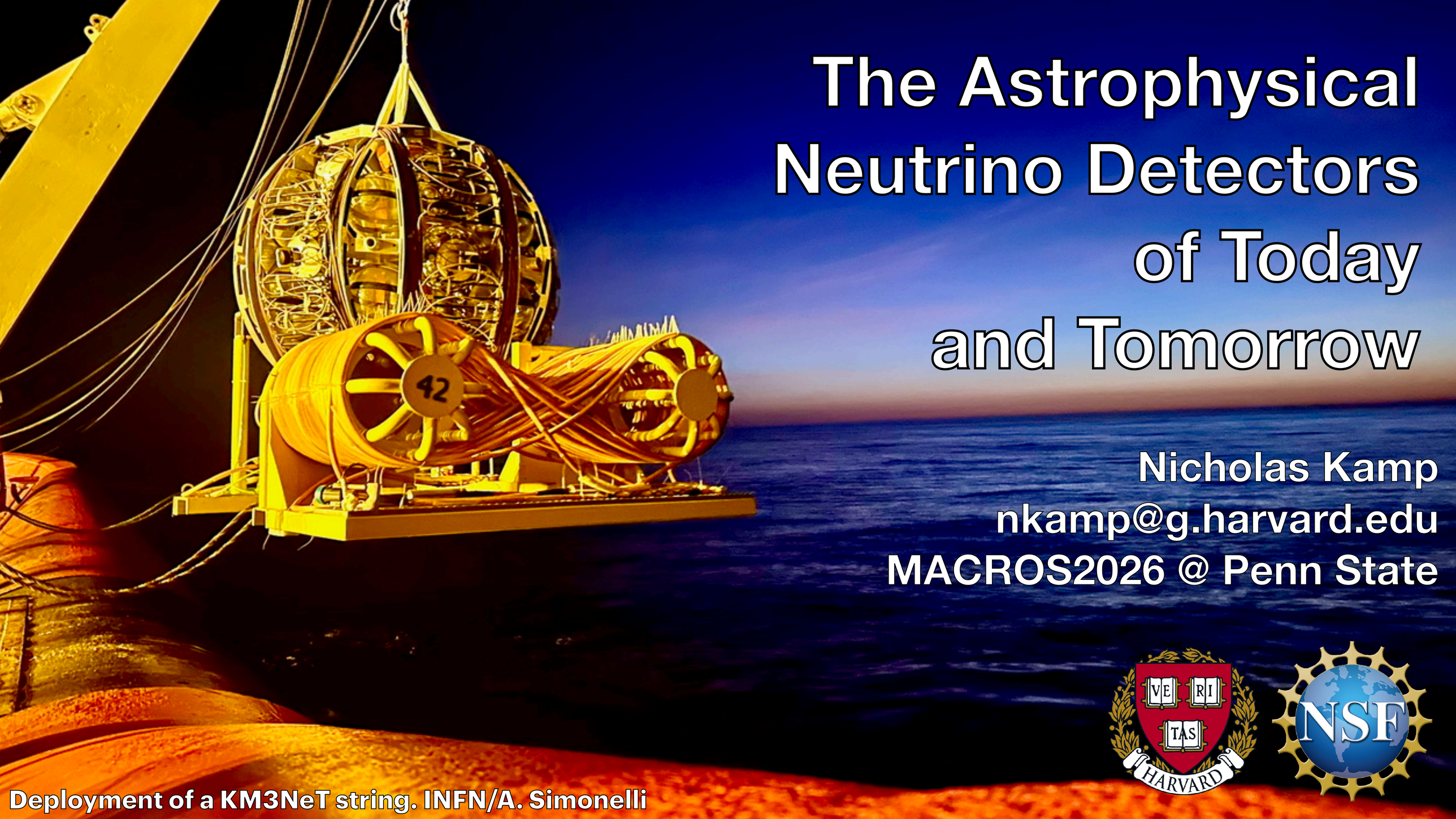
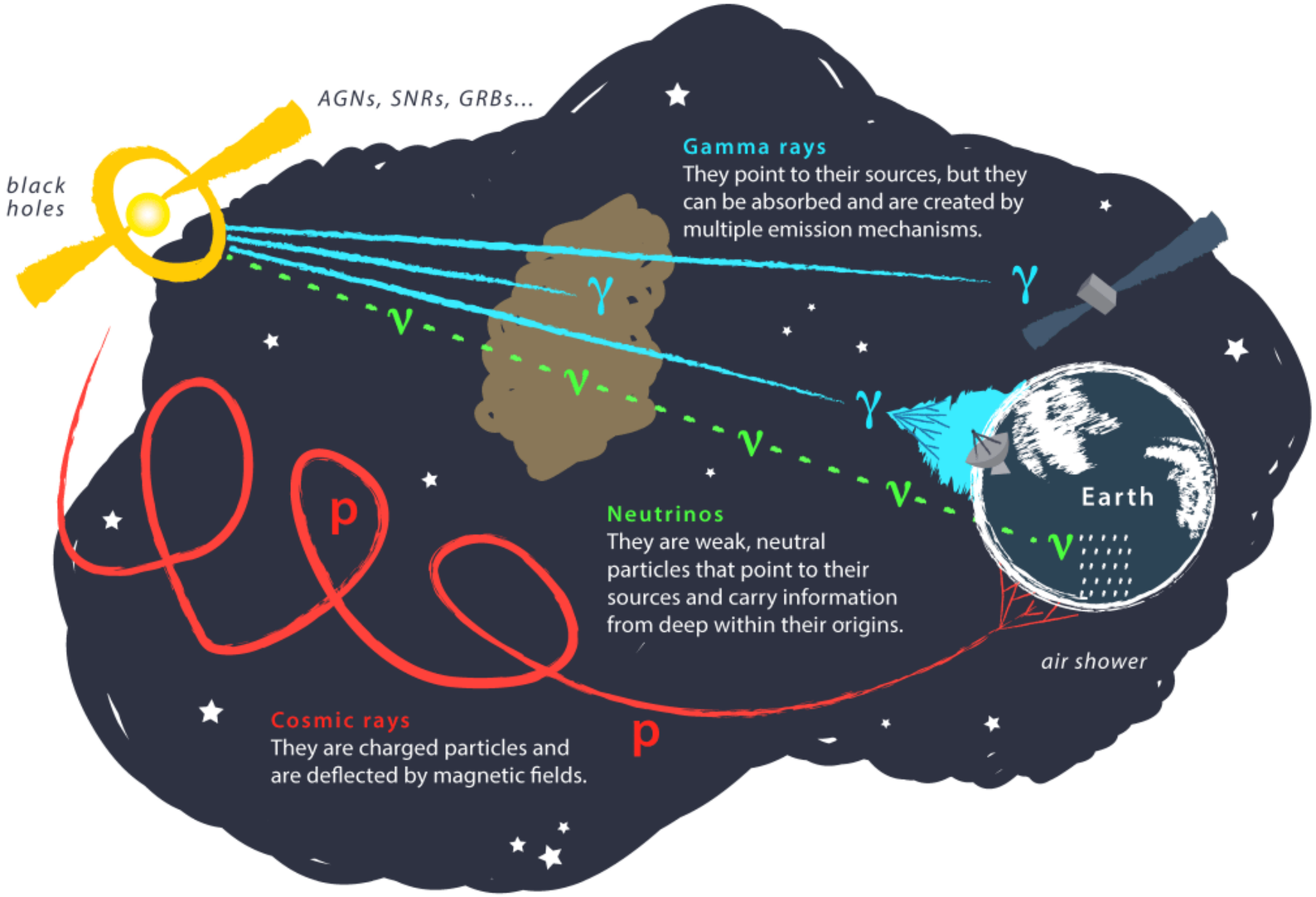


The Astrophysical Neutrino Detectors of Today and Tomorrow

Nicholas Kamp
nkamp@g.harvard.edu
MACROS2026 @ Penn State

Deployment of a KM3NeT string. INFN/A. Simonelli

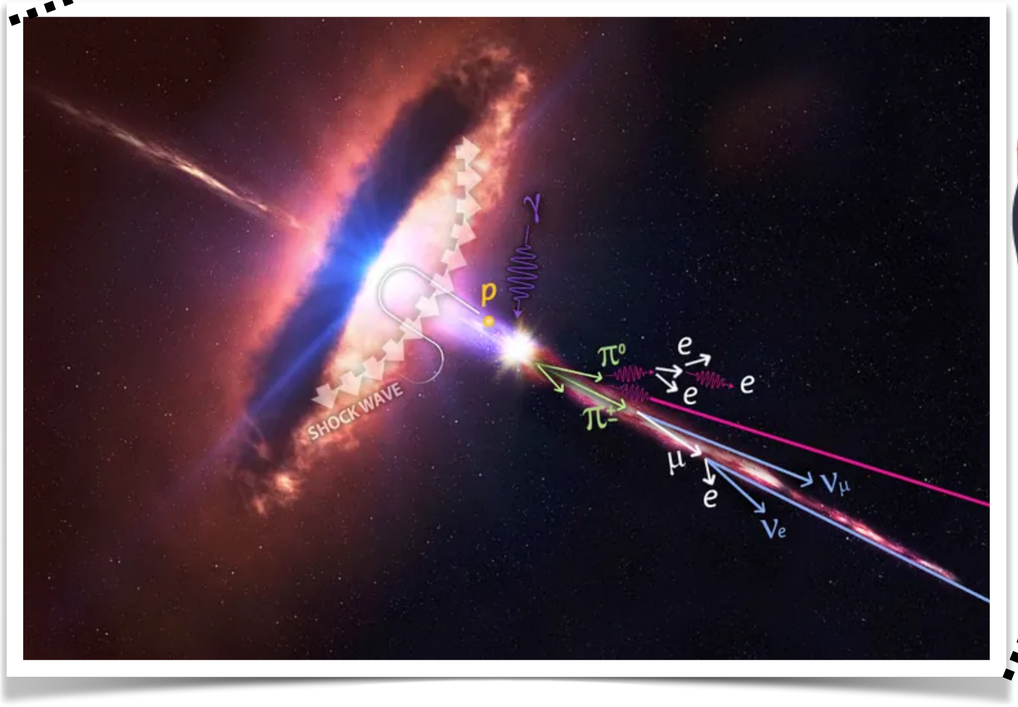
Why are we interested in astrophysical neutrinos?

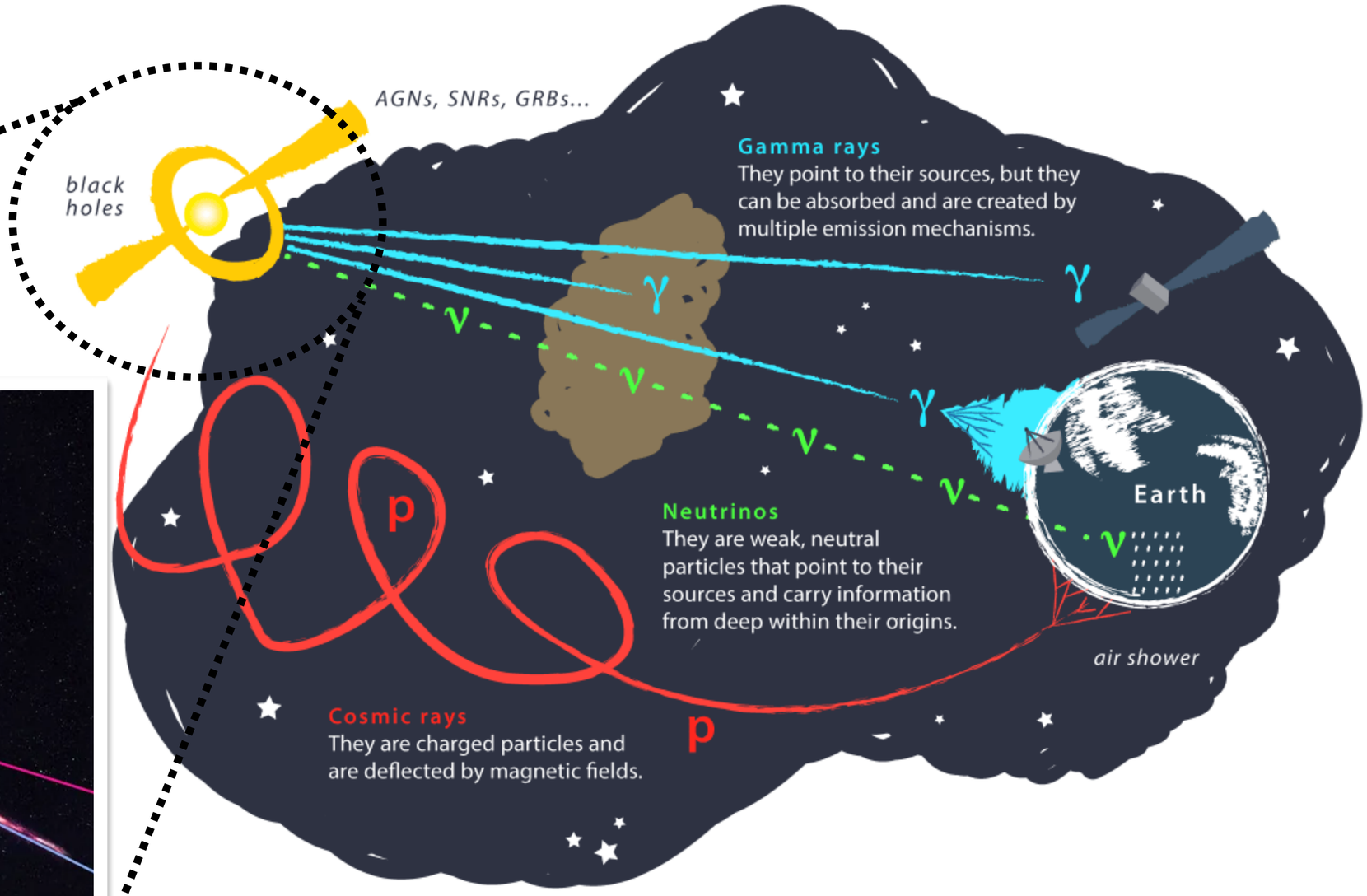


Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

Why are we interested in astrophysical neutrinos?

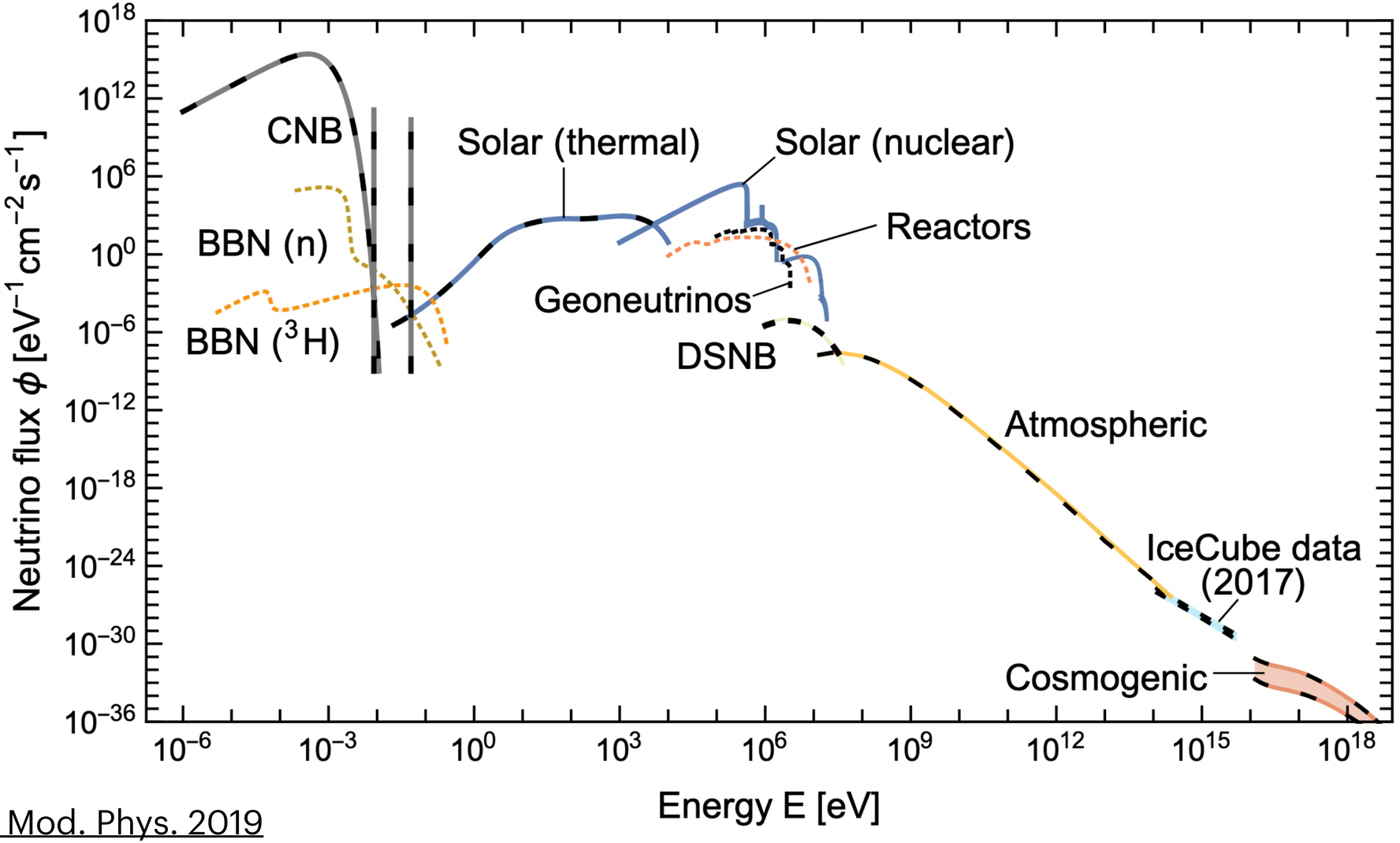
Intimate connections between neutrinos, photons, and cosmic rays at the source





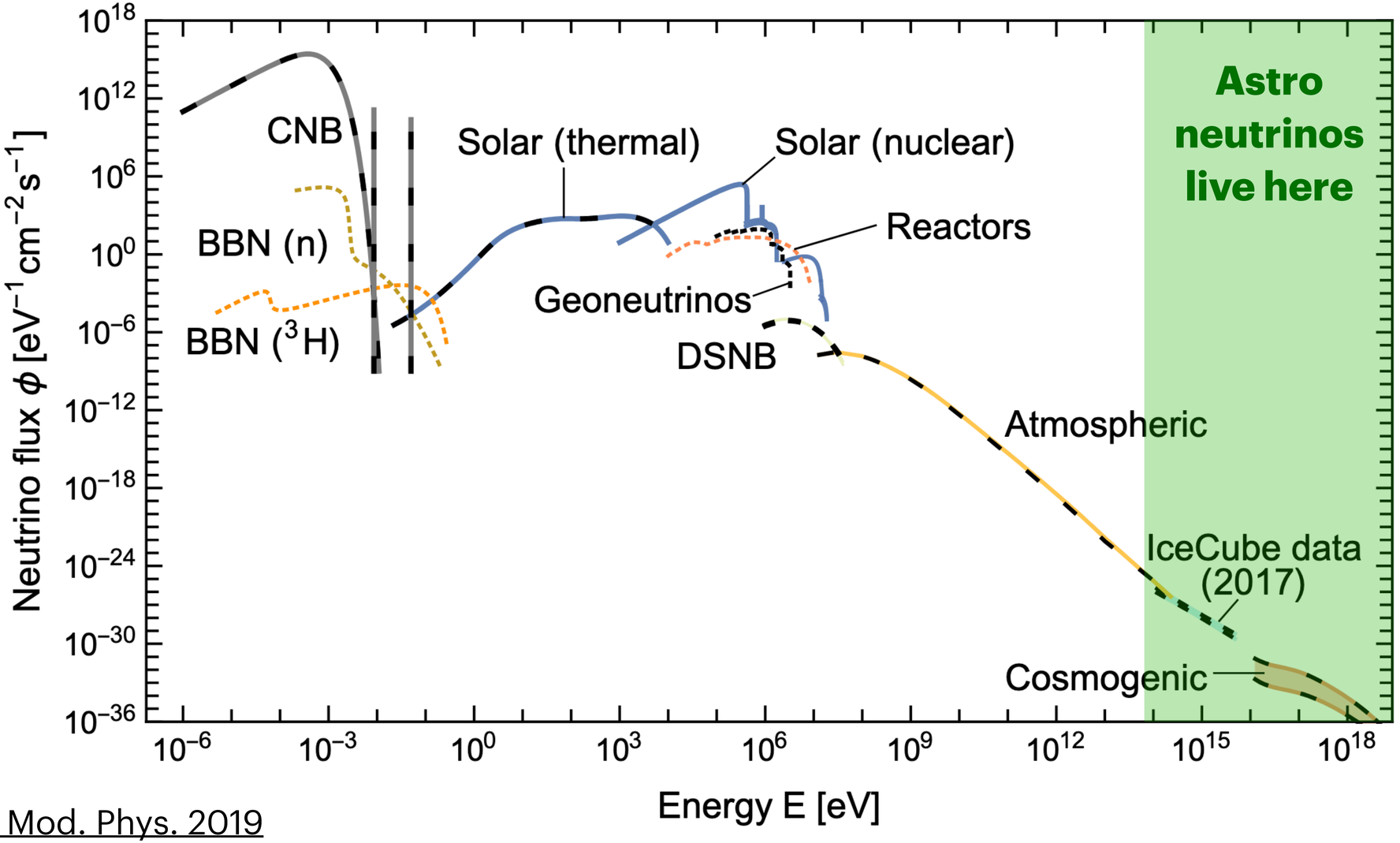
Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

The Grand Unified Neutrino Spectrum



Vitagliano+ Rev. Mod. Phys. 2019

The Grand Unified Neutrino Spectrum



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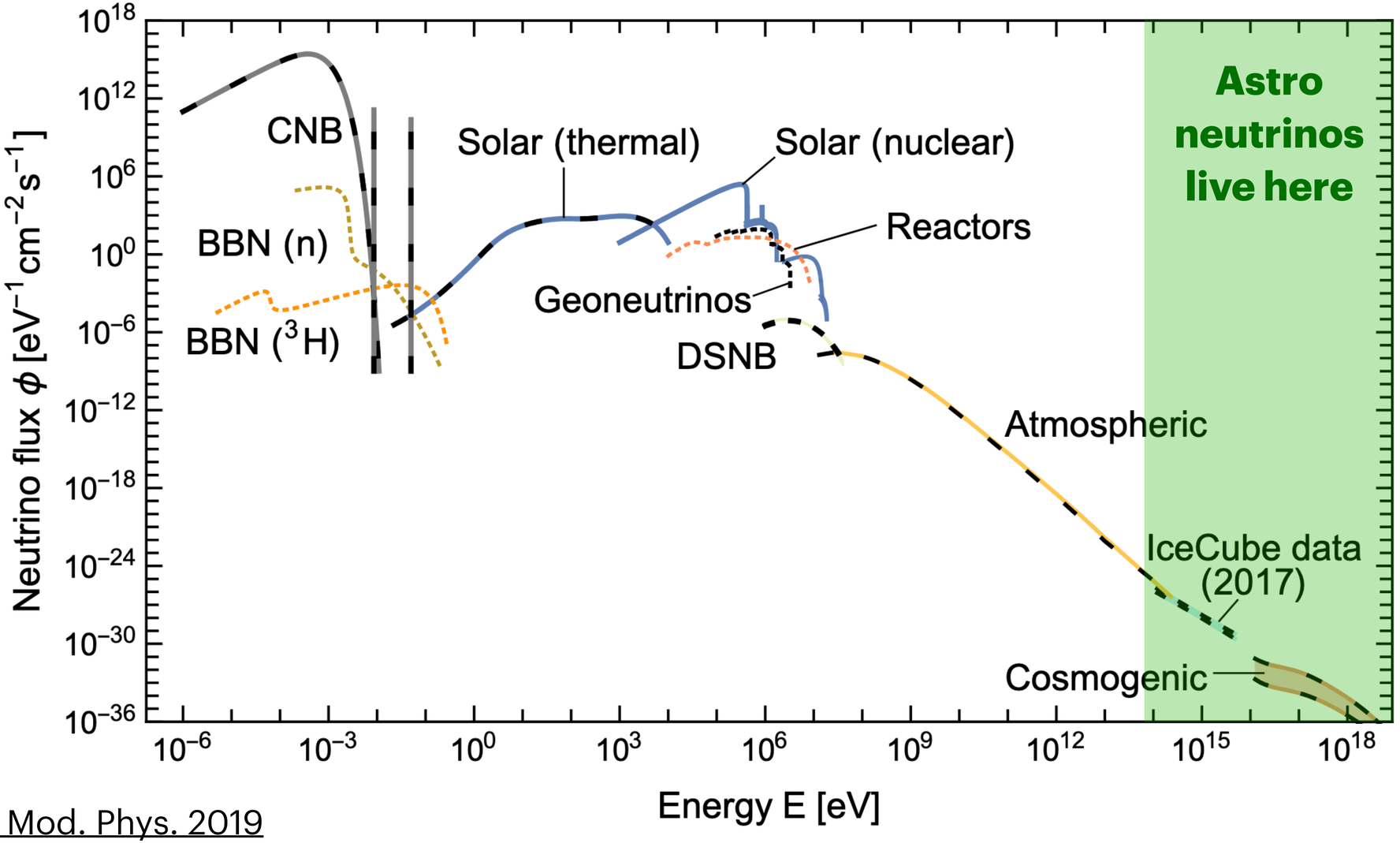
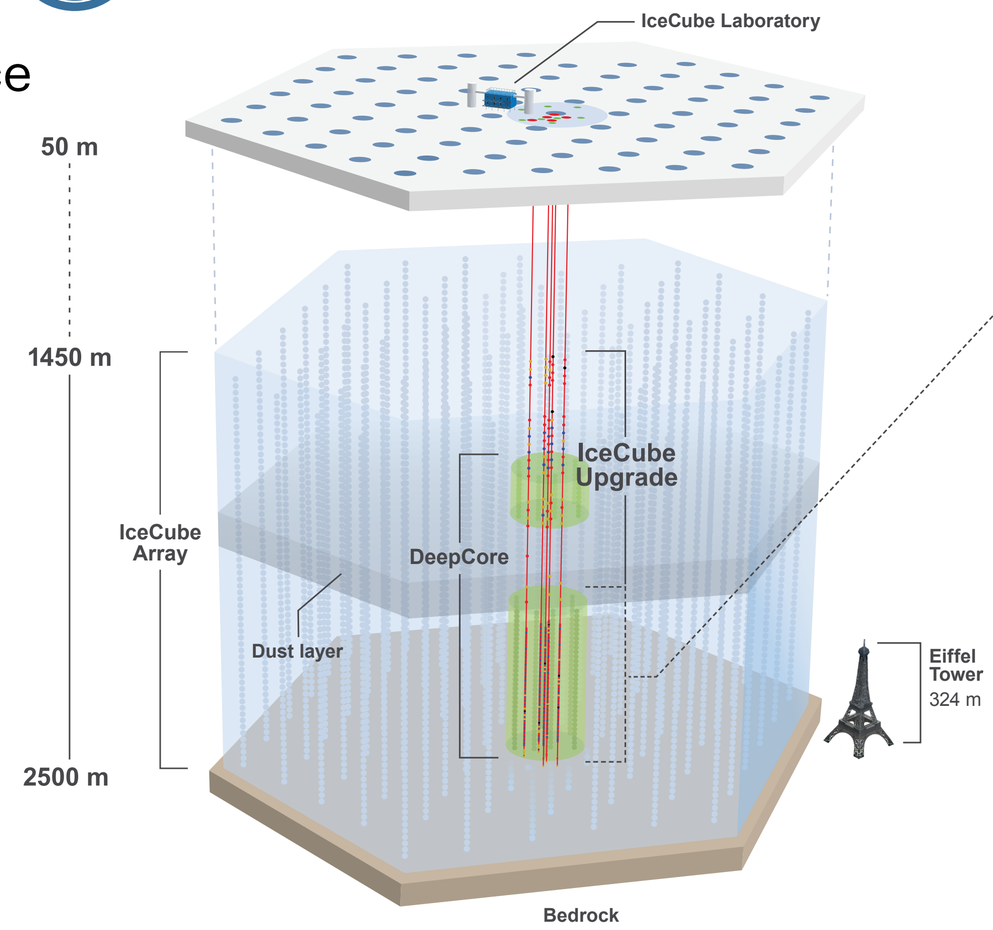


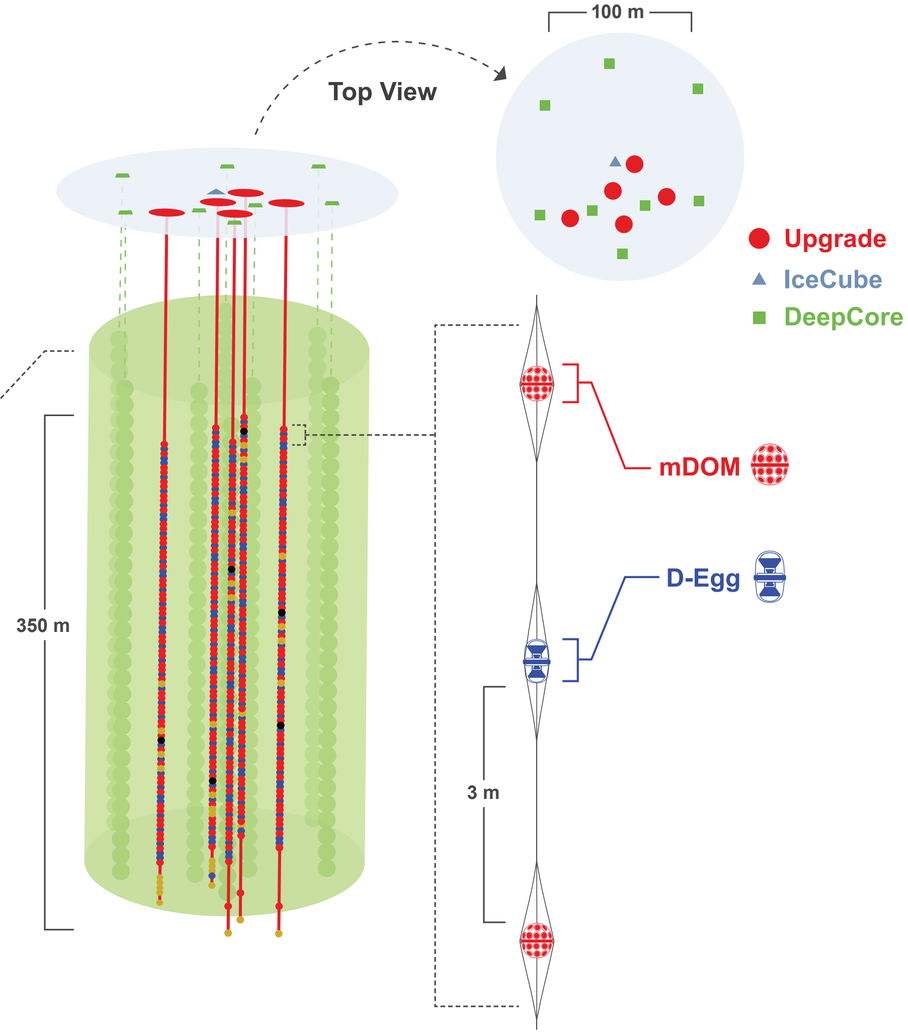
Large detectors needed!

Vitagliano+ Rev. Mod. Phys. 2019

The IceCube Detector(s)

A **cubic kilometer** of instrumented South Pole ice (~gigaton active mass)





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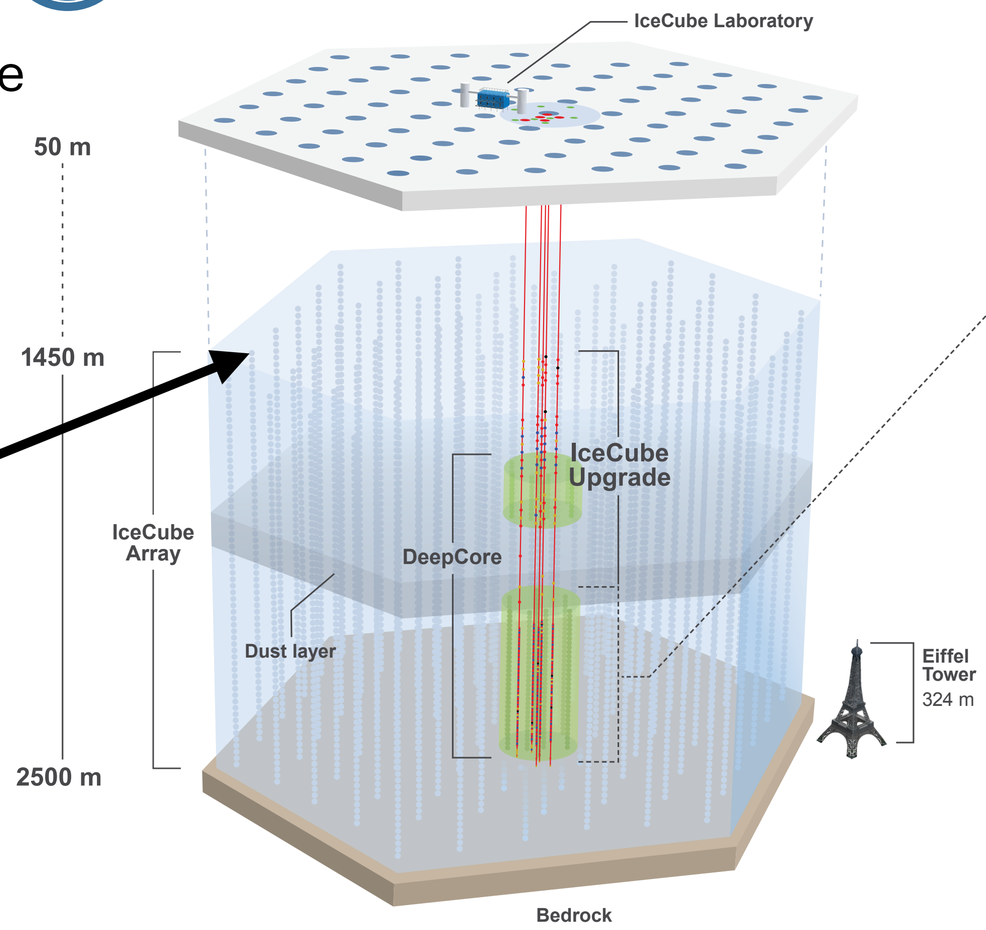
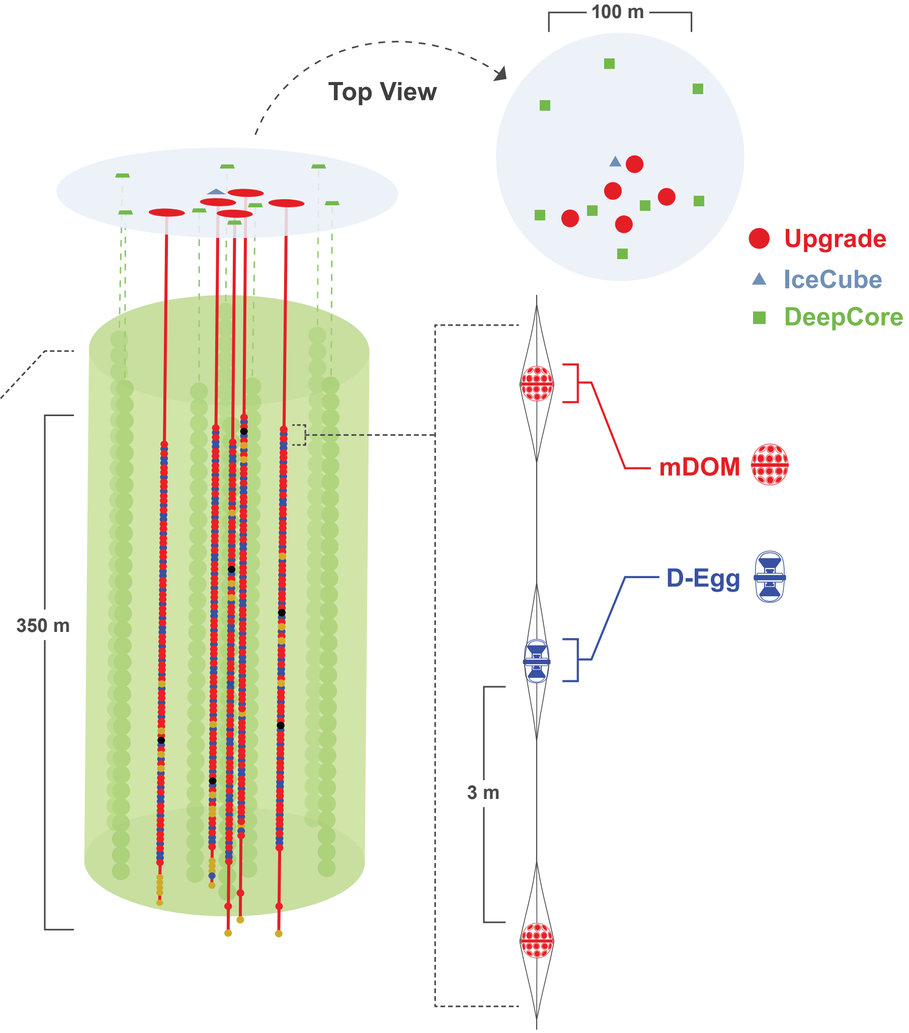
Digital Optical Module (DOM)





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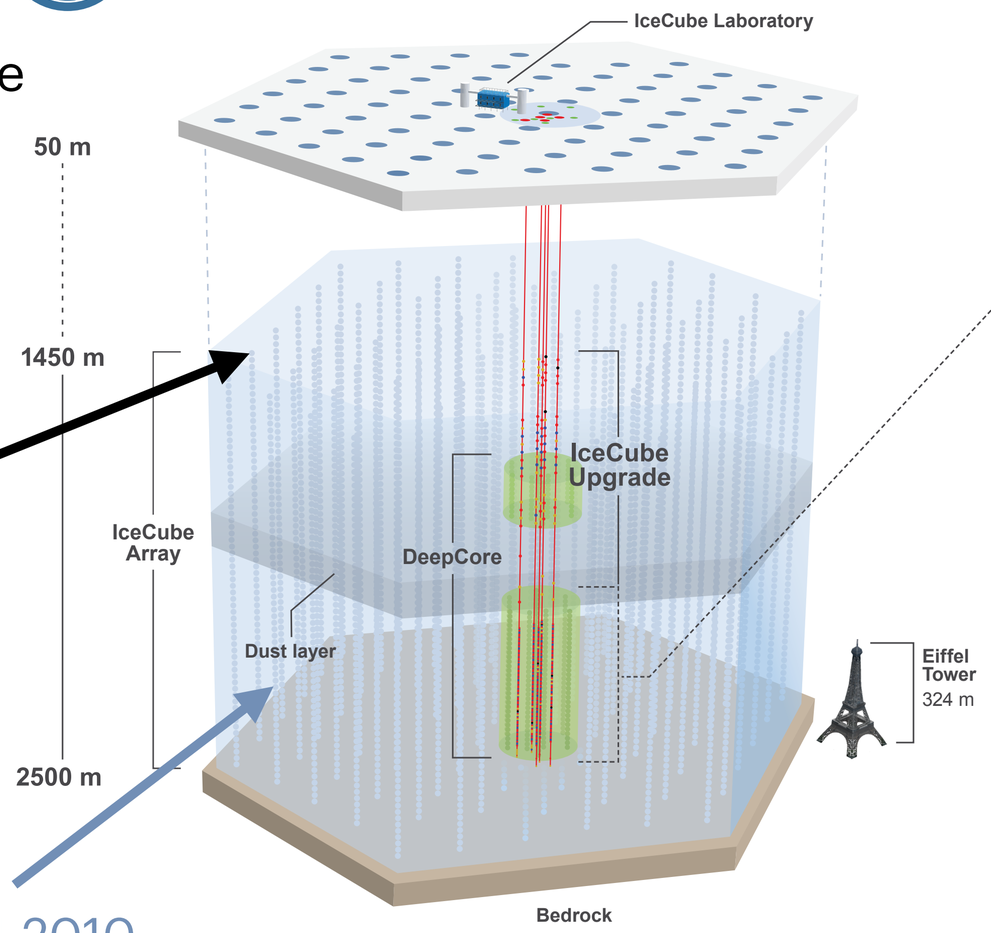

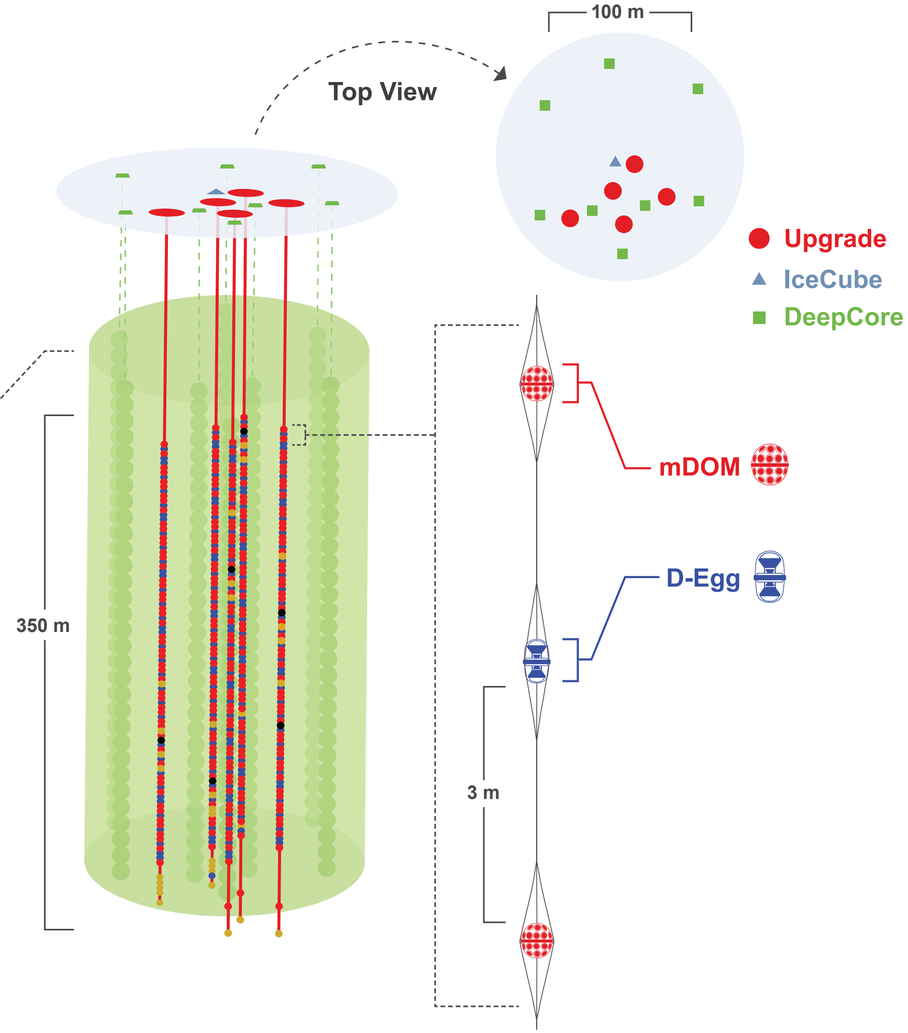

Main array constructed 2004-2010
Optimized for TeV+ energies

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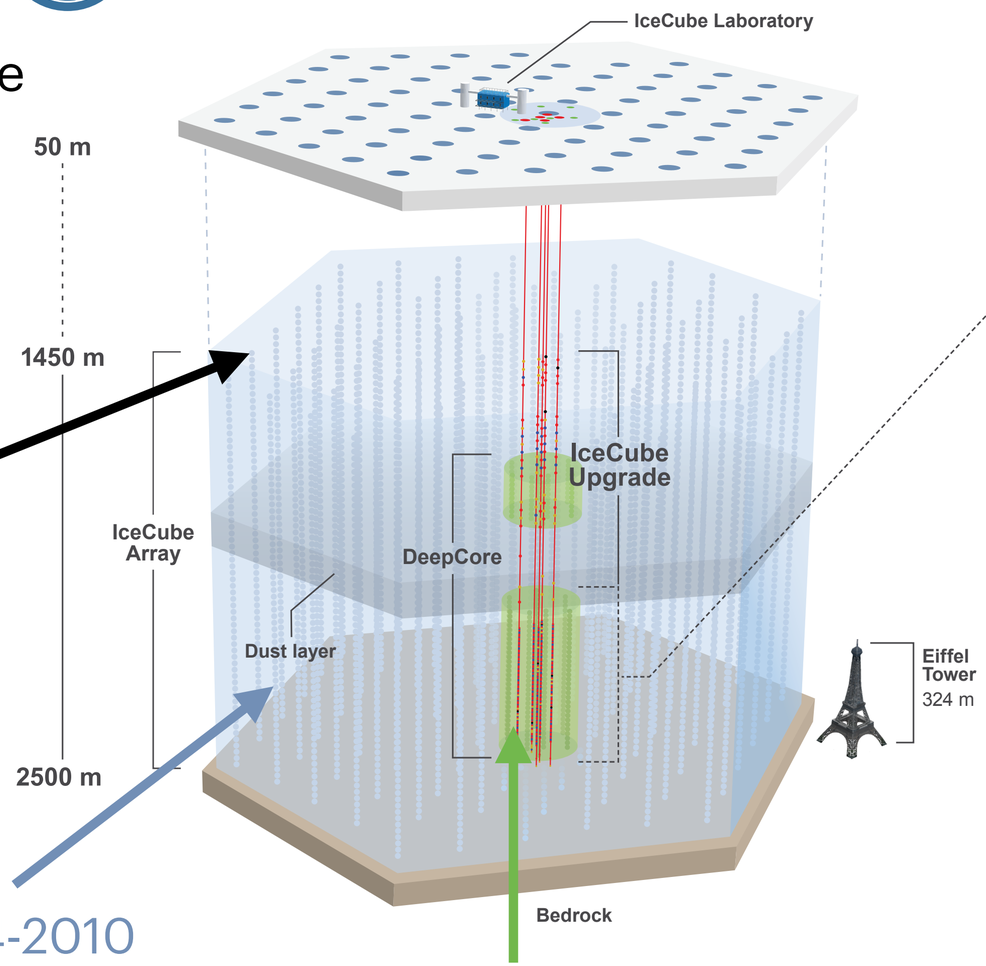

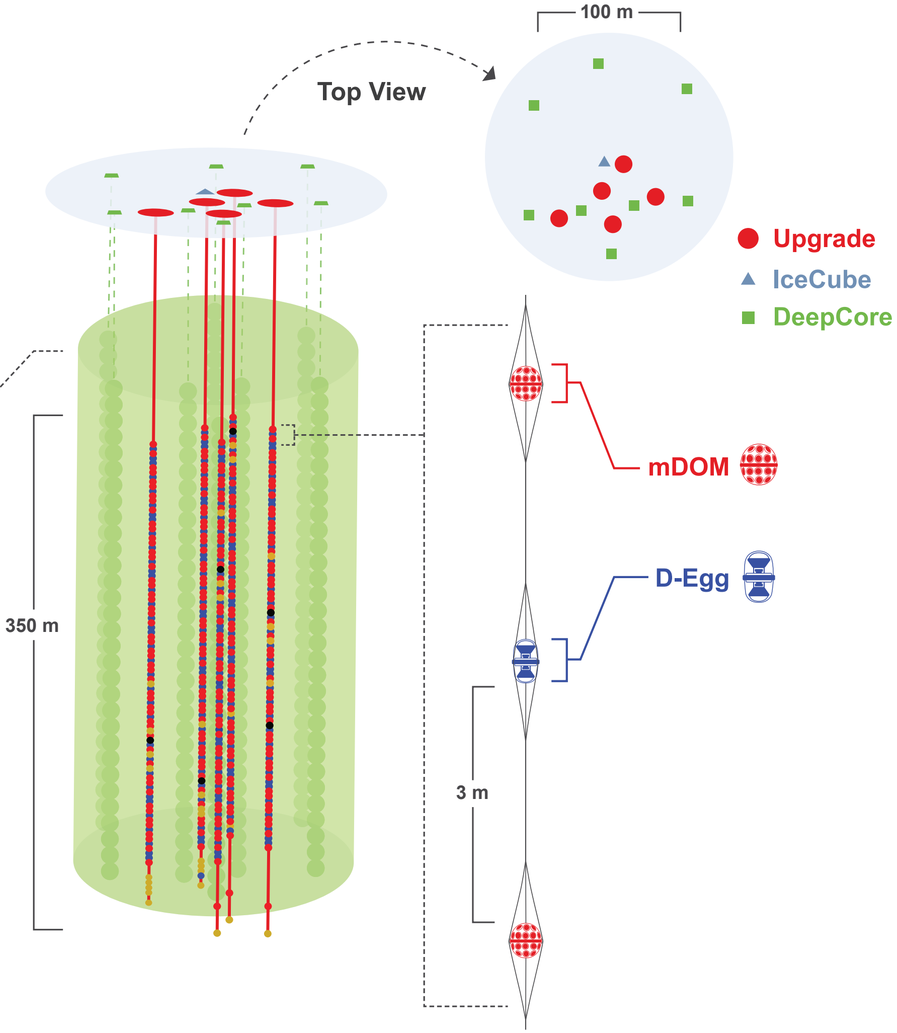

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DeepCore constructed 2009-2011
Threshold ~10 GeV

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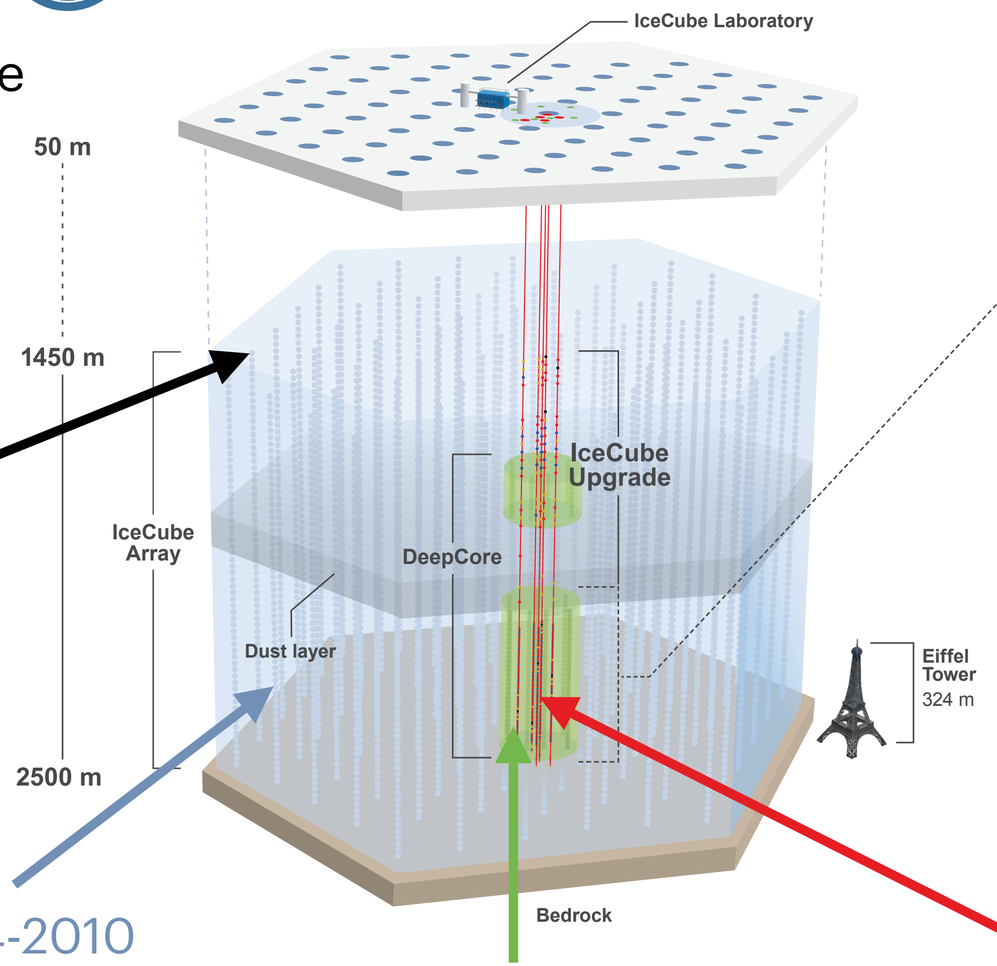
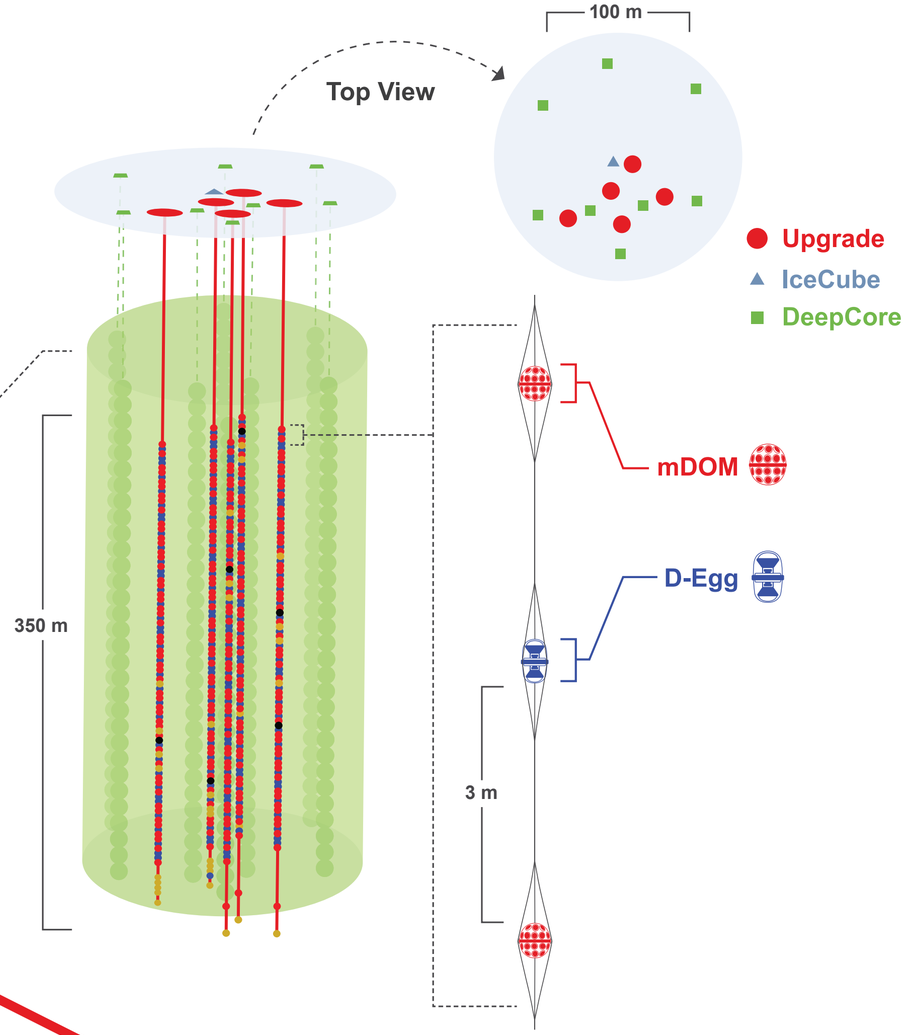




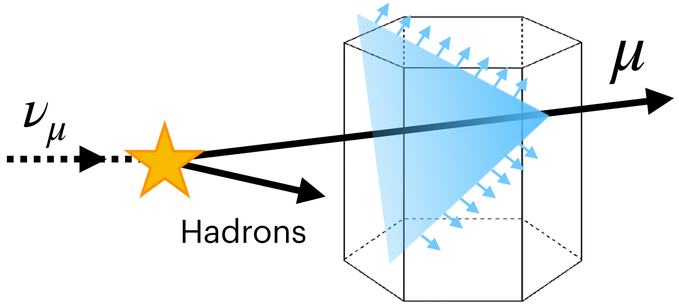
Main array constructed 2004-2010
Optimized for TeV+ energies

DeepCore constructed 2009-2011
Threshold ~10 GeV

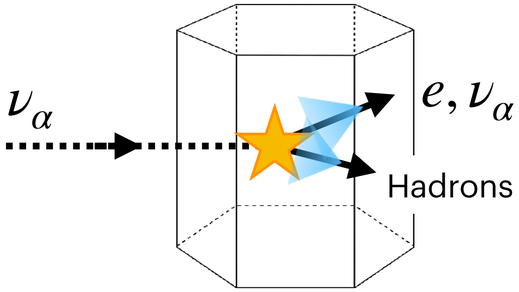
Upgrade deployed in Dec/Jan
Reduces threshold to ~1 GeV

IceCube “sees” neutrinos via Cherenkov radiation

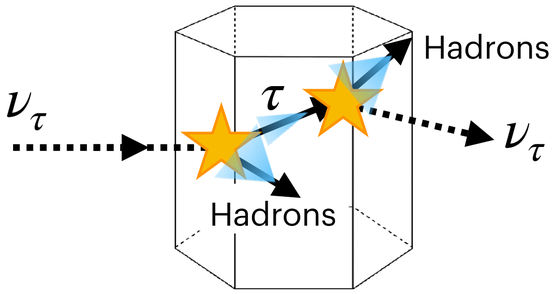
Track

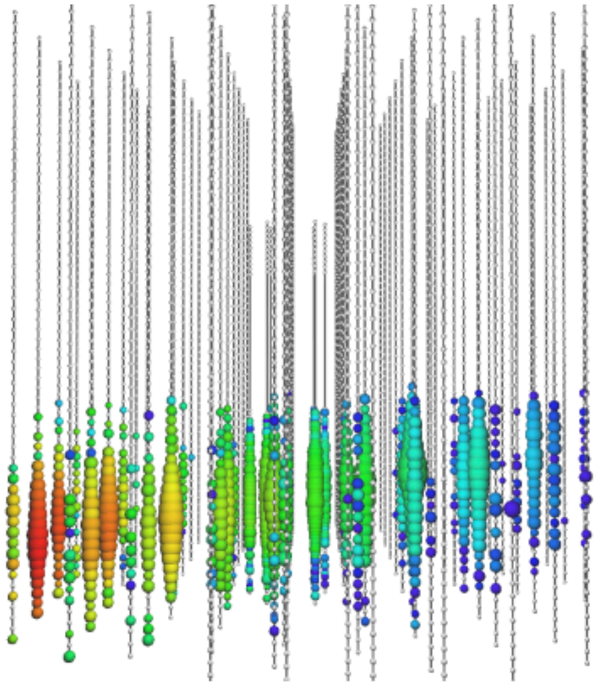


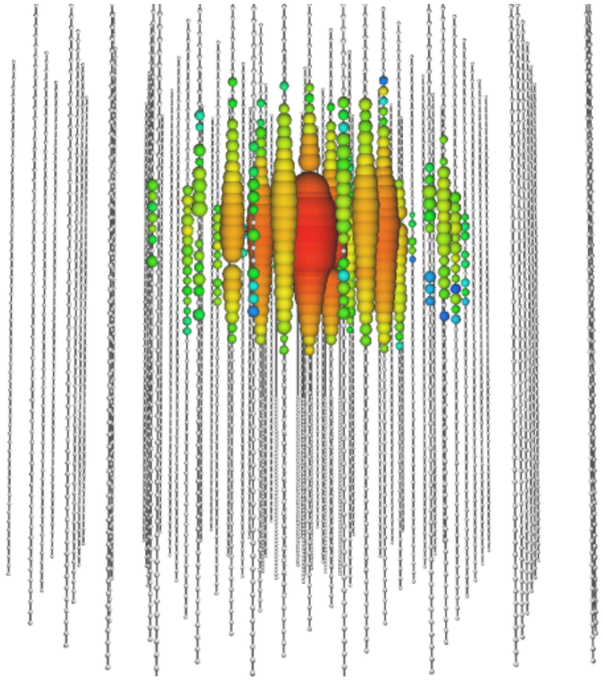
Cascade

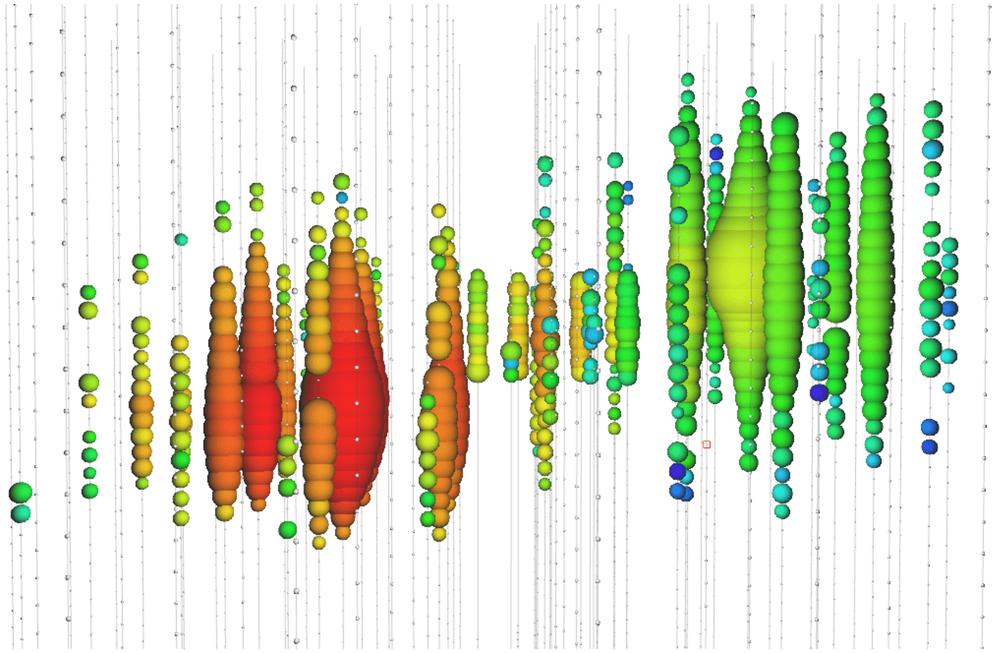


Double Cascade









Earliest photons **Latest photons**

IceCube has taught us a lot about neutrino astrophysics

1988

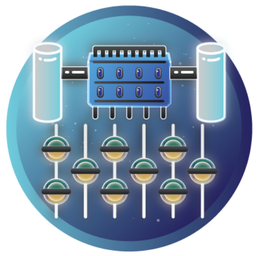
TELESCOPE IN THE ICE
ENVISIONED

2000

AMANDA
COMPLETED

2001

ATMOSPHERIC NEUTRINOS
DETECTED



2011

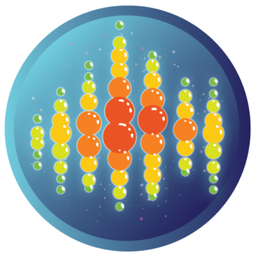
ICECUBE
COMPLETED

2013

ASTROPHYSICAL NEUTRINOS
DISCOVERED

2018

BLAZAR TXS 0506+056
NEUTRINO EMISSION IDENTIFIED

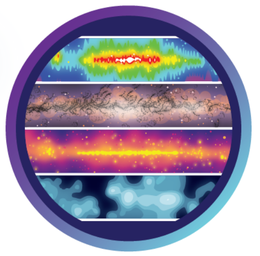


2021

GLASHOW RESONANCE
NEUTRINO IDENTIFIED

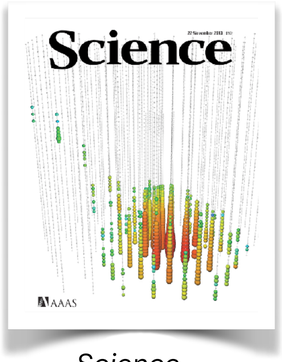
2022

ACTIVE GALAXY NGC 1068
NEUTRINO EMISSION IDENTIFIED



2023

MILKY WAY
NEUTRINO EMISSION IDENTIFIED



Science
Volume 342, Issue 6161

Science
Volume 361, Issue 6398

Nature
Volume 591, pg 220–224

Science
Volume 378, Issue 6619

Science
Volume 380, Issue 6652

NSF | IceCube Neutrino Observatory

Where do astro neutrinos come from?

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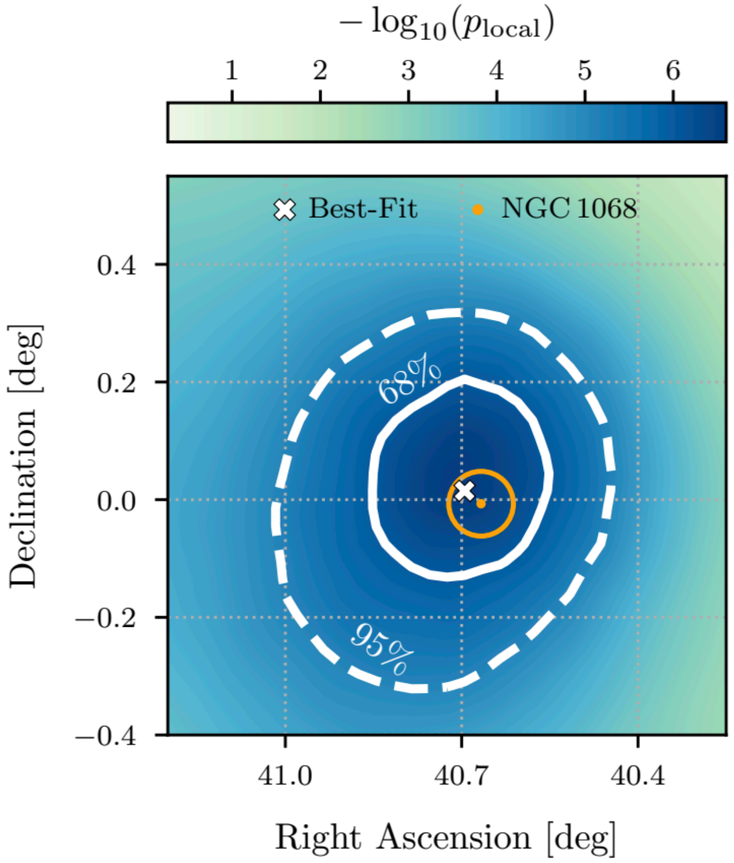
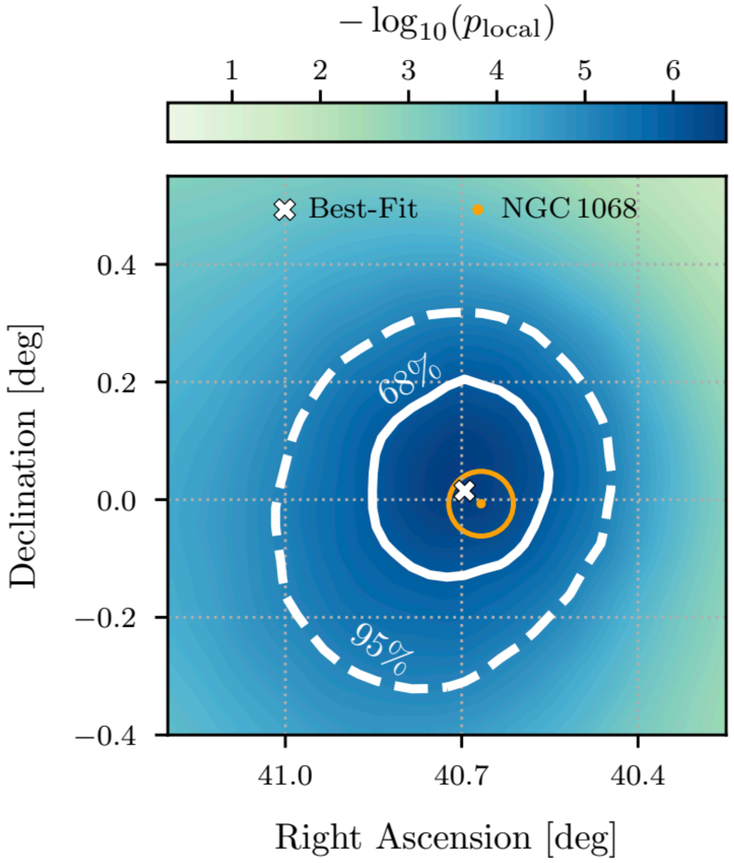


Brightest spot on the sky: NGC 1068

with a global significance of 4.0σ

IceCube Science Vol 378 (2022)

Where do astro neutrinos come from?



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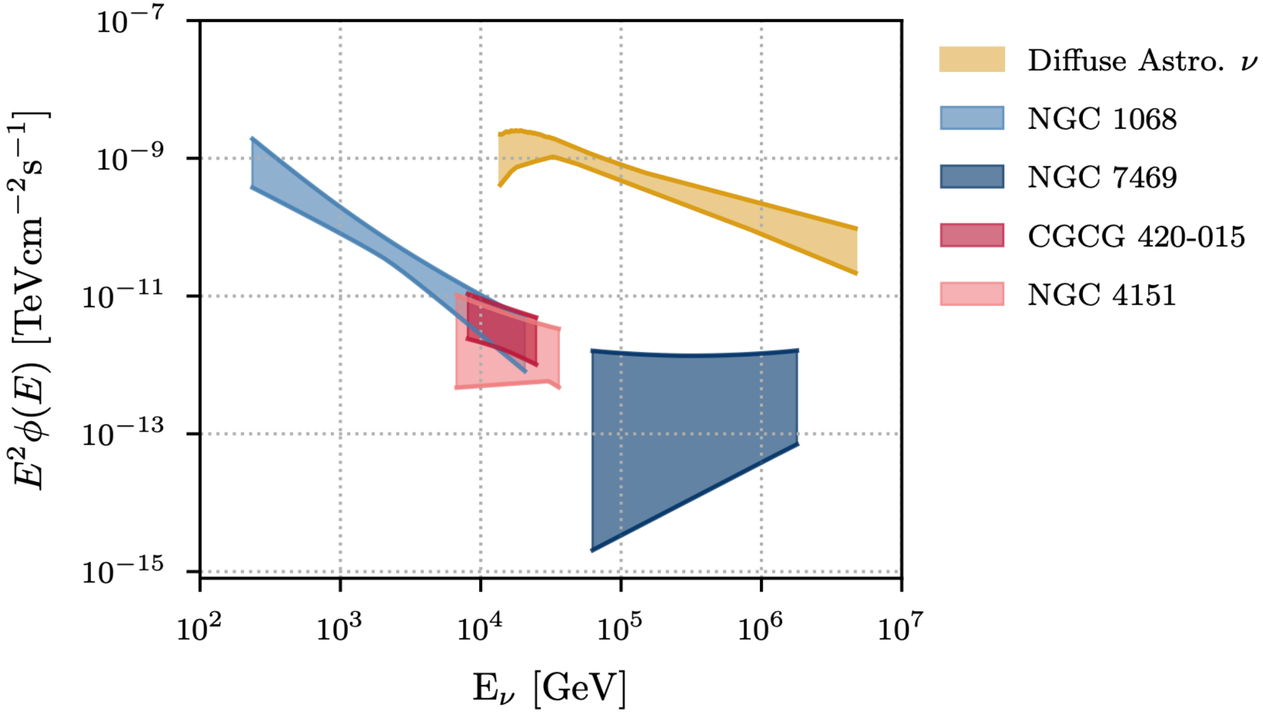


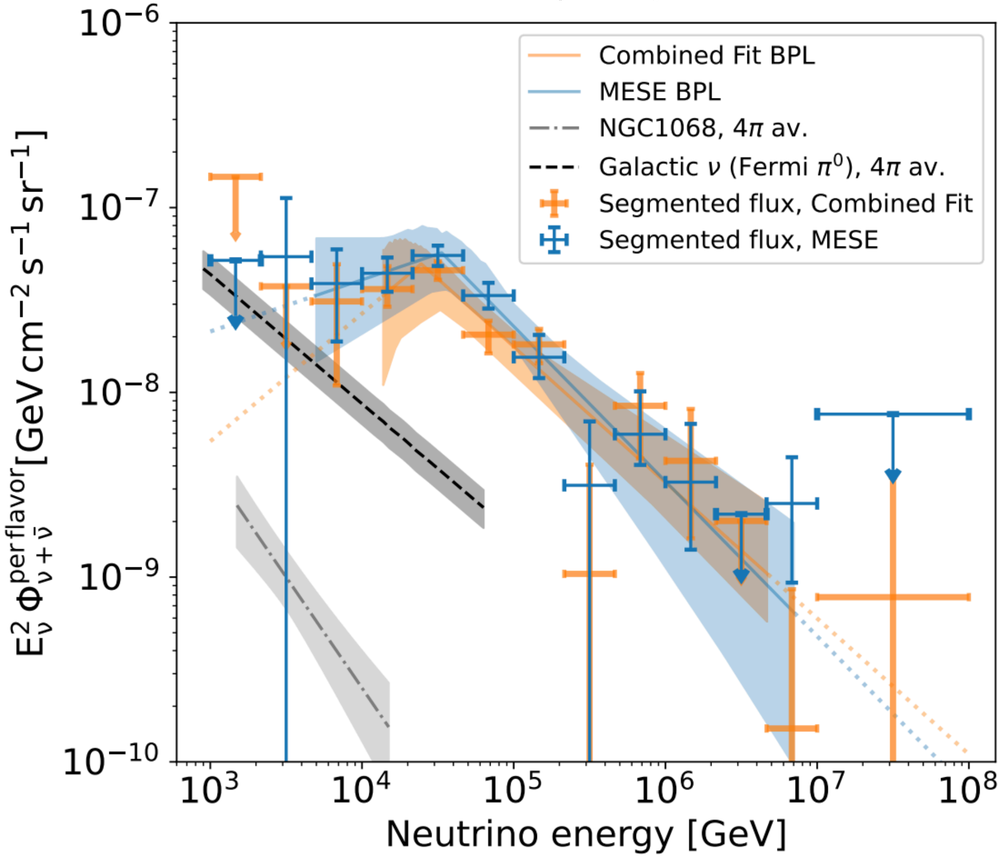
3.3σ evidence for neutrino emission from a population of similar X-ray bright active galactic nuclei

IceCube 2510.13403

What is the energy spectrum of astro neutrinos?

What is the energy spectrum of astro neutrinos?

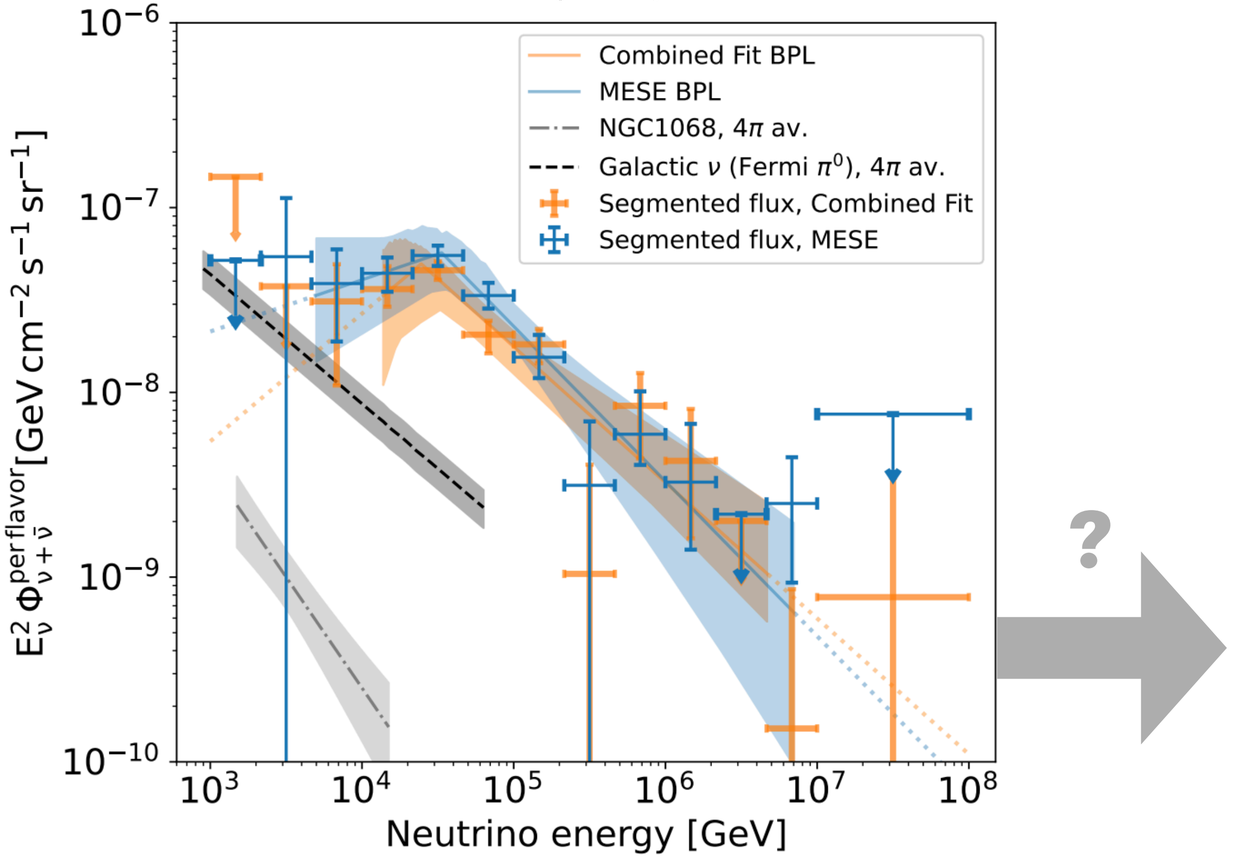
IceCube PRL Vol 136 (2026)



At lower energies, emerging evidence for a break from the single power description

What is the energy spectrum of astro neutrinos?

IceCube PRL Vol 136 (2026)



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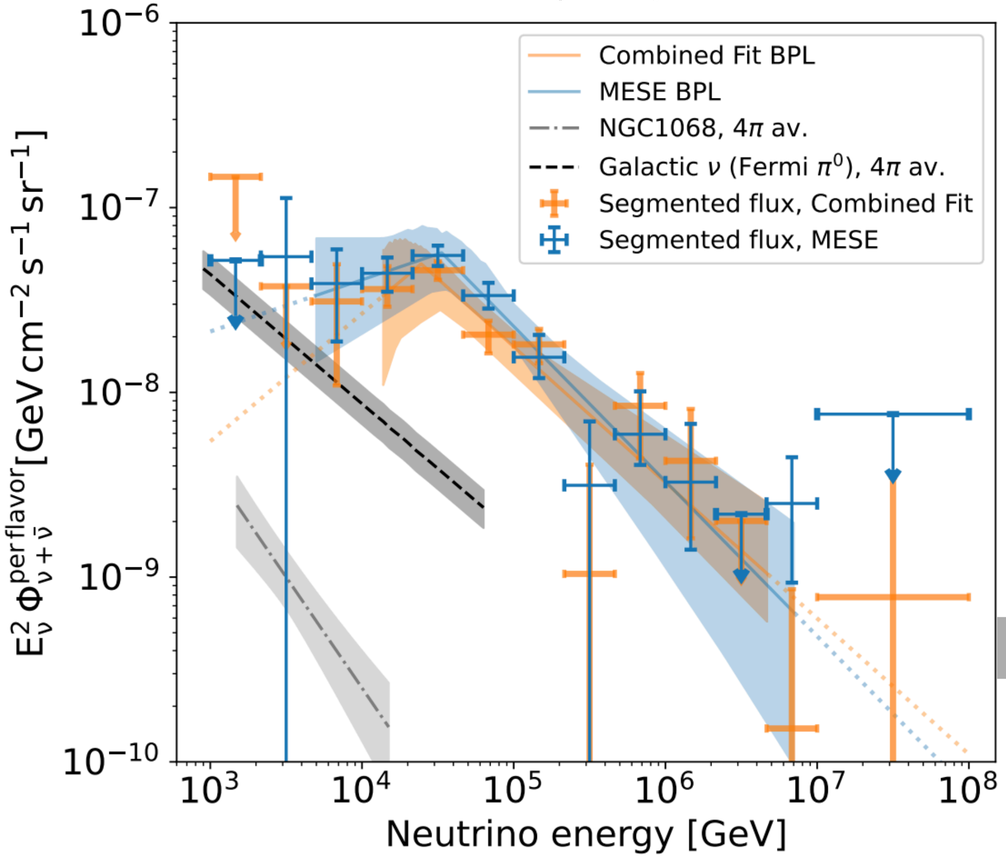
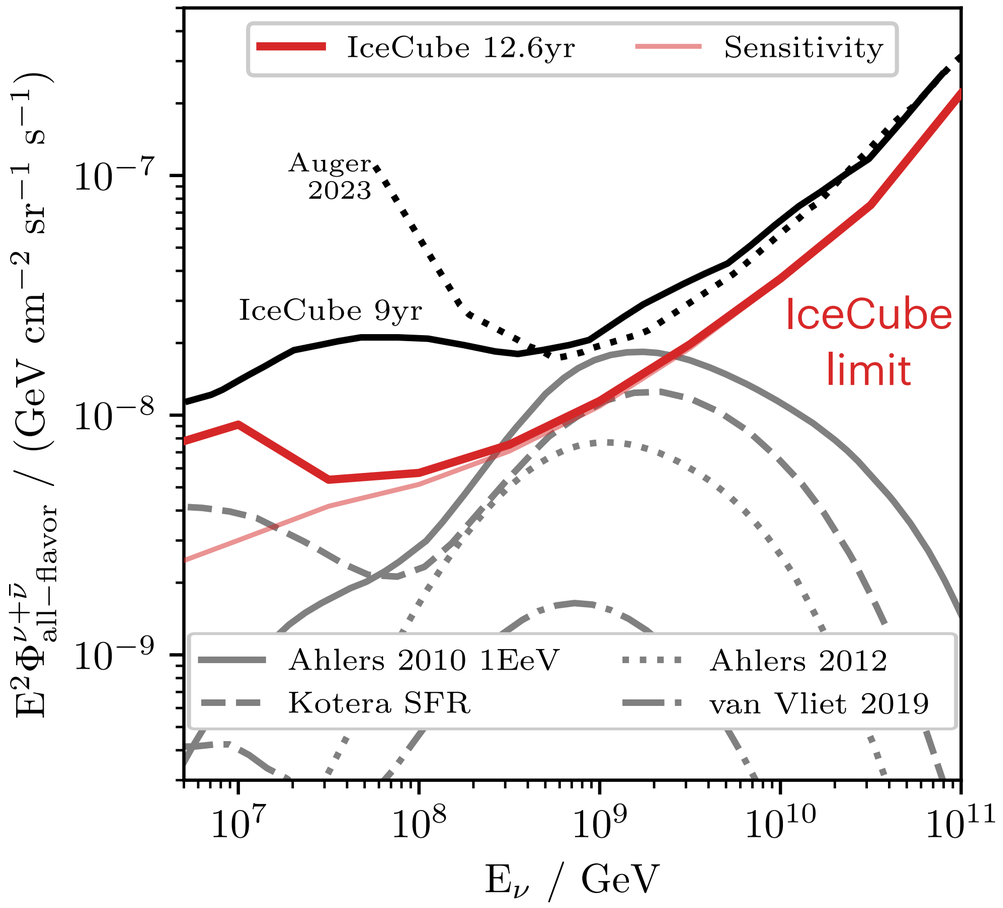
IceCube PRL Vol 136 (2026)



?

IceCube PRL Vol 135 (2025)



At lower energies, emerging evidence for a break from the single power description

At higher energies, IceCube places limits only

What is the flavor composition of astro neutrinos?

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Neutrinos **decohere** over astrophysical distance scales, predicting

$$\{f_e, f_\mu, f_\tau\} \sim \{1/3,\ 1/3,\ 1/3\}$$

at the detector

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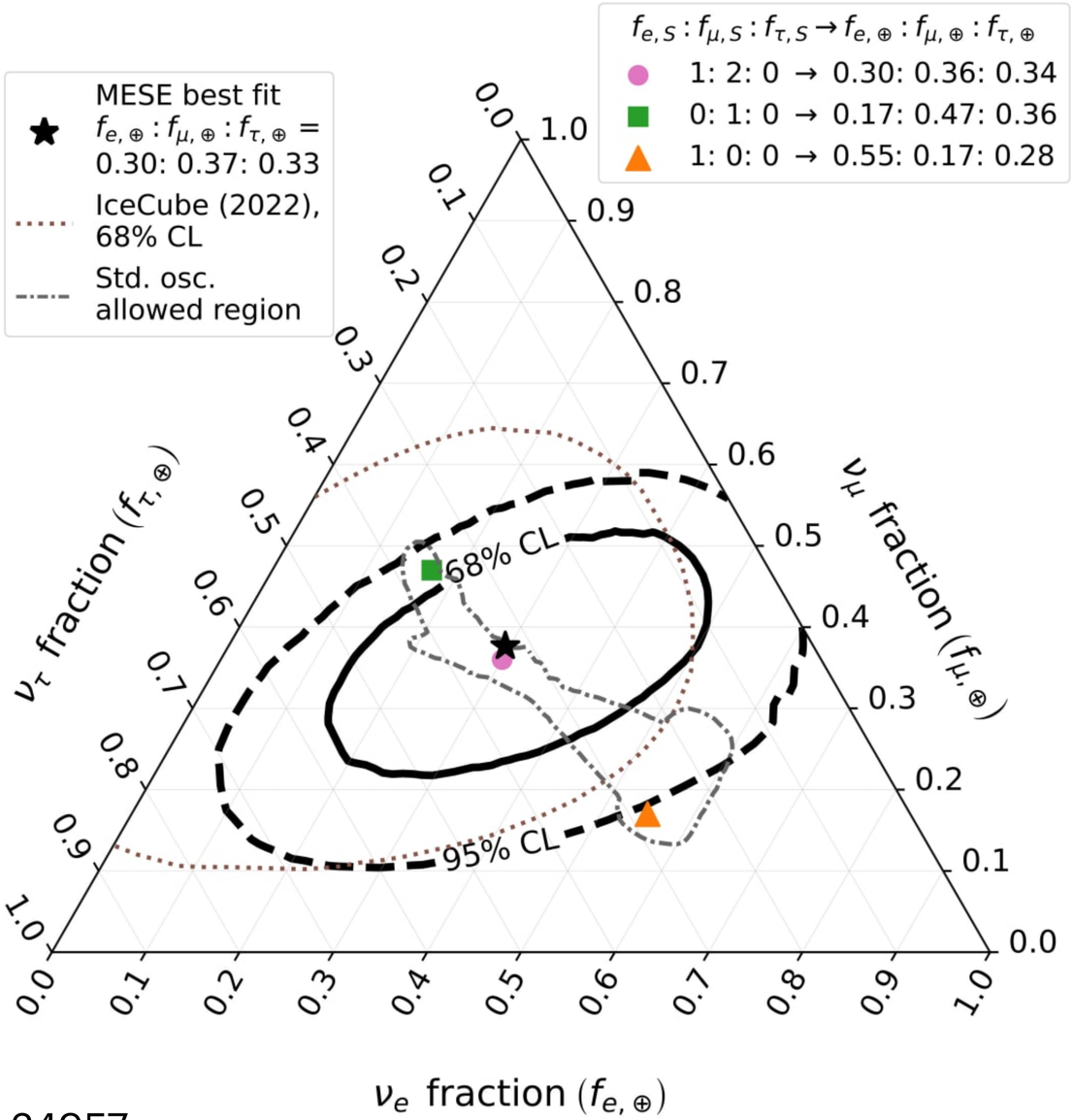
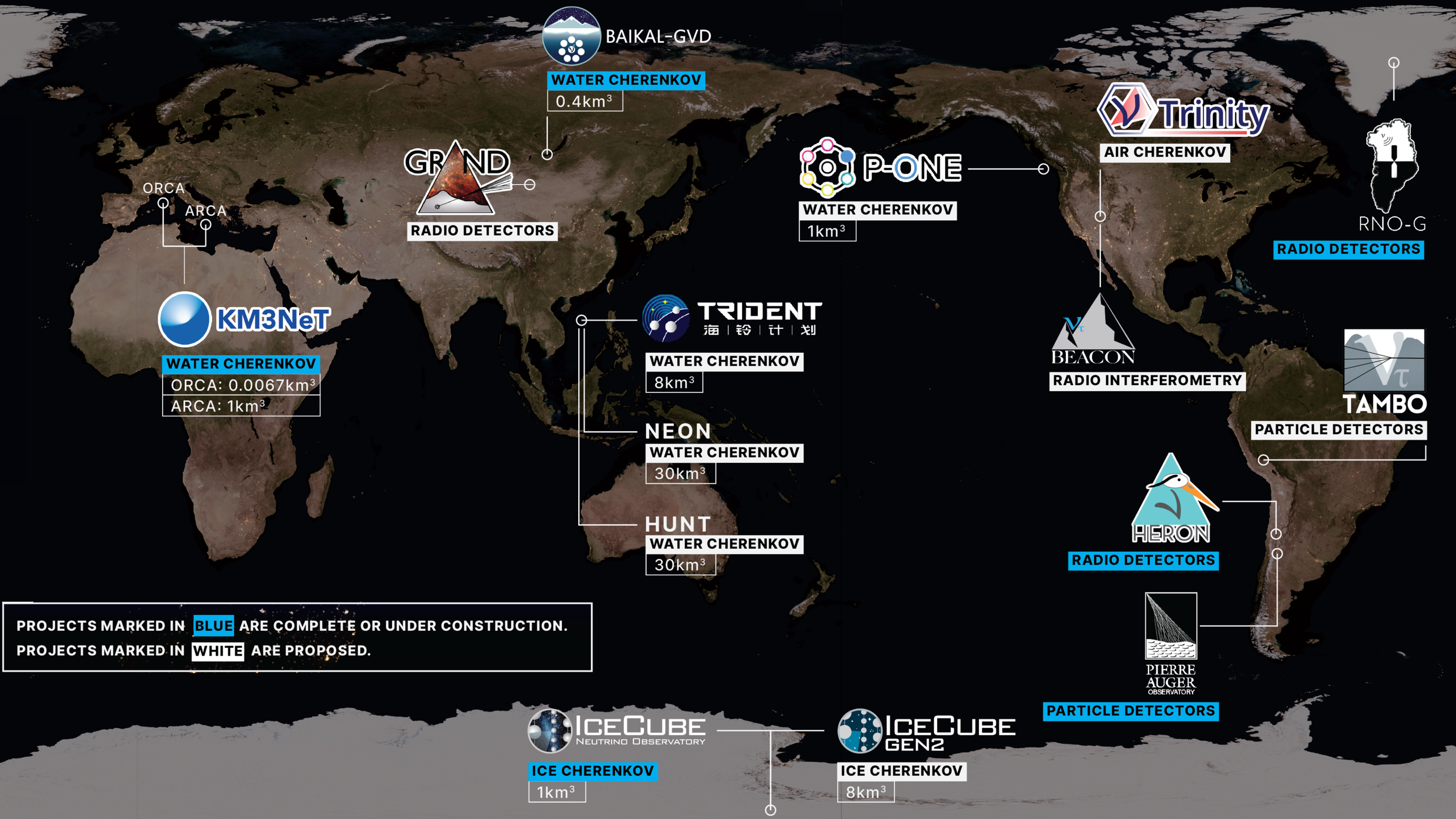
at the detector

Recent IceCube results show the first **closed contour** at 1σ in flavor space, and **reject neutron decay** as the main production mechanism



IceCube 2510.24957

But IceCube is not the only game in town


BAIKAL-GVD
WATER CHERENKOV
0.4km³
GRAND
RADIO DETECTORS
ORCA
ARCA
KM3NeT
WATER CHERENKOV
ORCA: 0.0067km³
ARCA: 1km³
P-ONE
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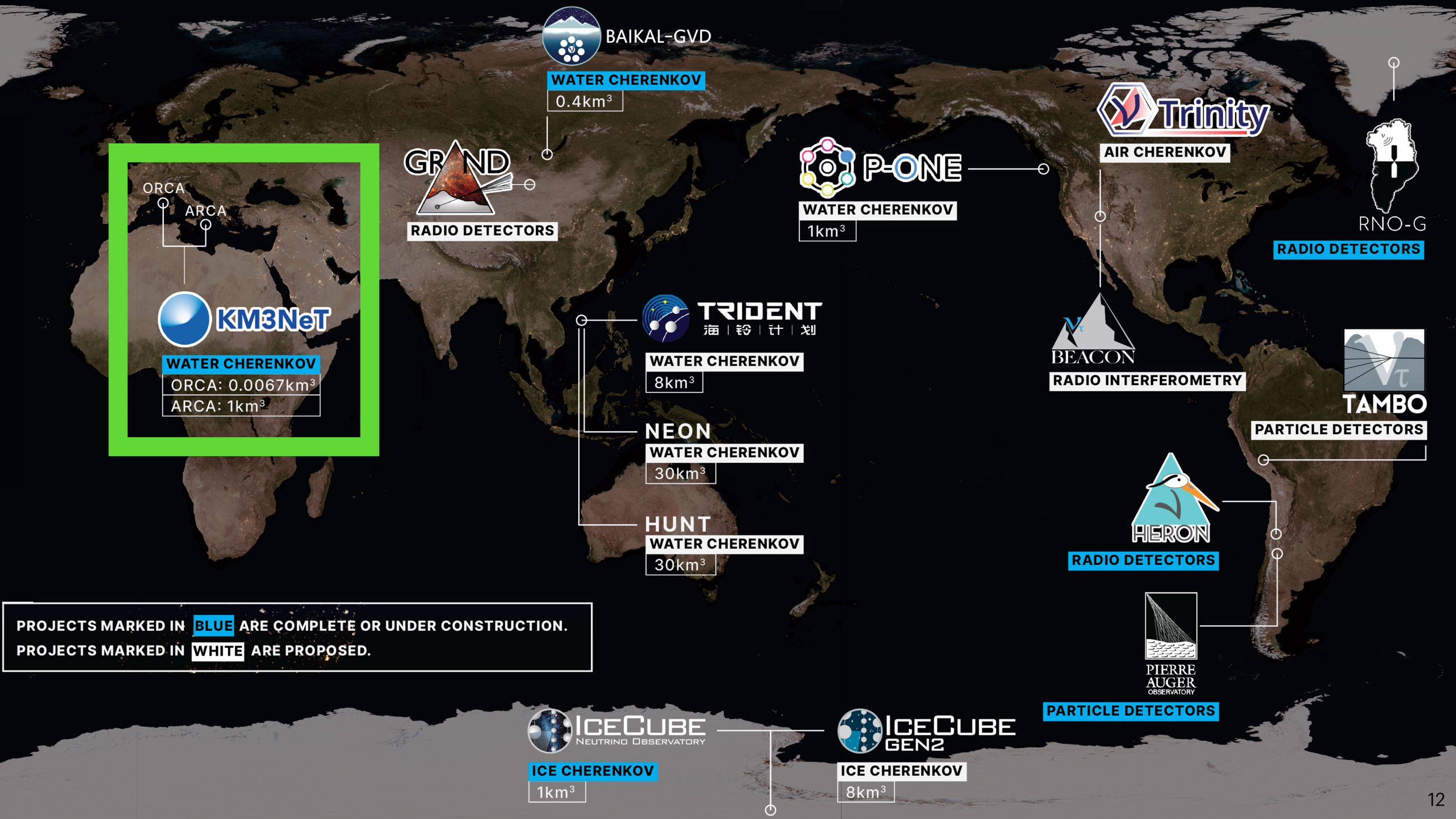
1km³
Trinity
AIR CHERENKOV
RNO-G
RADIO DETECTORS
TRIDENT
海 | 铃 | 计 | 划
WATER CHERENKOV
8km³
BEACON
RADIO INTERFEROMETRY
TAMBO
PARTICLE DETECTORS
NEON
WATER CHERENKOV
30km³
HUNT
WATER CHERENKOV
30km³
HERON
RADIO DETECTORS
PIERRE AUGER OBSERVATORY
PARTICLE DETECTORS
PROJECTS MARKED IN BLUE ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN WHITE ARE PROPOSED.
ICECUBE NEUTRINO OBSERVATORY
ICE CHERENKOV
1km³
ICECUBE GEN2
ICE CHERENKOV
8km³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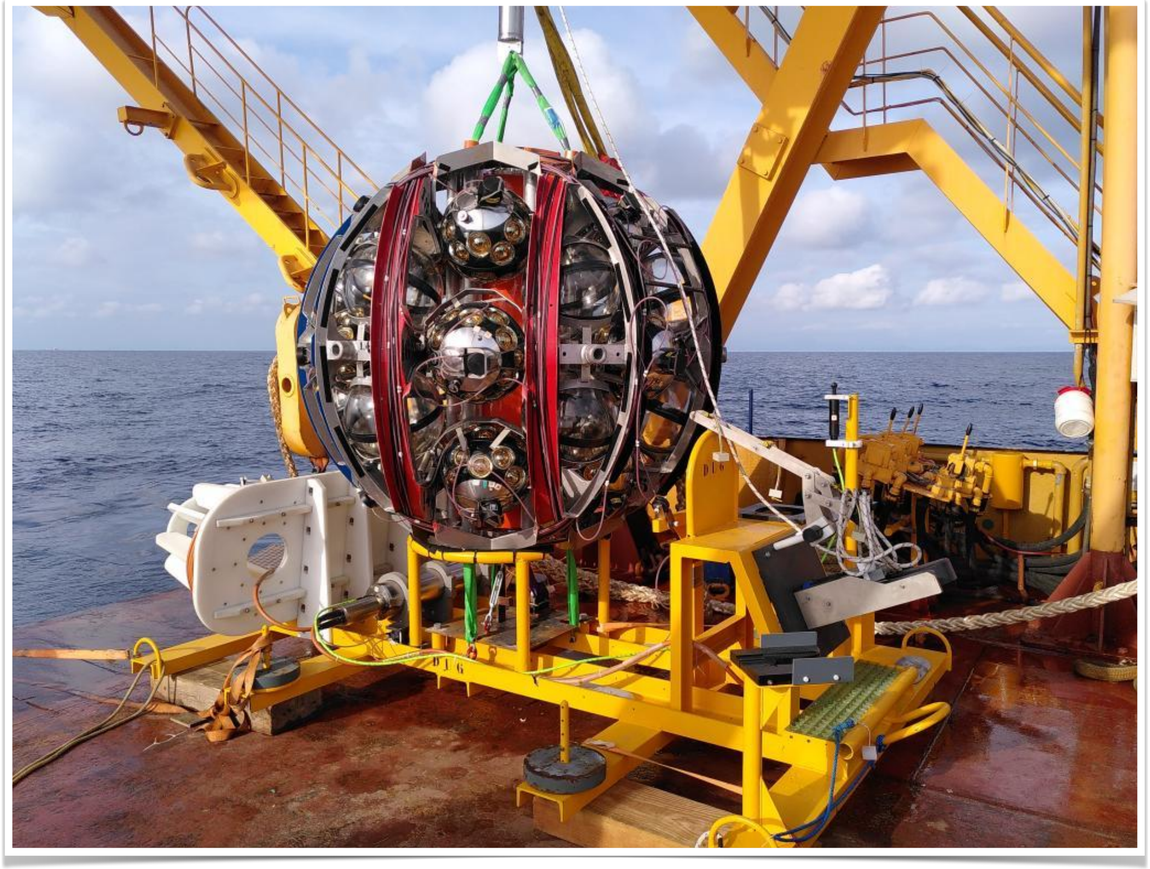
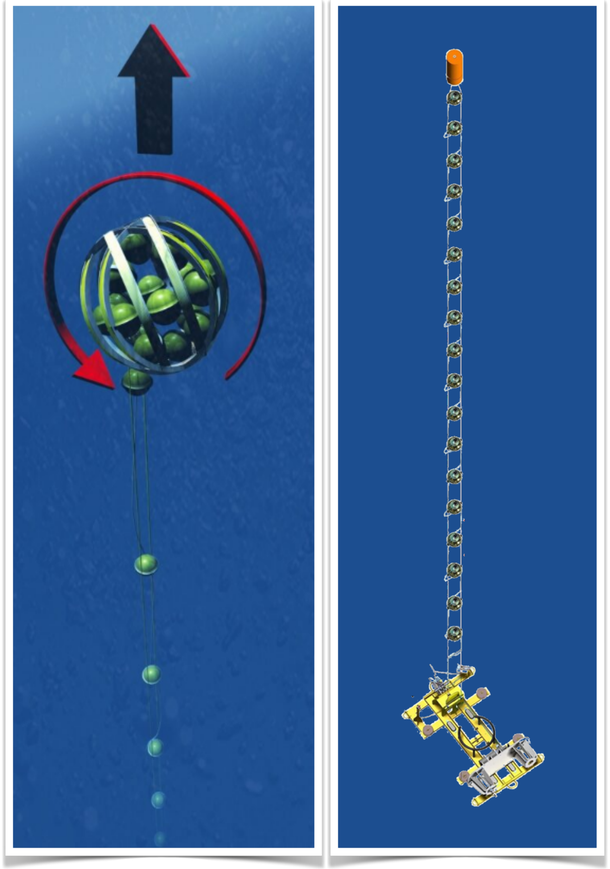
The KM3NeT Detection Units

31 3” photo-multiplier tubes per Digital Optical Module (DOM)



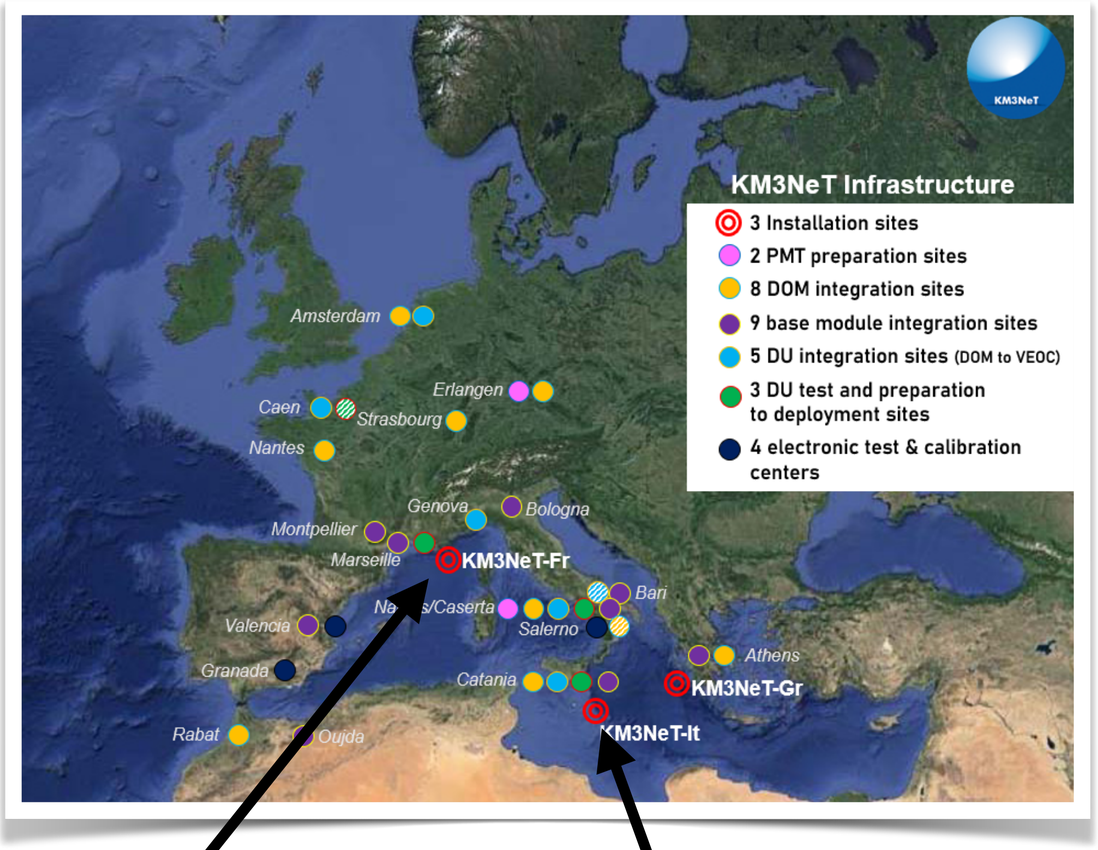
18 DOMs per Detection Unit (DU)

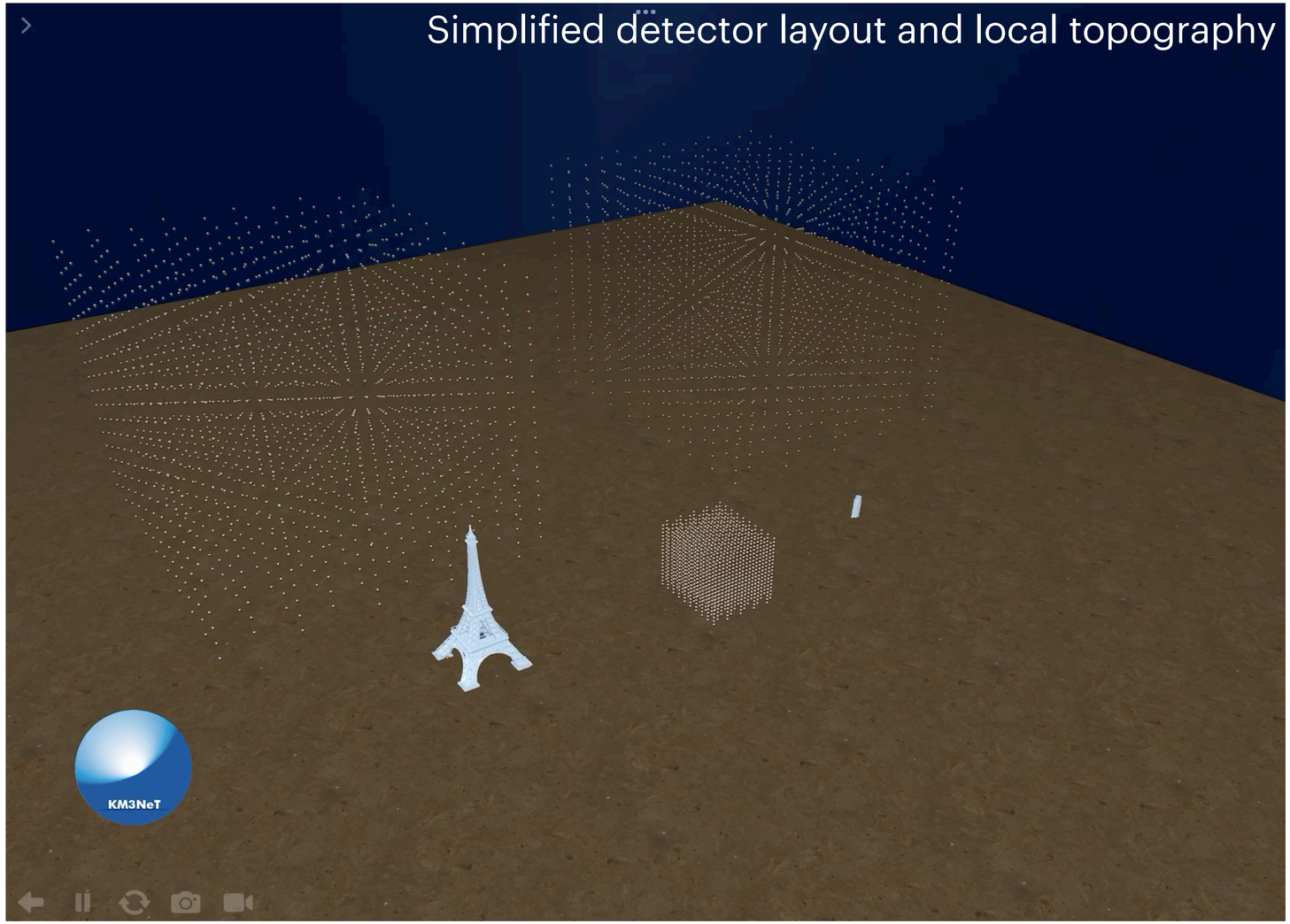


Each DU is unraveled before reaching the sea floor

KM3NeT 2016 KM3NeT 2022

The KM3NeT Detectors: ORCA and ARCA





ORCA

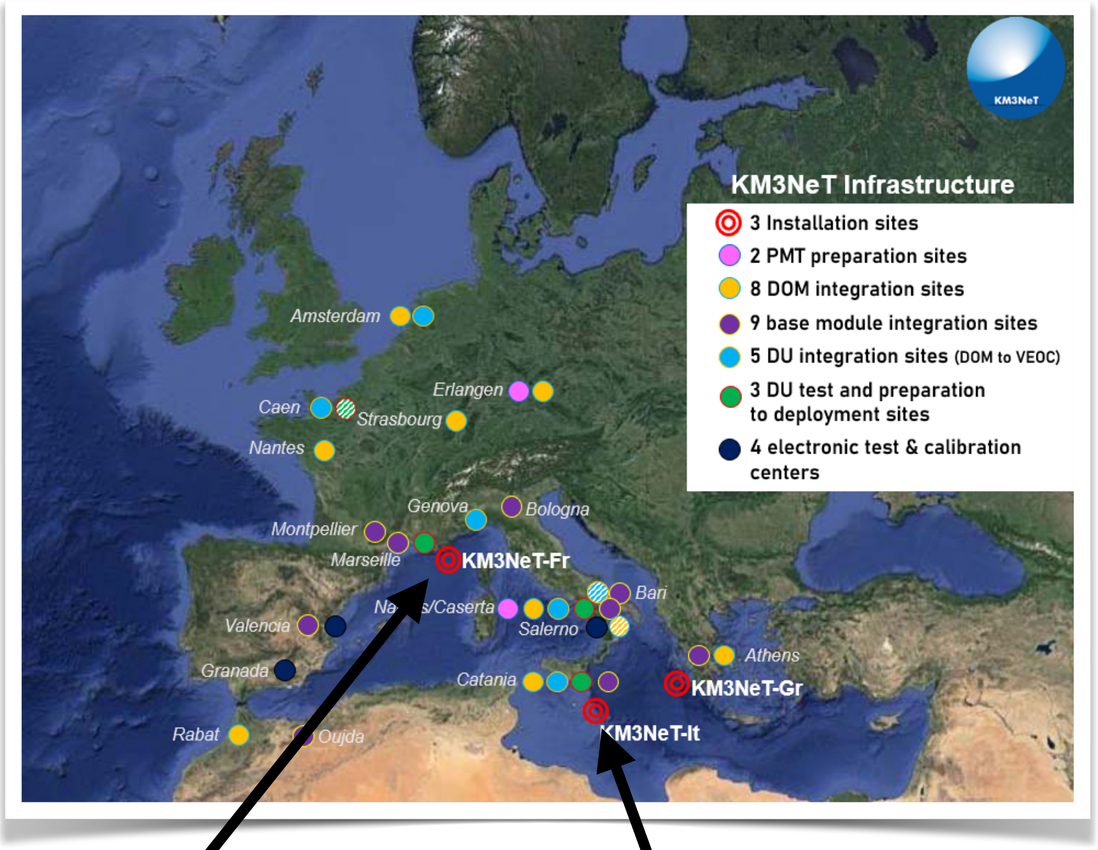
Oscillation Research with Cosmics in the Abyss

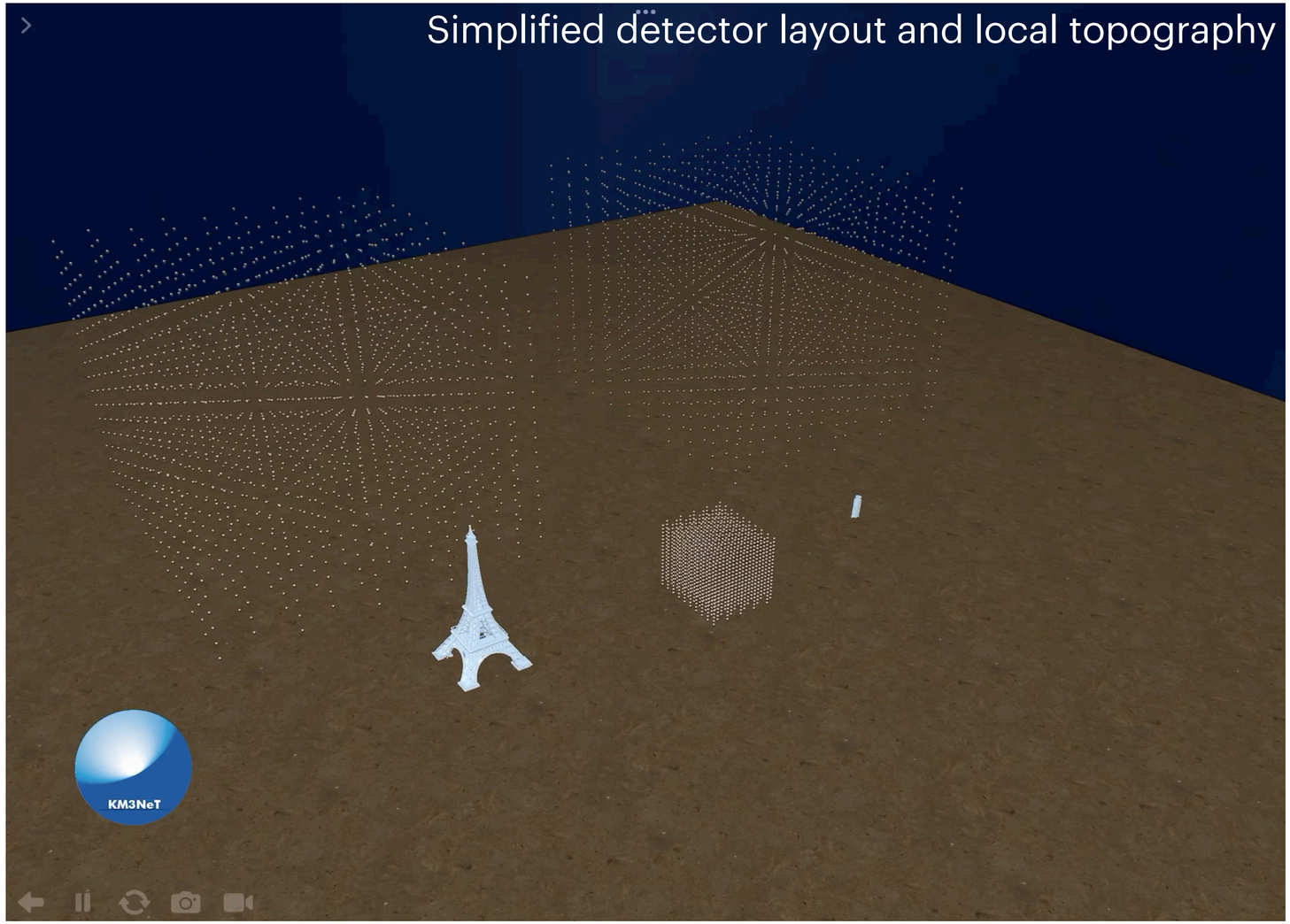
ARCA

Astroparticle Research with Cosmics in the Abyss

KM3NeT 2016

The KM3NeT Detectors: ORCA and ARCA





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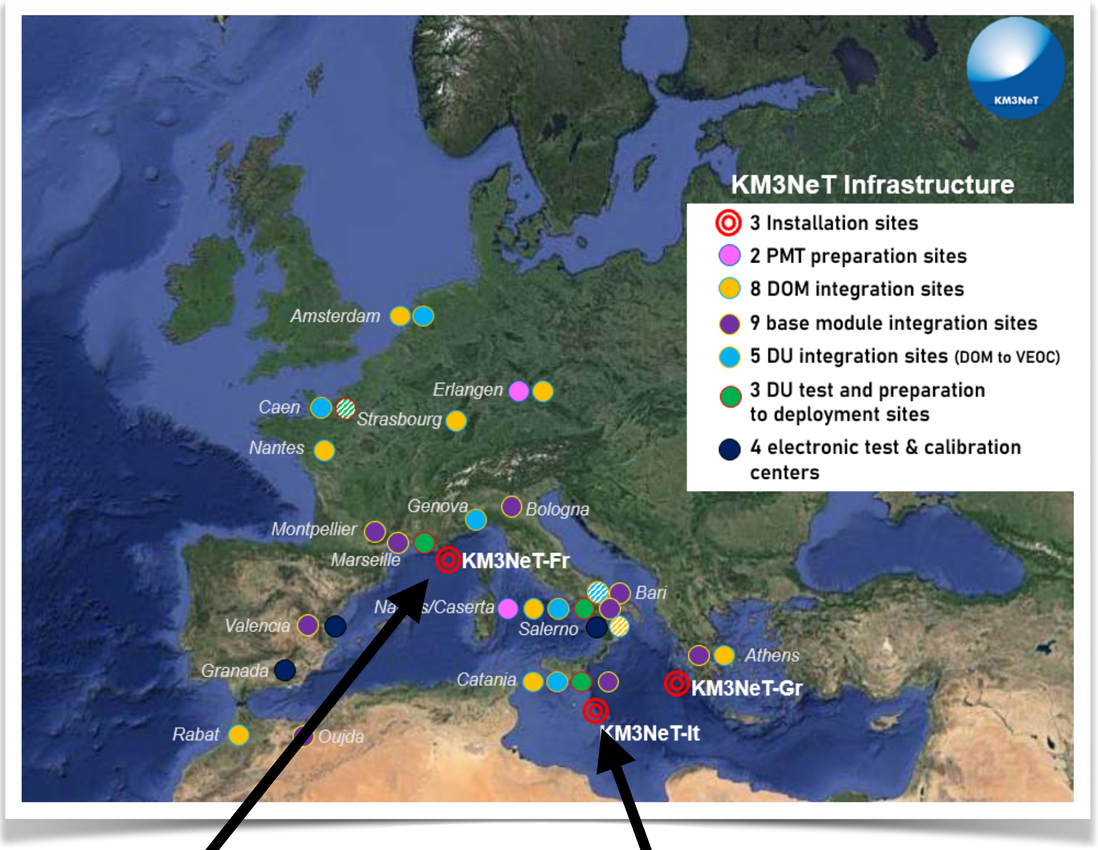
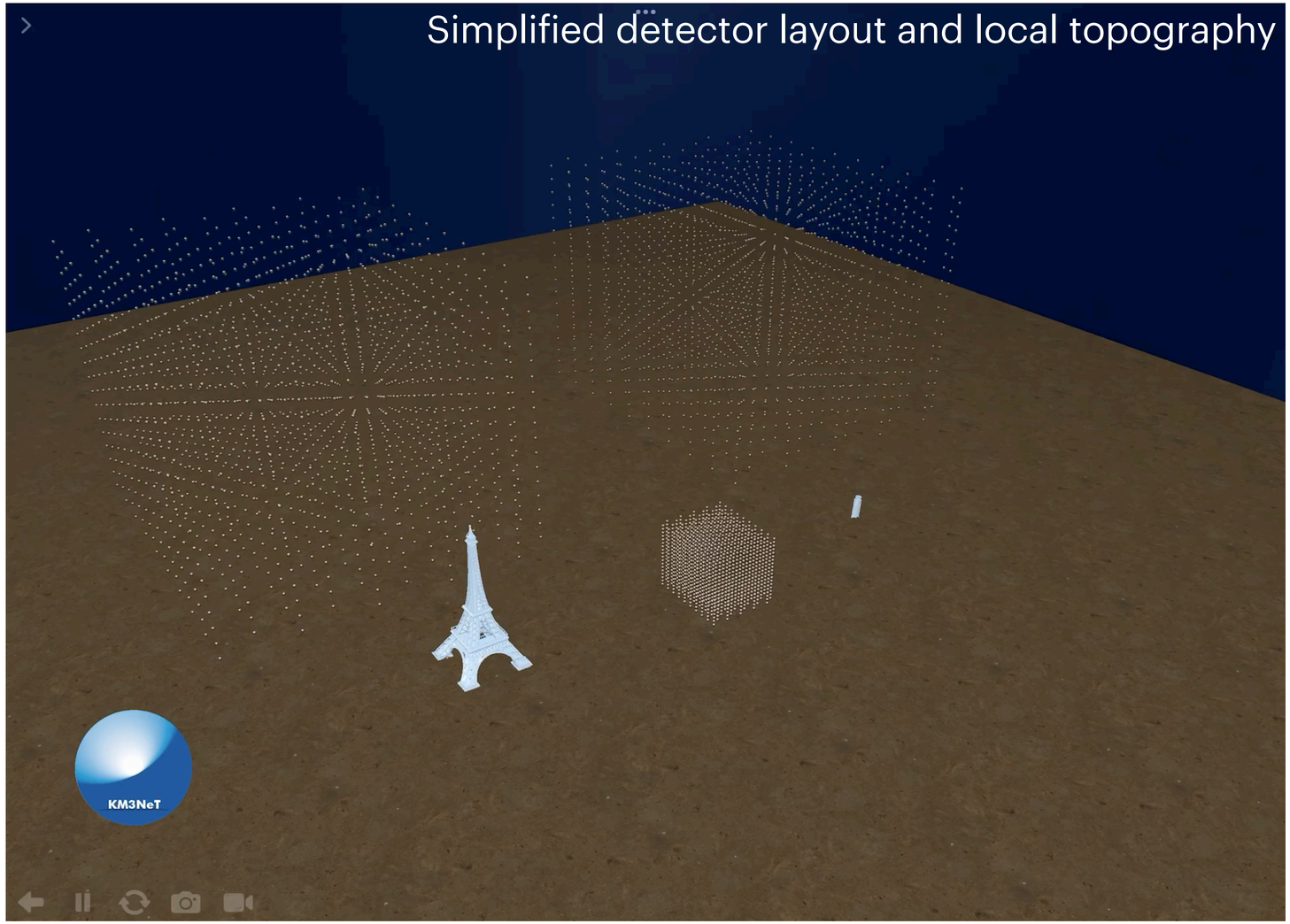




ORCA

Oscillation Research with Cosmics in the Abyss

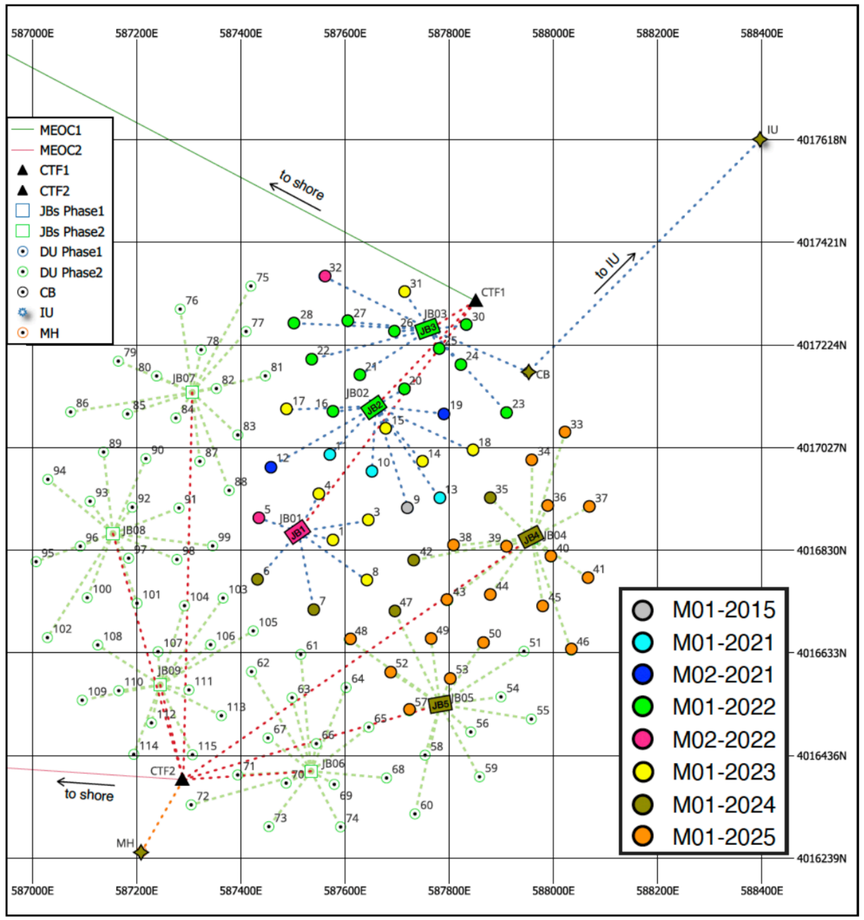
ARCA

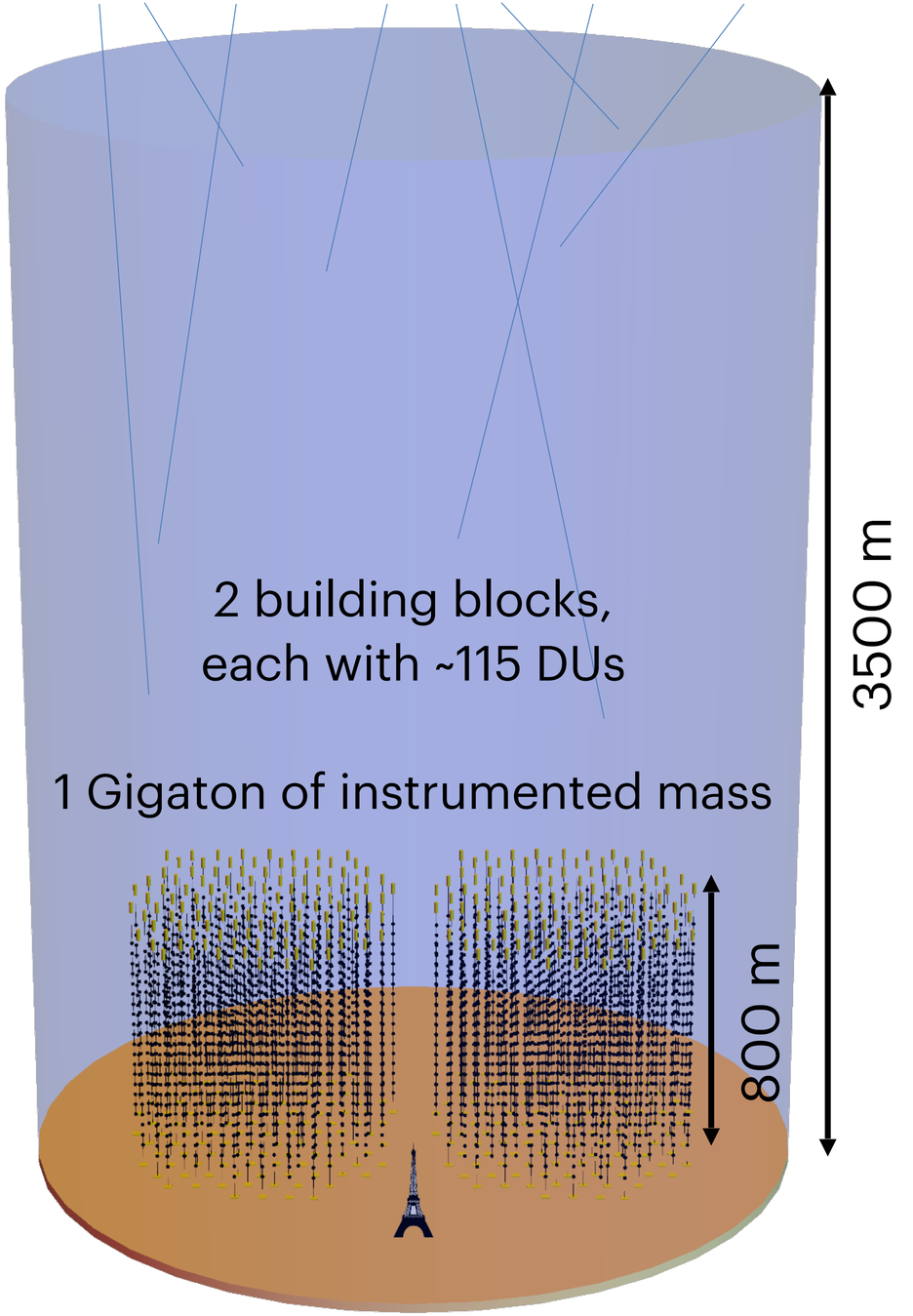
Astroparticle Research with Cosmics in the Abyss

KM3NeT 2016

The KM3NeT/ARCA Detector

Under construction: 51 / 230 DUs deployed





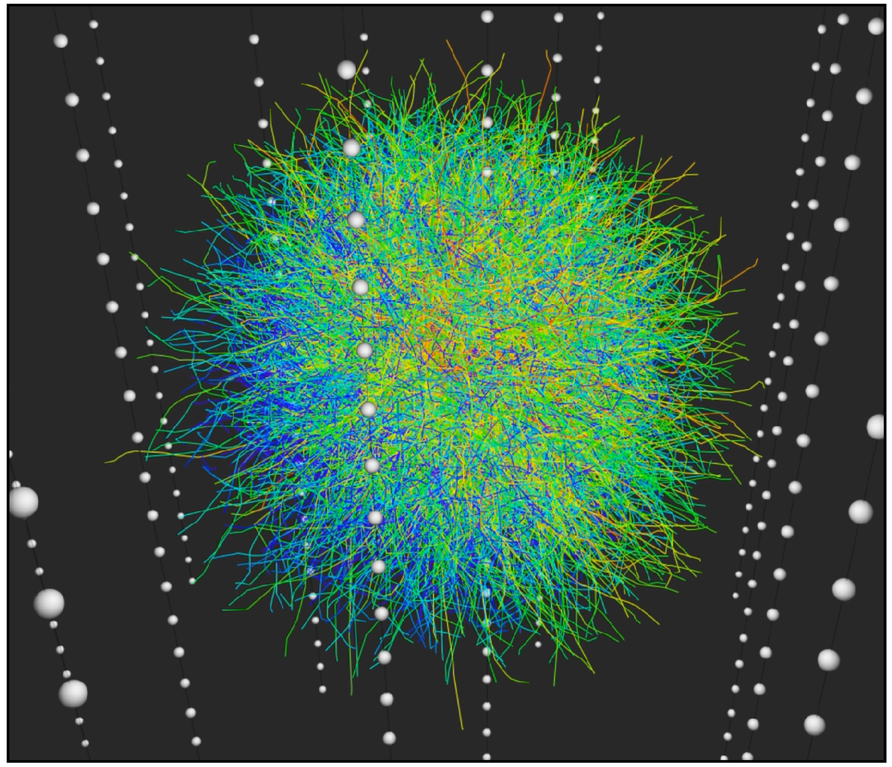
KM3NeT 2016

D. Dornic, ICRC 2025

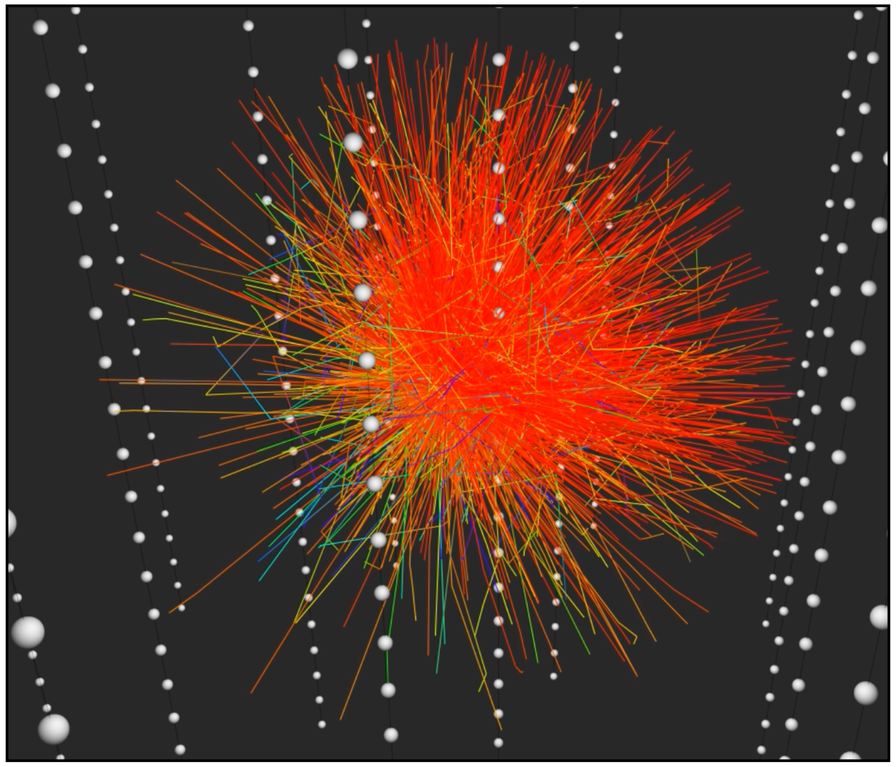
Reconstruction in Ice v.s. Water

A 10 TeV cascade example

Ice: short scattering length, long absorption length



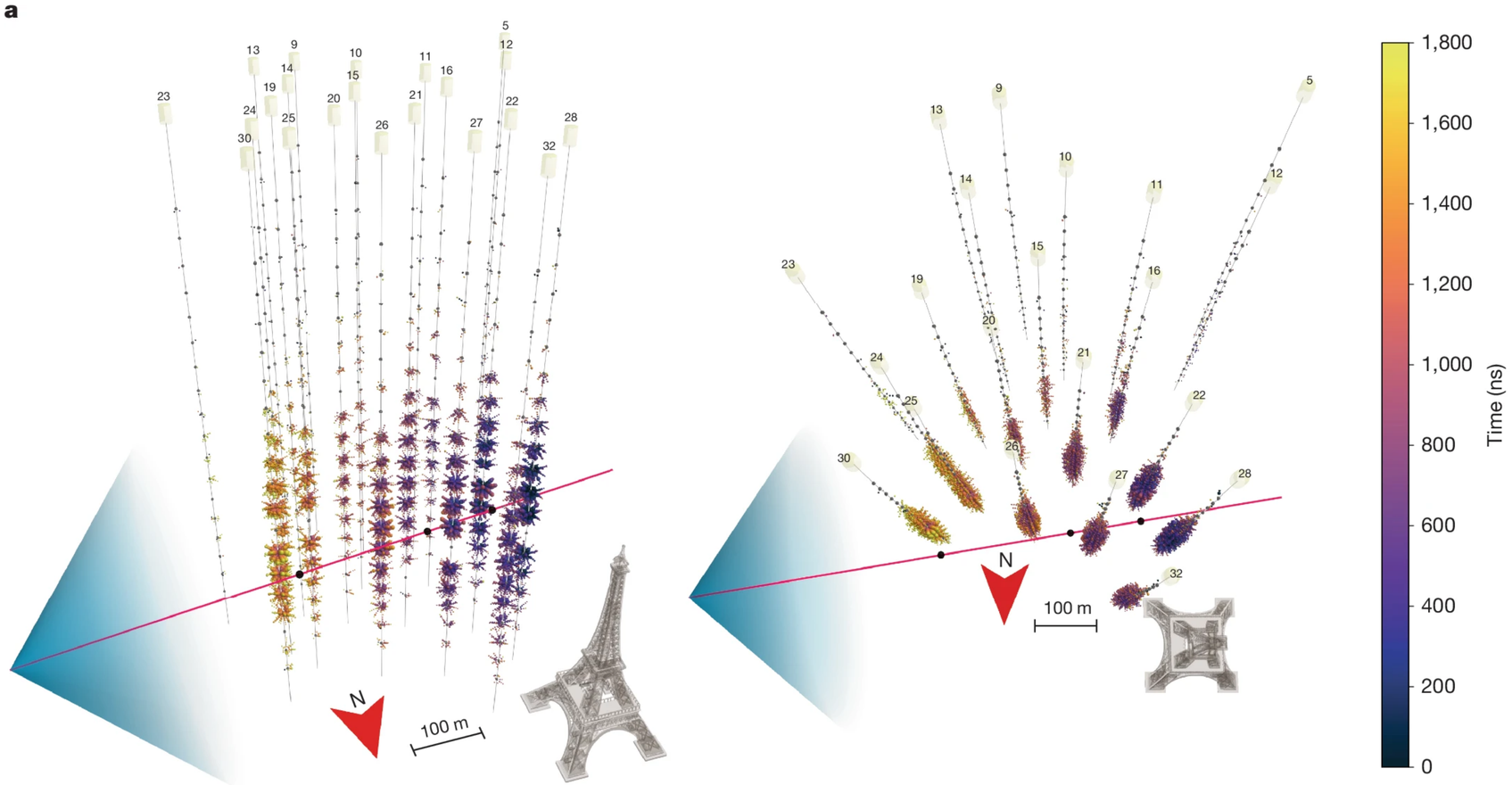
Water: short absorption length, longer scattering length



The Observation of KM3-230213A

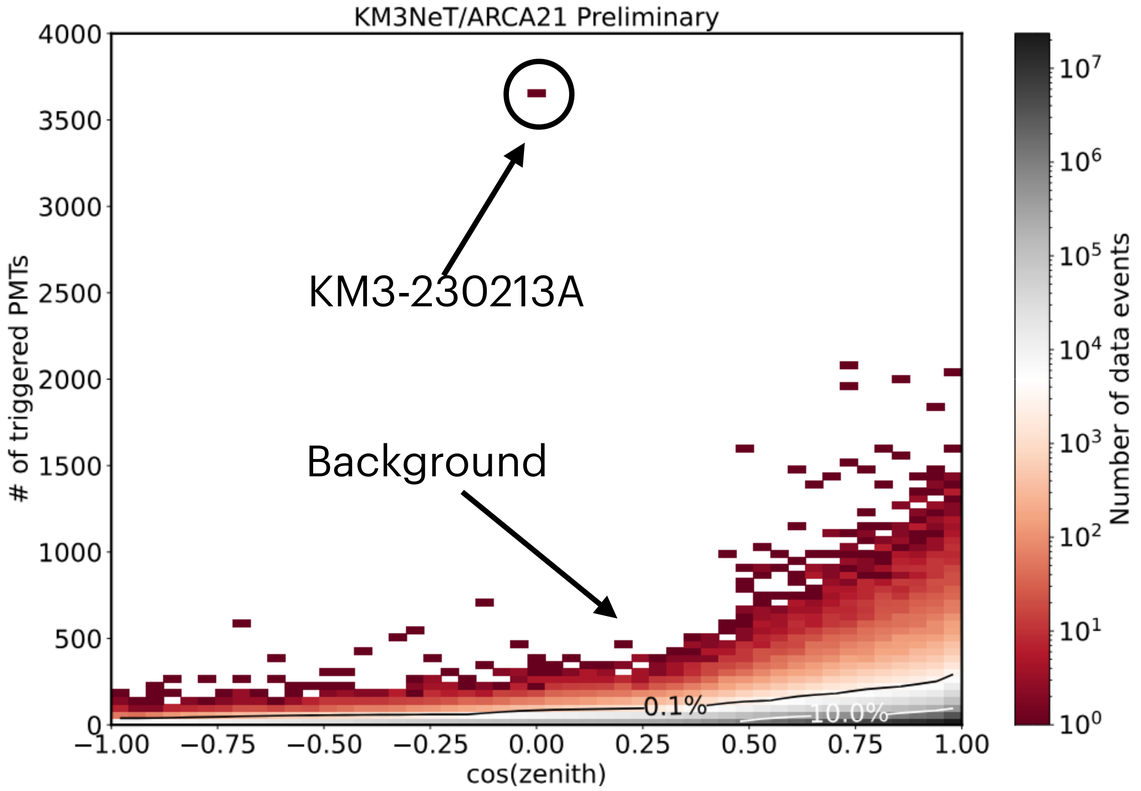
Nature Volume 638 Issue 8050

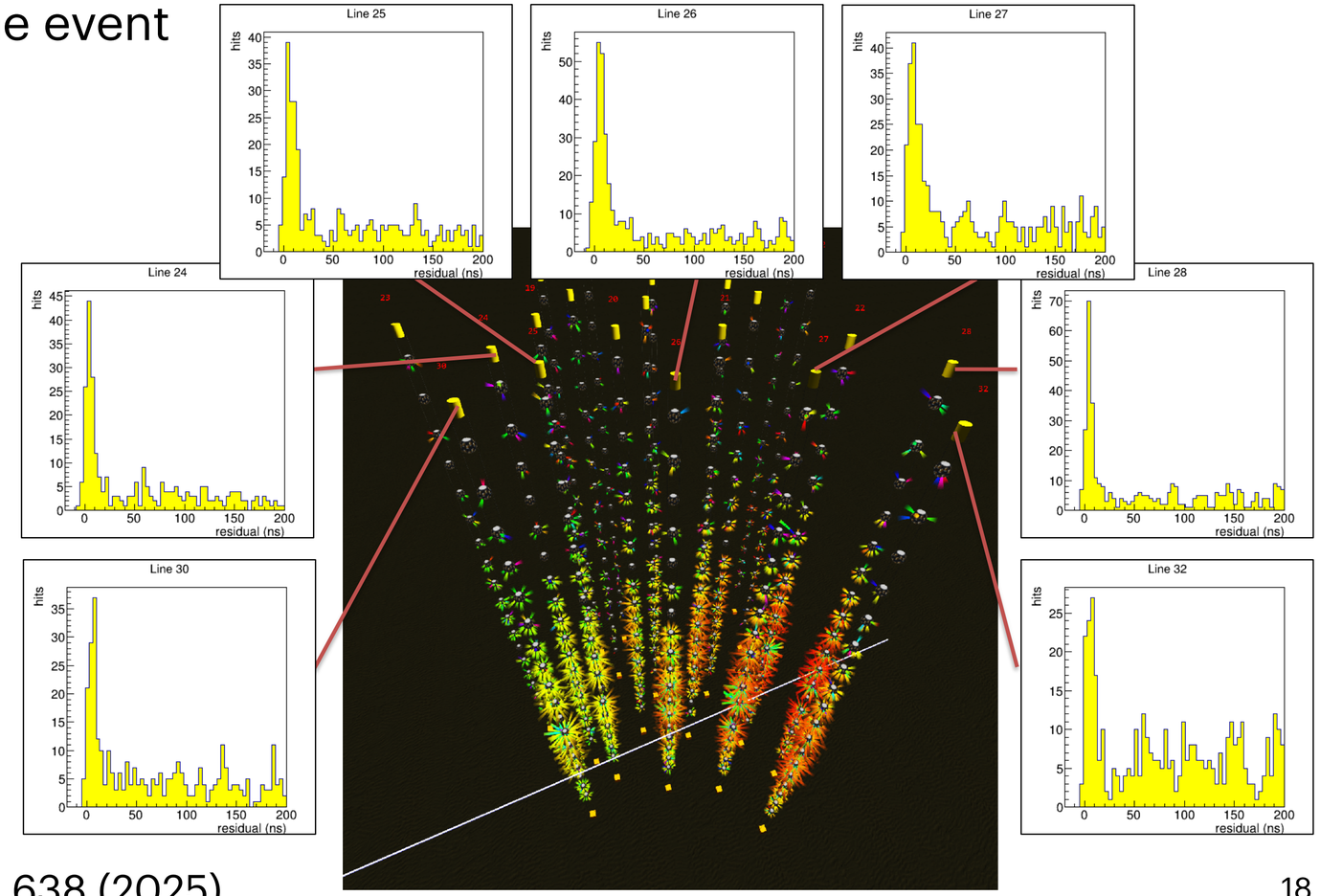
$$E_\mu = 120^{+110}_{-60}\ \text{PeV} \implies E_\nu \gtrsim 100\ \text{PeV}!$$



The Observation of KM3-230213A

- High-energy muon detected on 13 February 2023 with 21-DU configuration
- Horizontally-going, consistent with neutrino hypothesis
- 3,672 PMTs (35%) triggered during the event

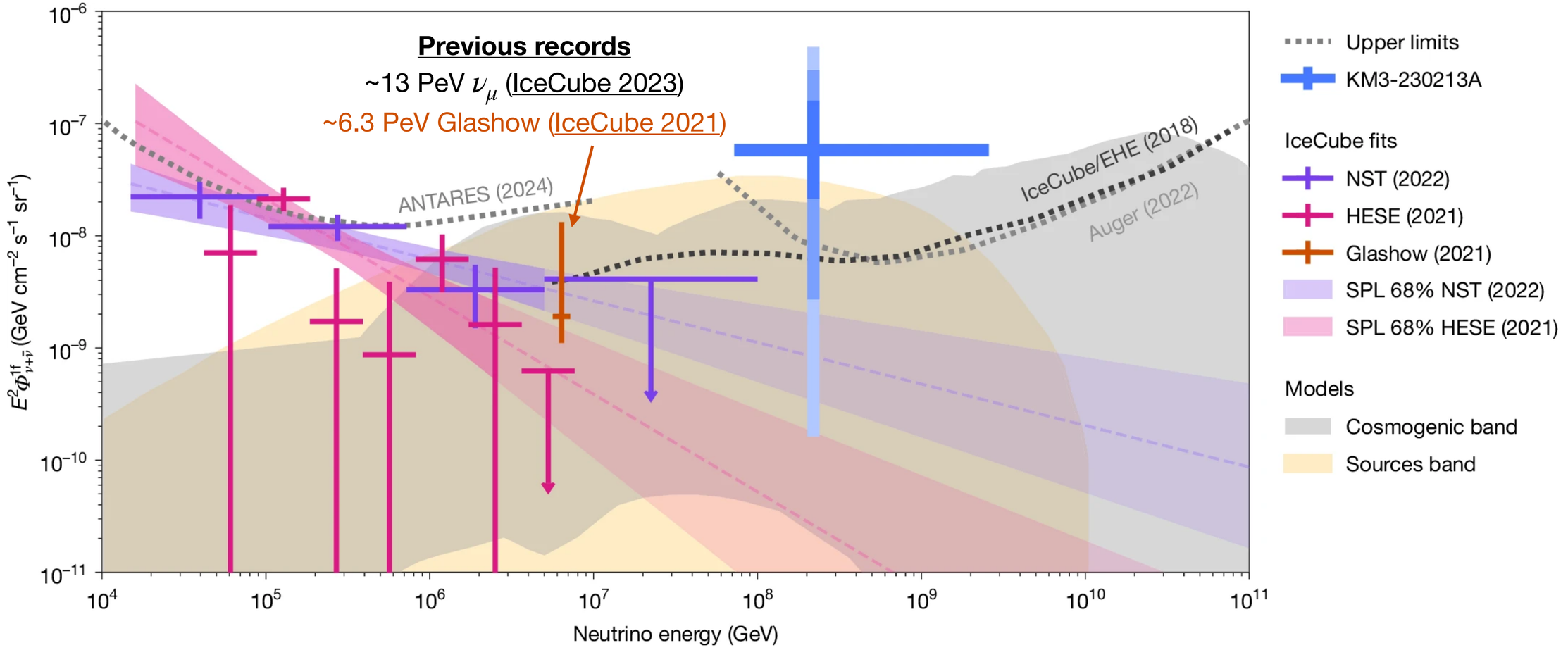




KM3NeT Nature Vol 638 (2025)

Astrophysical Neutrino Flux After KM3-230213A

$$E_\nu = 220^{+570}_{-110}\ \text{PeV and } E^2\Phi^{1f}_{\nu+\bar{\nu}} = 5.8^{+10.1}_{-3.7} \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



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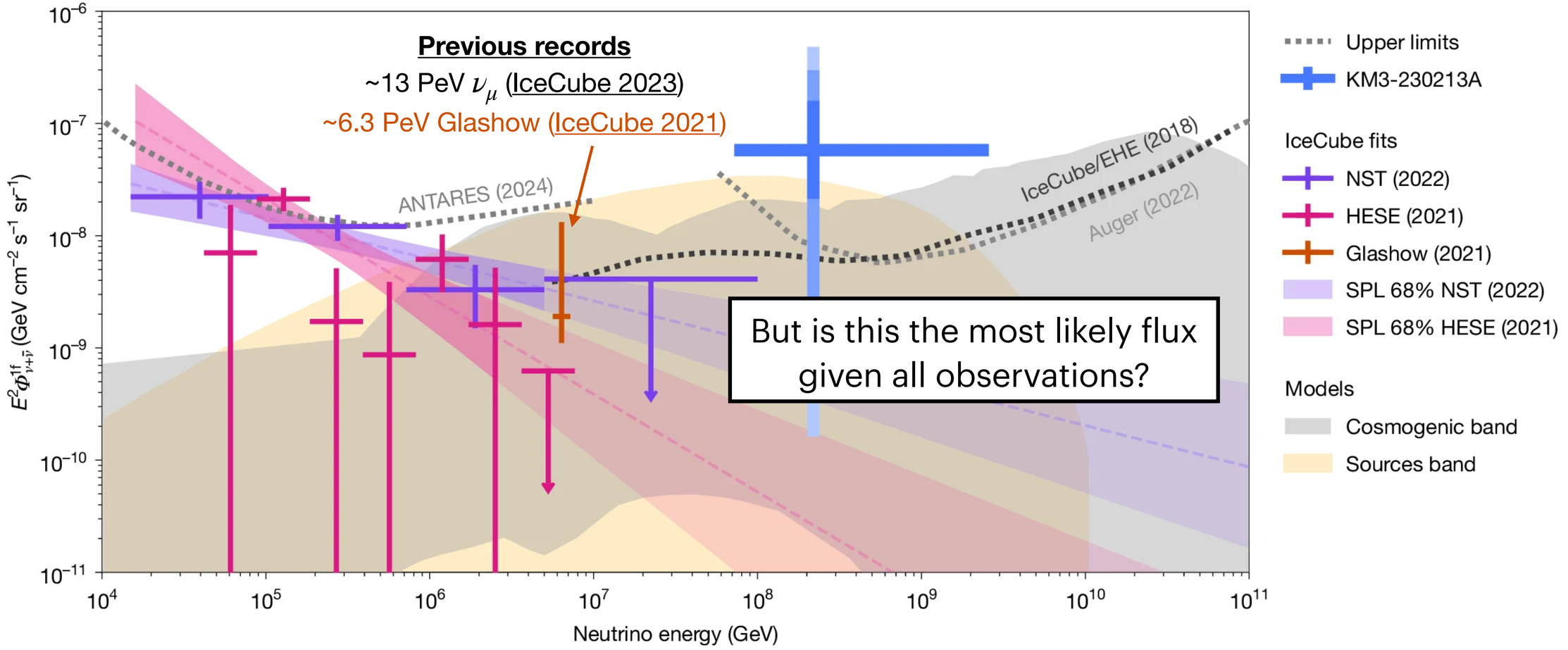
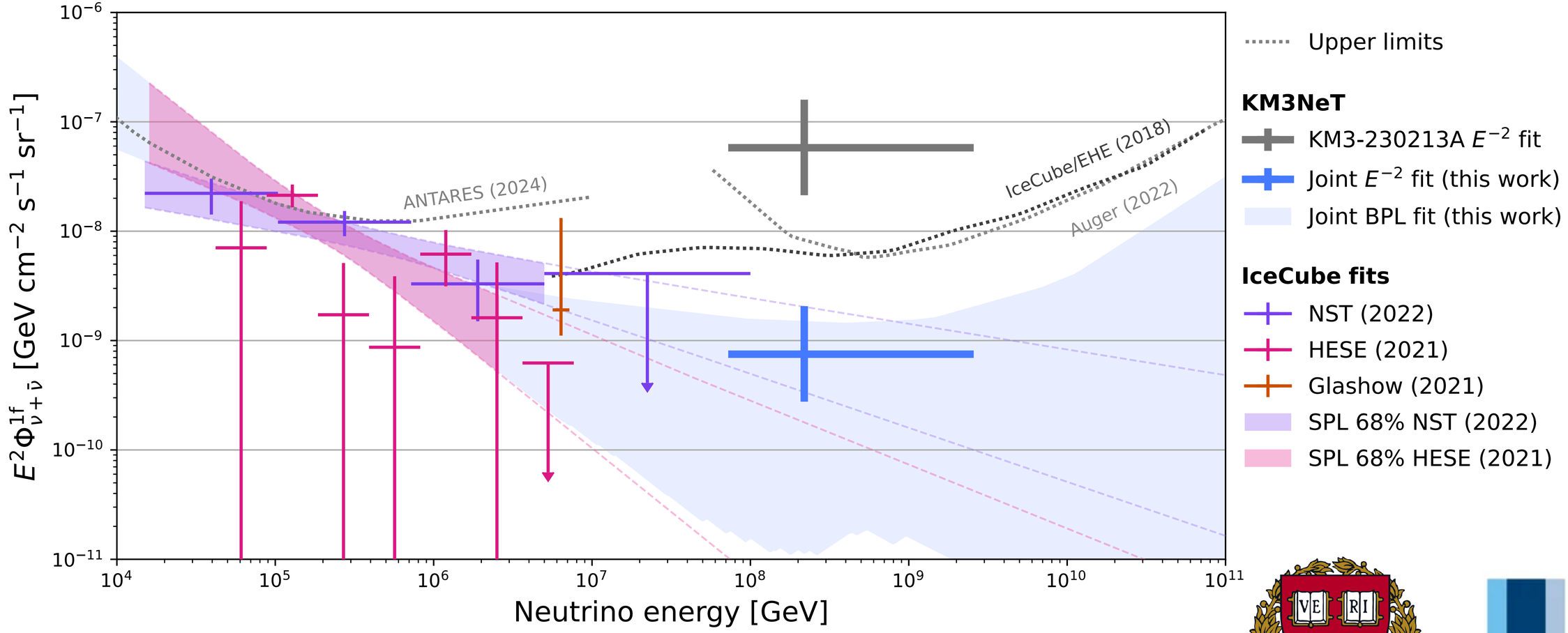


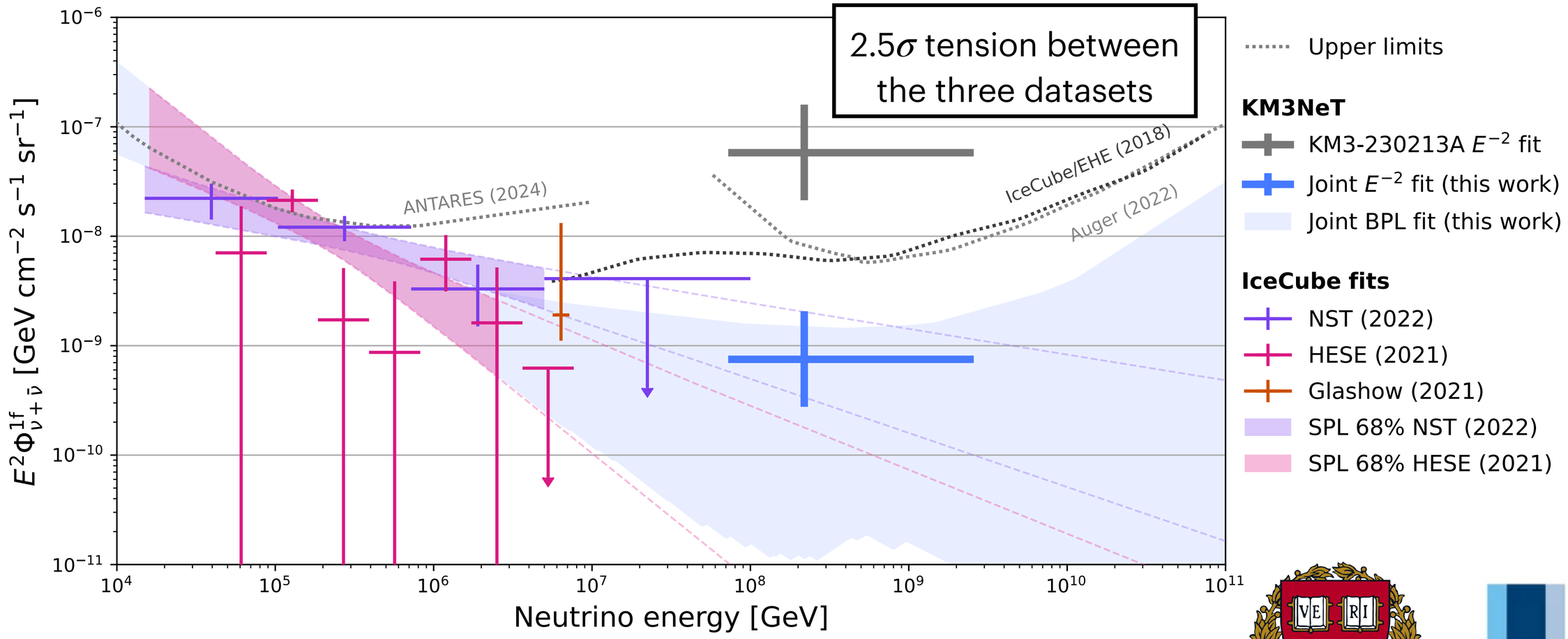
KM3NeT Nature Vol 638 (2025)

Joint fit between KM3NeT, IceCube, and Auger in the energy window of KM3-230213A



KM3NeT (incl NK) PRX Vol 15 (2025)

Joint fit between KM3NeT, IceCube, and Auger in the energy window of KM3-230213A



 KM3NeT (incl NK) PRX Vol 15 (2025)

Where did this neutrino come from?

D. Dornic, ICRC 2025

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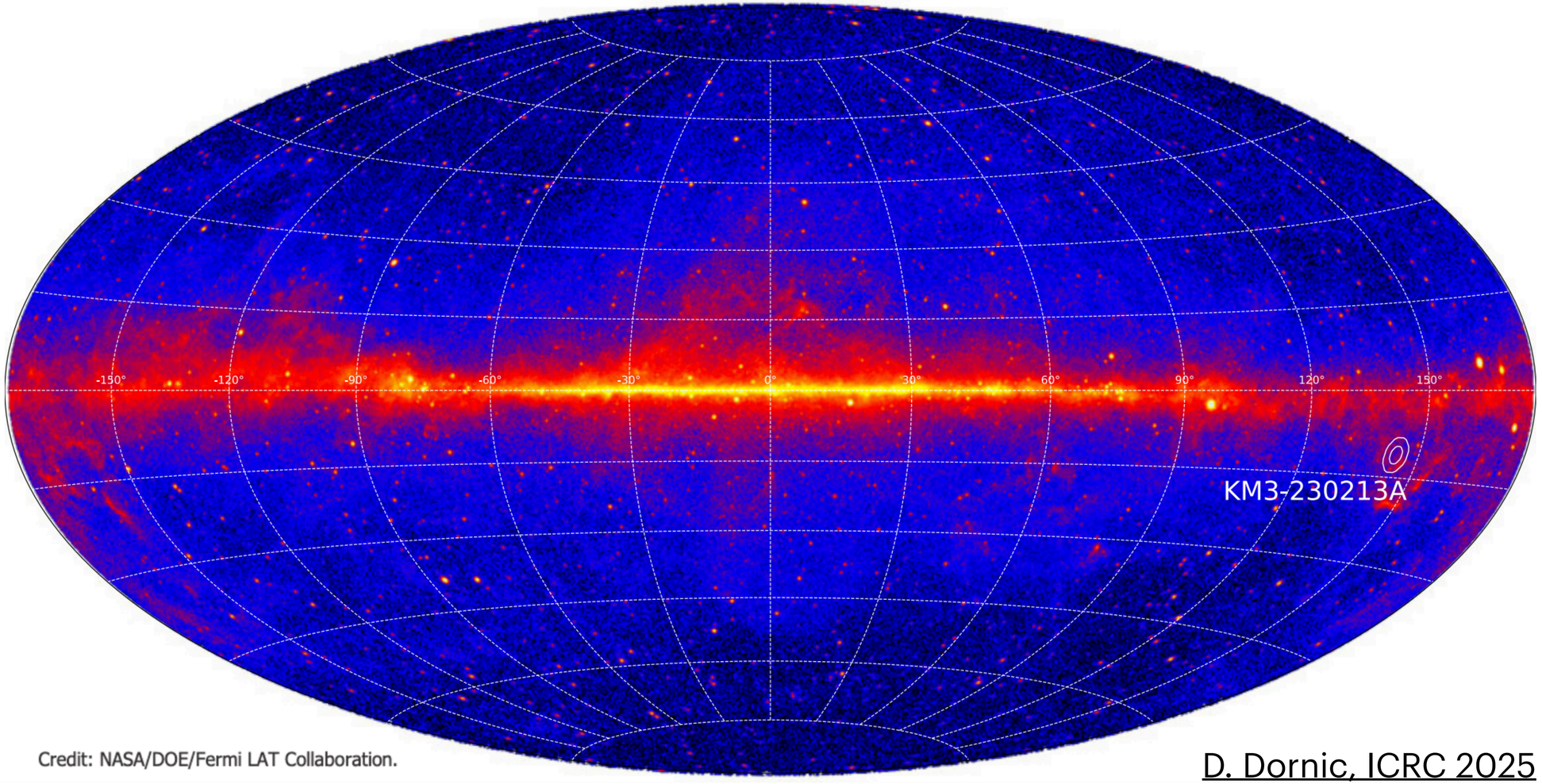
Celestial coordinates: (RA, dec) = (94.3°, –7.8°)
R(68%) = 1.5°, R(90%) = 2.2°, R(99%) = 3.0°



Credit: NASA/DOE/Fermi LAT Collaboration.

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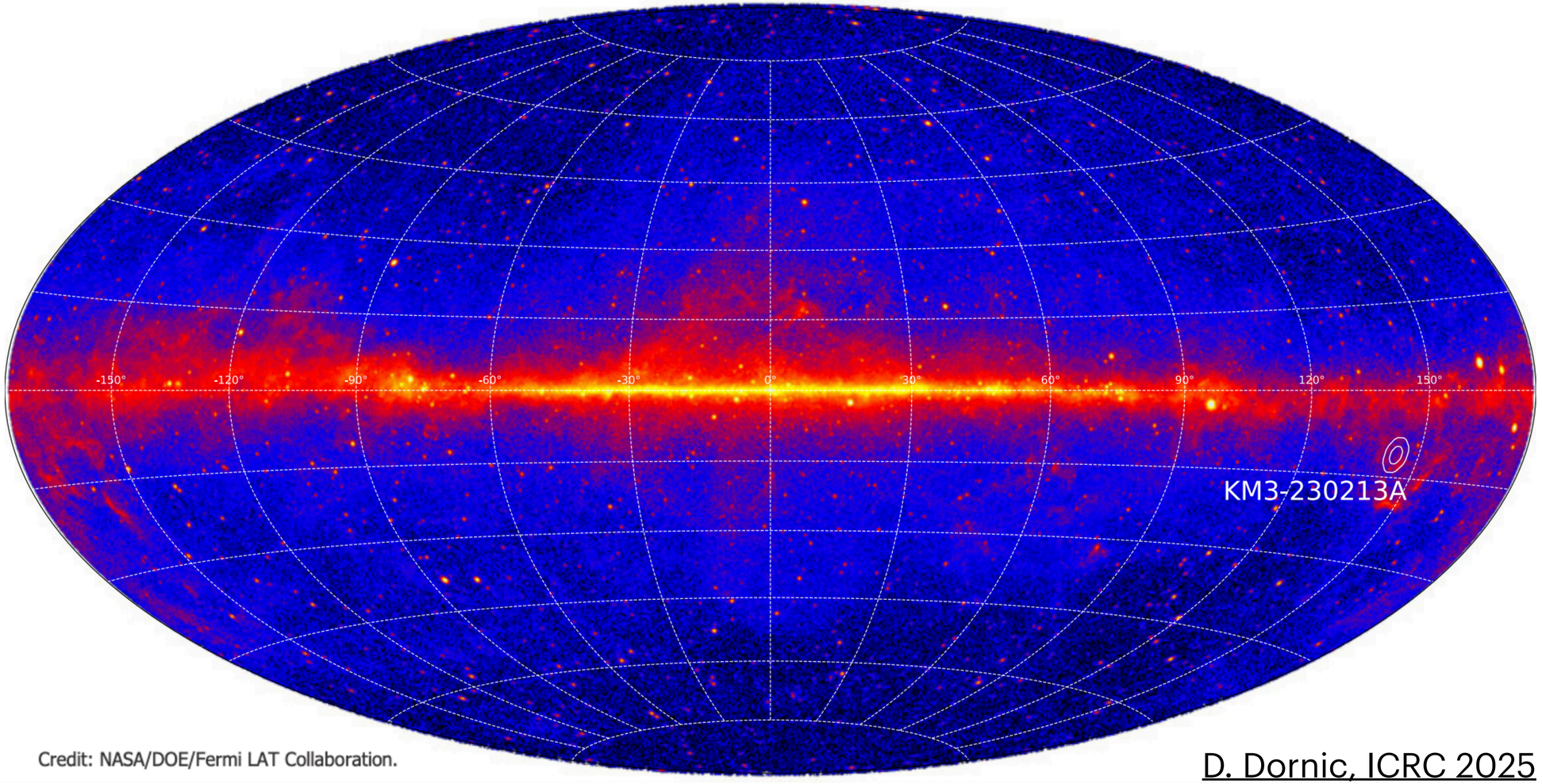
Work in progress: improved acoustic emitter position accuracy -> improved directional uncertainties



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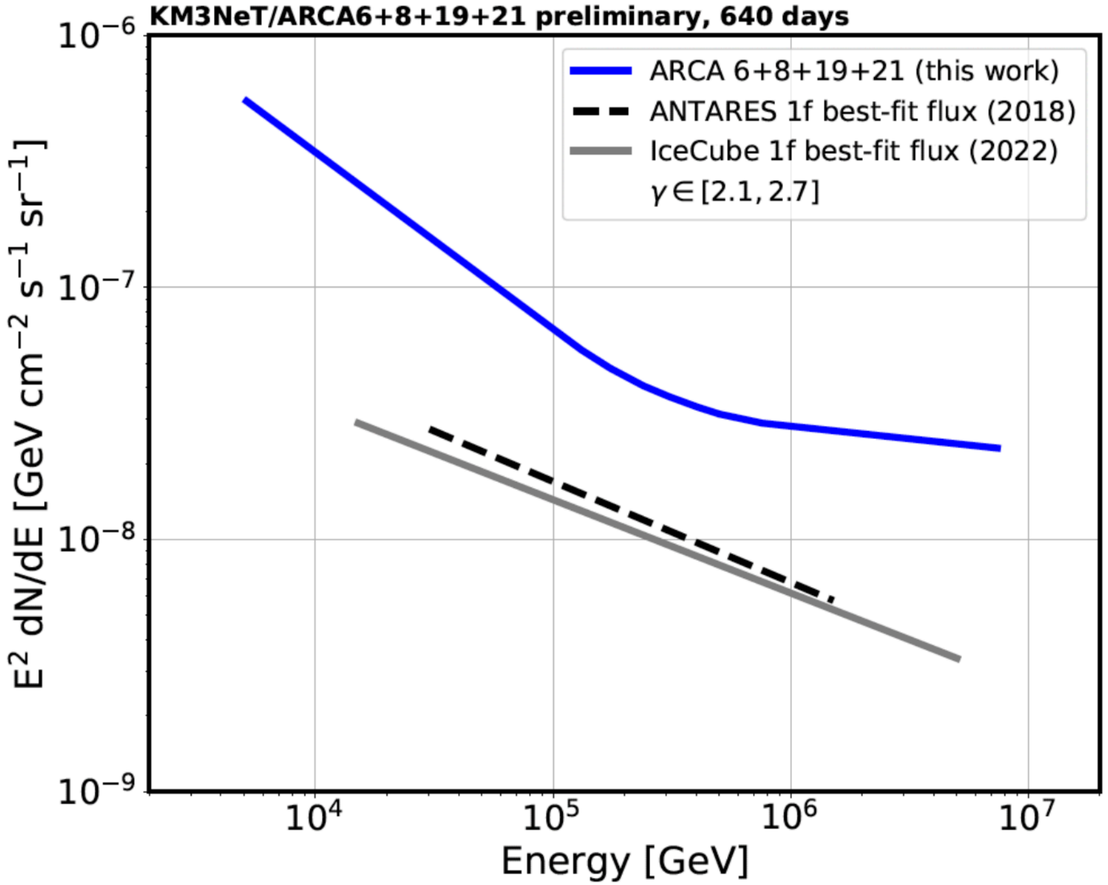
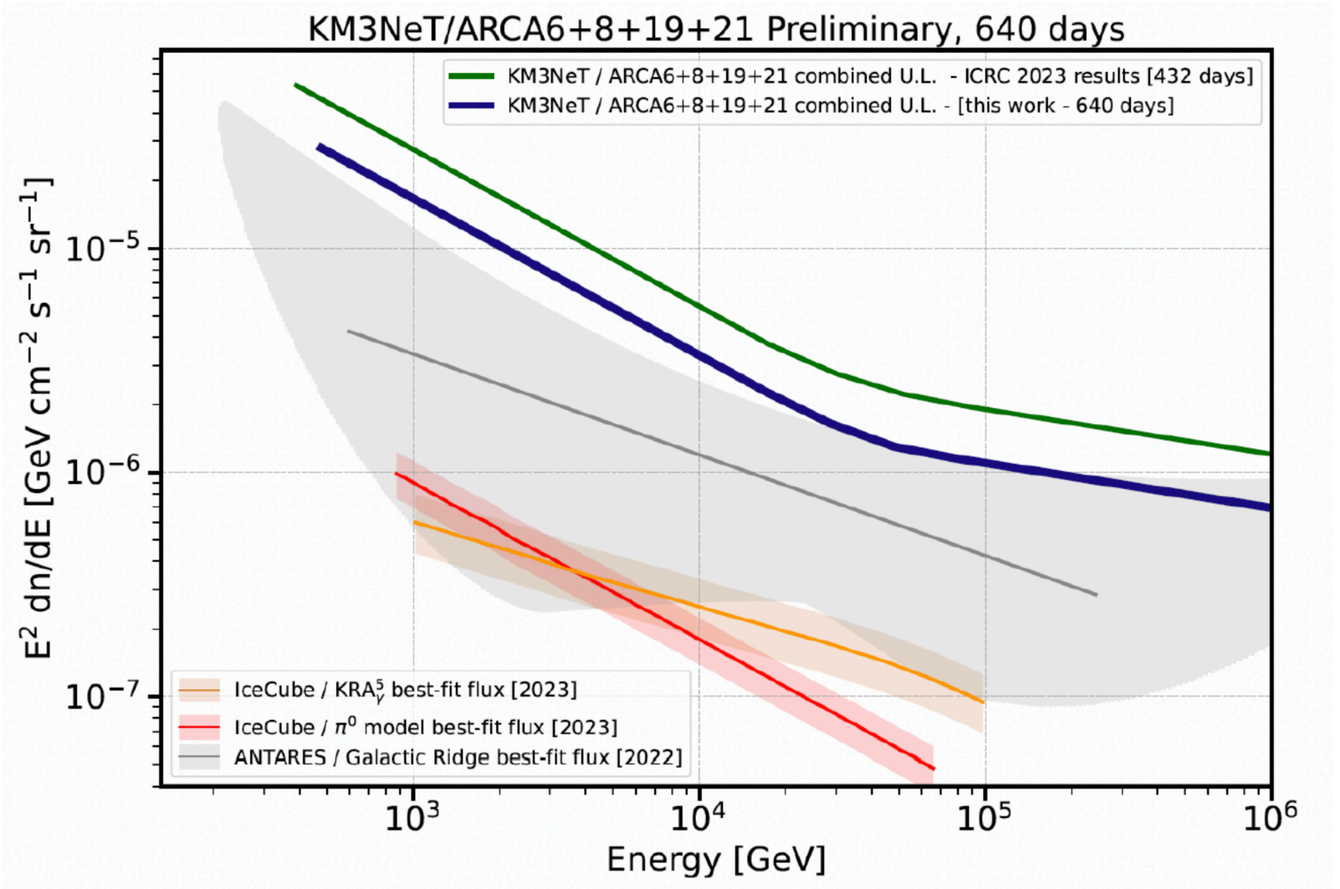
Really we need more data

Other ARCA{6-21} Highlights

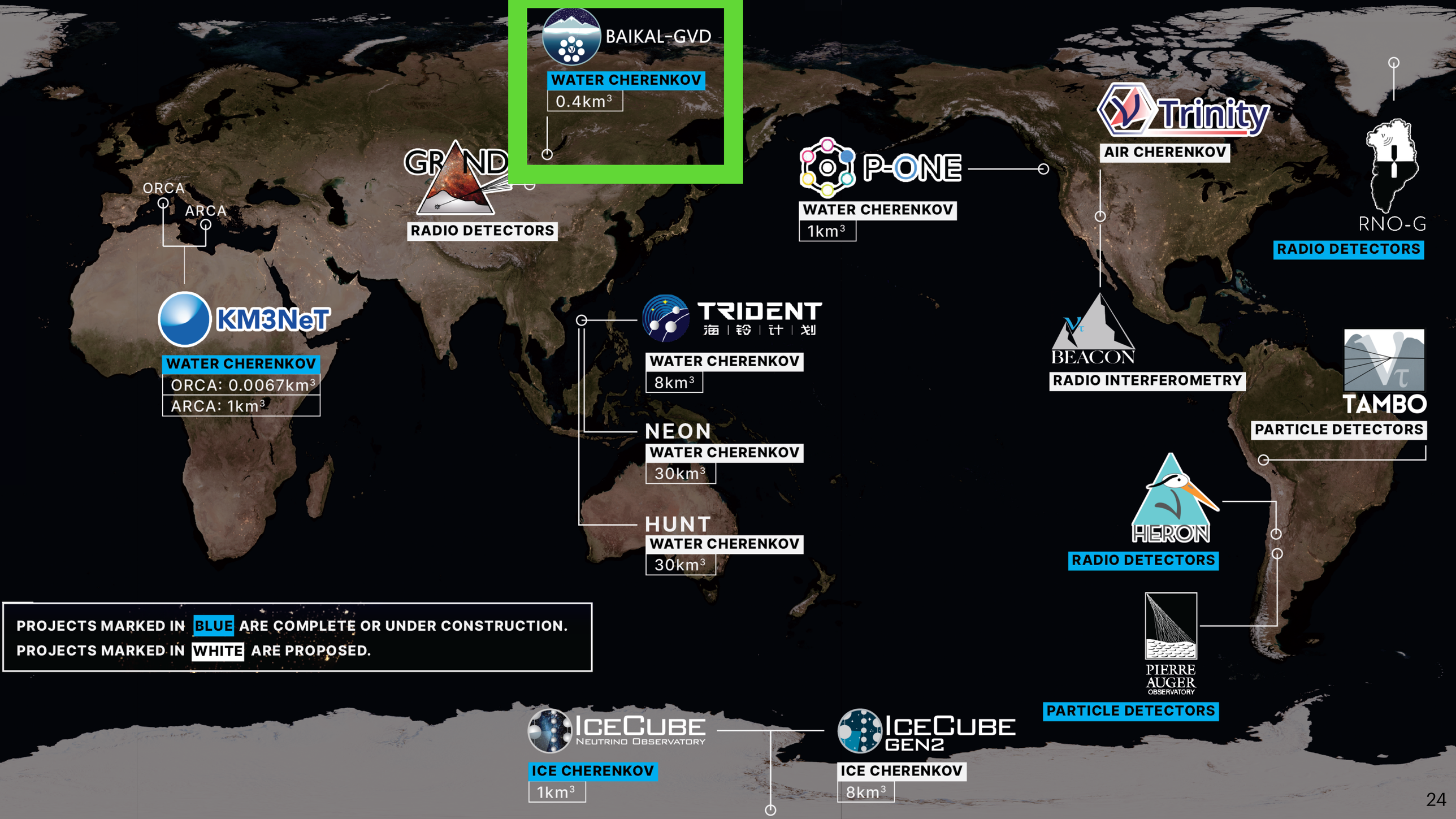


Diffuse flux 90% CL upper limit approaching best fits from IceCube and ANTARES



Galactic ridge flux 90% CL upper limit also approaching best fits from IceCube and ANTARES

D. Dornic, ICRC 2025


BAIKAL-GVD
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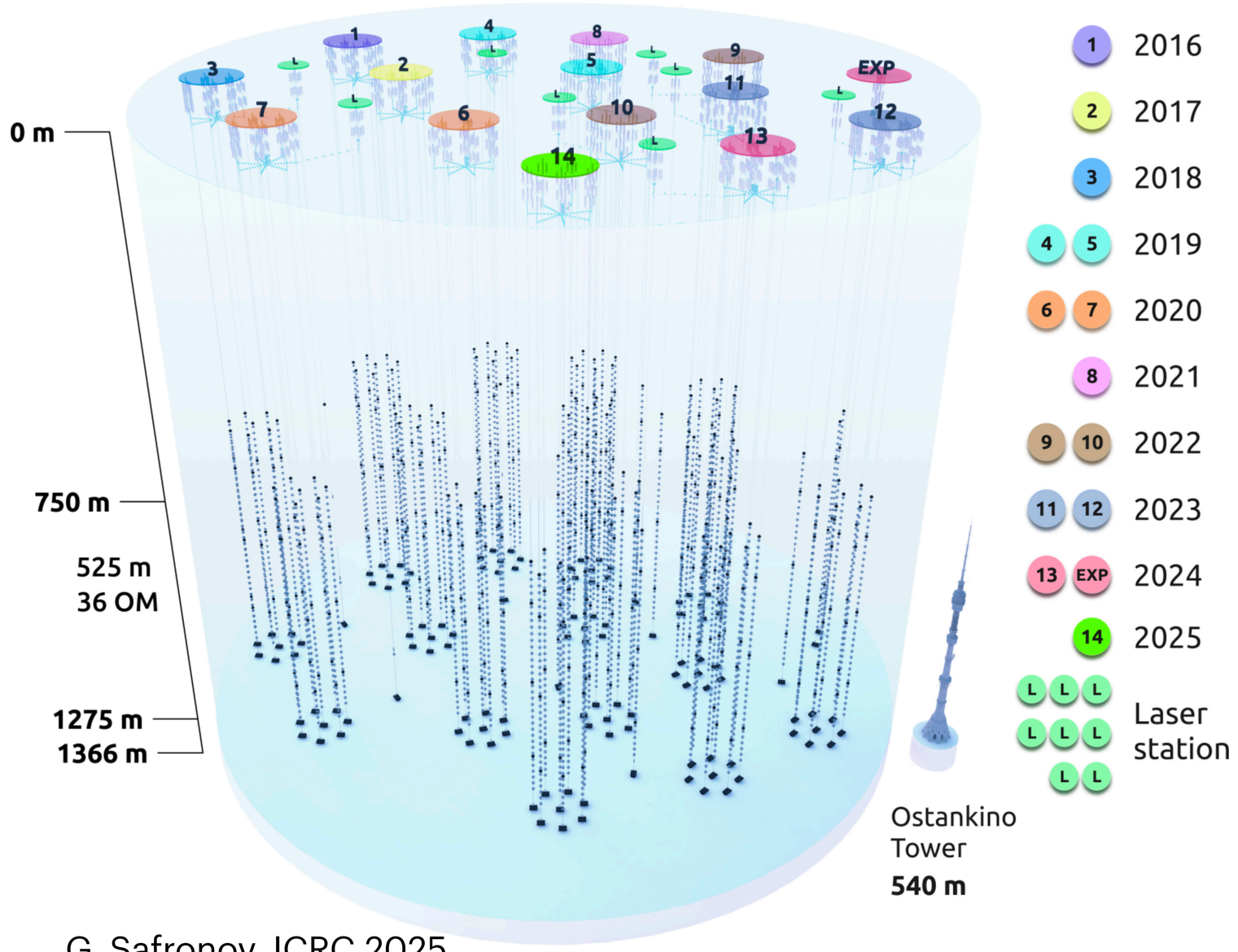
The Baikal-GVD Detector

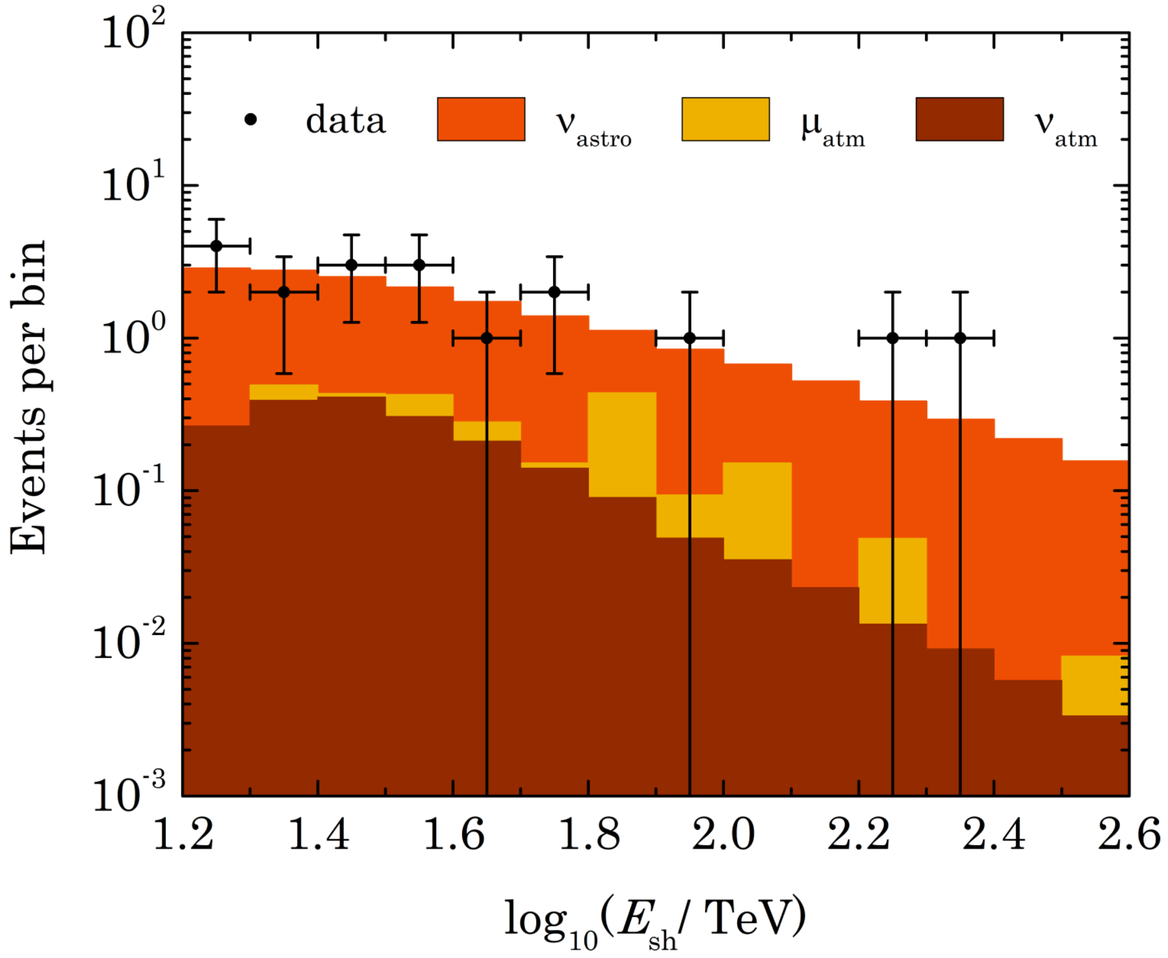
117 strings arranged into 14 clusters in Lake Baikal, Siberia

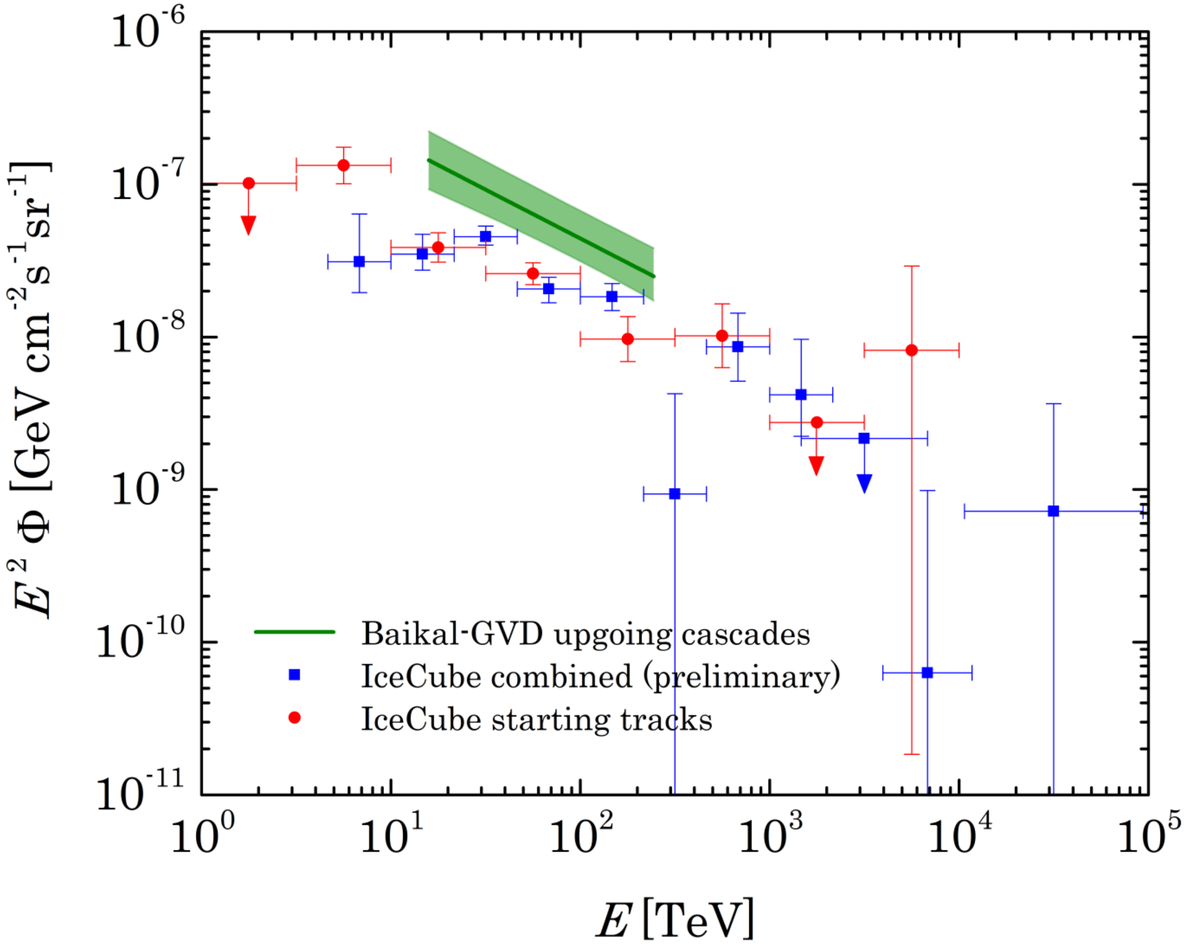
Currently 0.7 km^3, planned to reach ~1 km^3 in next three years



G. Safronov, ICRC 2025

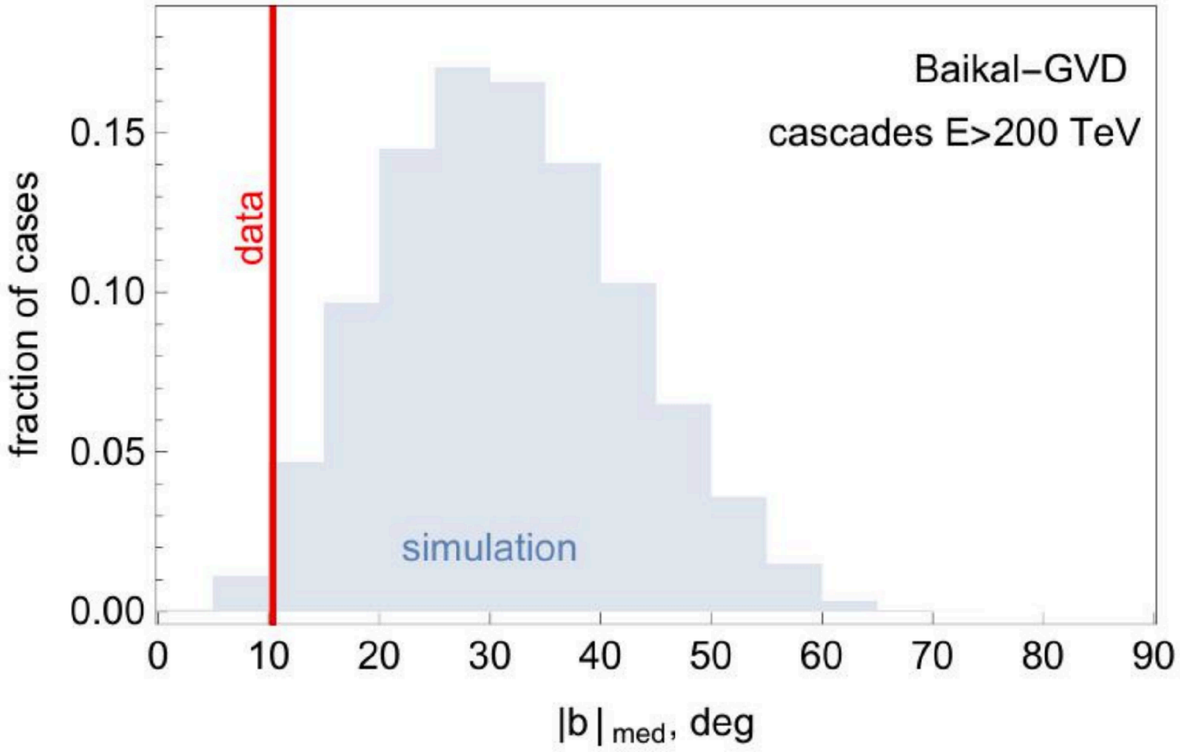
Baikal-GVD Observes the Diffuse Astrophysical Neutrino Flux at 5.1σ





Baikal-GVD 2507.01893

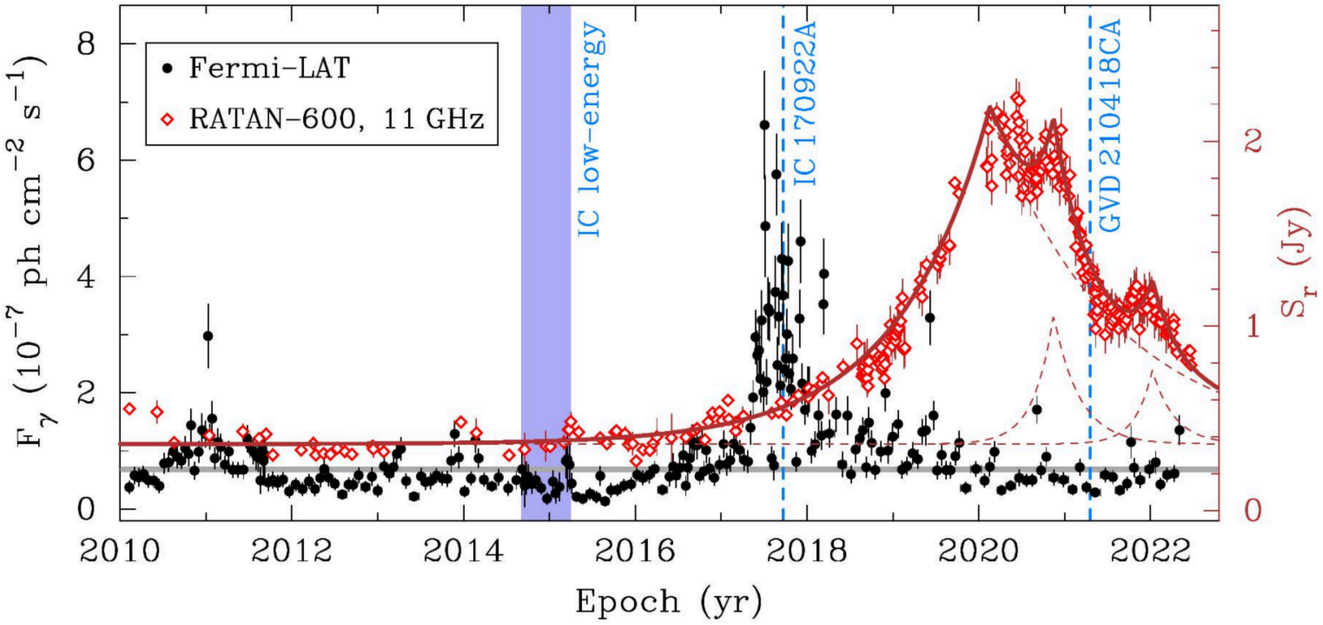
Other Baikal-GVD Highlights



8 cascade candidates with E>200 TeV

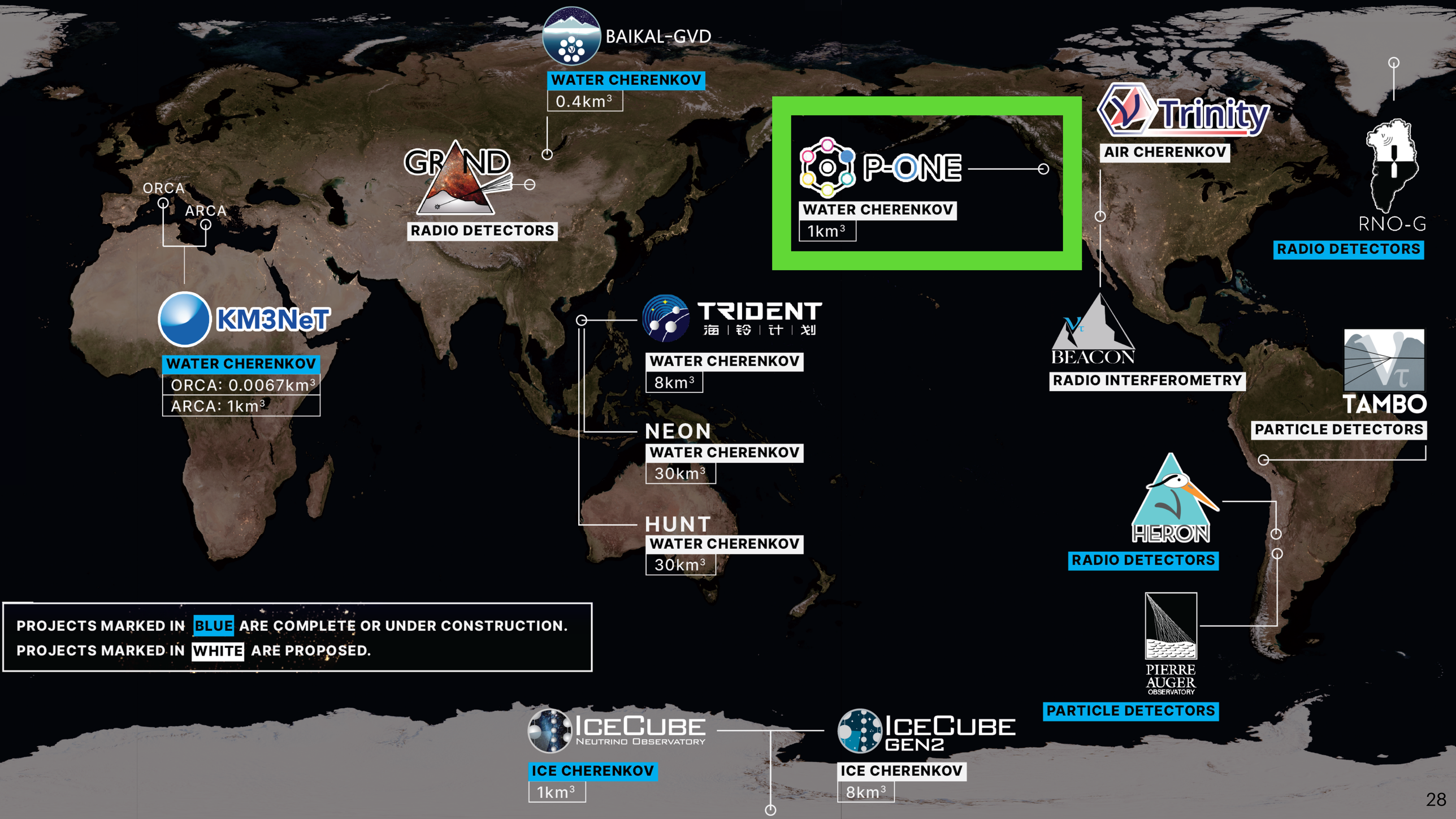
2.5σ hint for **galactic plane origin**

Baikal-GVD, ApJ 2025



~220 TeV neutrino from the direction of **TXS 0506 + 056** during a **radio flare**

Baikal-GVD. MNRAS 2024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The Pacific Ocean Neutrino Experiment (P-ONE)

Cubic km water Cherenkov array off the coast of Vancouver, Canada

Leverages **existing oceanographic investment** from Canadian funding agencies

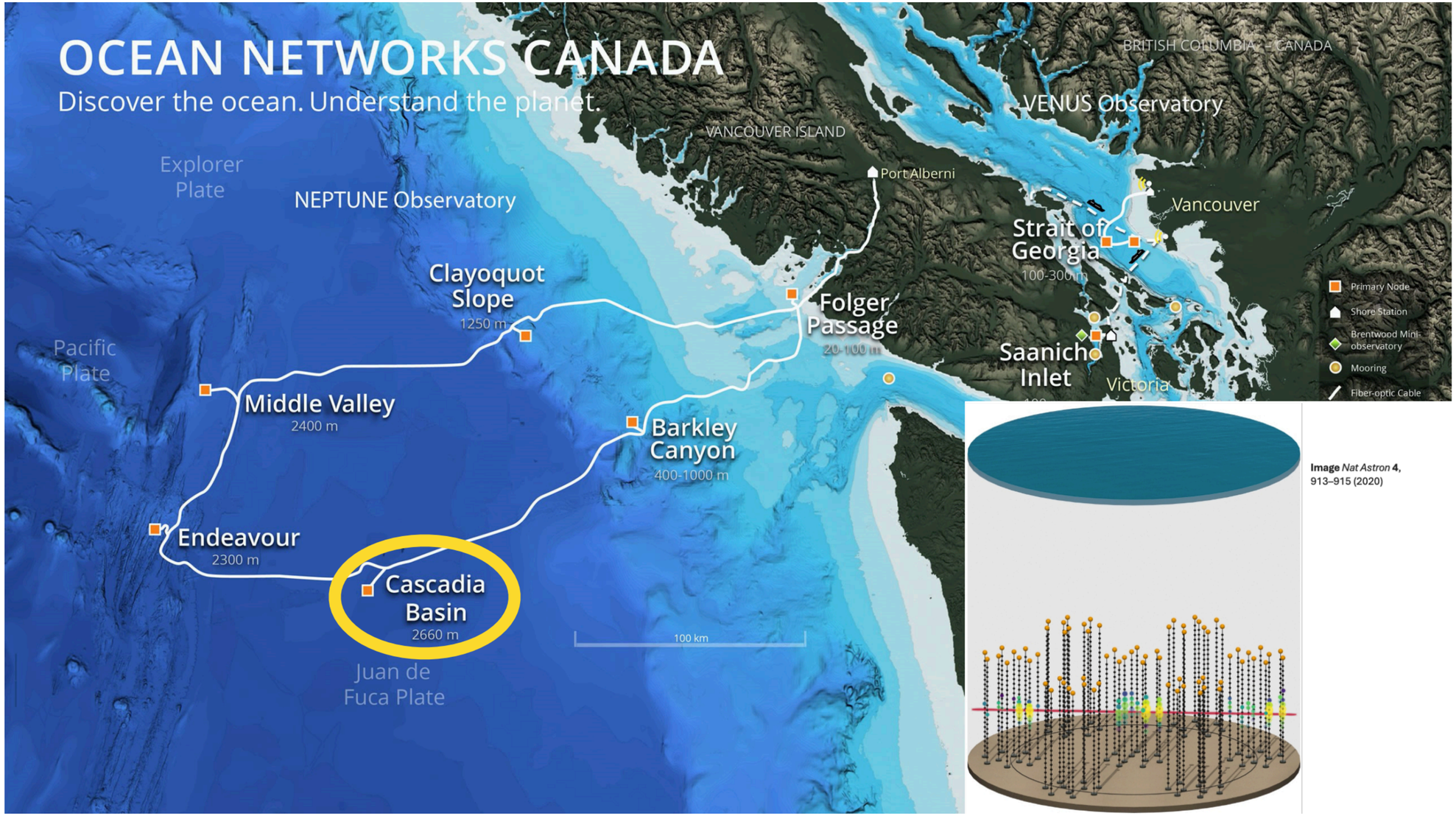
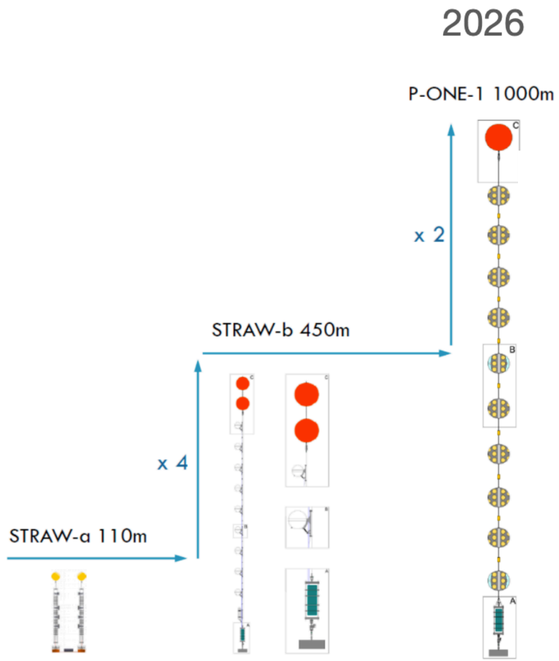


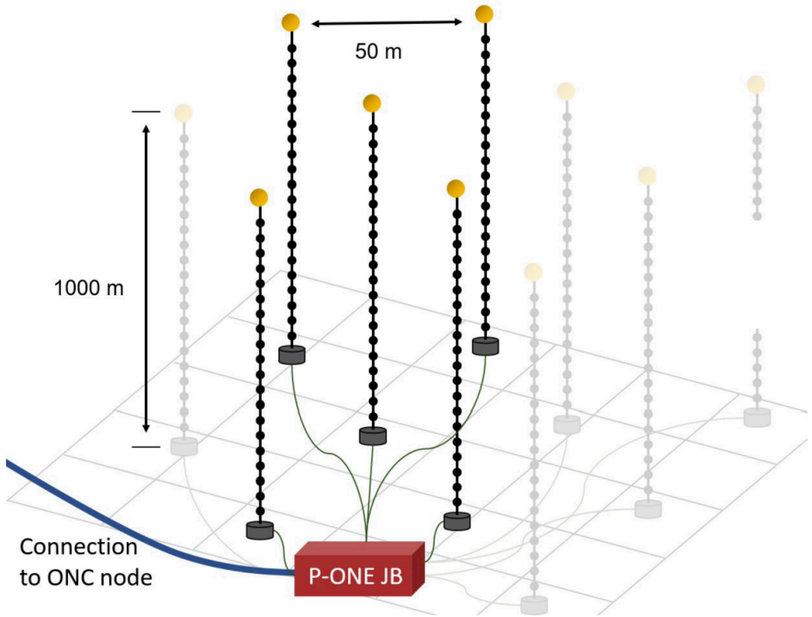
Image *Nat Astron* **4**, 913–915 (2020)

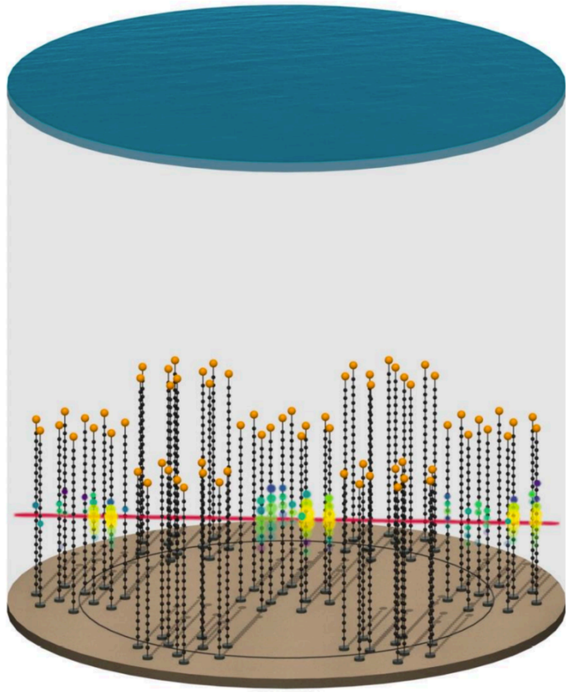
D. Grant, Lake Louise Winter Institute 2026

P-ONE Construction Schedule

First string to be deployed in 2026, first cluster by 2028







Pathfinder
Phase 1 (2018 — 2023)

Demonstrator (first cluster)
Phase 2 (2025 — 2028)
~20M project **funding secured** (CFI/ERC/NSF)

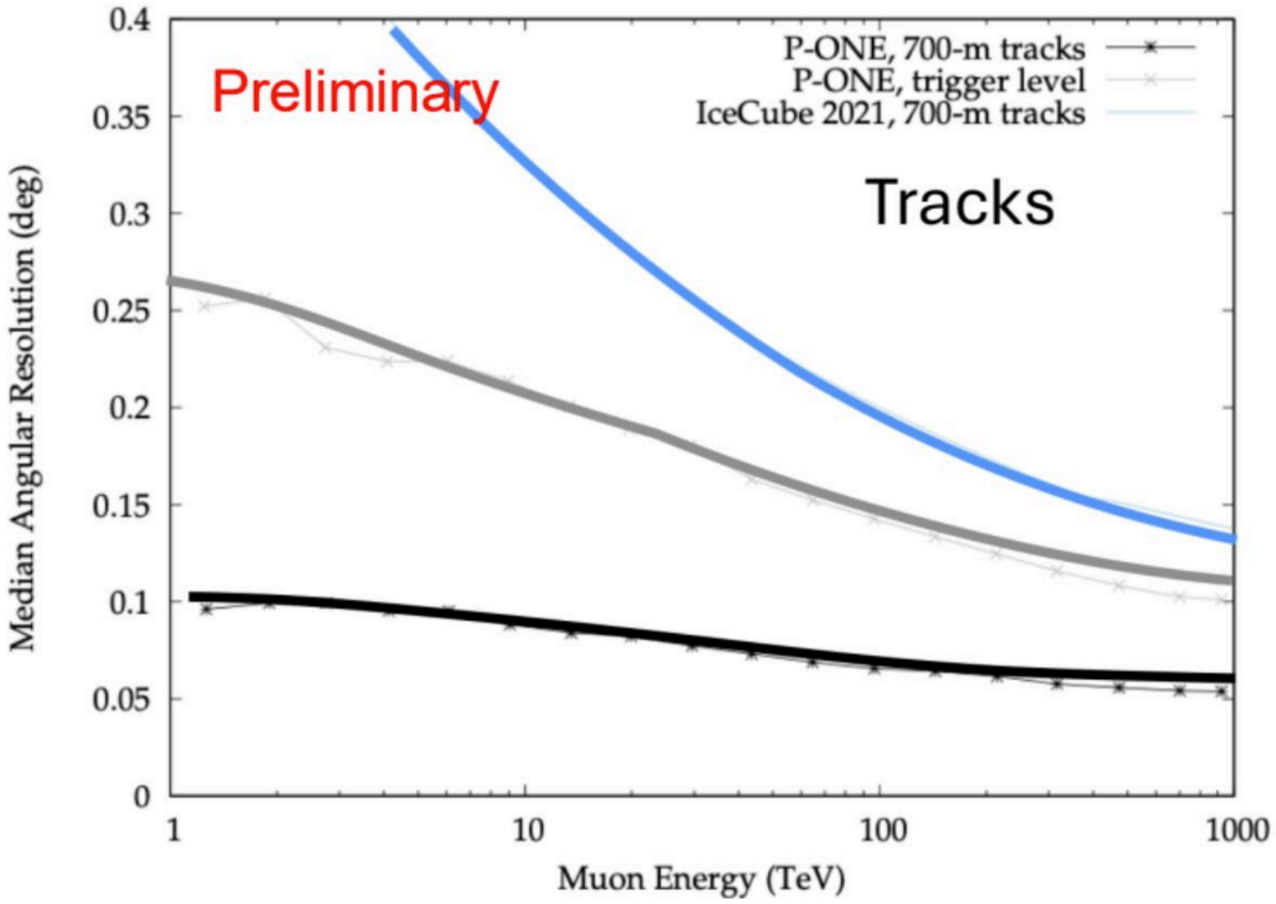
P-ONE
Phase 3 (2028+)
O(100M)-scale

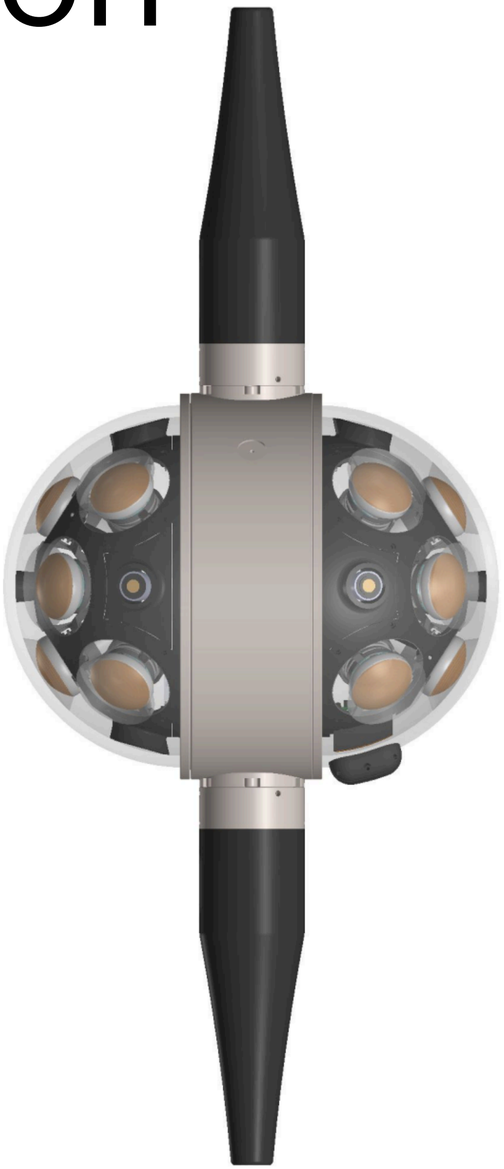
D. Grant, Lake Louise Winter Institute 2026

P-ONE Focuses on Precision

Optical modules will have **sub-100 ps time synchronization** and **full waveform readout**

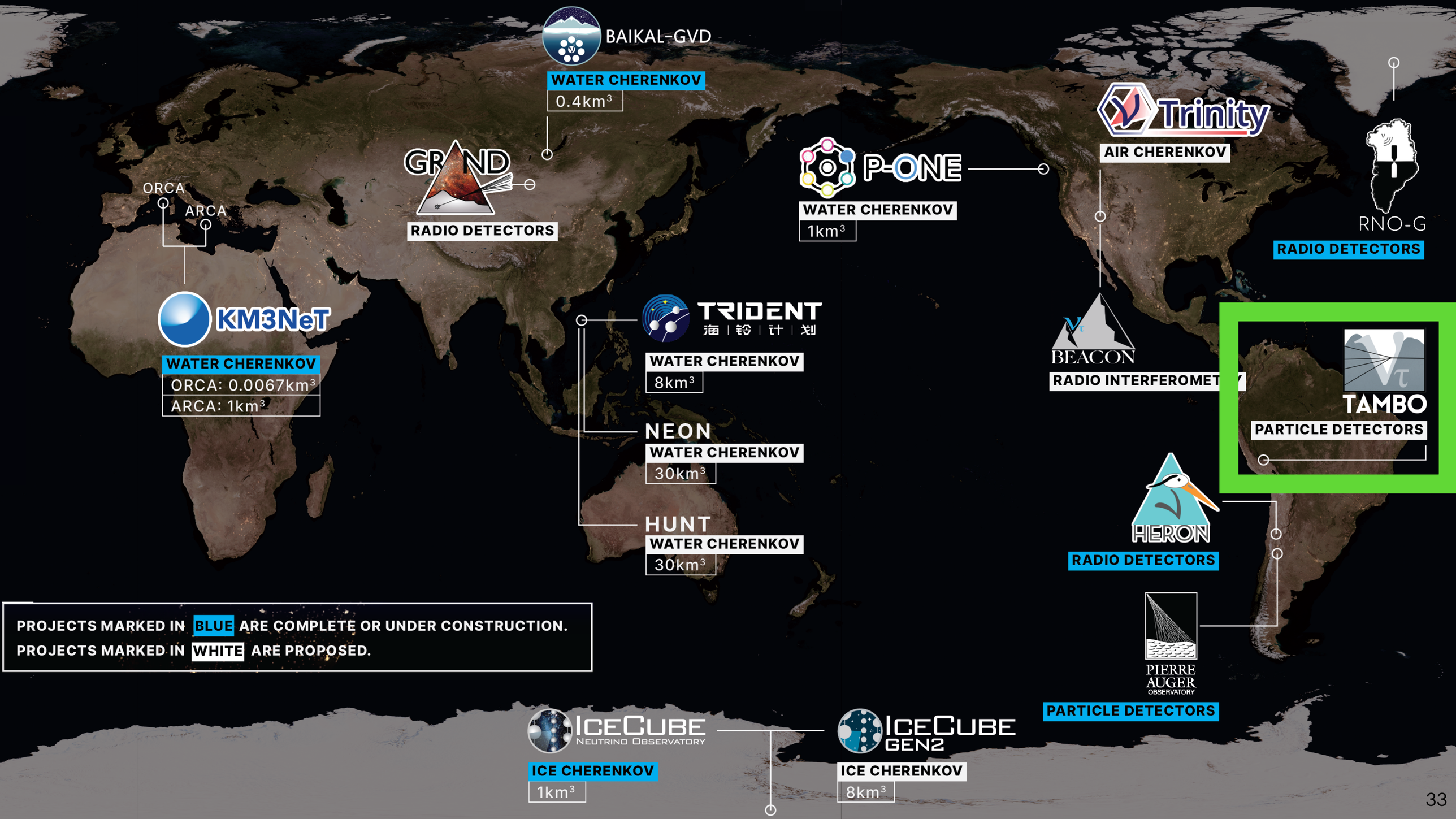
Leads to excellent **angular resolution**, crucial for **source identification**





P. Krause, Lake Louise Winter Institute 2026

What about non-water Cherenkov detection techniques?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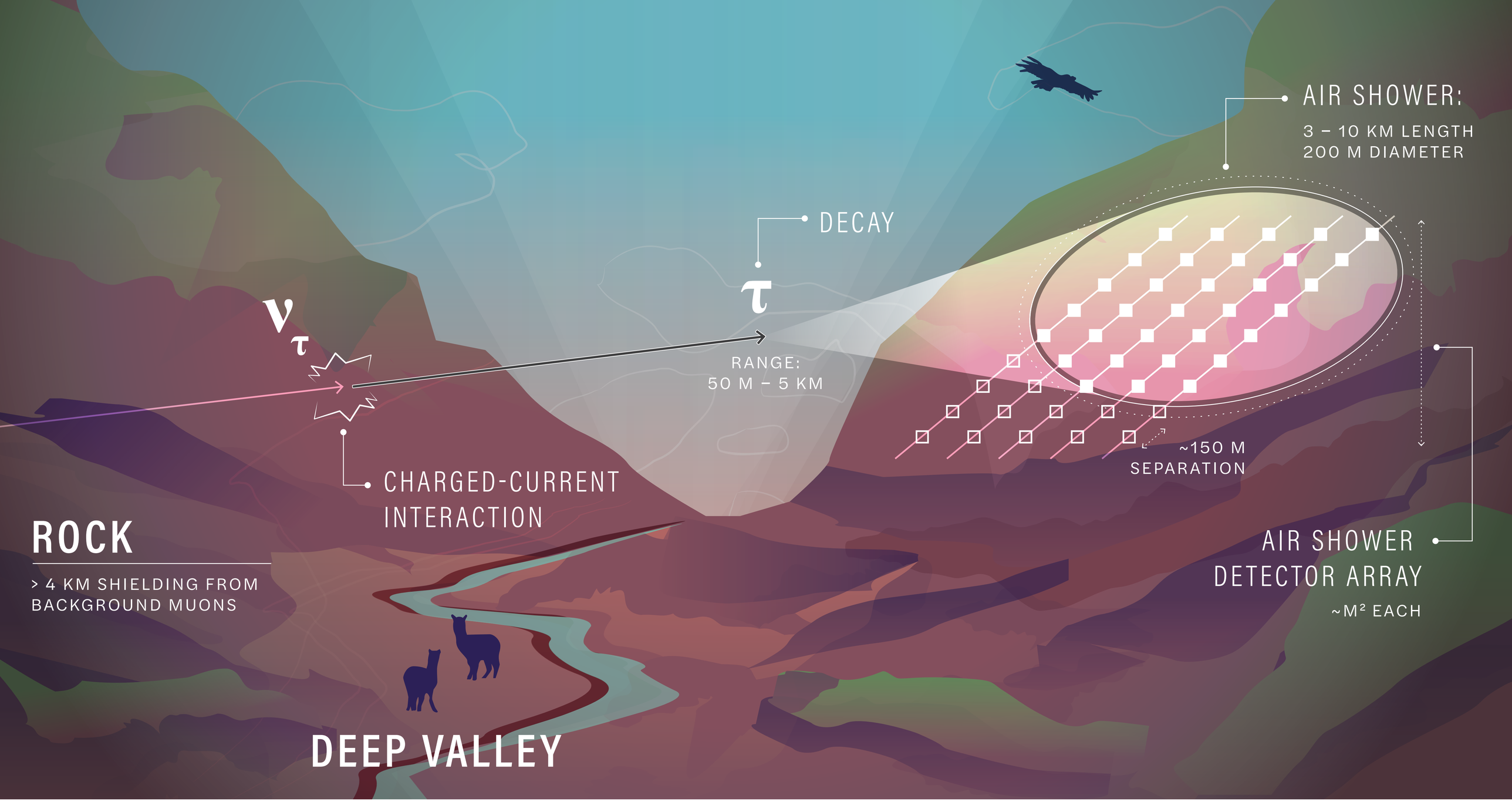
AIR SHOWER:
3 – 10 KM LENGTH
200 M DIAMETER
DECAY
τ
RANGE:
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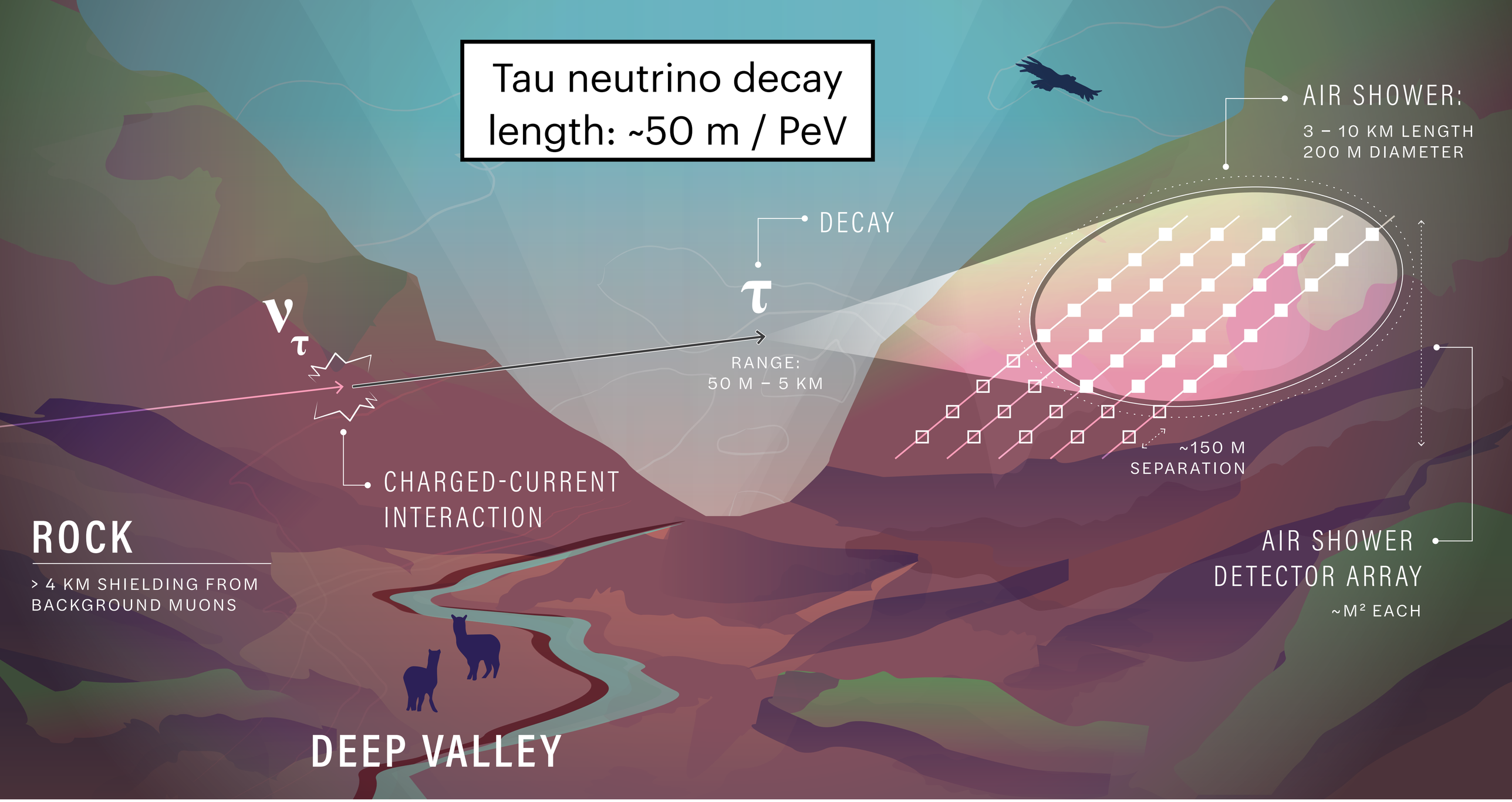
ν τ
CHARGED-CURRENT
INTERACTION
~150 M
SEPARATION
AIR SHOWER
DETECTOR ARRAY
~M² EACH
ROCK
> 4 KM SHIELDING FROM
BACKGROUND MUONS
DEEP VALLEY


Tau neutrino decay length: ~50 m / PeV
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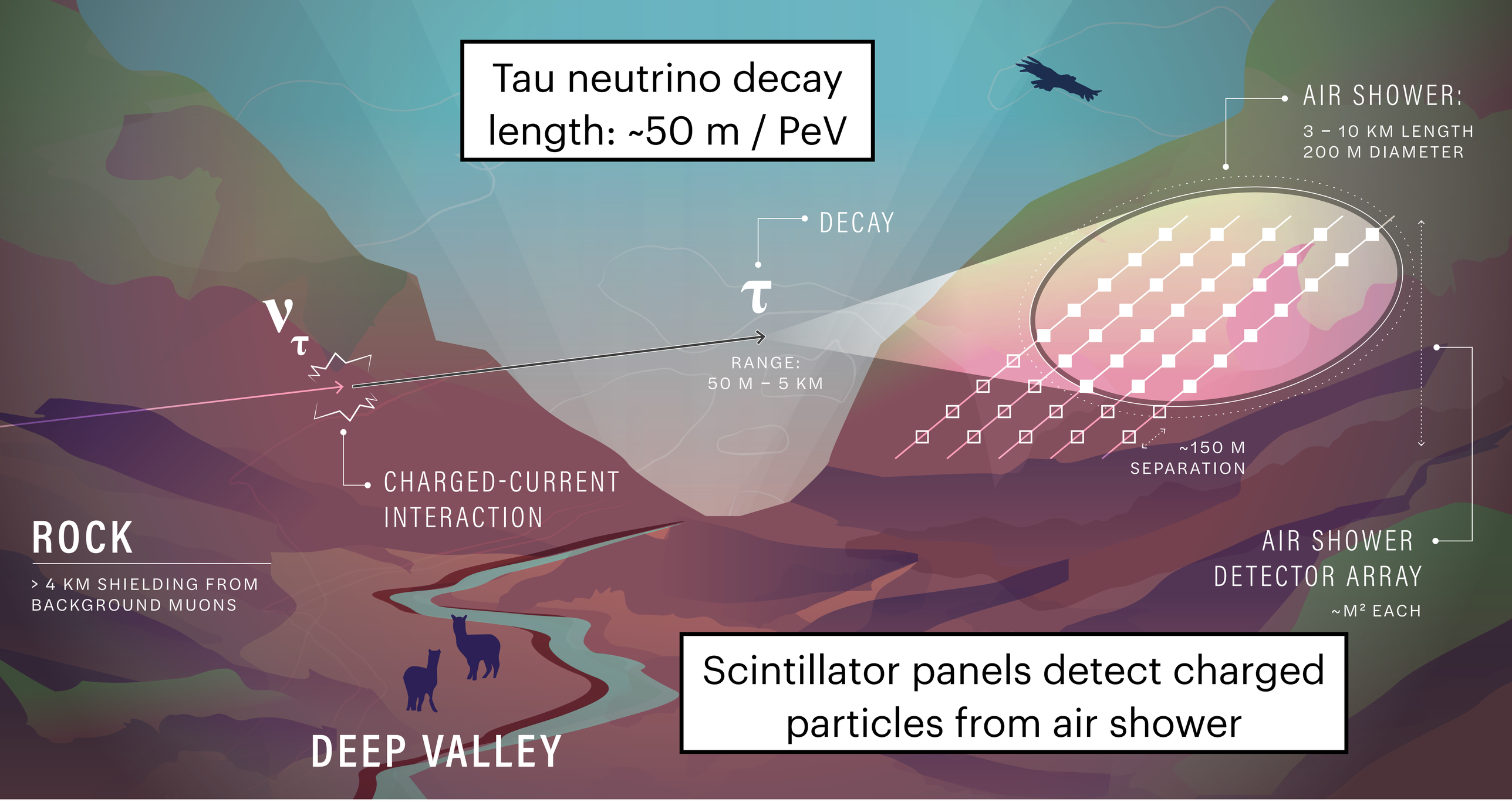
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Scintillator panels detect charged particles from air shower
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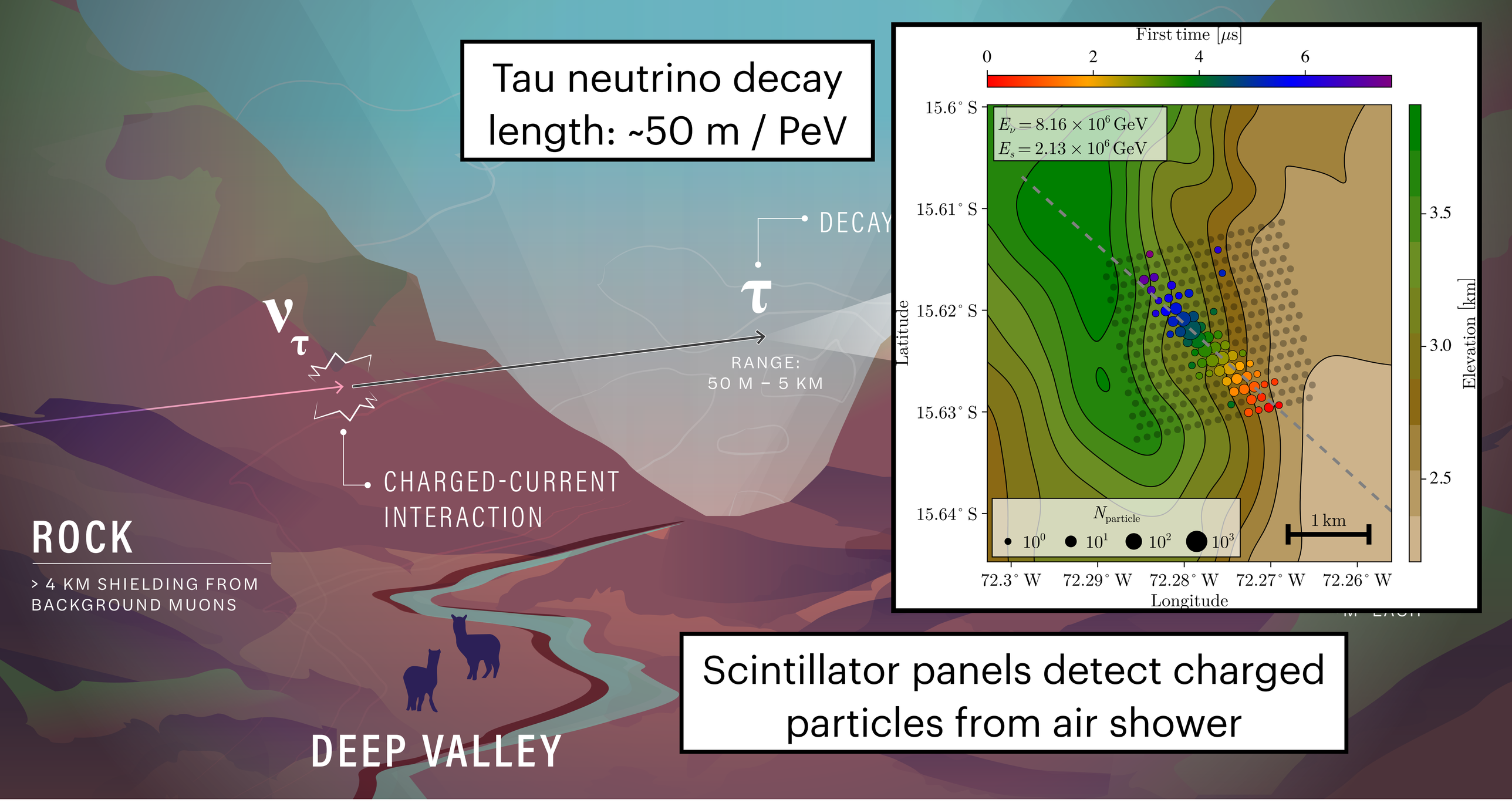
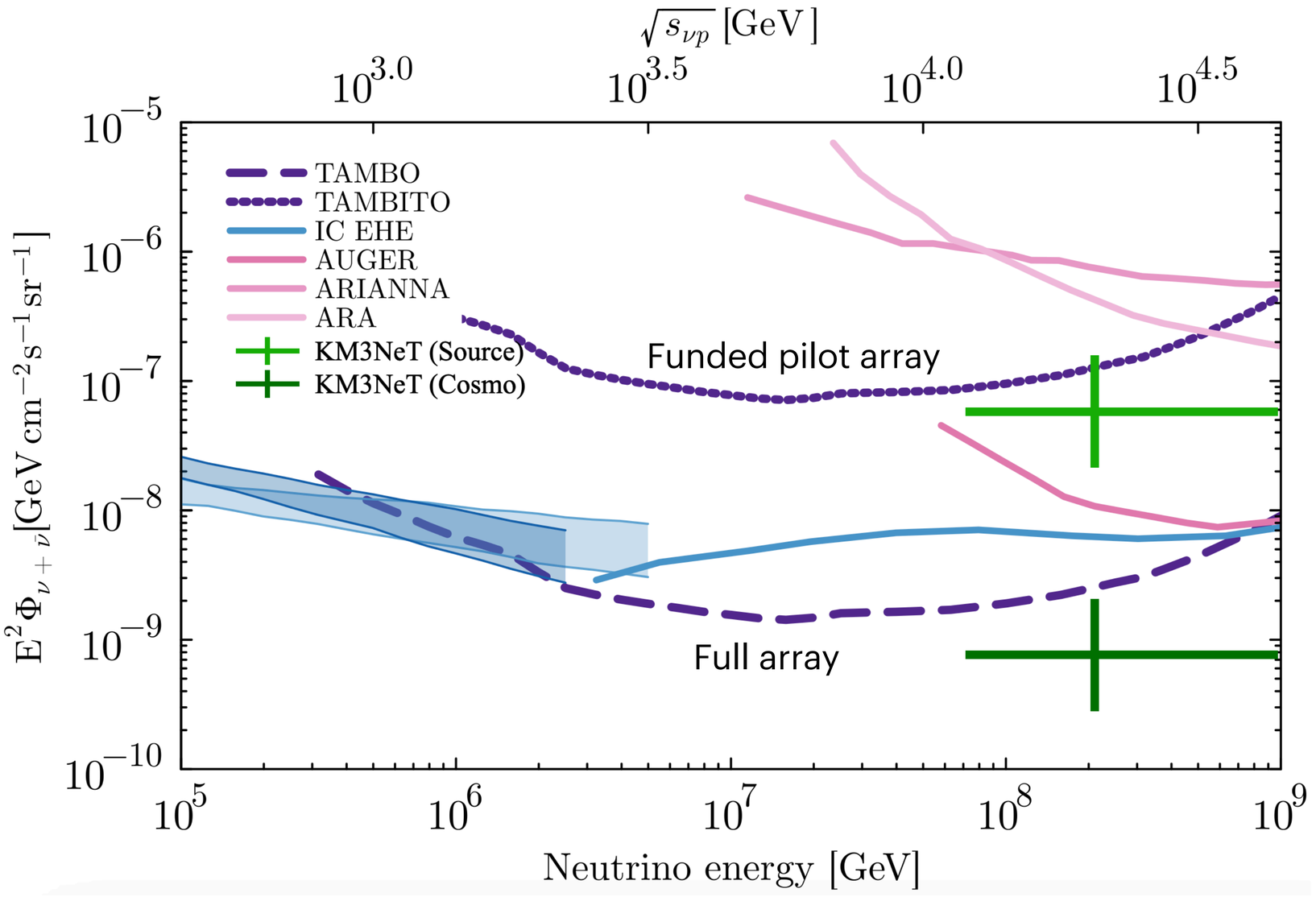
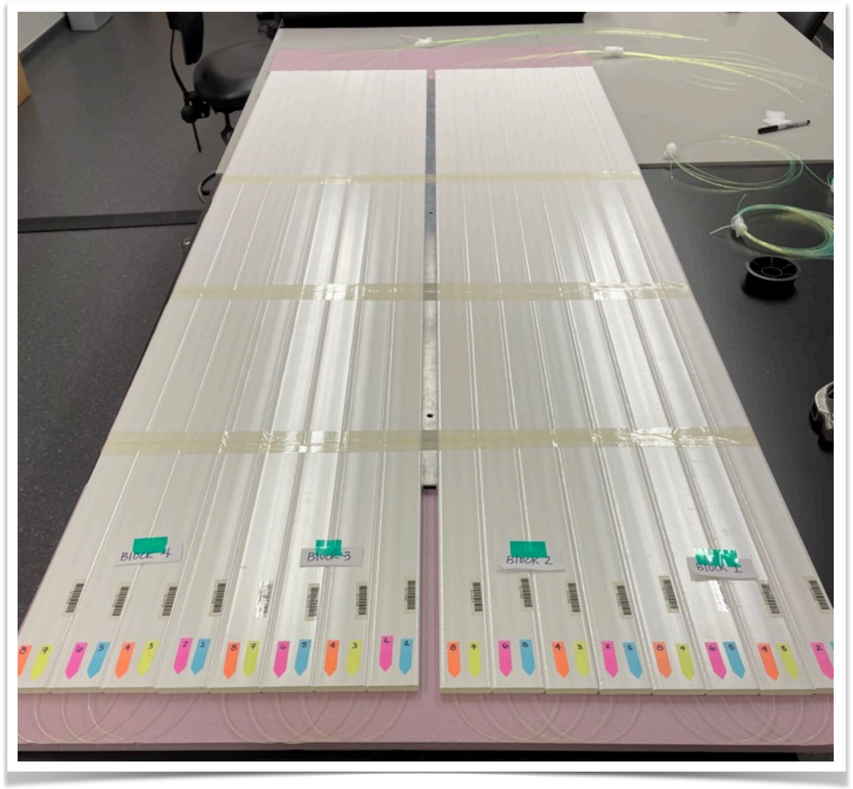


Scintillator panels detect charged particles from air shower

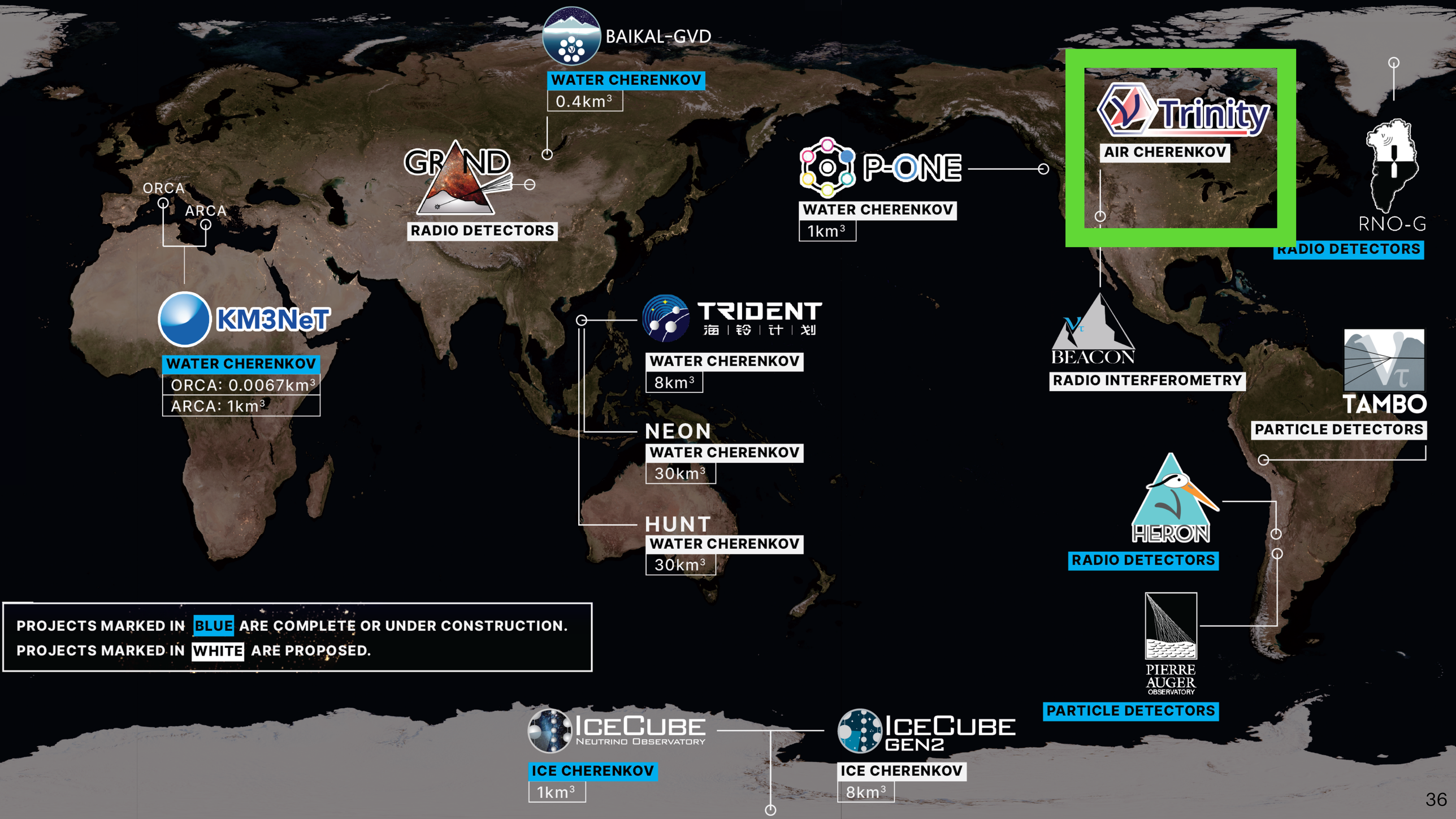
TAMBITO Pilot Array Construction Underway





Scintillator panel for TAMBITO in our local lab @ Harvard

TAMBO 2507.08070


BAIKAL-GVD
WATER CHERENKOV
0.4km³
GRAND
RADIO DETECTORS
ORCA
ARCA
KM3NeT
WATER CHERENKOV
ORCA: 0.0067km³
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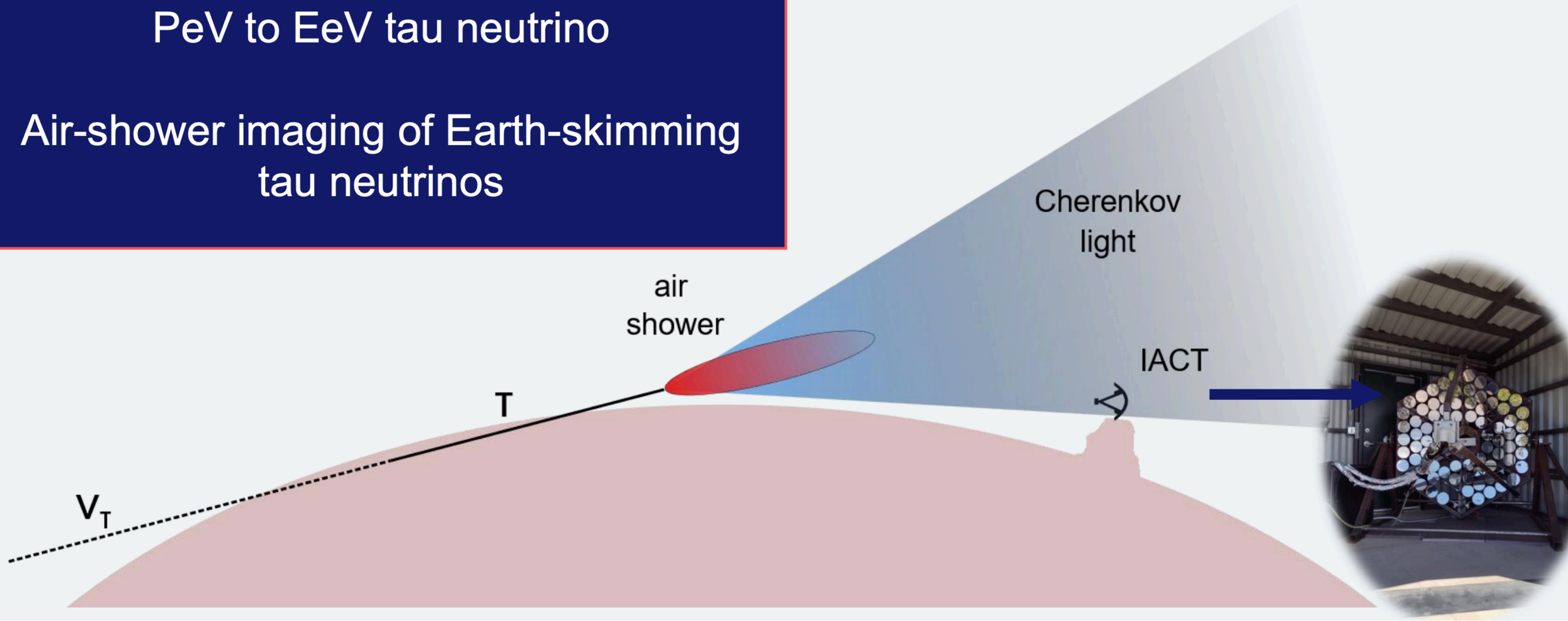
PROJECTS MARKED IN WHITE ARE PROPOSED.
ICECUBE NEUTRINO OBSERVATORY
ICE CHERENKOV
1km³
ICECUBE GEN2
ICE CHERENKOV
8km³

Trinity: Cherenkov light from air showers

PeV to EeV tau neutrino

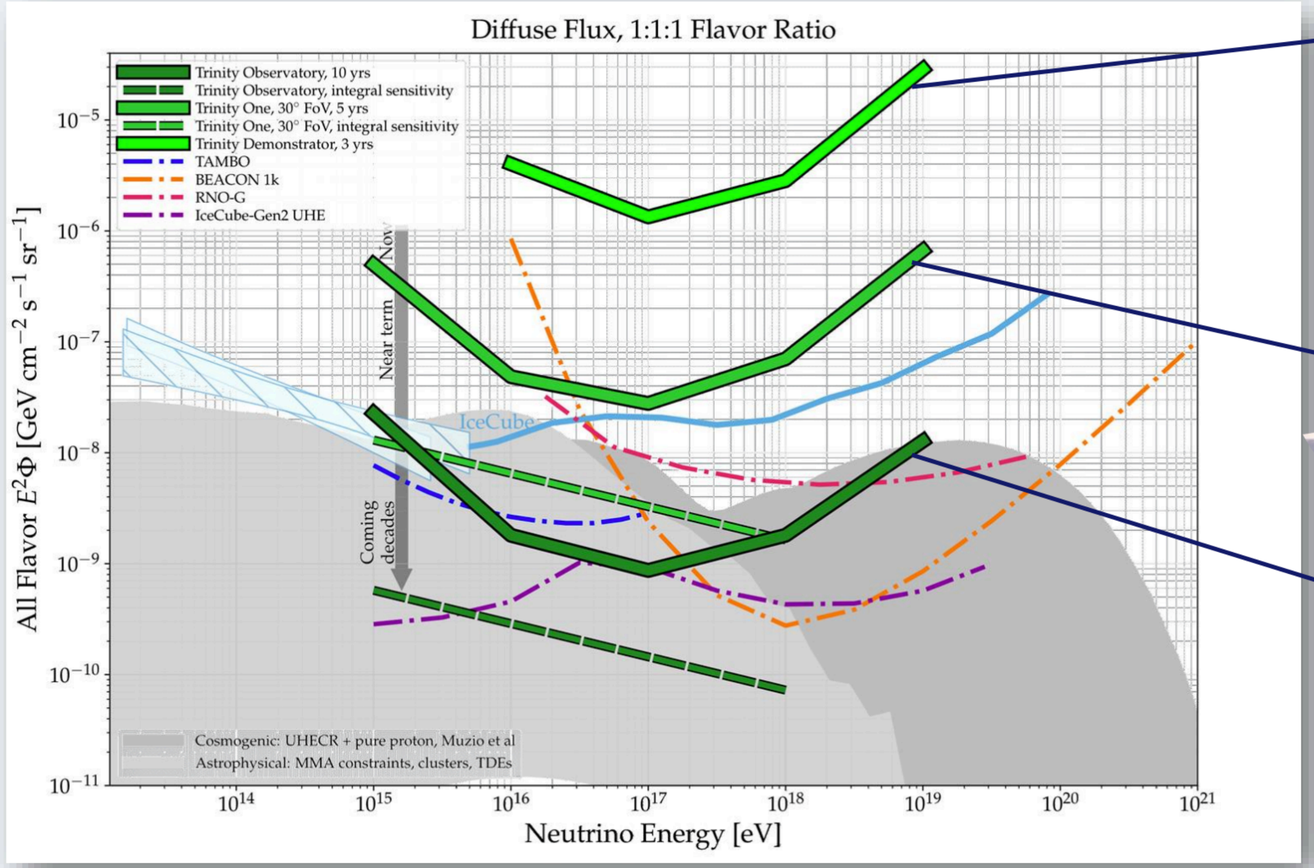
Air-shower imaging of Earth-skimming tau neutrinos

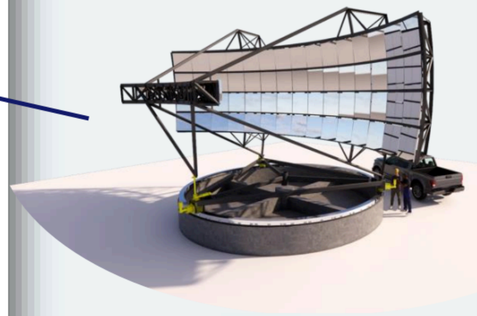


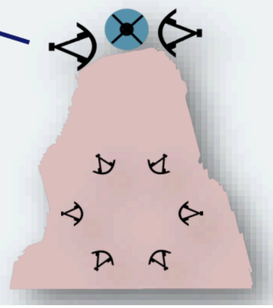
S. Stepanoff, ICRC 2025

Status: Moving from Demonstrator to Trinity One

Trinity Timeline







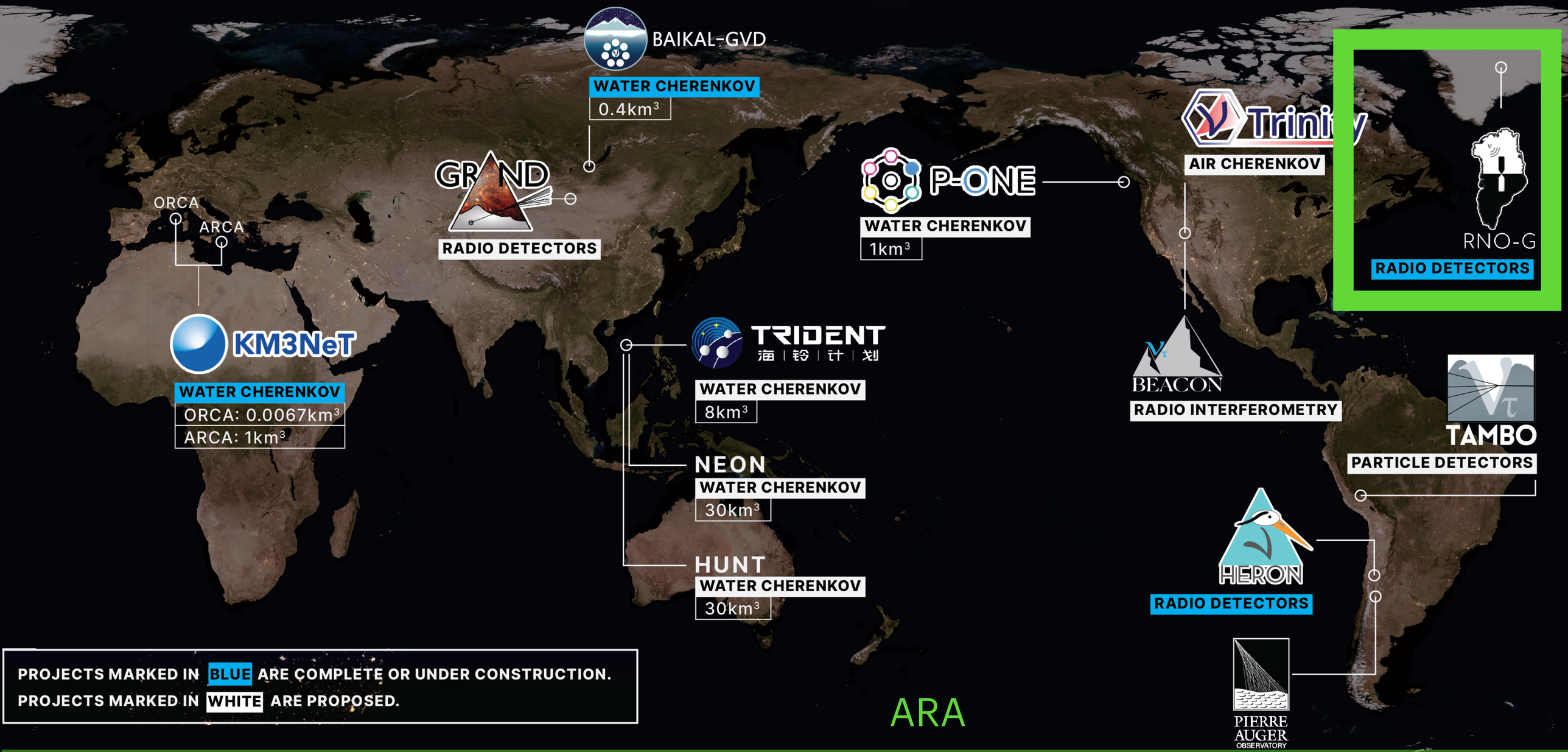
Trinity Demonstrator
Funded 2021, first light 2023

Trinity One
Development starting ~2026

Trinity Observatory
Development starting ~2031

S. Stepanoff, ICRC 2025

Trinity 2503.11864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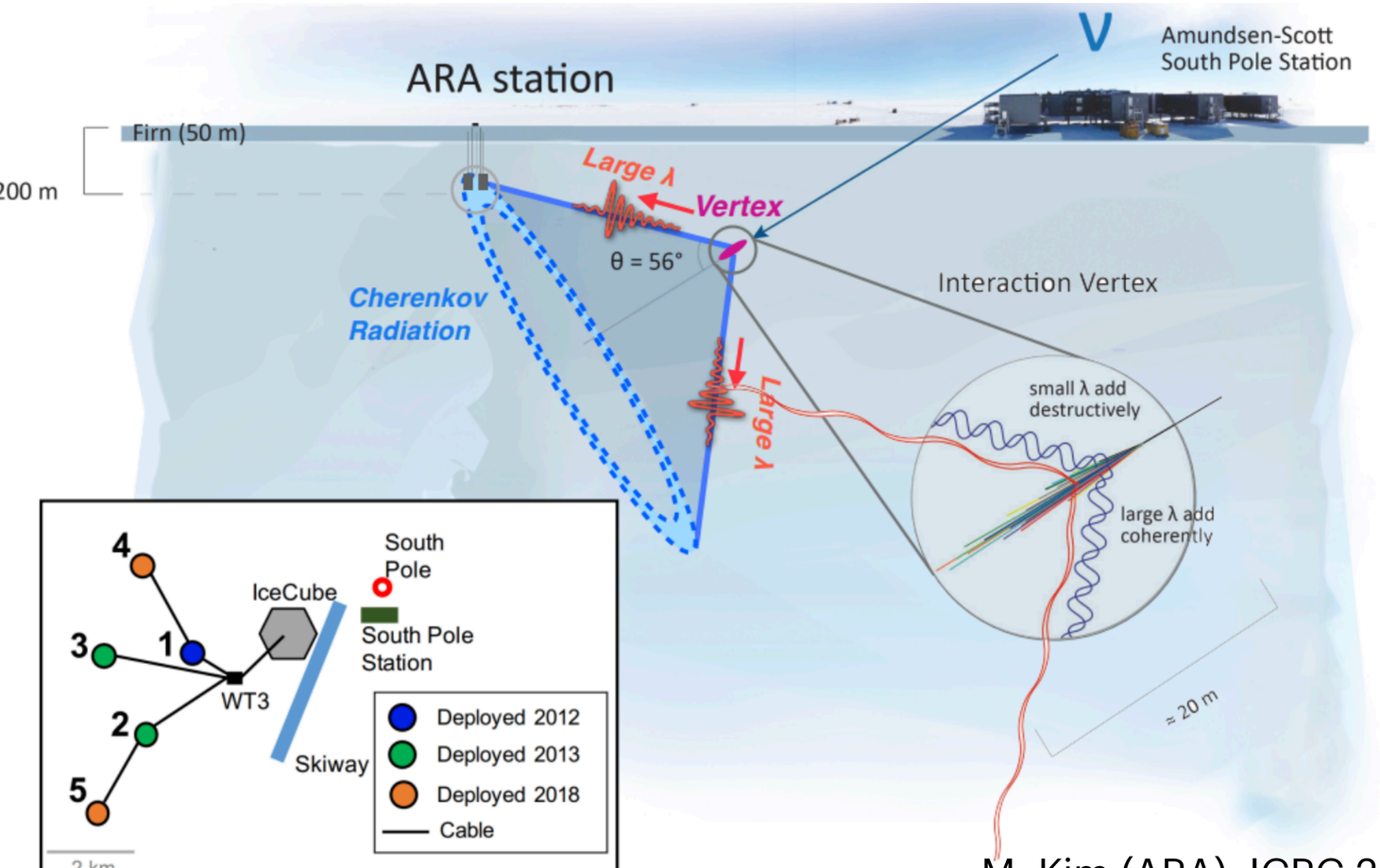
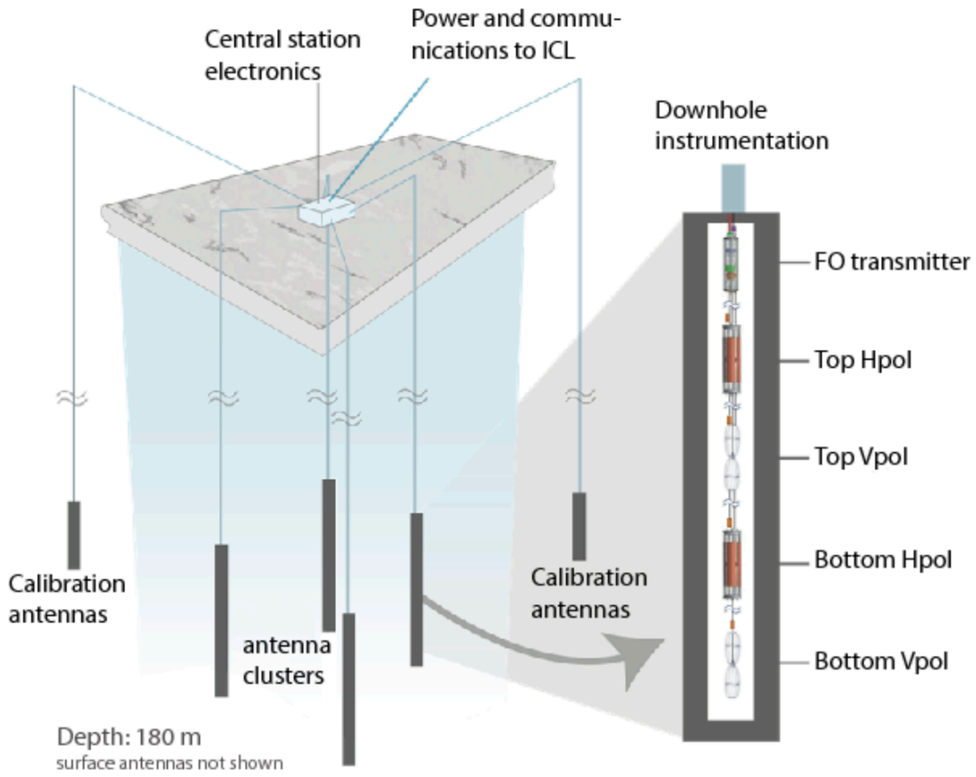
Askaryan Radiation for Neutrino Detection

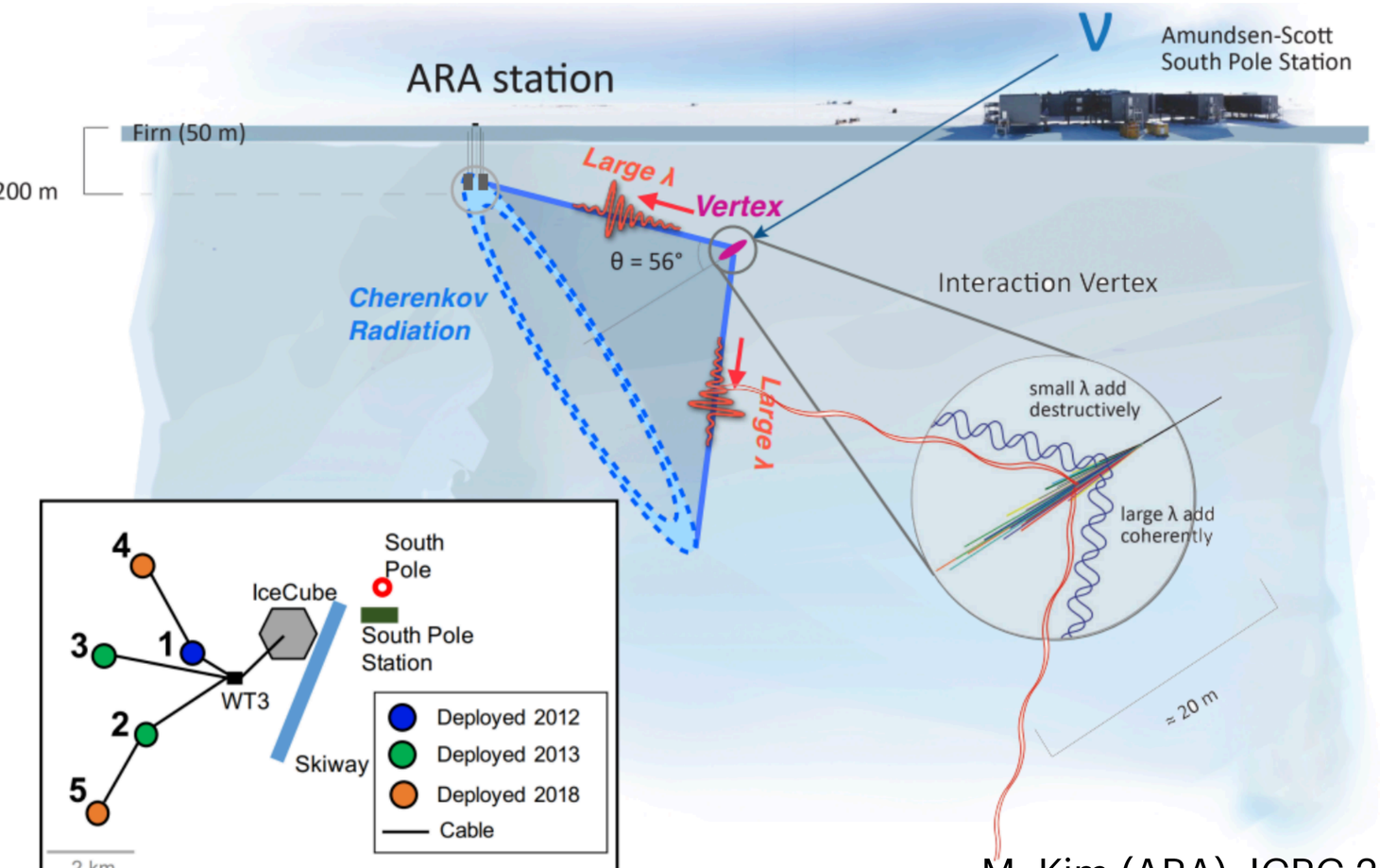


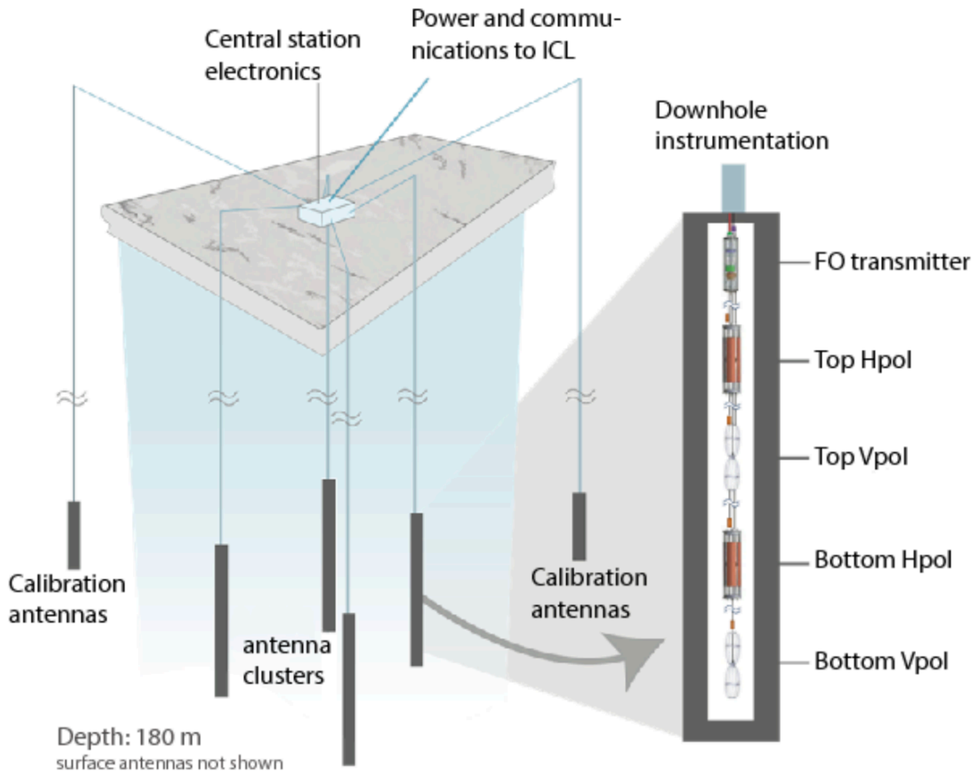


M. Kim (ARA), ICRC 2023

Askaryan Radiation for Neutrino Detection

Askaryan radio emission:
Coherent Cherenkov radiation from particles in a shower with net charge anisotropy





M. Kim (ARA), ICRC 2023

Askaryan Radiation for Neutrino Detection

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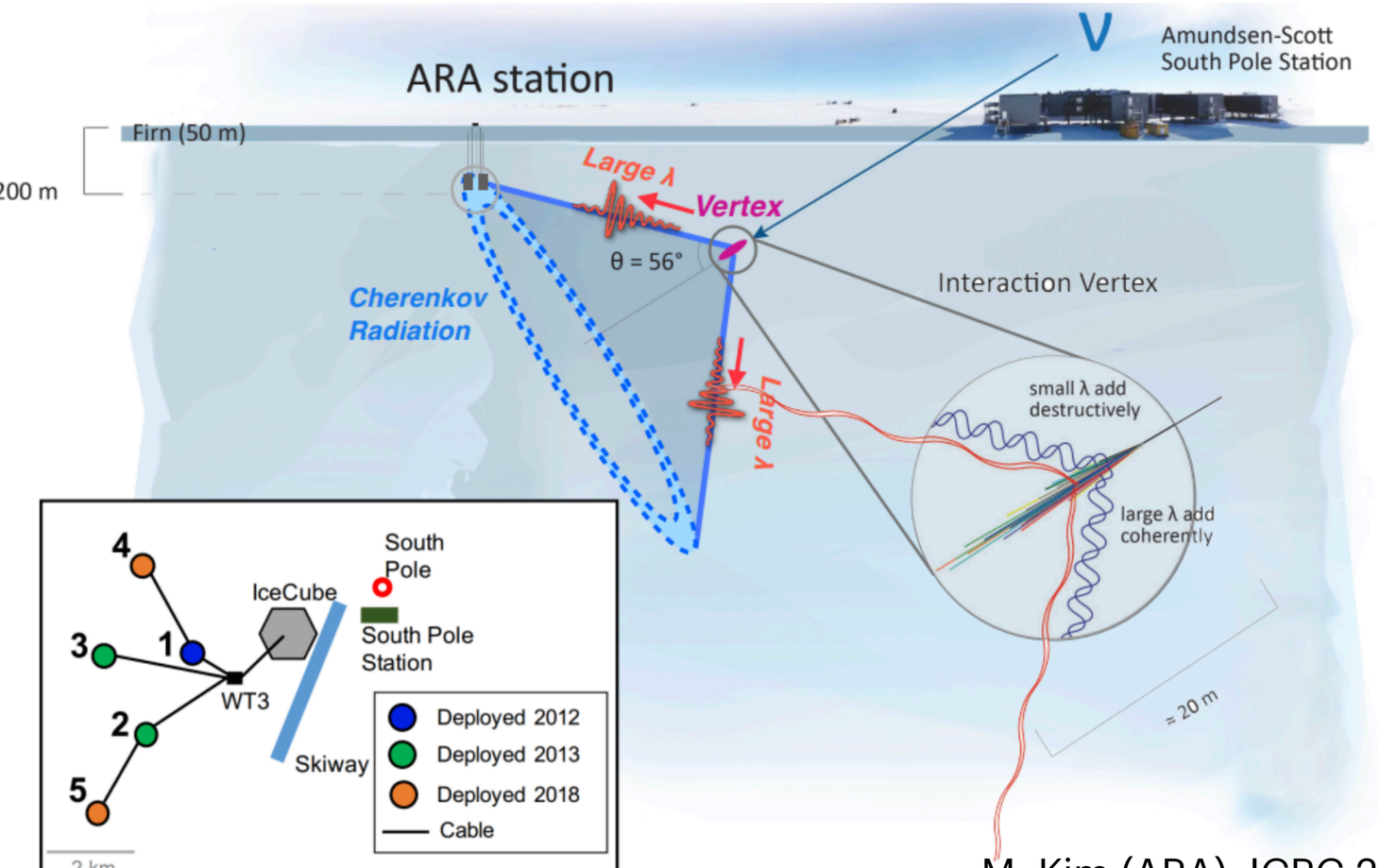
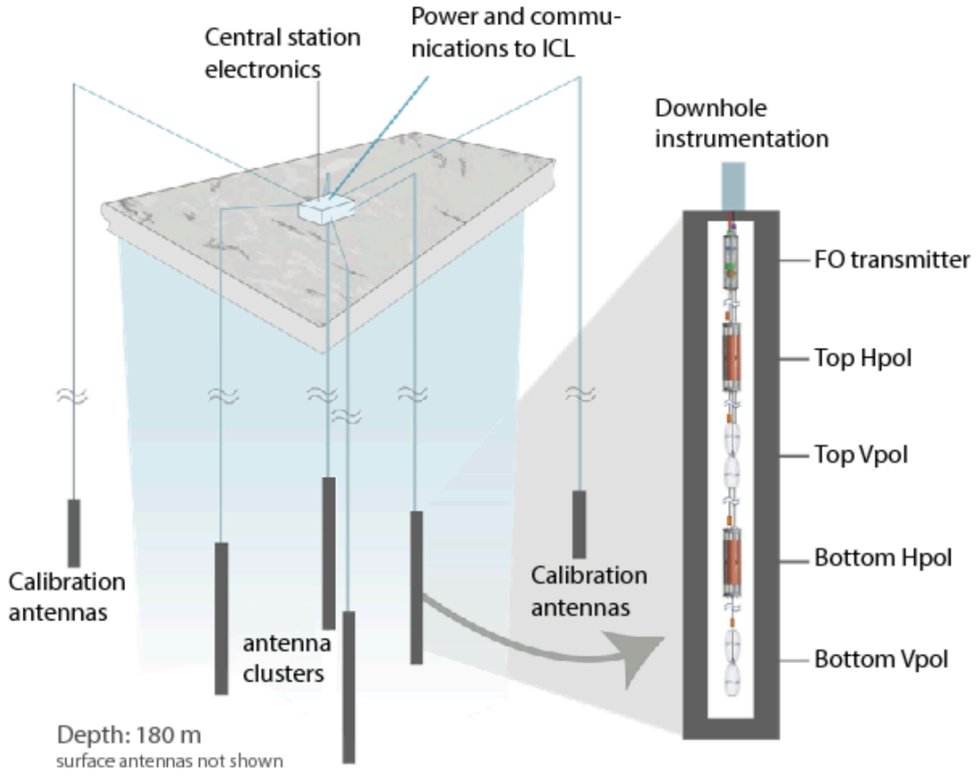
Coherent Cherenkov radiation from particles in a shower with net charge anisotropy

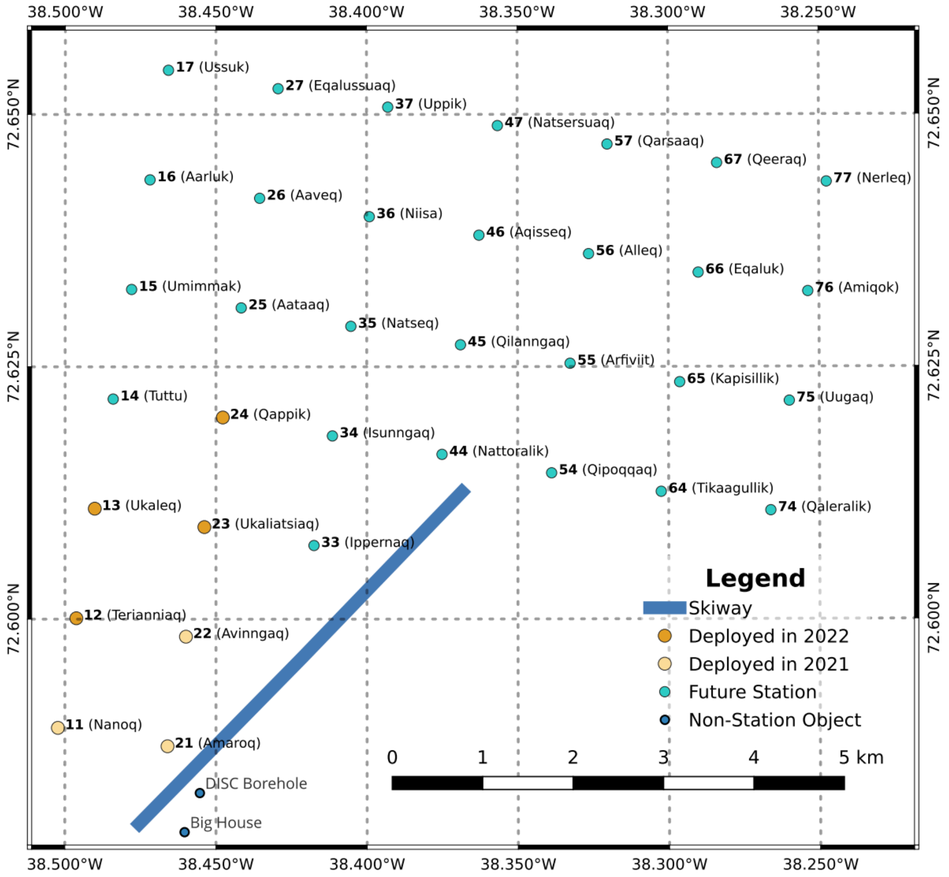
Polarization of radio emission gives information on **shower direction**

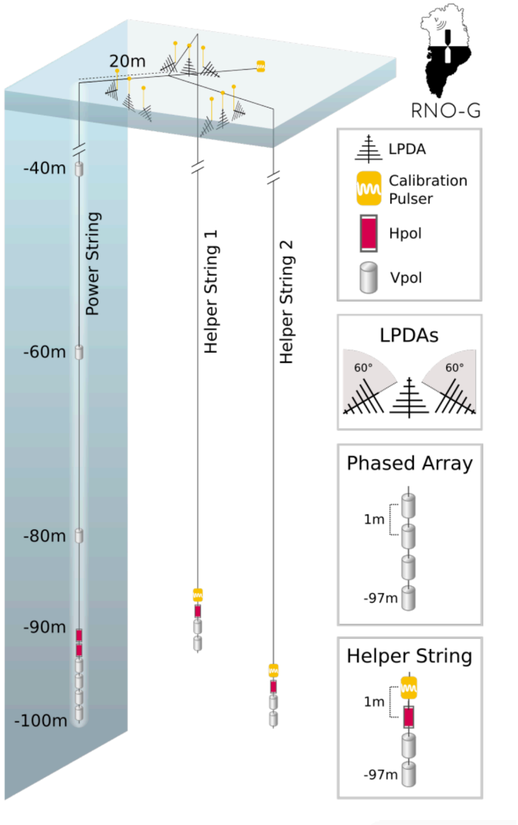




M. Kim (ARA), ICRC 2023

Radio Neutrino Observatory in Greenland

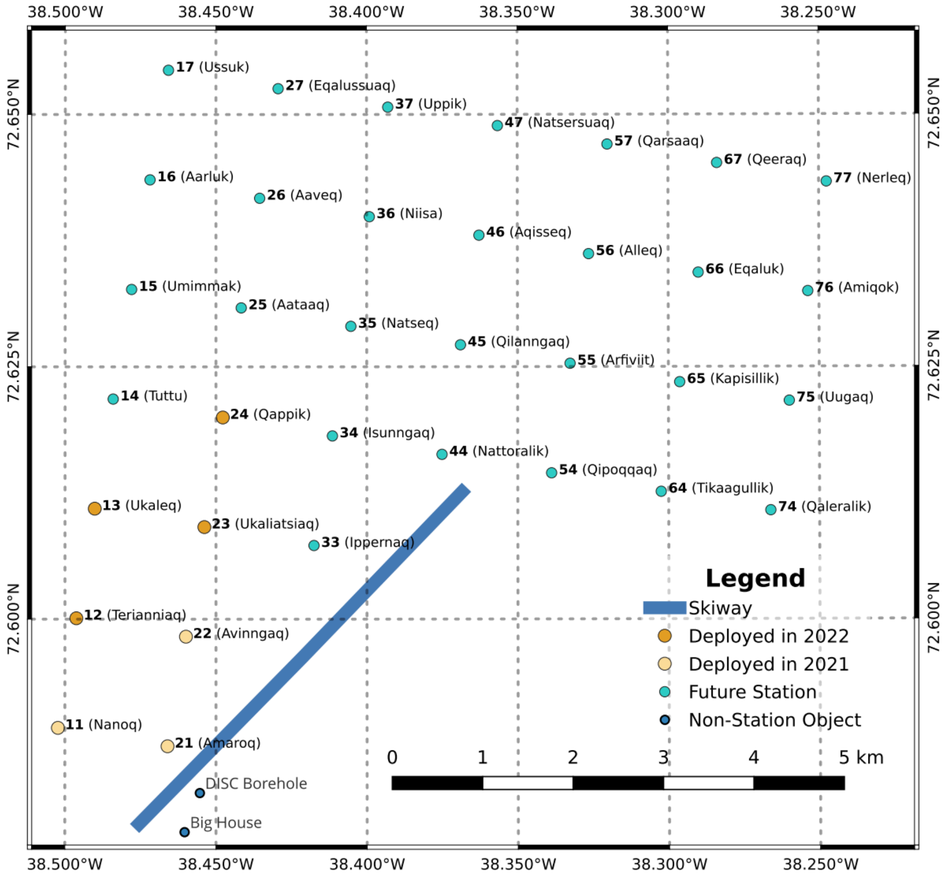


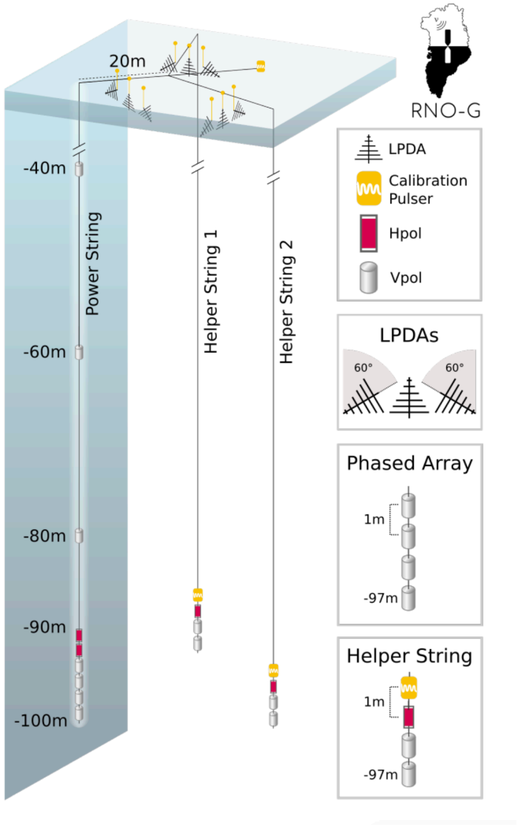


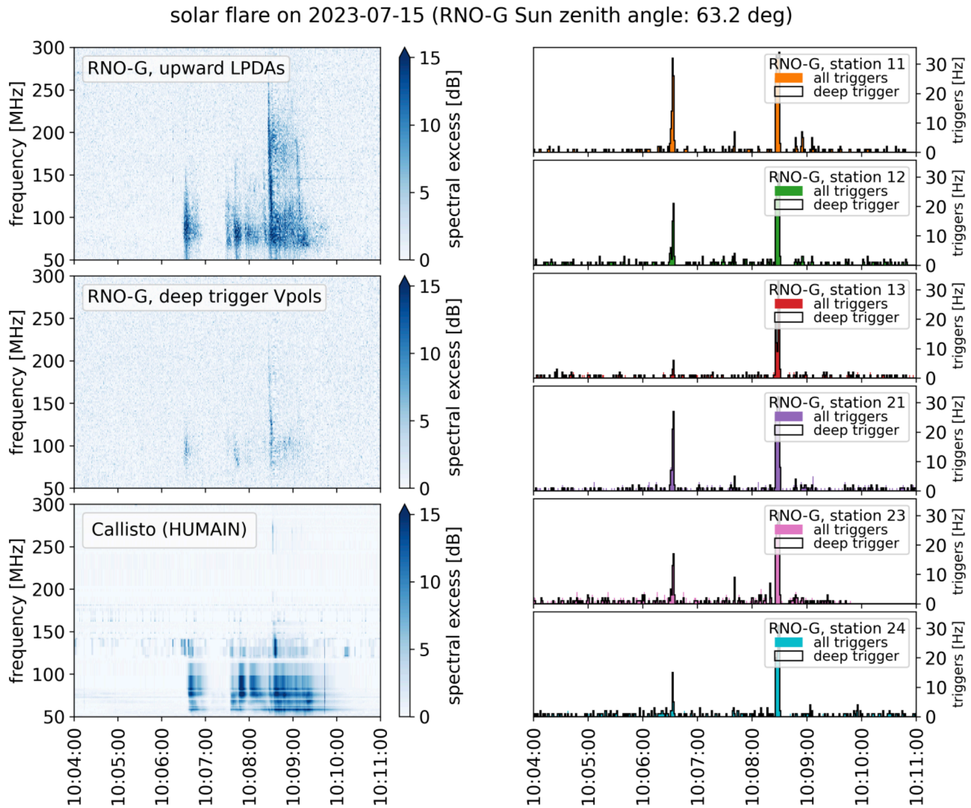
8/35 radio stations deployed

RNO-G, JINST 2025

Radio Neutrino Observatory in Greenland



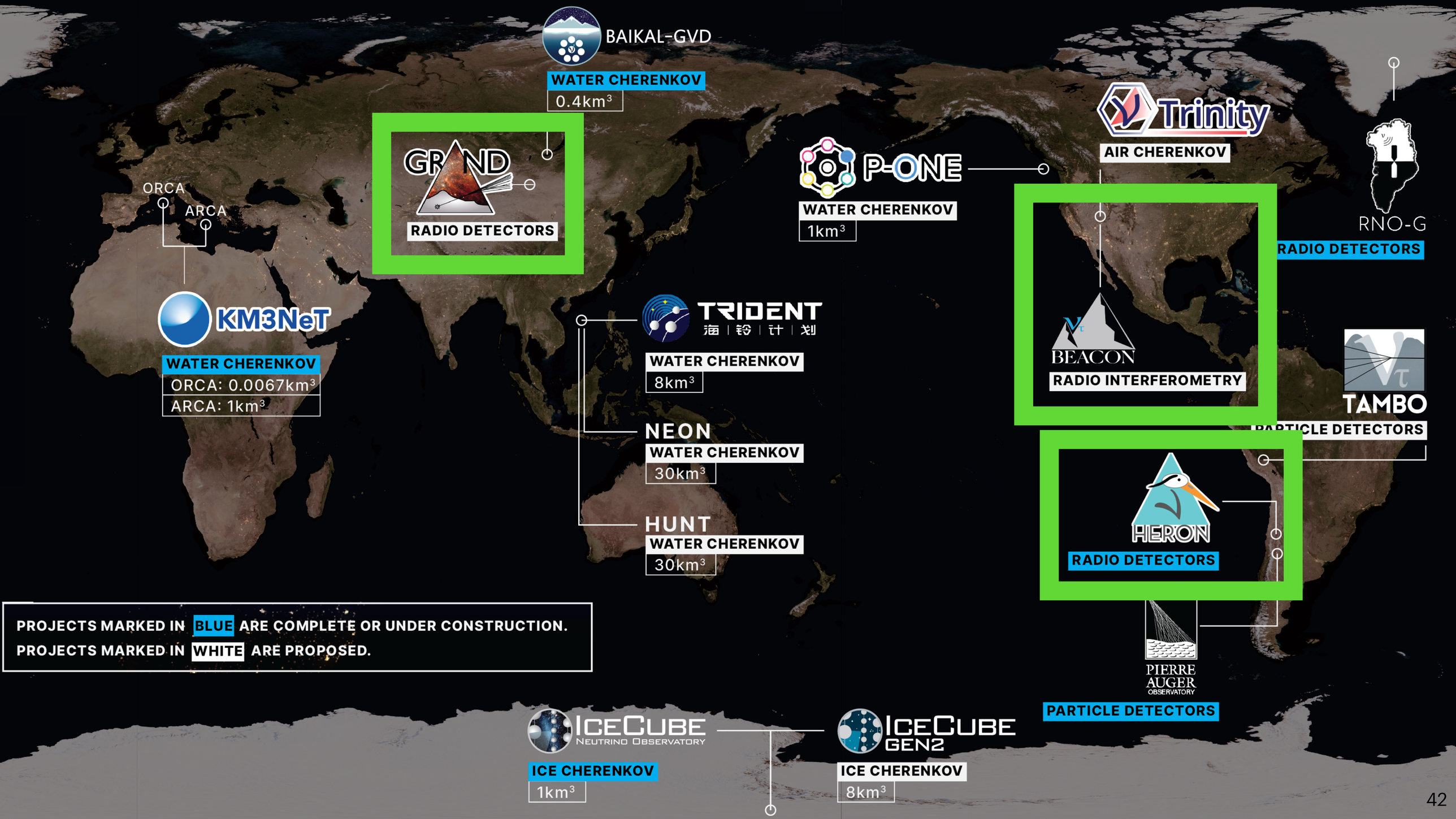




8/35 radio stations deployed

Saw a solar flare on 15 July 2023!

RNO-G, JINST 2025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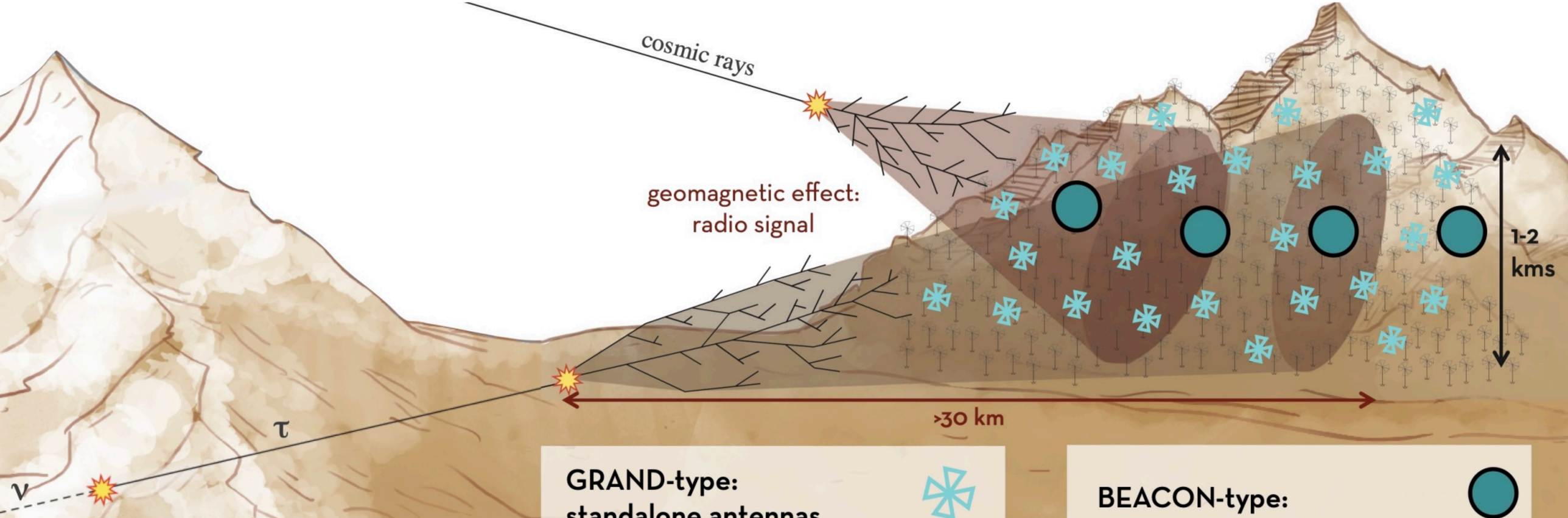
GRAND, BEACON, and HERON



GRAND-type:
standalone antennas
15 around each station
autonomous & external triggering
reconstruction

BEACON-type:
phased stations
24 antennas per station
low energy threshold for triggering

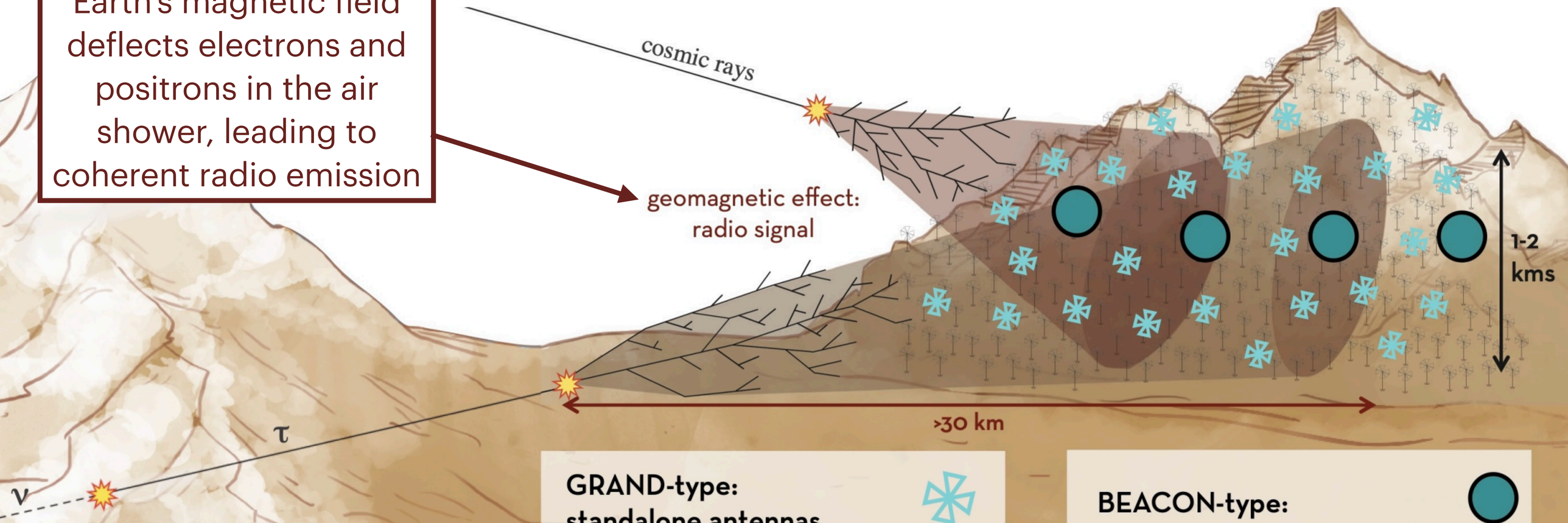
Kotera (HERON), ICRC 2025

Martineau-Huynh (GRAND), ICRC 2025

Zeolla (BEACON), ICRC 2025

GRAND, BEACON, and HERON

Earth's magnetic field deflects electrons and positrons in the air shower, leading to coherent radio emission



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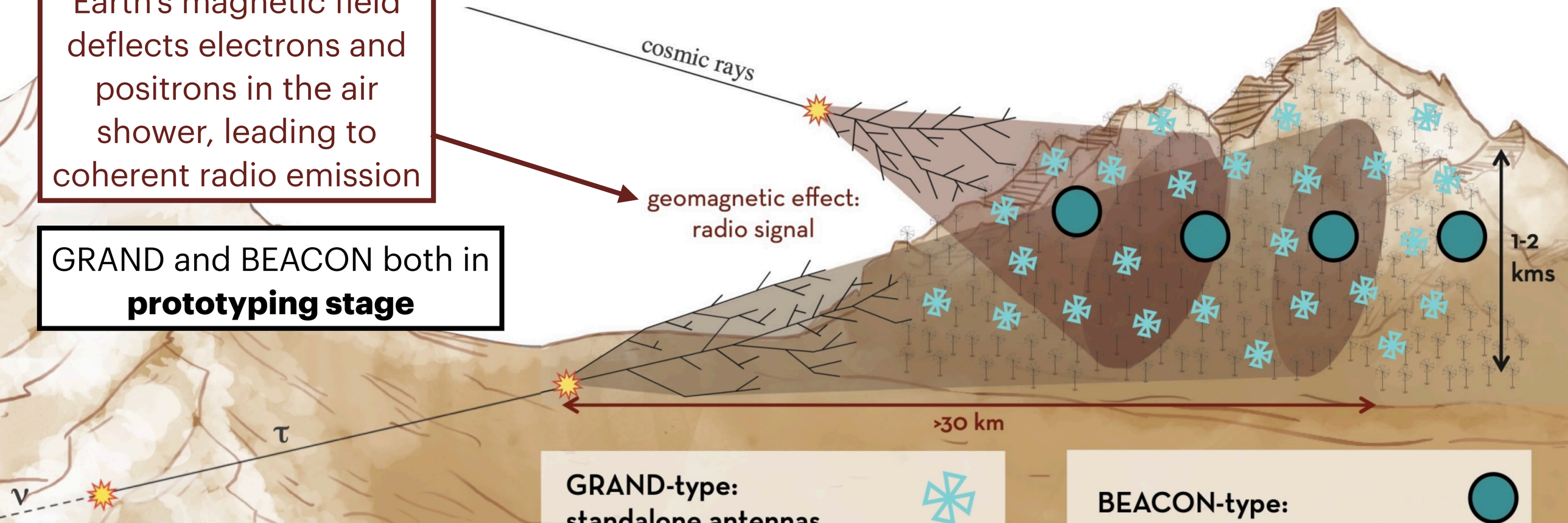
GRAND and BEACON both in **prototyping stage**



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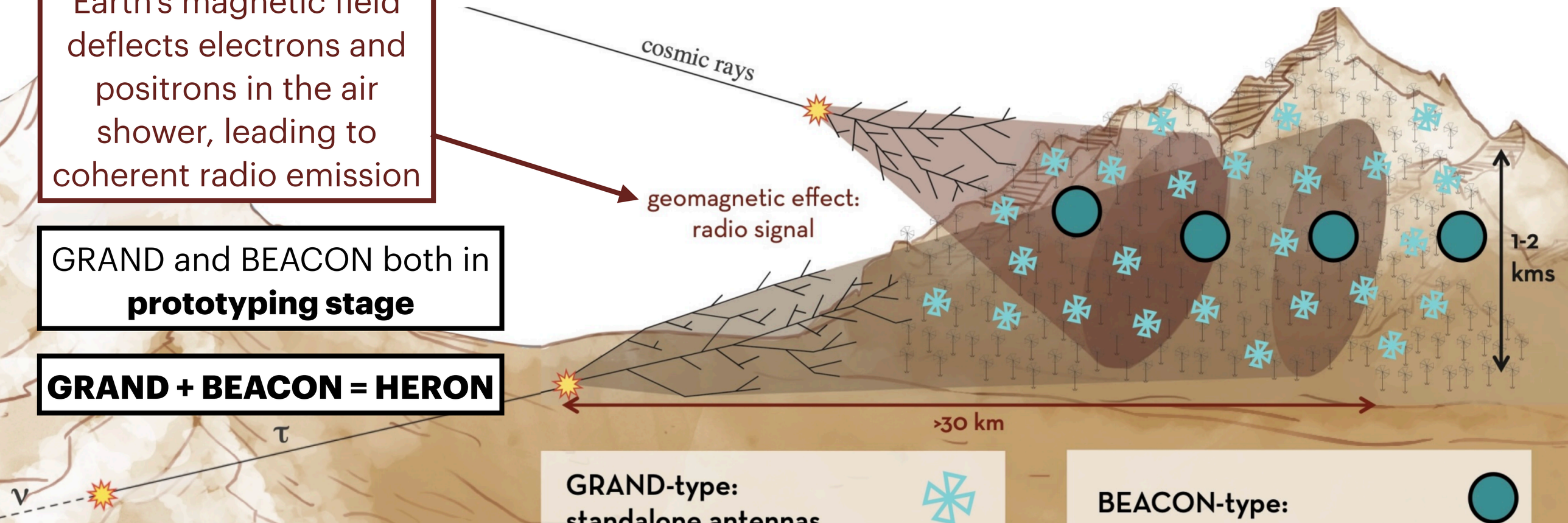
GRAND + BEACON = HERON



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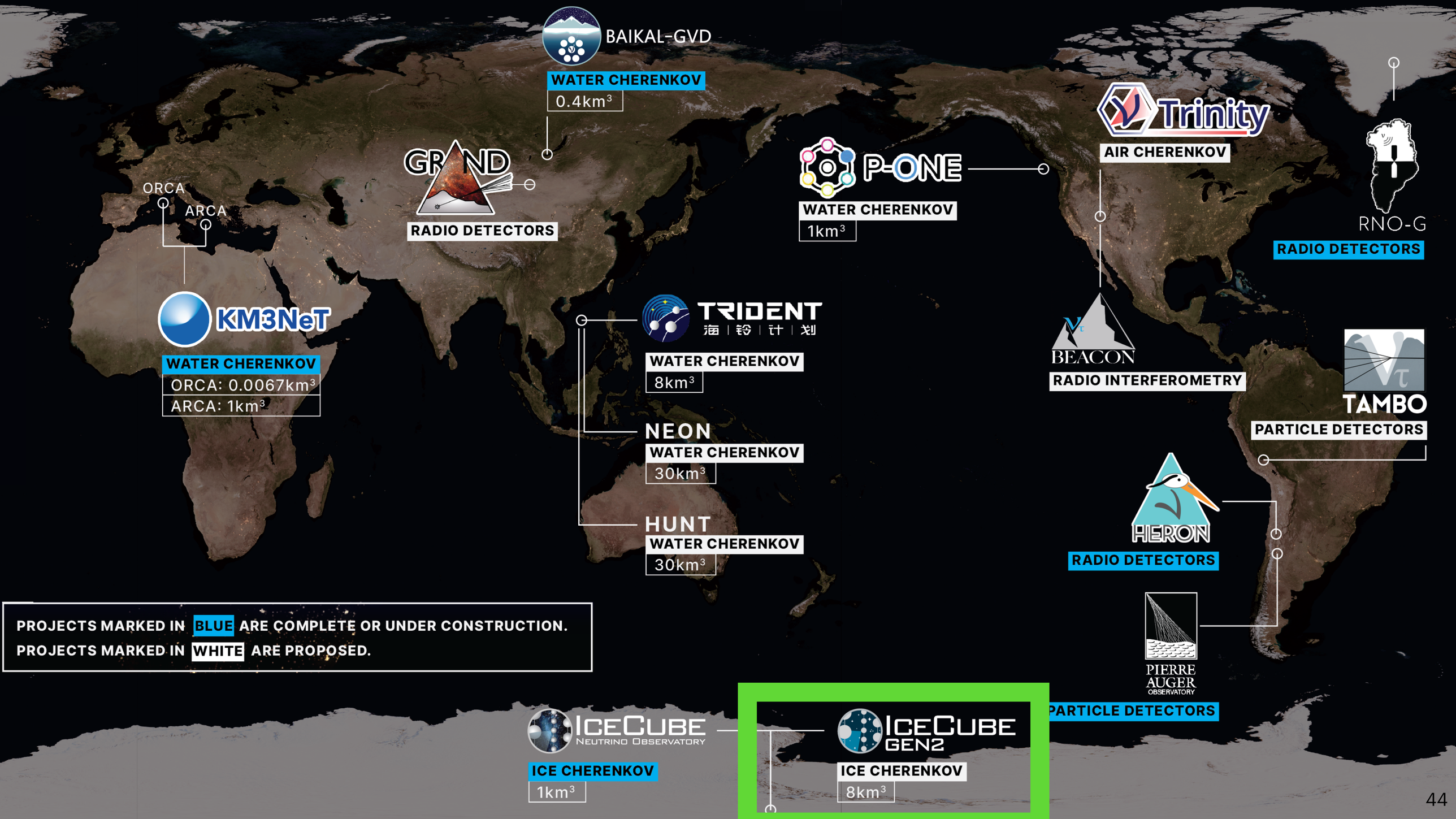
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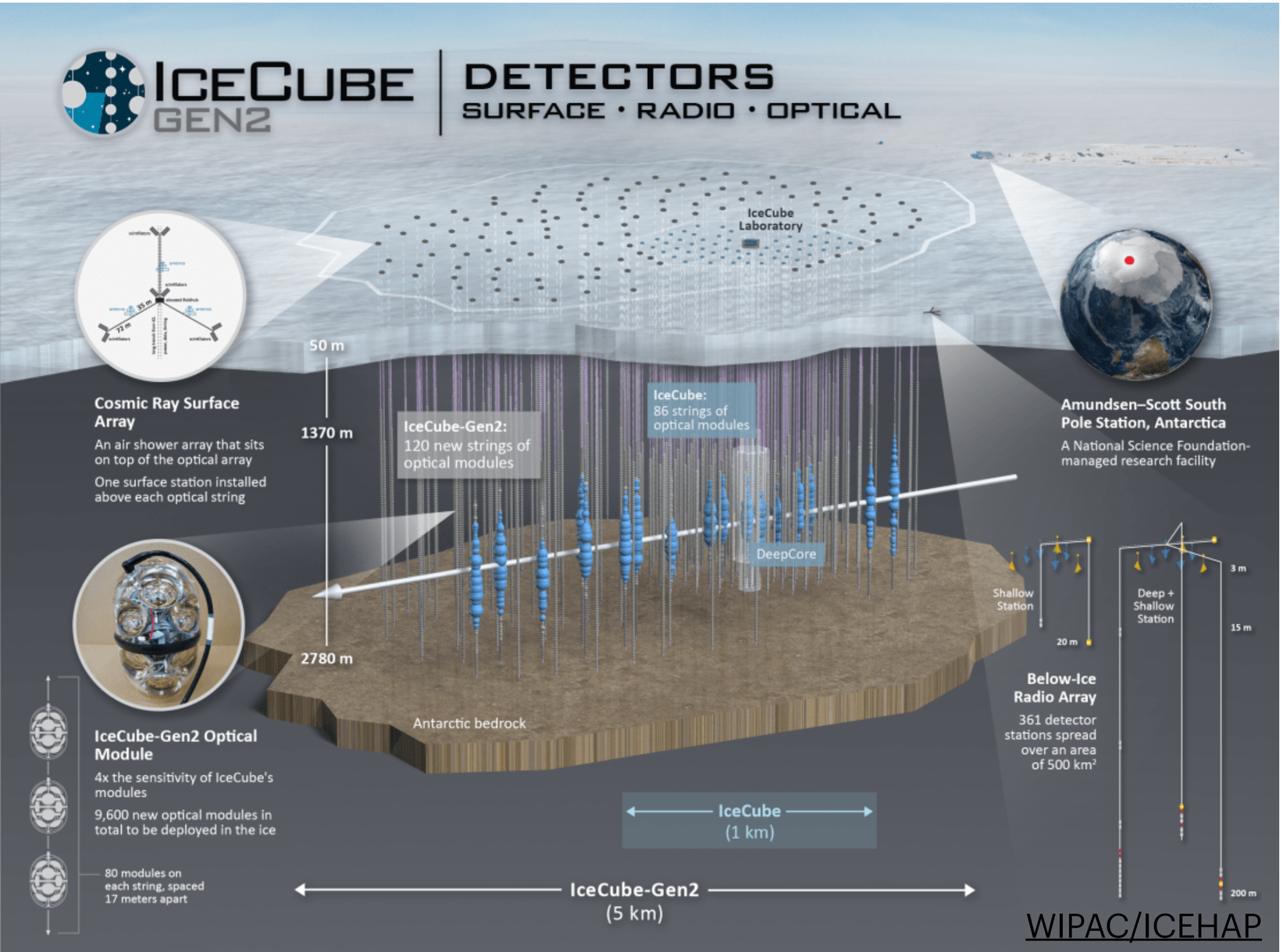
IceCube-Gen2: A Combination of Techniques



WIPAC/ICEHAP

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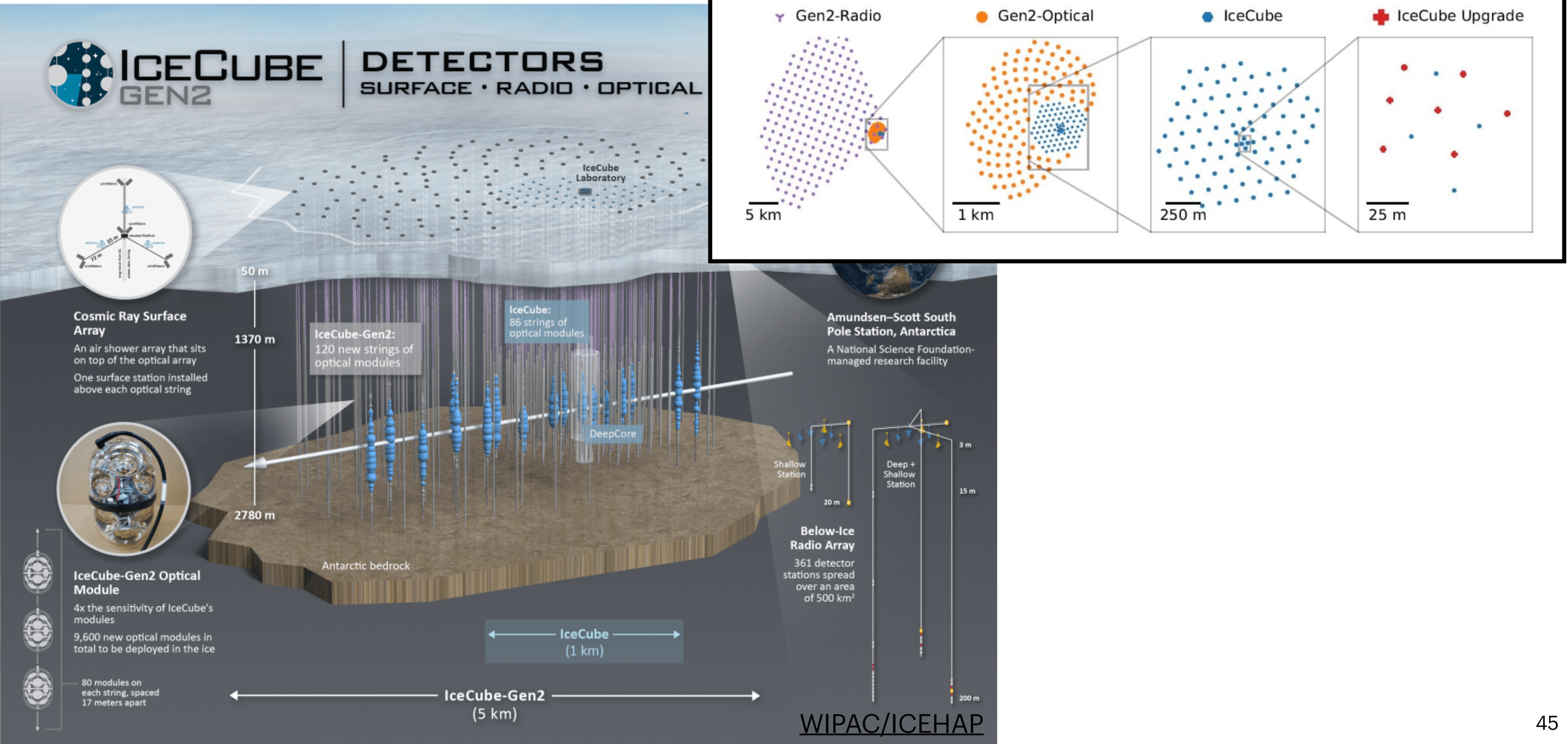

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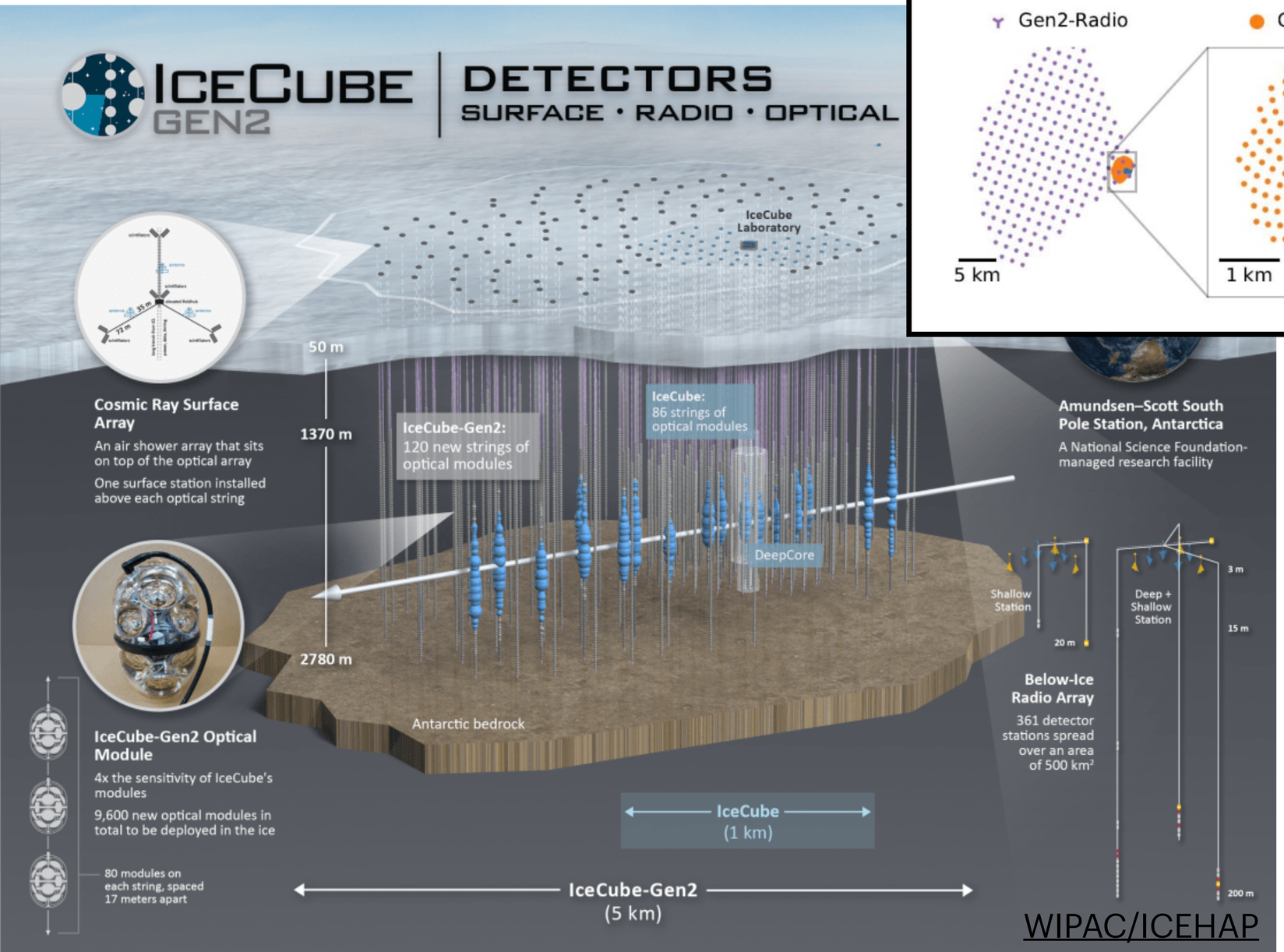

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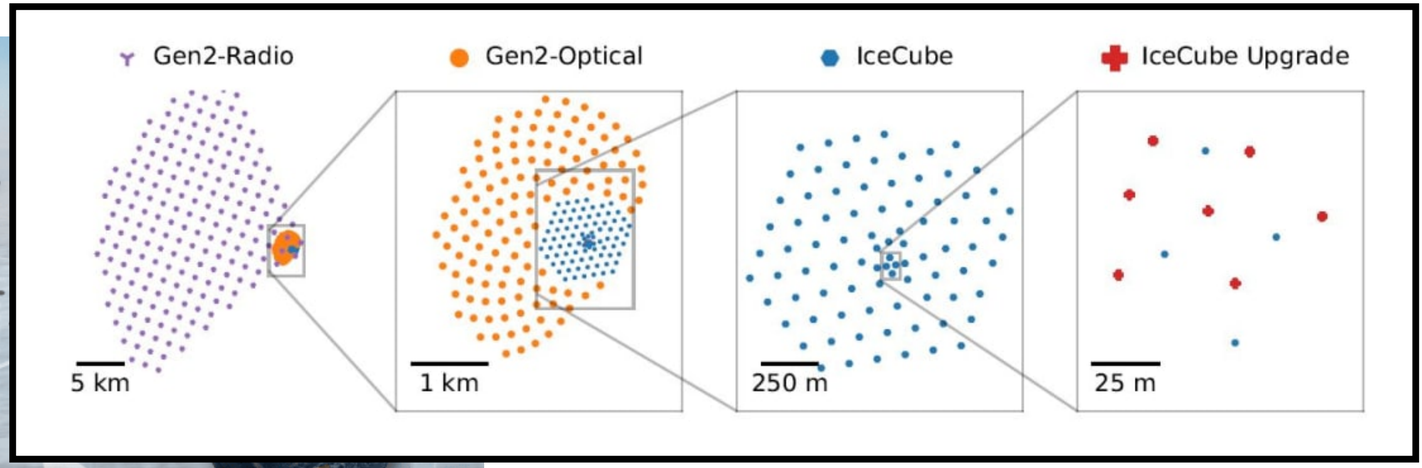
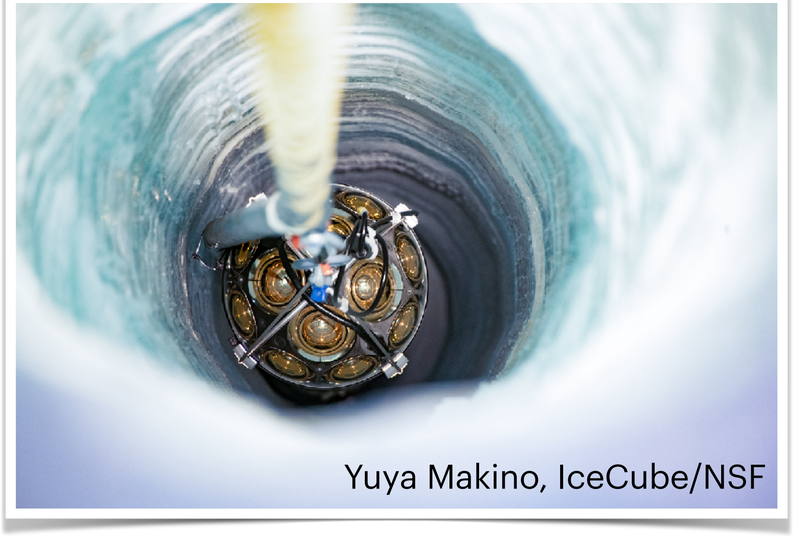
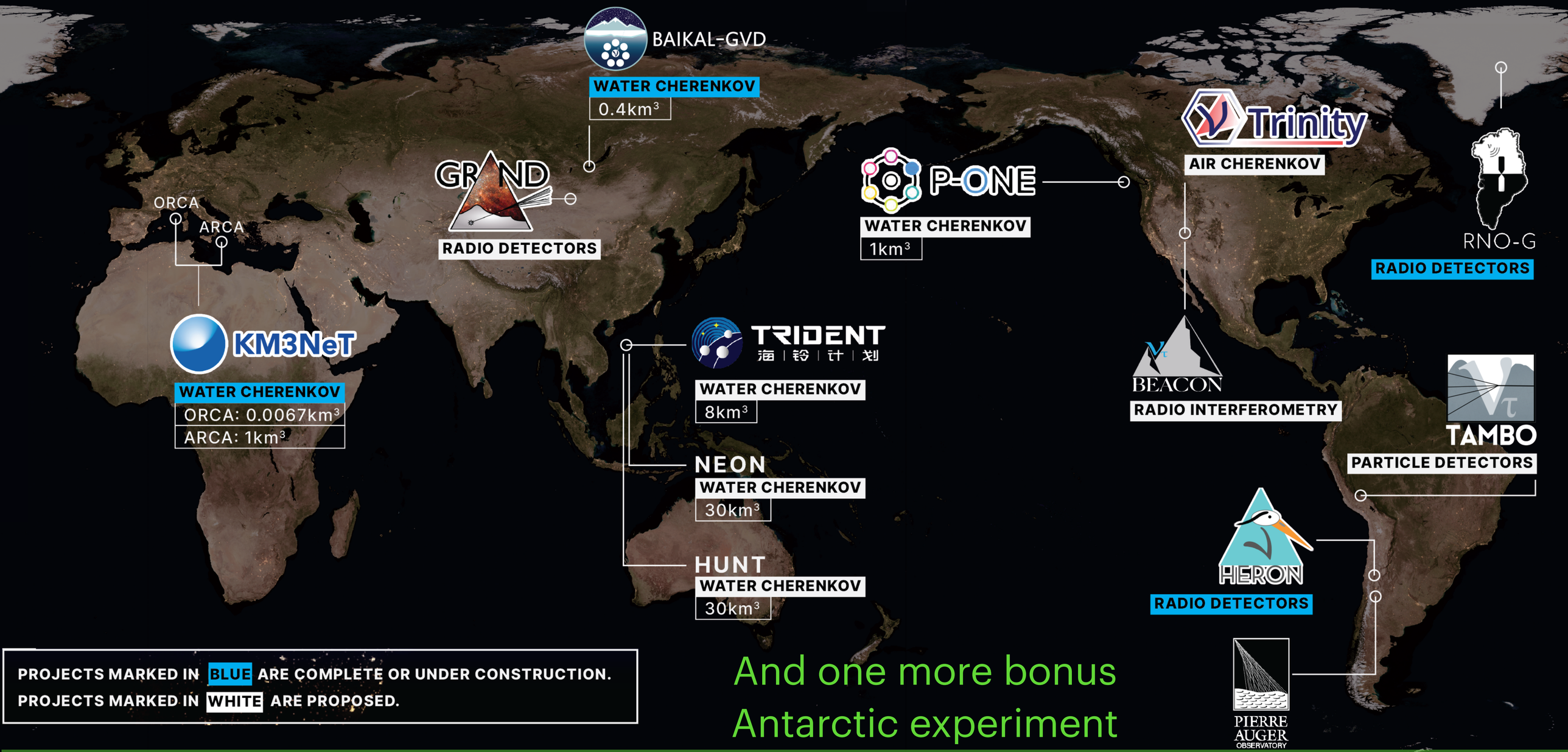




Upgrade deployed over Dec/Jan!

first step en route to Gen2

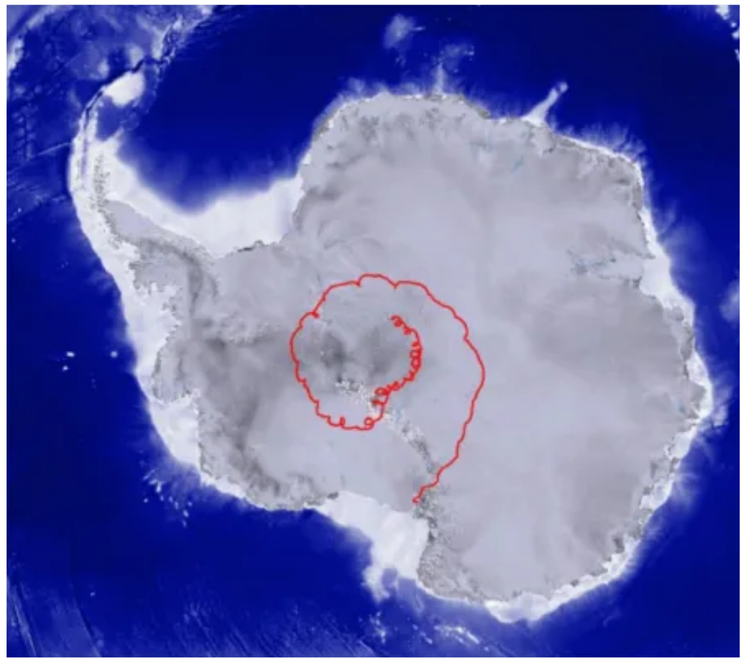


And one more bonus
Antarctic experiment

The Payload for Ultrahigh Energy Observations (PUEO)

Balloon-based detector observing **Askaryan and geomagnetic** radio emission from neutrino interactions in ice

First flight on December 19, 2025!



A. Verbeck, *PUEO's Antarctic flight advances neutrino research* Abarr, ICRC 2025

So what’s the “best” technology?

- Depends what you care about

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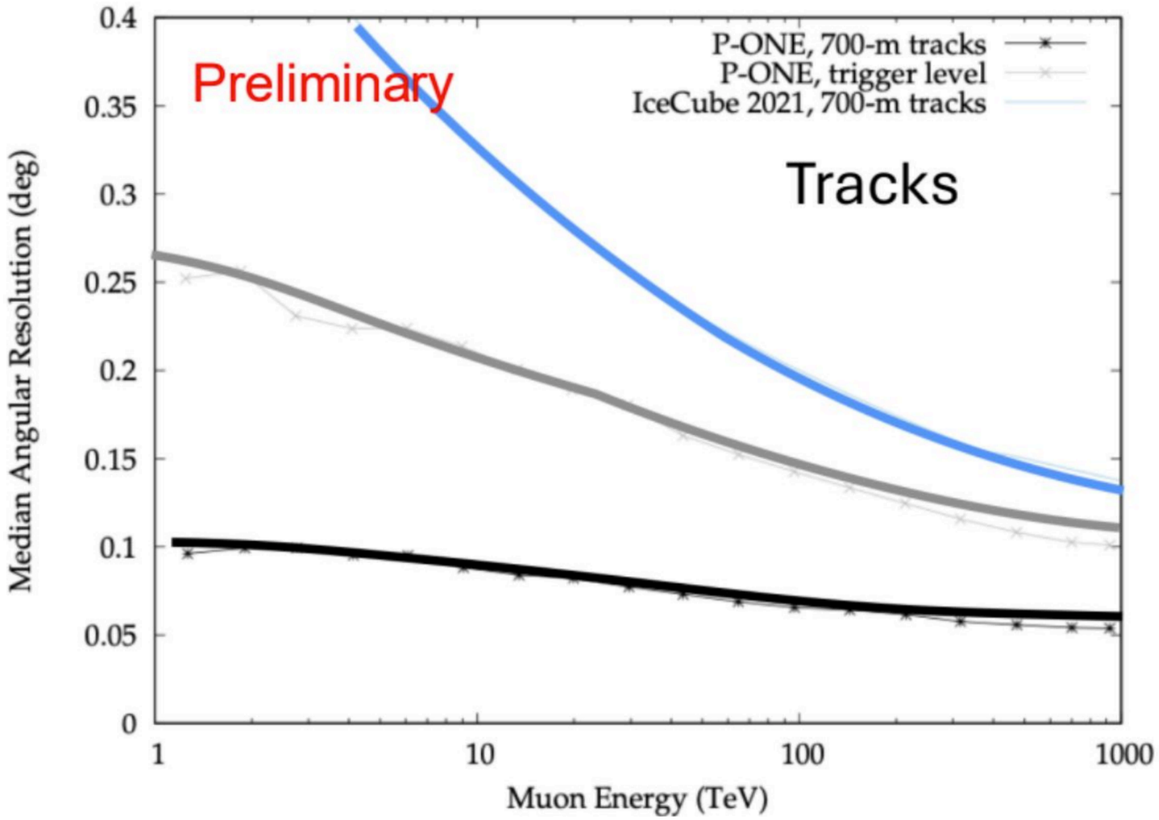
Depends what you care about

- **Angular resolution?** Mostly ~sub-degree, but some advantage in water Cherenkov



P. Krause, Lake Louise Winter Institute 2026

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- **Angular resolution?** Mostly ~sub-degree, but some advantage in water Cherenkov
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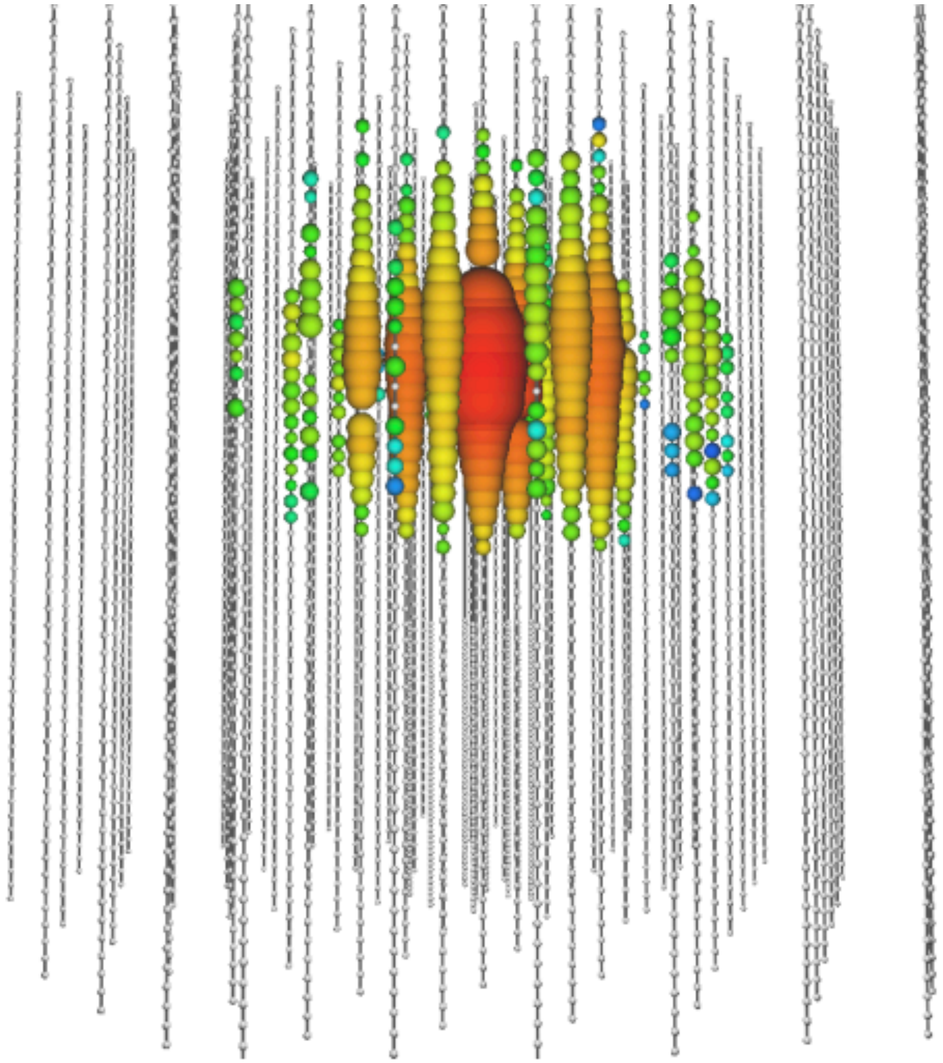

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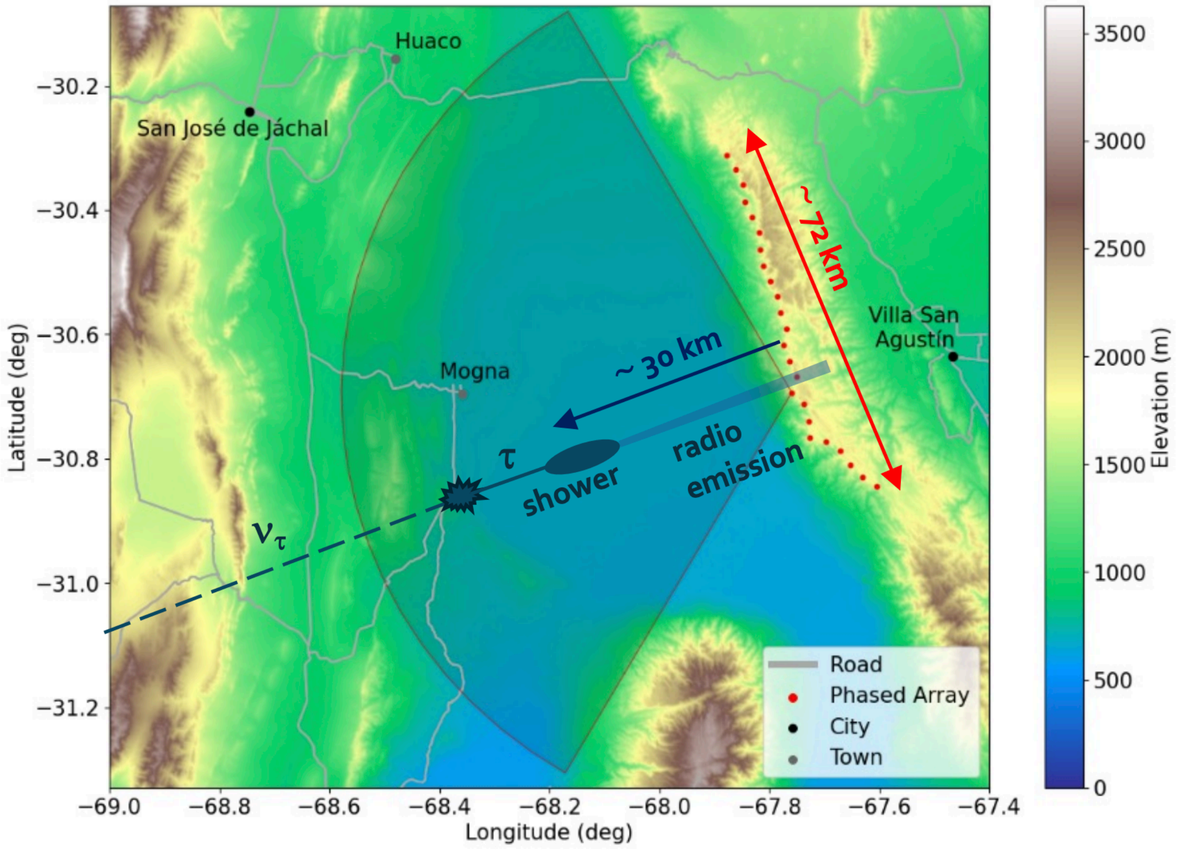

Kotera (HERON), ICRC 2025

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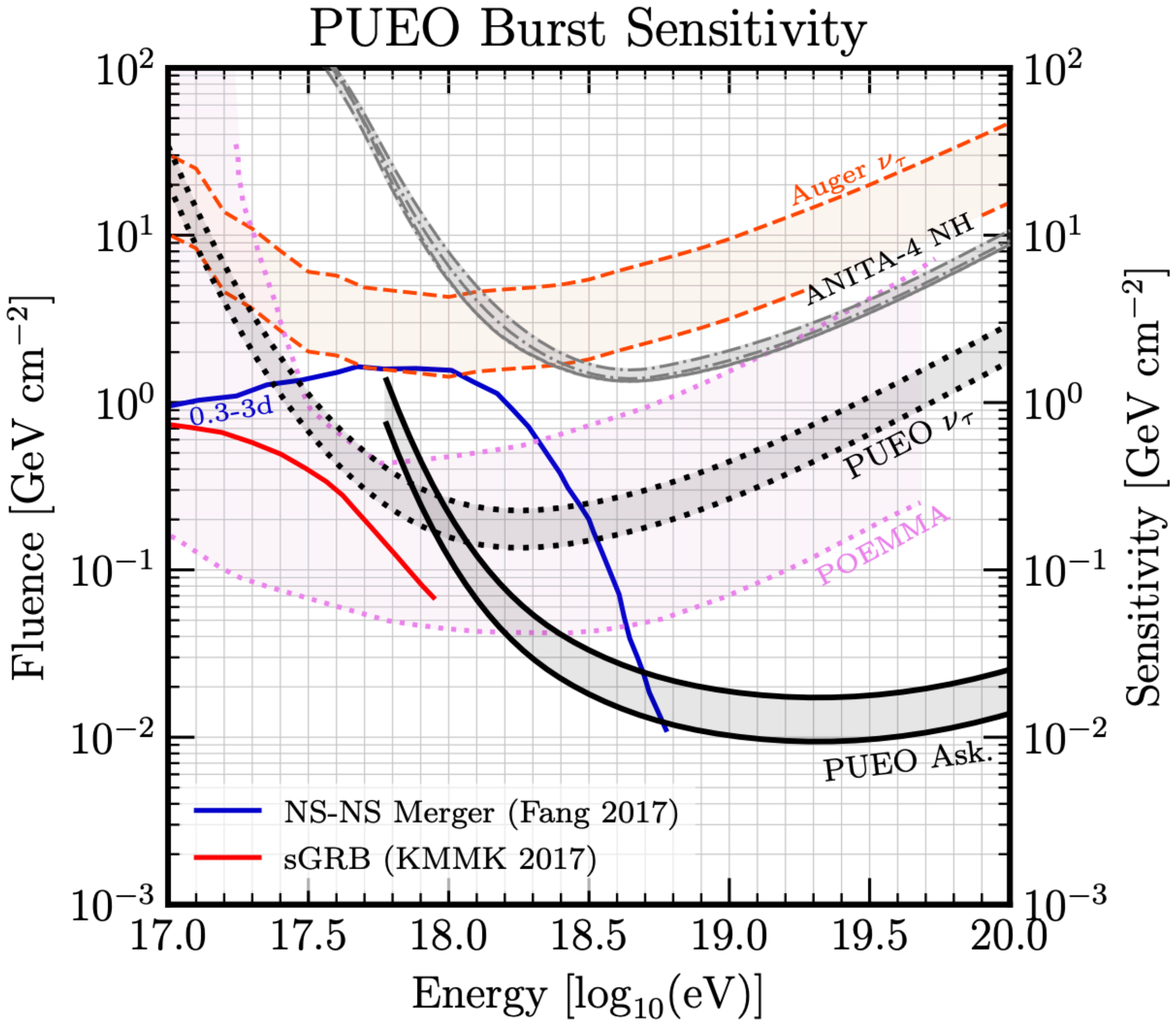
- **Transients?** Balloons have large instantaneous volume



A. Vieregg, ICRC 2021

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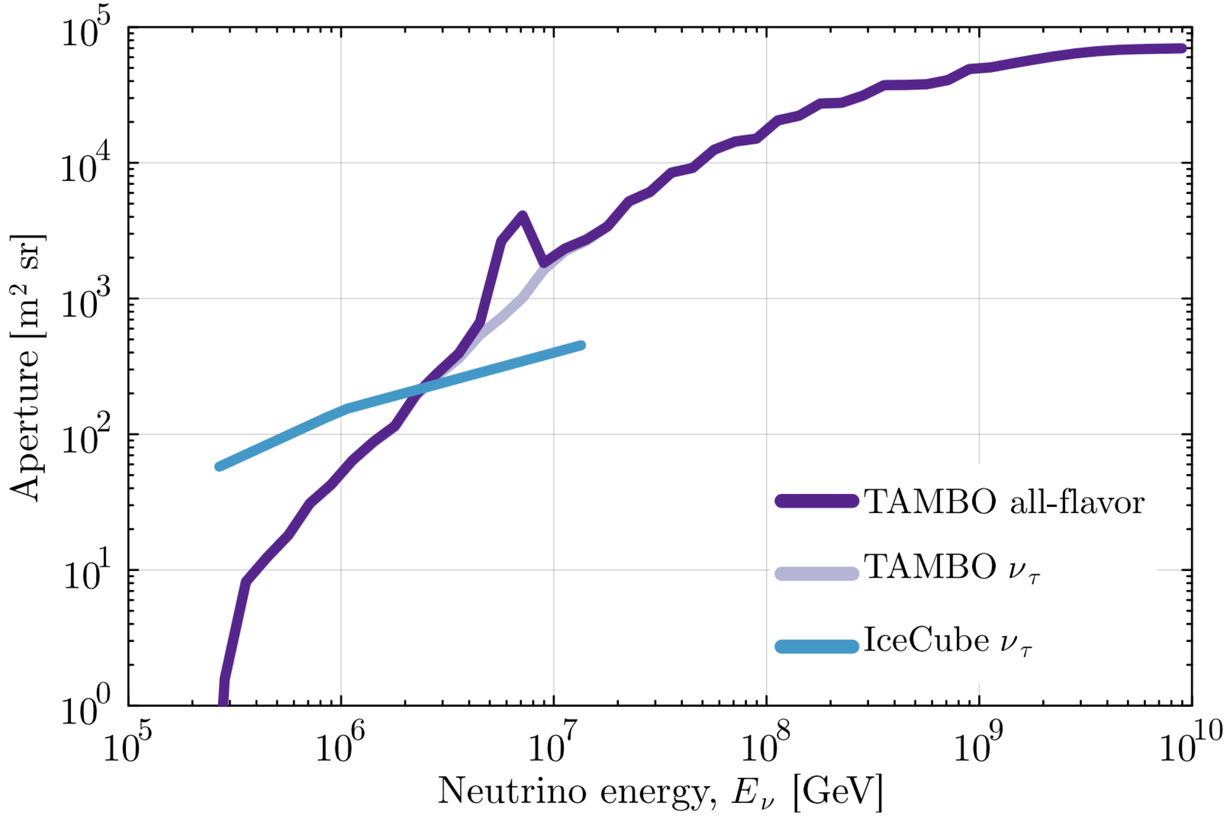
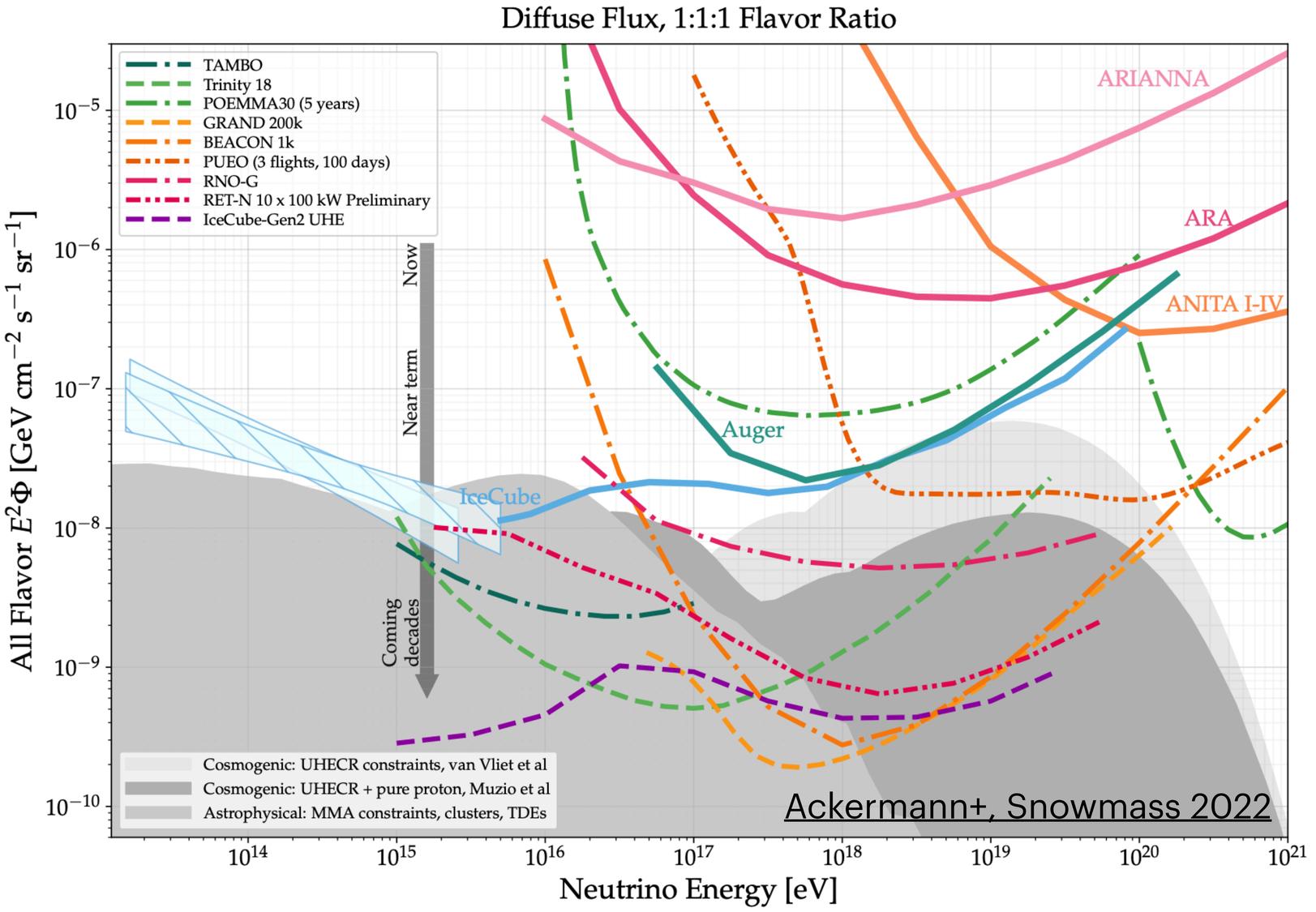
- **Active volume?** Radio wins here
- **Transients?** Balloons have large instantaneous volume
- **Flavor?** Air shower experiments are optimized for tau neutrinos



TAMBO 2507.08070

In the end, we will need all technologies to cover the UHE regime



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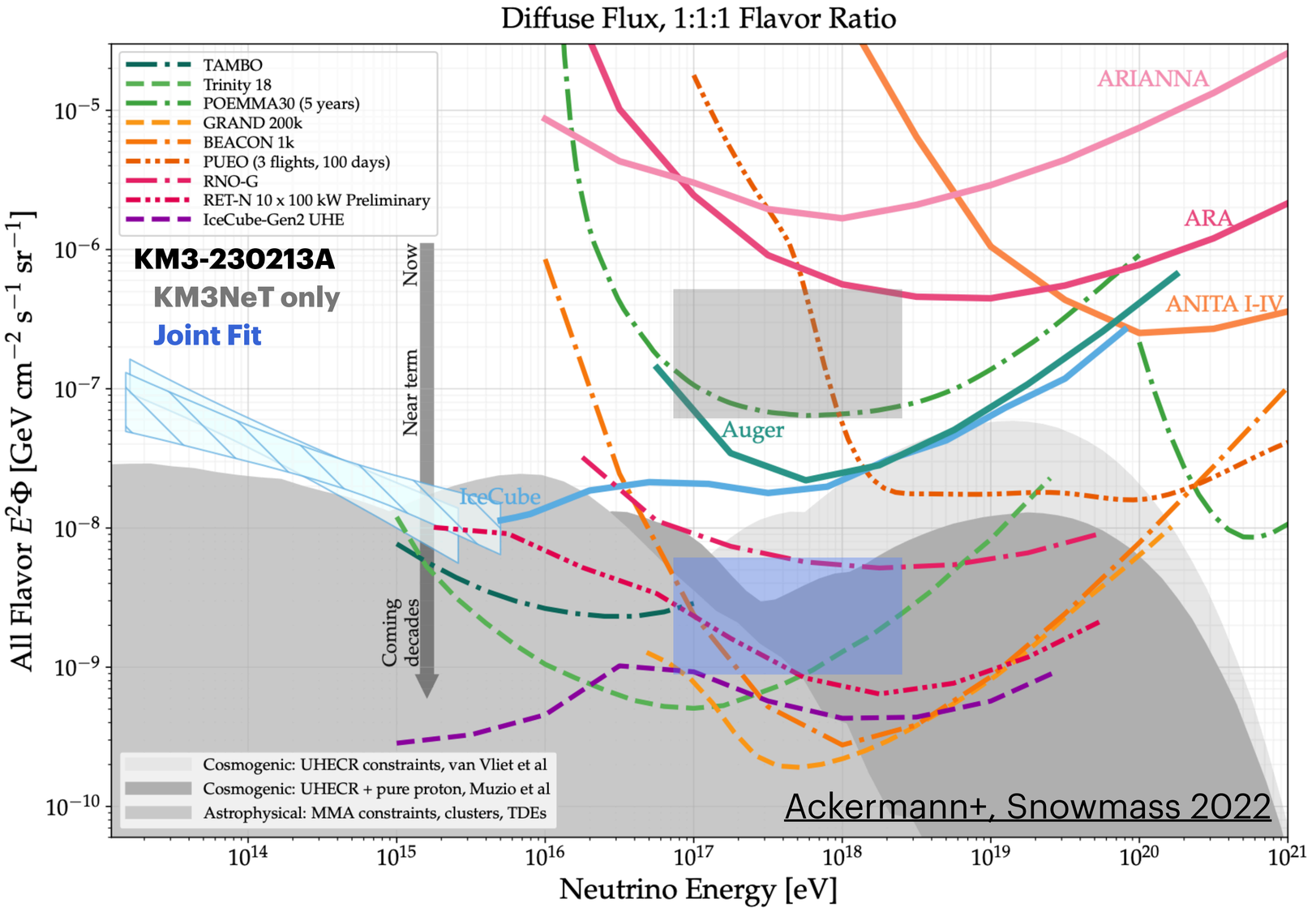
And test KM3NeT's 220 PeV neutrino



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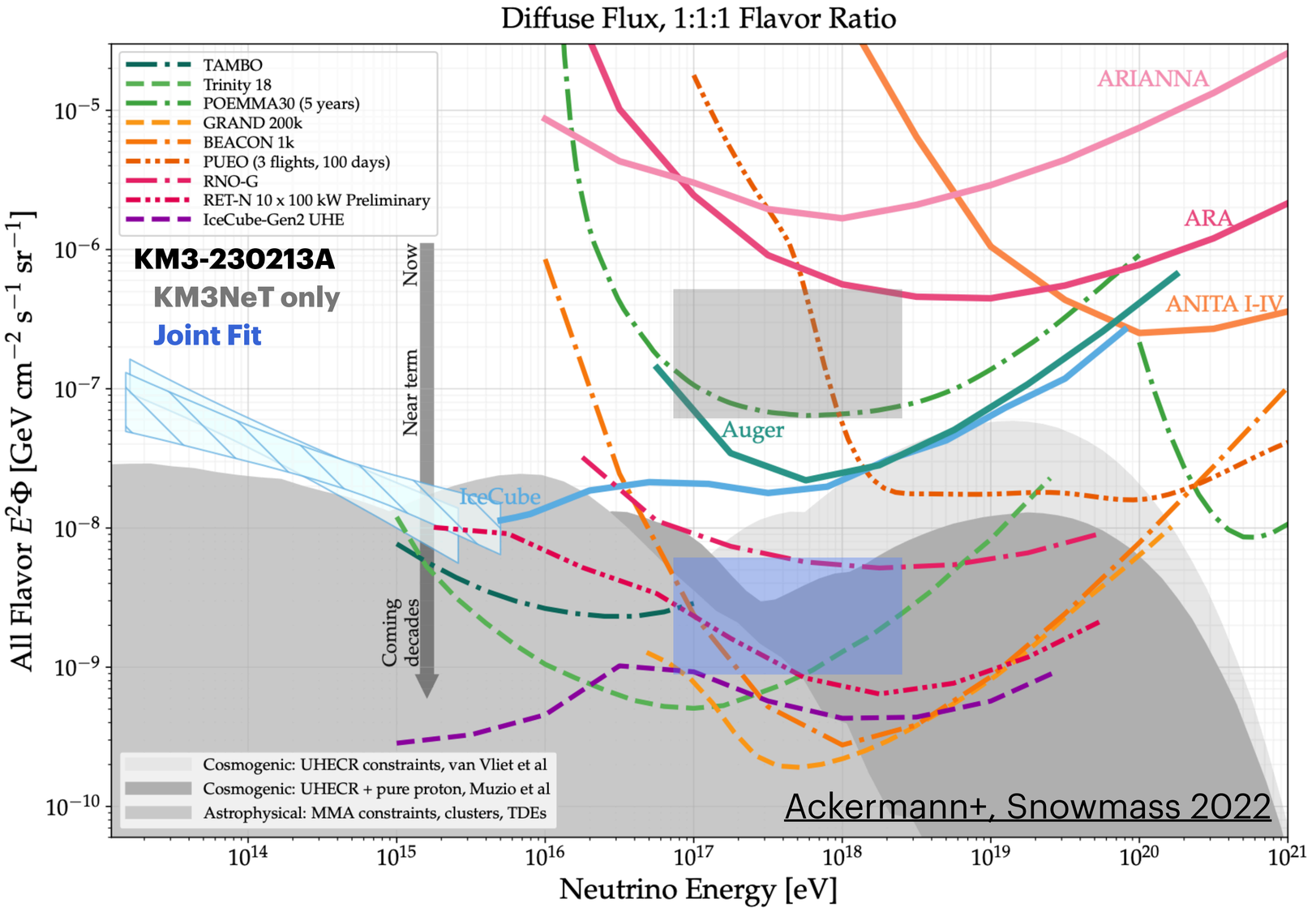
It's an exciting time for neutrino astrophysics!



Thank you!

Backups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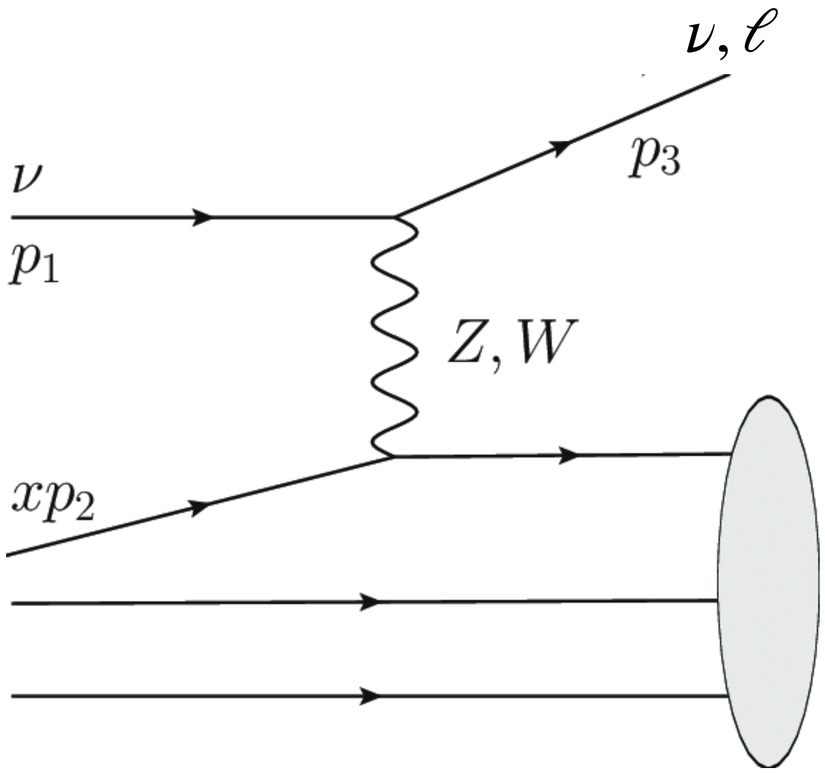
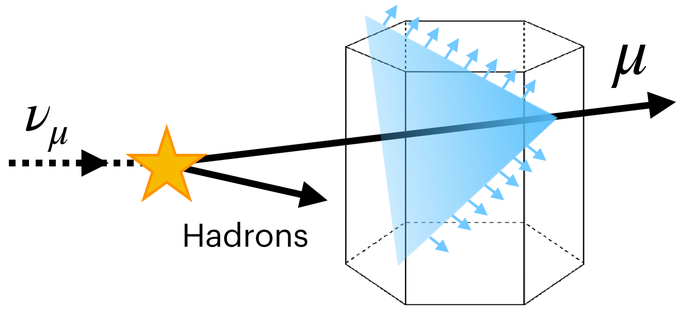
ICE CHERENKOV
1km³
ICECUBE GEN2
ICE CHERENKOV
8km³

IceCube “sees” neutrinos via Cherenkov radiation

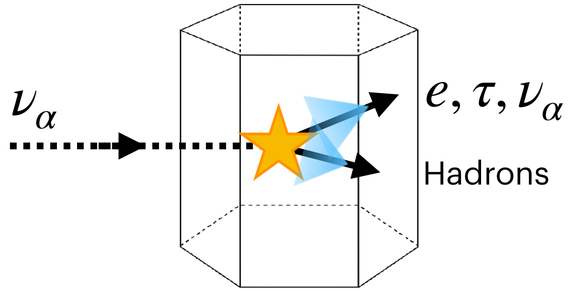
Neutrino deep inelastic scattering

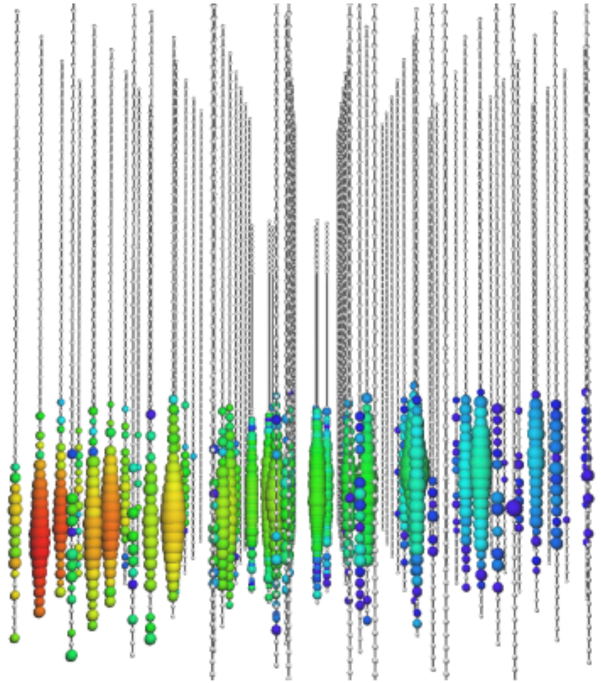


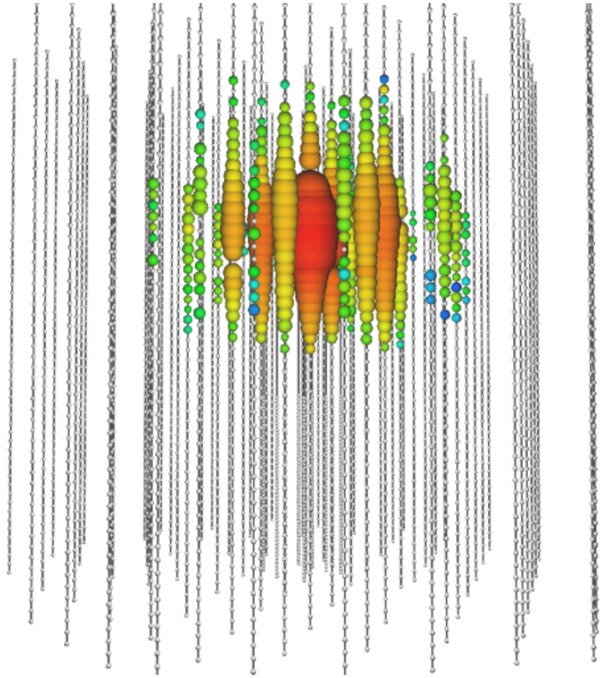
Track



Cascade



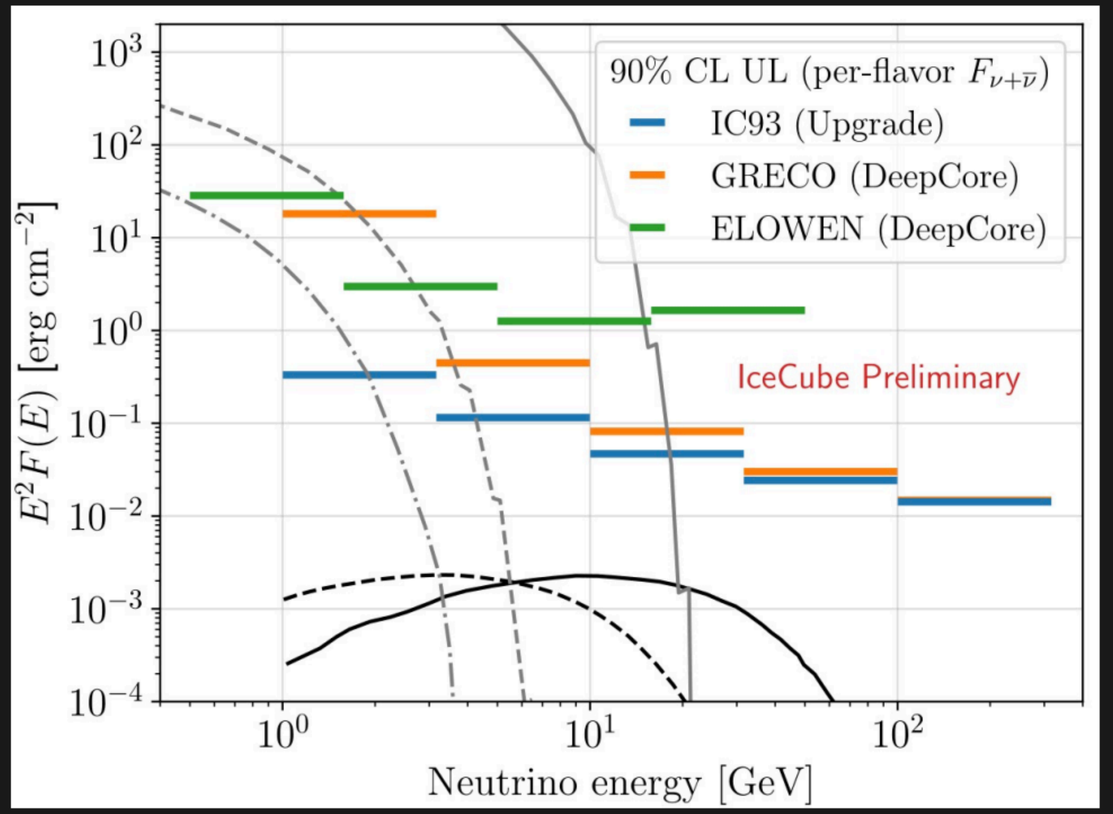




Earliest photons **Latest photons**

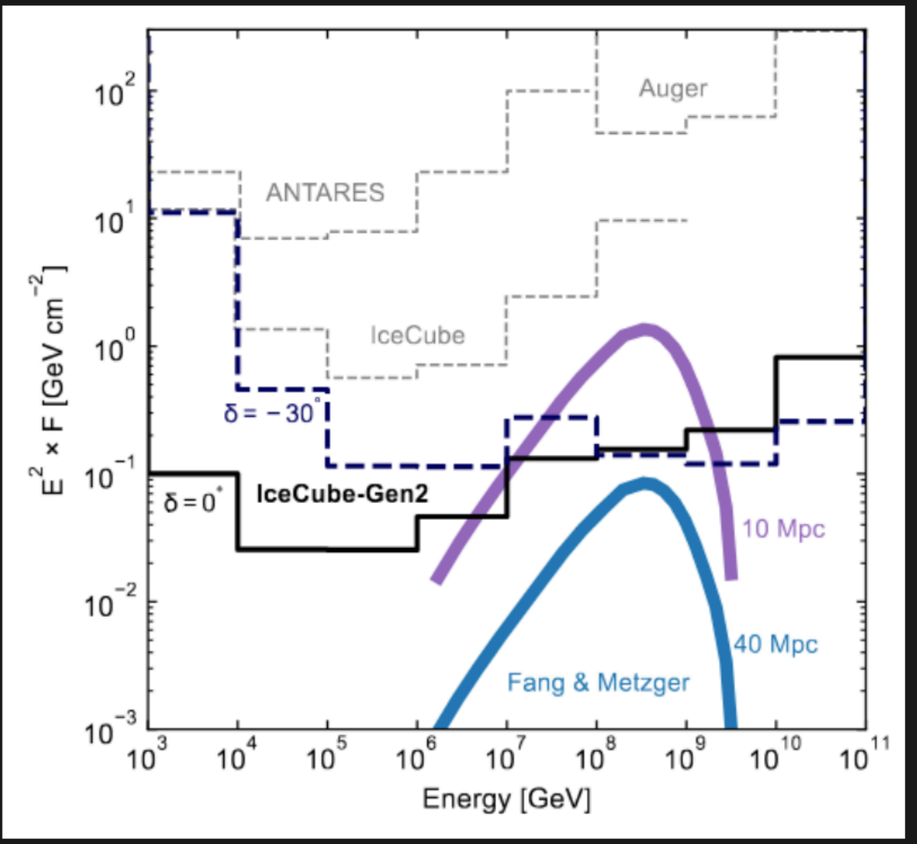
Looking into the future: astrophysical sensitivities

PoS(ICRC2025)1076



Upgrade vs DeepCore differential sensitivities (TW=1000s, decl. = 20°). Emission models for llGRBs (black) and magnetizedprotoneutron stars (grey) are shown.

Gen2 TDR



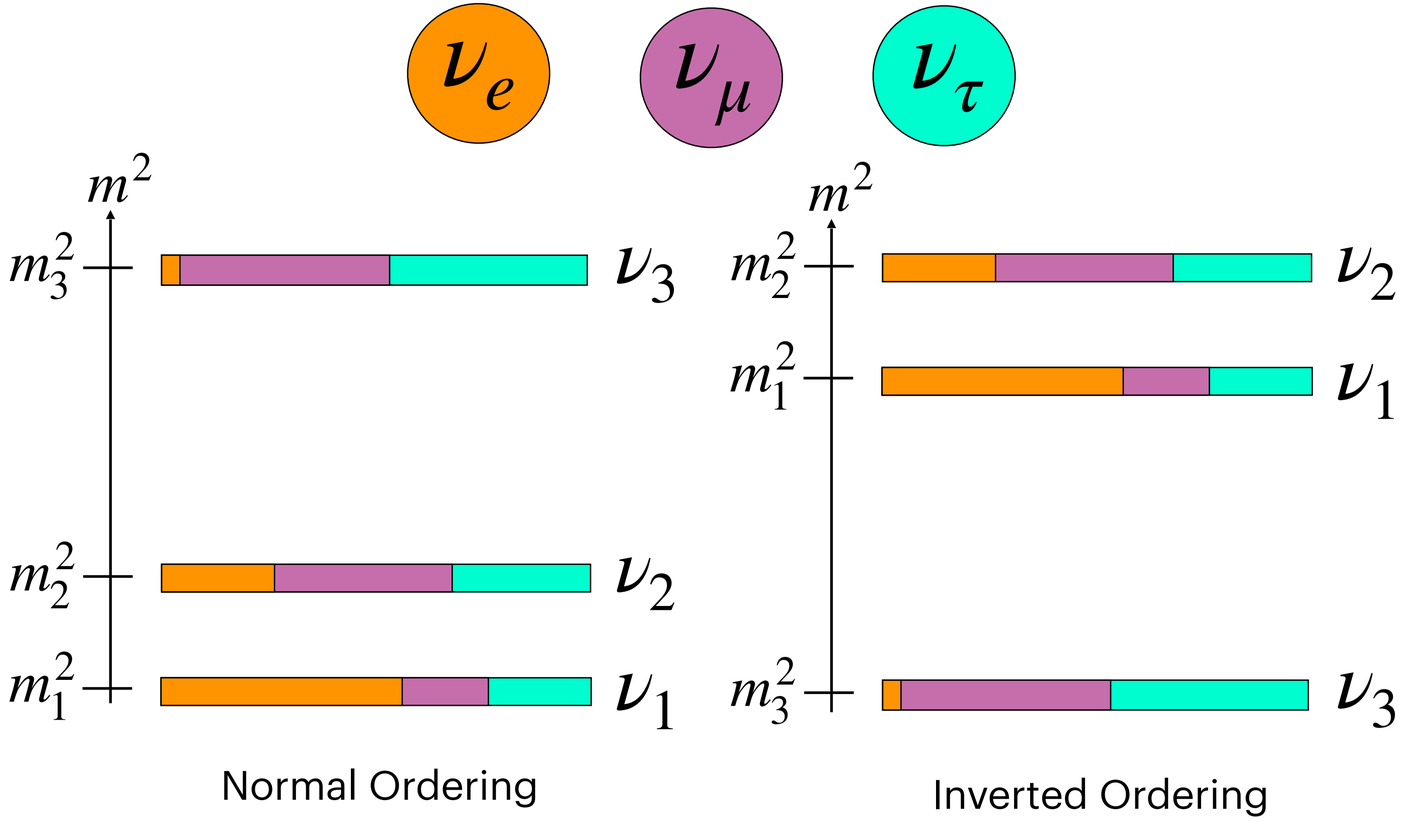
Gen2 sensitivities (TW=14 days, decl. = 0° & -30°). Emission model for an event like GW170817 is shown.

Neutrino Oscillations Overview

- Neutrinos exhibit quantum mechanical oscillations between flavor as they propagate
- Neutrino telescopes can address two open questions:
  tau unitarity and the **mass ordering**

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) \approx 4\,|\,U_{\alpha i}\,|^2\,|\,U_{\beta i}\,|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



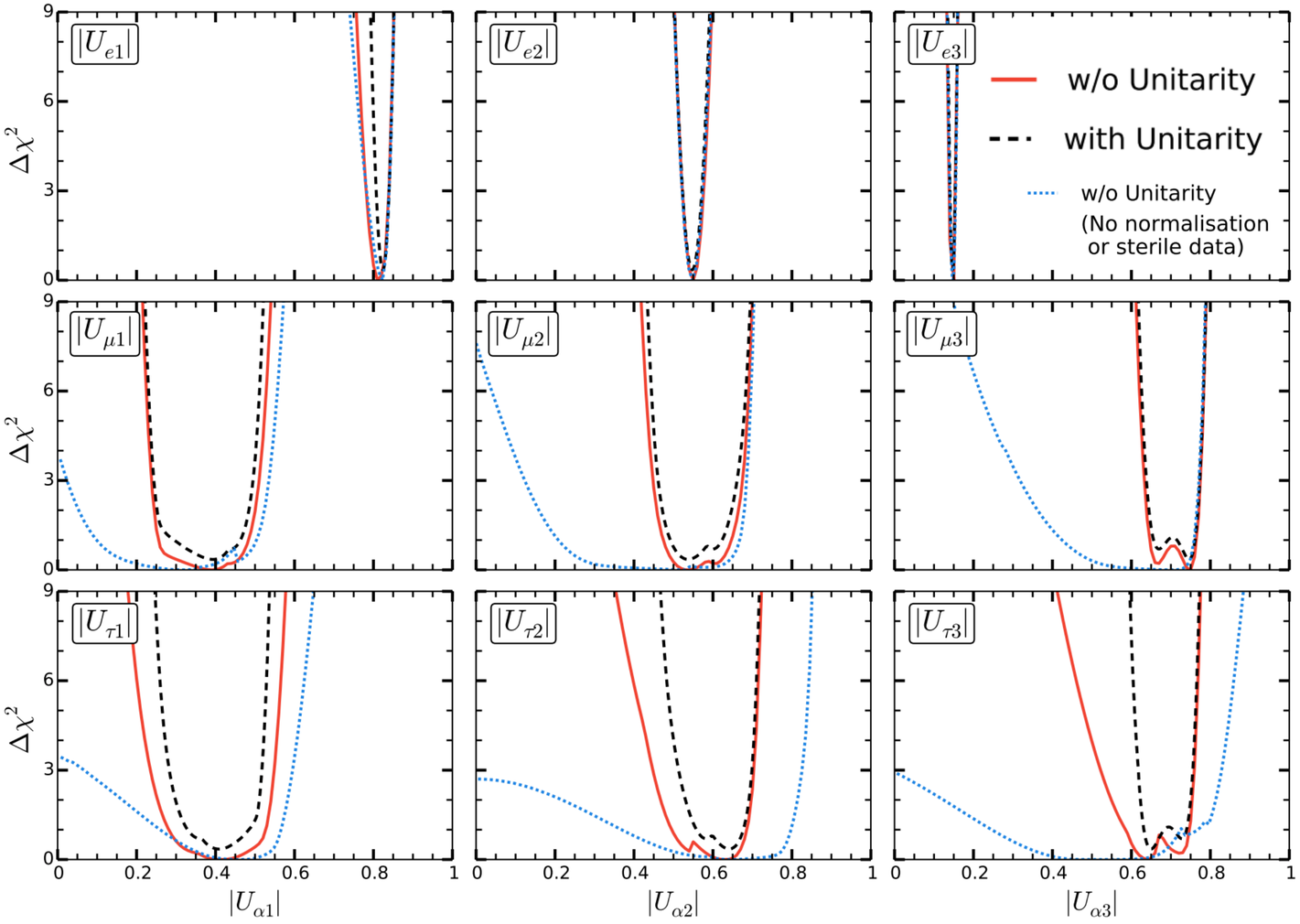
Open Question 1: Tau Unitarity

Tau row of PMNS matrix constrained mostly by unitarity assumption:

$$|U_{ei}|^2 + |U_{\mu i}|^2 + |U_{\tau i}|^2 = 1$$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

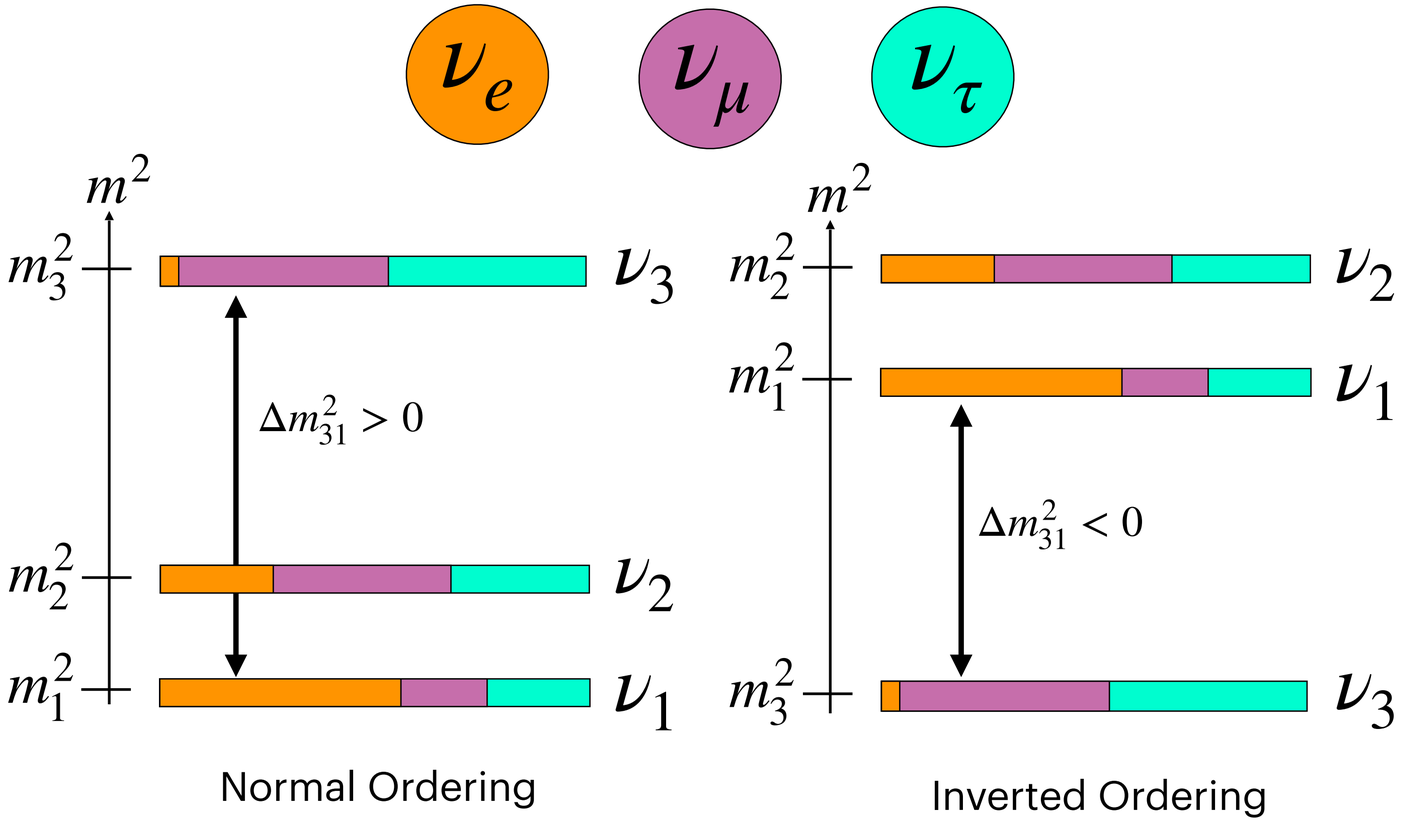
Neutrino telescopes can test that assumption



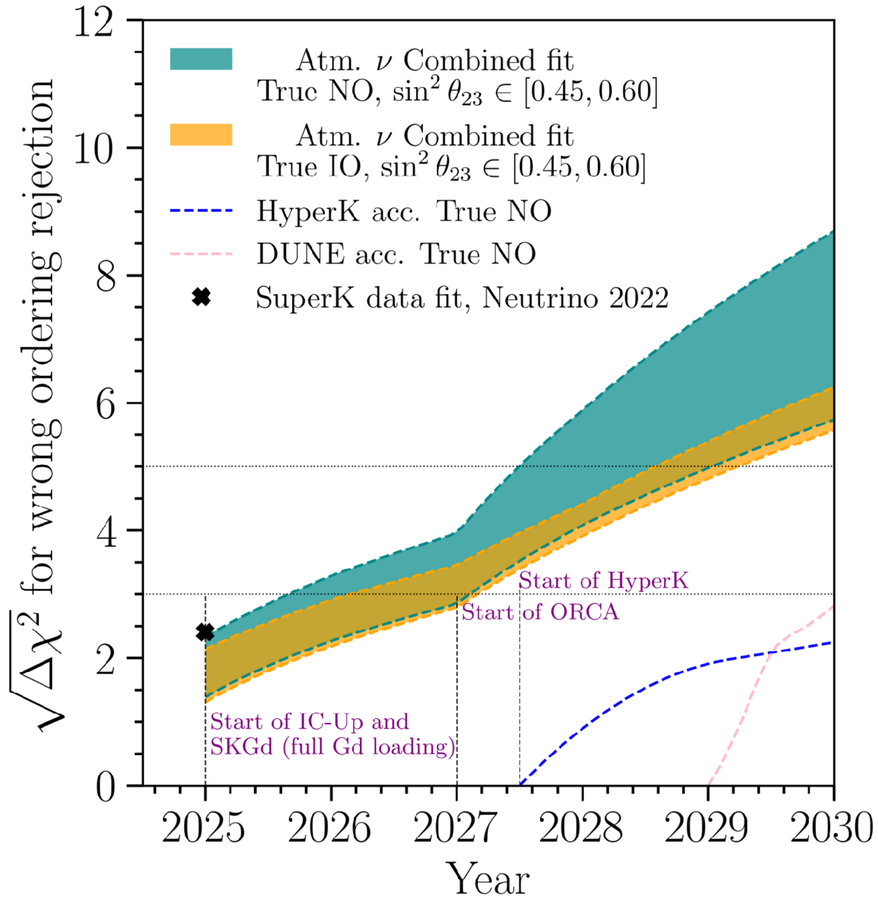
Parke, Ross-Lonergan PRD 2015

Open Question 2: Mass Ordering

We don't know the sign of Δm^2_{31}

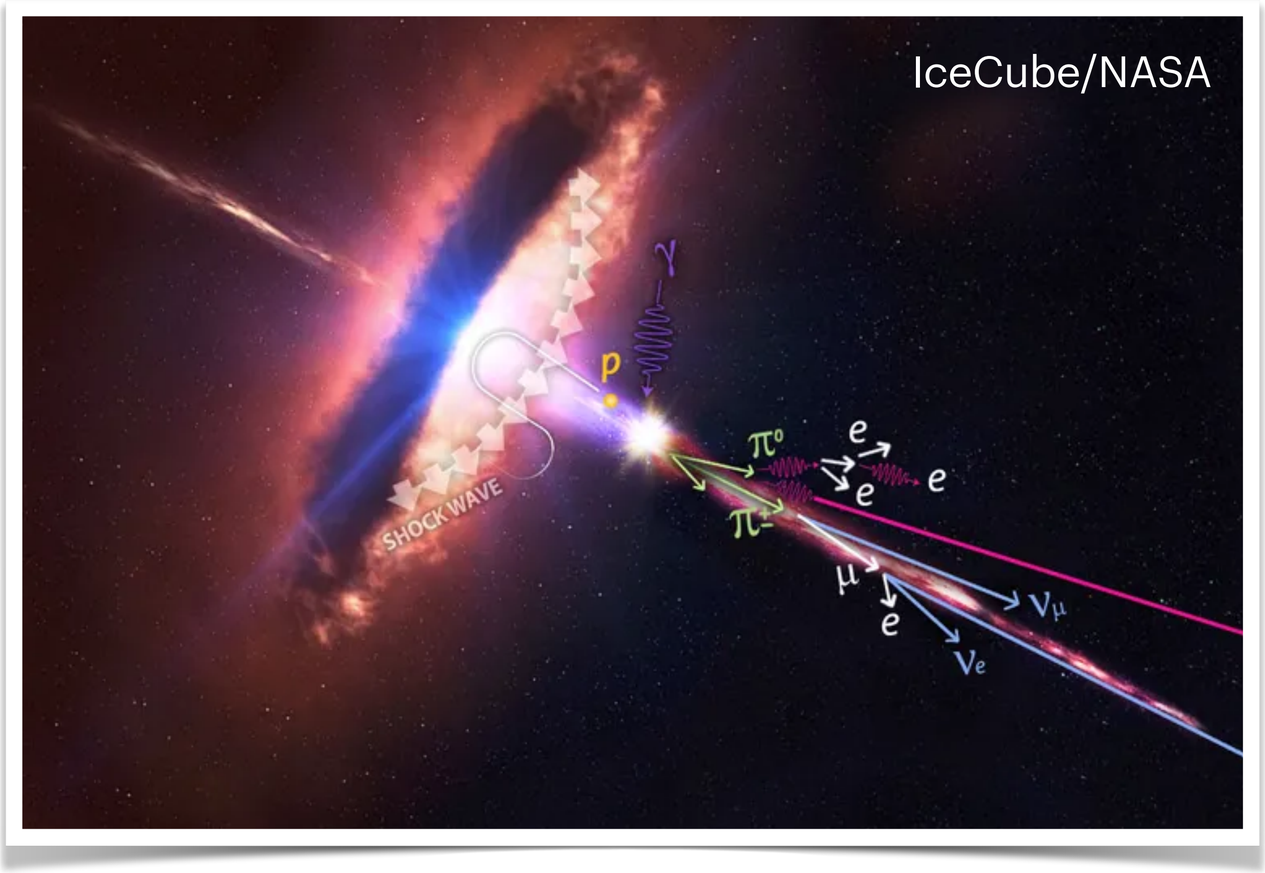


Argüelles, Fernández, Martínez-Soler, Jin PRX 2023



Neutrino telescopes can reach 5σ by the end of the decade

But they are also excellent **particle physics** experiments



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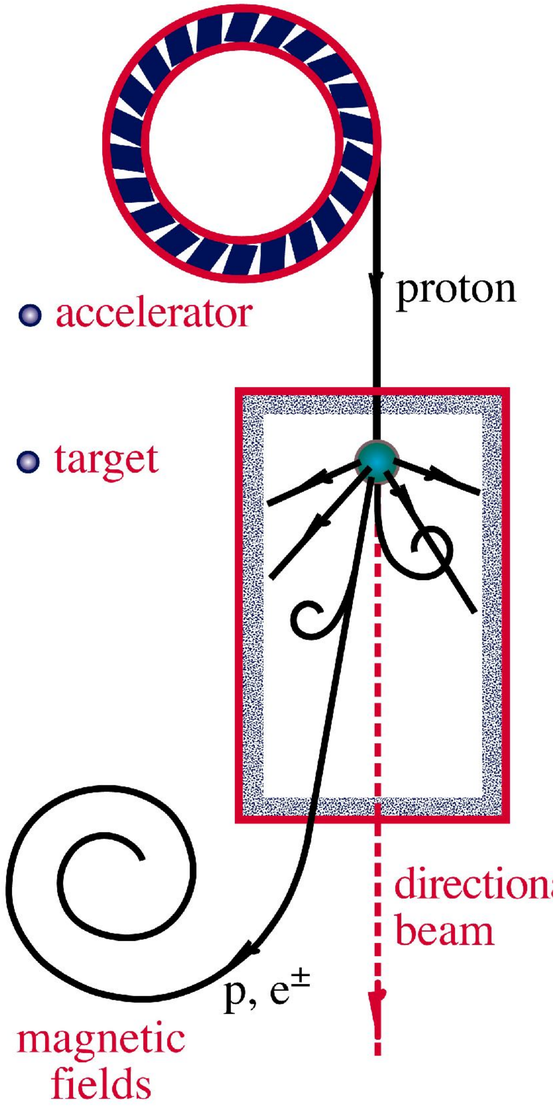
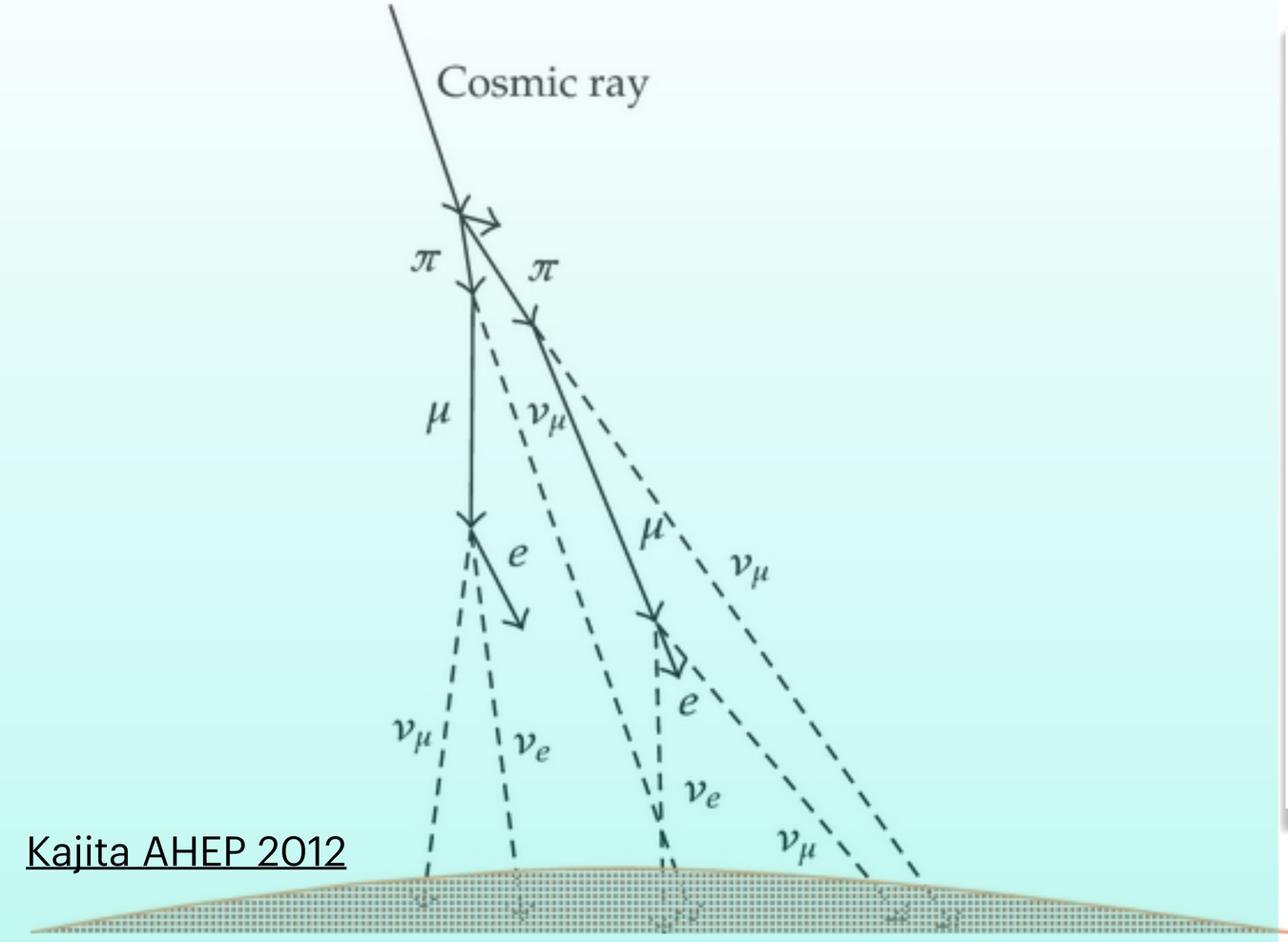


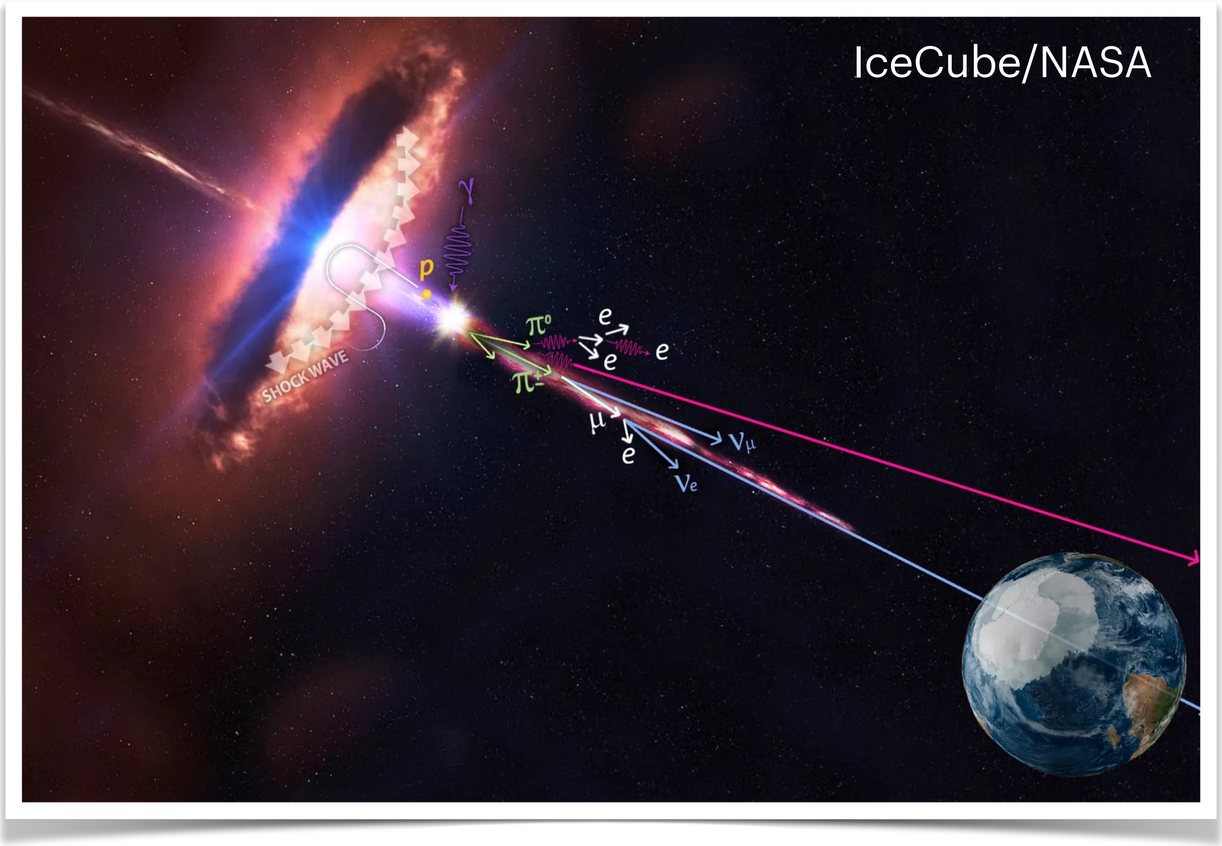
In fact, neutrino telescopes see two beam dumps

Atmospheric neutrinos (~100,000/yr)

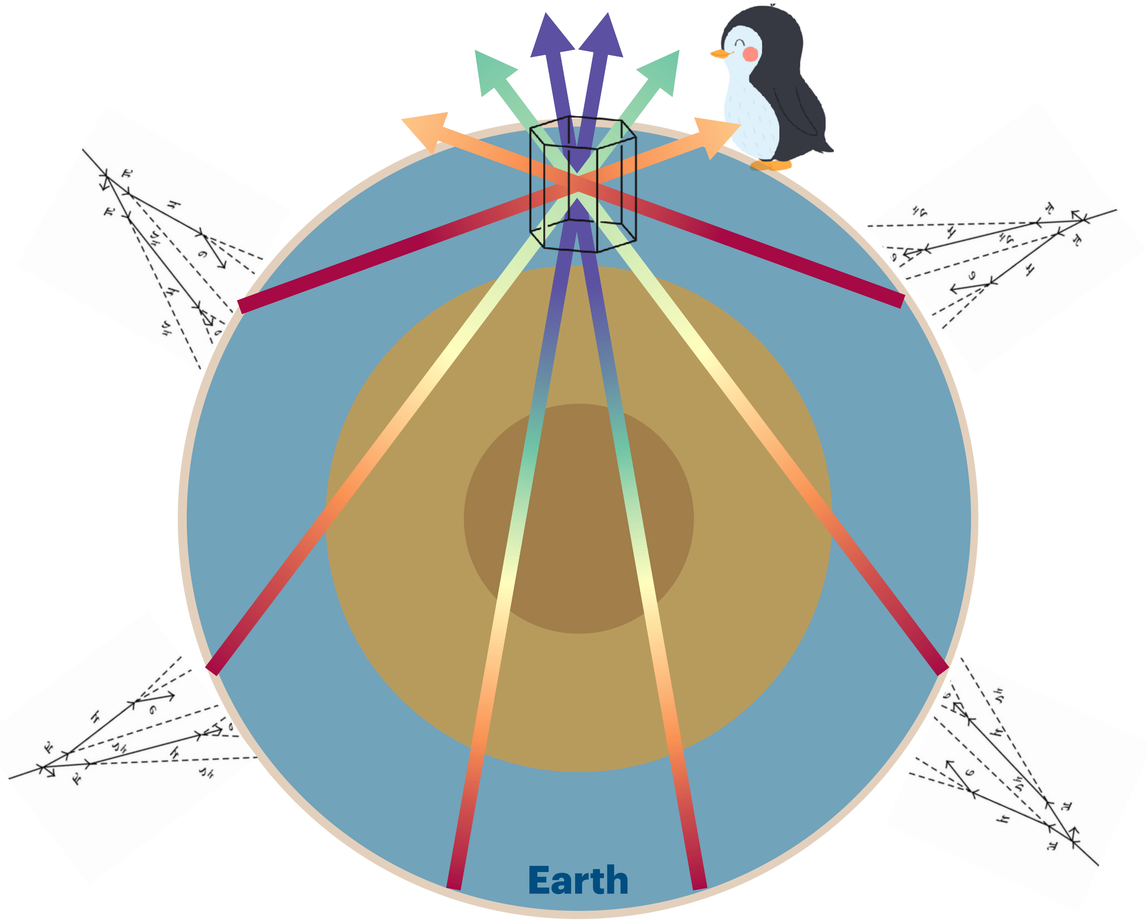


Kajita AHEP 2012

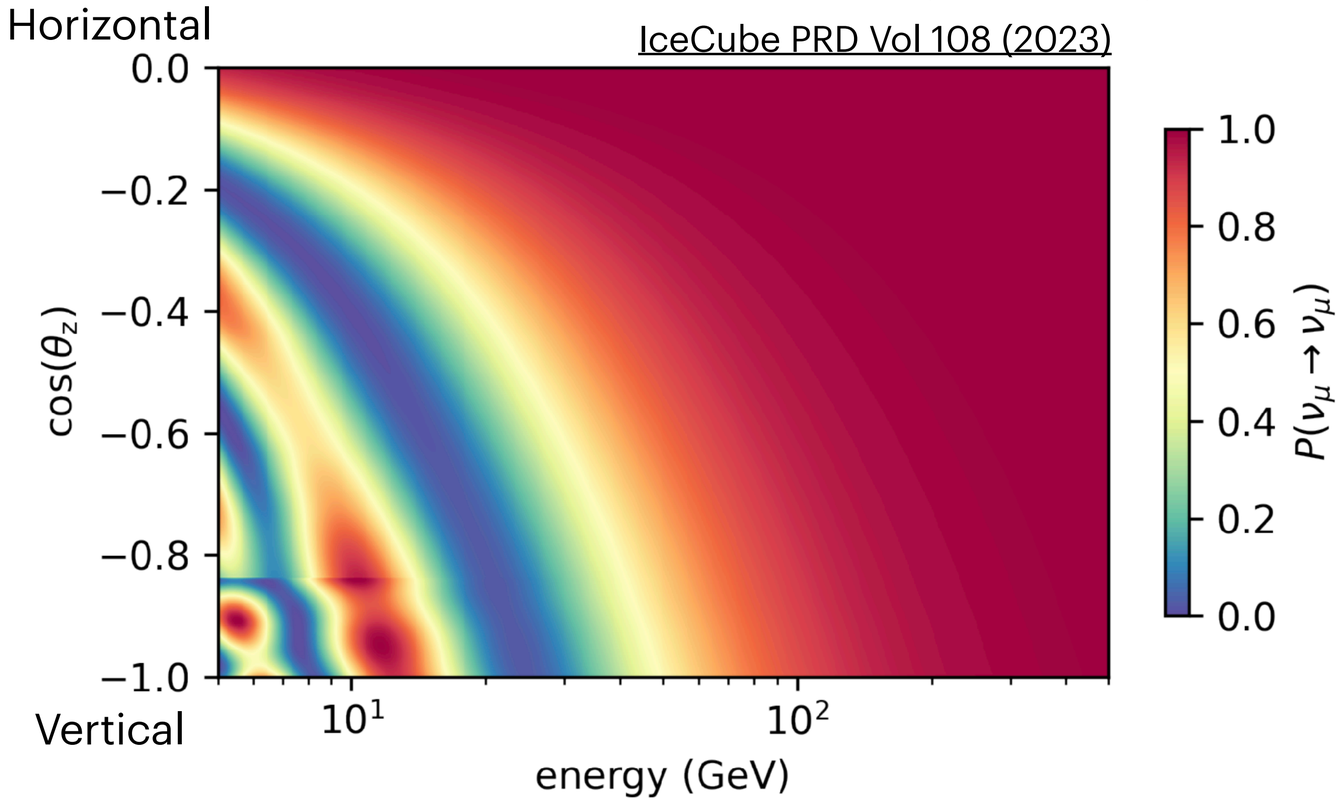
Cosmic neutrinos (~100/yr)



Neutrino telescopes measure $\nu_\mu \rightarrow \nu_\tau$ atmospheric neutrino oscillations



$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



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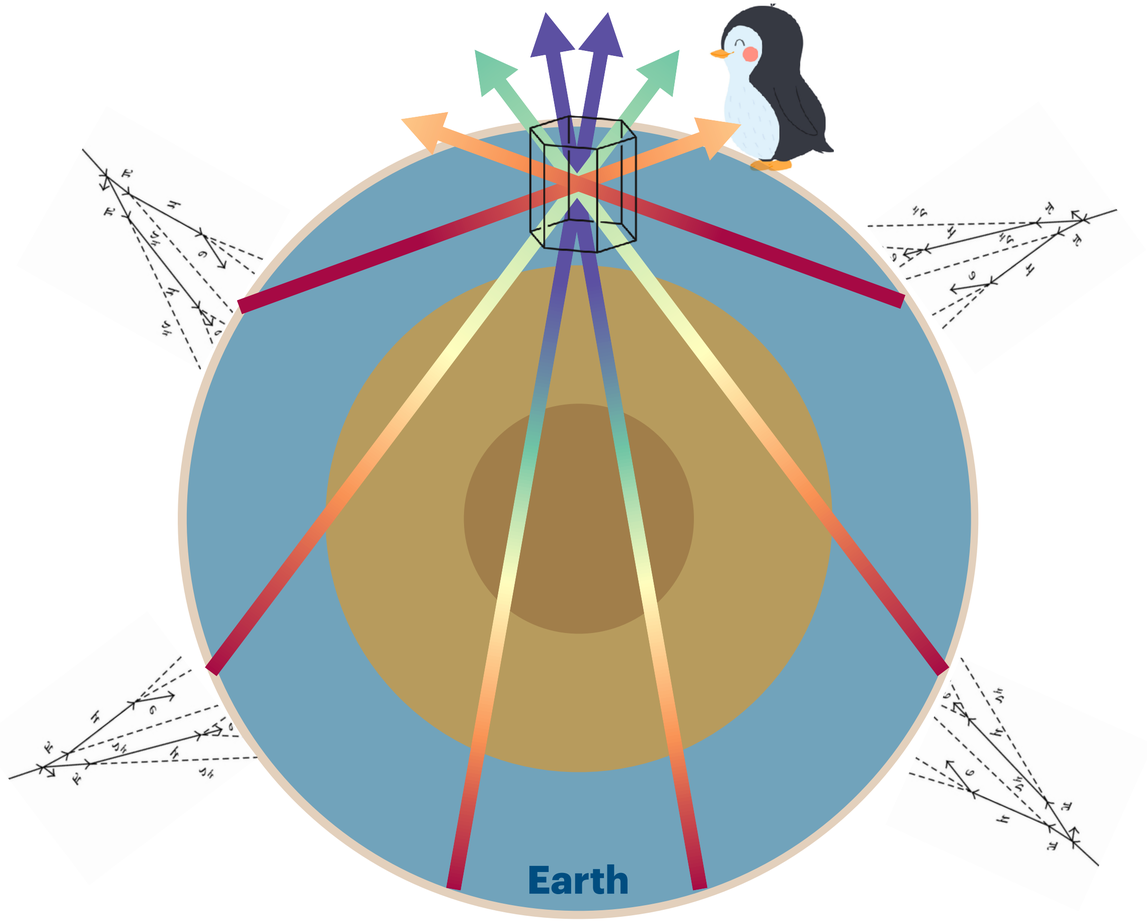

Range of baselines constrains un-oscillated flux

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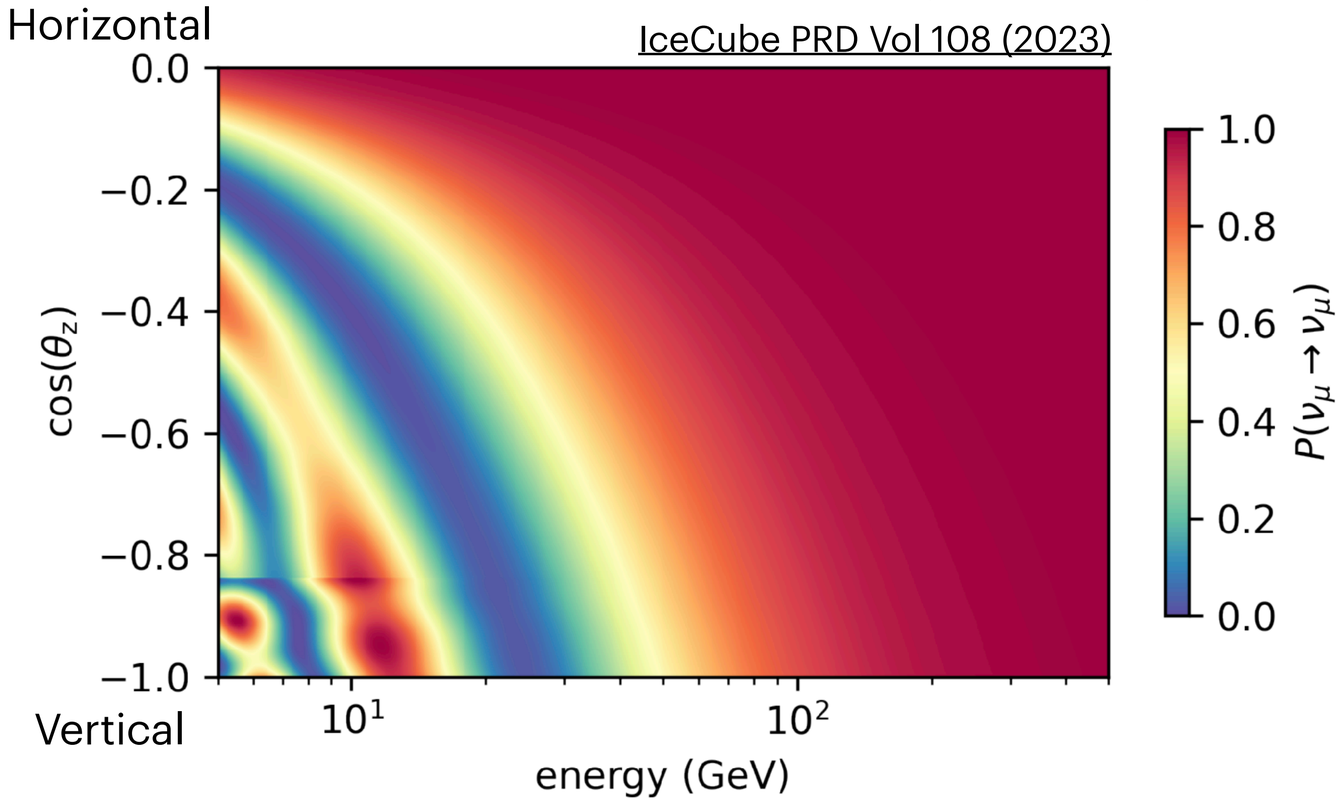

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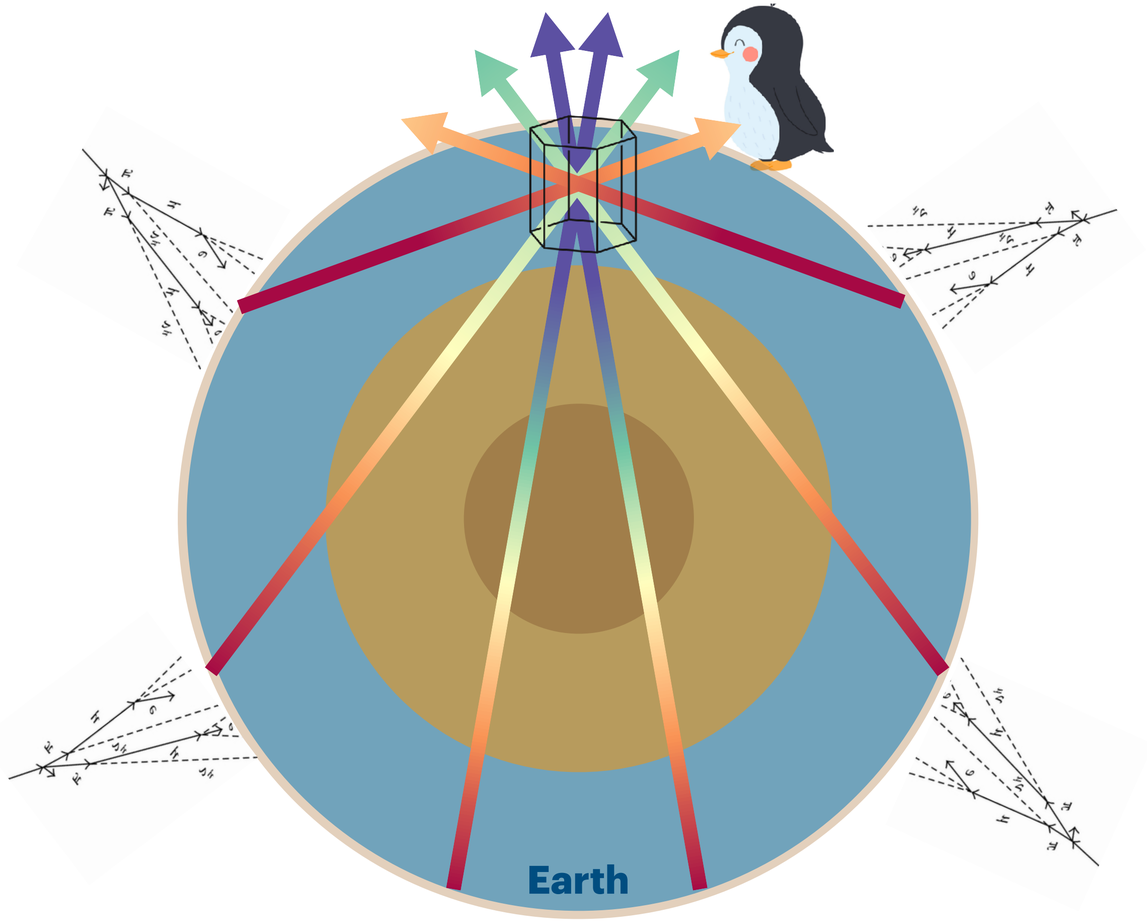

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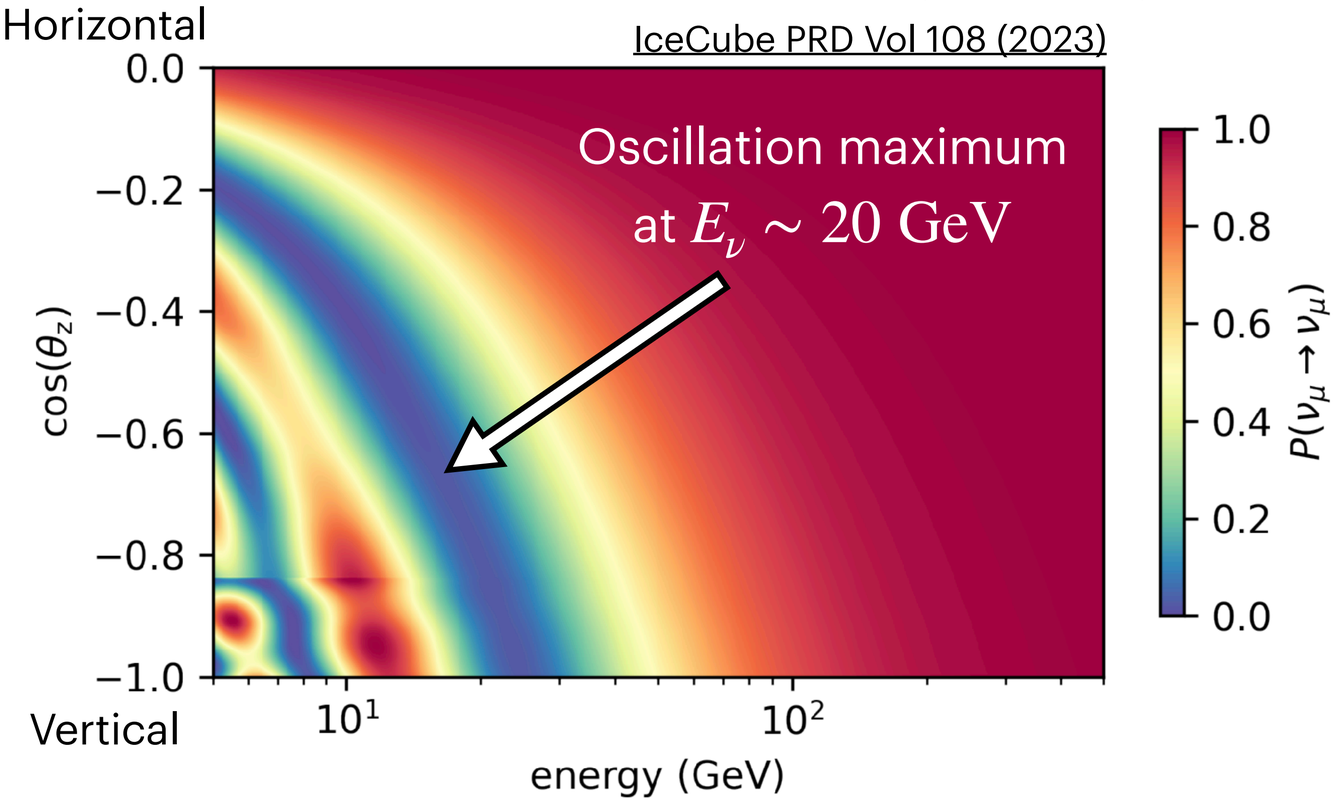
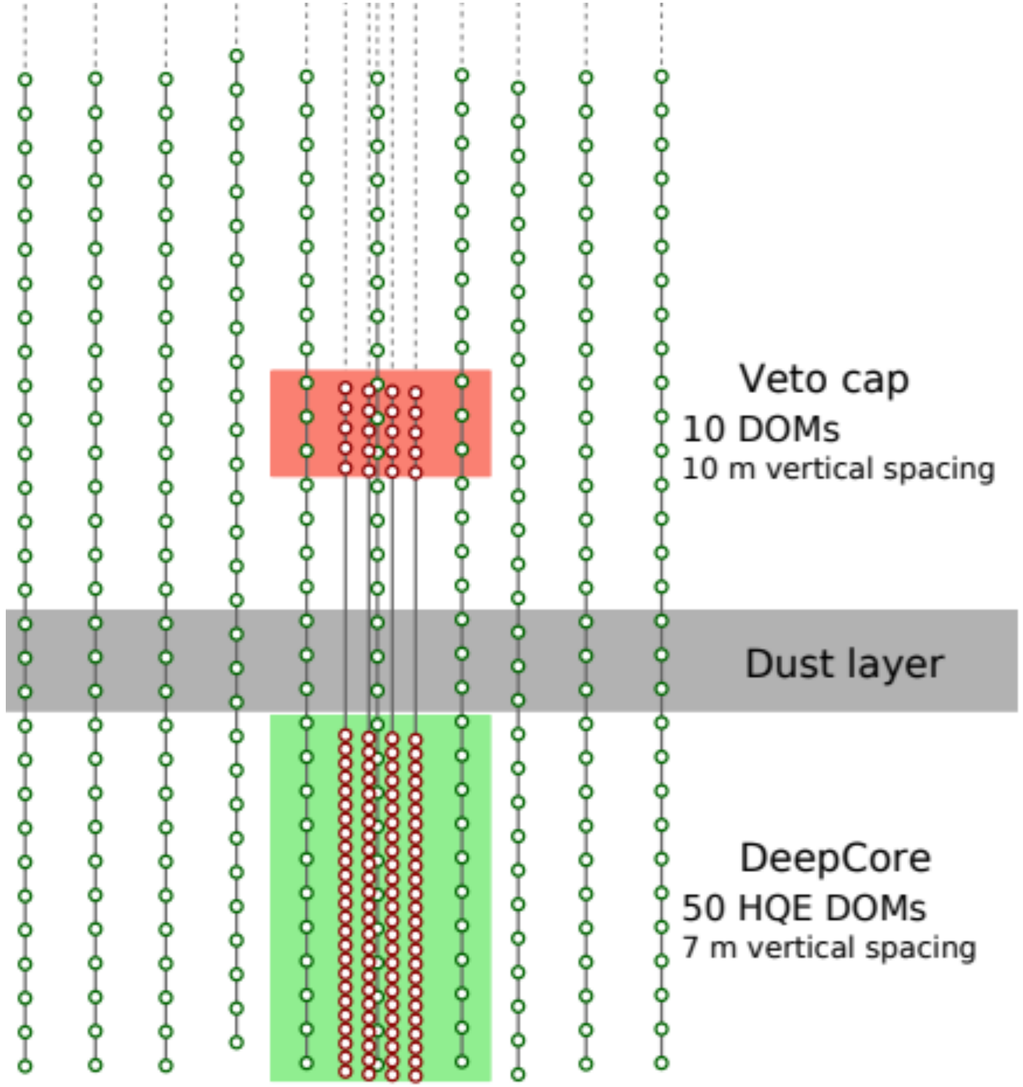
IceCube PRD Vol 108 (2023)

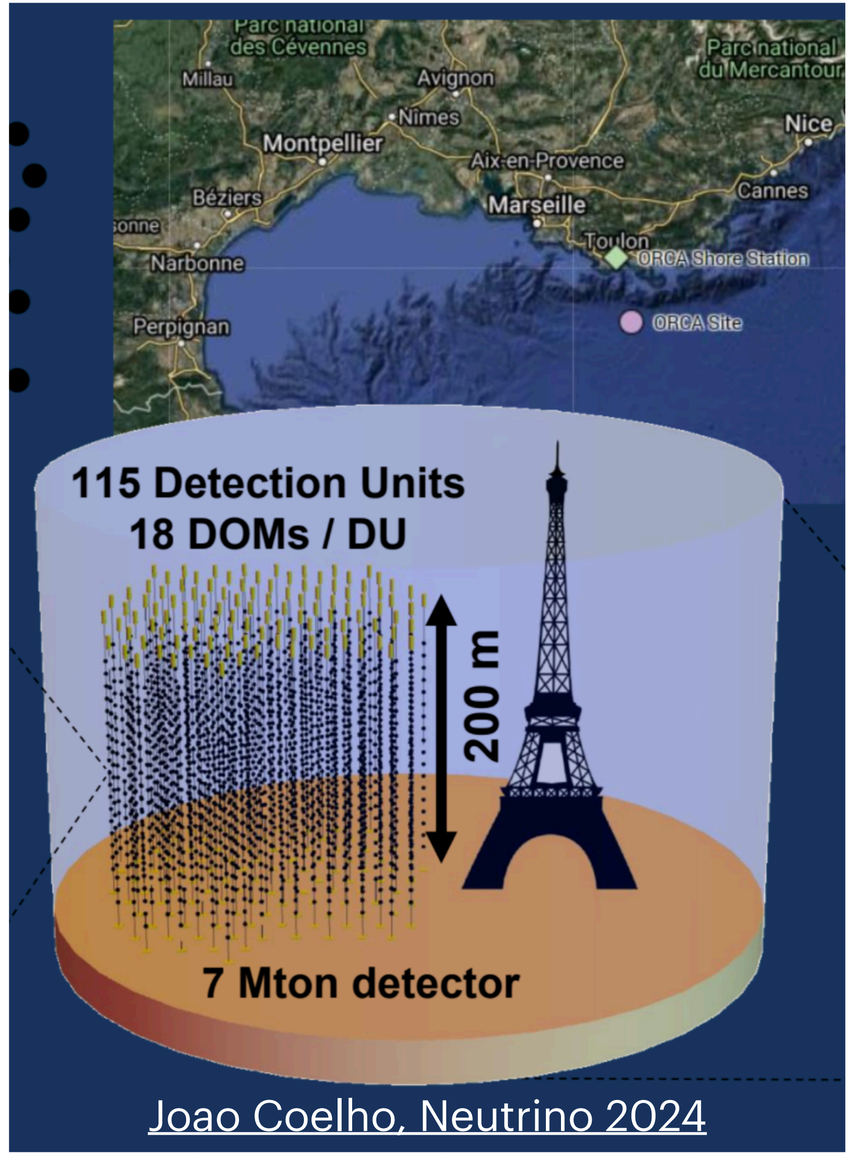


Oscillation measurements require dedicated denser arrays



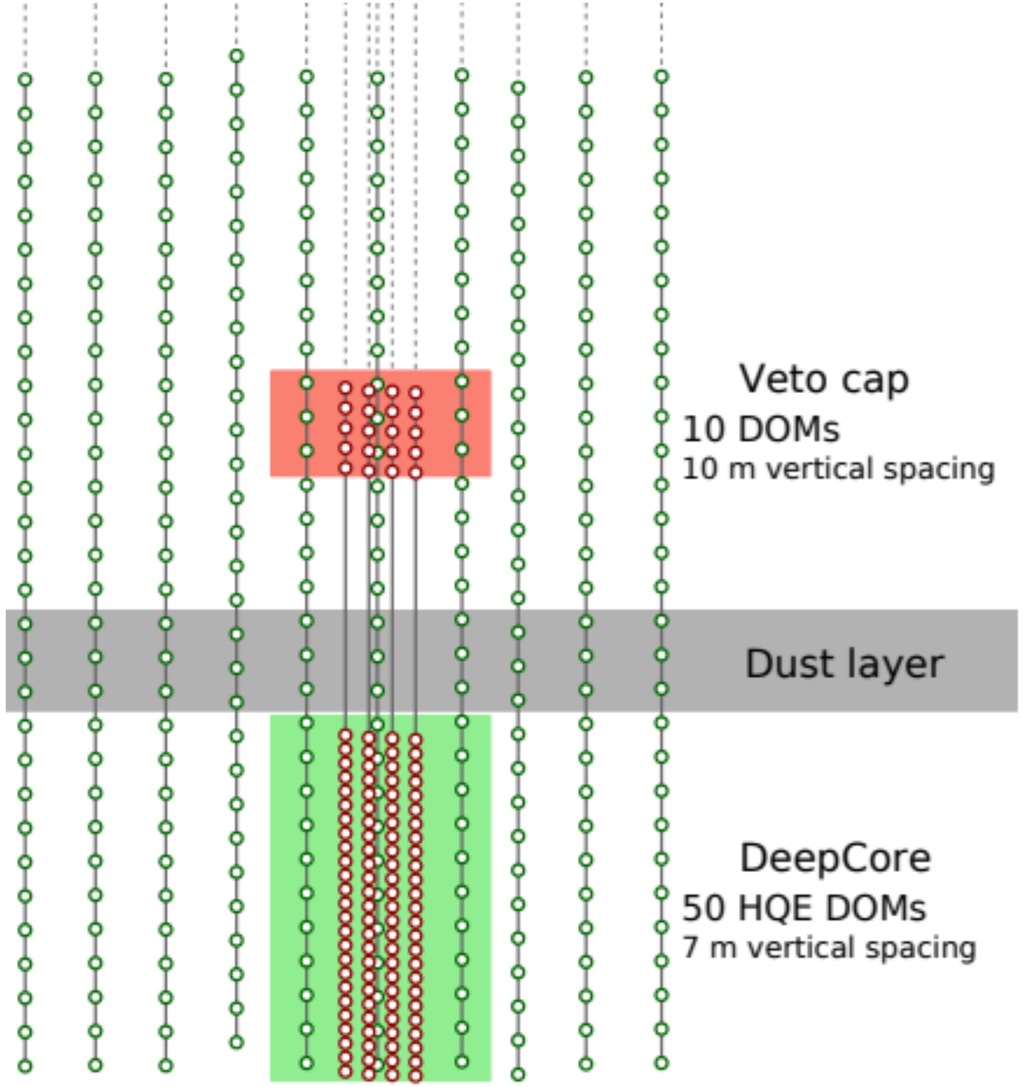
IceCube Astroparticle Physics Vol 35 (2011)

IceCube DeepCore



KM3NeT/ORCA

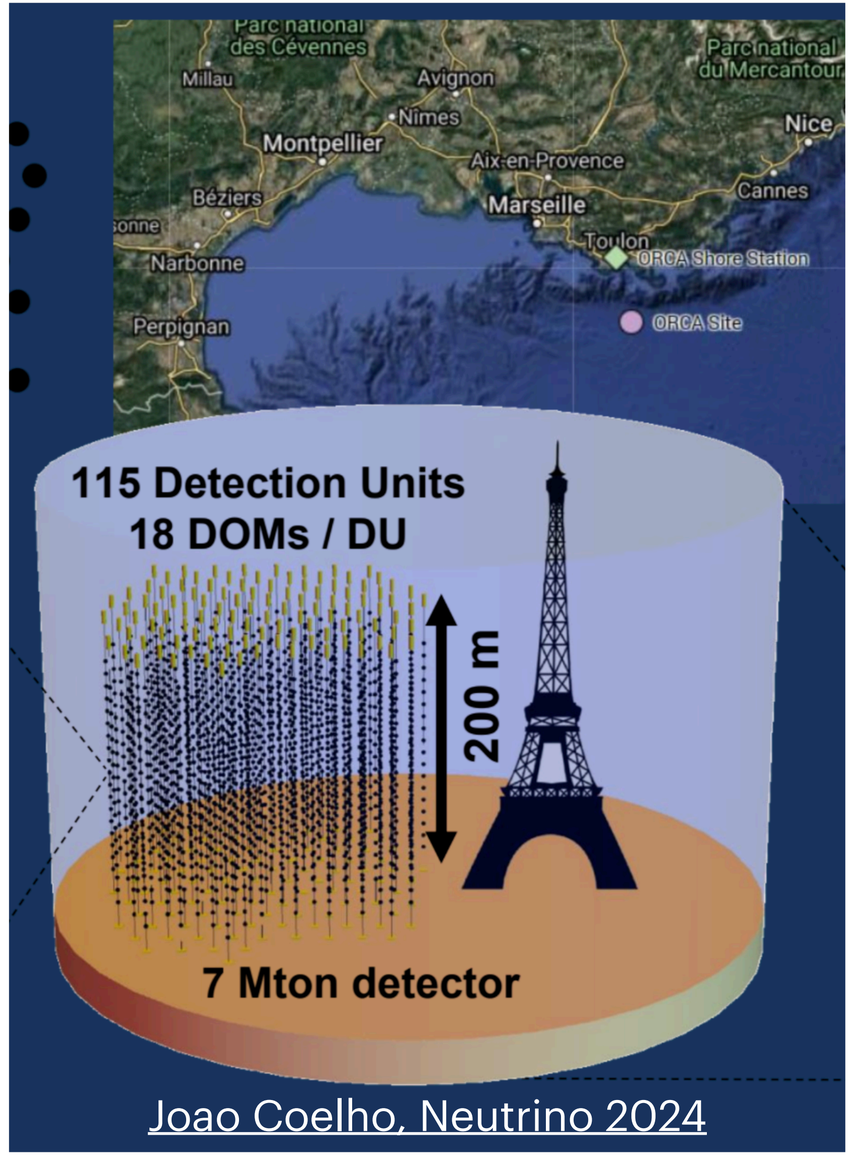
Oscillation measurements require dedicated denser arrays



IceCube Astroparticle Physics Vol 35 (2011)

IceCube DeepCore

Still ~100x larger than SuperK!



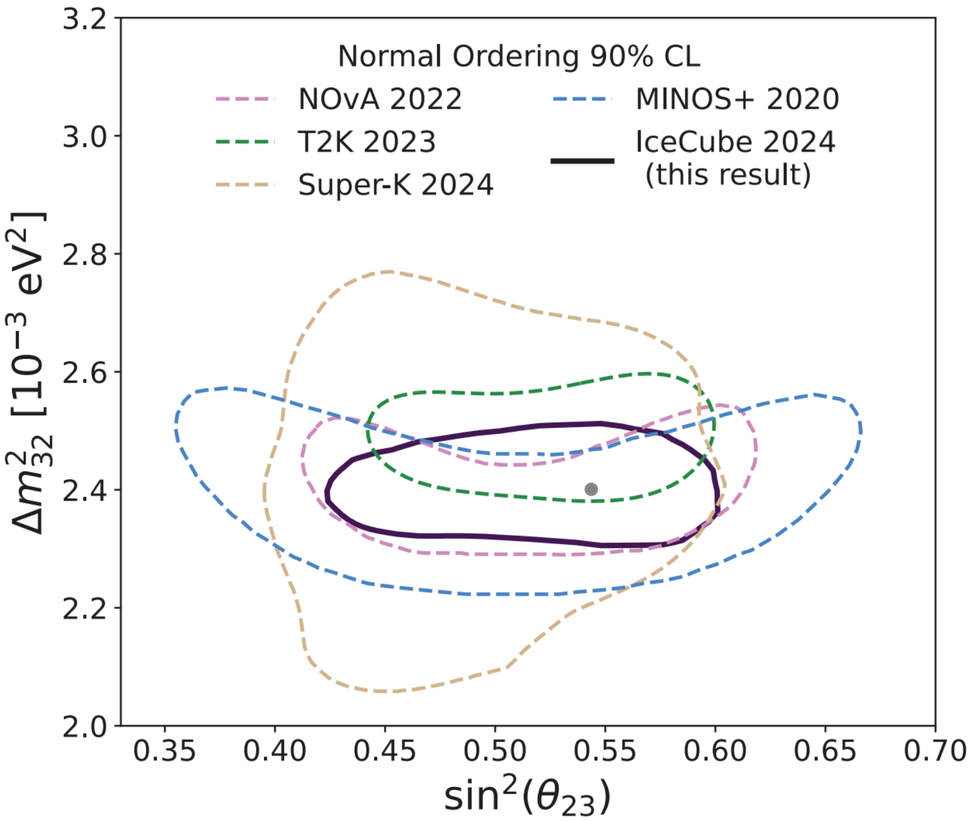
Joao Coelho, Neutrino 2024

KM3NeT/ORCA

IceCube Oscillation Results

IceCube Oscillation Results

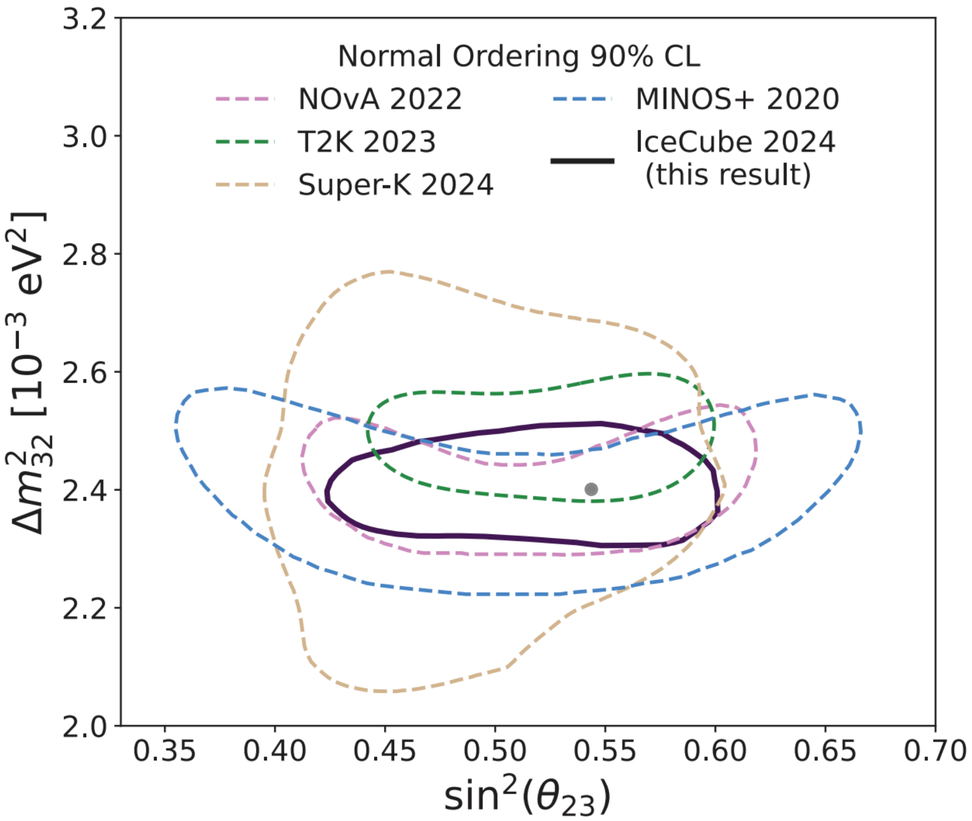
Competitive with accelerator experiments,
but at higher energies



IceCube PRL Vol 134 (2025)

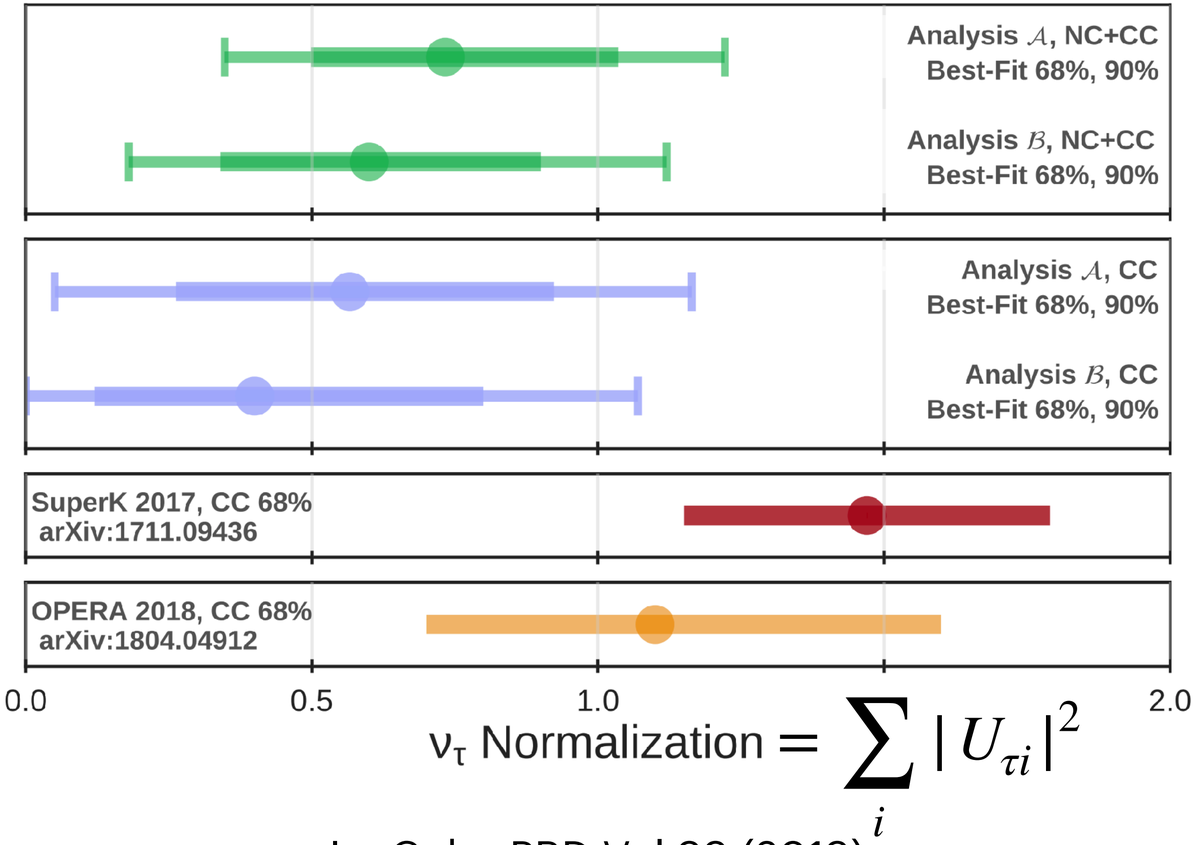
IceCube Oscillation Results

Competitive with accelerator experiments,
but at higher energies



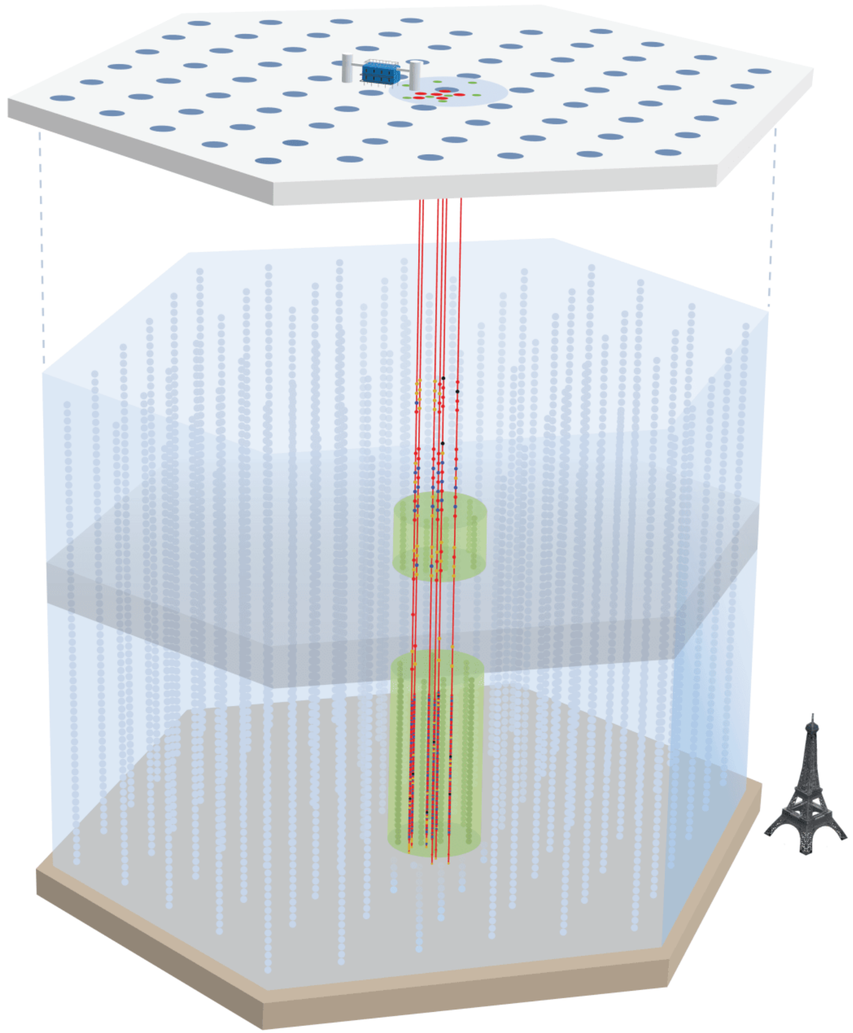
IceCube PRL Vol 134 (2025)

Higher energies also enable tests of **tau unitarity**

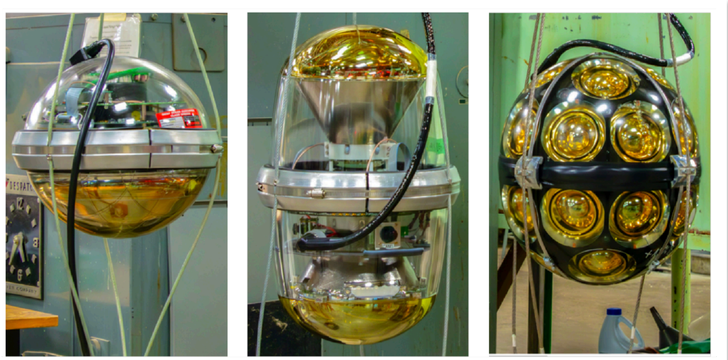


IceCube PRD Vol 99 (2019)

Up Next: The IceCube Upgrade



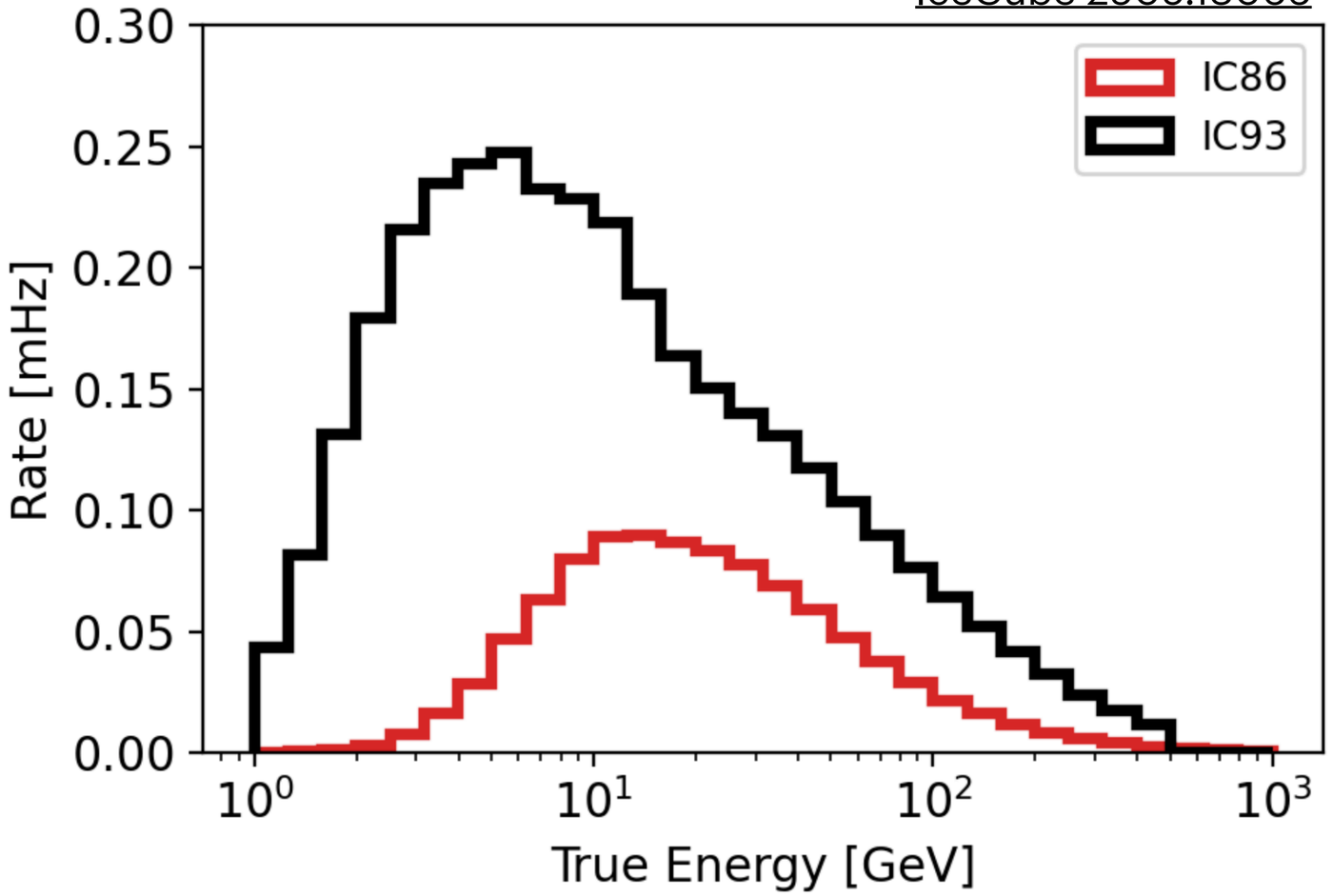
Six new strings deployed over Dec-Jan!



Colton Hill, Yuya Makino, IceCube/NSF

The Upgrade pushes the neutrino energy threshold down to ~1 GeV

IceCube 2509.13066

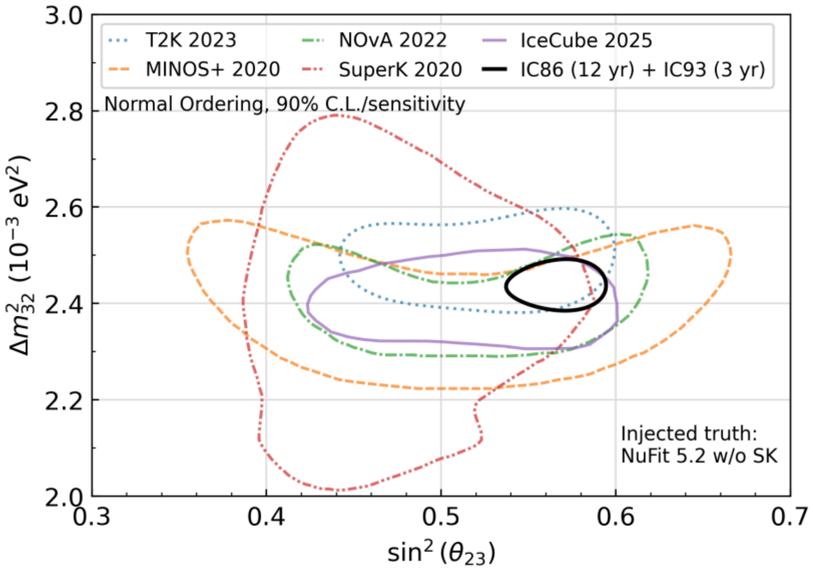


Upgrade Oscillation Sensitivities

IceCube 2509.13066

Upgrade Oscillation Sensitivities

Strong sensitivity to θ_{23}, Δm^2_{32}



IceCube 2509.13066

Upgrade Oscillation Sensitivities

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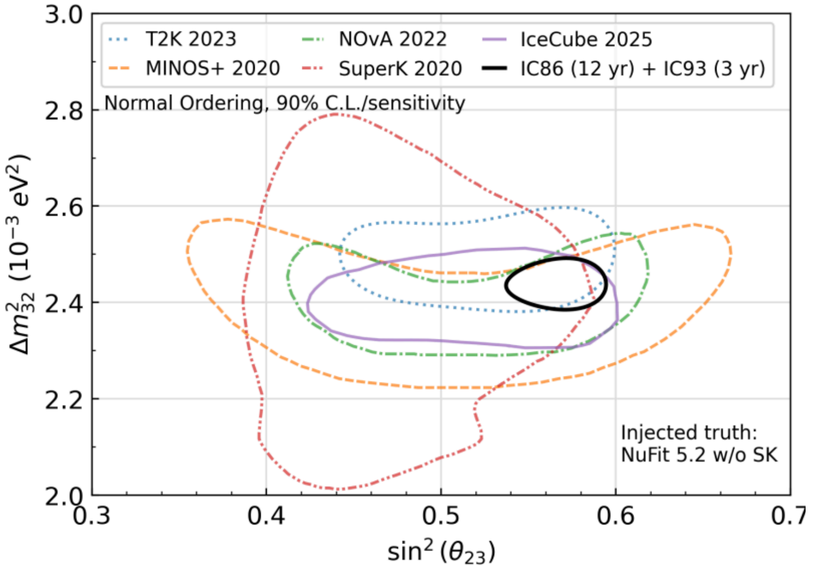
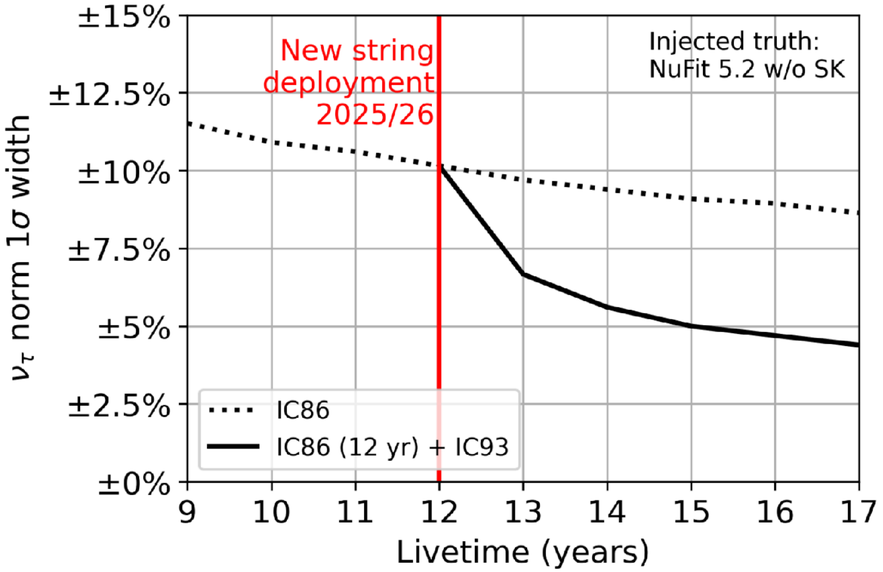


~5% tau normalization sensitivity



IceCube 2509.13066

Upgrade Oscillation Sensitivities

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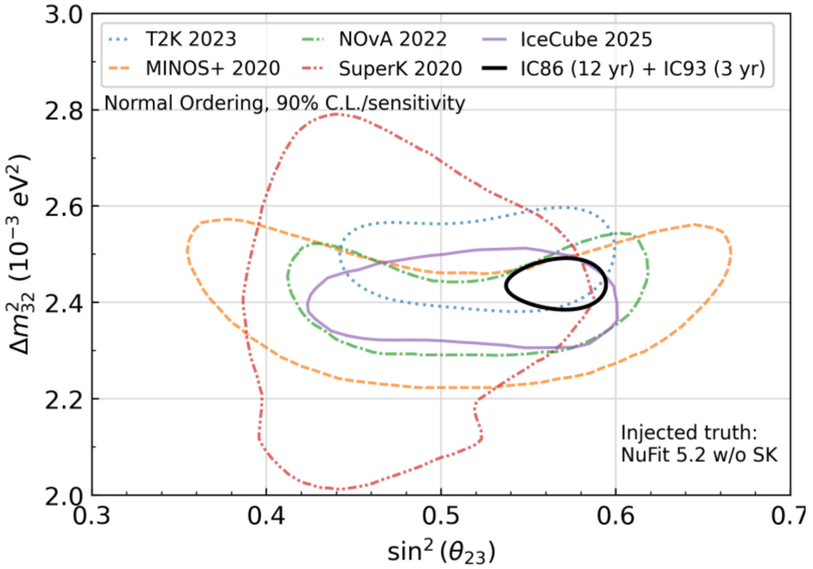

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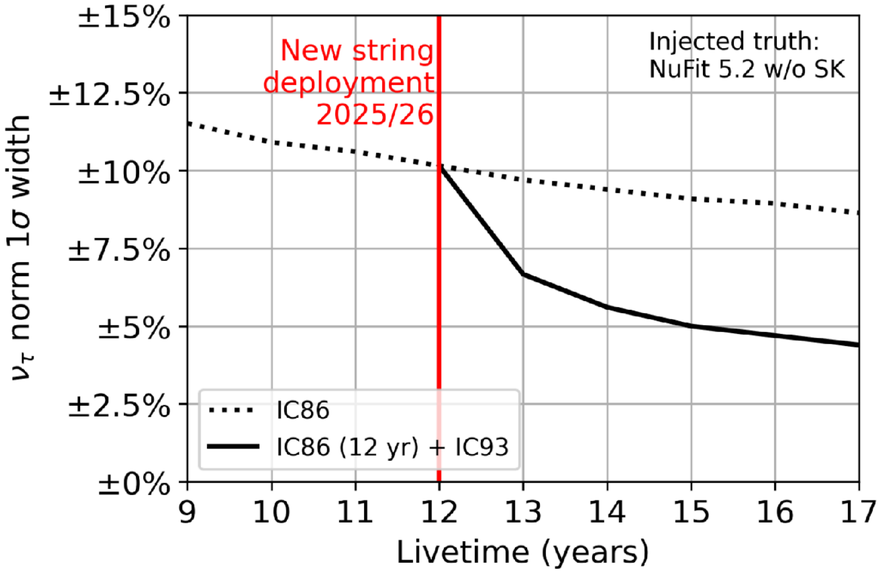
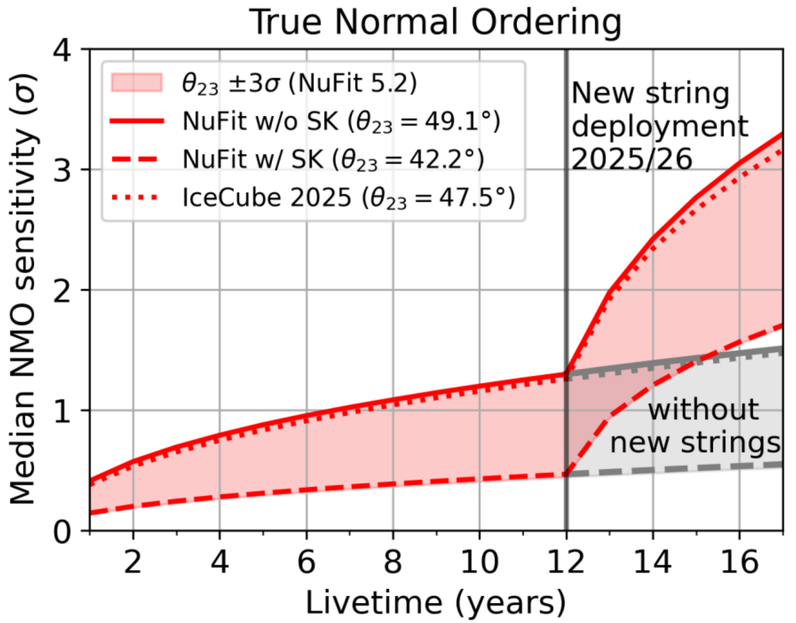
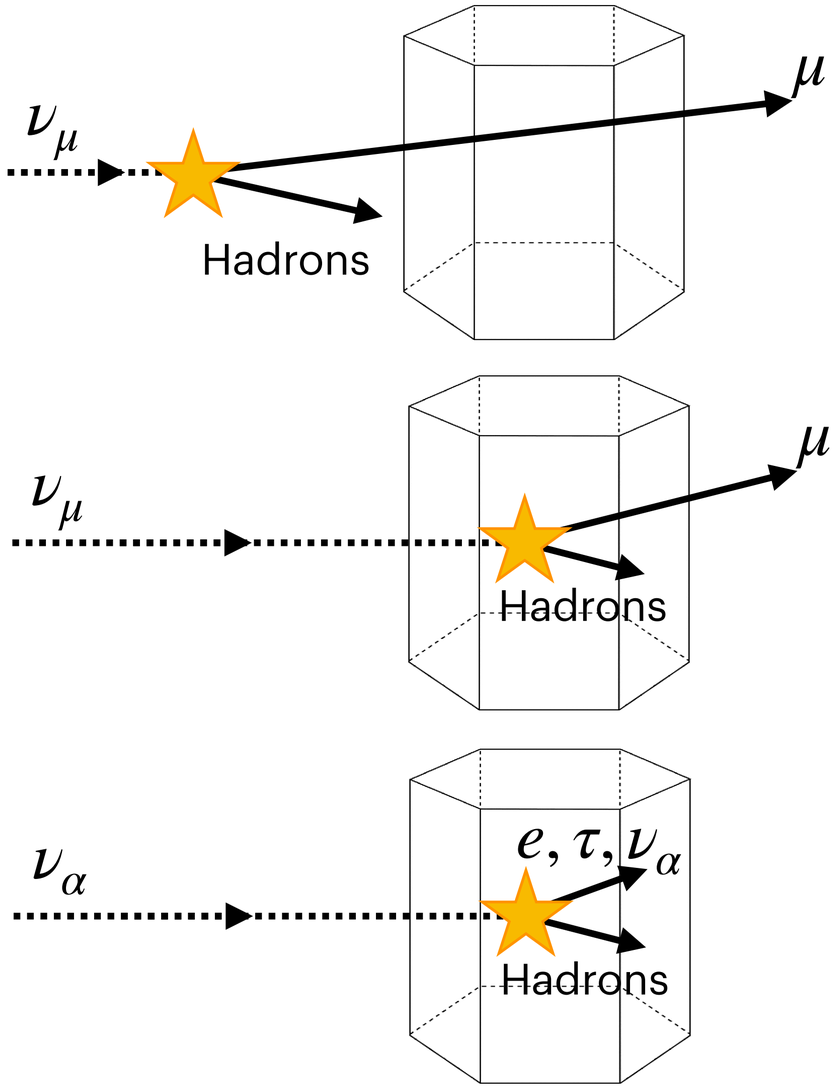


1.5-3σ mass ordering sensitivity



IceCube 2509.13066

Neutrino Telescope Event Categories



<u>"Through-going track"</u>

ν_μ charged-current DIS outside the active volume

<u>"Starting track"</u>

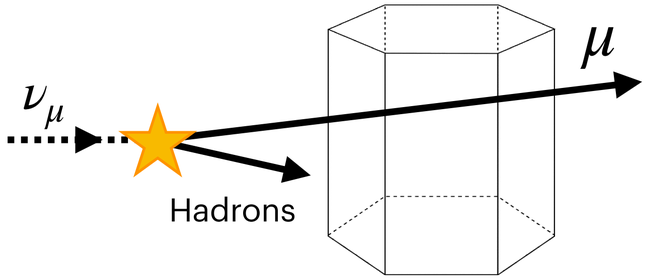
ν_μ charged-current DIS inside the active volume

<u>"Cascade"</u>

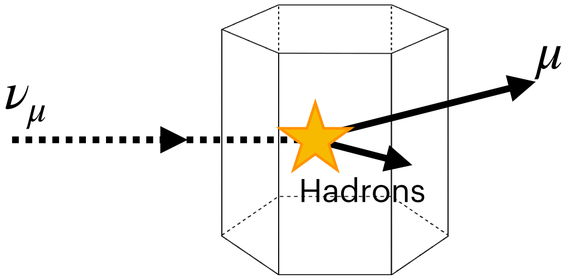
$\nu_{e,\tau}$ charged-current DIS or ν_α neutral-current DIS inside the active volume

Neutrino Telescope Event Signatures

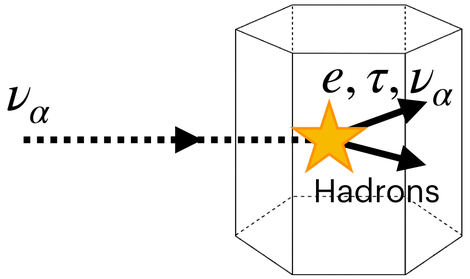
Through-going track

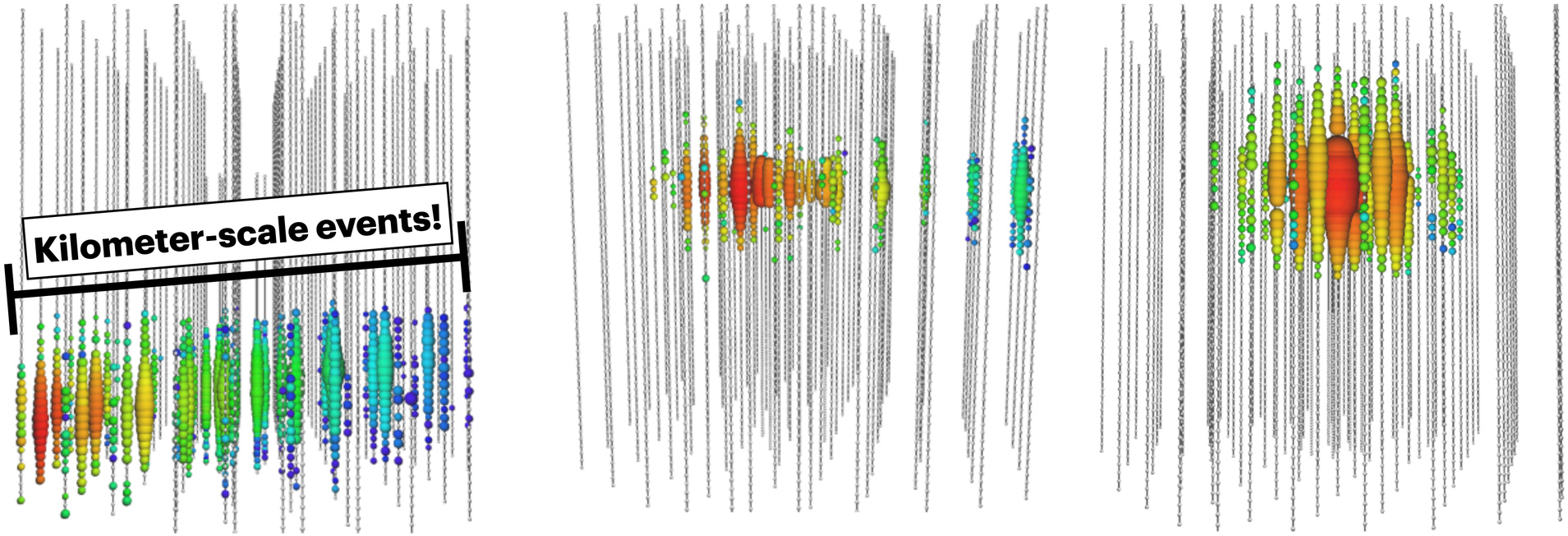


Starting track



Cascade

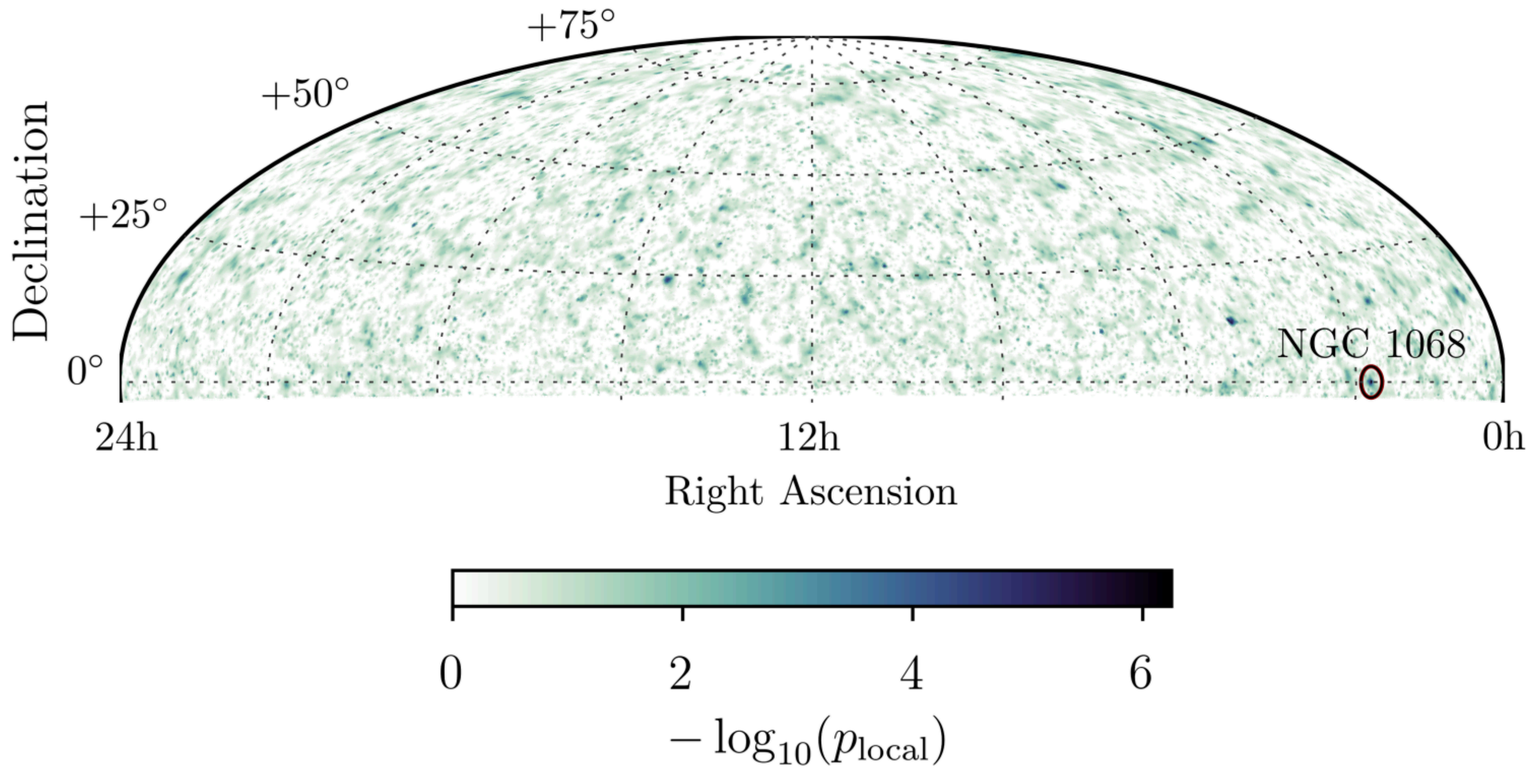


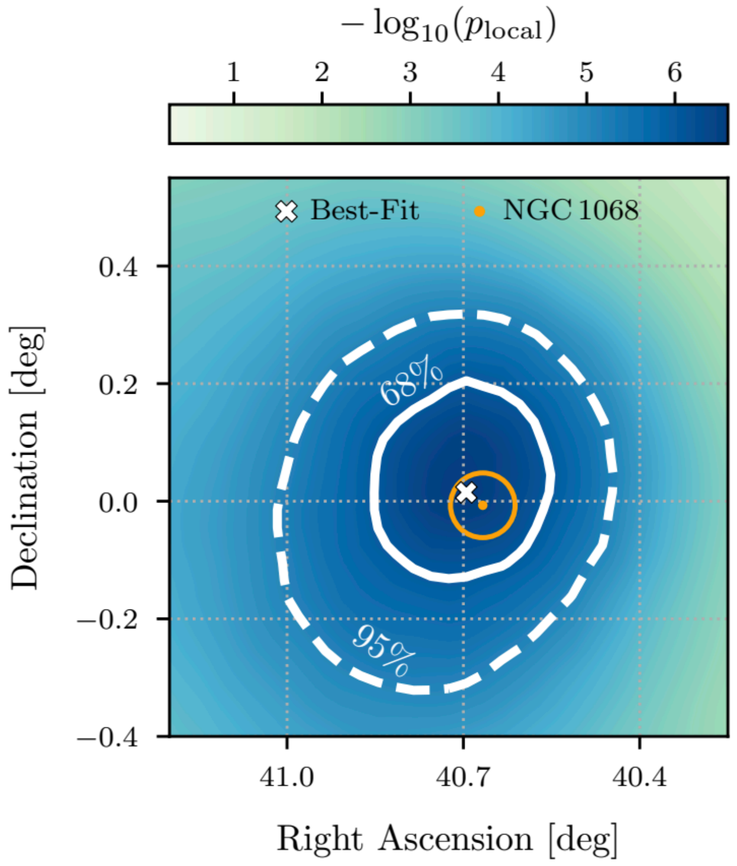


Earliest photons **Latest photons**

Where do cosmic neutrinos come from?

Strategy: look for clustering on the sky

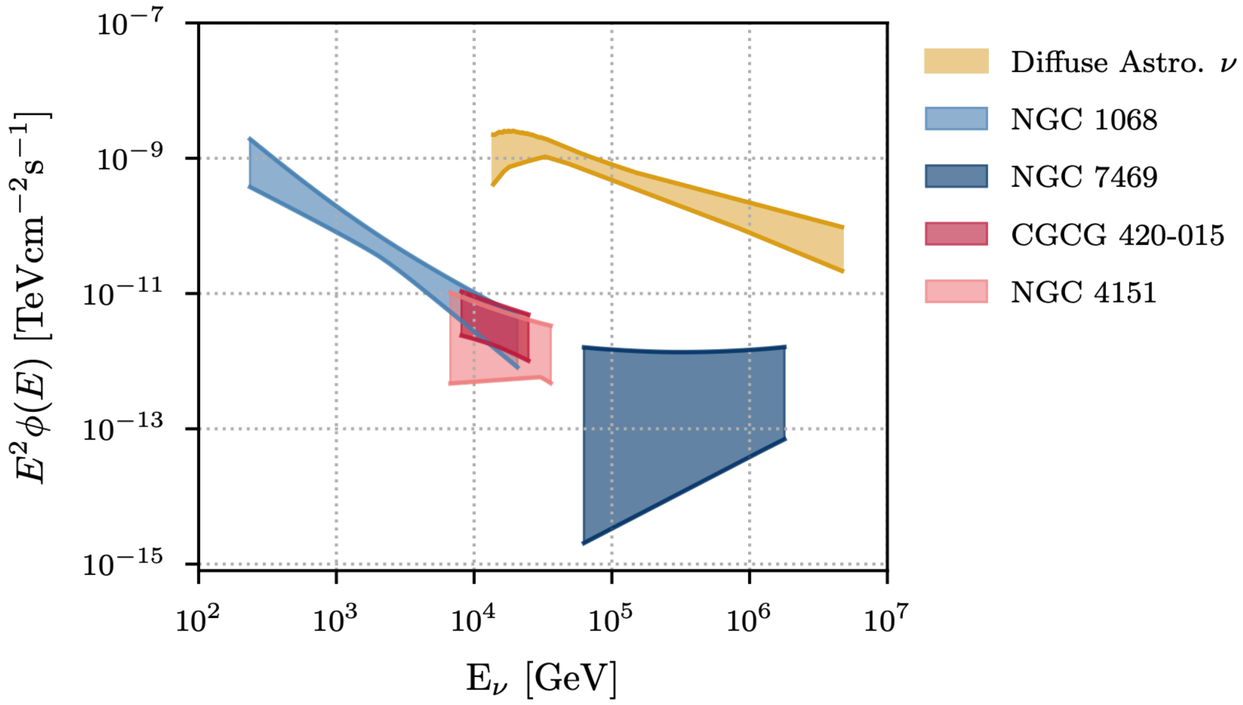




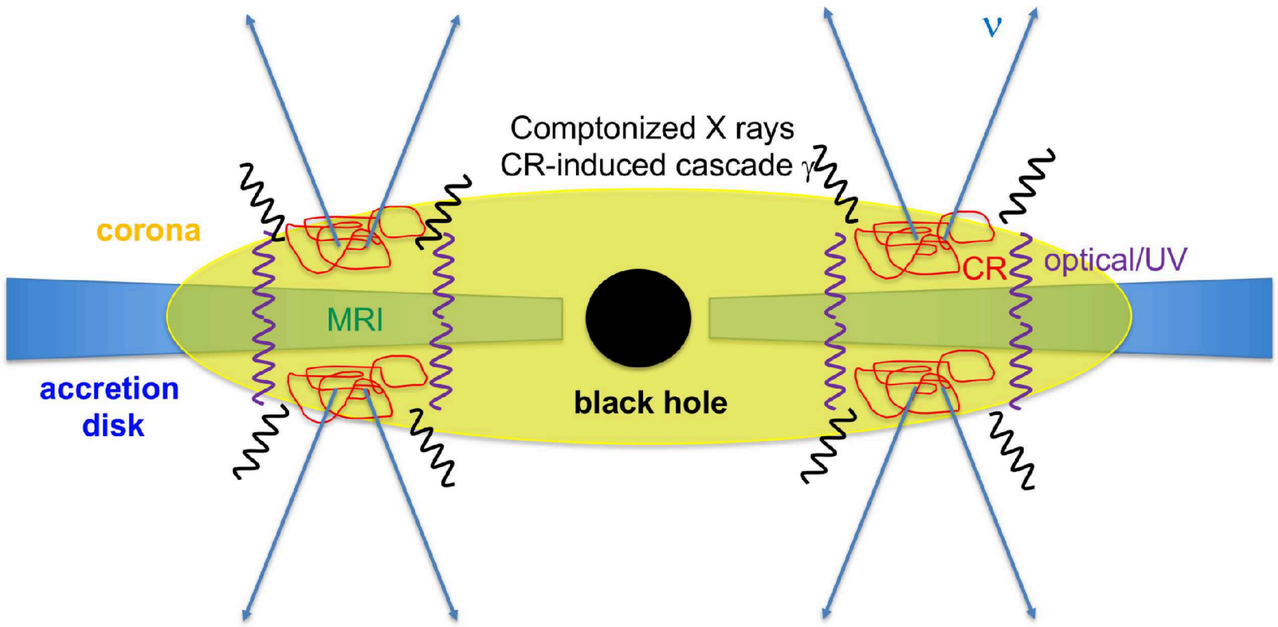
Brightest spot: NGC 1068 with a global significance of 4.0σ

IceCube Science 2022 IceCube 2510.13403

New: 3.3σ evidence for neutrino emission from a population of X-ray bright active galactic nuclei



IceCube 2025



Murase, Kimura, Mészáros PRL 2020

First association of cosmic neutrinos to a population of sources

Recent result: 3.3σ evidence for neutrino emission from X-ray bright Seyfert galaxies

47 X-ray bright AGN

Most significant source	NGC 7469	345.82	8.87	5.5	1.9	4.1 (3.8σ)	2.1 (2.4σ)
Binomial test	11 Sources					4.8 (4.2σ)	3.3 (3.3σ)
Other sources in binomial excess	NGC 4151	182.64	39.41	27.6	2.7	2.9 (3.1σ)	–
	CGCG 420-015	73.36	4.06	35.3	2.7	2.4 (2.7σ)	–
	Cygnus A	299.87	40.73	3.4	1.6	2.2 (2.5σ)	–
	LEDA 166445	42.68	54.70	57.1	4.4	1.8 (2.1σ)	–
	NGC 4992	197.27	11.63	27.3	2.9	1.6 (2.0σ)	–
	NGC 1194	45.95	−1.10	43.2	4.4	1.5 (1.8σ)	–
	Mrk 1498	247.02	51.78	39.9	3.6	1.4 (1.7σ)	–
	MCG +4-48-2	307.15	25.73	36.7	3.2	1.4 (1.7σ)	–
	NGC 3079	150.49	55.68	33.8	3.6	1.3 (1.7σ)	–
	Mrk 417	162.38	22.96	4.4	2.0	1.3 (1.6σ)	–

$$2\mathscr{L}_{\text{mass}} = m_D \overline{N_R} \nu_L + m_D \overline{\nu_L^C} N_R^C + m_R \overline{N_R^C} N_R + \text{h.c.}$$

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Lepton-number breking term.

Dirac neutrinos: $M_R = 0$

See-saw scenario: $M_R \gg M_D$

Quasi-Dirac scenario: $M_R \ll M_D$

Dirac See Saw Scenario: Z. K. Silagadze, *Phys. Atom. Nucl. 60, 272* (1997); A. S. Joshipura, S. Mohanty, and S. Pakvasa *Phys. Rev. D 89, 033003* (2014); P.-H. Gu and H.-J. He JCAP 12, 010; E. Ma and R. Srivastava *Phys. Lett. B 741, 217* (2015); J. W. F. Valle and C. A. Vaquera-Araujo *Phys. Lett. B 755, 363* (2016); S. Centelles Chuli´a, R. Srivastava, and J. W. F. Valle *Phys. Rev. D 98, 035009* (2018); Z. G. Berezhiani and R. N. Mohapatra, *Phys. Rev. D 52, 6607* (1995), …

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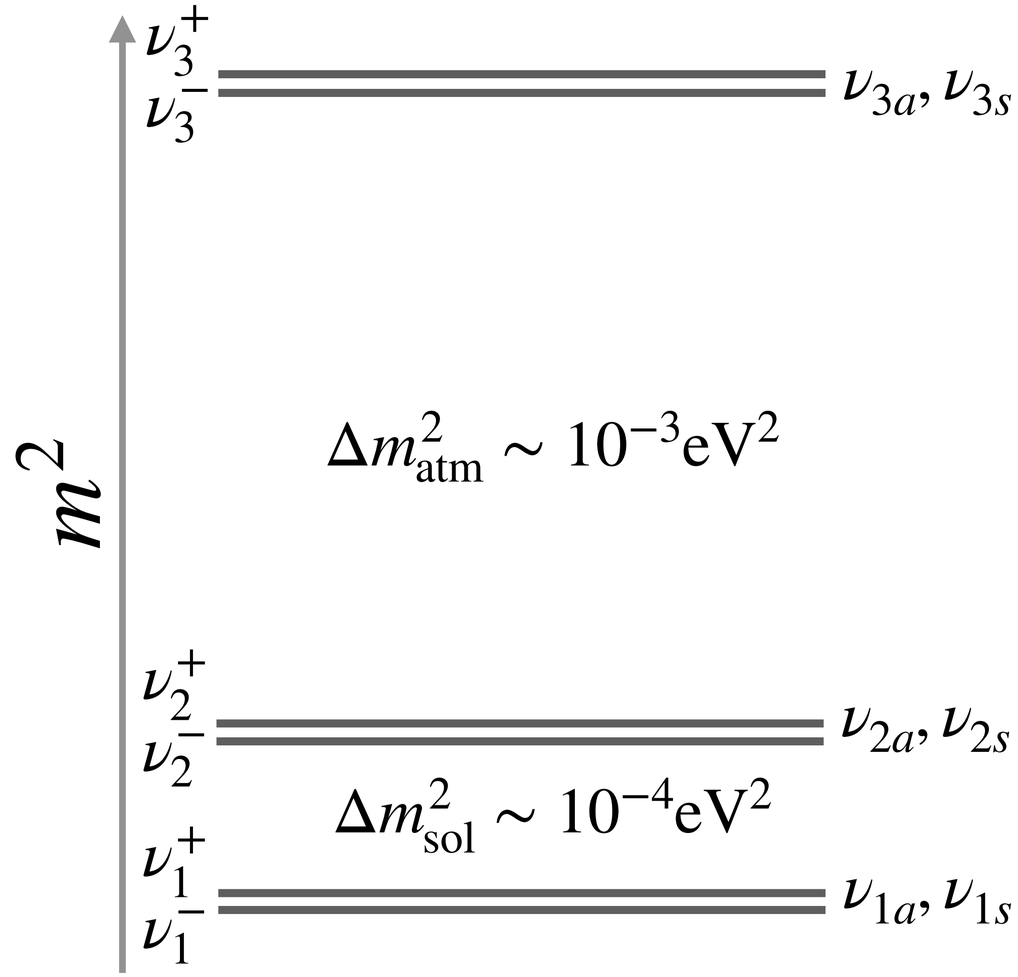
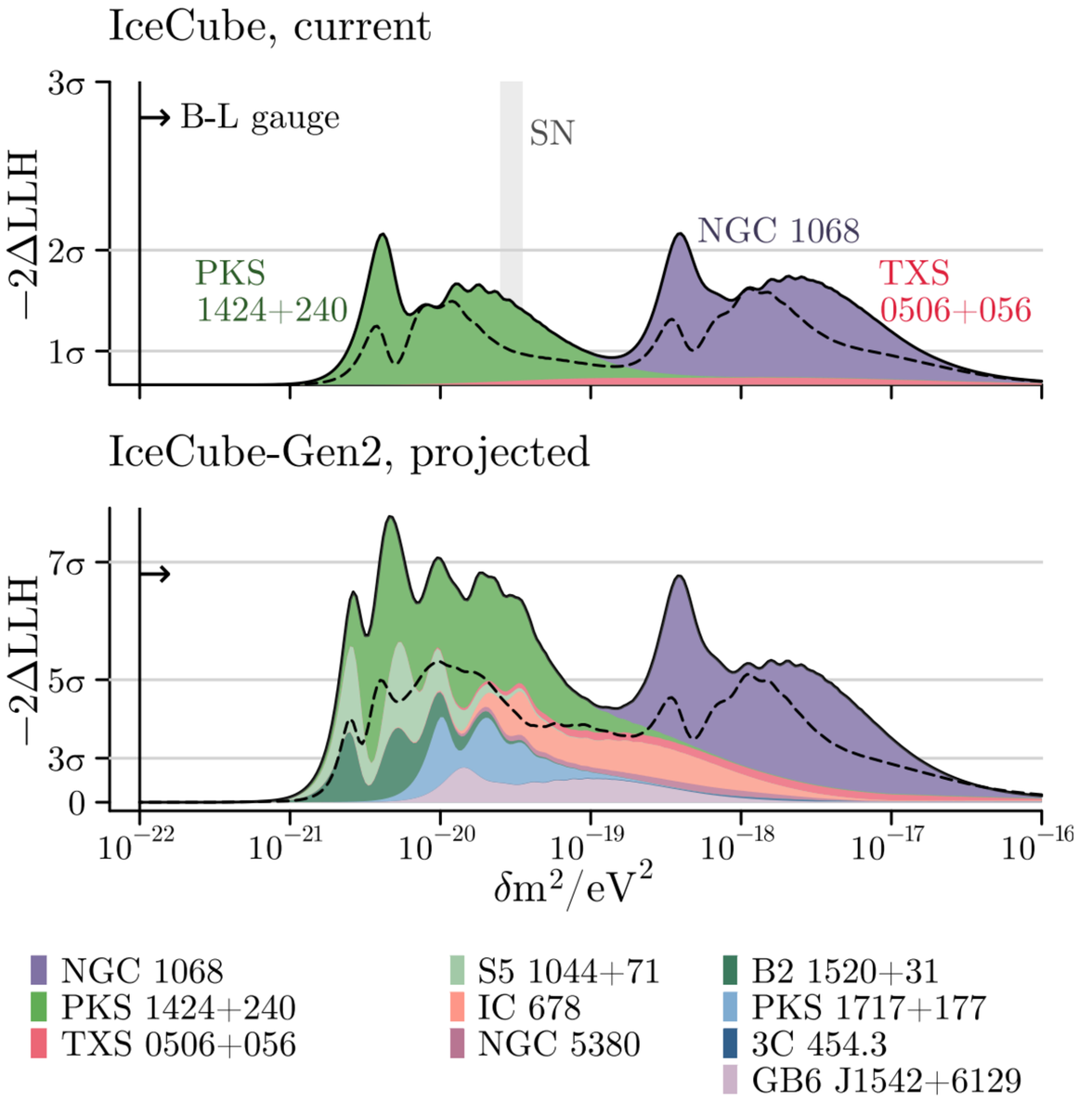
Unique probe of **neutrino mass generation** via the Dirac seesaw scenario



J. W. Valle Phys.Rev.D 28 (1983) 540


IceCube, current
3σ
2σ
1σ
−2ΔLLH
B-L gauge
SN
NGC 1068
PKS
1424+240
TXS
0506+056
IceCube-Gen2, projected
7σ
5σ
3σ
0
−2ΔLLH
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
10^{-16}
$\delta m^2/eV^2$
NGC 1068
PKS 1424+240
TXS 0506+056
S5 1044+71
IC 678
NGC 5380
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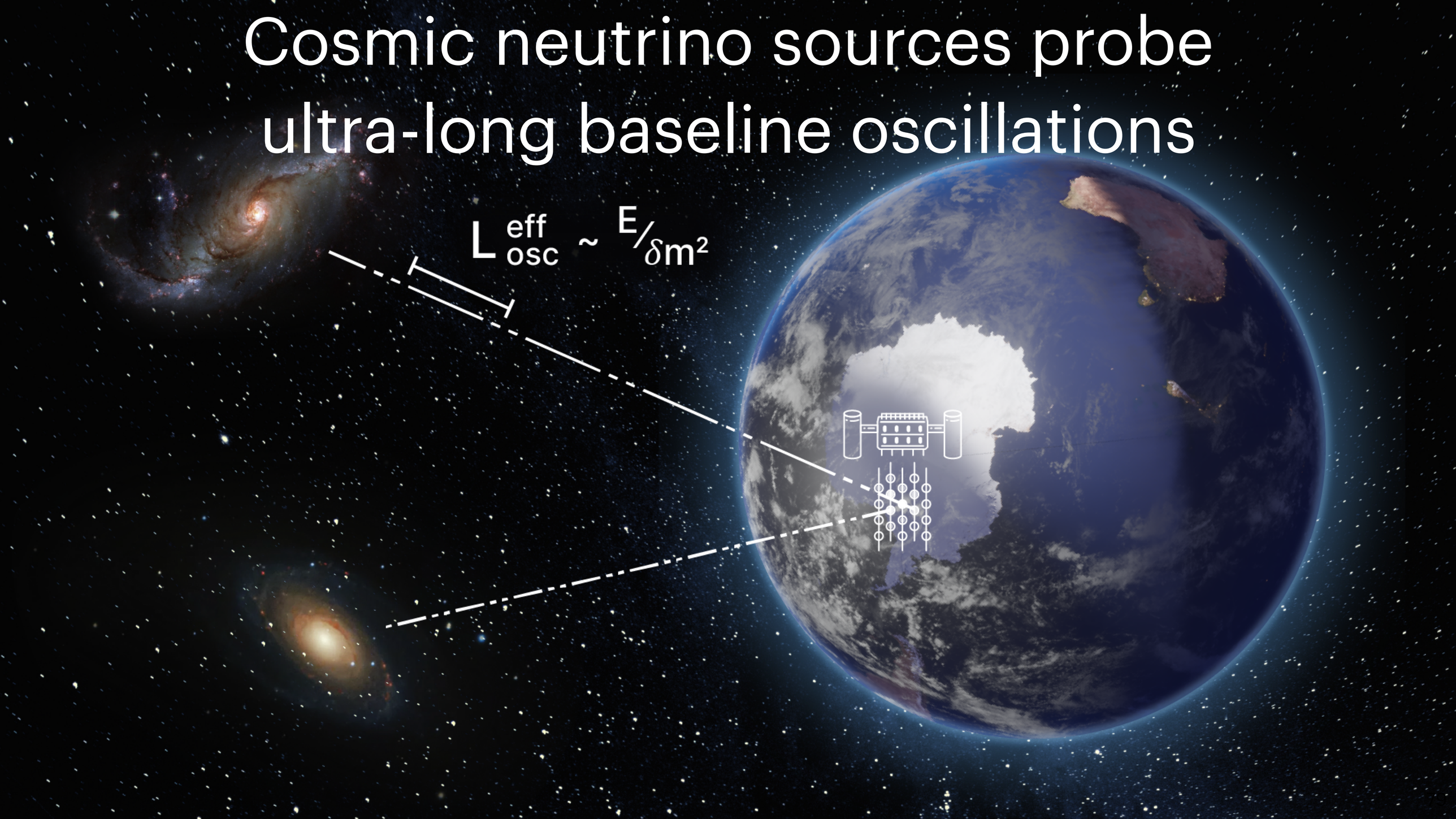
PKS 1717+177
3C 454.3
GB6 J1542+6129

Cosmic neutrino sources probe ultra-long baseline oscillations



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$L^{eff}_{osc} \sim E/\delta m^2$

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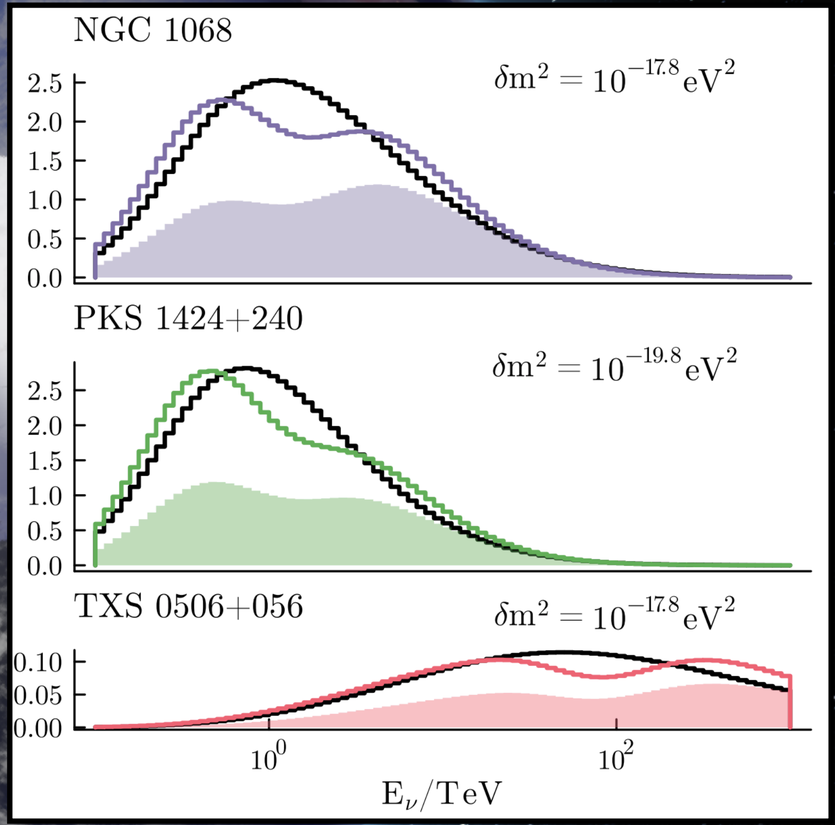

Carloni, Martínez-Soler, Argüelles, Babu, Bhupal Dev PRD 2022

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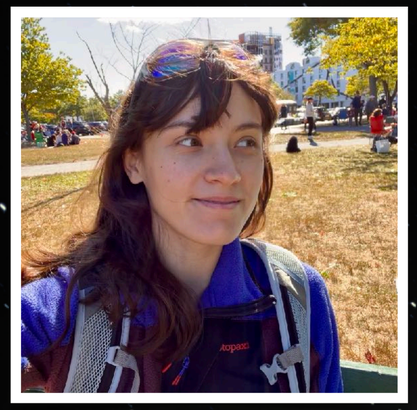

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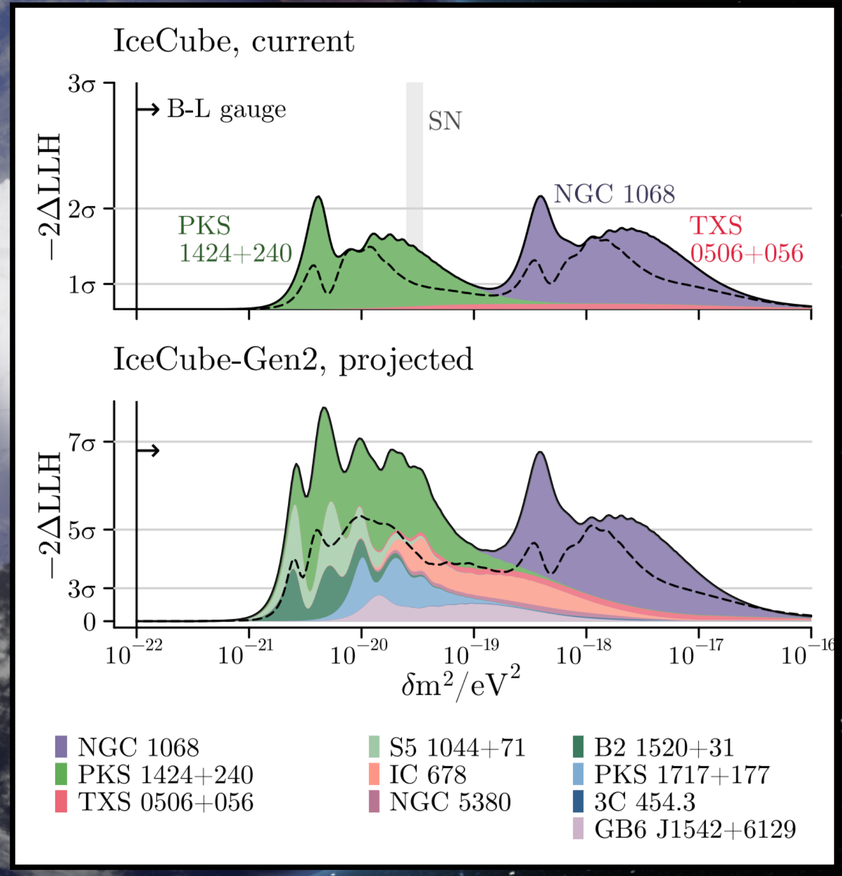


Carloni, Martínez-Soler, Argüelles, Babu, Bhupal Dev PRD 2022

Upgrade FAQ

What happened to make the string break?

We are still investigating the cause for the failure. During the drilling of string 87, the drill remained at a depth of around 680 m for an extended period, creating a wider hole at that depth. This led to slower and potentially different refreezing conditions compared to the other holes, so we are investigating this as a possible cause.

Do you know if other strings will break?

We monitor each device for indications of hole refreezing, and current data indicate that all but one deployed device/quad are now fully embedded in ice, and we are closely monitoring this remaining string (string 92). We continue to monitor the performance of all strings as commissioning progresses.

How will this impact physics sensitivities?
Studies of the impact on detector performance are ongoing. Based on preliminary indications, we expect the impact on low-energy event rates to be modest.

How are the new strings in the Upgrade performing otherwise?

Commissioning is progressing well. We have established communication with over 90% of our modules on active strings. The collaboration continues to monitor detector performance as part of routine operations.

Are there any unique devices on string 87 that are not on one of the other strings?

There are no devices unique to 87 that are not working elsewhere

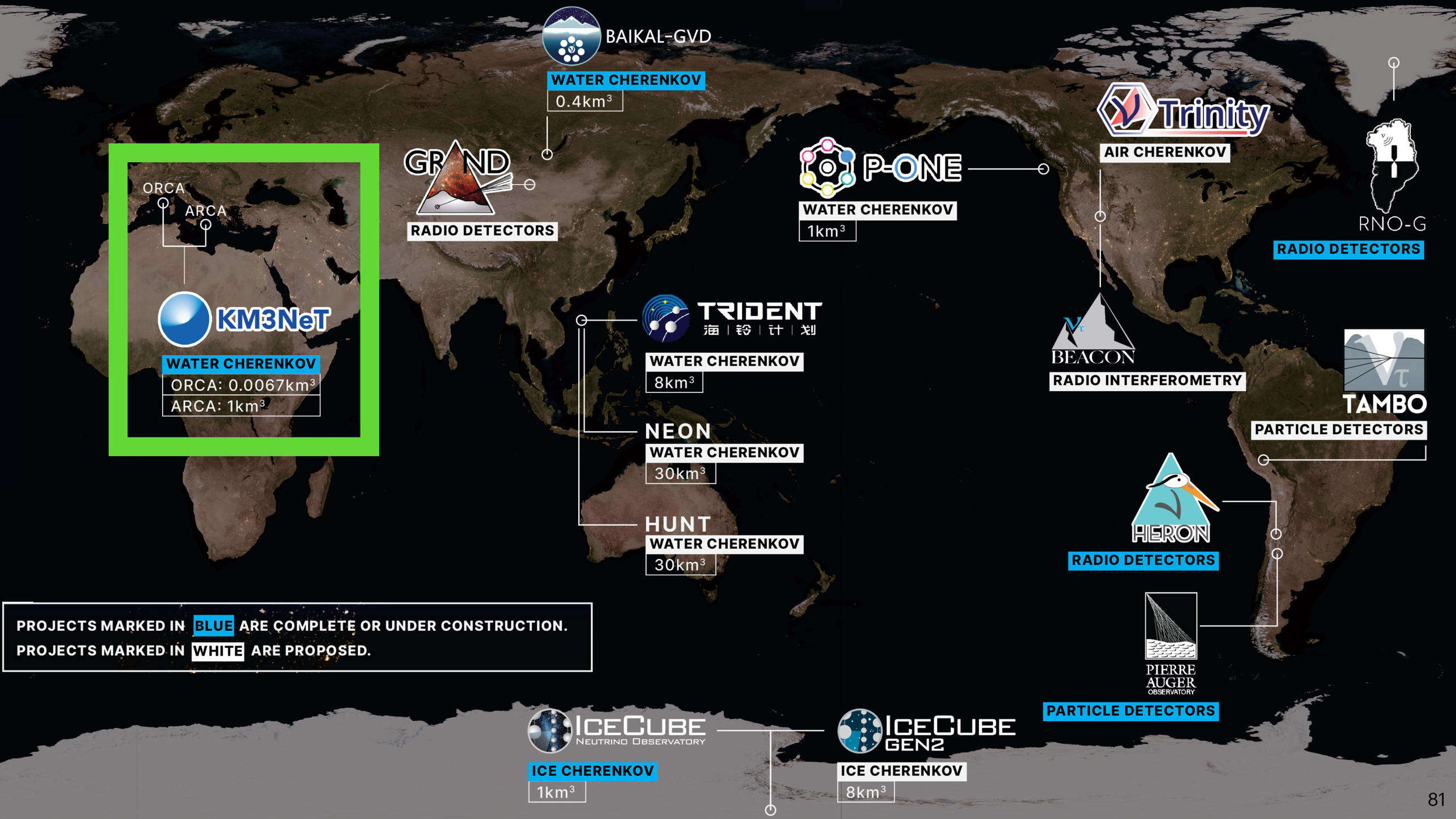
Do I need to update my Upgrade figures to include only five strings?

We have new graphics available for use in talks, showing the five string configuration. We have uploaded these to the gallery. Please use these moving forward.
How will this change what you do for Gen2?

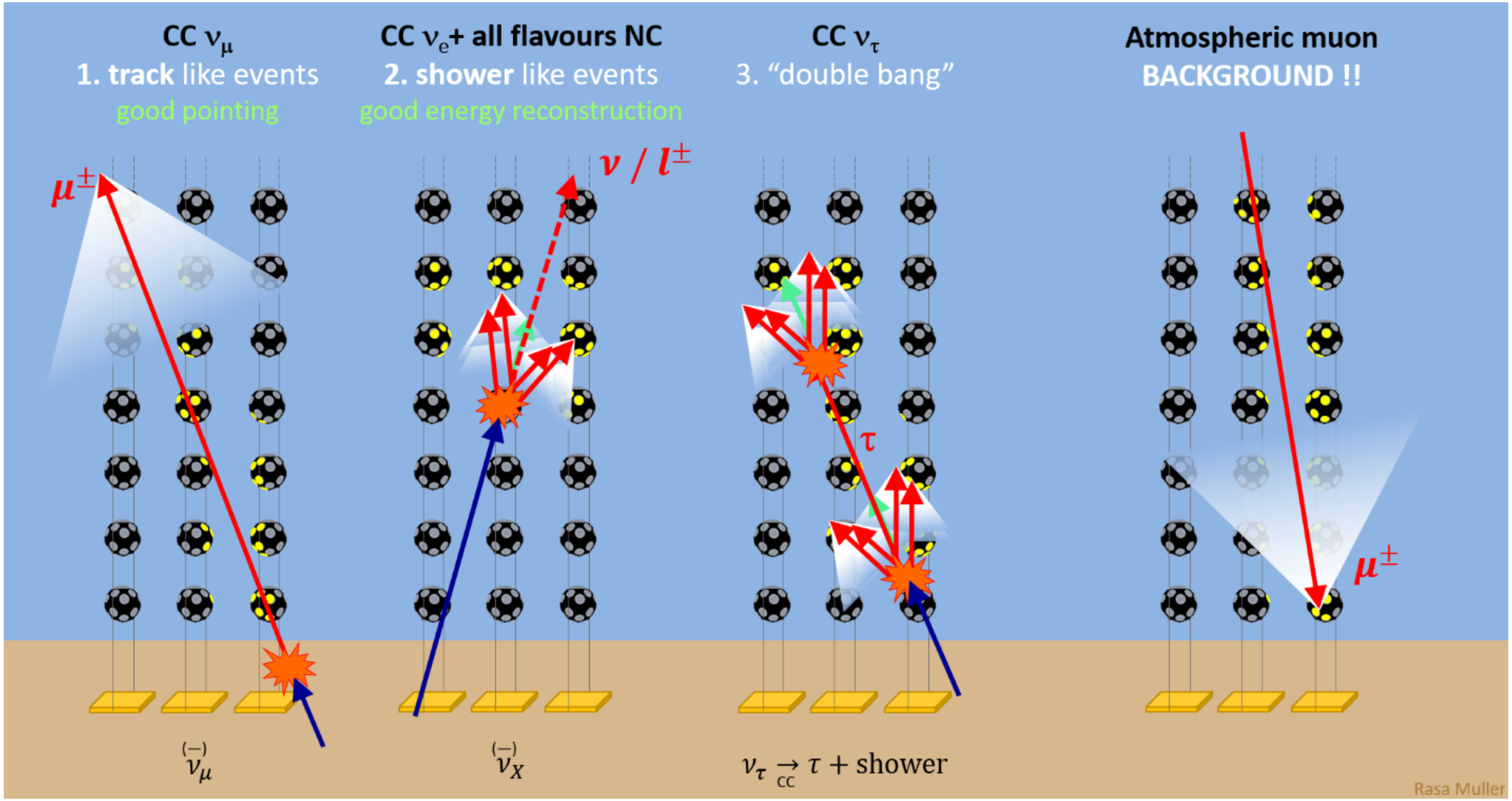
We will incorporate lessons learned from this event into the cable design and drilling strategy for Gen2.

What happened to the seventh string that was planned?

An unexpected drilling challenge arose at a late stage in the season. Despite the challenge, the South Pole crew was able to quickly react and finish drilling the sixth string. After careful consideration and discussion, the team determined that it was not viable to drill the seventh hole.

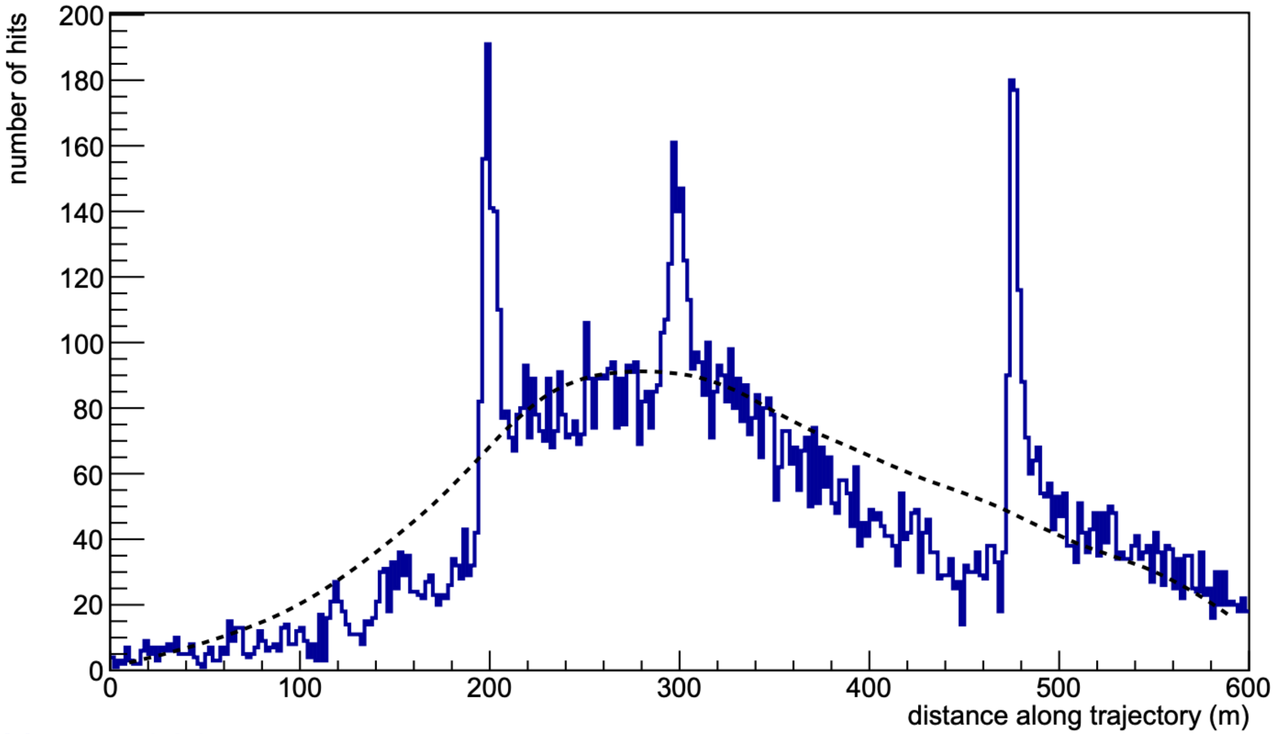

BAIKAL-GVD
WATER CHERENKOV
0.4km³
GRAND
RADIO DETECTORS
ORCA
ARCA
KM3NeT
WATER CHERENKOV
ORCA: 0.0067km³
ARCA: 1km³
P-ONE
WATER CHERENKOV
1km³
Trinity
AIR CHERENKOV
RNO-G
RADIO DETECTORS
TRIDENT
海 | 铃 | 计 | 划
WATER CHERENKOV
8km³
BEACON
RADIO INTERFEROMETRY
TAMBO
PARTICLE DETECTORS
NEON
WATER CHERENKOV
30km³
HUNT
WATER CHERENKOV
30km³
HERON
RADIO DETECTORS
PIERRE AUGER OBSERVATORY
PARTICLE DETECTORS
PROJECTS MARKED IN BLUE ARE COMPLETE OR UNDER CONSTRUCTION.
PROJECTS MARKED IN WHITE ARE PROPOSED.
ICECUBE NEUTRINO OBSERVATORY
ICE CHERENKOV
1km³
ICECUBE GEN2
ICE CHERENKOV
8km³

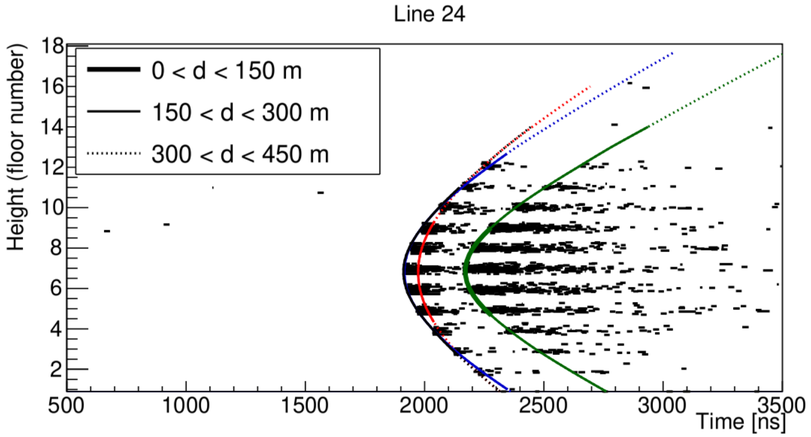
What does KM3NeT see?

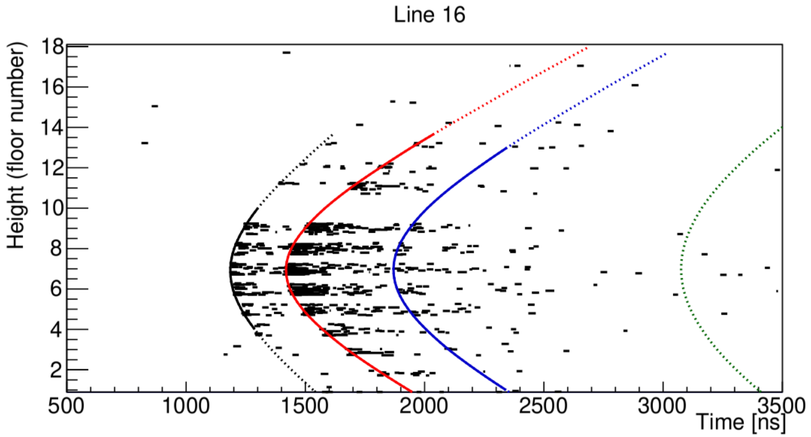


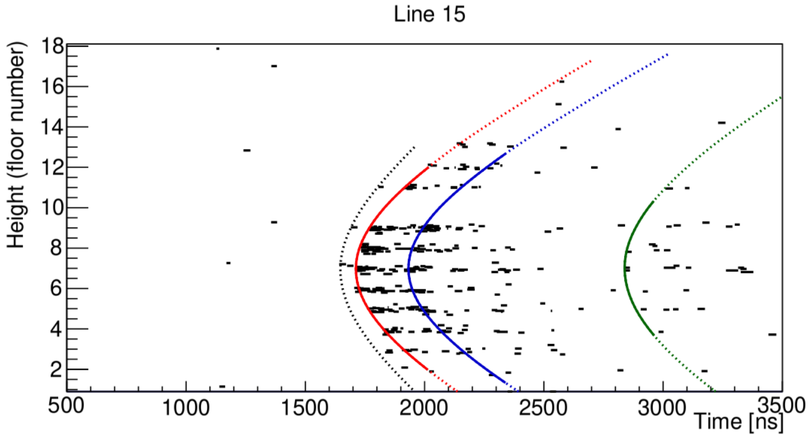
Muon Energy Deposition

Three large showers observed along the path of the muon, consistent with stochastic radiative energy losses





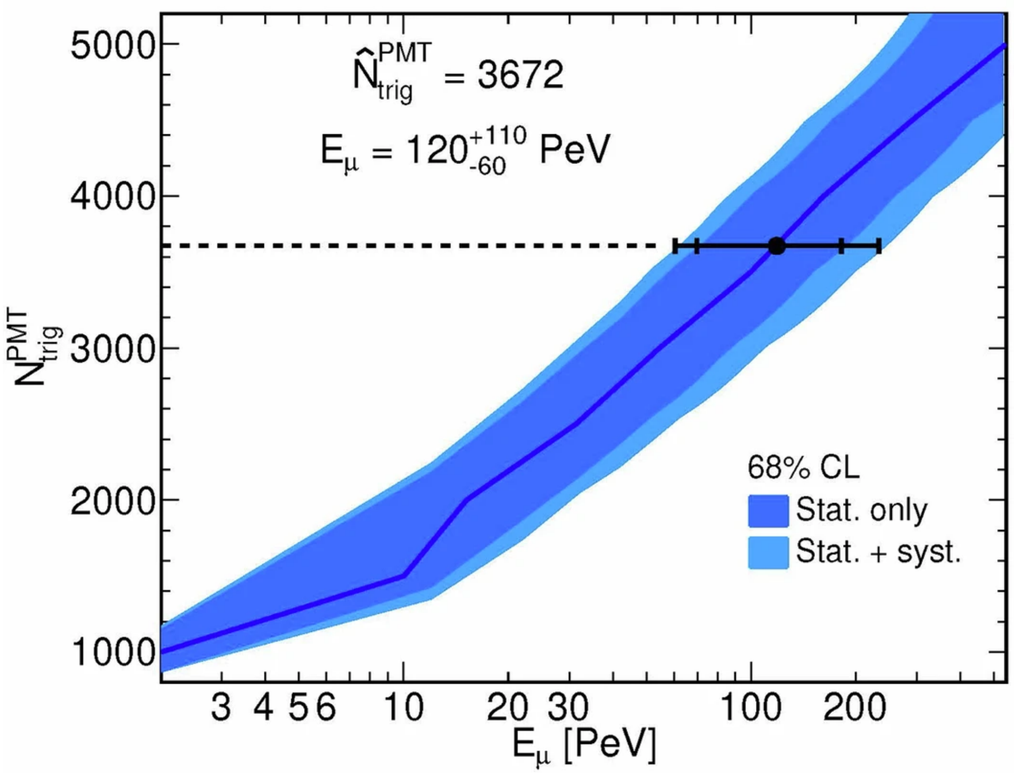


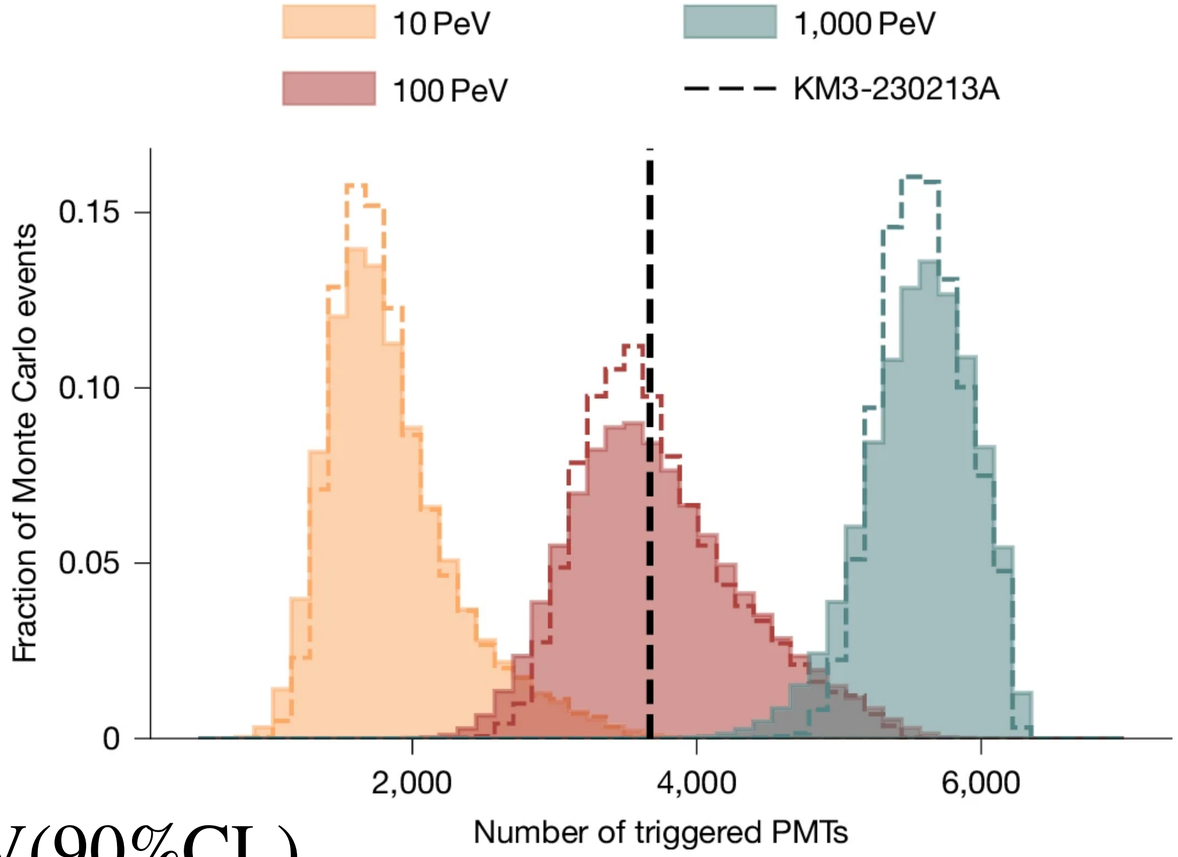


[KM3NeT Nature 2025]

Muon Energy Measurement

Energy estimate is based on the number of triggered PMTS, which is robust to detector uncertainties and environmental backgrounds

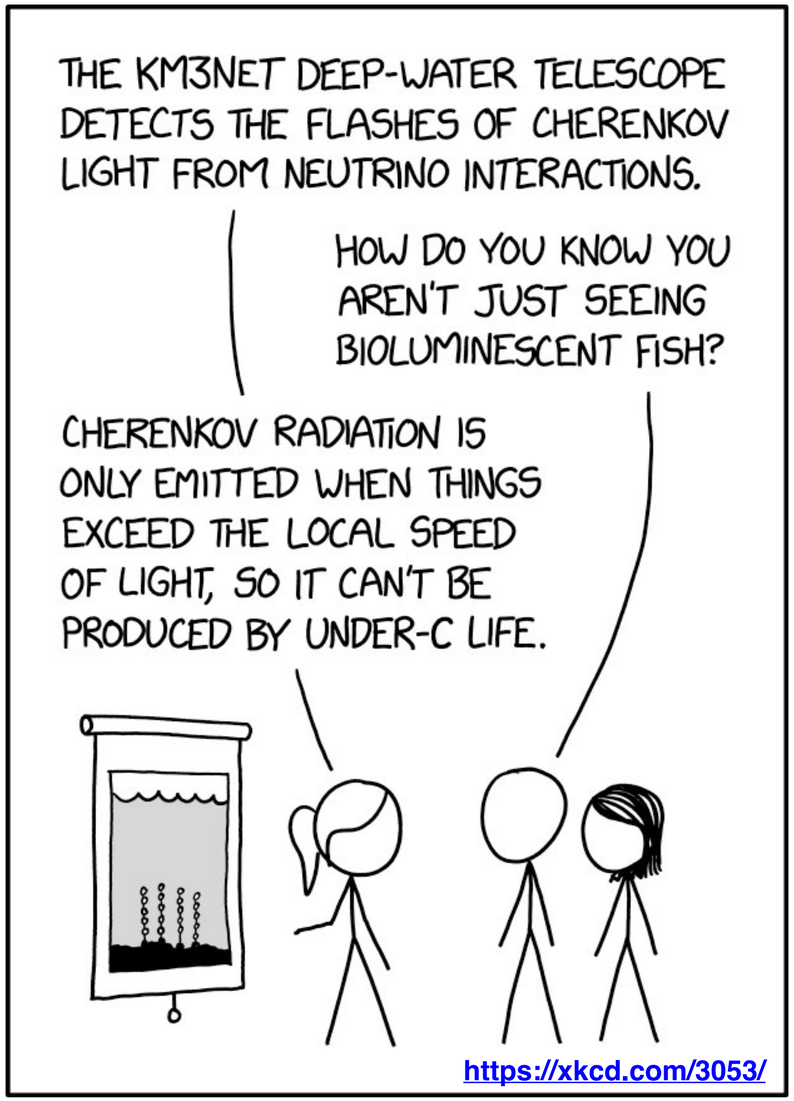




$$E_\mu \in [35{,}380]\text{PeV}(90\%\text{CL})$$

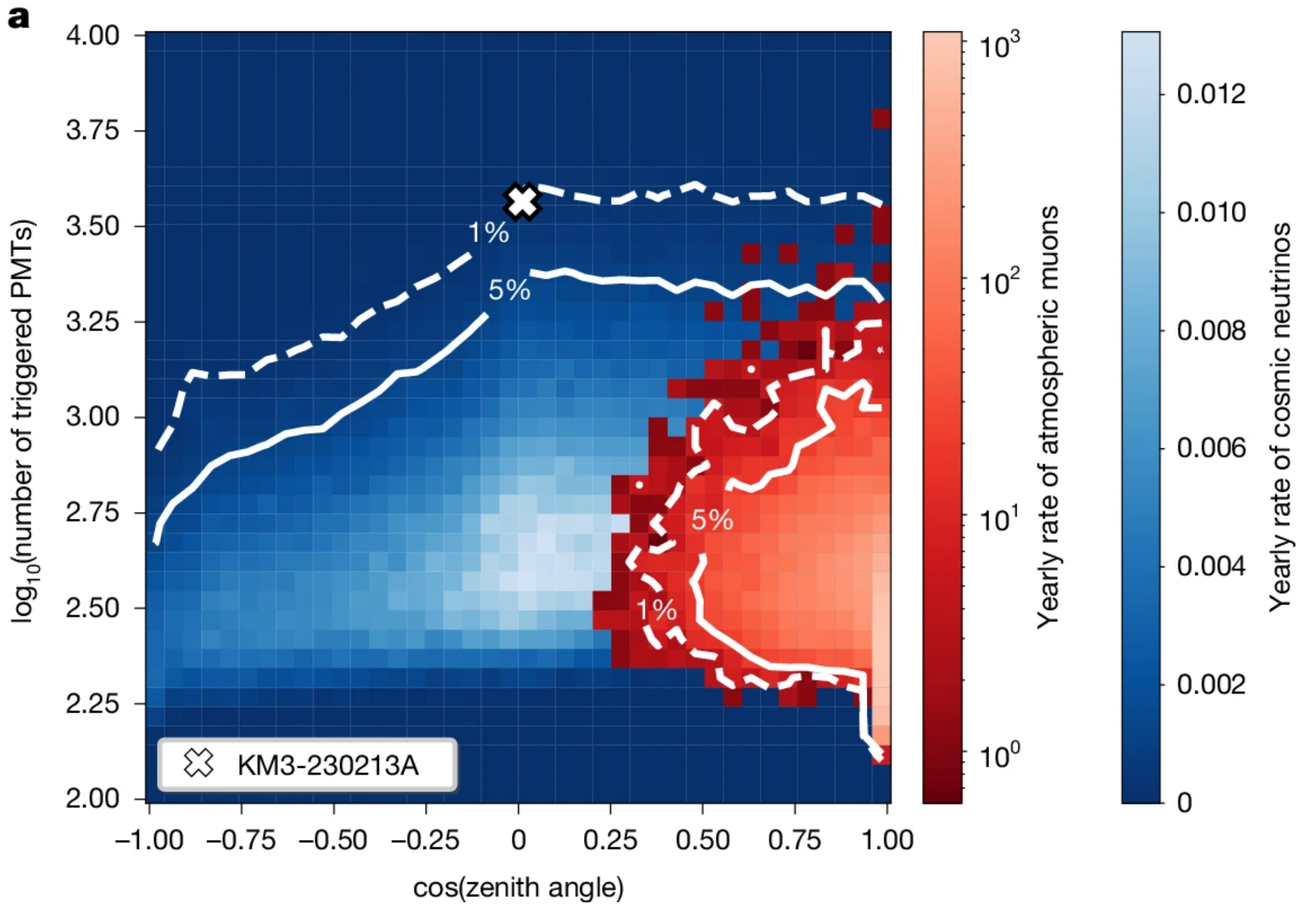
KM3NeT Nature 2025

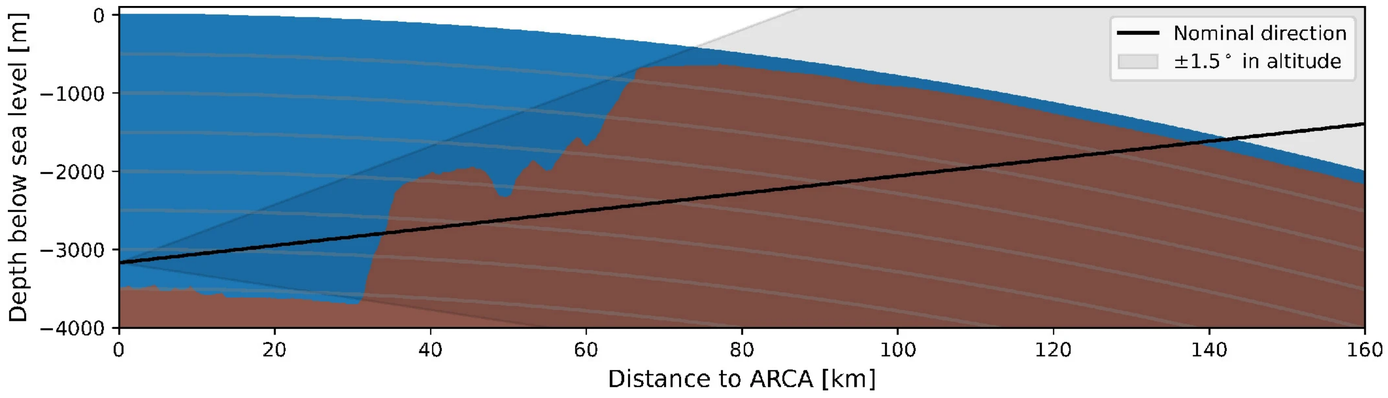
How do we know this is a neutrino?



Backgrounds

- $\theta_{\text{zenith}} = 0.6° \pm 1.5°$, where the angular uncertainty is dominated by uncertainties in the absolute position of DUs
- Considering the natural overburden, an upper limit on the atmospheric muon background at 100 PeV:
  - $\ll 10^{-10}$ events per year within 2σ of the reconstructed direction
  - $\ll 10^{-4}$ events per year within 5σ of the reconstructed direction
- Atmospheric neutrino background above 100 PeV is approximately $(1 - 5) \times 10^{-5}$ events per year, dominated by the prompt component

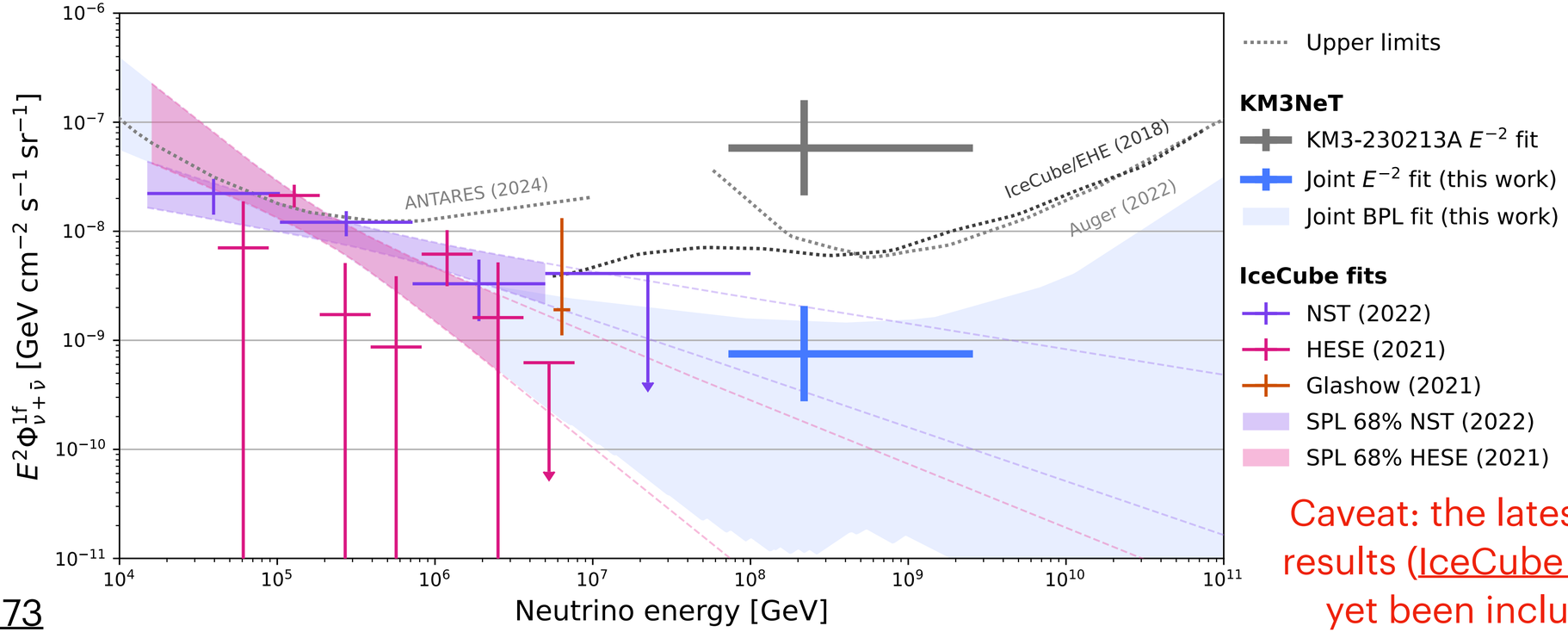




KM3NeT Nature 2025

KM3-230213A Within the Global Landscape

- We perform a joint fit between KM3NeT, IceCube, and Auger in the energy window of KM3-230213A
- Most likely E^{-2} flux from joint fit: $E^2\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}} = 7.5^{+13.1}_{-4.7} \times 10^{-10}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$
- KM3NeT-only fit E^{-2} flux: $E^2\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}} = 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$

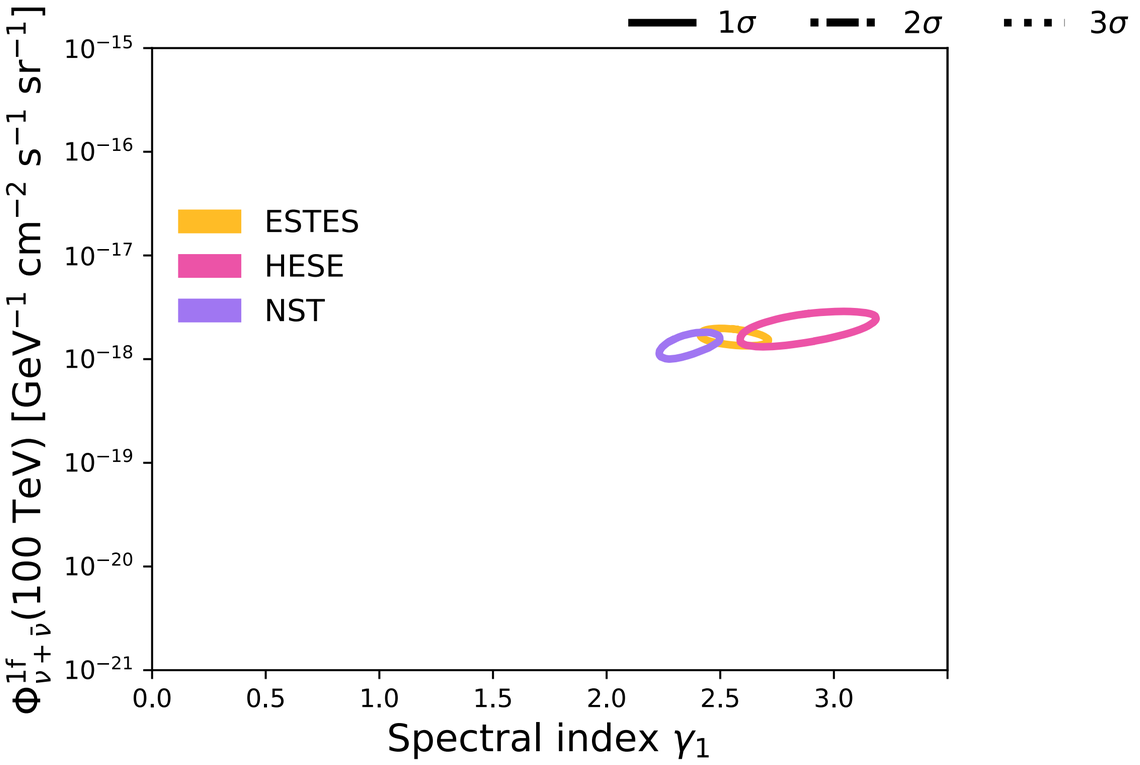


KM3NeT 2502.08173

Caveat: the latest IceCube EHE results (IceCube 2025) have not yet been included in the fit

Is there tension between KM3-230213A and null observations from IceCube and Auger?

We consider a generic single-power-law flux model in the UHE region



KM3NeT (incl Argüelles, NK, Wen) PRX 2025 See also Li+ 2502.04508 [1] Maltoni Schwetz 2003 [2] Gelman+ 1996

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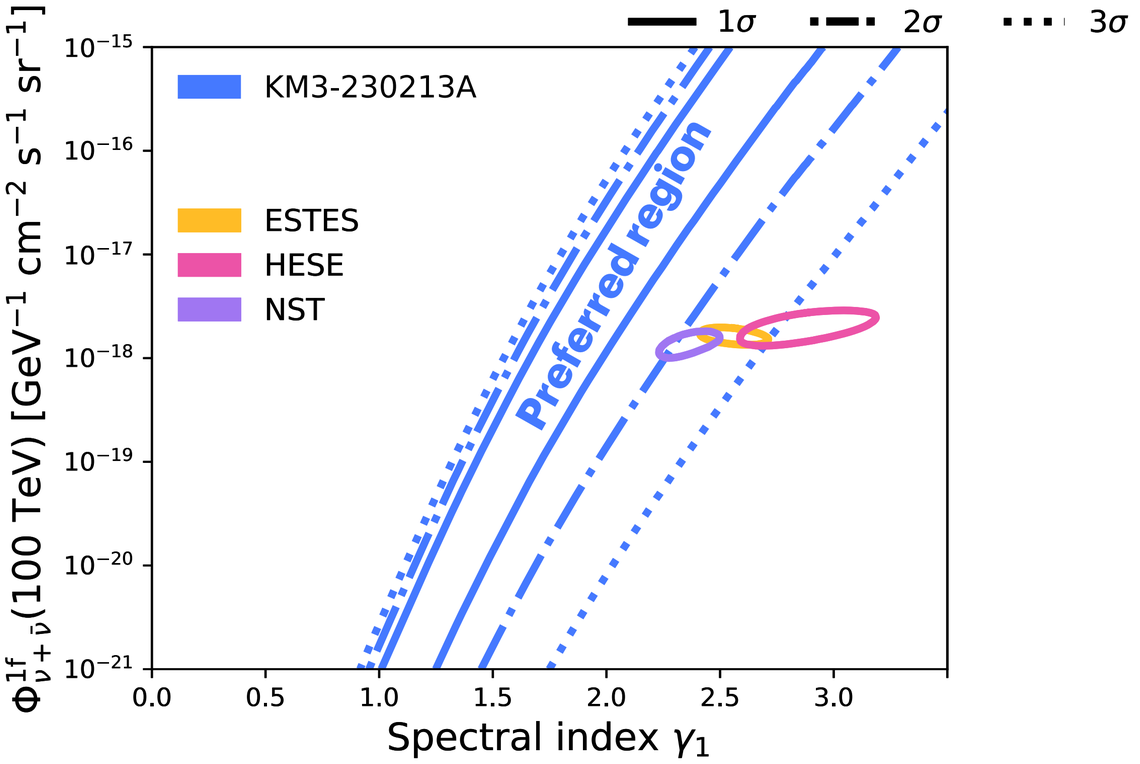

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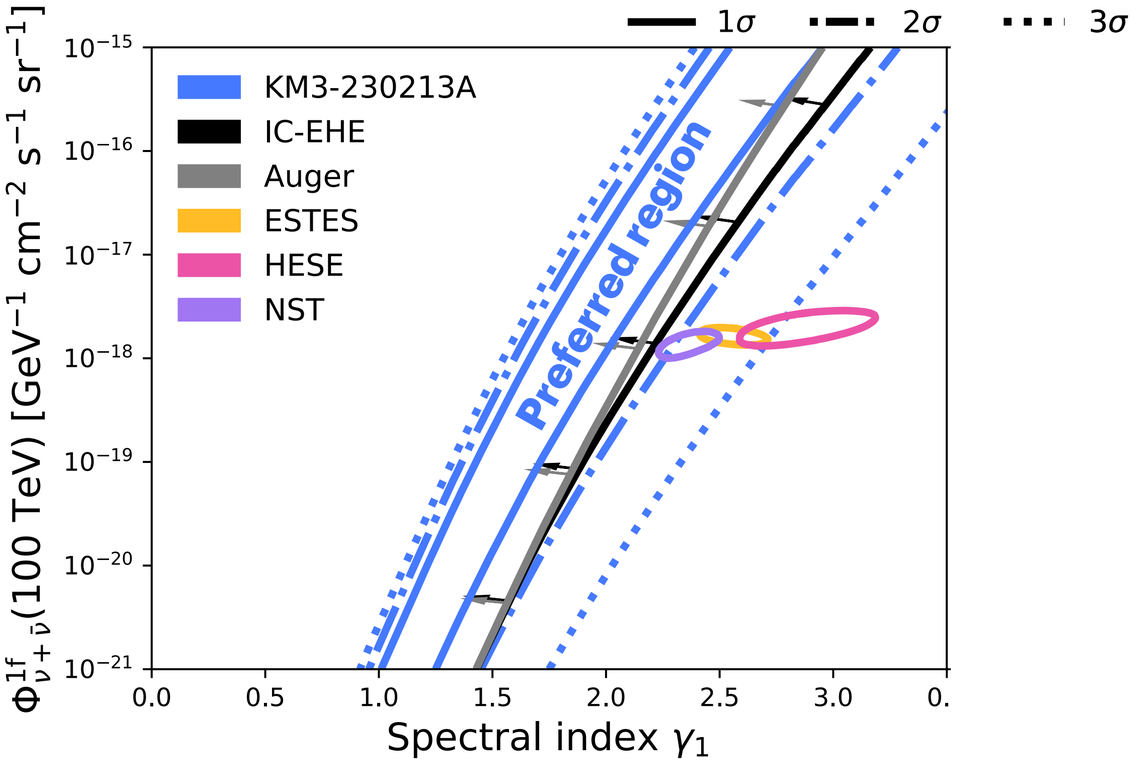

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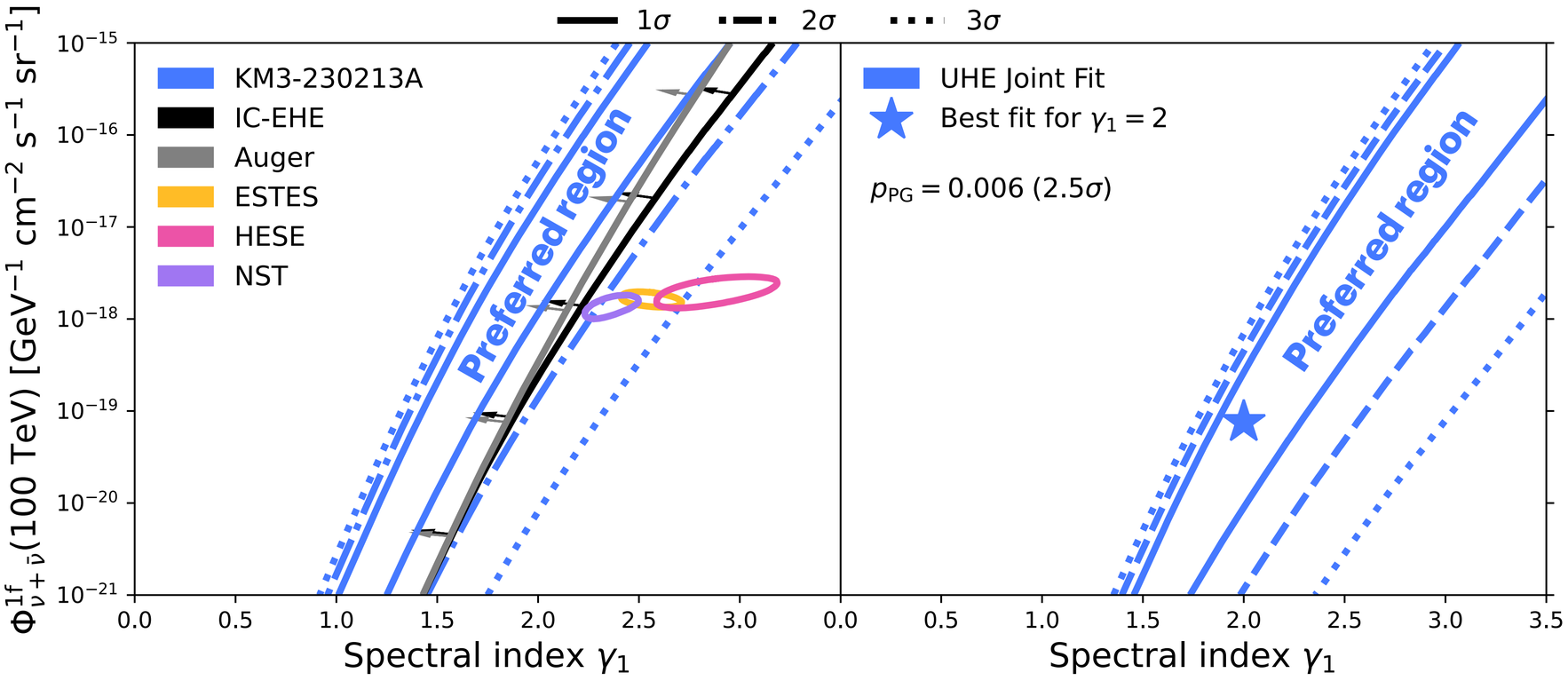

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Frequentist test

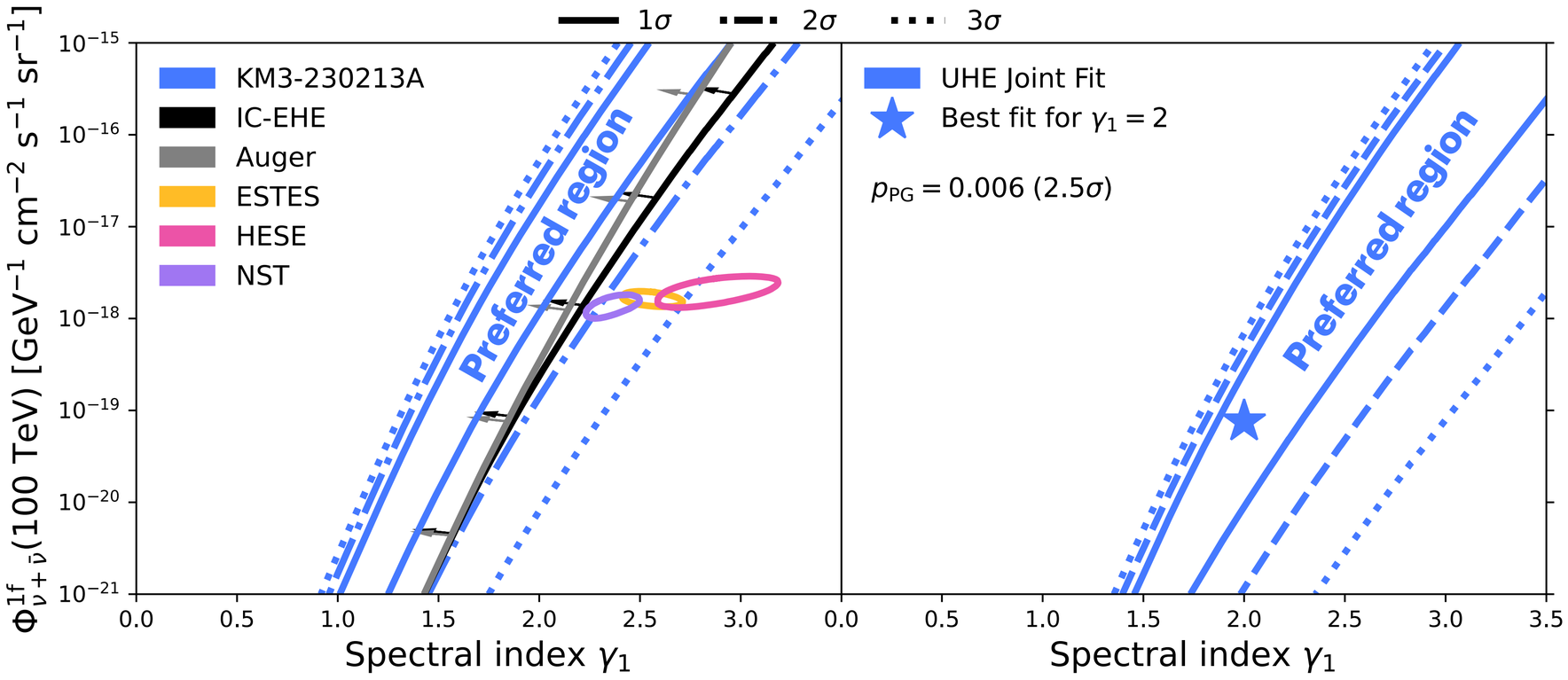
Parameter goodness of fit [1]

$$z_{\mathrm{PG}} = 2.5\sigma$$

Bayesian test

Posterior predictive check [2]

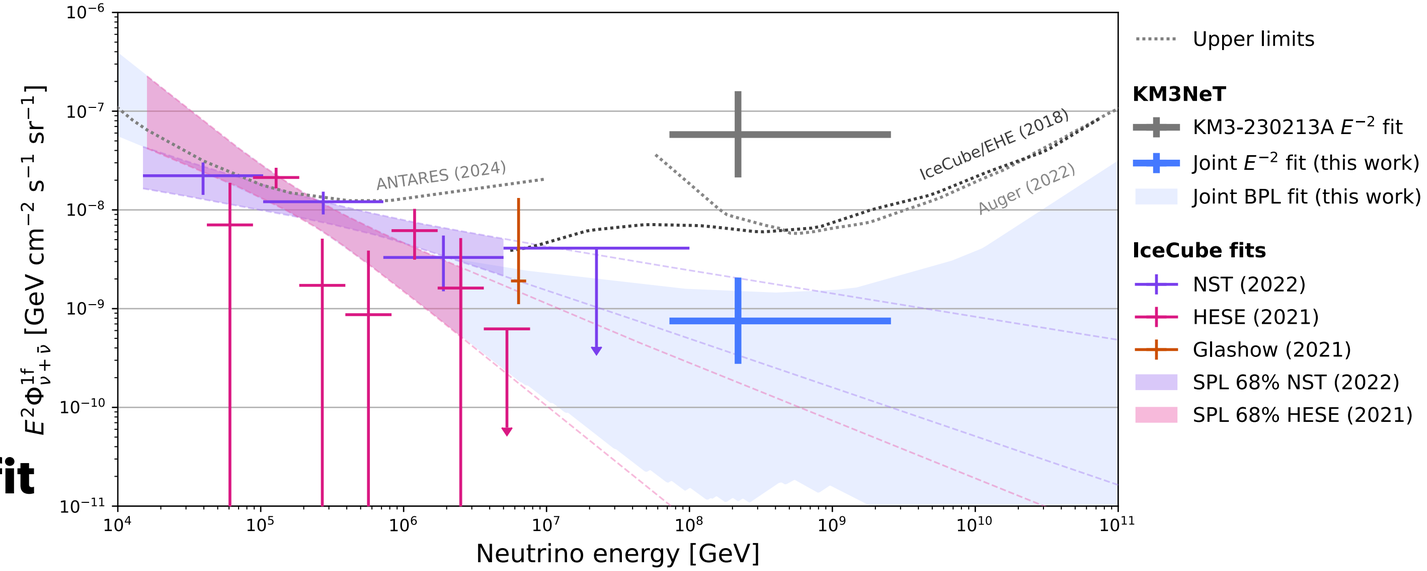
$$z_{\mathrm{PPC}} = 2.5\sigma$$

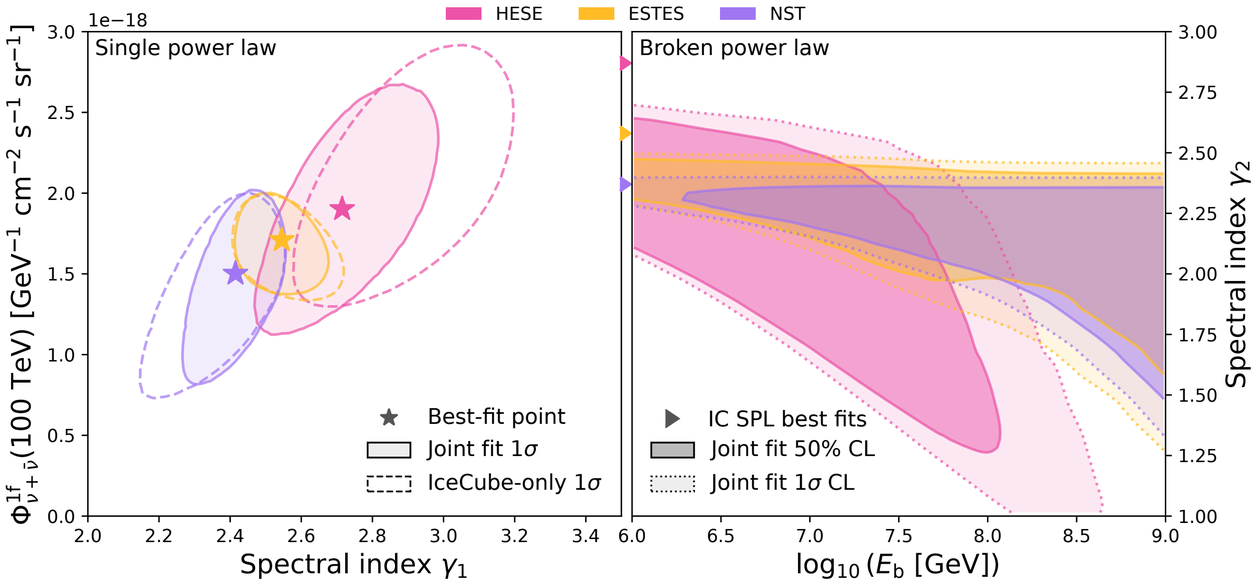


KM3NeT (incl Argüelles, NK, Wen) PRX 2025 See also Li+ 2502.04508 [1] Maltoni Schwetz 2003 [2] Gelman+ 1996

Is there evidence for a new component?

- We perform fits to a single and broken power law flux hypothesis across the entire astrophysical neutrino spectrum
- Three IceCube measurements below 10 PeV: HESE, ESTES, and NST
- **No preference for BPL over SPL in the global fit**





UHE Sample(s)	KM3-230213A			Global		
HE Sample	HESE	ESTES	NST	HESE	ESTES	NST
Bayes factor $\mathcal{B}$	27.0	8.7	3.9	1.2	0.6	0.3
LR p-value (%)	0.4	1.7	5.9	33	86	100

See also Muzio, Yuan, Lu 2502.06944

KM3NeT 2502.08173

Outline

1. The KM3NeT deep-sea neutrino telescope

2. The observation and reconstruction of KM3-230213A

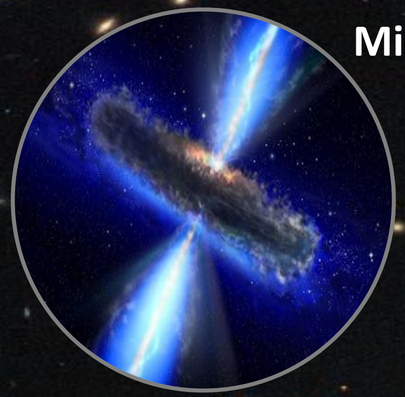
3. The implications of KM3-230213A

Covered in a series of companion papers:

KM3NeT 2502.08387 KM3NeT 2502.08484 KM3NeT 2502.08508 KM3NeT 2502.08173 KM3NeT 2502.12070

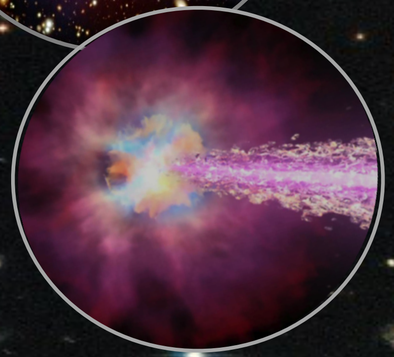
Where did this neutrino come from?

Active Galactic Nuclei (AGN)

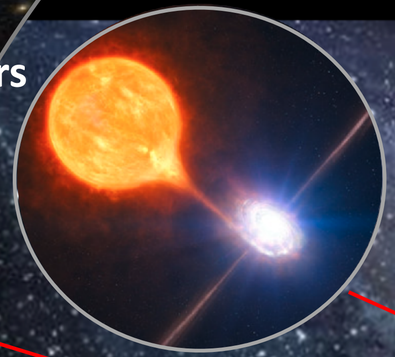


Galaxy clusters

Gamma-ray Bursts



Microquasars



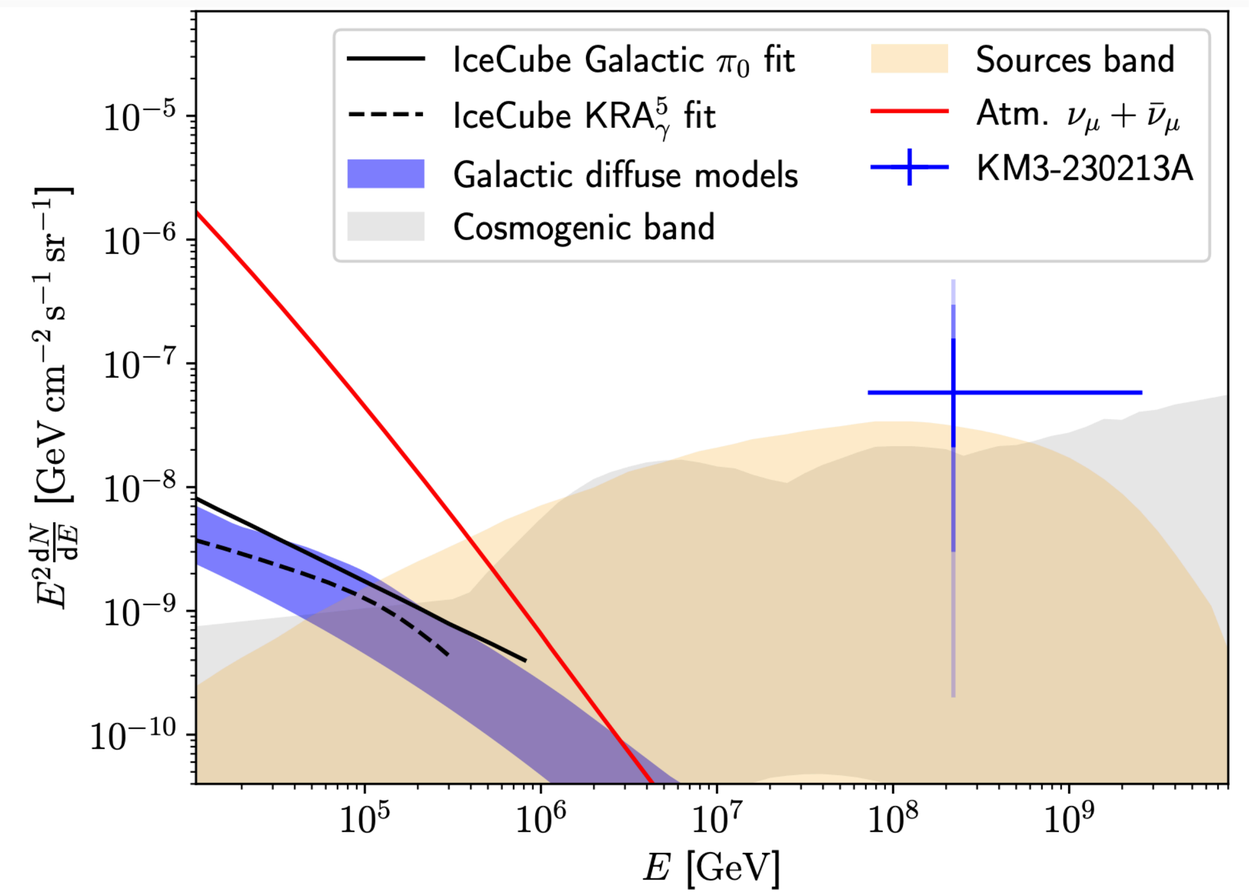
Supernova Remnants

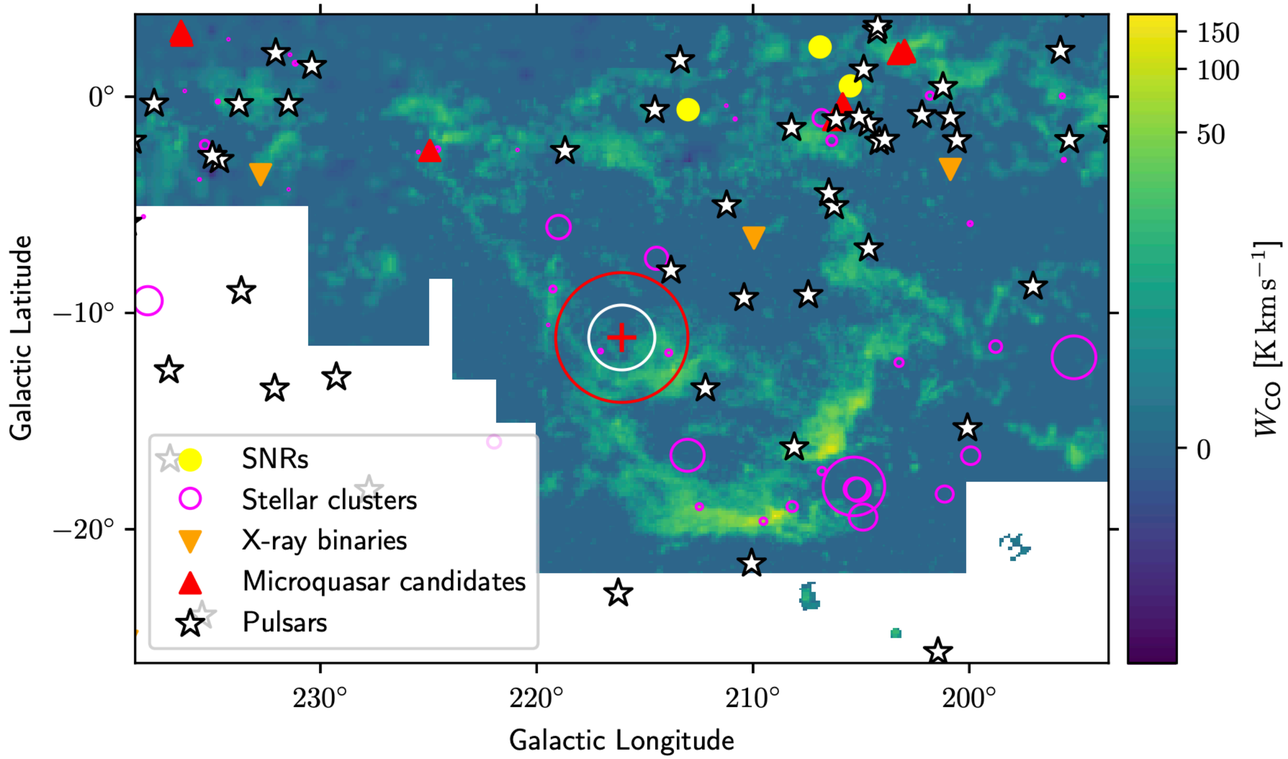
We live here in the Milky Way

ν ν ν ν ν

Adapted from R. Coniglione

Source Hypothesis: Galactic





Low flux from Galactic diffuse emission and lack of potential cosmic ray accelerators along KM3-230213A direction

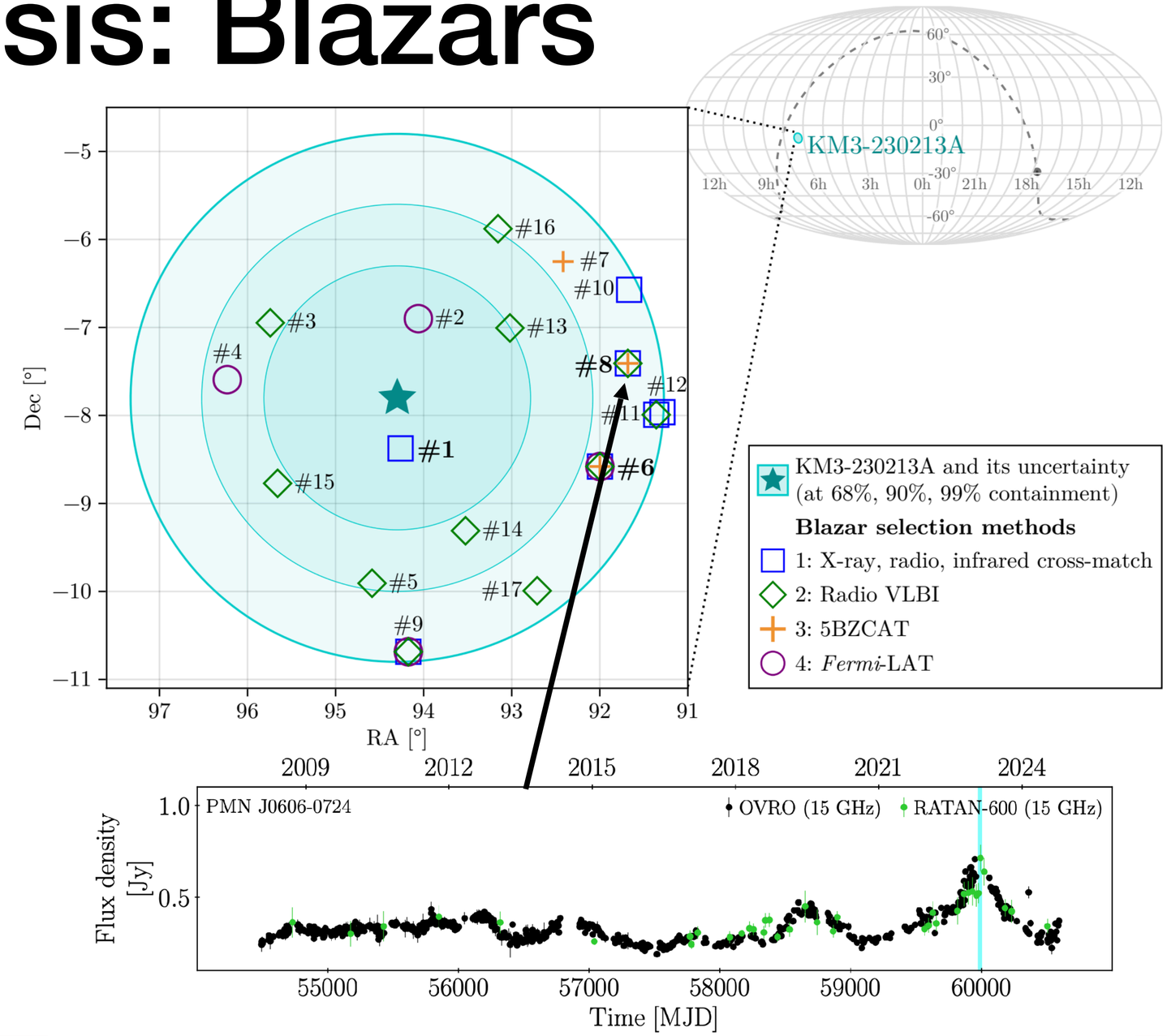
$\Longrightarrow$ Galactic origin unlikely

KM3NeT 2502.08387

KM3NeT 2502.08484

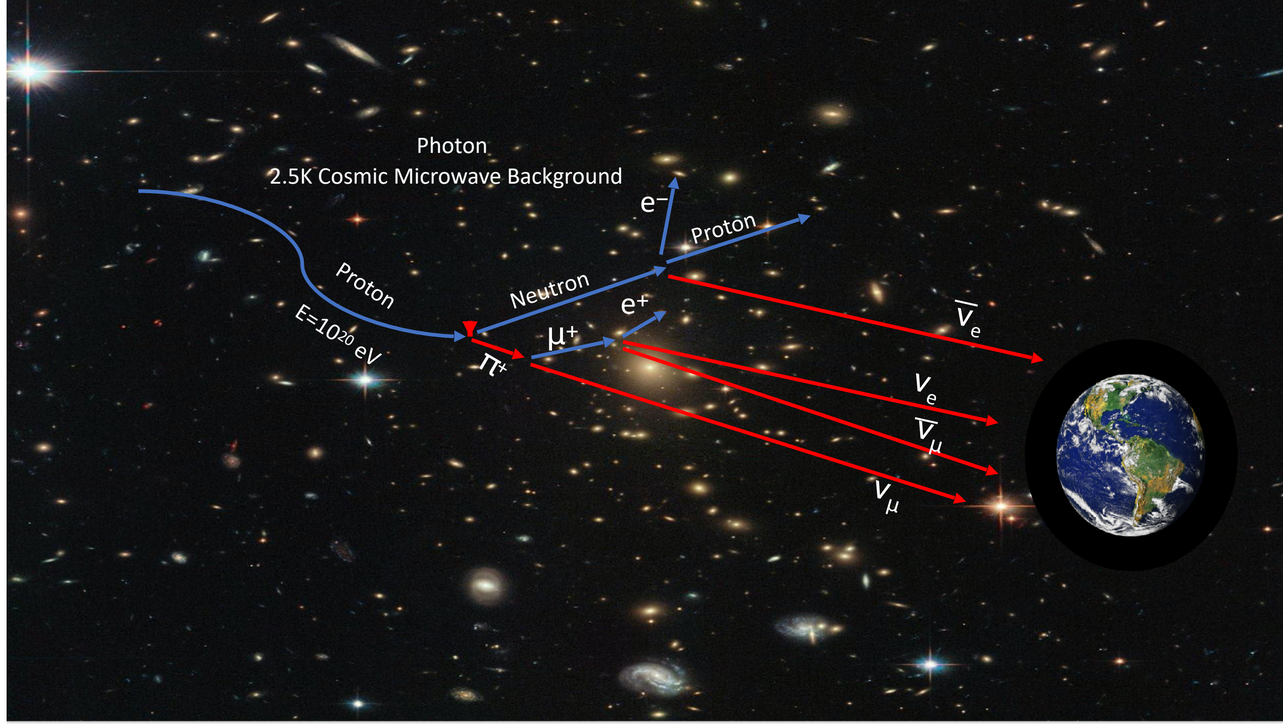
Source Hypothesis: Blazars

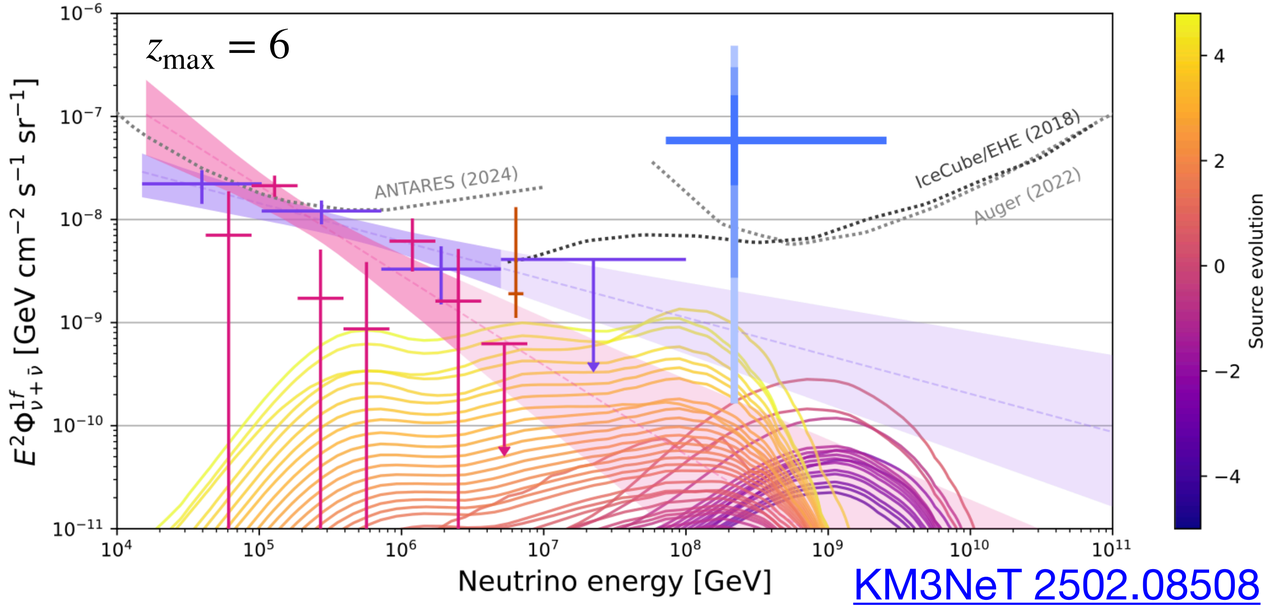
- Blazars are a promising extragalactic source of cosmic neutrinos
- 17 candidate blazar sources are identified within the 99% C.L. window in celestial coordinates
- A few interesting candidates in temporal coincidence; largest pre-trial significance is $p = 0.26\%$
- At this time, however, **KM3-230213A cannot be conclusively associated with an episode of enhanced multiwavelength emission from a blazar**



Source Hypothesis: Cosmogenic

- Cosmic ray source redshift evolution parameterized by $S(z) = (1+z)^m$, where $m \in [-5,5]$
- $m \ll 0 \Longrightarrow$ nearby sources dominate, intermediate-mass CR composition at source, **lower cosmogenic neutrino flux**
- $m \gg 0 \Longrightarrow$ distant sources dominate, heavier-mass CR composition at source, **higher cosmogenic neutrino flux**





KM3NeT 2502.08508

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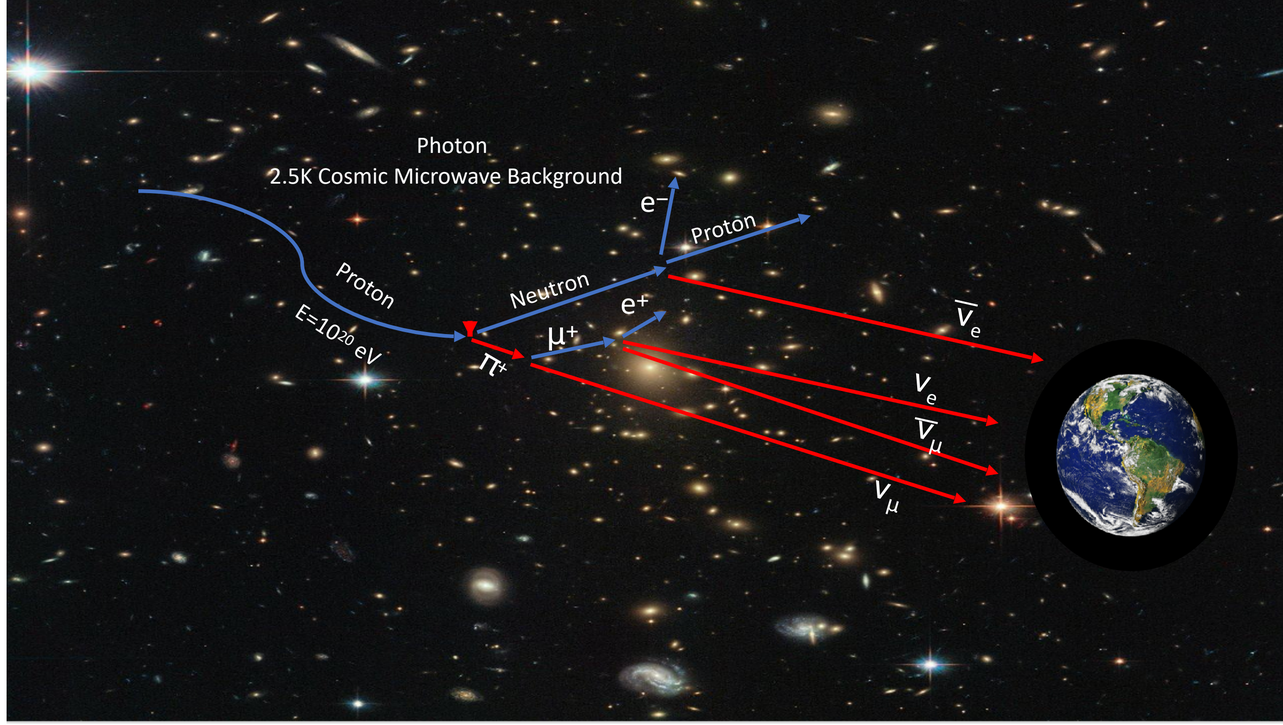
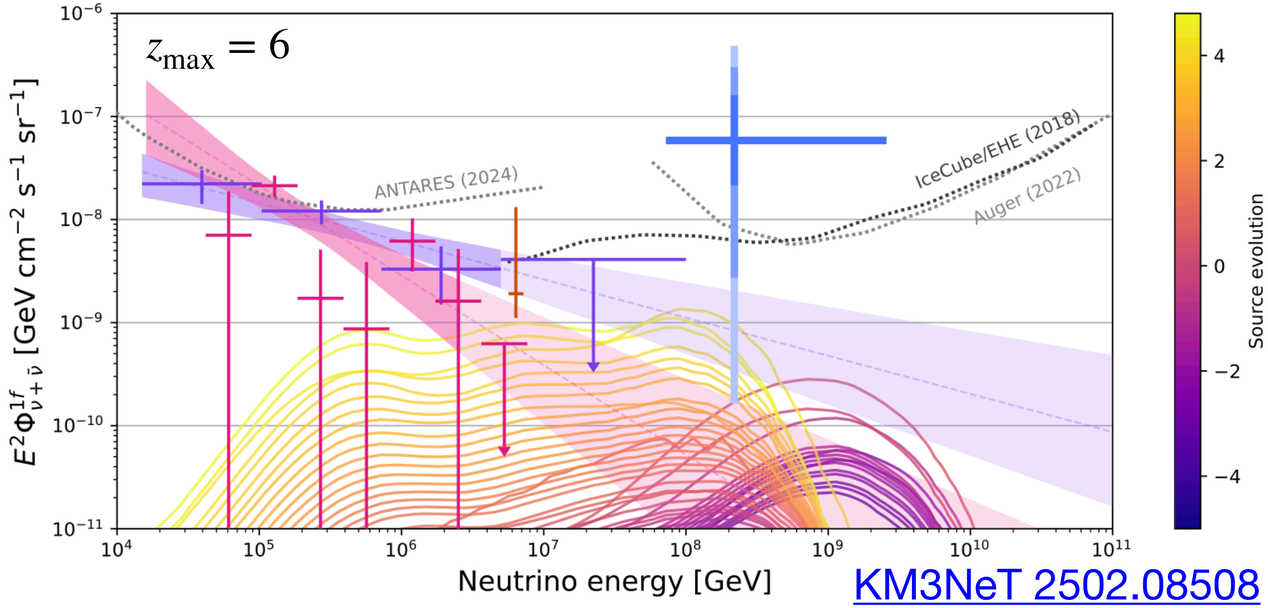
Preferred by KM3-230213A





KM3NeT 2502.08508

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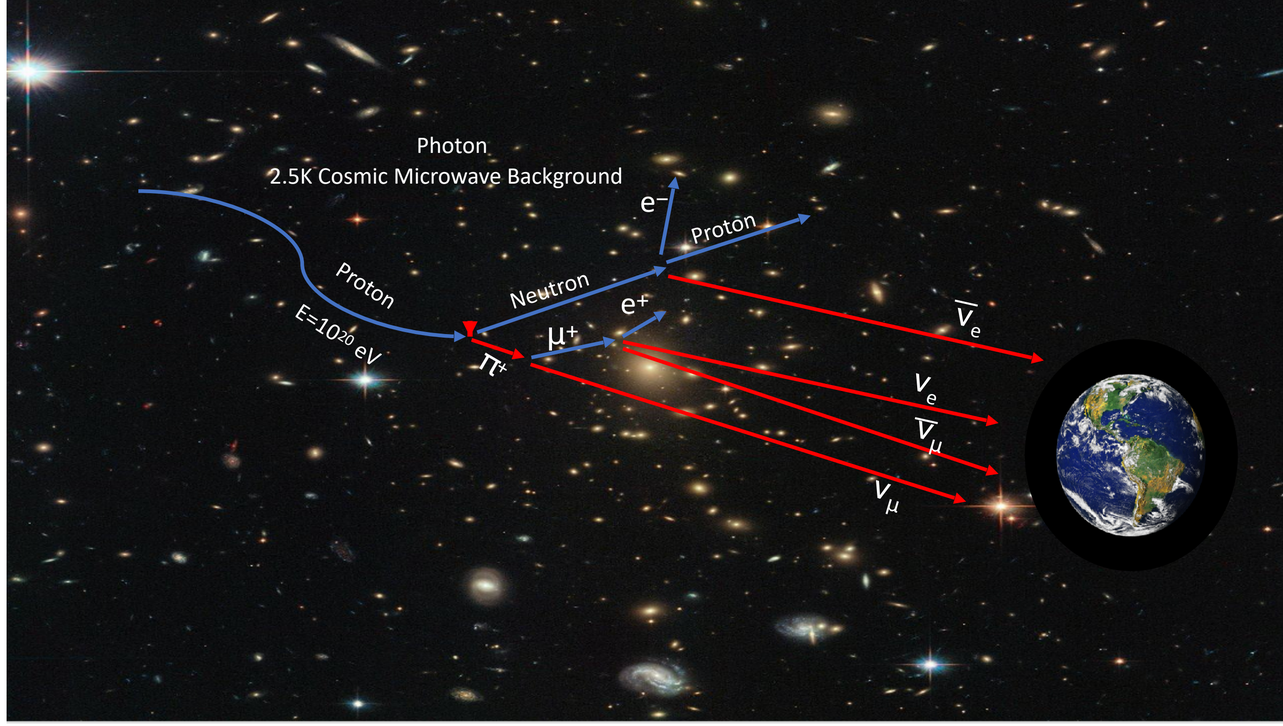
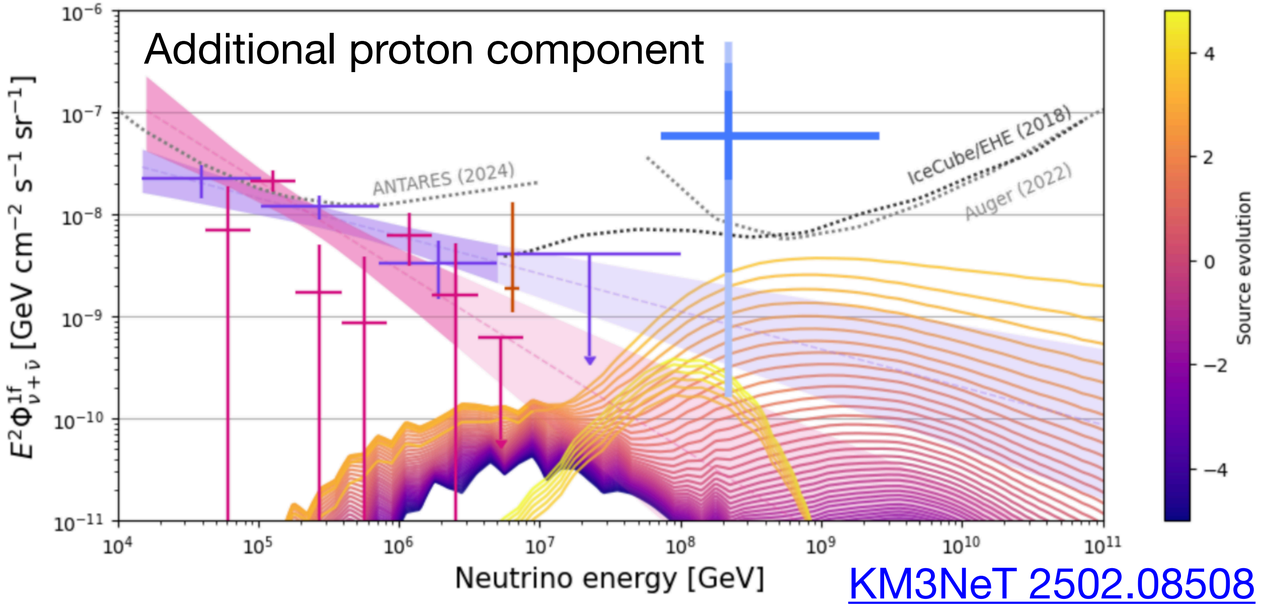
Preferred by KM3-230213A

An additional subdominant proton component can enhance the cosmogenic neutrino flux at the highest energies

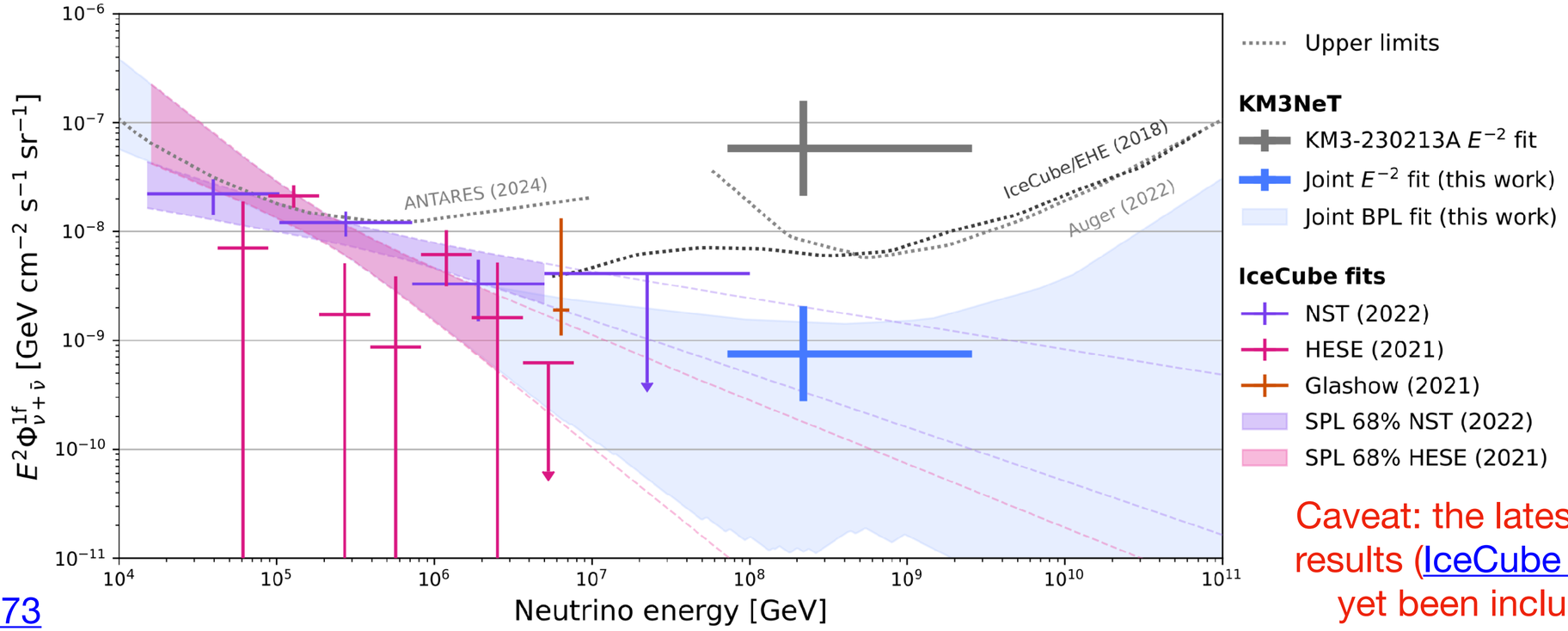




KM3NeT 2502.08508

KM3-230213A Within the Global Landscape

- We perform a joint fit between KM3NeT, IceCube, and Auger in the energy window of KM3-230213A
- Joint fit E^{-2} flux: $E^2\Phi^{1f}_{\nu+\bar{\nu}} = 7.5^{+13.1}_{-4.7} \times 10^{-10}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$
- KM3NeT-only fit E^{-2} flux: $E^2\Phi^{1f}_{\nu+\bar{\nu}} = 5.8^{+10.1}_{-3.7} \times 10^{-8}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$



[KM3NeT 2502.08173]

Caveat: the latest IceCube EHE results ([IceCube 2025]) have not yet been included in the fit

Is there tension between KM3-230213A and null observations from IceCube and Auger?

We consider a generic single-power-law flux model in the UHE region

Frequentist test

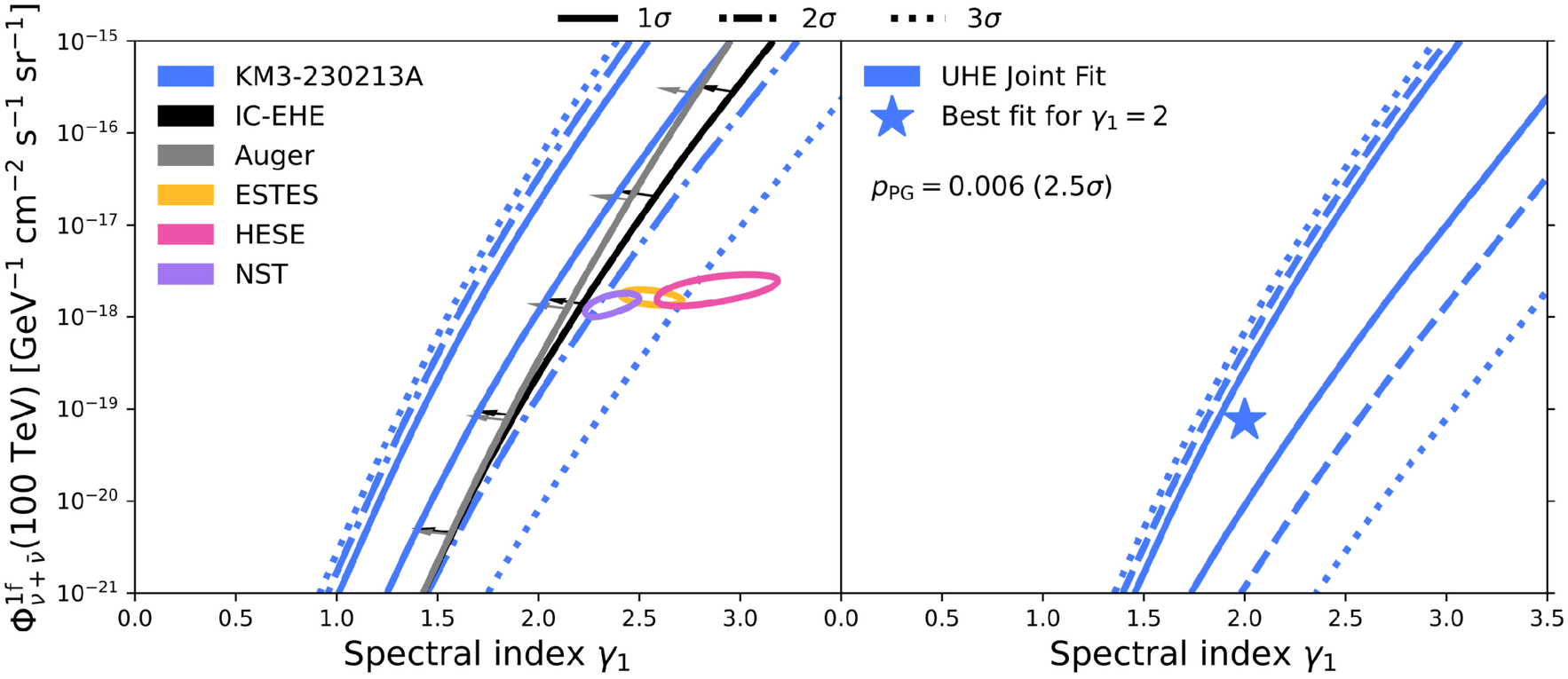
Parameter goodness of fit [1]

$z_{\mathrm{PG}} = 2.5\sigma$

Bayesian test

Posterior predictive check [2]

$z_{\mathrm{PPC}} = 2.5\sigma$

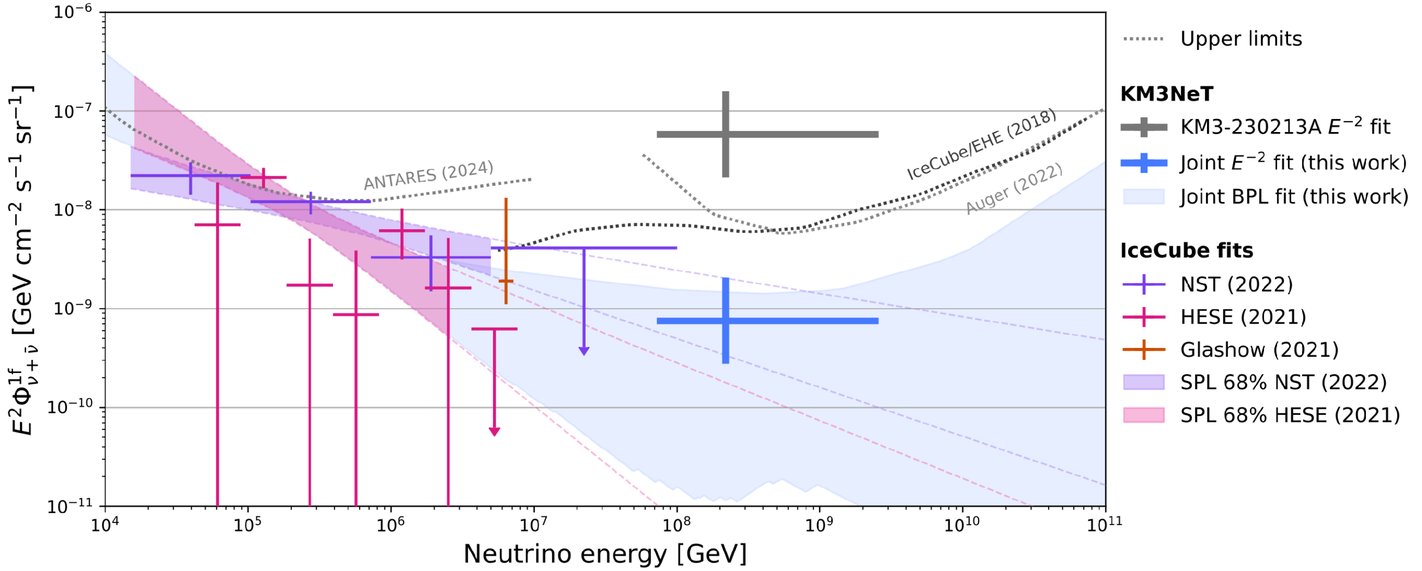


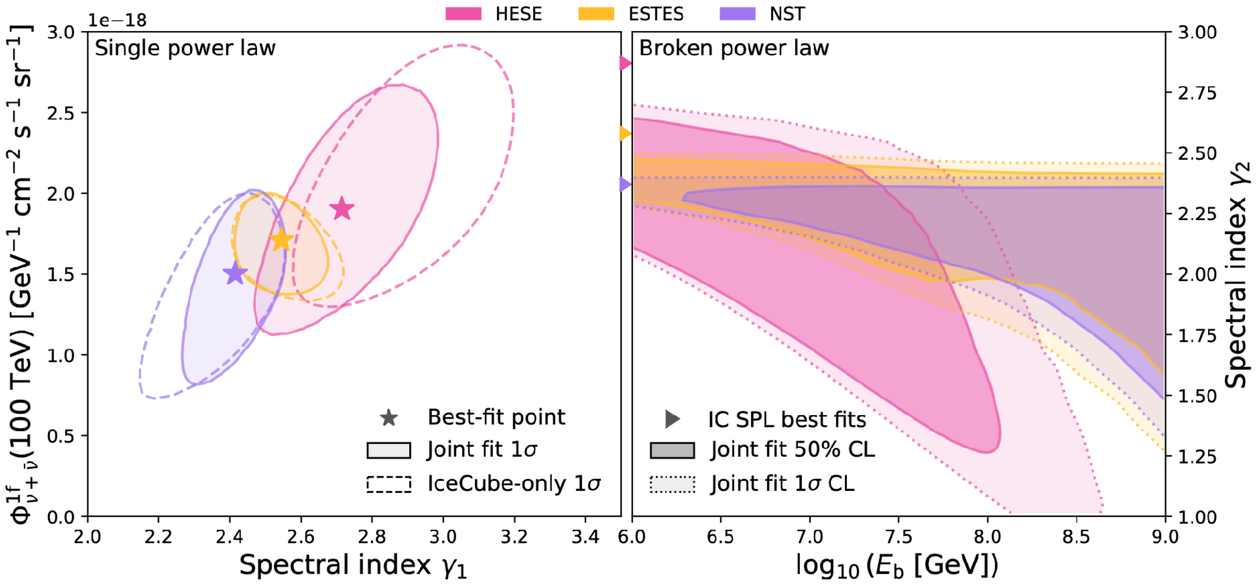
KM3NeT 2502.08173

[1] Maltoni Schwetz 2003 [2] Gelman+ 1996

Is there evidence for a new component?

- We perform fits to a single and broken power law flux hypothesis across the entire astrophysical neutrino spectrum
- Three IceCube measurements below 10 TeV: HESE, ESTES, and NST
- **No preference for BPL over SPL in the global fit**





UHE Sample(s)	KM3-230213A			Global		
HE Sample	HESE	ESTES	NST	HESE	ESTES	NST
Bayes factor $\mathcal{B}$	27.0	8.7	3.9	1.2	0.6	0.3
LR p-value (%)	0.4	1.7	5.9	33	86	100

KM3NeT 2502.08173

Full KM3NeT/ARCA230 Sensitivity

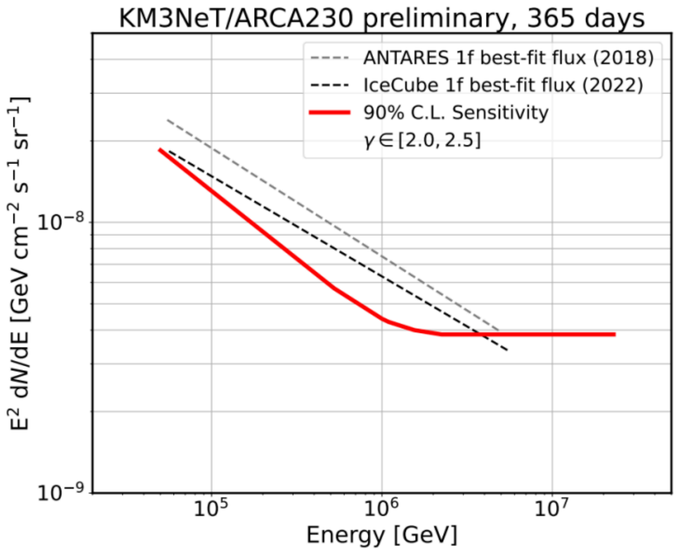


Figure 3: Sensitivity (90% CL) as the envelope for different spectral indices with respect to the neutrino energy.

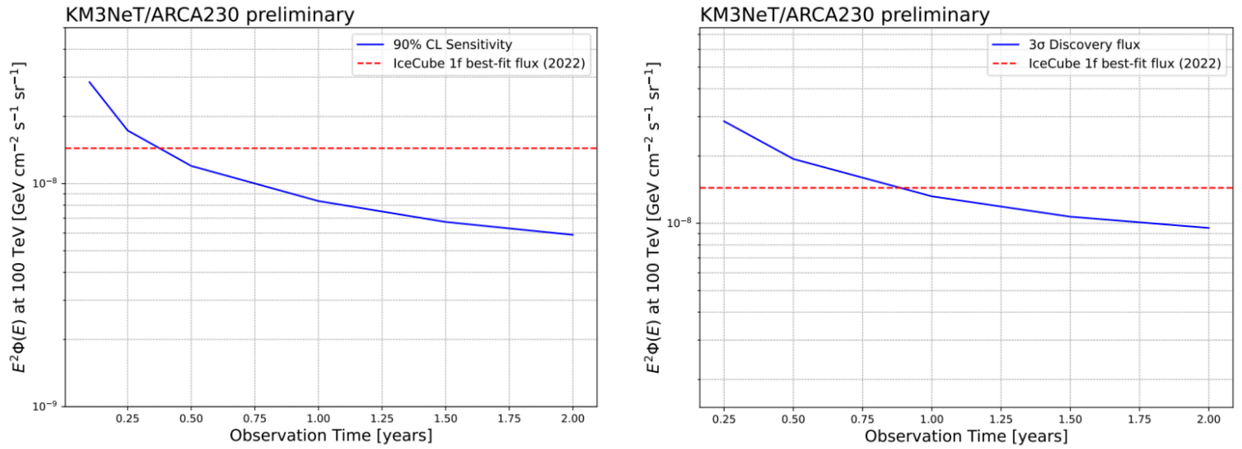
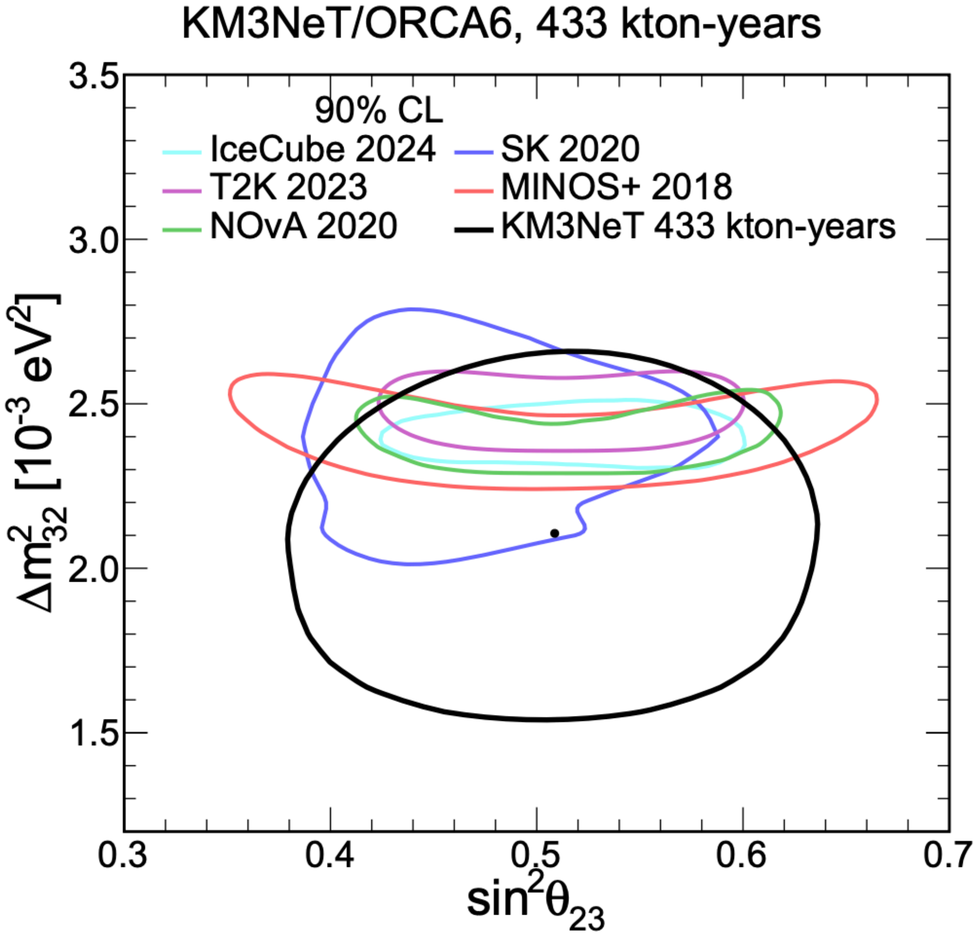


Figure 4: 90% C.L. sensitivity (left) and discovery flux for 3σ significance (right) shown as a function of the ARCA230 operation time for the flux as measured in [2].

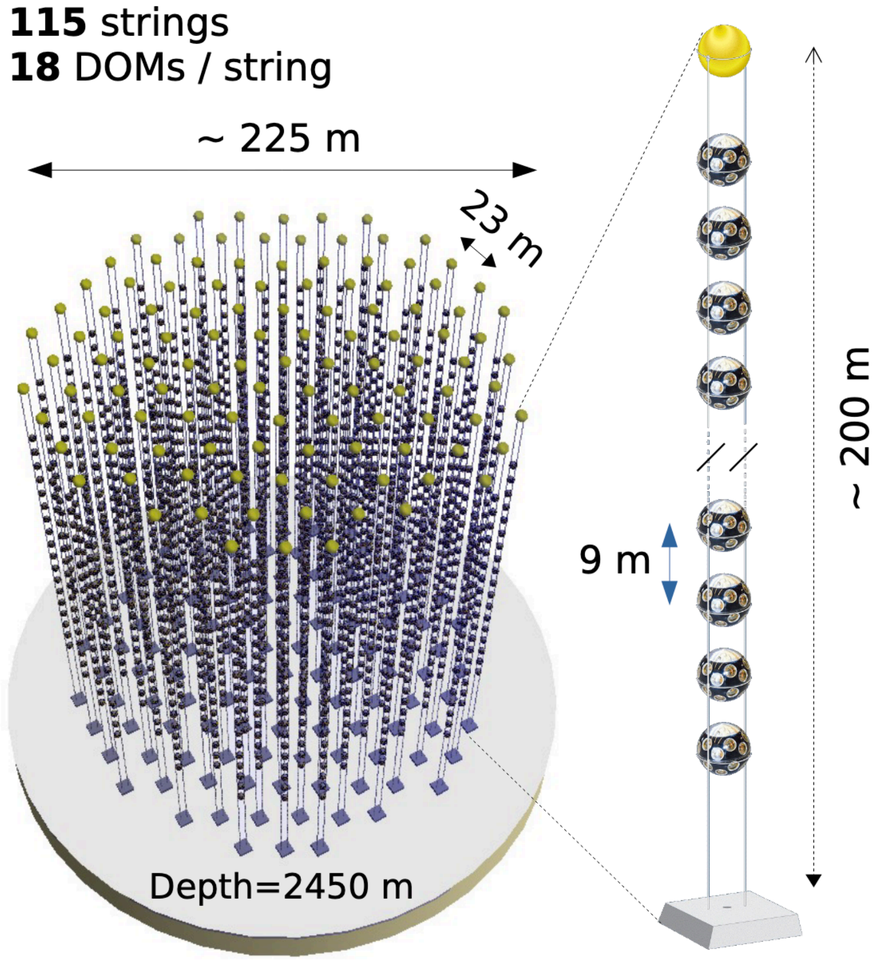
Karagiannis+ ICRC 2025

Also Up Next: KM3NeT/ORCA

Competitive measurement using only using 6/115 ORCA strings



KM3NeT JHEP Vol 2024 (2024)

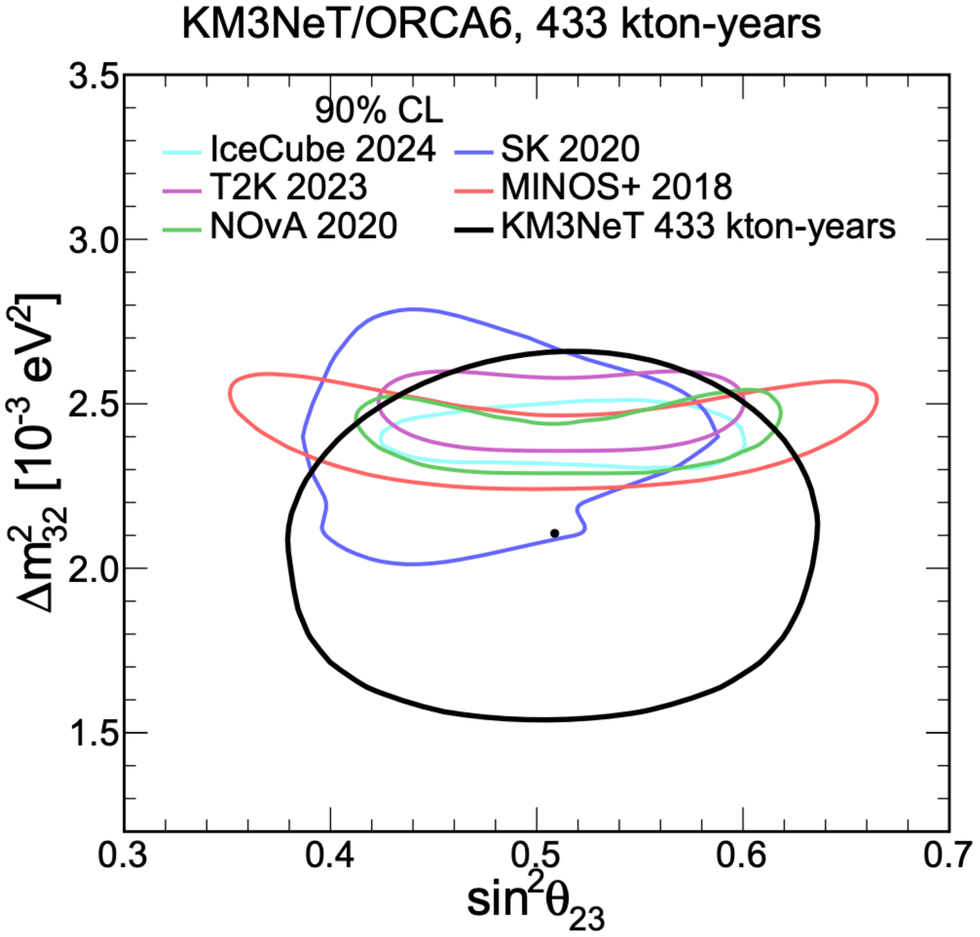


Akindinov+ EPJ-C 2019

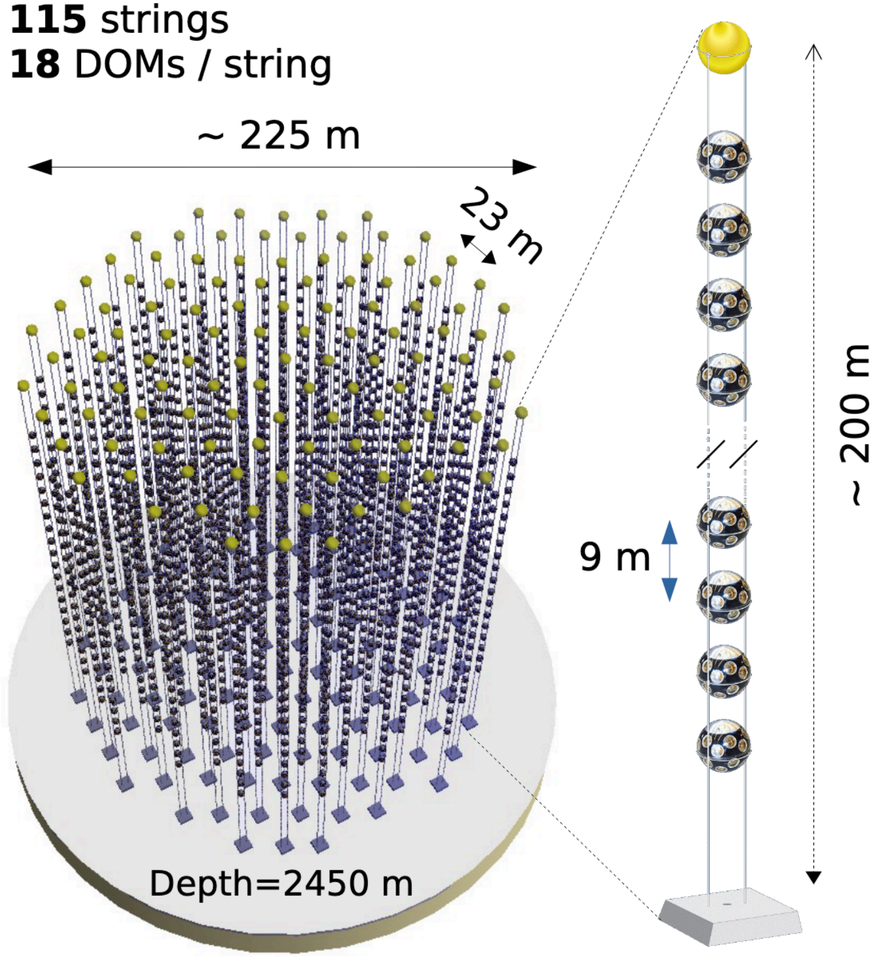
Also Up Next: KM3NeT/ORCA

Competitive measurement using only using 6/115 ORCA strings

33 strings deployed as of July 2025



KM3NeT JHEP Vol 2024 (2024)

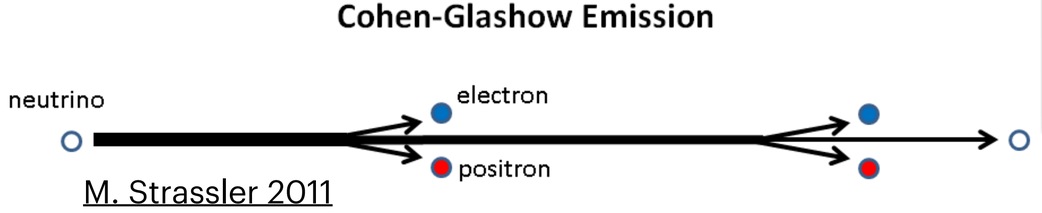


Akindinov+ EPJ-C 2019

KM3-230213A constrains Lorentz symmetry

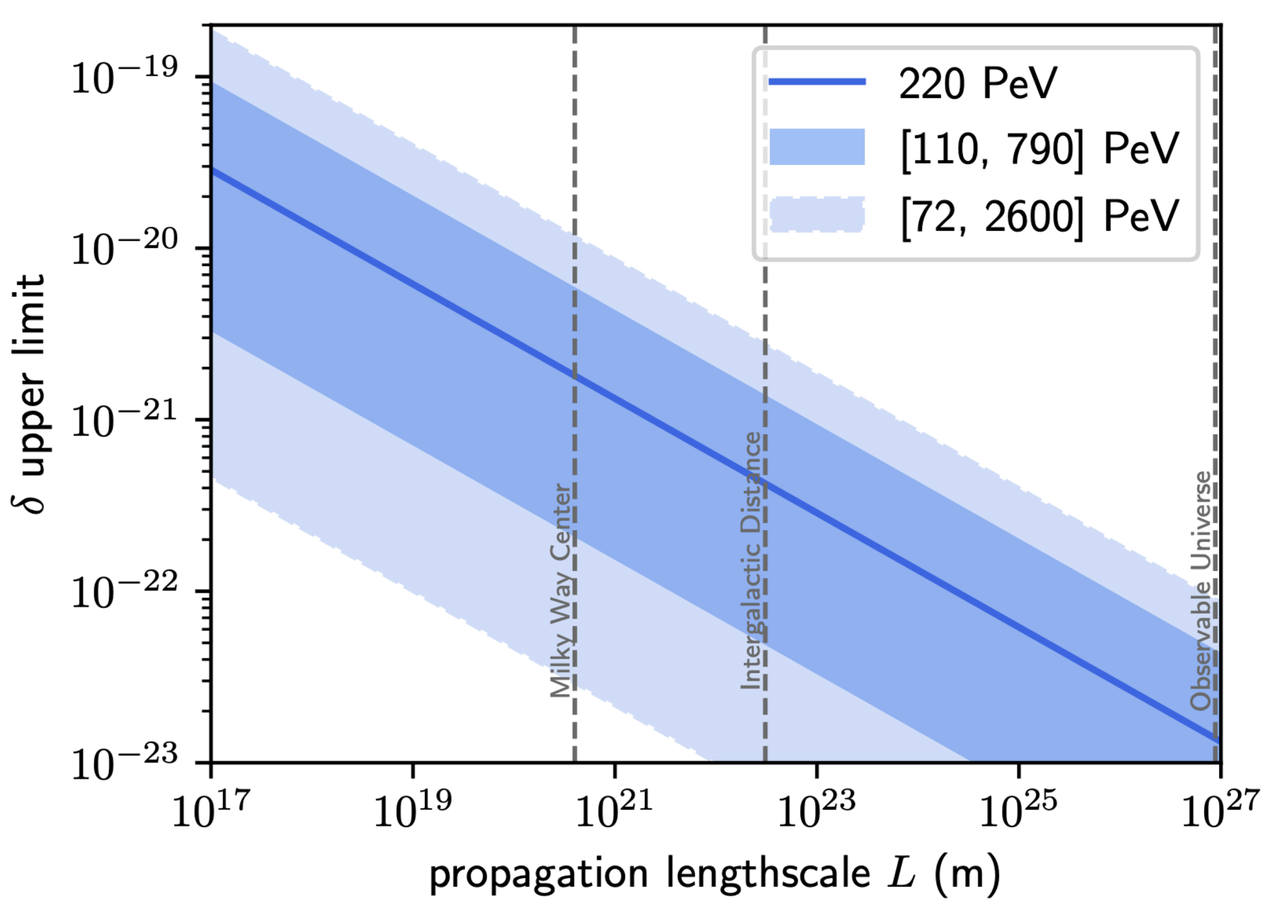
Alex Wen

- Effective superluminal neutrinos lose ei
  $(\nu \to \nu e^+ e^-)$
- $\Gamma \propto E^5 \delta^3$, where $\delta \equiv c_\nu^2 - 1$
- Thus, a high energy neutrino can se
  strong upper limit on δ



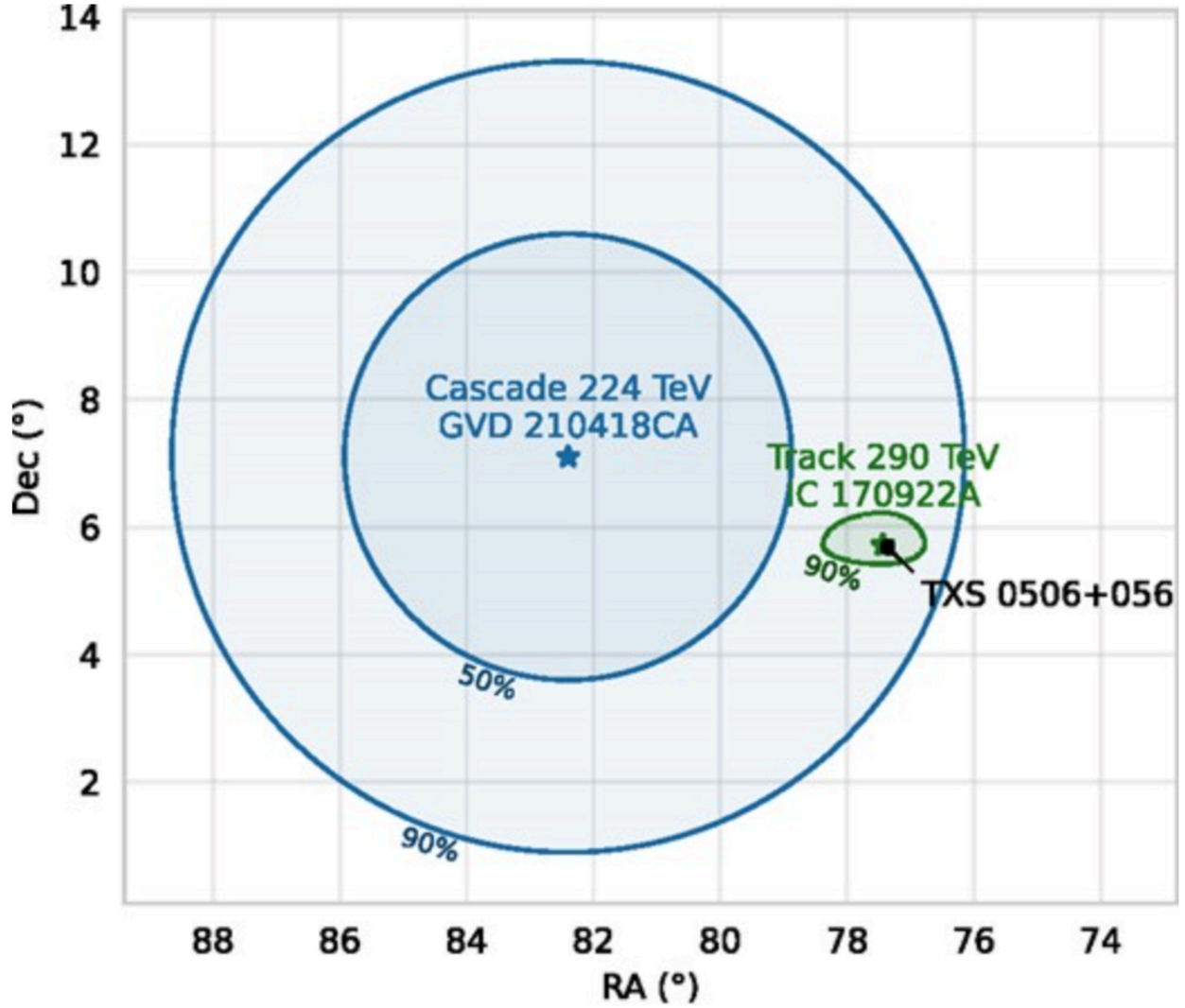
M. Strassler 2011

Method	Energy scale	Limit on δ
IceCube TXS 0506+056	~ 290 TeV	2.4×10^{-18}
Stecker et al. (Ref. [21])	60 TeV–2 PeV	$2 \times 5.2 \times 10^{-21}$
KM3-230213A (conservative)	~ 220 PeV	1.8×10^{-21}
KM3-230213A (extragalactic)	~ 220 PeV	4.2×10^{-22}



KM3NeT Communications Physics Vol 8 (2025)

Baikal-GVD for TXS 0506+056



Askaryan v.s. Geomagnetic

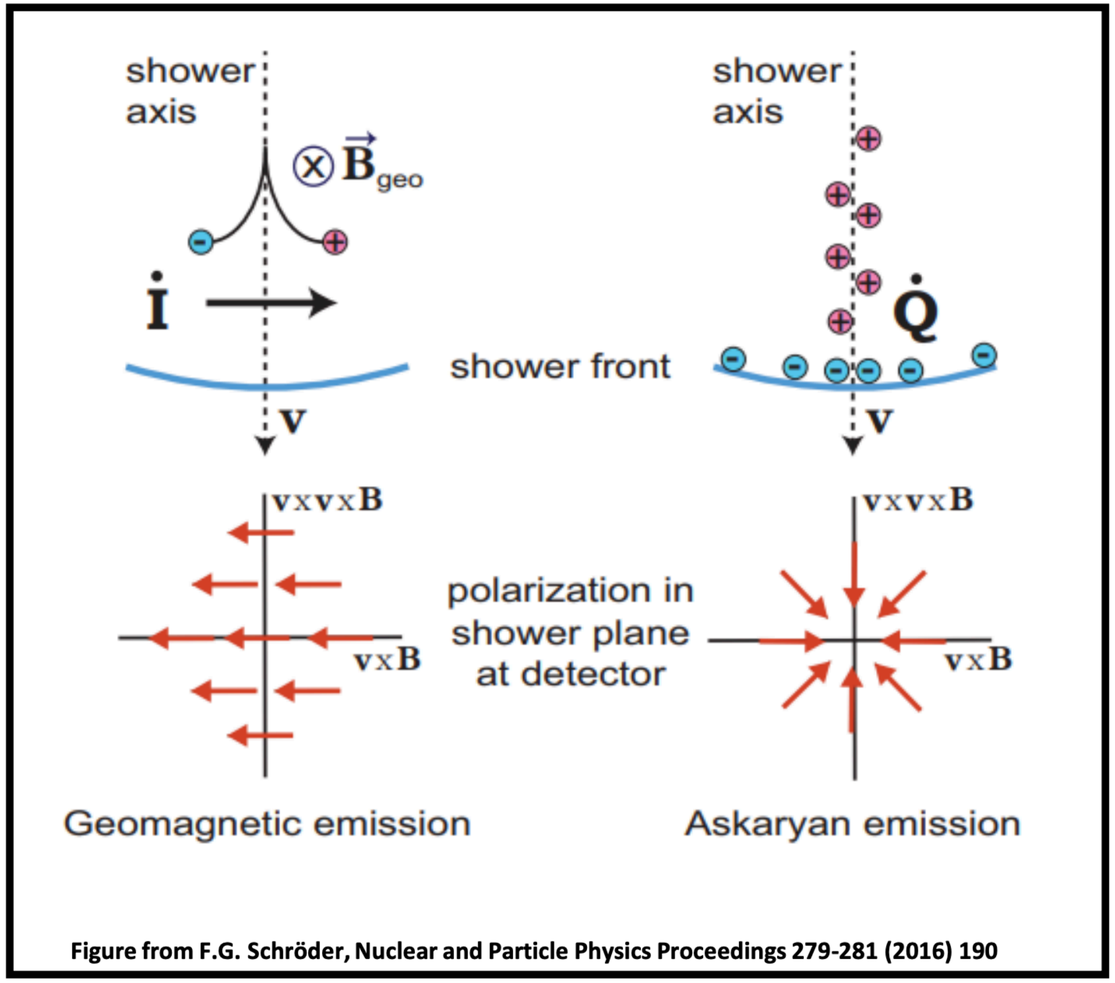
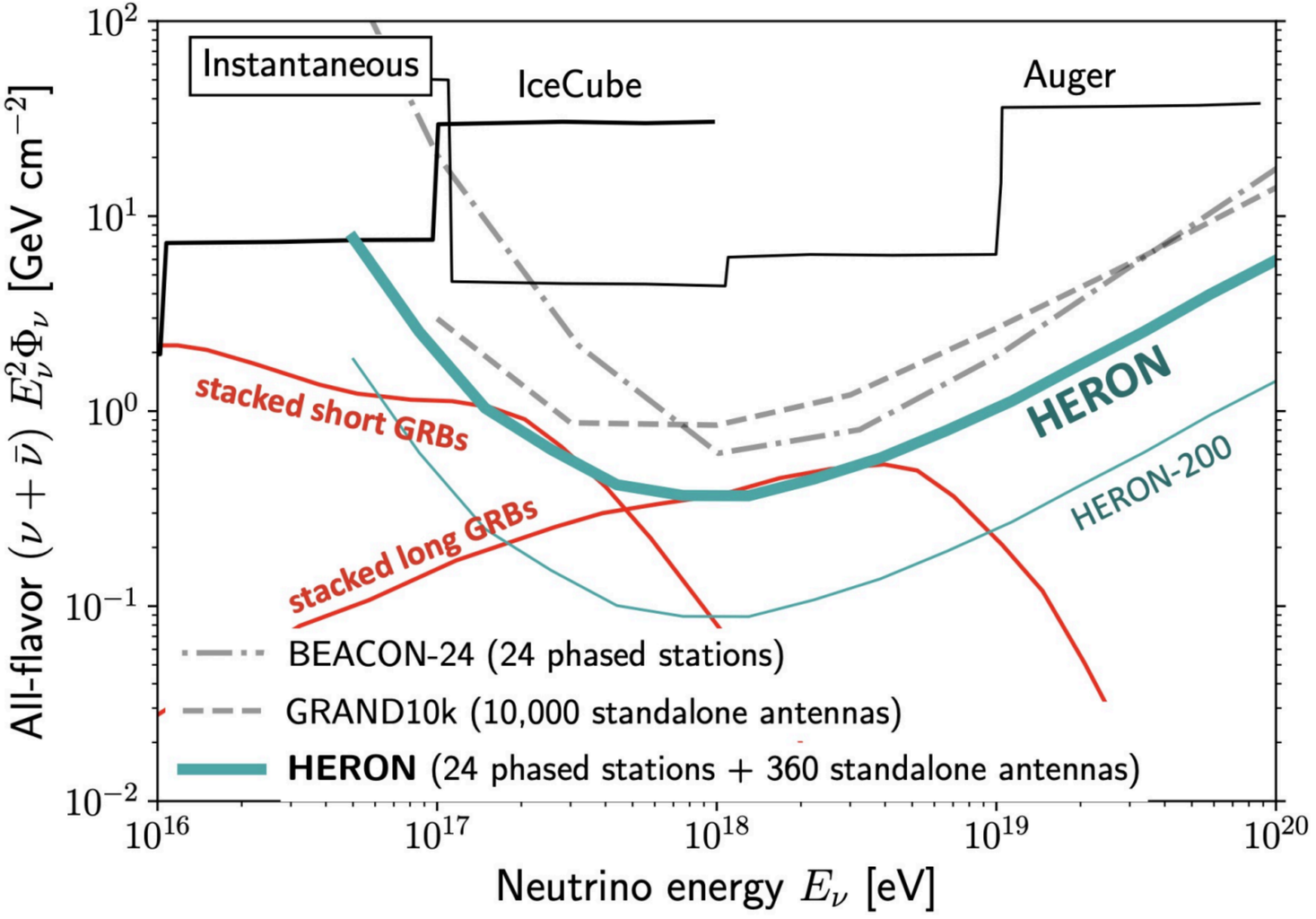


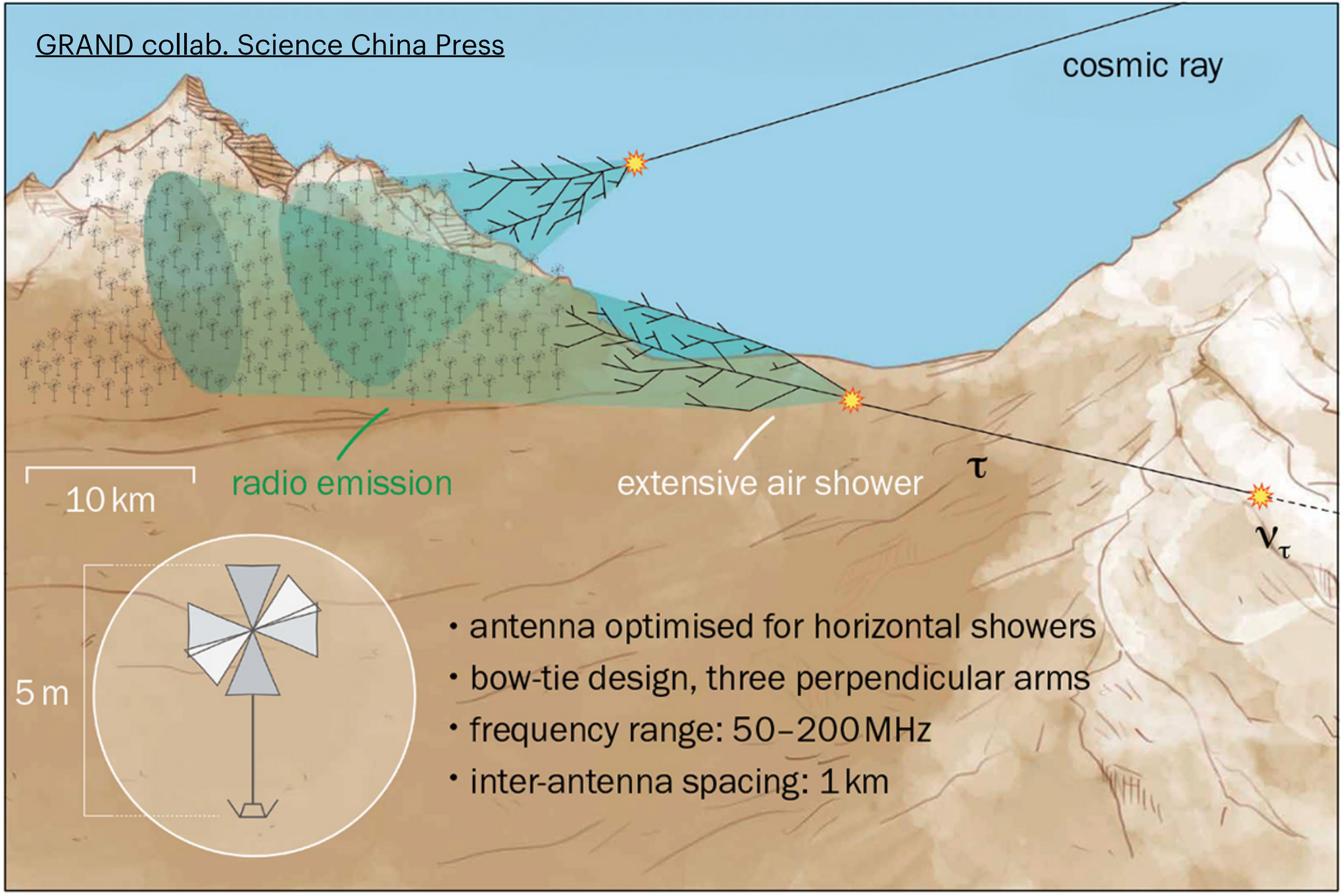
Figure from F.G. Schröder, Nuclear and Particle Physics Proceedings 279-281 (2016) 190

Zeolla ICRC 2025

GRAND + BEACON = HERON

Kotera (HERON), ICRC 2025



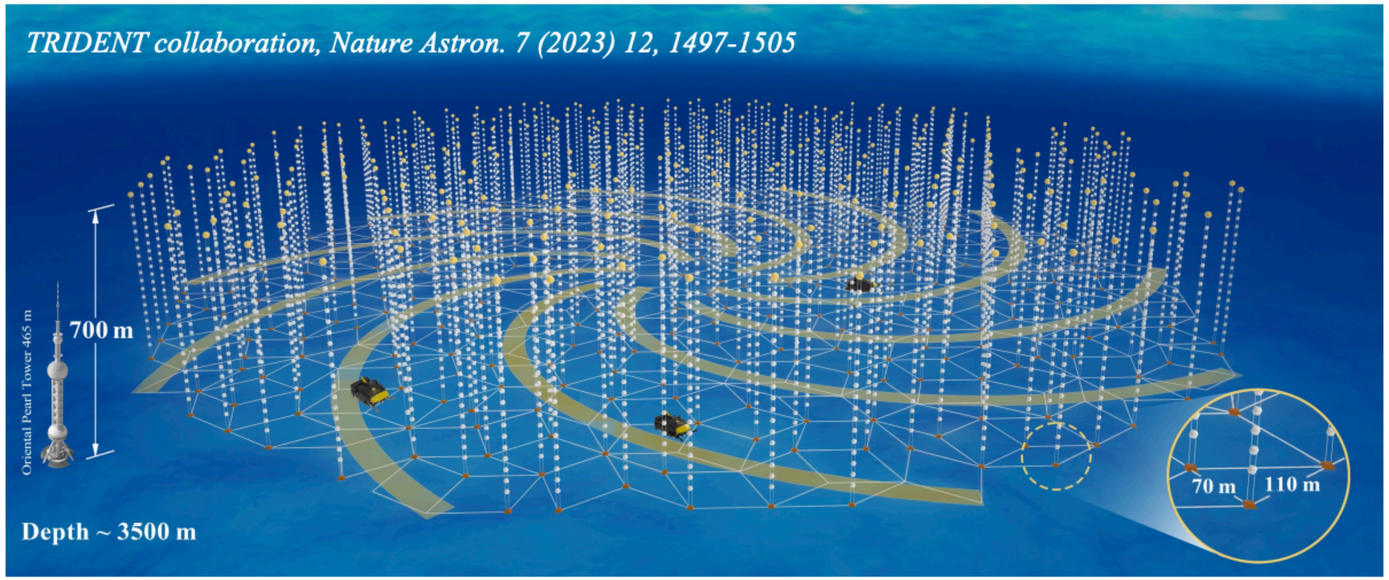

GRAND collab. Science China Press
cosmic ray
radio emission
extensive air shower
τ
ν_τ
10 km
5 m
• antenna optimised for horizontal showers
• bow-tie design, three perpendicular arms
• frequency range: 50–200 MHz
• inter-antenna spacing: 1 km

Conceptual Design of TRIDENT & TRIDENT Phase-I

TRIDENT 海 | 铃 | 计 | 划

TRIDENT full array:

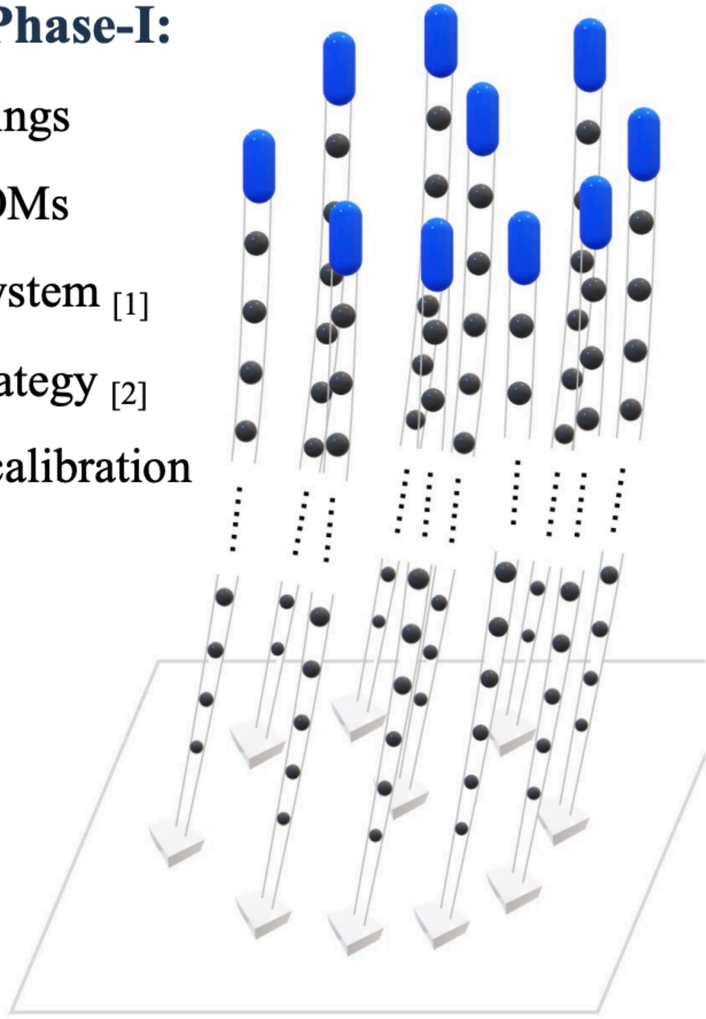
- Water depth: ~3500m
- Number of strings: ~1000, 20,000 hDOMs, Penrose-tiling
- Inter-string distance: 70m/110m Inter-DOM distance: 30m
- Detection Volume: ~8 km^3



CCSN detection: PoS(ICRC2025)-1004 *Earth-tomography: PoS(ICRC2025)-1059*
Prompt atmospheric neutrinos: PoS(ICRC2025)-1062

TRIDENT Phase-I:

- First 10 strings
- ~ 200 hDOMs
- Acoustic system [1]
- Trigger Strategy [2]
- Real-time calibration



[1] *PoS(ICRC2025)-1102* [2] *PoS(ICRC2025)-1231*

W. Tian, ICRC 2025