# Anatomy of large-volume neutrino telescopes

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17th Baksan school on particle astrophysics
April 3-11 2025, Terskol

# Development of large-volume neutrino telescopes

Initial idea: M.A. Markov 1960

Development of large-volume telescopes was initiated with DUMAND project at Hawaii in 1975 followed by projects at Baikal, South Pole and Mediterranean

Technically difficult process of detector deployment

First proof-of-concept with detection of upgoing atmospheric neutrino happened in mid-1990s at Baikal

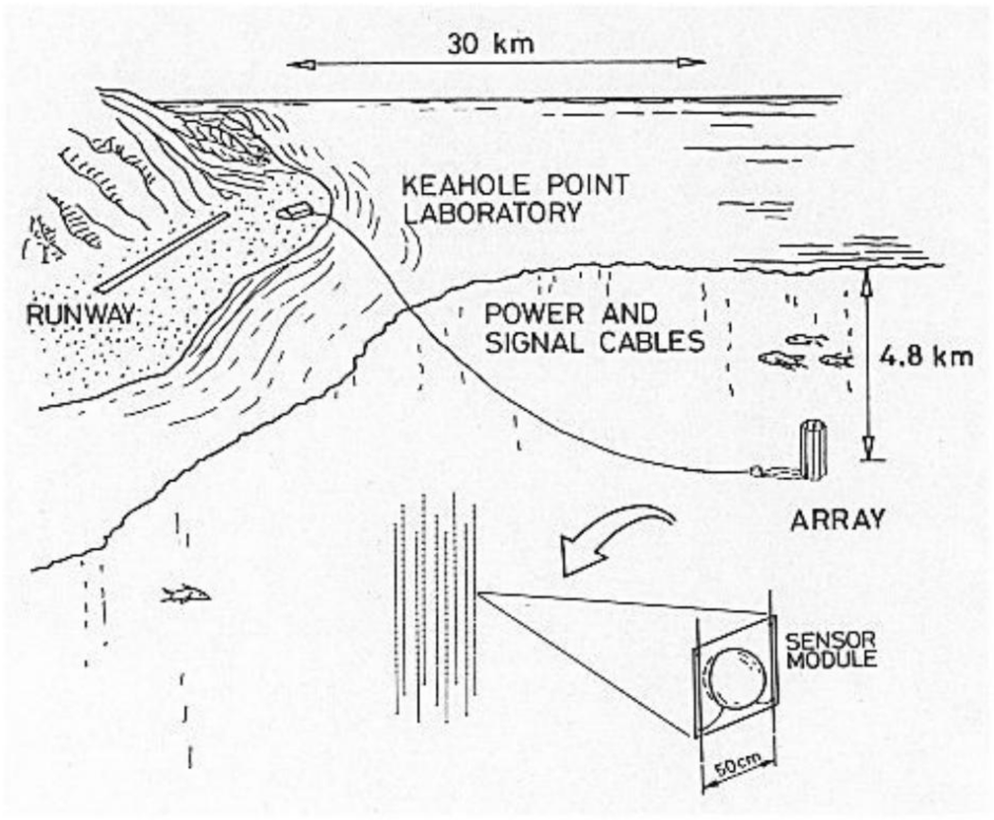
Observation of astrophysical neutrino flux in 2013 at South Pole

# First steps of large-volume neutrino telescope projects

# DUMAND

Deep Underwater Muon And Neutrino Detector

4800 m depth at Hawaii shore




Initiated as a series of meetings starting in 1973

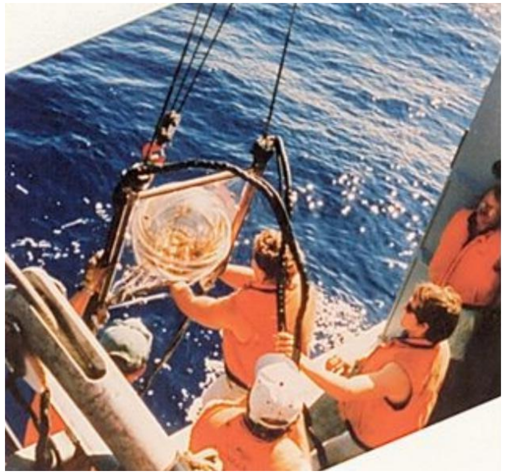
Inital suggestion: 1.23 km$^3$ array

Project funded in 1980

Many conferences in 1970 paved the way for underwater telescope components design

Sucessfull prototype test in 1987
Atm. muon flux observed

Project terminated in 1995



useful reading: **A. Roberts "The birth of high-energy astronomy: A personal history of the DUMAND Project", Rev. Mod. Phys. 64, 259 (1992)**

# Baikal

First operations on Lake Baikal started in 1980

- Leading role of INR RAS LNAHE laboratory led by Grigory Domogatsky

Platform "106km" Circum-Baikal railway was chosen as a site for future neutrino telescope

Features of the location:

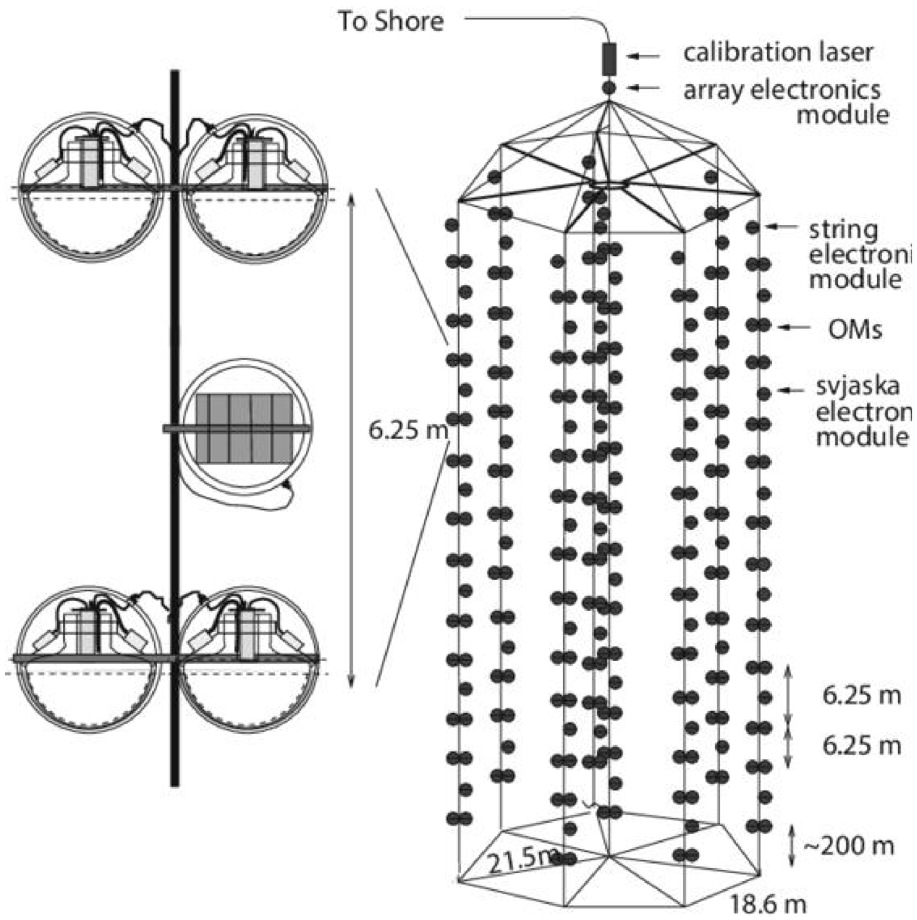
- Deepest fresh water lake in the world
- Clean and transparent water
- Railroad access
- Thick ice cover for 1.5 months each year allows detector deployment and maintenance

Depth: ~ 1370 m
Absorption length: ~ 22 m

# Baikal

NT-200: first full-scale large-volume neutrino telescope

Fully-deployed in 1998, later upgraded to NT-200+ with additional strings



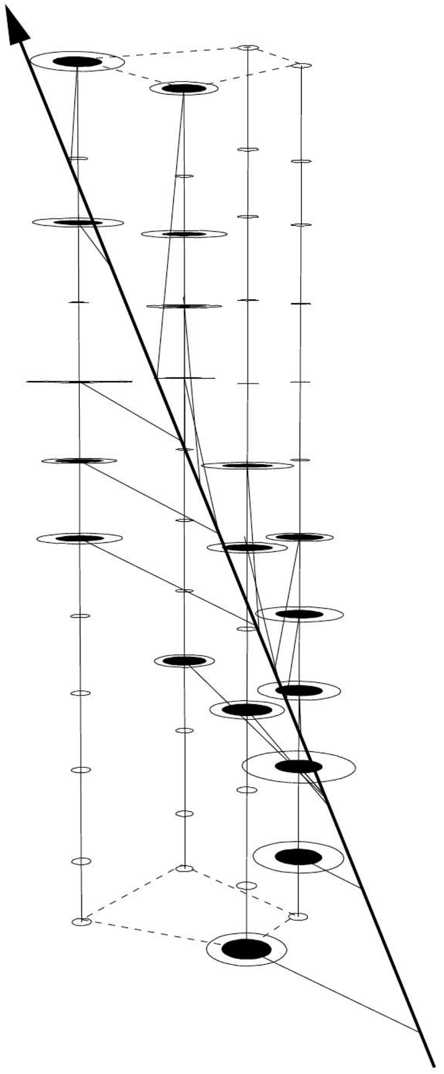

First-ever upgoing muon events detected by unaccomplished 3-string detector in mid 1990-s (NT-36, 96)

- Succesfull proof of principle

Rather small detector

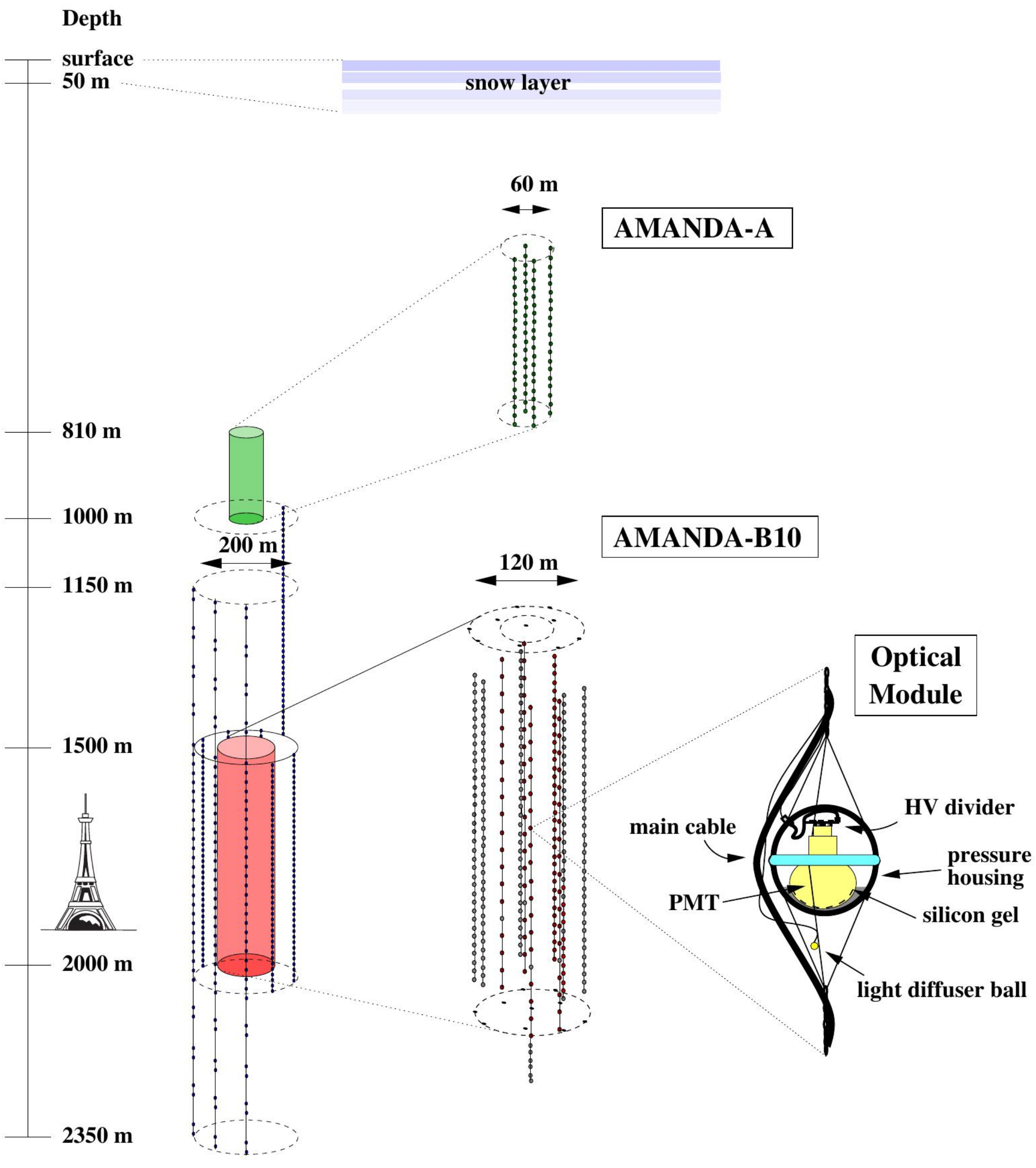
- Height: 72m
- Diameter: 43m

**Instrumented volume: ~100 kt**



One of the first neutrino candidate events
NT-96, 1996
**[arXiv:astro-ph/9705244]**

# AMANDA




AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

End of 1980: idea to build
telescope in Antarctic Ice Shield
F. Halzen and J.G. Learned “High energy neutrino detection in deep polar ice” (1988)

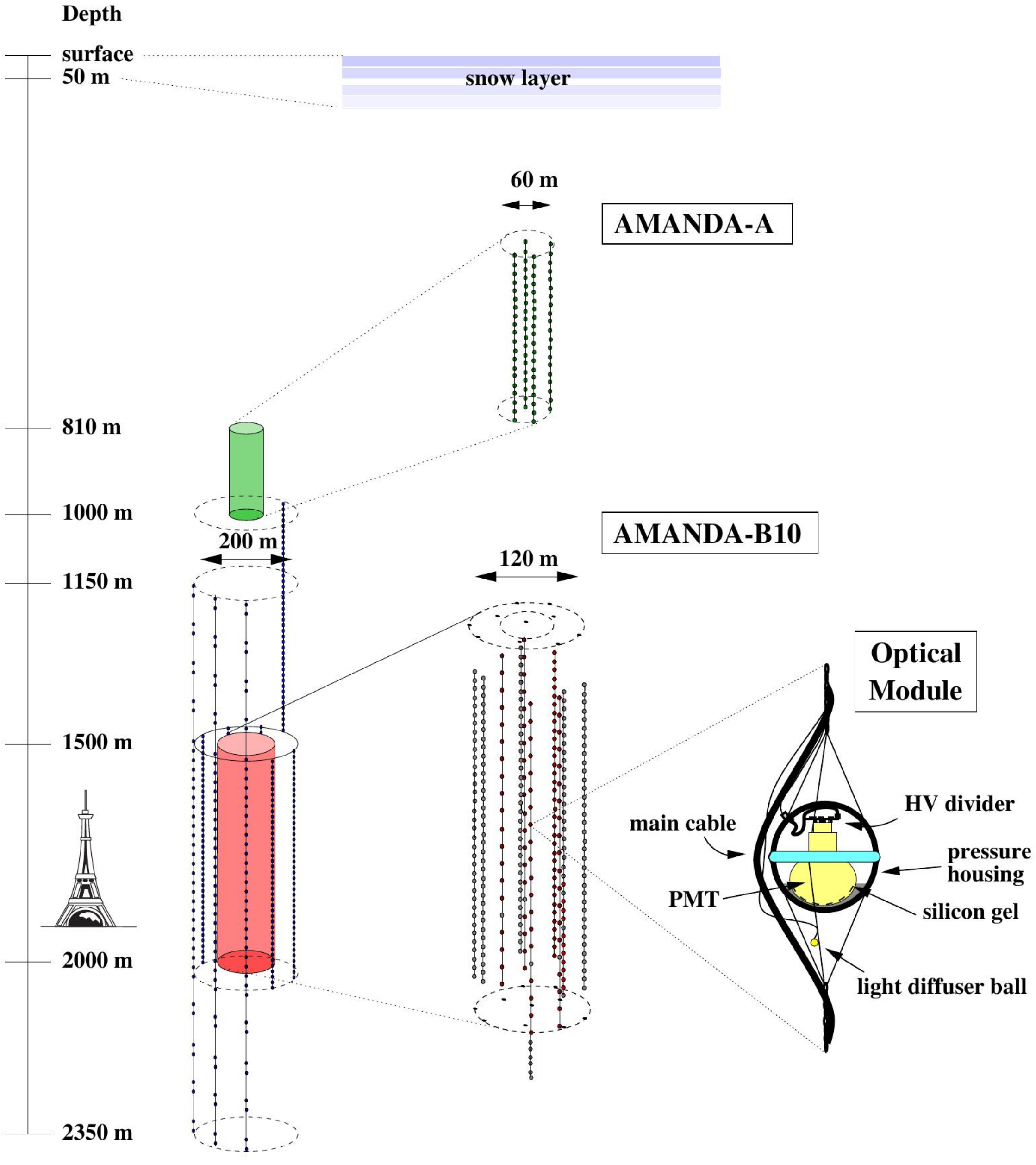
First tests of PMTs in polar ice in 1991

First array at 800-100m depth in 1993/94: AMANDA-A
- Discovered too strong light scattering

Array at 1500-2000m gradually contructed until 2000

**Instrumented volume: ~6 Mt**

# AMANDA

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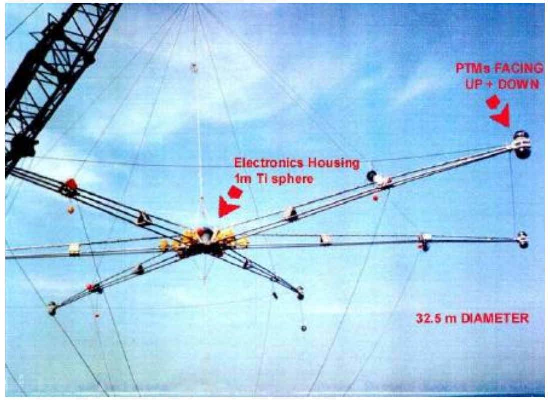
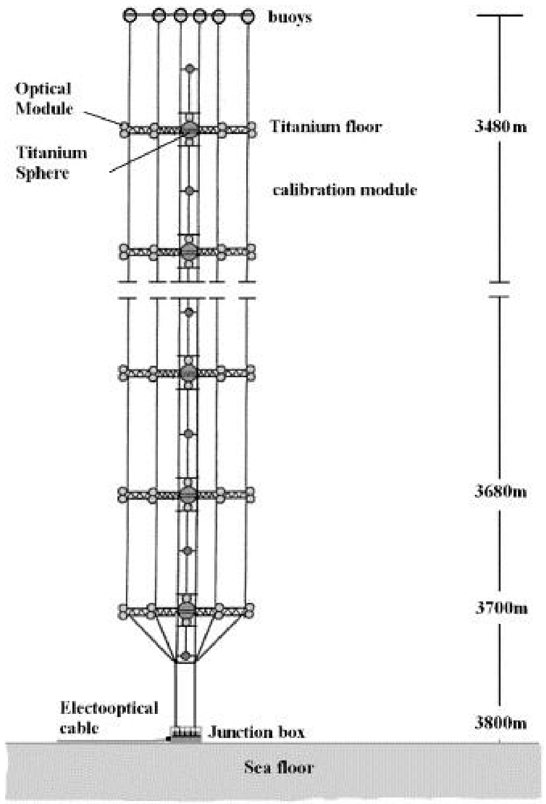
Basis for the IceCube neutrino telescope

Useful fictional reading:
**Mark Bowen "The telescope in the ice"**
**(available in Russian)**

# Mediterranean projects

**NESTOR** tower




Efforts to build large neutrino detector in Mediterranean sea started in late 1980s

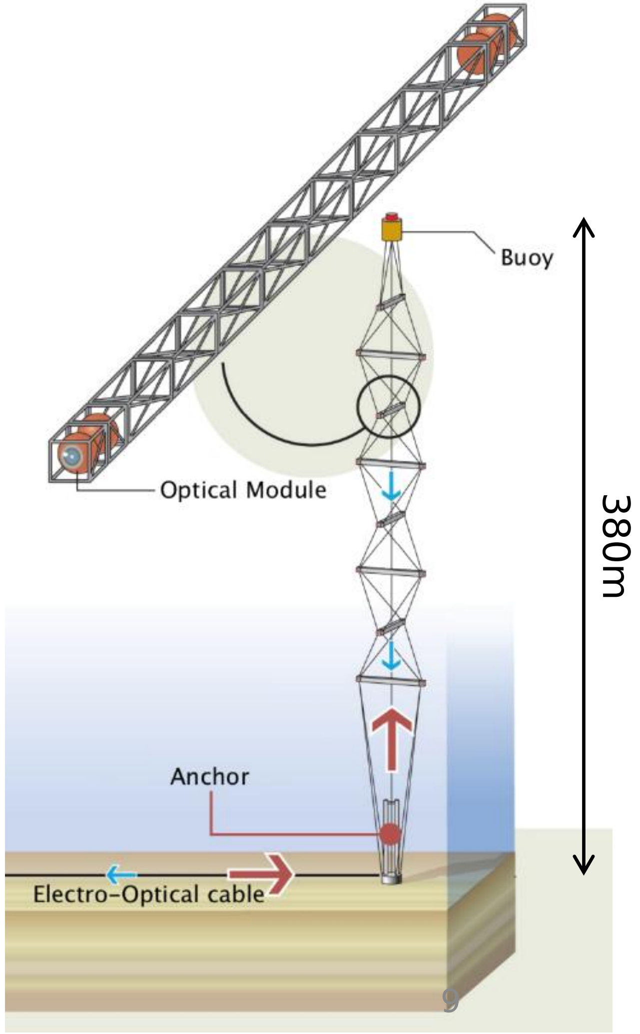
**NESTOR** project (near Greece), first project in Mediterranean

- Sea surveys in 1989, 1990s, conferences
- Tests of principal components, e.g. string with 5 15-inch PMTs in 1992
- One floor of a tower prototype deployed in 2003 at 4000m depth and took data for 1 month

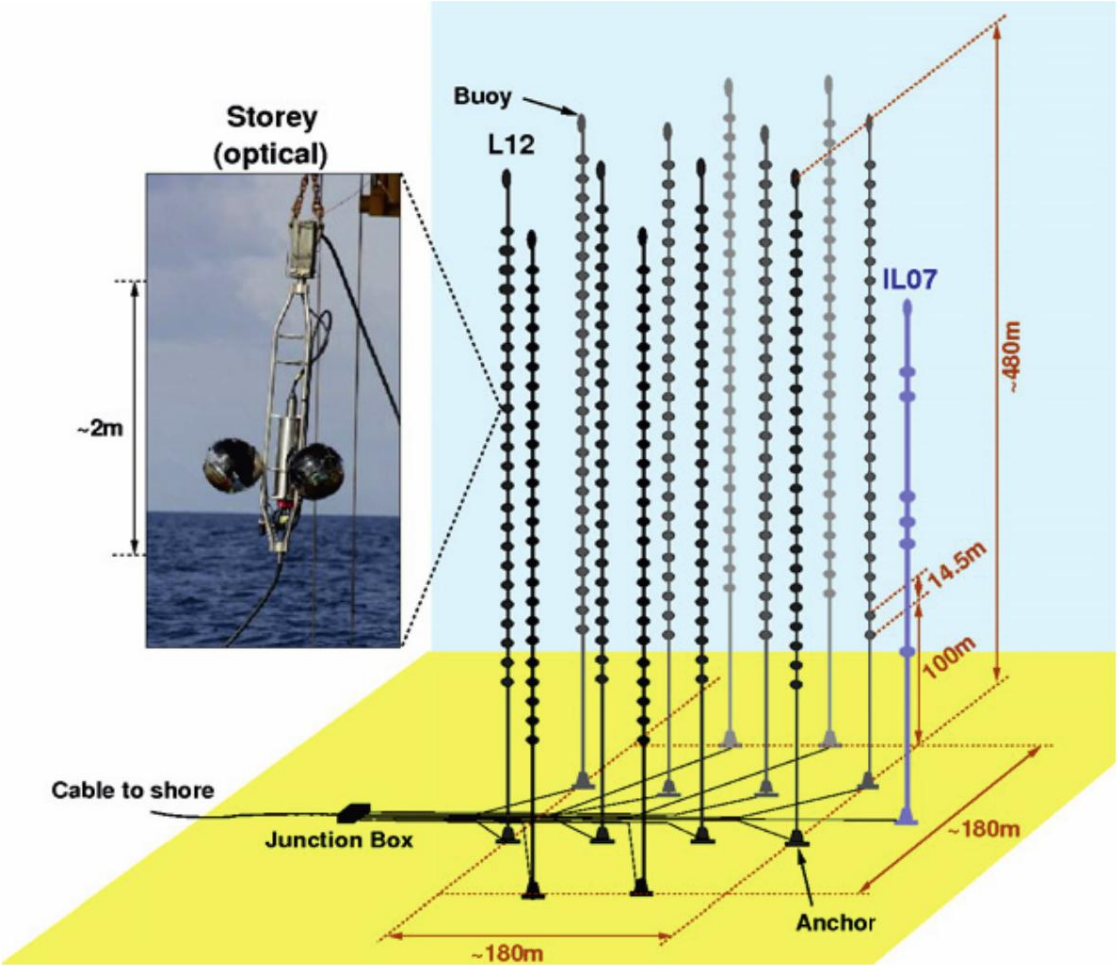
**NEMO** project (South Italy):

- Started in 1998
- First prototype in 2007
- Nemo Phase 2 deployment in 2013
- 1 year operation at record depth of 3500m

**NEMO** Phase II
depth 3500m



# ANTARES




**depth: 2475m**

Proposal in 1999
Started full-scale operation in 2008
Shut down in 2022

12 strings with 25 “storeys”
Each storey holds 3 PMTs

**Instrumented volume: ~12 Mt**

ANTARES was a succesfull project although not reaching volume required for astrophysical neutrino detection

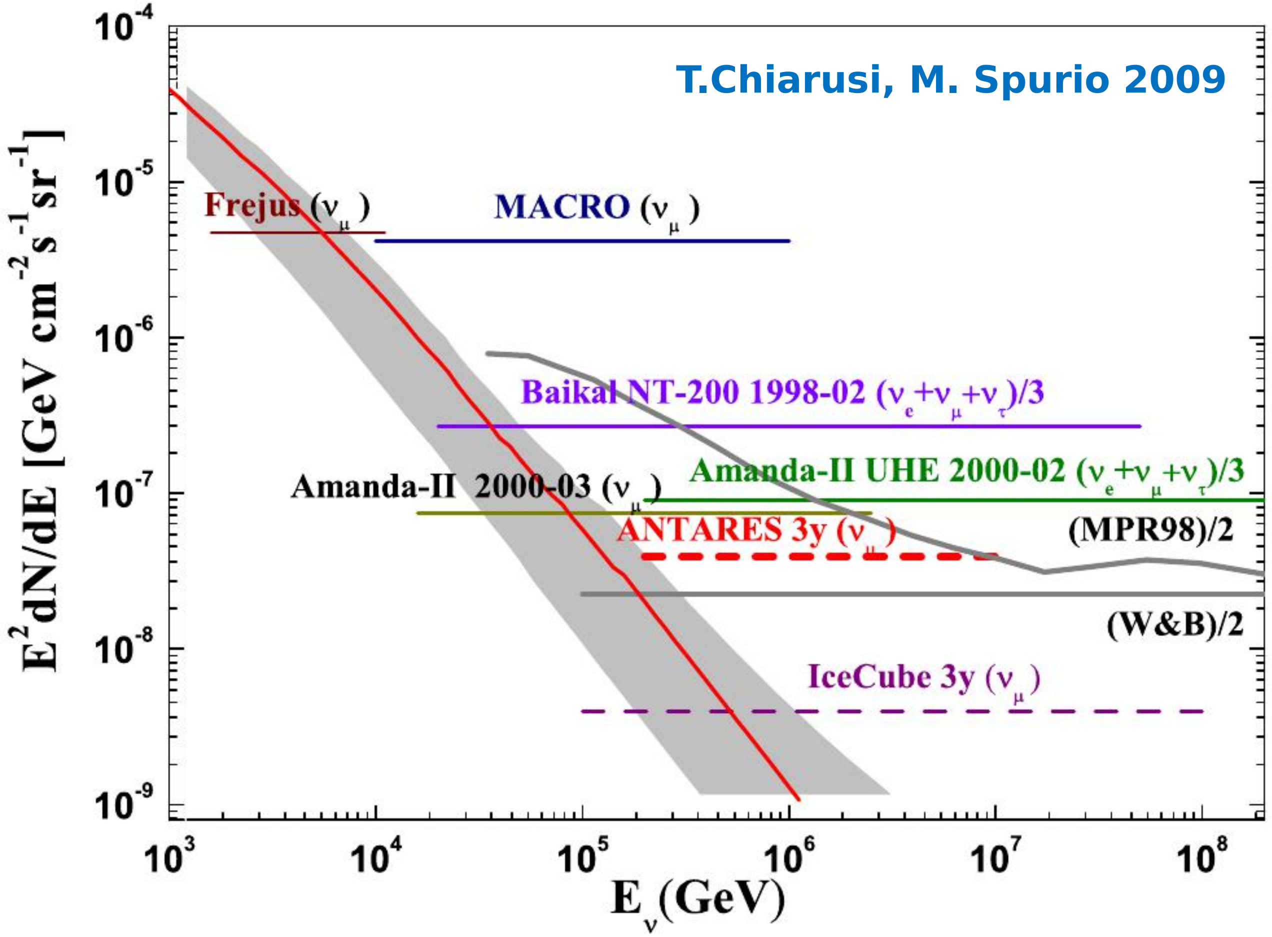
# Selected experimental results

# Approaching the neutrino diffuse flux

First diffuse flux constraints

First constraints on diffuse flux:
- Baikal-GVD (1998)
- AMANDA (2000)

Flux discovery by IceCube in 2013




Sensitivities from ANTARES and IceCube are shown in dashed lines

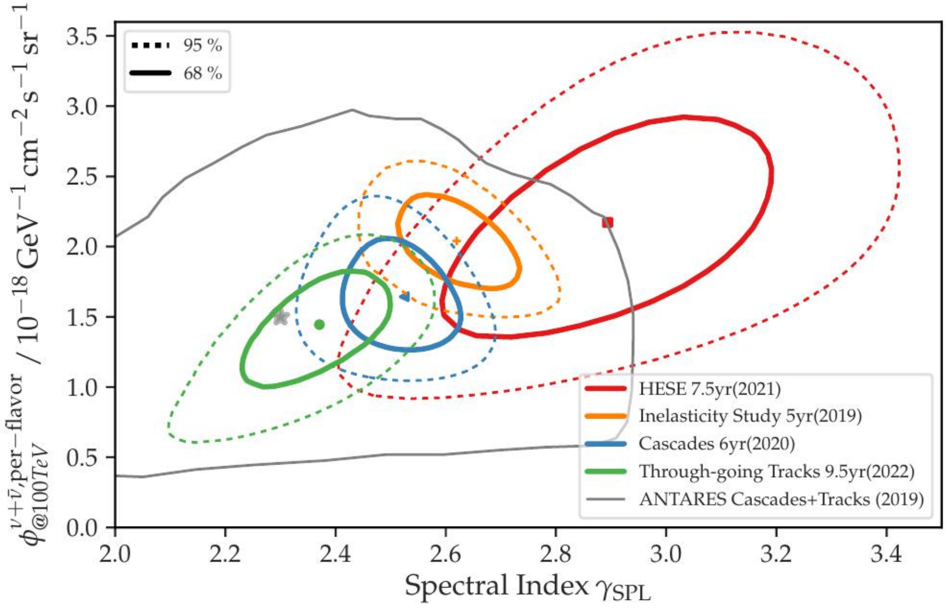
# Diffuse neutrino flux

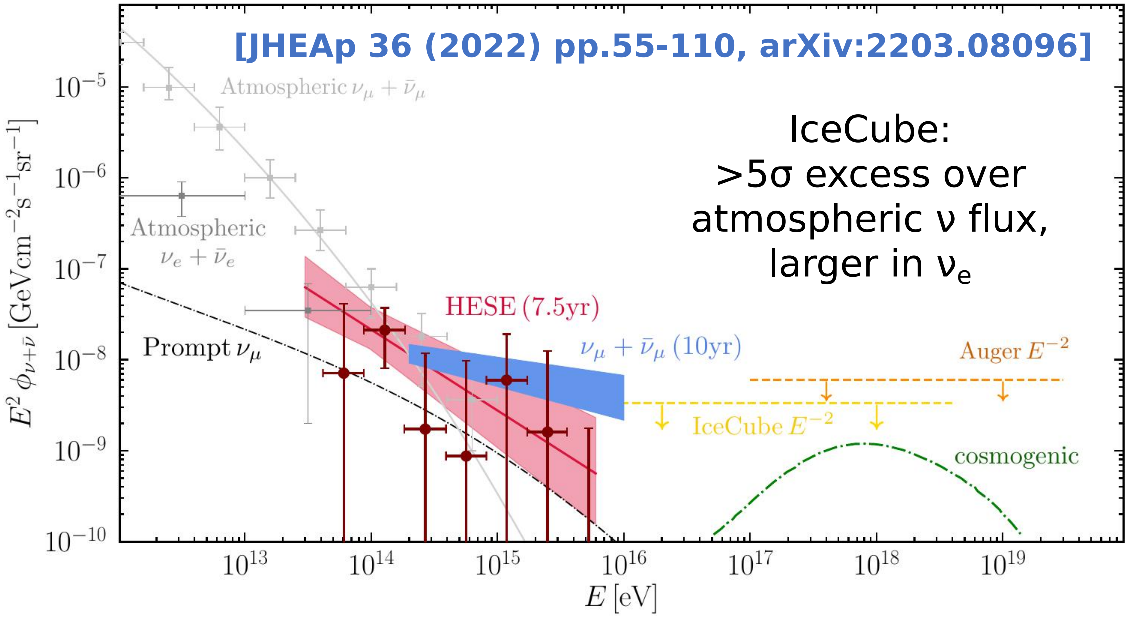
Presently the presence of TeV - PeV diffuse astrophysical neutrino flux is established by the IceCube with significance well above 5σ (e.g. [Astrophys.J. 928 (2022) 50, arXiv:2111.10299] )

Neutrino energy spectrum is usually fitted as one-component power law:

$$\phi_{\nu+\bar{\nu}} = \phi_0 (E/E_0)^{-\gamma_{SPL}}$$

[JHEAp 36 (2022) pp.55-110, arXiv:2203.08096]




Different powers for different IC analyses and event sets: ~ **2.3** < $\gamma_{SPL}$ < ~**2.9**

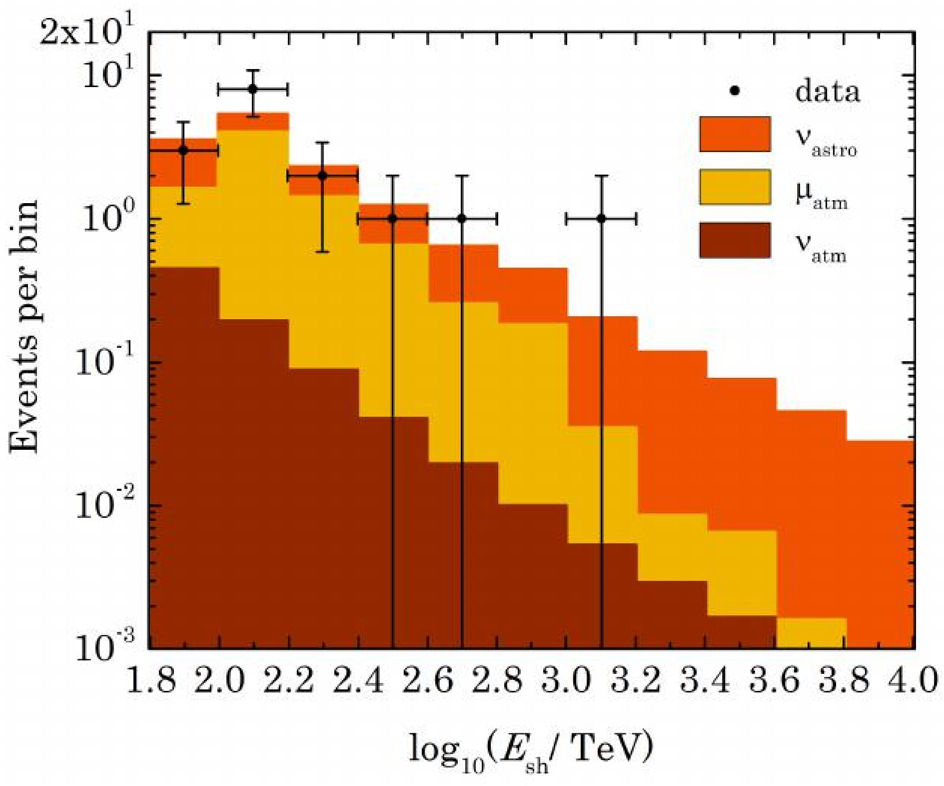
ANTARES data: excess significance 1.8σ
[PoS(ICRC2019)891]

# Diffuse neutrino flux: Baikal-GVD

Most of the Baikal-GVD data were processed with HE cascade analysis algorithms

**Four years dataset: 04.2018 - 03.2022**

14328 events $E_{sh}$>10 TeV, $N_{hit}$ > 11 after quality cuts




**All-sky analysis:**

- $E_{sh}$ > 70 TeV, $N_{hit}$ > 19
- 16 events were selected
- 8.2 background ev. expected
  - 7.4 $\mu_{atm}$, 0.8 $\nu_{atm}$
- 5.8 $\nu_{astro}$ ev. expected
- Largest energy event: ~1.2 PeV

All-sky diffuse flux significance: 2.22σ

Phys.Rev. D 107, 042005 (2023)

# Diffuse neutrino flux: Baikal-GVD

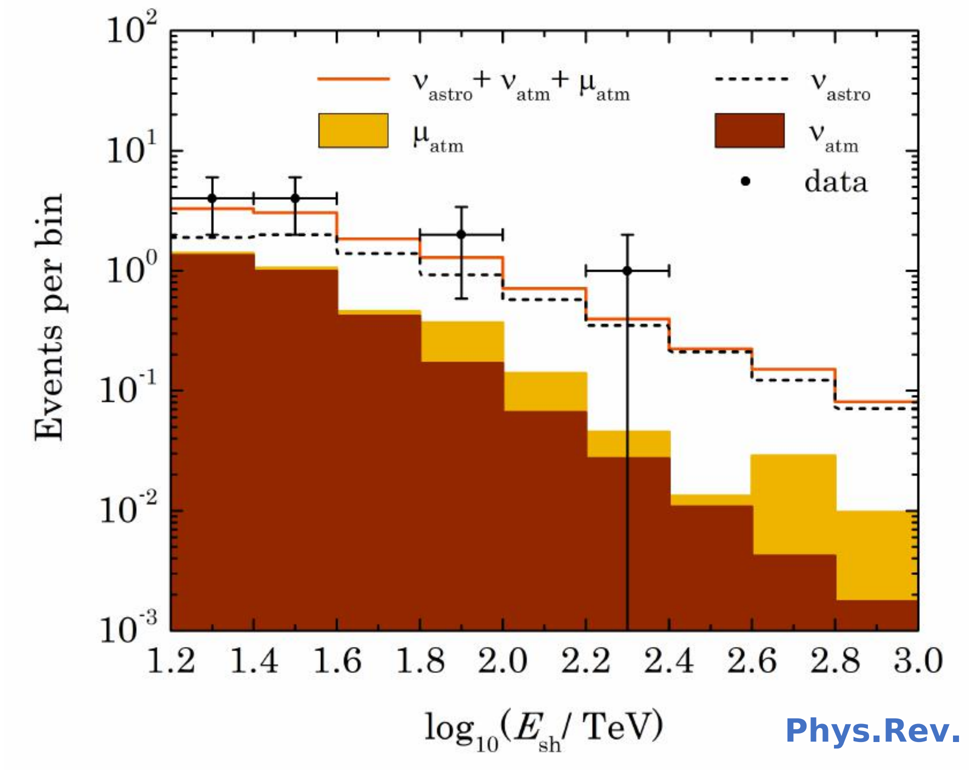
**Analysis of upward-going events**

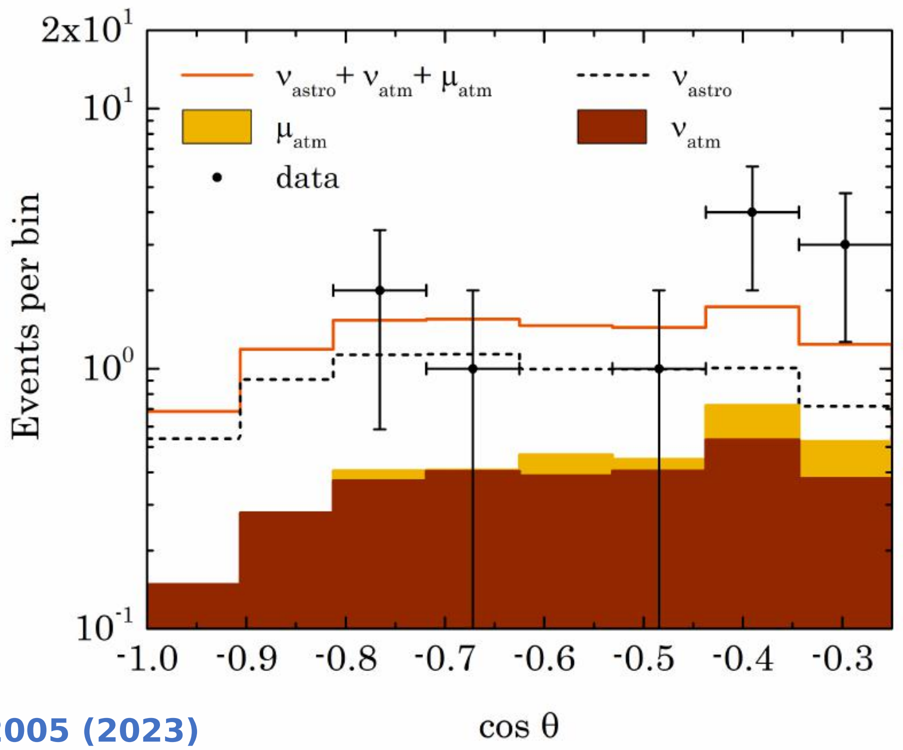
- Zenith angle cut: cos(θ) < - 0.25
- Loosened cuts: $E_{sh}$ > 15 TeV, $N_{hit}$ > 11
- 11 events selected
- 3.2±1.0 atm. background ev. are expected
  - 0.5 $\mu_{atm}$, 2.7 $\nu_{atm}$
- Highest energy: 224 TeV

**Significance of diffuse flux in upward-going events: 3.05σ !**

Main uncertainties

- Absorption length ±5%
- OM sensitivity ±10%
- $\nu_{atm}$ flux normalisation ±15%



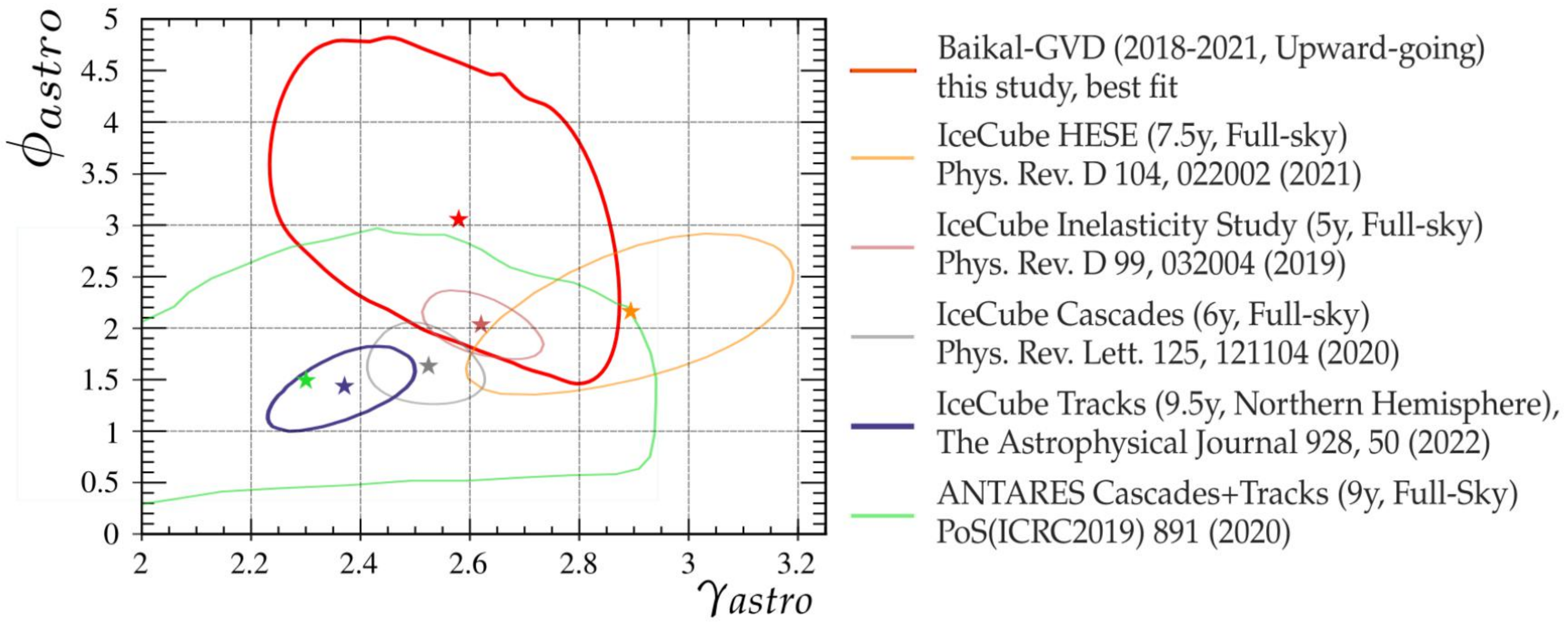




Phys.Rev. D 107, 042005 (2023)

# Diffuse neutrino flux: Baikal-GVD

Extraction of spectrum power and flux normalisation:

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




**First "non-IceCube" evidence for diffuse $\nu_{astro}$ flux at above 3σ !**

Phys.Rev. D 107, 042005 (2023)

# Diffuse neutrino flux: Baikal-GVD

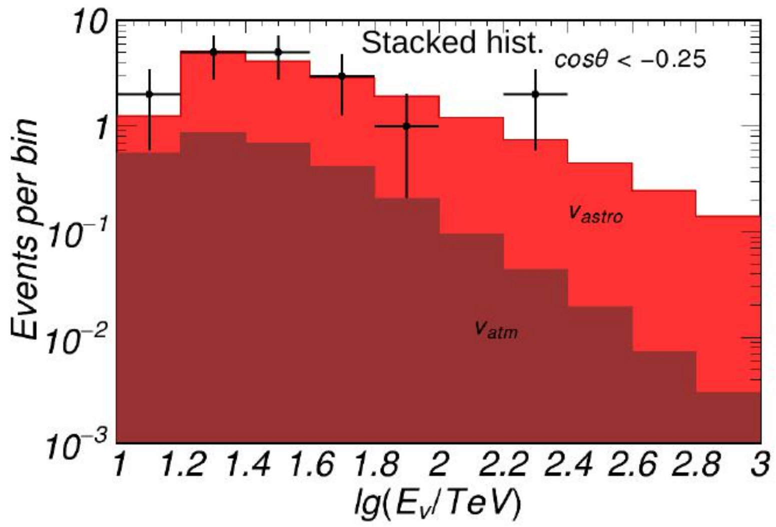
An update of upgoing events analysis adding season 2023

Event selection:
E>15 TeV && $N_{hit}$>11 && cosθ<-0.25 && $N_{hit\_\mu}$<2

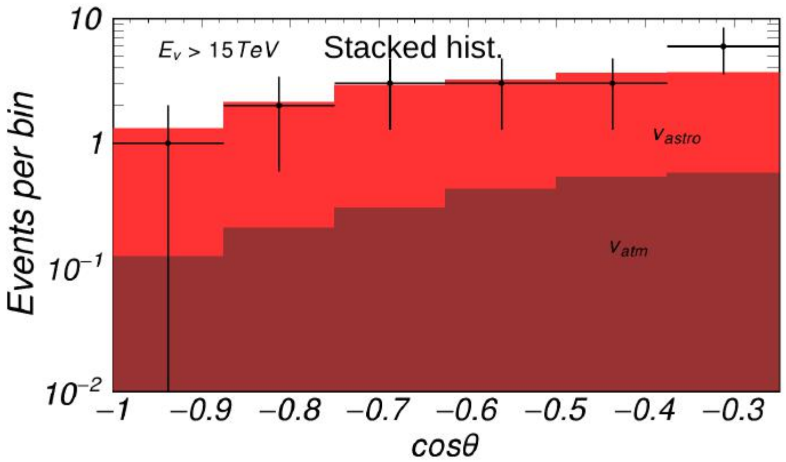
Expected:
0.4 events from atm. muons
2.1 events from atm. neutrinos
14.6 events for Baikal-GVD best fit $E^{-2.58}$ astrophysical flux

| Date | $N_{data}$ | $N_{bg}$ | P-value | Significance (no syst.) | Significance (stat.&syst.) |
| --- | --- | --- | --- | --- | --- |
| 18-23 | 18 | 2.5 | $2.15\times10^{-10}$ | 6.24σ | 5.3σ !!! |

Energy distribution (18-23)




Zenith distribution (18-23)



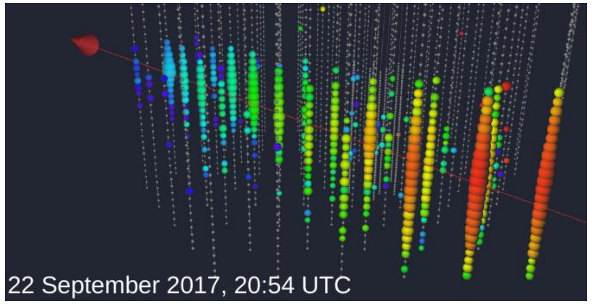
# IceCube, TXS 0506

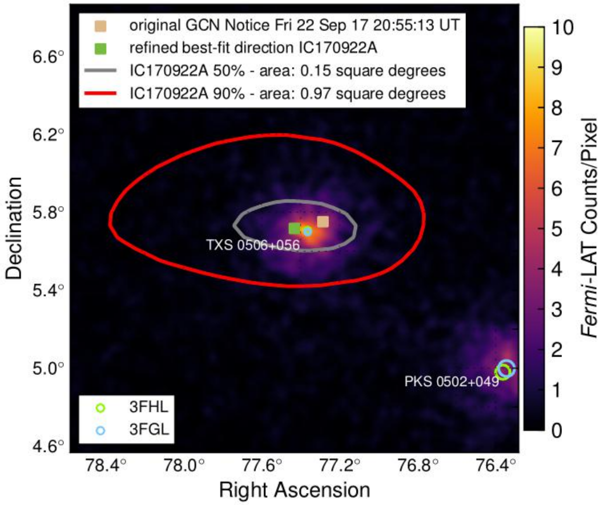
**22.09.2017**: IceCube alert event IC170922A, ~290 TeV muon track in the direction of TXS 0506+056 blazar

FERMI follow-up (28.09): TXS0506+056 in the flaring state

Alert followed by MAGIC and other ground-based and space telescopes

[Science 361, eaat1378 (2018)]

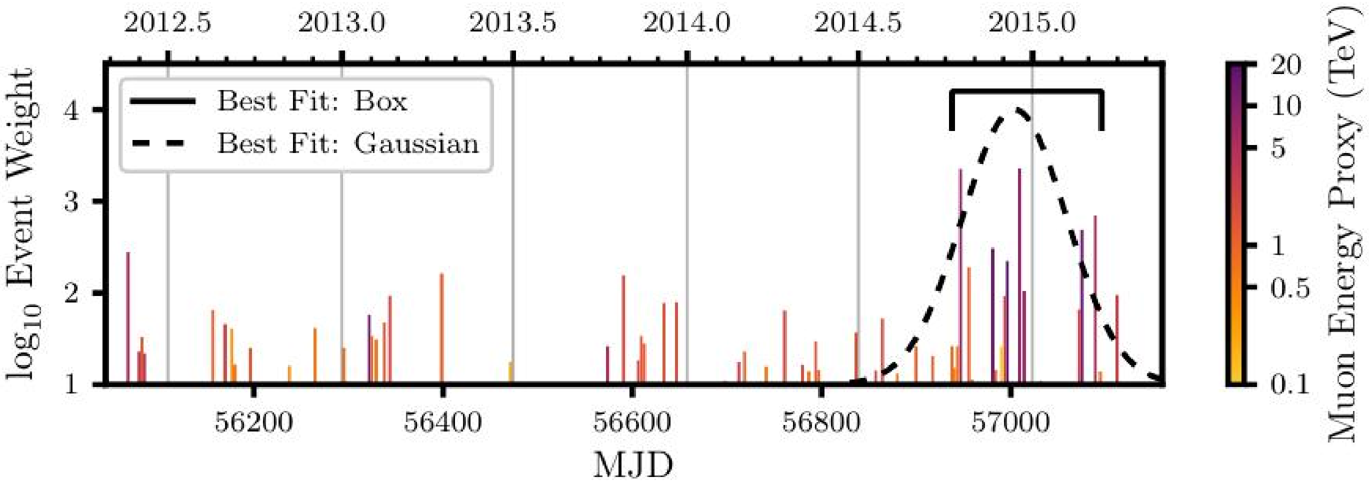



Search of events associated with TXS0506 in pre-alert data

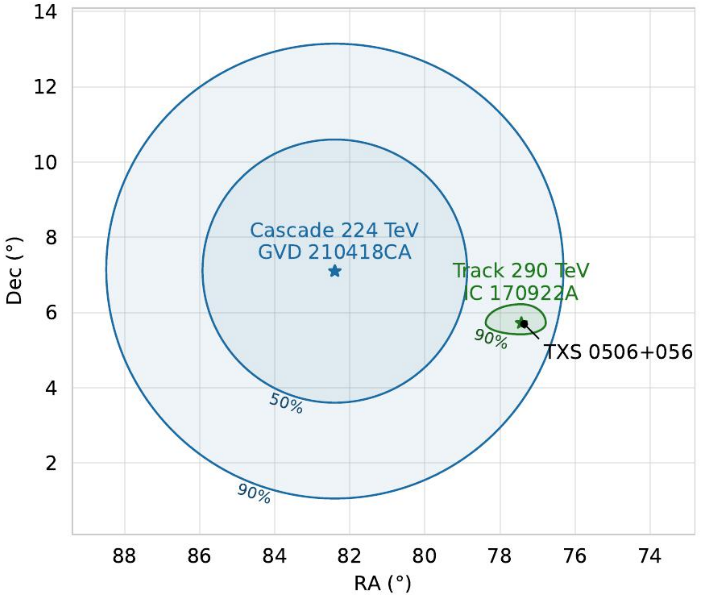
3.5σ post-trial significance

[Science 361, 147-151 (2018)]




TXS0506+056 is considered as the first high-energy neutrino source

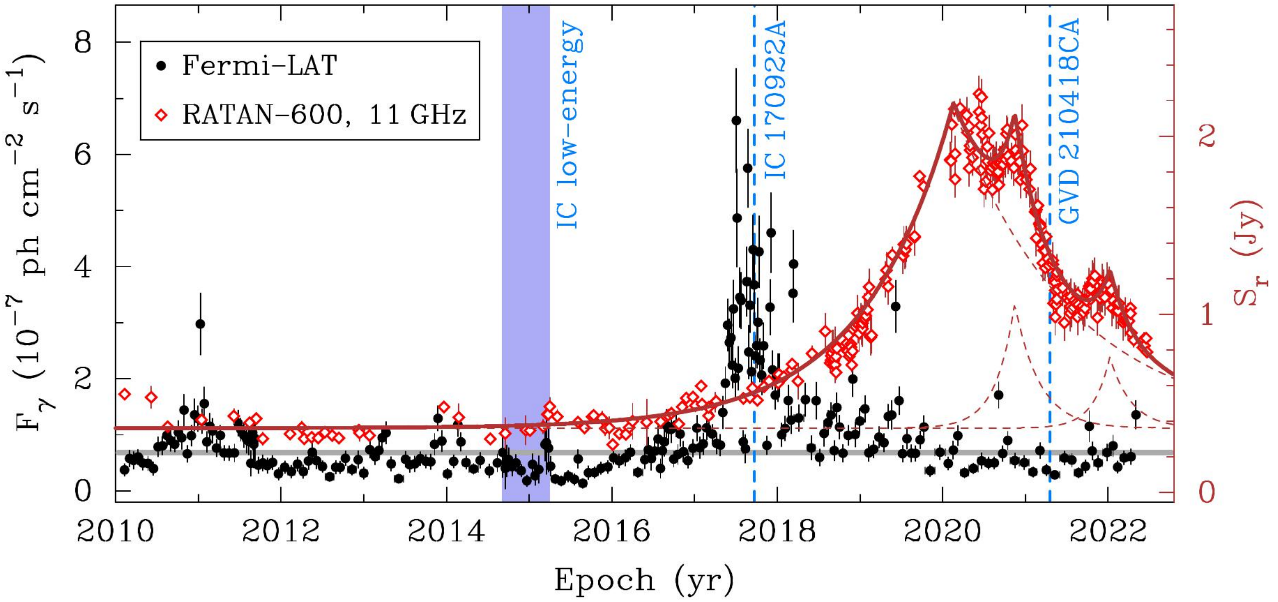
# Baikal-GVD: TXS0506 coincidence




[MNRAS 527 (2024) 8784]

Upgoing cascade analysis, highest energy event (18.04.2021):

- 224 TeV, 24 hits
- Neutrino source candidate TXS 0506+056 is within 90% containment circle
- Signalness: 97.1% (probability of astro origin)
- Chance coincidence probability (E>200 TeV): 0.0074



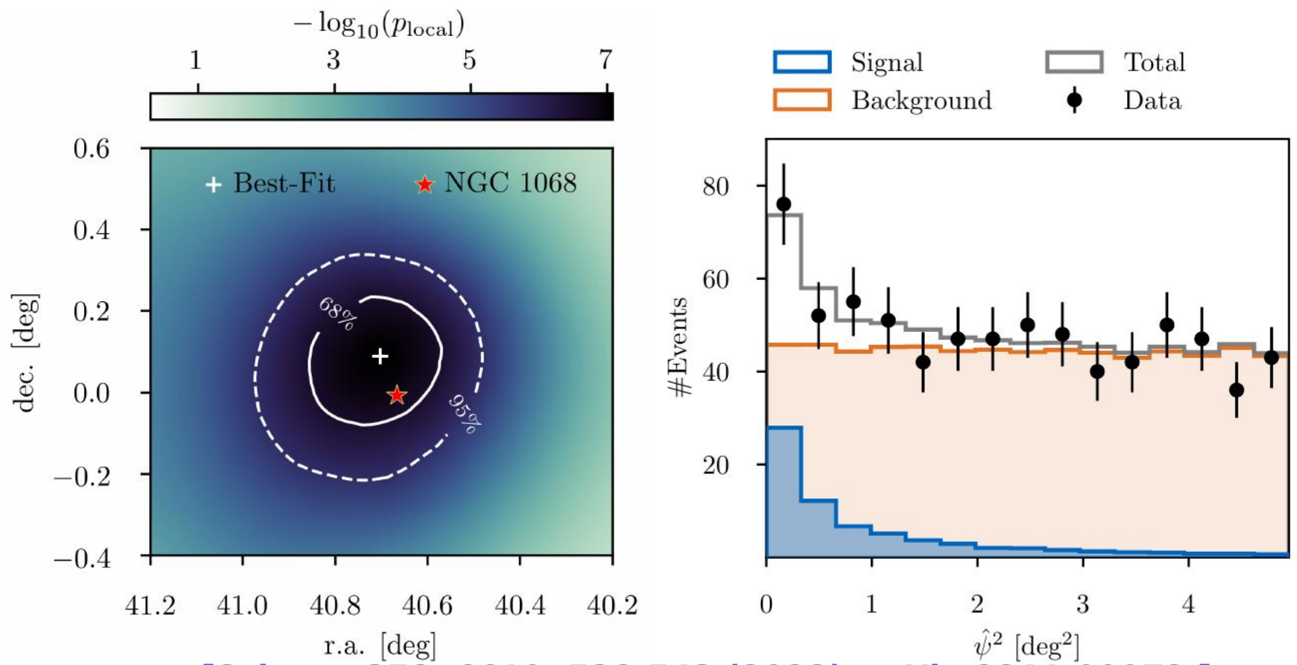

Analysis of RATAN-600 radiotelescope data (11GHz) showed increased activity

- IC event registered during γ flare
- Baikal event during radio flare
- Consistency with IC observations: 8% or 13% depending on ν spectrum assumption

# IceCube, NGC 1068 galaxy

NGC 1068: Seyfert II galaxy, 14.4 Mpc

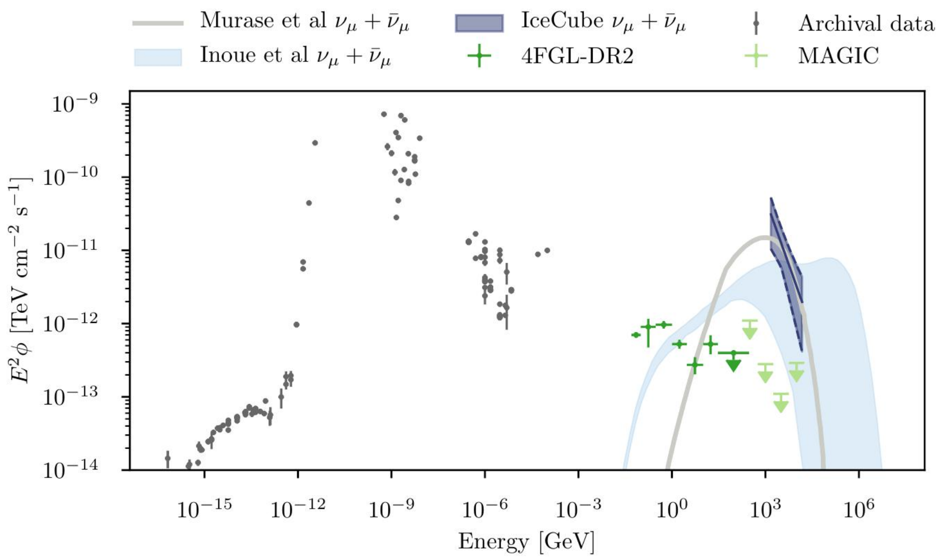
IC point source search with muon tracks:
NGC 1068 significance: 2.9σ
[Phys. Rev. Lett. 124, 051103 (2020)]




[Science 378, 6619, 538-543 (2022), arXiv:2211.09972 ]

New analysis
- 2011 - 2020: 3186 days of data-taking
- Refined reconstruction and calibrations
- $E_\nu$ > 100 GeV, 670000 events after cuts

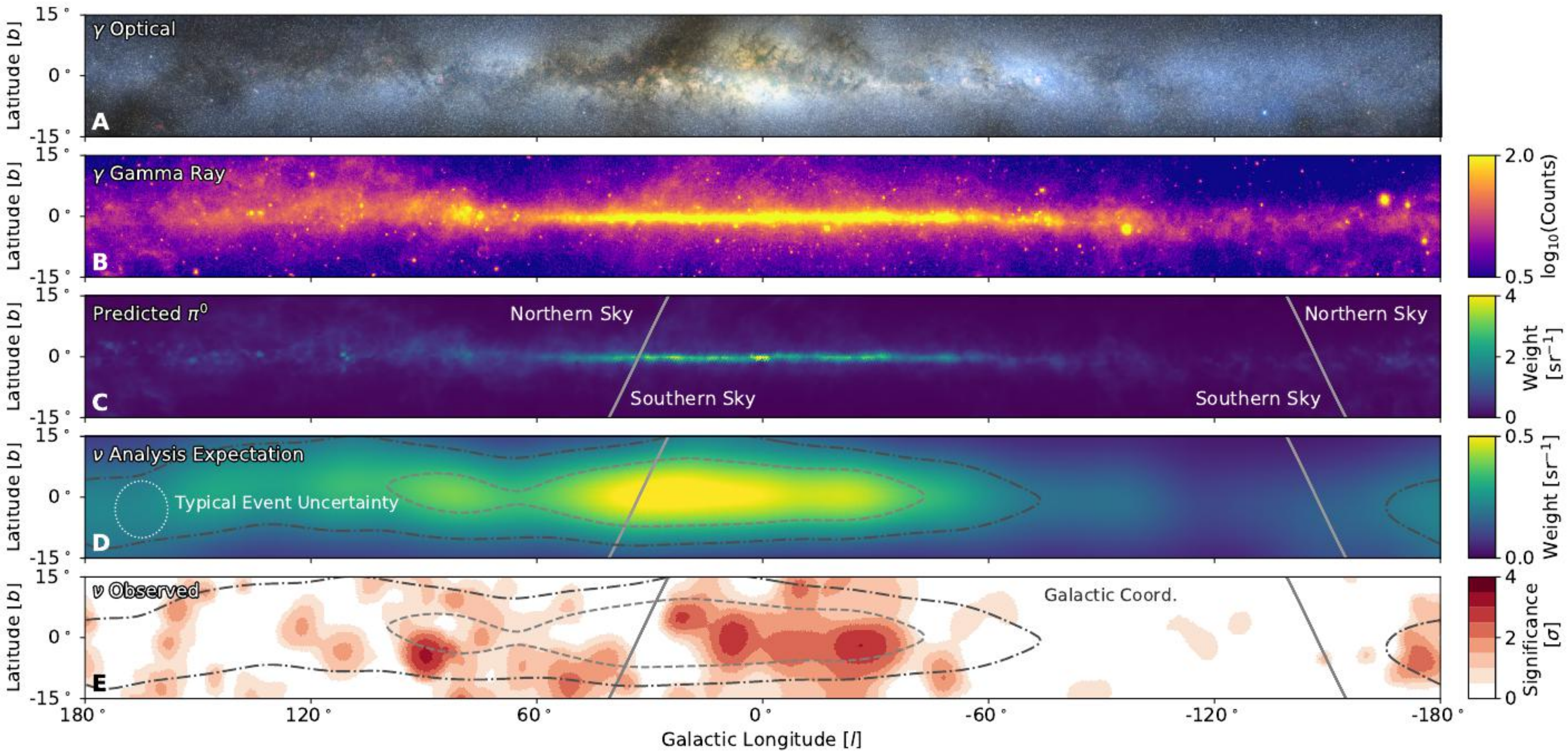
$79^{+22}_{-20}$ events above background: 4.2σ significance!
Second high-energy neutrino source candidate




Main contribution from $E_\nu$ ~ 1.5 - 15 TeV
- Soft spectrum

# Milky Way galaxy in neutrinos

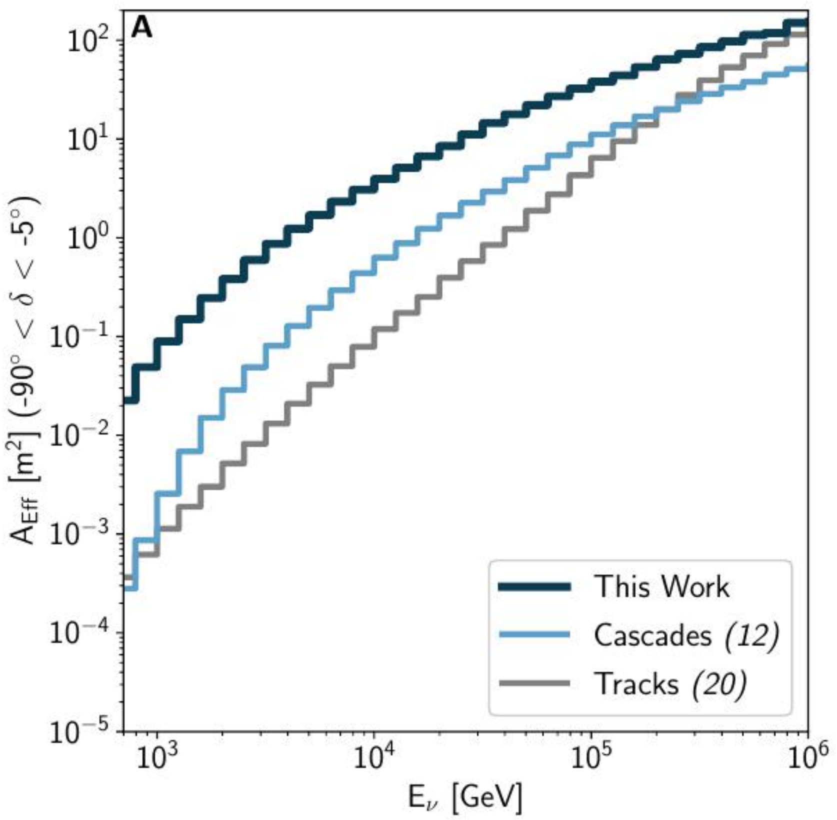
IceCube 2023,
Milky Way galaxy
in neutrino




Science 380, 6652, 1338-1343 (2023), arXiv:2307.04427

# IceCube galactic neutrino

Impressive effective area improvement




Science 380, 6652, 1338-1343 (2023), arXiv:2307.04427

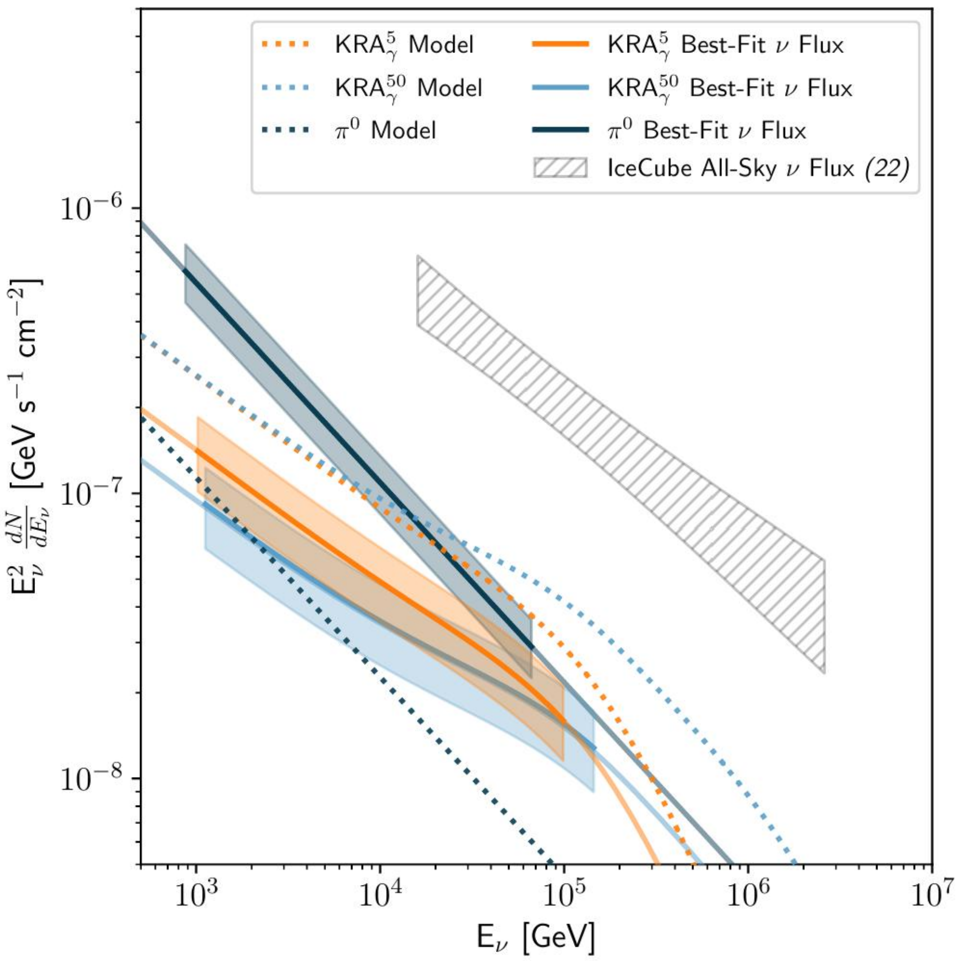
Search for galactic neutrino in cascade events

- 10 years, 500 GeV - multi-PeV events
- Active use of machine learning methods
- 20 times improvement in statistics wrt. the previous cascade statistics

With these events test three predefined emission models:

$\pi^0$, $\mathrm{KRA}_\gamma^5$, and $\mathrm{KRA}_\gamma^{50}$

# IceCube galactic neutrino




Test the significance of spatial templates: emission model covolved with detector acceptance and spatial resolution

Significance 4.71σ, 4.37σ and 3.96σ for $\pi^0$, KRA$_\gamma^5$, and KRA$_\gamma^{50}$

The most significant ($\pi_0$) post-trial: 4.48σ

Galactic point source catalogue search gave no significant results

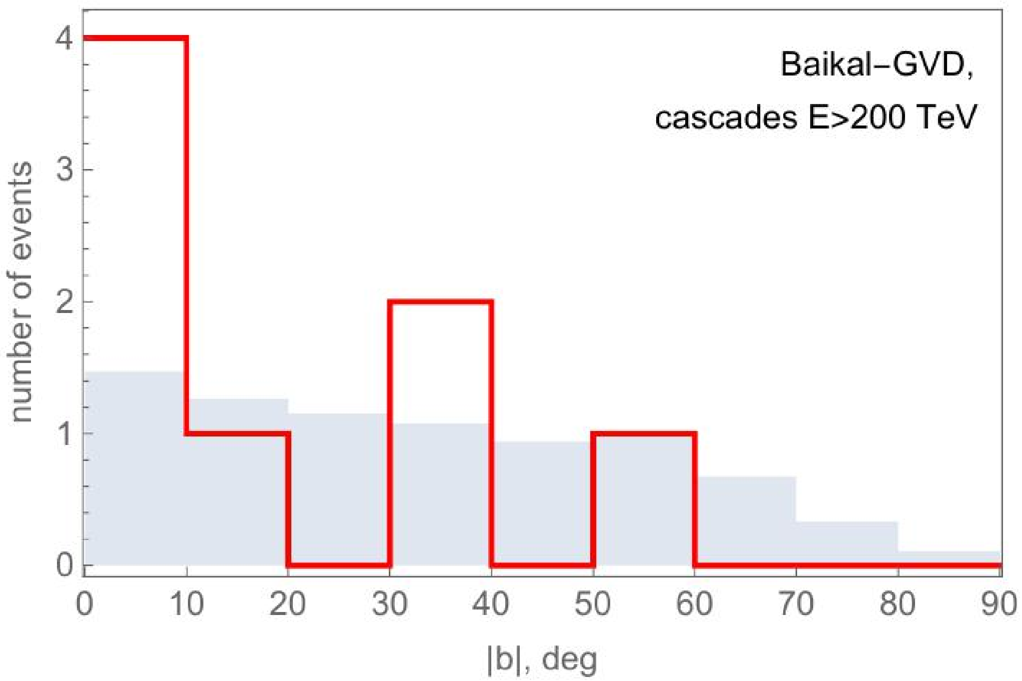
Galactic flux: less than ~6-13% contribution to total neutrino flux at 30 TeV

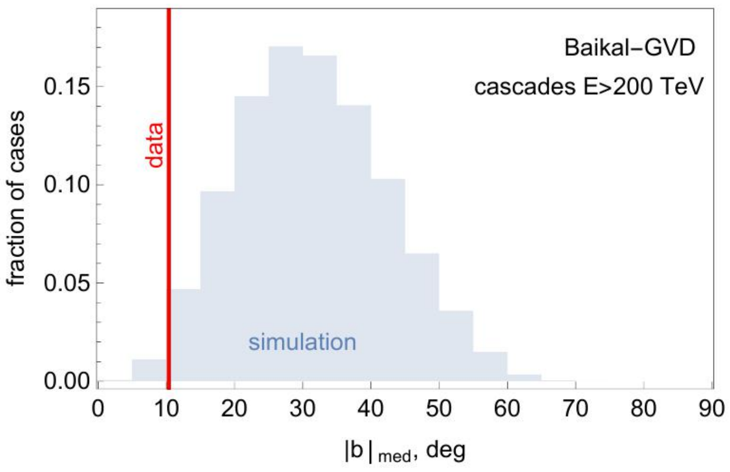
Science 380, 6652, 1338-1343 (2023), arXiv:2307.04427

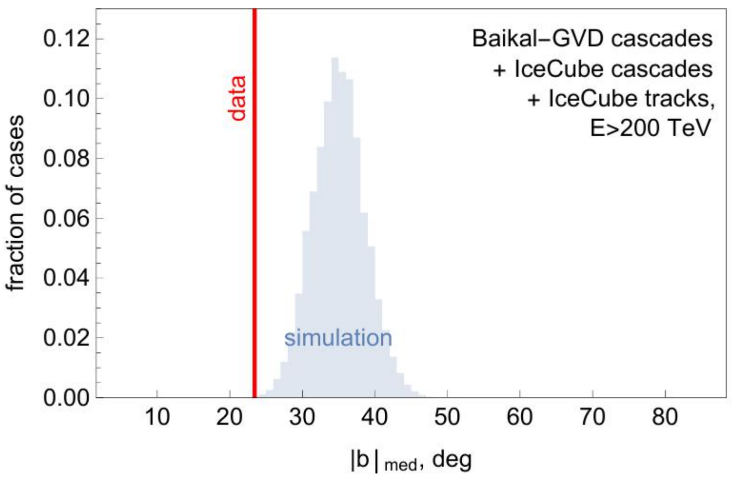
# Baikal-GVD galactic plane

**ApJ, 982:73 (6pp), 2025**

- High-energy cascades April 2018 - March 2024 (6 years)
- Test the Galactic excess at E>200 TeV (8 events, 64% of astrophysical origin)
- Simple model-independent test using median of galactic latitude $|b|_{med}$
- Galactic component is visible with a significance of 2.5σ
- IceCube cascades and tracks also demonstrate the Galactic excess
- Fraction of Galactic events reaches several tens of percent at E>200 TeV



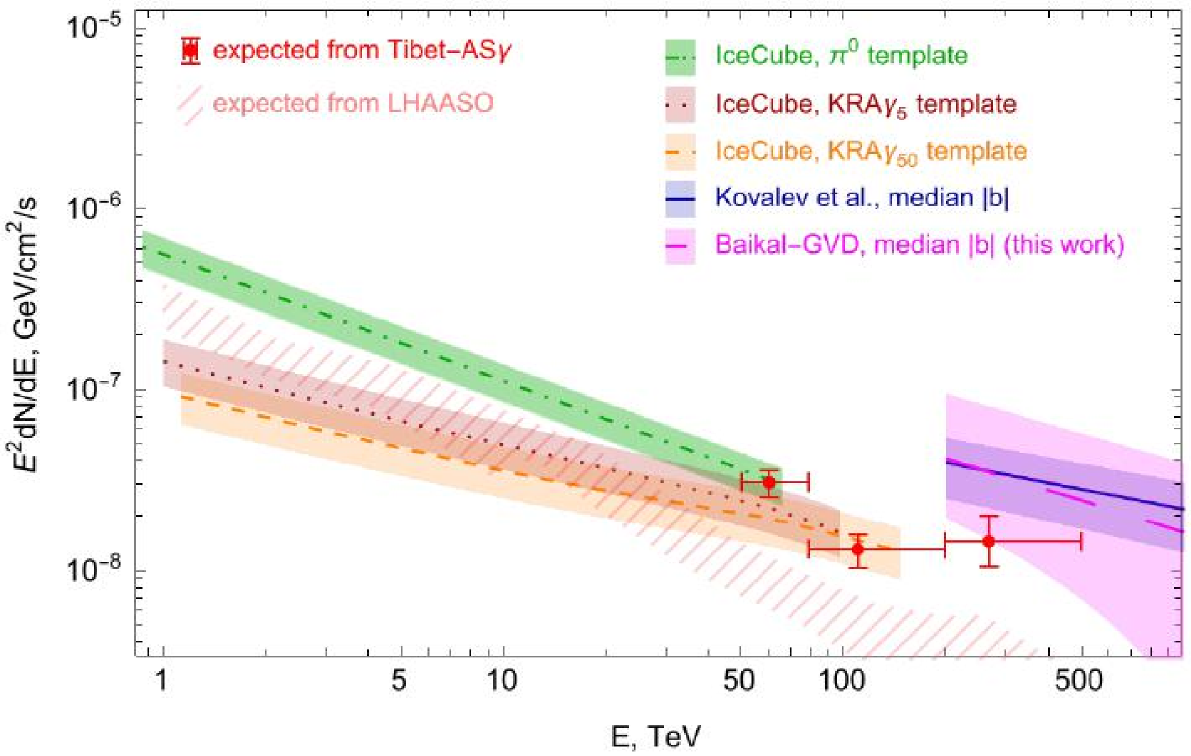




| Sample | $\|b\|_{med}$ observed | $\langle \|b\|_{med} \rangle$ expected | $p$ |
|---|---|---|---|
| Baikal-GVD cascades | 10.4° | 31.4° | $1.4 \cdot 10^{-2}$ (2.5σ) |
| IceCube cascades | 12.4° | 31.9° | $8.7 \cdot 10^{-3}$ (2.6σ) |
| combined cascades | 12.4° | 31.5° | $1.7 \cdot 10^{-3}$ (3.1σ) |
| IceCube tracks | 24.7° | 36.0° | $1.8 \cdot 10^{-3}$ (3.1σ) |
| all cascades+tracks | 23.4° | 35.0° | $3.4 \cdot 10^{-4}$ (3.6σ) |

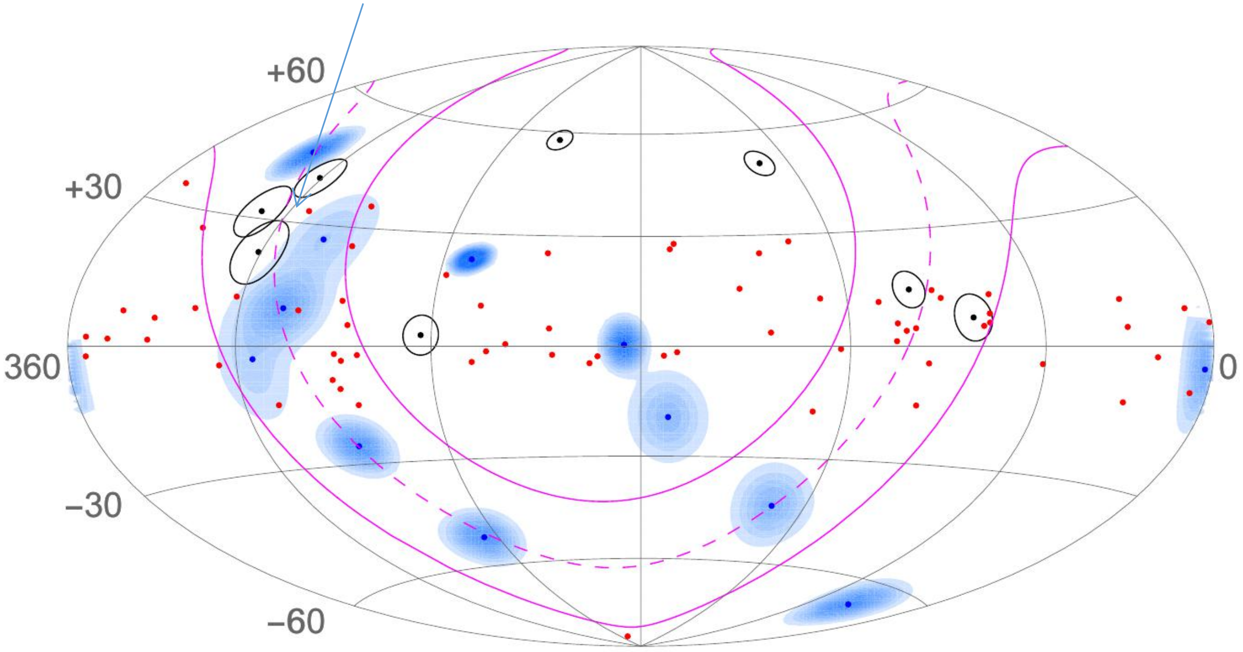
# Baikal-GVD galactic plane

ApJ, 982:73 (6pp), 2025

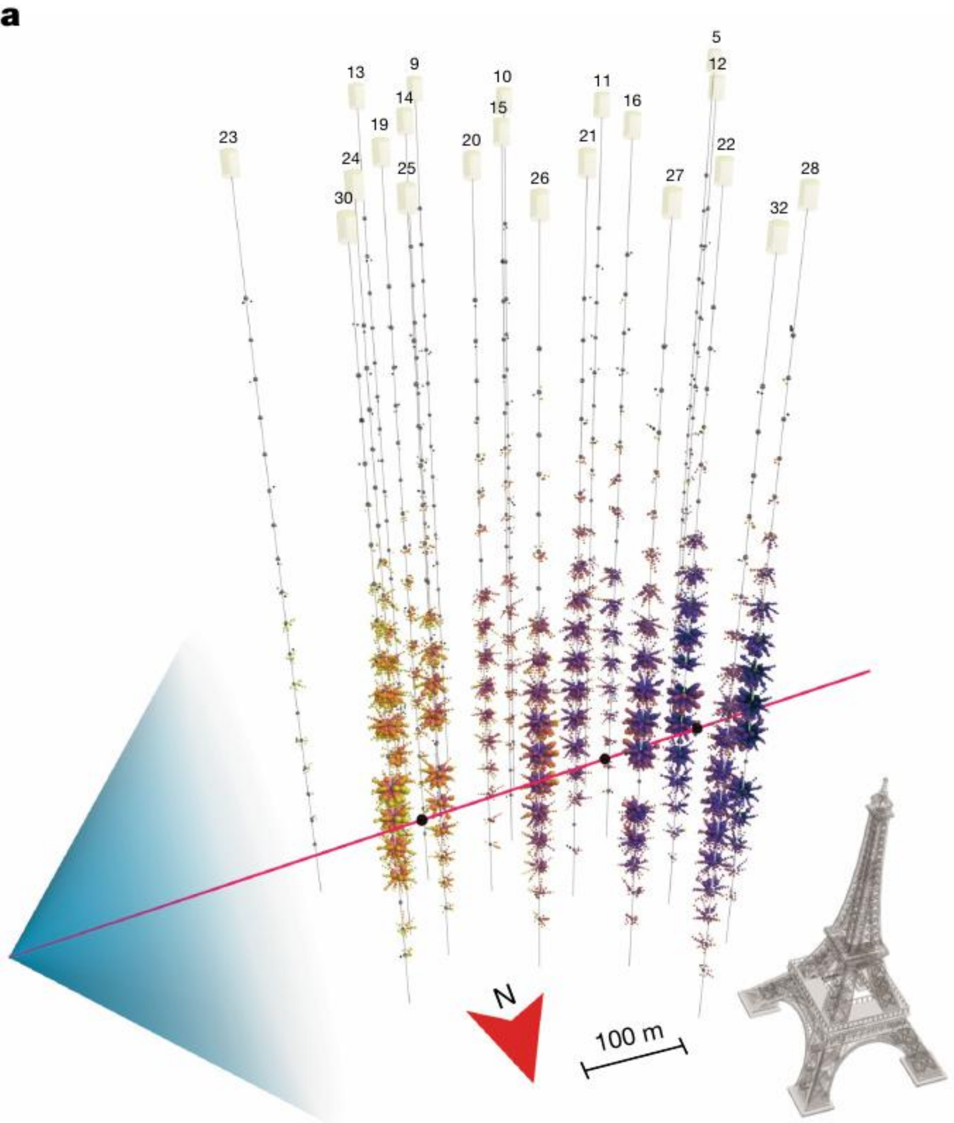
- Very rough estimate of the Galactic neutrino flux is obtained
- Agrees with Galactic gamma-ray diffuse emission by Tibet-ASγ
- Some event clustering towards the Cygnus region (the brightest region of diffuse γ-ray emission in the northern sky)




Cygnus region



# High-energy KM3NeT event



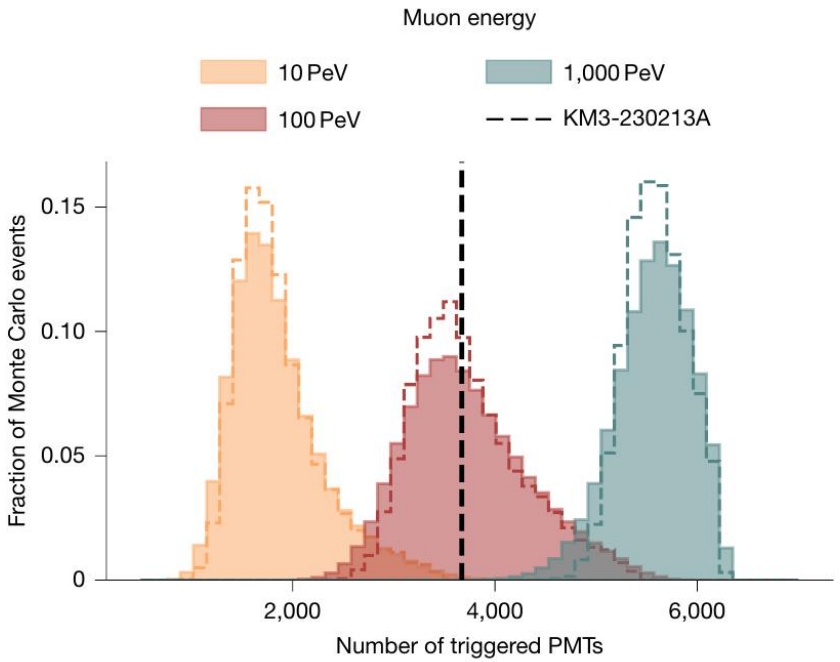

An extremely high-energy event was detected by 21 detection lines of KM3NeT on 13.02.2023

- 0.6° above the horizon, 1.5° 68% angular error

Muon contamination

- Muon from that direction would cross 300 km.w.e.
- $10^{-10}$ events per year for 100 PeV muon assuming 2° angular error

Median neutrino energy: 220 PeV,
68%: 110-790 PeV, 90%: 72 PeV - 2.6 EeV



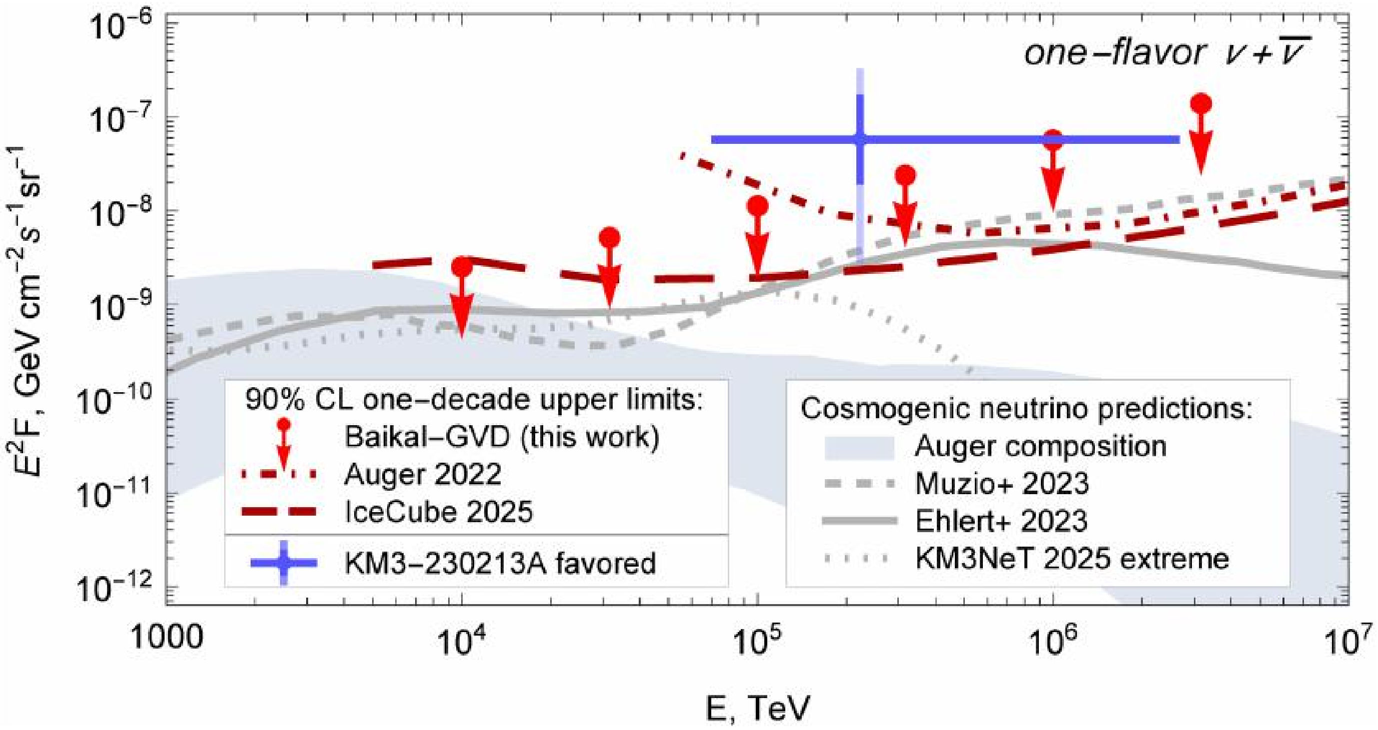
# High-energy KM3NeT event

Neutrino flux was estimated by KM3NeT
Flux limits were obtained by IceCube and Baikal-GVD

expected number of events

| | |
|---|---|
| IC/NST: | 0.014 |
| IC/ESTES: | 0.0034 |
| IC/HESE: | 0.00054 |
| GVD: | 0.006 |

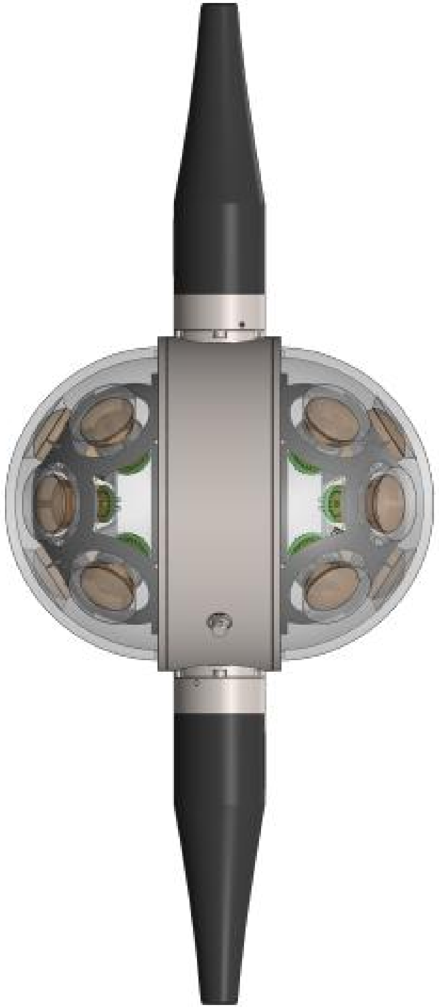
**Zh. Djilkibaev, Rubakov70 conference**



# Future telescopes

# Planned telescopes

# P-One telescope



Connect telescope strings to existing underwater communication lines

Modular structure

70 1 km-long strings

20 modules per string

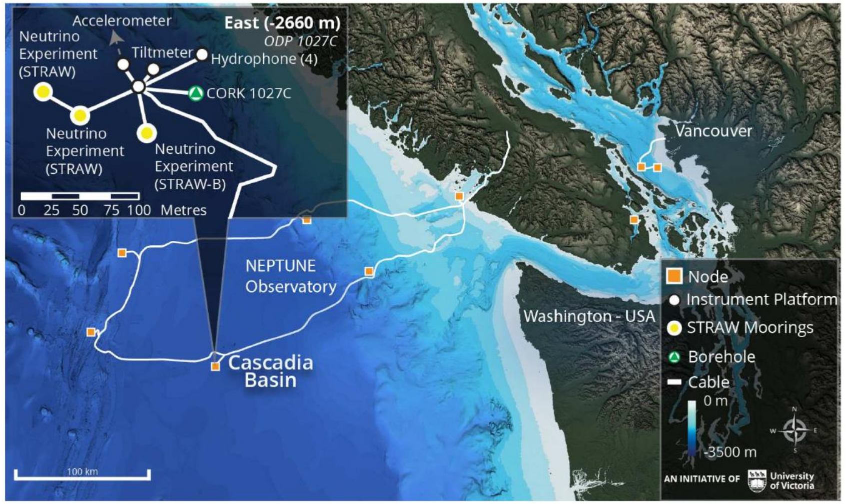
Each module: 16 3” PMTs

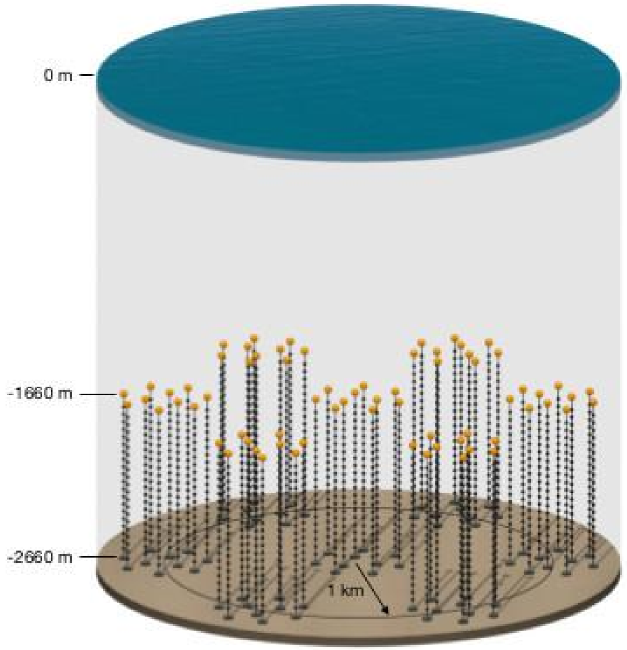
Instrumented water volume: ~3 km³

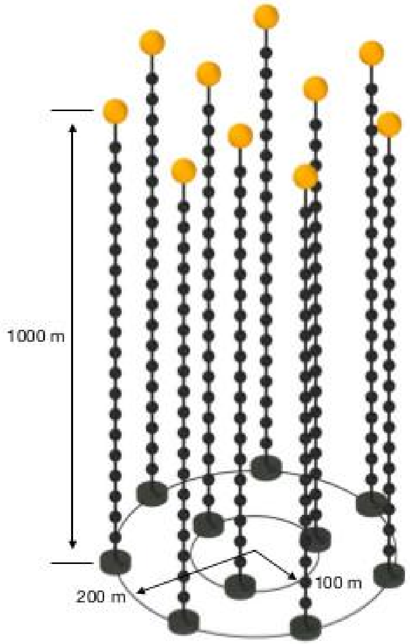
Water absorption: ~28m

Pathfinder strings since 2018

**PoS(ICRC2023)1219**



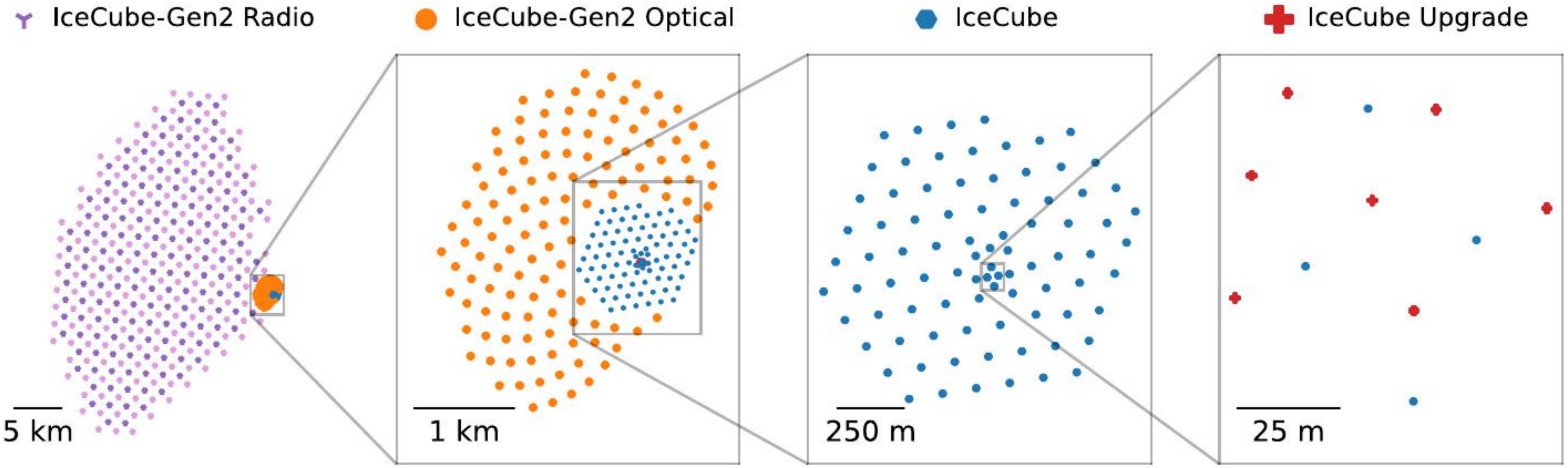



# IceCube-Gen2

IceCube plans large complex upgrade including radio and optical arrays

D-Egg

2 8” PMTs




+ Surface array

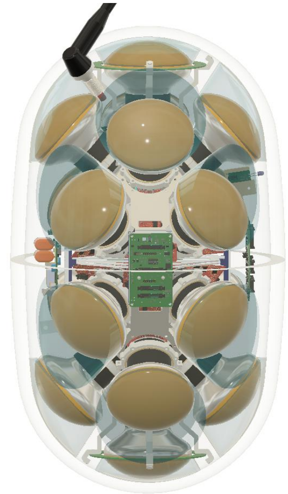
mDOM

24 3” PMTs

Deployment of competing PMTs in the IceCube upgrade in 25/26

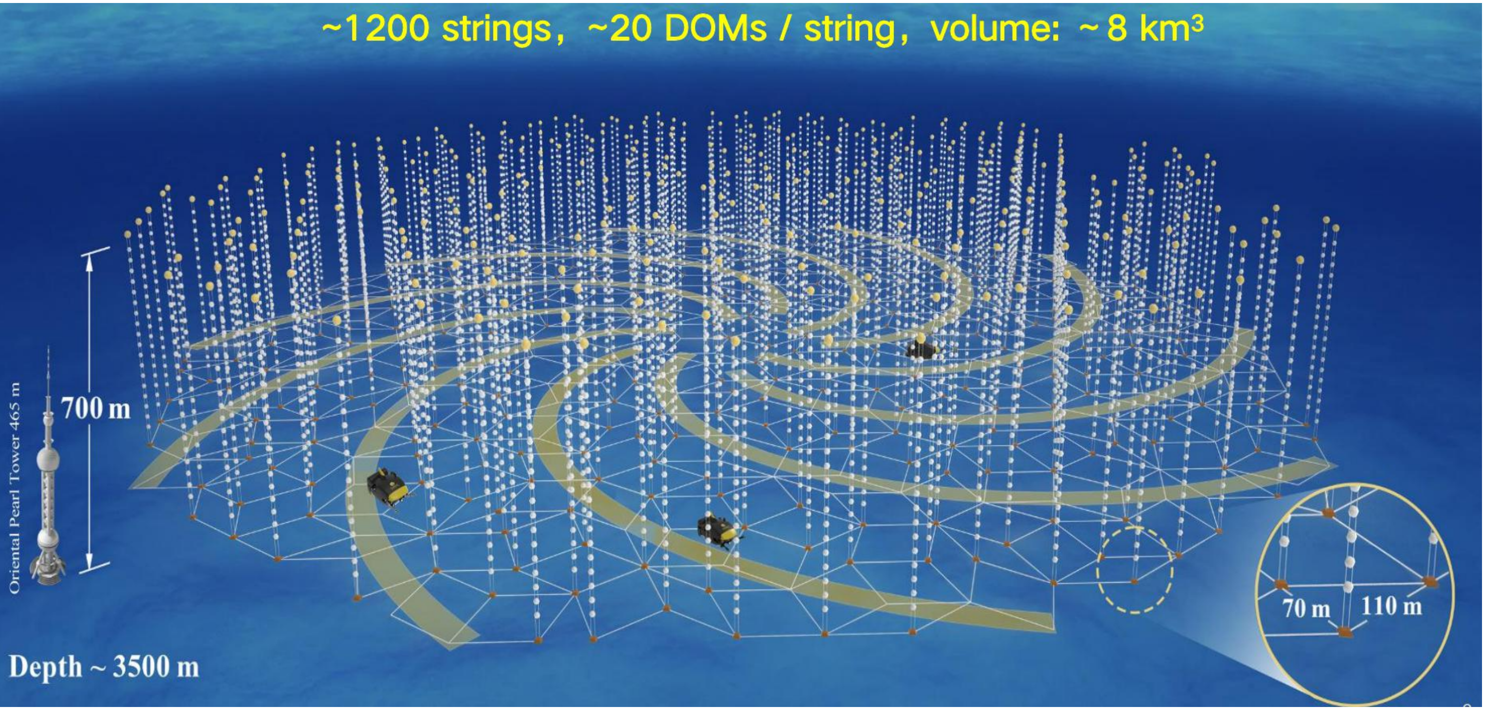
Ice-Cube Gen2
Long optical module

16 or 18 PMT



IceCube-Gen2 TDR **arXiv:2008.04323, J.Phys.G 48 (2021) 6, 060501**

# TRIDENT

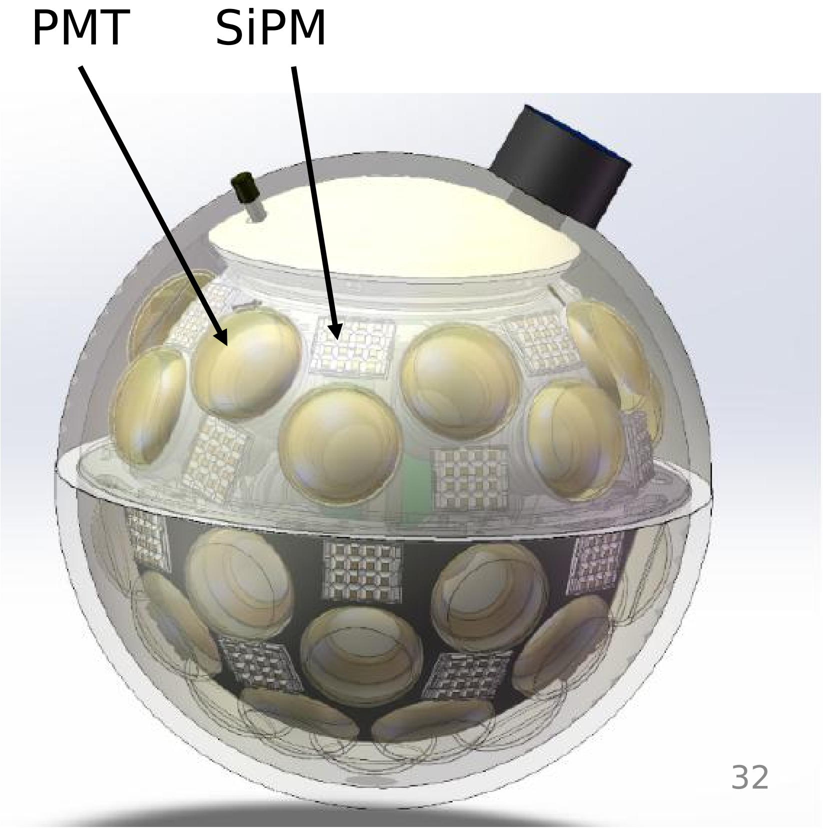



Pathfinder: 2019–2022 → Phase I: 2022–2026 → Full detector: 2026–

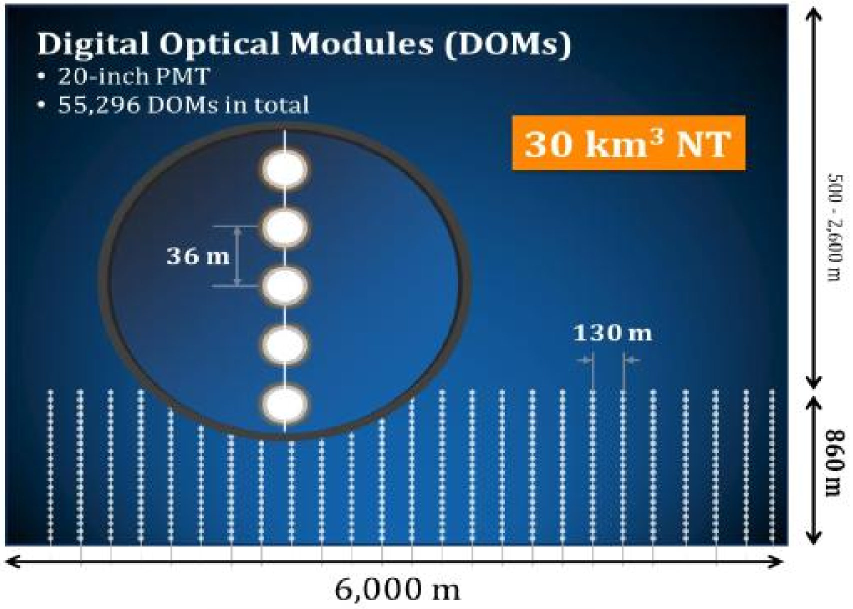
Xin Xiang, MANTS 2024, March 24

Hybrid OMs incorporating both PMTs and SiPM

SiPM are very fast and thus improve time measurement



# HUNT




Possible layouts.

Very large volume neutrino telescope project: 30 $km^3$

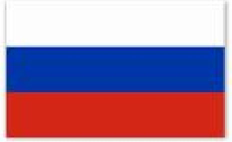
Two locations are considered

| | Lake Baikal | South China Sea |
|---|---|---|
| **Absorption length** | ~20 m | **~25 m** |
| **Depth** | ~1366 m | **~2500 m (better atmospheric muon background rejection)** |
| **Deployment Cost** | **~K$ /string** | High |
| **Reparability** | **Work on the ice (low cost)** | Difficult to be repaired |
| **Power Supply cable** | **~10 km cable** | ~100 km cable or battery |
| **Construction and Deployment** | **~5 years (Feb. to Apr. every year)** | Rely on deep-ocean facilities |

HUNT have deployed two prototype strings in lake Baikal in joint IHEP-Baikal-GVD effort

# Baikal-GVD status and future

# Baikal-GVD Collaboration




- Institute for Nuclear Research of the Russian Academy of Sciences, Russia
- Joint Institute for Nuclear Research, Russia
- Irkutsk State University, Russia
- Skobeltsyn Research Institute of Nuclear Physics, Russia
- St. Petersburg State Marine Technical University, Russia
- National Research Nuclear University MEPHI, Russia
- Comenius University,  Slovakia
- Czech Technical University in Prague, Czech Republic
- Institute of Nuclear Physics ME RK, Kazakhstan

~ 65 physicists and engineers

# Baikal-GVD detector status

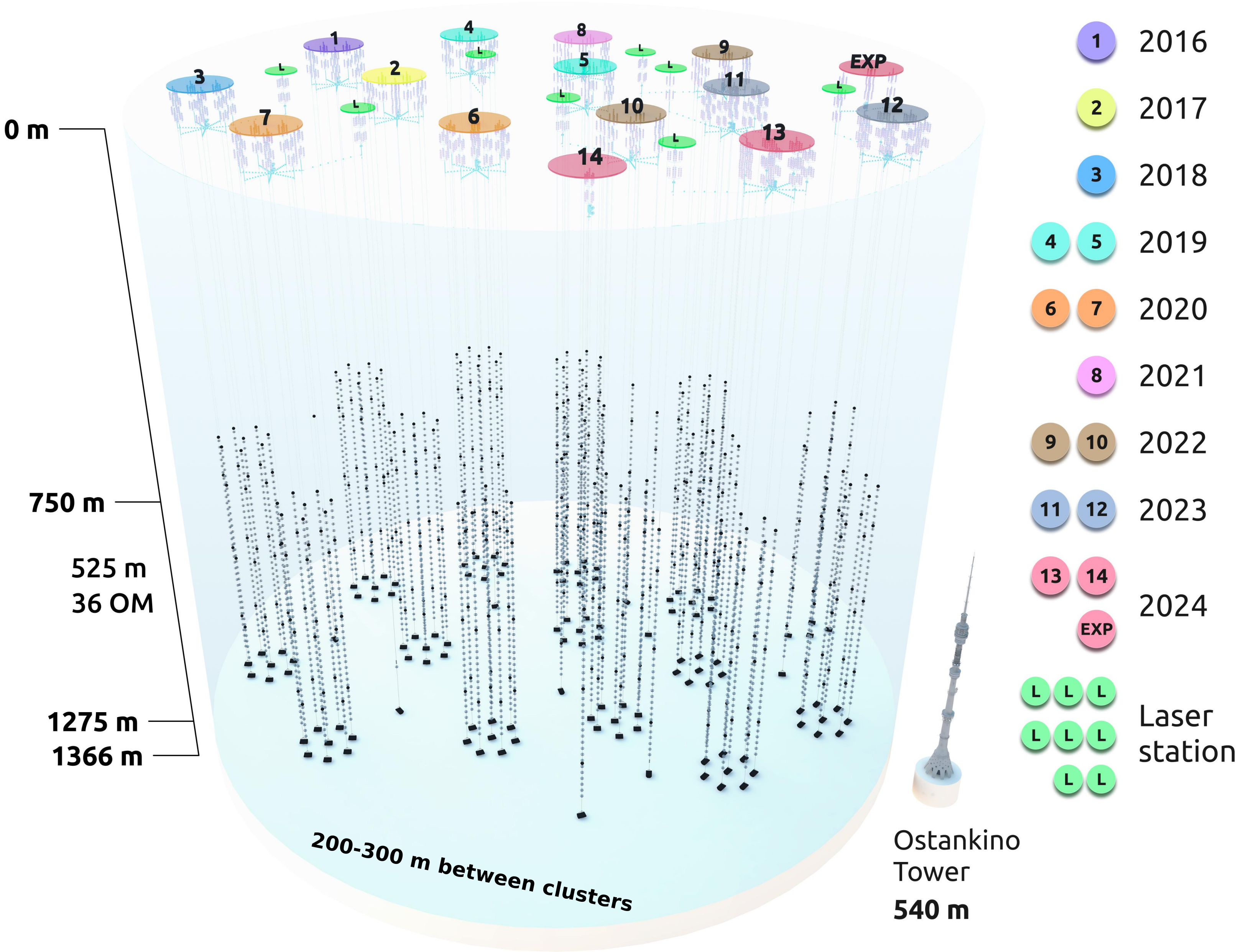
Presently detector consists of 117 strings arranged into 14 independent detectors - **clusters**

- 4212 OMs in total

Baikal-GVD cluster:

- 8 regular strings, 525 m is instrumented with optical modules (OM), 15m step between OM
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs

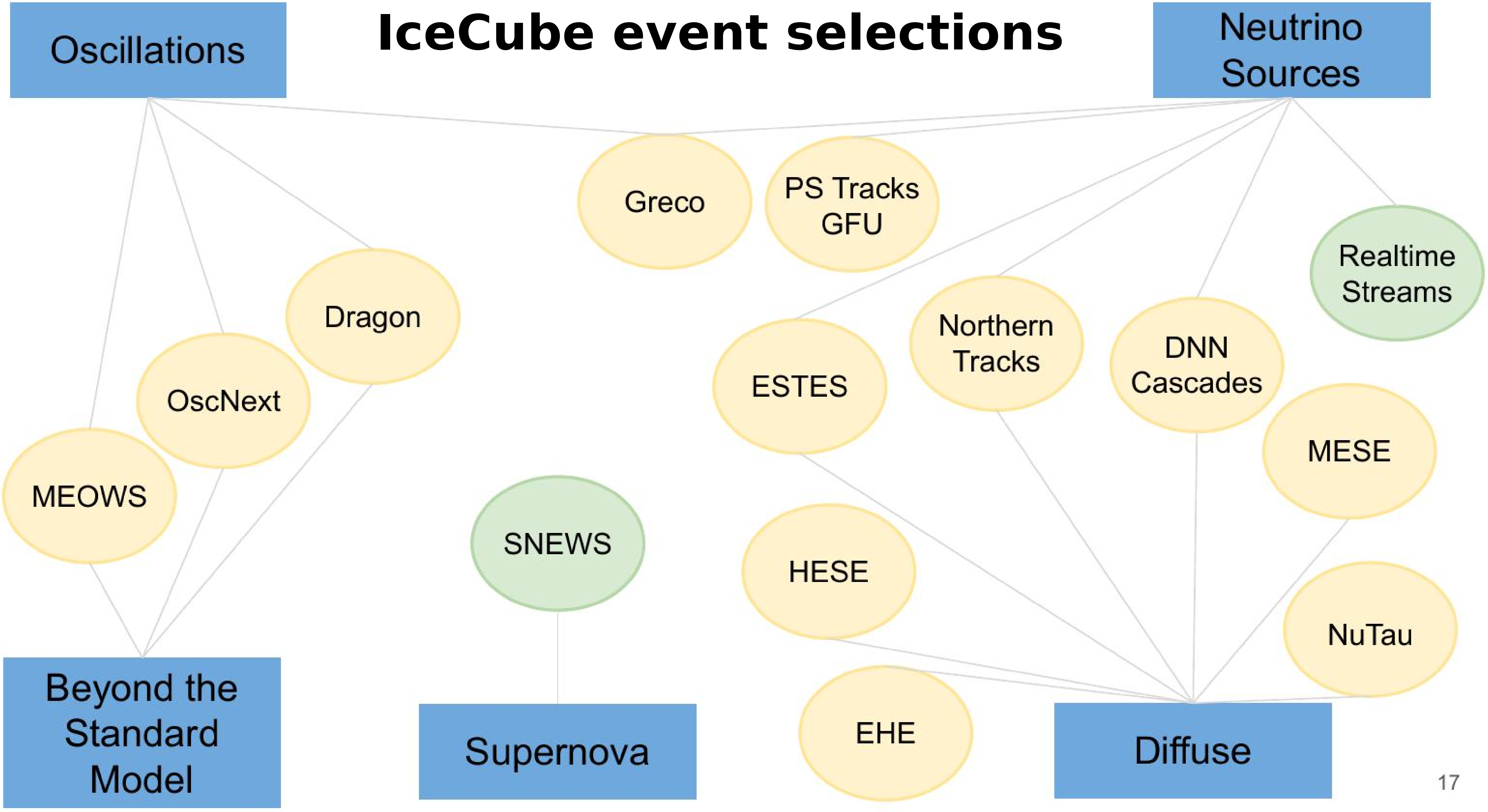
**Detection volume: ~0.6 Gt**



# Baikal-GVD shore center


# Baikal-GVD winter deployment campaign

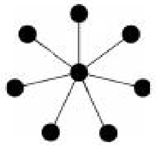
# IceCube event selections



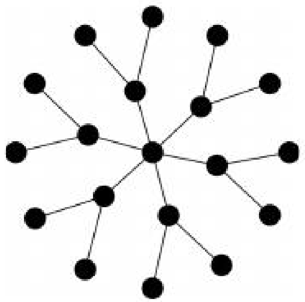

**14 event selections at IceCube ... 2 at Baikal-GVD**

# Toward Baikal project GVD+ / preliminary

## Configuration



Cluster Baikal-GVD, 8 Strings
Distance between strings 60 m
D=120 m



Cluster GVD+, 19 Strings
Distance between strings ~80…100 m
D=300…380 m

$\mathbf{V_{GVD+/Cluster} / V_{GVD/Cluster} \sim 6...10}$

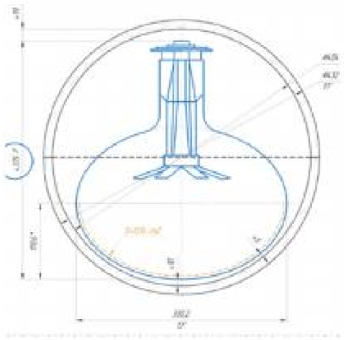
## Data acquisition system

**Architecture**
Cluster-Strings-Sections.

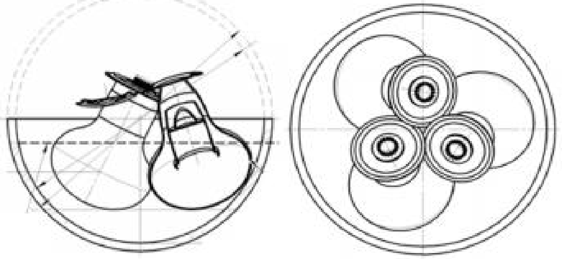
**Implementation**
- Fiber-optical DAQ.
- Data, Trigger and Synchro transmitted via a single optical line.
- The timing accuracy of the signals is better than 1 ns.
- OM outputs analog pulses (OM consumption less than 1 W).

## Optical module

**OM with one 13” PMT**
- NEW PMT.
- Glass sphere 17”.
- Expected parameters:
  QE > 26%, TTS < 4 ns.



**OM with three 8” PMT**
- PMT N6082.
- Glass sphere 20”.
- Parameters:
  QE > 26%, TTS < 2 ns.

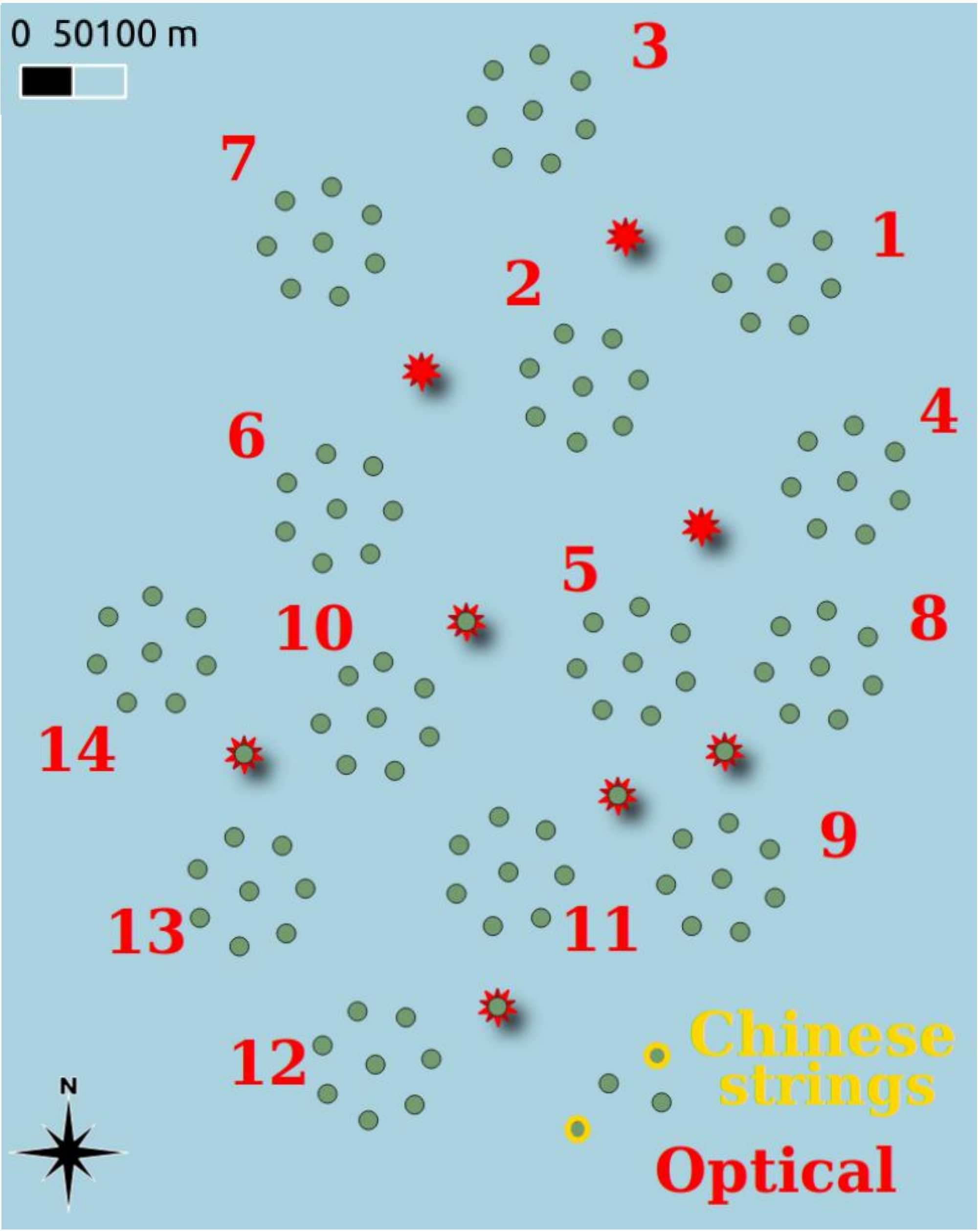


**Detector design in progress**

**Welcome to Baikal-GVD!**

# BACKUP

# Expedition 2025



# Diffuse neutrino flux: Baikal-GVD

**Preliminary:** An update of analysis adding data from 04.2022 - 03.2023 (10 cluster detector)

Comparison of statistical significances for old and new samples

**All-sky analysis**

| Seasons | $N_{data}$ | $N_{bckg}$ | P-value | σ(stat.) |
|---|---|---|---|---|
| 18-21 | 16 | 8.2 | $2.09 \times 10^{-2}$ | 2.31 |
| 18-22 | 28 | 14.5 | $1.06 \times 10^{-3}$ | 3.07 |

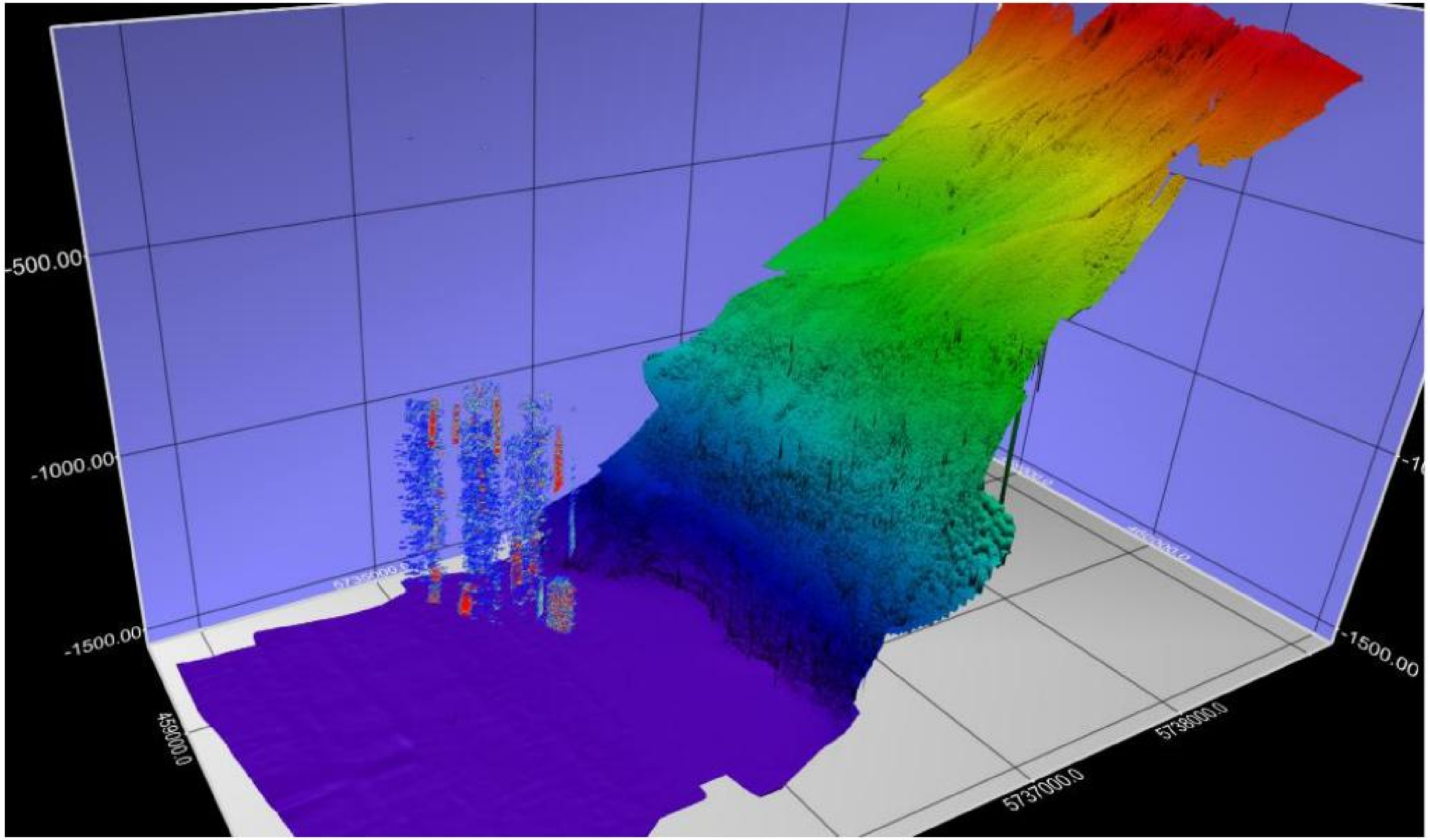
**Upgoing analysis**

| Seasons | $N_{data}$ | $N_{bckg}$ | P-value | σ(stat.) |
|---|---|---|---|---|
| 18-21 | 11 | 3.2 | $1.7 \times 10^{-3}$ | 3.13 |
| 18-22 | 19 | 5.7 | $1.11 \times 10^{-5}$ | 4.24 |

Significance of excess over atmospheric background increases

# Baikal-GVD

Acousitc profile of Baikal shore in the region of the telescope




Baikal-GVD is 1 km$^3$ neutrino telescope being constructed since 2015

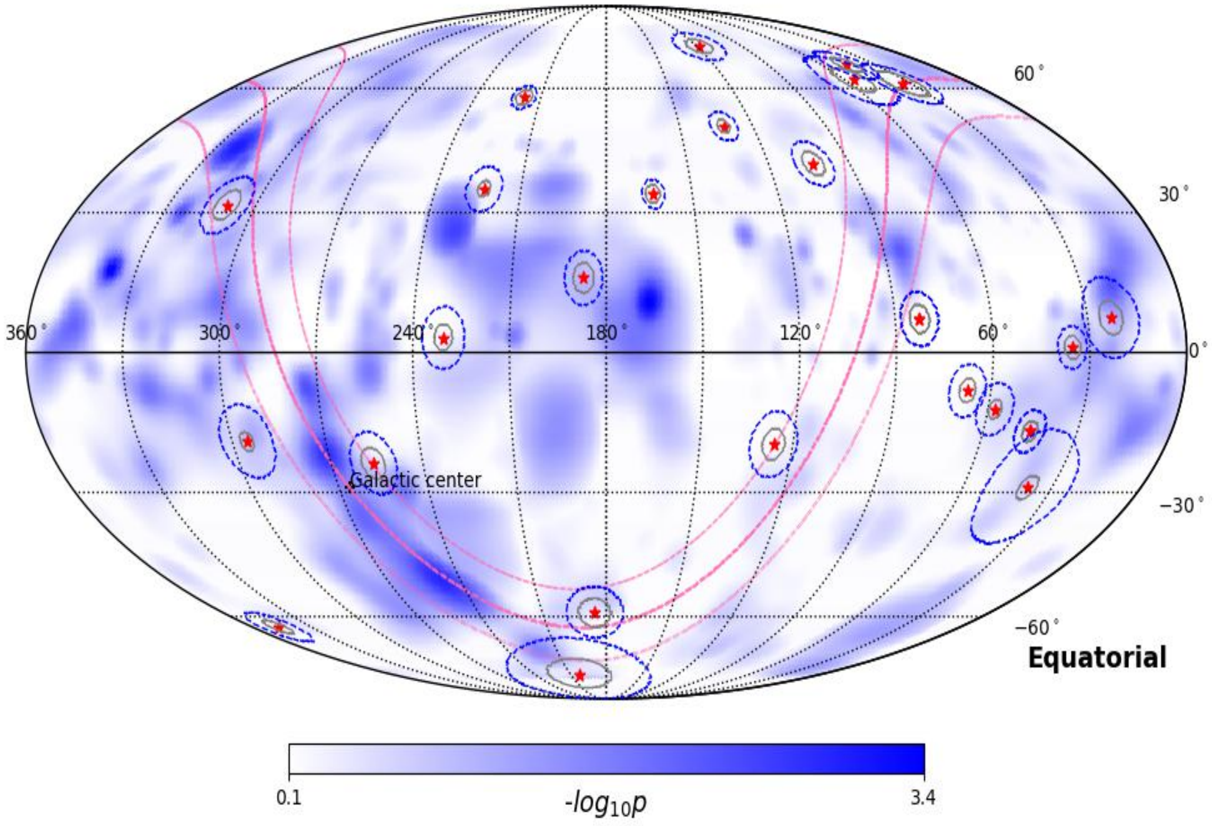
Max depth at the location: ~1370m
Flat lakebed

Absorption length: 22m
Effective scattering length > 100m

# Baikal-GVD galactic plane

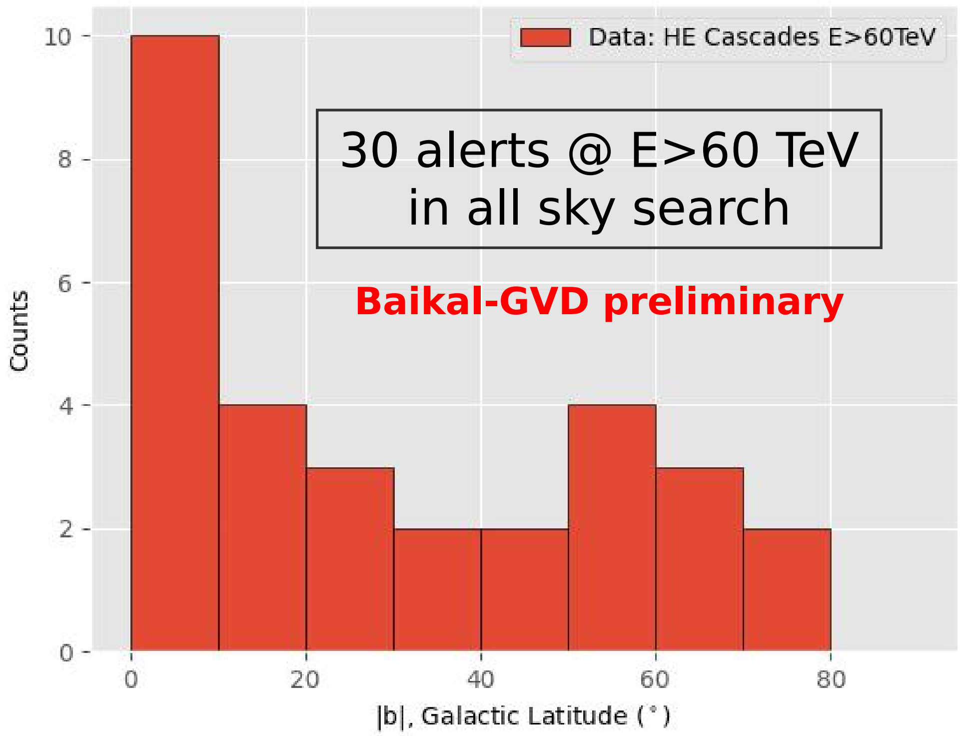
Hint on alert events concentration near galactic plane

Baikal-GVD: 25 all sky alerts for **04/2018-03/2022**




Baikal-GVD alerts compared to IC galaxy plane analysis

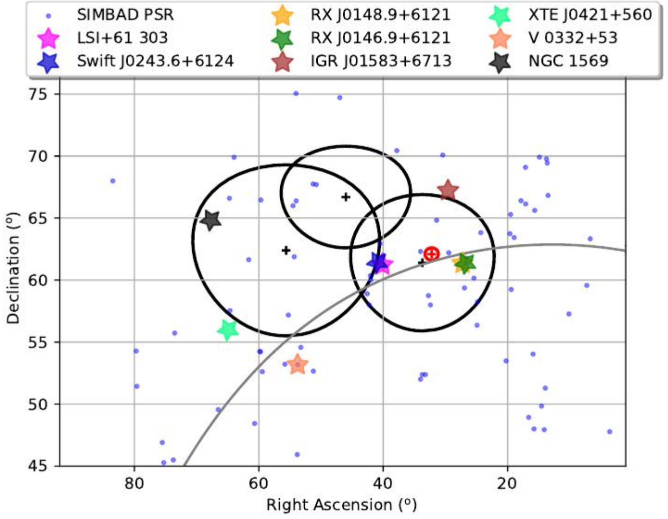
Extended dataset of
all-sky alerts **04/2018 - 03/2023**




Analysis continues

# Baikal-GVD HE cascade sky map

[MNRAS 526 (2023) 942]

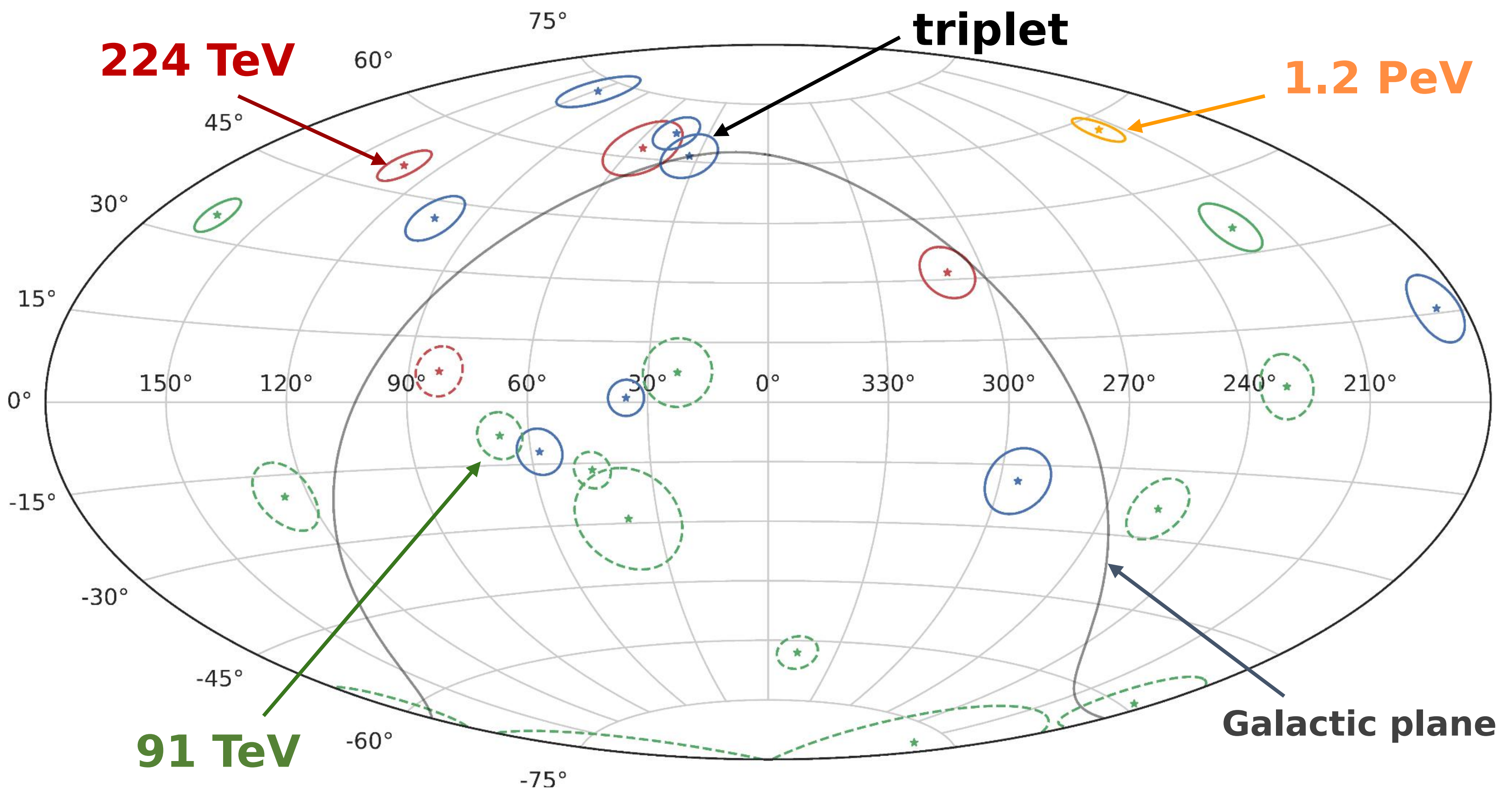



Three events close to the Galactic plane (grey line)

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

Intriguing coincidence in view of IC galactic plane analysis [Science 380, 6652, 1338-1343 (2023)]

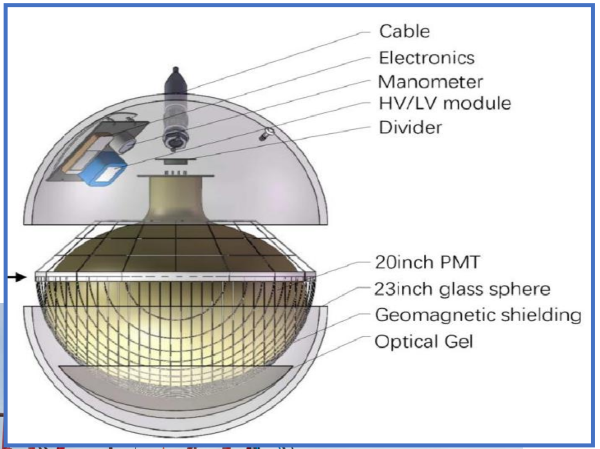
Best fit positions and 90% angular uncertainty regions




color represents energy:
$E_{rec}$ < 100 TeV
100 TeV < $E_{rec}$ < 200 TeV
200 < $E_{reco}$ < 1000 TeV
$E_{rec}$ > 1 PeV

# Expedition 2025

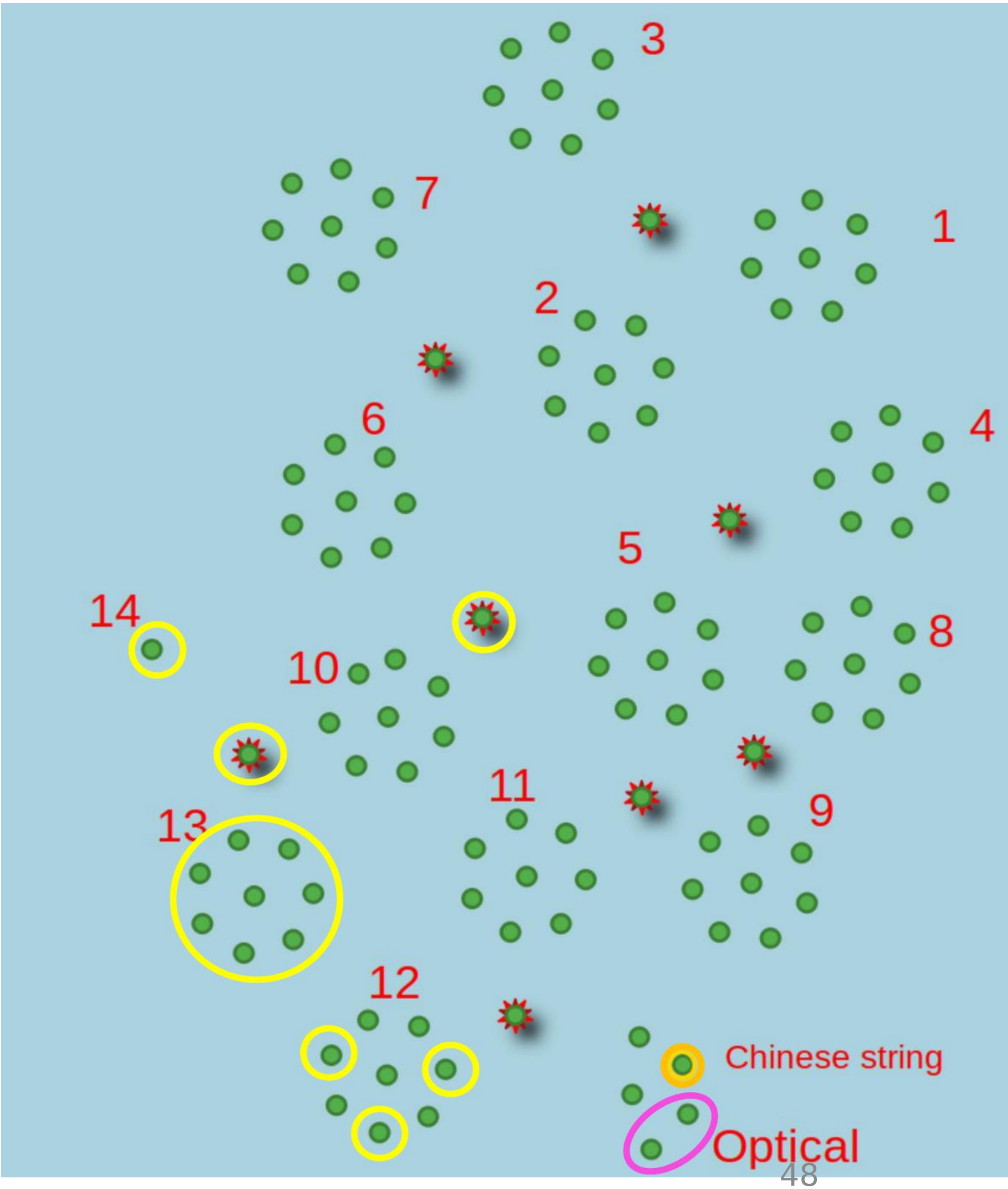
**Succesfull 2024 deployment campaign 16/02 - 07/04**
- 14 regular strings carrying 36 OMs installed
- 2 strins added to experimental (“optical”) cluster
- Pilot string for HUNT project



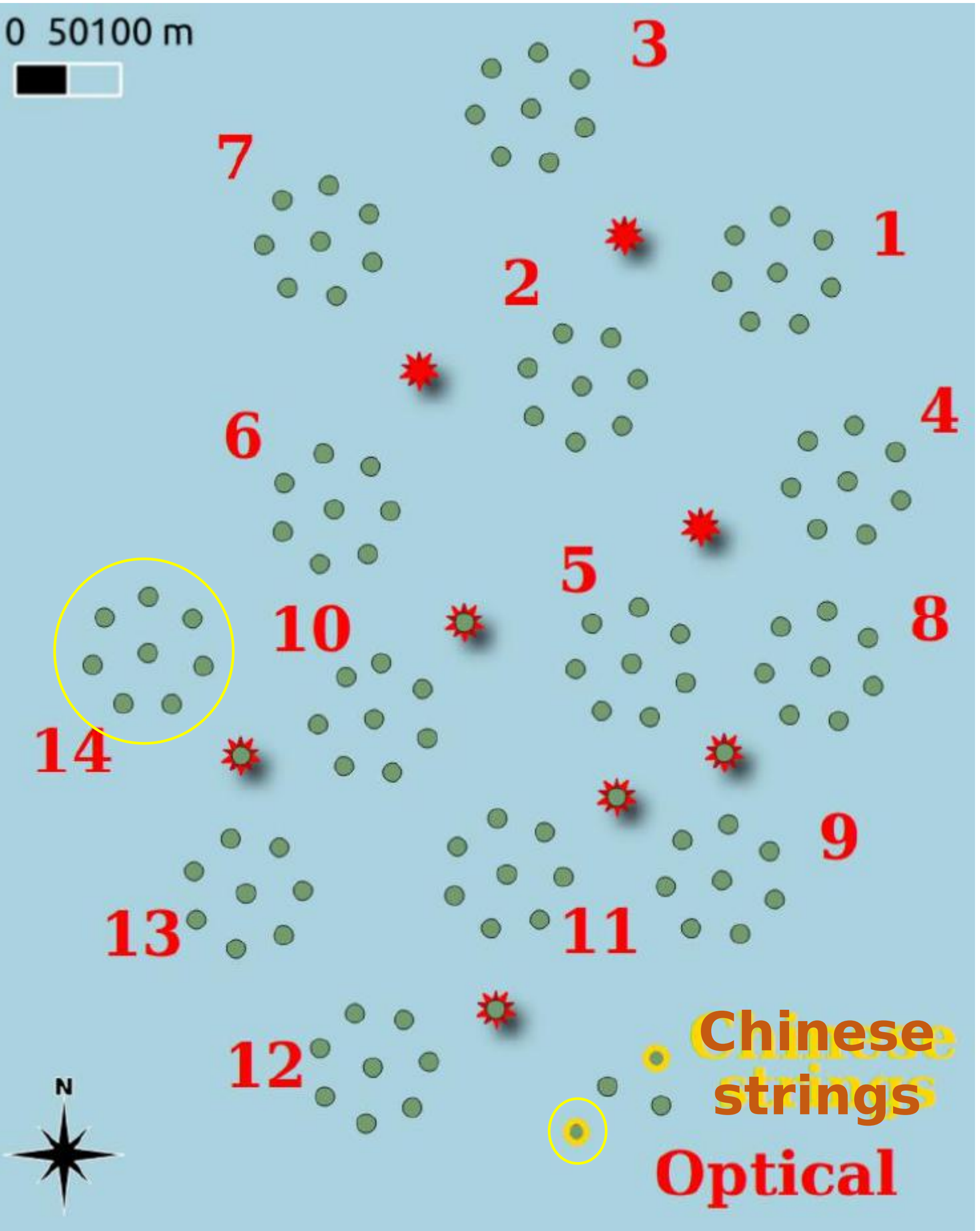

**HUNT** - next generation neutrino telescope project **[PoS(ICRC2023)1080]**

OMs based on 20-inch PMT

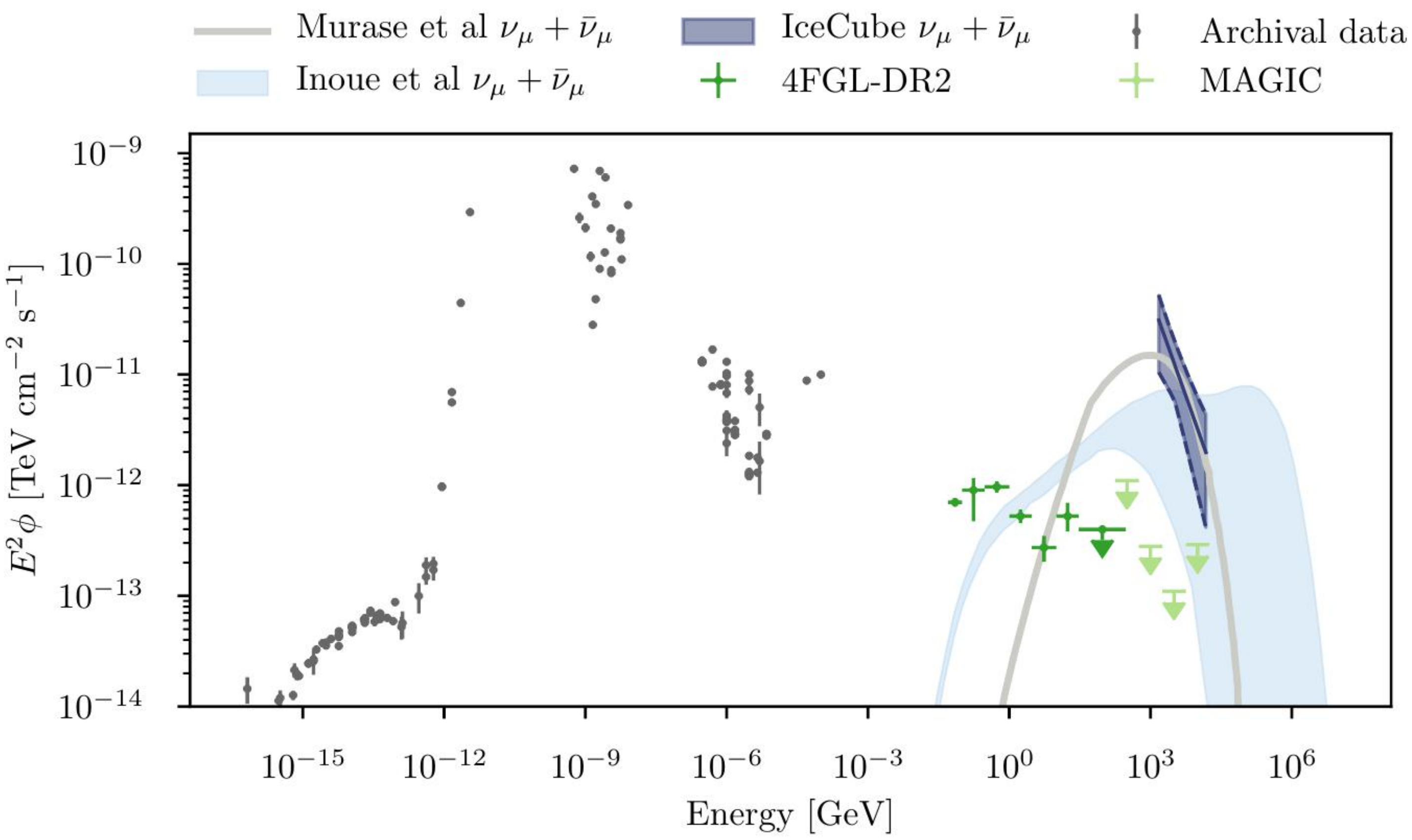
Pilot string with 12 OMs deployed as a part of experimental cluster in joint IHEP (Bejing) and Baikal-GVD effort



# Expedition 2025




# IceCube, NGC 1068 galaxy




Main contribution from $E_\nu$ ~ 1.5 - 15 TeV

- Soft spectrum

Neutrino spectrum in agreement with
**[Phys.Rev.Lett. 125 (2020) 011101, arXiv:1904.04226]**