7th International Conference on Particle
Physics and Astrophysics (ICPPA)
October 22-25, 2024
Moscow, Russia

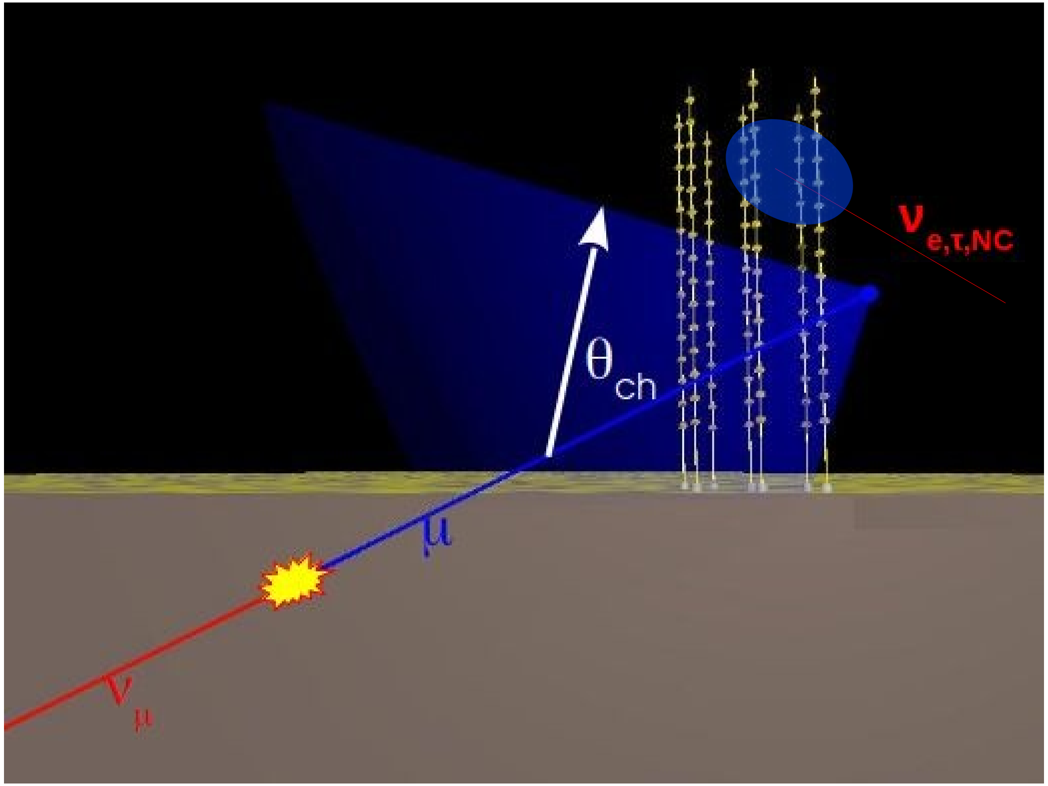
Neutrino astronomy at Lake Baikal

Dmitry Zaborov (INR RAS)
for the Baikal-GVD Collaboration

Outline

- Current status of (High Energy) Neutrino Astronomy
- Baikal-GVD and its first results
- Future prospects

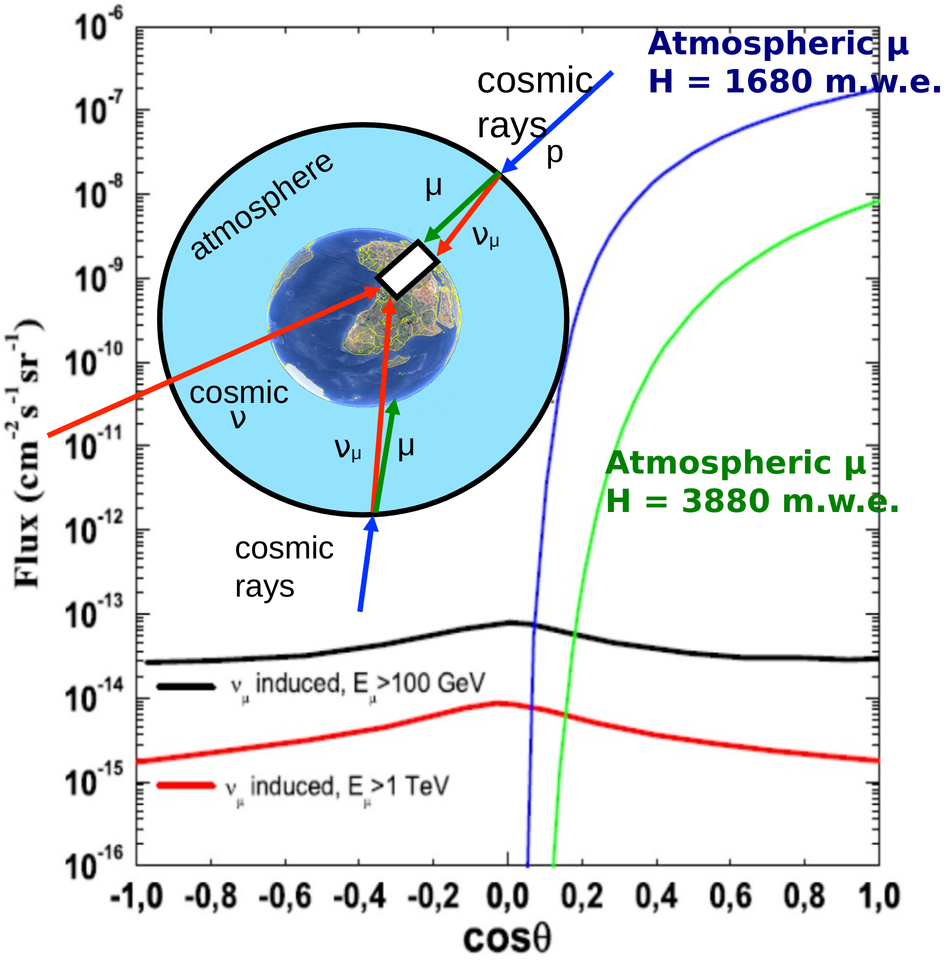
Neutrino telescope operation principle



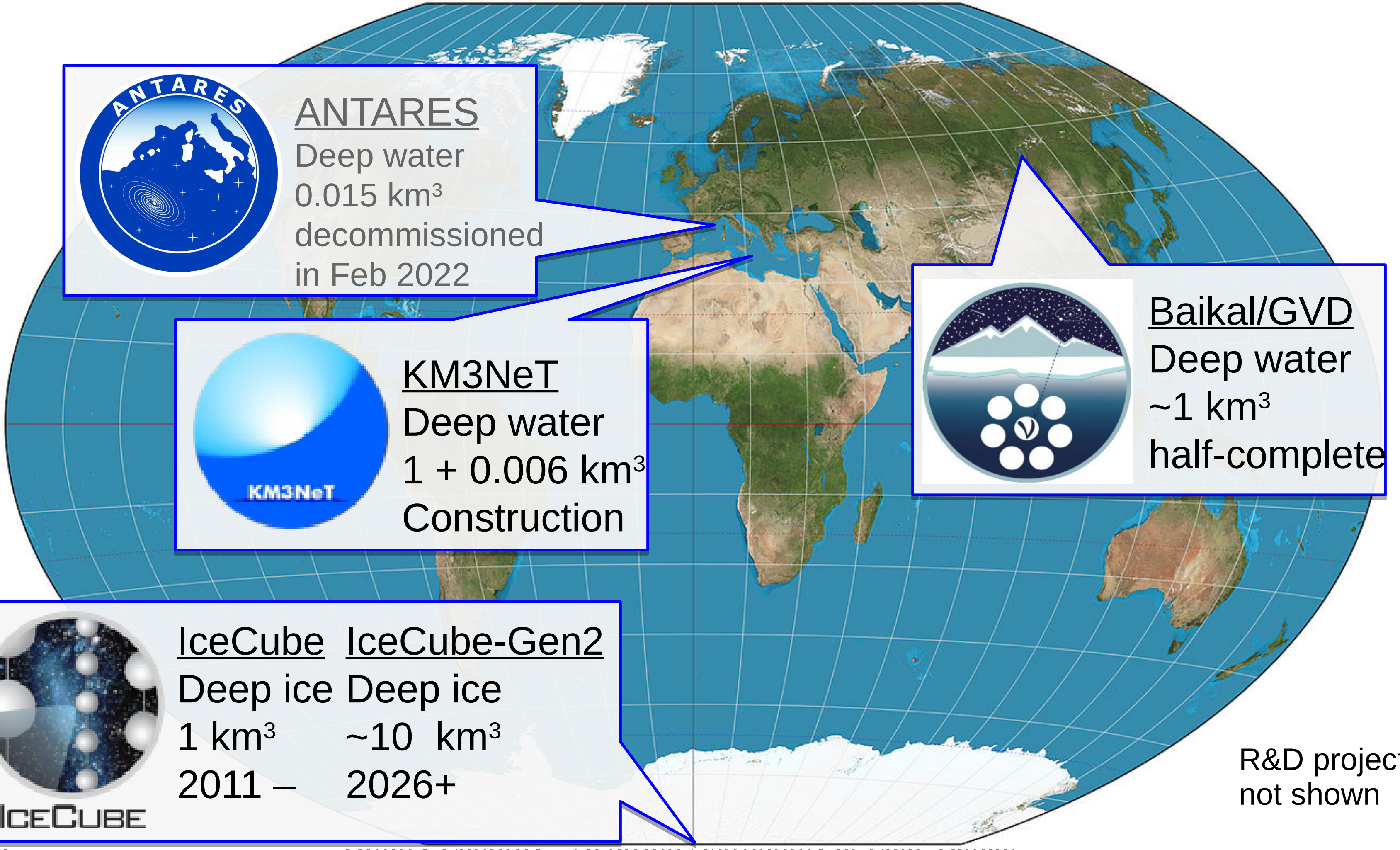
- Large arrays of photo-sensors (PMTs) in water or ice
- Detect Cherenkov light
- “Tracks”: ν_μ CC
- “Cascades”: ν_e & ν_τ CC + NC
- Direction reconstructed from hit positions and times (0.1° – 1° for tracks; a few ° for cascades)
- Energy reconstructed from hit charges (~ 5-30% for cascades; ~ factor 2 – 3 for tracks)

Backgrounds

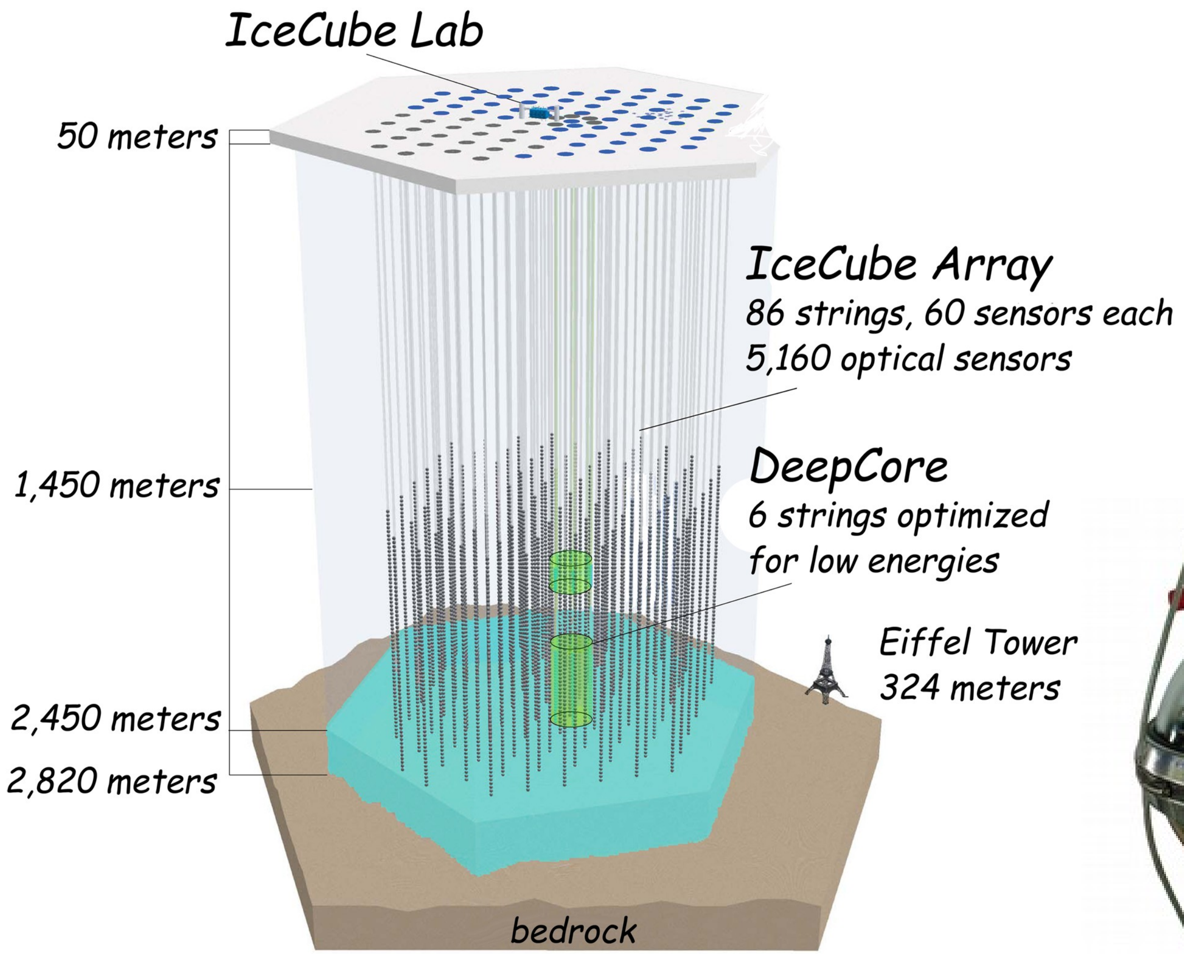
- Atmospheric neutrinos
  - All-sky, soft spectrum
  - For downgoing events, atmospheric muons can be used as veto (at very high energy)
- Atmospheric muons
  - Downgoing only (Earth acts as filter)
- Environmental background light: natural radioactivity (e.g. ^{40}K), bioluminescence, chemiluminescence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



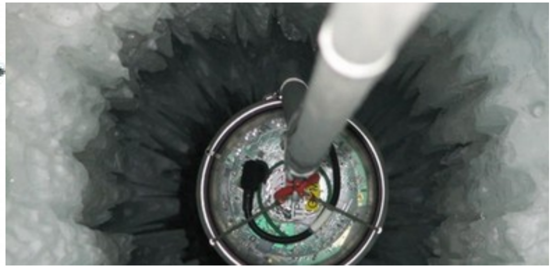
Neutrino telescope world map 2024



IceCube

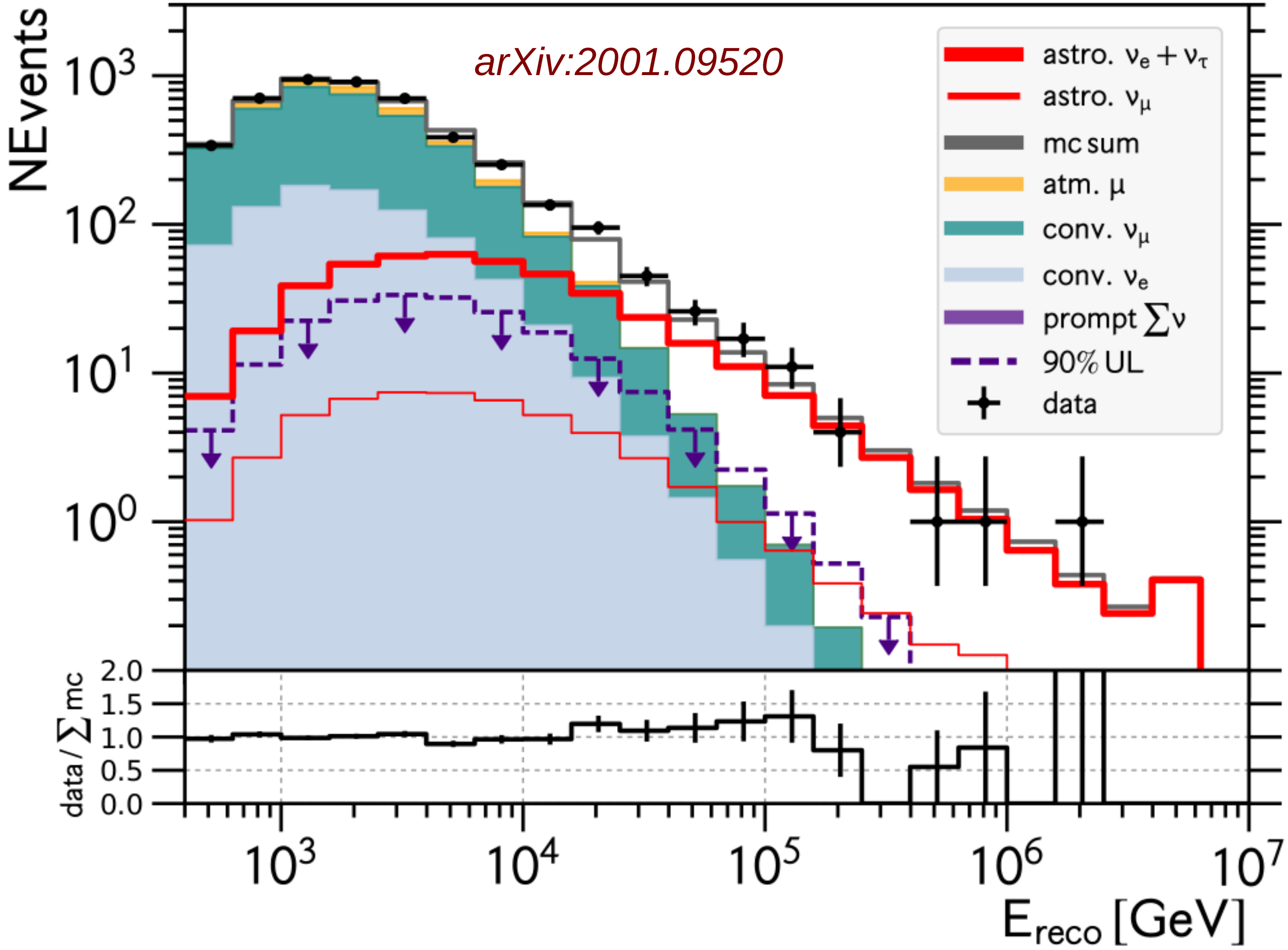


- 1 km^3-scale neutrino detector at South Pole
- Construction started in 2005
- Completed by 2011



Diffuse neutrino flux (IceCube)

IceCube cascades



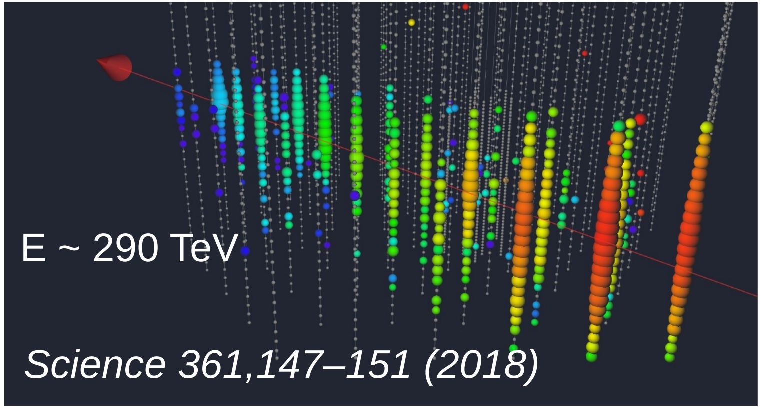
Science 342 (2013) [4.1 σ]
PRL 113:101101 (2014) [5.9 σ]
APJ 833 (2016) 1,3 [5 σ, tracks]
PRL 125:121104 (2020) [~10 σ]
...

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

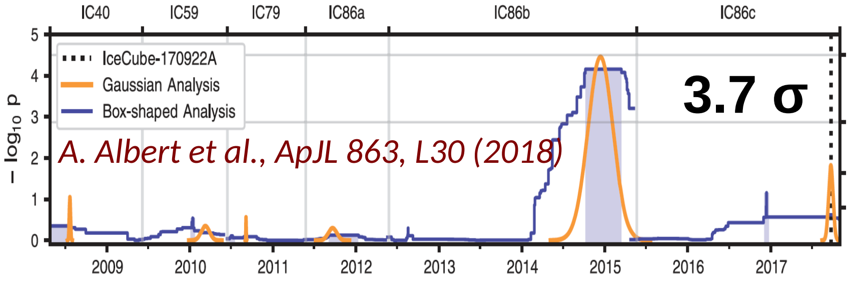
Individual neutrino sources observed by IceCube

TXS 0506+056 (blazar at z= 0.34 (1.7 Gpc))

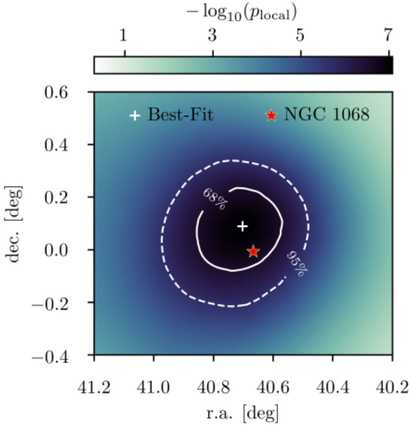
High-energy IceCube ν coincident with a γ-ray flar from the blazar TXS 0506+056 (Sep 22, 2017)

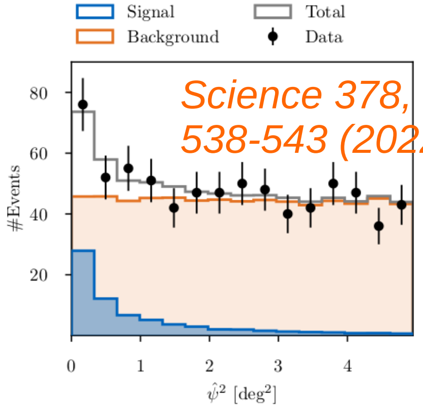


neutrino flare found in earlier IceCube data



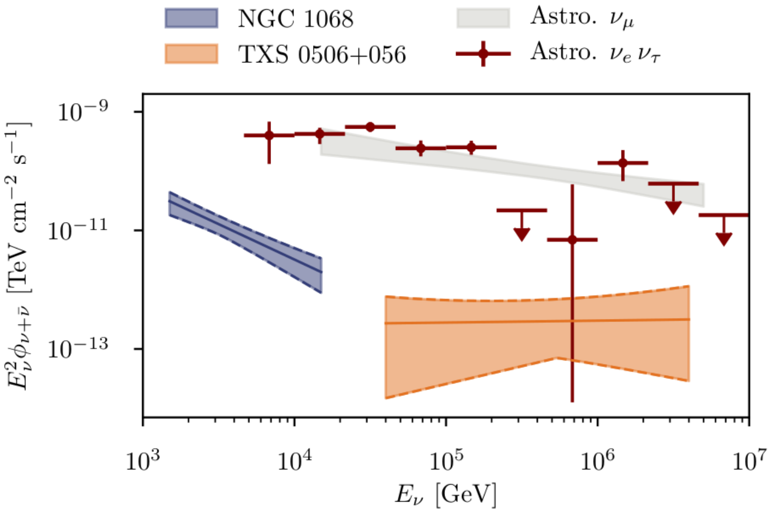
NGC 1068 (Seyfert, 14.4 Mpc)





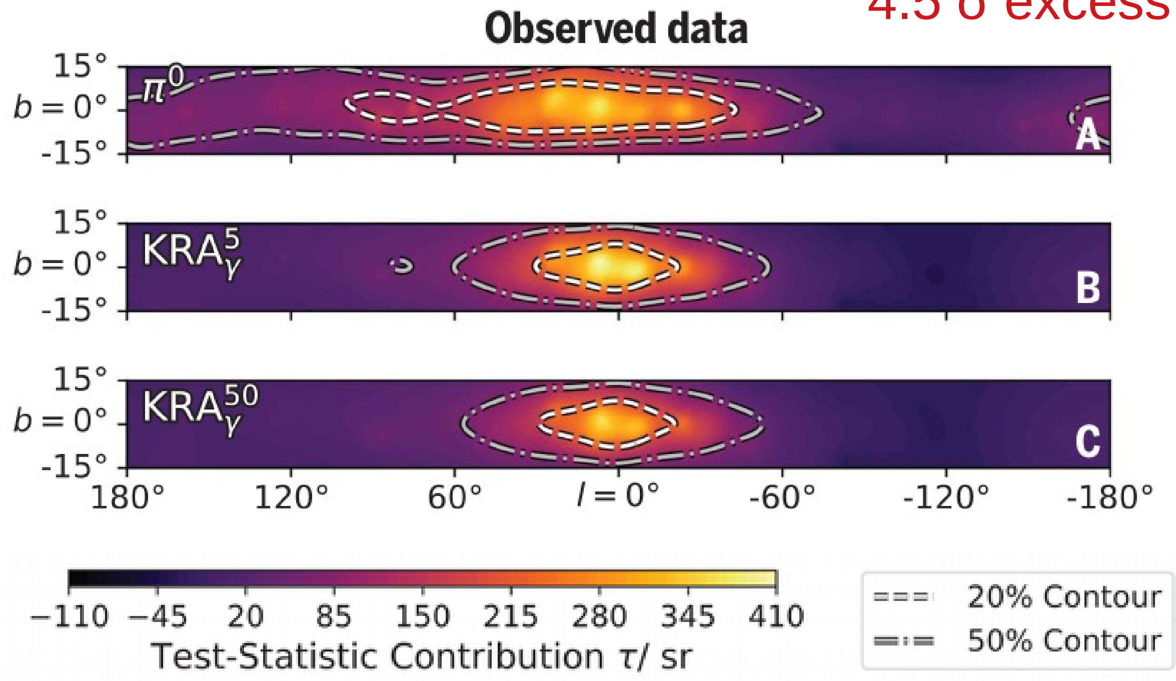
4.2 σ

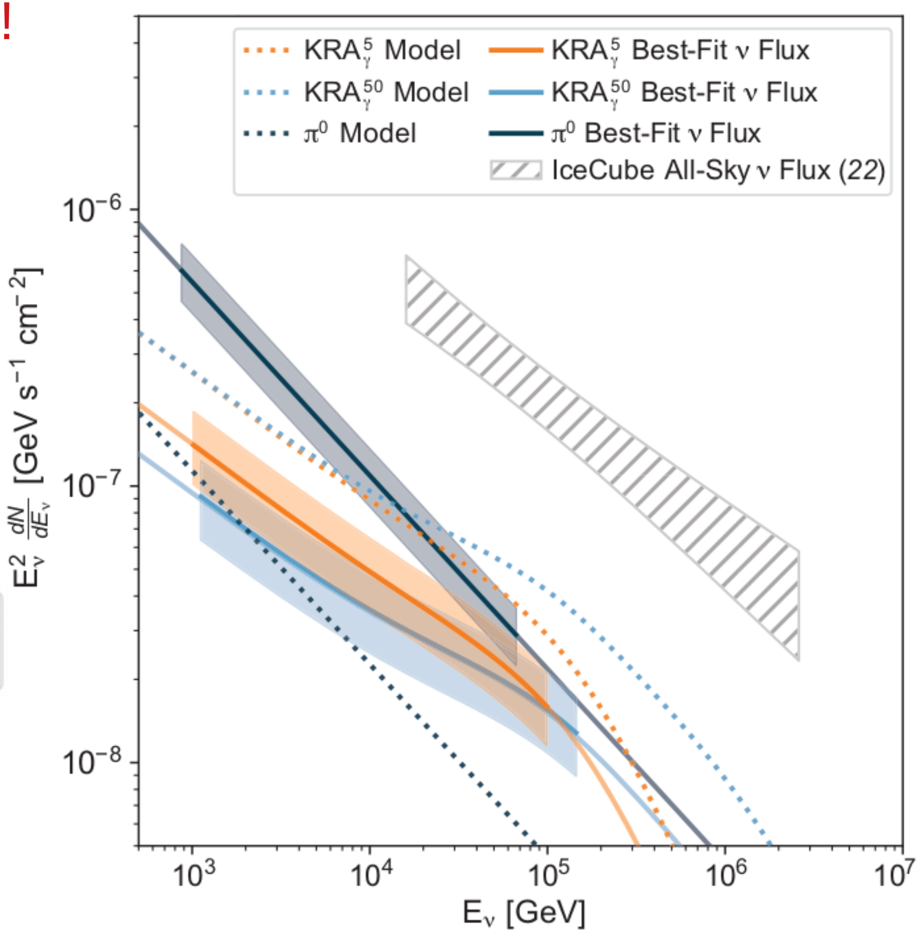
(10 yr of IceCube data)



Galactic Diffuse neutrino flux observed by IceCube

4.5 σ excess!



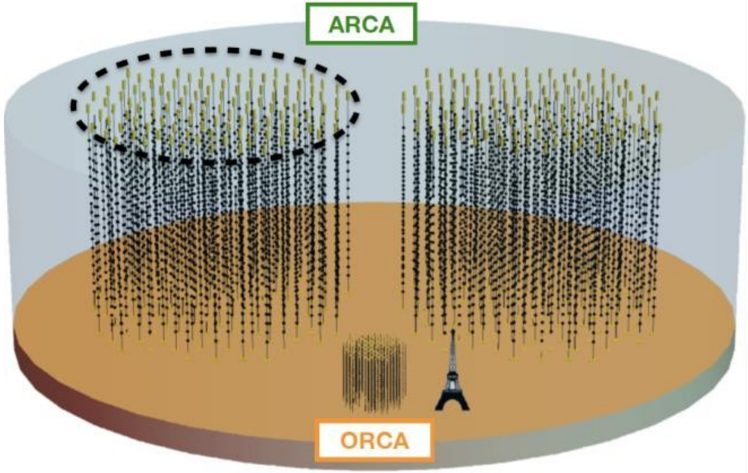


Three pre-defined Galactic emission templates used, all giving (different) positive results

Unresolved sources could contribute

Science, 380 (2023) 1338-1343

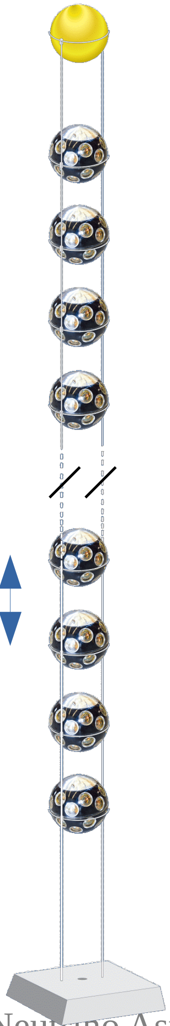
KM3NeT – ARCA (under construction)



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



36 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

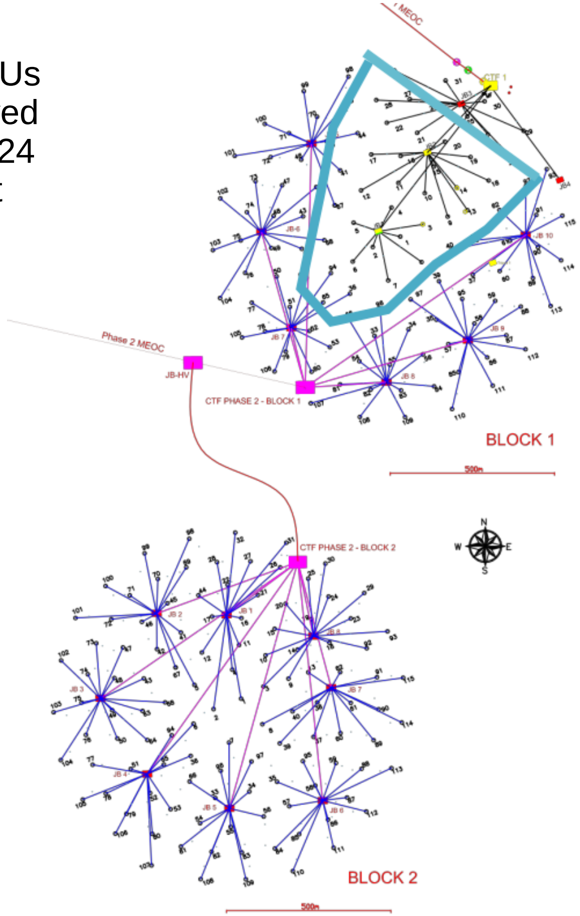
✔ Uniform angular coverage
✔ Directional information
✔ Digital photon counting
✔ All data to shore

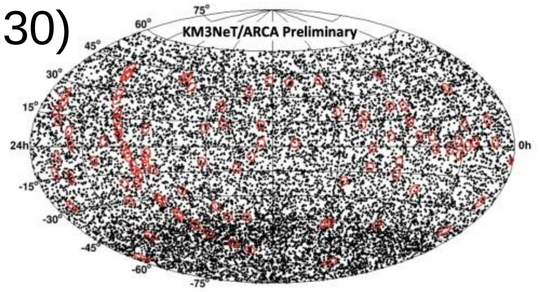
Optical background (mainly ^{40}K): 5-10 kHz

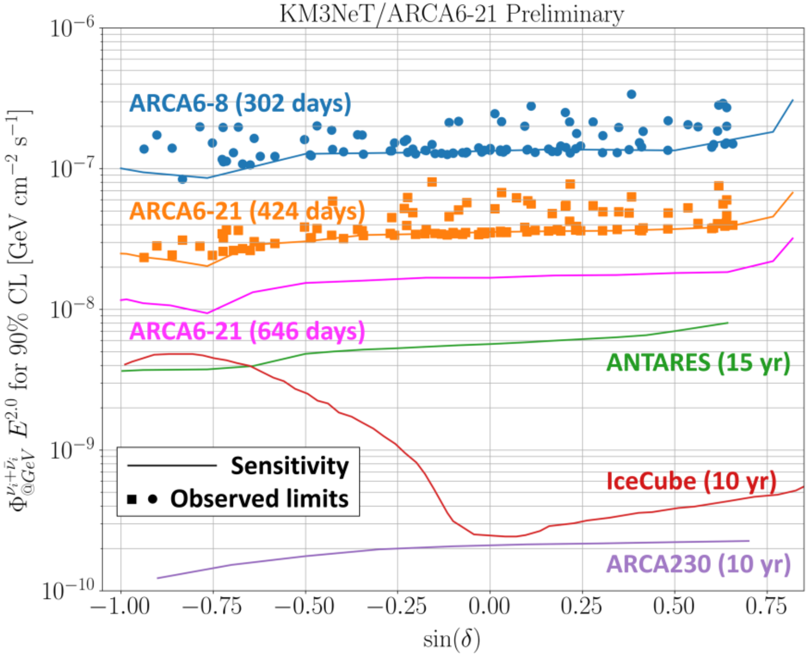
KM3NeT/ARCA – current status

28+5 = 33 Detection units deployed (out of 230)

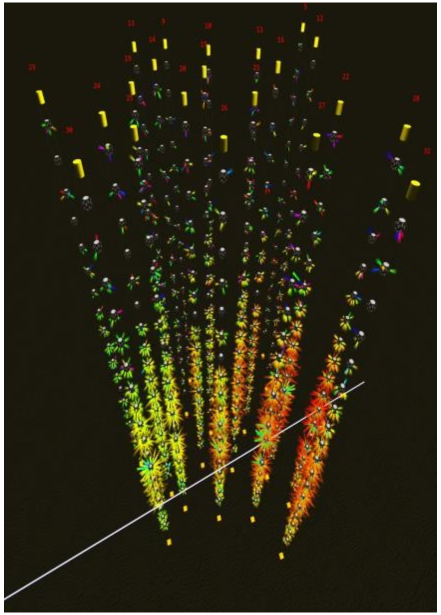
Five DUs deployed in Oct'24 not yet shown here







A neutrino candidate event with E > 10 PeV (from 1° above horizon)

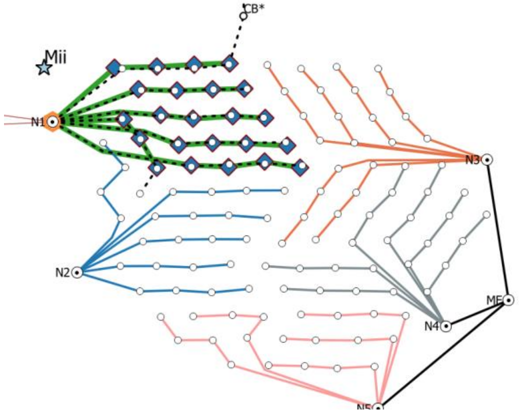


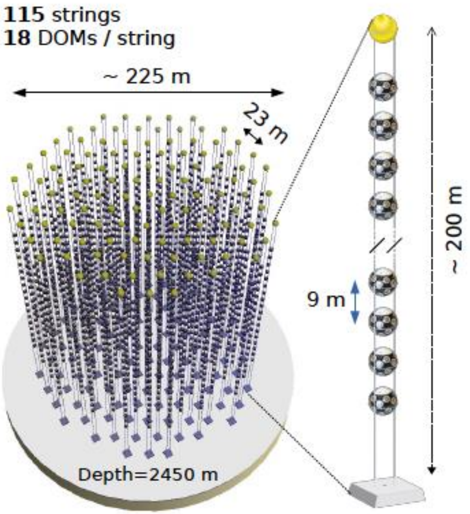
ICHEP'2024

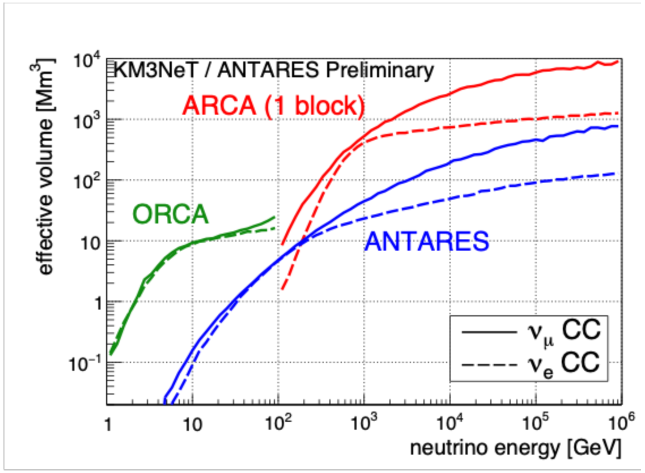
KM3NeT/ORCA – current status

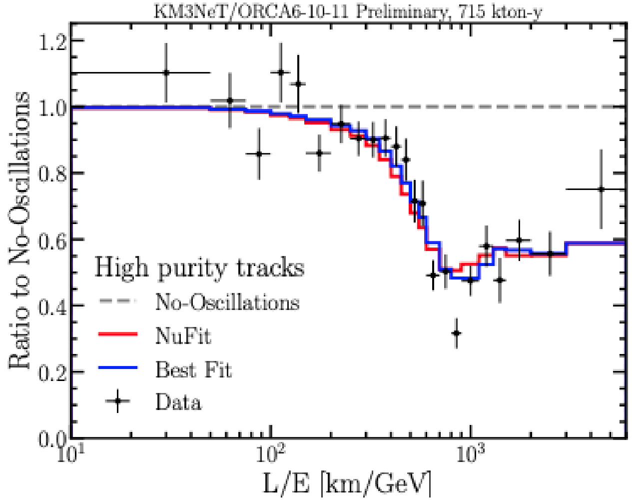
23 Detection units deployed (out of 115)

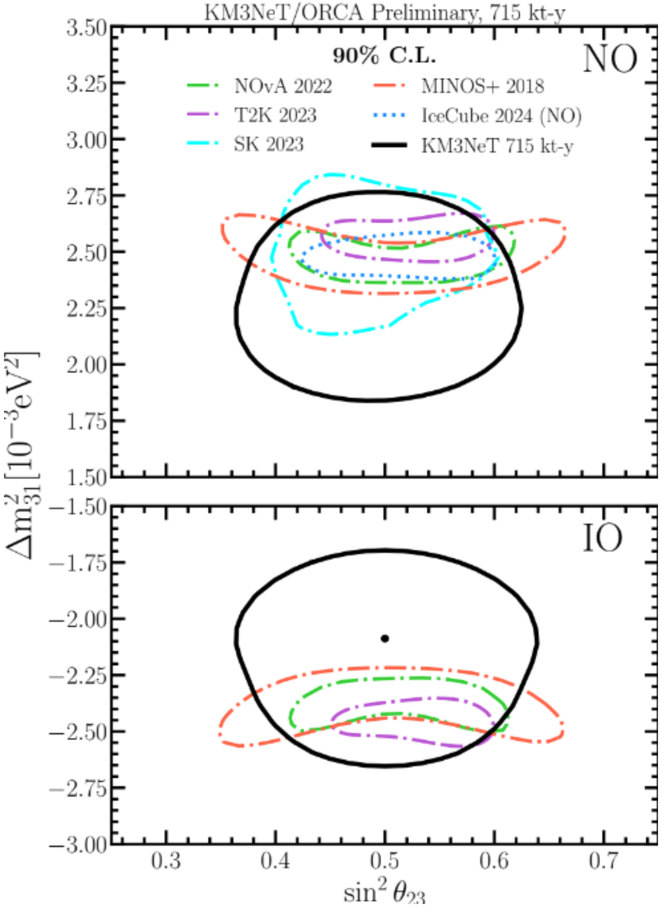
P. Coyle, ICHEP'2024





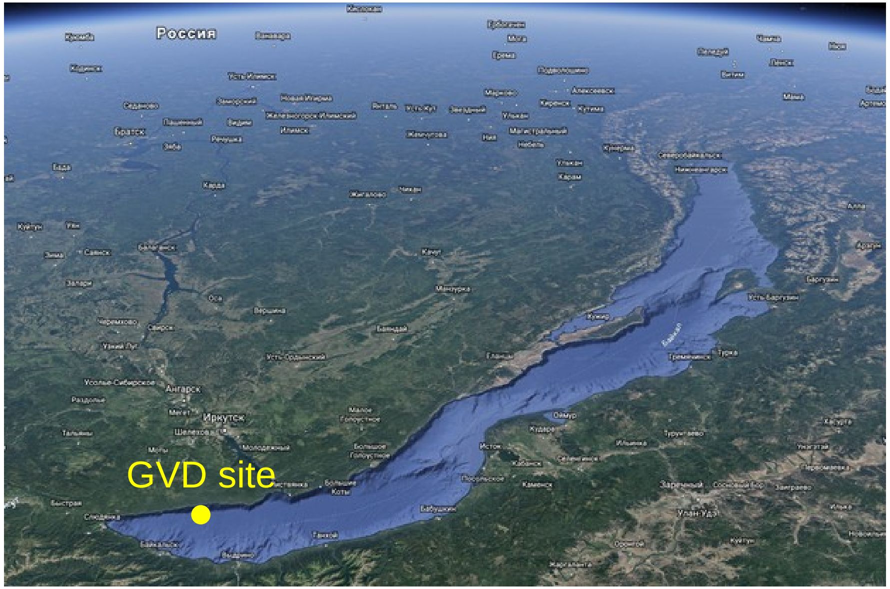




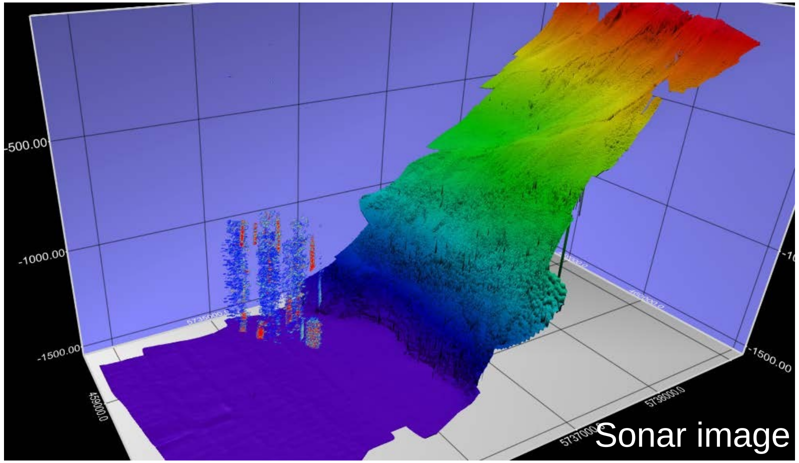


Baikal-GVD and its first results

Baikal-GVD site



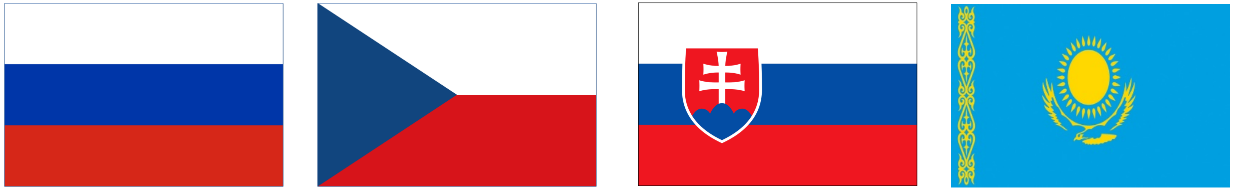
- 51° 46’ N 104° 24’ E
- Southern basin of Lake Baikal
- ~ 4 km away from shore
- Flat area at depths 1366 – 1367 m
- Stable ice cover for 6–8 weeks in February – April: detector deployment & maintenance



- 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 collaboration (as of Oct 2024)

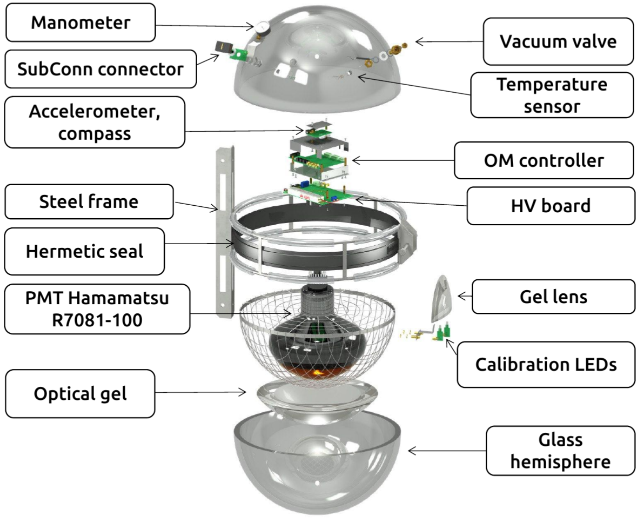
11 organisations from 4 countries, ~60 collaboration members



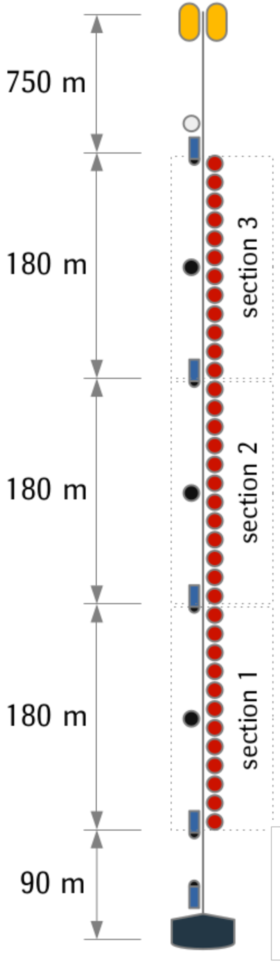
- Institute for Nuclear Research RAS (Moscow)
- Joint Institute for Nuclear Research (Dubna)
- Irkutsk State University (Irkutsk)
- Skobeltsyn Institute for Nuclear Physics MSU (Moscow)
- Nizhny Novgorod State Technical University (Nizhny Novgorod)
- Saint-Petersburg State Marine Technical University (Saint-Petersburg)
- Institute of Experimental and Applied Physics, Czech Technical University (Prague, Czech Republic)
- LATENA (St. Petersburg)
- INFRAD (Dubna)
- Comenius University (Bratislava, Slovakia)
- Institute of Nuclear Physics ME RK (Almaty, the Republic of Kazakhstan)

Baikal-GVD technology

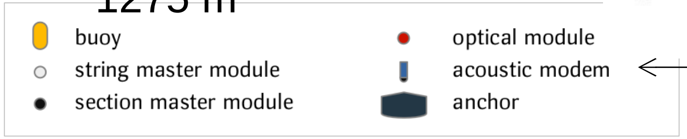
Optical module

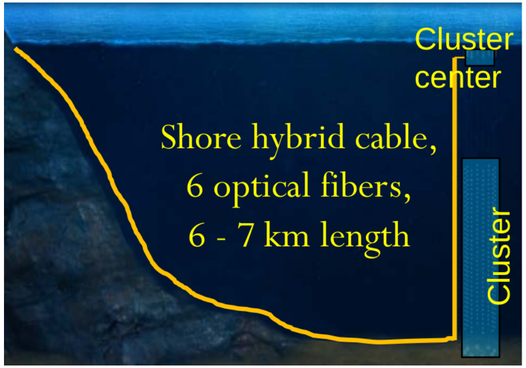


string

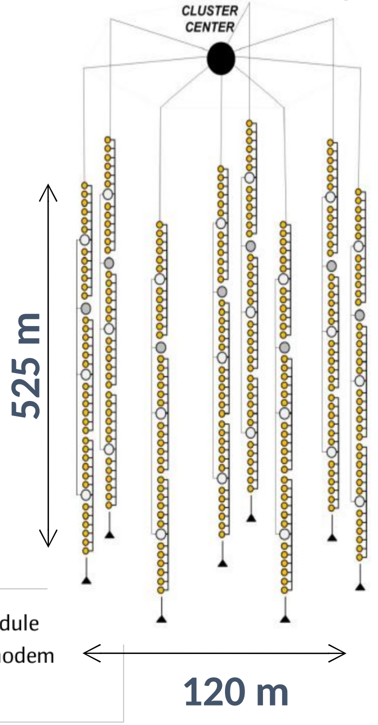


- **36 OMs** (10” high QE PMT, 15 m spacing, all PMTs look downward)
- **4 acoustic modems** of the positioning system
- **Section modules** digitize OM signals and send data to shore via shDSL/Ethernet
- Depths 750 m to 1275 m

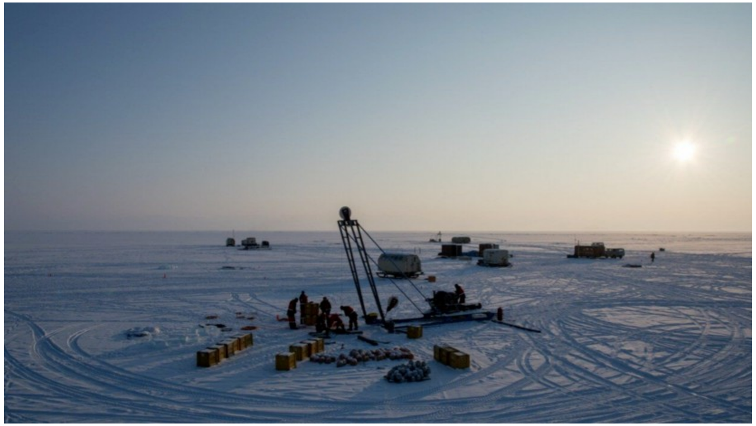




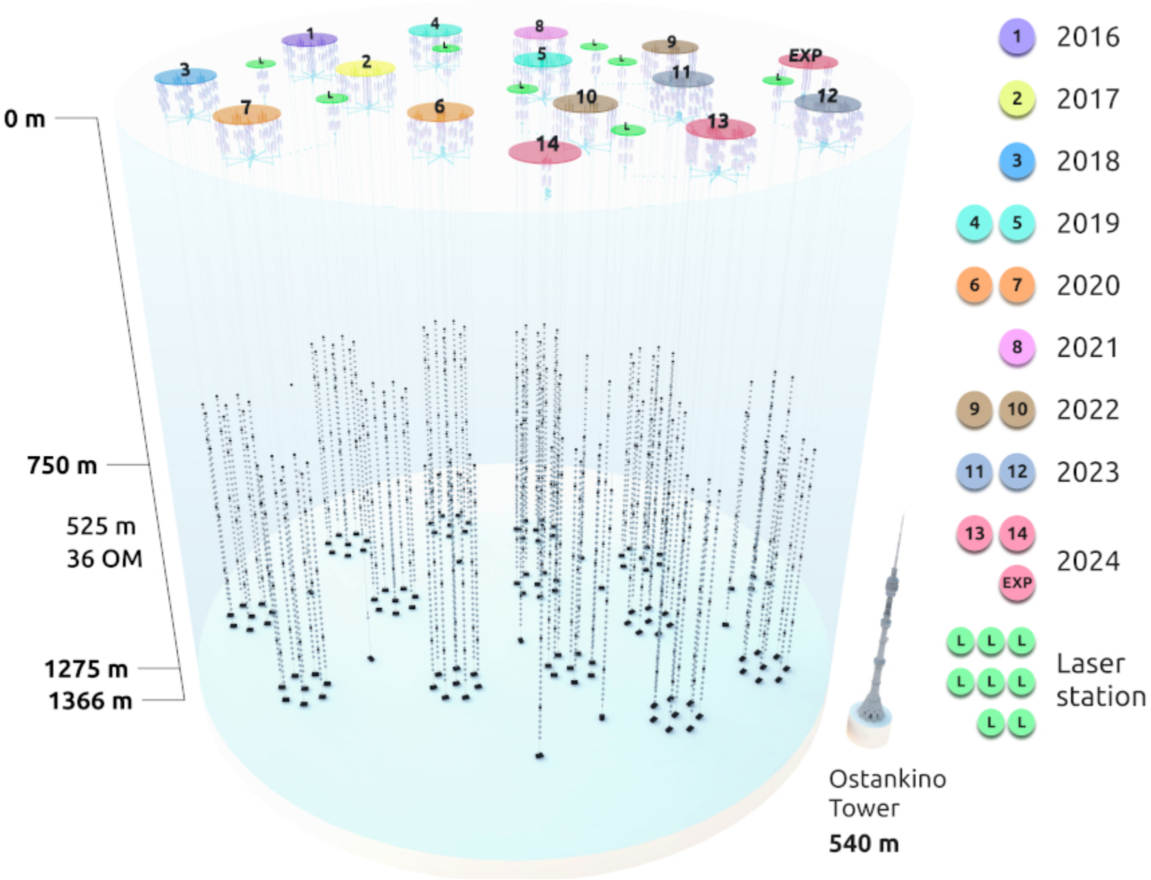
Cluster: 8 strings



Deployment



Baikal-GVD : current status



GVD = Gigaton Volume Detector

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	2880
2023	12	96	3456
2024	**14**	**114**	**4104**

14 clusters + 8 laser stations/inter-cluster strings + 4 experimental strings

Eff. volume 2024: **~ 0.6 km^3** (cascades, E ~ 1 PeV)

Search for upward-going cascade events

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

Data from 2018 – 2021

Event selection:

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

Expected:

0.95 events from atm. muons

3 events from atm. neutrinos

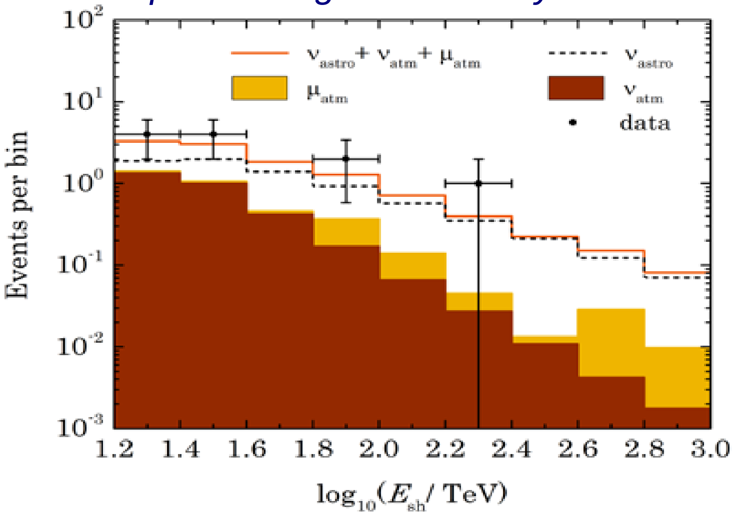
10 events for IceCube's $E^{-2.46}$ astrophysical flux

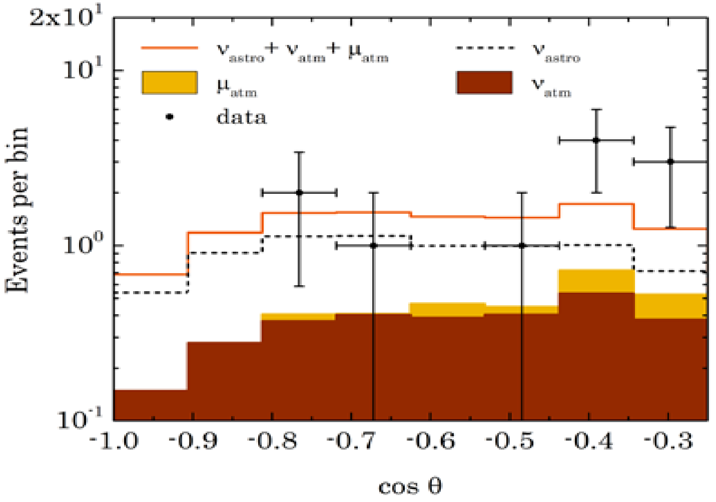
Found in data: 11 events

The "no diffuse flux" hypothesis is rejected with

P-value = 0.00268 (3.1 σ)

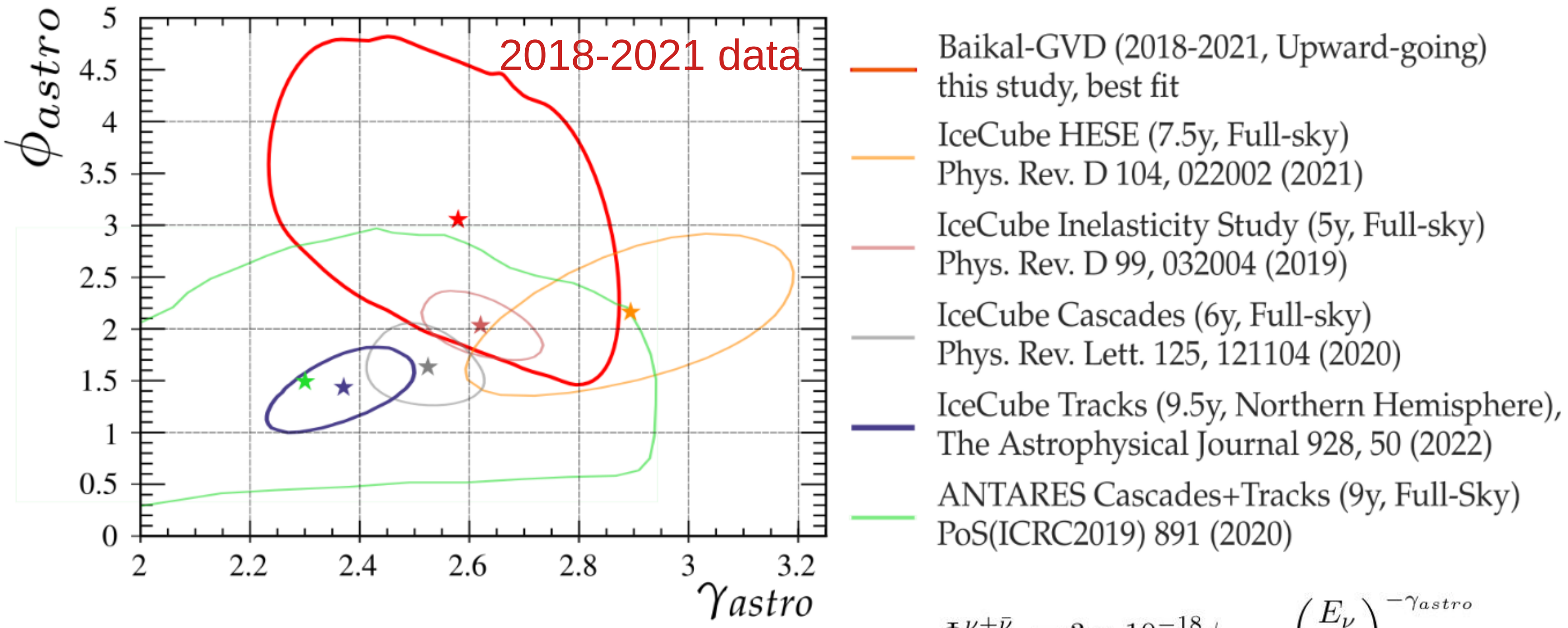
Statistical significance increases to 4.2 σ when 2022 data are added (not shown here)





Diffuse neutrino flux spectrum with Baikal-GVD

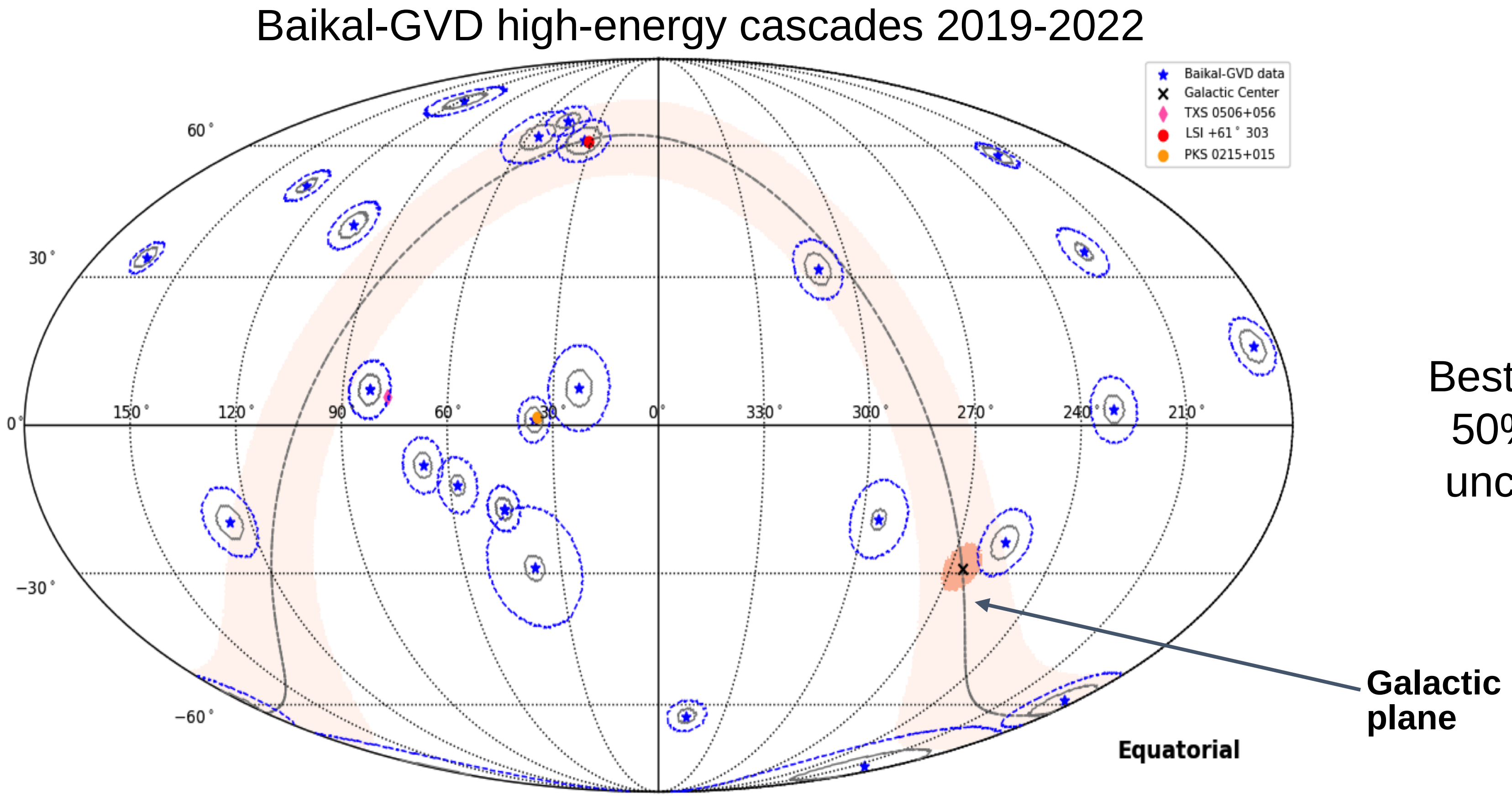
https://doi.org/10.1103/PhysRevD.107.042005



$$\Phi^{\nu+\bar{\nu}}_{astro} = 3 \times 10^{-18} \phi_{astro} \left(\frac{E_\nu}{E_0}\right)^{-\gamma_{astro}}$$

Analysis update (> 5 σ) is coming, stay tuned!

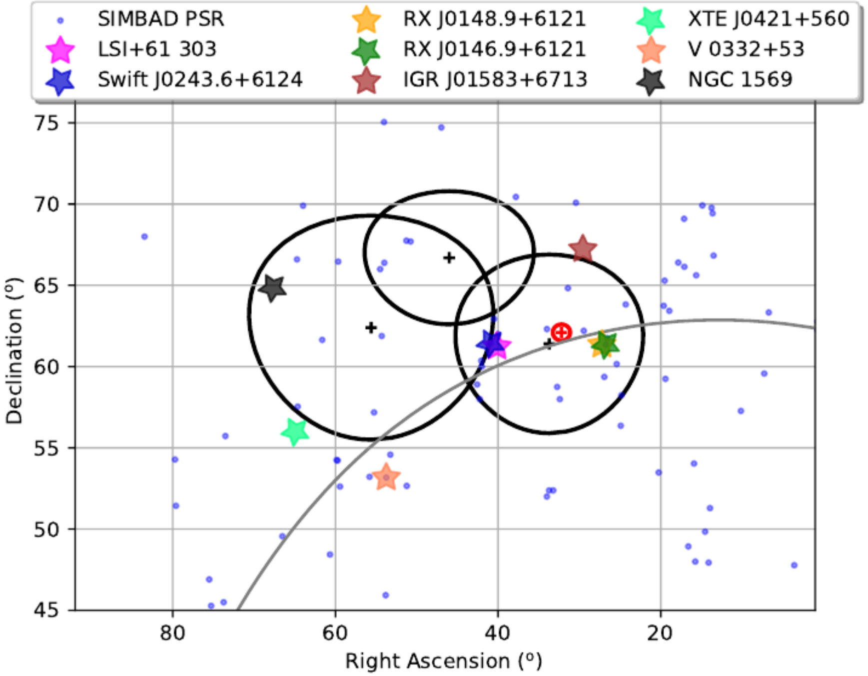
Baikal-GVD cascade events skymap (2018-2022)



Best fit positions and 50%, 90% angular uncertainty regions

https://doi.org/10.1093/mnras/stad2641

Event triplet near Galactic plane



Three events close to the Galactic plane (grey line)

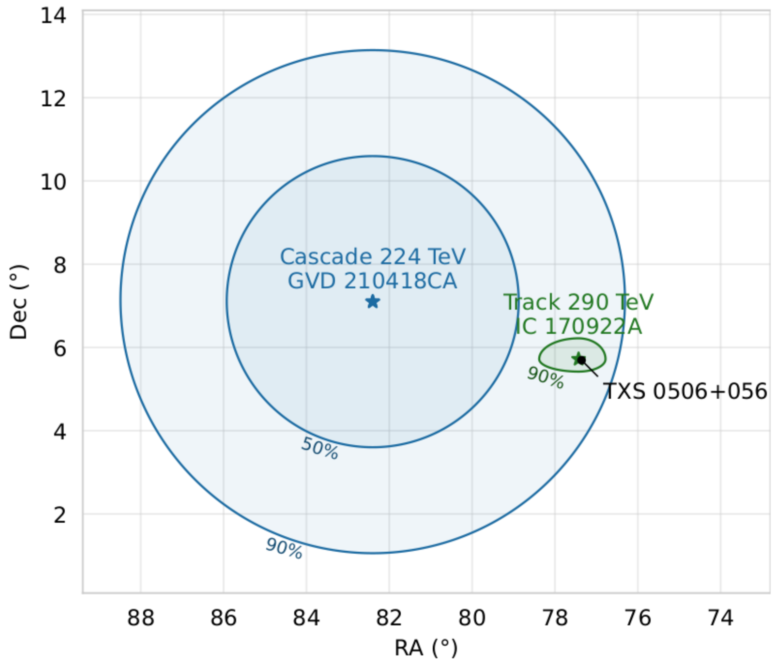
The red plus and circle – IC hotspot
[Aartsen & et al. ApJ, 835,151 (2017)]

LS I +61 303 is a γ-ray microquasar

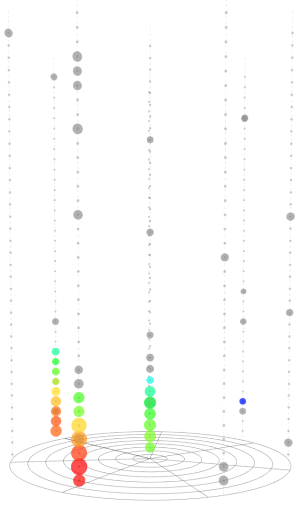
https://doi.org/10.1093/mnras/stad2641

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

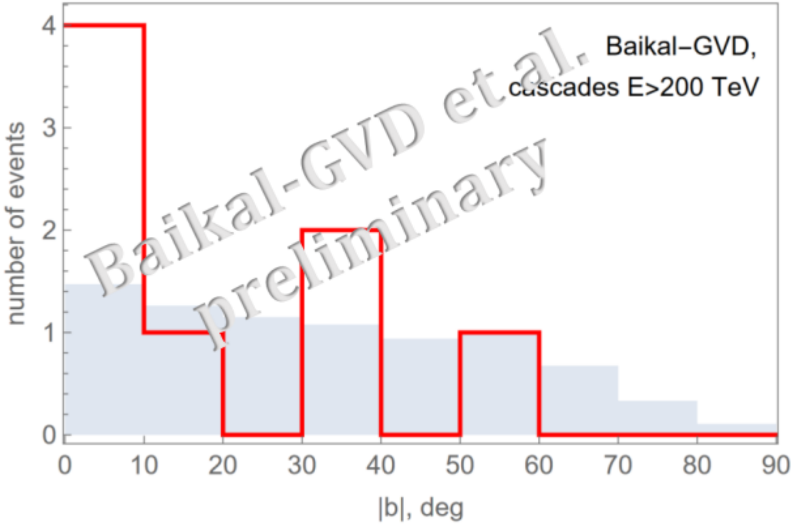
This event is probably of astrophysical origin (signalness = 97%)

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

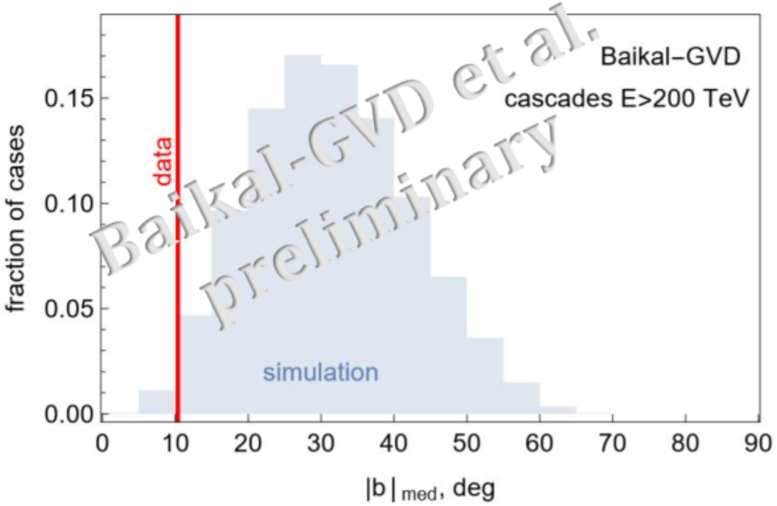
https://doi.org/10.1093/mnras/stad3653

Probing Galactic neutrino flux above 200 TeV with Baikal-GVD

– test the Galactic excess at E>200 TeV
– Baikal-GVD cascades 2018-2023
– simplest, model-independent median |b| test like in *Kovalev et al. [APJL 940 (2022) L41)]*



NEW!

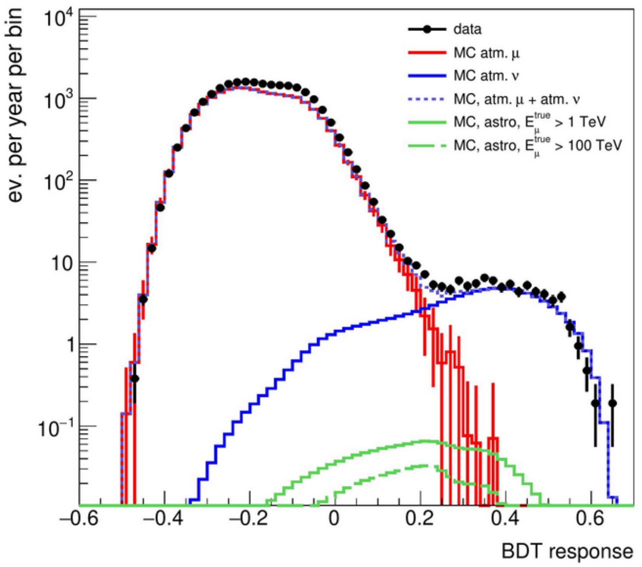


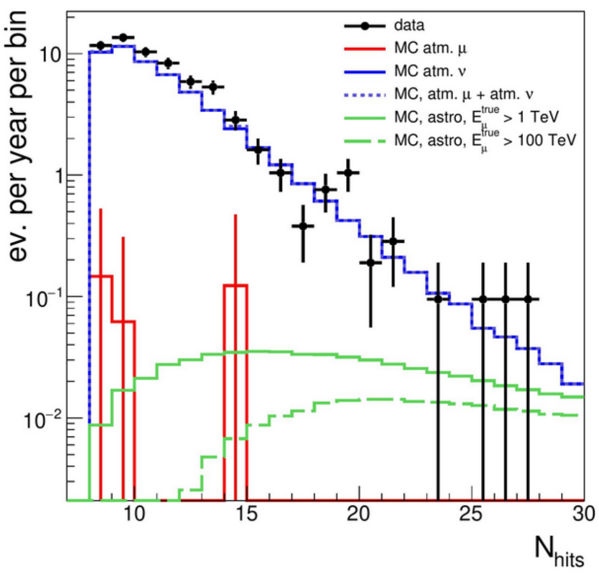
Sample	$\|b\|_{\rm med}$ observed	$\langle \|b\|_{\rm med} \rangle$ expected	p
Baikal-GVD cascades	10.4°	31.4°	$1.4 \cdot 10^{-2}$ (2.5σ)
IceCube cascades	12.4°	31.9°	$8.7 \cdot 10^{-3}$ (2.6σ)
IceCube tracks	24.7°	36.0°	$1.8 \cdot 10^{-3}$ (3.1σ)
combined	23.4°	35.0°	$3.4 \cdot 10^{-4}$ (3.6σ)

Publication in preparation

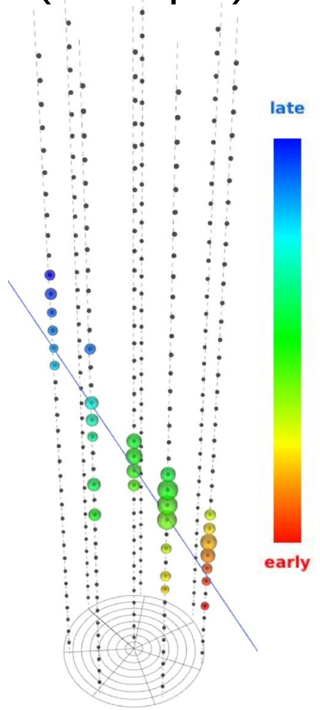
Analysis of track-like events

2020-2021 data





Neutrino candidate (example)



E = 100 TeV

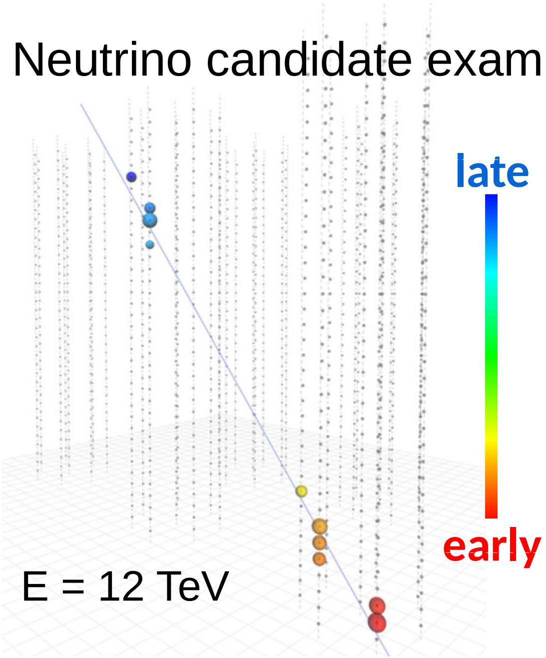
671 neutrino candidate events found in 2 yr of data (dominated by atmospheric neutrino)

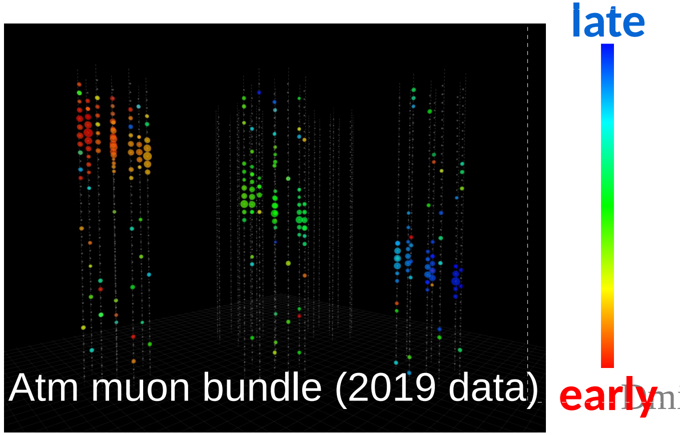
Work in progress...

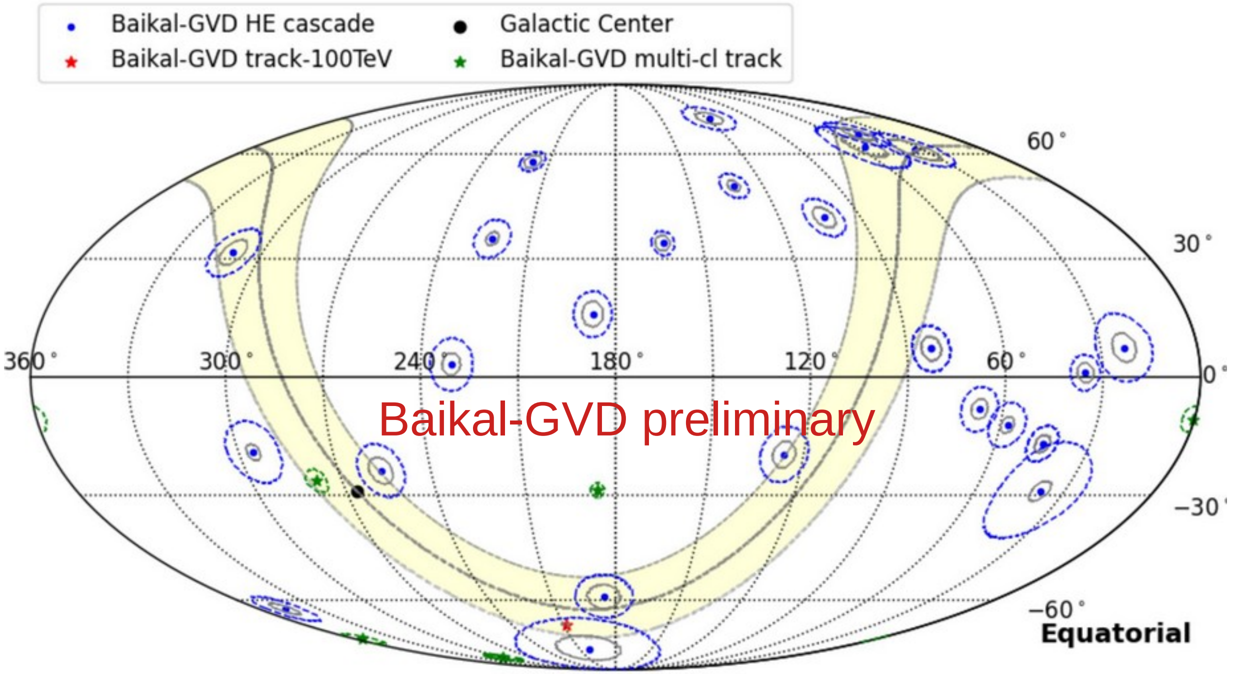
Also see Eur. Phys. J. C 81 (2021) 1025

Multi-cluster tracks

Neutrino candidate example





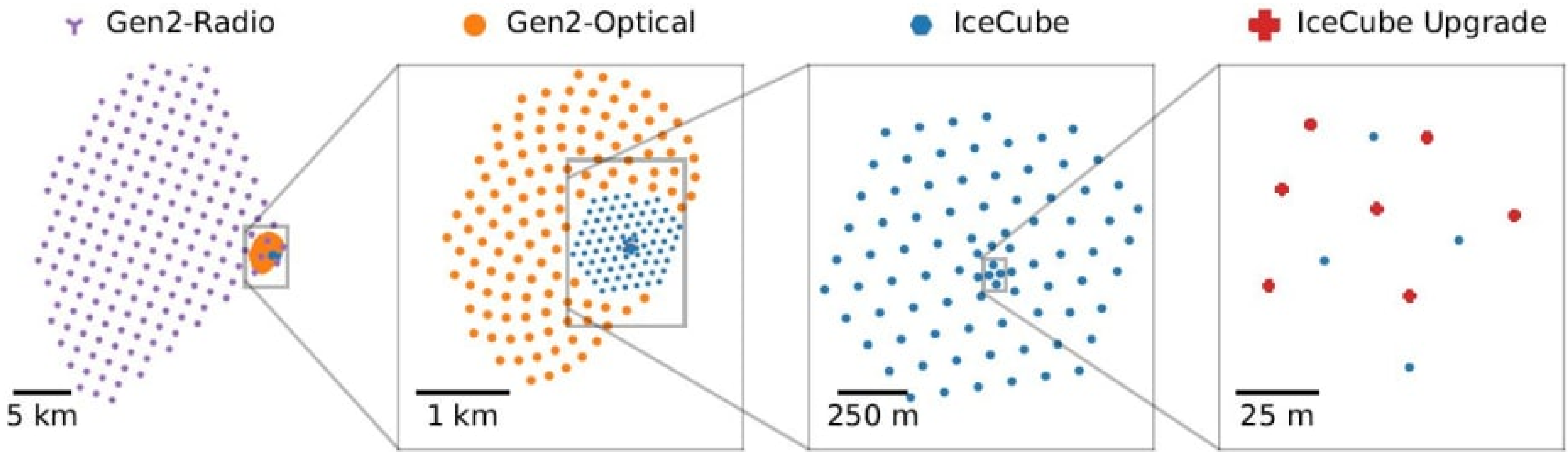


Green: Multi-cluster neutrino candidate events /
(150 days in 2019, dominated by atmospheric events)
Red: the 100 TeV single-cluster event
(high probability of astrophysical origin)

Future prospects

IceCube Gen2

plan to build ~8 km^3 optical array and a ~500 km^3 radio array

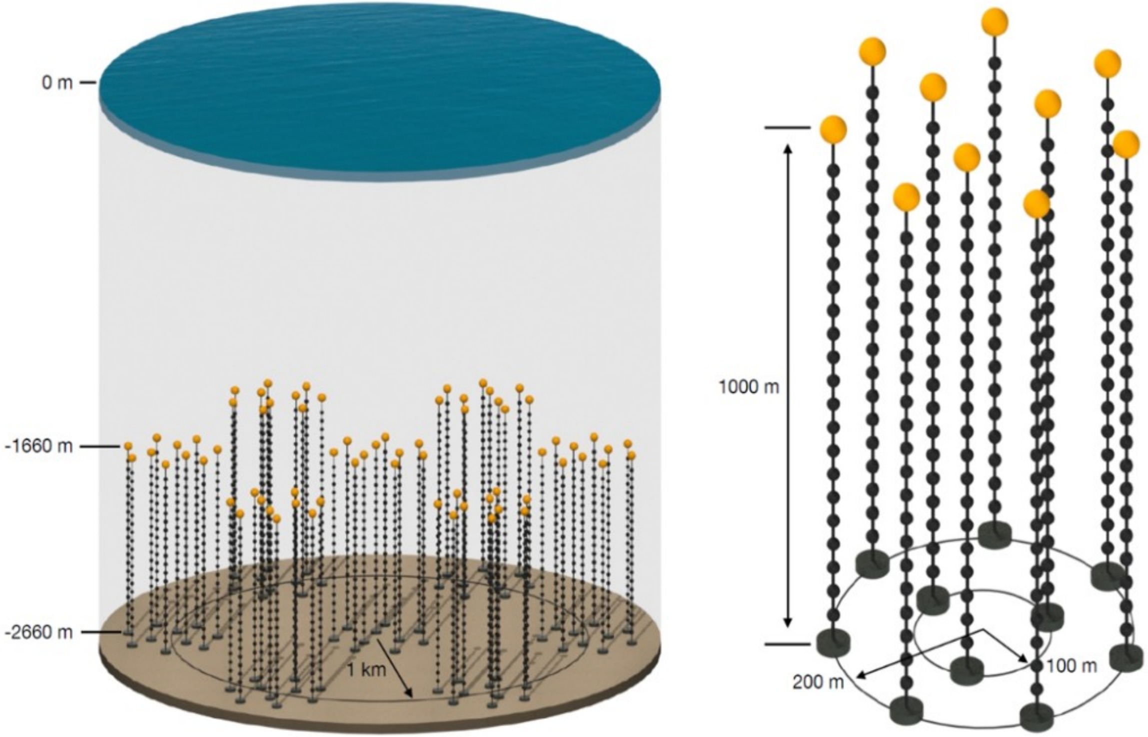


Optical: 120 new strings with 80 DOMs each (9600 OMs total)
→ sensitivity up to 8x IceCube

Radio : 200 stations at shallow depth (0-100 m)
→ sensitivity to E > 10 PeV

https://doi.org/10.1088/1361-6471/abbd48

P-ONE



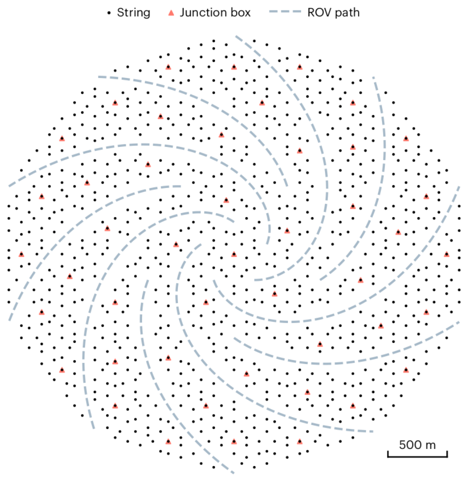
An initiative towards constructing a multi-cubic-kilometre neutrino telescope in the **Pacific Ocean** off the coast of **Canada**

Status: some prototype lines deployed

https://www.pacific-neutrino.org

Chinese neutrino telescope proposals (R&D phase)

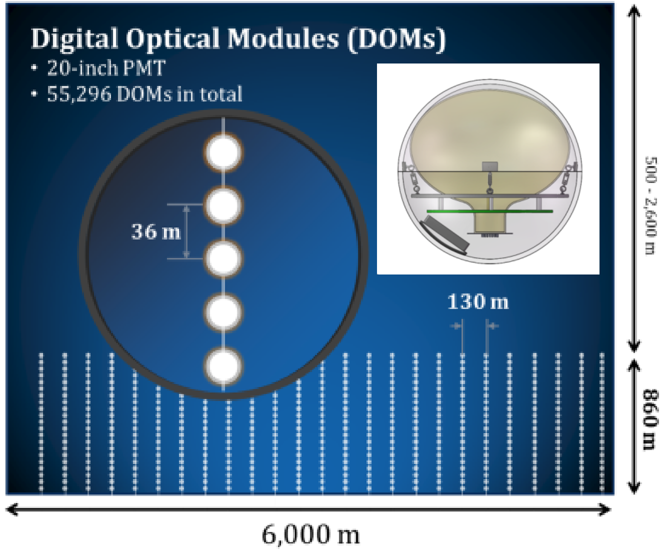
TRIDENT



- 7.5 km^3
- 24200 DOMs on 1211 strings
- **Hybrid DOMs** (PMTs + SiPMs)
- South China sea

doi:10.1038/s41550-023-02087-6

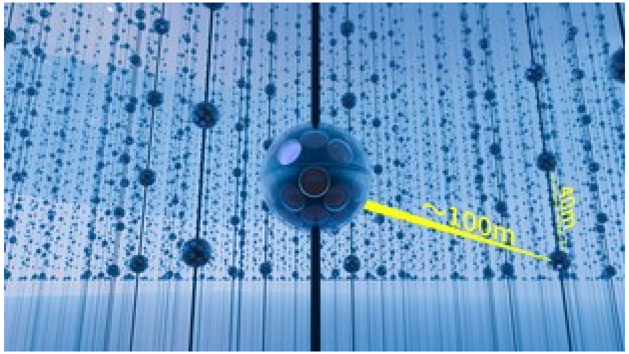
HUNT



- 30 km^3
- 55300 DOMs on 2304 strings
- **20” MCP-PMTs**
- **South China sea / Lake Baikal**

doi:10.22323/1.444.1080
doi:10.1088/1748-0221/19/08/T08006

NEON



- 10 km^3
- ~18000 DOMs on ~1000 strings
- **multi-PMT DOMs**
- South China sea

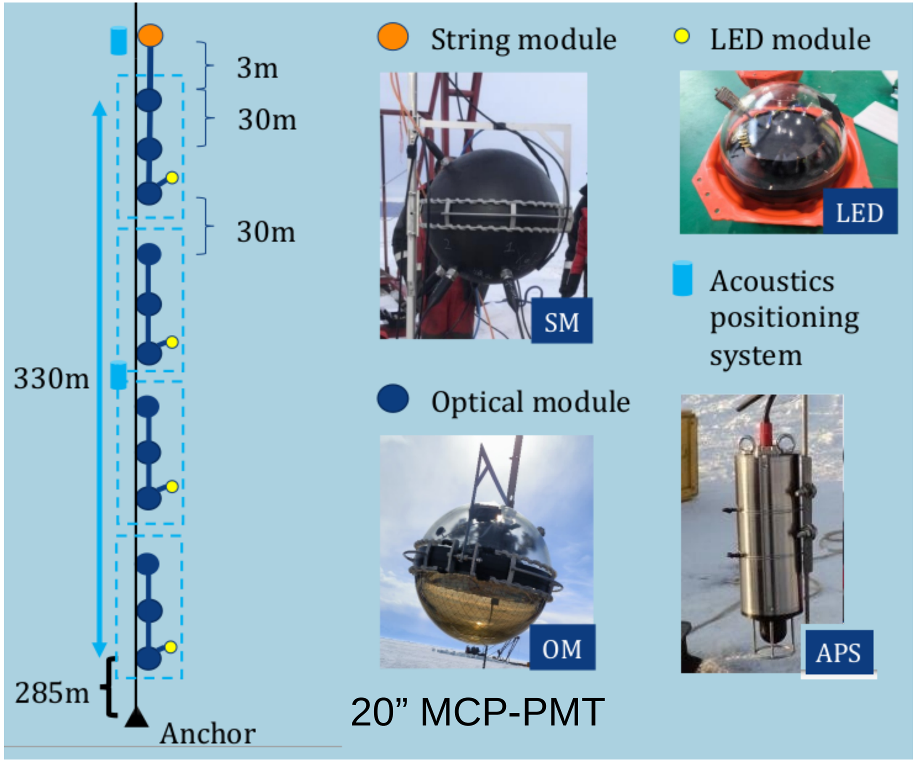
arXiv:2408.05122

Technological prototype strings at Lake Baikal (2024)

4 “experimental” strings using fiber optic technology for data transmission + standard Baikal-GVD OMs

HUNT prototype string deployed in 2024

IHEP (Beijing) & Baikal-GVD joint effort



20” MCP-PMT

Summary

- Baikal-GVD is a new neutrino telescope under construction in Lake Baikal
  - Volume approaching 0.6 km^3 (cascades, E ~ 1 PeV)
  - Angular resolution better than 1° (tracks)
  - Field of view complementary to IceCube
- The IceCube’s diffuse neutrino flux is confirmed by Baikal-GVD with a > 3σ significance
- Hints of Galactic and extragalactic neutrino sources are accumulating

Backup slides

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
Mediterranean sea	60 m	~ 260 m	doi:10.1016/ j.astropartphys.2004.11.006
Lake Baikal	24 m	~ 480 m	doi:10.1016/ j.nima.2012.06.035
South China sea	27 m	> 500 m	doi:10.1038/s41550-023-02087-6, arXiv:2407.19111
Pacific (P-ONE)	> 28 m	?	doi:10.1140/epjc/s10052-021-09872-5

Limits low energy performance and how sparse the detector can be

Limits angular resolution

Expected neutrino rates from individual sources

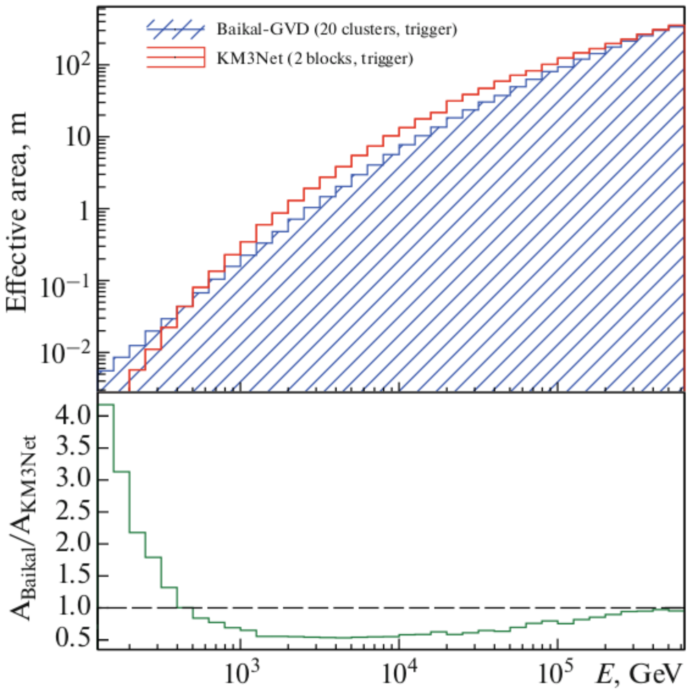


Fig. 2. 20-clustered Baikal-GVD effective area (blue) and 230-string KM3NeT effective area (red) at the trigger level [6].

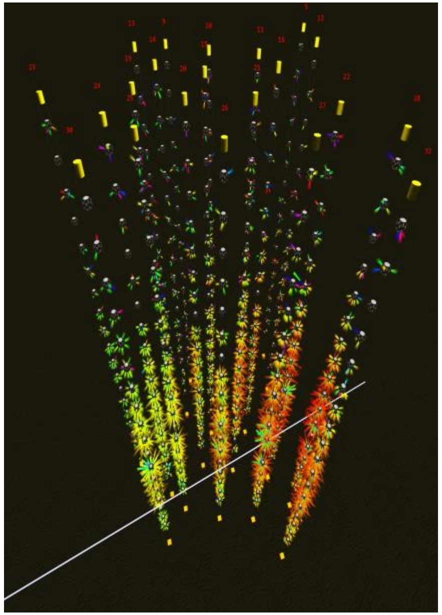
Table 2. Registration rate (counts/5 years) for KM3NeT/ARCA (ARCA) and Baikal-GVD (Baikal) at trigger (trig) and reconstruction (reco) levels. The first column shows the calculation results from [1]. The second and the third ones show our results for KM3NeT/ARCA and Baikal-GVD. These three columns are for the trigger level, and the fourth column shows the ratio for Baikal-GVD and KM3NeT/ARCA also at the trigger level. The fifth column shows Baikal-reconstruction registration rate, and in the rightmost column Baikal-GVD reconstruction-trigger ratio is presented

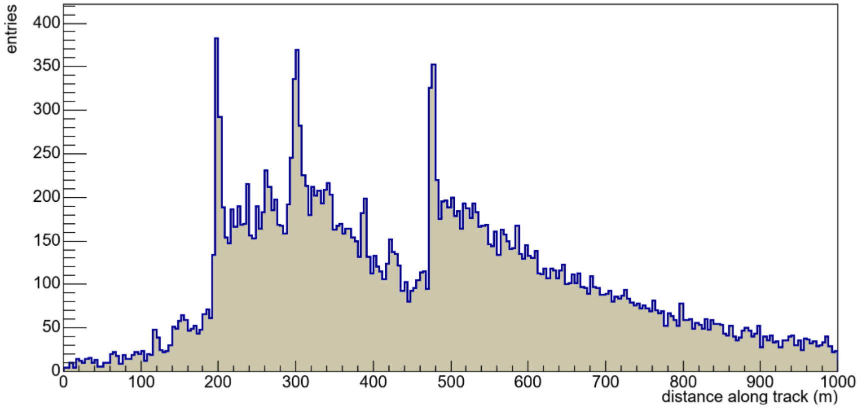
Source	ARCA trig [1]	ARCA (trig)	Baikal (trig)	$\frac{\text{Baikal}}{\text{ARCA}}$	Baikal (reco)	$\frac{\text{reco}}{\text{trig}}$
RX J1713.7-3946	20.0	17.9	11.4	0.64	2.3	0.20
Vela X	40.7	37.2	19.5	0.52	4.88	0.25
Vela Jr	25.6	23.7	13.6	0.58	2.83	0.21
HESS J1614-518 (1)	10.5	9.0	6.1	0.68	1.5	0.25
HESS J1614-518 (2)	9.1	8.4	5.2	0.62	1.2	0.23
Galactic center	7.0	5.5	3.9	0.71	0.93	0.24
MGRO J1908+06 (1)	4.1	3.5	1.6	0.46	0.31	0.19
MGRO J1908+06 (2)	7.1	5.8	3.1	0.54	0.80	0.26
MGRO J1908+06 (3)	8.3	6.7	3.8	0.56	1.0	0.28
NGC 1068	–	52.8	66.4	1.3	3.1	0.05
TXS 0506+056 (1)	–	5.8	3.4	0.59	0.97	0.29
TXS 0506+056 (2)	–	5.0	3.1	0.63	0.96	0.31

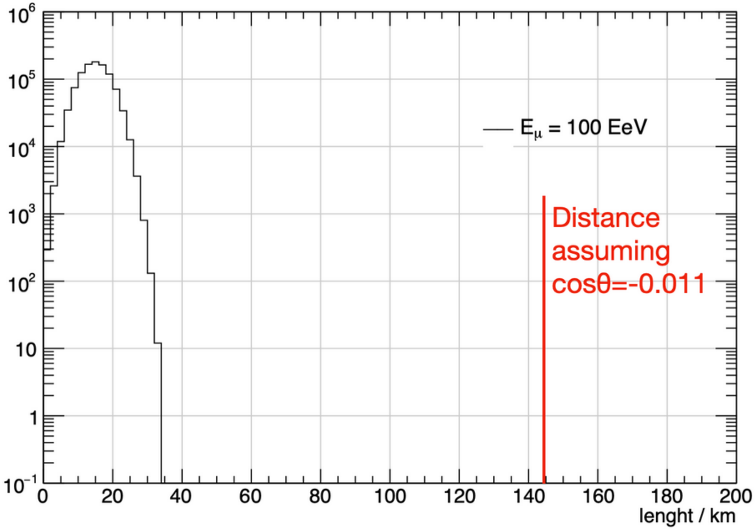
PHYSICS OF PARTICLES AND NUCLEI LETTERS Vol. 21 No. 4 2024

https://doi.org/10.1134/S1547477124700912

A PeV neutrino candidate event in KM3NeT/ARCA







A nearly horizontal muon

E > 10 PeV

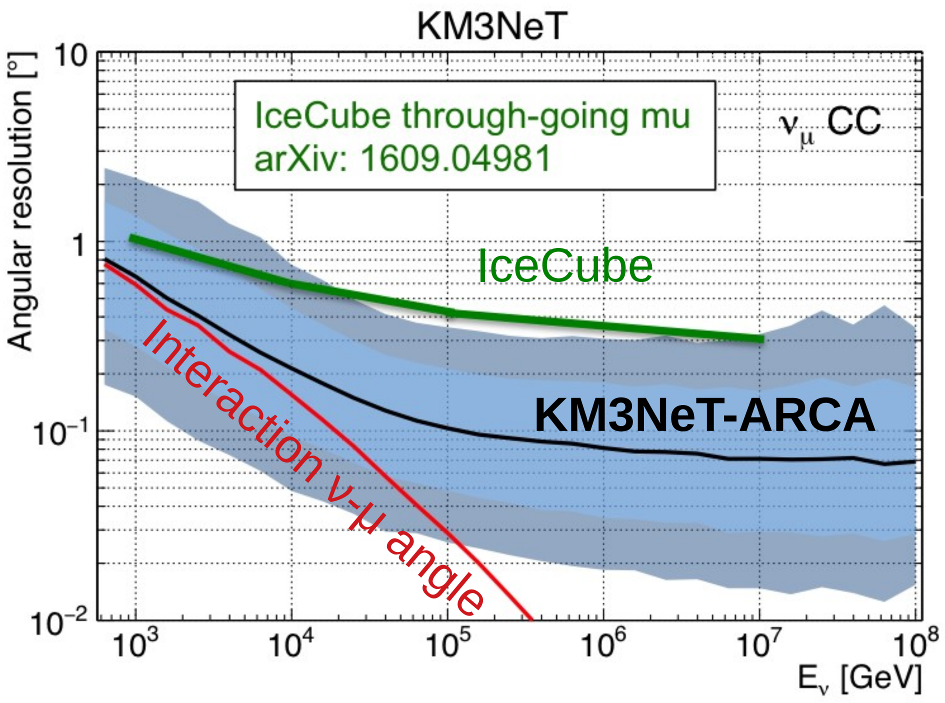
Event consistent with
a neutrino-induced muon

Atmospheric muon origin
disfavored

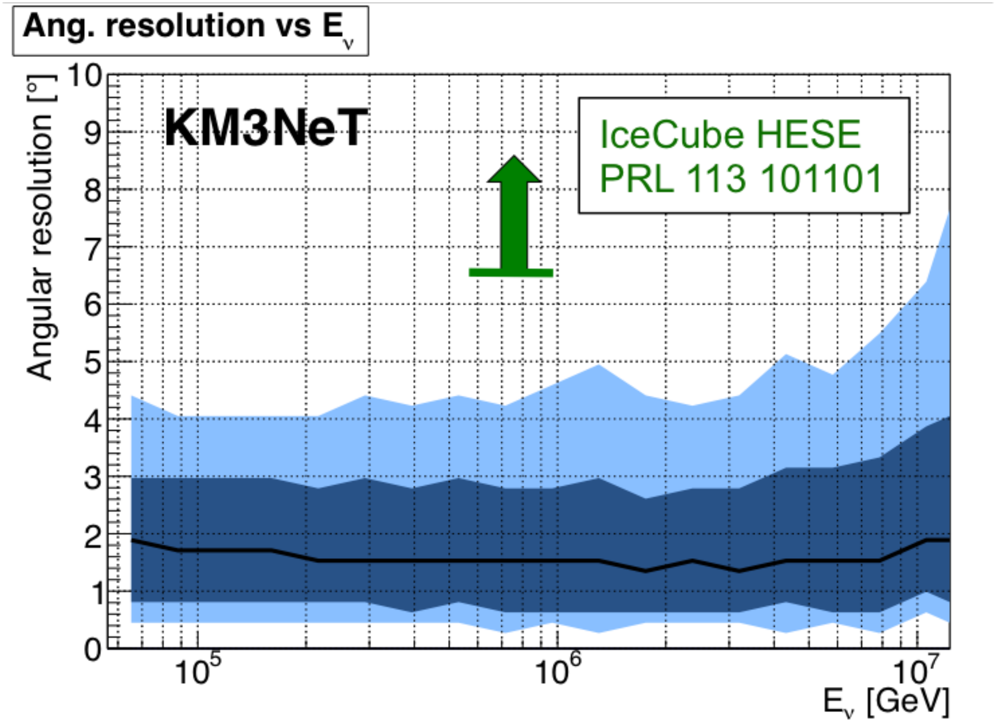
ICHEP'2024

ARCA - angular resolution

Tracks

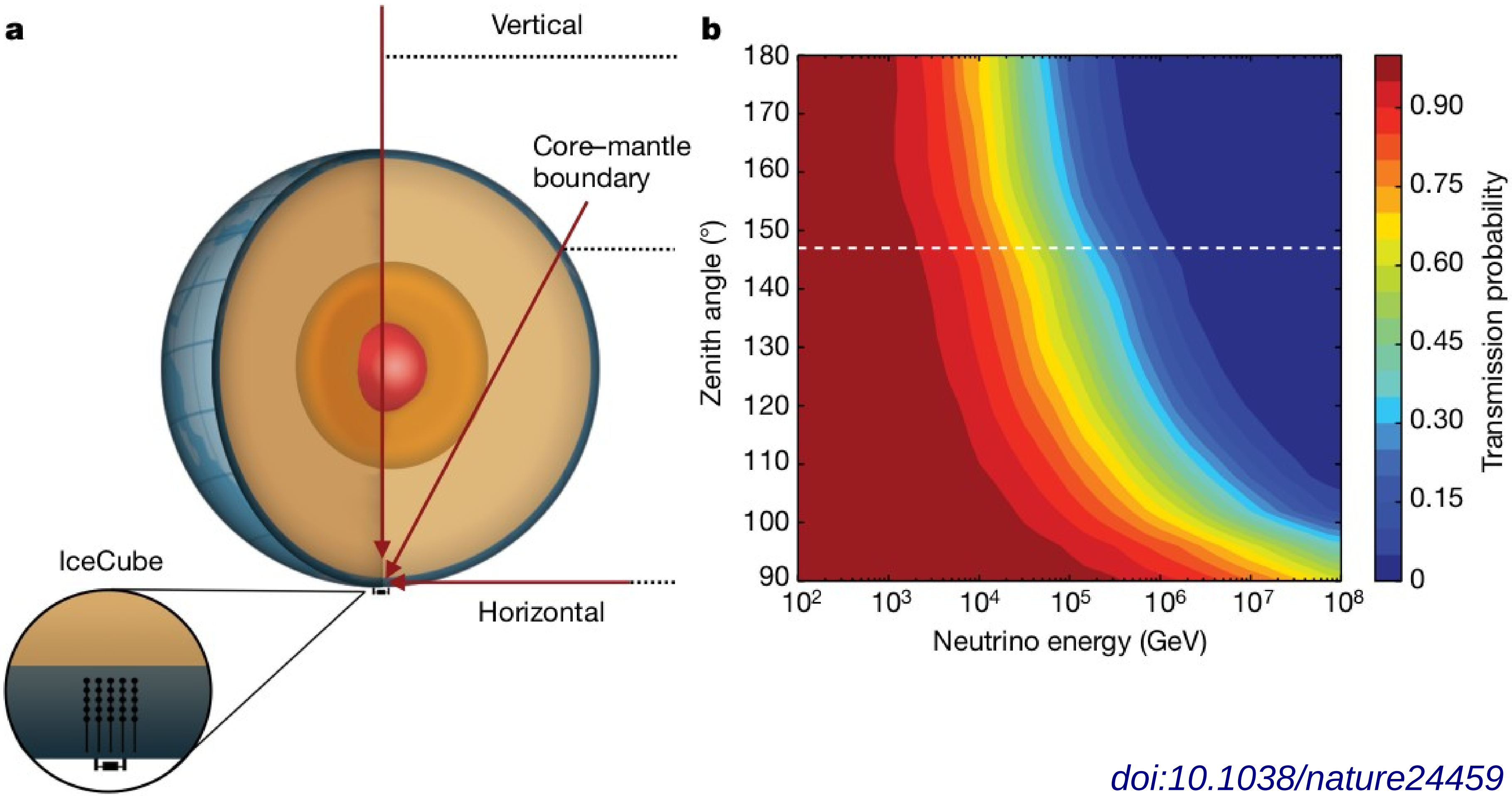


Showers



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

Neutrino absorption in the Earth



doi:10.1038/nature24459

Neutrino as astrophysical messenger

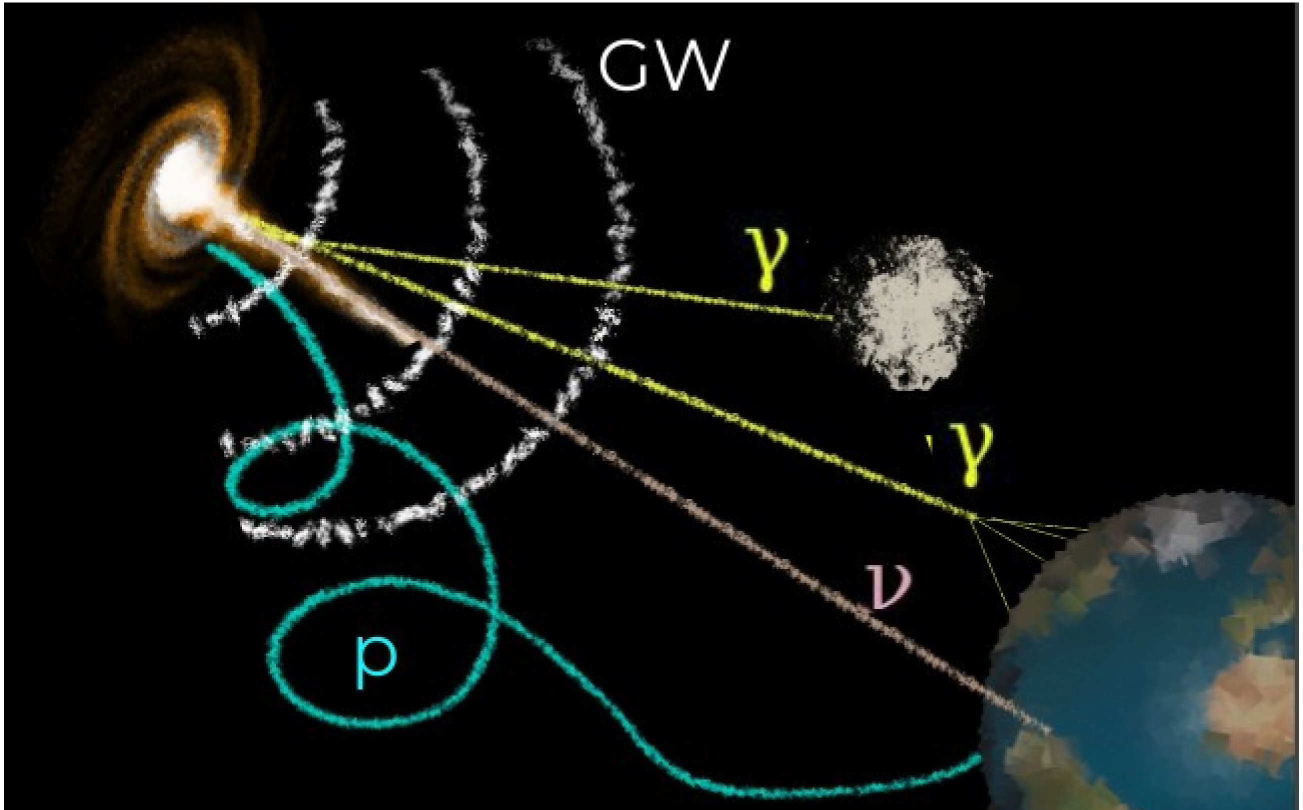


Image adapted from R. Ruiz

- 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

Neutrino production recipe

1) Accelerate protons (or heavier ions)

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*

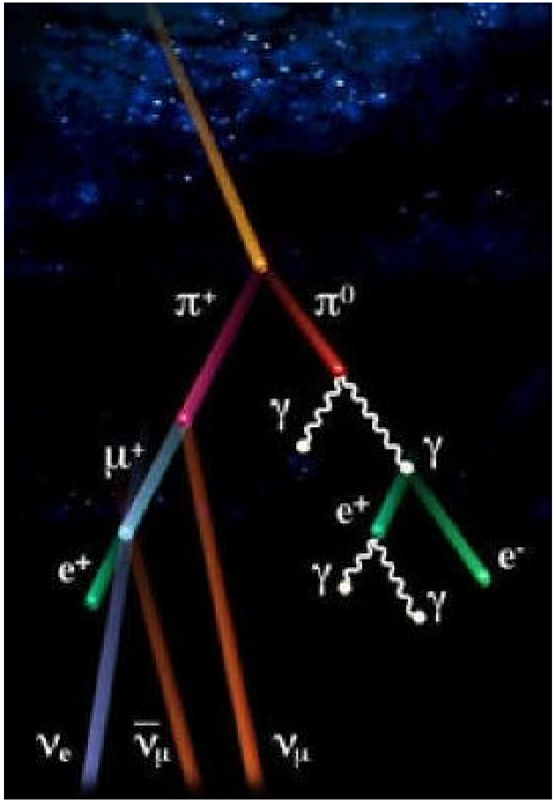


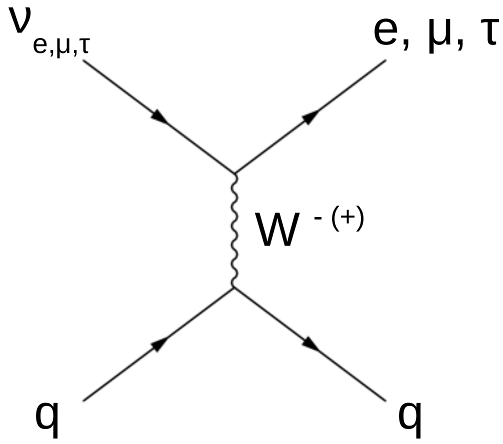
Figure from Relner et al, PRD (2008)

* Other hadrons also contribute

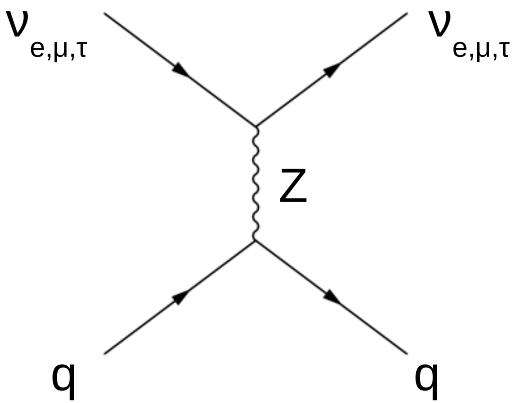
The sites where this processes occurs are under debate

Neutrino interactions at high energy

Charged current (CC)

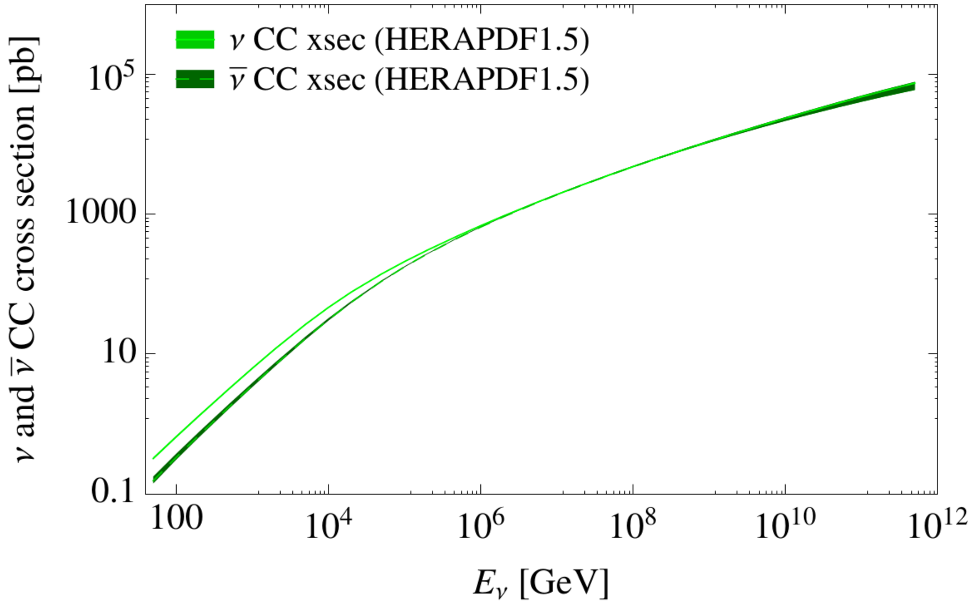


Neutral current (NC)



At high energies, the dominant process is deep inelastic scattering on quarks

Interaction probability rises with energy

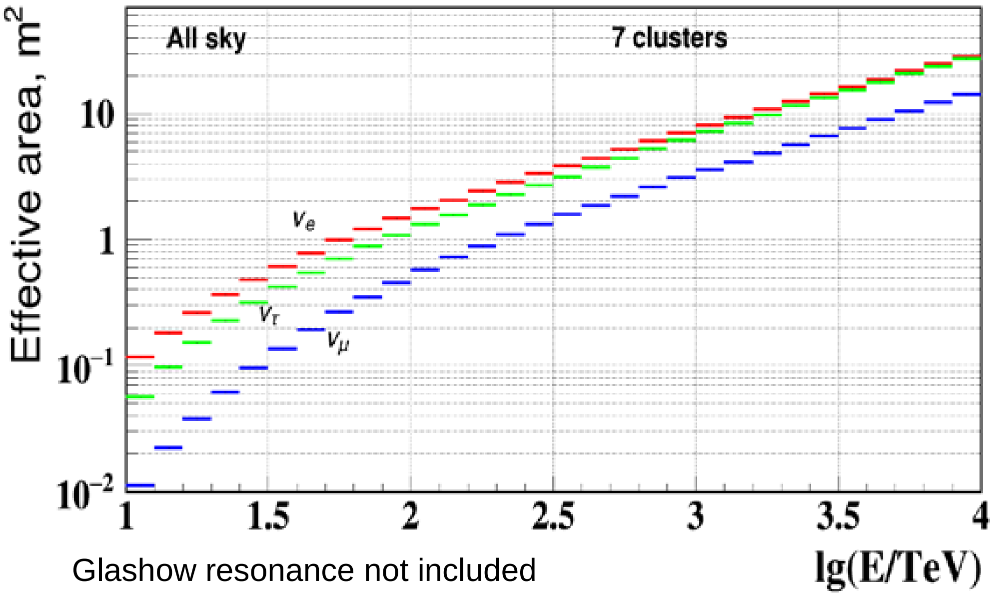


A. Cooper-Sarkar, P. Mertsch, and S. Sarkar, JHEP 2011, 42.

Cascade analysis : effective area and rates

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

neutrino effective area for cascade detection



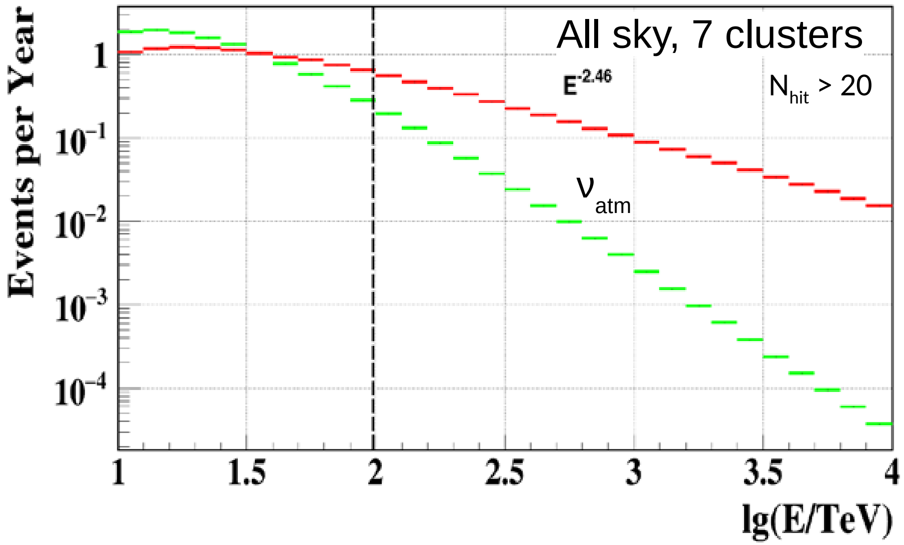
Glashow resonance not included

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

Assumption for astrophysical neutrino energy spectrum (IceCube fit):

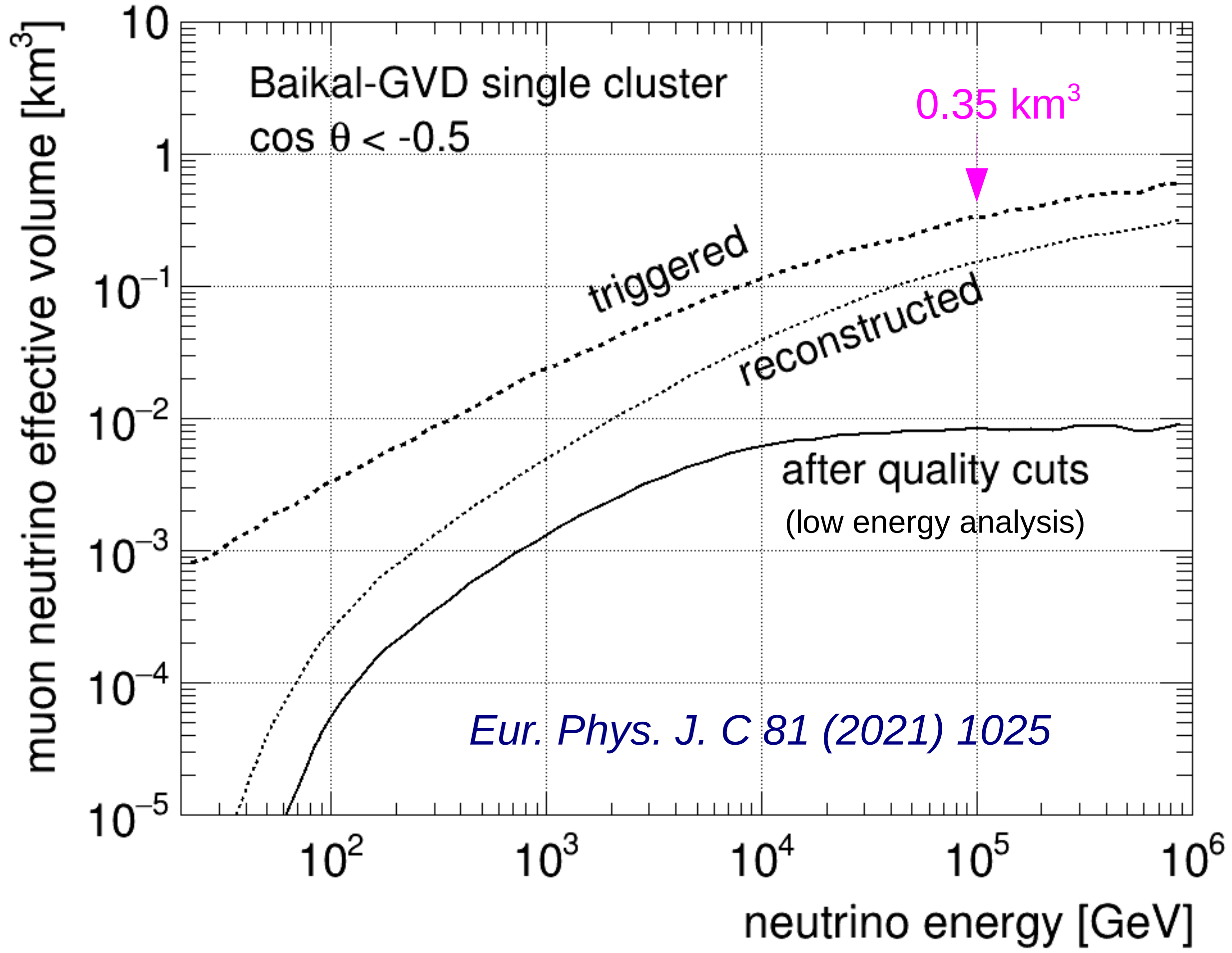
$4.1 \bullet 10^{-6}\ E^{-2.46}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

Expected number of cascade events per year



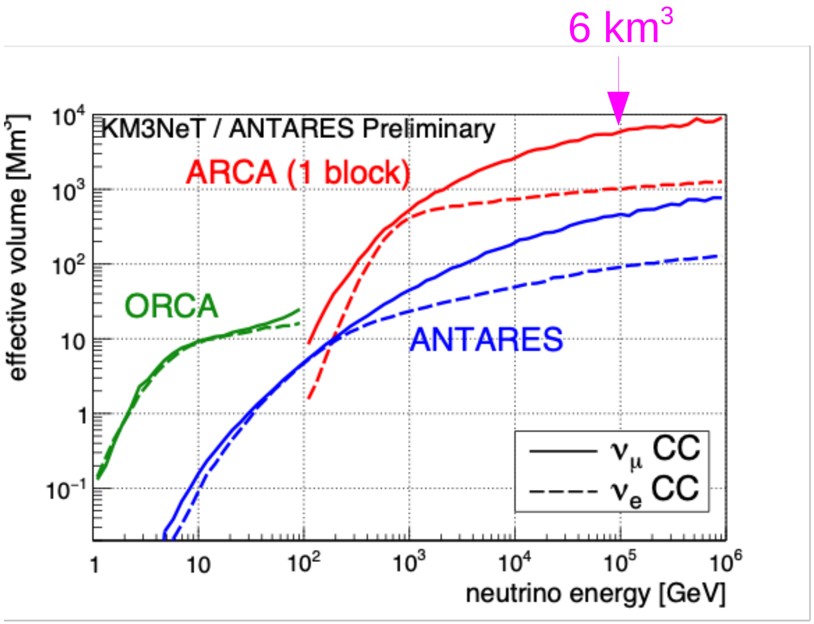
3–4 ev/yr with E_{sh}>100 TeV for 7 clusters

Neutrino effective volume for tracks (one GVD cluster)



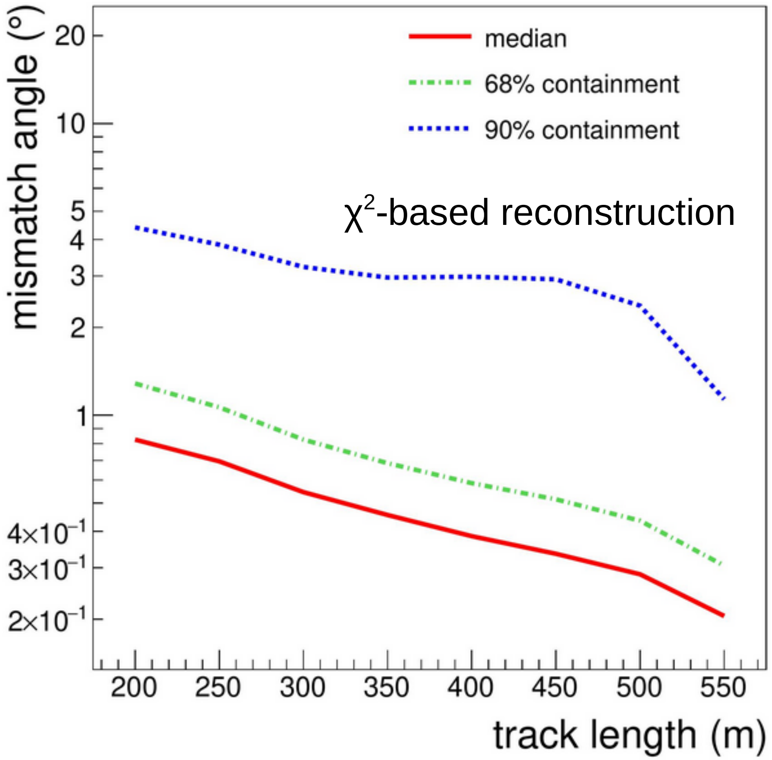
Energy threshold ~ 200 GeV (higher than in ANTARES)

Optimal for E > 100 TeV



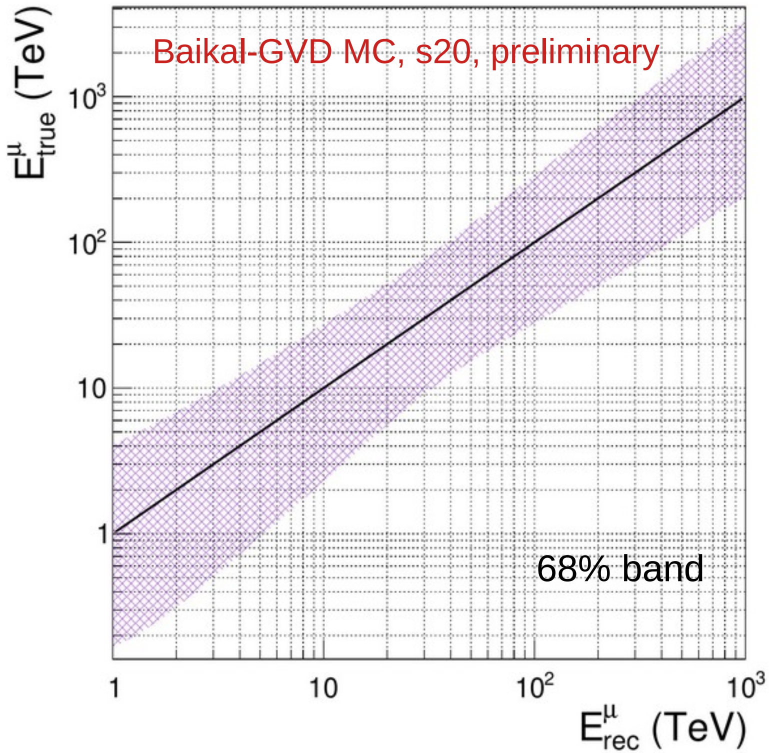
Expected performance for tracks

Angular resolution



Improvements expected from likelihood-based reconstruction (under development)

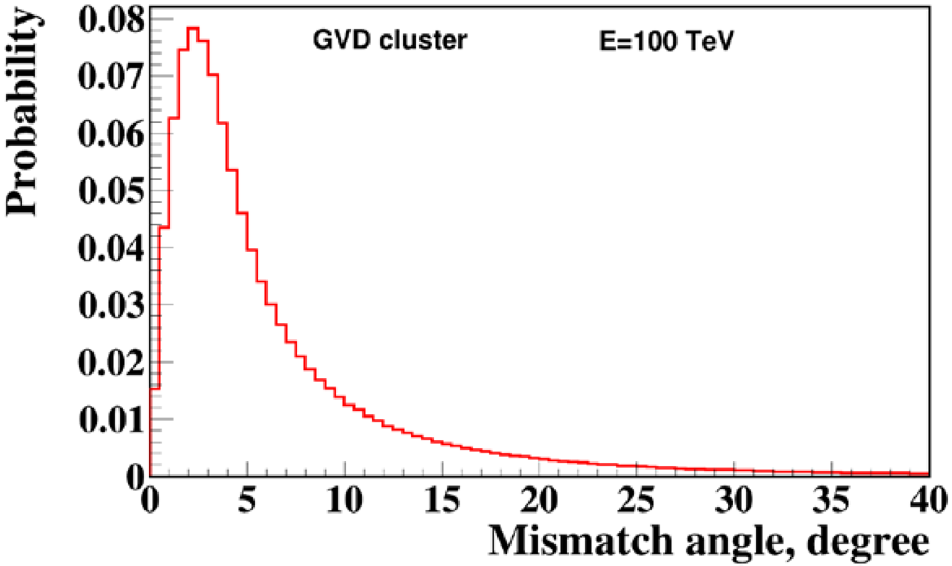
Energy reconstruction

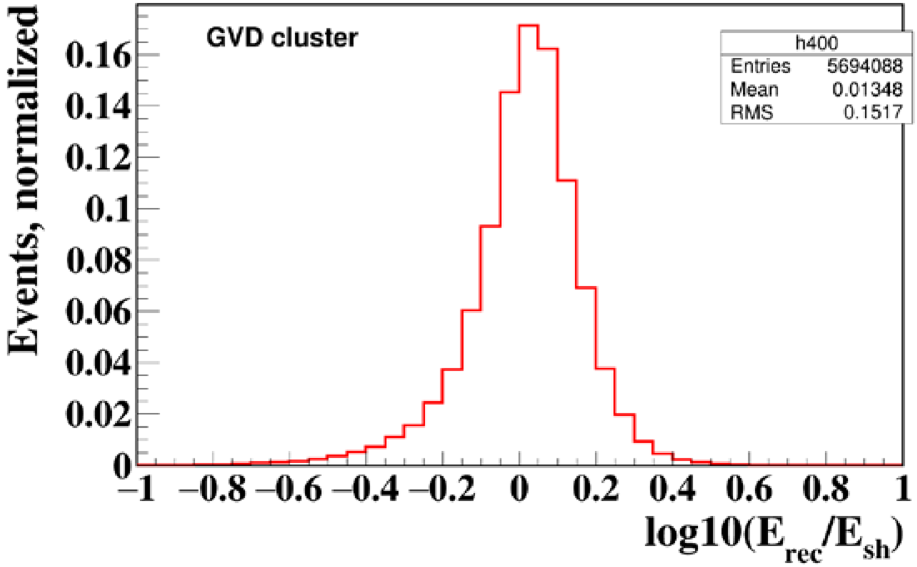


energy resolution ~ factor 3 at E ~ 100 TeV (±34% containment band)

G. Safronov et al. @ ICRC 2021 & ICRC 2023

Cascade analysis performance





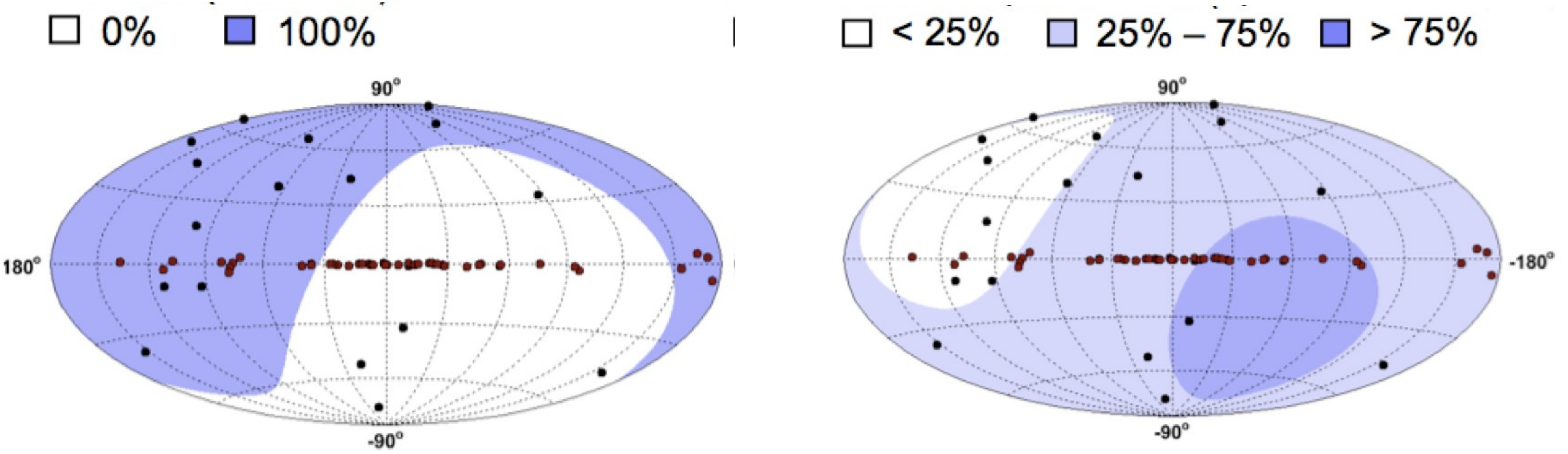
Directional resolution for cascades:
median mismatch angle ~ 4.5°

Energy resolution : δE/E ~ 10 – 30%

Sky visibility with upgoing tracks

South Pole (IceCube)

Northern hemisphere: Mediterranean



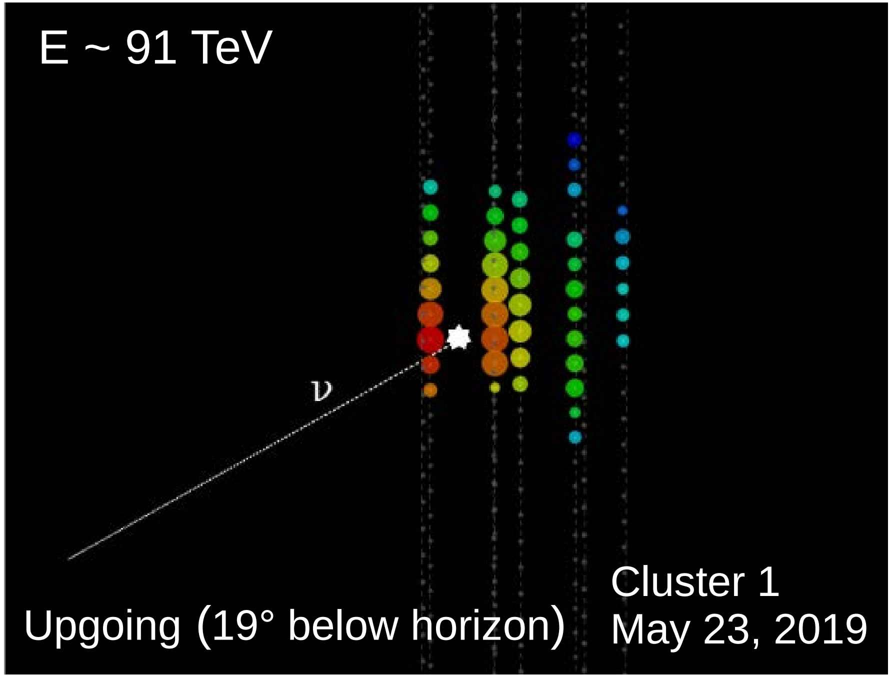
Complementary sky coverage

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

Upward-going cascade #1

Preliminary

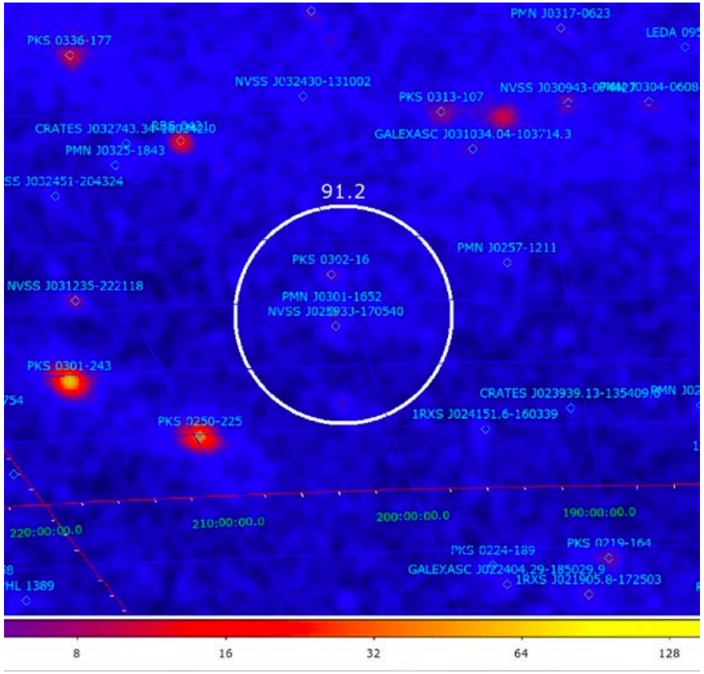
GVD2019_1_114_N



Contained event (50 m off central string)

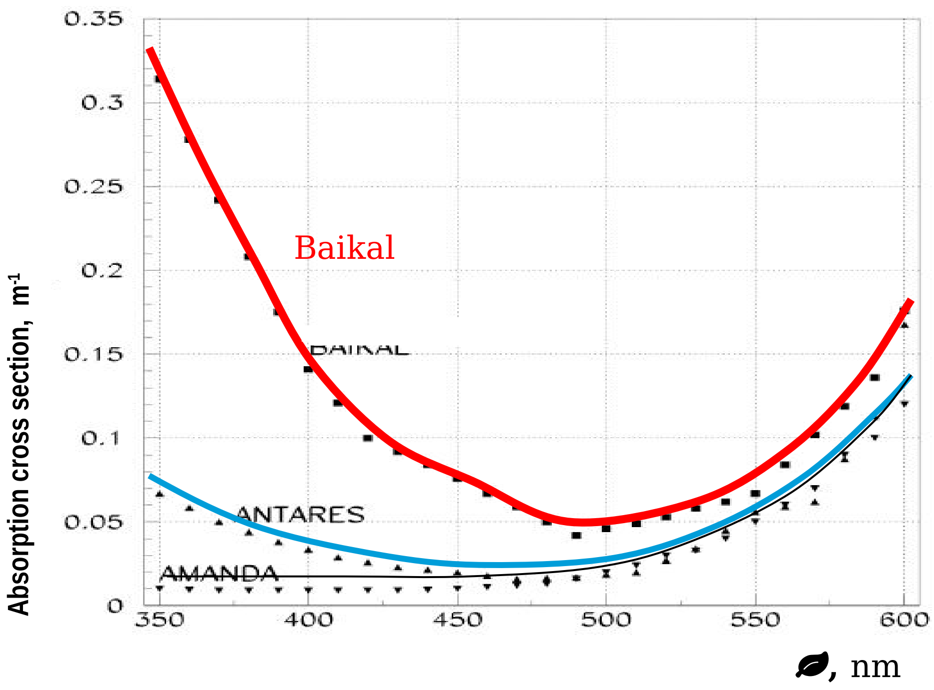
Excellent candidate for a neutrino event of astrophysical origin

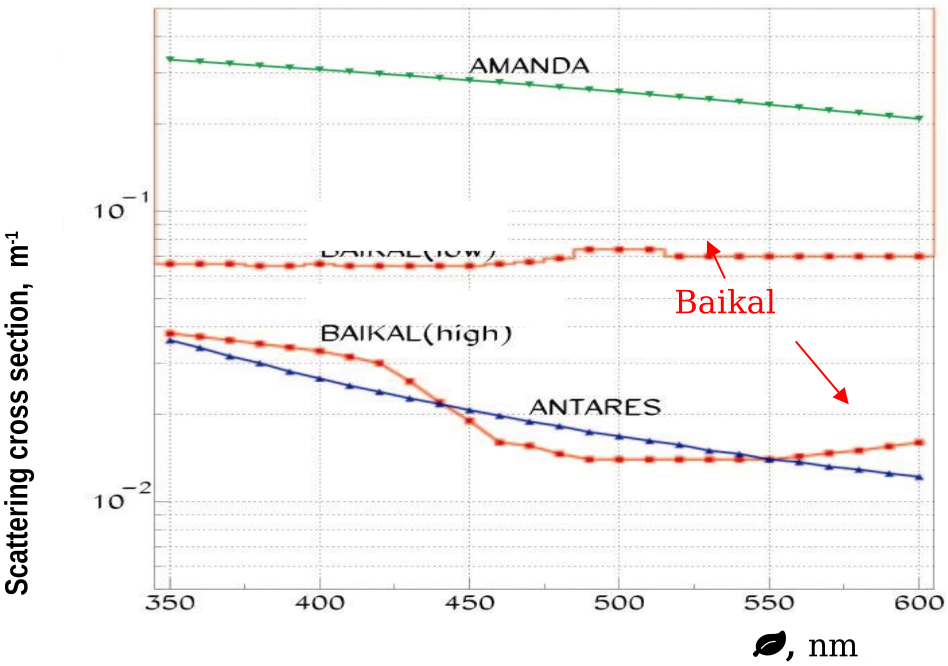
Sky plot of γ-ray sources
(credit: D.Semikoz, A.Neronov)



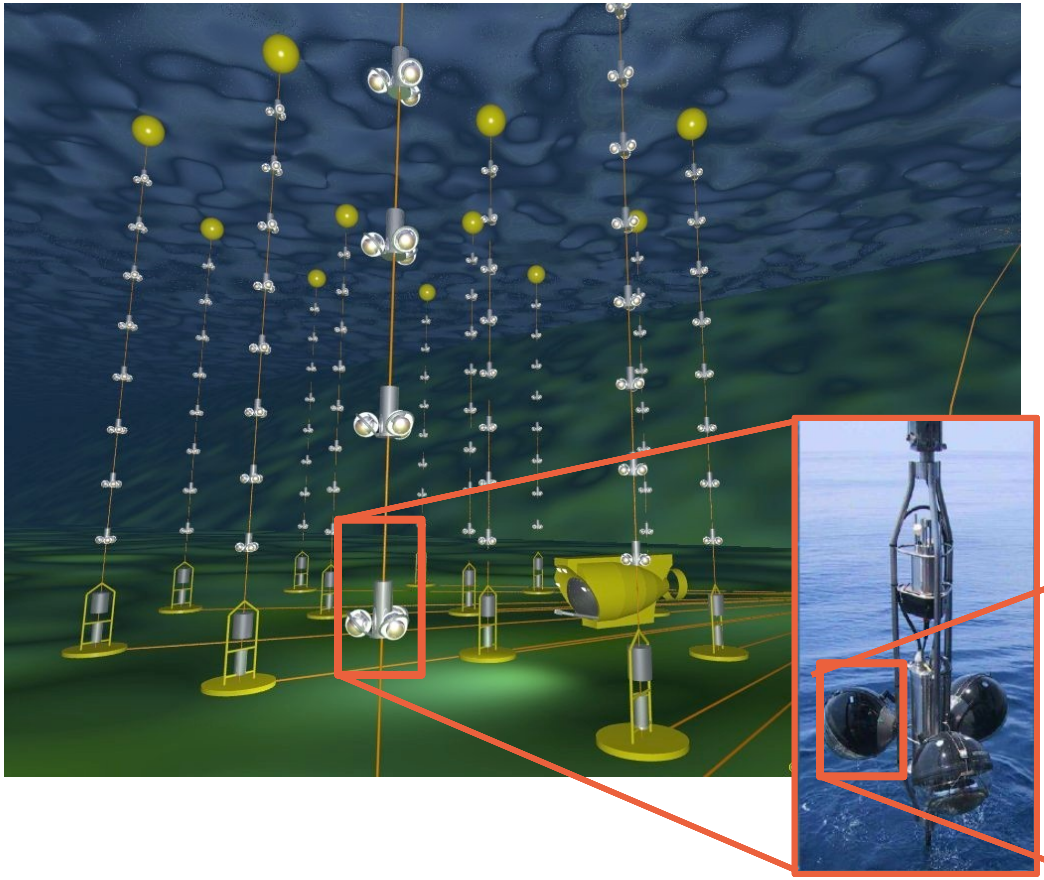
known sources in 3 degree circle:
PKS 0302-16 : unknown type of source
PMN J0301-1652 : unknown type of source

Water optical properties





ANTARES in Mediterranean sea



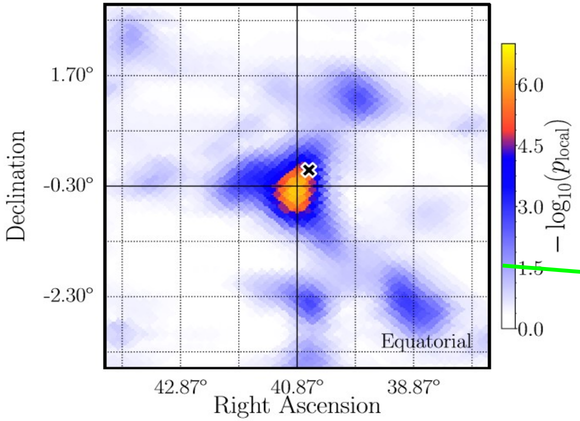
- 40 km offshore Toulon, France
- 2.5 km depth
- 885 optical modules on 12 strings
- ~ 12 Mton instrumented volume

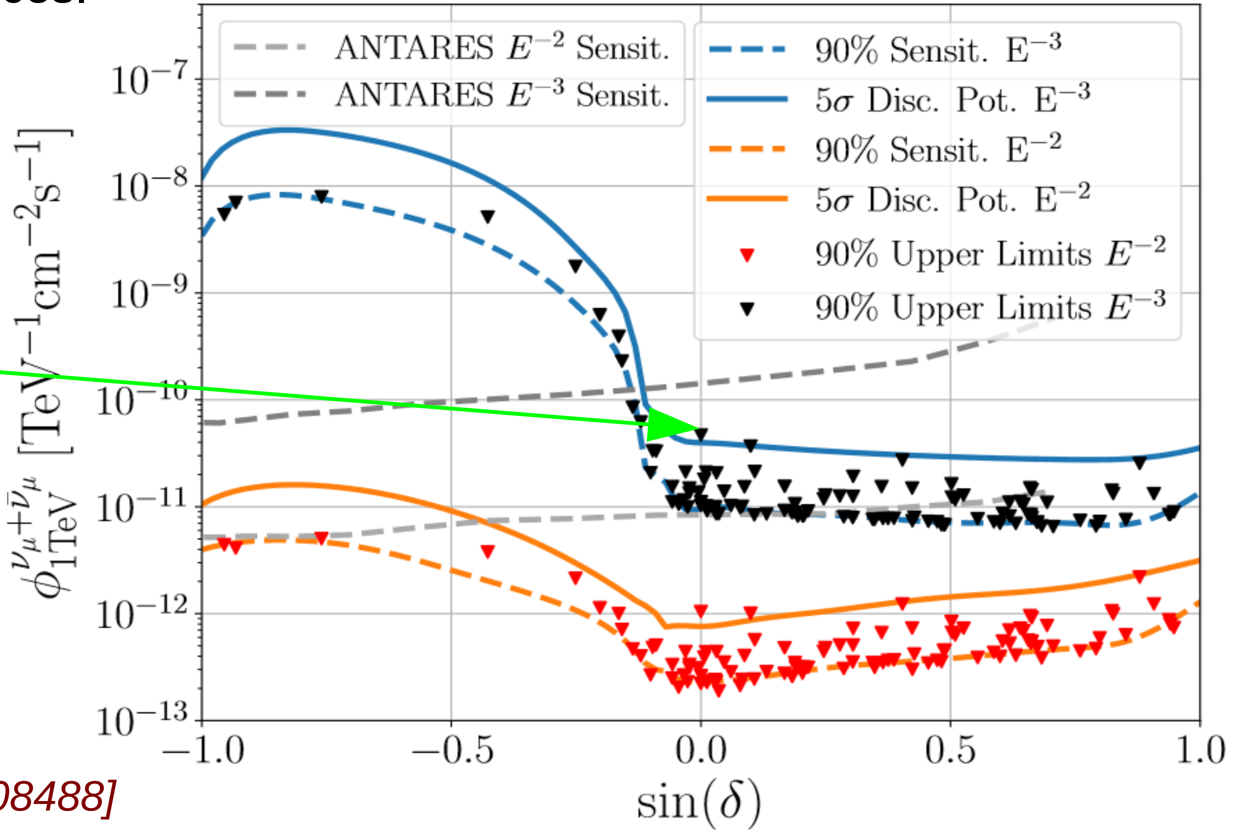
ANTARES OM:
10” Hamamatsu PMT

- 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]