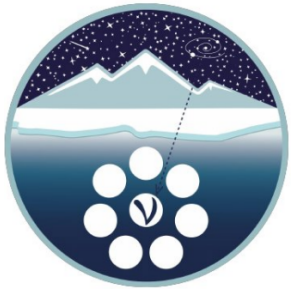


ICHEP 2022
6-13 July 2022

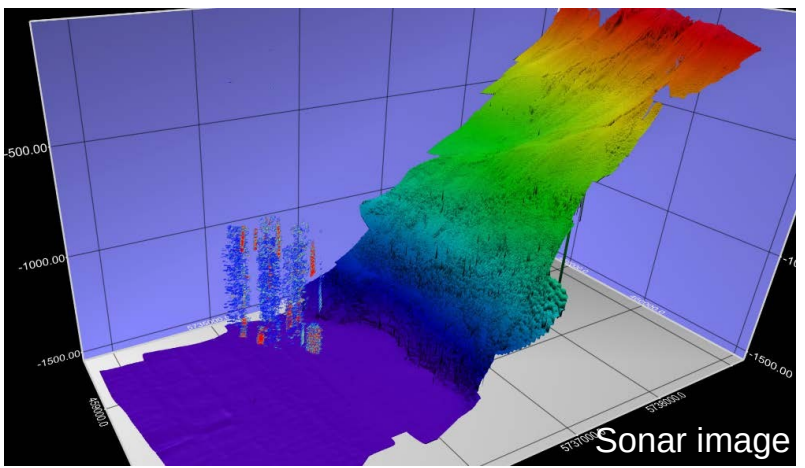
Recent results from the Baikal-GVD neutrino telescope

Dmitry Zaborov
on behalf of the Baikal-GVD Collaboration

Baikal-GVD site

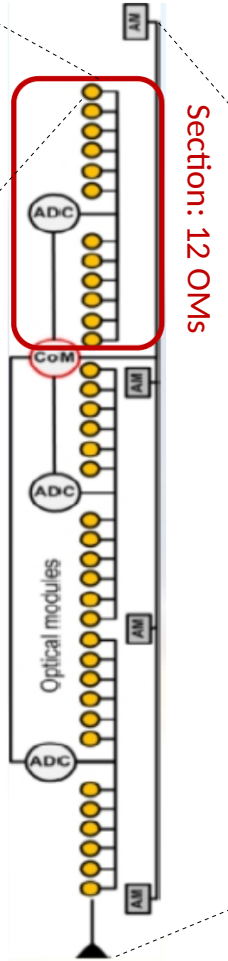
- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance

- 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”)

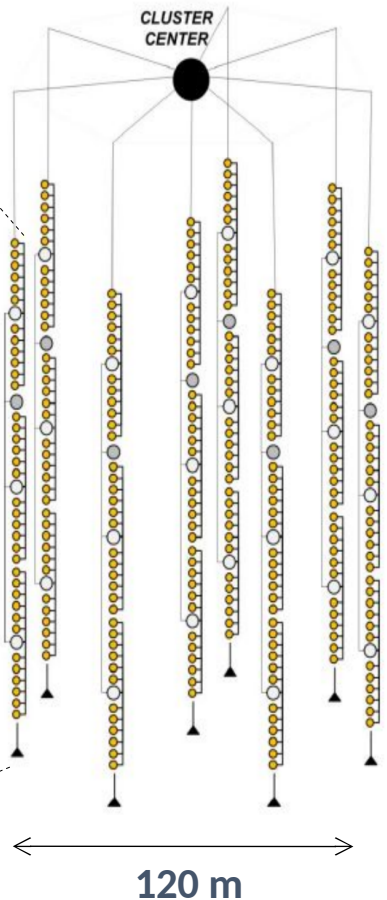


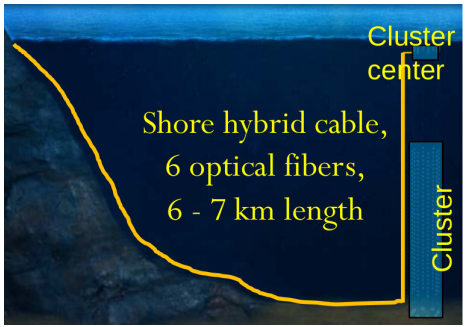
GVD building blocks

Optical Module



Cluster





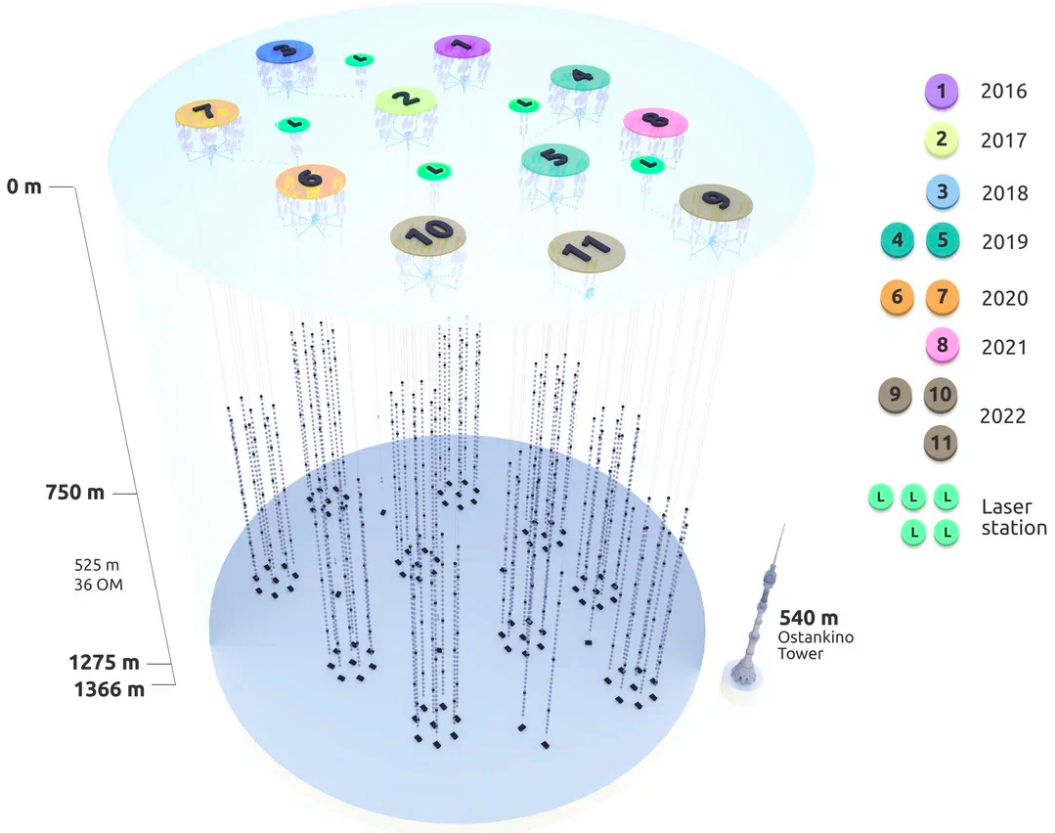
String:

- **36 OMs**, 15 m spacing, downward-looking
- **4 acoustic modems** (positioning system)
- **4 electronics modules** (section and string control)
- Depths from 750 m to 1275 m

Cluster:

- 8 strings (288 OMs)
- 60 m spacing between strings
- Central electronics located at 30 m depth
- Trigger: 4 p.e. + 1.5 p.e. hits on adjacent OM within 100 ns
- Inter-section synchronization by common trigger (~ 2 ns accuracy)
- Internal network: shDSL 5.7 Mbit
- Connection to shore: optic fiber

Baikal-GVD construction status



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

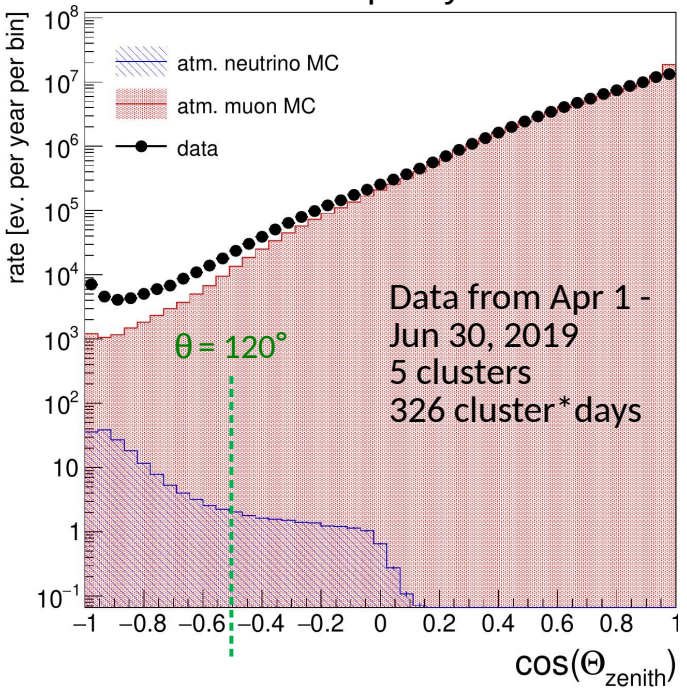
Deployment schedule

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

Eff. volume 2022: ~ 0.5 km^3 (cascades, E > 100 TeV)

Single-cluster tracks: a BDT-enhanced χ^2-based analysis

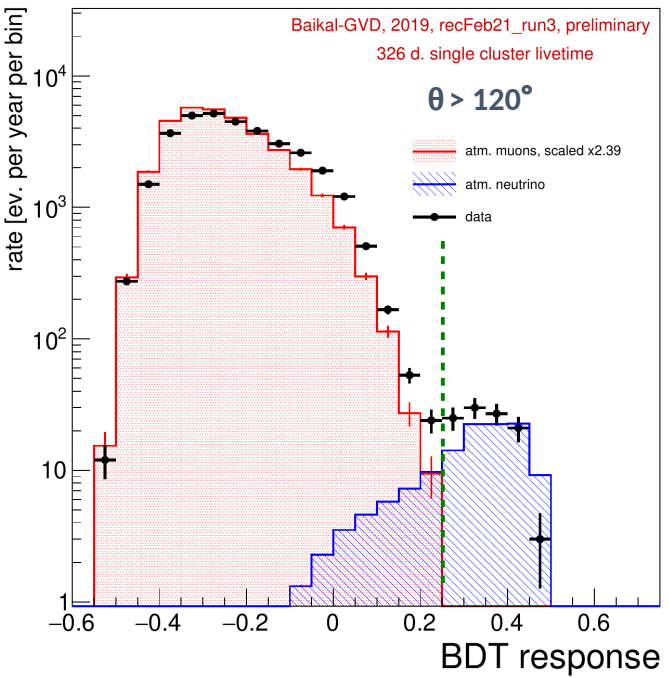
Before quality cuts



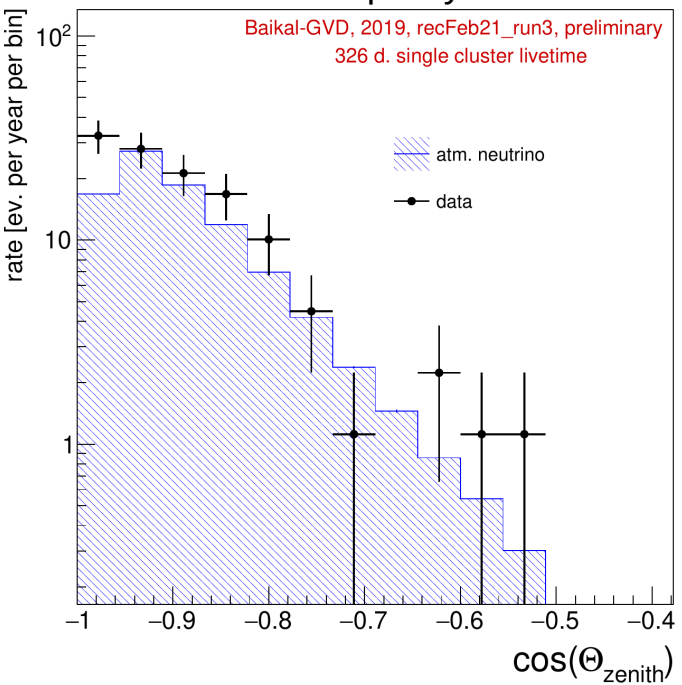
mis-reconstructed & upgoing

downgoing

Near-horizon directions to be covered with a multi-cluster analysis



After quality cuts

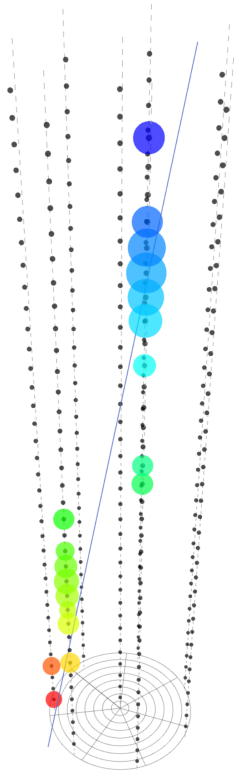


G. Safronov, Neutrino 2022
PoS-ICRC2021-1063
Eur. Phys. J. C 81 (2021) 1025

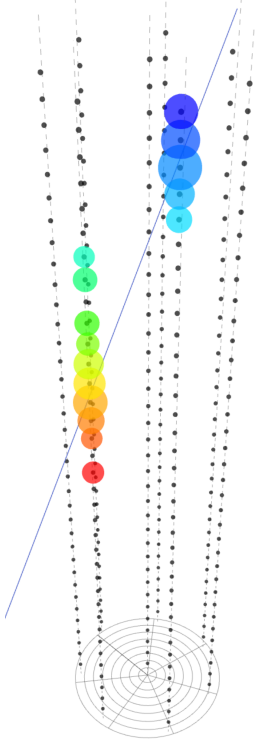
MC expected: 81.2
Observed events: 106

data-MC discrepancies under study

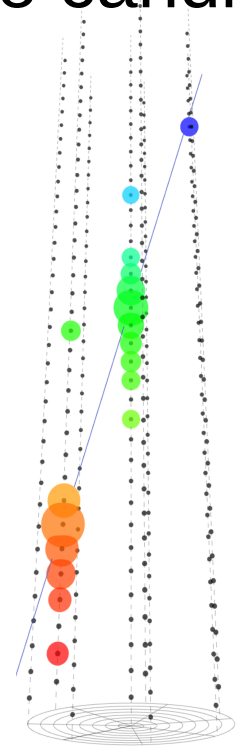
Track-like neutrino candidate events



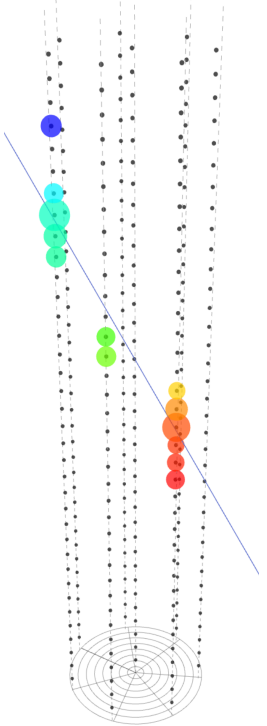
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



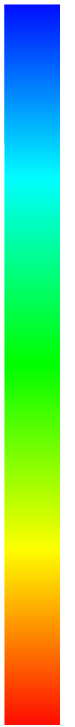
cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15



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



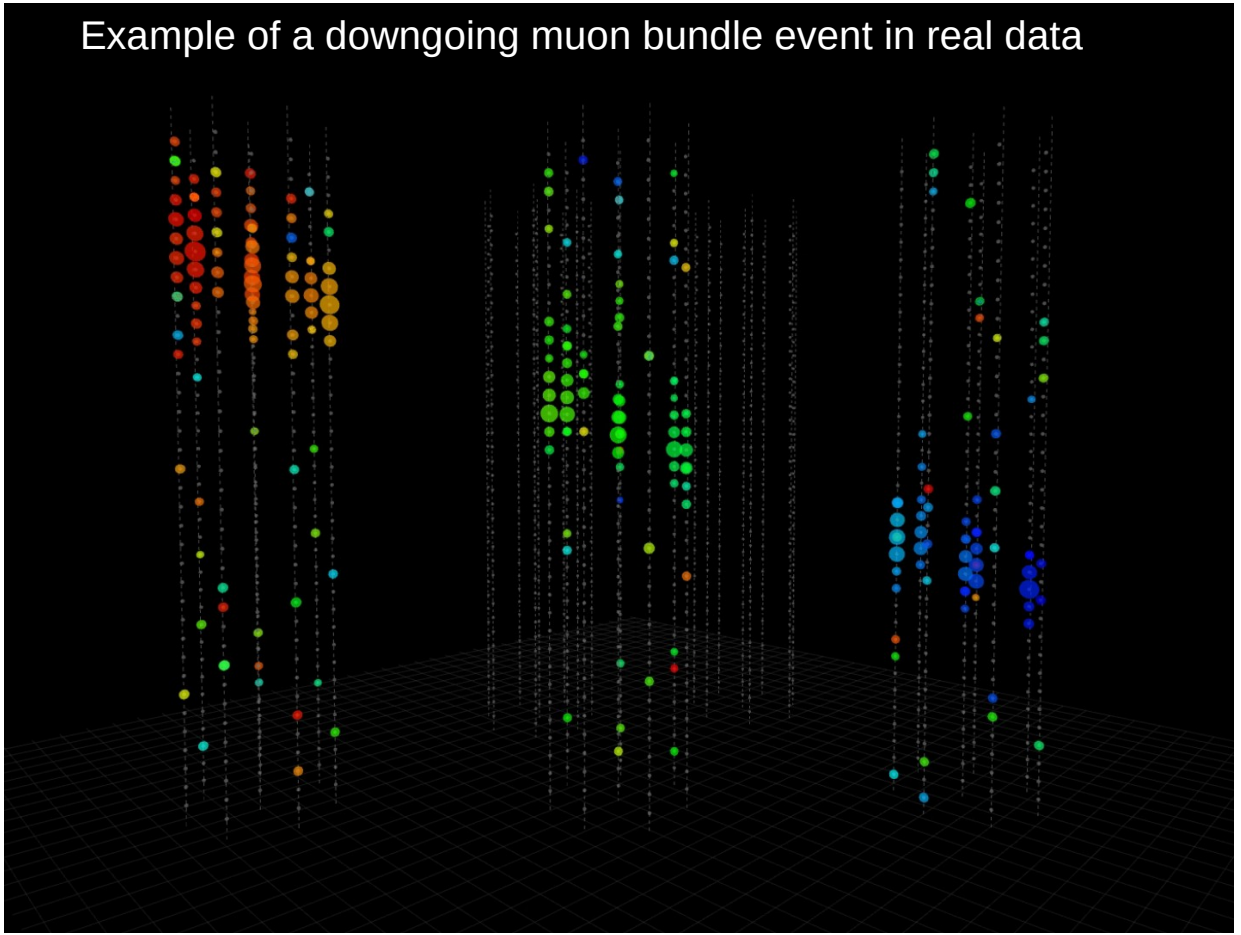
cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13

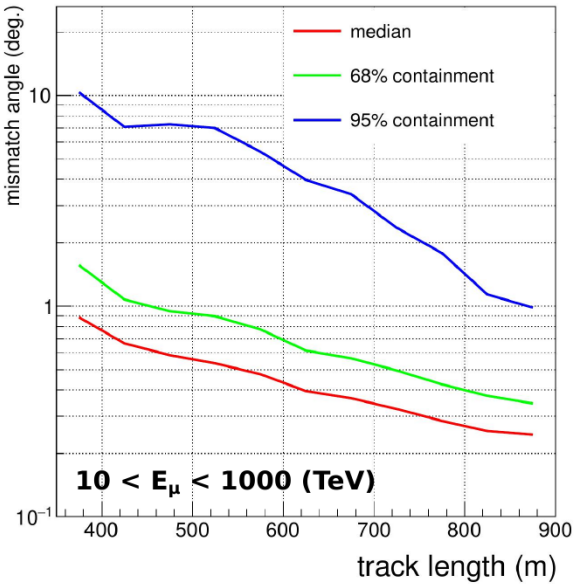


Multi-cluster tracks

late

early





Work in progress !

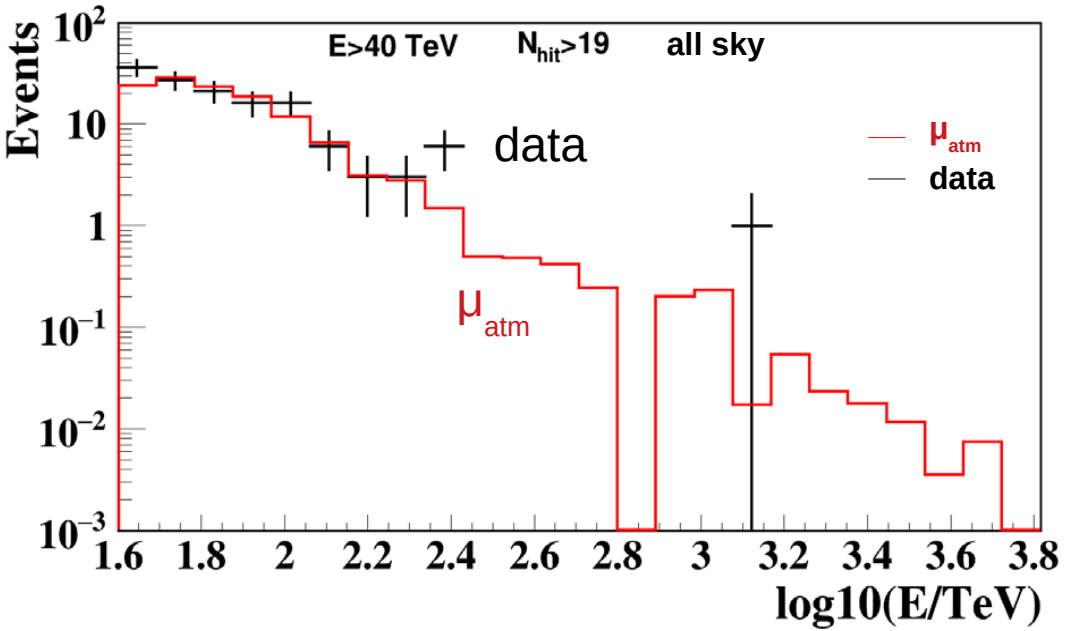
Cascade analysis : data and MC

Preliminary

Data from 2018-2021, livetime: 5522 days single-cluster equivalent

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

MC atmospheric neutrinos – L.Volkova (1980)



135 events with E > 40 TeV
23 events with E > 100 TeV

All-sky search for HE cascades

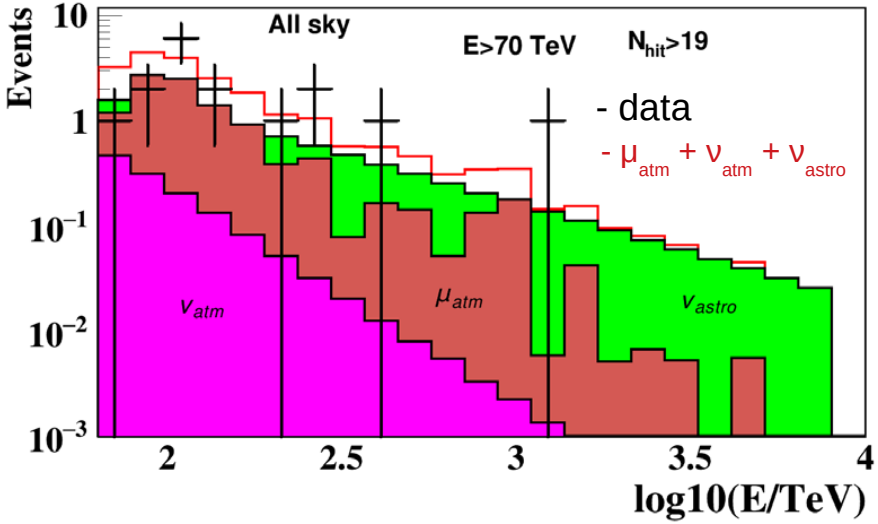
Preliminary!

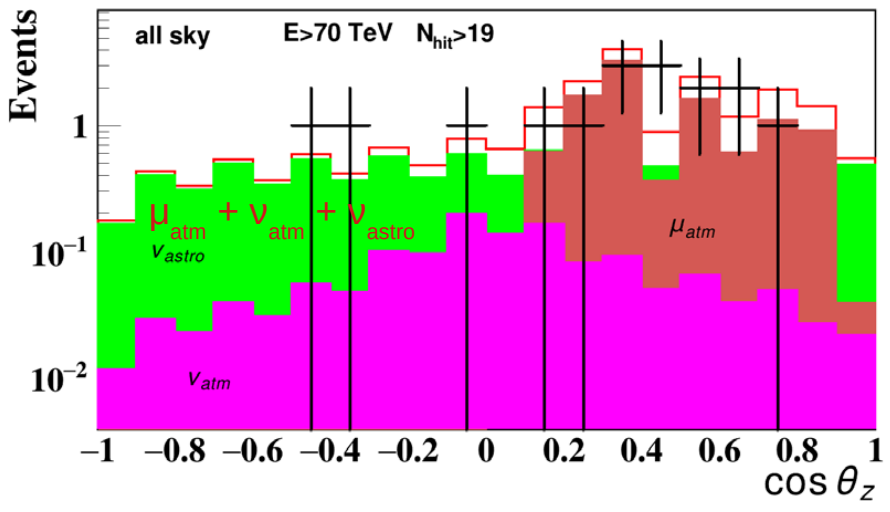
Additional selection requirements:
(N_{Type_2} = 0, E_{rec} ≥ 70 TeV) or
(N_{Type_2} = 1, E_{rec} ≥ 100 TeV)
N_{Type_2} is number of hits in time interval where hits from muons are expected

Expected:
8.7 events from atm. muons
0.8 events from atm. neutrinos
7.8 events for IceCube's $E^{-2.46}$ astrophysical flux

Found in real data: 16 events

Probability for the background-only hypothesis (stat. errors only)
P-value = 0.033 (2.13 σ)





Search for upward moving events

Preliminary!

Additional selection requirements:

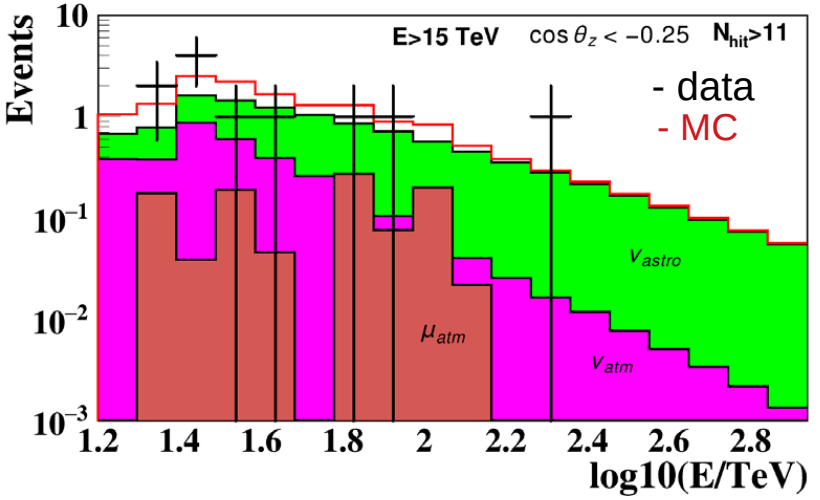
$E > 15$ TeV & $N_{hit} > 11$ & $\cos\theta_z < -0.25$

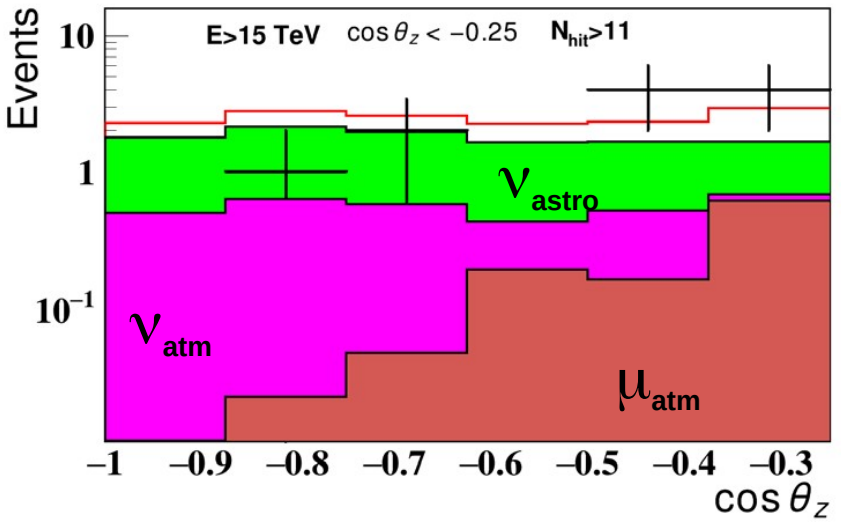
Expected:
0.95 events from atm. muons
3 events from atm. neutrinos
10 events for IceCube's $E^{-2.46}$ astrophysical flux

Found in data: 11 events

The "no diffuse flux" hypothesis is rejected with

P-value = 0.00268 (3σ)

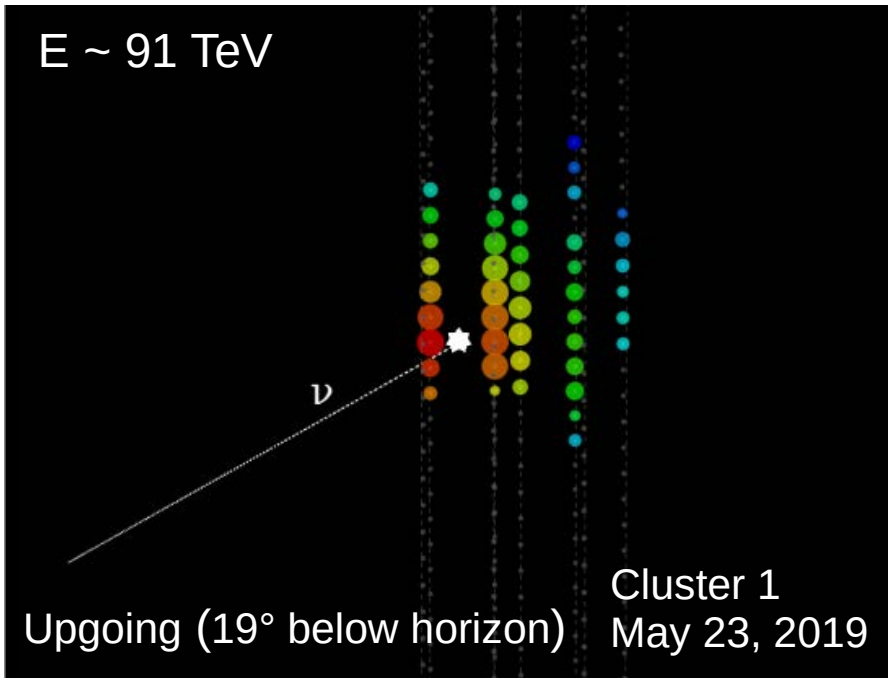




Upward-going cascade #1

Preliminary

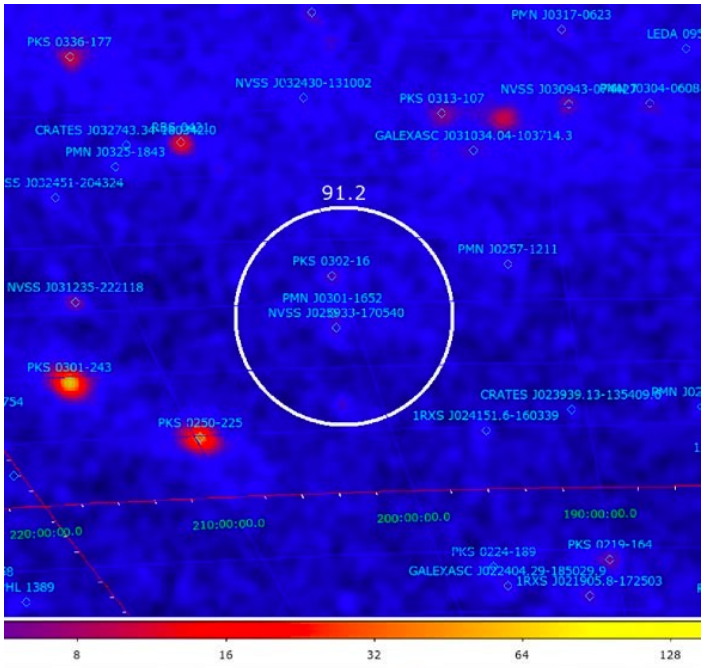
GVD2019_1_114_N



Contained event (50 m off central string)

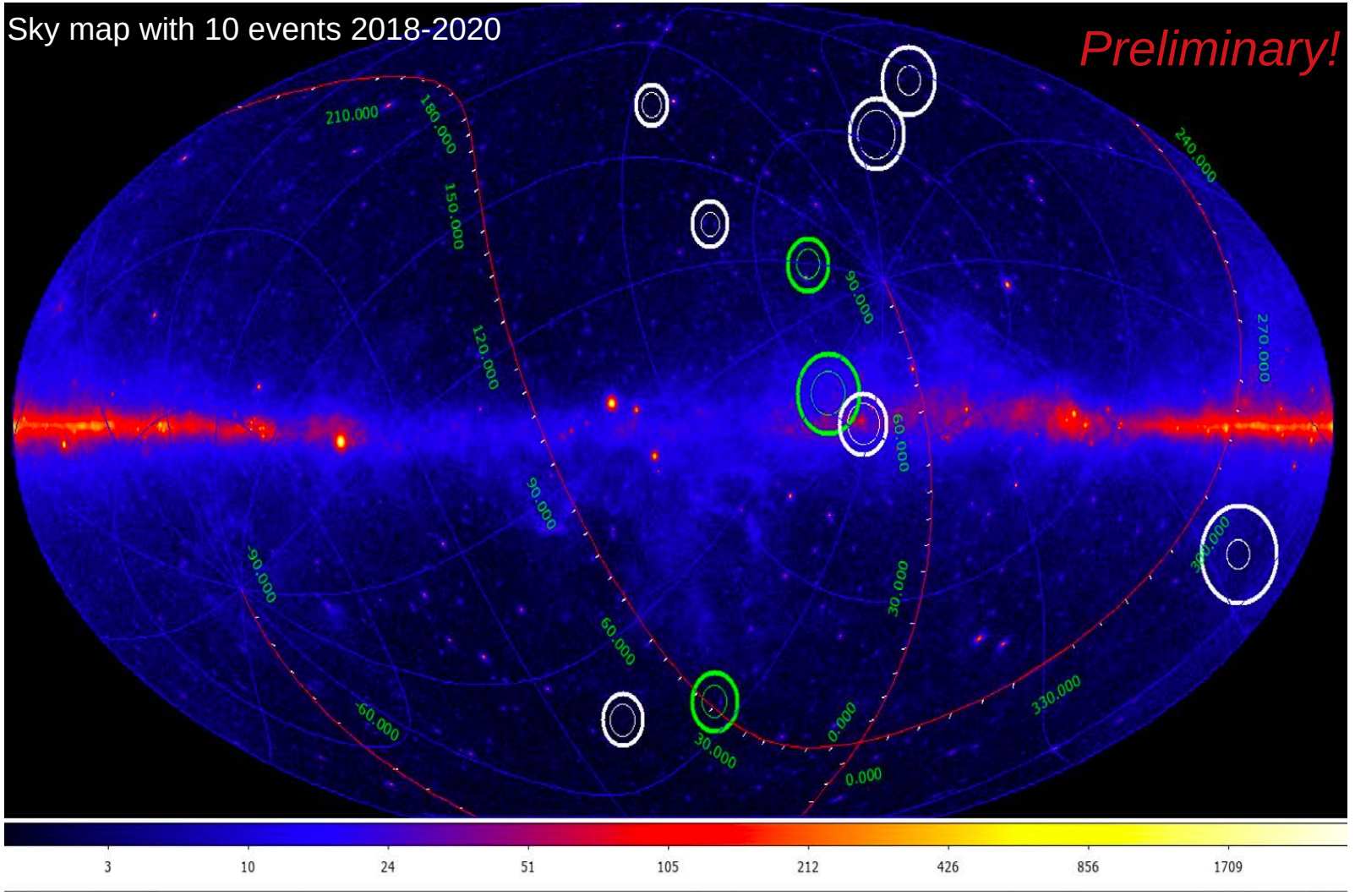
Excellent candidate for a neutrino event of astrophysical origin

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

Ten most prominent cascade events (downgoing+upgoing)



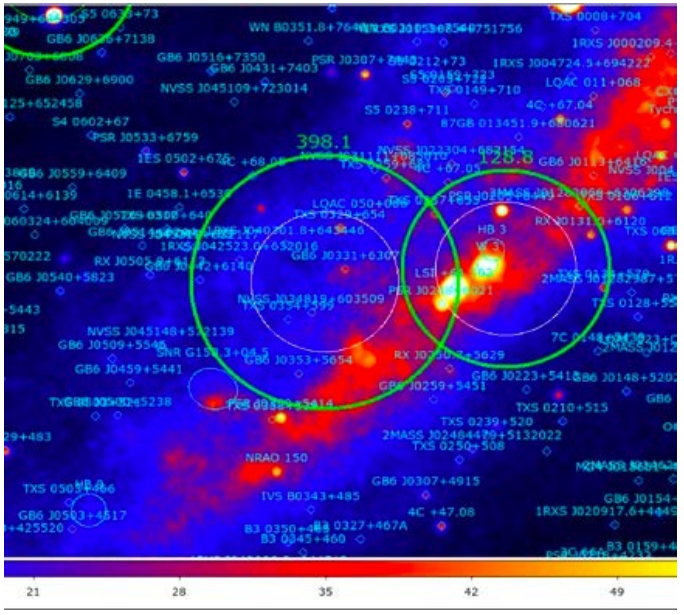
Background image: Fermi LAT

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

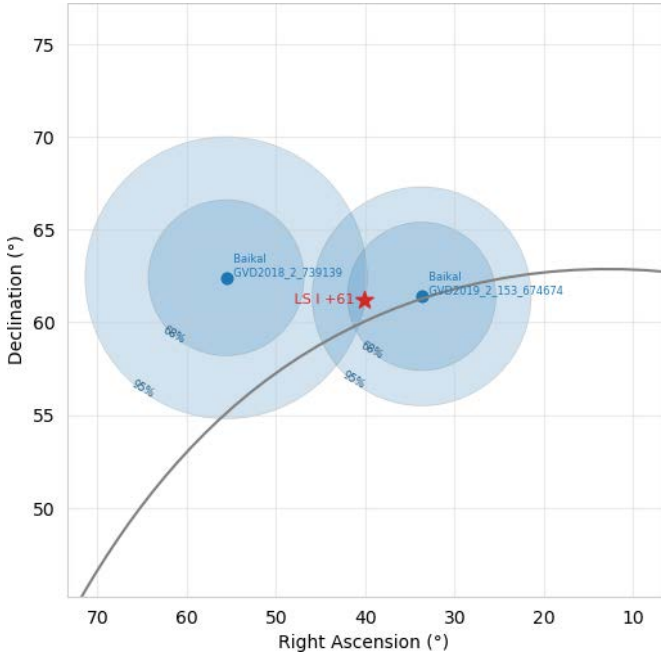
White circles: Baikal-GVD events 2019-2020

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 microquasar

3.1° from GVD_2019_153_N and 7.4° from GVD_2018_656_N (both are downgoing events)

Using the PSFs of all 10 events, the chance probability to observe such a doublet near LSI +61 303 was estimated as 0.007 (2.7 σ) [not corrected for the “look elsewhere effect”]

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

Dec 8, 2021 20:02: IceCube “Astrotrack Bronze” neutrino event in vicinity of bright blazar PKS 0735+17

Active state of PKS 0735+17 reported in optical (MASTER), HE gamma-rays (Fermi LAT), X-rays (Swift XRT) and radio

Baikal-GVD found a downward-going (30° above horizon) **cascade-like event 4 hr after** the IceCube event
5.30° from the best-fit direction of IceCube-211208A
4.68° from PKS 0735+17

E ≈ 43 TeV
PSF 50% (68%) containment radius = 5.5 deg (8.1 deg)

Pre-trial p-value = 0.0044 (2.85 σ) [24 hr, 5.5 deg cone]

Trial factor ~ 40 (total number of IceCube alerts analyzed)

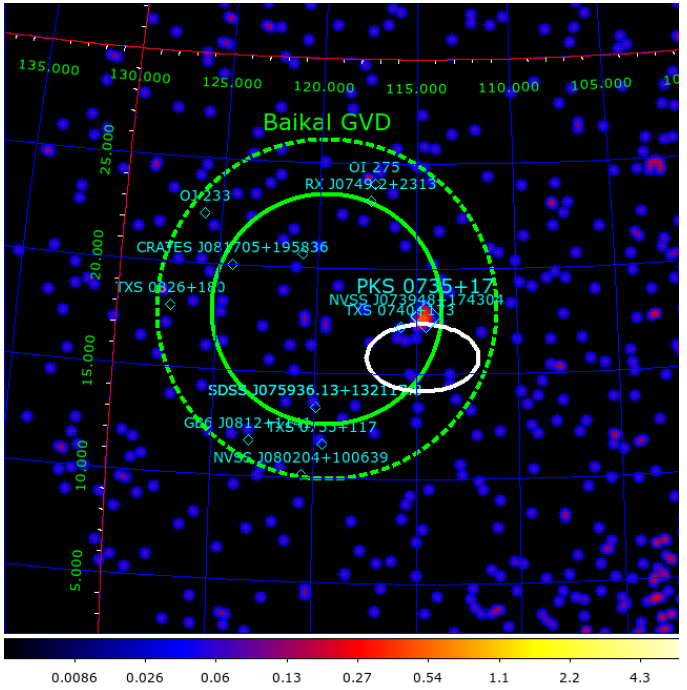


Image by D.Semikoz & A.Neronov

ATeL 15112

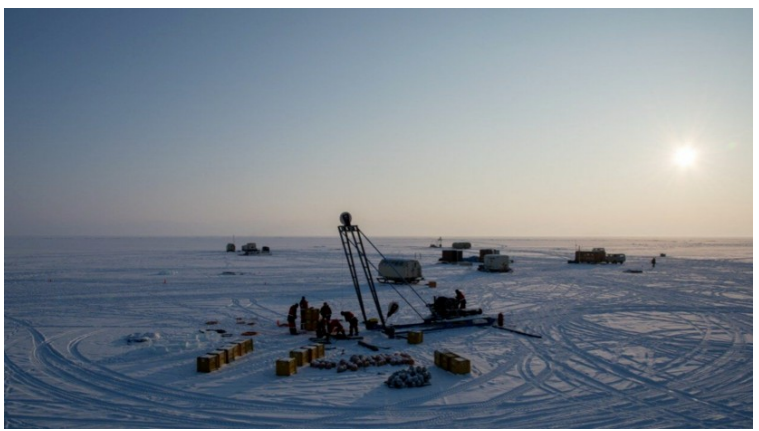
Also see N. Sahakyan et al., arXiv:2204.05060

Conclusion

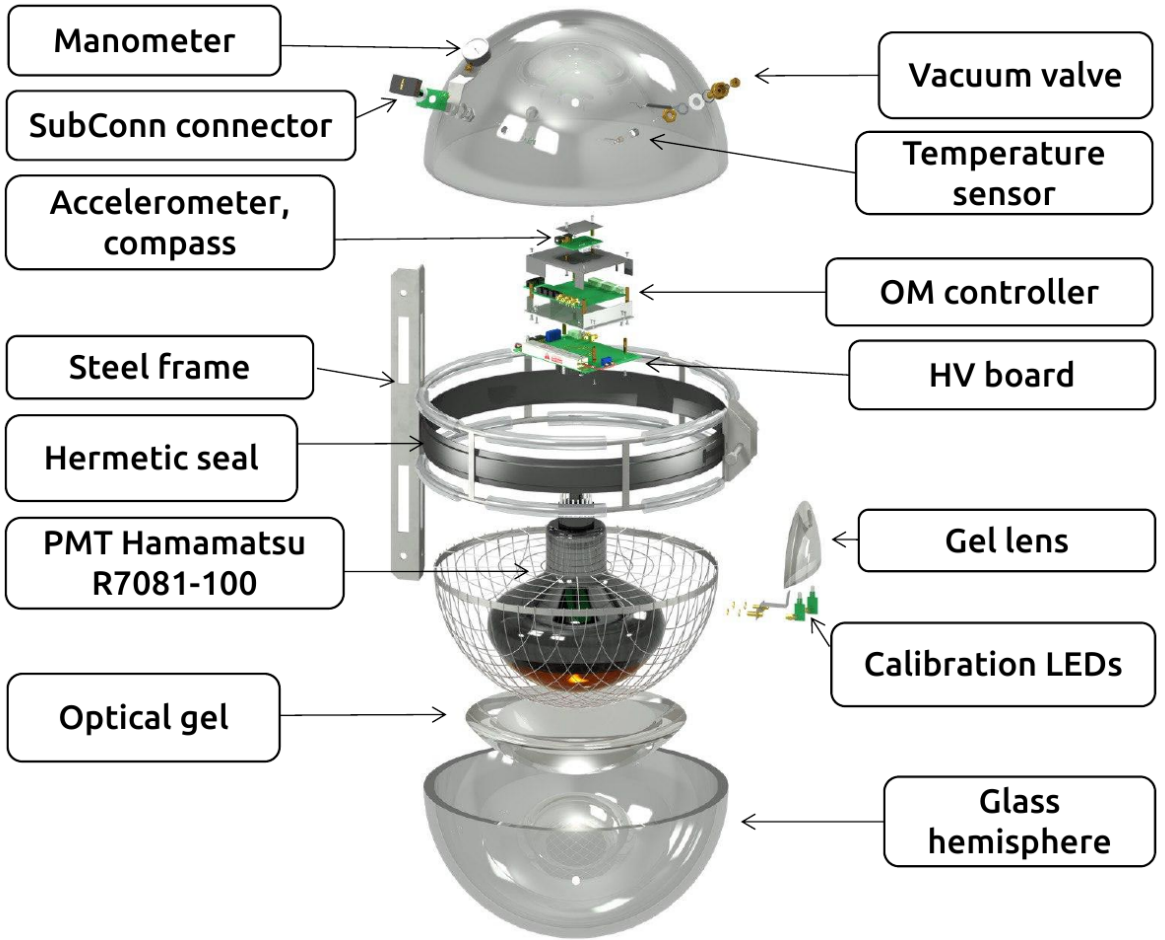
- Baikal-GVD is a new neutrino telescope under construction in Lake Baikal
  - Volume already approaching the ~ 0.5 km^3 mark
  - Angular resolution better than 1° (for tracks)
  - Field of view complementary to IceCube
- The IceCube’s diffuse neutrino flux is confirmed by Baikal-GVD with a 3σ significance
- Hints of possible new neutrino sources are accumulating

Backup slides

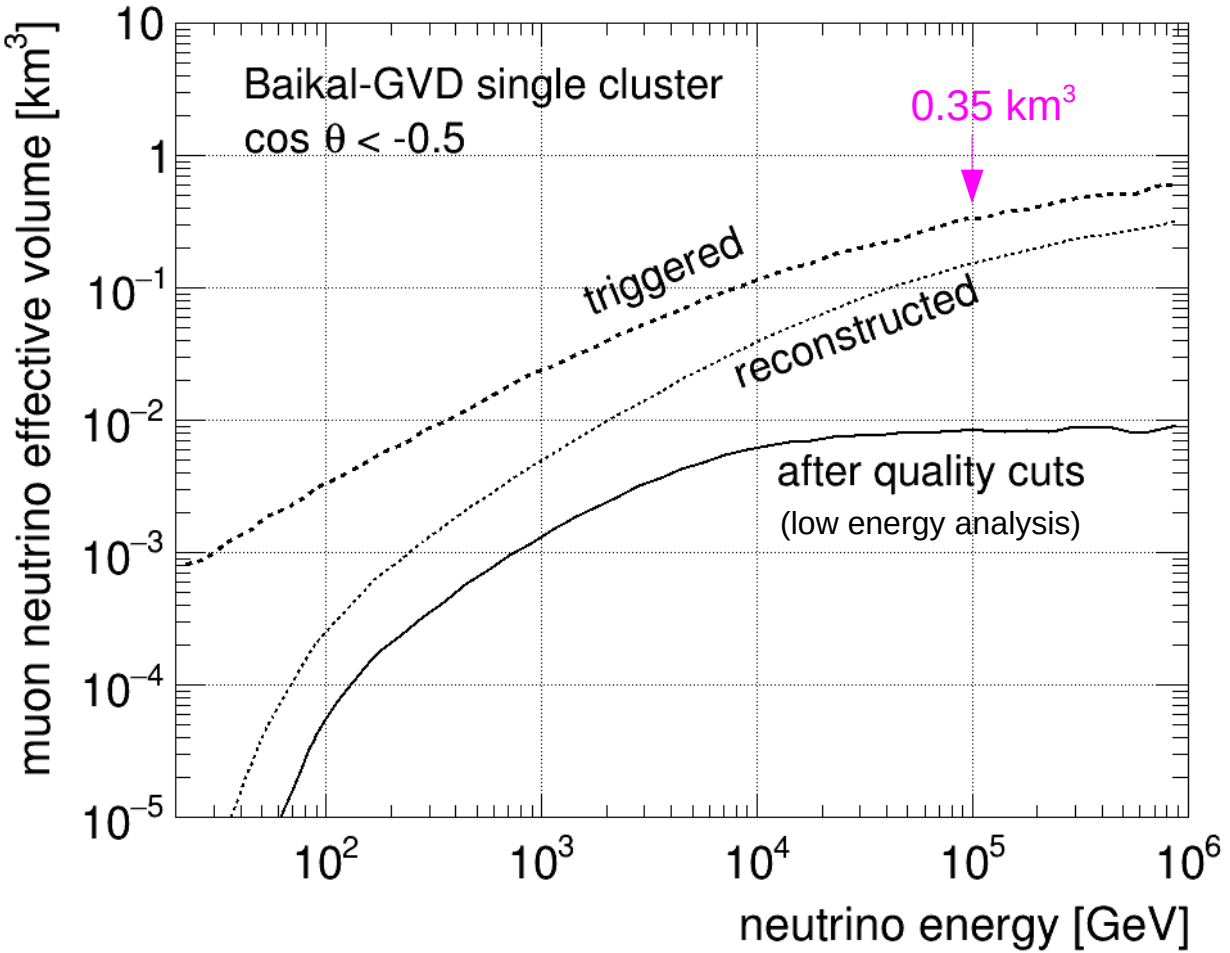
Deployment



Baikal-GVD optical module



Neutrino effective volume for tracks (one GVD cluster)

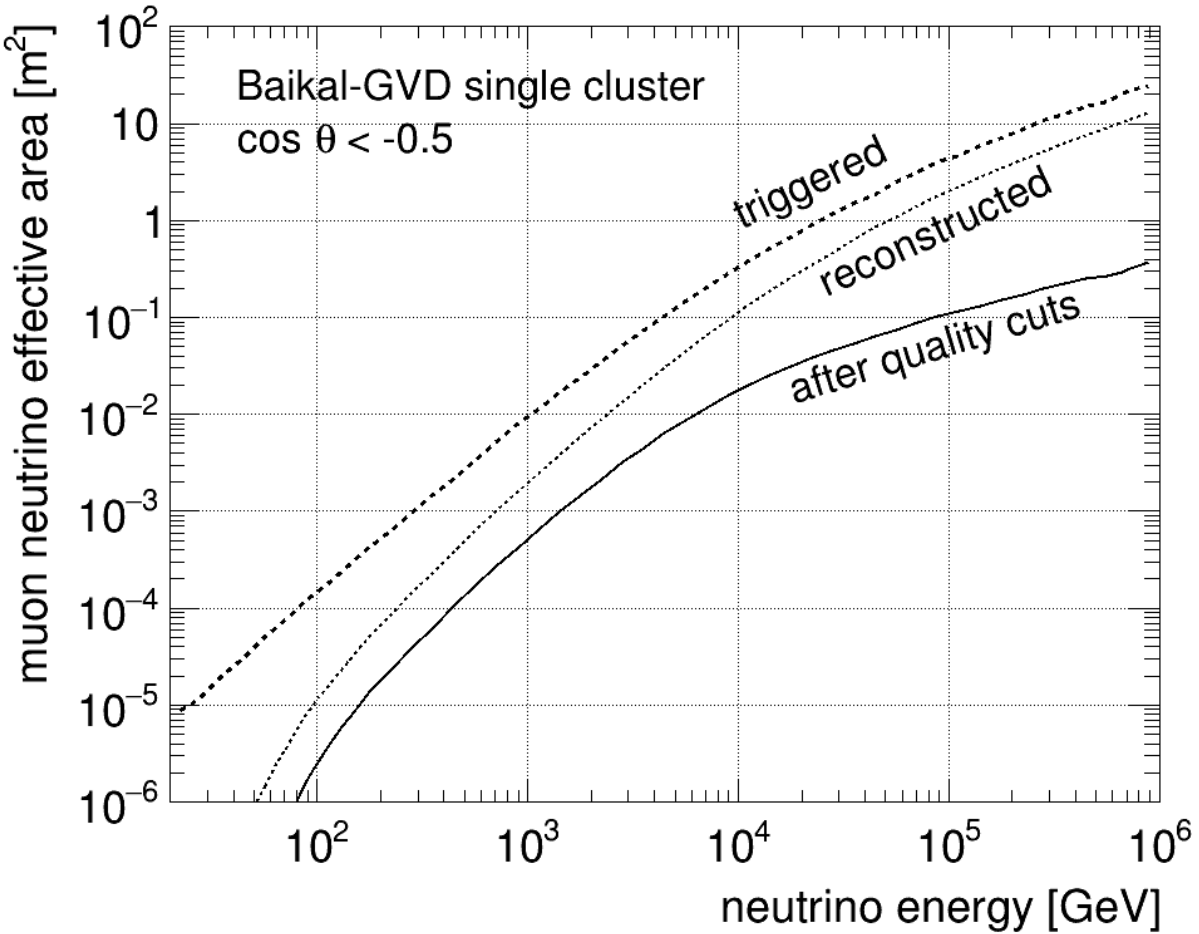


Energy threshold ~ 200 GeV
(higher than in ANTARES)

Fully efficient at E > 100 TeV

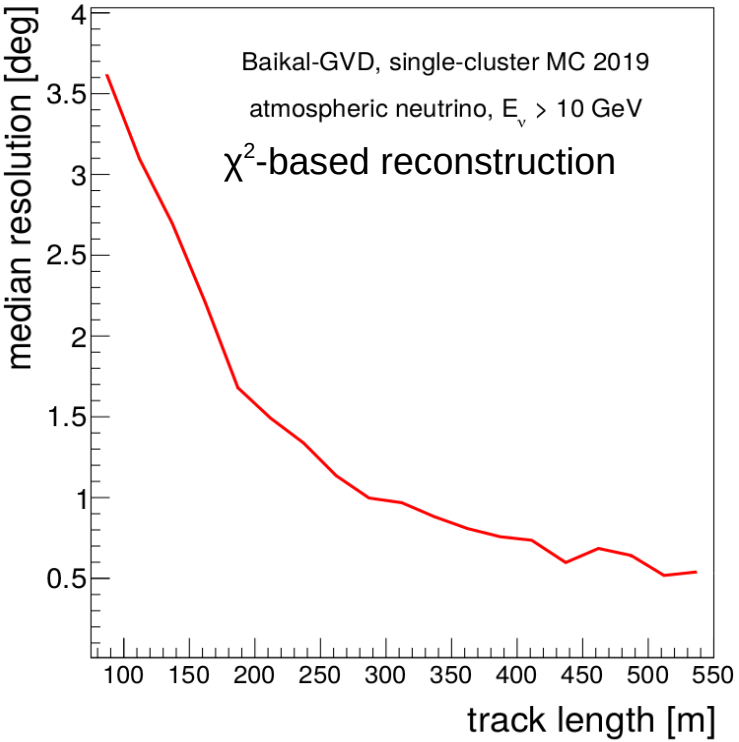
Eur. Phys. J. C 81 (2021) 1025

Neutrino effective area for tracks : one GVD cluster



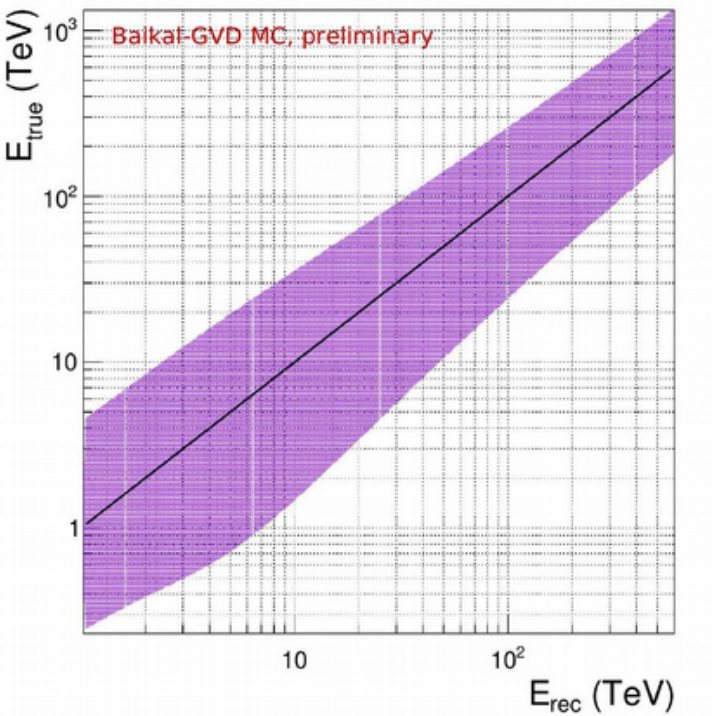
Expected performance for tracks

Angular resolution



Improvements expected from likelihood-based reconstruction (under development)

Energy reconstruction

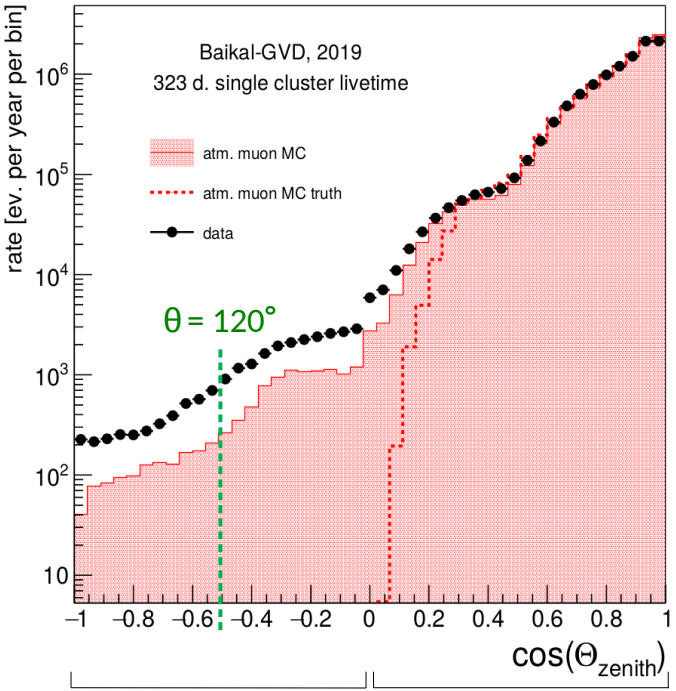


energy resolution ~ factor 3 at E ~ 100 TeV (±34% containment band)

G. Safronov @ ICRC 2021

Single-cluster tracks: a simple cut-based analysis

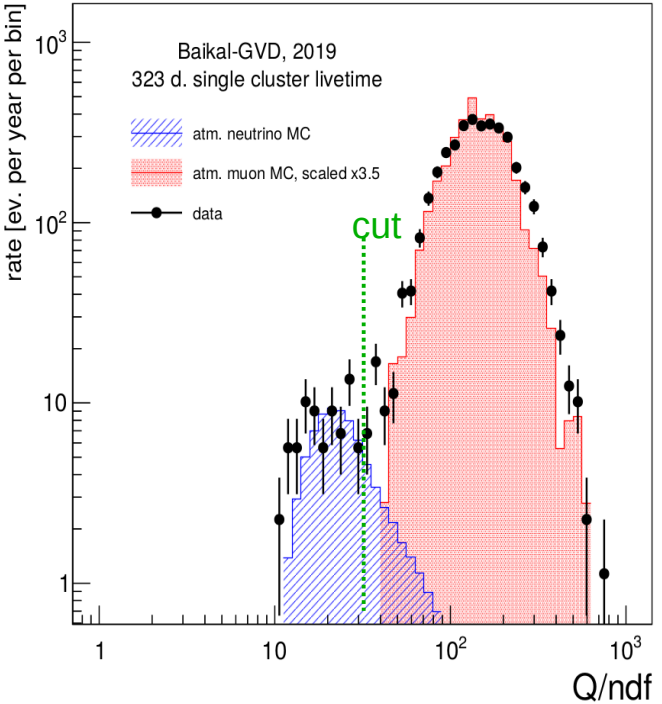
Before quality cuts



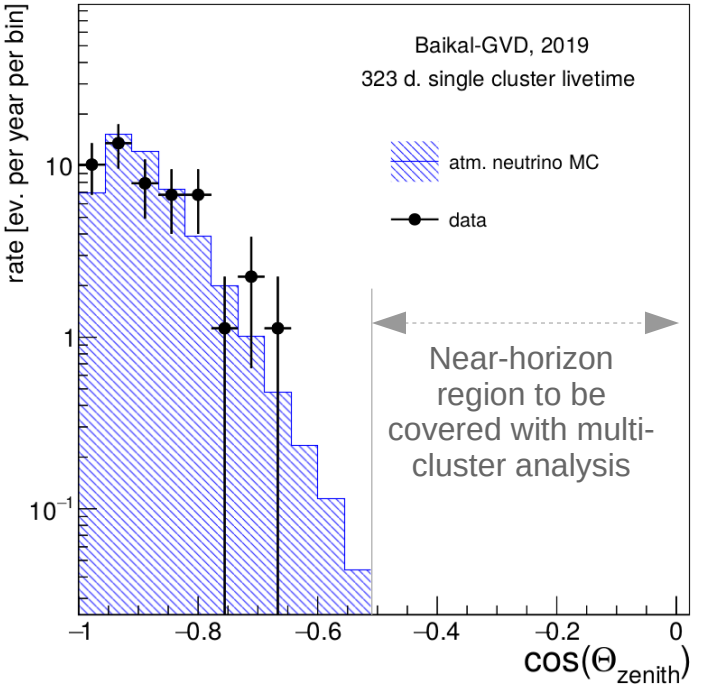
mis-reconstructed as upgoing

downgoing

Fit quality: upgoing events, θ > 120°



After quality cuts



Data from Apr 1 - Jun 30, 2019; 5 clusters; ~ 10 000 000 events

Median energy of the neutrino sample ≈ 500 GeV

Data-MC discrepancies are under study

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

MC expected: 43.6

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

Observed events: 44

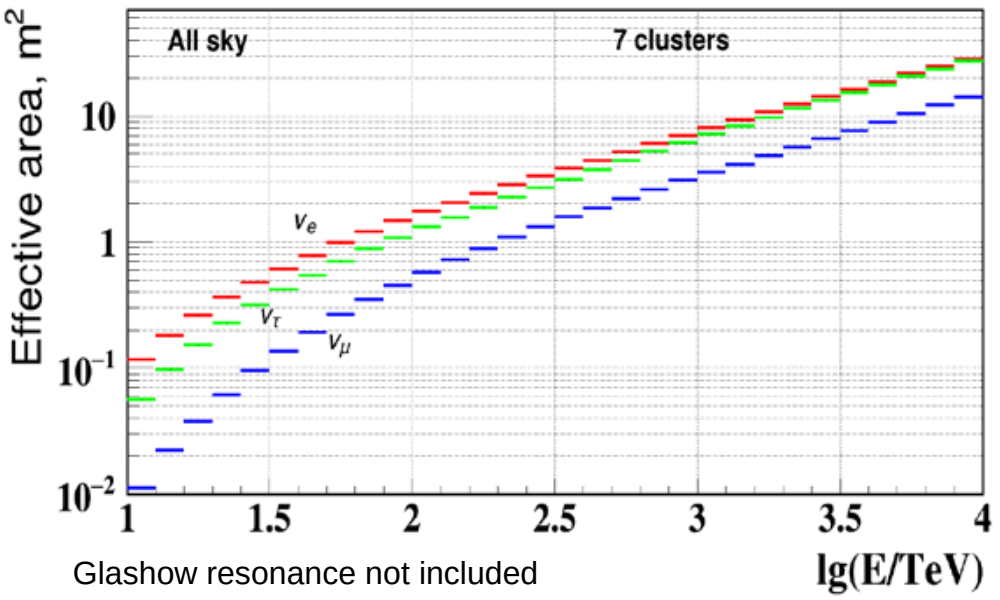
Cascade analysis : effective area and rates

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

Assumption for astrophysical neutrino energy spectrum (IceCube fit):

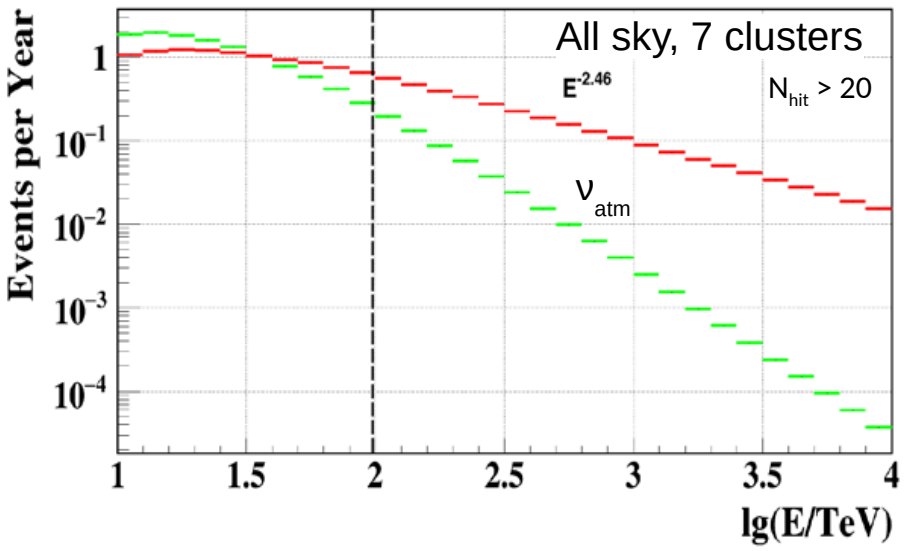
$4.1 \cdot 10^{-6}\ E^{-2.46}\ \mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$

neutrino effective area for cascade detection



Glashow resonance not included

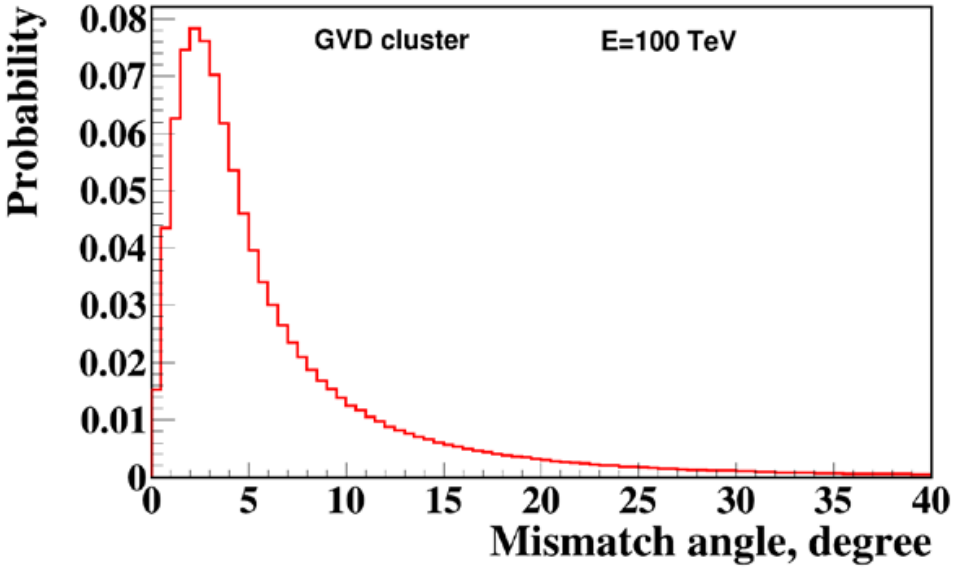
Expected number of cascade events per year



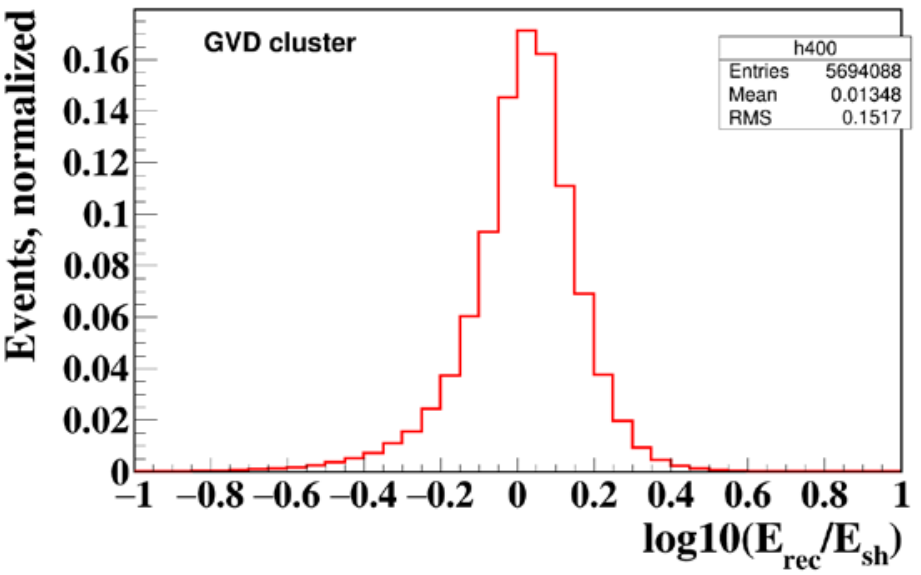
Effective volume for E > 100 TeV ~ **0.35 km³**

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

Cascade analysis performance

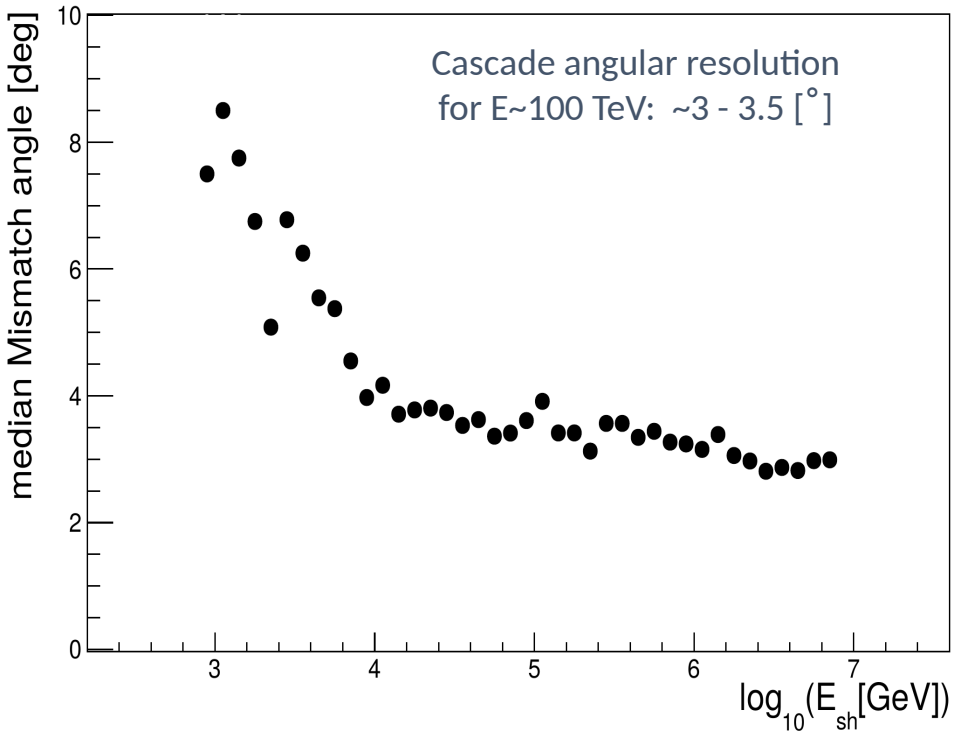


Directional resolution for cascades:
median mismatch angle ~ 4.5°

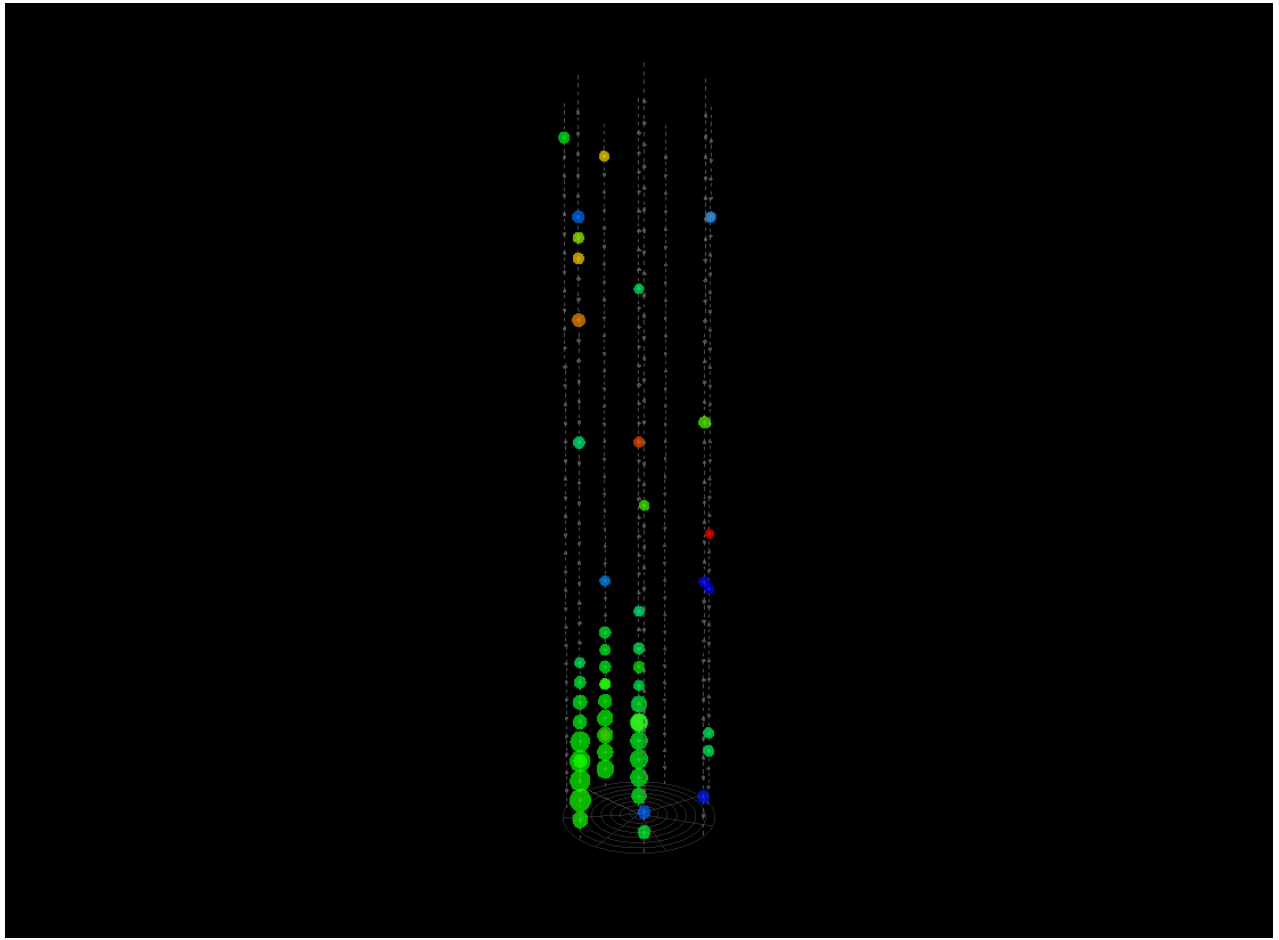


Energy resolution : δE/E ~ 30%

Cascade analysis angular resolution



Upward-going cascade event #2



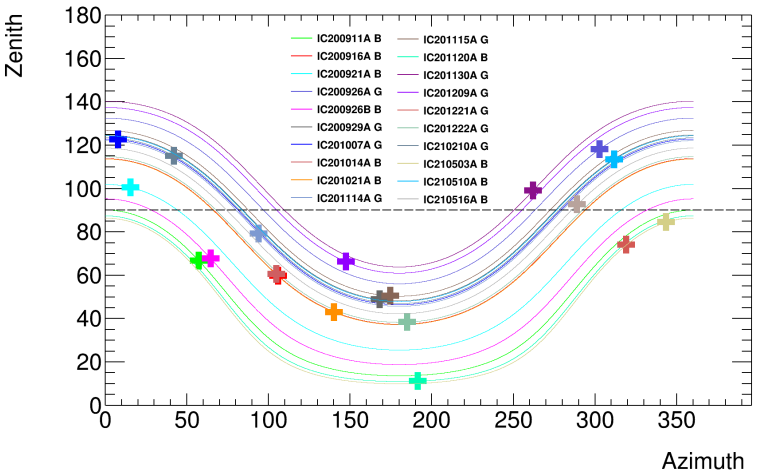
Energy E = 224 TeV (±30%);
distance from central string
r = 70 m;
Zenith angle = 115°

GVD follow up of IceCube alerts

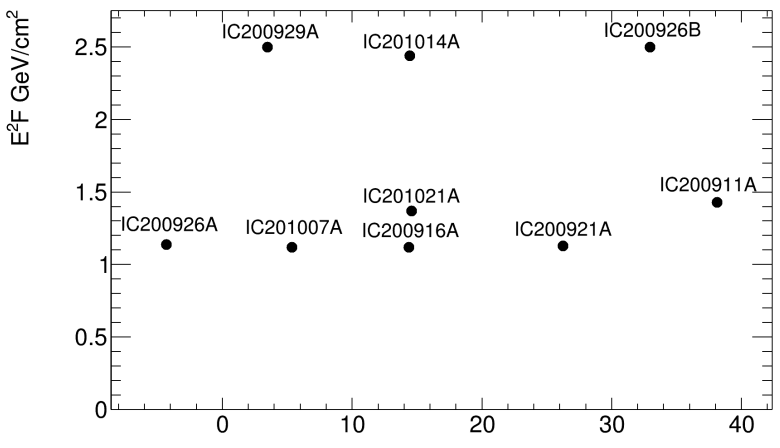
Since Sep 2020, following IC alerts (GCN / upgoing muons)

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



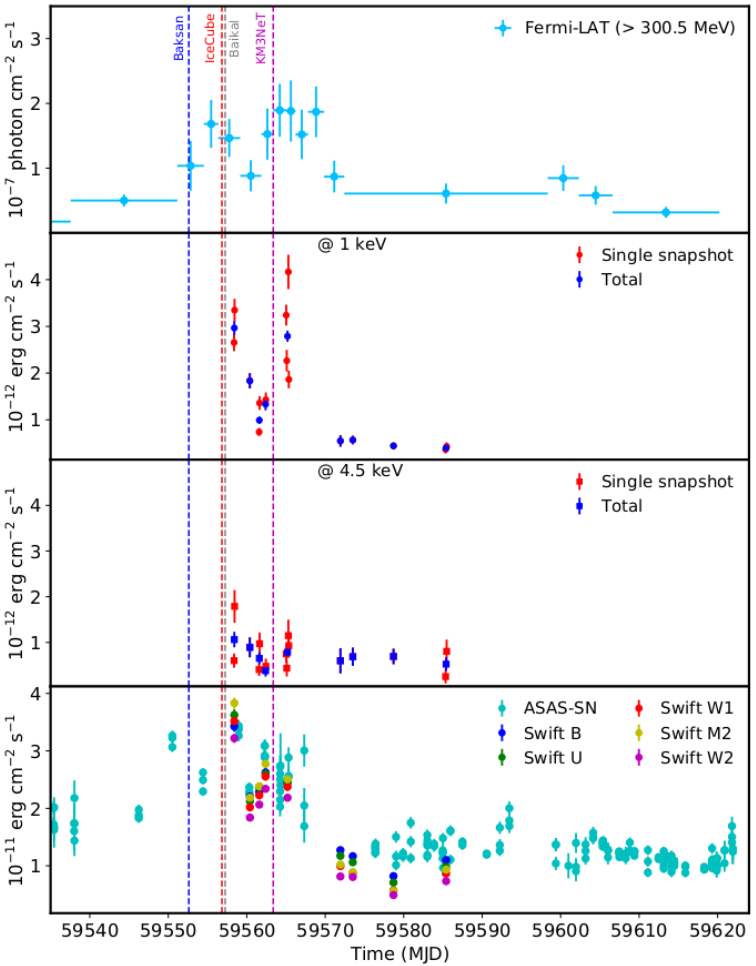
Baikal-GVD upper limits



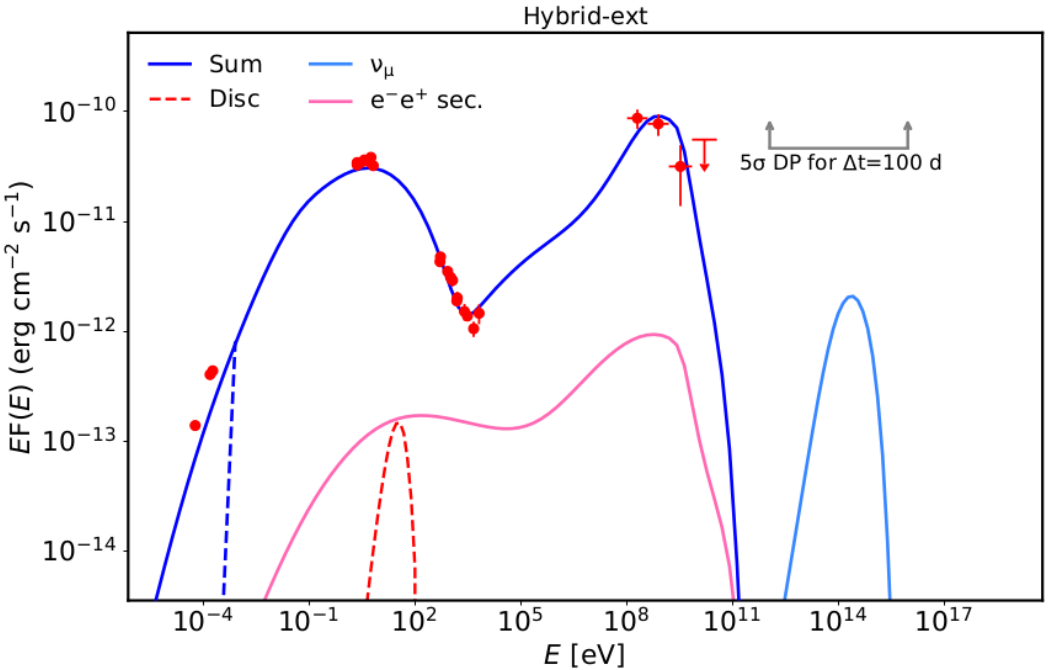
A.D. Avrorin et al., Astronomy Letters, Vol.47, N 2, 114 (2021)
http://dx.doi.org/10.1134/S1063773721020018

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

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.

Water optical properties