JINR-ISU summer school
Bolshie Koty
11-18 July 2023

High Energy Neutrino Astronomy

Lecture 2

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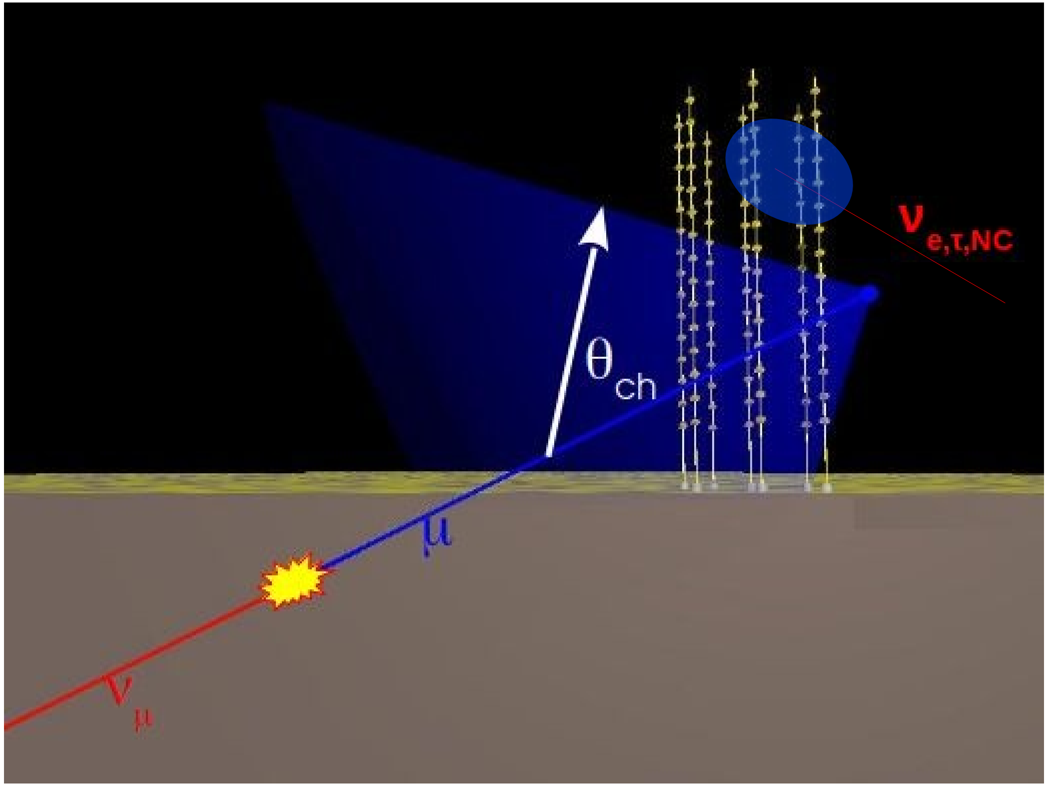
Plan

- Neutrino telescope operation principle
- History and current status of the field
- Baikal-GVD detector and first results
- Future prospects

Neutrino telescopes: how it works

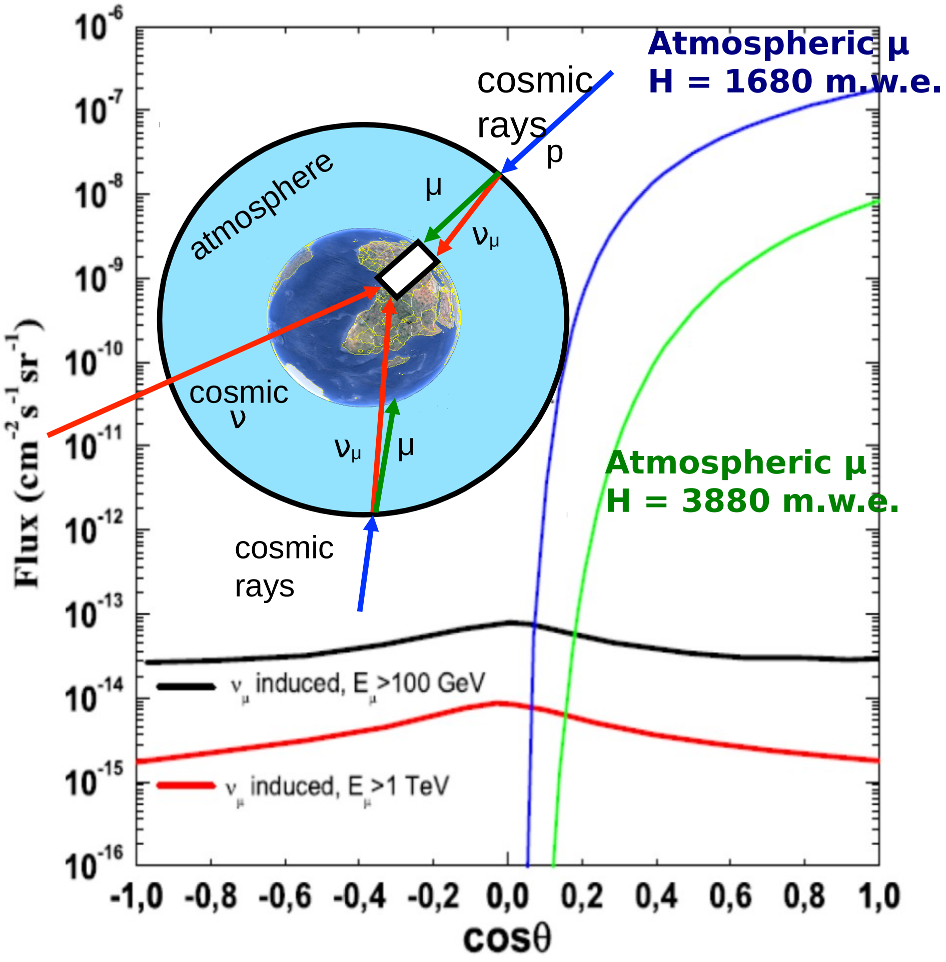
Neutrino telescope : operation principle



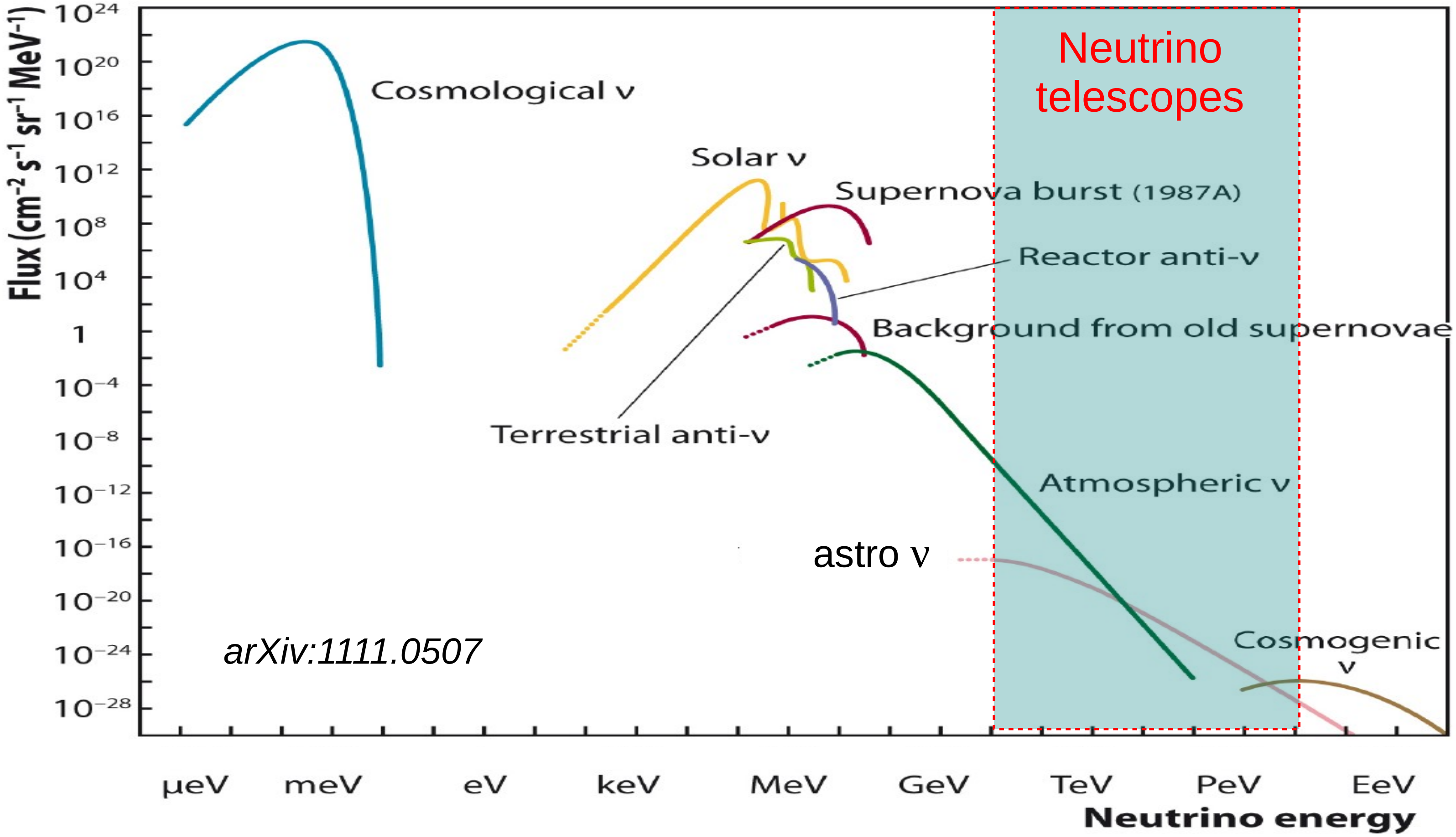
- Large arrays of PMTs in water or ice
- Cherenkov light detected by PMTs
- "Tracks": ν_μ CC
- "Cascades": ν_e & ν_τ CC + NC
- Direction reconstructed from hit positions and times
- Energy reconstructed from hit charges

Backgrounds

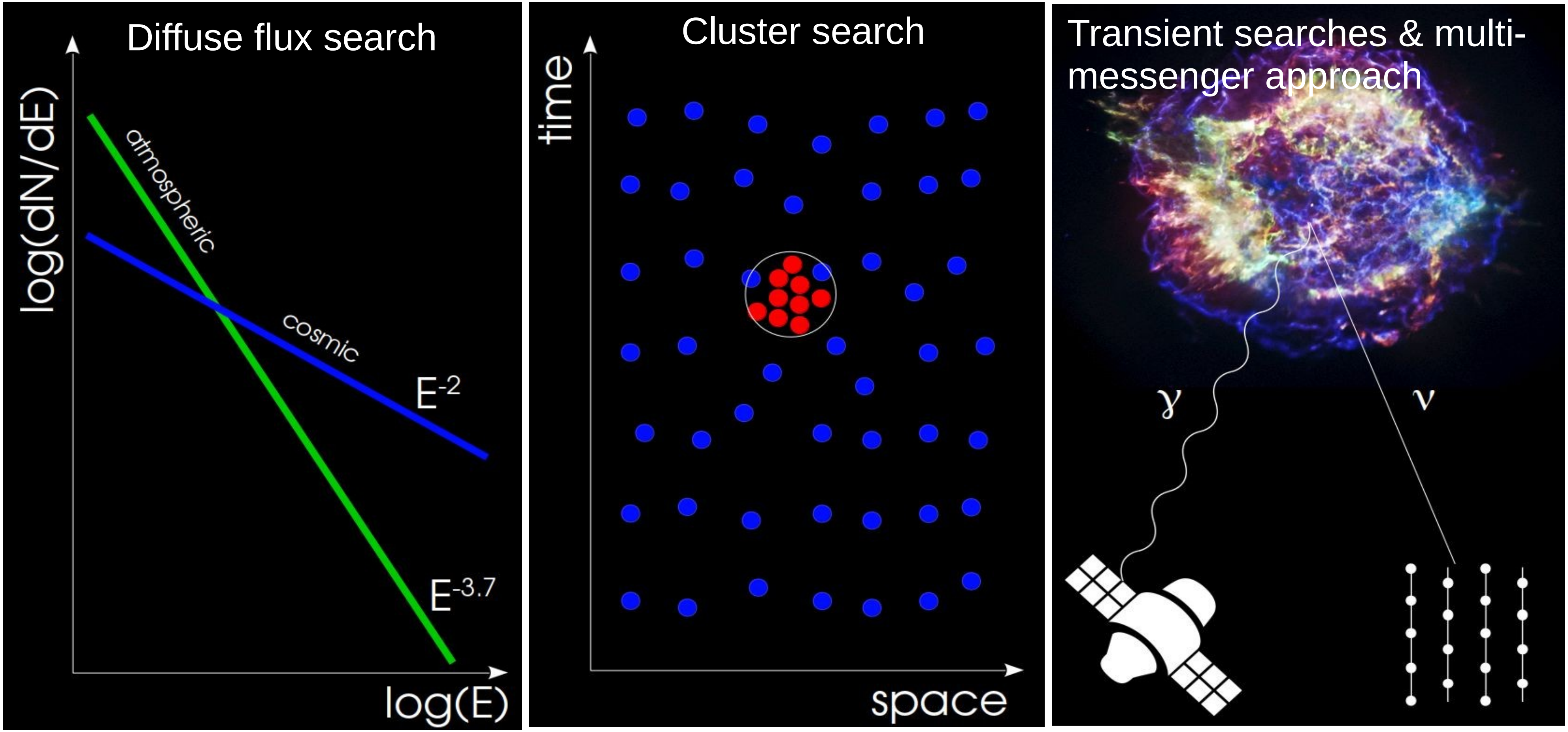
- Atmospheric neutrinos
  - All-sky, soft spectrum
  - For downgoing events, atmospheric muons can be used as veto (at very high energy)
- Atmospheric muons
  - Downgoing only (Earth acts as filter)
- Environmental background light: natural radioactivity (e.g. ^{40}K), bioluminescence, chemiluminescence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



Where we are on the energy scale



3 ways to detect astrophysical neutrino signal



Pictures borrowed from talk by R. Ruiz

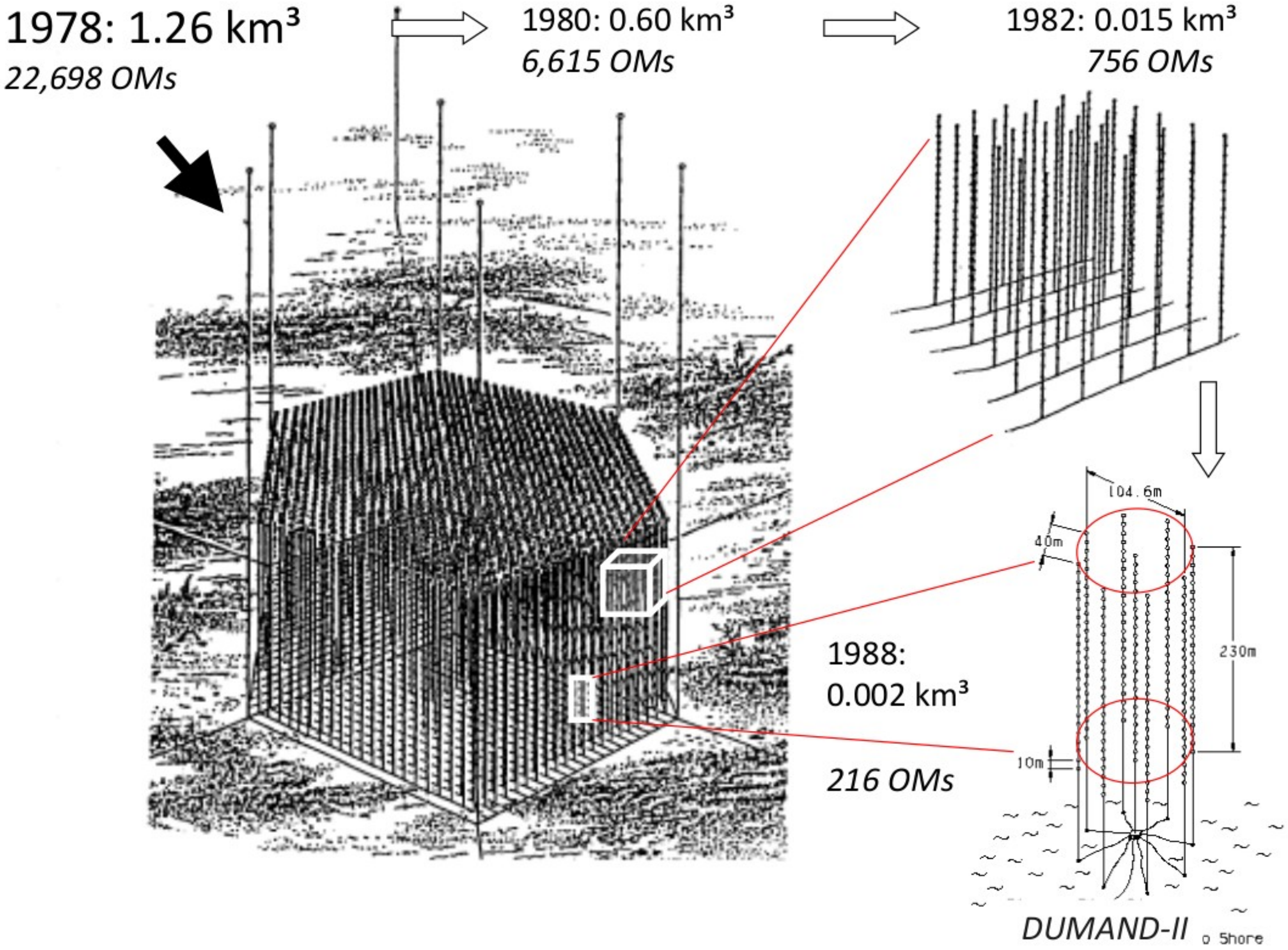
Neutrino Astronomy
history and current status
(not including Baikal-GVD)

Neutrino astronomy: origin

- 1960: Kenneth Greisen & Frederick Reines discuss first prospects for large undergound neutrino detectors. Greisen: “As a detector, we propose a large Cherenkov counter, about 15 m in diameter, located in a mine far underground.”
  → MeV-GeV neutrino detectors

- 1960: Moisey Markov: “… install detectors deep in a lake or a sea and to determine the direction of charged particles with the help of Cherenkov radiation.”
  → high energy neutrino astronomy

The DUMAND project



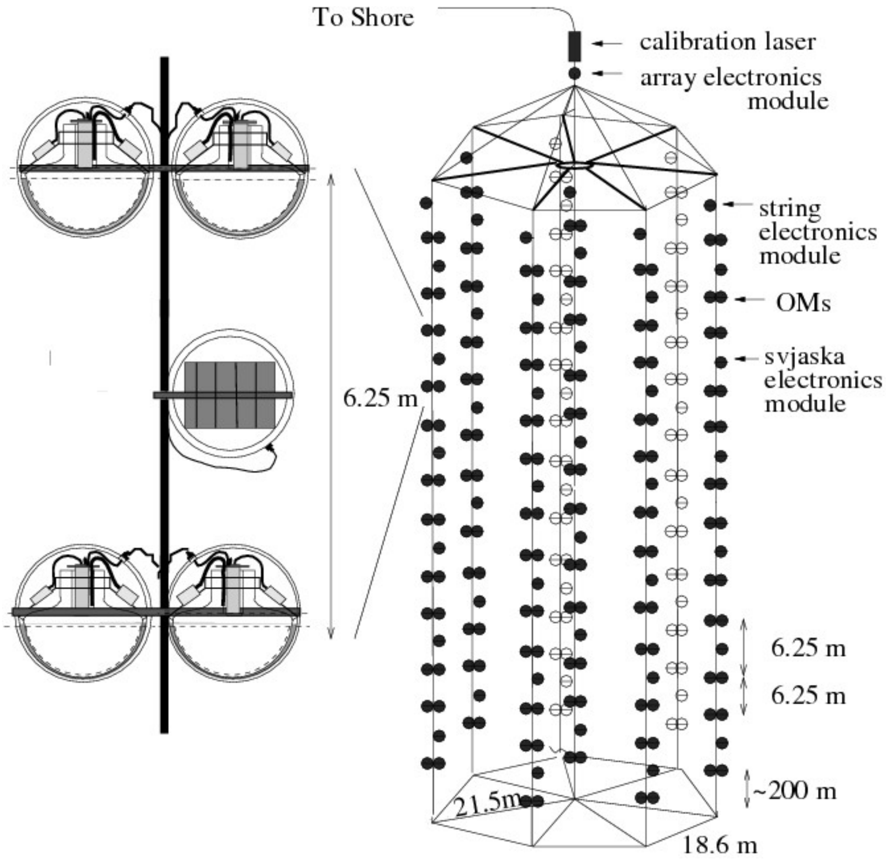
In 1987, a 7-PMT test string operated from a vessel near Hawaii and measured the muon intensity as a function of depth.

In Dec 1993, a first of three prepared strings was deployed and linked to shore, but water leaks developed, terminating the communication to shore.

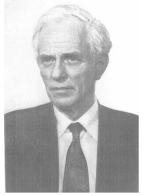
1995 project closed

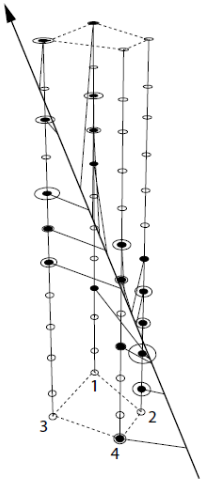
For details
see e.g. arXiv:1903.11481

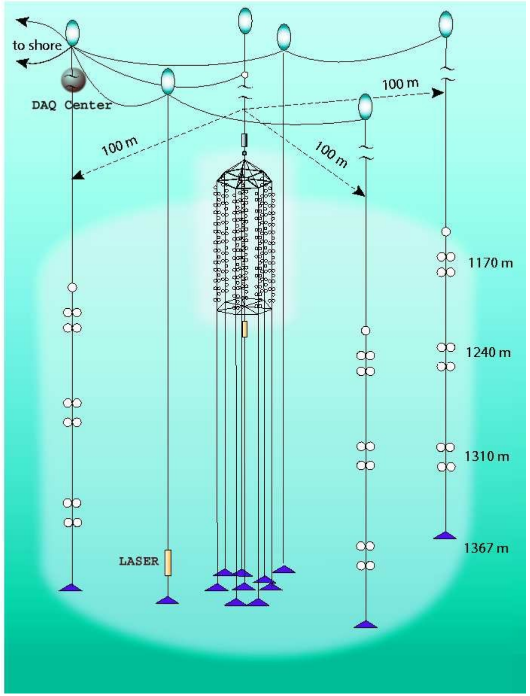
Baikal NT-200 and NT-200+



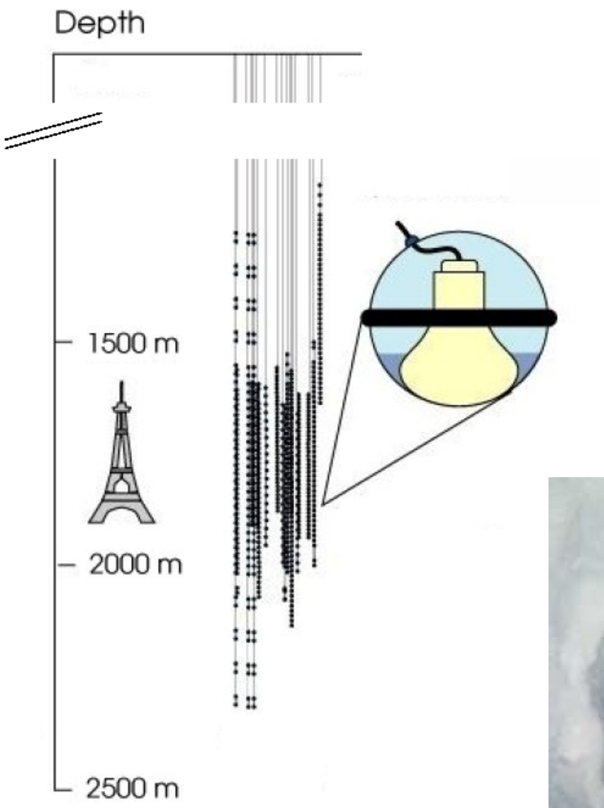
- A. Chudakov, ~1980: proposal to build a neutrino telescope in lake Baikal
- 1981: first shallow-water tests
- 1993-1998: construction of NT-200 (192 PMTs on 8 strings)
- 2005-2006: 3 external strings added→ NT-200+

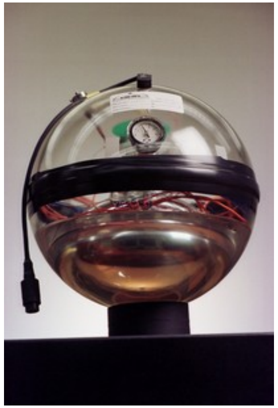






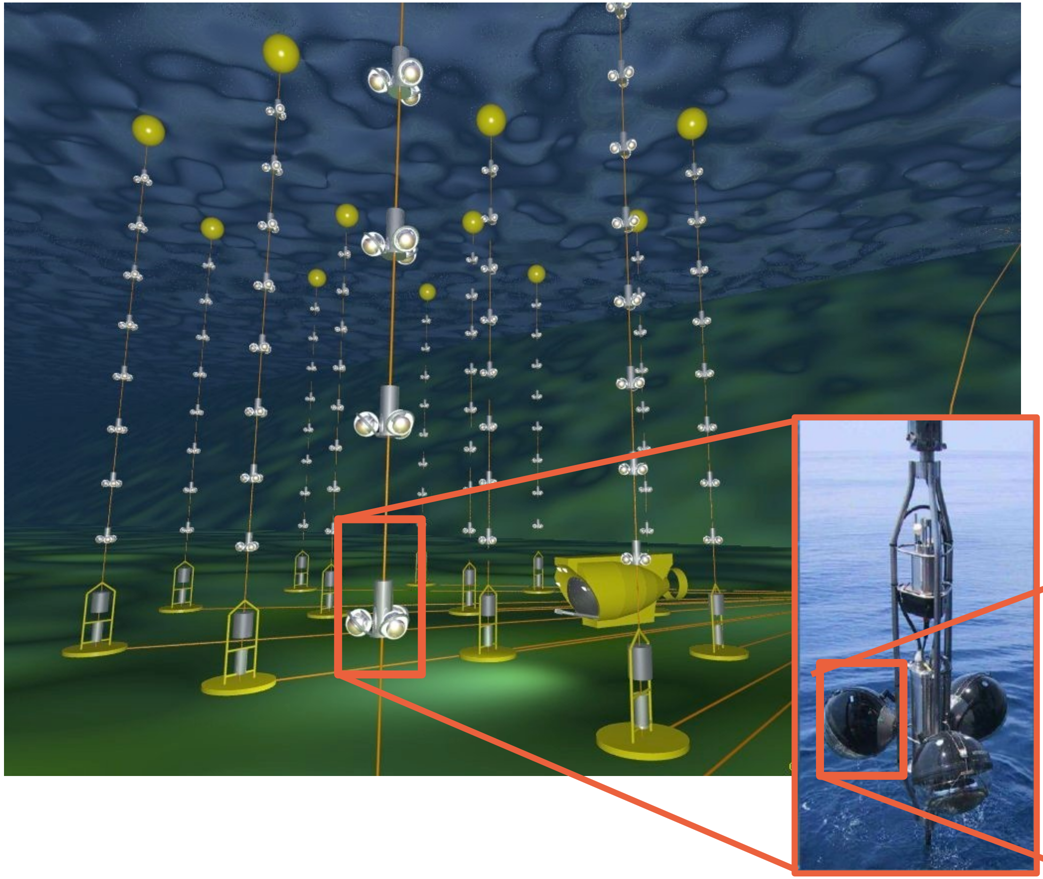
AMANDA at South pole





- 1988: proposal to build a neutrino telescope in Antarctic ice (F. Halzen)
- 1993-1994: first small array deployed
- 1995-2000: construction
- 677 optical modules on 19 strings
- 2009: detector turned off (superseded by IceCube)

ANTARES in Mediterranean sea



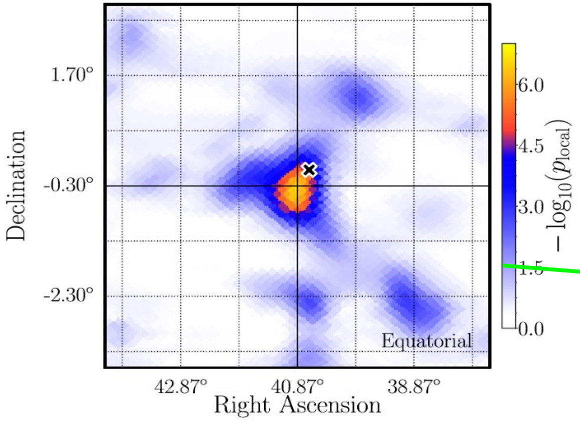
- 40 km offshore Toulon, France
- 2.5 km depth
- 885 optical modules on 12 strings
- ~ 12 Mton instrumented volume

ANTARES OM:
10” Hamamatsu PMT

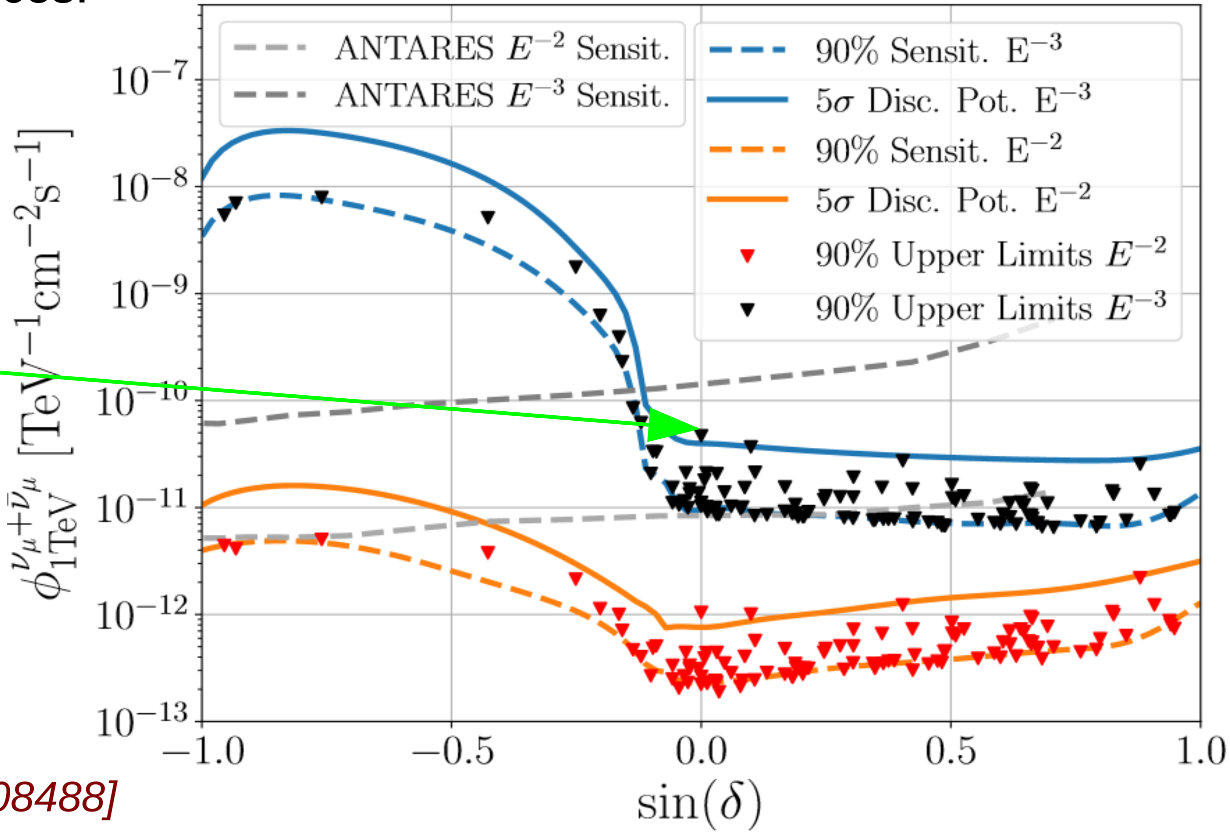
- Array completed in 2008
- Dismantled in Feb 2022

ANTARES 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.

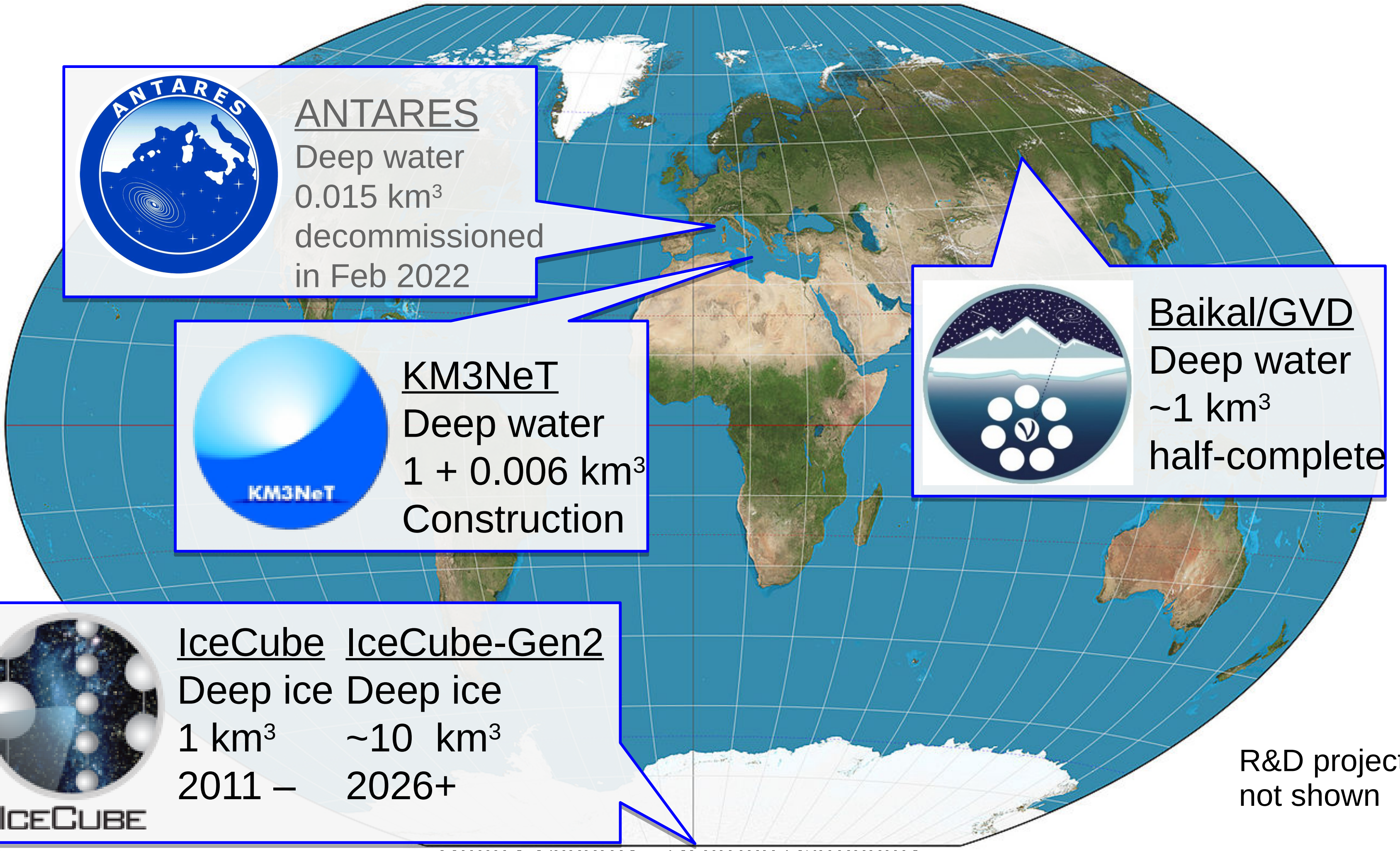


Strongest excess
(2.6 σ post trial) close to
galaxy NGC 1068 (cross)



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

Neutrino telescope world map 2023



ANTARES
Deep water
0.015 km^3
decommissioned
in Feb 2022

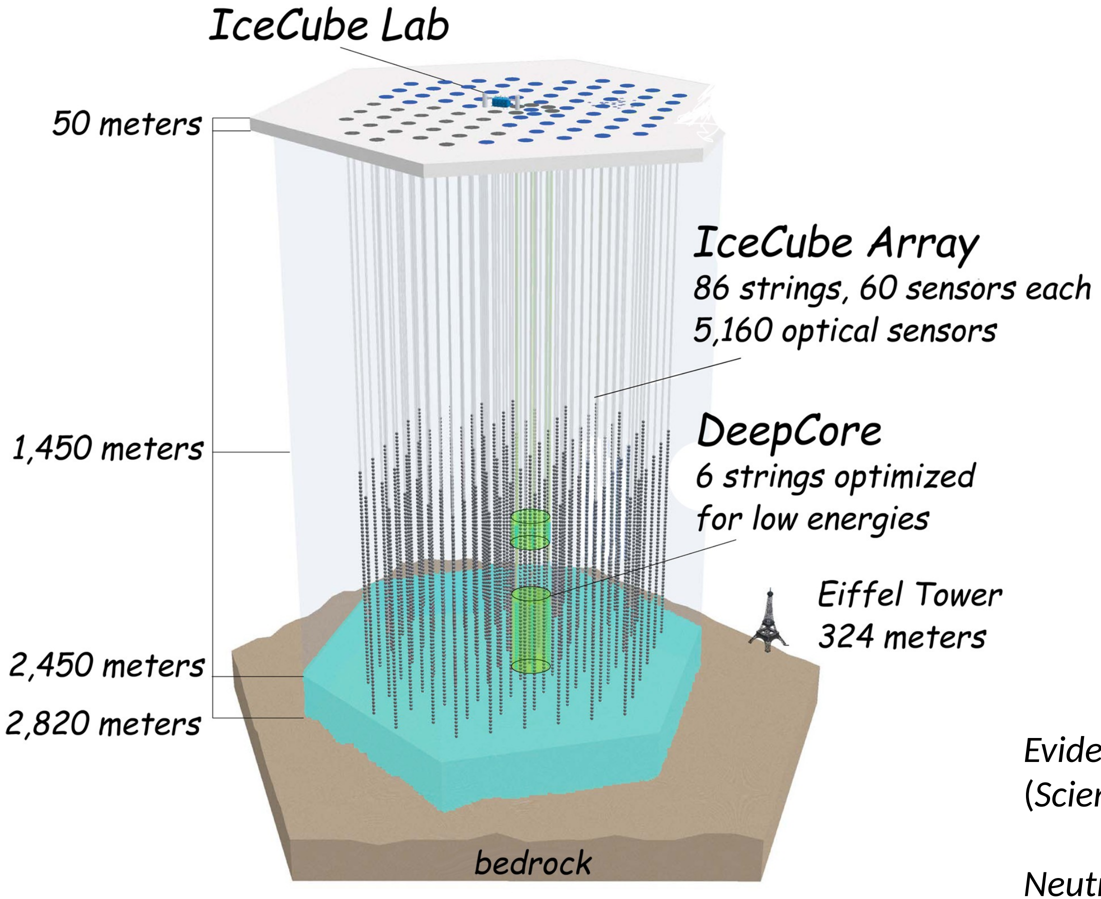
KM3NeT
Deep water
1 + 0.006 km^3
Construction

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

IceCube



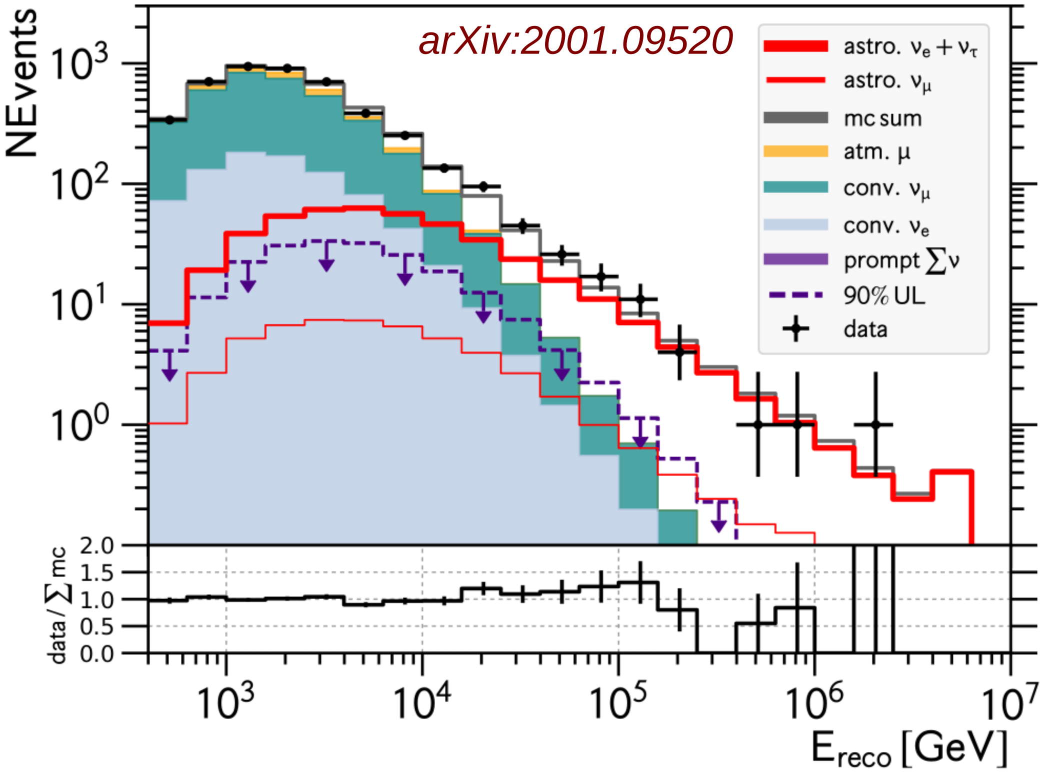
- Construction started in 2005
- Complete in 2010
- 1 km^3-scale neutrino detector
- Still fully operational as of 2023

Evidence for High-Energy Extraterrestrial Neutrinos with IceCube (*Science* 2013, 342, 1242856)

Neutrino emission from the direction of the blazar TXS 0506+056 (*Science* 2018, 361, 147)

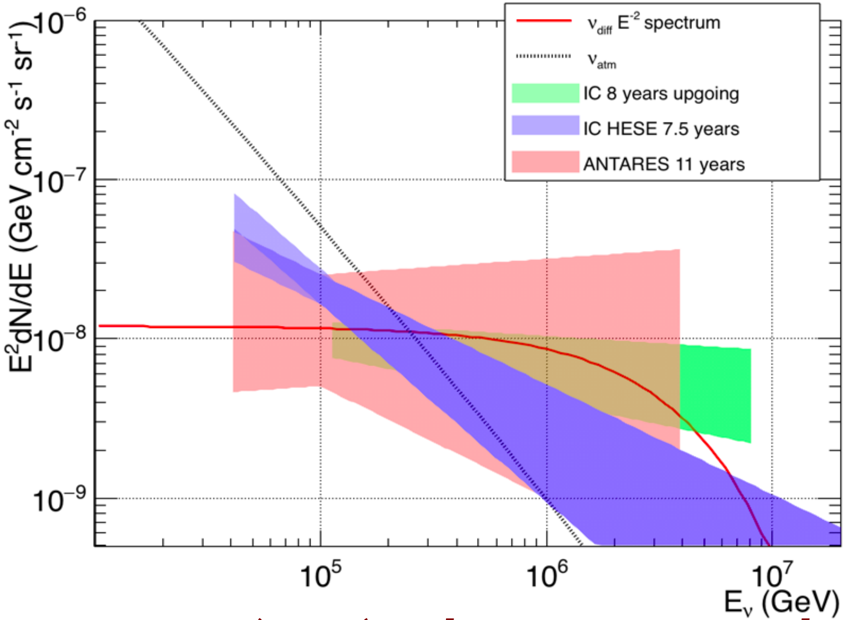
Diffuse neutrino flux

IceCube cascades



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

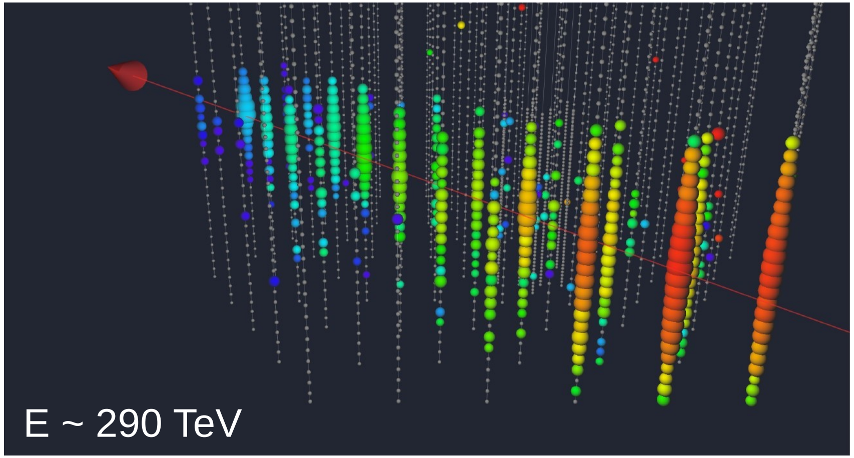
The existence of a diffuse neutrino flux is firmly established, but its origin remains unknown



ApJ 853 (2018) L7 [arXiv:1711.07212]

D. Samtleben, Neutrino 2020

TXS 0506+056



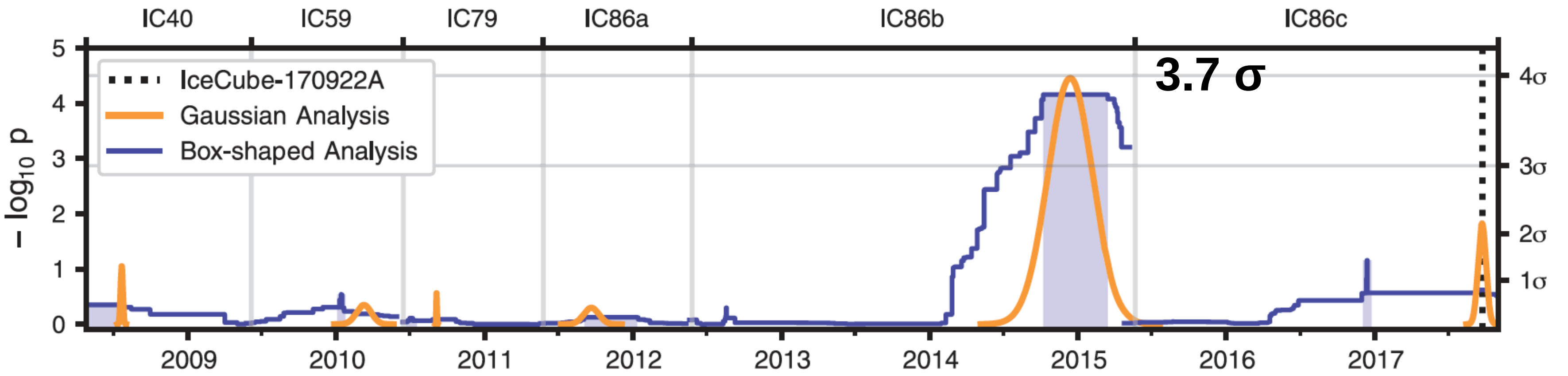
A blazar (BL Lac) at z= 0.34 (5.7 Gly)

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

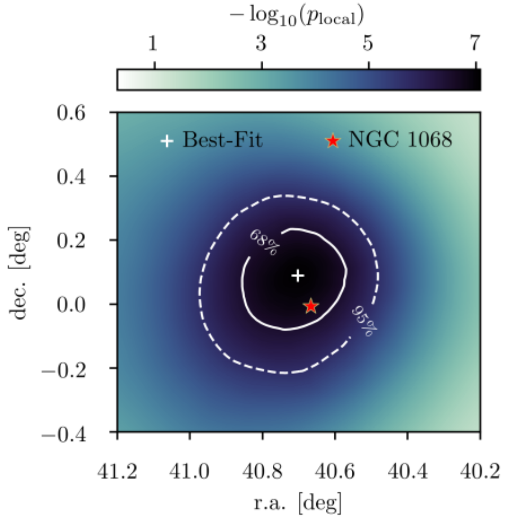
Science 361,147–151 (2018)

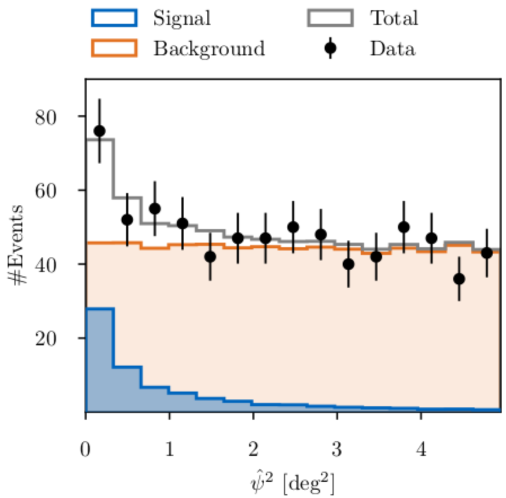
Another, neutrino-only flare found in earlier IceCube data

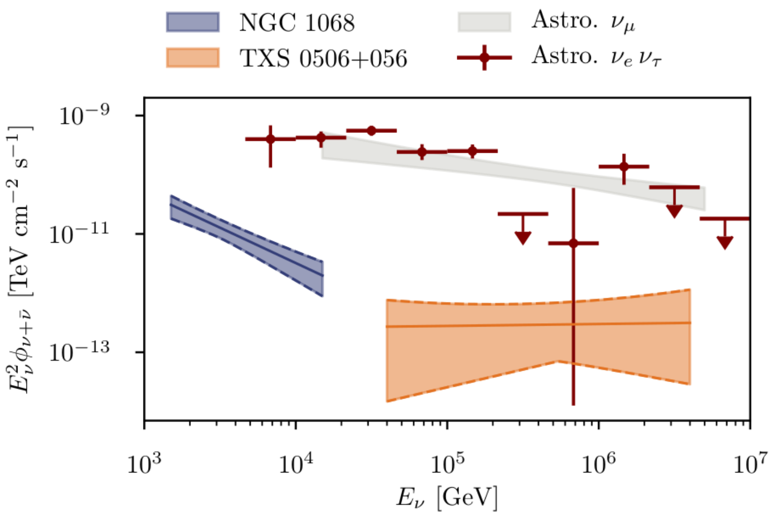
A. Albert et al., ApJL 863, L30 (2018)



NGC 1068





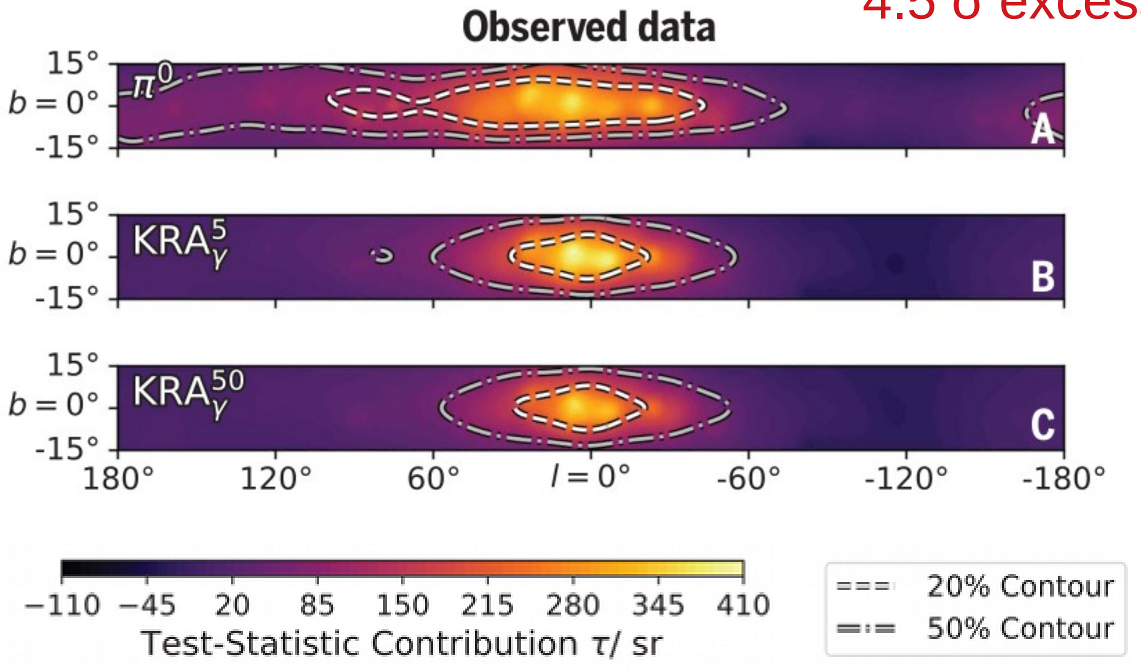


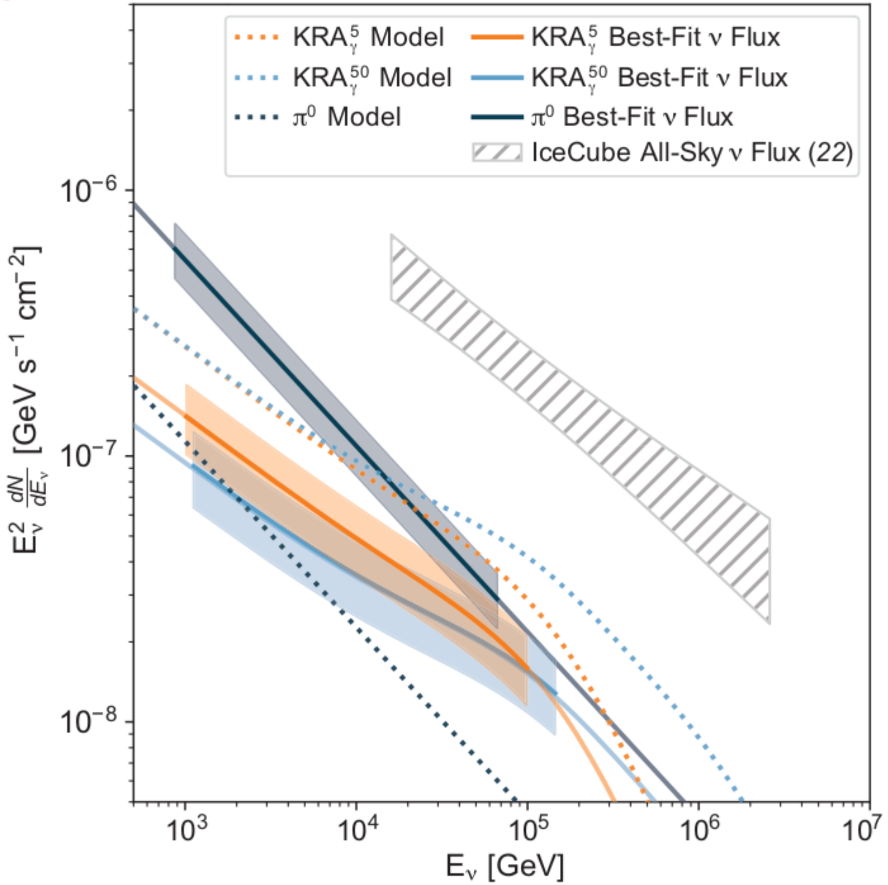
- NGC 1068 is a nearby active galaxy (Seyfert II)
- NGC 1068 is also known as a “starburst” galaxy
- 14.4 Mpc (47 Mly) from Earth
- Detected at 4.2 σ with 10 yr of IceCube data

Science 378, 6619, 538-543 (2022)

Galactic Diffuse neutrino flux observed by IceCube NEW!

4.5 σ excess!



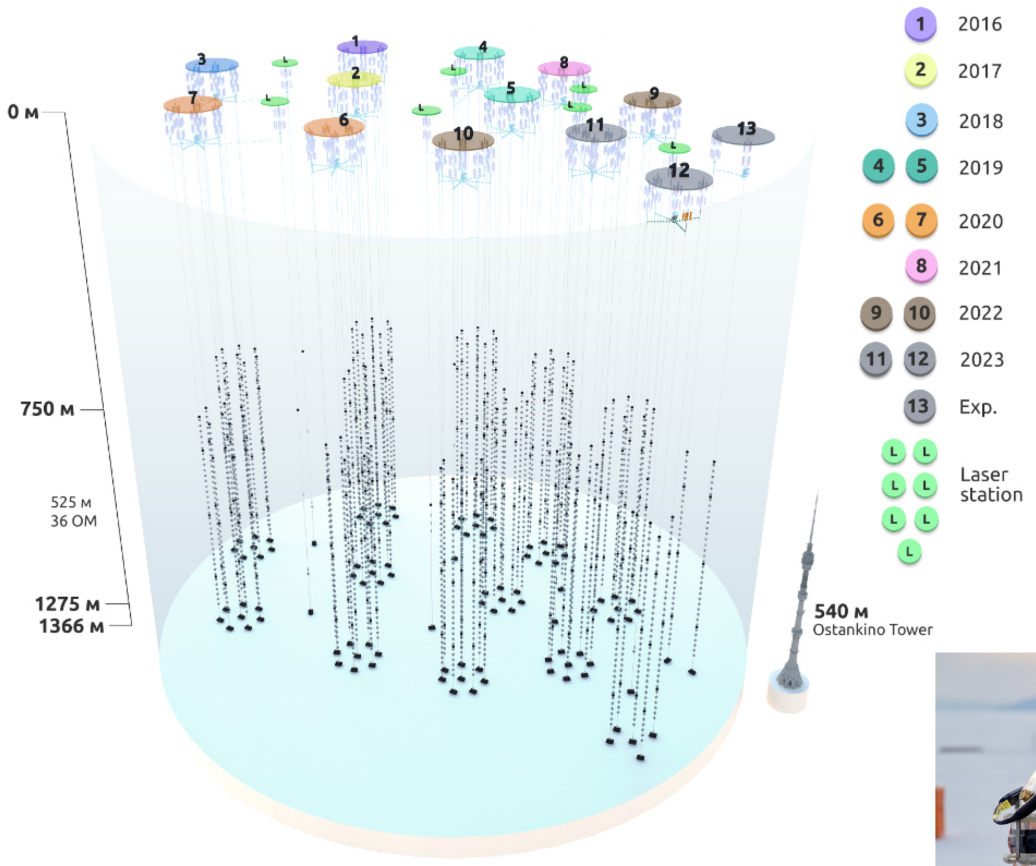


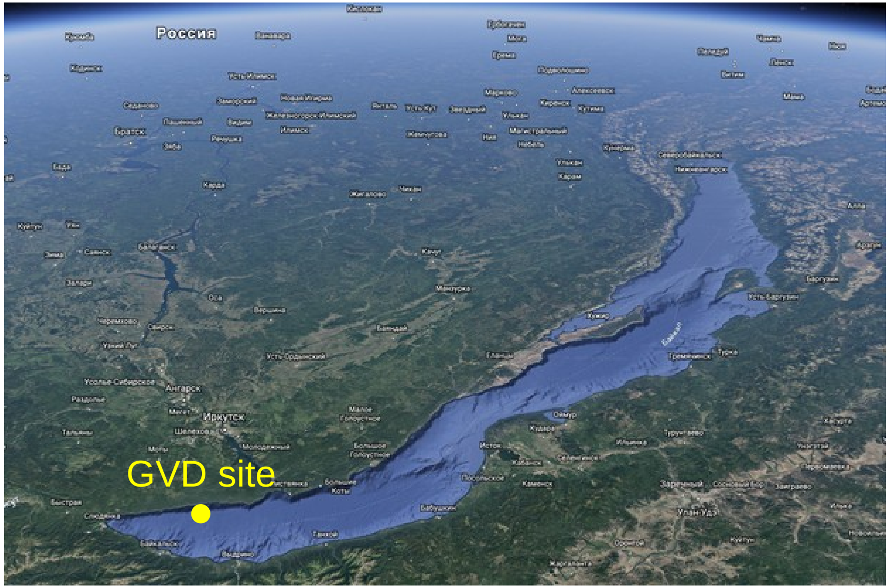
The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources

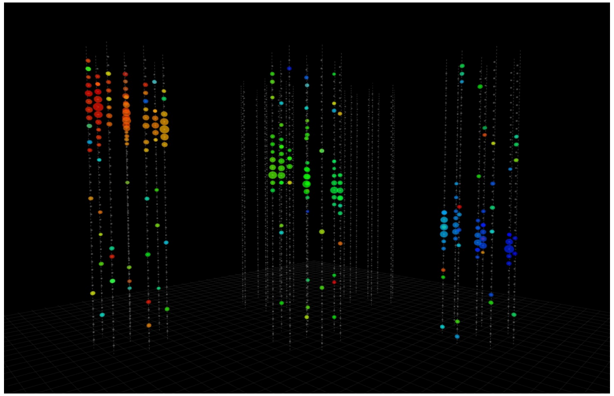
Science, 380 (6652)

Baikal-GVD

GVD = Gigaton Volume Detector

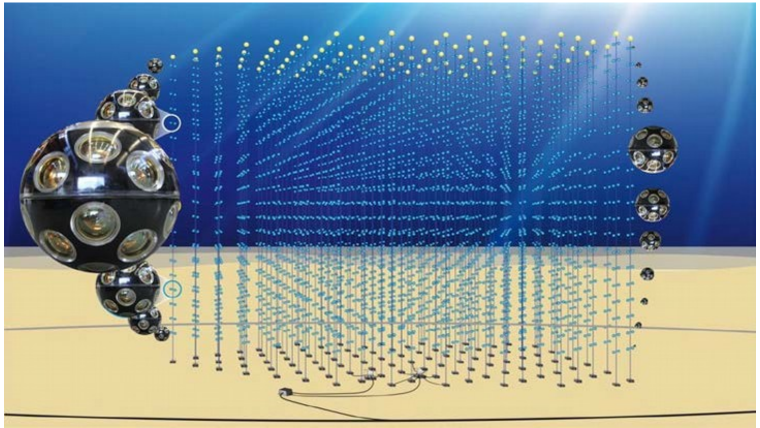






Status as of July 2023:
3456 Optical Modules on 96 strings

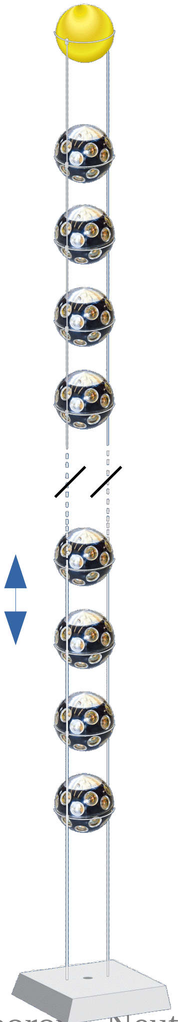
KM3NeT – ARCA (under construction)



Volume : 1 km^3

2 x 115 strings
18 DOMs / string
31 PMTs / DOM
Total: **128 000 PMTs (3")**

Vertical spacing: 36 m
Horizontal spacing: 90 m



Mediterranean sea, 80 km offshore Sicily
Depth 3500 m

Digital Optical Module

← 17" →

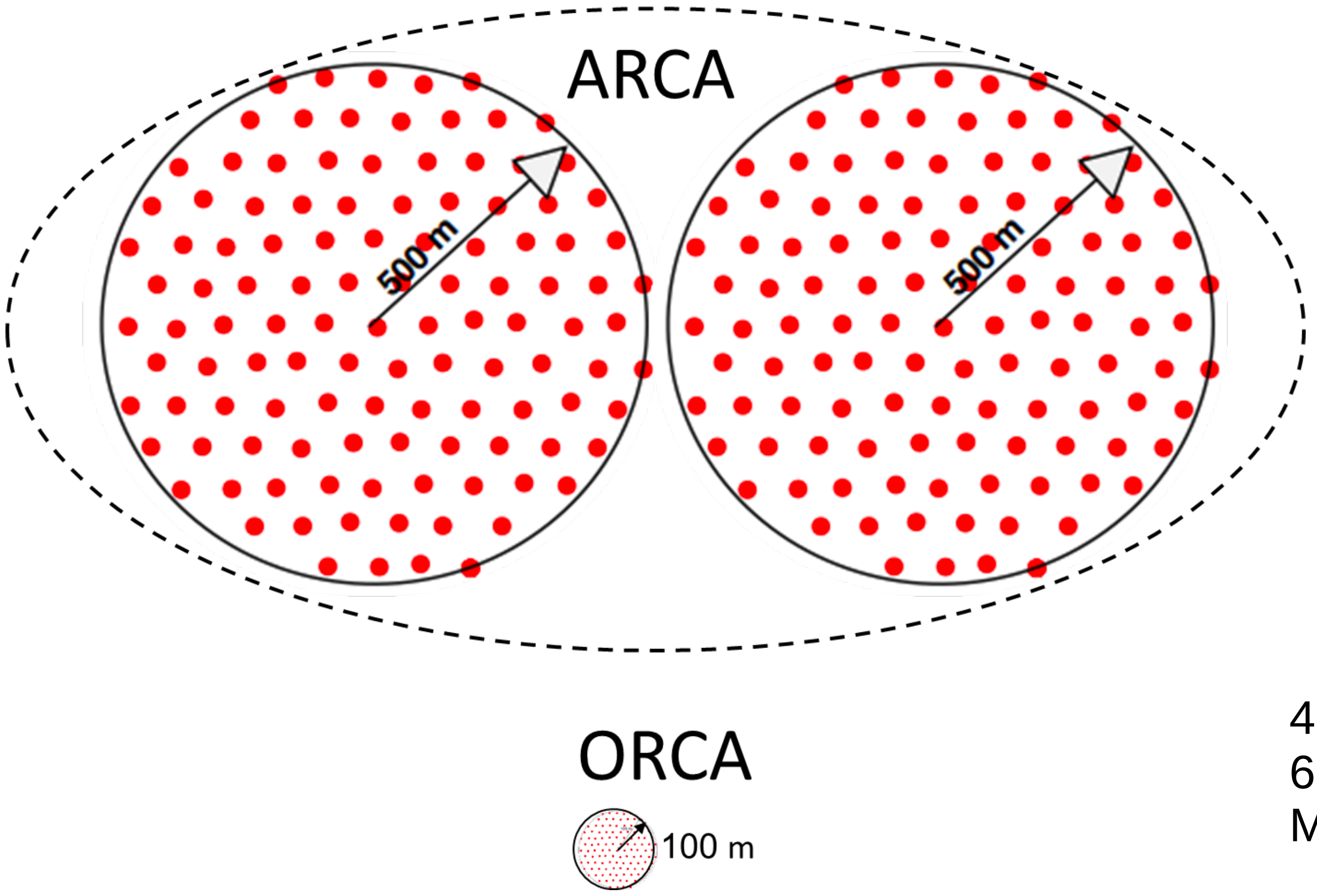
- 31 x 3" PMTs
- PMT HV
- LED & piezo
- FPGA readout
- DWDM

photocathode area similar to a 17" PMT

✔ Uniform angular coverage
✔ Directional information
✔ Digital photon counting
✔ All data to shore

Optical background (mainly ^{40}K): 5-10 kHz

KM3NeT - ARCA & ORCA

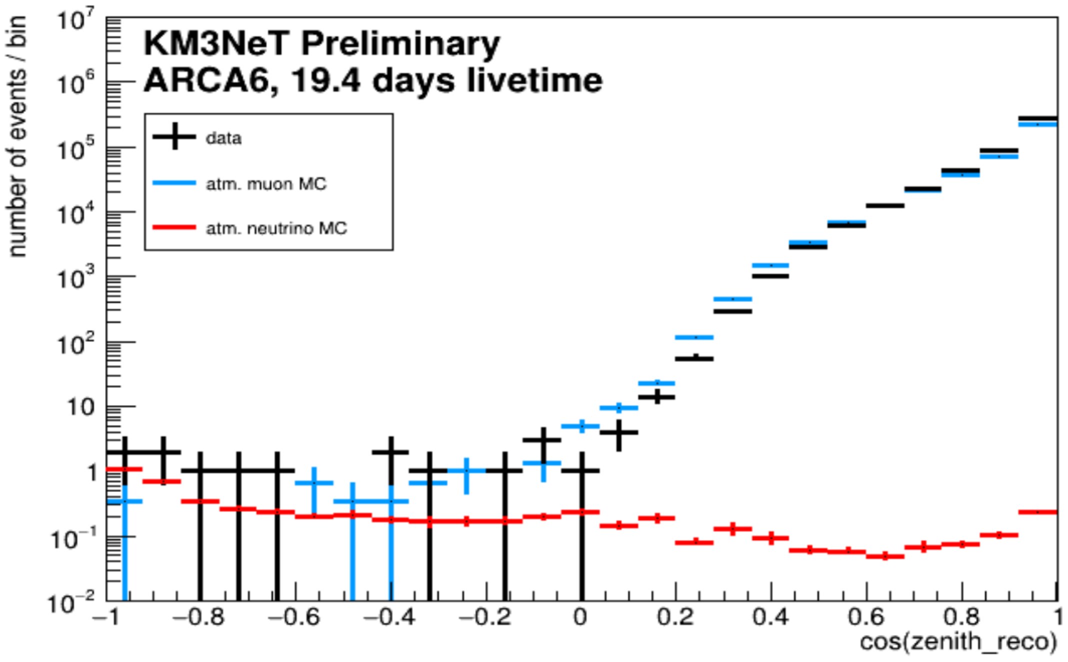


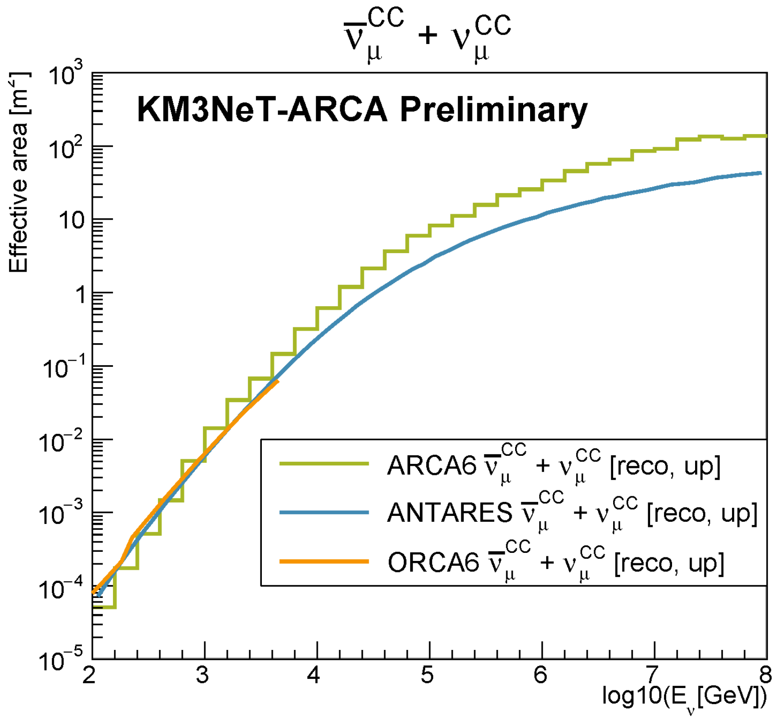
80 km offshore Sycily (Italy)
1 km3
Main goal: neutrino astronomy

40 km offshore France
6 Mt (0.006 km^3)
Main goal: neutrino mass ordering

KM3NeT - ARCA : current status

21 detection units operational out of 230 planned



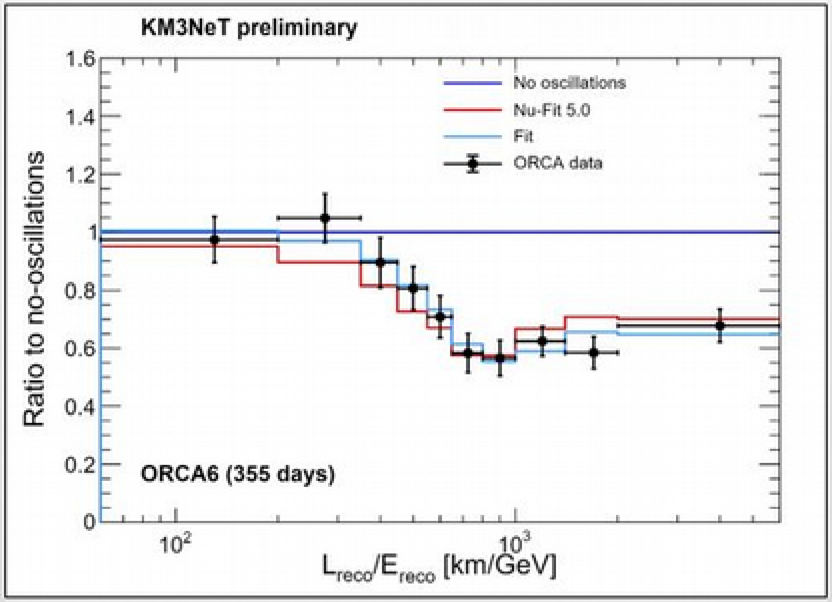


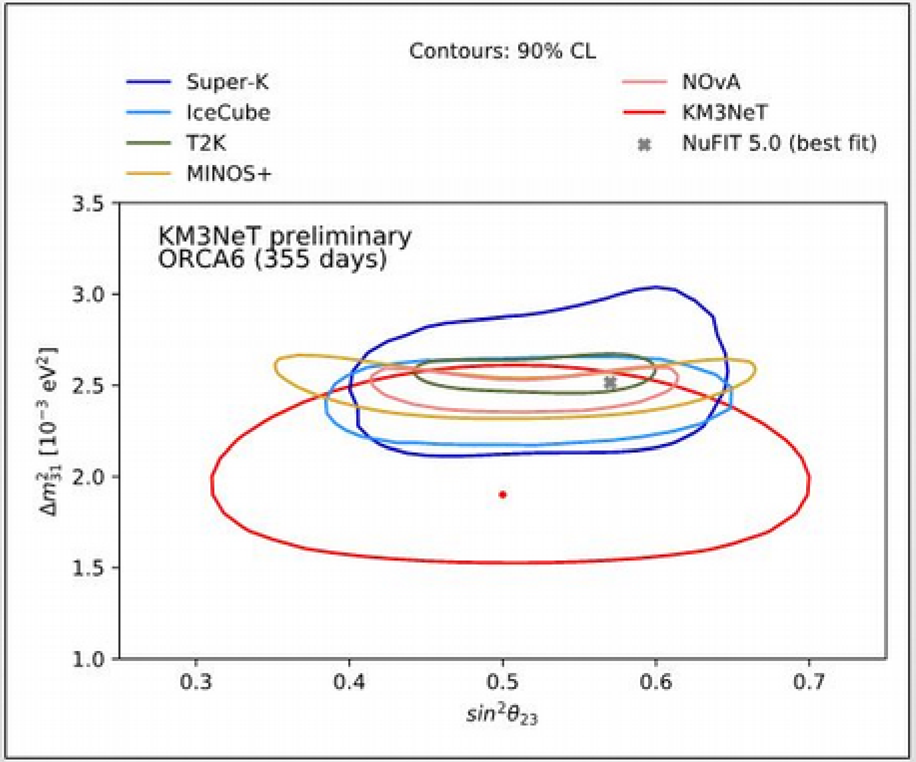
KM3NeT - ORCA : current status

8 Detection Units deployed (out of 115 planned)

First results on neutrino oscillations already public

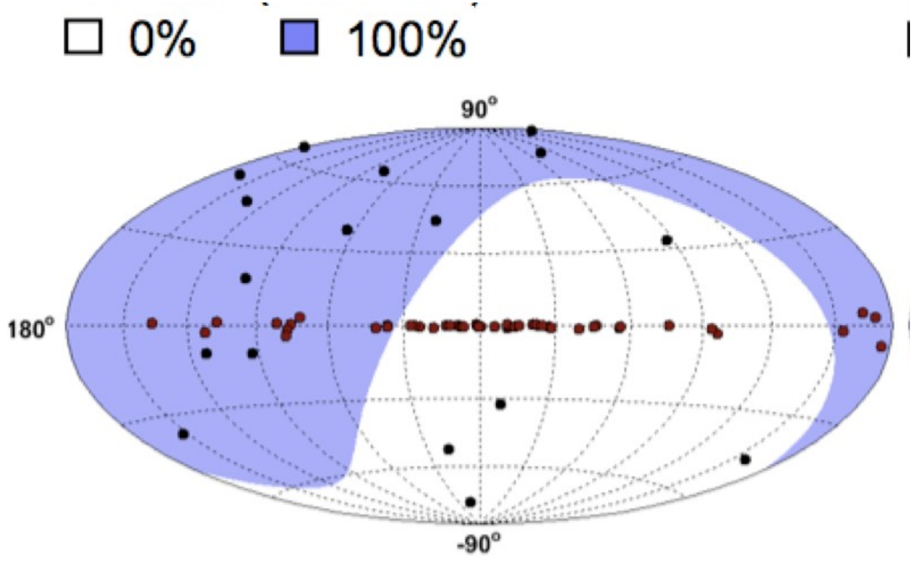
1 year of data with 6 lines of ORCA



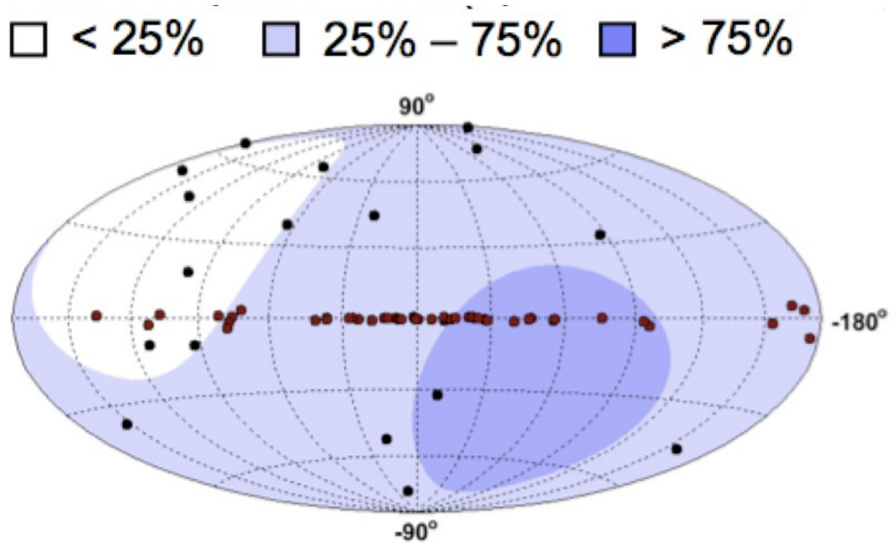


Sky visibility with upgoing tracks

South Pole (IceCube)



Northern hemisphere
(Mediterranean)



Complementary sky coverage

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

Water/Ice optical properties

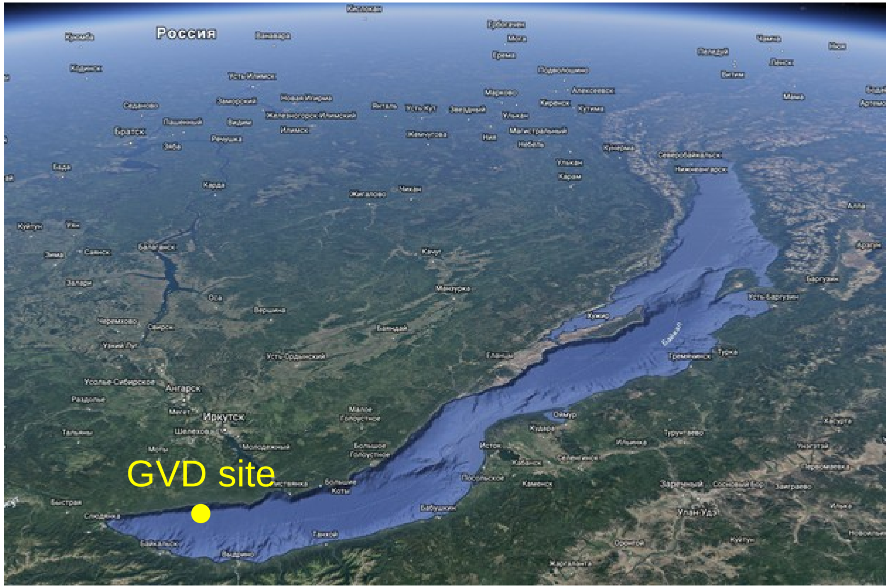
	Light absorption length	Effective light scattering length	Journal ref.
Antarctic ice (IceCube)	16-270 m	5-100 m	doi:10.1016/ j.nima.2013.01.054
Lake Baikal	24 m	~ 480 m	doi:10.1016/ j.nima.2012.06.035
Mediterranean sea	≈ 60 m	~ 260 m	doi:10.1016/ j.astropartphys.2004.11.006

Limits low energy performance.
Limits how sparse the detector can be.

Limits angular resolution

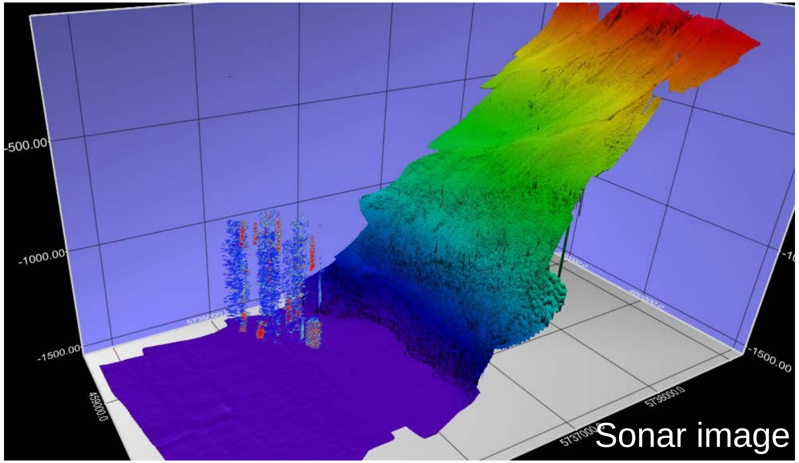
Baikal-GVD

Baikal-GVD site

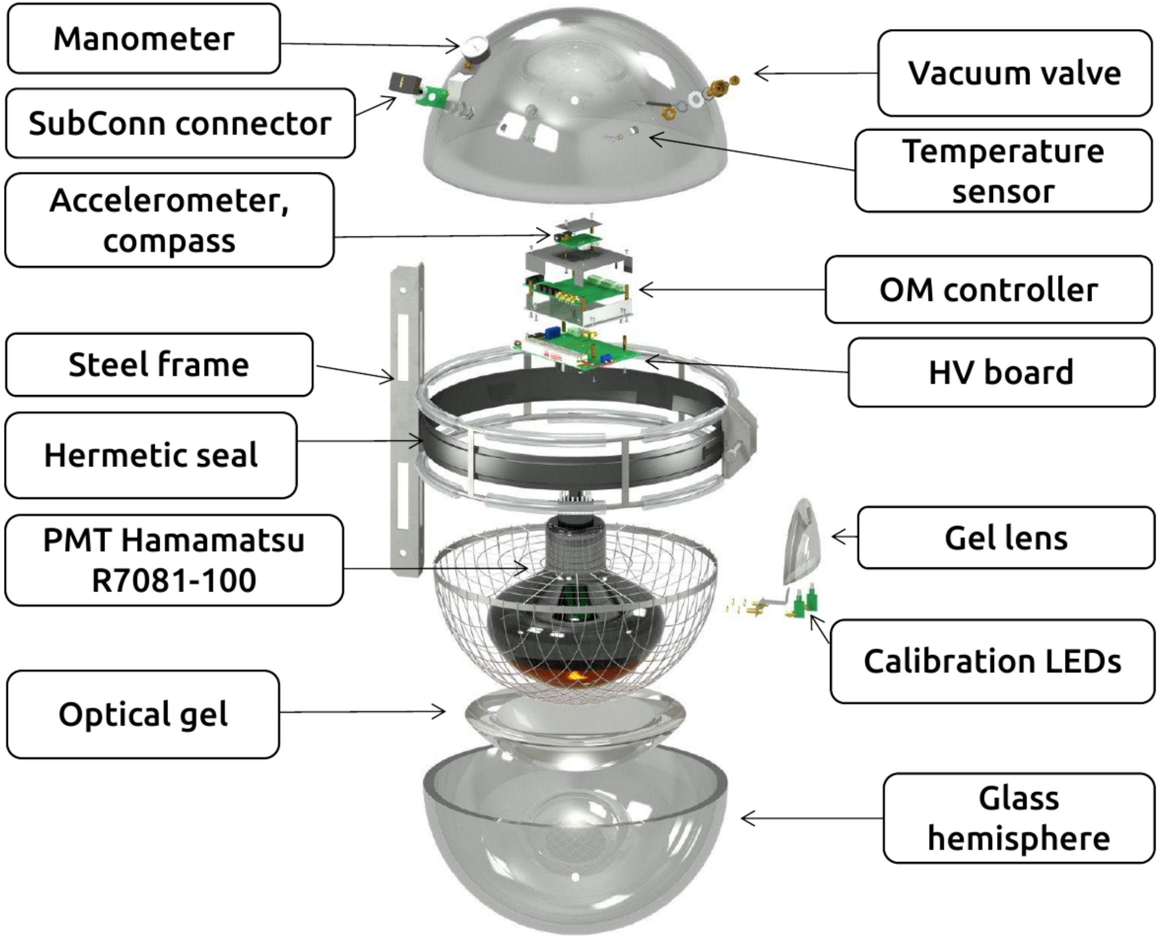


- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance

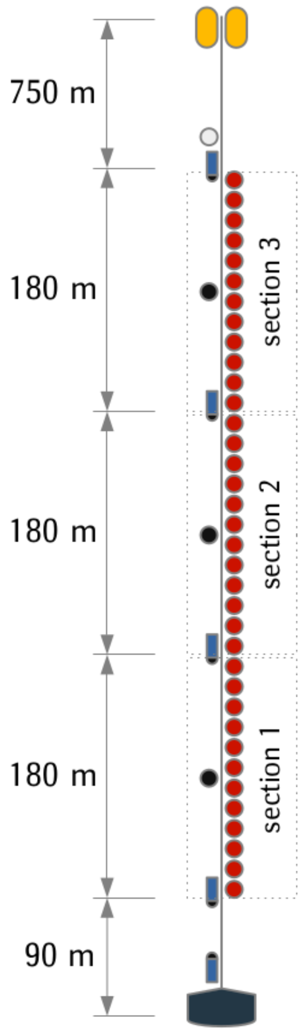
- High water transparency
  - Absorption length: 22 m
  - Scattering length: 30 – 50 m (L_{eff} ≈ 480 m)
- Moderately low optical background: 15–40 kHz (PMT R7081-100 ∅10”)



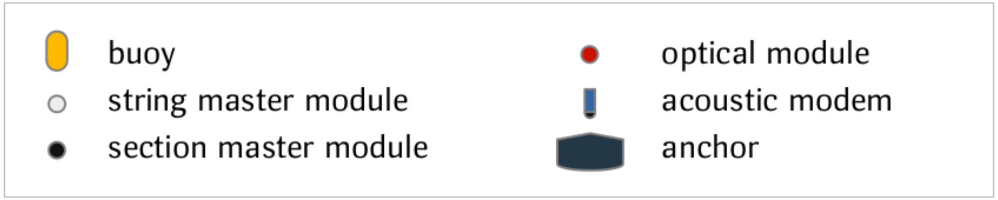
Baikal-GVD optical module



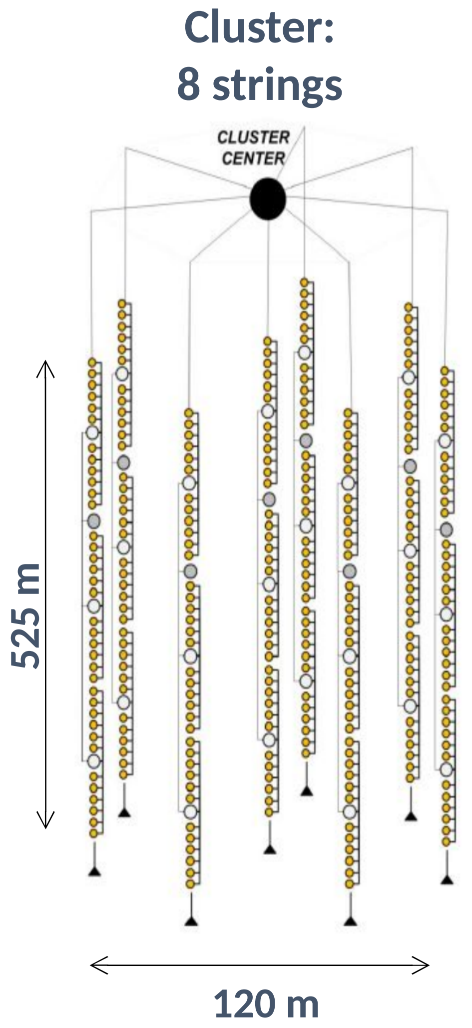
GVD string



- **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

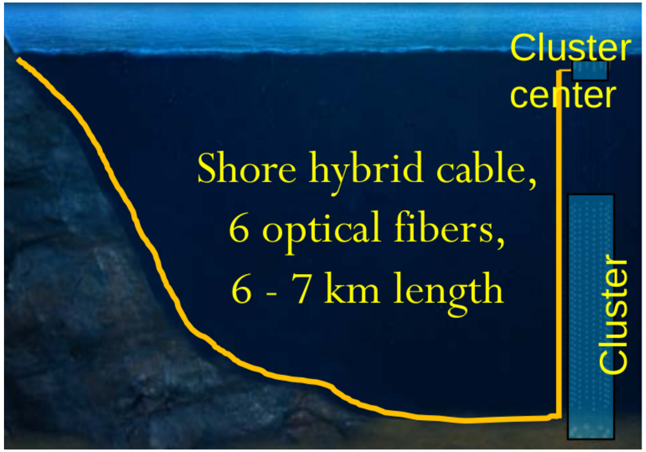


GVD cluster



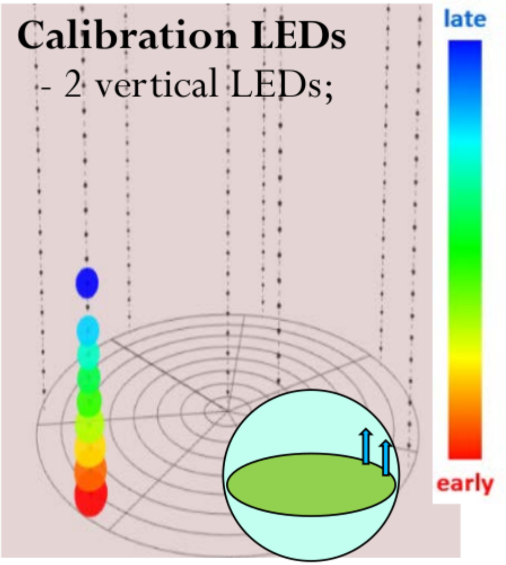
Cluster

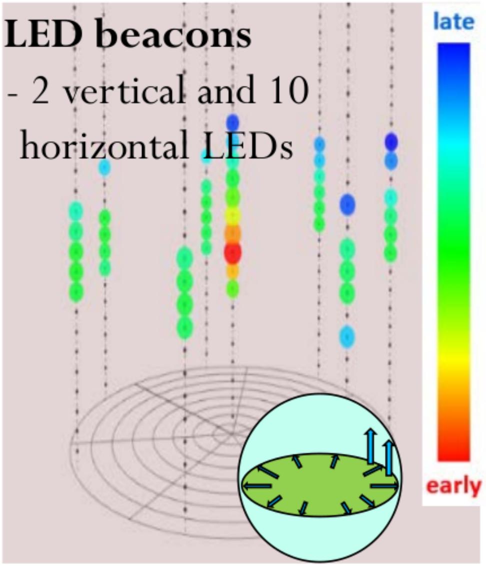
- 8 strings (288 OMs)
- 60 m step between strings
- Central electronics (power, trigger, data transmission) located at 30 m depth
- Hardware trigger: 4 p.e. + 1.5 p.e. on adjacent OMs in 100 ns window
- Inter-section synchronisation by common trigger (~ 2 ns accuracy)
- Internal network: shDSL Ethernet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



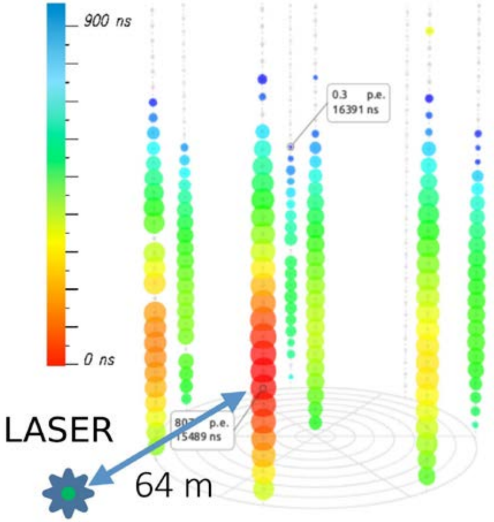
Calibration devices

- 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

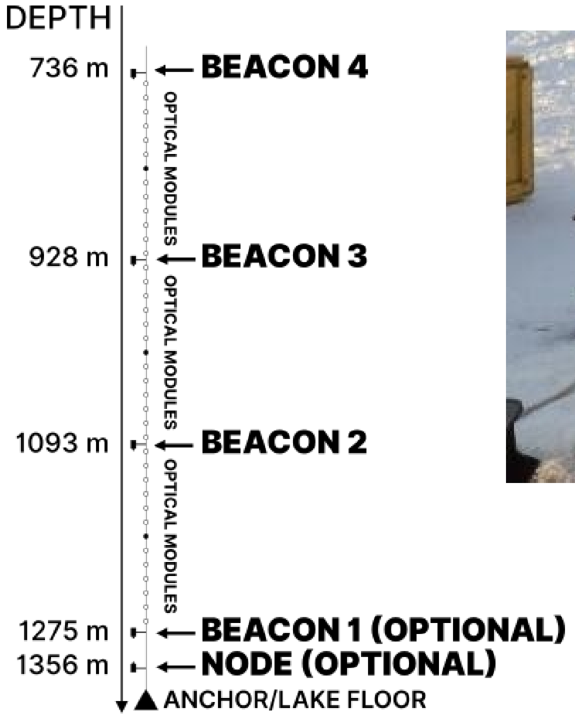


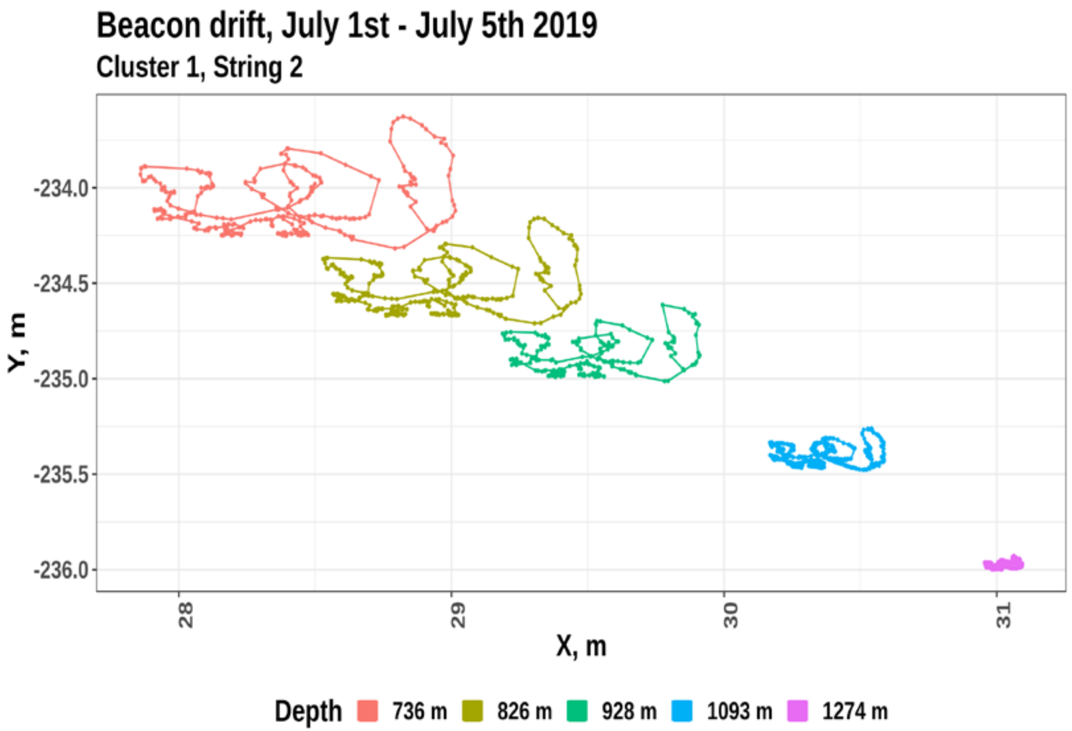


Calibration accuracy ~2 ns



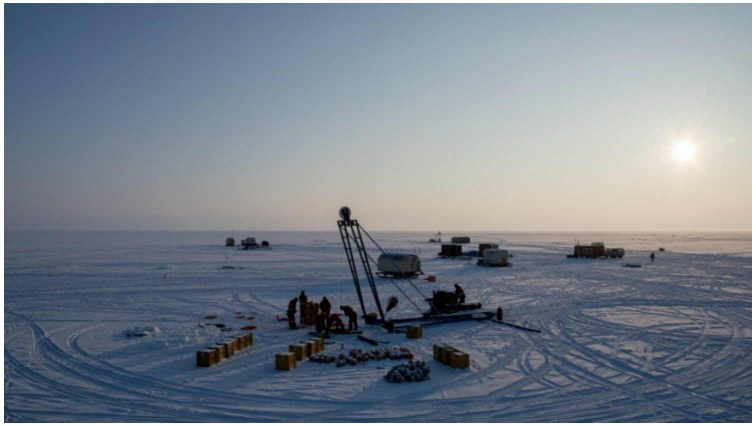
Acoustic positioning





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

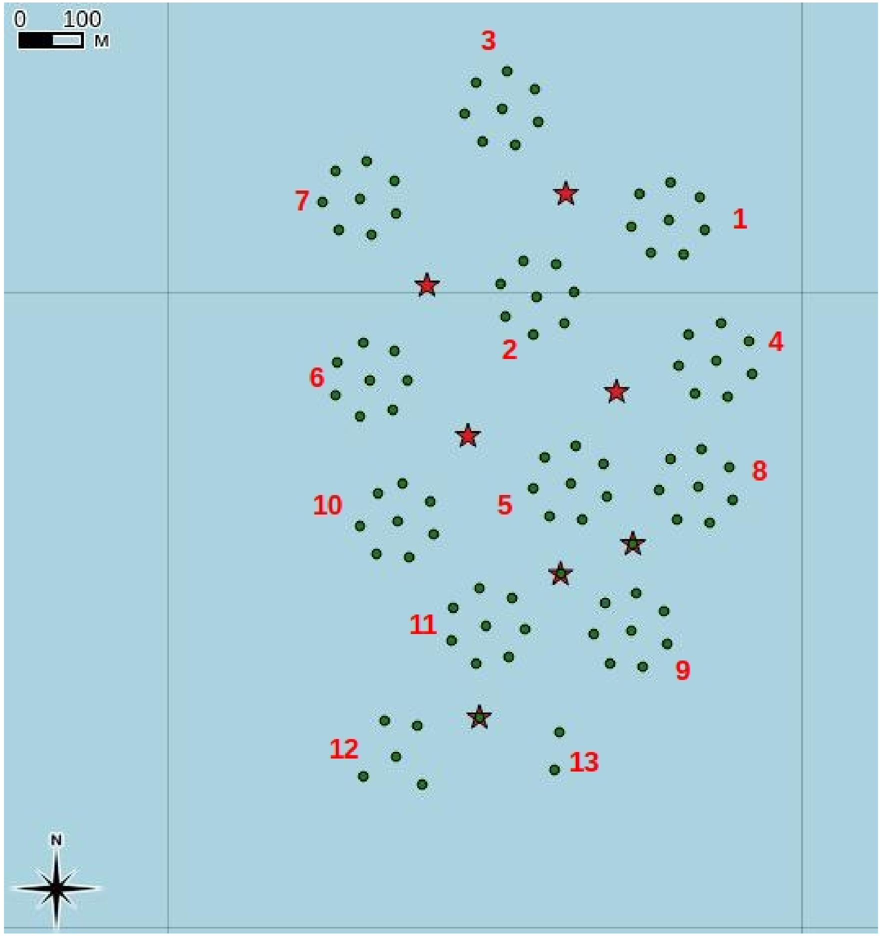


Status 2023 (end of the expedition)

- 12 regular clusters
- 96 strings
- 3456 Optical Modules

+ 2 “experimental” strings using fiber optic technology for data transmission

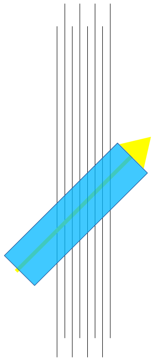
+ additional inter-cluster strings with lasers



Baikal-GVD performance and first results

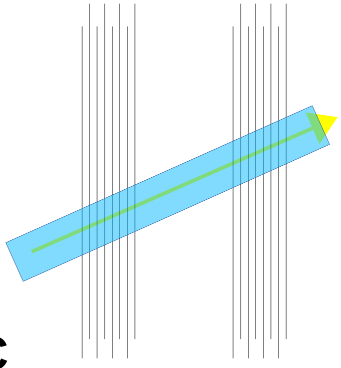
Event types

Single-cluster tracks



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

Multi-cluster tracks

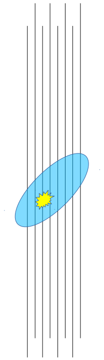


- Moderately low energy threshold
- Optimal sensitivity to inclined tracks
- Best angular resolution

ν_μ CC

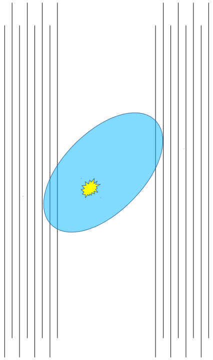
NC, ν_e ν_τ CC

Single-cluster cascades



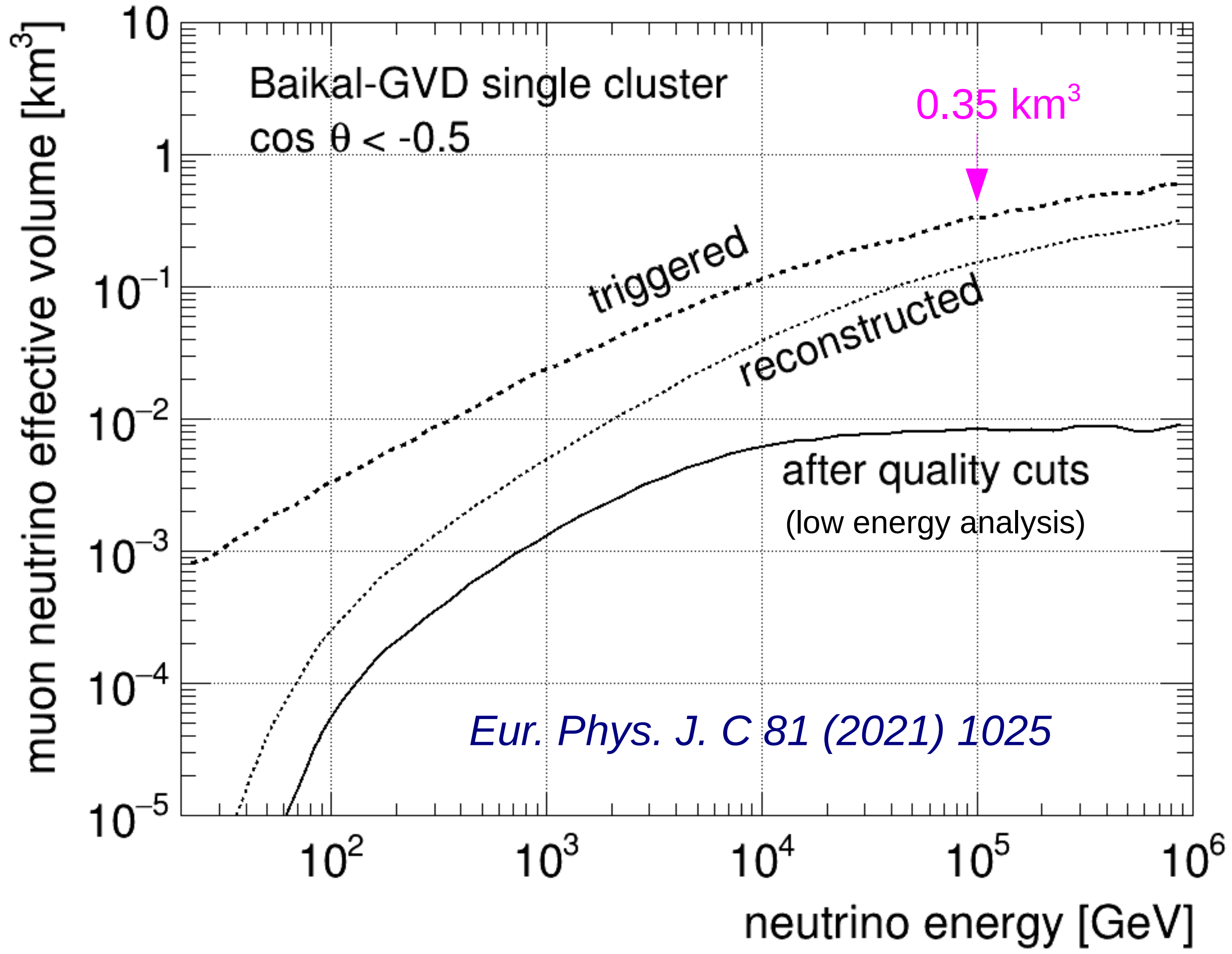
- High energy threshold
- Good energy resolution
- Relatively rare events

Multi-cluster cascades



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

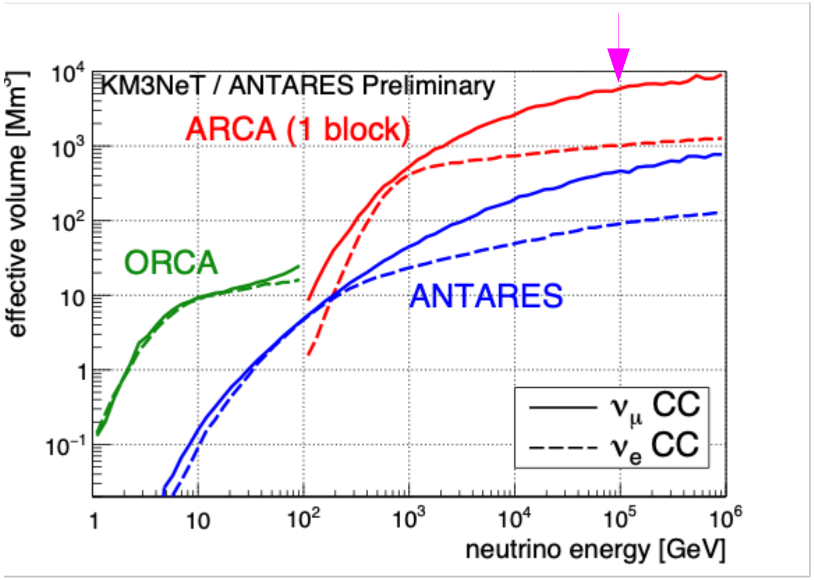
Neutrino effective volume for tracks (one GVD cluster)



Energy threshold ~ 200 GeV (higher than in ANTARES)

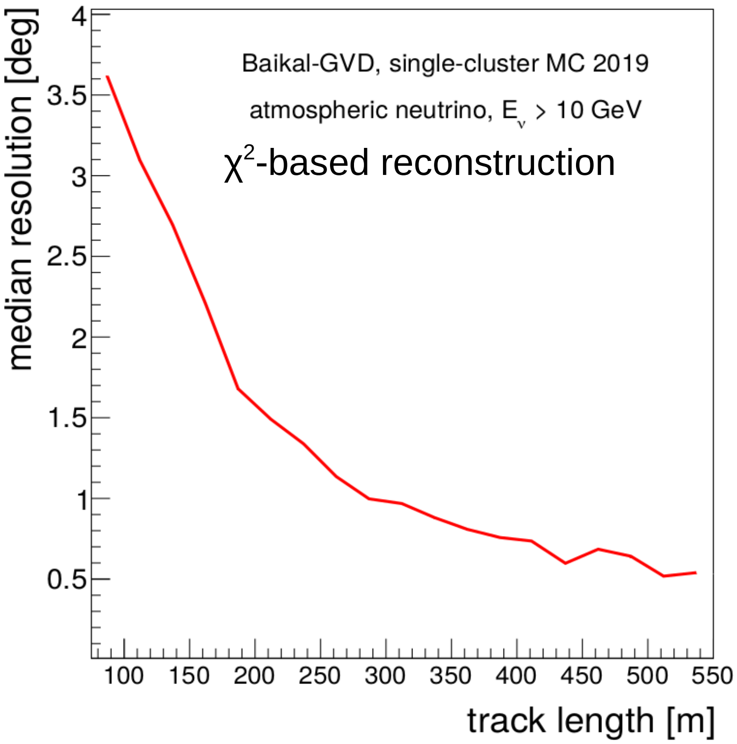
Fully efficient at E > 100 TeV

6 km³



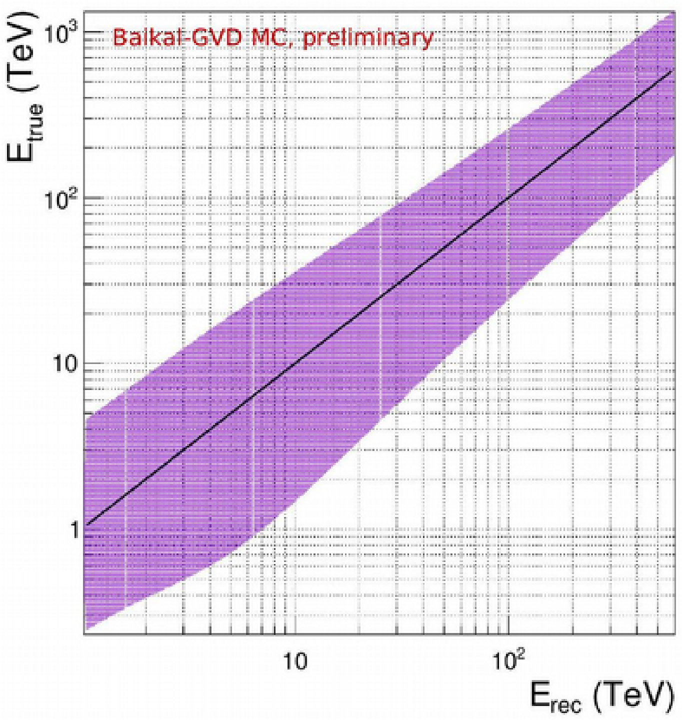
Expected performance for tracks

Angular resolution



Improvements expected from likelihood-based reconstruction (under development)

Energy reconstruction

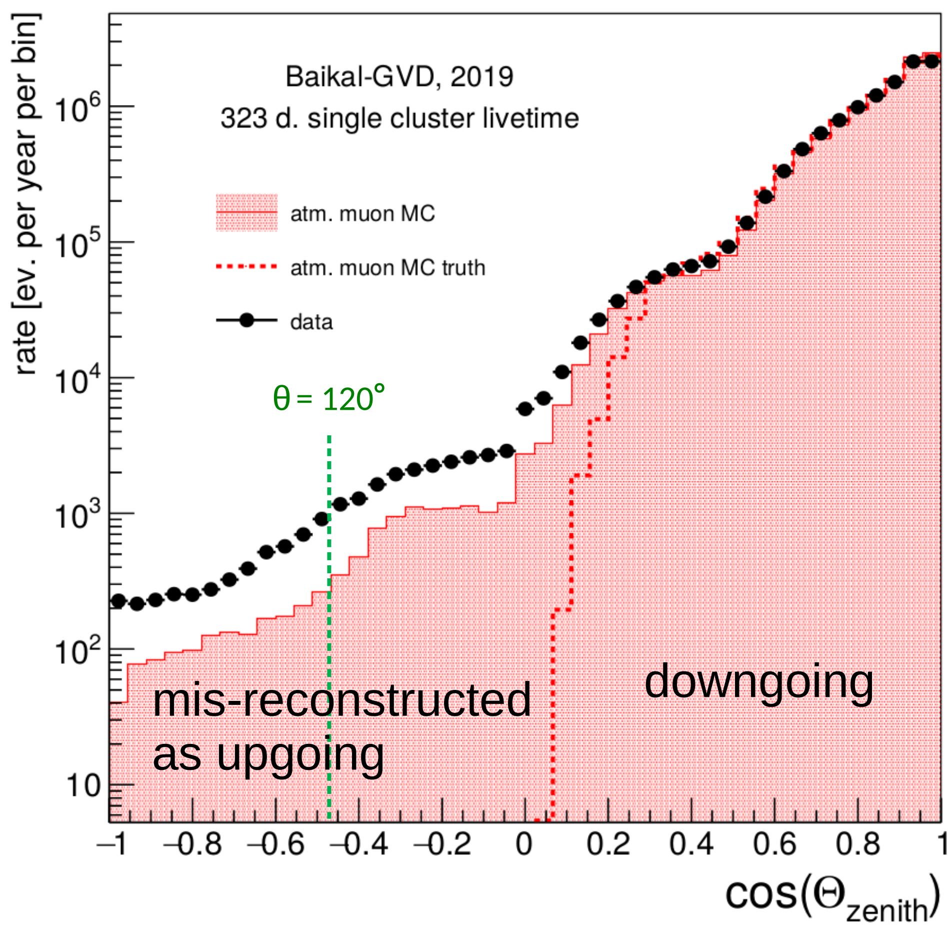


energy resolution ~ factor 3 at E ~ 100 TeV (±34% containment band)

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

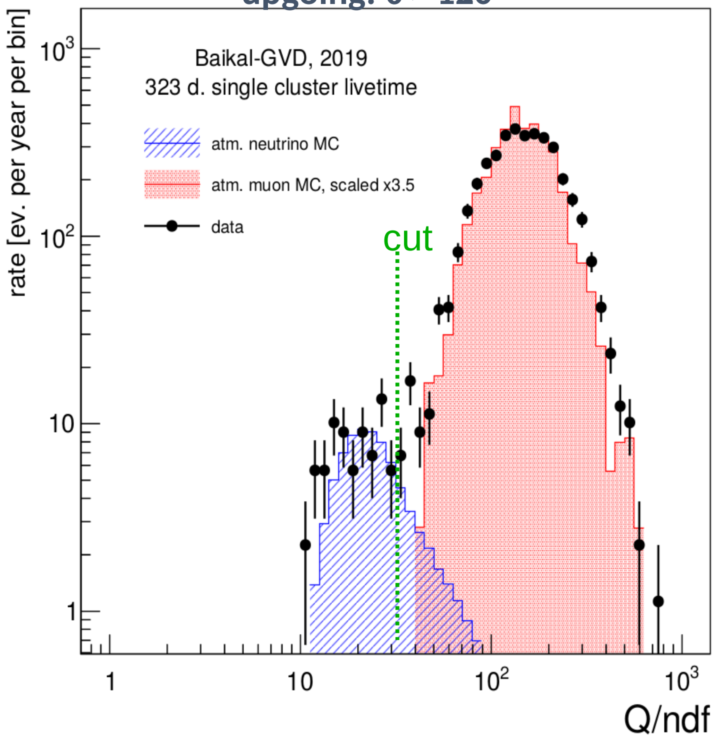
MC underpredicts the rate of misreconstructed events in the upgoing region by a factor of 3.5 (under study)

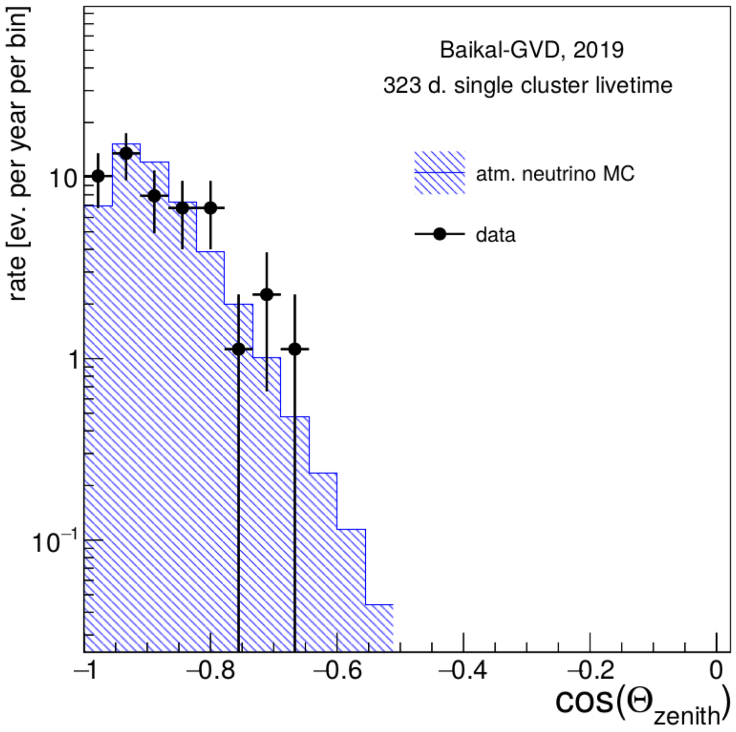
NB: most of these events are muon bundles (average multiplicity ~ 10)

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

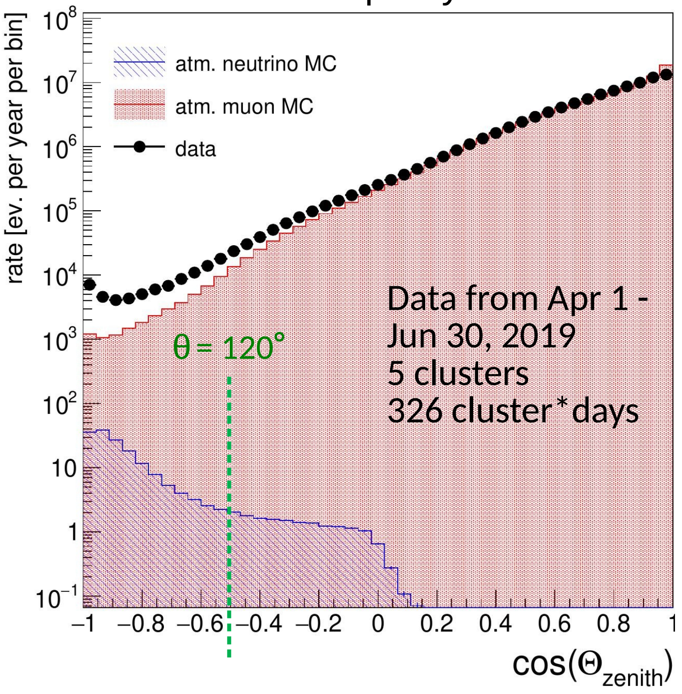
Observed events: 44

Median energy of this sample ≈ 500 GeV

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

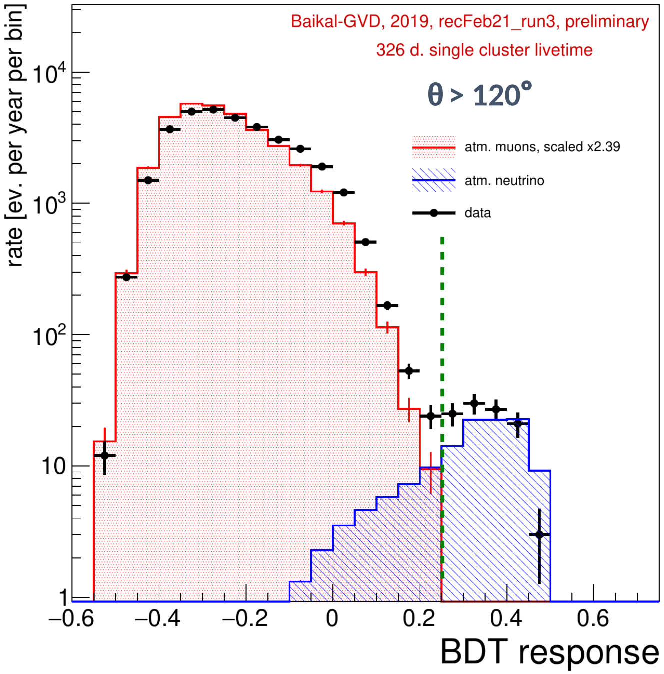
Single-cluster tracks: a BDT-enhanced χ^2-based analysis

Before quality cuts

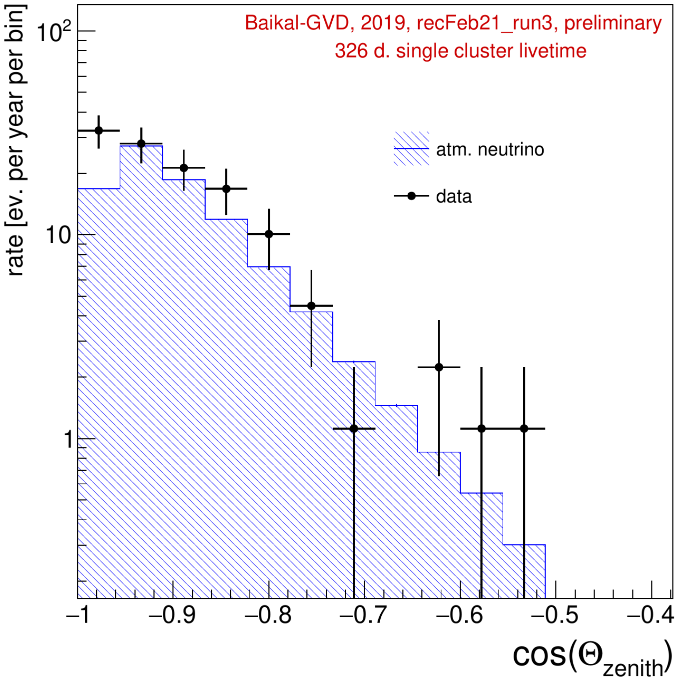


mis-reconstructed & upgoing

downgoing



After quality cuts



G. Safronov, Neutrino 2022

PoS-ICRC2021-1063

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

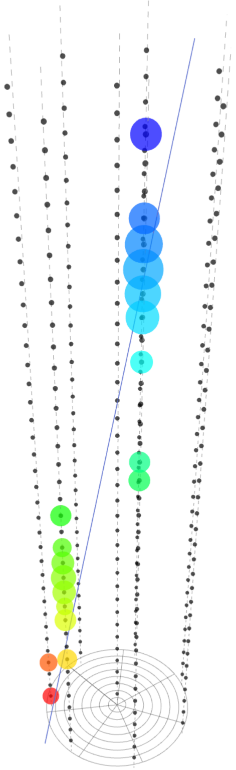
MC expected: 81.2

Observed events: 106

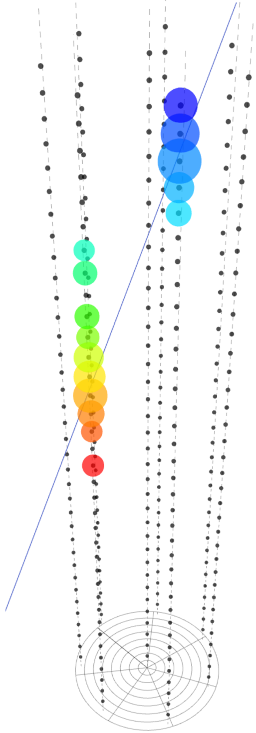
data-MC discrepancies under study

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

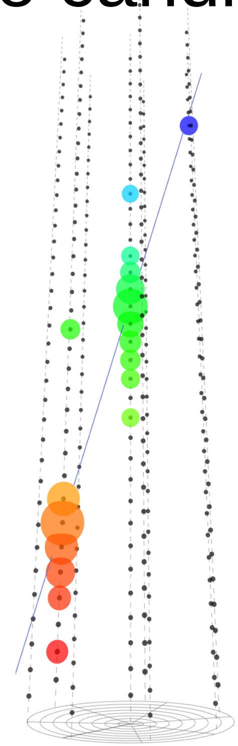
Track-like neutrino candidate events



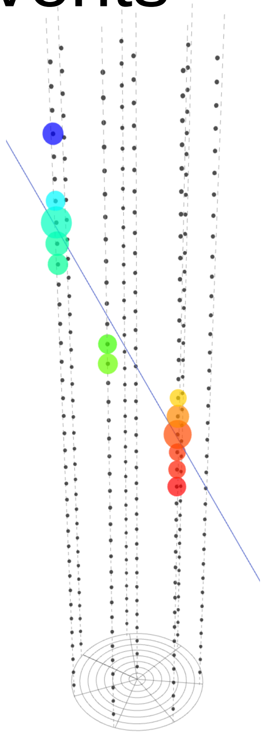
cluster 3, run 122
evt. 1549343
θ_{zenith} = 169.78°
$N_{strings}$ = 3
N_{hits} = 19



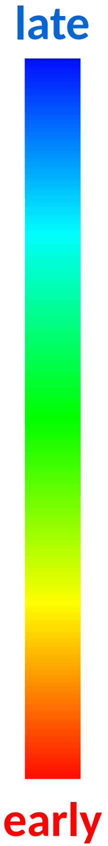
cluster 1, run 157
evt. 1414137
θ_{zenith} = 161.78°
$N_{strings}$ = 2
N_{hits} = 15



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



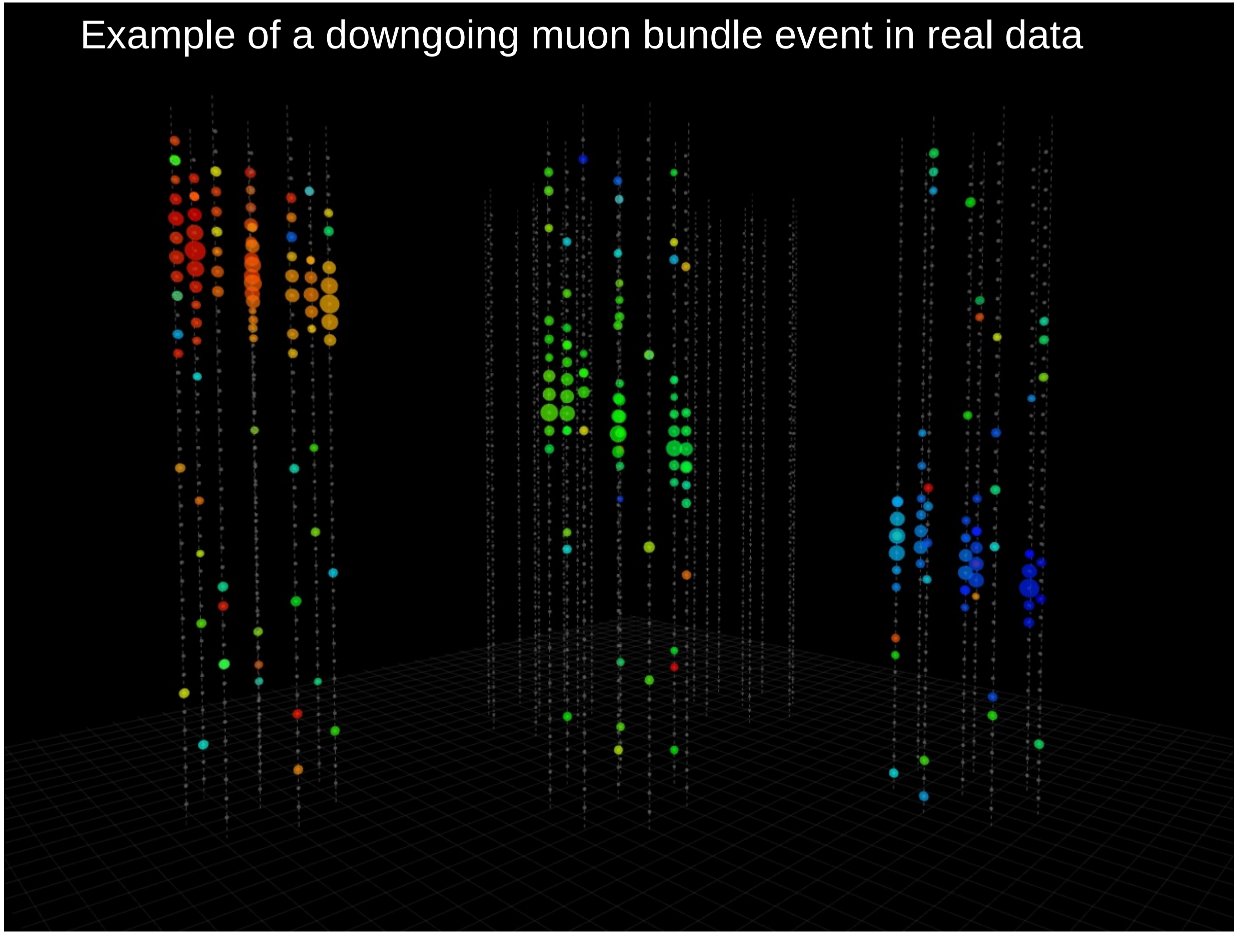
cluster 5, run 162
evt. 1939721
θ_{zenith} = 148.07°
$N_{strings}$ = 3
N_{hits} = 13

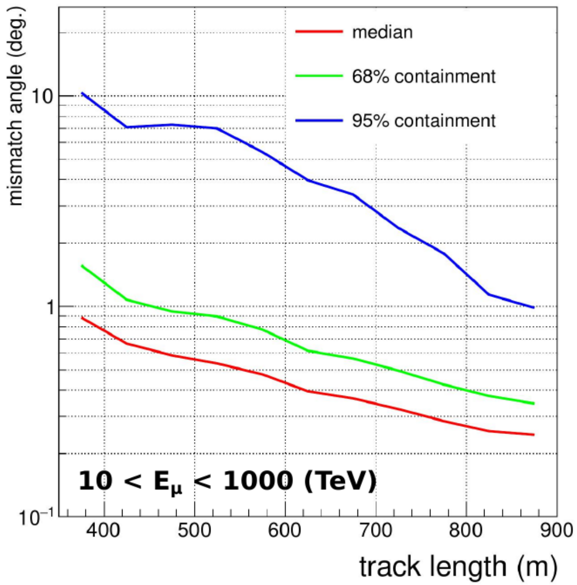


Multi-cluster track events

late

early





Median energy ~ 4 TeV

Work in progress !

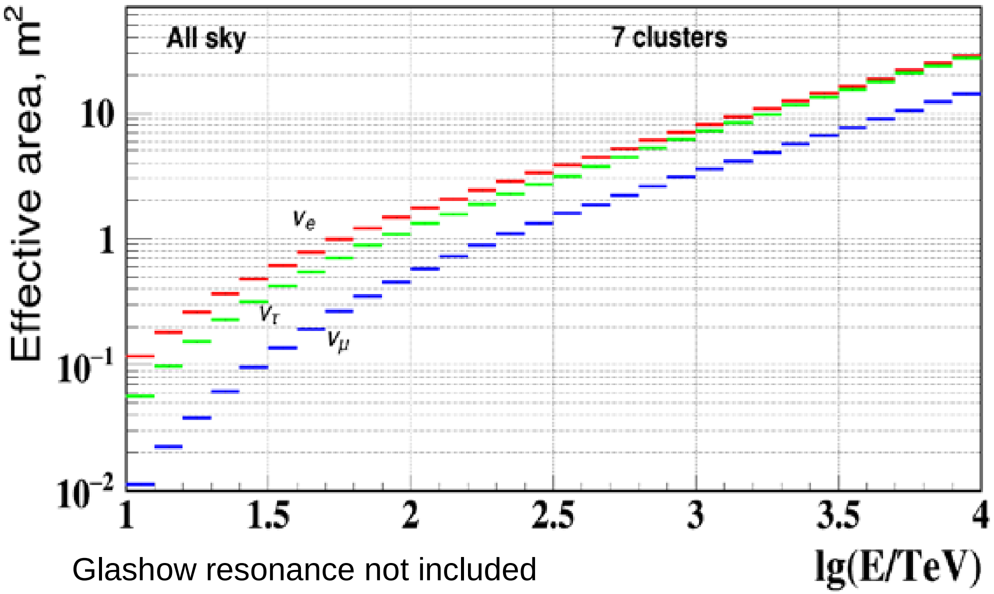
Cascade analysis : effective area and rates

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

Assumption for astrophysical neutrino energy spectrum (IceCube fit):

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

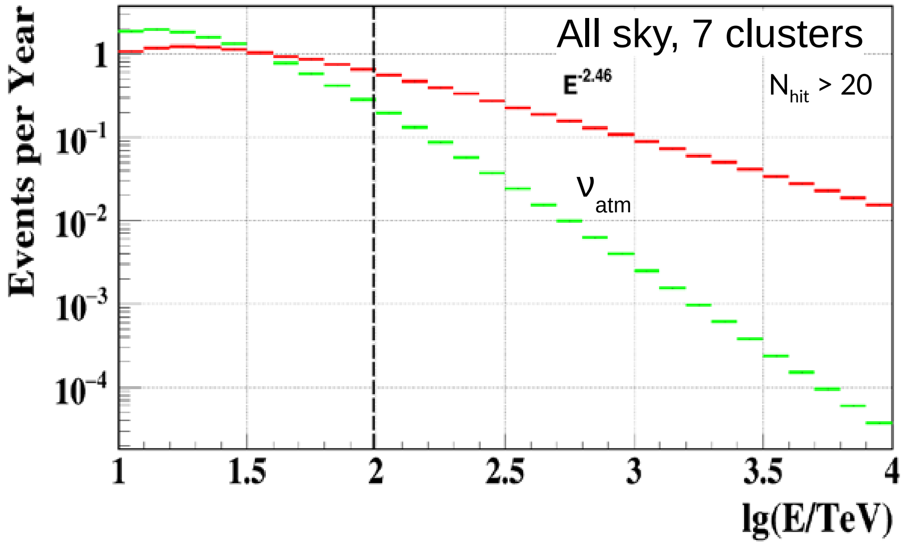
neutrino effective area for cascade detection



Glashow resonance not included

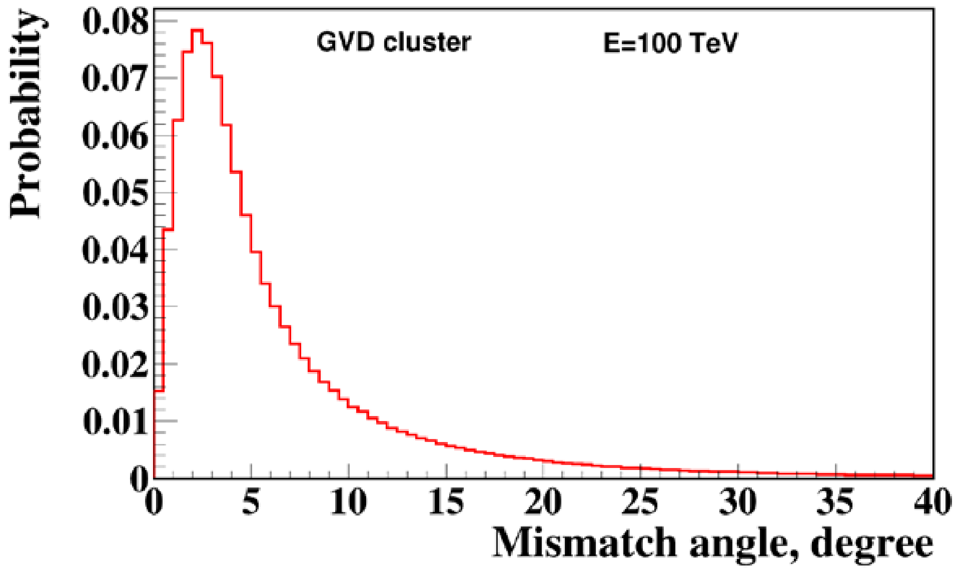
Effective volume for E > 100 TeV ~ **0.35 km³**

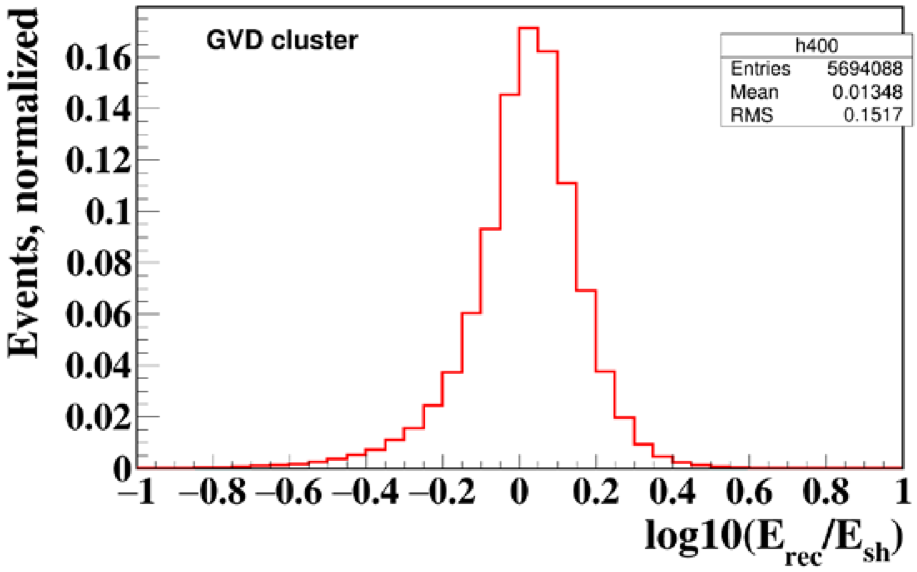
Expected number of cascade events per year



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

Cascade analysis performance





Directional resolution for cascades:
median mismatch angle ~ 4.5°

Energy resolution : δE/E ~ 30%

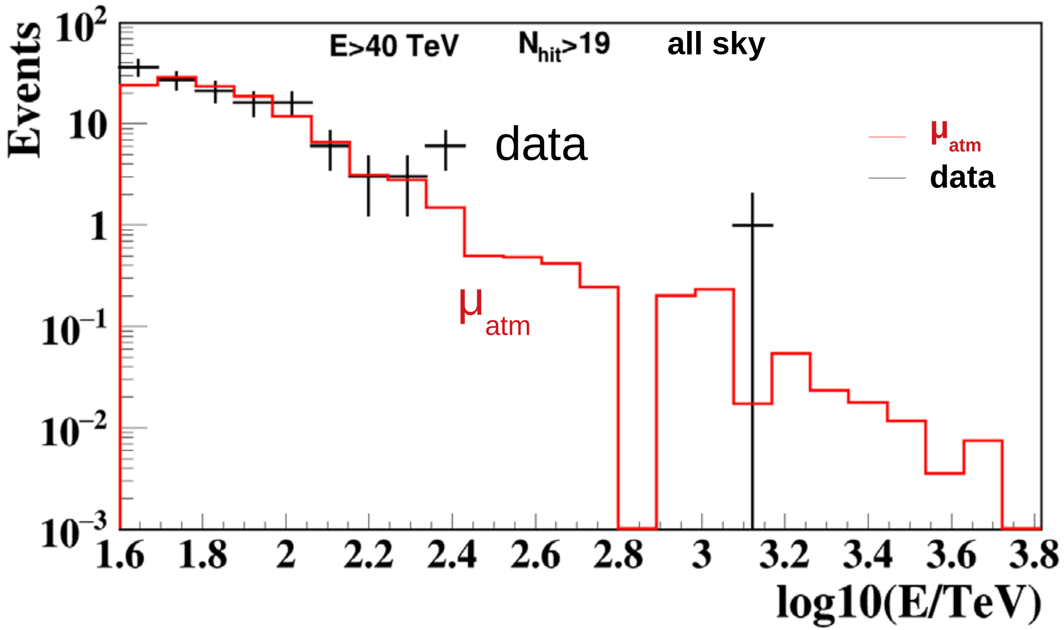
Cascade analysis : data and MC

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

Search for upward moving cascade events

https://doi.org/10.1103/PhysRevD.107.042005

Additional selection requirements:

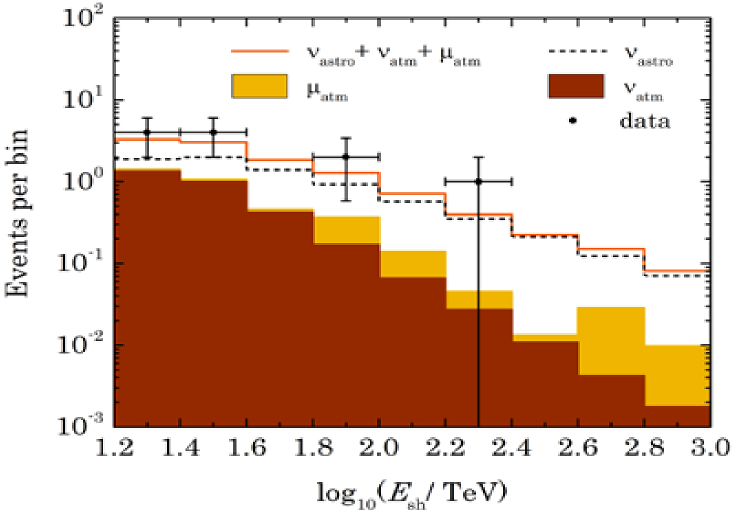
$E > 15$ TeV & $N_{hit} > 11$ & $\cos\theta_z < -0.25$

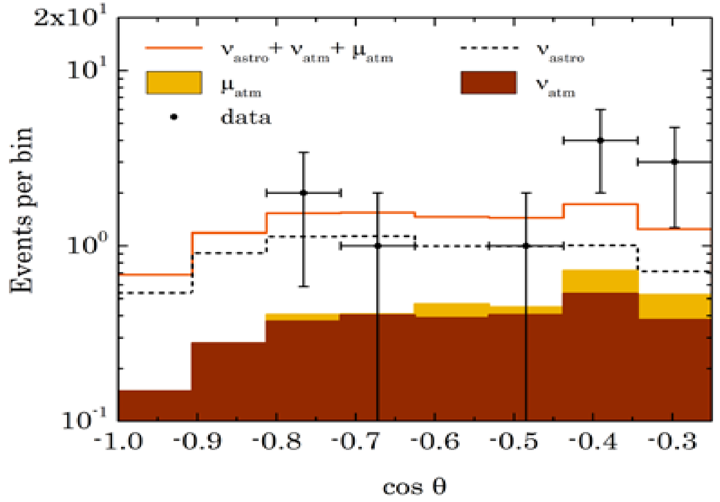
Expected:
0.95 events from atm. muons
3 events from atm. neutrinos
10 events for IceCube's $E^{-2.46}$ astrophysical flux

Found in data: 11 events

The "no diffuse flux" hypothesis is rejected with

P-value = 0.00268 (3σ)

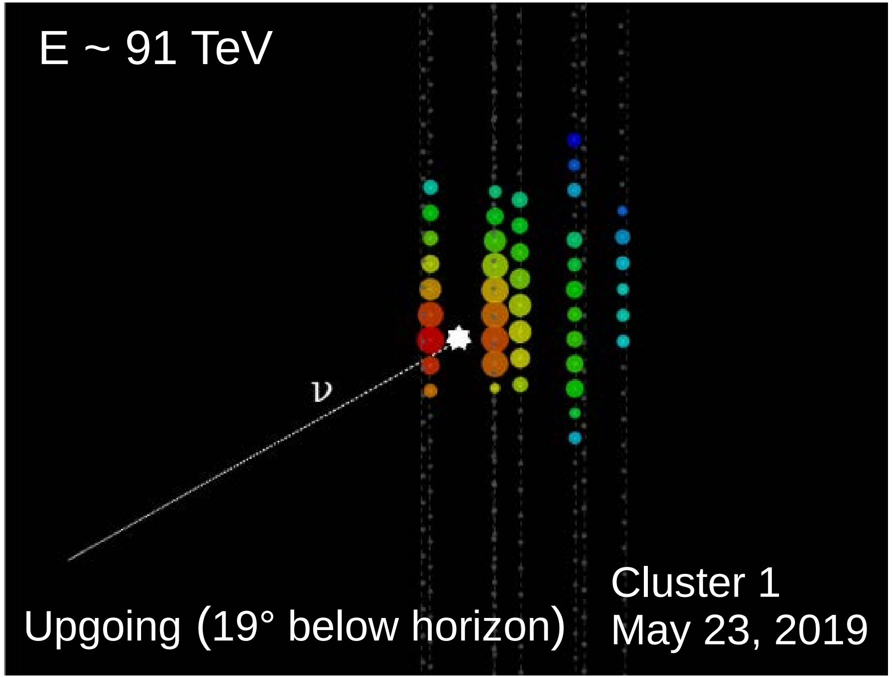




Upward-going cascade #1

Preliminary

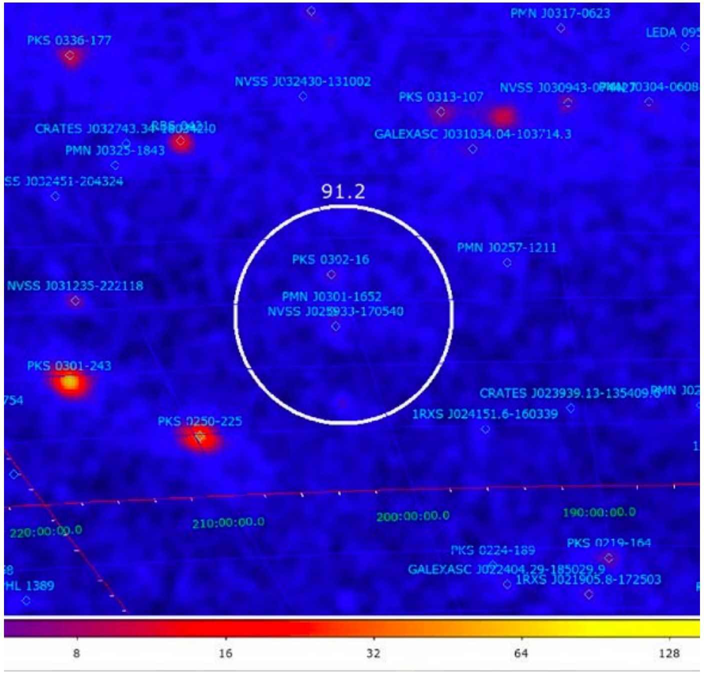
GVD2019_1_114_N



Contained event (50 m off central string)

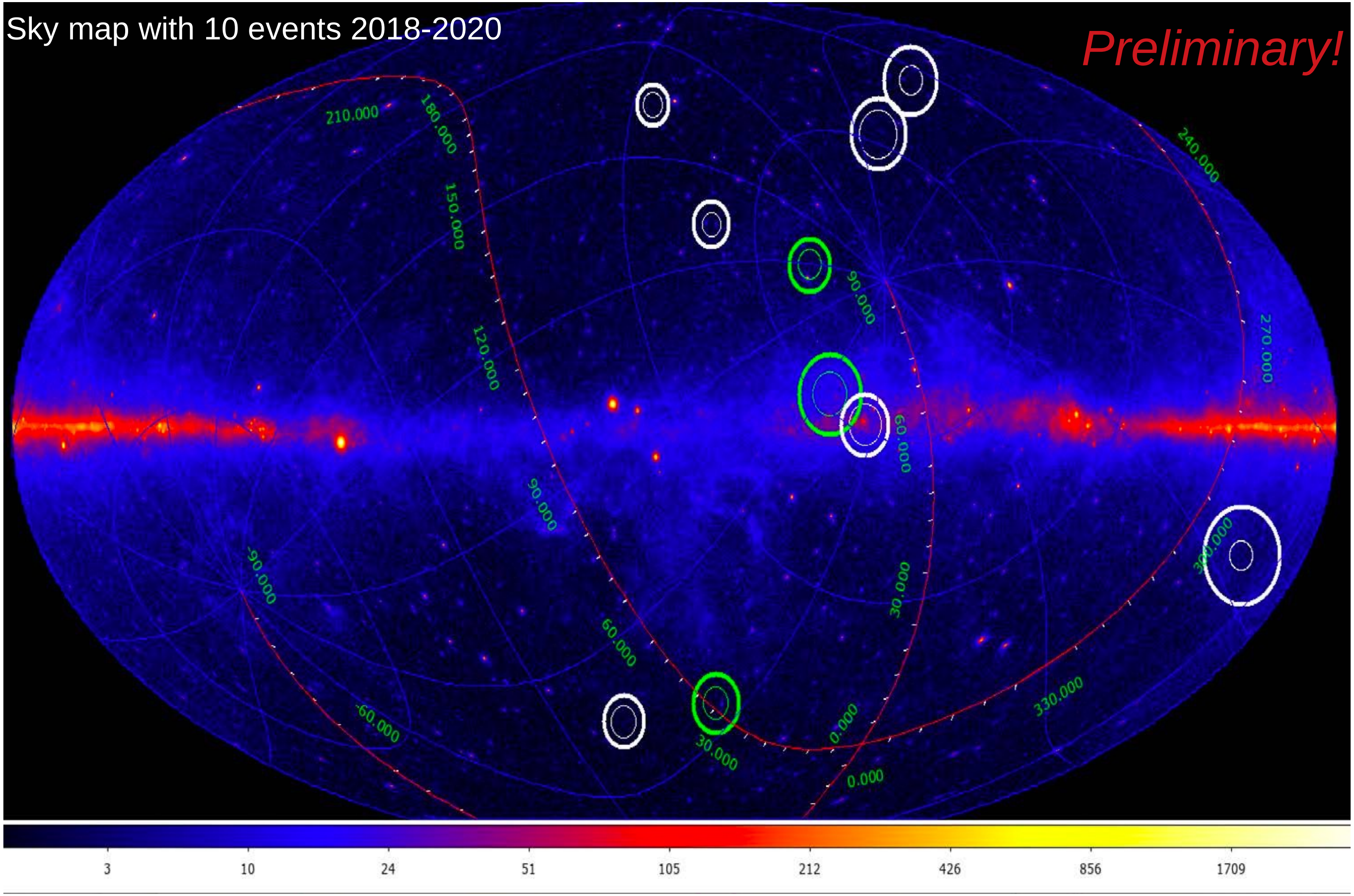
Excellent candidate for a neutrino event of astrophysical origin

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)



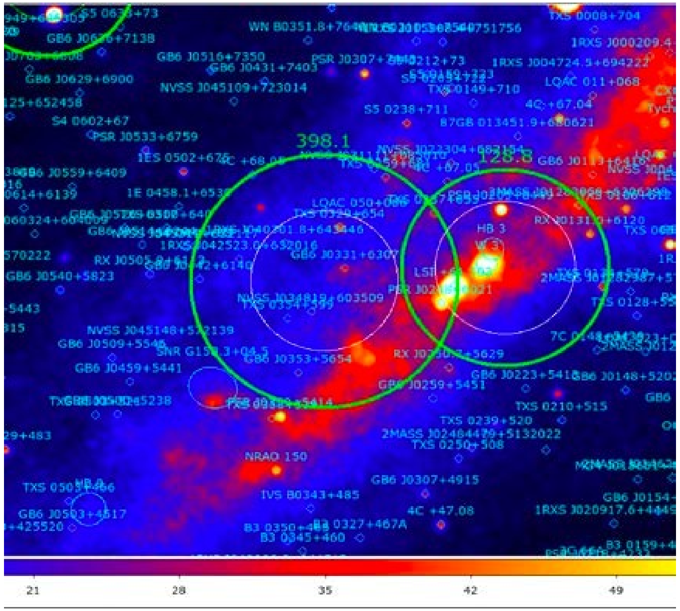
Background image: Fermi LAT

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

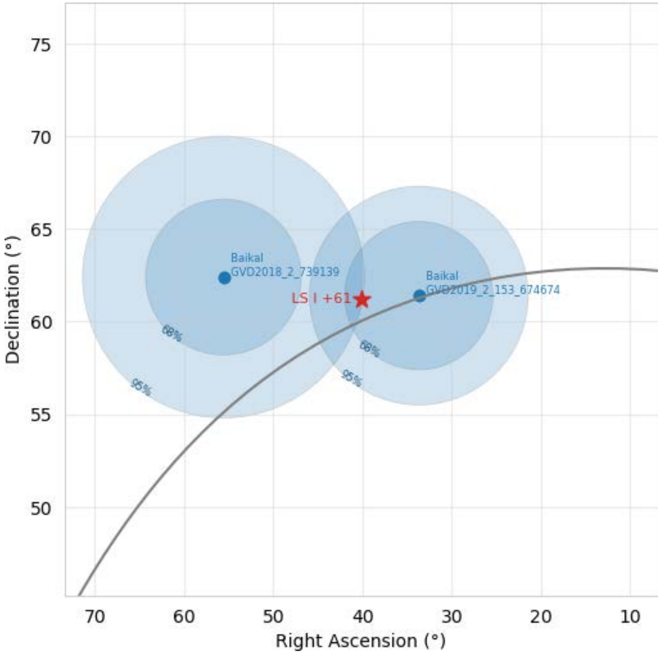
White circles: Baikal-GVD events 2019-2020

Event doublet near Galactic plane *Preliminary*

Sky map of Fermi sources



LS I +61 303 and the two Baikal-GVD events



LS I +61 303 – γ-ray microquasar

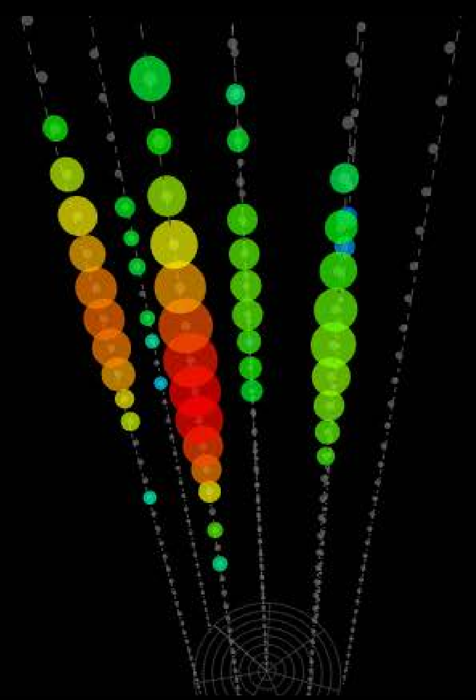
3.1° from GVD_2019_153_N and 7.4° from GVD_2018_656_N (both are downgoing events)

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”]

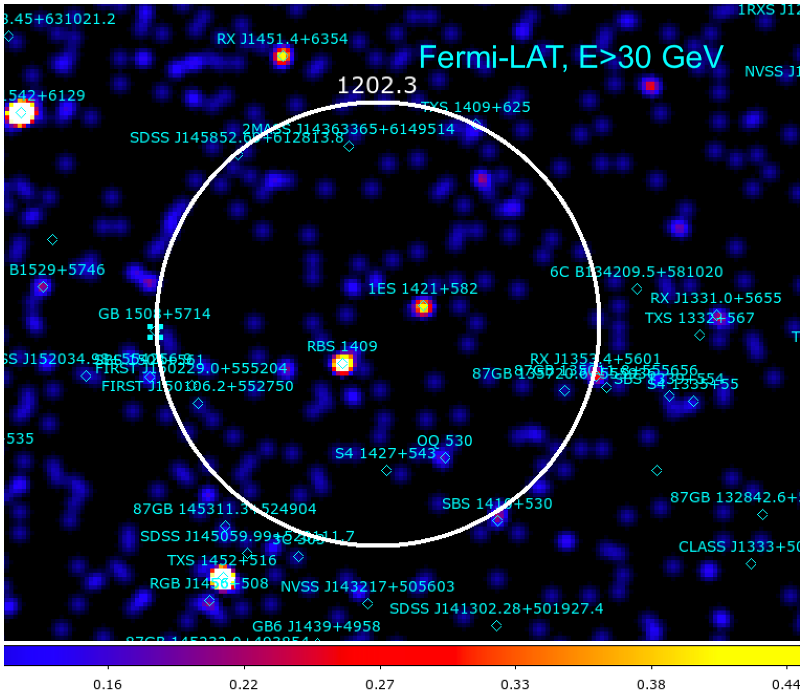
A 1 PeV cascade event (downgoing)

Preliminary

GVD_2019_112_N



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

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)

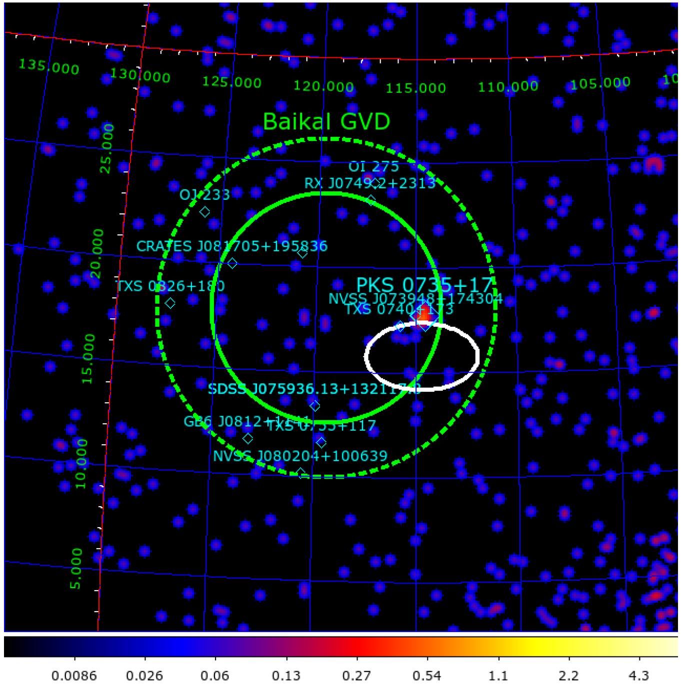


Image by D.Semikoz & A.Neronov

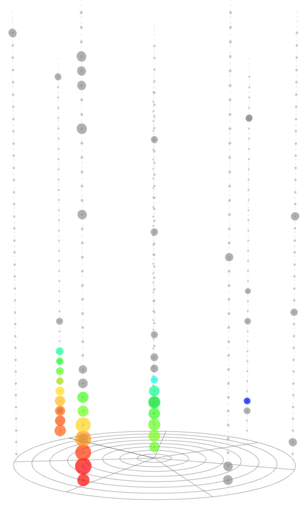
ATeL 15112

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

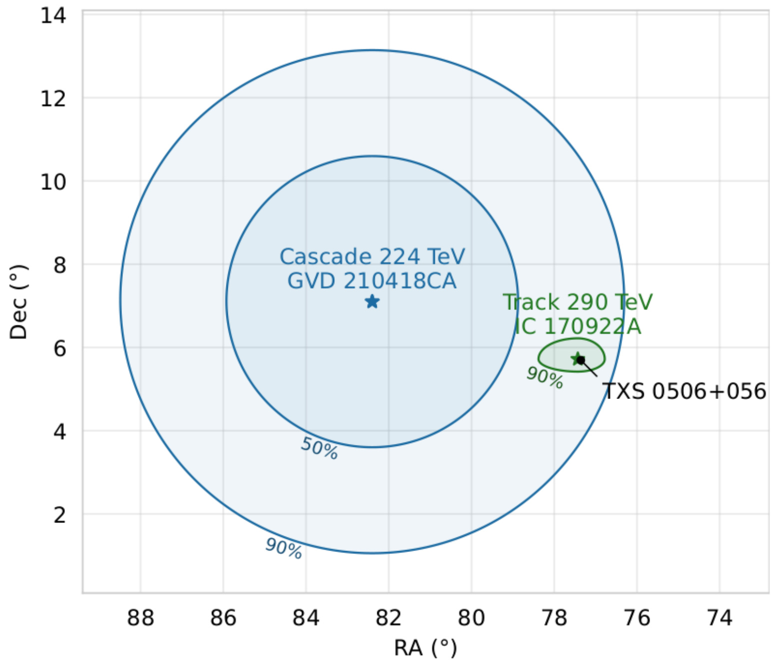
A high energy neutrino from the direction of TXS 0506+056

Analysis of data collected between April 2018 and March 2022 yields a sample of 11 high quality cascade-like neutrino candidate events, one of which lies within 90% error circle from TXS 0506+056

GVD210418CA



MJD = 59322.94855324
Zenith = 115°
RA, Dec = 82.4°, 7.1°
E = 224±75 TeV



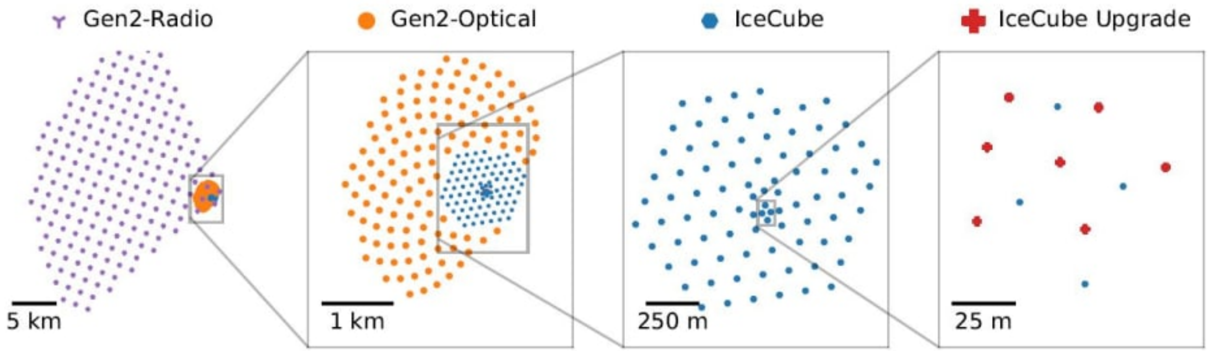
This event is probably of astrophysical origin (signalness = 97%)

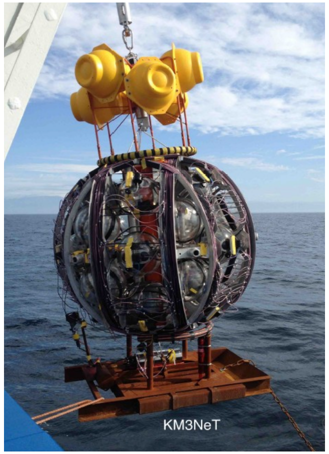
The chance probability for such an association to occur randomly due to the background is p = 0.0074

arXiv:2210.01650

Prospects

- IceCube: plan to build ~8 km³ optical array and a ~500 km³ radio array
- KM3NeT: finish construction
- Baikal-GVD: discussions on for further detector extensions (10 km³?)



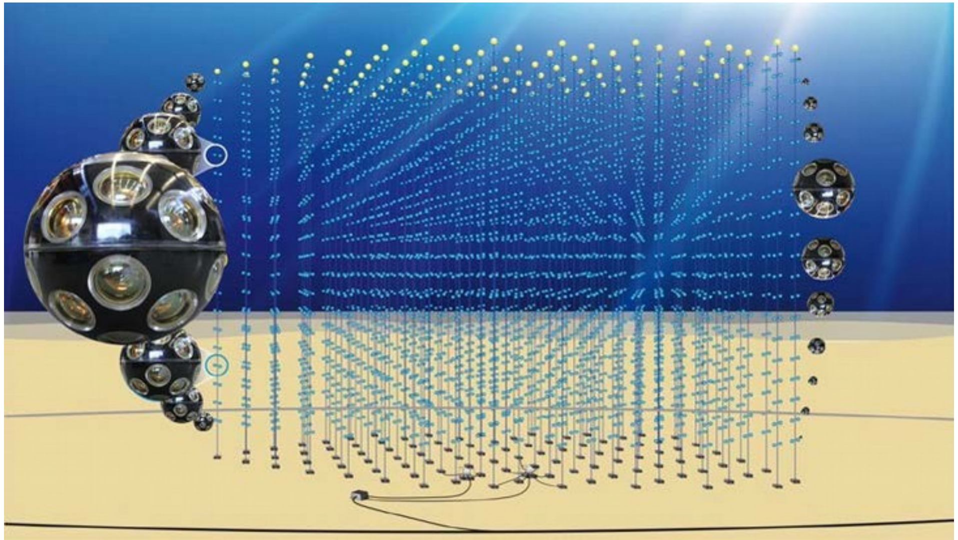


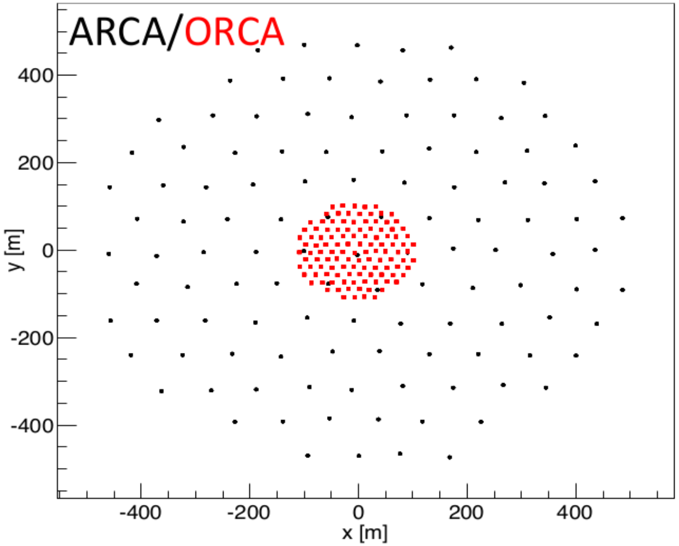
Conclusion

- Three 1 km^3 neutrino telescopes operate or under construction: IceCube, KM3NeT, and Baikal-GVD
- Discoveries so far:
  - All-sky diffuse flux
  - Galactic diffuse flux (4.5 σ)
  - two sources >3 σ : TXS 0506 & NGC 1068
- Baikal-GVD is entering the game

Backup slides

KM3NeT ARCA & ORCA



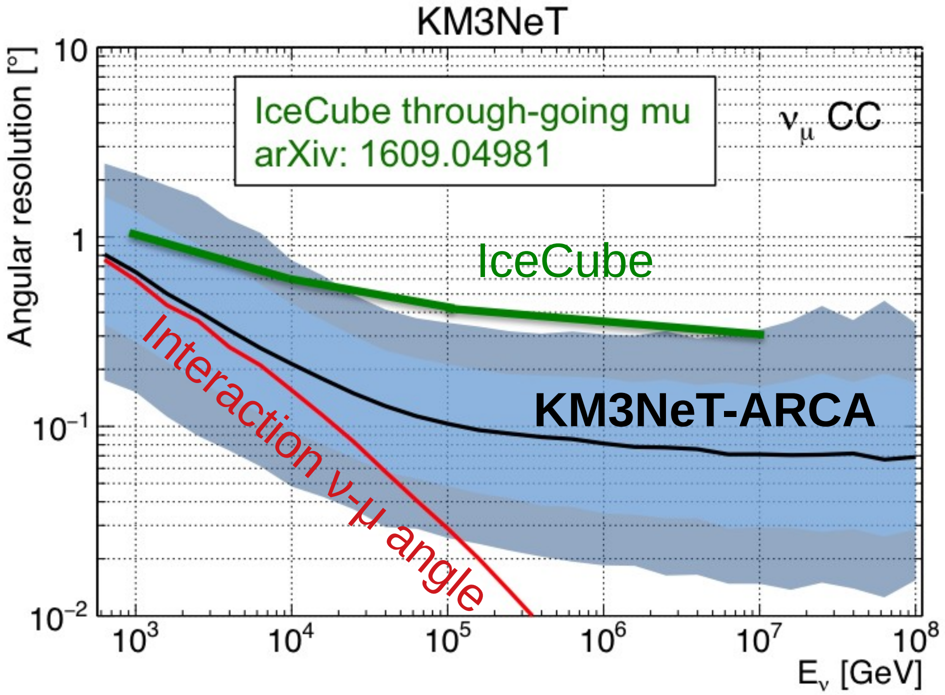


	String spacing (m)	OM spacing (m)	Depth (m)	Instrumented mass (Mt)	N strings
ORCA	23	6	2450	8	115
ARCA	90	36	3400	1000	230

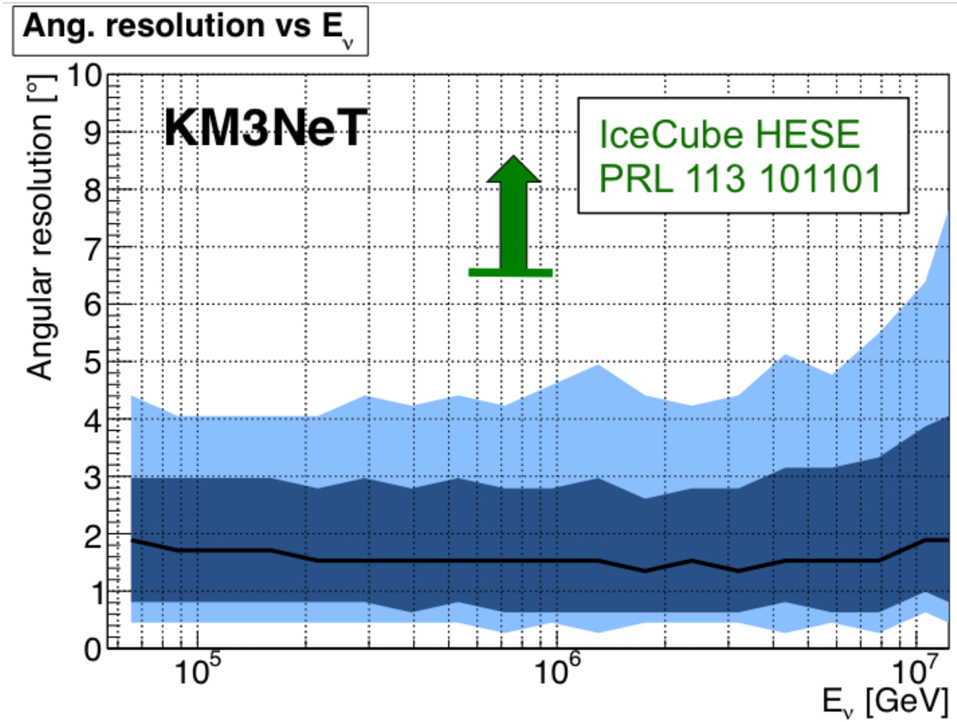
– 18 DOMs/string
– 31 PMTs/DOM

ARCA - angular resolution

Tracks



Showers

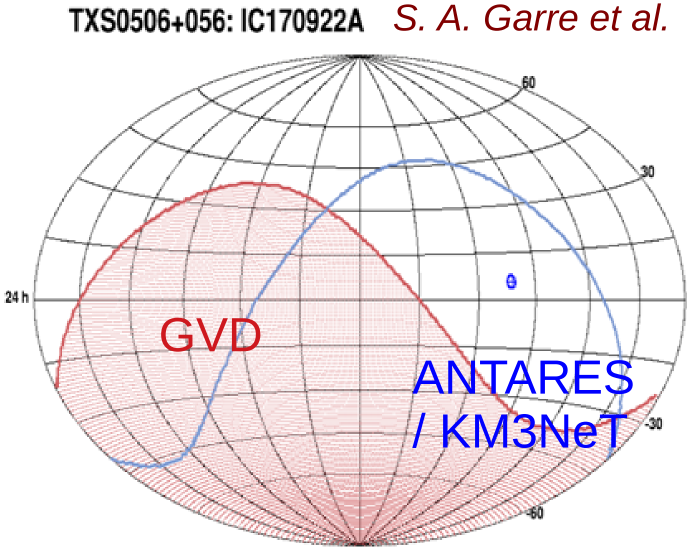


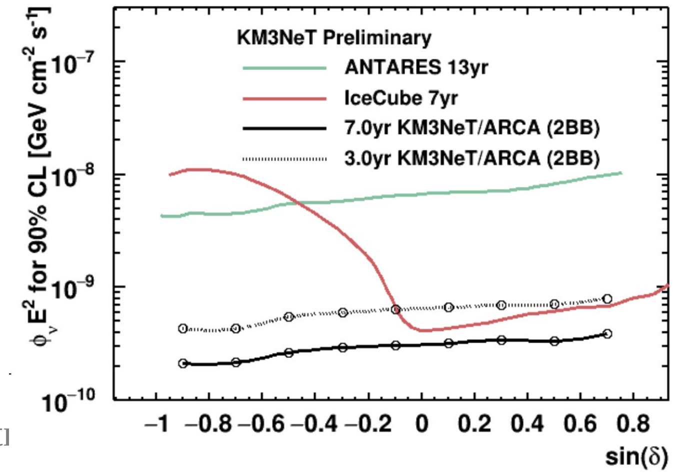
~ 0.1° angular resolution for tracks (E>100 TeV); ~ 2° for showers

Why two neutrino telescopes in the North

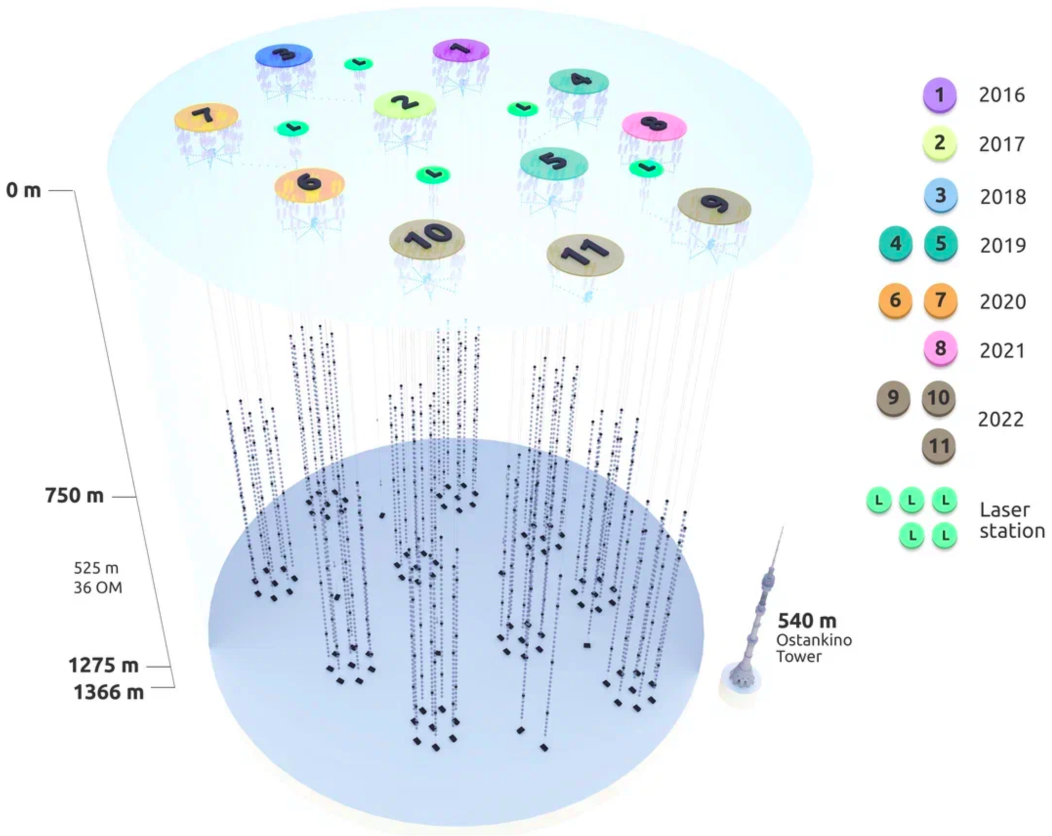
- Improved all-sky coverage
  - important for short transients
- Sensitivities add up
  - neutrino astronomy is still limited by low statistics
- Optimize local funding opportunities
  - Funding opportunities often come with geographic restrictions

S. A. Garre et al.





Baikal-GVD construction status 2022 and schedule



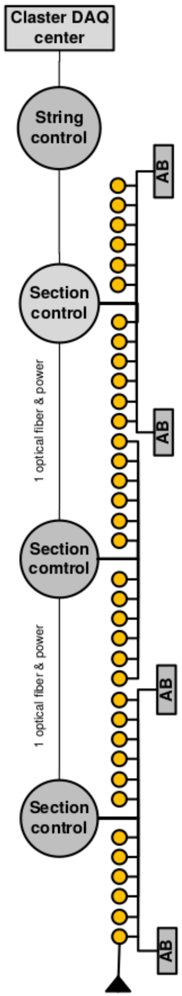
10 clusters + 1 special string (laser+36 OM)
+ 2 experimental strings + 4 laser stations

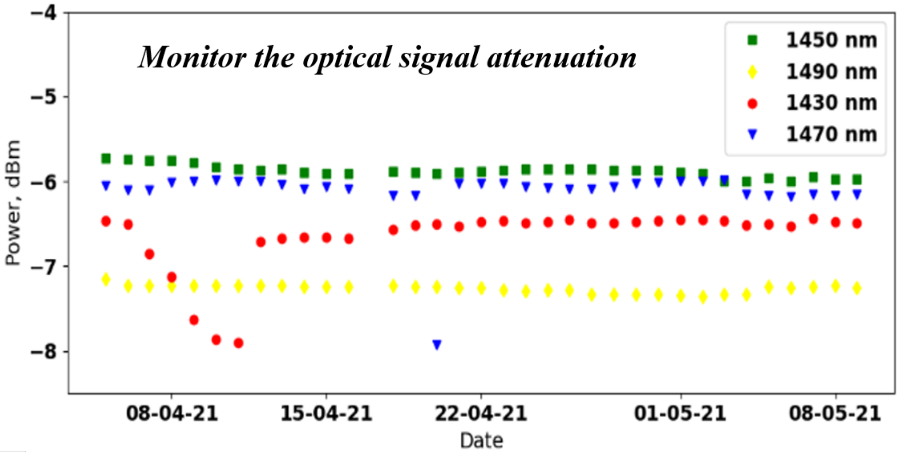
Deployment schedule

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

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

Experimental string with optic fiber DAQ





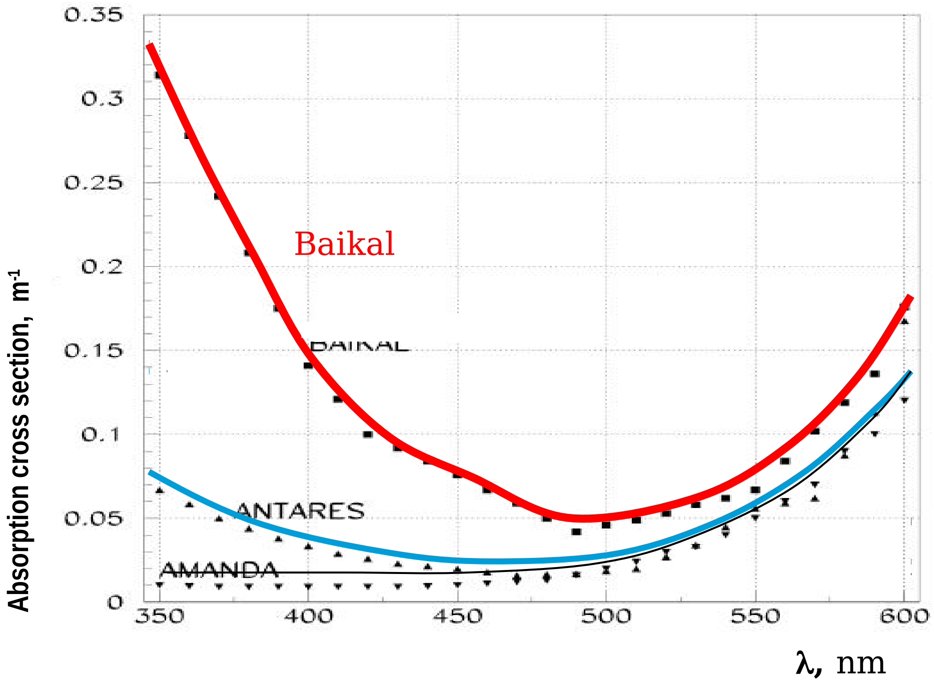
Developing technological solutions for second stage of Baikal-GVD deployment (2024+)

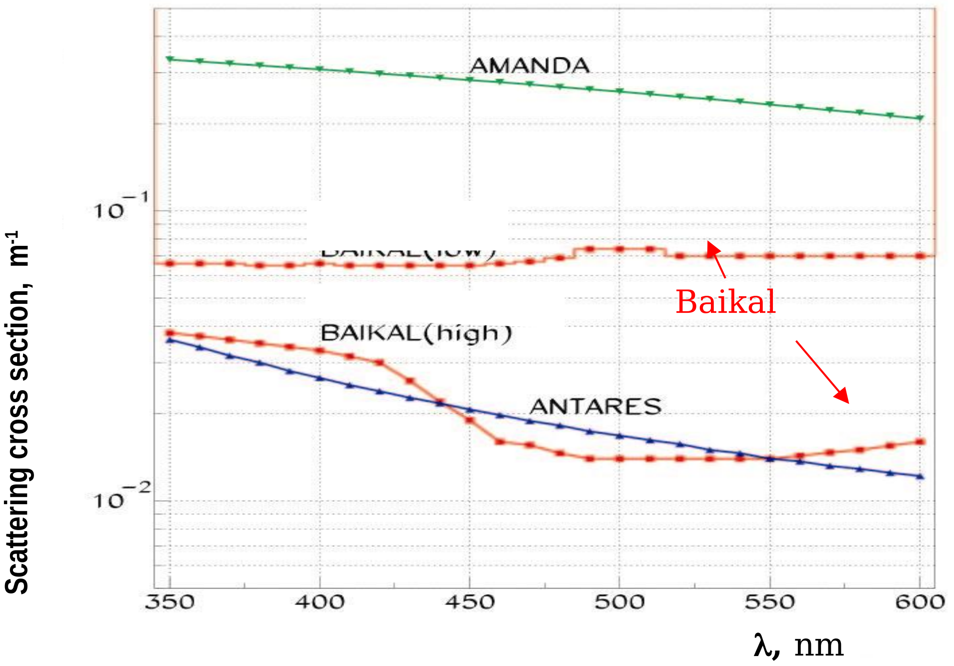
Advantages:

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

See poster by V. Aynutdinov @ ICRC 2021

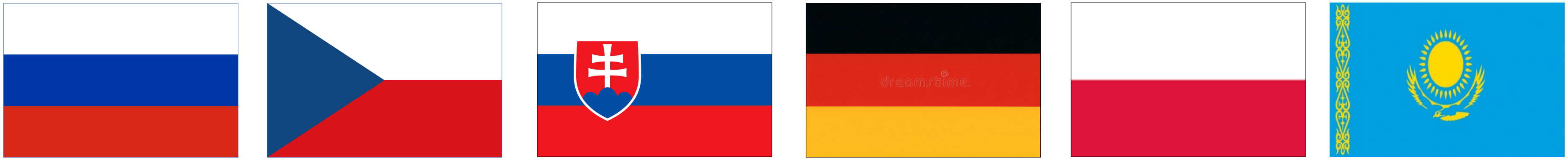
Water optical properties





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)

All-sky search for HE cascades

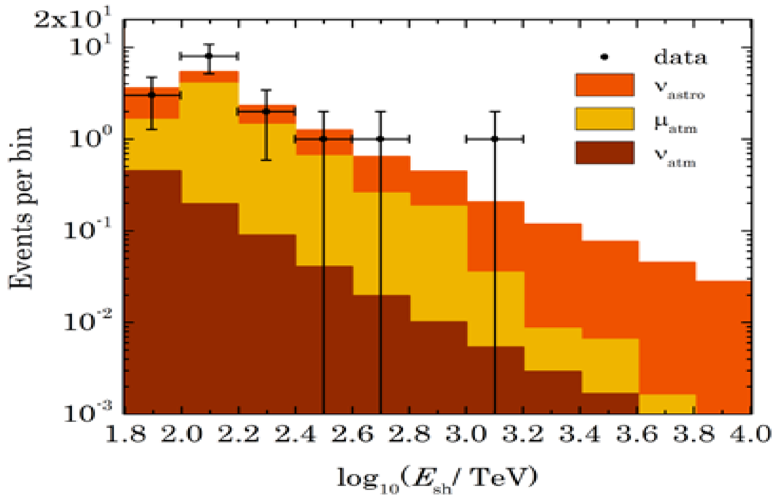
https://doi.org/10.1103/PhysRevD.107.042005

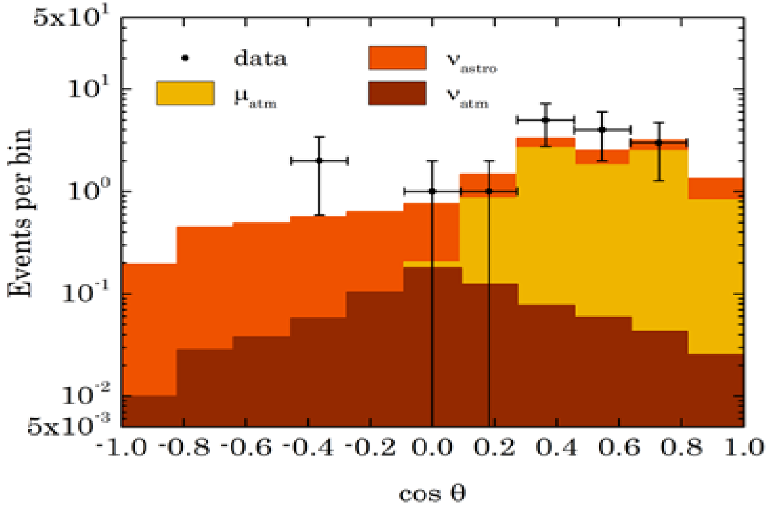
Additional selection requirements:
(N_{Type_2} = 0, E_{rec} ≥ 70 TeV) or
(N_{Type_2} = 1, E_{rec} ≥ 100 TeV)
N_{Type_2} is number of hits in time interval where hits from muons are expected

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

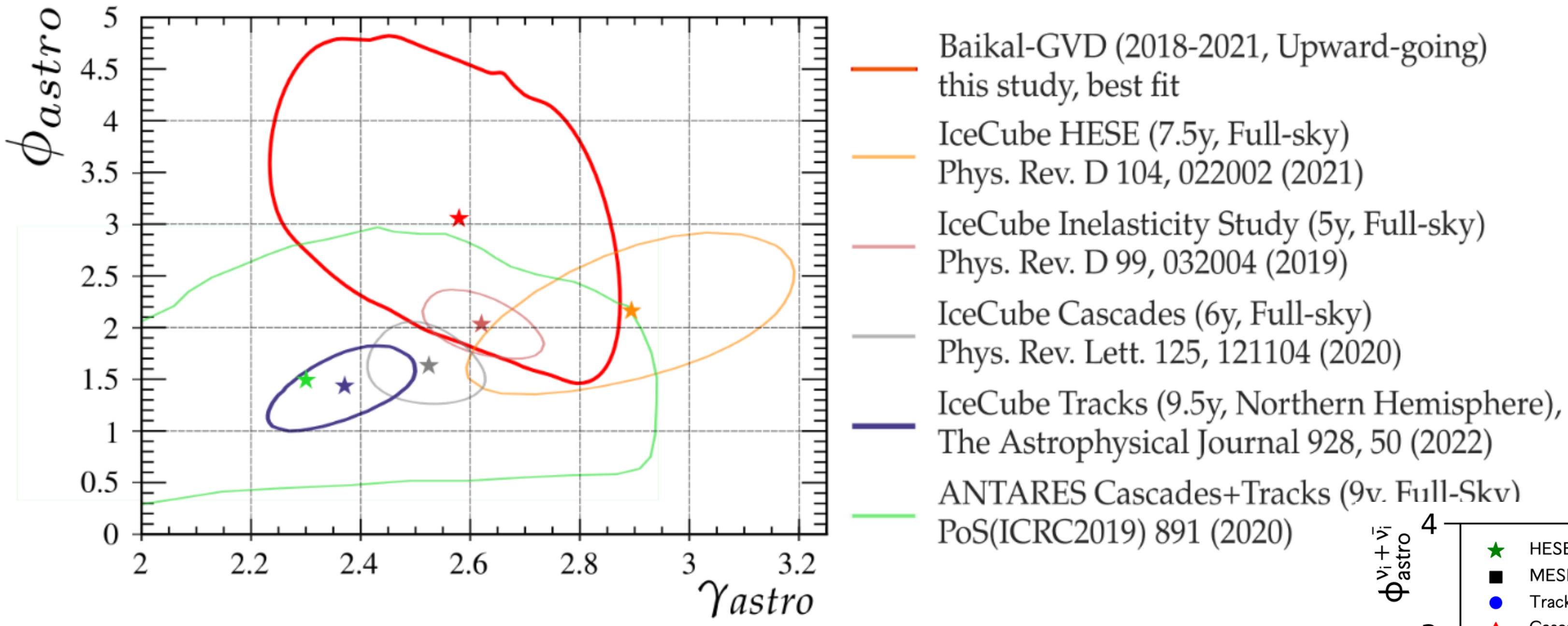
Found in real data: 16 events

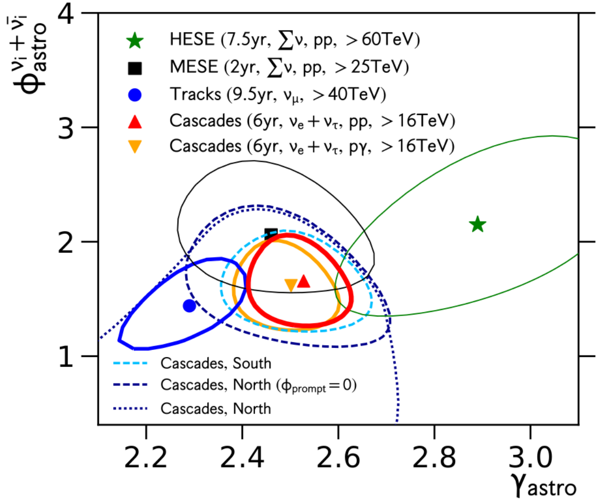
Probability for the background-only hypothesis (stat. errors only)
P-value = 0.033 (2.13 σ)





Diffuse neutrino flux





Track reconstruction with a χ^2-based algorithm

Initial hit selection

↓

Track prefit — Using vector sum

↓

Refined hit selection

↓

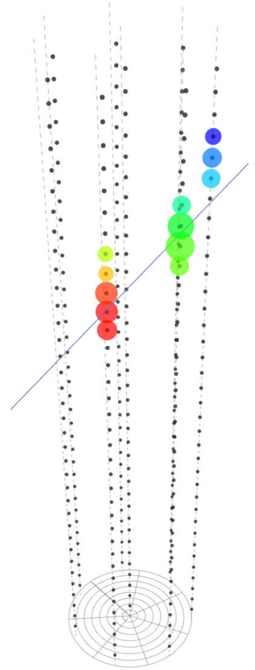
Main track fit

Minimize quality function

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

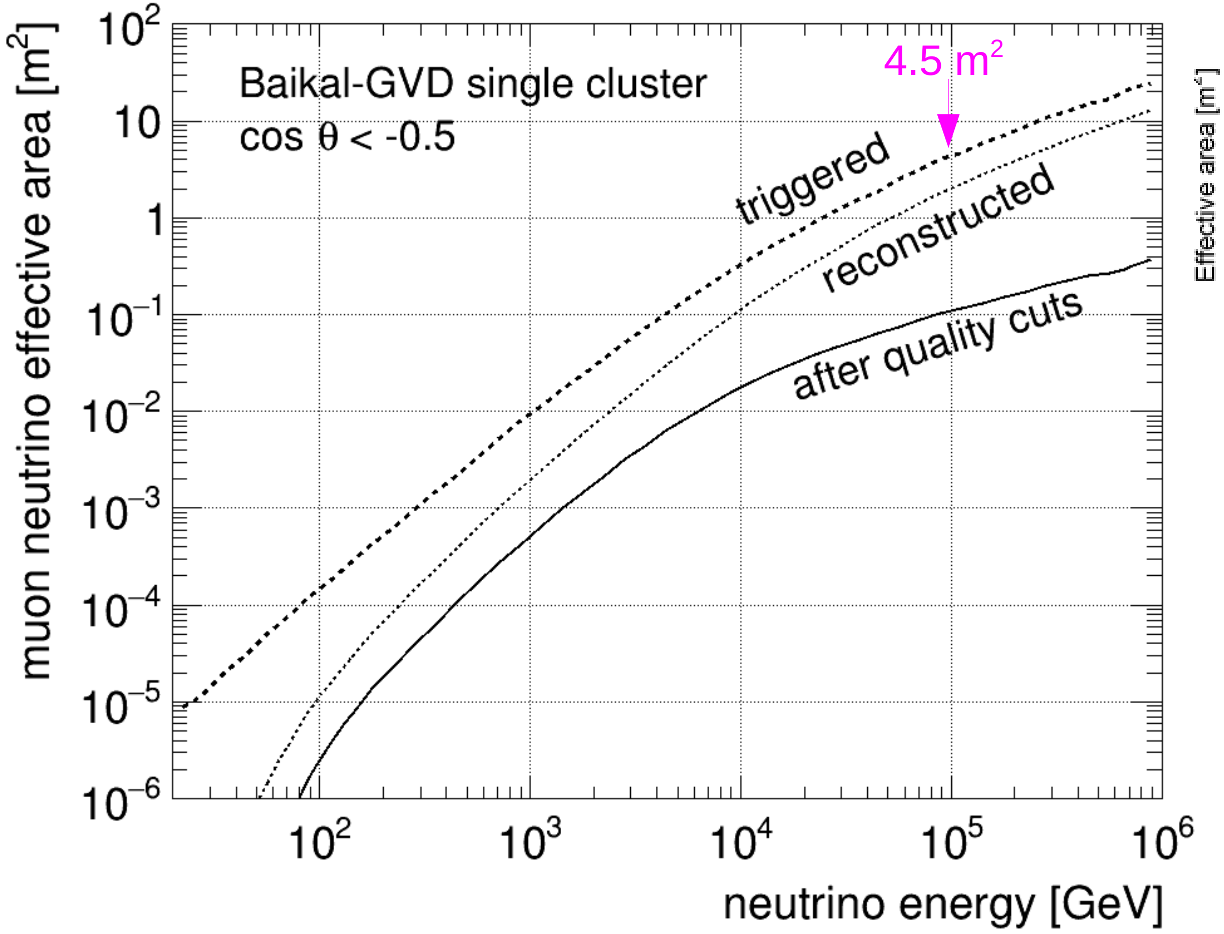
Time residuals ($\chi^2(t)$)

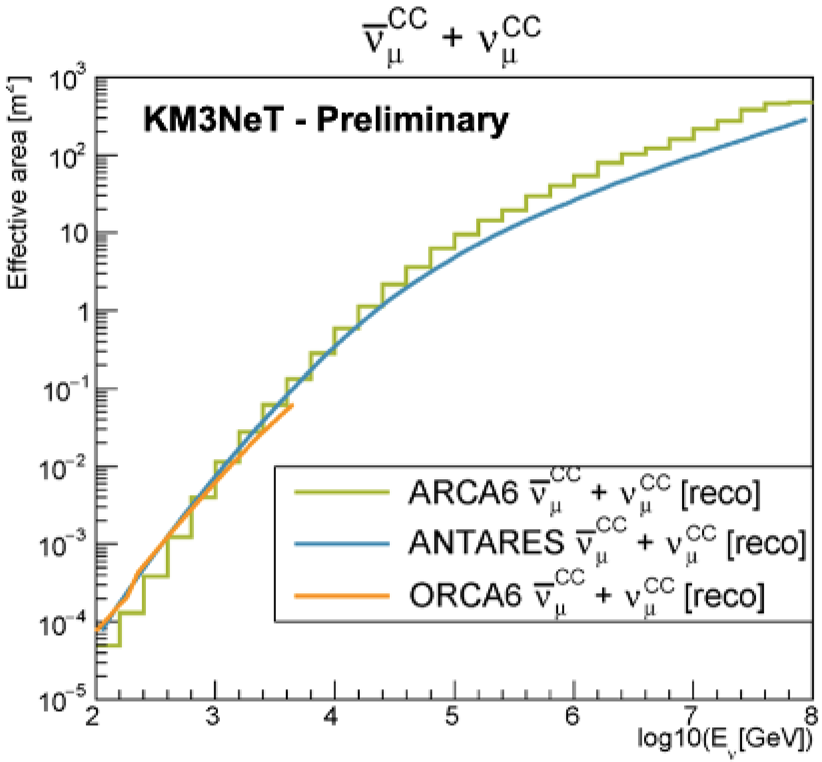
Hit charge and distance ($f(q, r)$)



See talk by G. Safronov at ICRC 2021

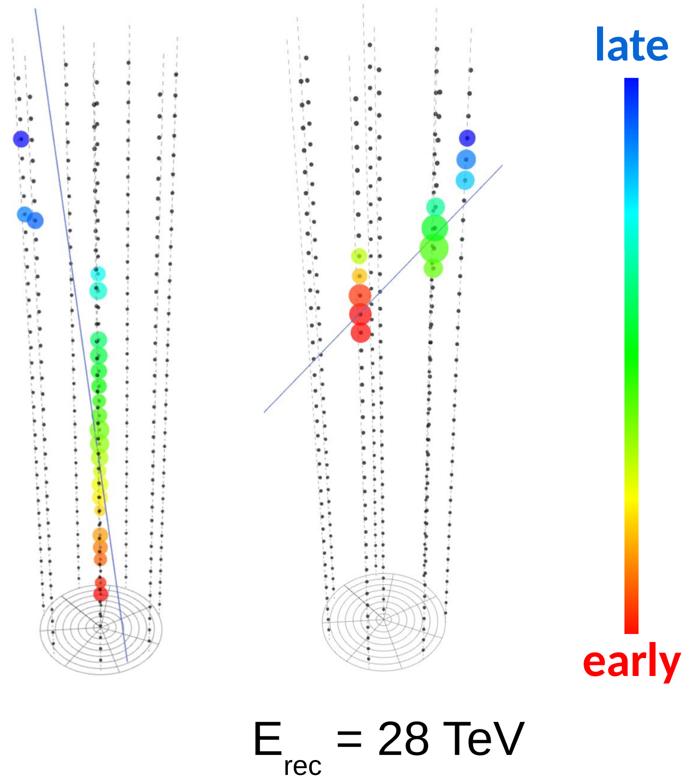
Neutrino effective area for tracks : one GVD cluster





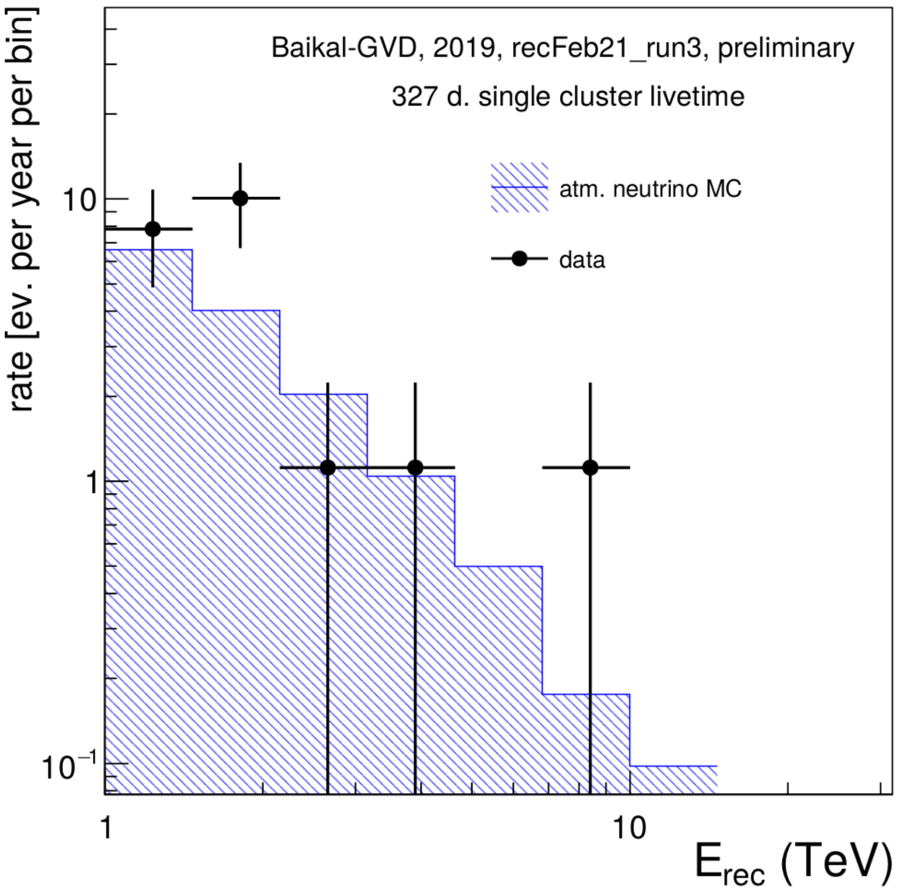
Track reco : ongoing improvements

- 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
- ...

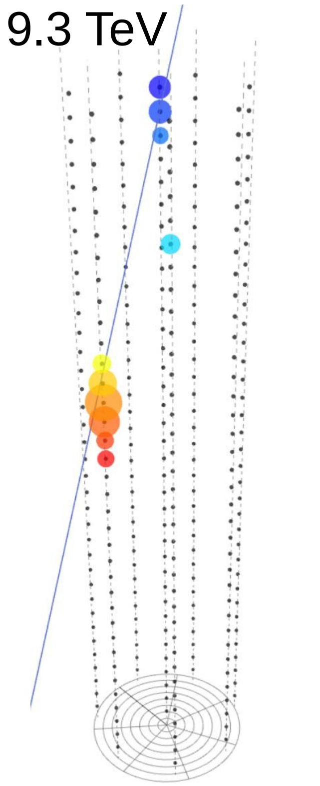


Reconstructed energy for tracks

Example plot for a set of neutrino candidate events



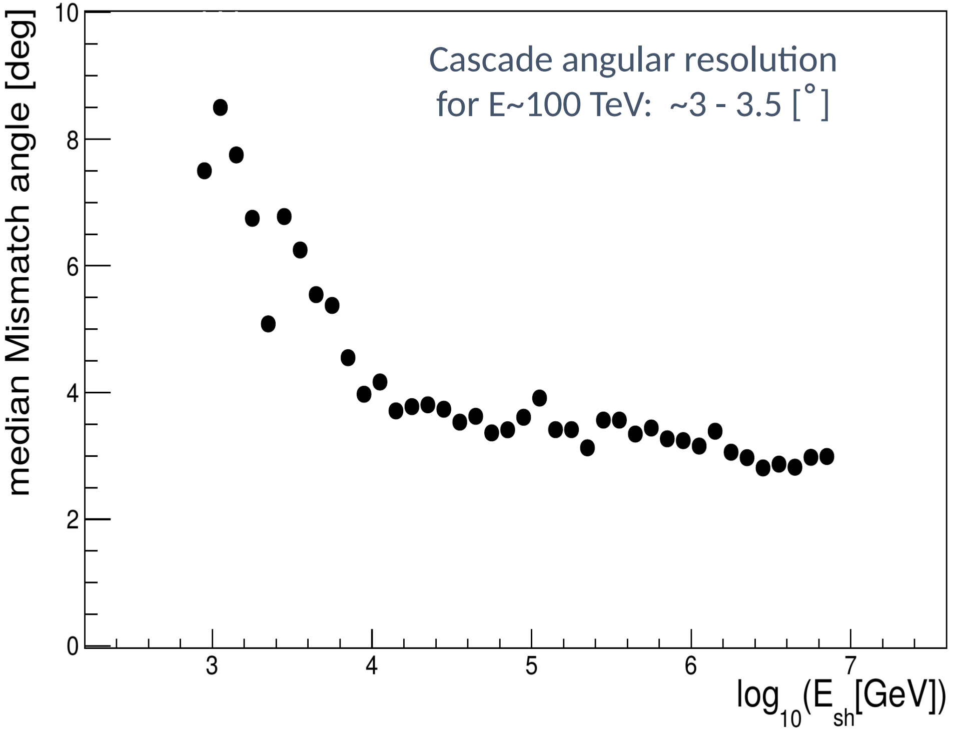
- dE/dx energy estimator -
- Works for E > 1 TeV
- Largest measured energy in cut-based low-energy neutrino candidate sample:



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

see talk by G. Safronov at ICRC 2021

Cascade analysis angular resolution

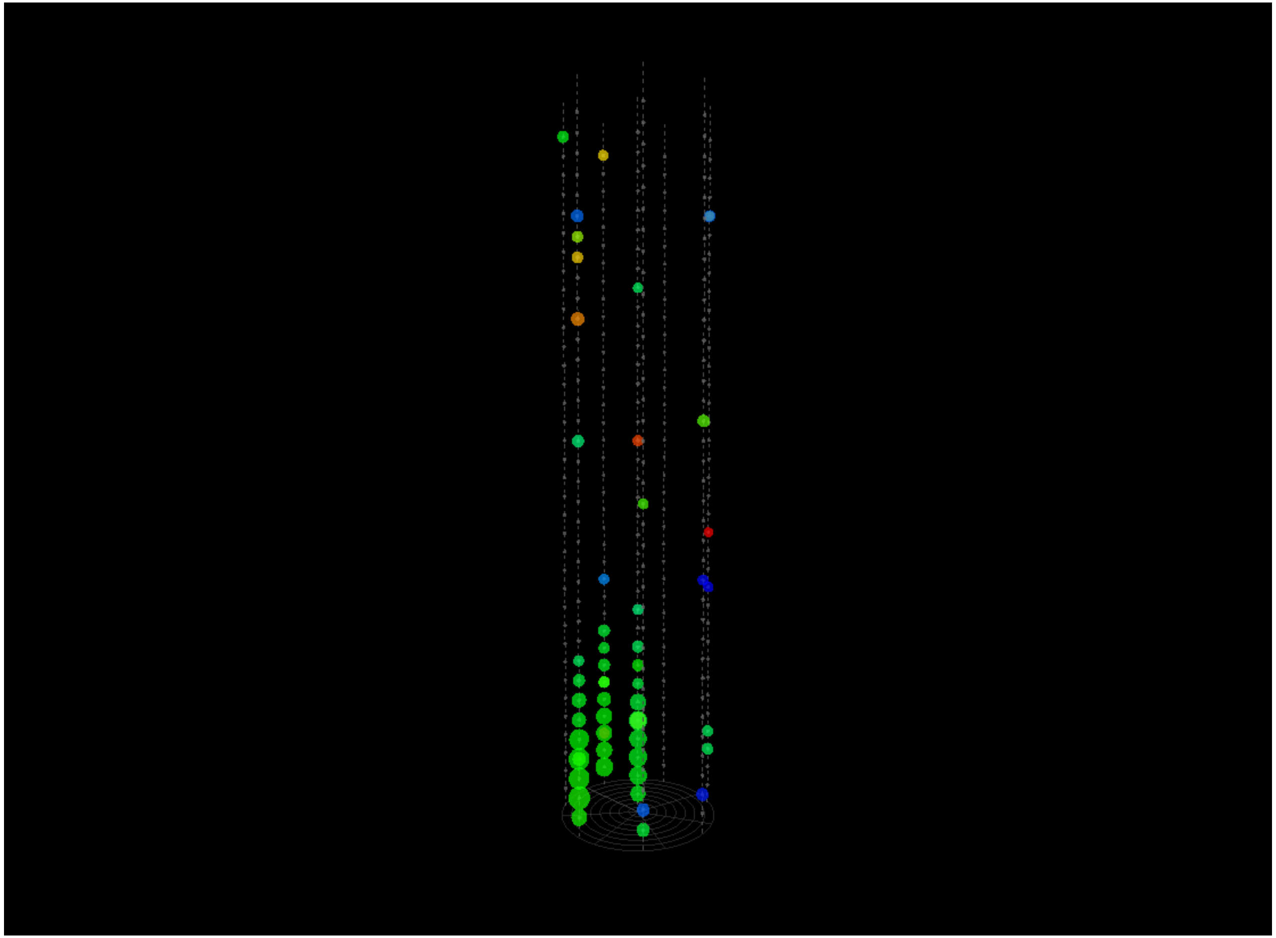


Selected events (2018-2020)

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

Upward-going cascade #2

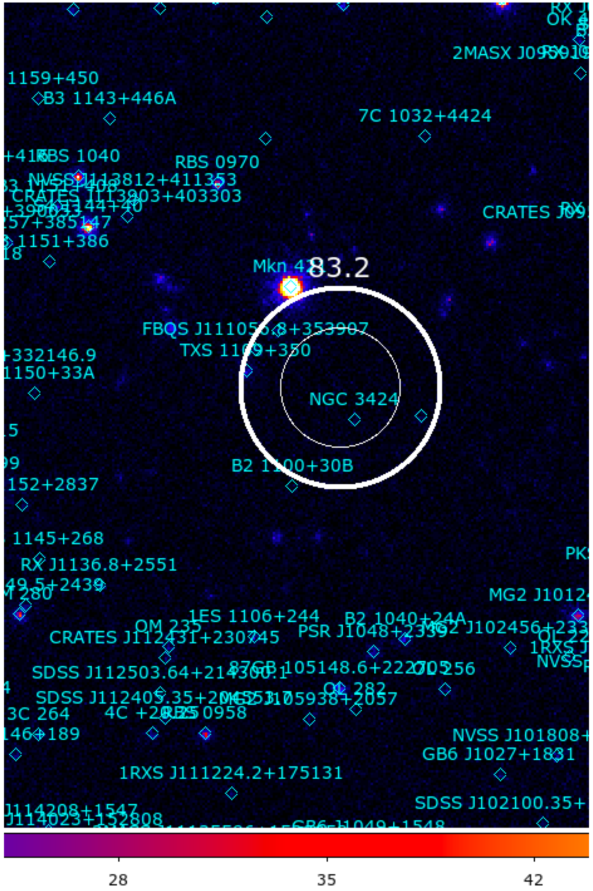


Energy E = 224 TeV (±30%);
distance from central string
r = 70 m;
Zenith angle = 115°

Another event of potential interest

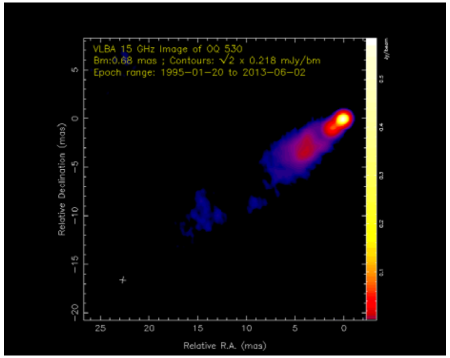
GVD_2019_663

Mrk 421 just outside the error circle



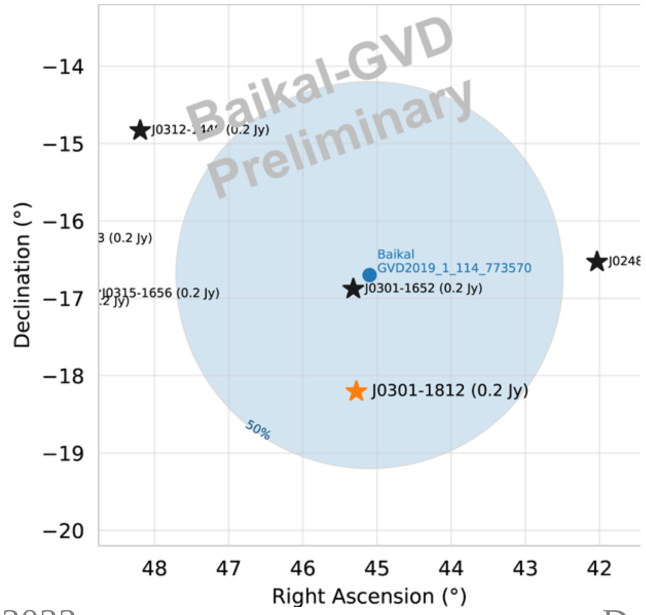
Radio-loud blazars – promising neutrino sources

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

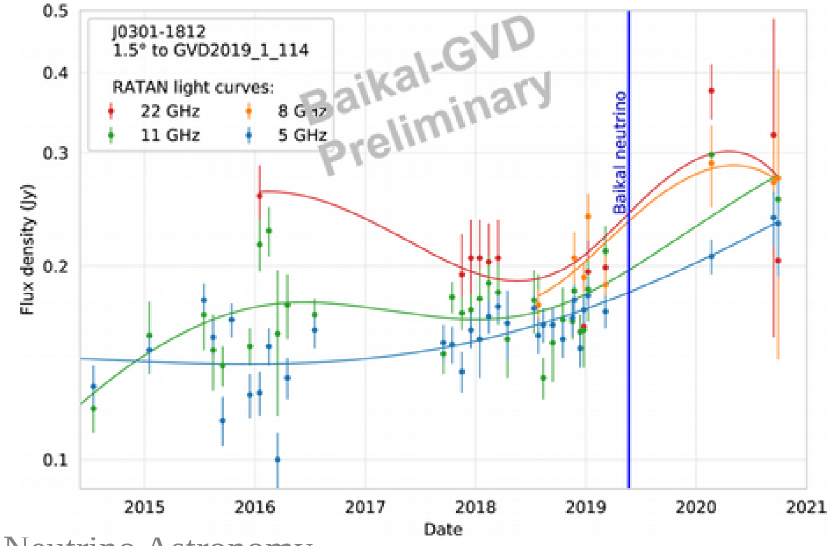


GVD2019_1_114_N

radio-bright blazars nearby



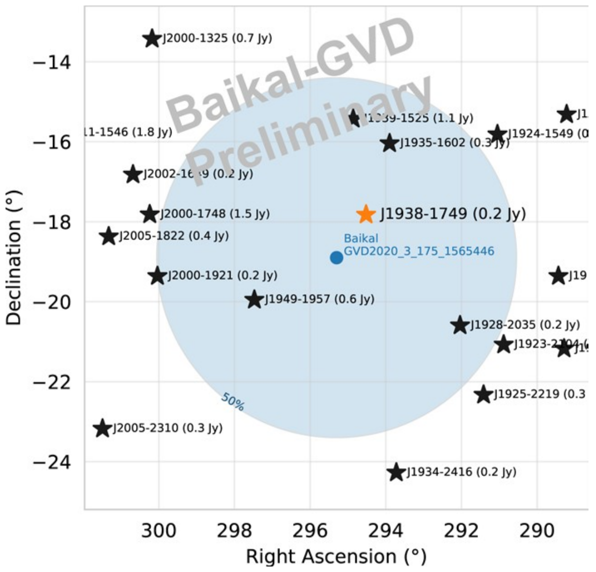
Light curves of J0301-1812 measured by RATAN-600

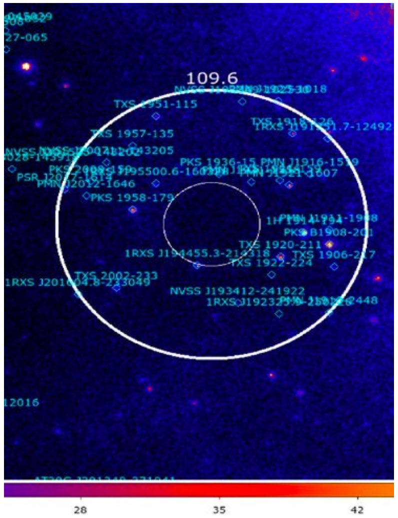


Radio-loud blazars – promising neutrino sources (2)

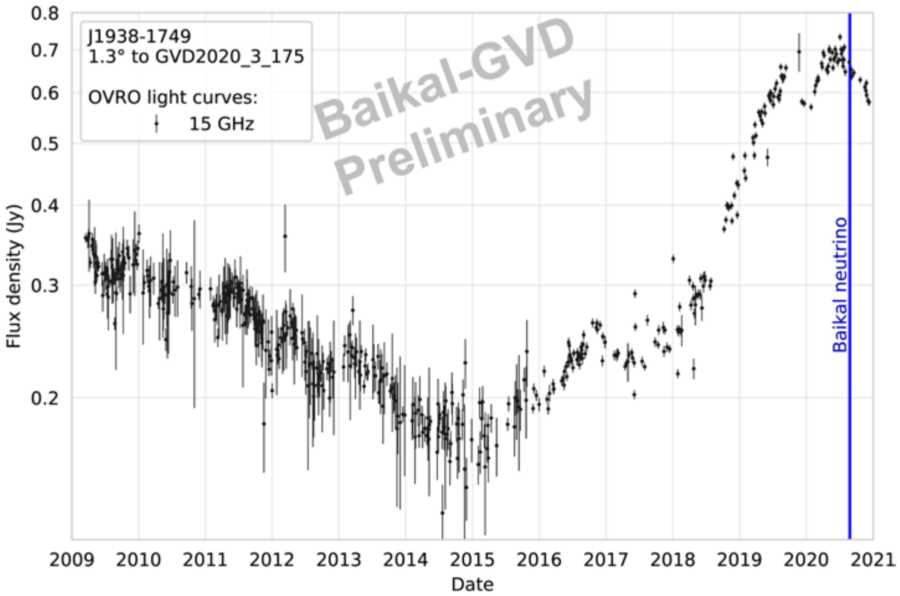
GVD2020_3_175_N

radio-bright blazars nearby





Light curves of J1938-1749 measured by OVRO



GVD follow up of ANTARES alerts

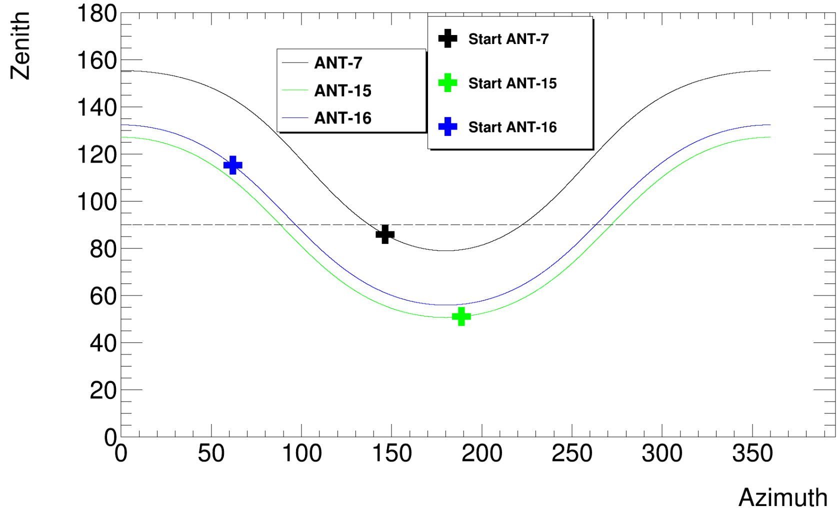
Following ANTARES upgoing μ alerts (<E> = 7 TeV)
Time windows: ±500 sec, ±1 hour and ±1 day
Both upgoing and downgoing cascades are looked for

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

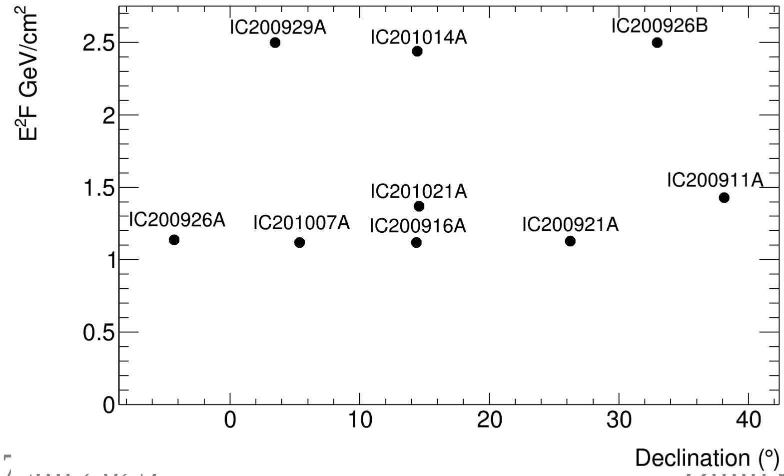
O. Suvorova et al. @ Neutrino 2022
O. Suvorova and A.Garre @ ICRC 2021

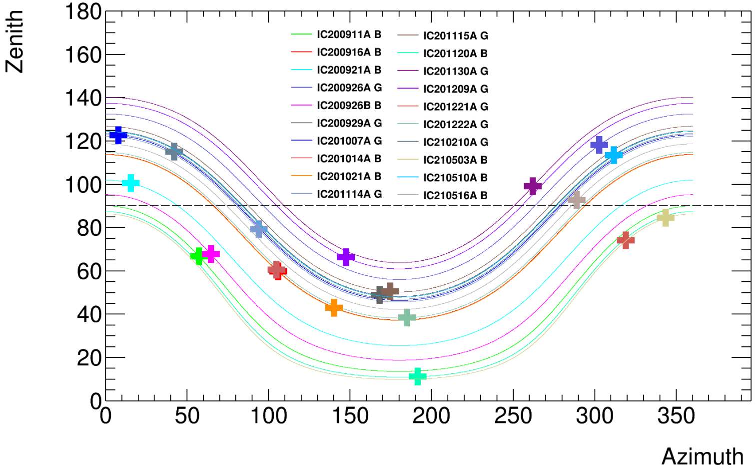
GVD follow up of IceCube alerts

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





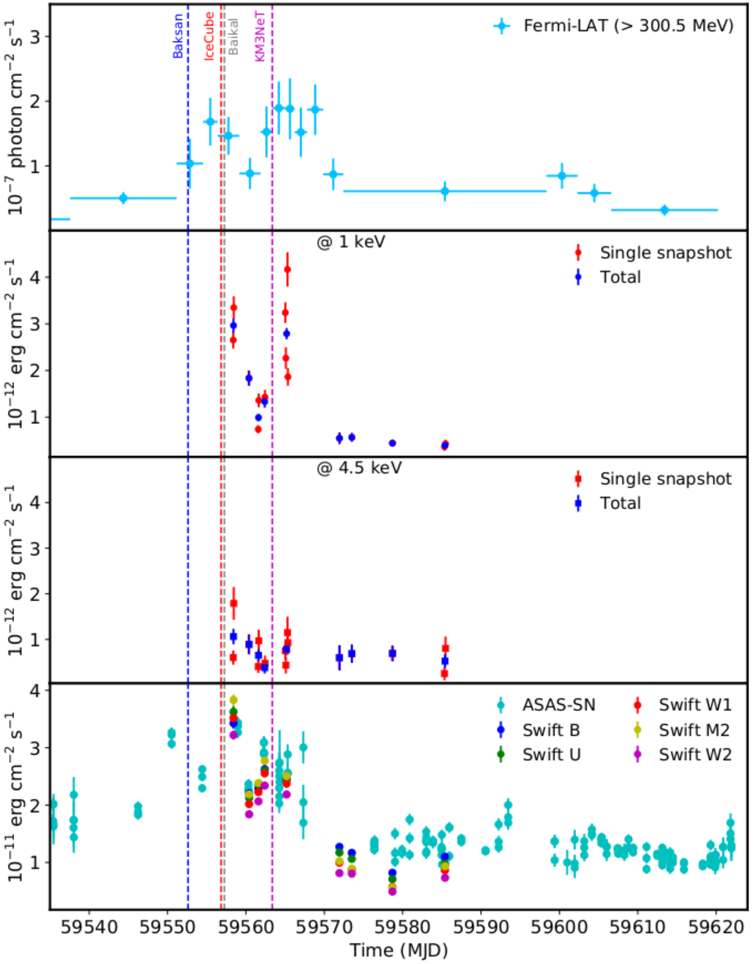
A.D. Avrorin et al., Astronomy Letters, Vol.47, N 2, 114 (2021)

http://dx.doi.org/10.1134/S1063773721020018

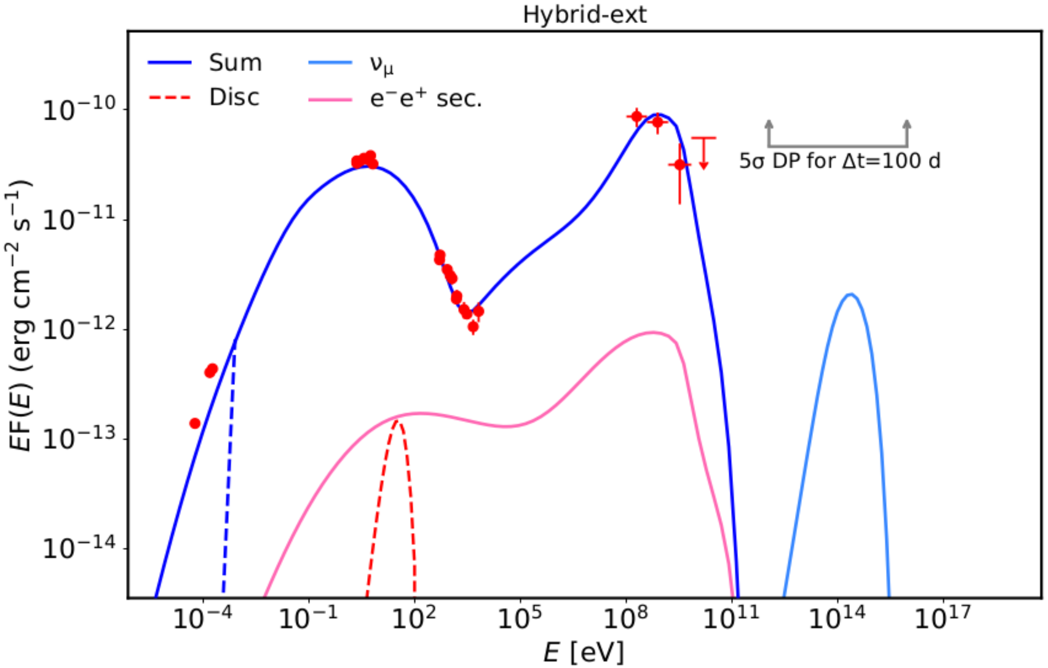
V.Y. Dik et al., JINST 16 (2021) C11008

https://doi.org/10.1088/1748-0221/16/11/C11008

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.

AGN origin of the diffuse neutrino flux?

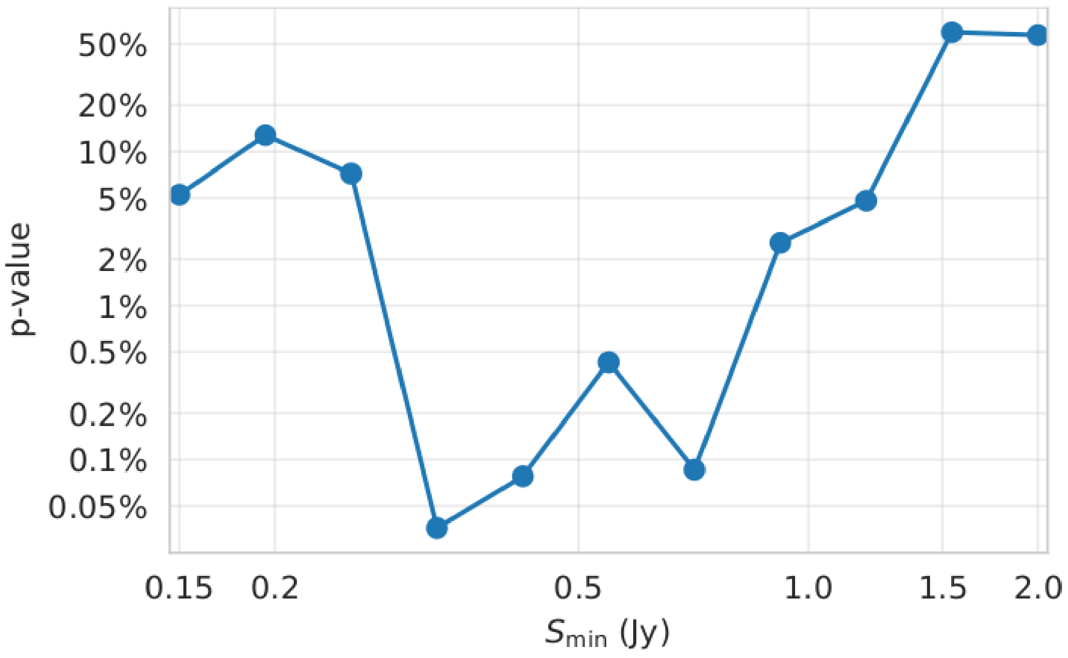


Figure 2. Pre-trial p-values for a range of VLBI flux density cutoffs. The threshold values $S_{\rm min}$ split the interval 0.15-2 Jy into ten parts uniformly in log-scale. The lowest p-value of $4 \cdot 10^{-4}$ is attained for the threshold of 0.33 Jy.

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]

Neutrino absorption in the Earth

doi:10.1038/nature24459