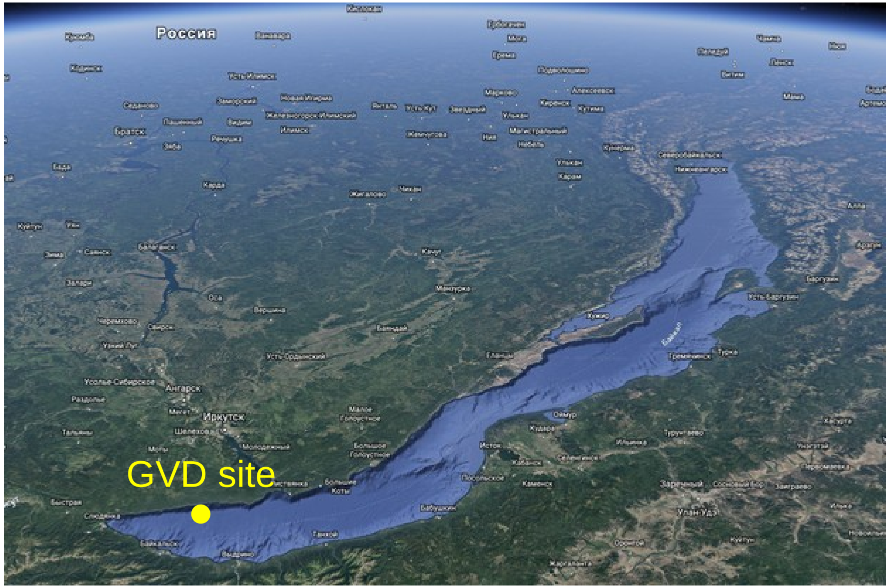
Baikal-GVD collaboration (as of Feb 2022)

11 organisations from 6 countries, ~70 collaboration members



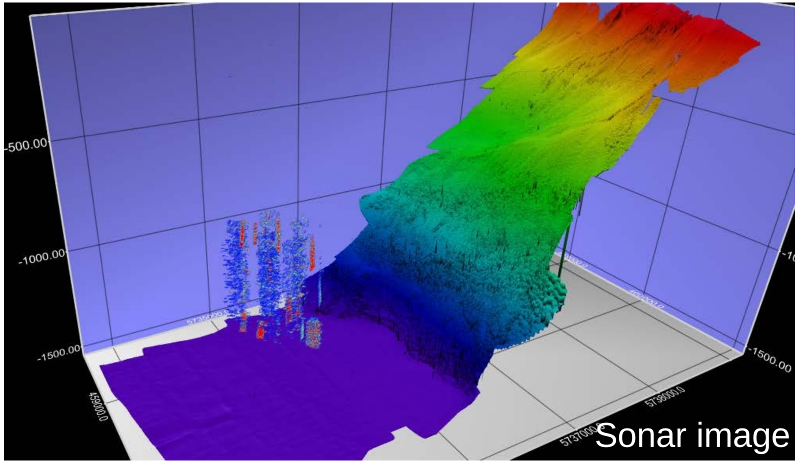
- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (Saint-Petersburg)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- EvoLogics (Berlin, Germany)
- Comenius University (Bratislava, Slovakia)
- Krakow Institute for Nuclear Research (Krakow, Poland)
- Institute of Nuclear Physics (Almaty, the Republic of Kazakhstan)

Baikal-GVD site

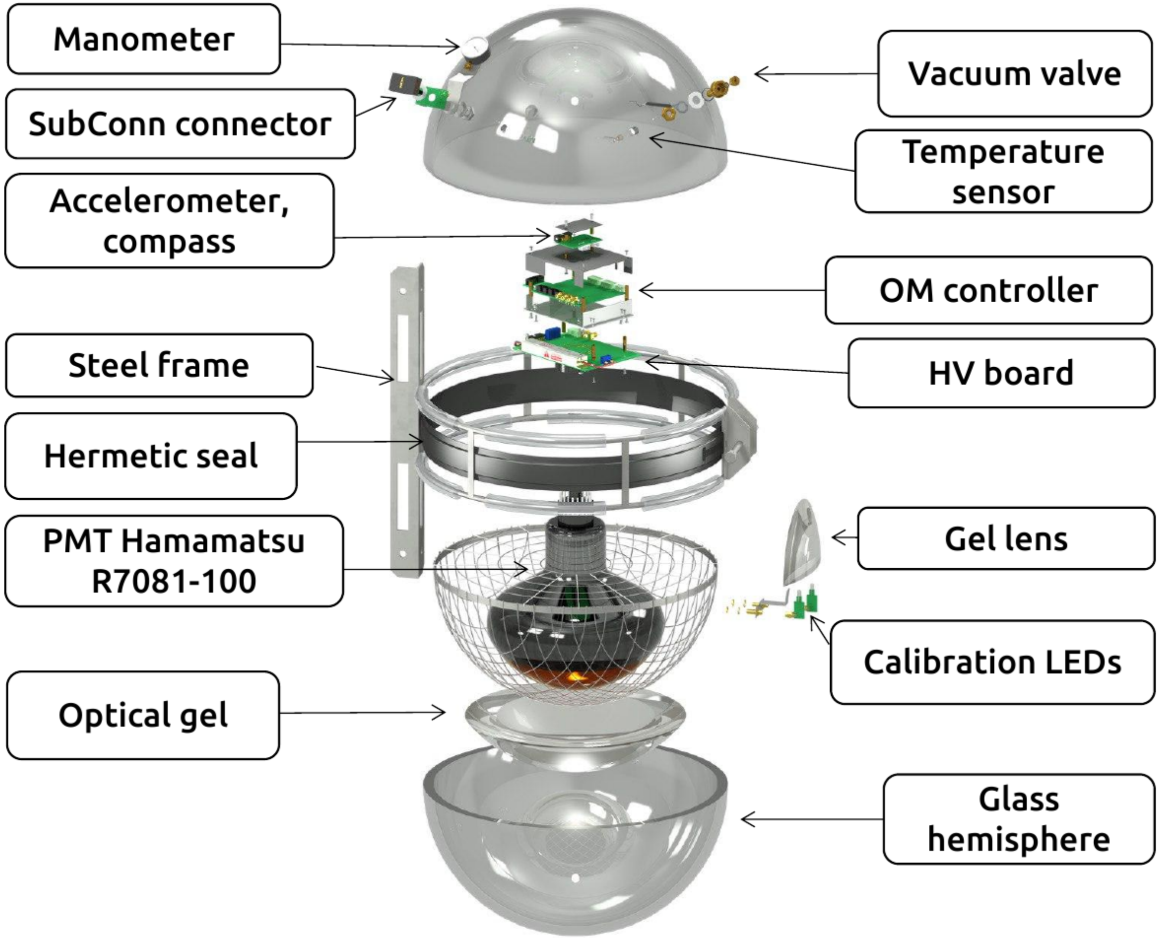


- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance

- High water transparency
  - Absorption length: 22 m
  - Scattering length: 30 – 50 m (L_{eff} ≈ 480 m)
- Moderately low optical background: 15–40 kHz (PMT R7081-100 ∅10”)



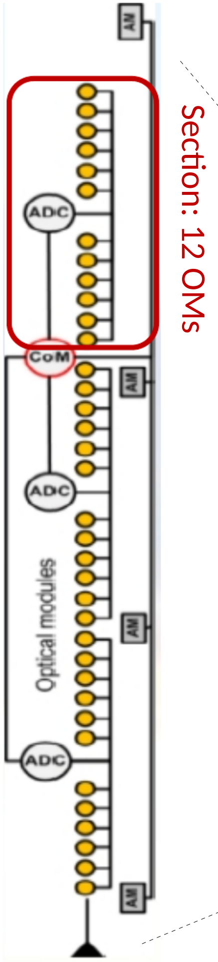
Baikal-GVD optical module



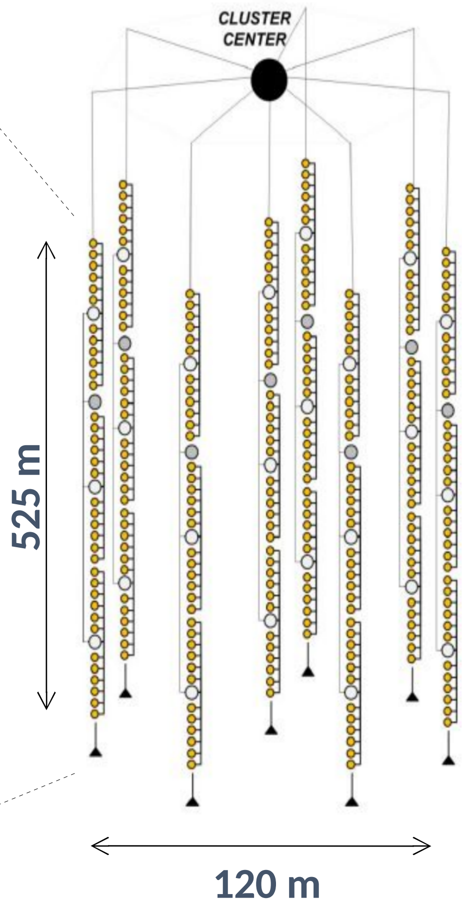
GVD cluster

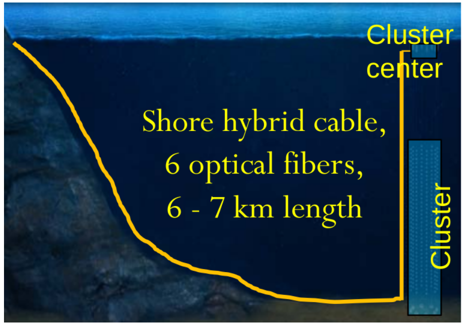
String

- **36 OMs**, 15 m spacing, downward-looking
- **4 acoustic modems**
- **4 electronics modules** (3 section modules + 1 string module)
- Data network: shDSL 5.7 Mbit
- Depths from 750 m to 1275 m



Cluster



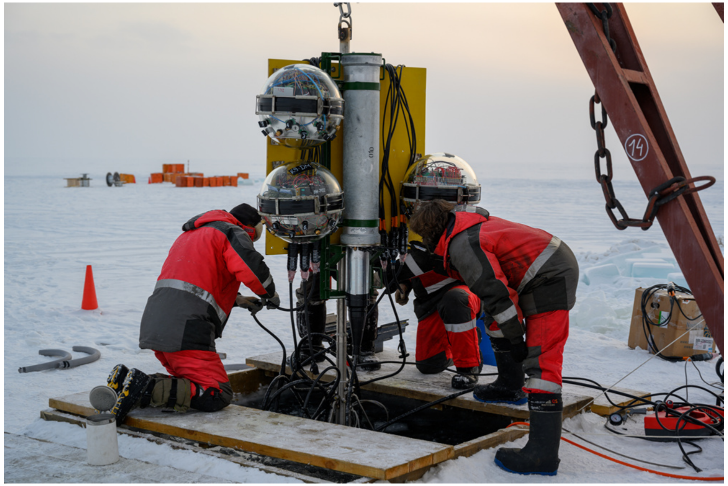


Cluster

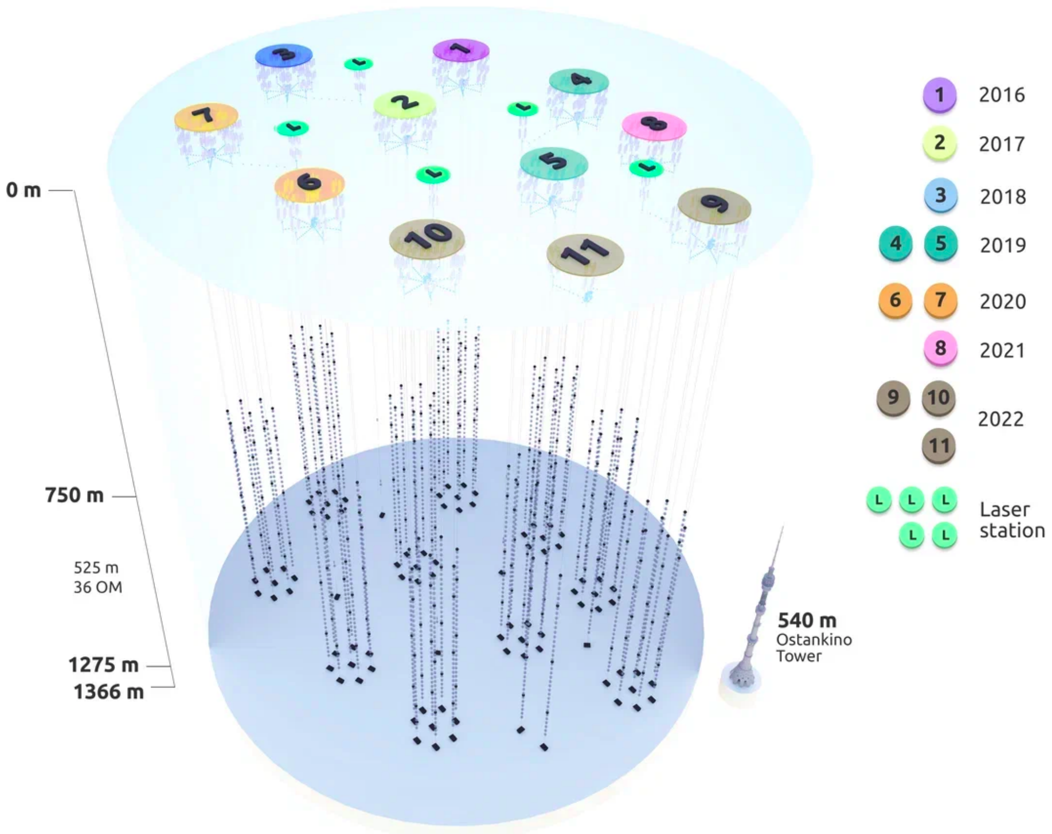
- 8 strings (288 OMs)
- 60 m spacing between strings
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger: 4 p.e. hit + 1.5 p.e. hit on adjacent OM in 100 ns window
- Inter-section synchronization by common trigger (~ 2 ns accuracy)
- Internal network: shDSL 5.7 Mbit
- Connection to shore: Ethernet / optic fiber

Экспедиция 2022

- Установлено:
  - два новых кластера (16 гирлянд)
  - 1 дополнительная межкластерная гирлянда (36 ОМ + лазер)
  - 2 экспериментальные гирлянды на оптоволоконной технологии связи (активно 48 ОМ)
  - 1 отдельная лазерная станция
- Проведён плановый ремонт ранее установленного оборудования



Baikal-GVD construction status 2022 and schedule



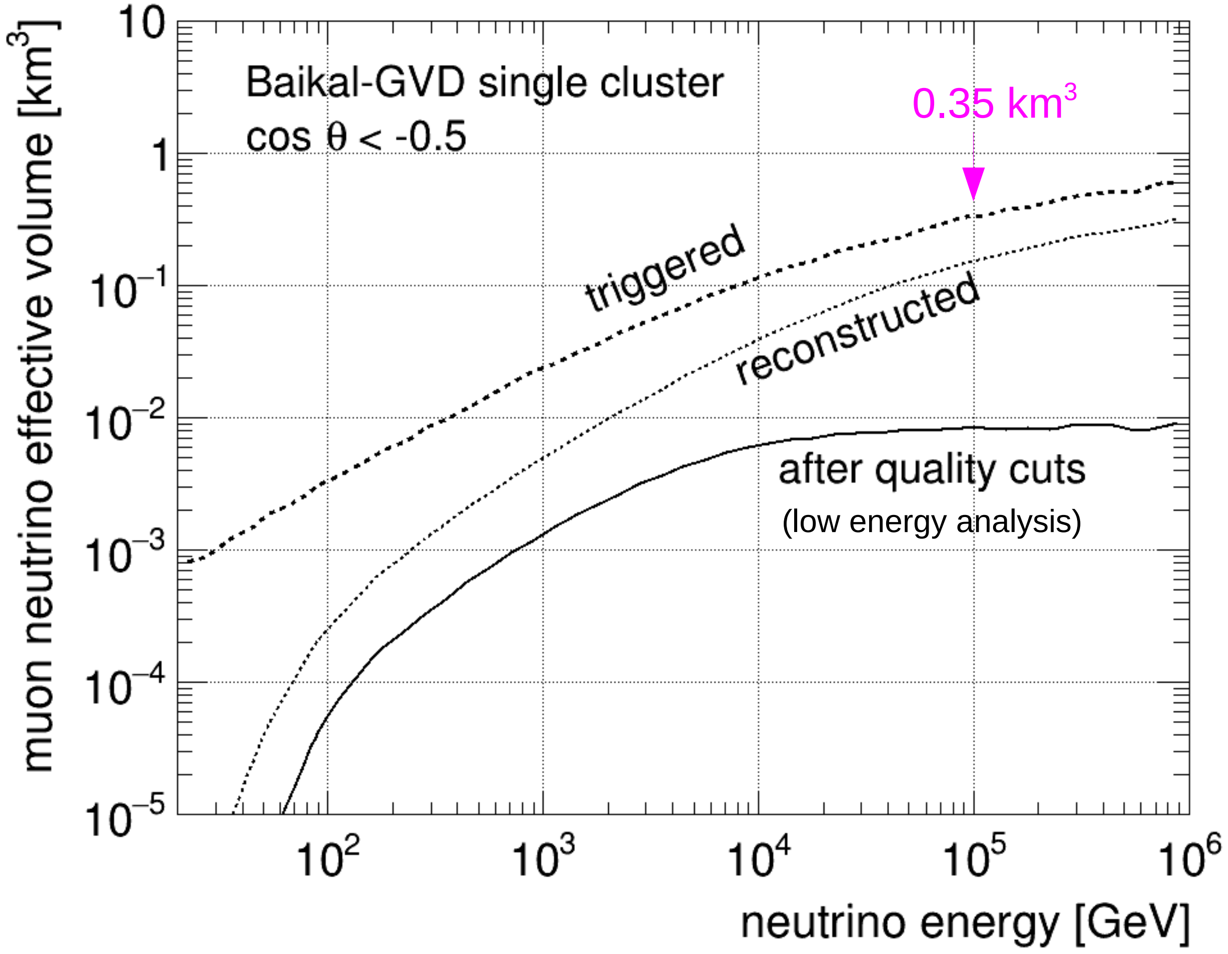
10 clusters + 1 special string (laser+36 OM)
+ 2 experimental strings + 4 laser stations

Deployment schedule

Year	Number of clusters	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 + 3**	**2880 + 84**
2023	12	96	3456
2024	14	112	4032

Effective volume 2022: 0.50 km^3 (cascades E > 100 TeV)

Neutrino effective volume for tracks (one GVD cluster)



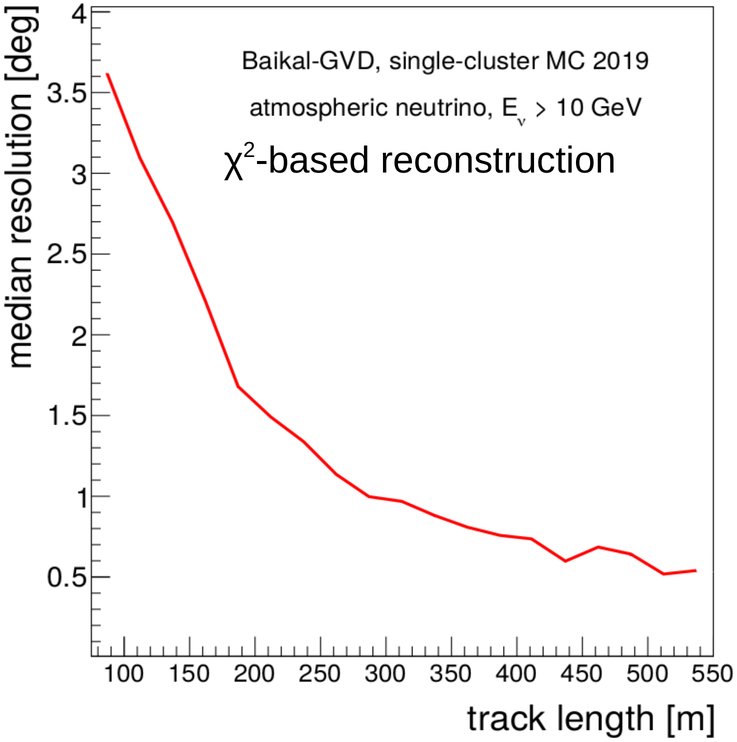
Energy threshold ~ 200 GeV (higher than in ANTARES)

Fully efficient at E > 100 TeV

Eur. Phys. J. C 81 (2021) 1025

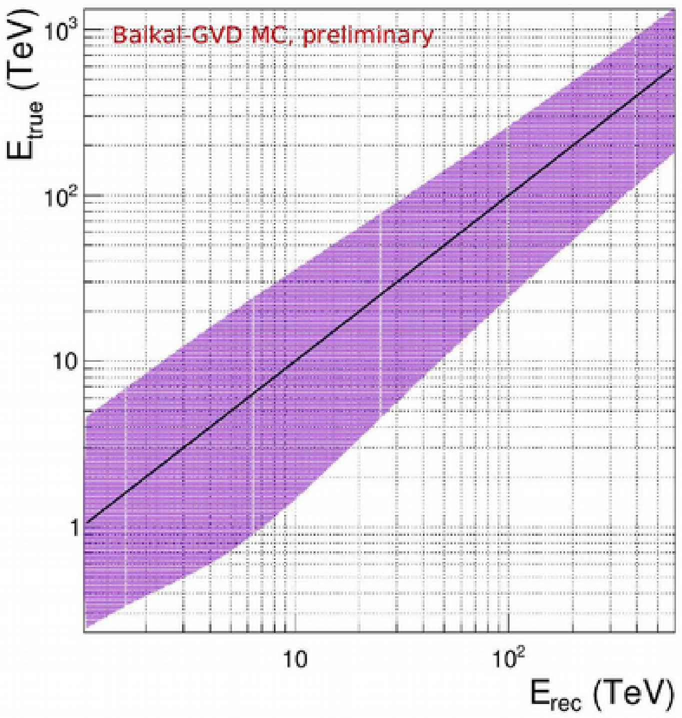
Expected performance for tracks

Angular resolution



Improvements expected from likelihood-based reconstruction (under development)

Energy reconstruction

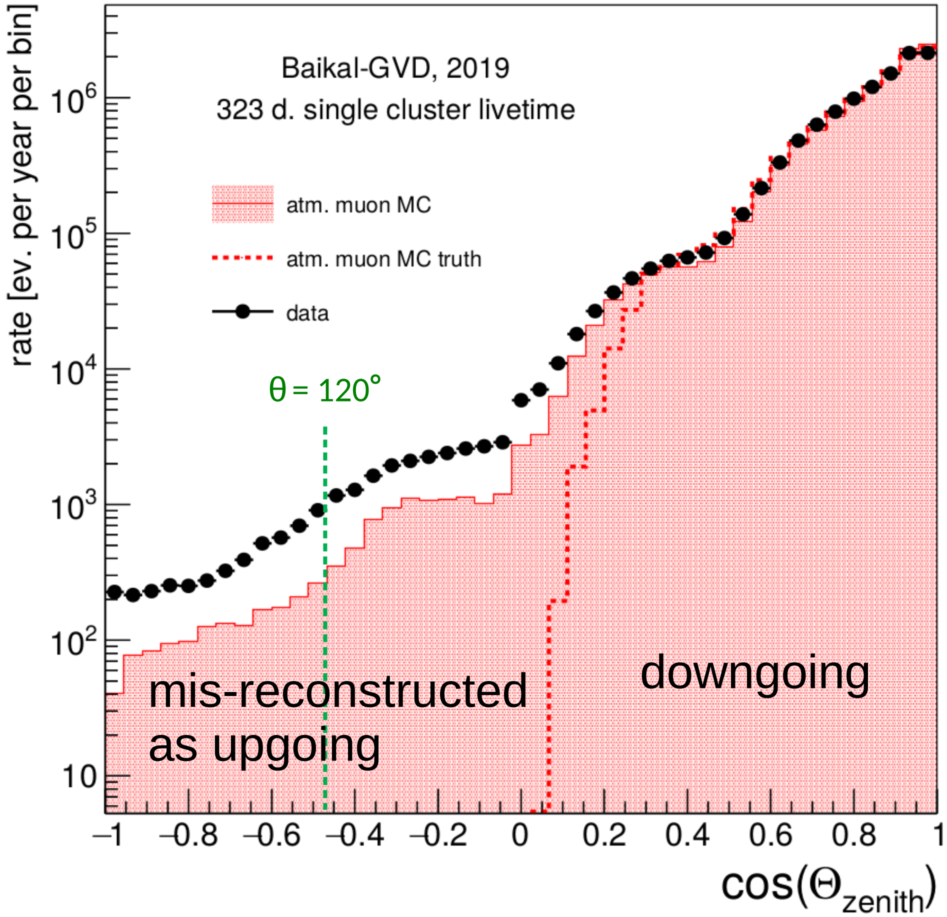


energy resolution ~ factor 3 at E ~ 100 TeV (±34% containment band)

G. Safronov @ ICRC 2021

Atmospheric muons with Baikal-GVD (single cluster)

Before quality cuts



Data taken between Apr 1 and Jun 30, 2019 with 5 clusters

~ 9 800 000 events reconstructed with at least 8 hits on at least 2 strings

Good agreement for cos(zenith) > 0.2

MC underpredicts the rate of misreconstructed events in the upgoing region by a factor of 3.5 (under study)

NB: most of these events are muon bundles (average multiplicity ~ 10)

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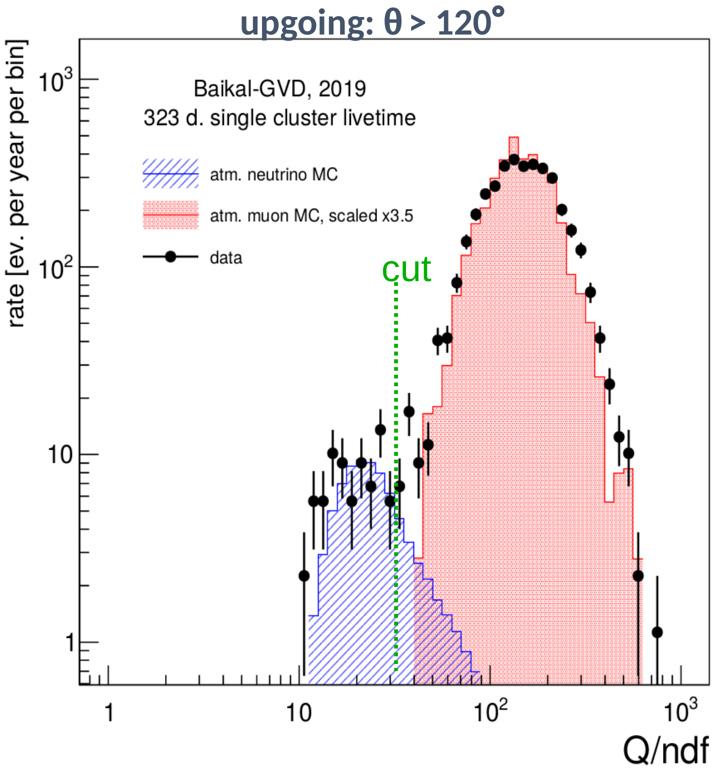
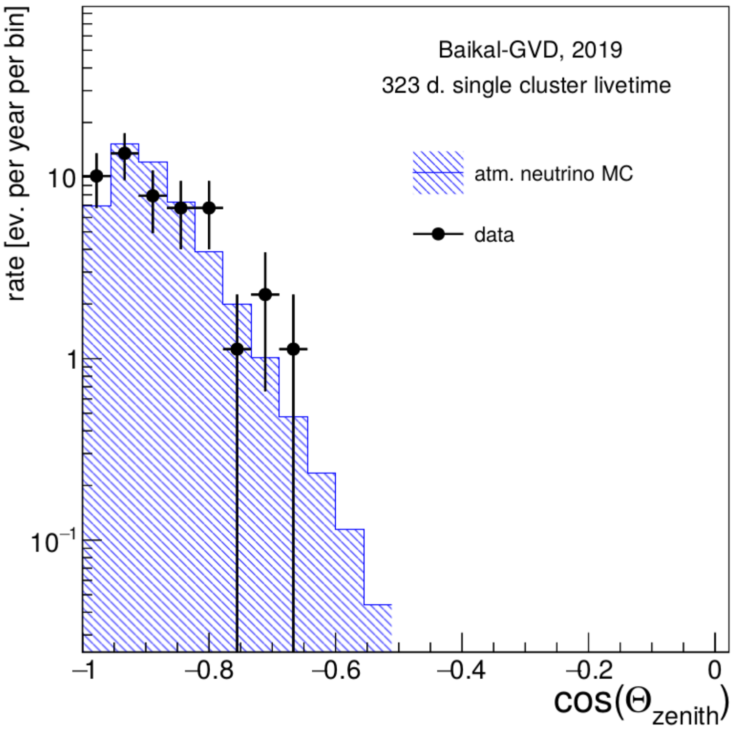
Atmospheric neutrinos with Baikal-GVD (single cluster)





MC expected: 43.6
- atm. neutrino : 43.6
- atm. muons: < ~ 1

Observed events: 44

Median energy of this sample ≈ 500 GeV

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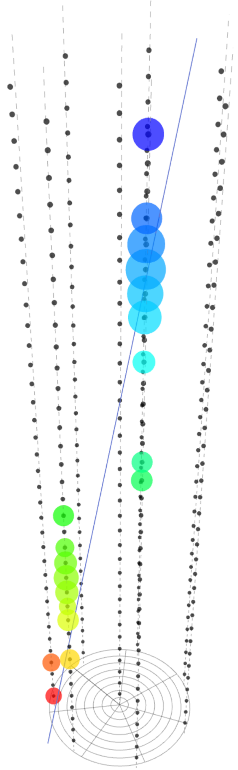
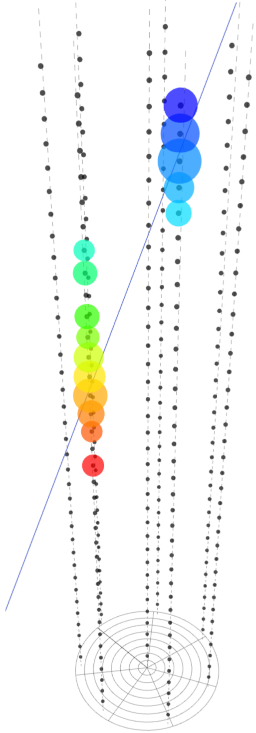
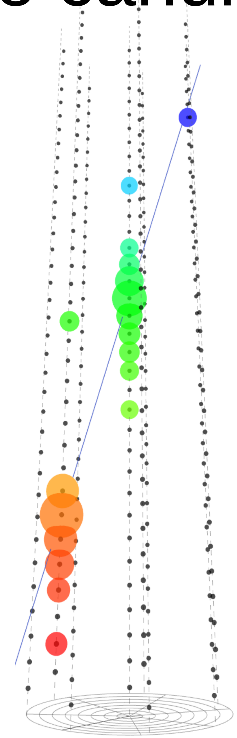
Track-like neutrino candidate events



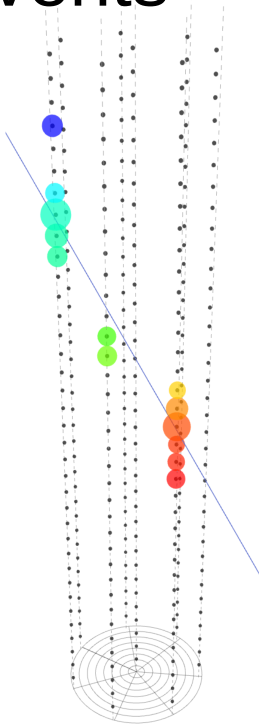
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



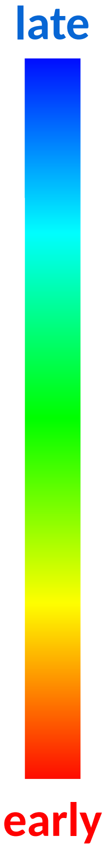
cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15



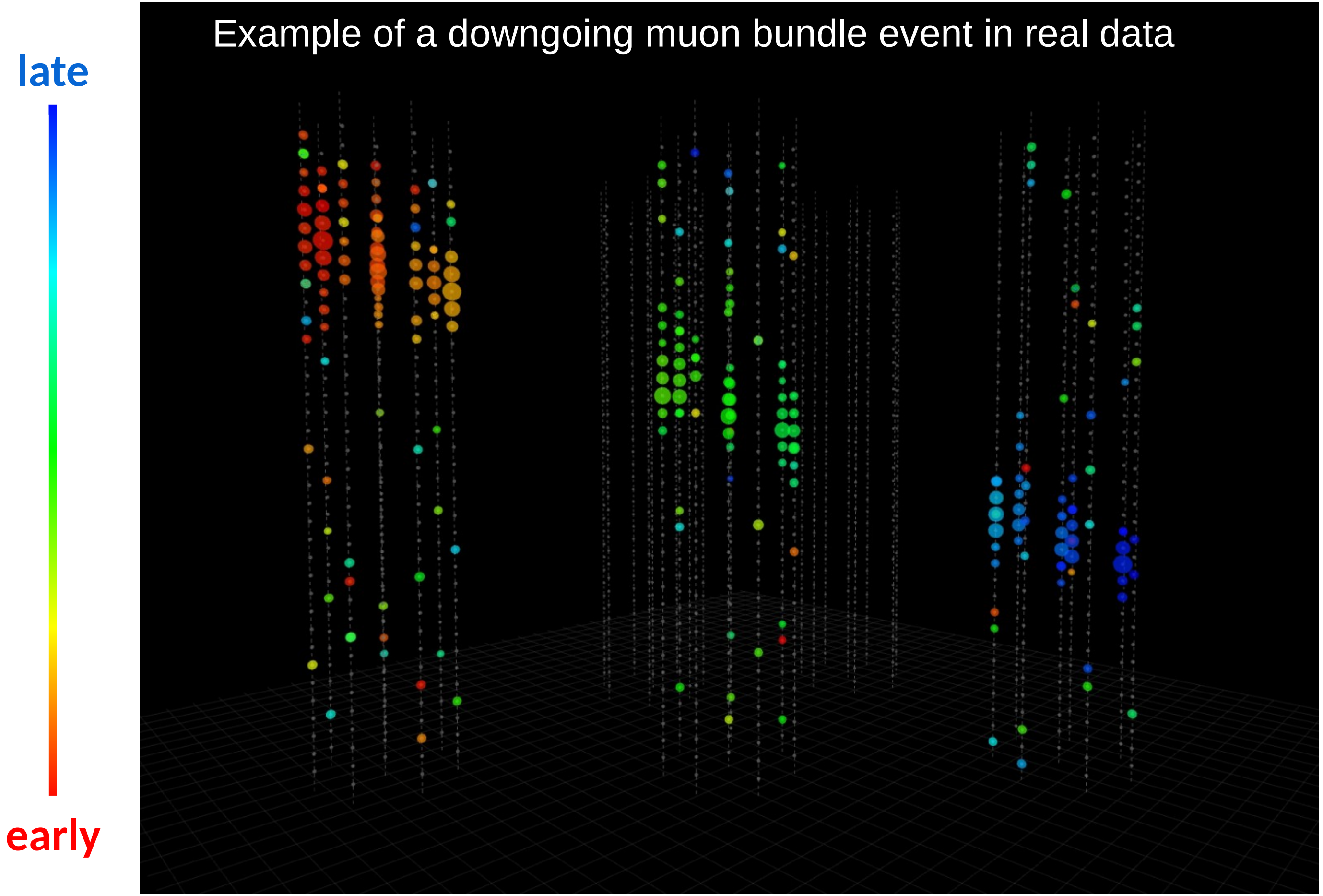
cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18



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



Multi-cluster track events



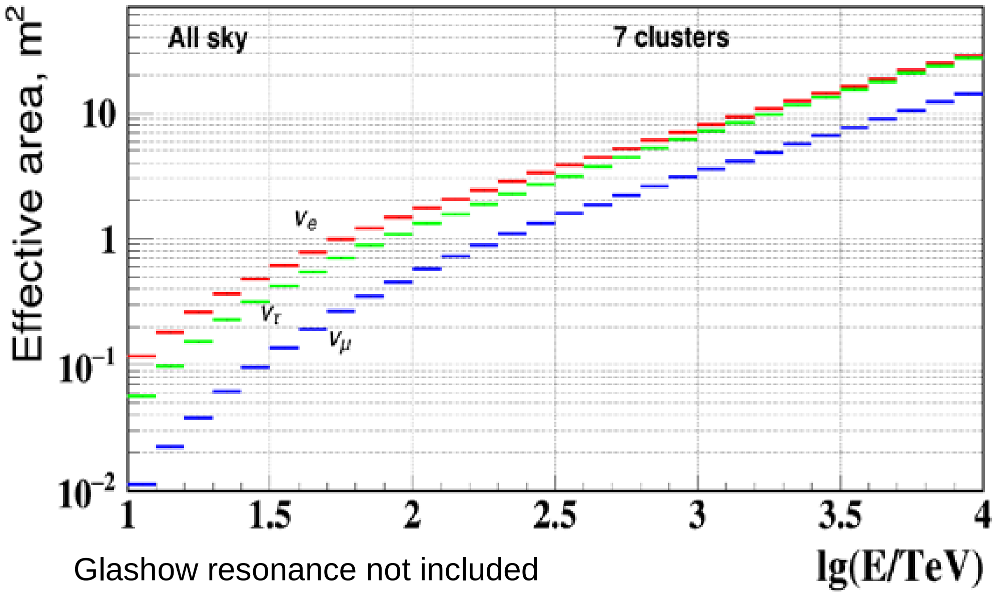
Work in progress !

Cascade analysis : effective area and rates

Analysis sensitive to all-flavour CC
and NC interactions over the whole sky

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

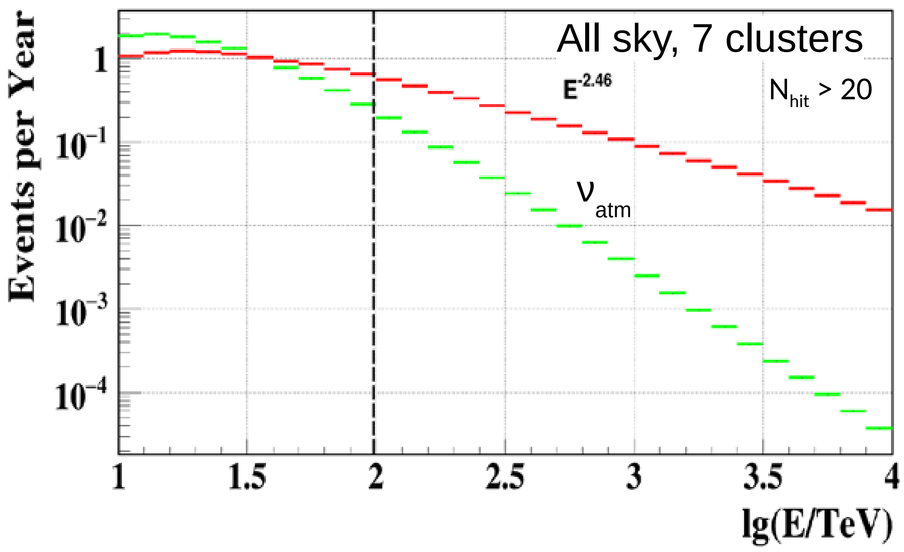
neutrino effective area for cascade detection



Glashow resonance not included

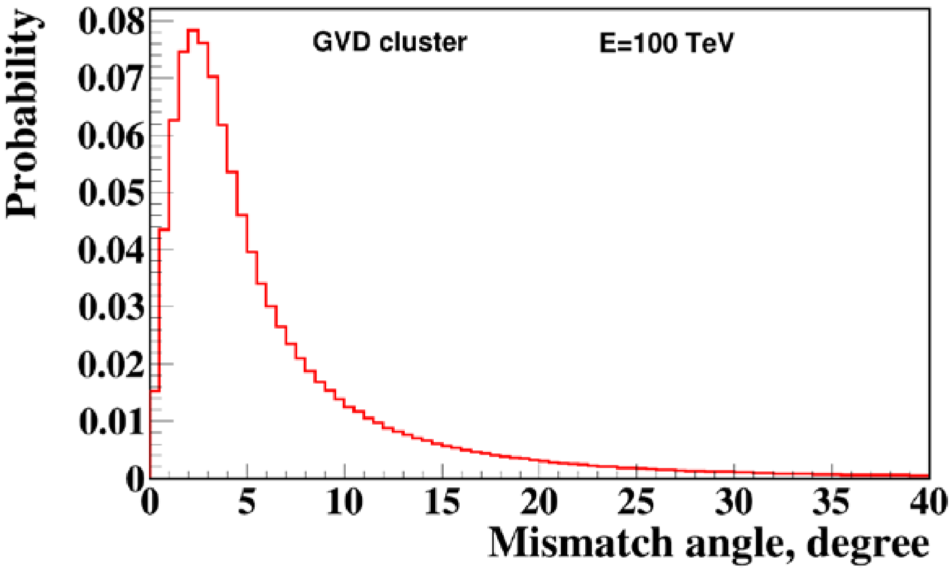
Effective volume for E > 100 TeV ~ **0.35 km³**

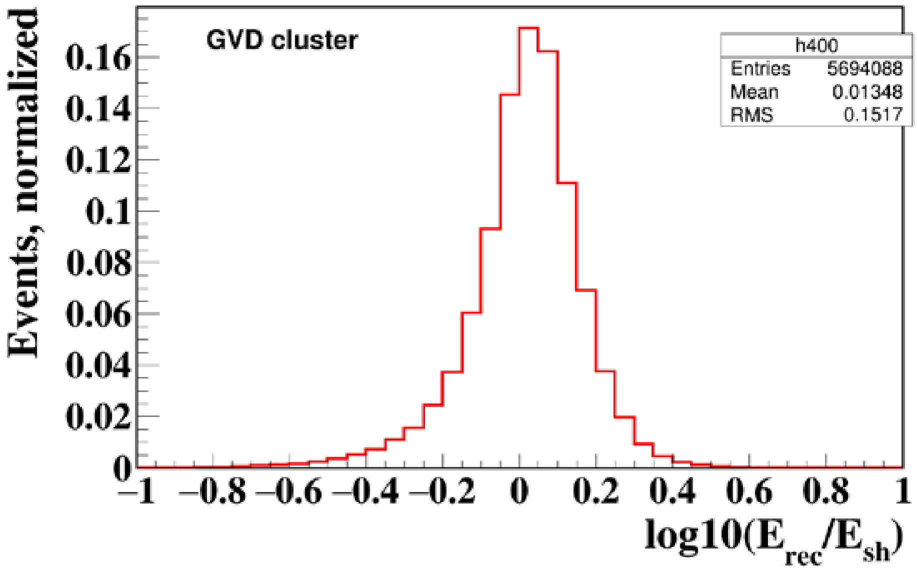
Expected number of cascade events per year



3–4 ev/yr with E_{sh}>100 TeV for 7 clusters

Cascade analysis performance





Directional resolution for cascades:
2°- 4° - median mismatch angle

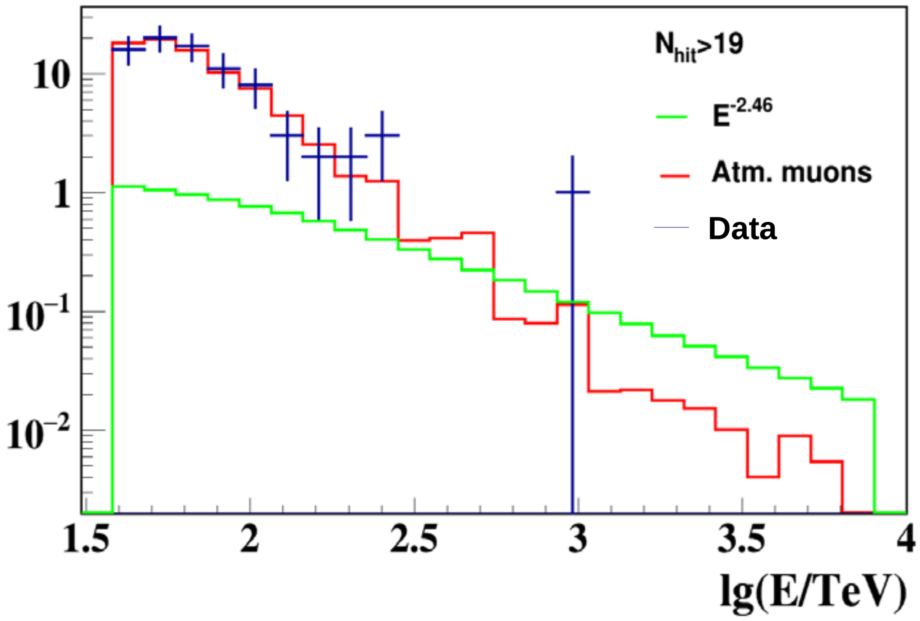
Energy resolution : δE/E ~ 10%-30%

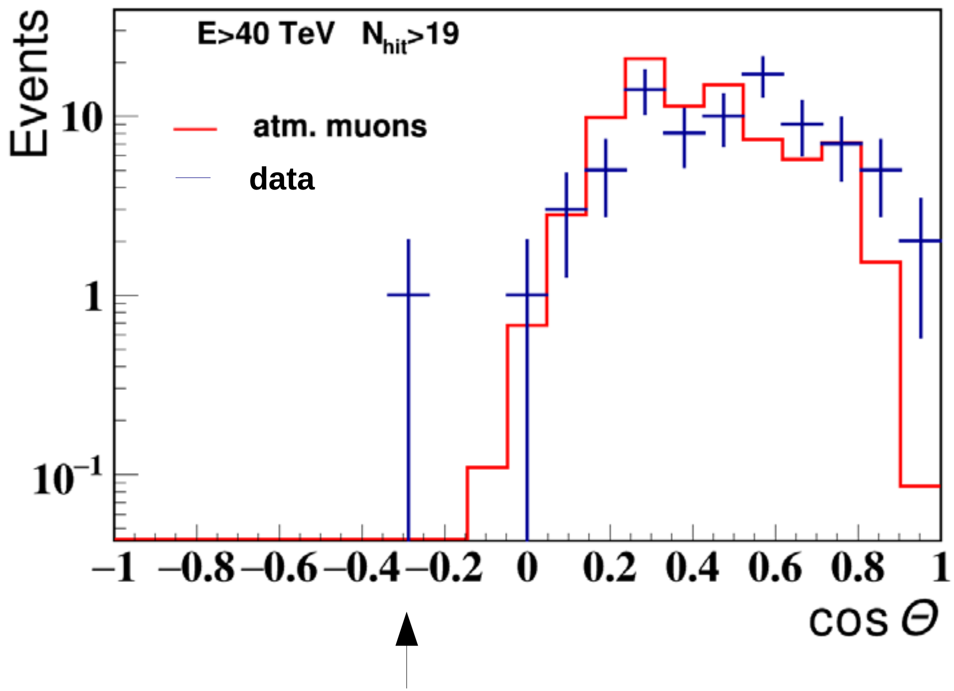
Cascade analysis : data and MC

Preliminary

Data from 2019-2020, livetime: 2915 days single-cluster equivalent

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



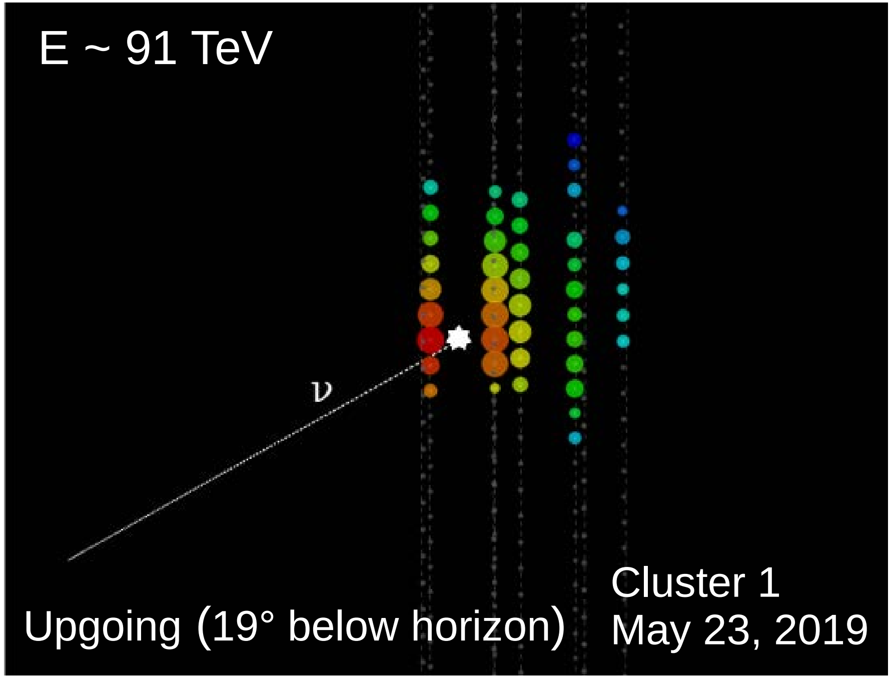


One upgoing cascade: E ≈ 91 TeV

Upward-going cascade

Preliminary

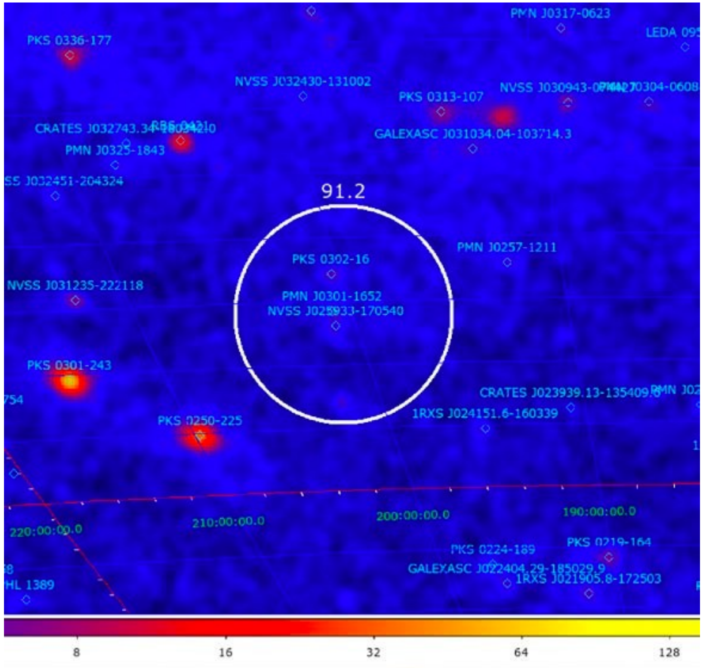
GVD2019_1_114_N



Contained event (50 m off central string)

Excellent candidate for a neutrino event of astrophysical origin

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

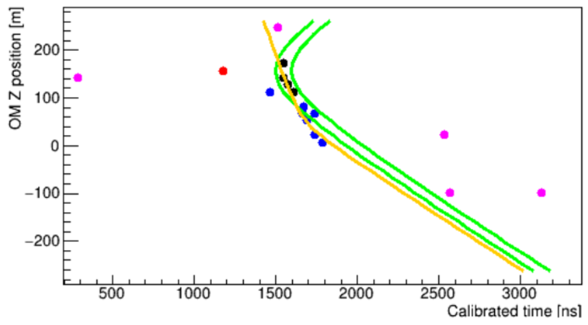


known sources in 3 degree circle:
PKS 0302-16 : unknown type of source
PMN J0301-1652 : unknown type of source

Improved cascade event selection

Preliminary

Search for early hits from muon track

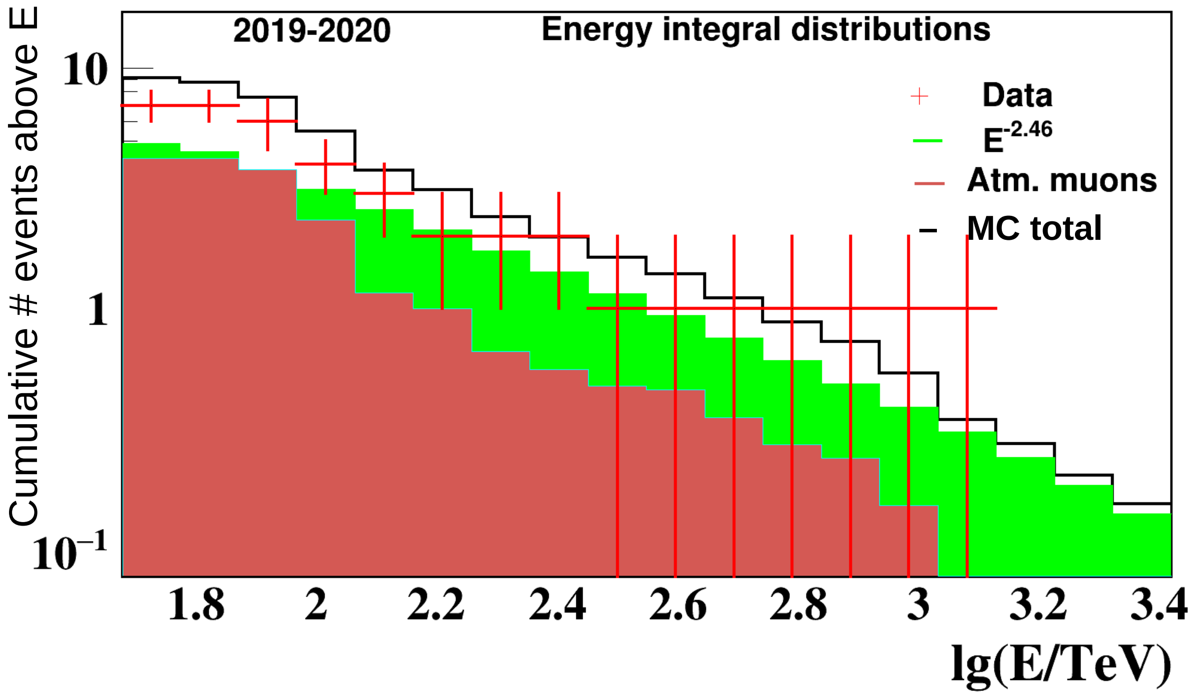


Use it in event selection

This improves atmospheric muon rejection by an order of magnitude

After final cuts:
MC atm. muons : 4 events
MC astrophys. flux: 5 events
data (2019-2020) : 7 events

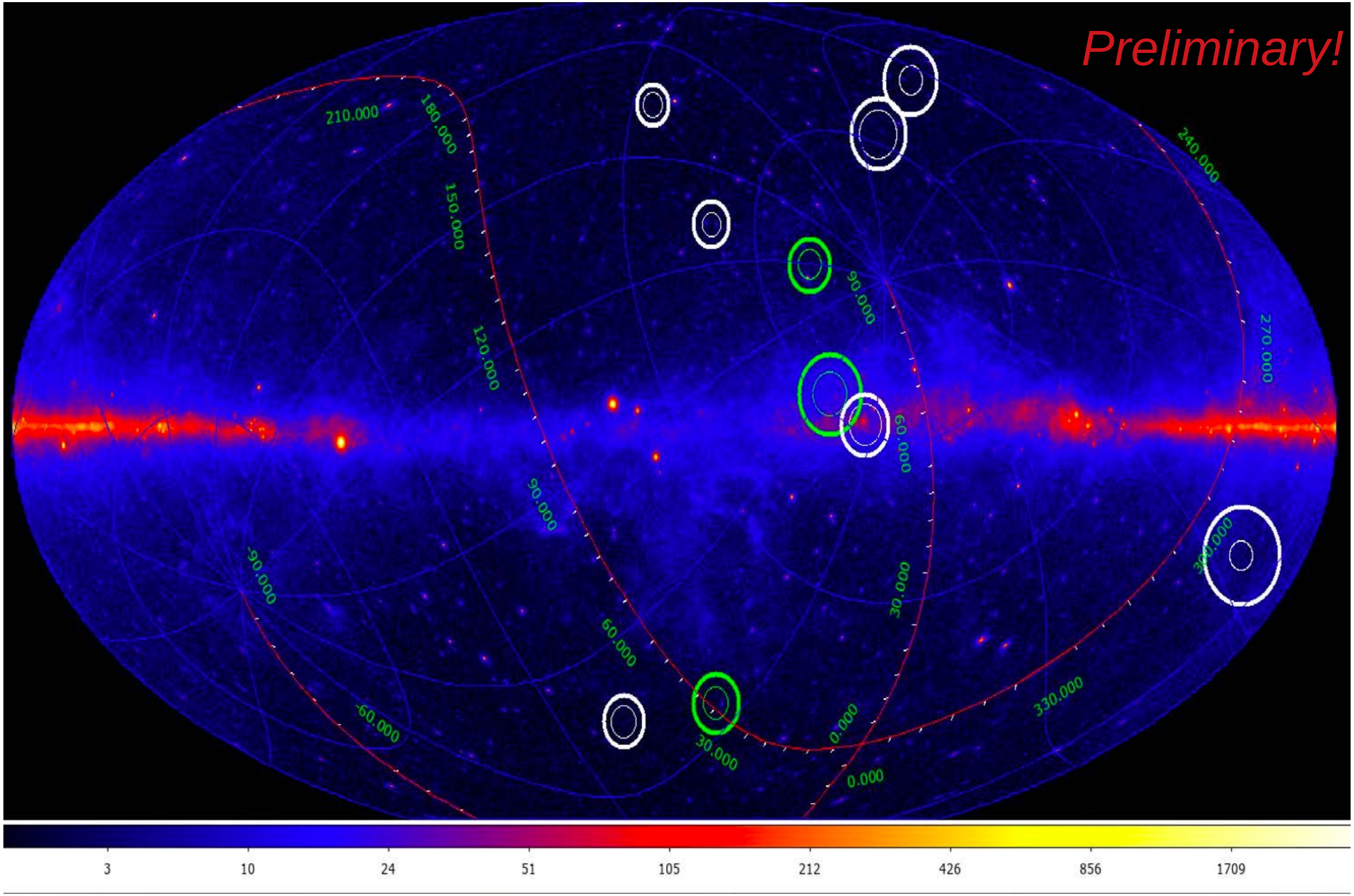
+3 events in 2018 data



> 50% purity expected for E > 100 TeV neutrino sample

See talks by Zh. Dzhilkibaev and Z. Bardačová @ ICRC 2021

Sky map with 10 Baikal-GVD cascade events



Legend

Background image: Fermi LAT

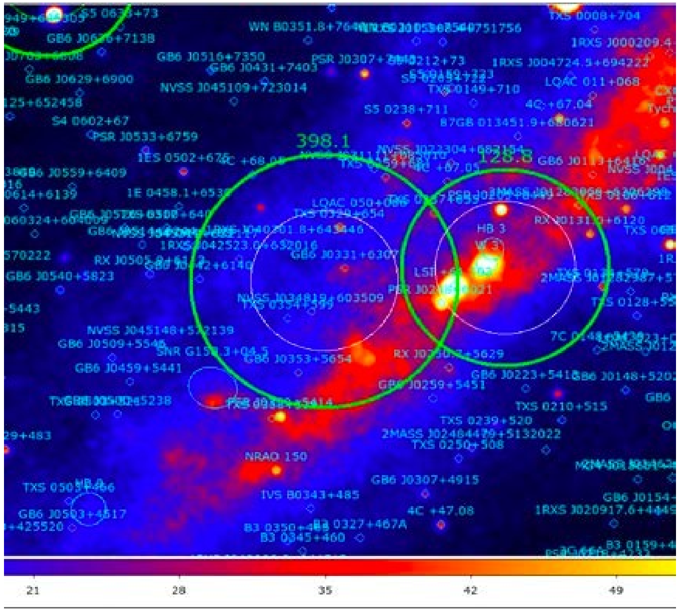
Green circles: Baikal-GVD events 2018 (50% and 90% C.L. regions)

White circles: Baikal-GVD events 2019-2020

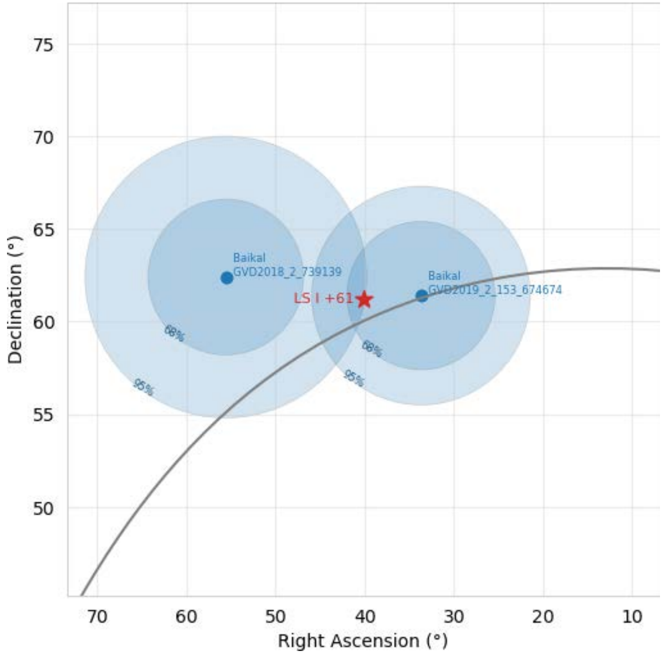
Event doublet near Galactic plane

Preliminary

Sky map of Fermi sources



LSI +61 303 and the two Baikal-GVD events



LSI +61 303 – γ- ray active microquasar

3.1° from GVD_2019_153_N and 7.4° from GVD_2018_656_N

Using PSFs of all 10 events the chance probability to observe such a doublet near LSI +61 303 was estimated: p-value = 0.007 or 2.7 σ (preliminary)

GVD follow up of ANTARES alerts

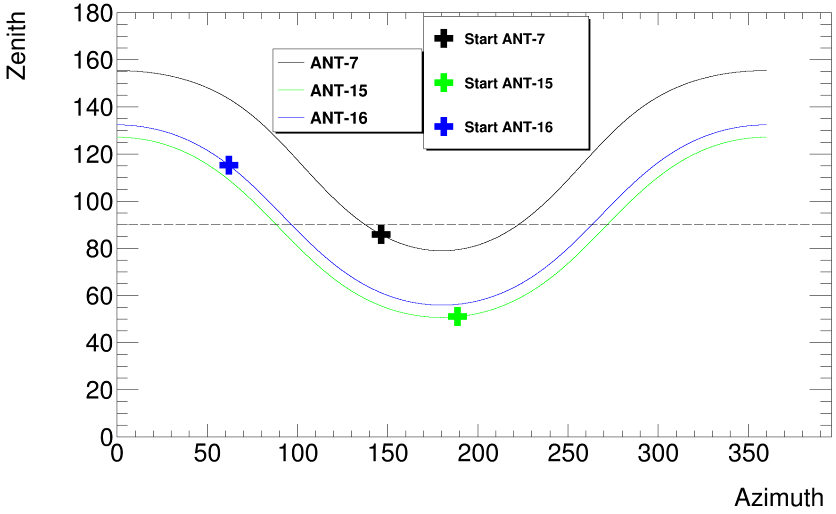
Following ANTARES upgoing μ alerts (<E> = 7 TeV)
Time windows: ±500 sec, ±1 hour and ±1 day
Both upgoing and downgoing cascades are looked for

Since Dec 2018, ~ 50 alerts have been analysed

3 potentially interesting events

ANT alert	GVD cluster	$T\text{-}T_{alert}$, hours	Energy, TeV
A7	3	+20.8	13.5
A7	3	-23.2	**158**
A7	2	-3.2	2.9
A15	2	+20.4	3.0
A15	3	-0.64	3.98
A16	2	-18.7	3.99
A16	4	-14.35	3.89

Source visibility



No prompt coincidence in time and direction was found

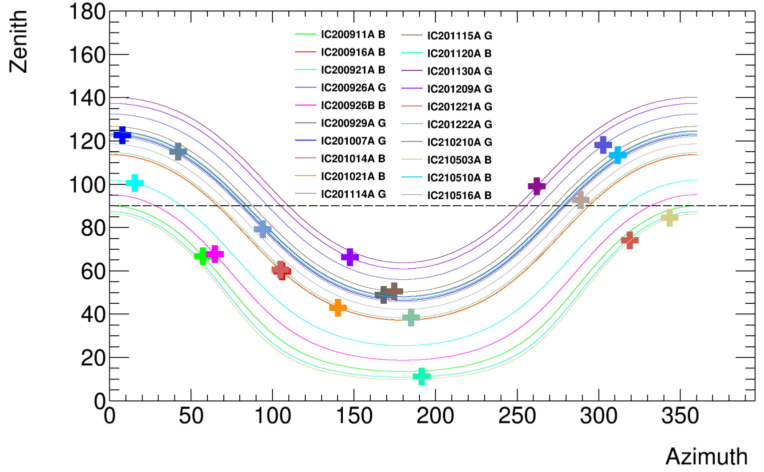
See talks by O. Suvorova and A.Garre @ ICRC 2021

GVD follow up of IceCube alerts

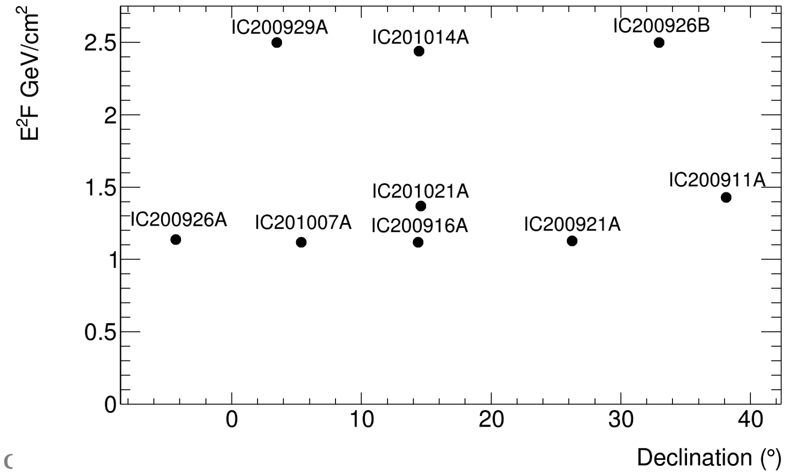
Since Sep 2020, following IC alerts (GCN / upgoing muons)

No statistically significant coincidence was found in this analysis, except possibly IceCube-211208A (see next slide)

90% upper limits derived for E-2 spectrum, equal fluence in all flavors, for E 1 TeV – 10 PeV and ±12 hr interval



Baikal-GVD upper limits



A.D. Avrorin et al., Astronomy Letters, Vol.47, N 2, 114 (2021)
http://dx.doi.org/10.1134/S1063773721020018

V.Y. Dik et al., JINST 16 (2021) C11008
https://doi.org/10.1088/1748-0221/16/11/C11008

Baikal-GVD follow up of IceCube-211208A / PKS 0735+17

Dec 8, 2021 20:02: IceCube “Astrotrack Bronze” neutrino event
Dec 9, 2021: MASTER reports optical activity of PKS 0735+17
(slightly outside the 90% IceCube uncertainty region)
… PKS 0735+17 observed in HE gamma-rays (Fermi LAT), X-rays
(Swift XRT) and radio
… ANTARES reports upper limits for PKS 0735+17 (no detection)
… KM3Net reports a neutrino with a background p-value = 0.14
… **Baikal-GVD** reports a downward-going (30° above horizon)
cascade-like event 4 hr after the IceCube event from the direction
RA=119.44°, Dec=18.00°, that is **4.68° from PKS 0735+17** and 5.30°
from the best-fit direction of IceCube-211208A

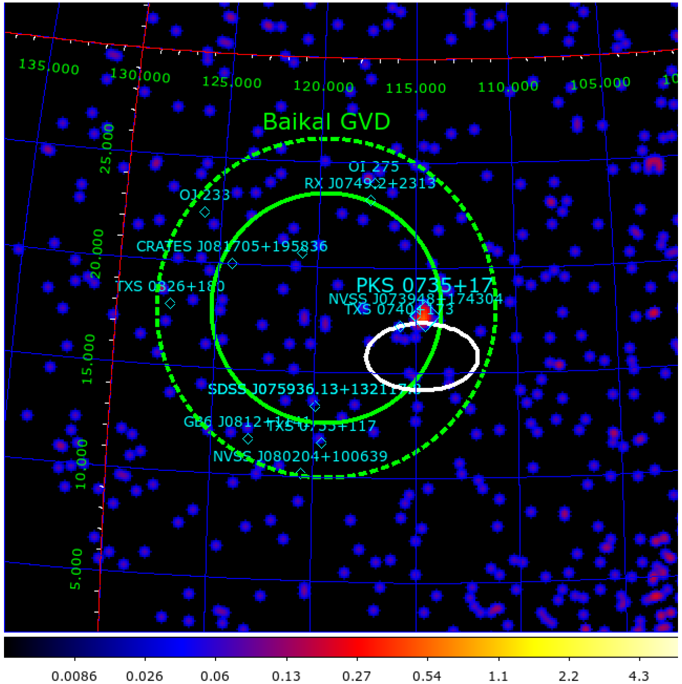


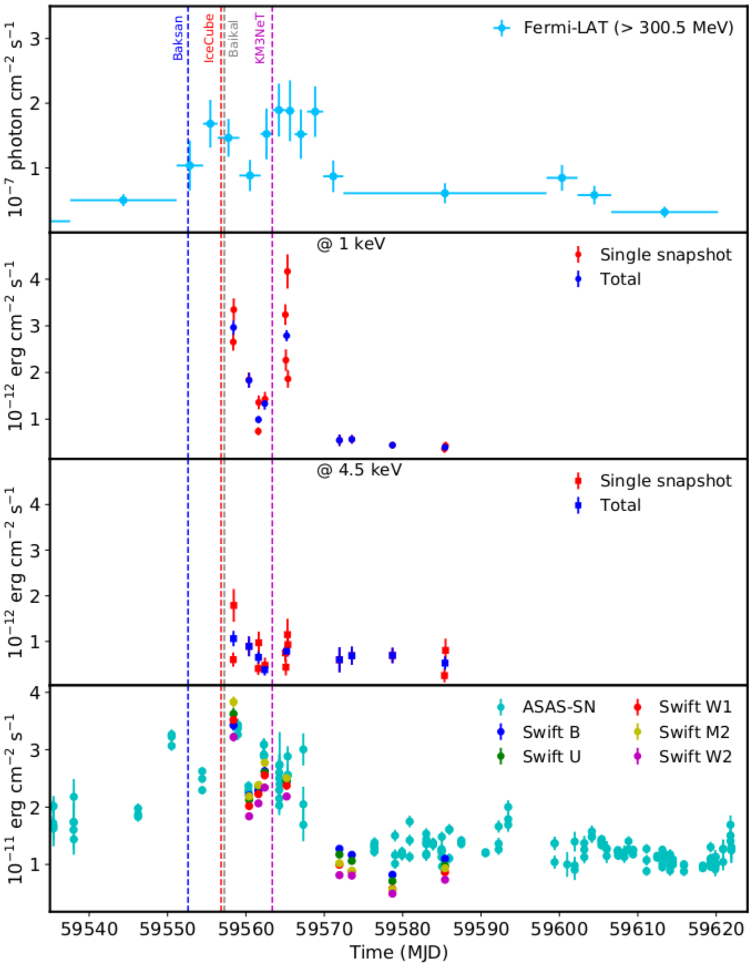
Image by D.Semikoz & A.Neronov

Estimated energy = 43 TeV
PSF 50% (68%) containment radius = 5.5 deg (8.1 deg)
Background estimate: 0.0044 events in the 5.5 deg cone in 24 hr
(2.85 σ). Trail factors to be scrutinized

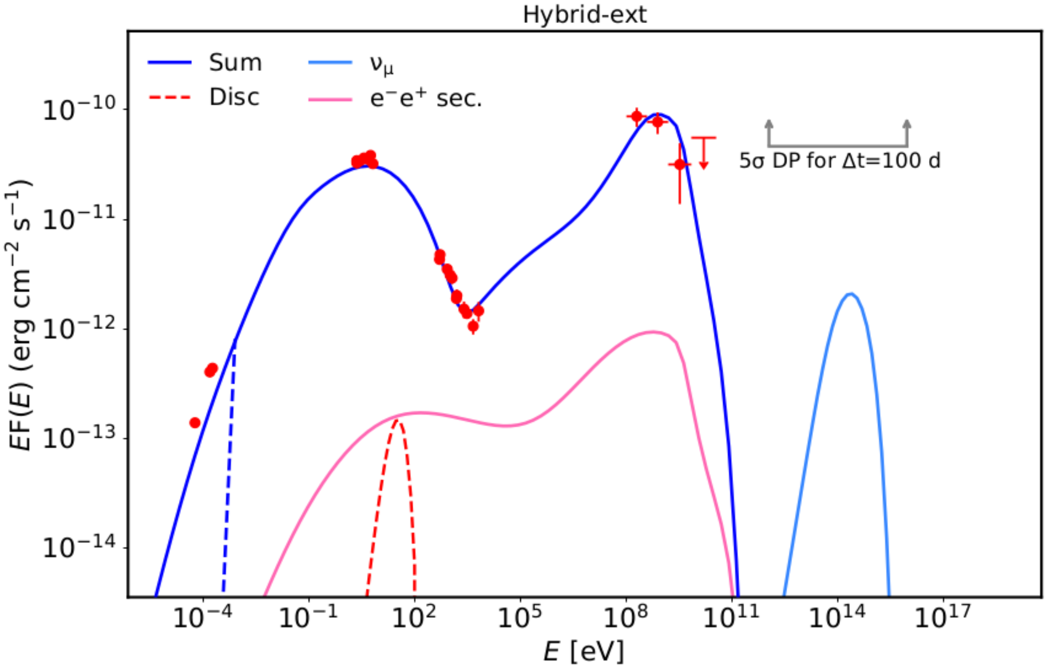
ATeL 15112

* PKS 0735+17 is a bright blazar very similar to TXS 0506+056

PKS 0735+17 : a neutrino-emitting blazar?



N. Sahakyan et al., arXiv:2204.05060



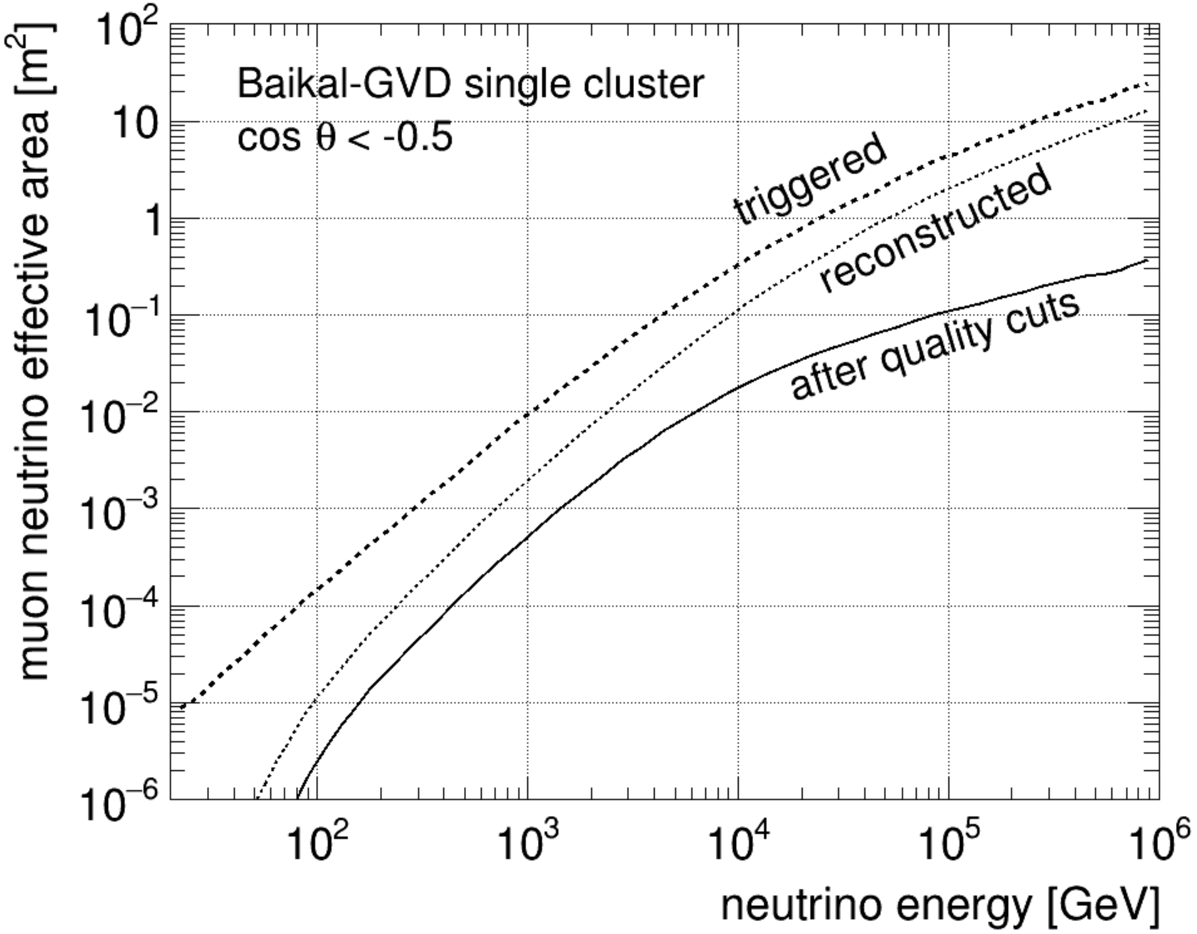
A model with PeV protons interacting with an external UV photon field predicts ~ 0.067 muon and antimuon neutrinos over the observed 3-week flare.

Заключение

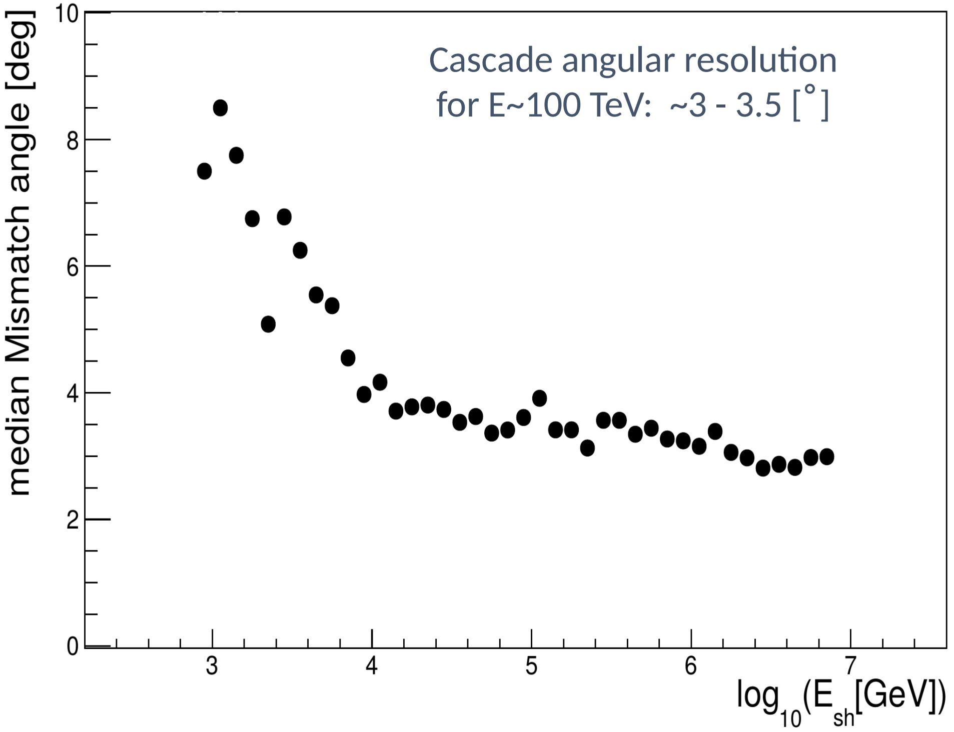
- Baikal-GVD – новый нейтринный телескоп в озере Байкал
  - Объём порядка 1 км^3 (по завершении строительства)
  - Угловое разрешение лучше 1° (для треков)
  - Область зрения эффективно дополняет IceCube
- Обнаружены первые намеки на возможные новые астрофизические источники нейтрино
- Идет набор данных с 10 кластерами (~ 0.5 км^3)

Backup slides

Neutrino effective area for tracks : one GVD cluster

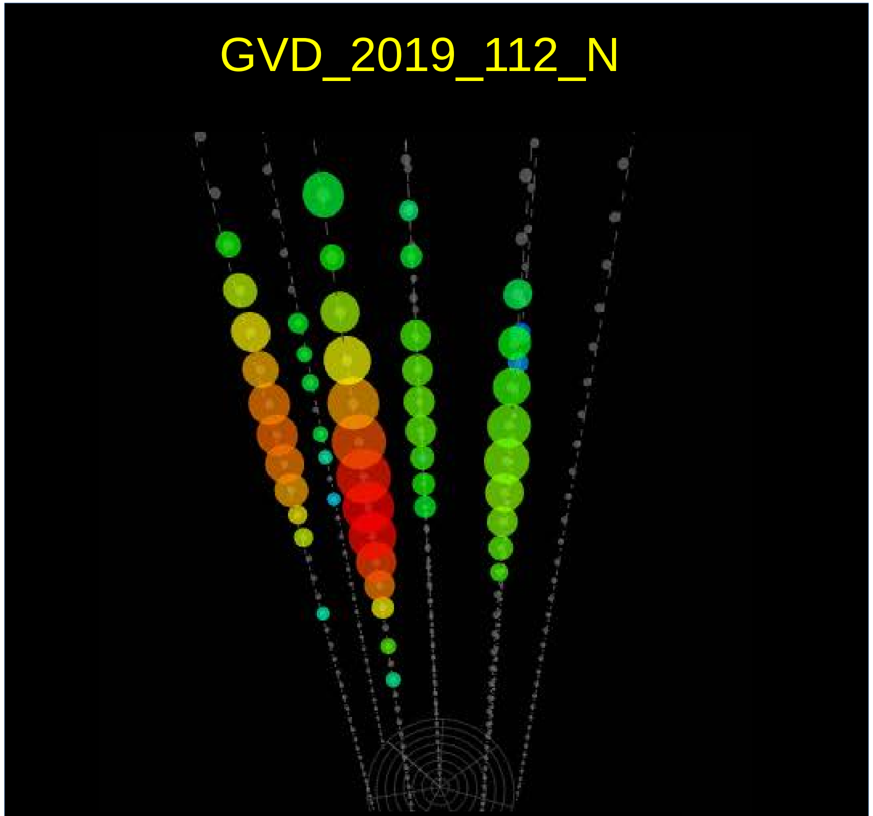


Cascade analysis angular resulution

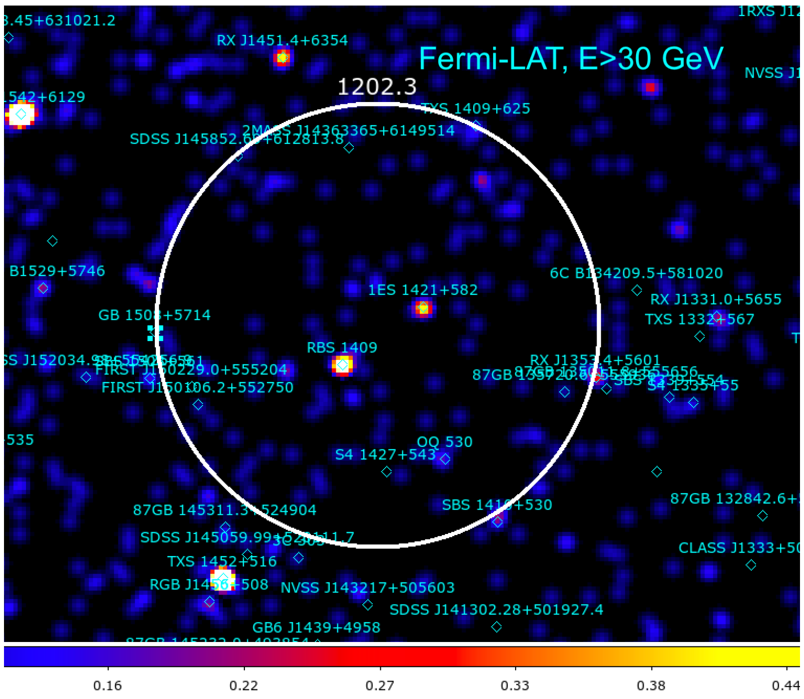


A 1 PeV cascade event (downgoing)

Preliminary



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



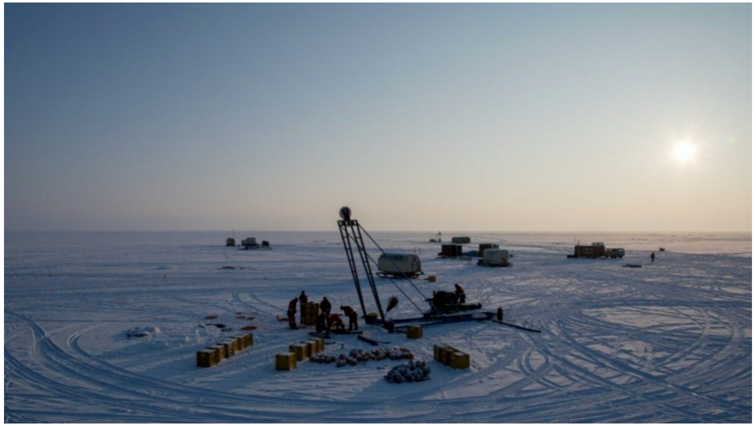
Fermi sources in 5° circle:
RBS 1409 BL Lac z=unknown
1ES 1421+582 z=unknown
both with hard spectrum

Selected events (2018-2020)

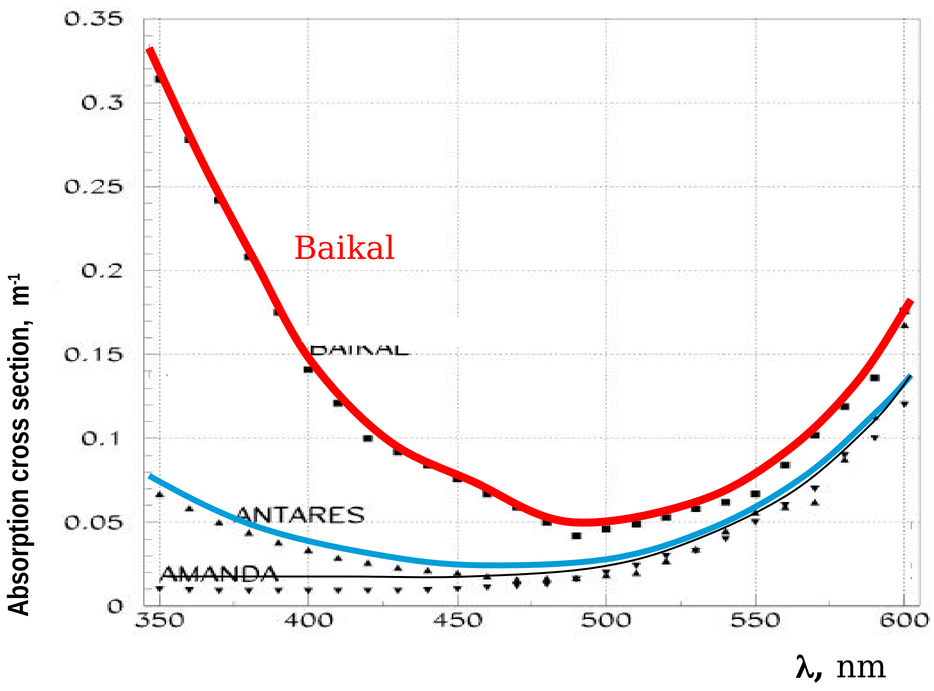
Preliminary

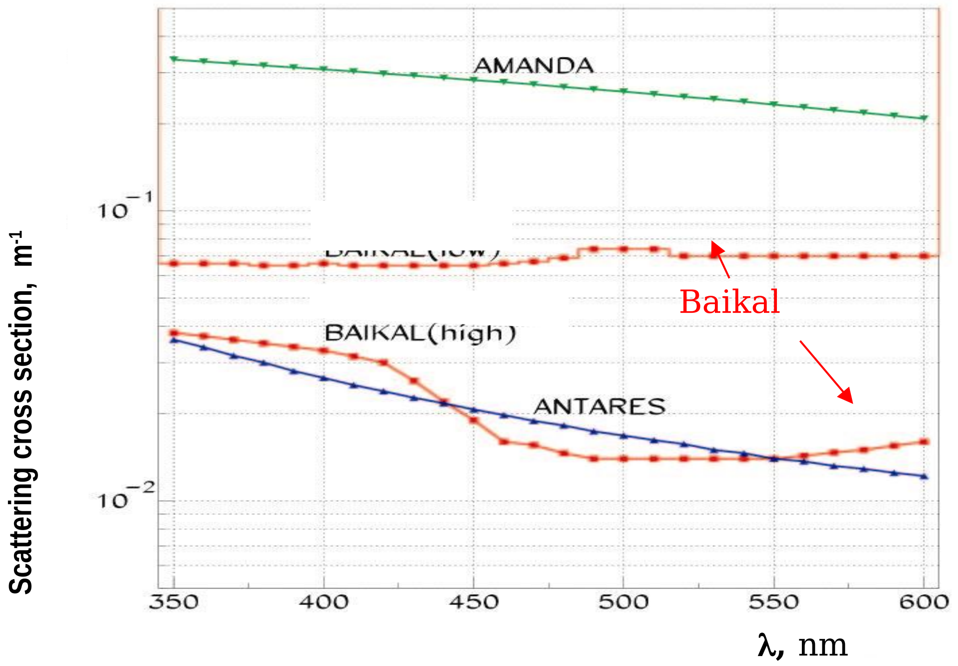
	E, TeV	θ_z, degree	φ, degree	R.A.	Dec
GVD2018_354_N	105	37	331	118.2	72.5
GVD2018_383_N	115	73	112	35.4	1.1
GVD2018_656_N	398	64	347	55.6	62.4
GVD2019_112_N	1200	61	329	217.7	57.6
GVD2019_114_N	91	109	92	45.1	-16.7
GVD2019_663_N	83	50	276	163.6	34.2
GVD2019_153_N	129	50	321	33.7	61.4
GVD2020_175_N	110	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

Deployment



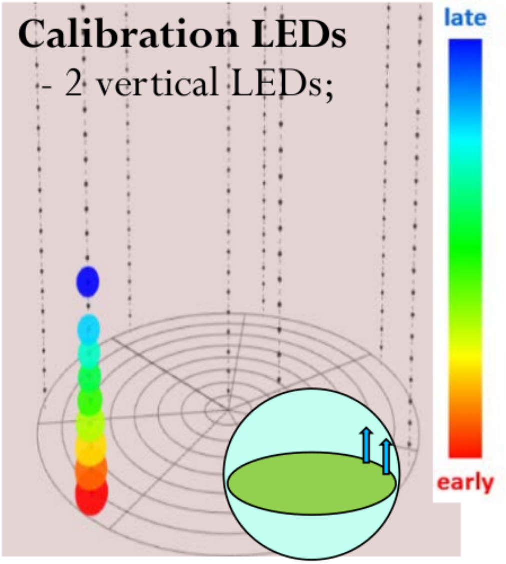
Water optical properties

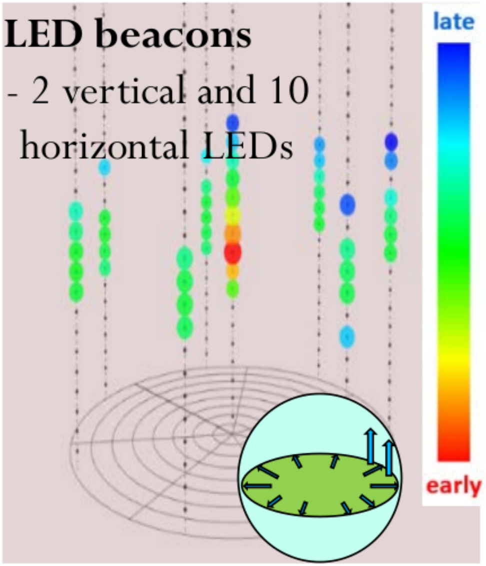




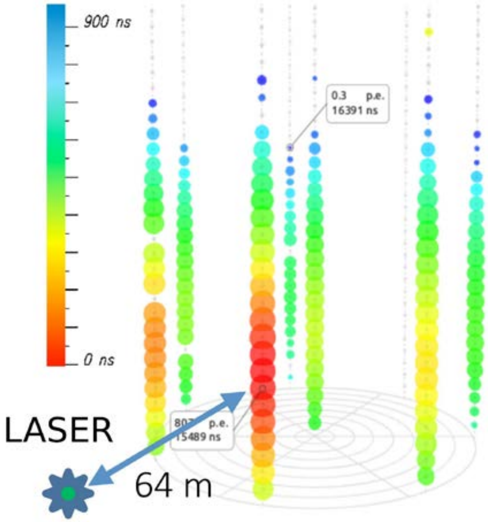
Calibration devices

- 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

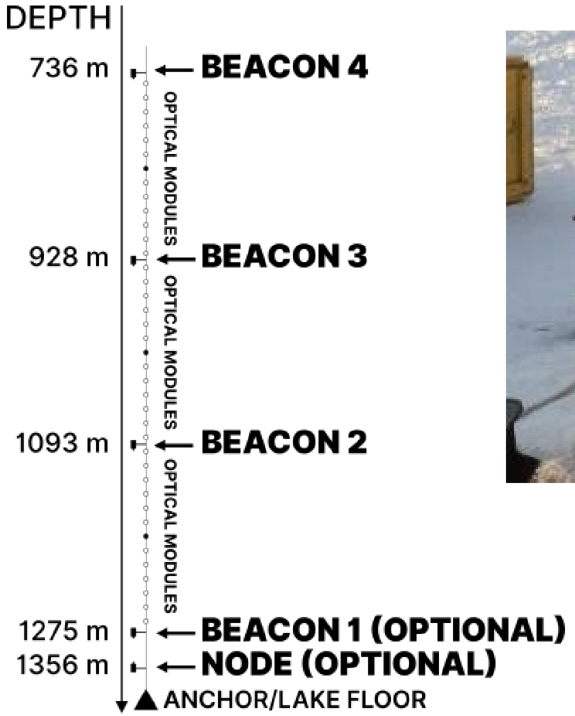


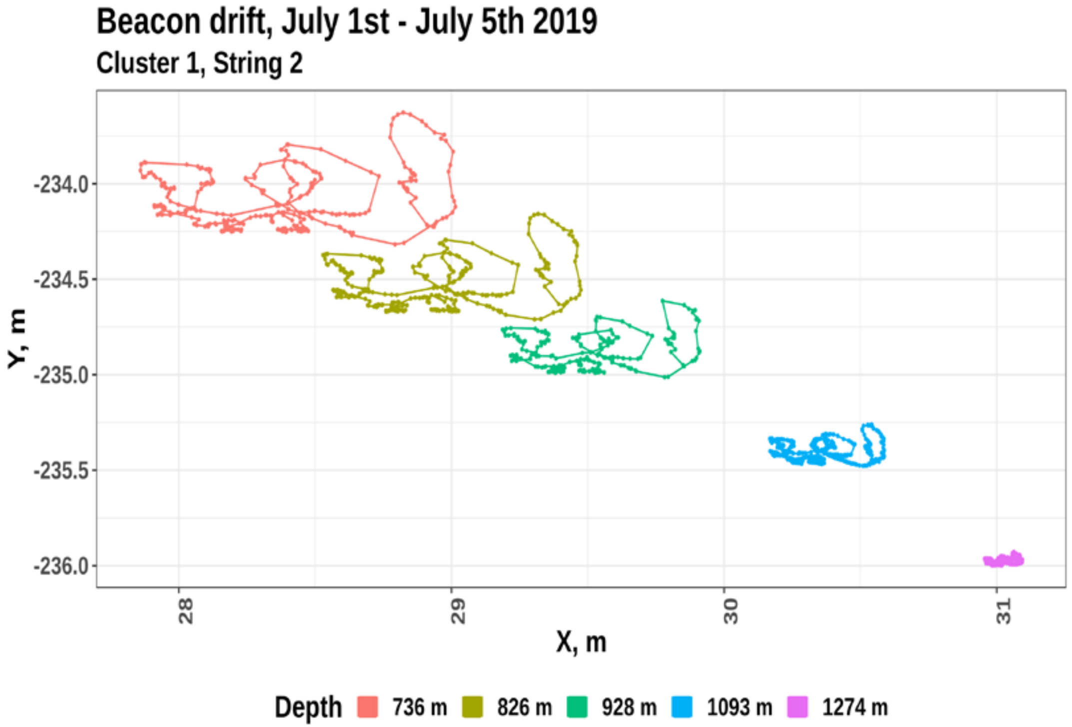


Calibration accuracy ~2 ns



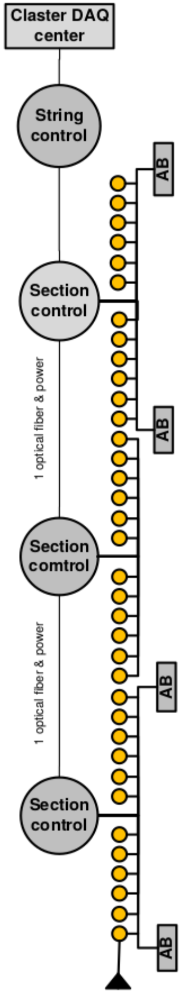
Acoustic positioning

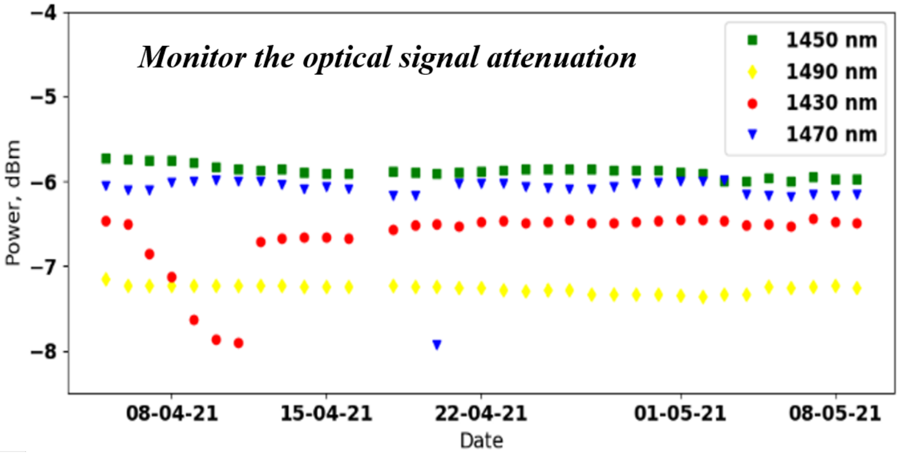




OM drift can reach tens of meters, depending on season and elevation
String geometry monitored with acoustic modems (4 AMs per string)
OM coordinates are obtained by interpolating AM coordinates, accuracy ~ 20 cm

Experimental string with optic fiber DAQ





Developing technological solutions for second stage of Baikal-GVD deployment (2024+)

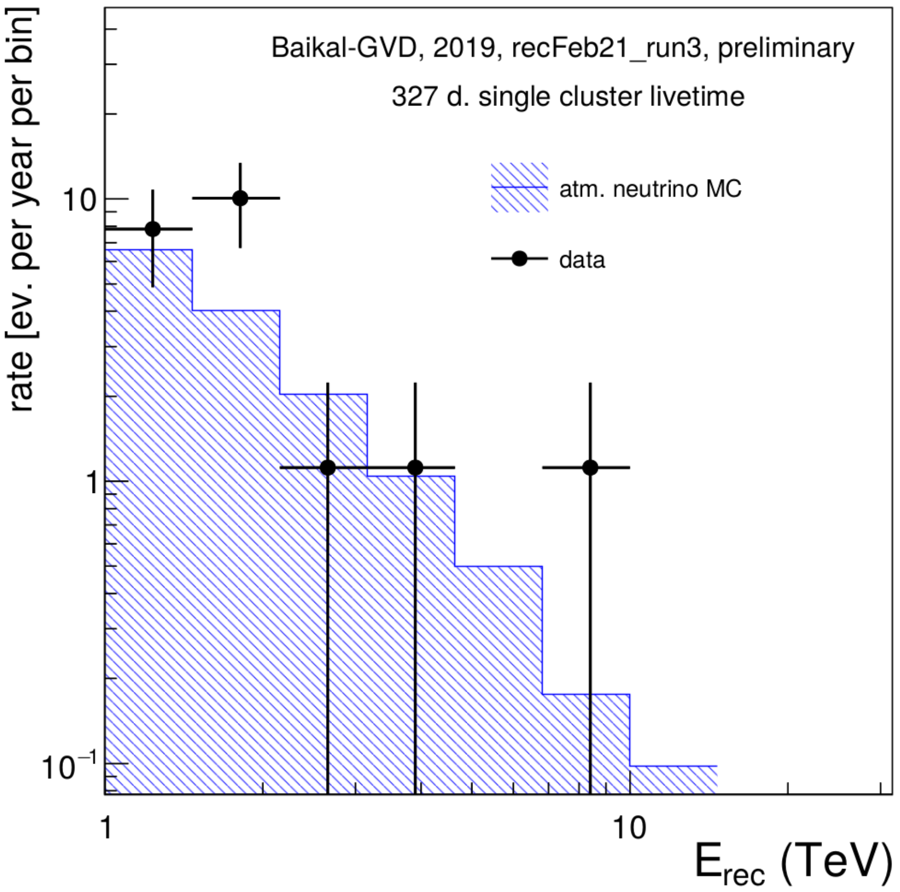
Advantages:

- flexible trigger conditions
- Improved neutrino detection efficiency
- Improved timing accuracy

See poster by V. Aynutdinov @ ICRC 2021

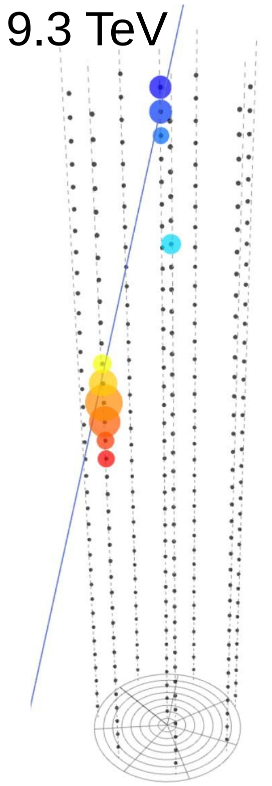
Reconstructed energy for tracks

Example plot for a set of neutrino candidate events



- dE/dx energy estimator -
- Works for E > 1 TeV
- Largest measured energy in cut-based low-energy neutrino candidate sample:

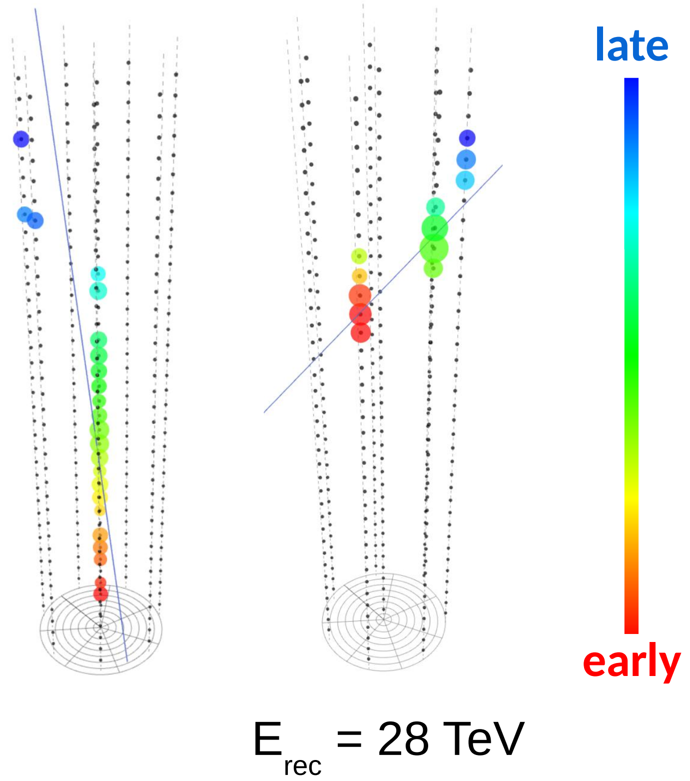
see talk by G. Safronov at ICRC 2021



cluster 1, run 84
evt. 473478
$\theta = 165.5°$
$N_{strings} = 3$
$N_{hits} = 10$

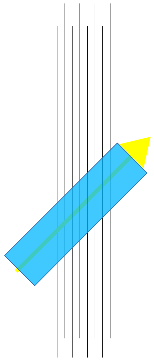
Track reco : ongoing improvements

- Event selection with BDT
  → G. Safronov @ ICRC 2021
- Improved hit selection using clique search → A. Avrorin & B. Shaybonov @ ICRC 2021
- Likelihood fitter
- Machine learning techniques
- ...



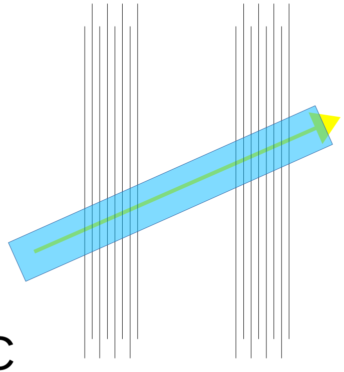
Event types

Single-cluster tracks



- Low energy threshold
- Optimal sensitivity to nearly vertical tracks
- 90% of recorded track events

Multi-cluster tracks

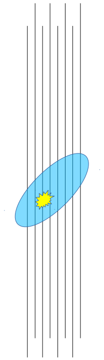


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- 10% of recorded track events

ν_μ CC

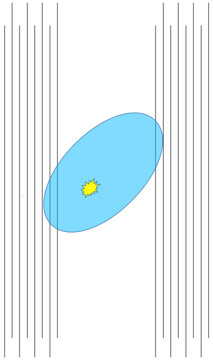
NC, ν_e ν_τ CC

Single-cluster cascades



- High energy threshold
- Good energy resolution
- Relatively rare events

Multi-cluster cascades



- Very high energy threshold
- Excellent energy resolution
- Very rare events

Neutrino absorption in the Earth

doi:10.1038/nature24459