Семинар
НИИЯФ МГУ
23 июня 2022

Нейтриный телескоп Baikal-GVD: состояние работ и последние результаты

Дмитрий Заборов

(ИЯИ РАН)

* GVD = Gigaton Volume Detector

Содержание доклада

1) Нейтринная астрономия высоких энергий

2) Установка Baikal-GVD: устройство и состояние работ

3) Оценки чувствительности эксперимента и полученные результаты

Часть I

Нейтринная астрономия высоких энергий

Neutrino as astrophysical messenger

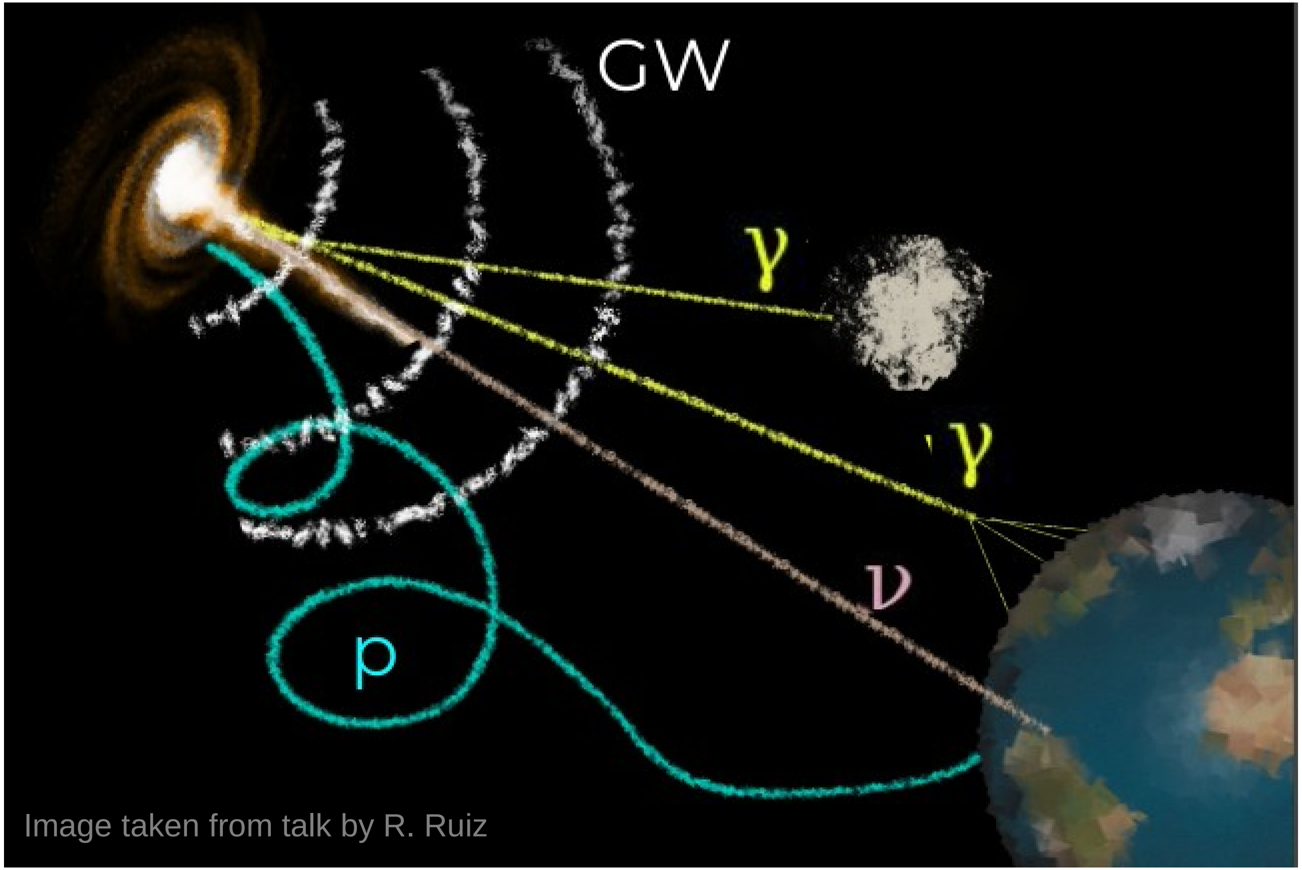
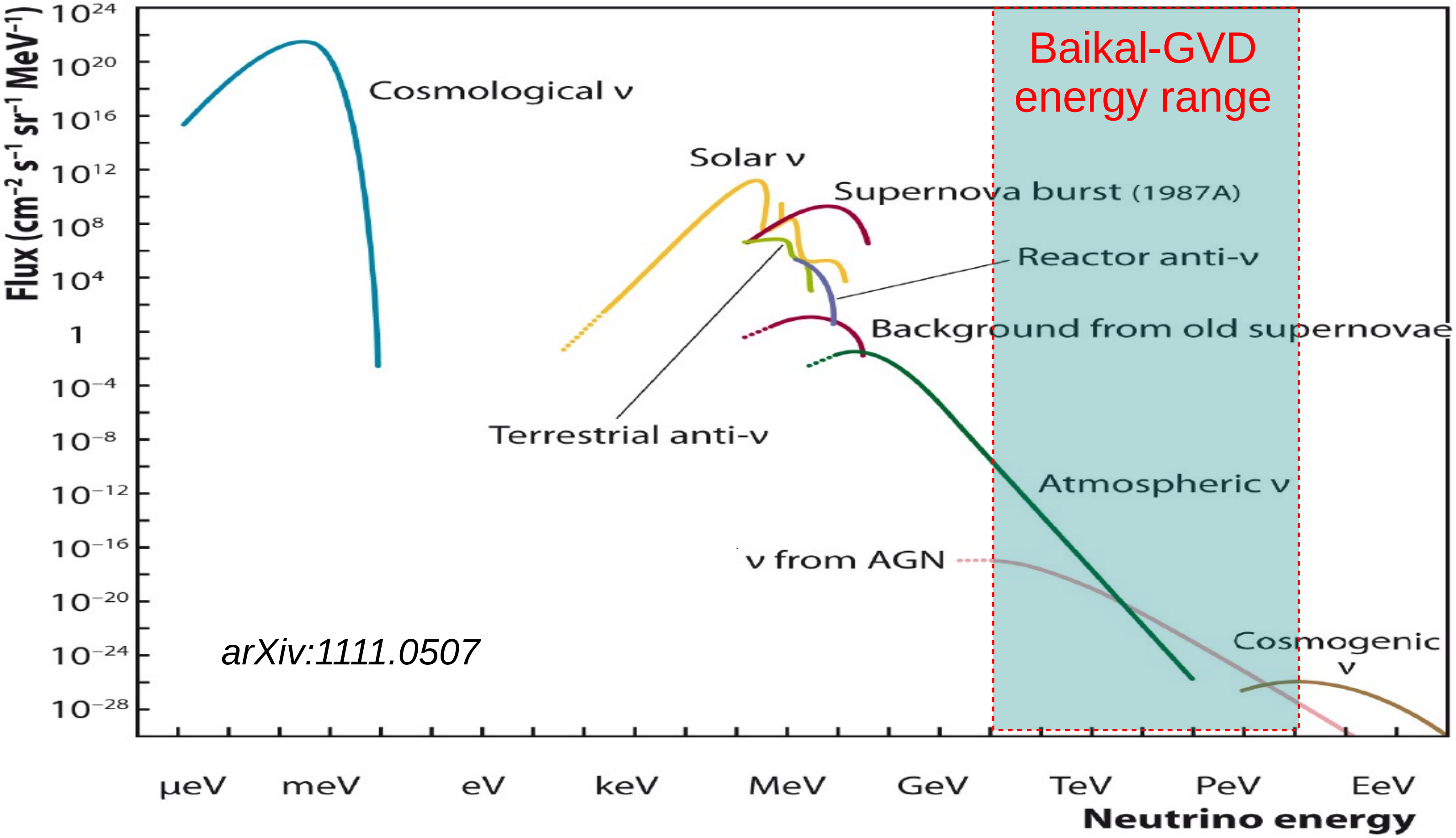


Image taken from talk by R. Ruiz

- Can escape from dense environments
- Travels unimpeded through gas and dust
- Does not interact with CMB and infrared background
- Stable (no decay)
- Not affected by magnetic fields
- Arrival direction points to the source
- High-energy neutrinos trace production and acceleration sites of cosmic rays

Where we are on the energy scale



How to make high energy neutrino

1) Accelerate protons

2) Have them interact with medium or radiation

In photon-reach environments: p γ → π
In proton-reach environments : p p → π

3) Decay pions

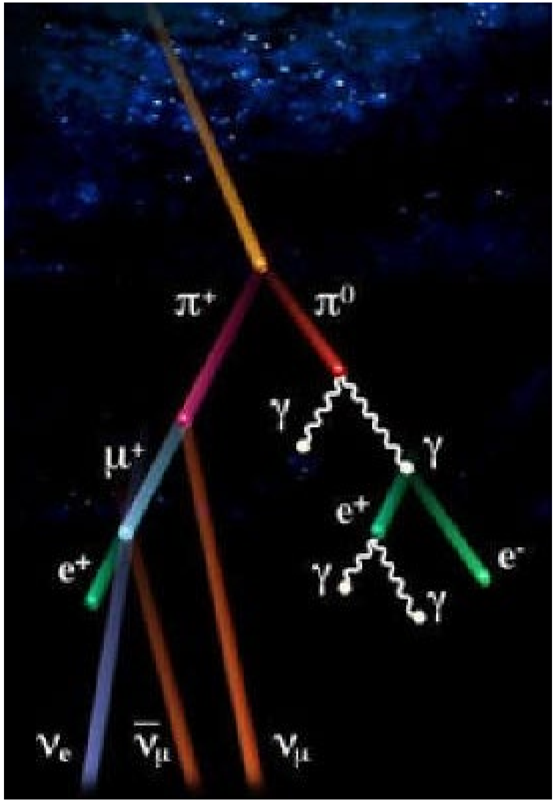
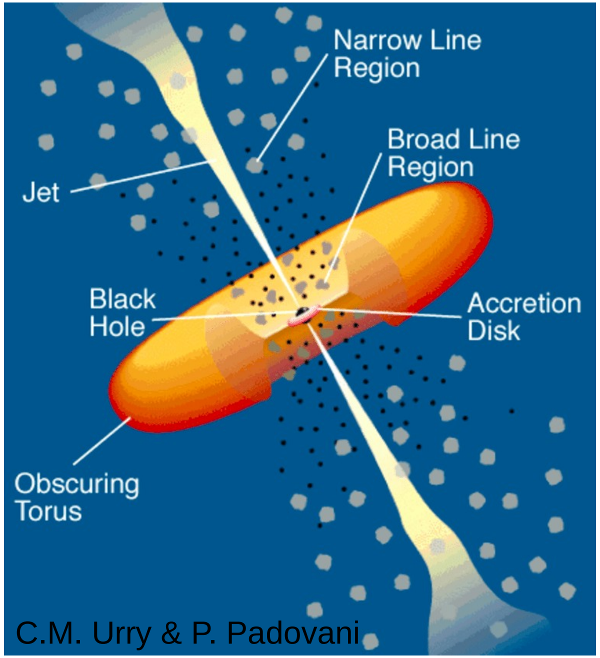
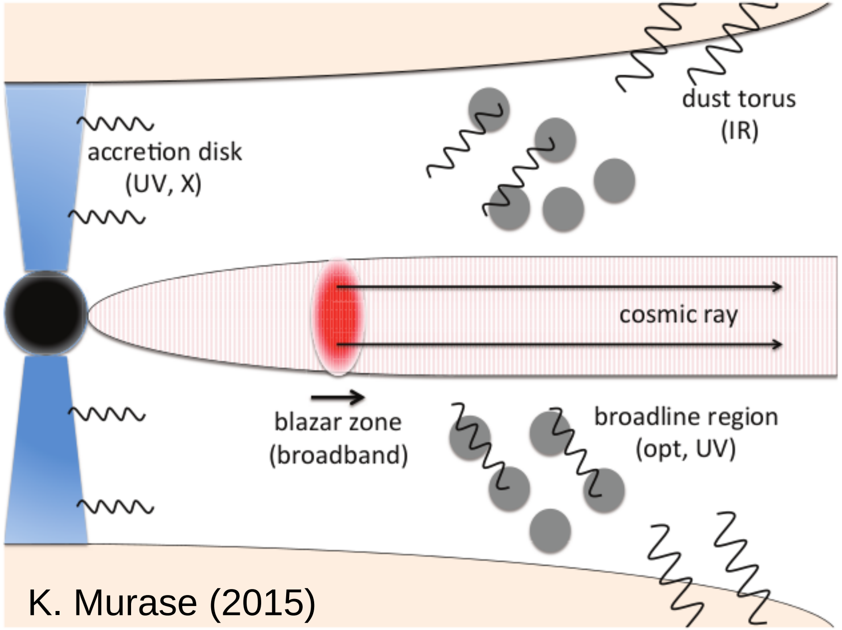


Figure from Relner et al, PRD (2008)

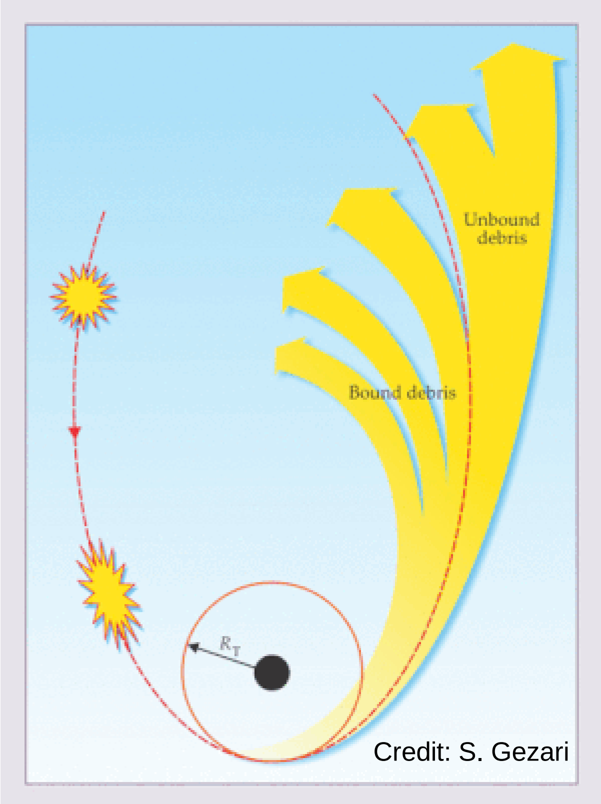
Potential neutrino sources: Active Galactic Nuclei



Example model



Tidal Disruption Events



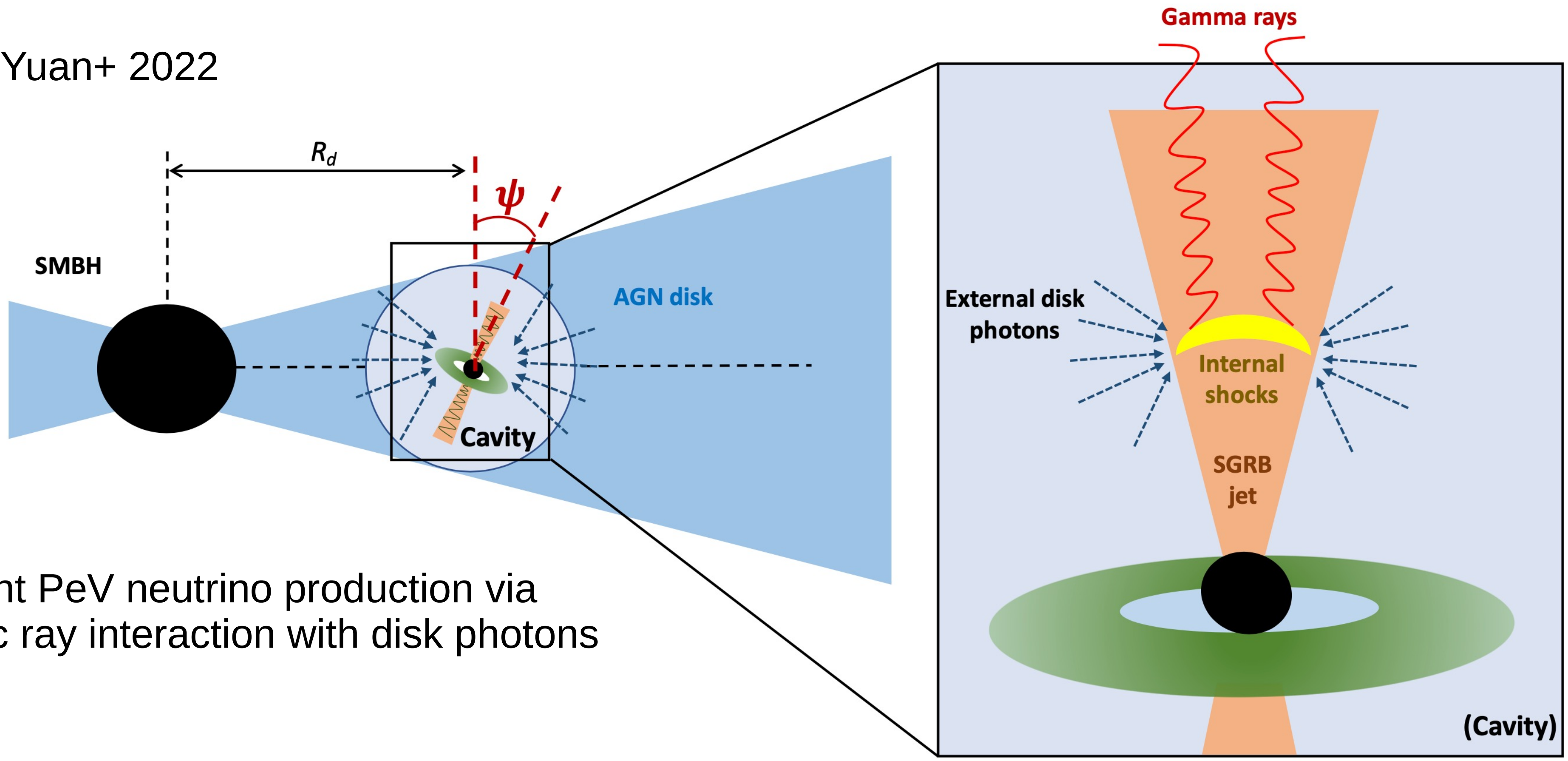
Star disrupted
in gravitational field
of supermassive black hole

R = Rocher limit

Also see *R. Stein et al., Nat. Astron. 5, 510 (2021)*

Neutron star mergers in AGN disks

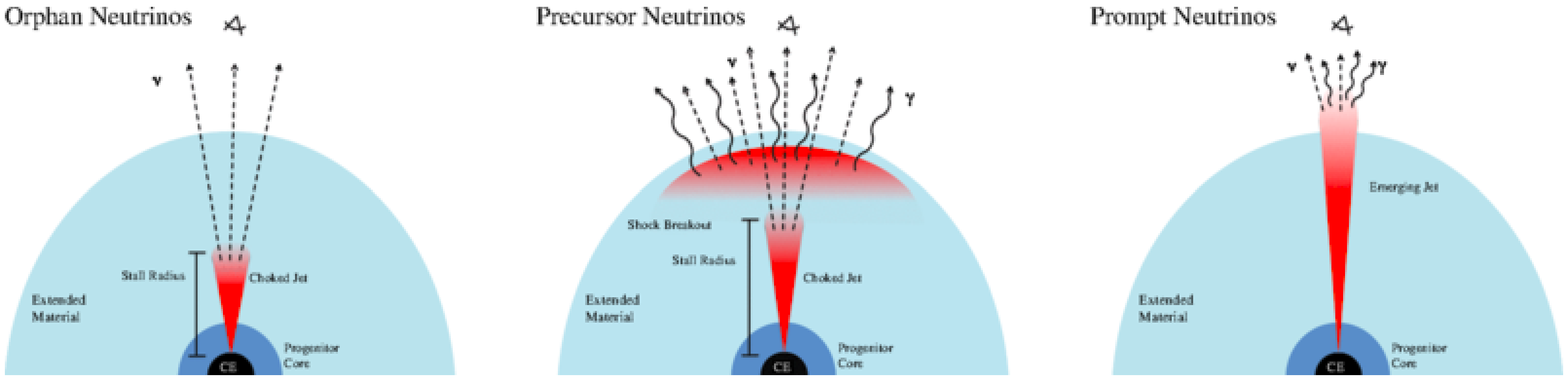
Yuan+ 2022



Efficient PeV neutrino production via cosmic ray interaction with disk photons

Also possible with black hole mergers (Kimura et al., 2021)

GRBs, choked jets (Supernovae)

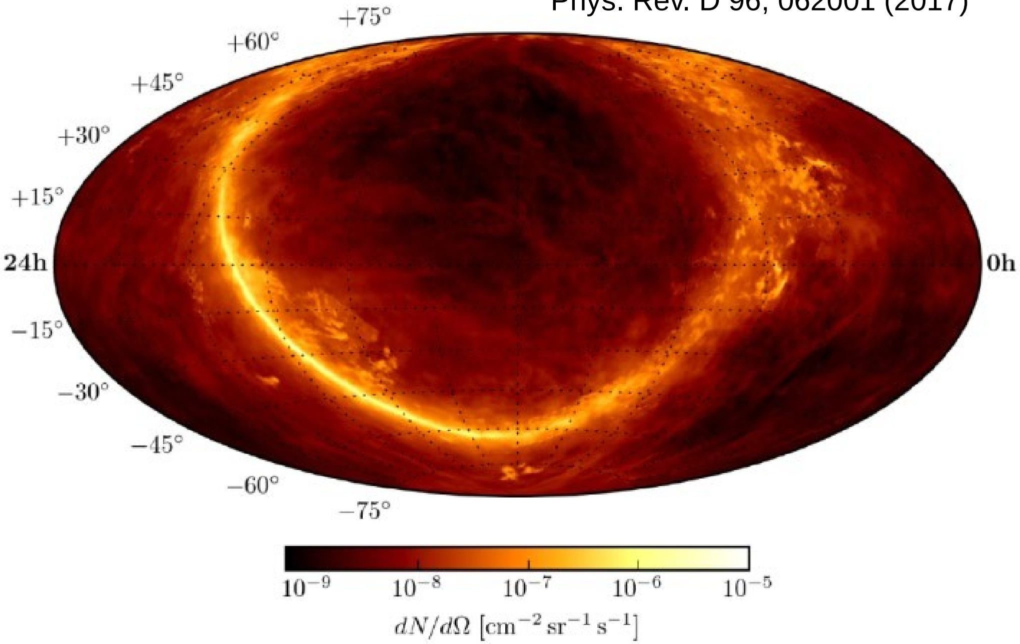


N. Senno, K. Murase, and P. Mészáros (2016)

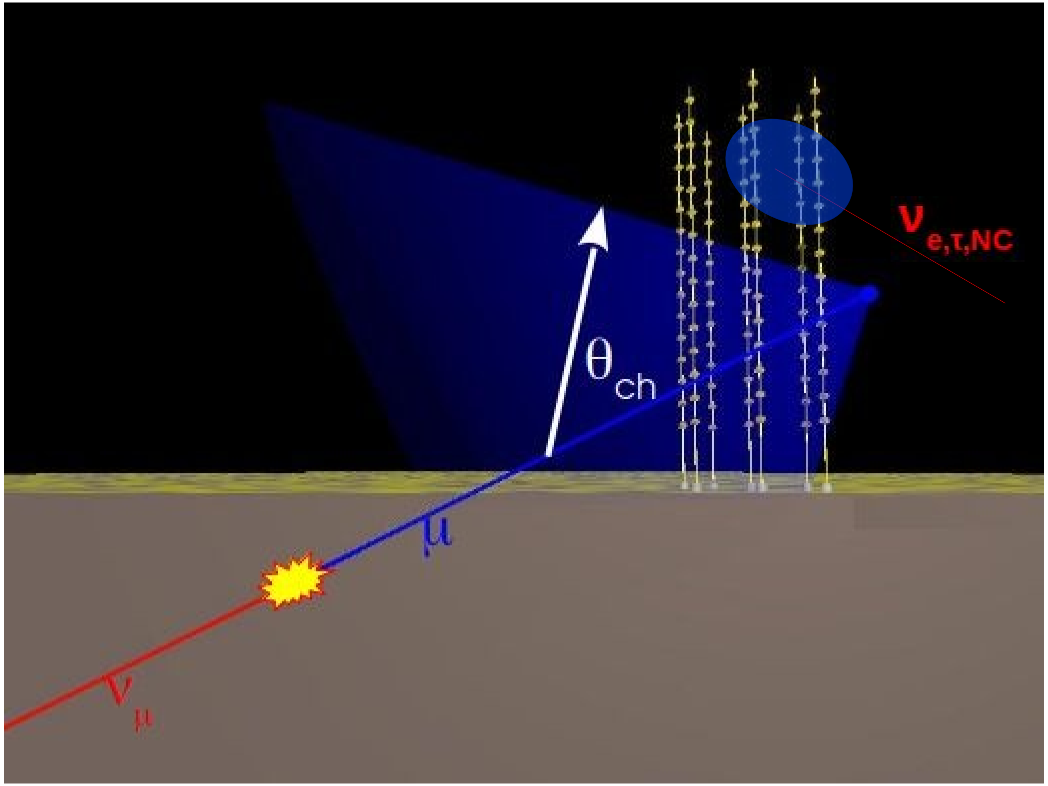
Possible Galactic neutrino sources

- Galactic Ridge / Galactic diffuse
- Supernova Remnants
- Pulsar Wind Nebulae?
- Microquasars
- Binaries
- Novae
- Galactic center

Phys. Rev. D 96, 062001 (2017)



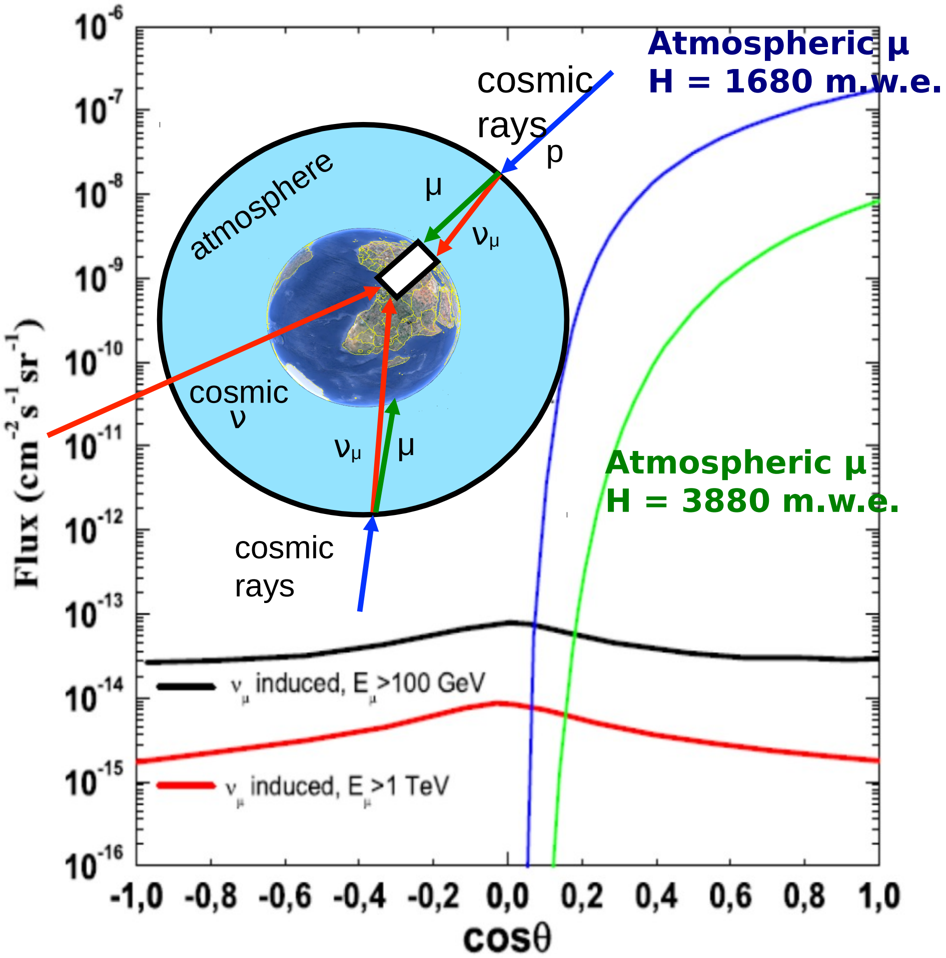
Neutrino telescope : how it works



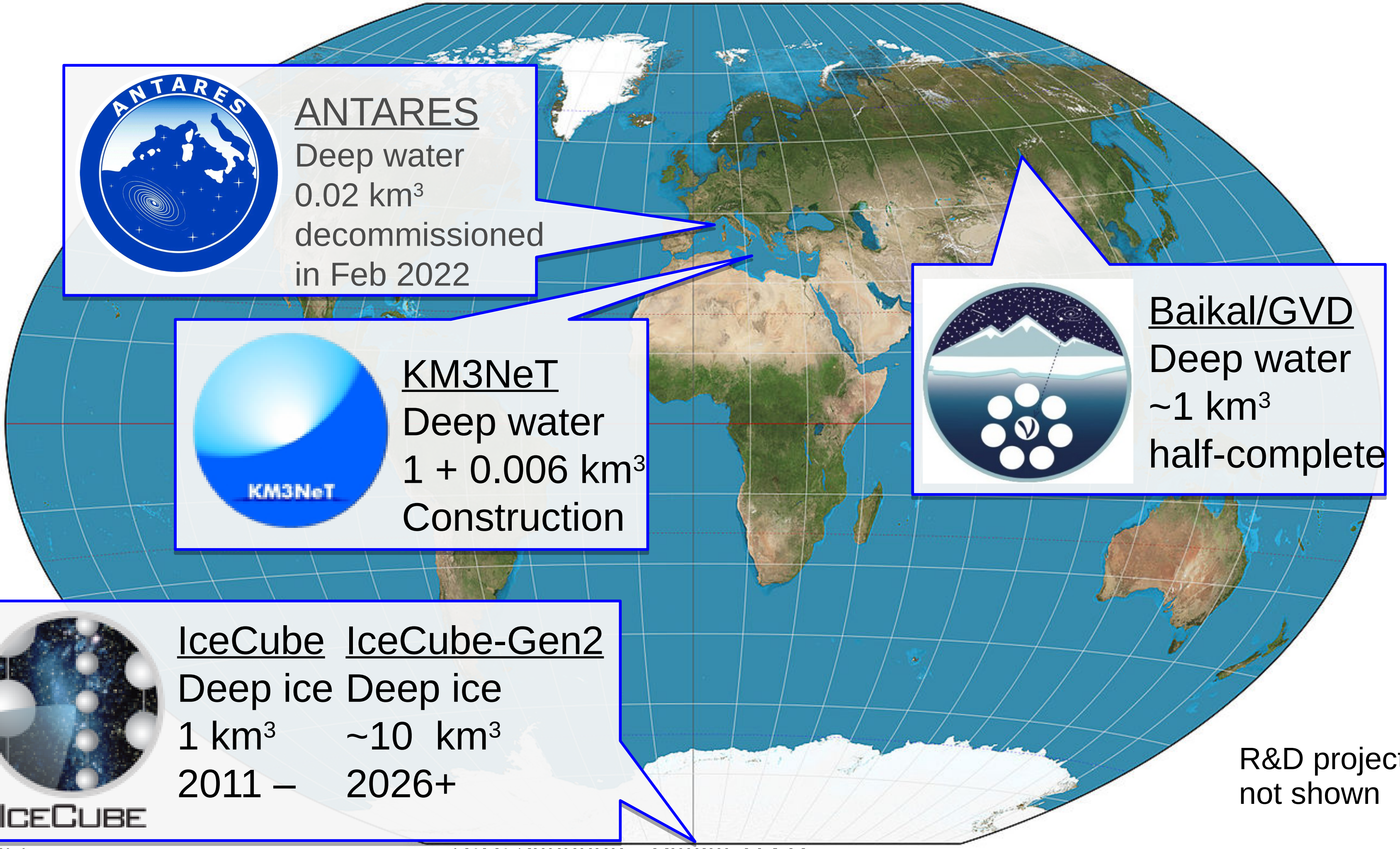
- Large arrays of PMTs in water or ice
- Cherenkov light detected by PMTs
- “Tracks”: ν_μ CC
- “Cascades”: ν_e & ν_τ CC + NC
- Direction reconstructed from hit positions and times
- Energy reconstructed from hit charges

Backgrounds

- Atmospheric neutrinos
  - All-sky, soft spectrum
  - For downgoing events, atmospheric muons can be used as veto (at very high energy)
- Atmospheric muons
  - Downgoing only (Earth acts as filter)
- Environmental background light: natural radioactivity (^{40}K), bioluminescence, chemiluminescence
  - Limits low energy sensitivity



Neutrino telescope world map 2022



ANTARES
Deep water
0.02 km³ → $0.02\ km^3$
decommissioned in Feb 2022

KM3NeT
Deep water
$1 + 0.006\ km^3$
Construction

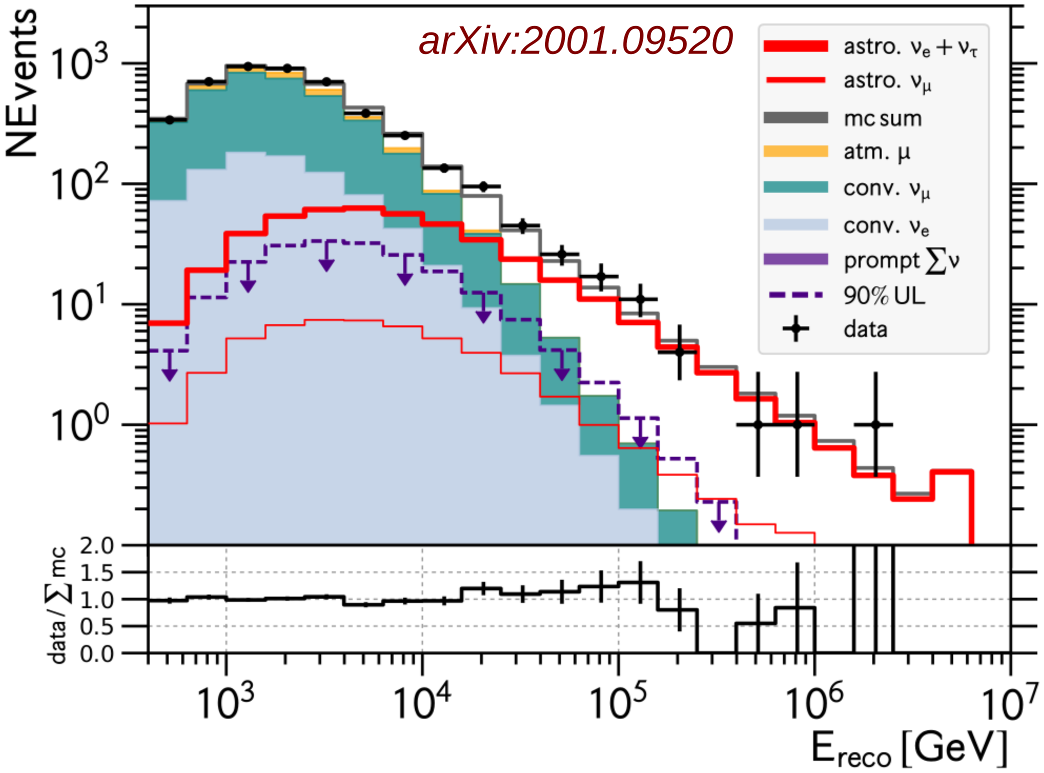
Baikal/GVD
Deep water
$\sim 1\ km^3$
half-complete

IceCube	IceCube-Gen2
Deep ice	Deep ice
$1\ km^3$	$\sim 10\ km^3$
2011 –	2026+

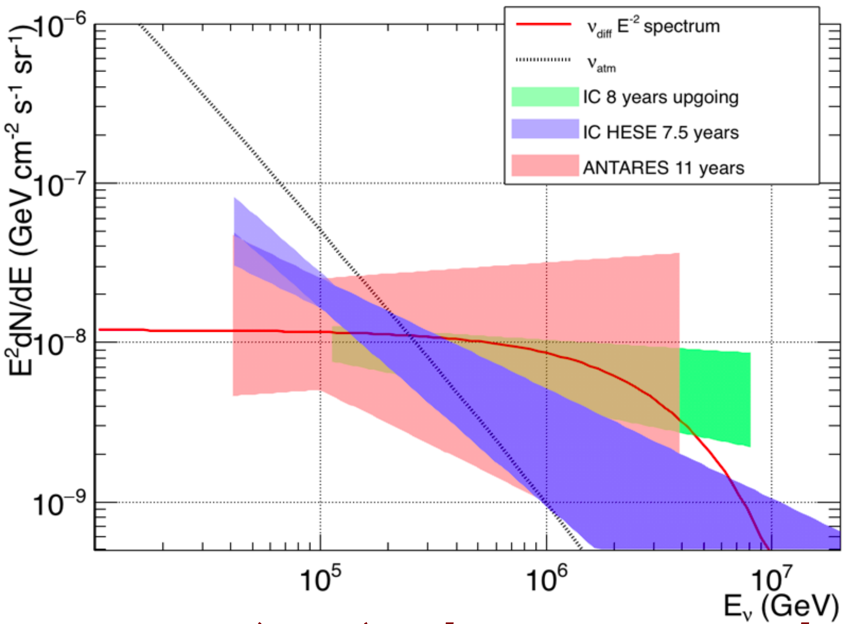
R&D projects not shown

Diffuse neutrino flux

IceCube cascades



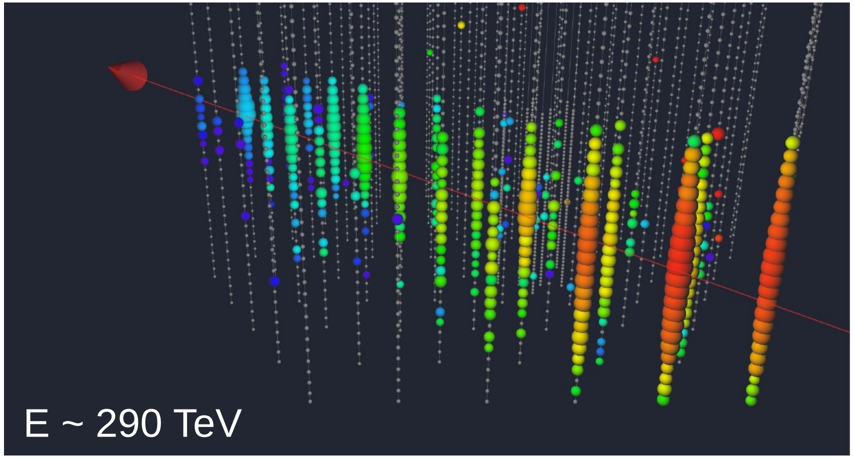
While the existence of a diffuse neutrino flux is firmly established, its origin remains unknown



Science 342 (2013) [4.1 σ]
PRL 113:101101 (2014) [5.9 σ]
PRL 125:121104 (2020) [~10 σ]

ApJ 853 (2018) L7 [arXiv:1711.07212]
D. Samtleben, Neutrino 2020

TXS 0506+056

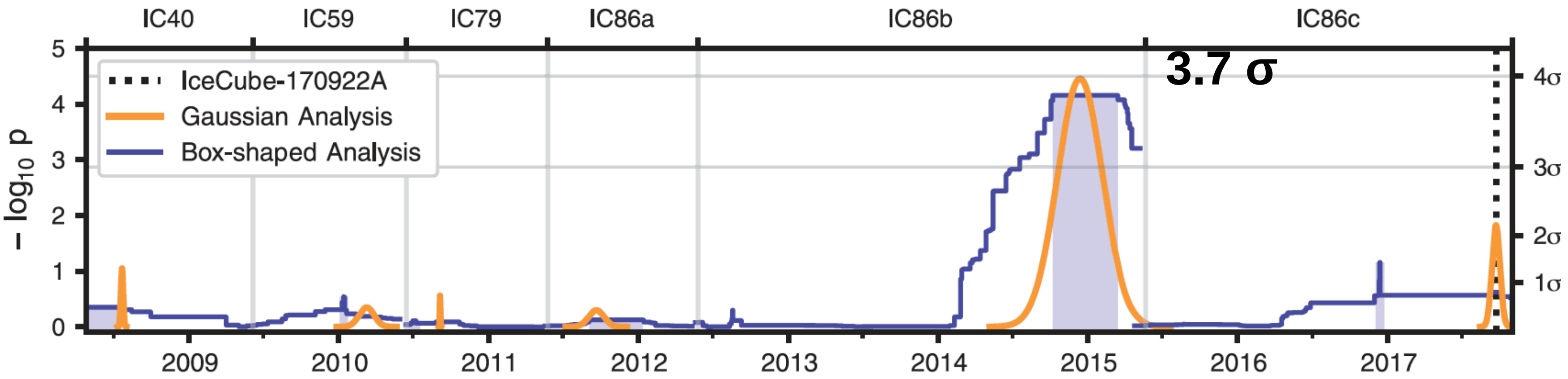


High-energy IceCube ν coincident with a γ-ray flare from the blazar TXS 0506+056 (Sep 22, 2017)

Science 361,147–151 (2018)

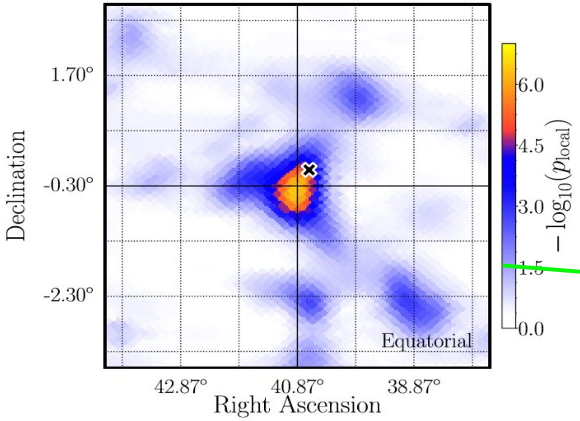
Another, neutrino-only flare found in earlier IceCube data

A. Albert et al., ApJL 863, L30 (2018)

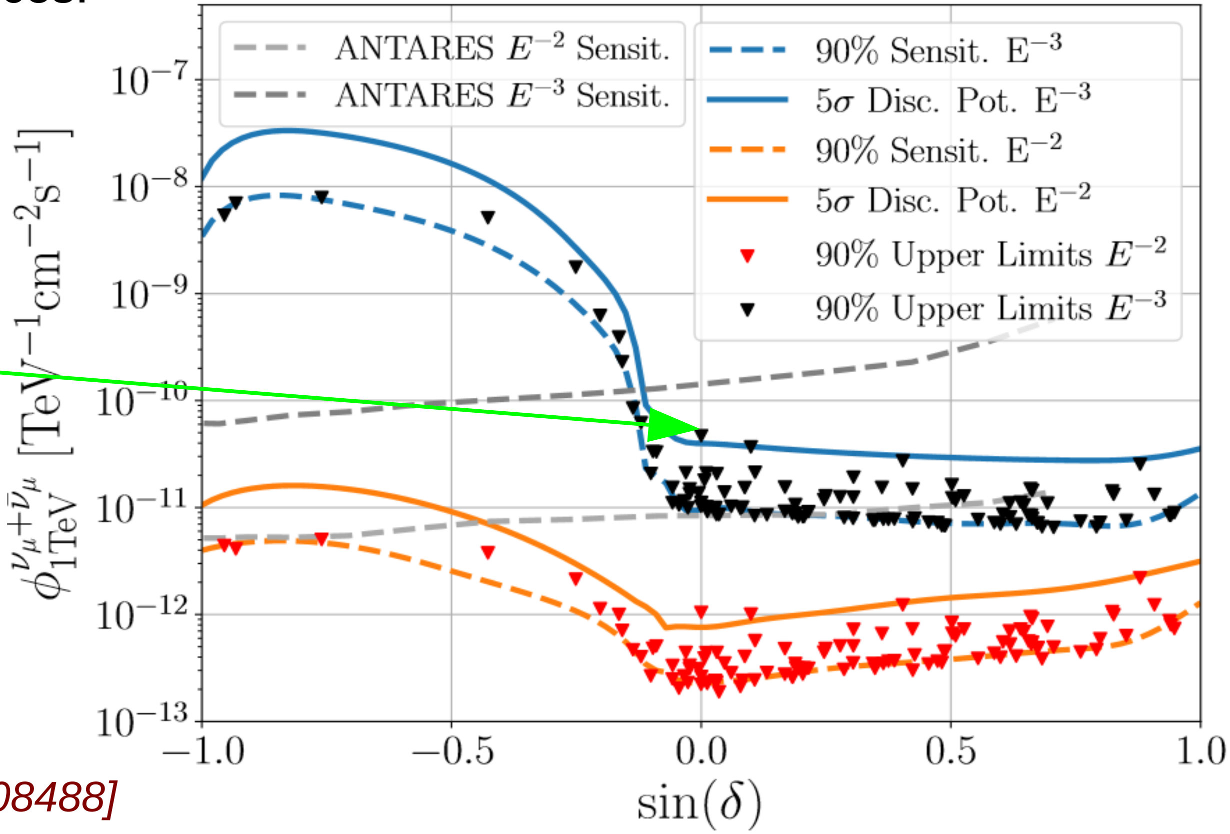


Point-source searches

Some evidence for non-uniform skymap in 10 years of IceCube data (3.3σ).
Mostly resulting from 4 extragalactic source candidates.
No indications for galactic sources.



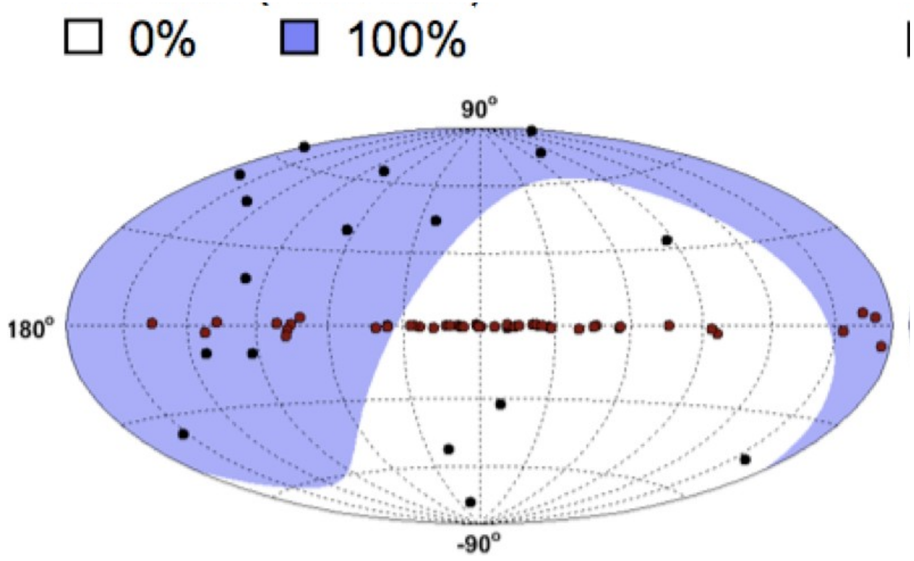
Strongest excess
(2.6 σ post trial) close to
galaxy NGC 1068 (cross)



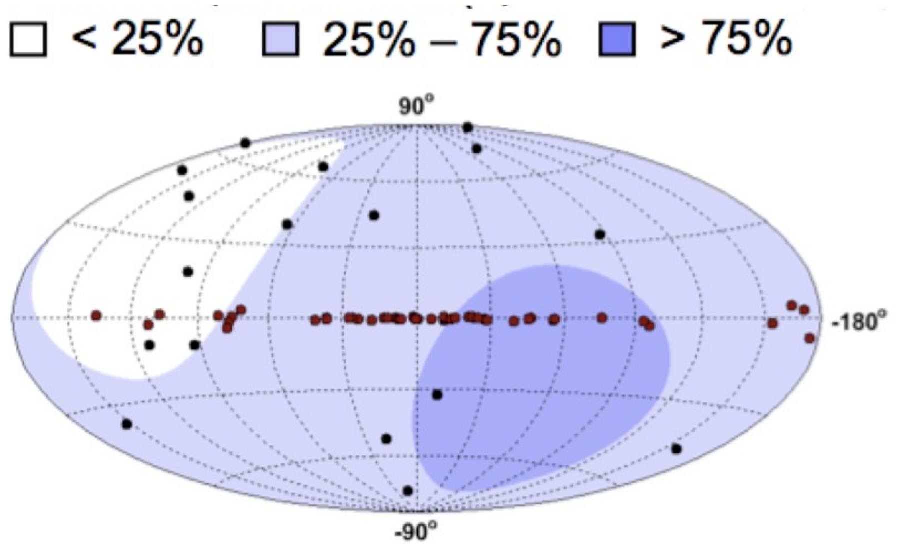
PRL 124, 051103 (2020) [arXiv:1910.08488]

Sky visibility with upgoing tracks

South Pole (IceCube)



Northern hemisphere
(Mediterranean)



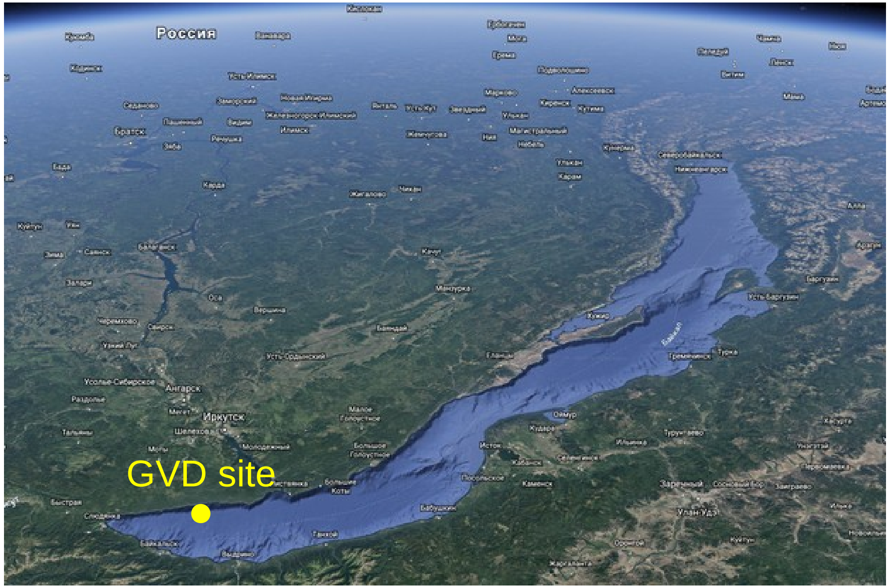
Complementary sky coverage

Galactic center better viewed from Northern hemisphere (through the Earth)

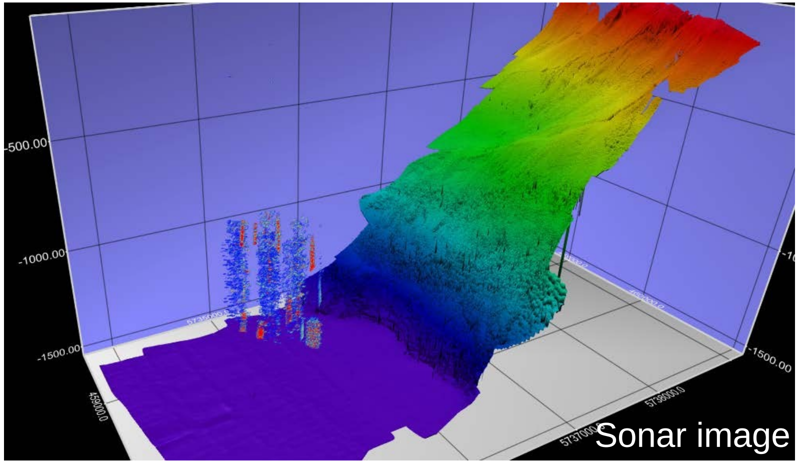
Часть II

Baikal-GVD

Baikal-GVD site

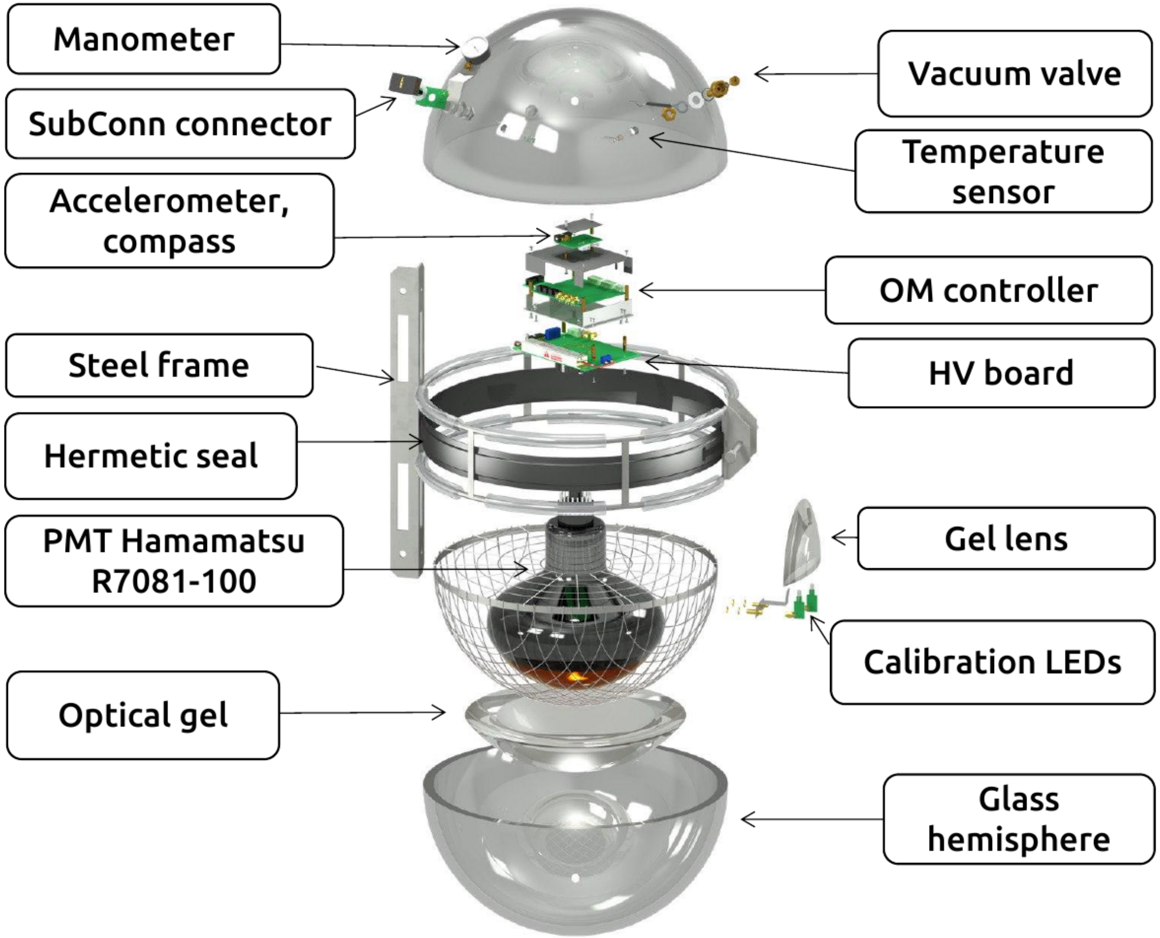


- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance

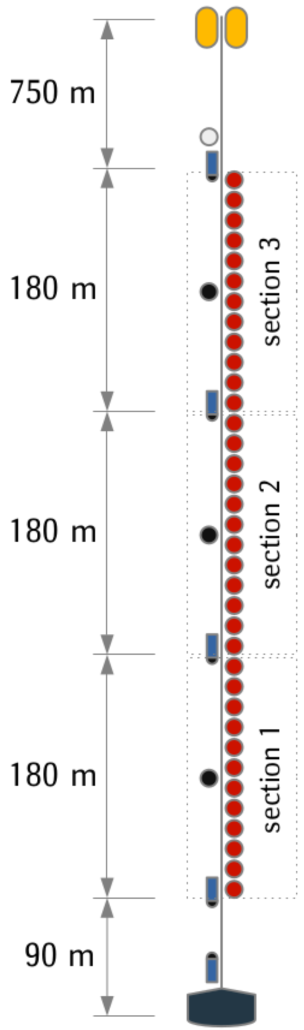


- High water transparency
  - Absorption length: 22 m
  - Scattering length: 30 – 50 m ($L_{eff} \approx 480$ m)
- Moderately low optical background: 15–40 kHz (PMT R7081-100 ∅10”)

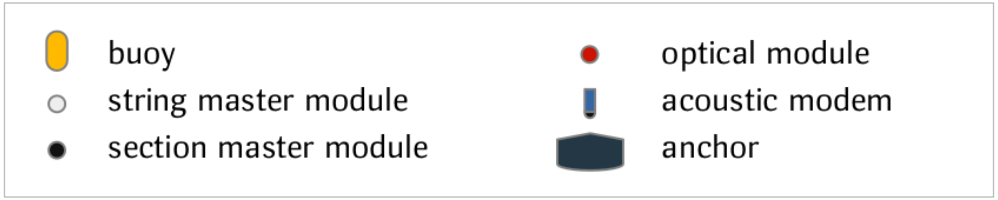
Baikal-GVD optical module



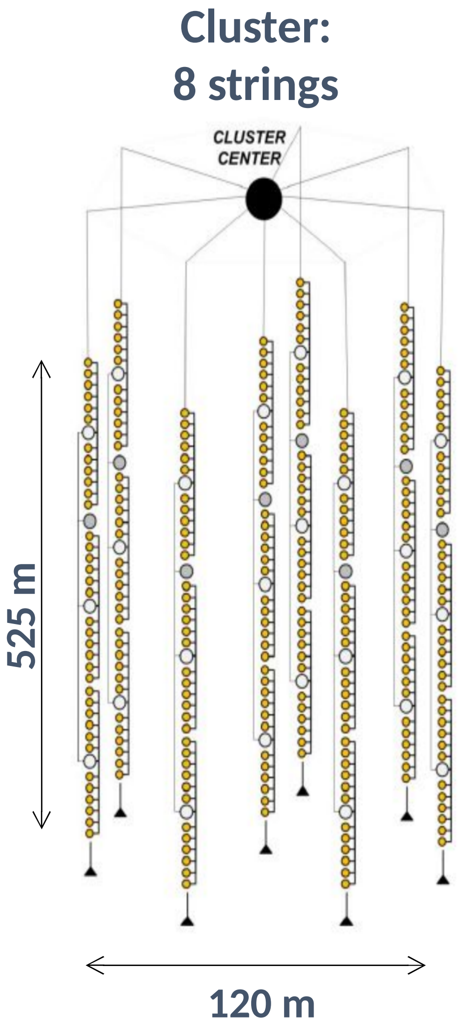
GVD string



- **36 OMs**, 15 m spacing, all PMTs look downward
- **4 acoustic modems** (AM) of the positioning system
- **3 section modules**, each serving 12 OMs (12-channel ADC, 200 MHz sampling; waveform measurement + trigger logic, events forming, data filtration)
- **1 string module** (a communication hub)
- Depths from 750 m to 1275 m

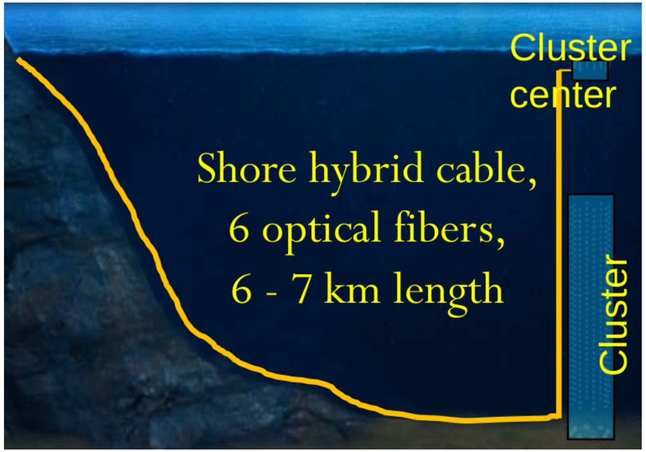


GVD cluster



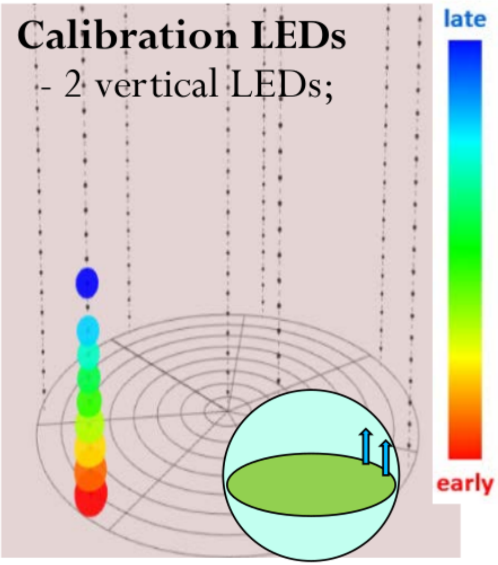
Cluster

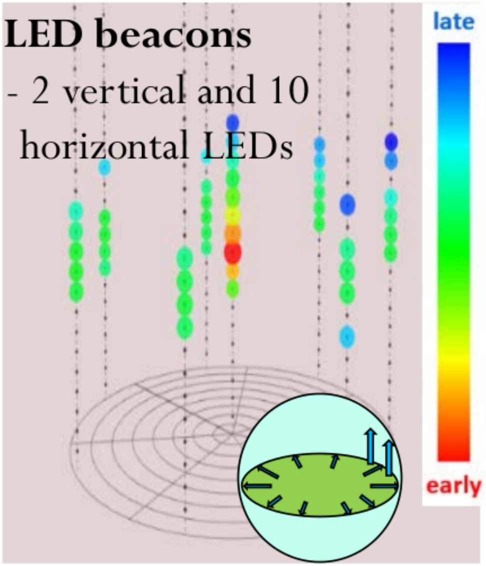
- 8 strings (288 OMs)
- 60 m step between strings
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger: 4.5 p.e. + 1.5 p.e. on adjacent OMs in 100 ns window
- Inter-section synchronisation by common trigger (~ 2 ns accuracy)
- Internal network: shDSL Ethernet extenders 5.7 Mbit
- Connection to shore:
  Ethernet / optic fiber



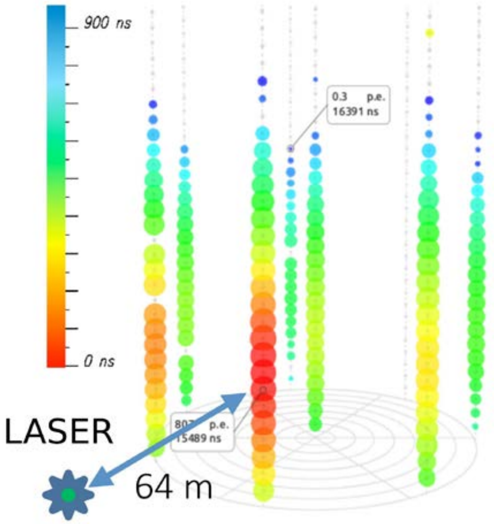
Calibration devices

- 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

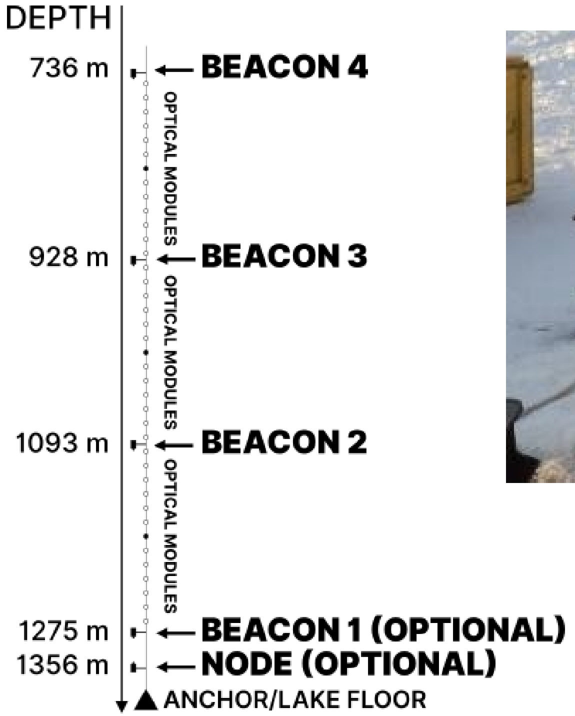


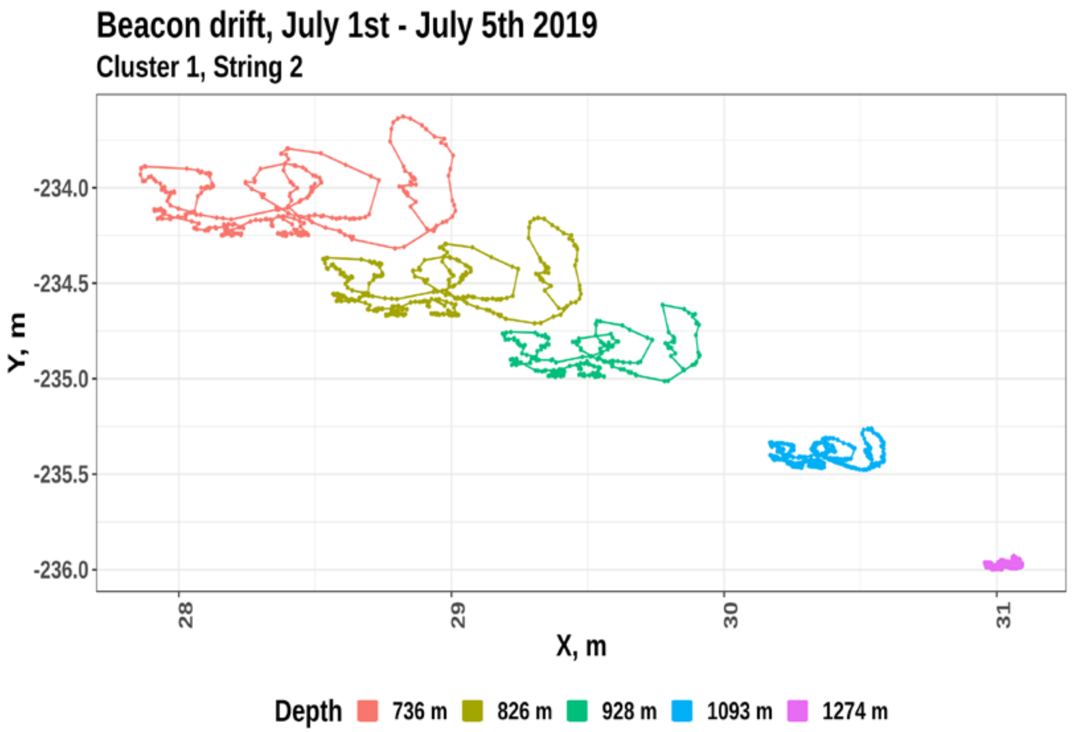


Calibration accuracy ~2 ns



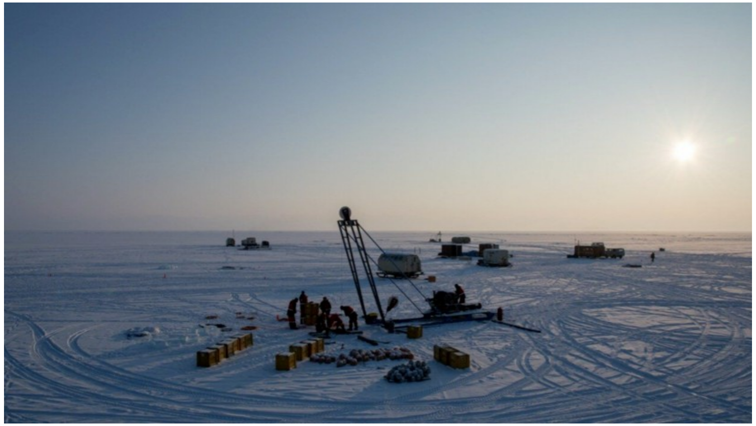
Acoustic positioning





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

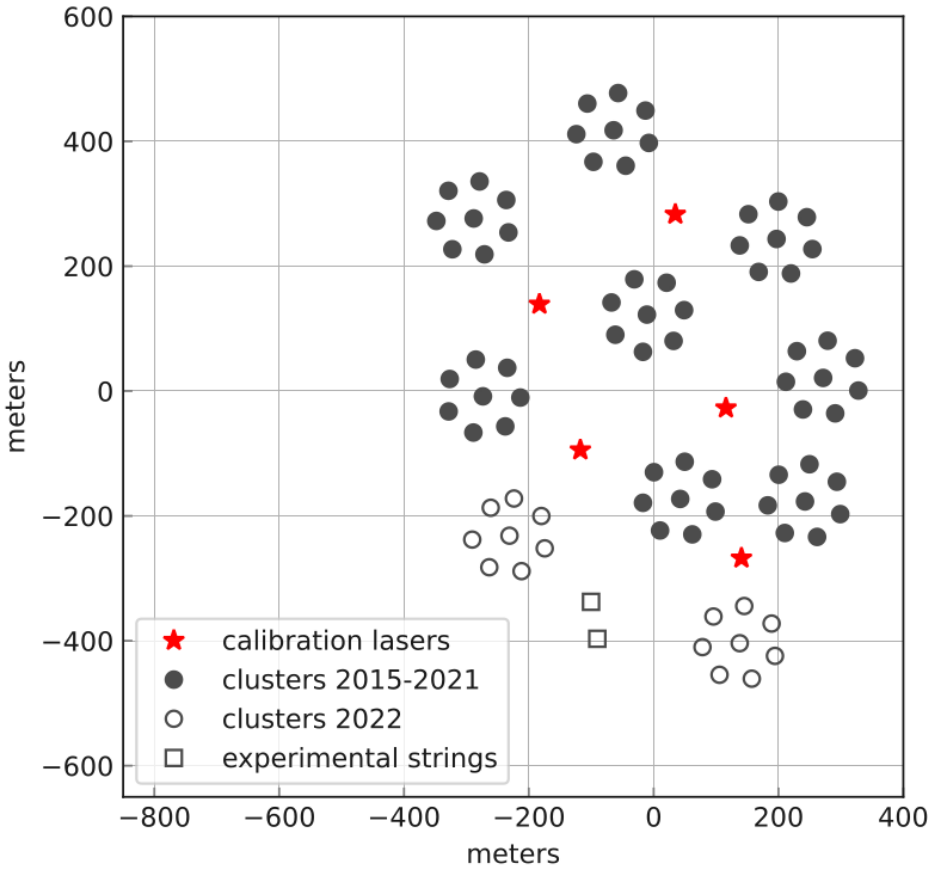
Deployment



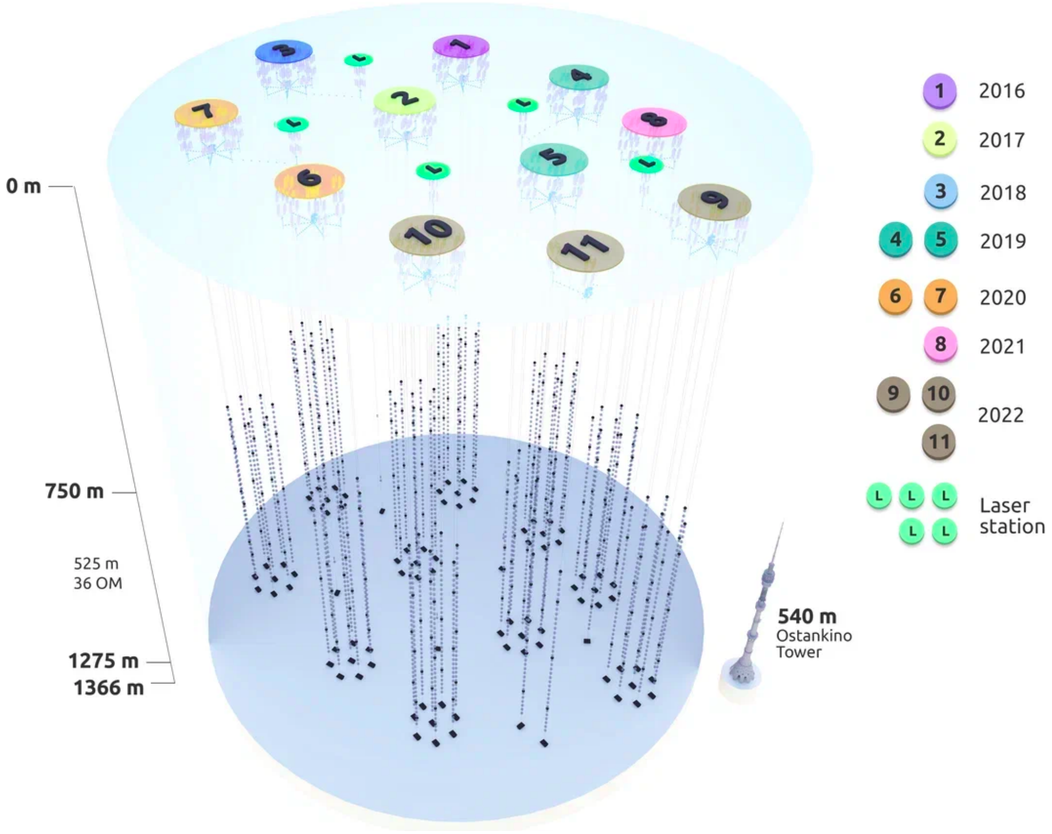
Экспедиция 2022

Установлено:

- два новых кластера (16 гирлянд)
- 2 экспериментальные гирлянды на оптоволоконной технологии связи (активно 48 ОМ)
- 1 дополнительная межкластерная гирлянда (36 ОМ + лазер)
- 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

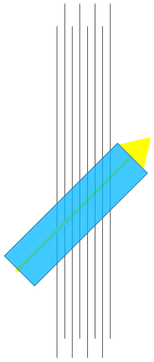
Effective volume 2022: 0.40 km^3 (cascades 100 TeV)

Часть III

Характеристики детектора Baikal-GVD и первые результаты

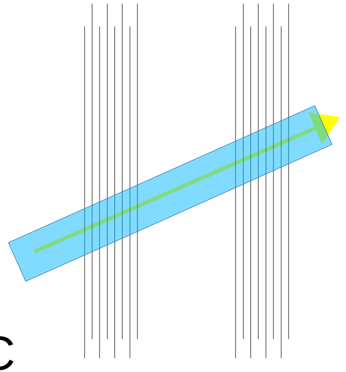
Event types

Single-cluster tracks



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

Multi-cluster tracks

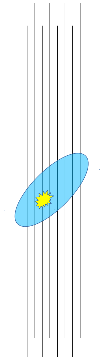


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- 10% of recorded track events

ν_μ CC

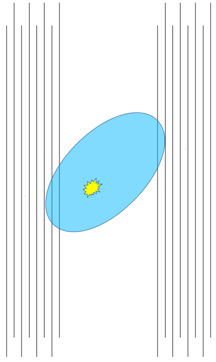
NC, ν_e ν_τ CC

Single-cluster cascades



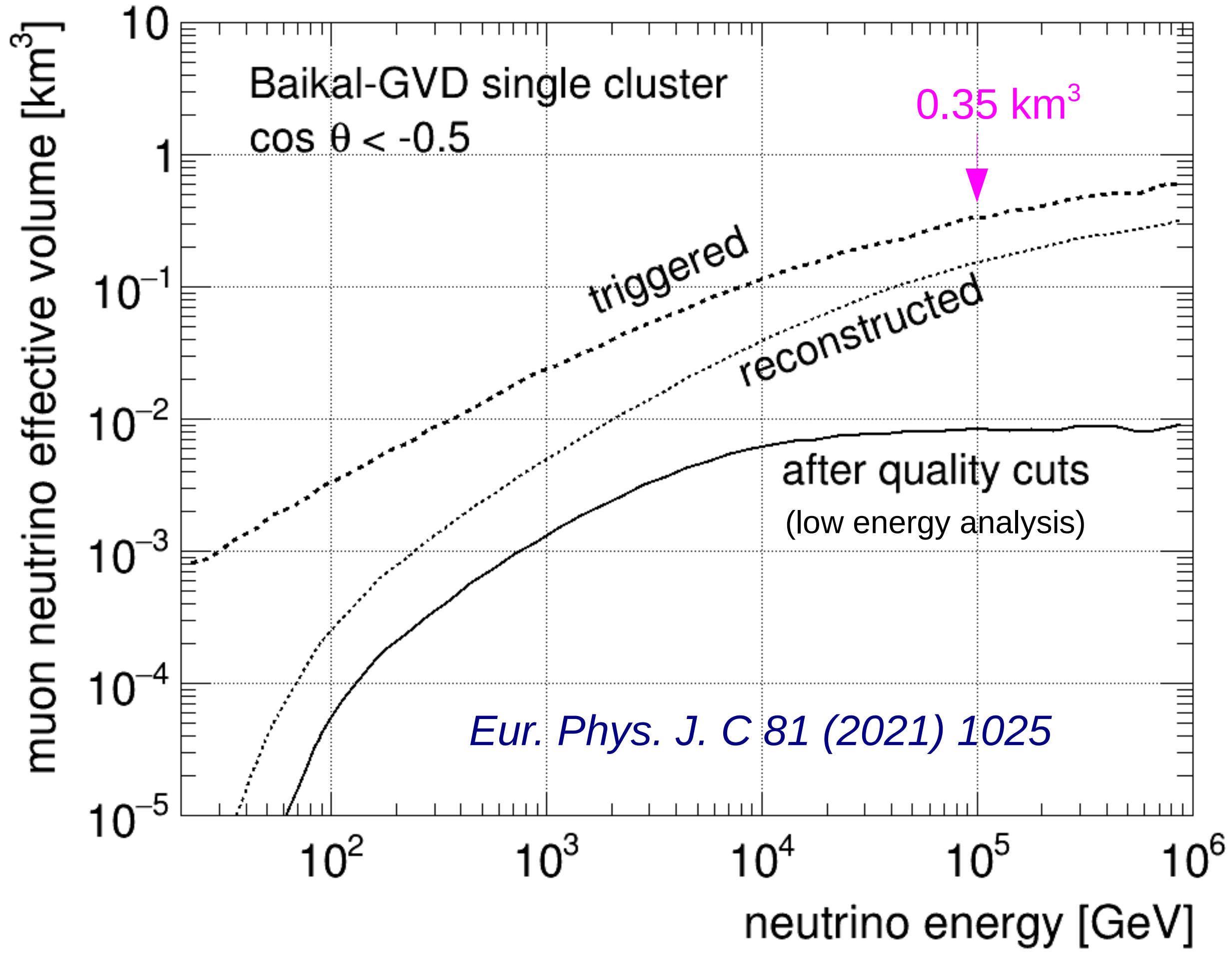
- High energy threshold
- Good energy resolution
- Relatively rare events

Multi-cluster cascades



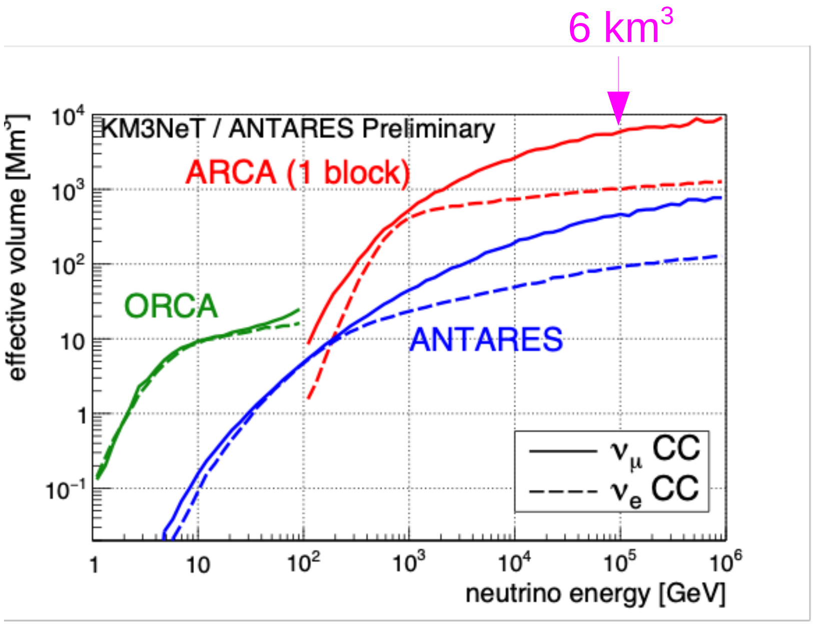
- Very high energy threshold
- Excellent energy resolution
- Very rare events

Neutrino effective volume for tracks (one GVD cluster)



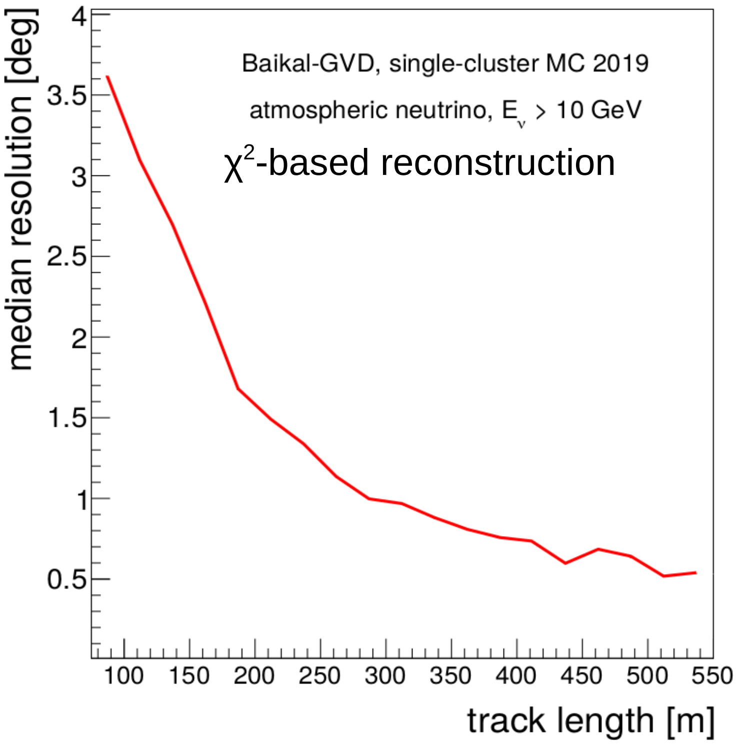
Energy threshold ~ 200 GeV (higher than in ANTARES)

Fully efficient at E > 100 TeV

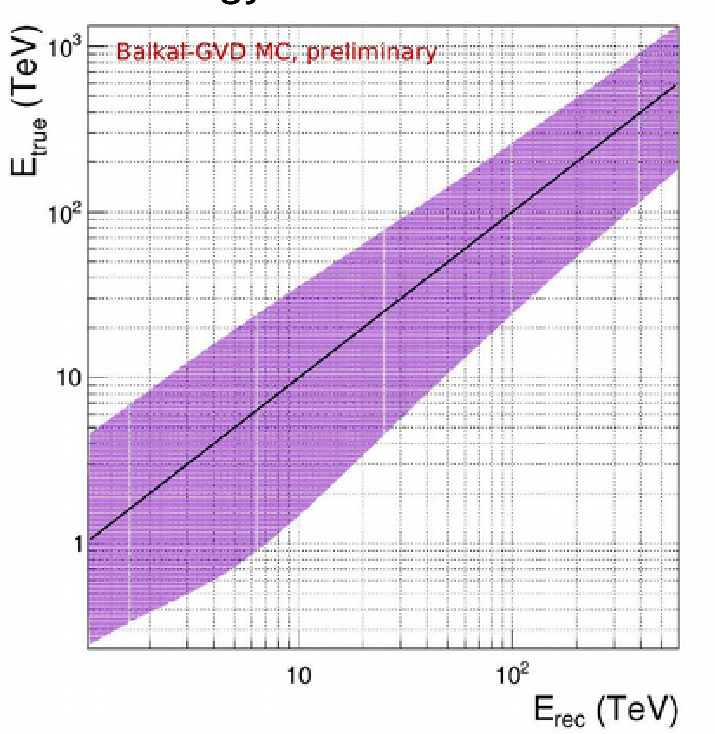


Expected performance for tracks

Angular resolution



Energy reconstruction



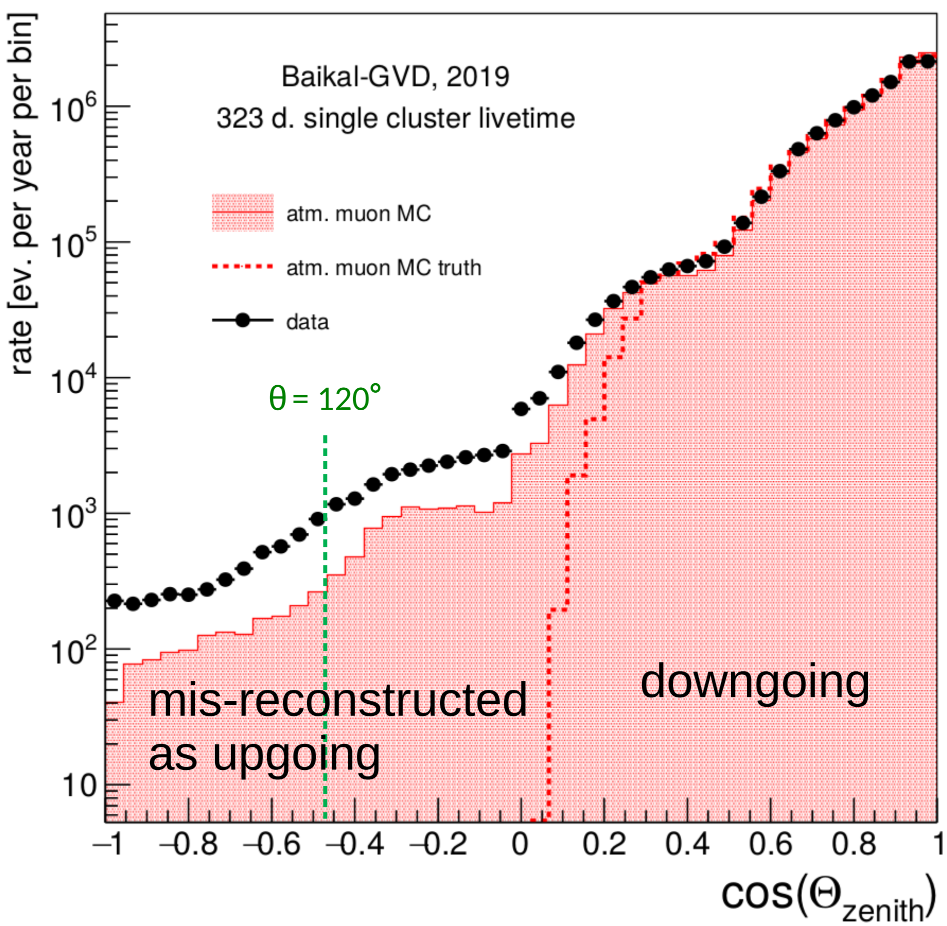
Improvements expected from likelihood-based reconstruction (under development)

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

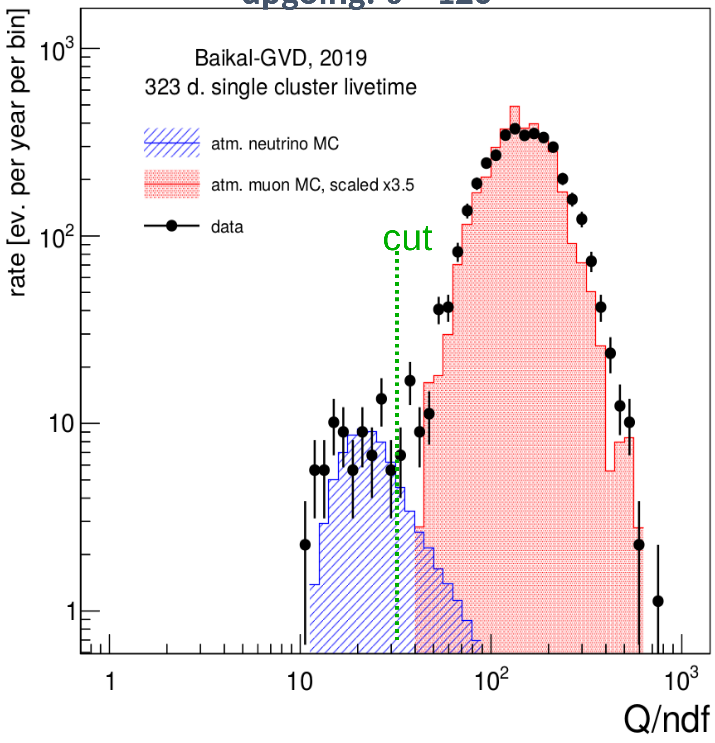
MC underpredicts the rate of misreconstructed events in the upgoing region by a factor of 3.5 (under study)

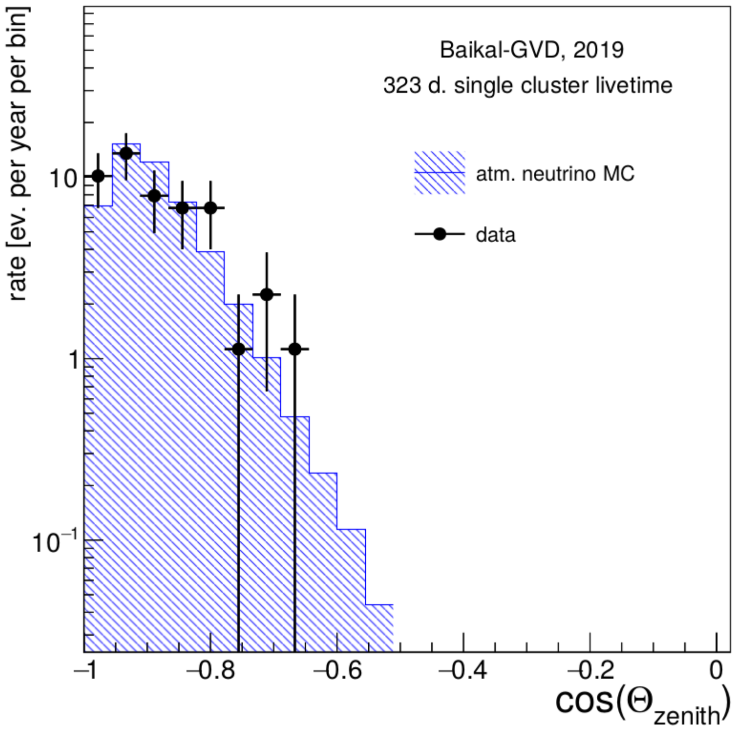
NB: most of these events are muon bundles (average multiplicity ~ 10)

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

Atmospheric neutrinos with Baikal-GVD (single cluster)

upgoing: θ > 120°





MC expected: 43.6

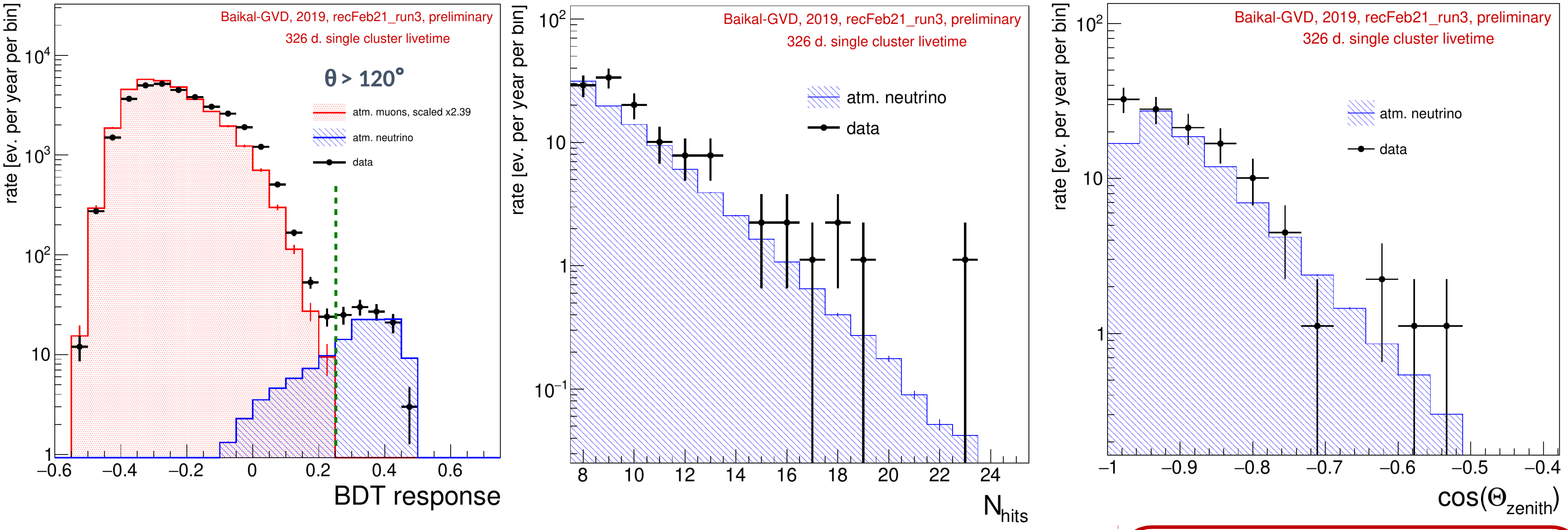
- atm. neutrino : 43.6
- atm. muons: < ~ 1

Observed events: 44

Median energy of this sample ≈ 500 GeV

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

Atmospheric neutrinos : improved analysis

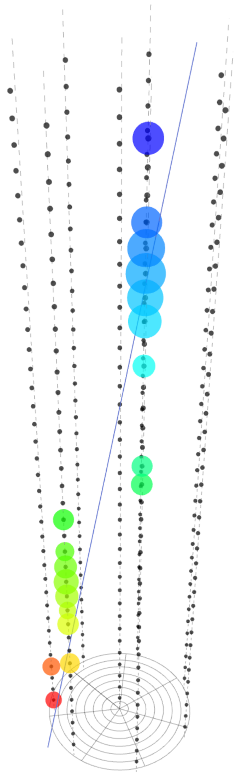


Hit finder: efficient hit-finding algorithm [PoS-ICRC2021-1063]
Track fit: χ2(t) - based fitter
Neutrino selection: boosted decision tree classifier (BDT) based on 15 track quality variables

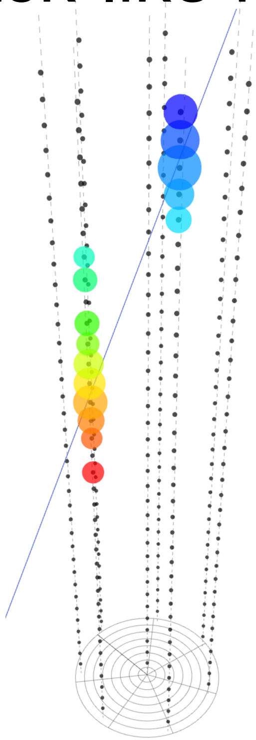
MC expected: 81.2
Observed events: 106
possible background contamination under study

G. Safronov, Neutrino 2022

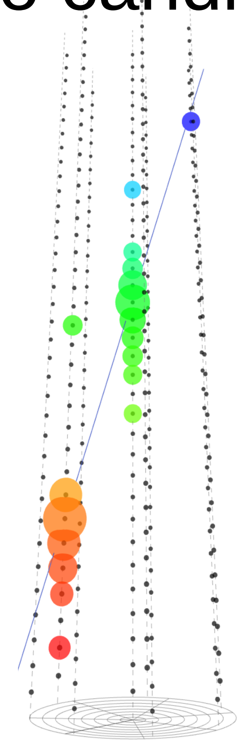
Track-like neutrino candidate events



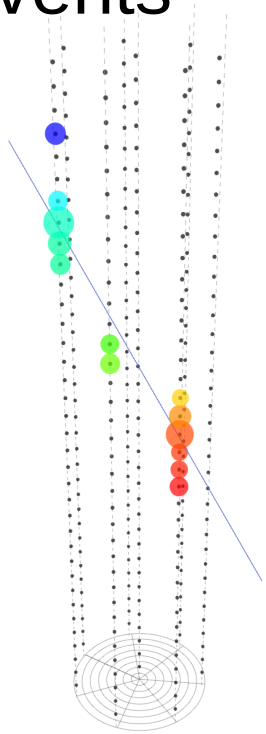
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



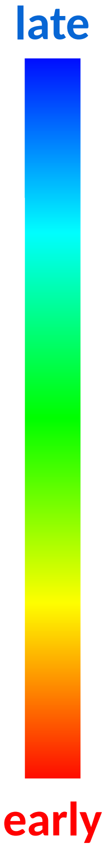
cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15



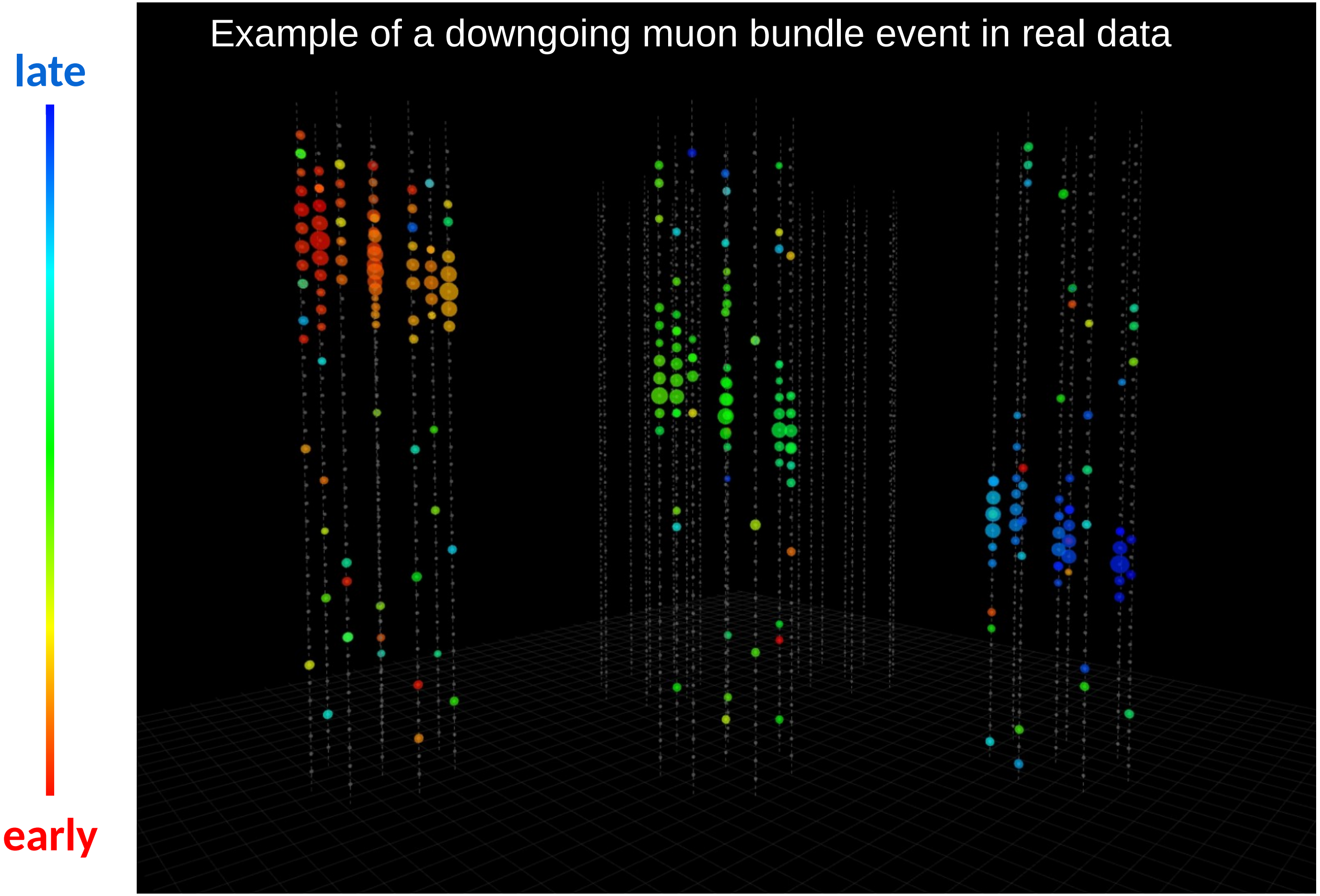
cluster 4, run 99
evt. 438088
θ_{zenith} = 162.22°
$N_{strings}$ = 3
N_{hits} = 18

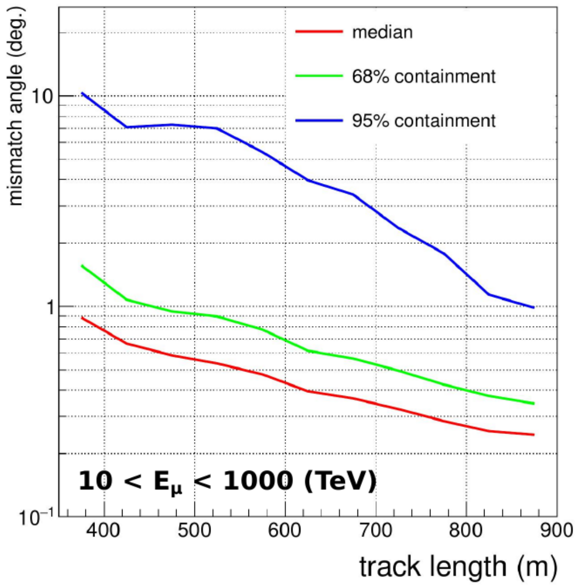


cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13



Multi-cluster track events





Median energy ~ 4 TeV

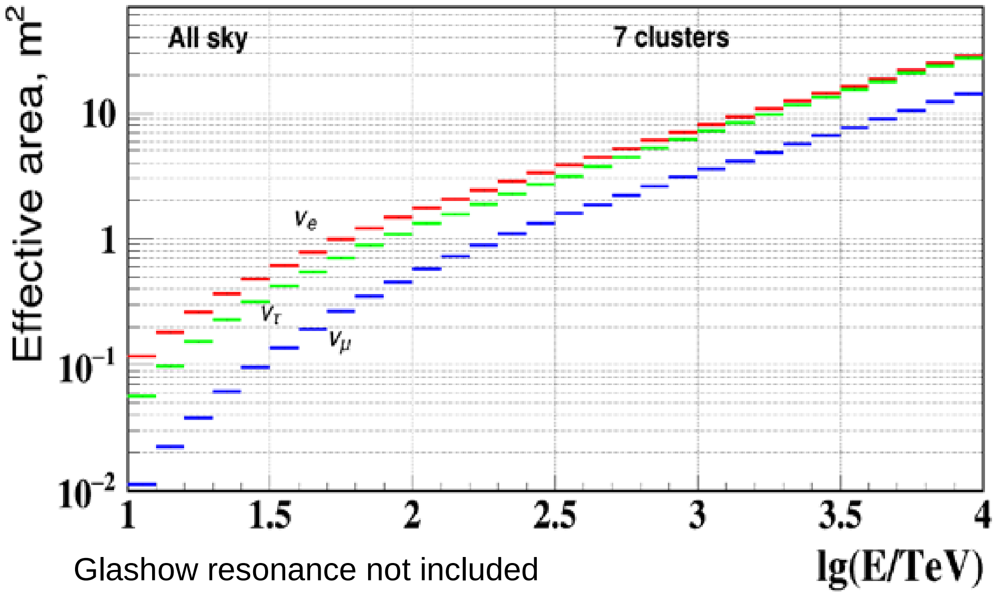
Work in progress !

Cascade analysis : effective area and rates

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

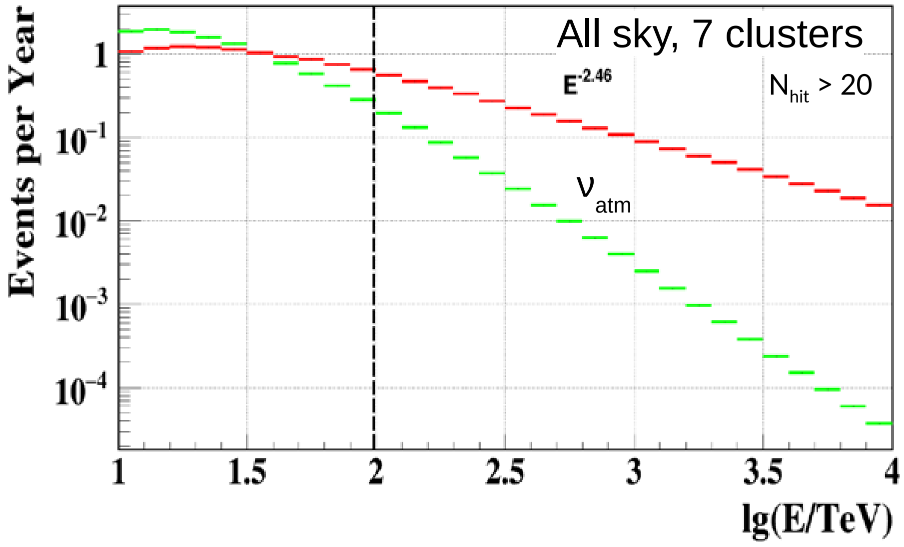
Assumption for astrophysical neutrino energy spectrum (IceCube fit):
$4.1 \bullet 10^{-6}\ E^{-2.46}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

neutrino effective area for cascade detection



Glashow resonance not included

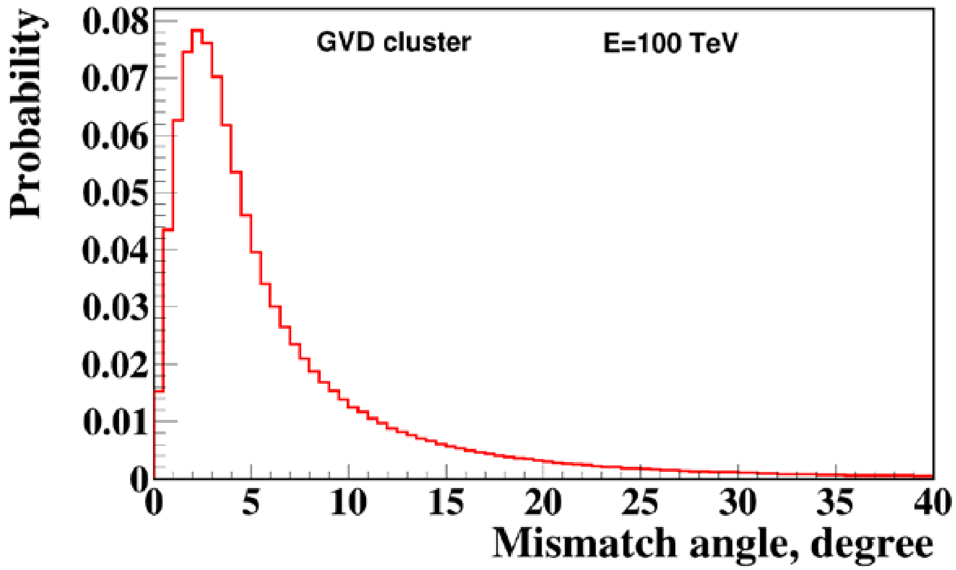
Expected number of cascade events per year

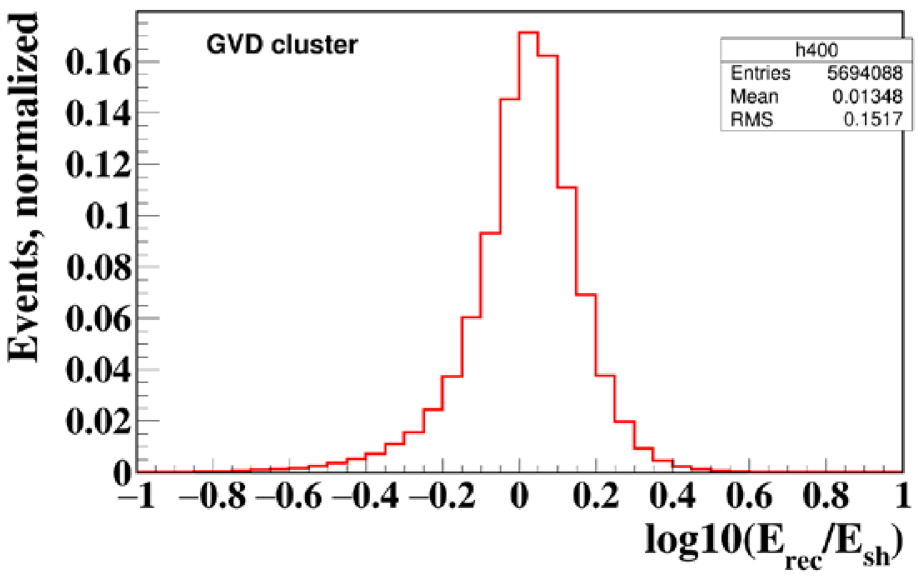


Effective volume for E > 100 TeV ~ **0.35 km³**

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%

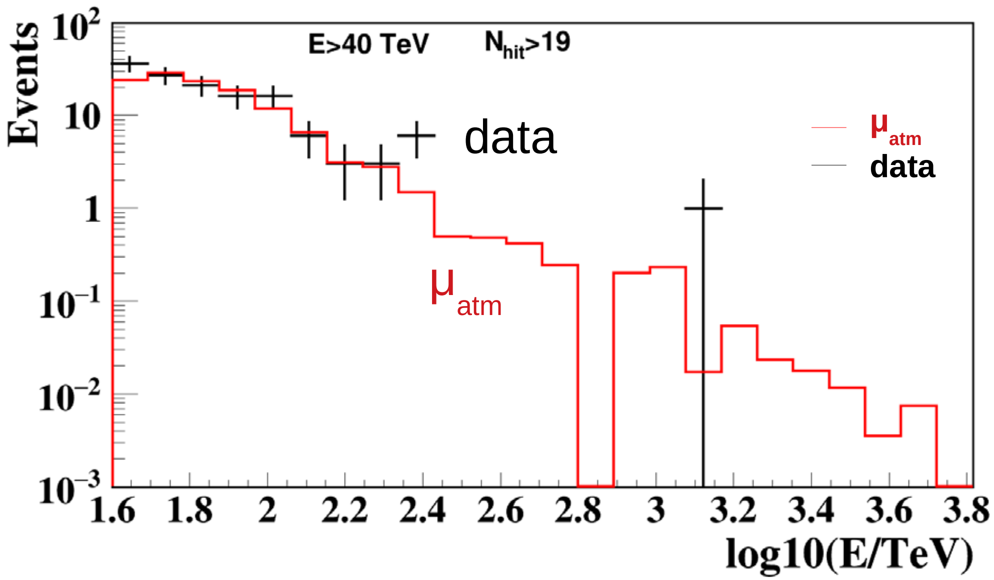
Cascade analysis : data and MC

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

JETP, 134 (2022) 399

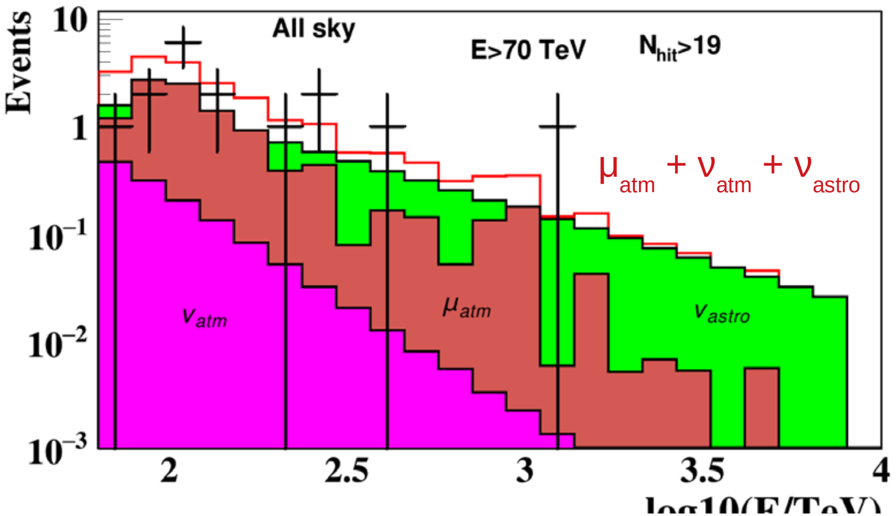
All-sky search for HE cascades

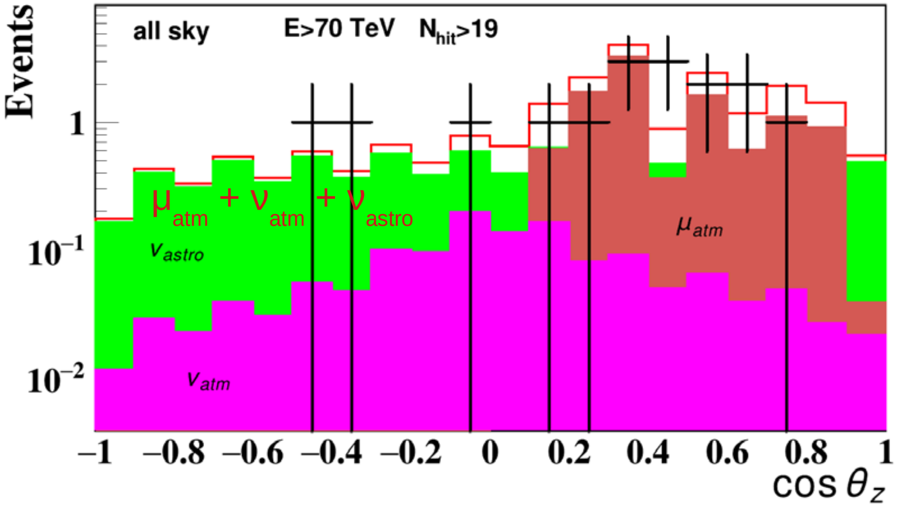
Preliminary!

Additional selection requirements:
(N Type_2 = 0, E rec ≥ 70 TeV) or
(N Type_2 = 1, E rec ≥ 100 TeV),
(N Type_2 – 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!

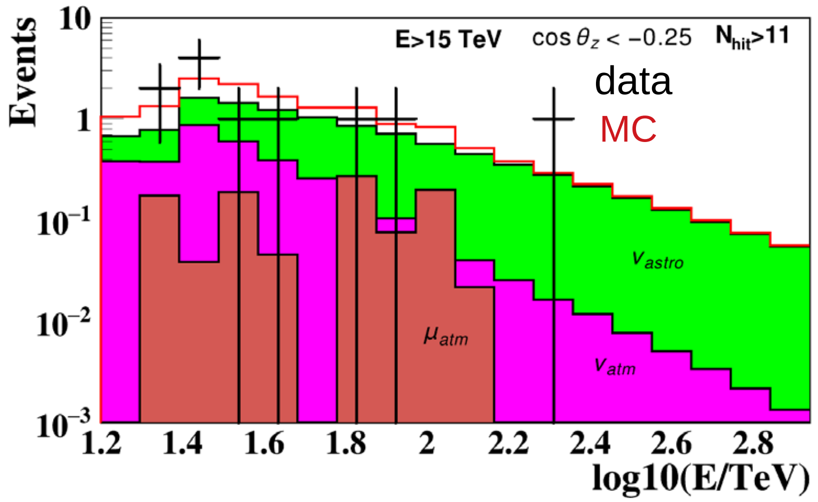
Additional selection requirements:

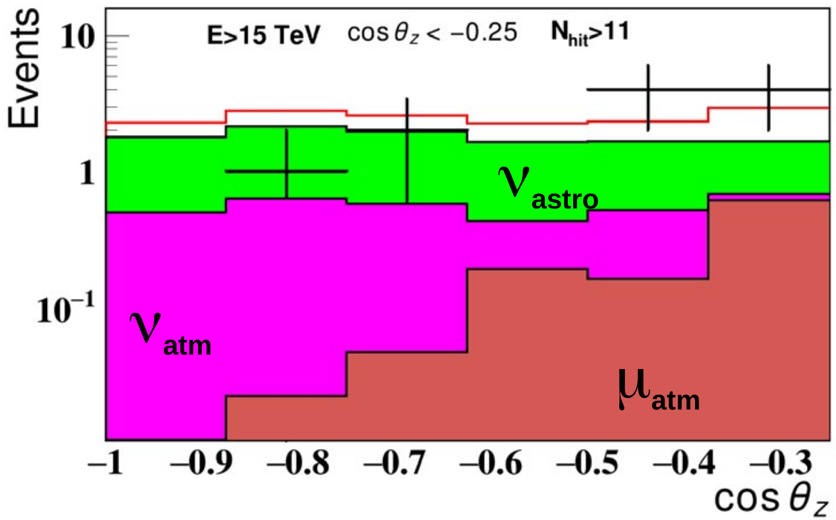
$E > 15$ TeV & $N_{hit} > 11$ & $\cos\theta_z < -0.25$

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

P-value = 0.00268 (3σ)

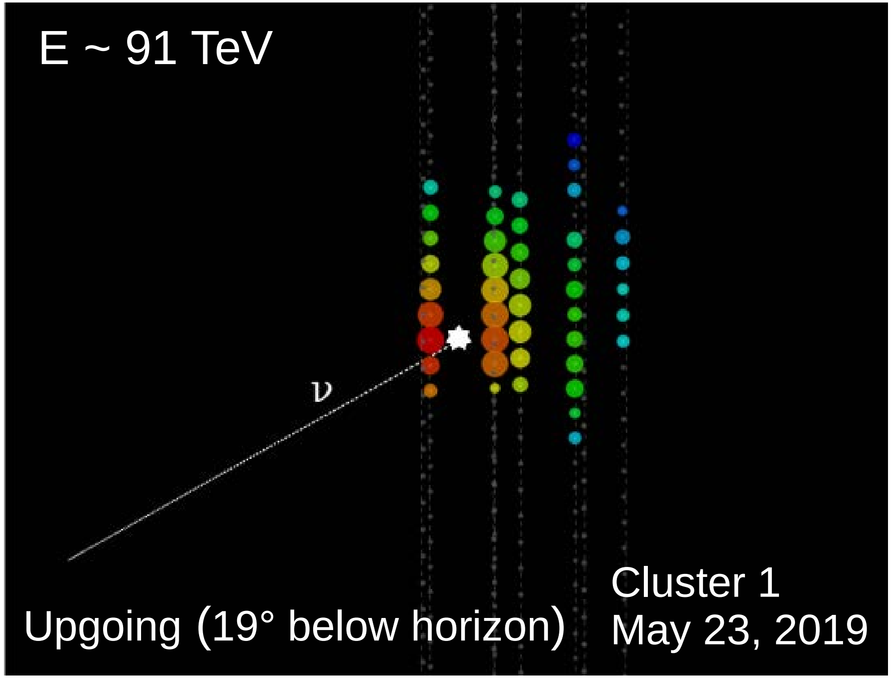




First upward-going cascade event

Preliminary

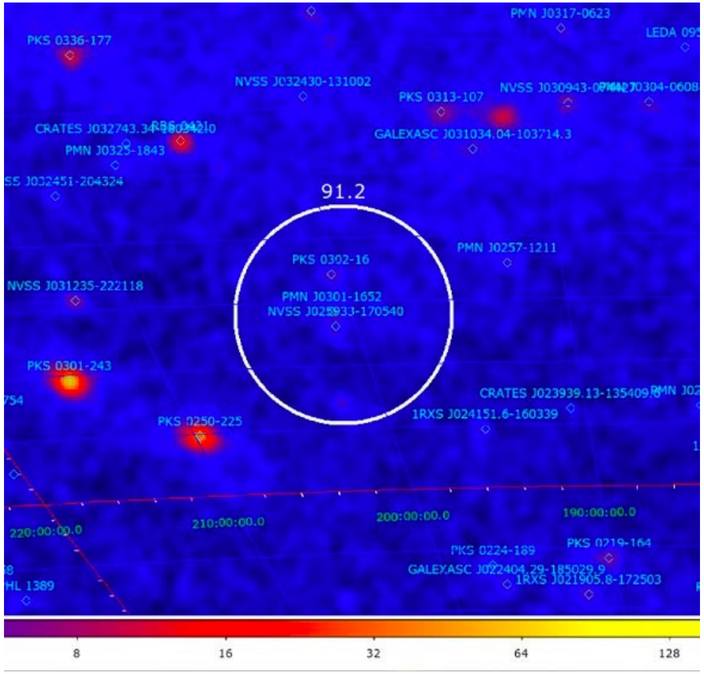
GVD2019_1_114_N



Contained event (50 m off central string)

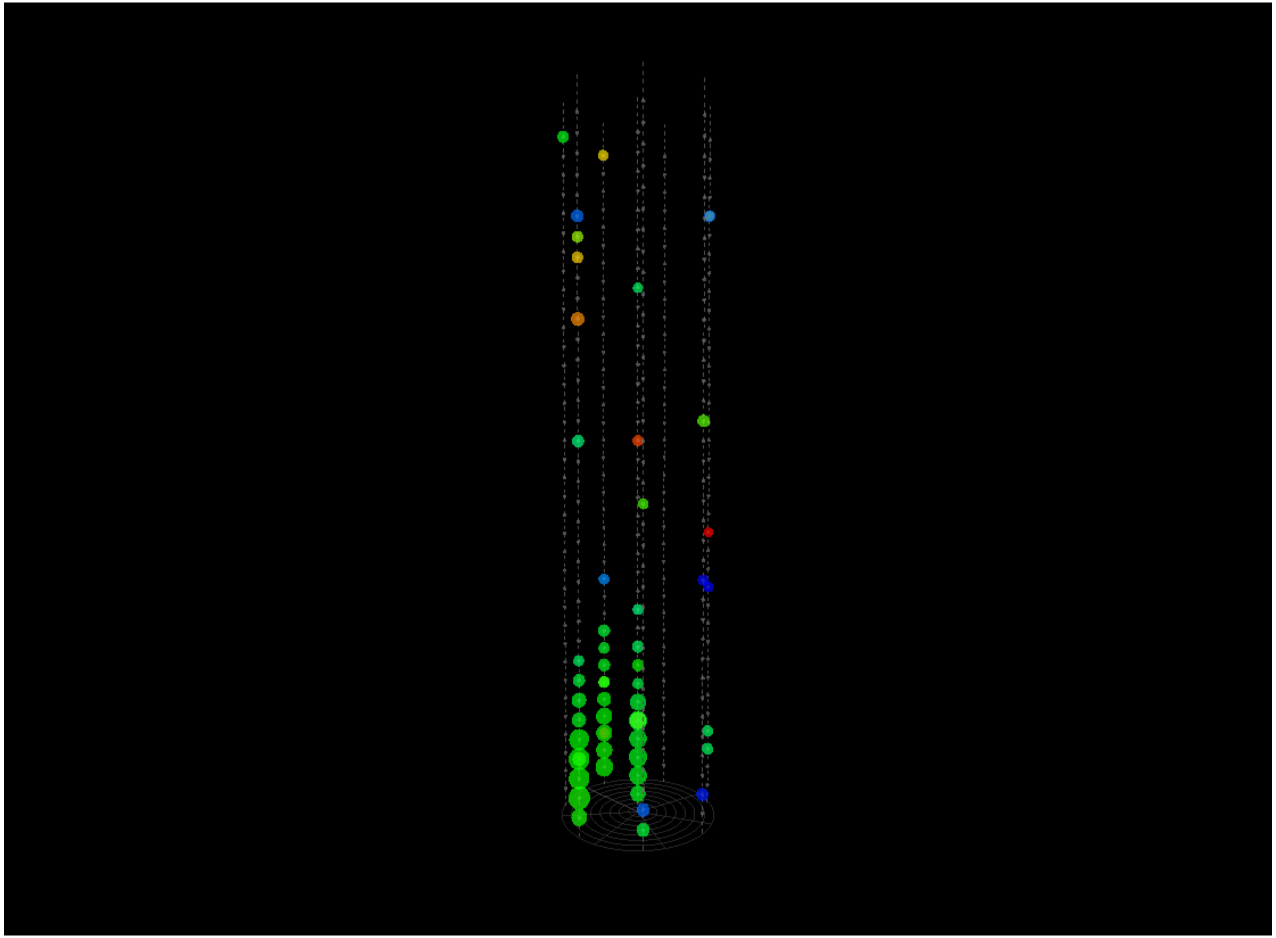
Excellent candidate for a neutrino event of astrophysical origin

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



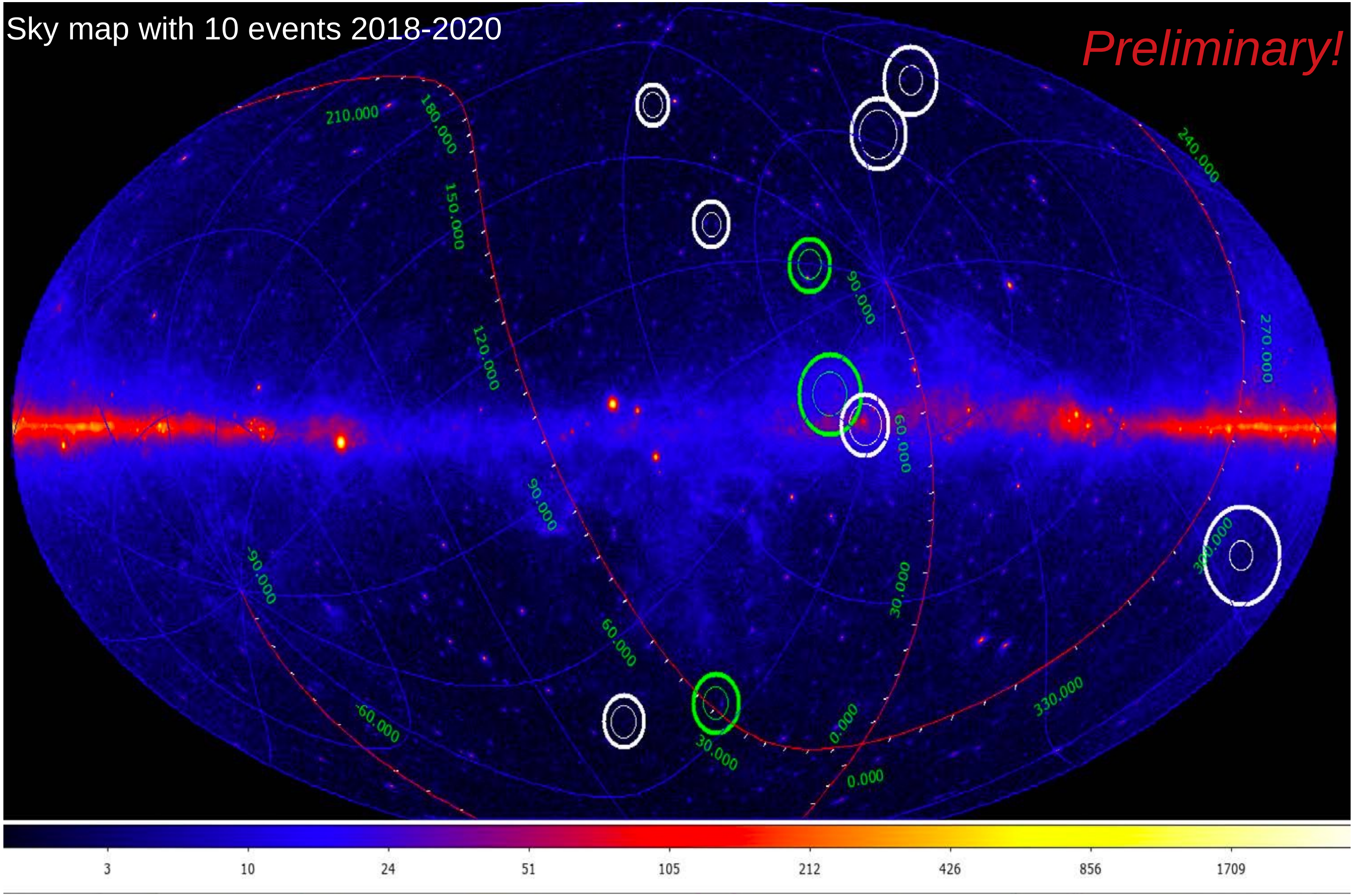
known sources in 3 degree circle:
PKS 0302-16 : unknown type of source
PMN J0301-1652 : unknown type of source

Second upward-going cascade event



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

Sky map with 10 Baikal-GVD cascade events



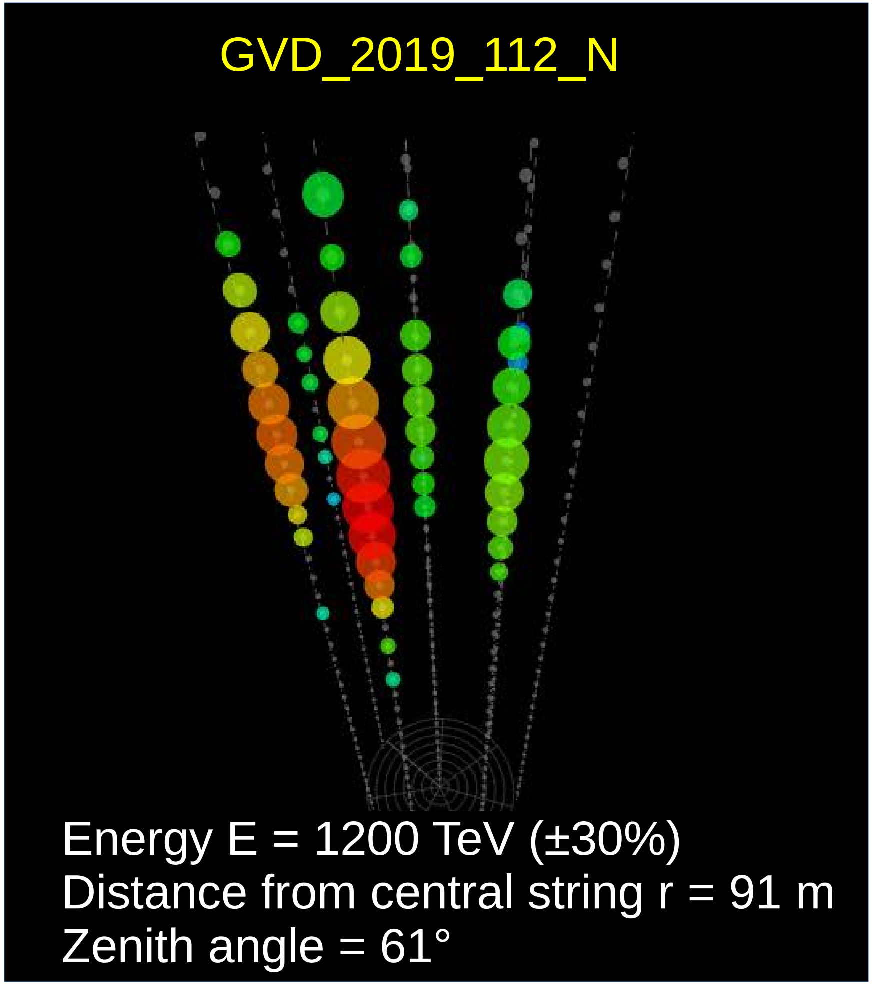
Background image: Fermi LAT

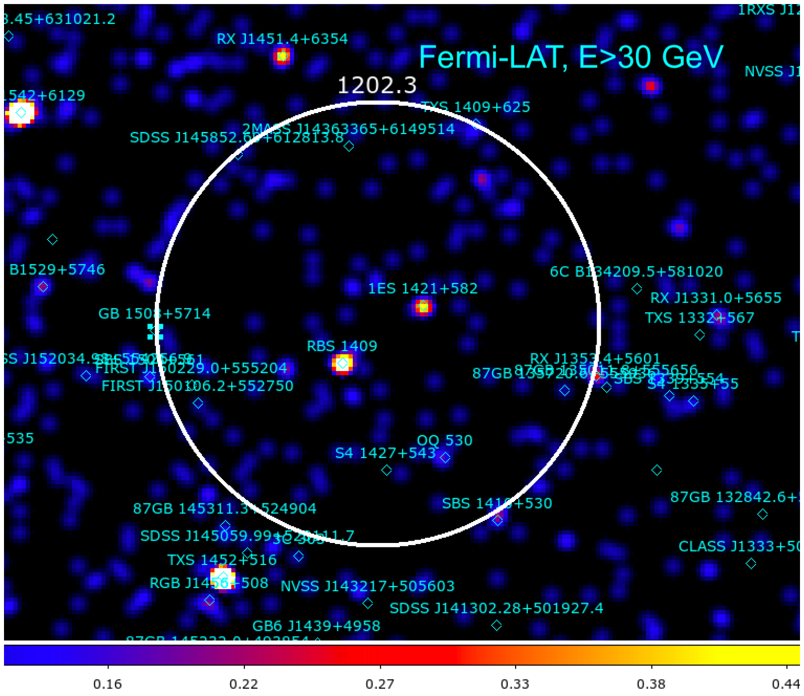
Green circles: Baikal-GVD events 2018 (50% and 90% C.L. regions)

White circles: Baikal-GVD events 2019-2020

A 1 PeV cascade event (downgoing)

Preliminary



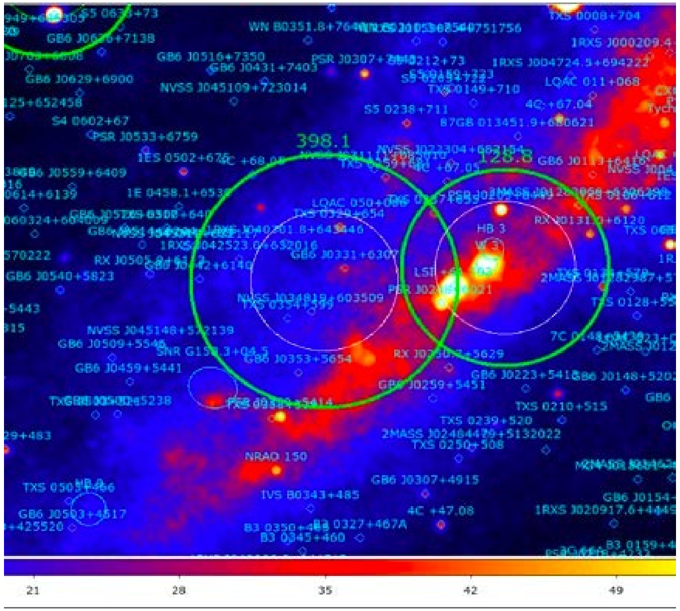


Fermi sources in 5° circle:
RBS 1409 BL Lac z=unknown
1ES 1421+582 z=unknown
both with hard spectrum

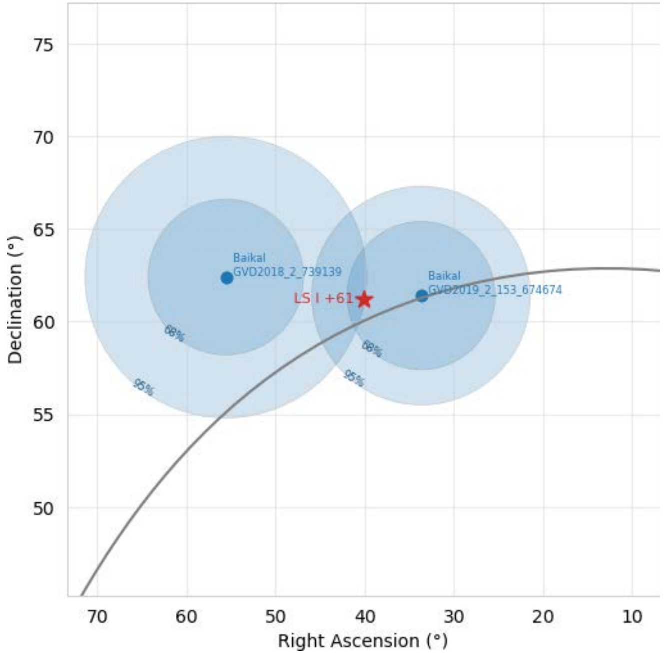
Event doublet near Galactic plane

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

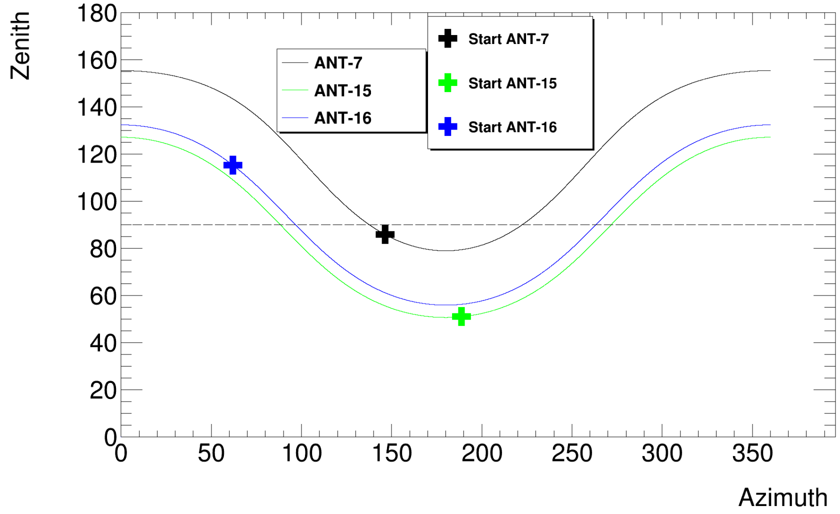
Following ANTARES upgoing μ alerts (<E> = 7 TeV)
Time windows: ±500 sec, ±1 hour and ±1 day
Both upgoing and downgoing cascades are looked for

Since Dec 2018, 60 alerts have been analysed

3 potentially interesting events

ANT alert	GVD cluster	$T-T_{alert}$, 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

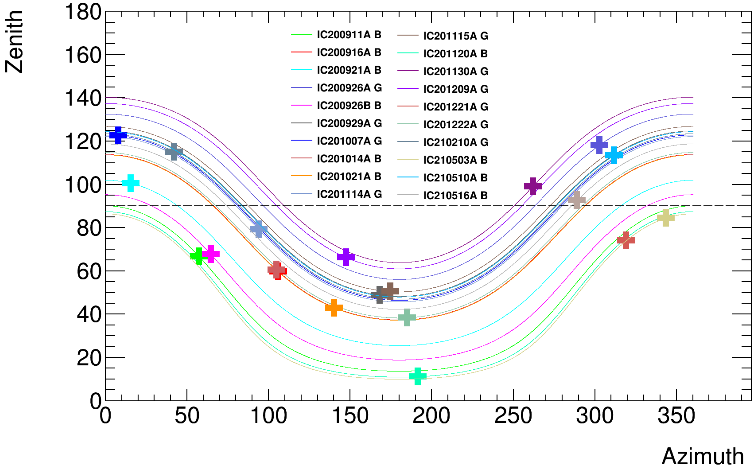
O. Suvorova et al. @ Neutrino 2022
O. Suvorova and A.Garre @ ICRC 2021

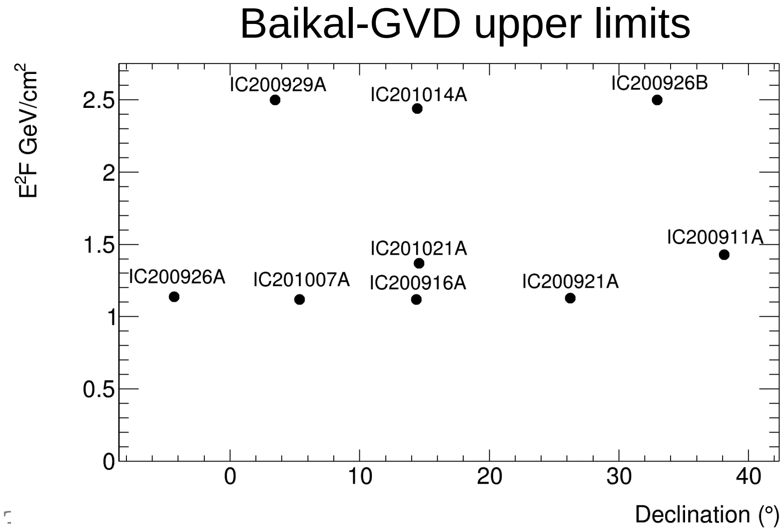
GVD follow up of IceCube alerts

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





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

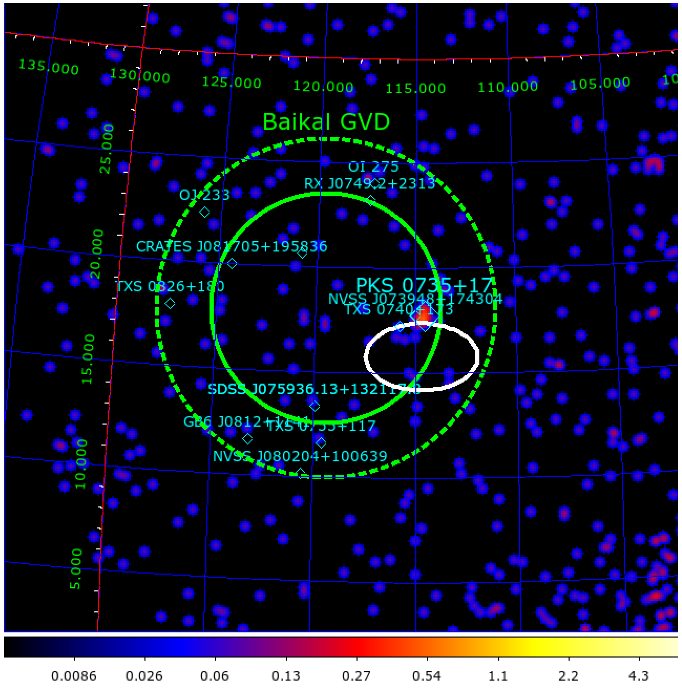


Image by D.Semikoz & A.Neronov

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

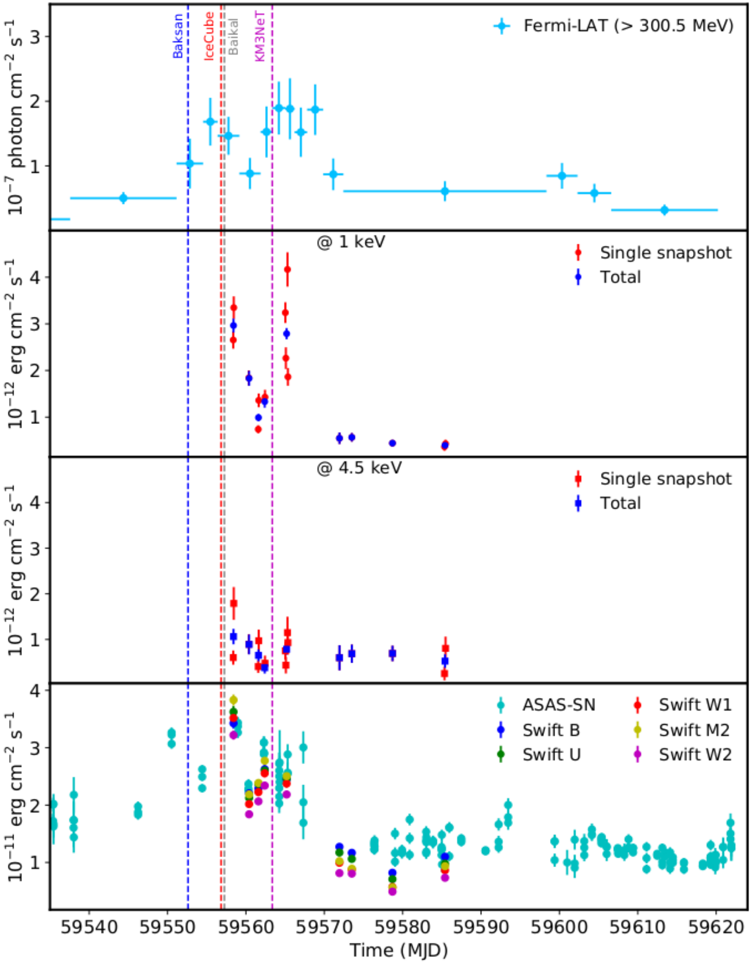
* PKS 0735+17 is a bright blazar very similar to TXS 0506+056

Заключение

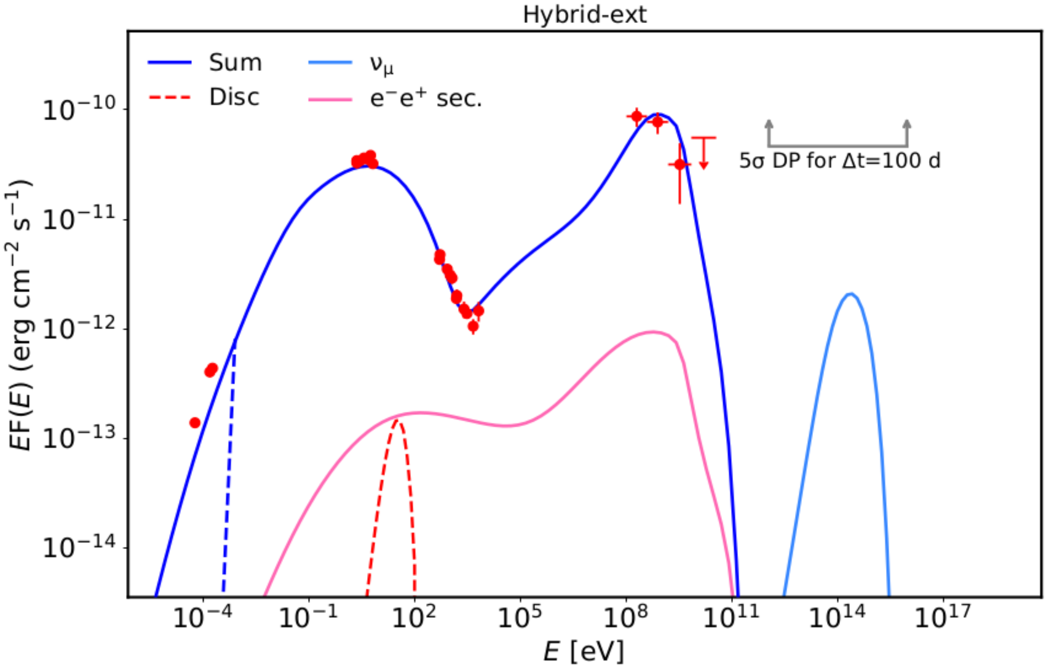
- Baikal-GVD – новый нейтринный телескоп в озере Байкал
  - Объём порядка 1 $км^3$ (по завершении строительства)
  - Угловое разрешение лучше 1° (для треков)
  - Область зрения эффективно дополняет IceCube
- Обнаружены первые намеки на ранее неизвестные источники нейтрино
- Идет набор данных с 10 кластерами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

Backup slides

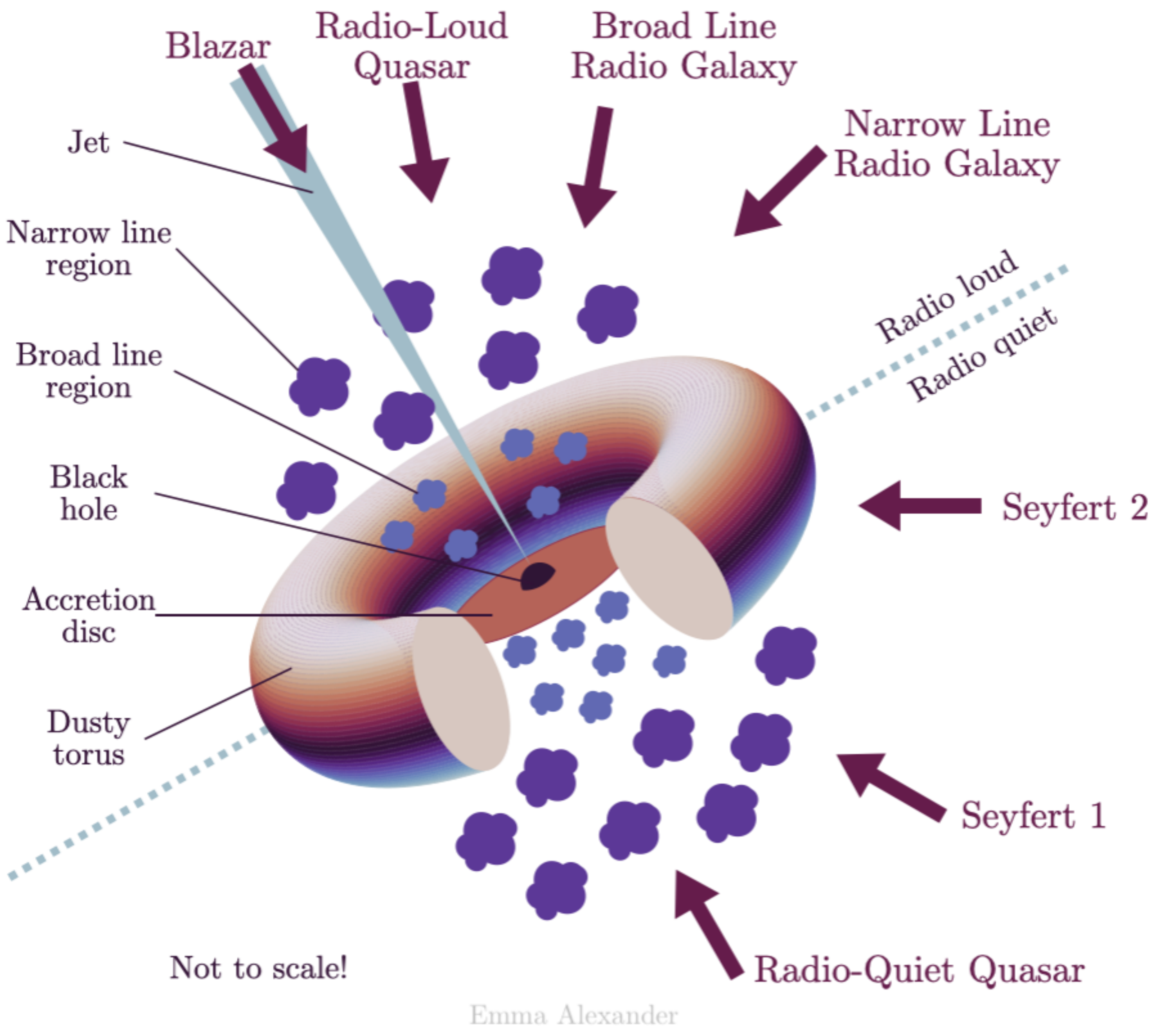
PKS 0735+17 : a neutrino-emitting blazar?



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.


Blazar
Radio-Loud Quasar
Broad Line Radio Galaxy
Narrow Line Radio Galaxy
Jet
Narrow line region
Broad line region
Black hole
Accretion disc
Dusty torus
Radio loud
Radio quiet
Seyfert 2
Seyfert 1
Radio-Quiet Quasar
Not to scale!
Emma Alexander

AGN origin of the diffuse neutrino flux?

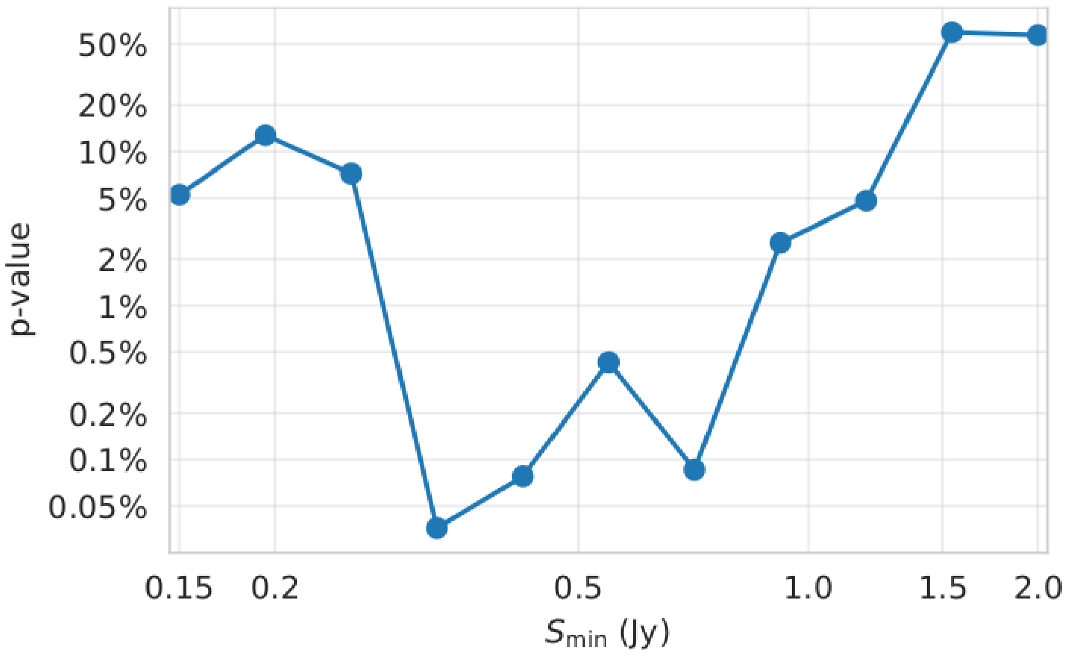
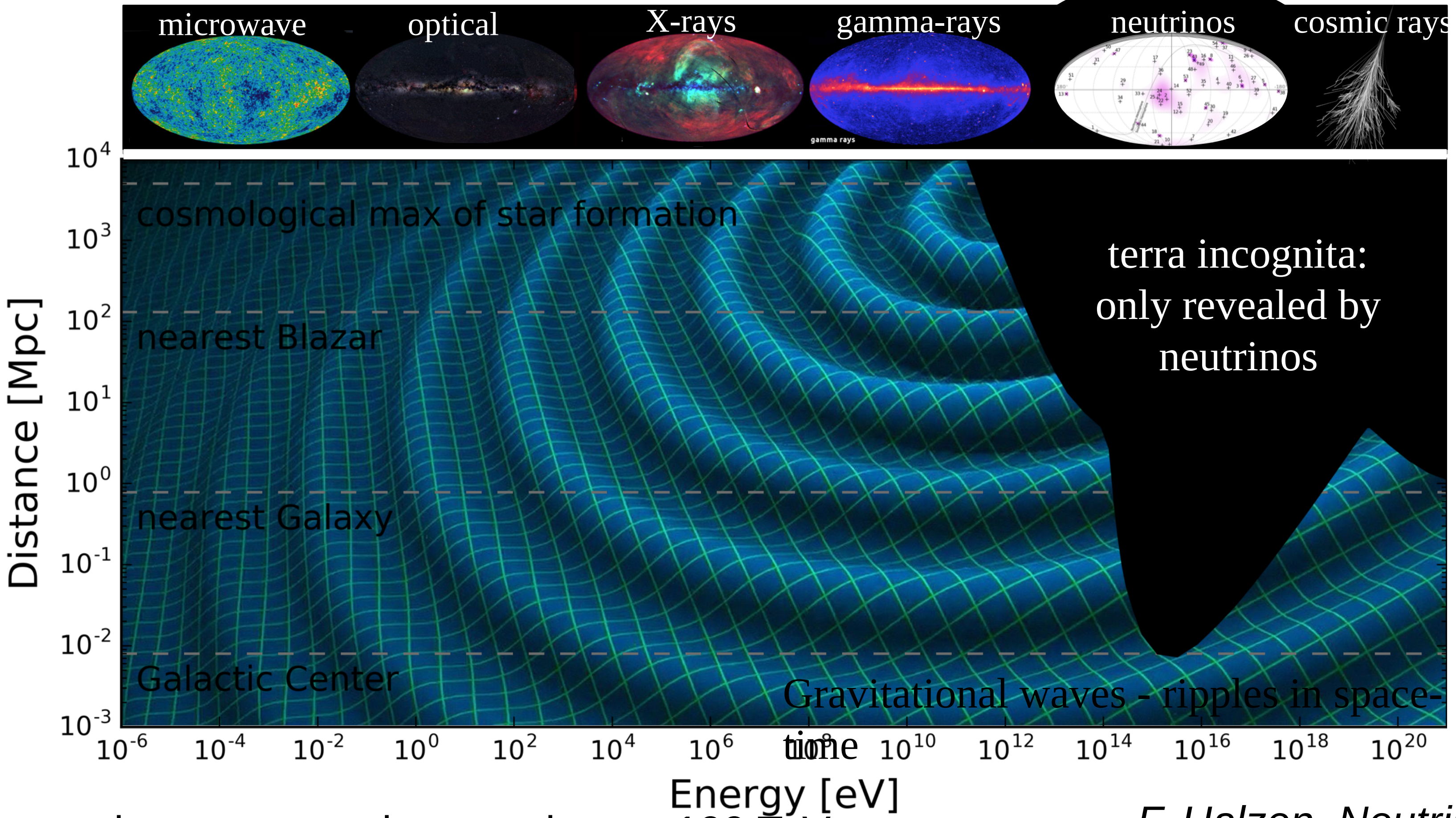


Figure 2. Pre-trial p-values for a range of VLBI flux density cutoffs. The threshold values $S_{\rm min}$ split the interval 0.15-2 Jy into ten parts uniformly in log-scale. The lowest p-value of $4 \cdot 10^{-4}$ is attained for the threshold of 0.33 Jy.

A. Plavin, Y. Kovalev, Yu. Kovalev, S. Troitsky: Directional association of TeV to PeV astrophysical neutrinos with active galaxies hosting compact radio jets, ApJ 908 (2021) 157 [arXiv:2009.08914]

Highest energy radiation in the Universe



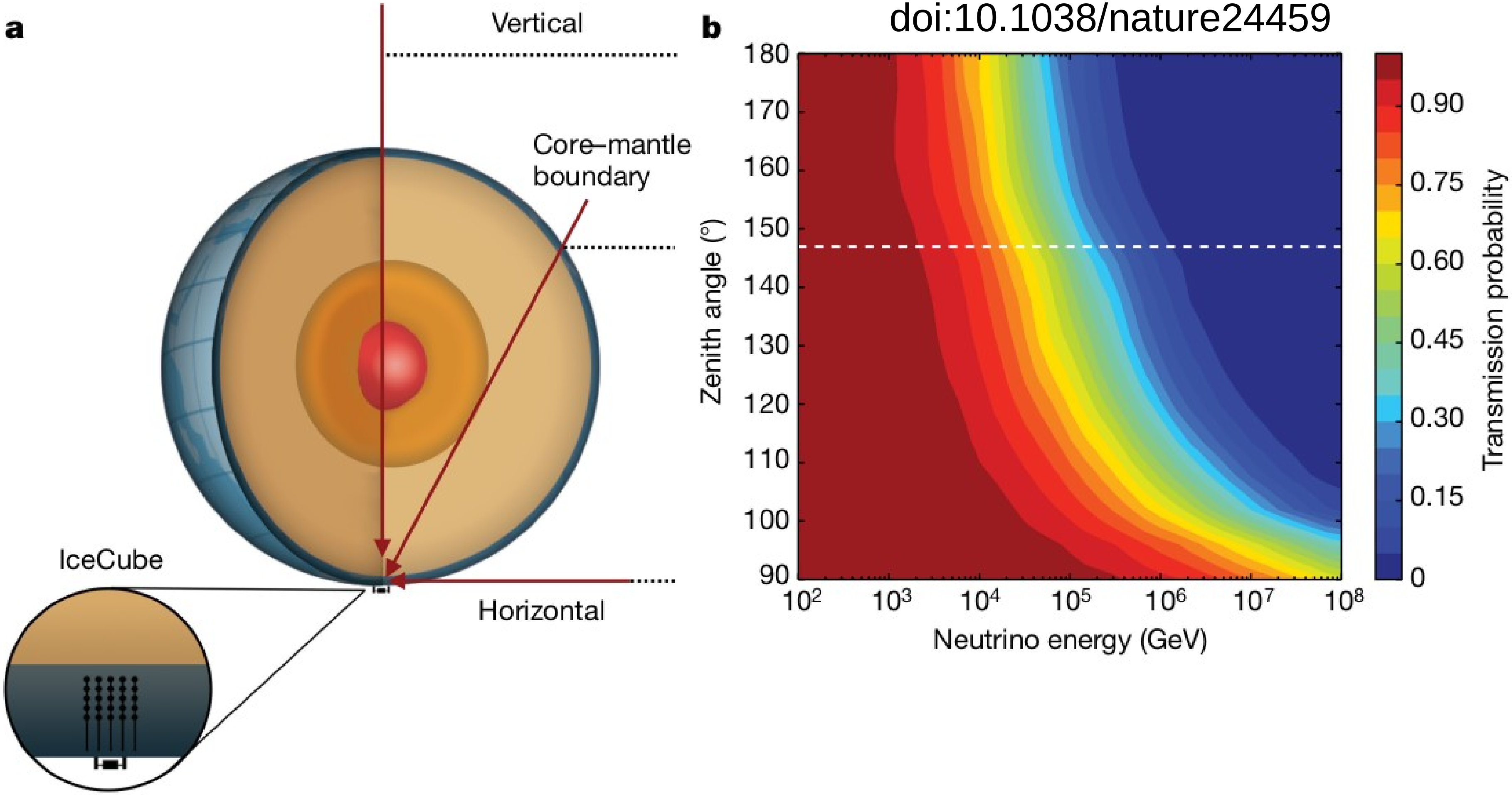
F. Halzen, Neutrino 2020

Universe is opaque to photons above ~100 TeV energy

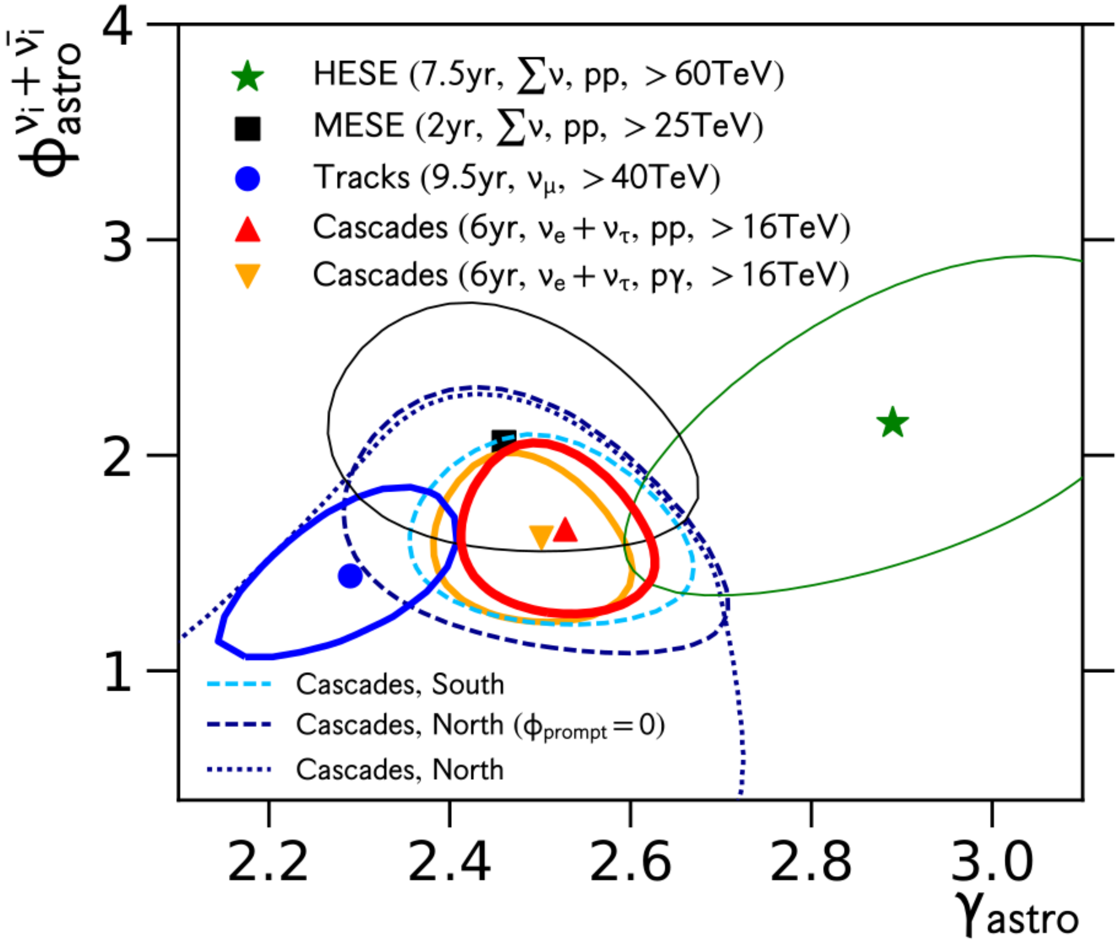
(due to interactions on CMB and EBL photons)

Neutrino absorption in the Earth

doi:10.1038/nature24459

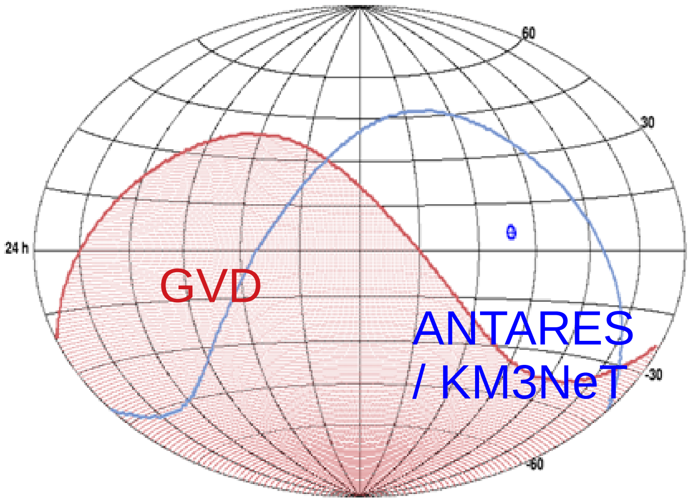


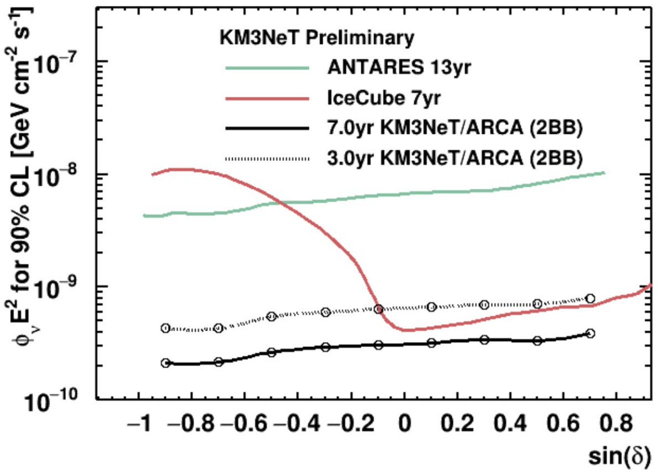
Diffuse neutrino flux



Why two neutrino telescopes in the North

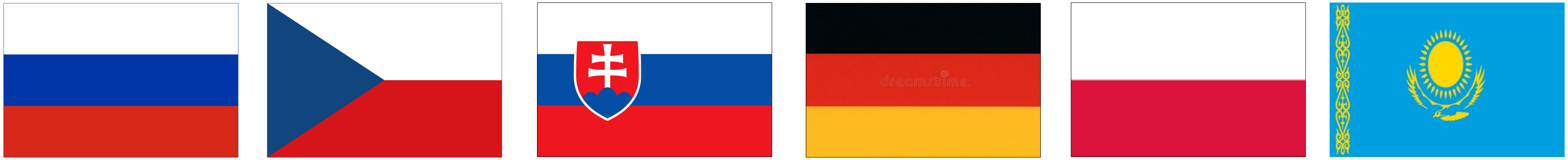
- Improved all-sky coverage
  - important for short transients
- Sensitivities add up
  - neutrino astronomy is still limited by low statistics
- Optimize local funding opportunities
  - Funding opportunities often come with geographic restrictions





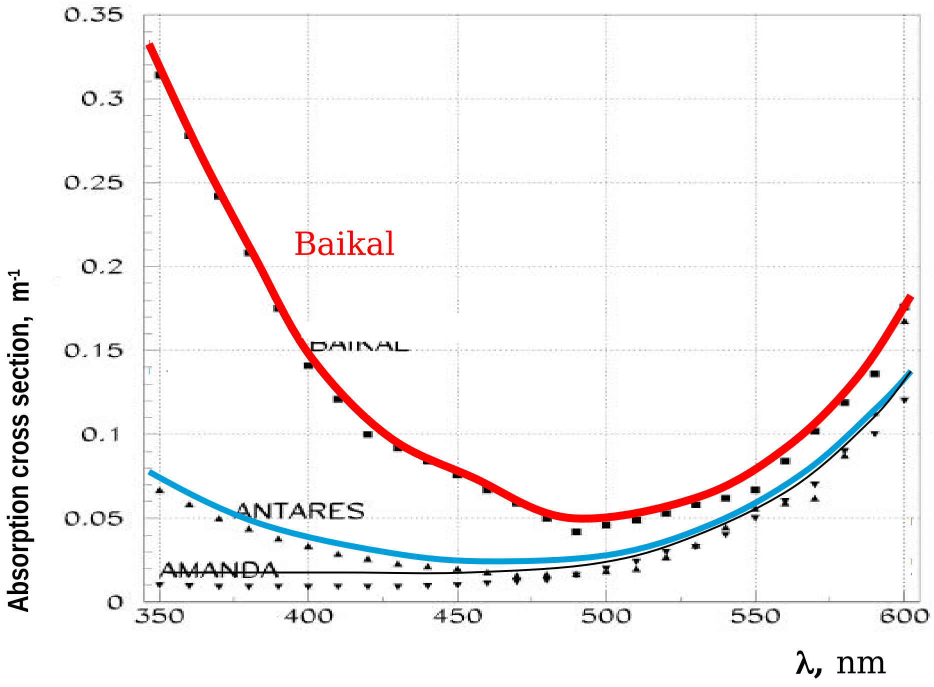
Baikal-GVD collaboration (as of Feb 2022)

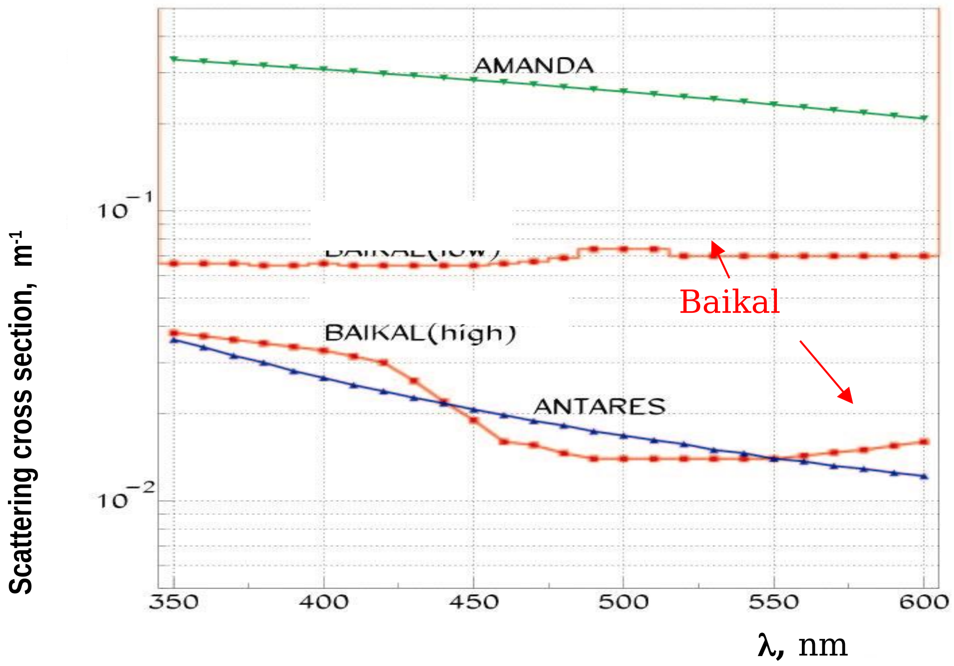
11 organisations from 6 countries, ~70 collaboration members



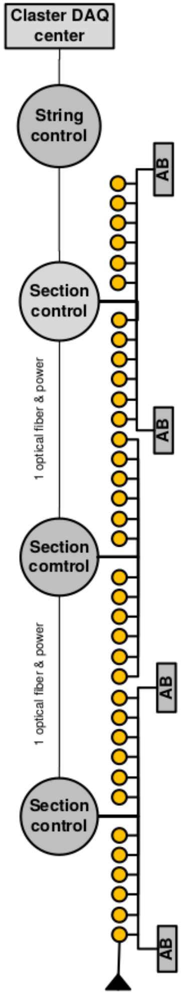
- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (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)

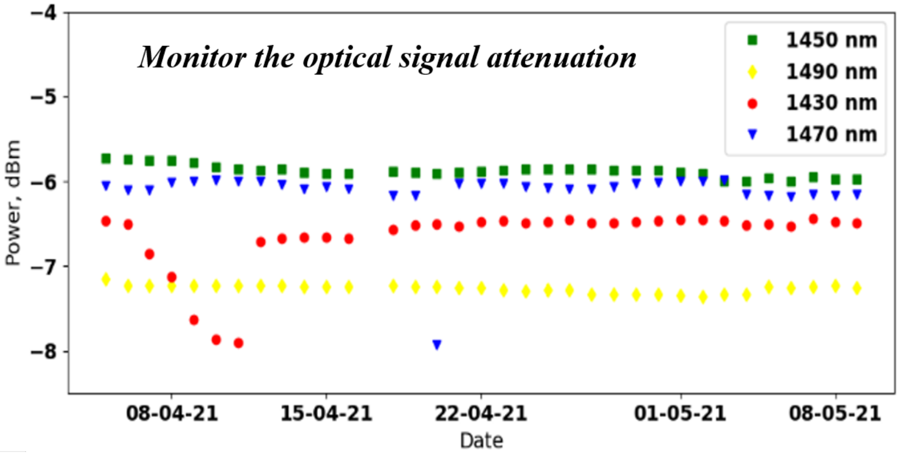
Water optical properties





Experimental string with optic fiber DAQ





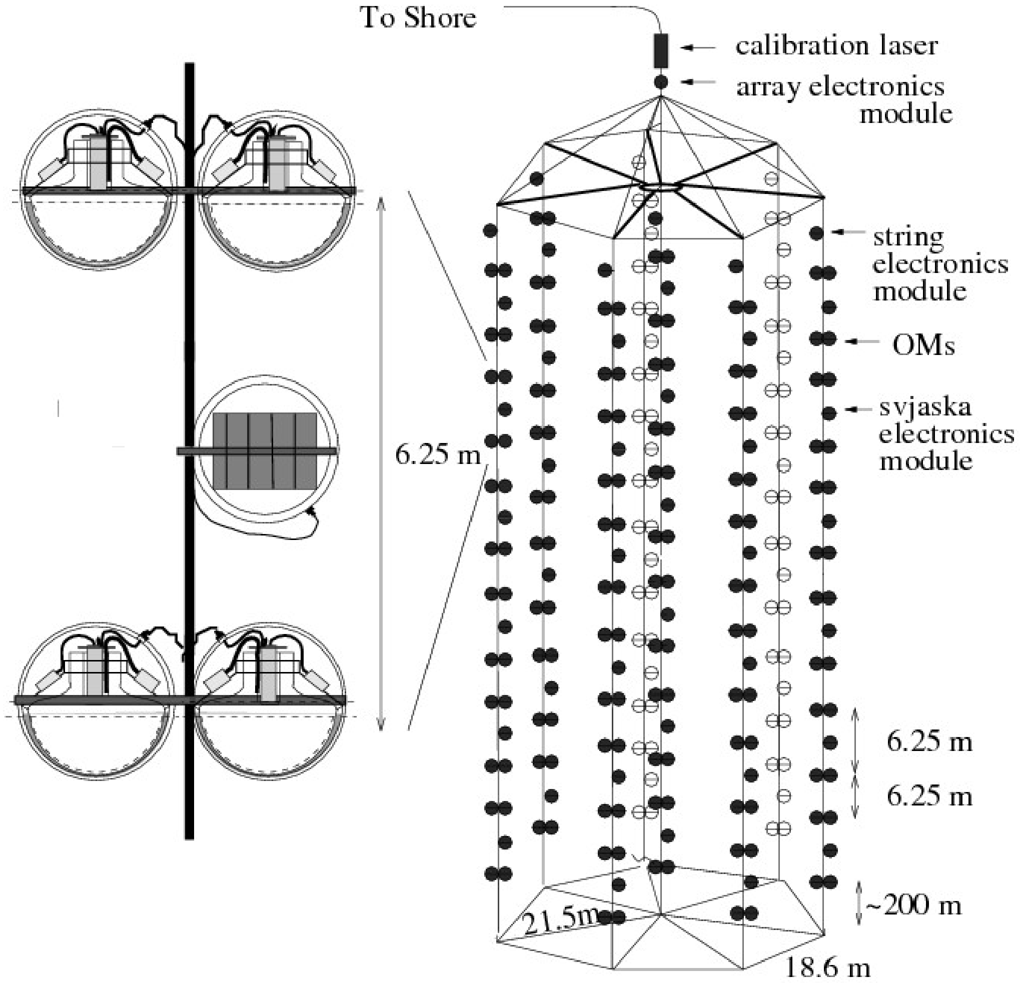
Developing technological solutions for second stage of Baikal-GVD deployment (2024+)

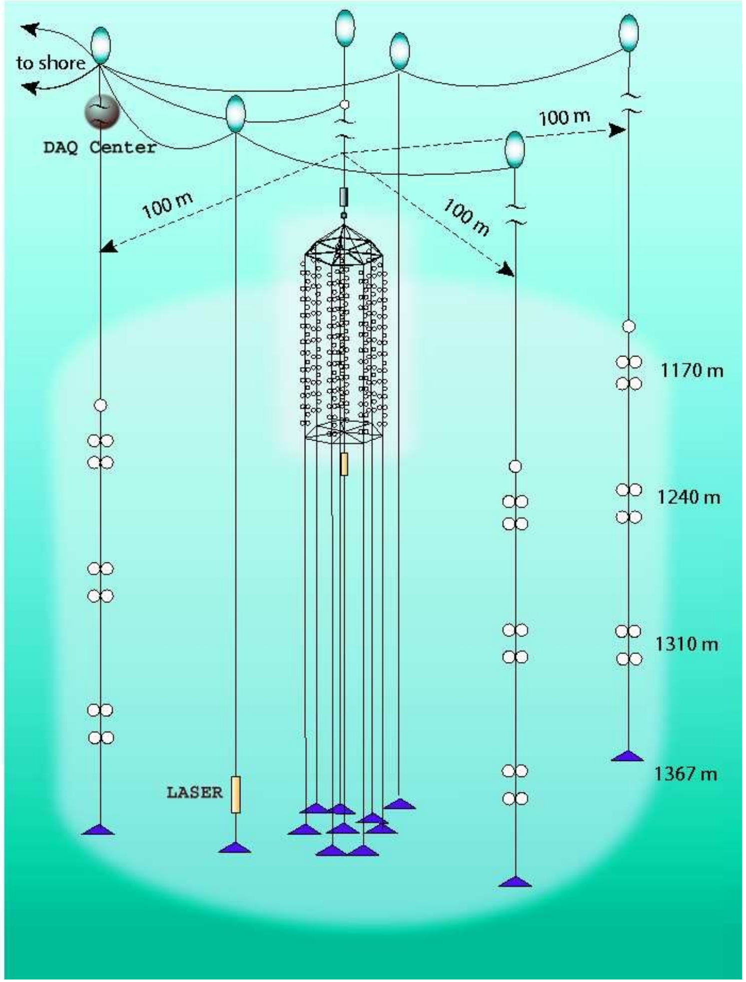
Advantages:

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

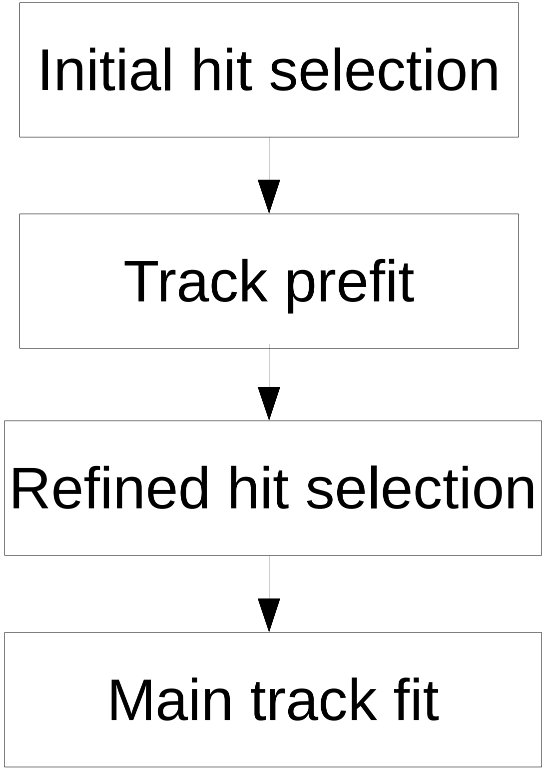
See poster by V. Aynutdinov @ ICRC 2021

Baikal NT-200 and NT-200+





Track reconstruction with a χ^2-based algorithm



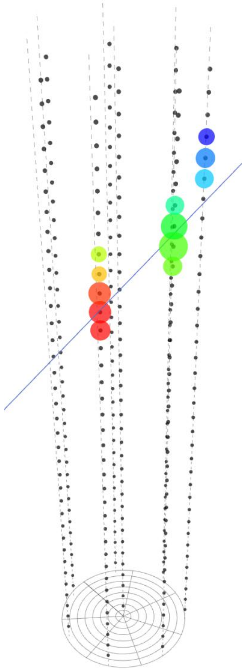
Using vector sum

Minimize quality function

$$Q = \chi^2(t) + f(q, r)$$

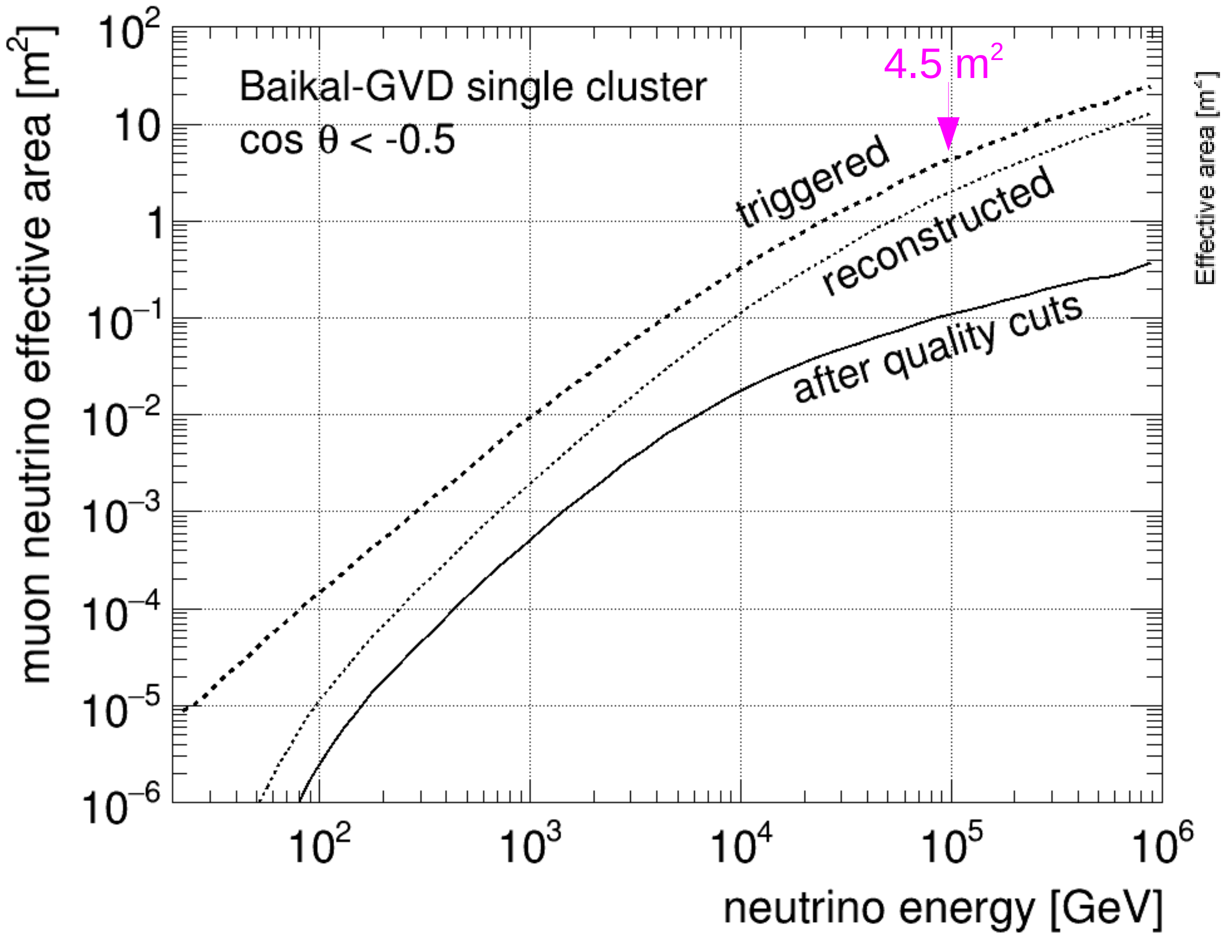
Time residuals

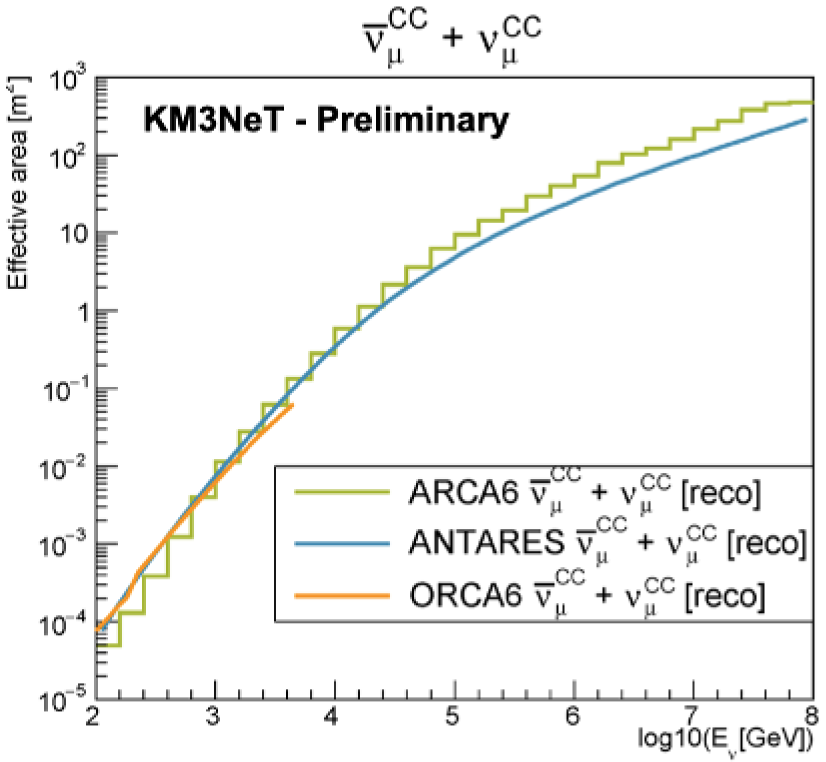
Hit charge and distance



See talk by G. Safronov at ICRC 2021

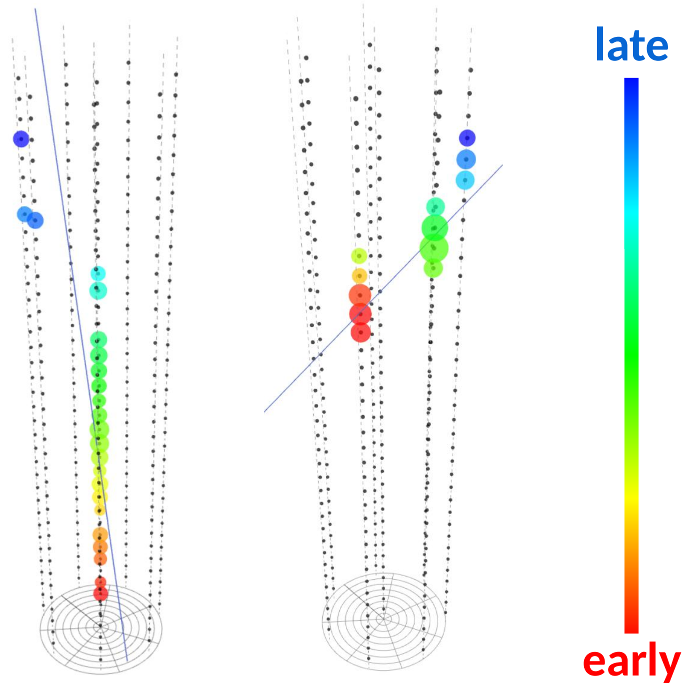
Neutrino effective area for tracks : one GVD cluster





Track reco : ongoing improvements

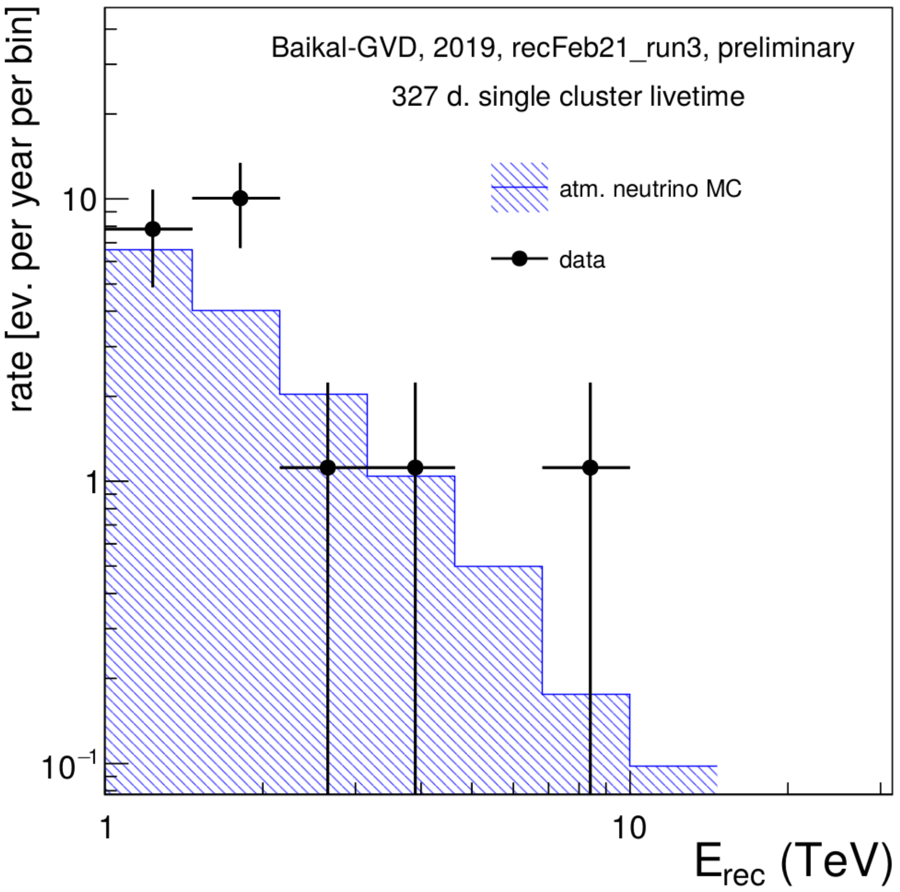
- Event selection with BDT
  → G. Safronov @ ICRC 2021
- Improved hit selection using clique search → A. Avrorin & B. Shaybonov @ ICRC 2021
- Likelihood fitter
- Machine learning techniques
- ...



E_{rec} = 28 TeV

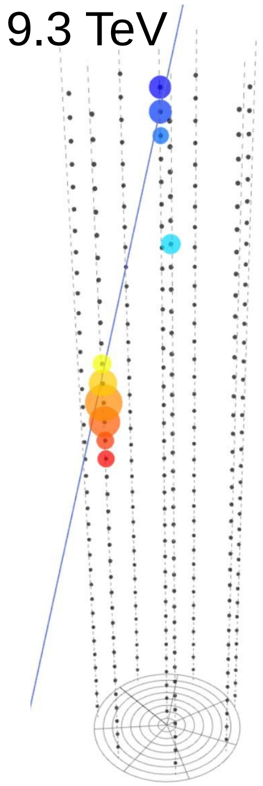
Reconstructed energy for tracks

Example plot for a set of neutrino candidate events



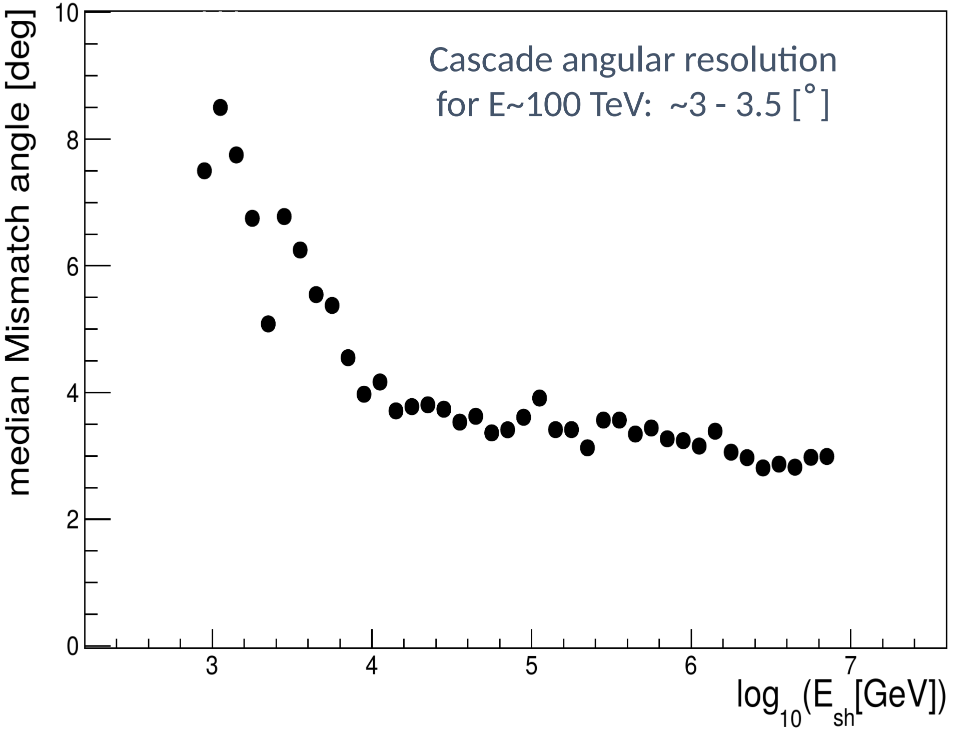
- dE/dx energy estimator -
- Works for E > 1 TeV
- Largest measured energy in cut-based low-energy neutrino candidate sample:

see talk by G. Safronov at ICRC 2021



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

Cascade analysis angular resolution



Selected events (2018-2020)

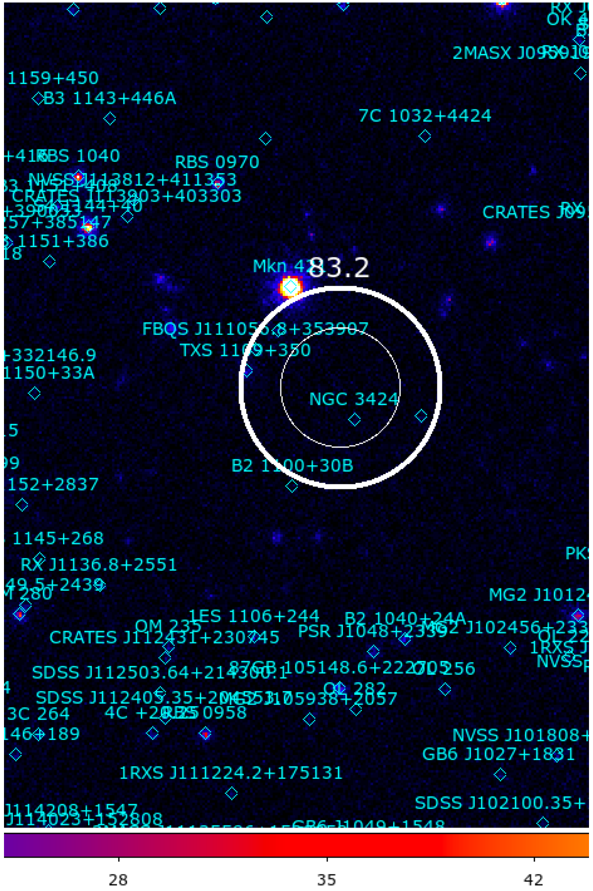
Preliminary

	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

Another event of potential interest

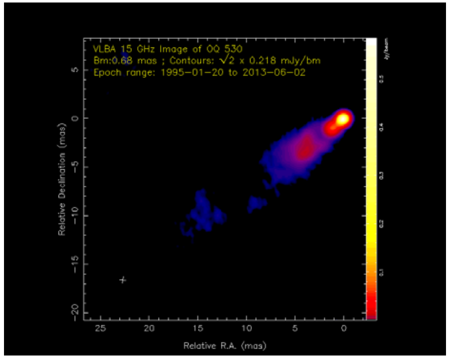
GVD_2019_663

Mrk 421 just outside the error circle



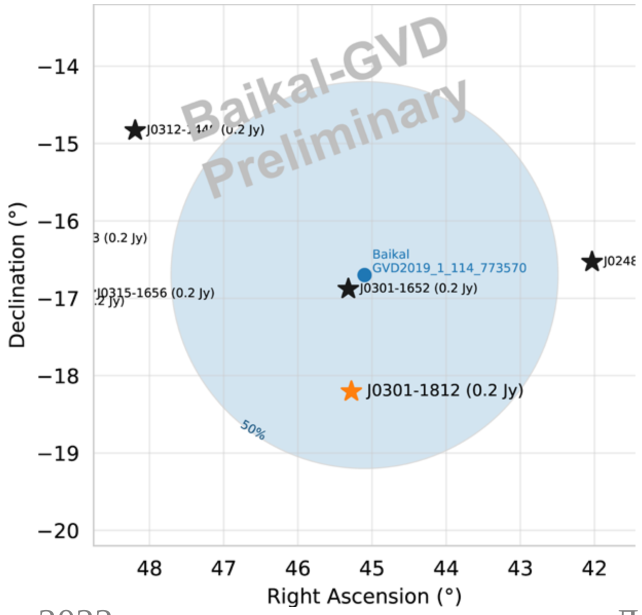
Radio-loud blazars – promising neutrino sources

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

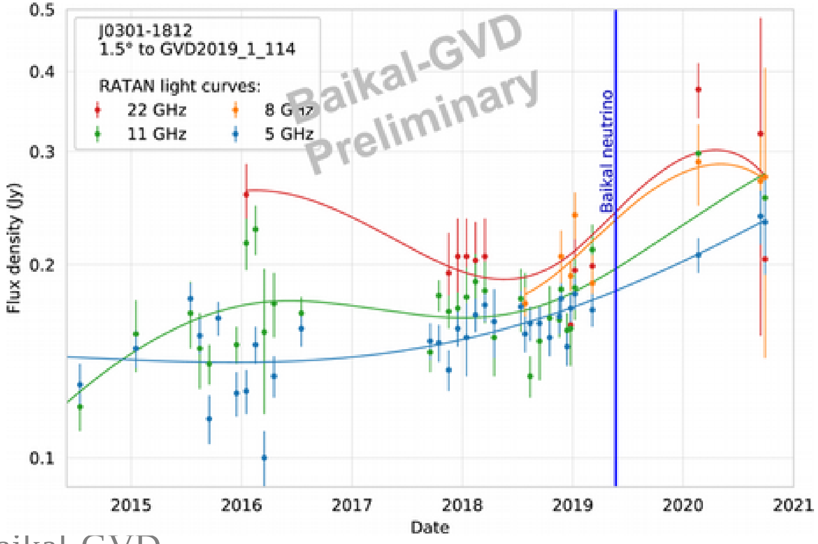


GVD2019_1_114_N

radio-bright blazars nearby



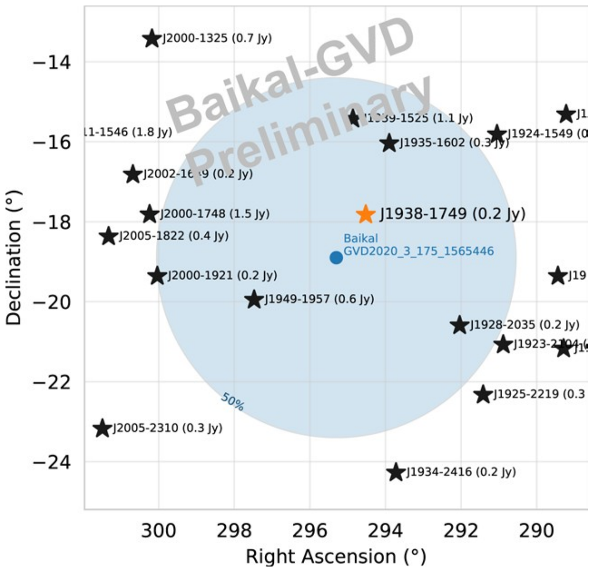
Light curves of J0301-1812 measured by RATAN-600

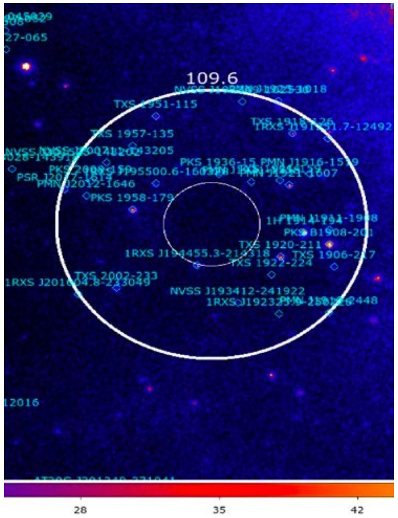


Radio-loud blazars – promising neutrino sources (2)

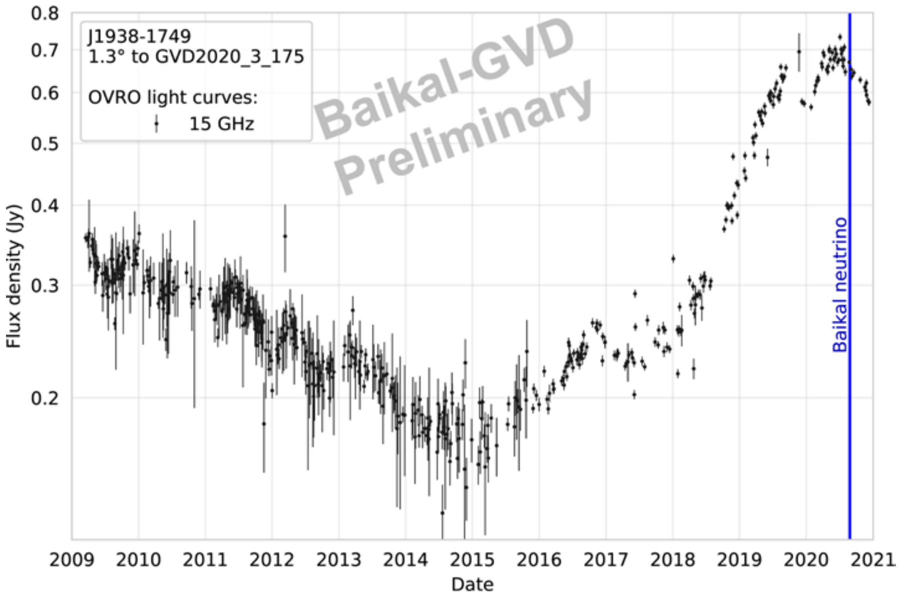
GVD2020_3_175_N

radio-bright blazars nearby



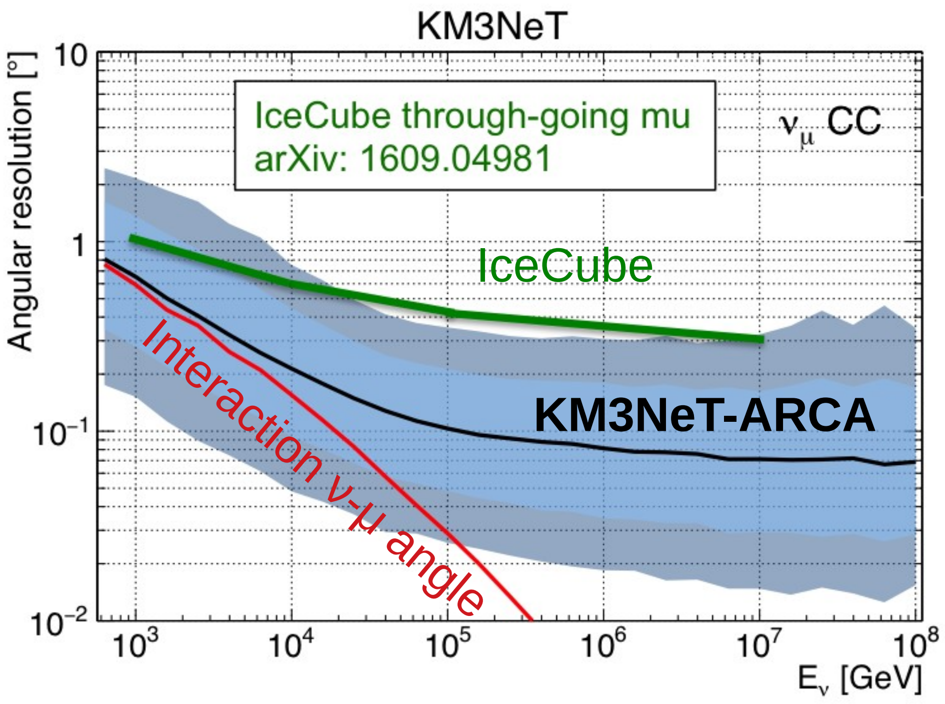


Light curves of J1938-1749 measured by OVRO

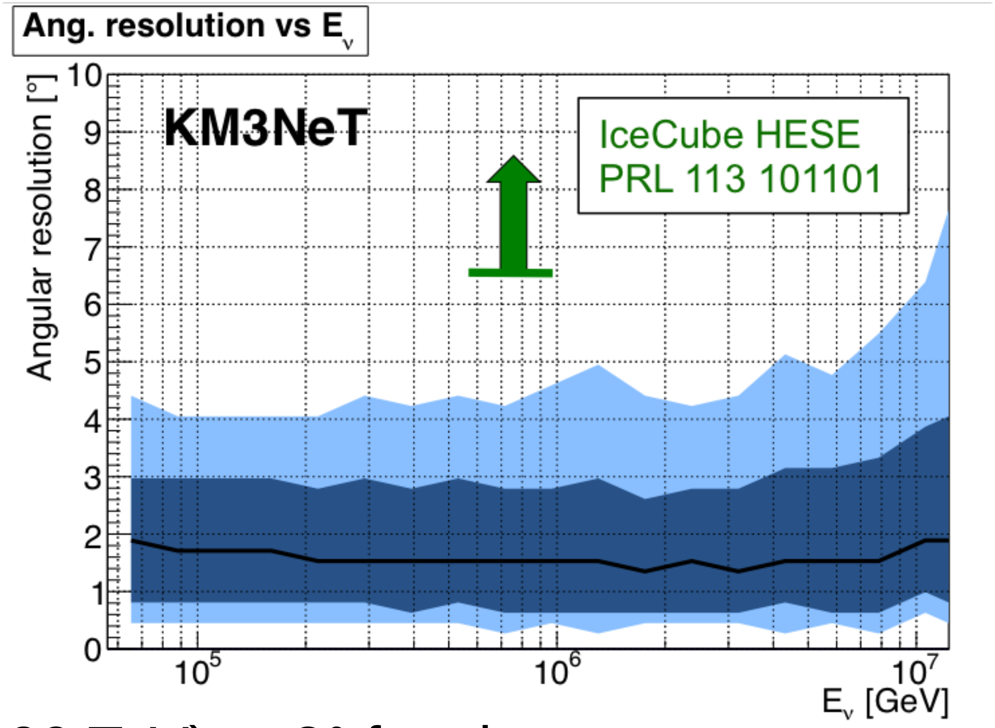


ARCA - angular resolution

Tracks



Showers



~ 0.1° angular resolution for tracks (E>100 TeV); ~ 2° for showers