Laboratori Nazionali del Sud

HIGH ENERGY ASTROPHYSICAL NEUTRINOS

PIERA SAPIENZA LNS - INFN on behalf of the KM3NeT collaboration

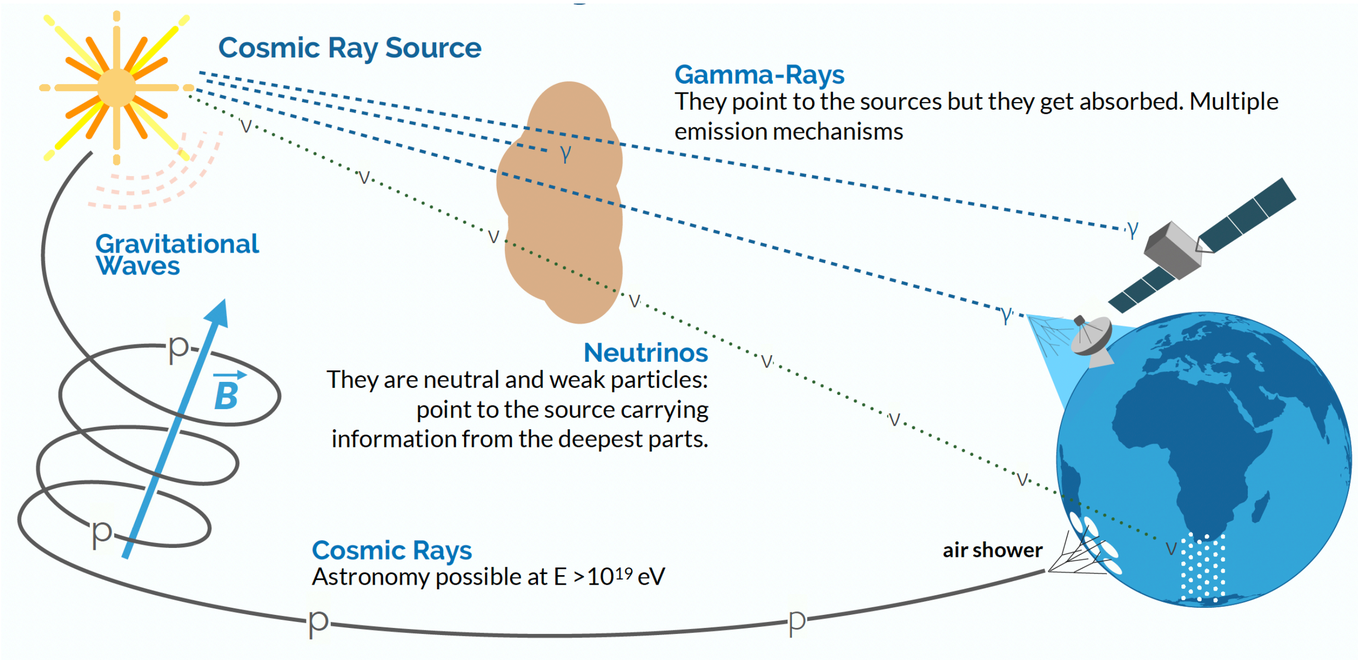
TAUP2025 25th August 2025 Xichang, CHINA

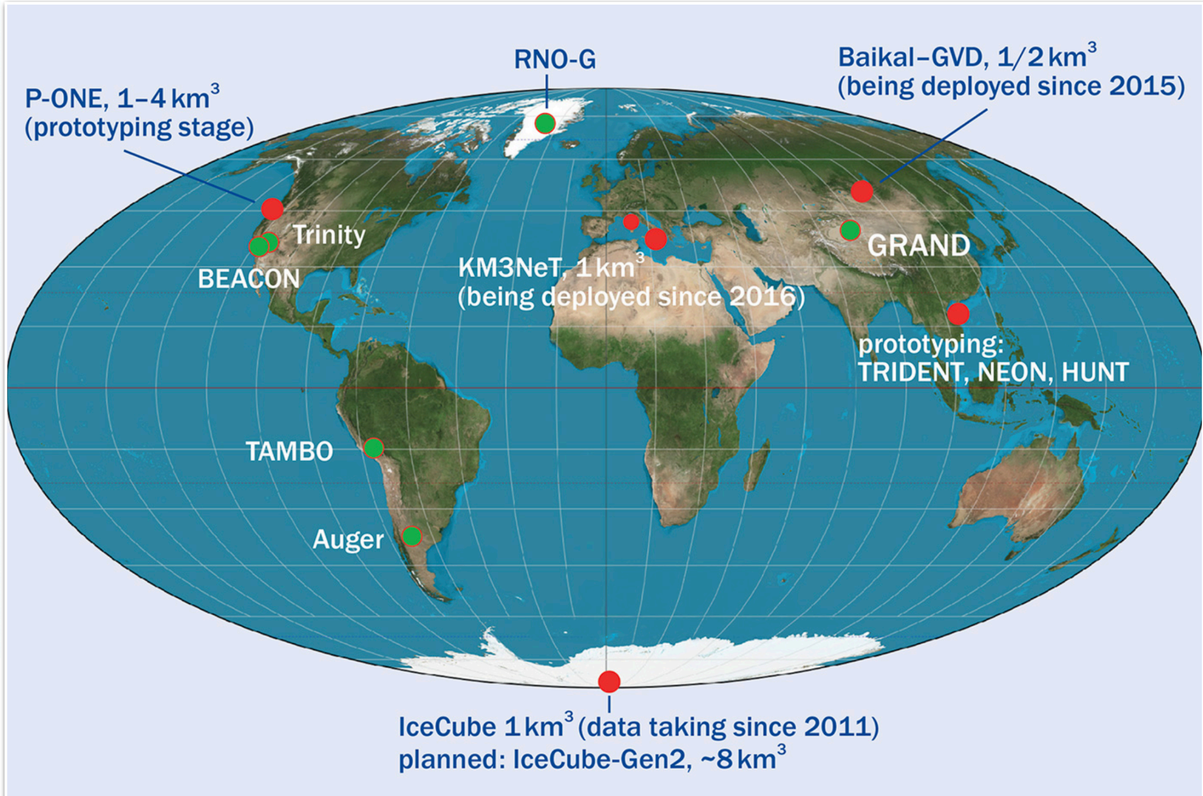
Neutrino astronomy

Neutrinos shed a new light on our Universe

Neutrinos interact weakly with matter, enabling them to image distant hadronic accelerators and environments that are otherwise obscured

In this talk I will present a review on neutrino astronomy focusing on high energy neutrinos observations from ice/water optical Cherenkov telescopes





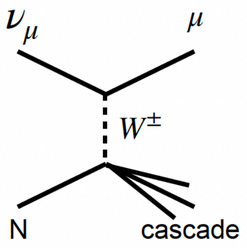
Optical Cherenkov HE neutrino telescopes

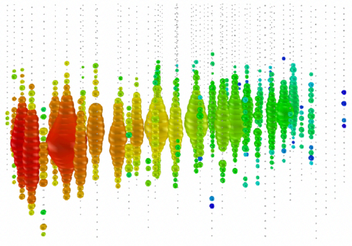
High energy neutrino detection requires volume of km^3-scale

- natural media to exploit optical Cherenkov effect in deep water or antarctic ice
  - threefold function: shield, target, radiator
- muons tracks are golden channel for neutrino astronomy

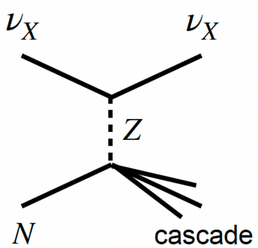
Extremely challenging experiments

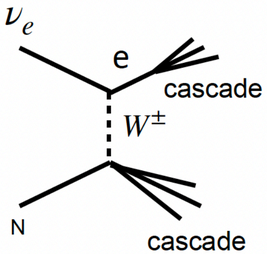
- harsh environments
- low signal rate and huge background

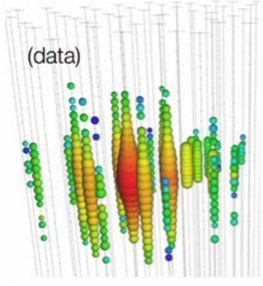




muon in IceCube







cascade in IceCube

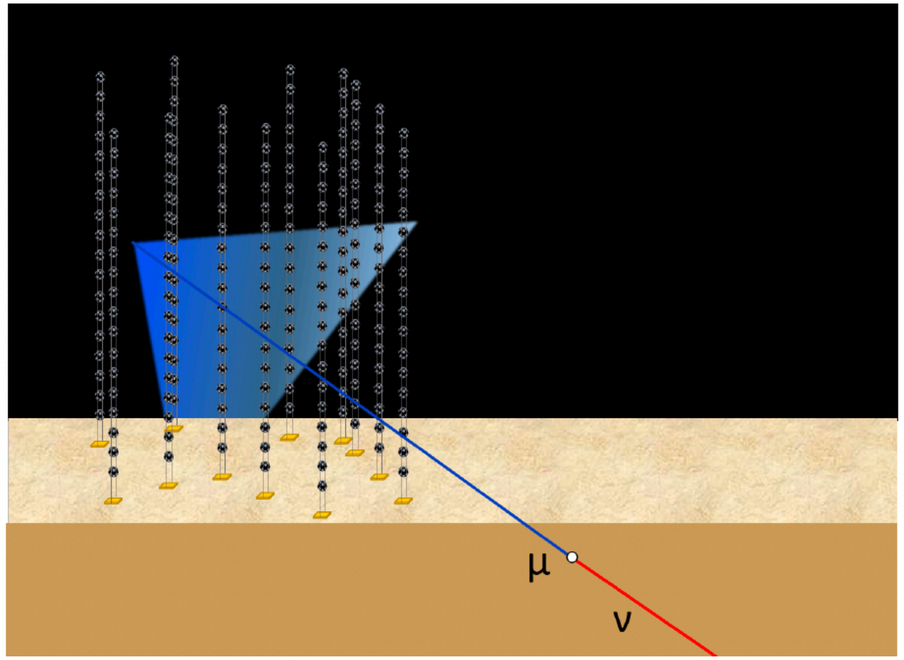
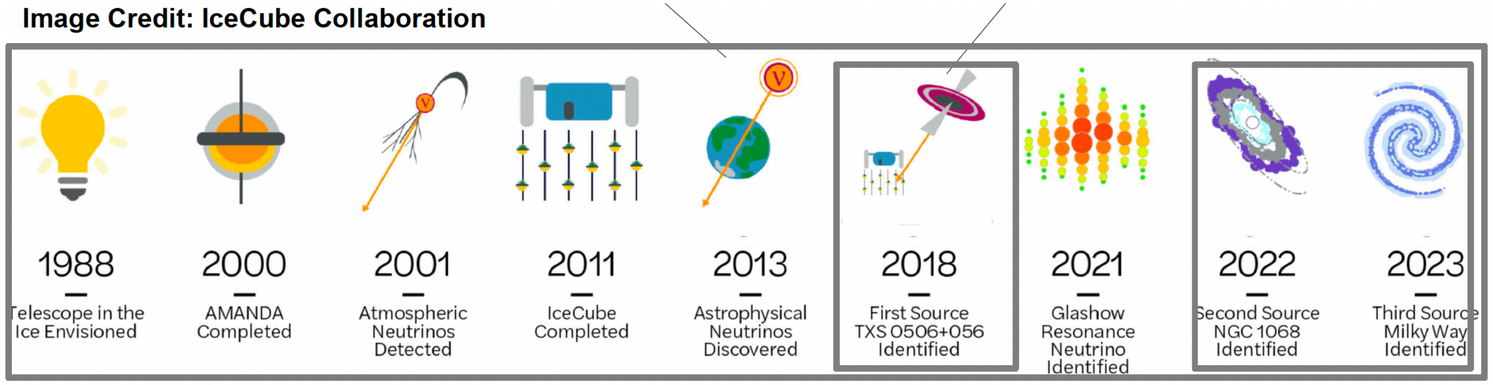


Image Credit: IceCube Collaboration



WATER PROPERTIES

Neutrino telescope	$L_{absorption}$ [488 nm]	$L_{scattering}$ [488 nm]
IceCube	190-200 m	20-26 m
KM3NeT	55-60 m	200 m
Baikal	20-25 m	40-80 m

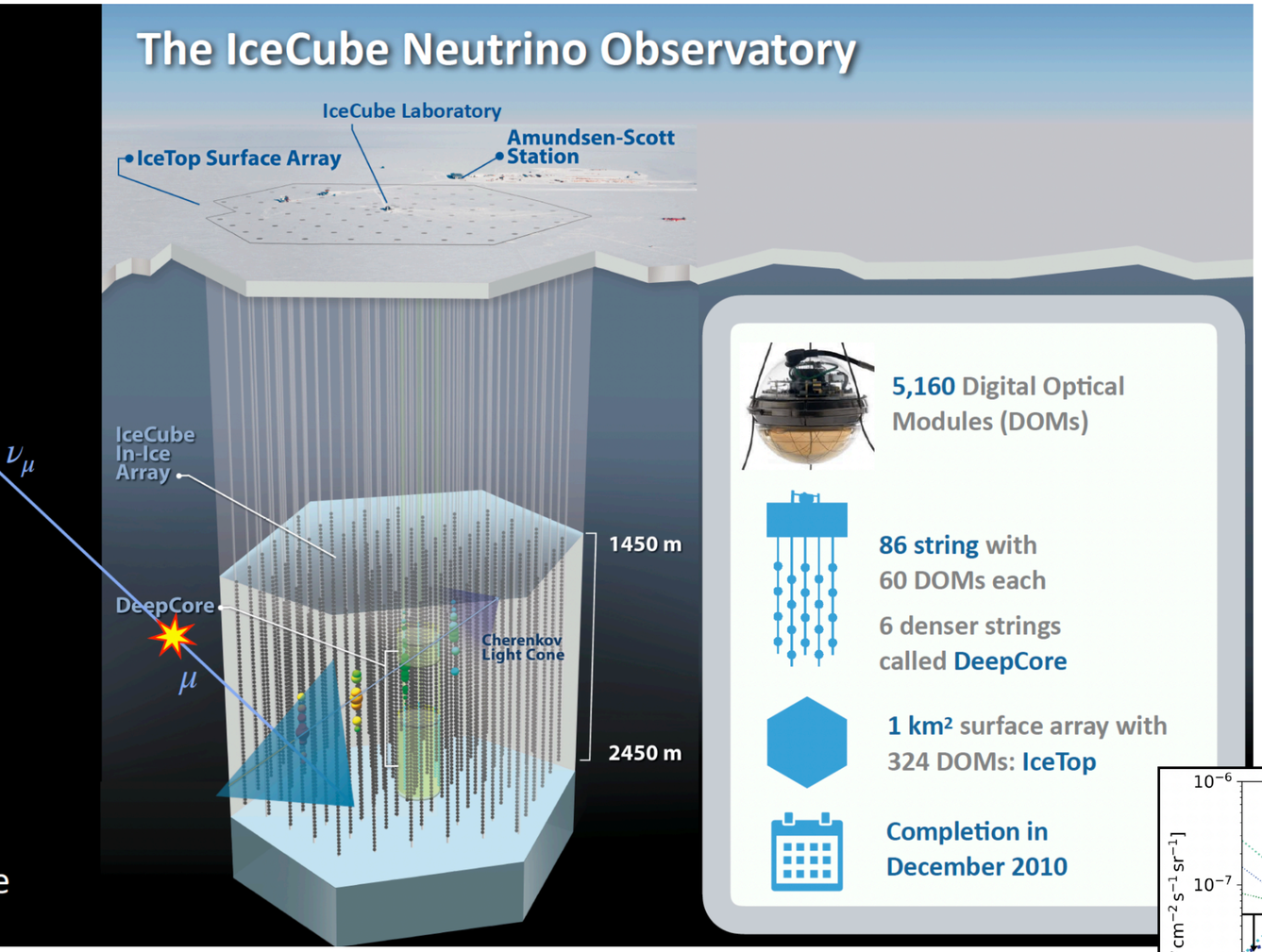
IceCube - Diffuse Flux

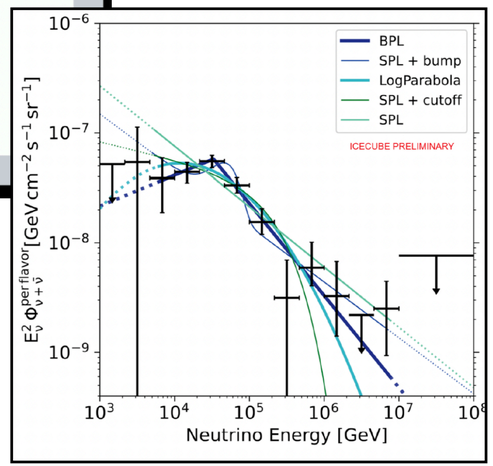
IceCube at South Pole is largest neutrino telescope in operation since 2011 with 1 km^3

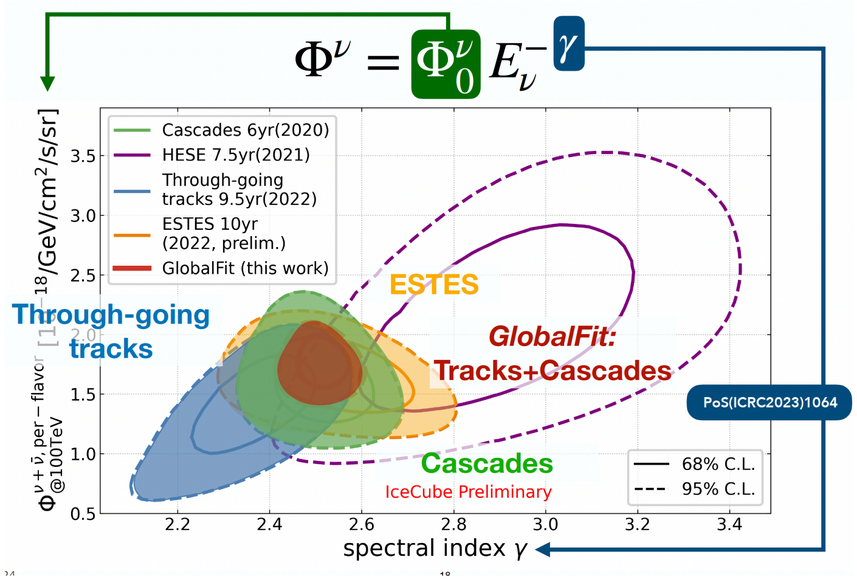
High energy neutrino astronomy *was* born with IceCube discovery of diffuse cosmic neutrino flux *Science 342 (2013)*

Following observations of diffuse cosmic neutrino flux in different cascade and track analysis

- spectrum flux and power index poorly constrained







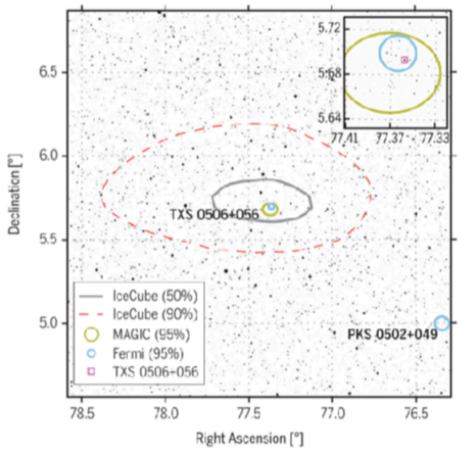
Aguilar-Sanchez Neutrino 2024

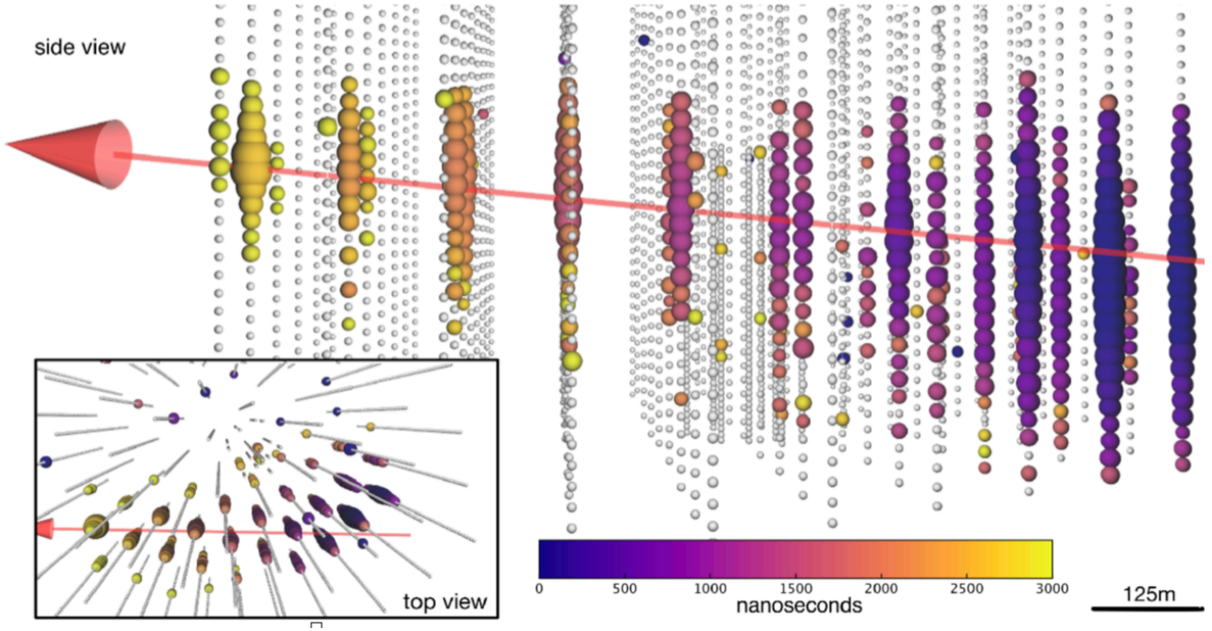
NEW! Preliminary analysis on MESE events (1 TeV - 10 PeV) presented at ICRC2025

4.7σ for broken power law: $\gamma_1 = 1.7 \pm 0.3, \gamma_2 = 2.8 \pm 0.1$

IceCube - Transient sources

IC-170922A detection initiated multi messenger astronomy - Science 2018





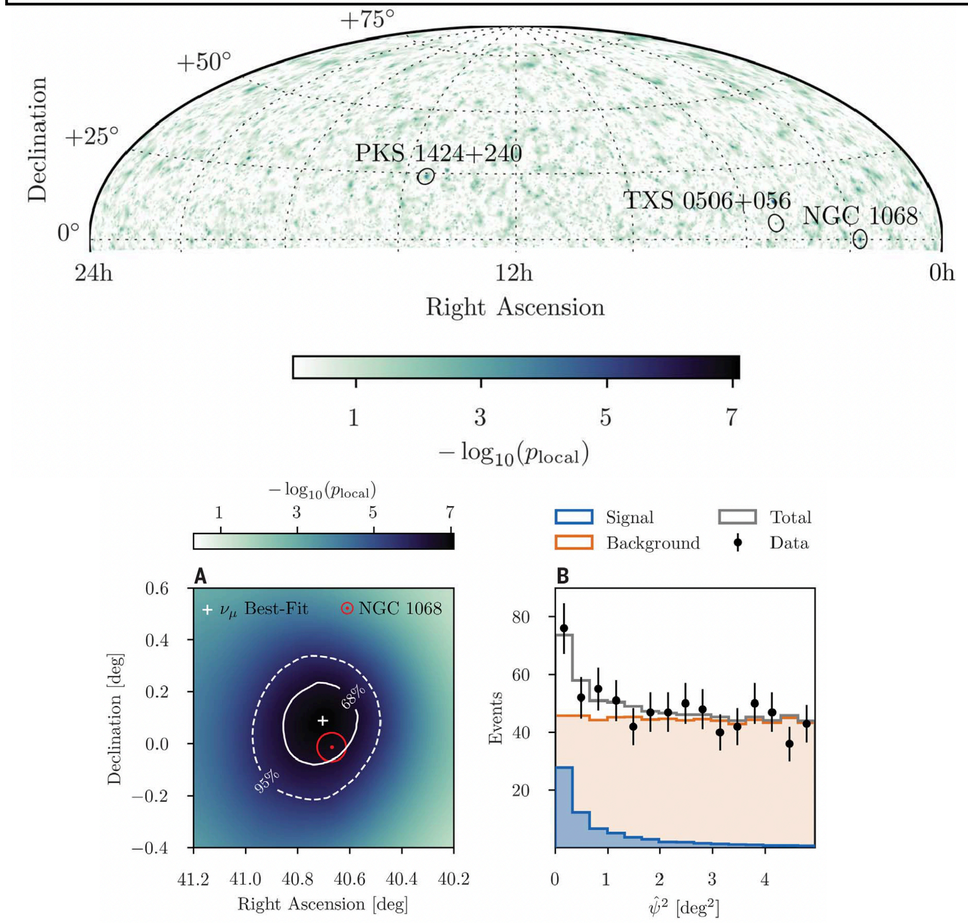
High neutrino alert followed by MAGIC detection of very high photons from TXS 0506+056 flaring blazar

- follow up by several other observatories (gamma, optical, radio, …)

see Nora Valtonen-Mattila talk on 28 August parallel session

IceCube - Point-like sources

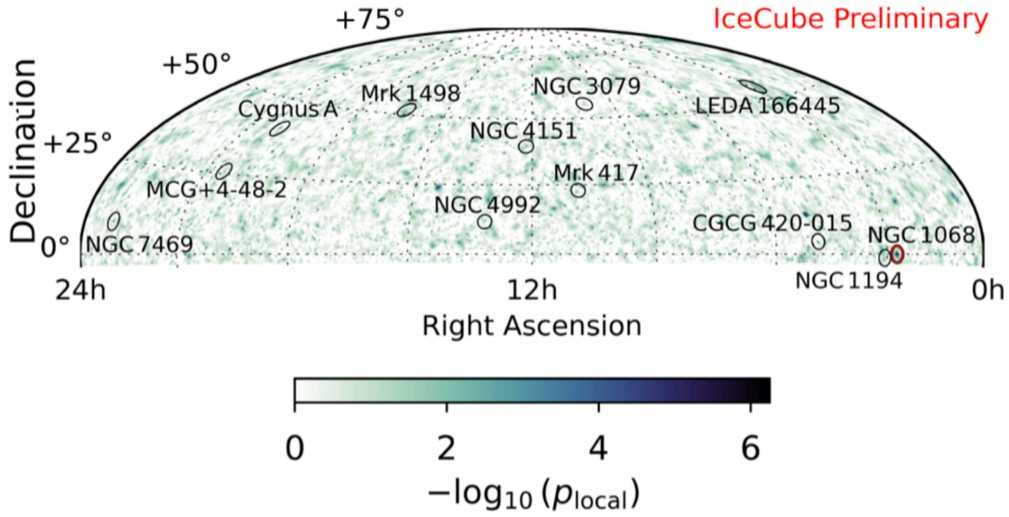
The first neutrino steady source NGC1068, Science 378, 538 (2022)

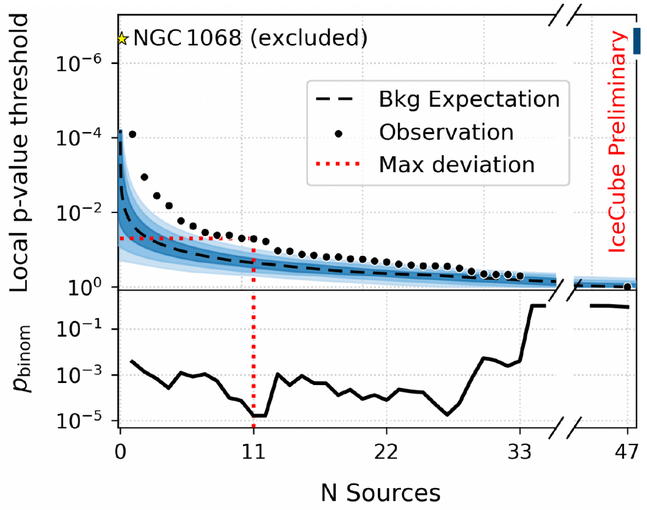


High-energy neutrinos detection at 4.2 sigma from active galaxy NGC 1068 powered by supermassive black hole

Flux more than an order of magnitude higher than the upper limit on emissions of TeV gamma rays

Search for neutrinos from Seyfert Galaxies





3.3 sigma excess observed stacking 11 sources over 47 (NGC 1068 excluded)

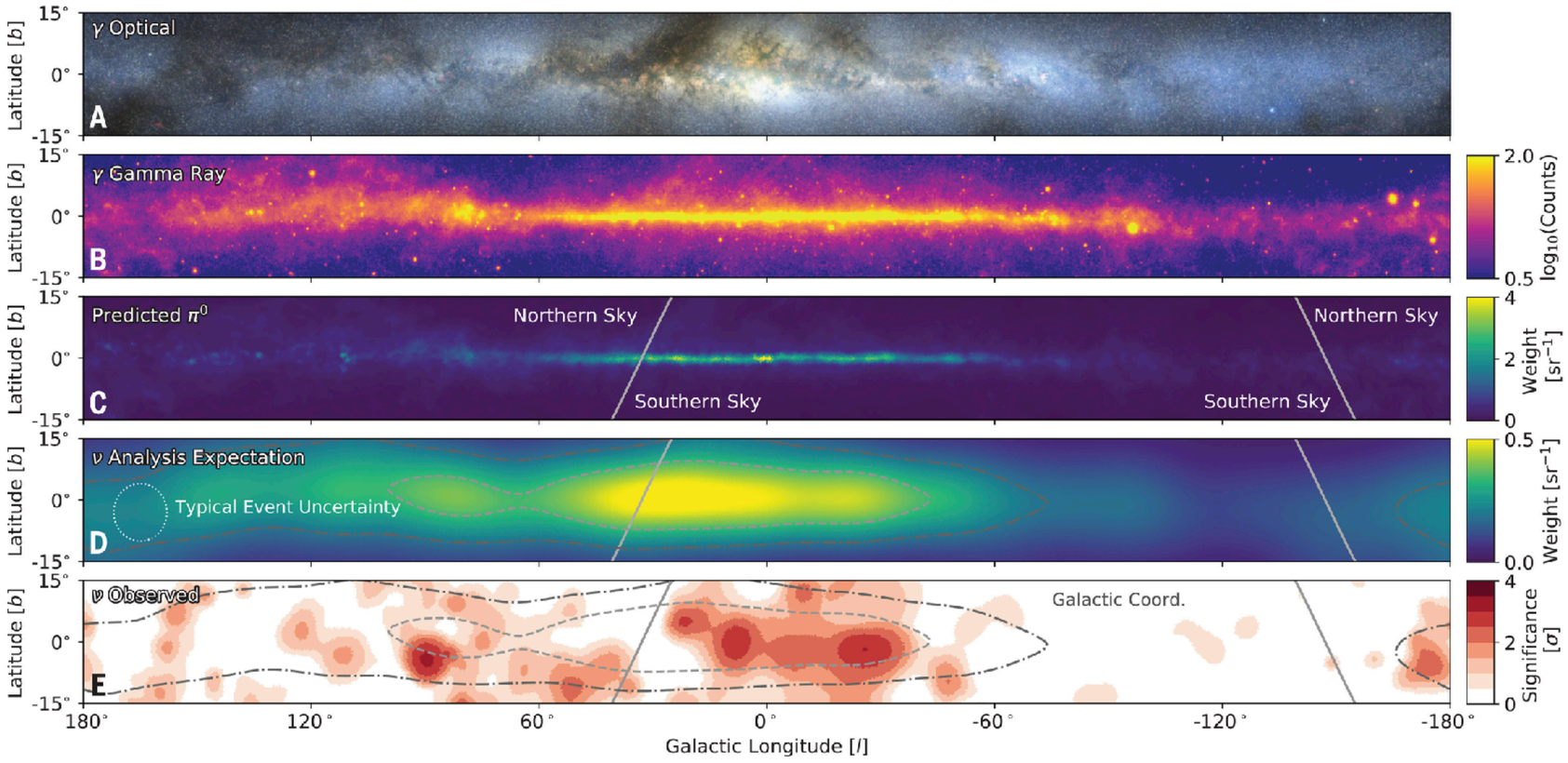
Aguilar-Sanchez Neutrino 2024

IceCube - Galactic Plane

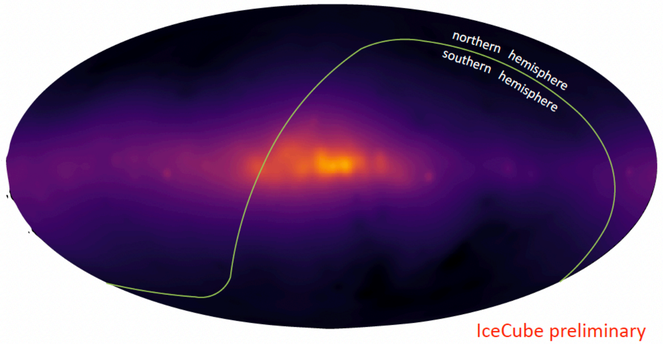
Neutrino detection from Galactic Plane at 4.5 sigma Science (2023)

- significance improvement presented at ICRC2025
  (+ 2.5 years of cascade data and upgoing tracks)

Observed flux does not agree with galactic diffuse models

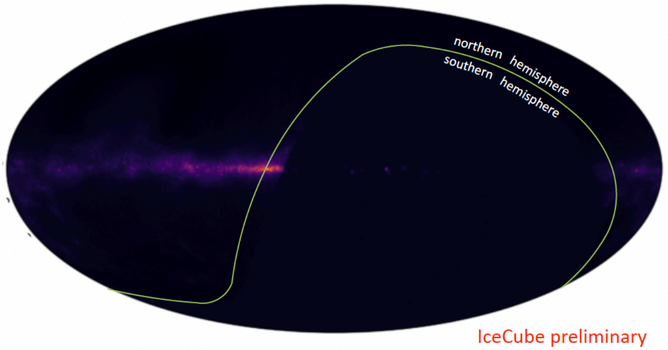


TS cascades (π^0)



IceCube preliminary

TS tracks (π^0)



IceCube preliminary

ANTARES 2007-2022

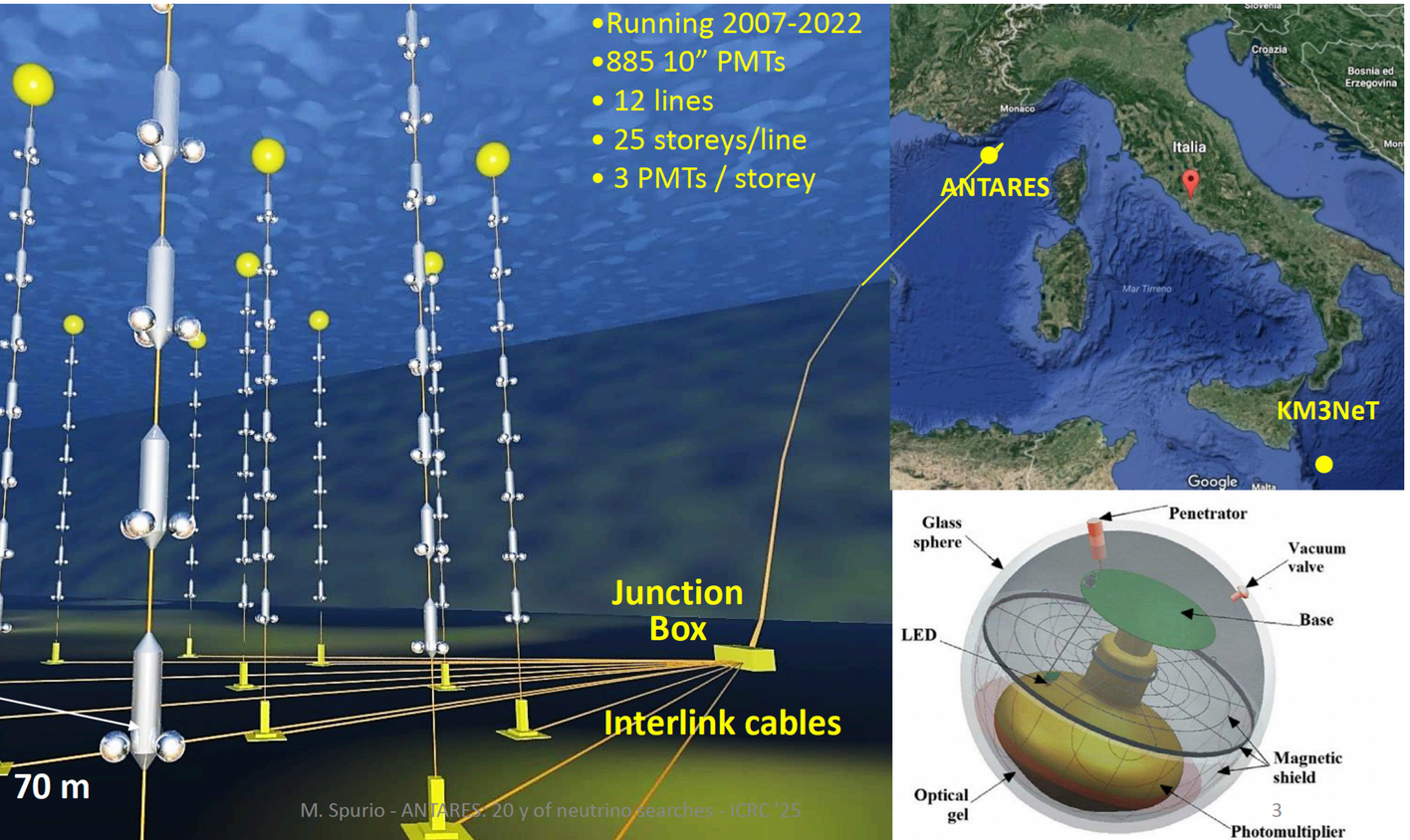
First deep underwater telescope

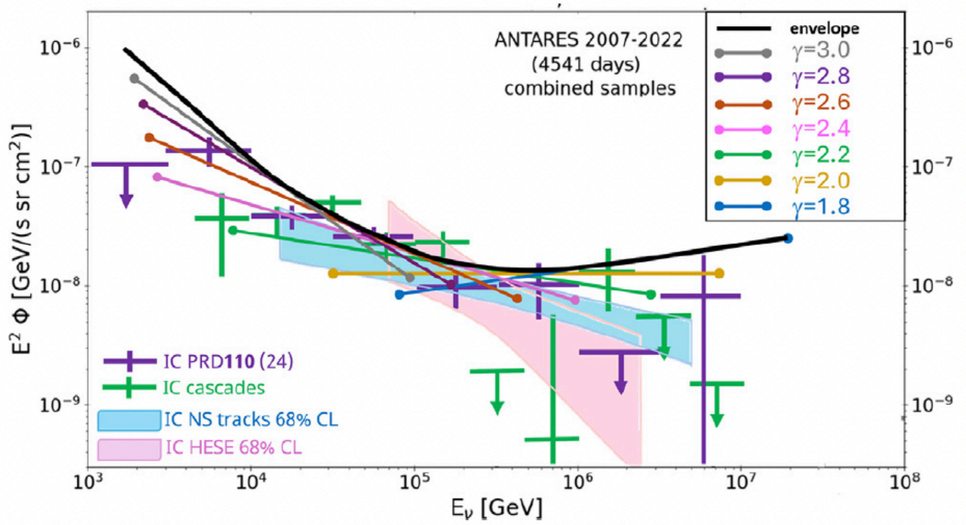
- survey of the southern neutrino sky
- paved the way to KM3NeT

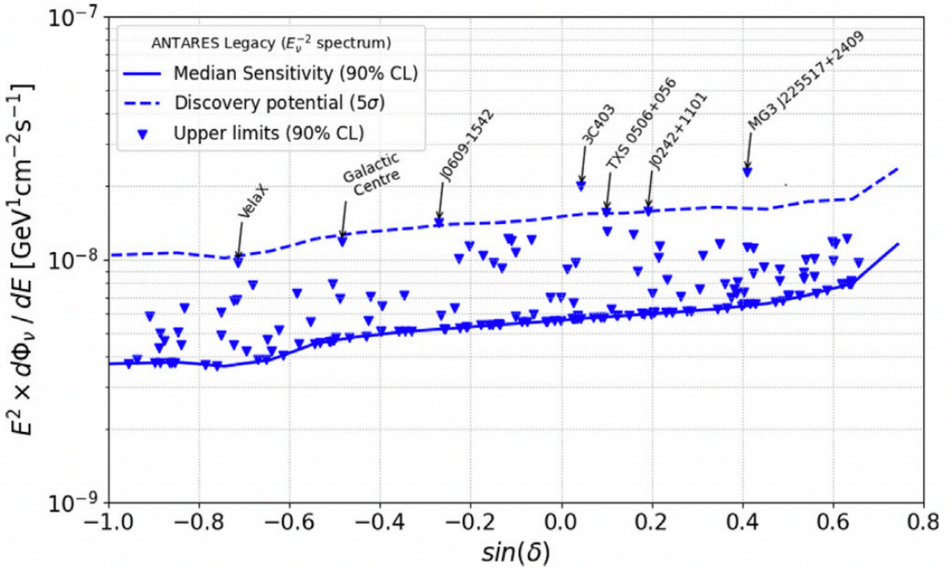
40 km off of Toulon (ORCA site)
Volume ~ 0.01 km^3, 2.5 km deep

No neutrino observation, but competitive limits

Main results on Legacy Paper Physics Reports vol 1121-24 (2025)



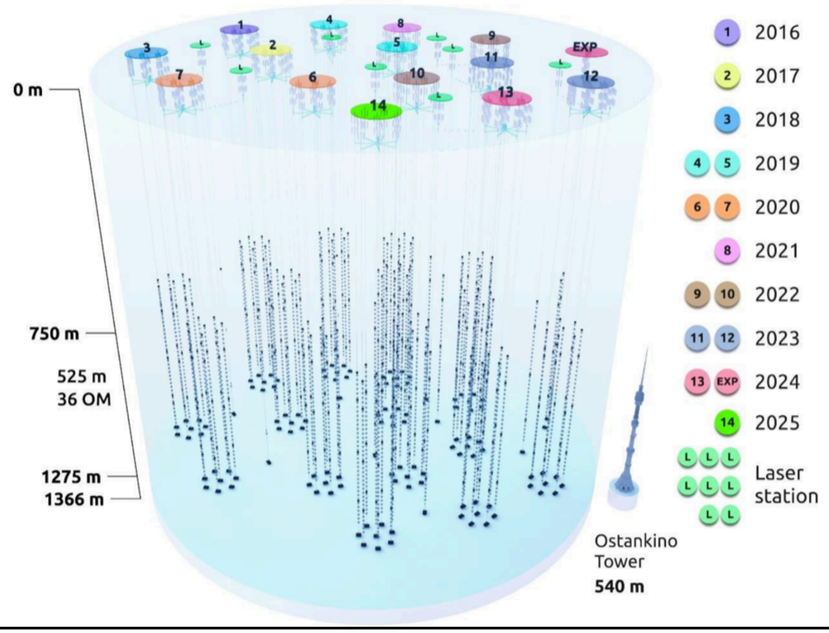




Best limit on point-like source in southern hemisphere
improvement of 20% adding ARCA6-21 data

see Vittorio Parisi talk today parallel session

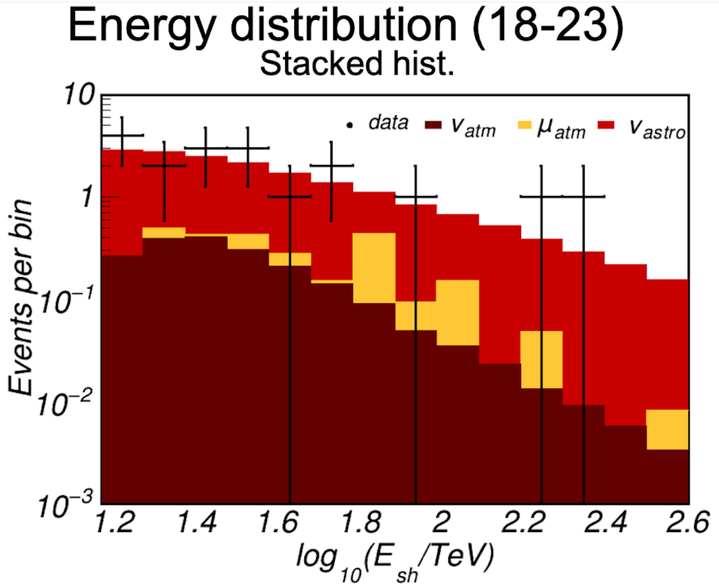
Baikal-GVD

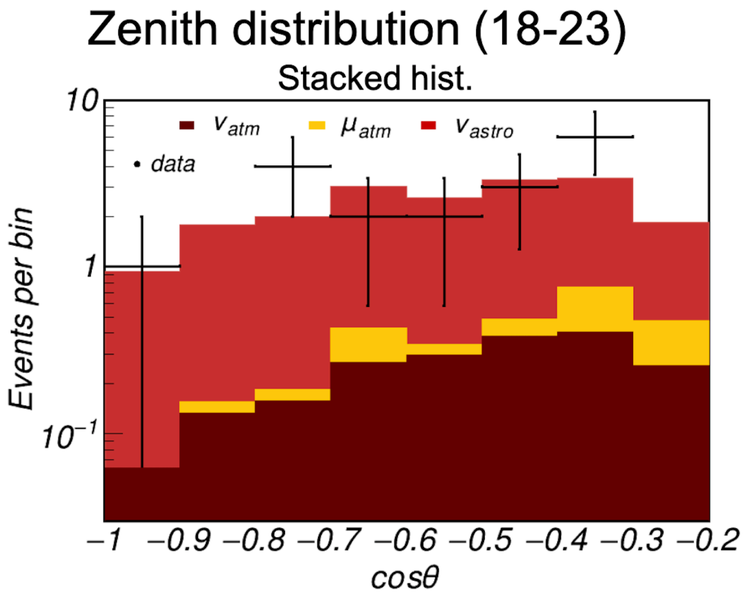


Size 1 km^3, in construction at Lake Baikal at 1400 m depth

14 clusters already deployed, actual size 0.7 km^3

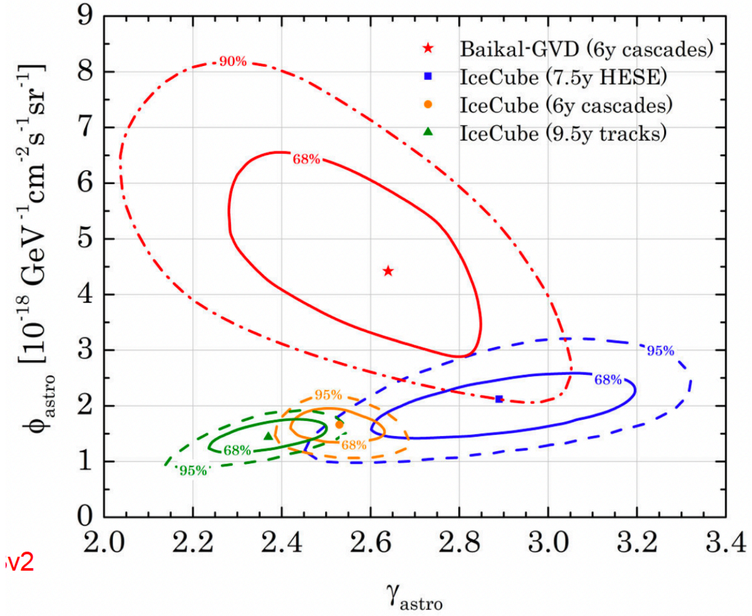
see Dmitry Zaborov talk on 28 August parallel session



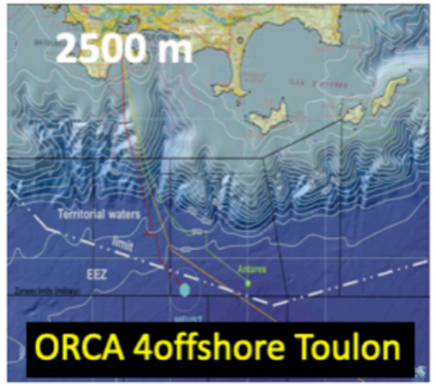


First independent observation of diffuse cosmic neutrino flux at 5.1 sigma!!!

- upgoing cascade on 2018-2023 data sample
- flux larger than IceCube flux

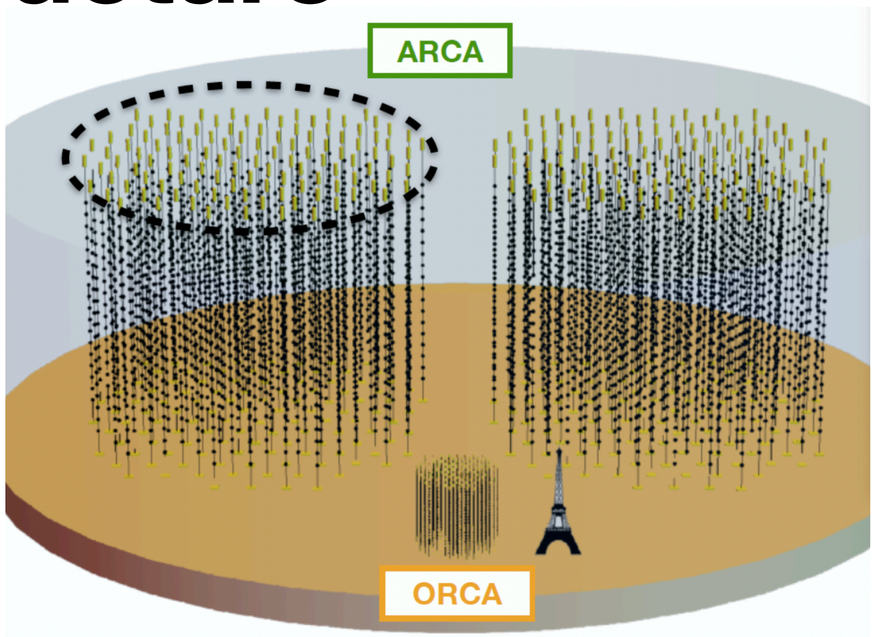


KM3NeT - a distributed infrastructure



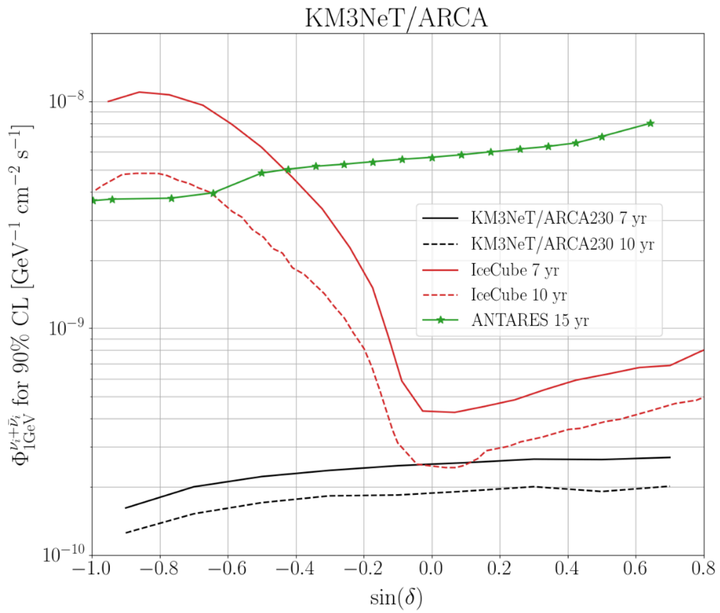
Two telescopes, one technology

- innovative with multi-PMT DOM that inspired several new projects



Oscillation Research
with **C**osmics In the **Abyss**

Astroparticle Research
with **C**osmics In the **Abyss**



see Vittorio Parisi talk today parallel session

Building blocks of 115 strings
DOM distance => Energy range
ARCA 2BB 1 km^3
51/230 strings deployed
ORCA 1 BB 7 Mton
28/115 strings deployed

KM3NeT with its large effective area, sky visibility and unprecedented angular resolution will improve neutrino discovery potential especially for point-like sources

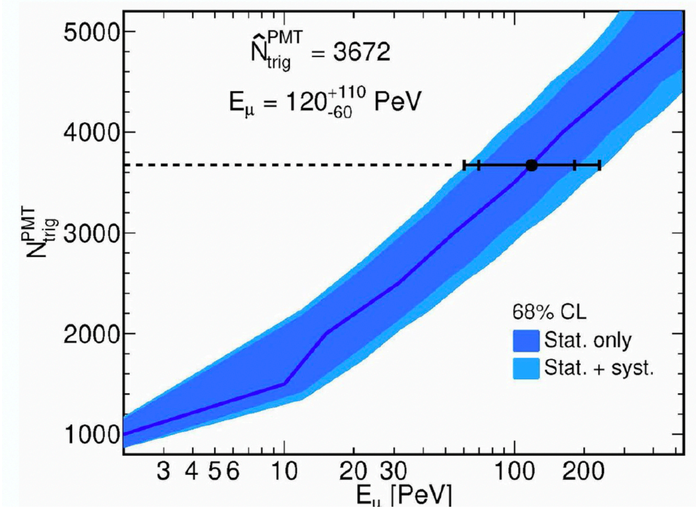
Uncharted territory: breaking into a new energy regime

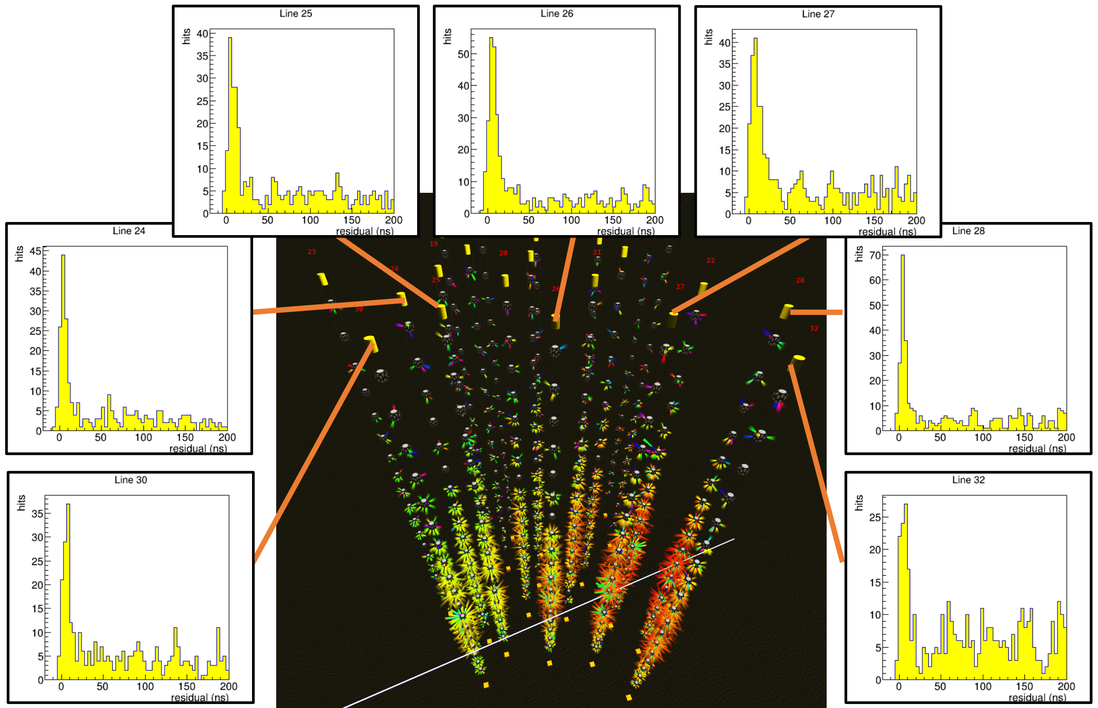
KM3NeT still in construction, detected the most energetic neutrino ever seen *Nature* **638**, 376–382 (2025)

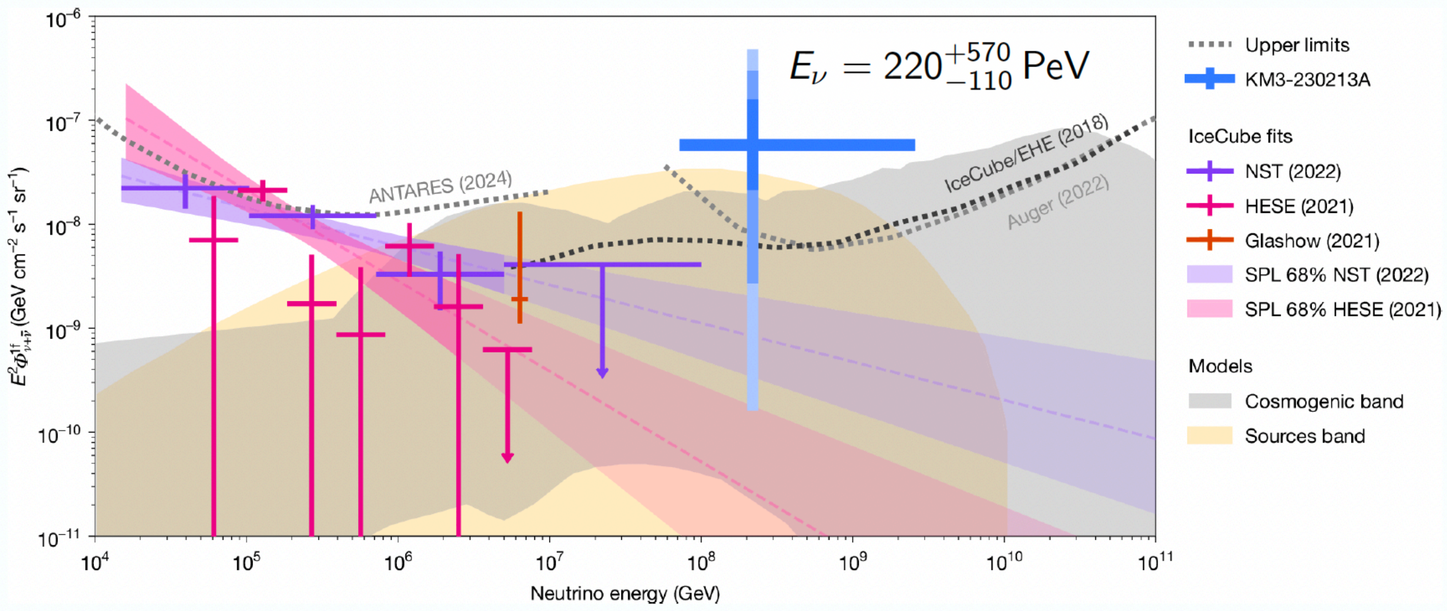
Local coordinates: (zenith, azimuth) = (89.4°, 259.8°):

- **Celestial coordinates: (RA, dec) = (94.3°, –7.8°)**
- R(68%) = 1.5°, R(90%) = 2.2°, R(99%) = 3.0°
- Limited by the absolute positioning of the detection elements (intrinsic reconstruction uncertainty of 0.12°)

A long baseline acoustic array deployed in July 2025 will allow more precise data (re)calibration







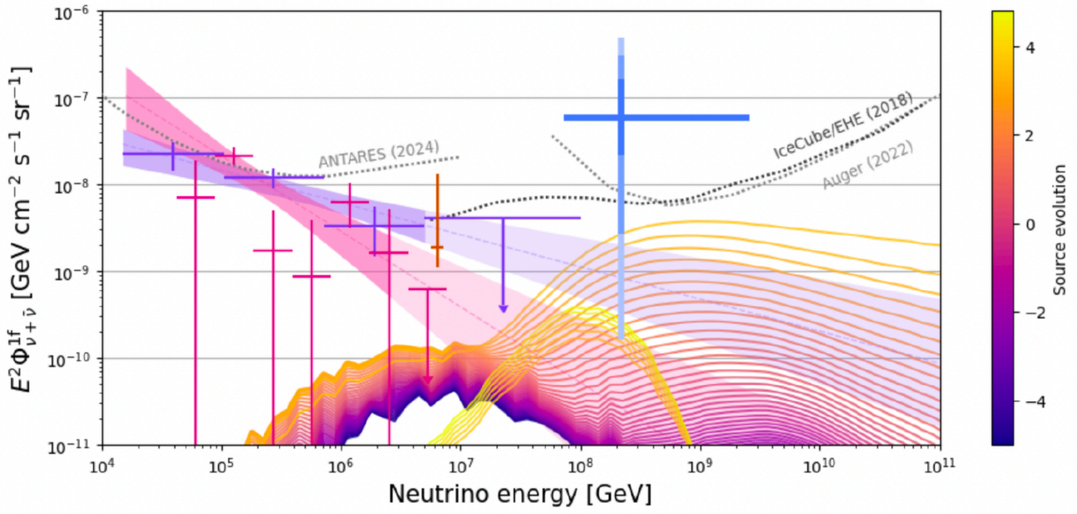
Moderated tension with IceCube and Auger no observations (2.5 sigma)

KM3-230213 1st UHE neutrino

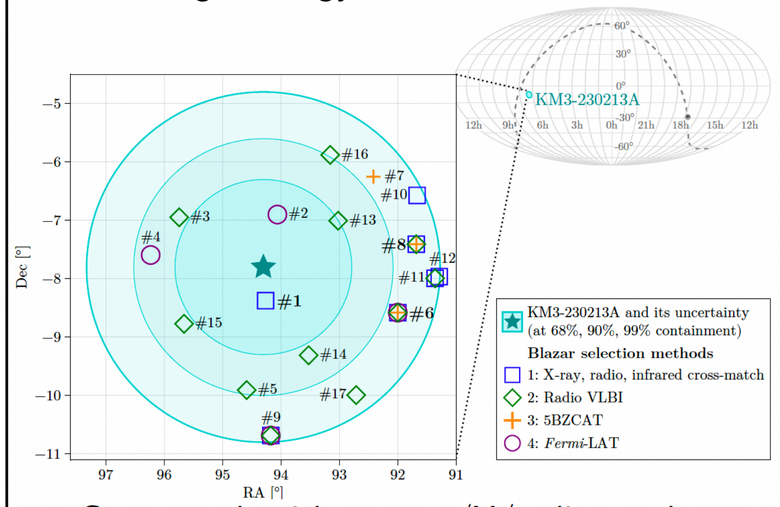
UHE neutrino can be cosmogenic or produced in most powerful accelerators such AGN, GRB, TDE,…

On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A - 2025 *ApJL* **984** L41

- constrains on Auger+ TA UHECR data
- subdominant fraction of proton at UHE
- high z



Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A

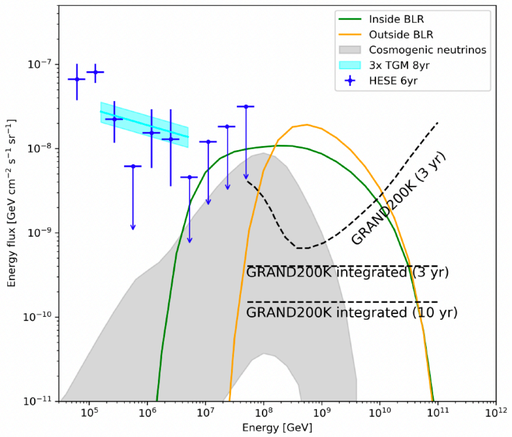


Crossmatch with gamma/X/radio catalogs

- **17 blazar candidates** identified
- 3 coincidence electromagnetic flares but **nothing conclusive**

KM3NeT collaboration arXiv: 2502.08484

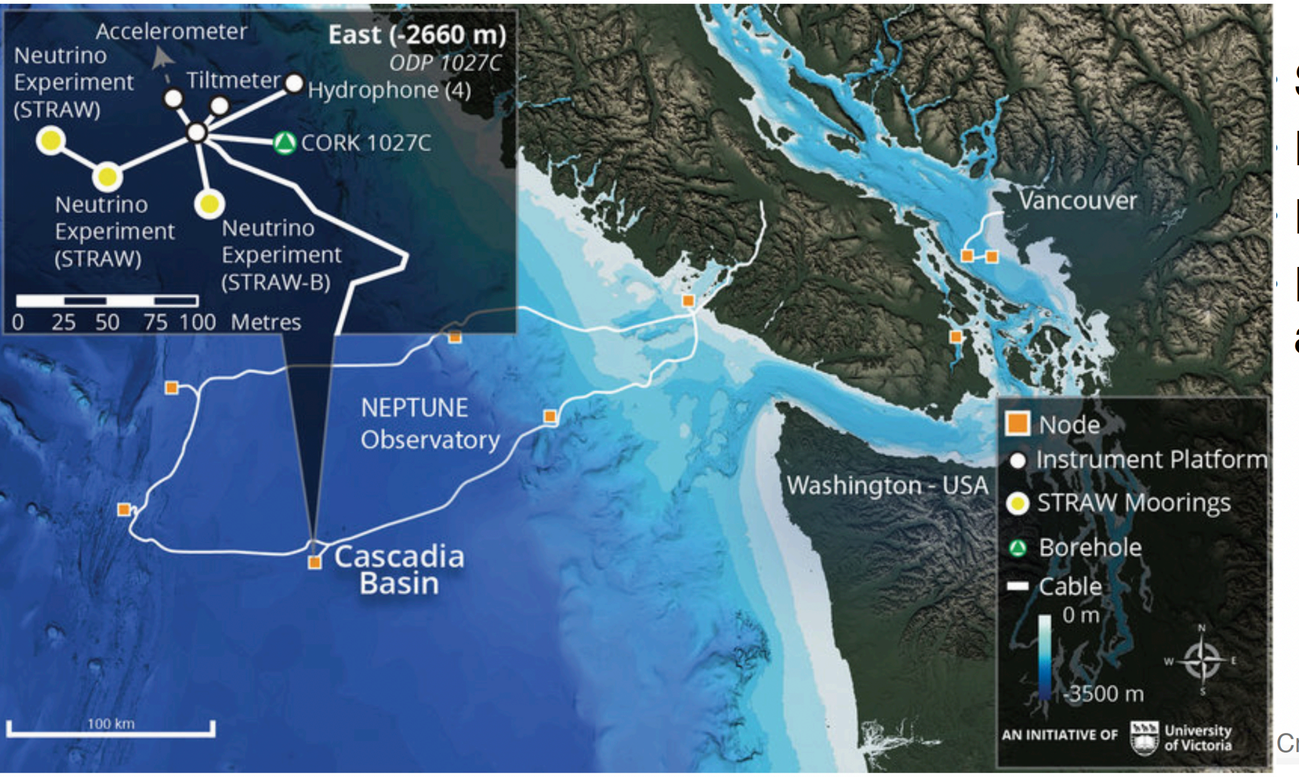
EeV Astrophysical neutrinos from FSRQs? C. Righi et al, Astronomy&Astrophysics (2020)



Exotics interpretations have also been proposed….

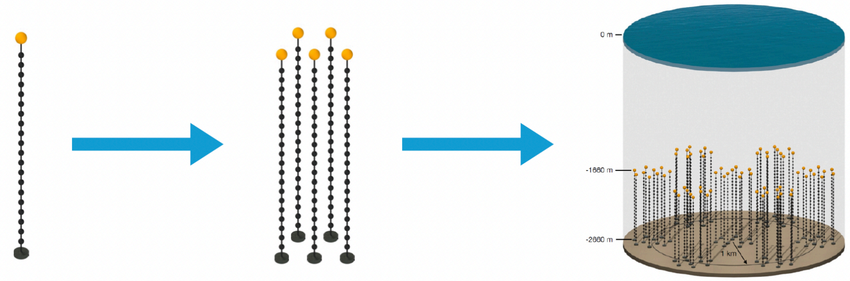
Future projects - P-ONE

1 km^3 project located in Cascadia Basin

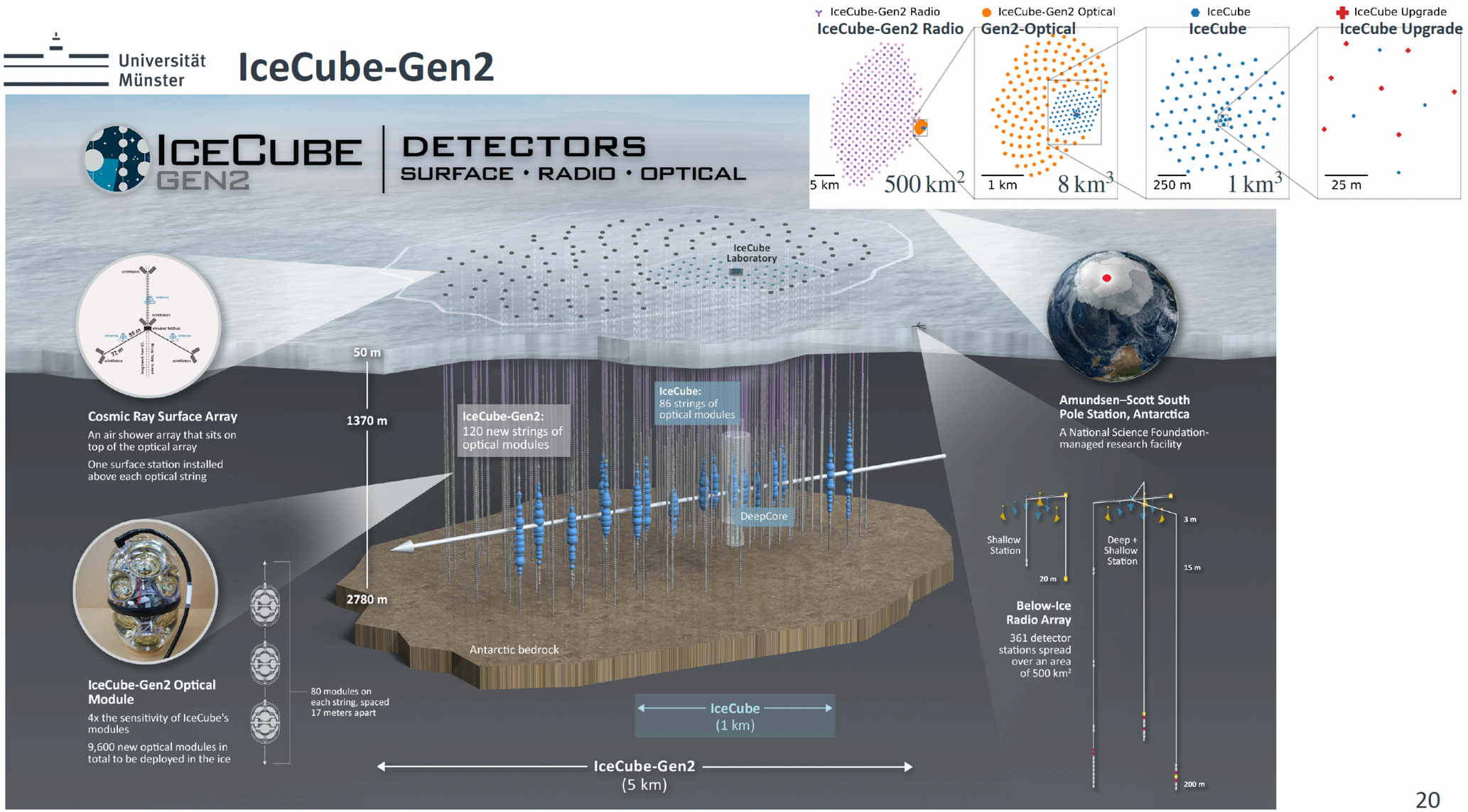


Source: Ocean Networks Canada

- Significant development milestone already achieved
- Final assembly and testing on-going
- First target of opportunity for deployment in the 2026 season
- First step towards the P-ONE Demonstrator (first ~5 lines, already funded) and P-ONE Array (planned, 80-100 lines)



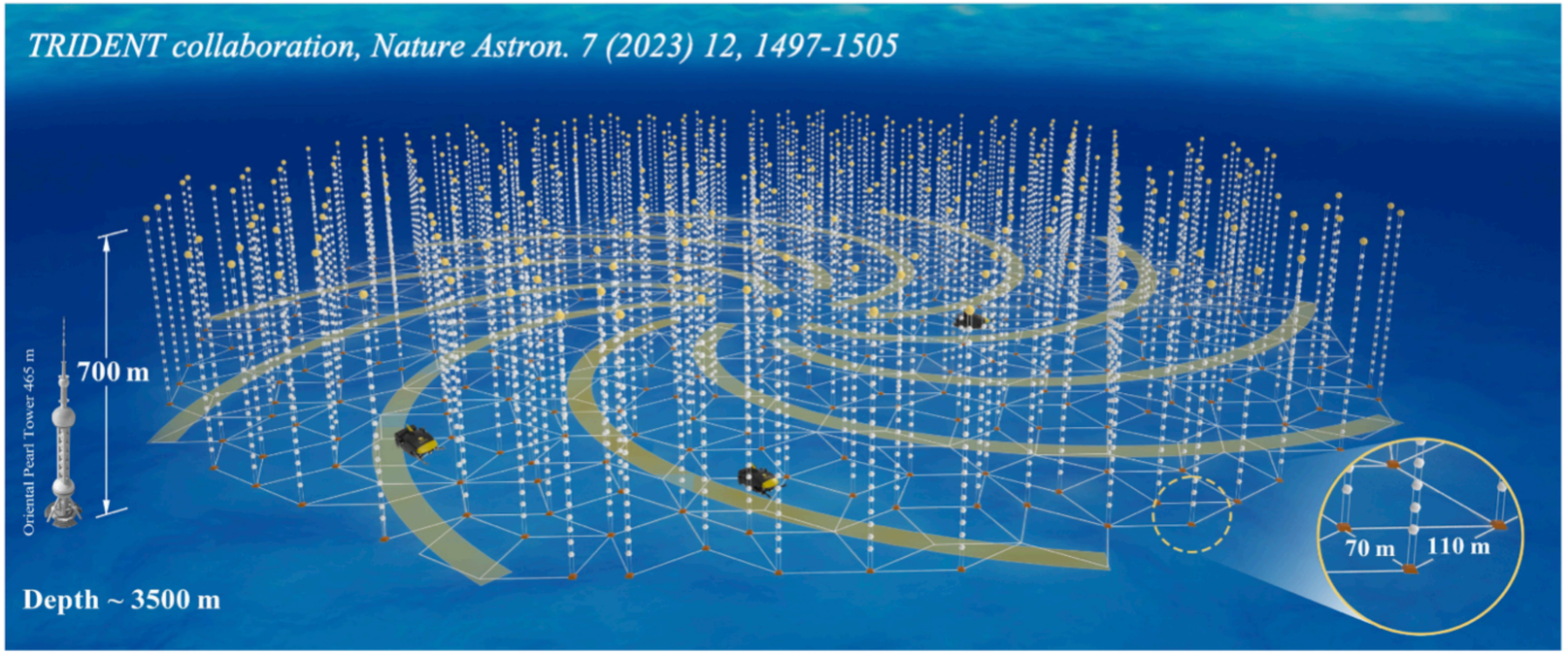
Future projects -IceCube-Gen2

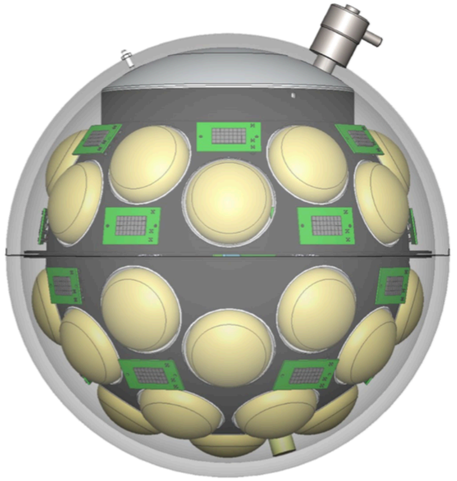


Future projects - TRIDENT

South China Sea

- Water depth: ~3500m
- Number of strings: ~1000, 20,000 hDOMs, Penrose-tiling
- Inter-string distance: 70m/110m Inter-DOM distance: 30m
- Detection Volume: ~8 km^3



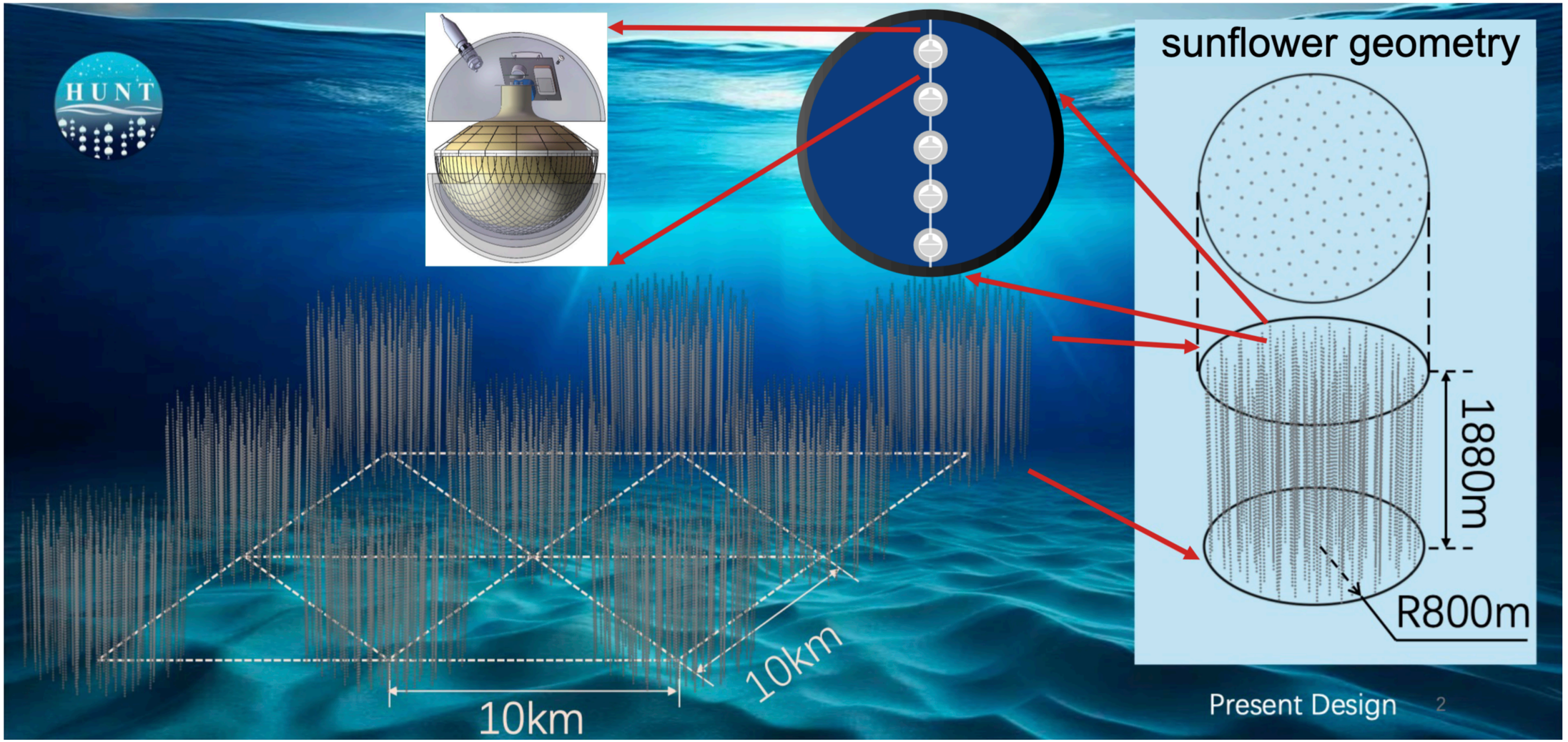


Hybrid optical module
multi-PMT + SiPM

see Xin Xiang and Iwan Morton-Blake talks on 28 August

Future projects - HUNT 30 km^3

South China Sea/Lake Baikal



Conclusions - Status of art

Neutrino astronomy is in its discovery phase with exciting observations from the three km^3 optical Cherenkov experiments already running

KM3NeT and Baikal construction to be completed

AUGER provided competitive limits at very high energy

see Piera Luisa Ghia and Rossella Caruso talks today

Several other projects are at design and prototyping phase

- IceCube-Gen2

- P-ONE, TRIDENT, HUNT

see Xin Xiang and Iwan Morton-Blake talks on 28 August

- Radio and particle detectors: GRAND*, RNO-G*, Trinity and BEACON, TAMBO *not covered in this talk*

*see Guoyuan Huang and Jethro Stoffels talks on 28 August

Conclusions - Highlights

- IceCube provided several strong evidences of diffuse cosmic neutrino flux
- IC-170922A alert in coincidence with flaring blazer TX0506+056 inaugurated neutrino multi-messenger astronomy
- Neutrinos from Galactic Plane observed by IceCube at > 4.5 sigma
- IceCube reported first evidence of neutrino emission from steady source NG1068
    - few other steady sources close to detection threshold
- Baikal provided first independent evidence of diffuse cosmic neutrino
- KM3NeT break into a unexplored region detecting a UHE neutrino with 220 PeV energy

Conclusions - Open questions

- **Diffuse neutrino cosmic flux**
  - large power index spread for different IceCube event selection
  - preliminary analysis of IceCube MESE events favor a broken power law
  - Baikal diffuse neutrino cosmic flux overshoot IceCube flux by about a factor two
  - source population not clearly identified
- **Few neutrino sources identified, not always associated with bright gamma sources**
- **Origin of UHE neutrino KM3-230213 cannot be established on the base of a single event**
- **…**

Conclusions - Perspectives

- **IceCube** with its huge exposure and ongoing developments will continue to be a key player increasing significance for several sources already spotted
- **Baikal,** actually largest telescope in the Northern Hemisphere, is expected to be completed around 2030 and will have an important role
- **KM3NeT**, with 51/230 strings already deployed and completion foreseen in 2030, will be a key player with a major role in source identification thanks to its unprecedented angular resolution
- **New generation projects**
- optical Cherenkov with larger volumes, up to tens of km^3 (IceCube-Gen2, TRIDENT, HUNT)
- radio experiments that allow to increase detection volume by two order of magnitude

will strongly increase HE neutrino detection rate enlarging discovery potential for neutrino sources and allowing to investigate the highest energy region where KM3-240213A stemmed out and beyond

High energy neutrino telescope operating in different locations will assure a **complete survey of the sky**, with large overlapping regions at the same time, their c**ooperative efforts** with combined analysis will boost high energy neutrino discovery potential providing a deeper understanding of the high energy Universe

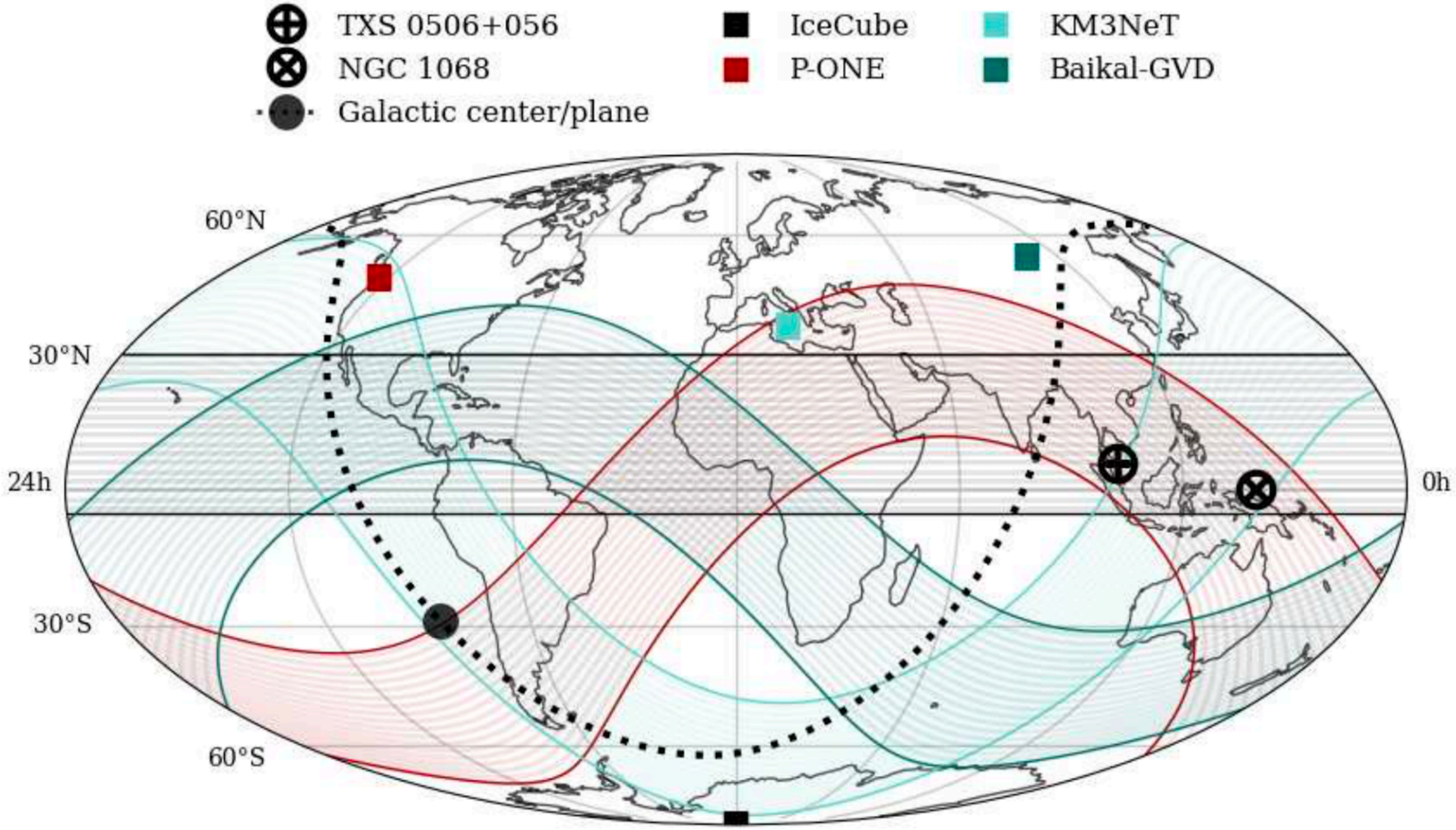
The future of Neutrino Astronomy looks bright!

THANK YOU

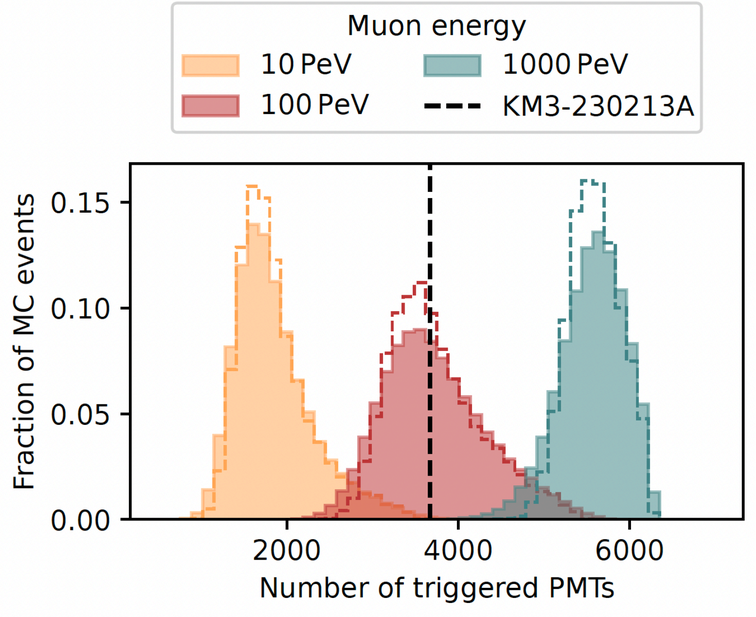
FOR

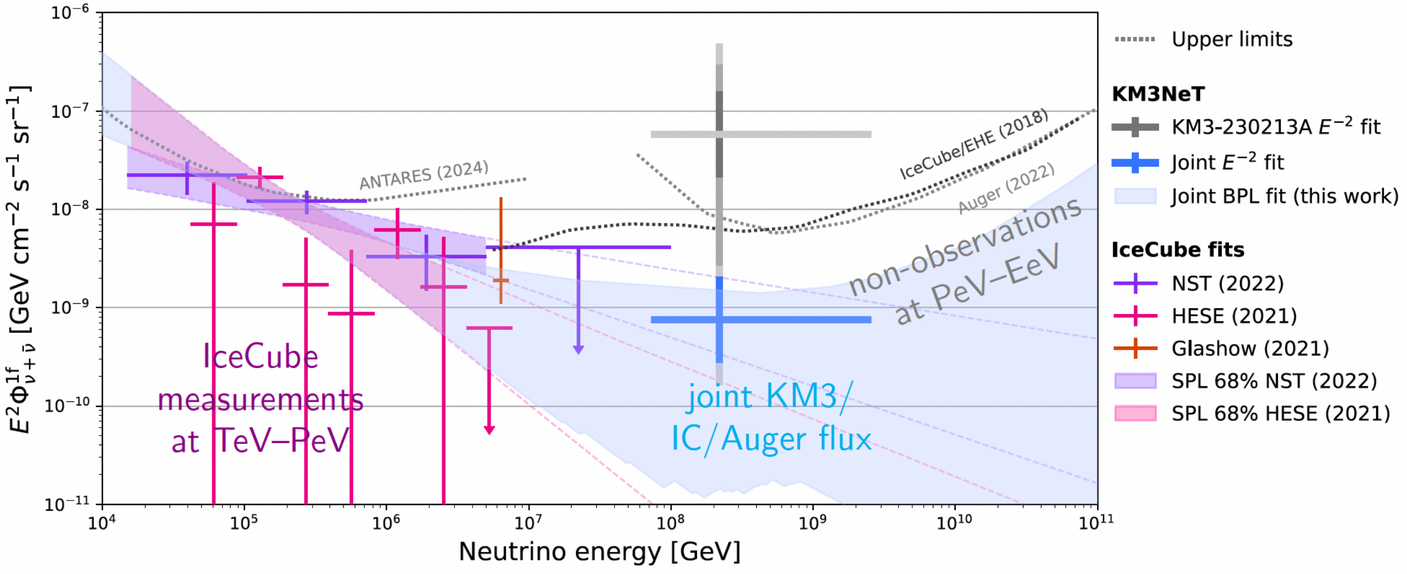
THE ATTENTION

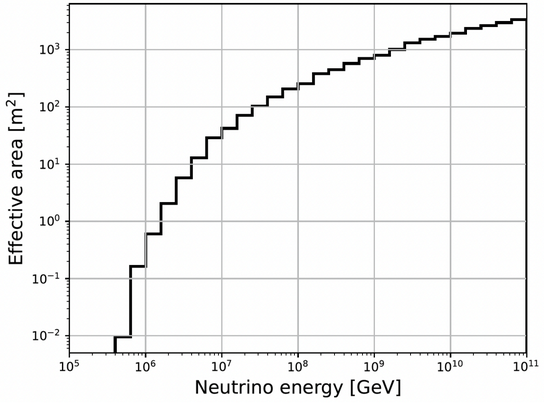
Sky visibility

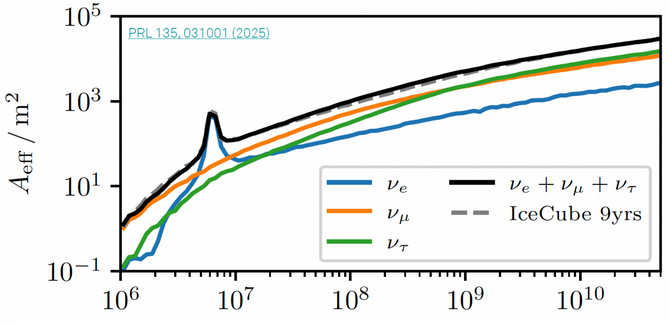


KM3-230213

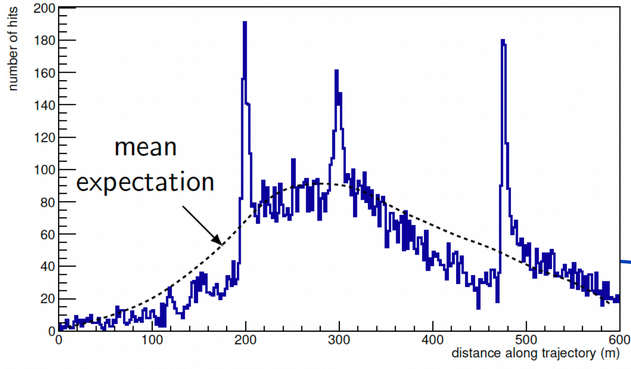


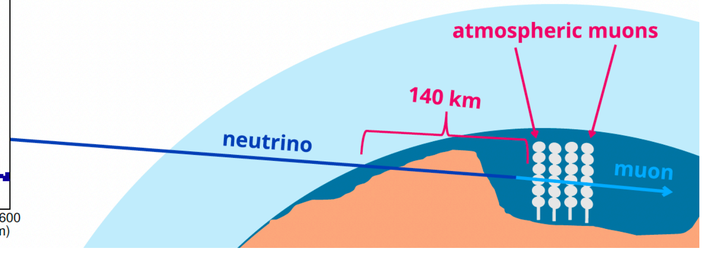






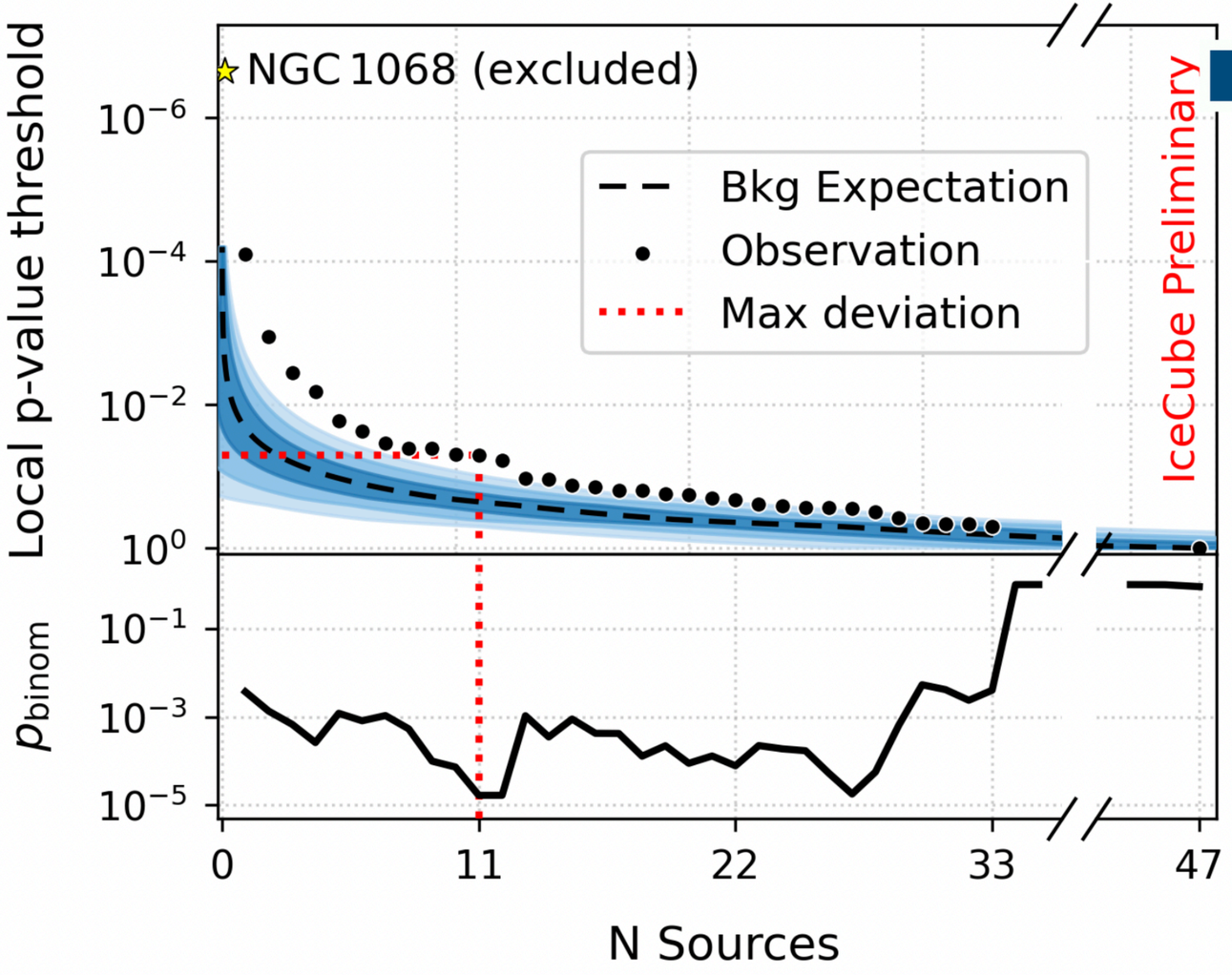
- **Stochastic losses** consistent with a single high-energy muon.
- Atmospheric muons do not survive more than 60 km, even at EeV energies.
  - Assuming event within 5σ error on direction, rate is $< 10^{-4}$ per year ($< 10^{-10}$ in nominal dir).
  - Muon bundles are also **unlikely** ($< 10^{-3}$ per year).
- Atmospheric neutrinos with such energies are very rare ($\sim 1 - 5 \cdot 10^{-5}$ per year).
- Most probably origin is therefore **cosmic**. $\boxed{E_\nu = 220^{+570}_{-110}\,\text{PeV}}$ (assuming E^{-2} spectrum).

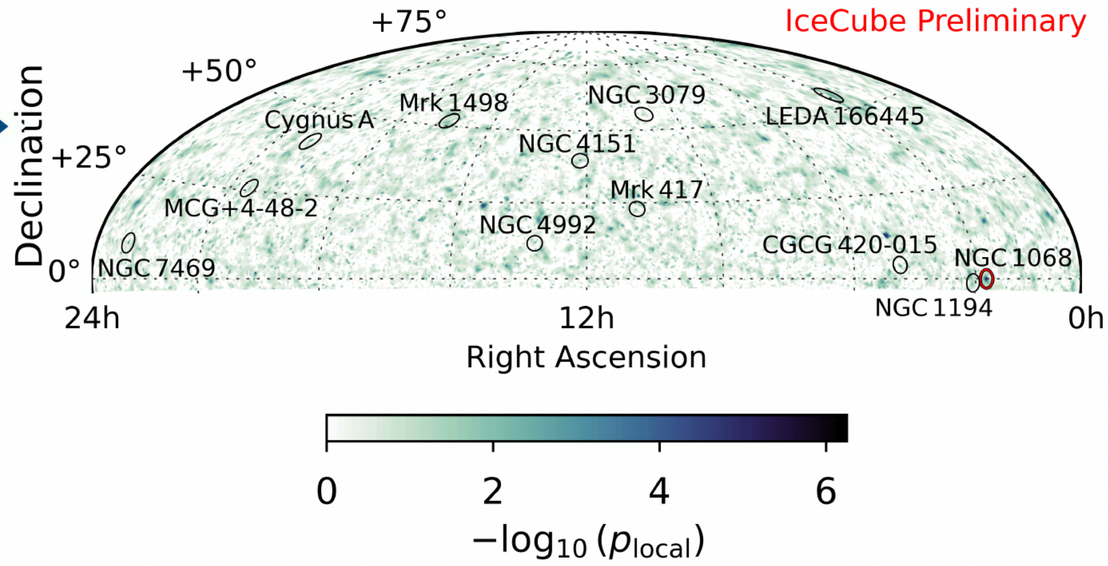




Searches for Neutrinos from Seyfert Galaxies

Binomial Test



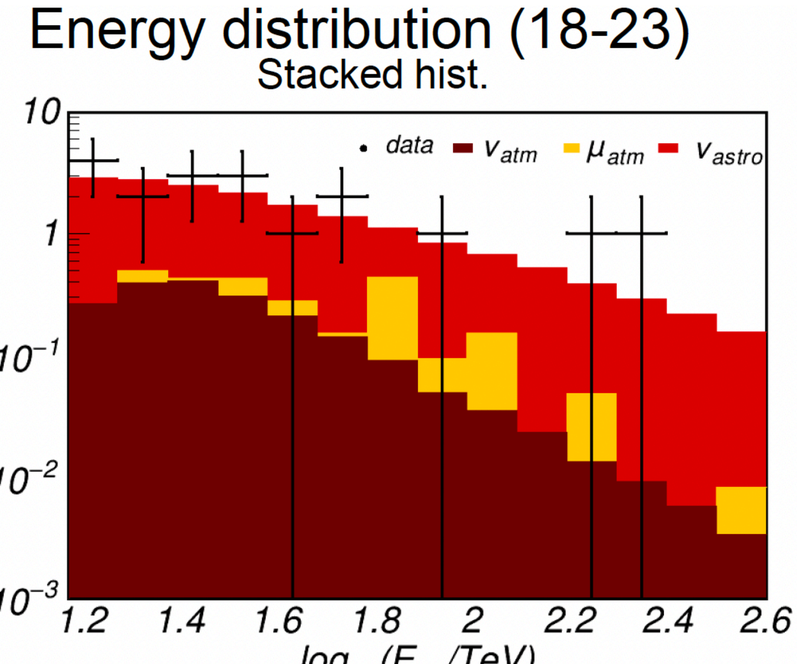


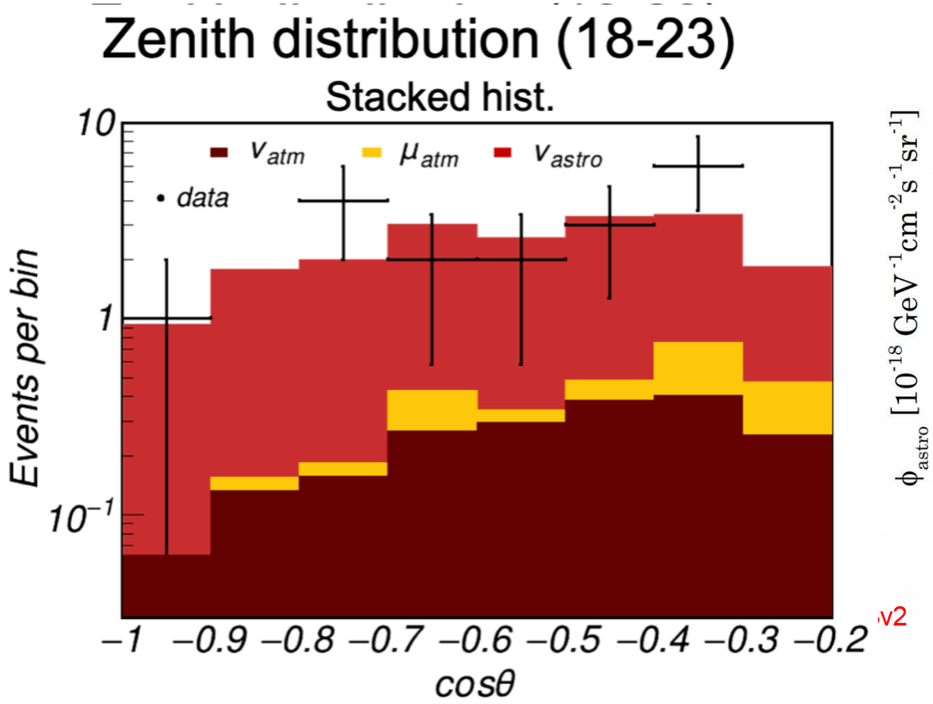
- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

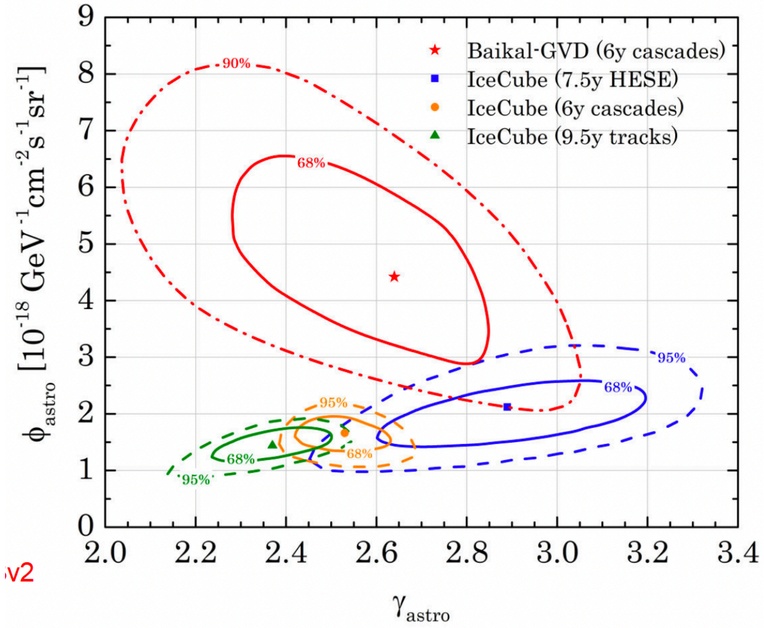
Baikal - Diffuse flux

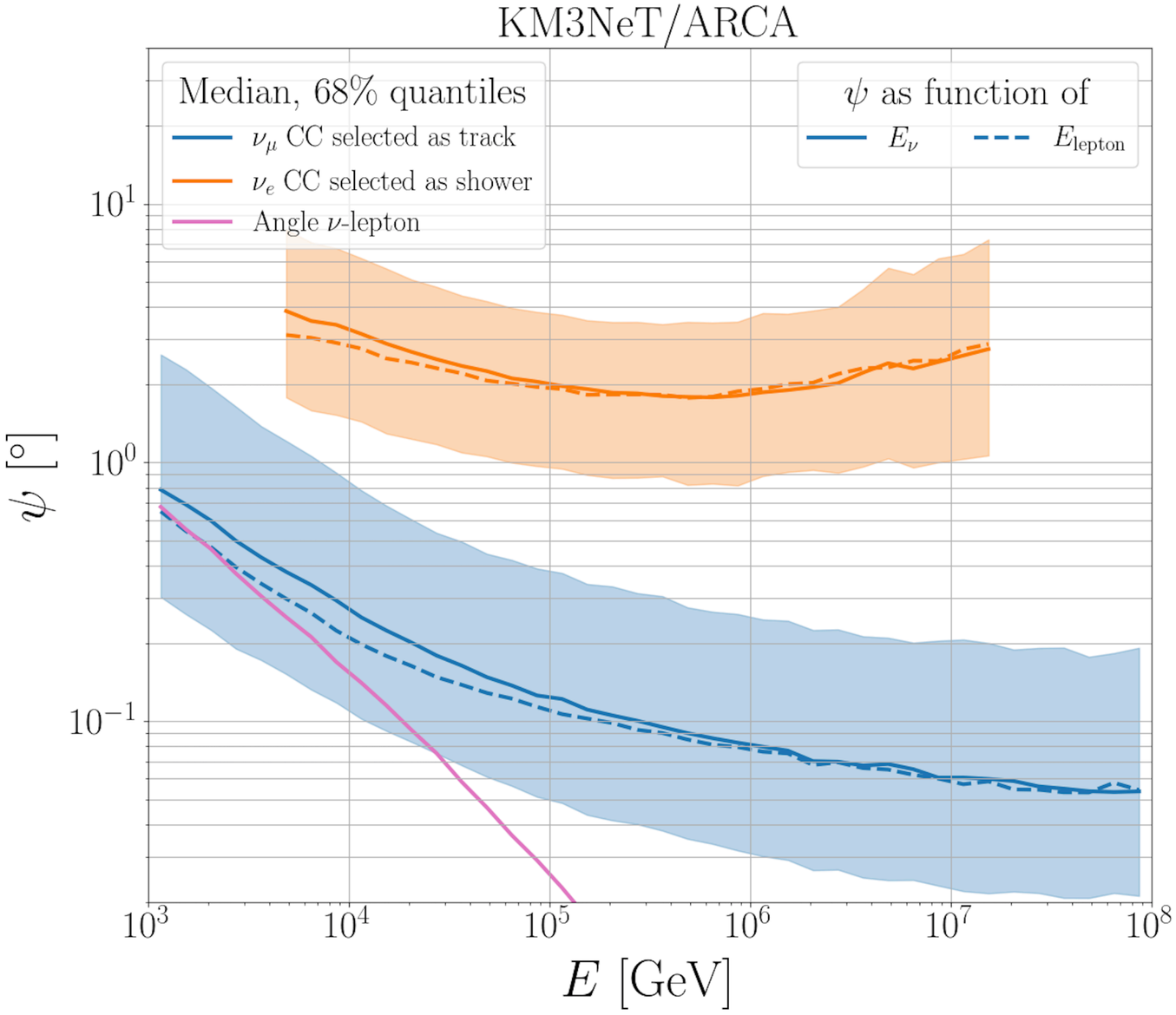
First independent observation of a cosmic neutrino flux at 5.1 sigma!

- upgoing cascade selection on 2018-2023 data sample
- 18 events found w.r.t 2.8 background events expected
- flux larger than IceCube flux








KM3NeT/ARCA
Median, 68% quantiles
ν_μ CC selected as track
ν_e CC selected as shower
Angle ν-lepton
ψ as function of
E_ν
E_{lepton}
ψ [°]
10^1
10^0
10^{-1}
10^3
10^4
10^5
10^6
10^7
10^8
E [GeV]

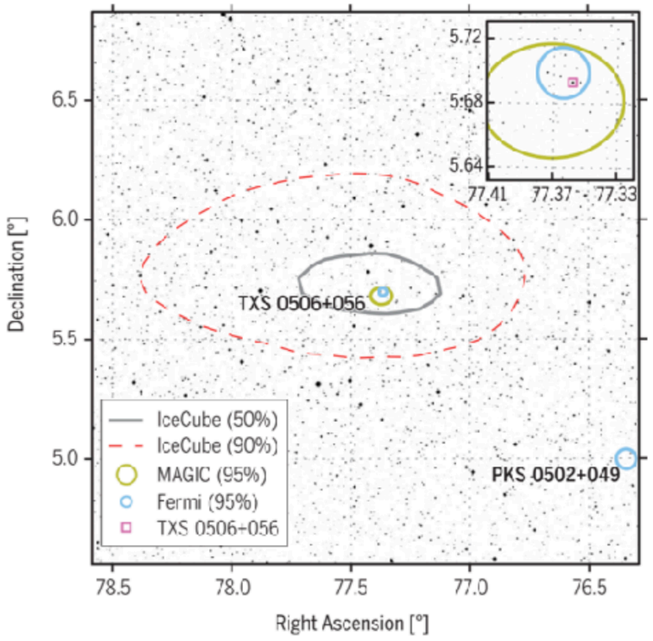
KM3NeT

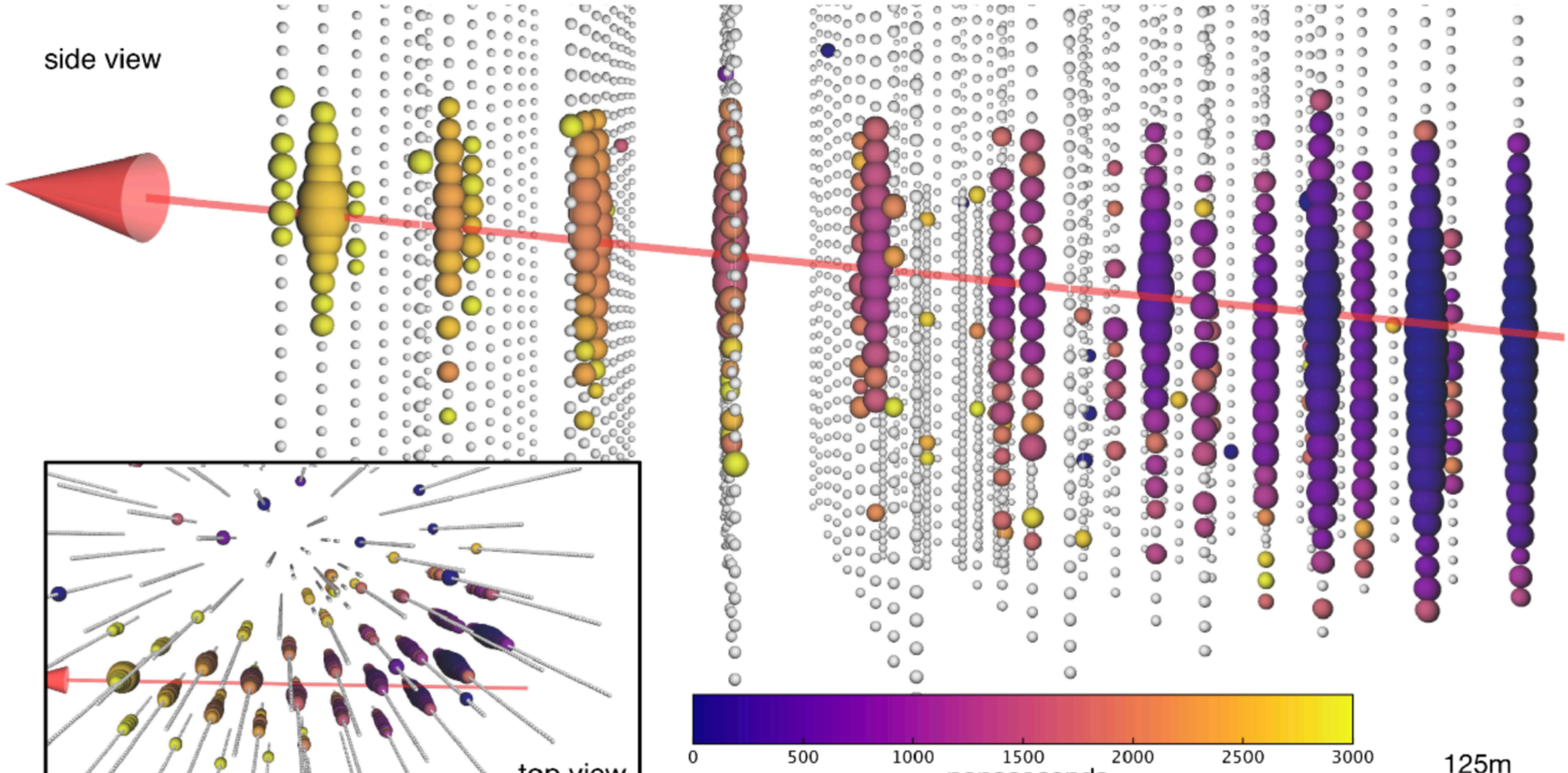
- Effective area
- photocathode area
- Multipmt design developed by km3 and adopted by several other experiments
- Water vs ice optical parameters, no bioluminescence and biofouling

Multi-messenger neutrino follow-up

IceCube-170922A coincident with flaring blazar TXS 0506+056

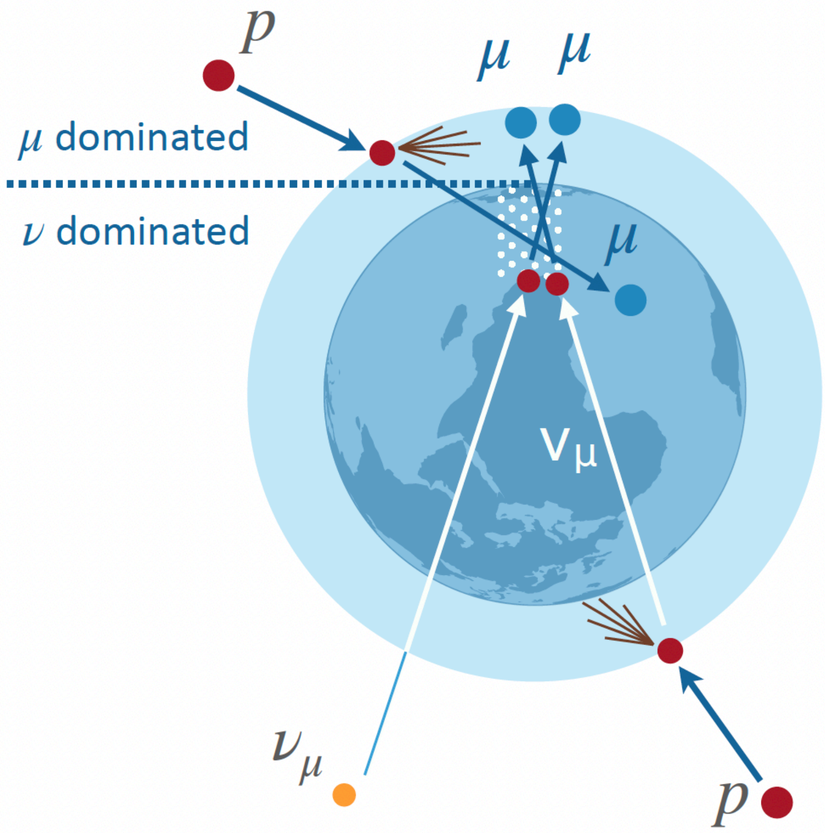
- Extreme high energy neutrino alert from IceCube followed by detection of very high energy photons from a flaring blazar



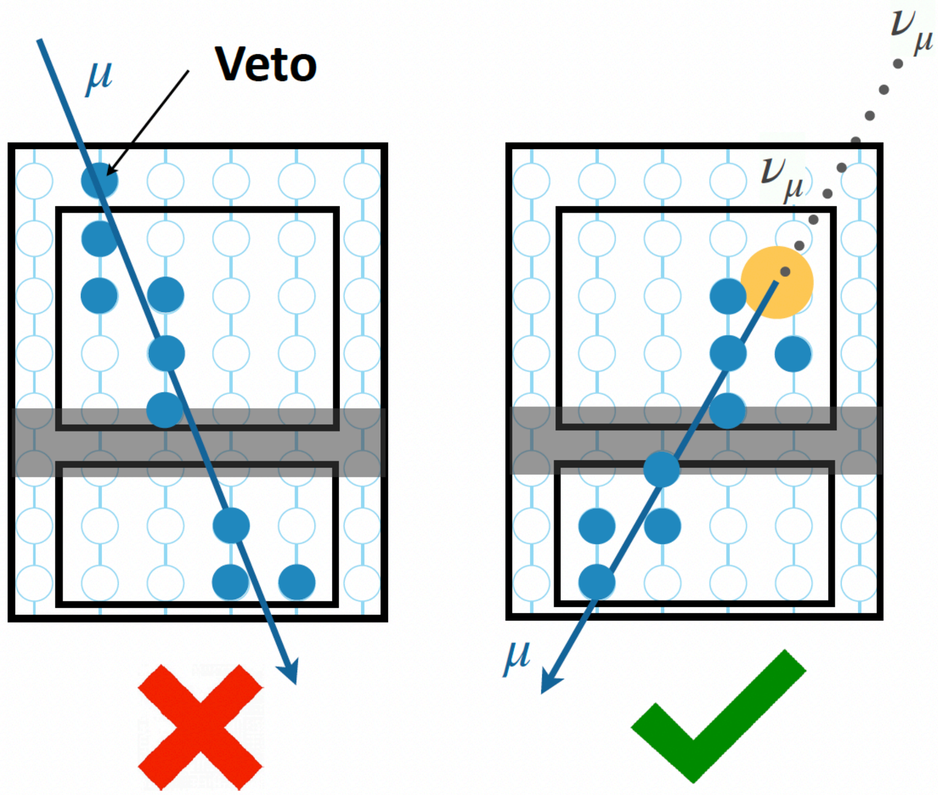


Background rejection

1 Using up-going **through-going muon** events using Earth as a shield against atmospheric muons.

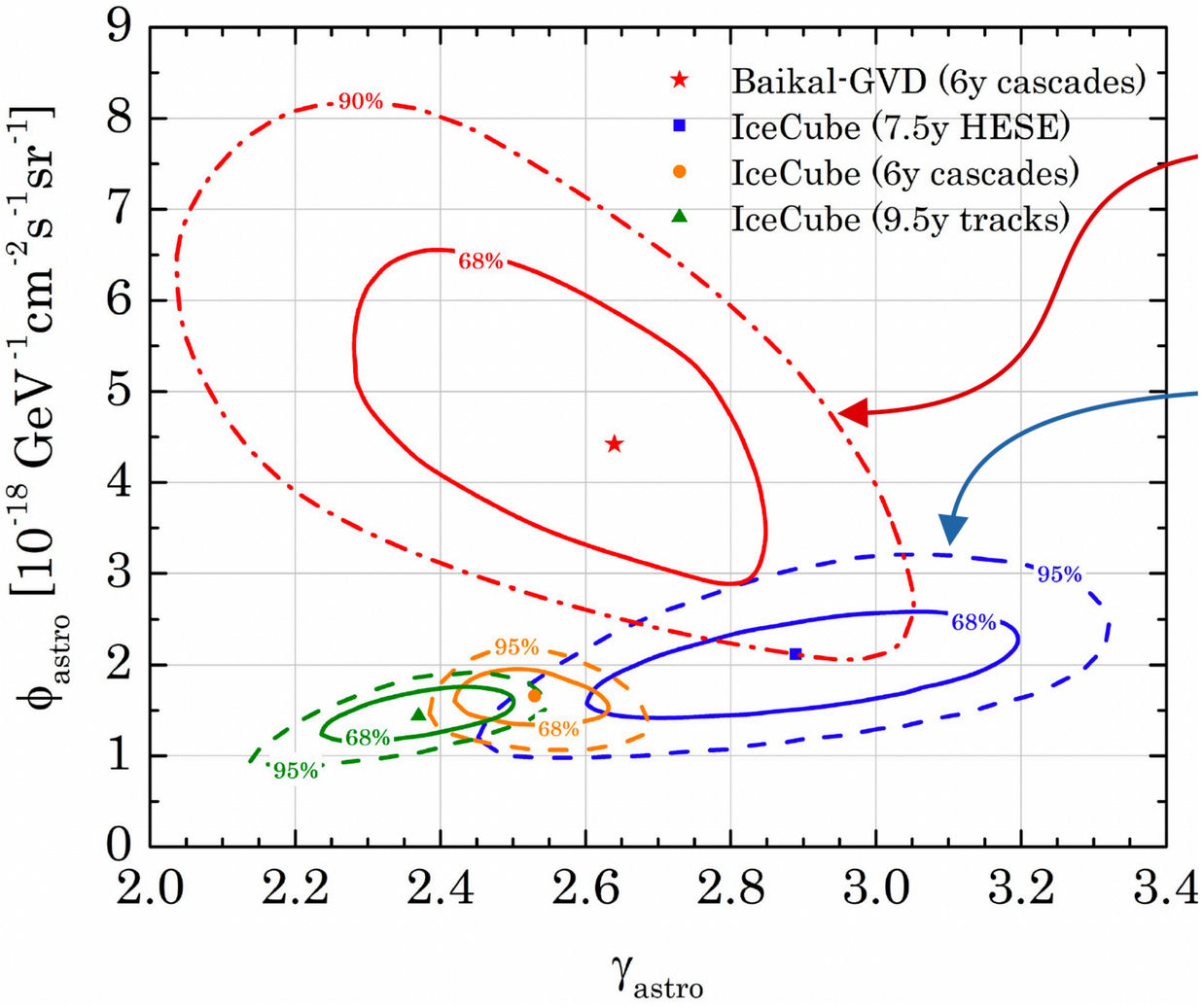


2 Using the outer layers as an active veto to select **starting events**.



High energy neutrino diffuse flux

- Power index from IceCube observations on diffuse neutrinos poorly constrained
- Cascade Baikal results, compatible at 90% C.L., enlarge/spread uncertainty region
- More results, in particular from Km3NeT, awaited with great interest



Perspectives

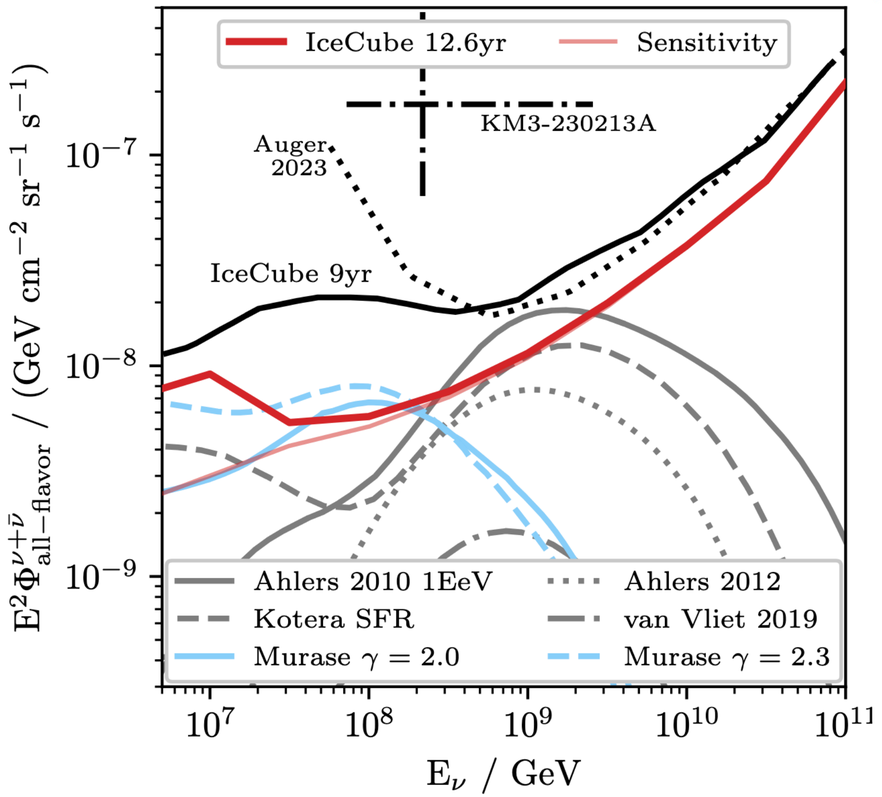
- Future observations should take advantage of radio based detector that can cover much larger areas

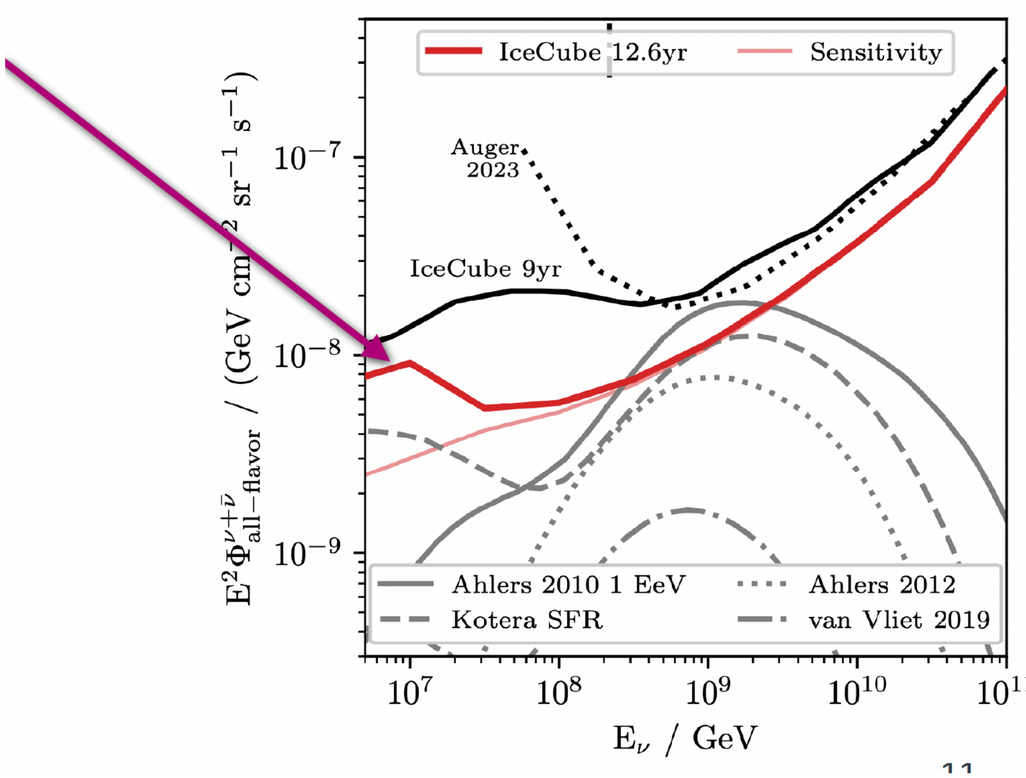
EHE neutrinos

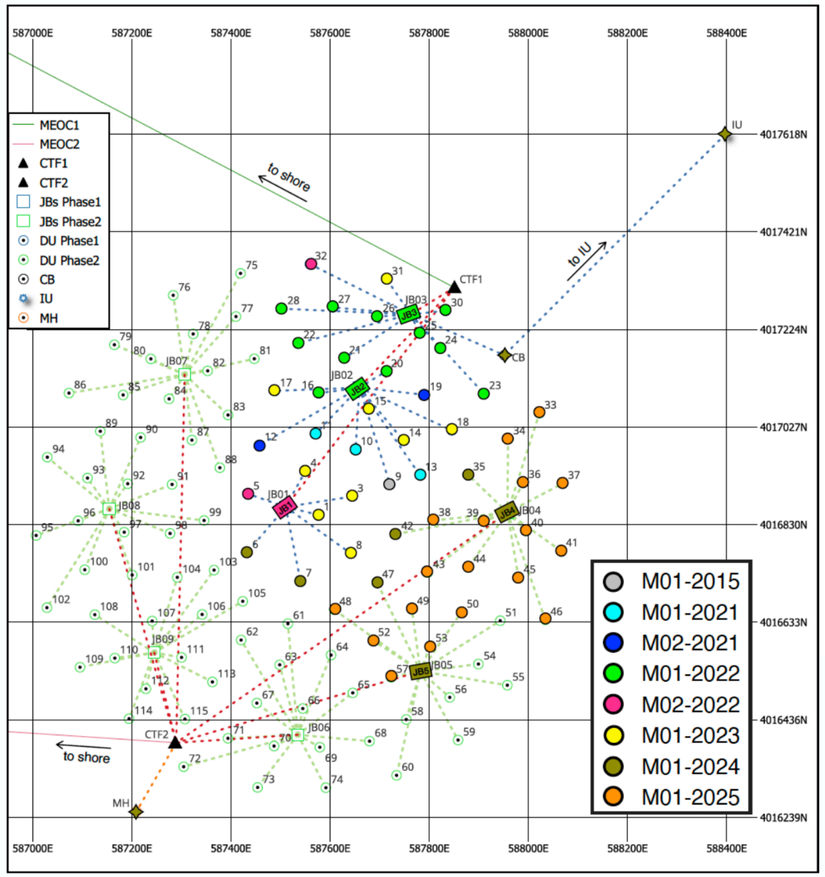
- Cosmogenic neutrinos

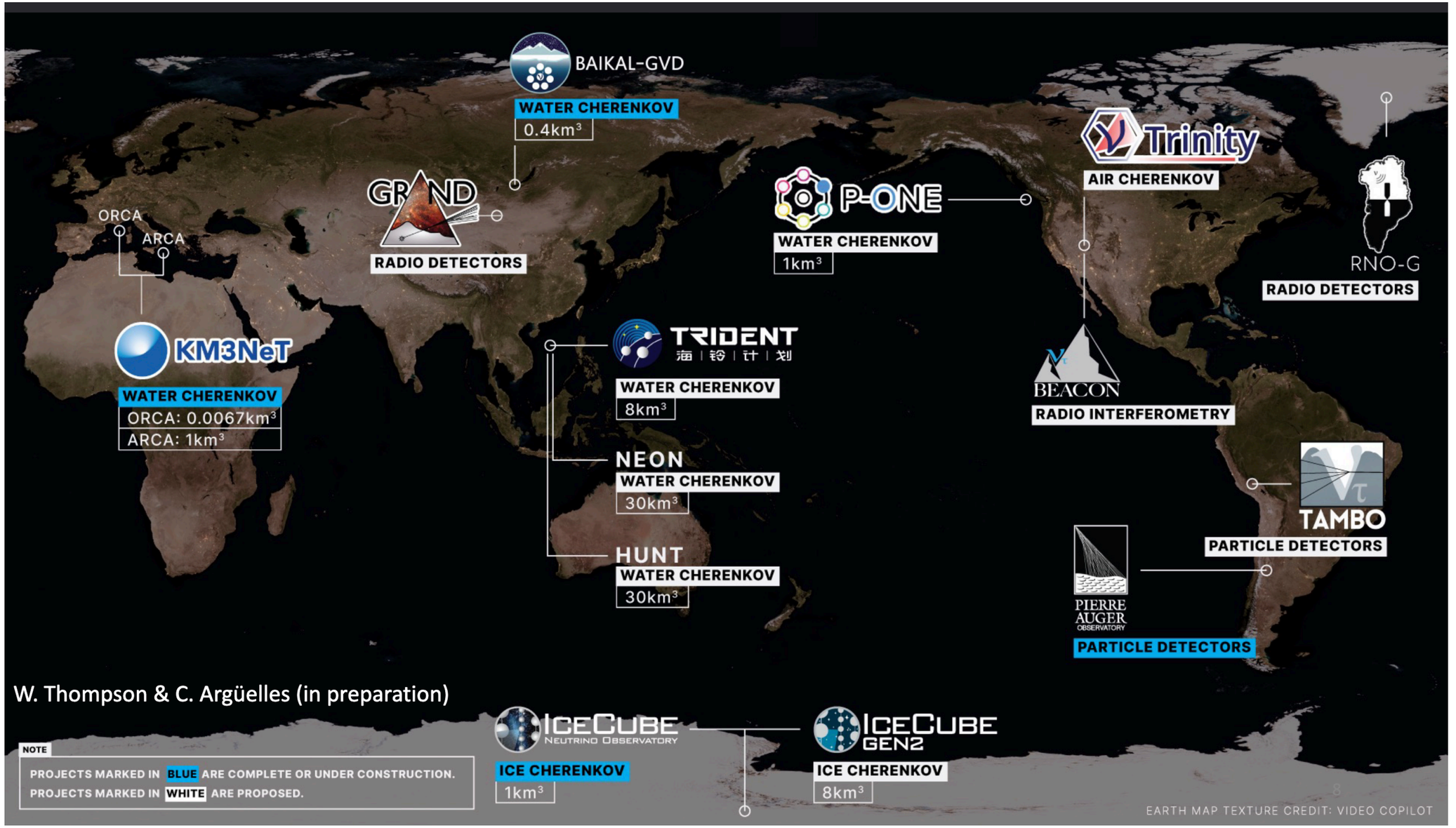
$$p_{\mathrm{UHECR}} + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$
$$\hookrightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu}$$

s






MEOC1
MEOC2
CTF1
CTF2
JBs Phase1
JBs Phase2
DU Phase1
DU Phase2
CB
IU
MH
to shore
to IU
to shore
M01-2015
M01-2021
M02-2021
M01-2022
M02-2022
M01-2023
M01-2024
M01-2025
587000E
587200E
587400E
587600E
587800E
588000E
588200E
588400E
4017618N
4017421N
4017224N
4017027N
4016830N
4016633N
4016436N
4016239N


BAIKAL-GVD
WATER CHERENKOV
0.4km³
GRAND
RADIO DETECTORS
ORCA
ARCA
KM3NeT
WATER CHERENKOV
ORCA: 0.0067km³
ARCA: 1km³
P-ONE
WATER CHERENKOV
1km³
Trinity
AIR CHERENKOV
RNO-G
RADIO DETECTORS
TRIDENT
海 | 铃 | 计 | 划
WATER CHERENKOV
8km³
BEACON
RADIO INTERFEROMETRY
NEON
WATER CHERENKOV
30km³
HUNT
WATER CHERENKOV
30km³
TAMBO
PARTICLE DETECTORS
PIERRE AUGER OBSERVATORY
PARTICLE DETECTORS
W. Thompson & C. Argüelles (in preparation)
ICECUBE NEUTRINO OBSERVATORY
ICE CHERENKOV
1km³
ICECUBE GEN2
ICE CHERENKOV
8km³
NOTE
PROJECTS MARKED IN BLUE ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN WHITE ARE PROPOSED.
EARTH MAP TEXTURE CREDIT: VIDEO COPILOT

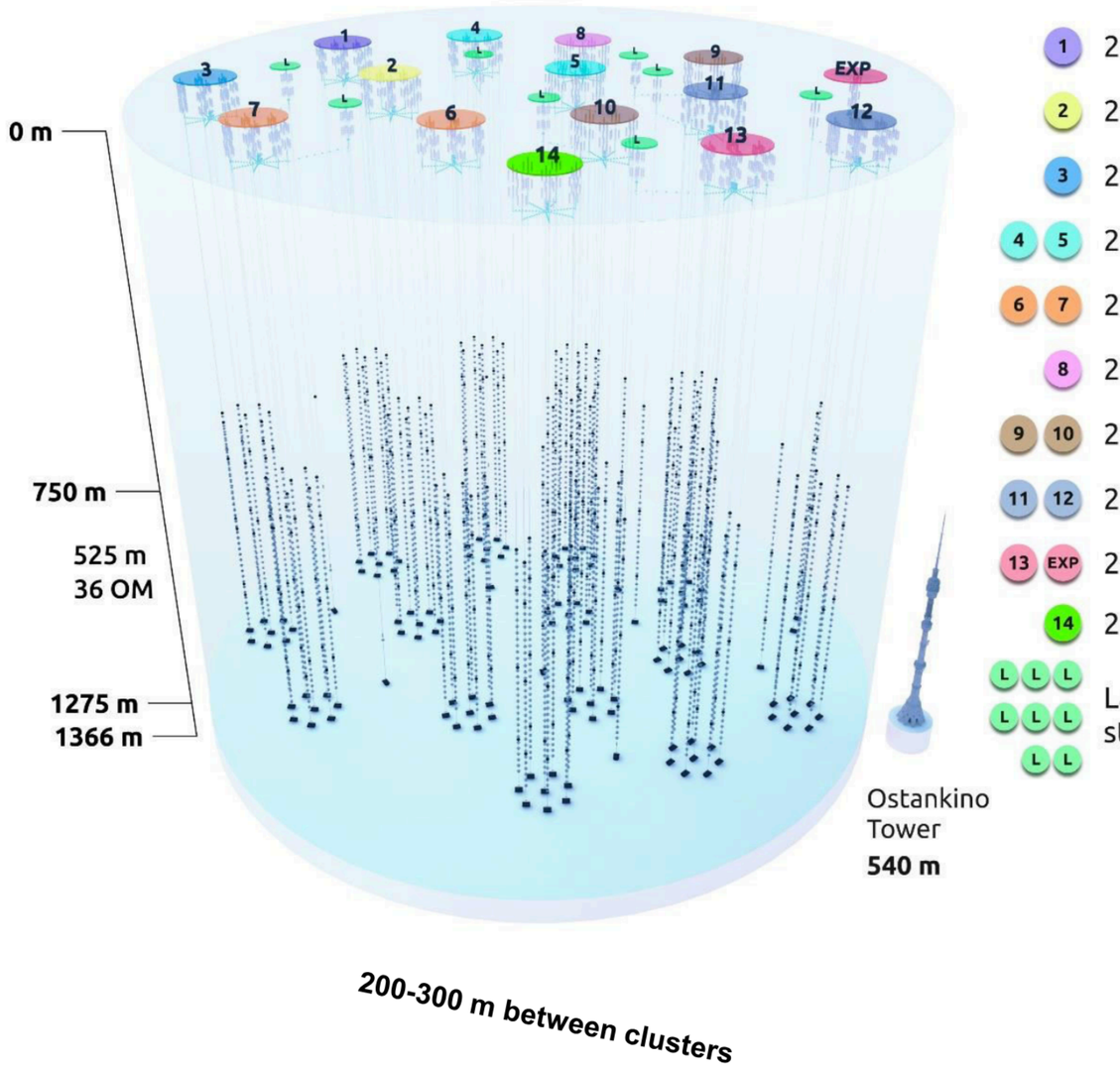
Presently detector consists of 117 strings arranged

into 14 independent **clusters**

- 4212 OMs in total
- more than 0.6 km^3 of water volume
- 8 laser stations/inter-cluster strings
- LED and laser beacons for calibration
- 4 experimental strings with the optic-fiber DAQ

Baikal-GVD cluster:

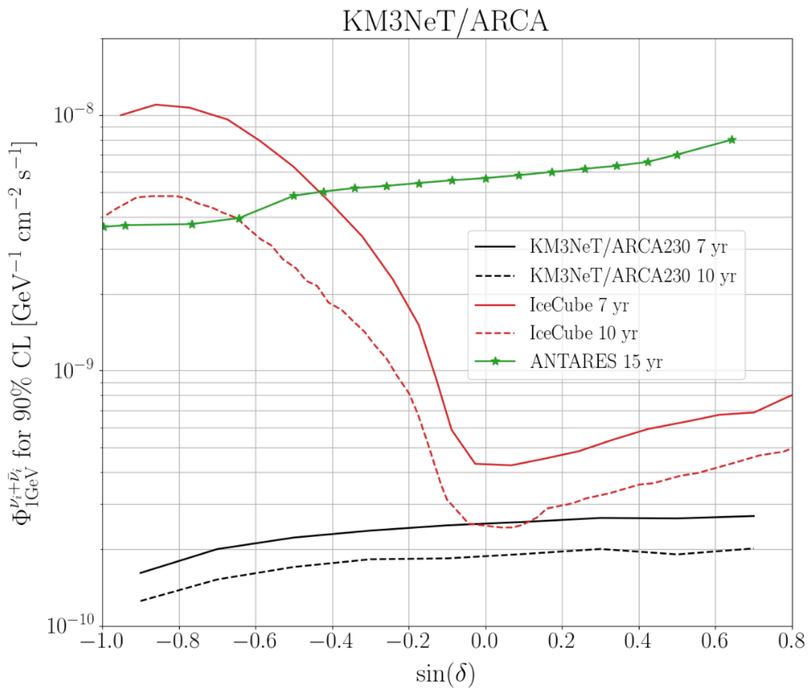
- 8 regular strings, 525 m is instrumented with optical modules (OM)
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs
- own control, trigger, and read-out systems



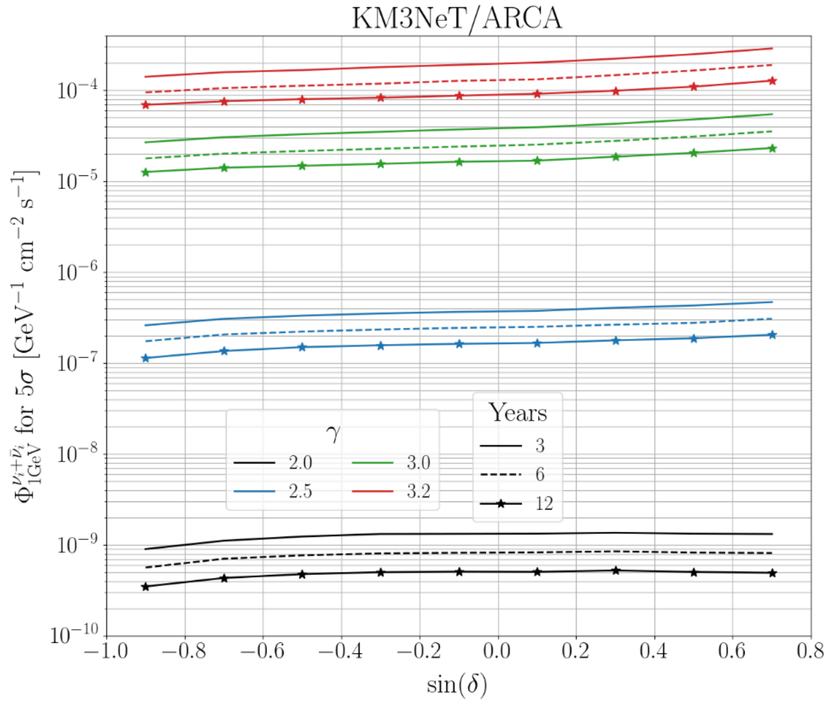
KM3NeT Point-like source sensitivity

Large effective area and unprecedented angular resolution will improve discovery potential for point-like sources

Point-like sensitivity E^{-2} spectrum



5 sigma discovery potential for different power index



- Refs