Credit M. Wolf - IceCube/NSF

Current results and a future outlook

Very large neutrino telescopes

IceCube

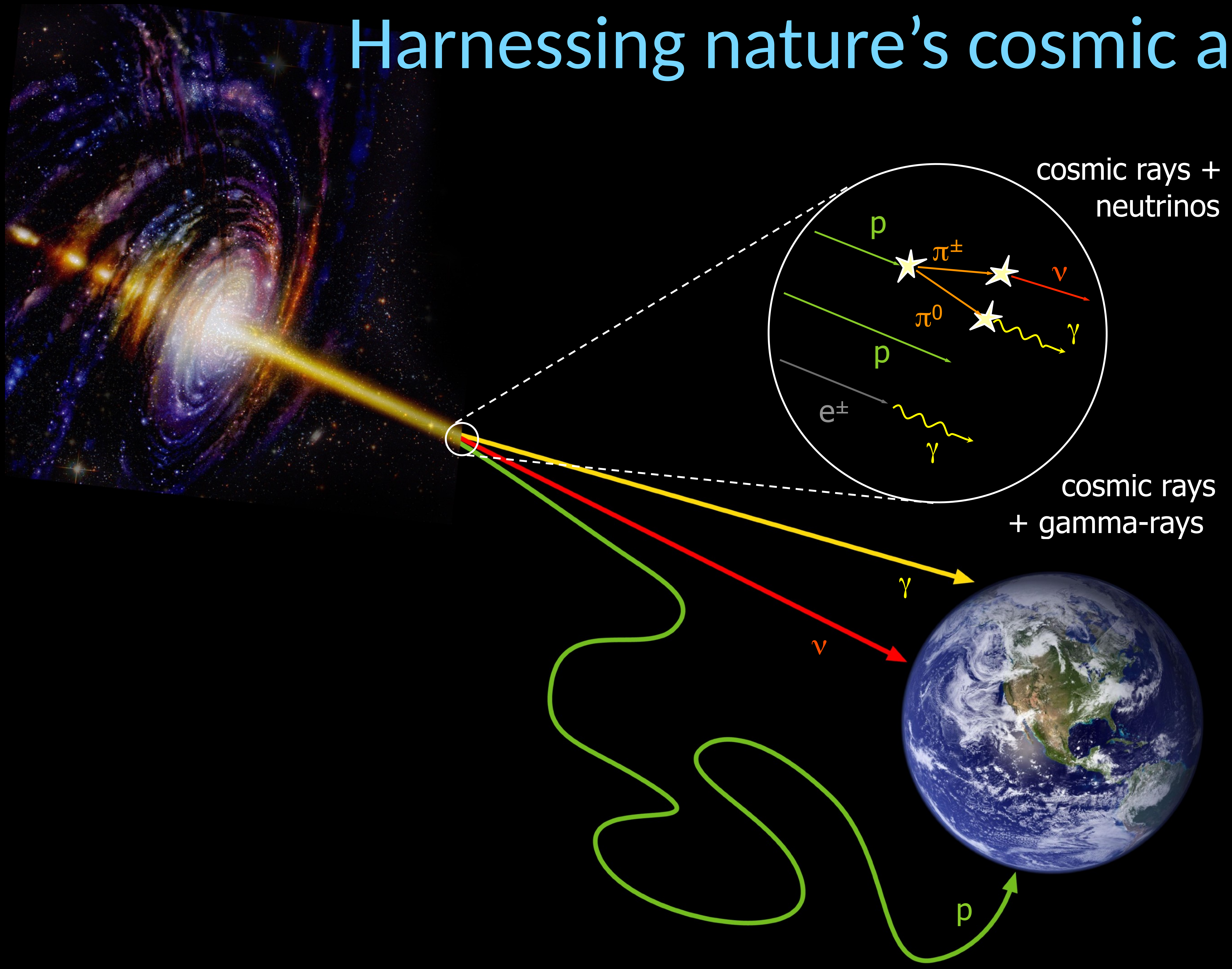
P-ONE

Darren R Grant — WNPPC — February 2024

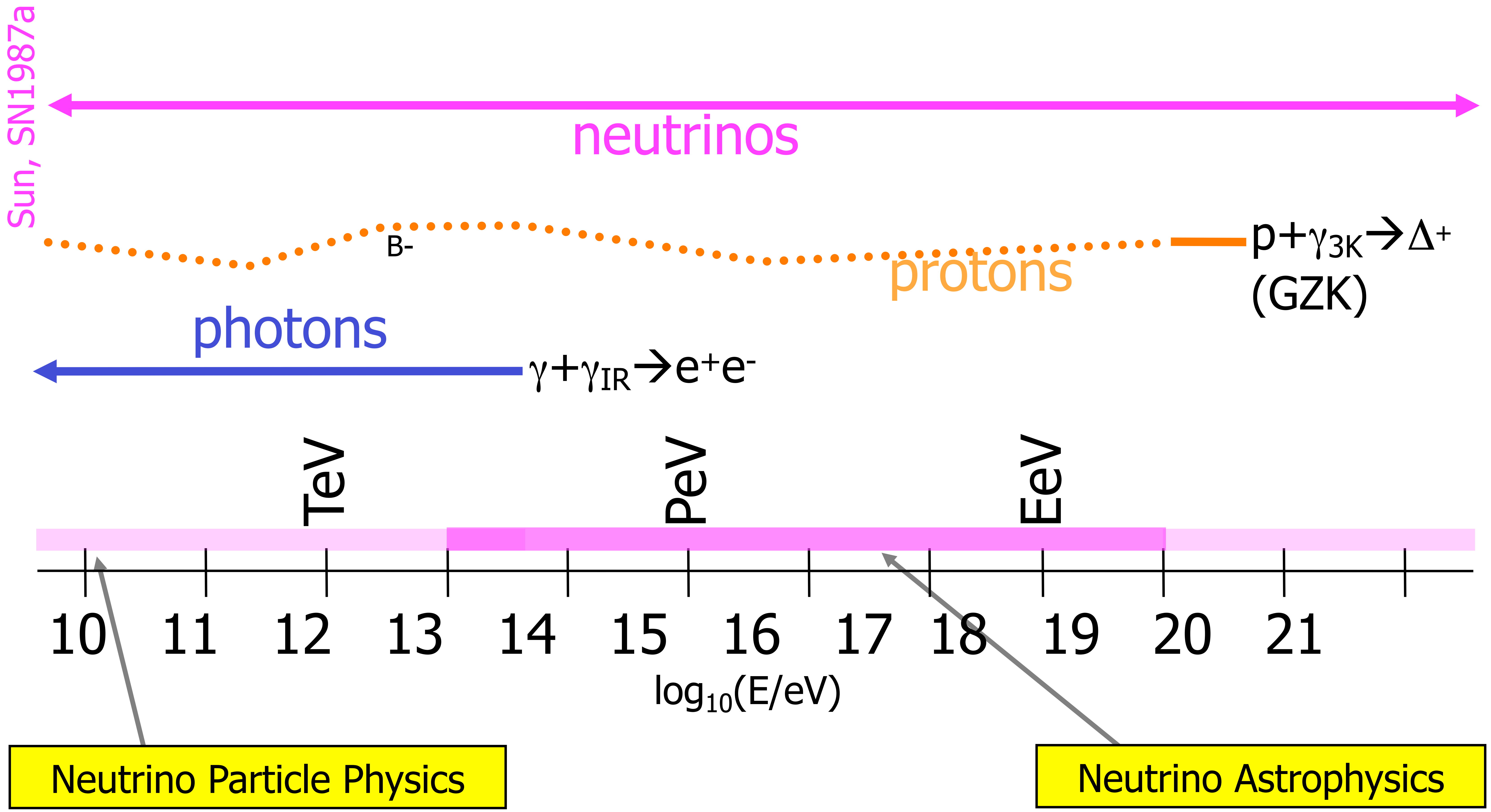
Canada Excellence Research Chairs
Chaires d'excellence en recherche du Canada

SFU SIMON FRASER UNIVERSITY

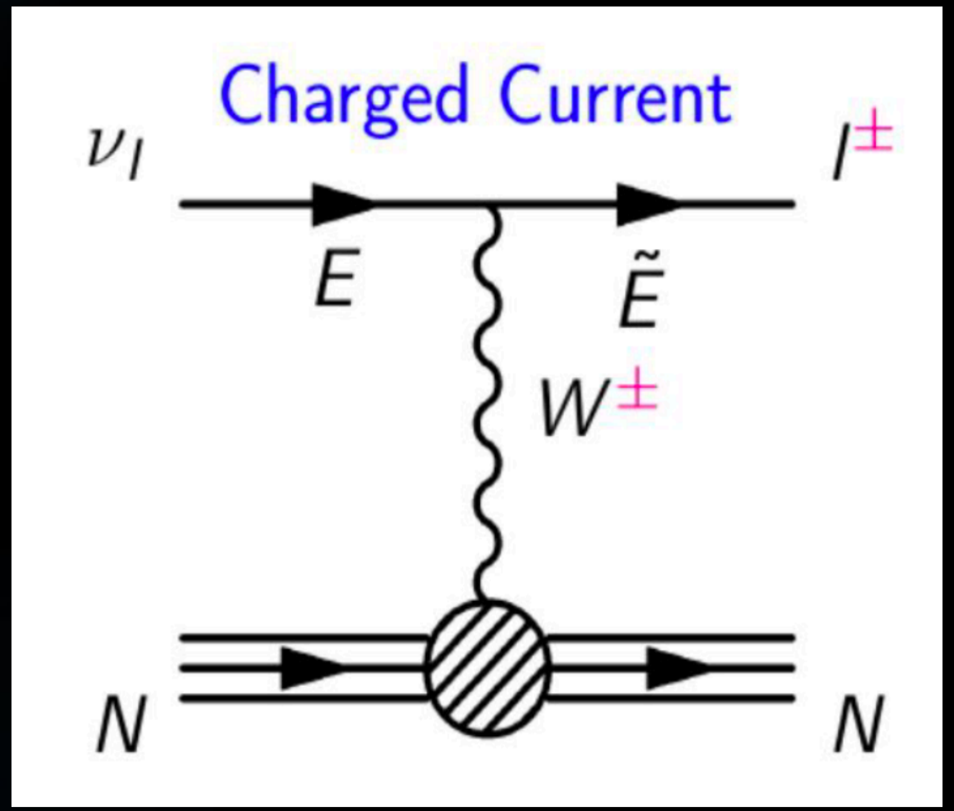
Harnessing nature's cosmic accelerators

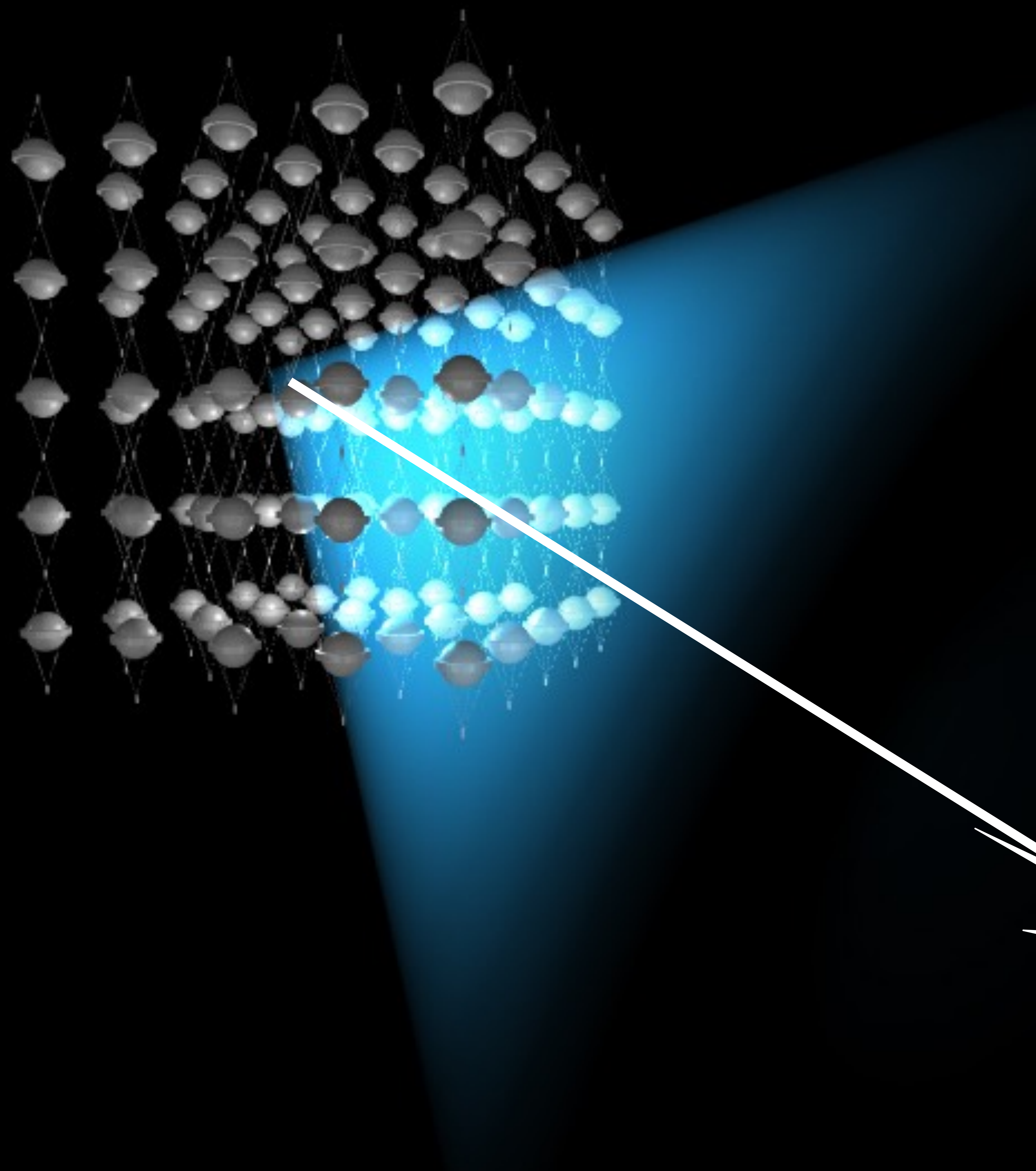


Cosmic messengers



charged secondary particles produced as the neutrino disappears





nuclear interaction

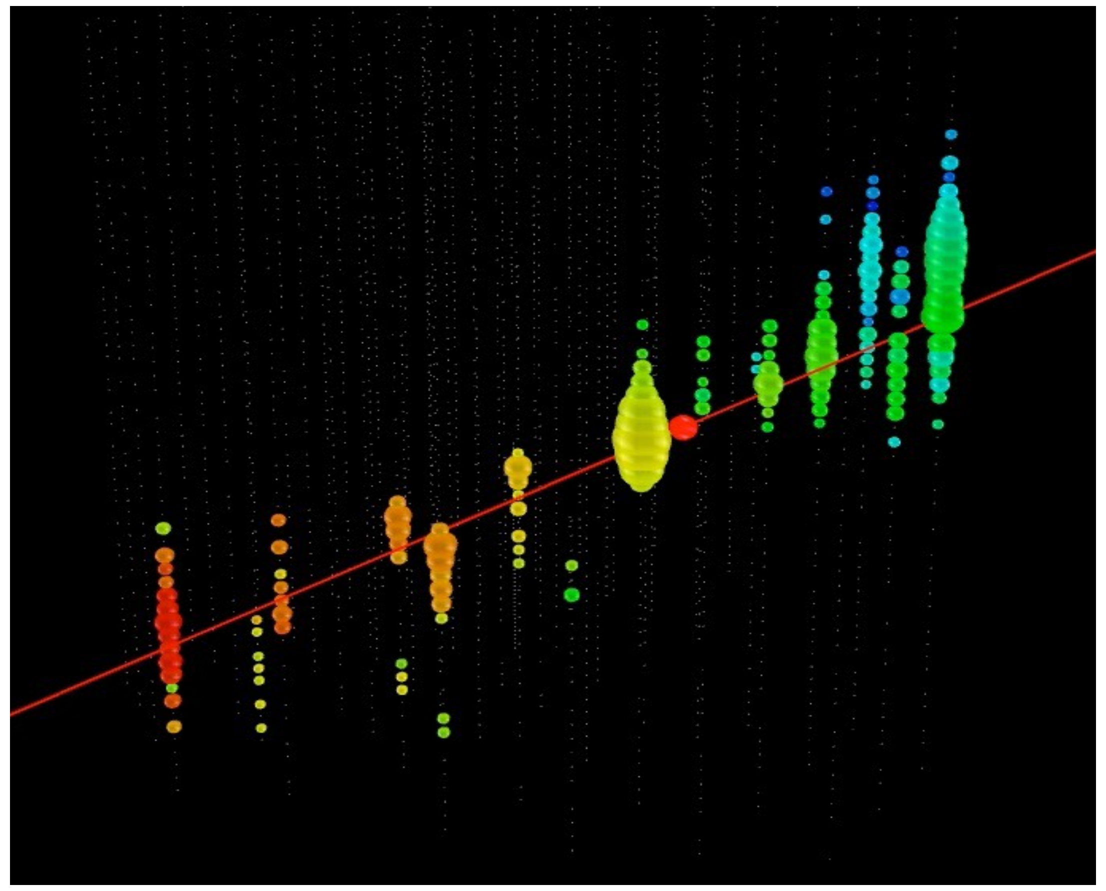
neutrino

• lattice of photomultipliers

Principles of high-energy neutrino detection - water Cherenkov

TeV-scale+

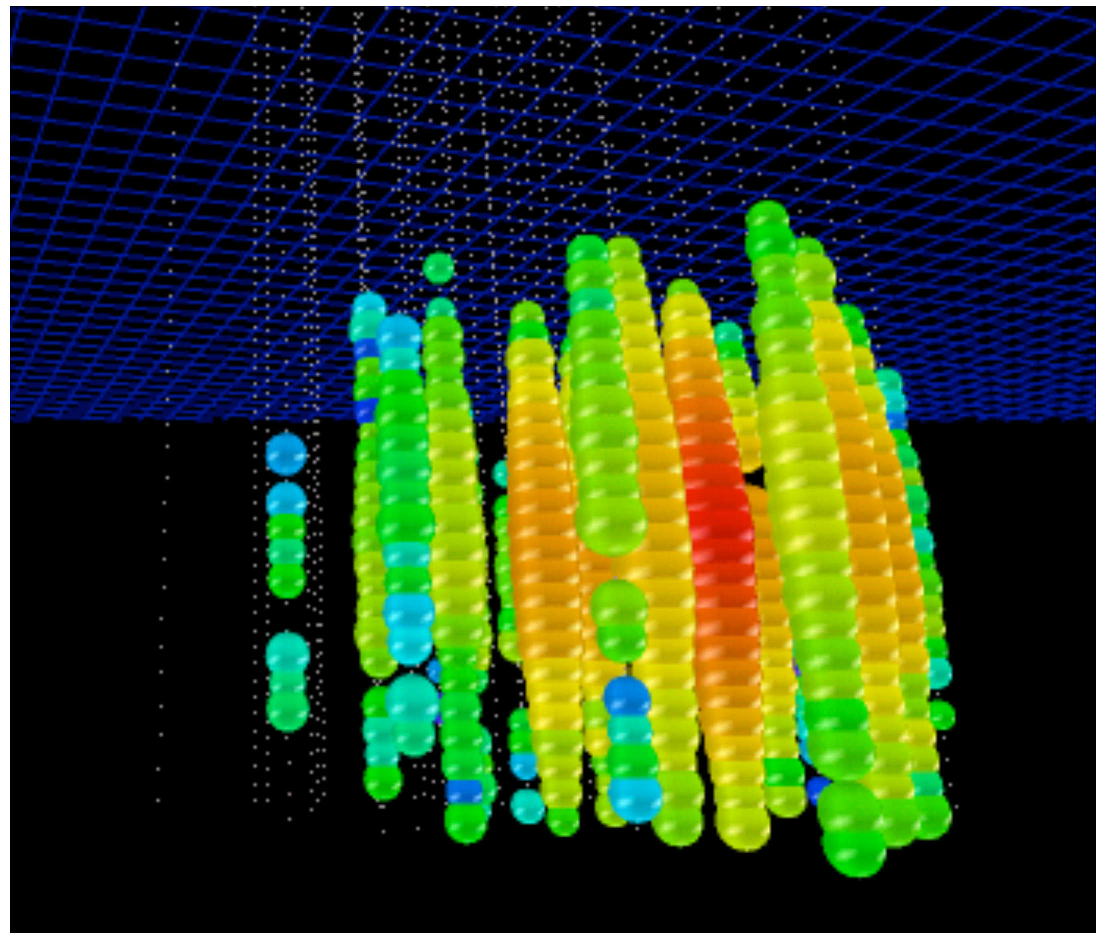
CC Muon Neutrino



track

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

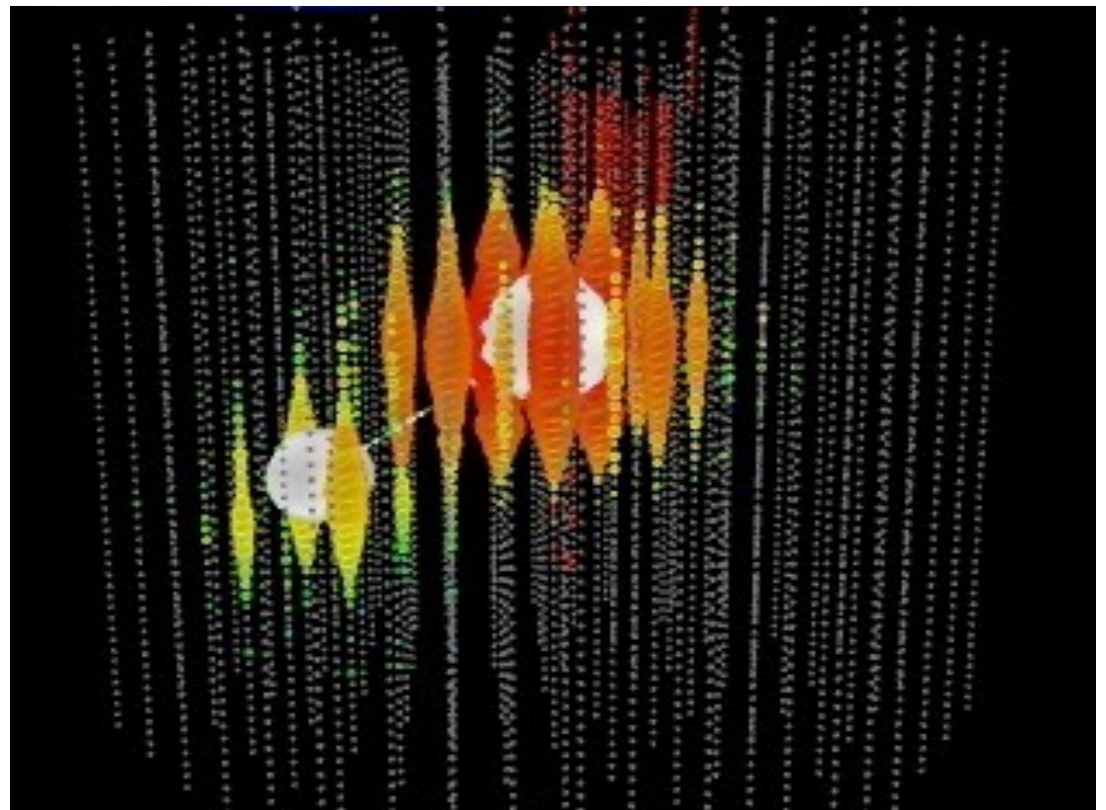
Neutral Current / Electron Neutrino



cascade

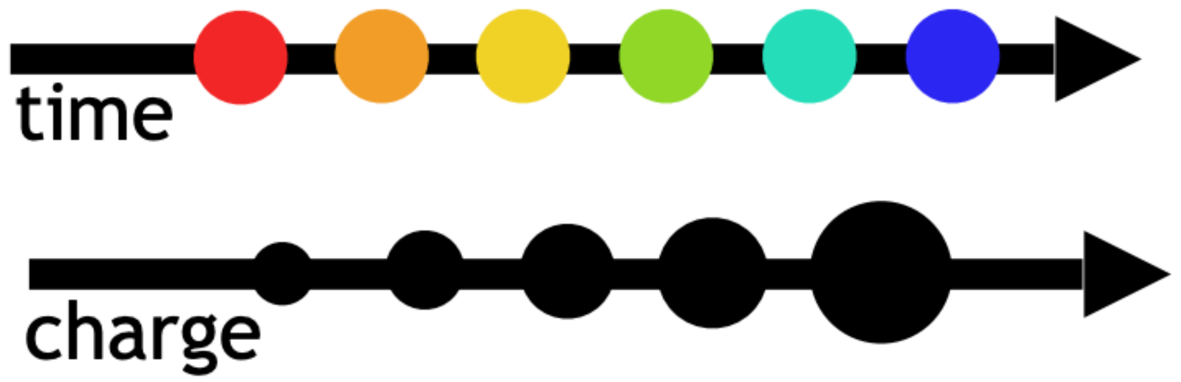
≈ ±15% deposited energy resolution
≈ 10° angular resolution (at energies ≳ 100 TeV)

CC Tau Neutrino

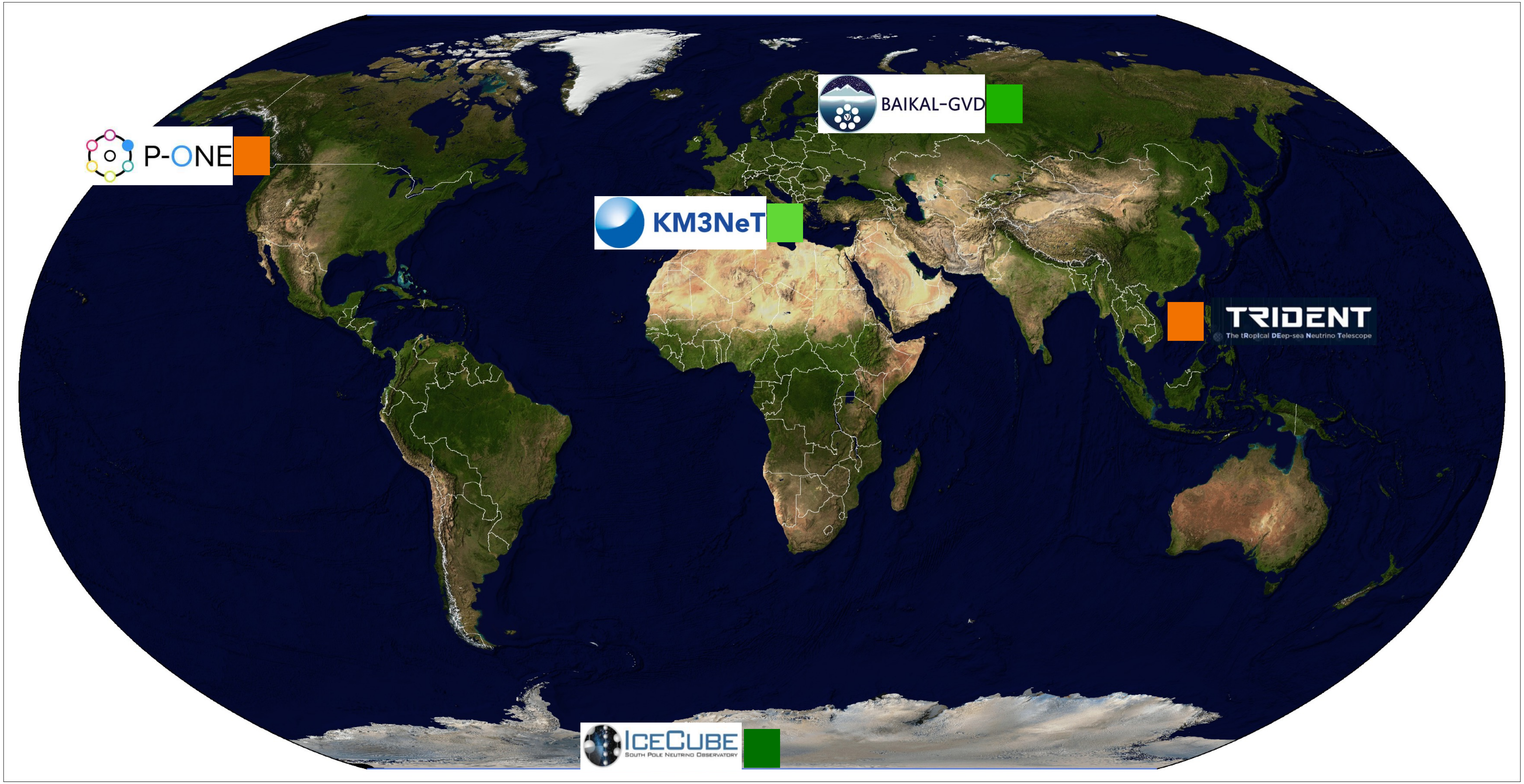


“double-bang” and other signatures

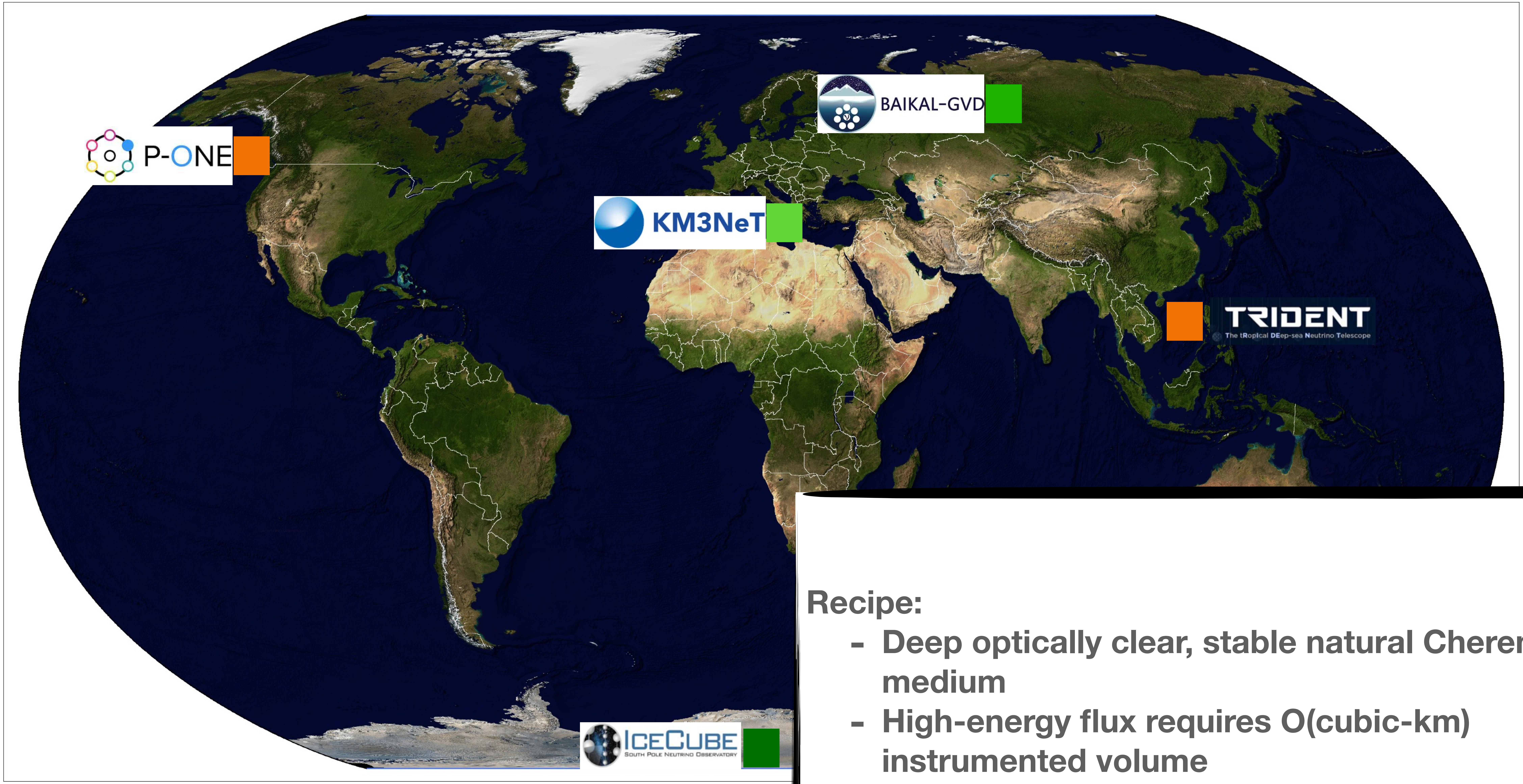
(τ decay length is 50 m/PeV)



High-energy neutrino telescopes — global view



High-energy neutrino telescopes — global view



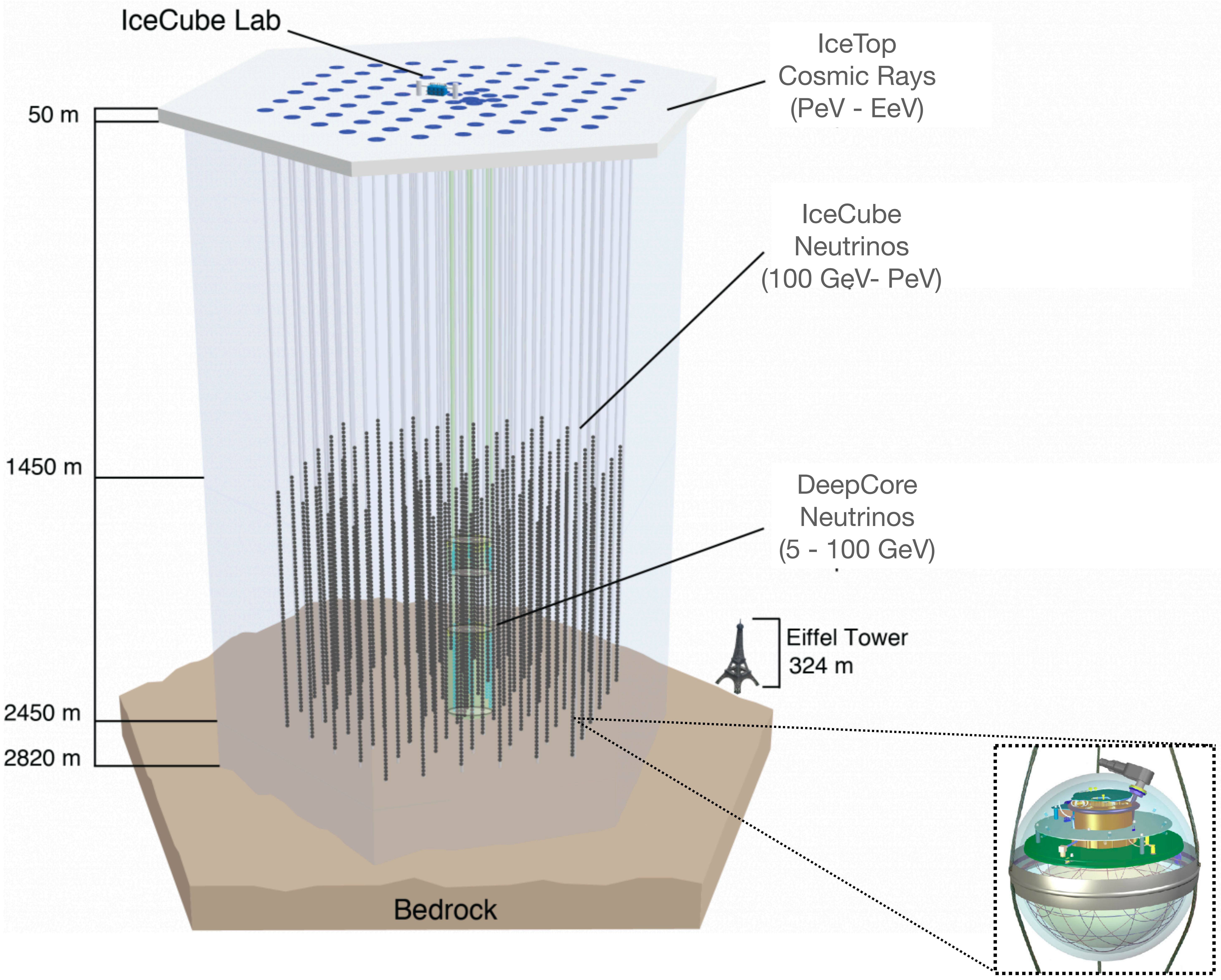
Recipe:

- Deep optically clear, stable natural Cherenkov medium
- High-energy flux requires O(cubic-km) instrumented volume

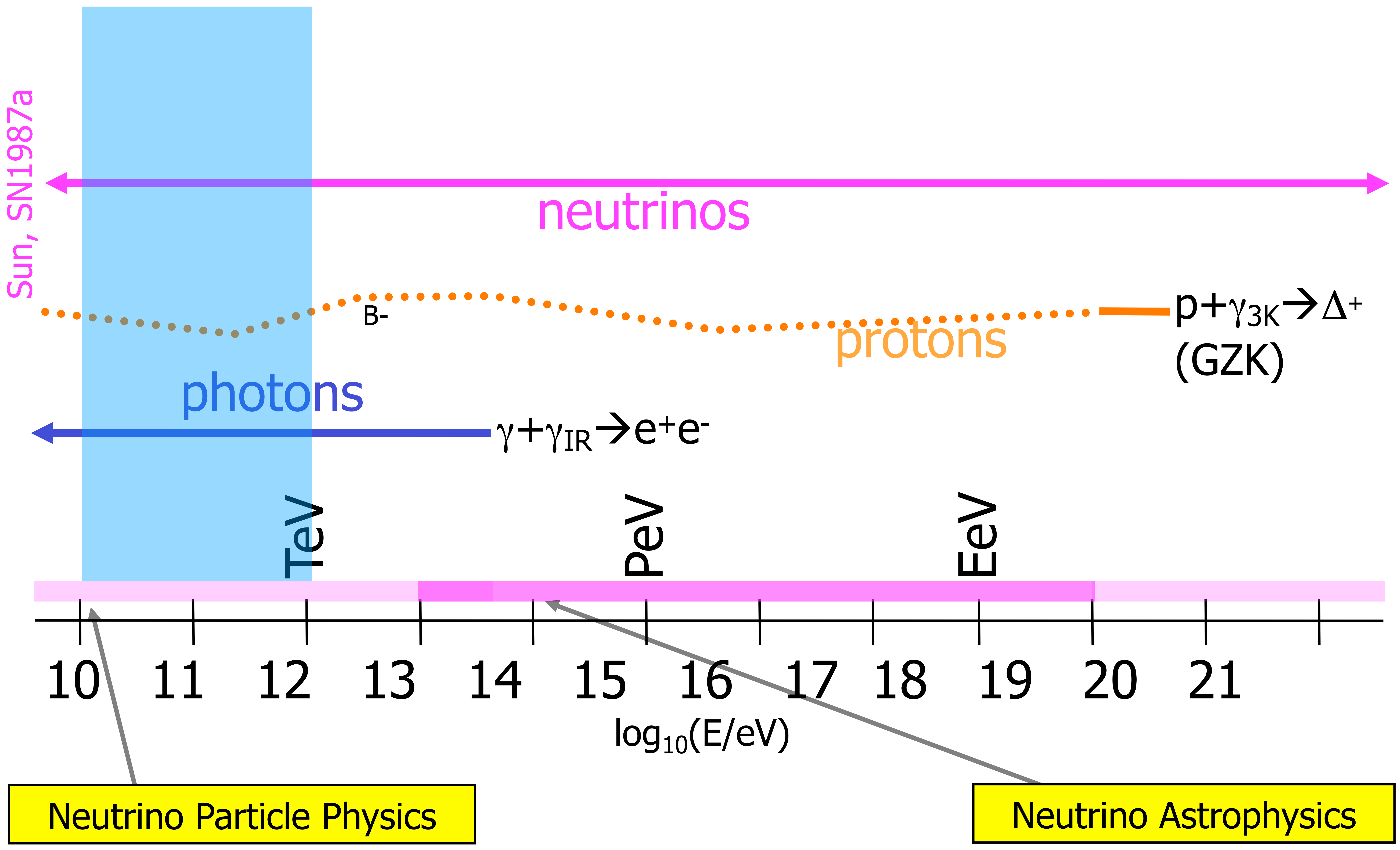
IceCube Neutrino Observatory

- Approximate cubic-km-scale hybrid observatory
    - Detection of Cherenkov photons with over 5000 digital optical modules (DOMs) deployed on a hexagonal grid of 86 'strings'
    - DOM and string spacing defines the energy response and thus physics of each detector region

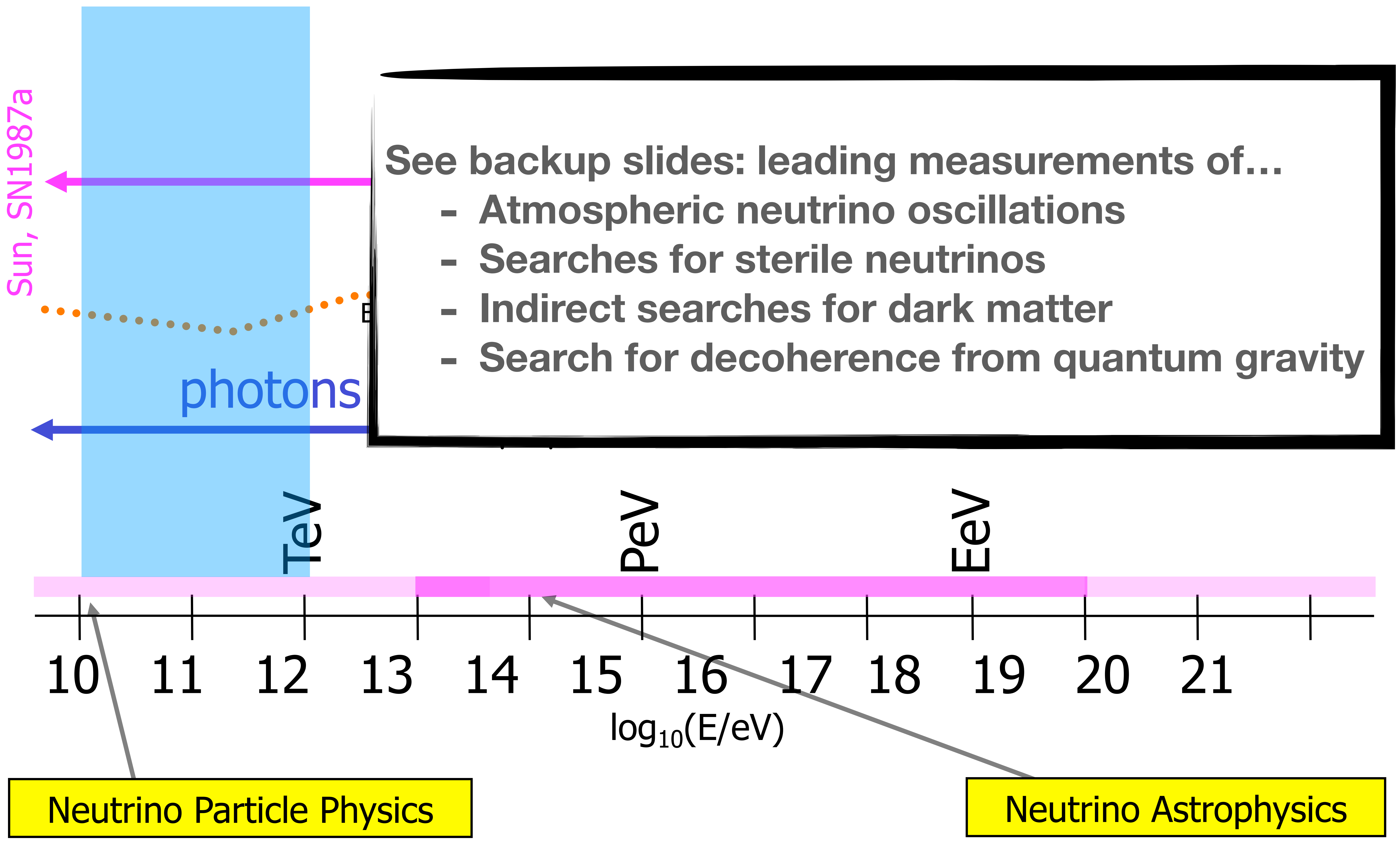
	Spacing [m] Horiz.	Spacing [m] Vertical	Energy threshold [GeV]
IceCube	125	17	~100
DeepCore	~50	7	~5



Cosmic messengers



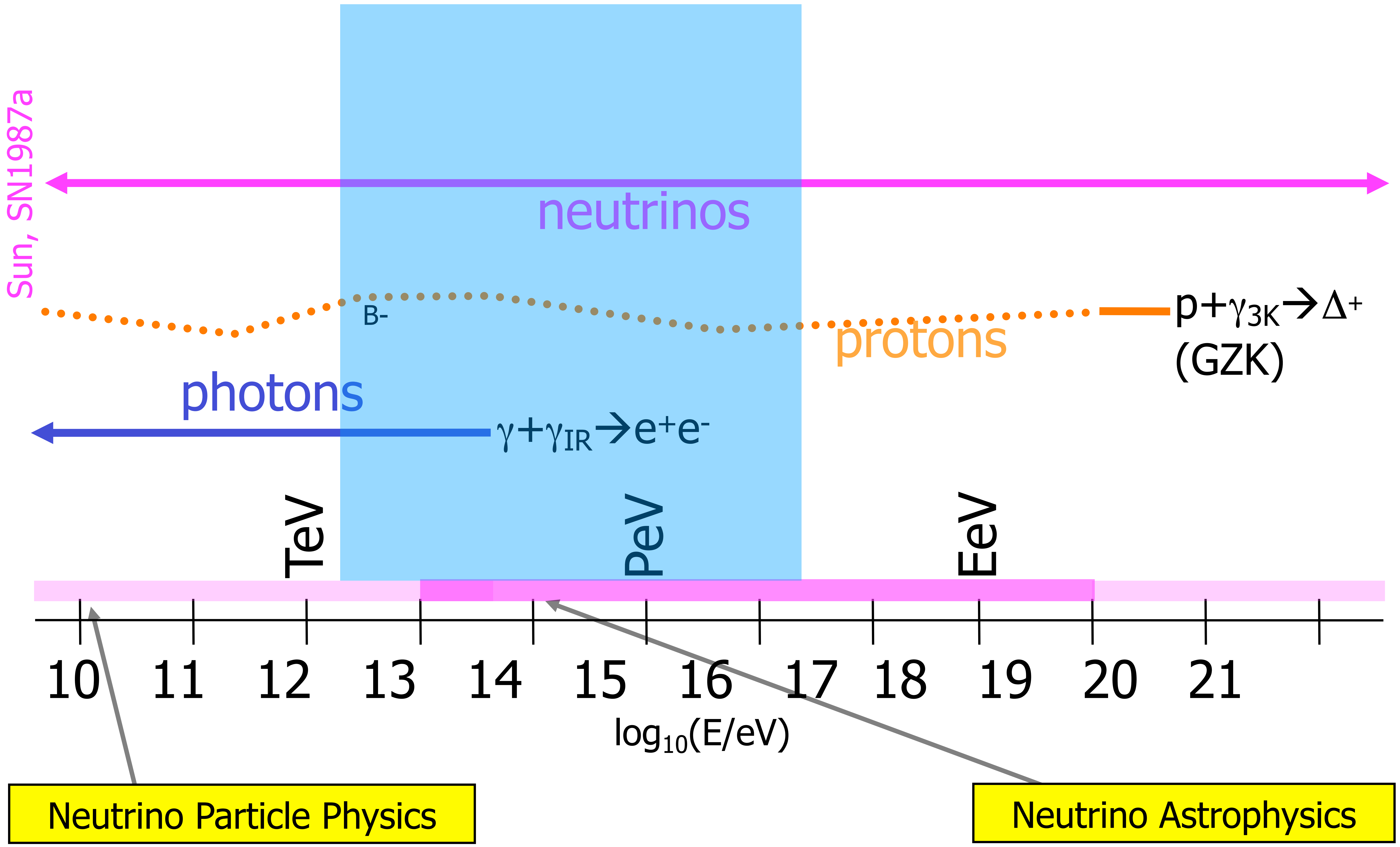
Cosmic messengers



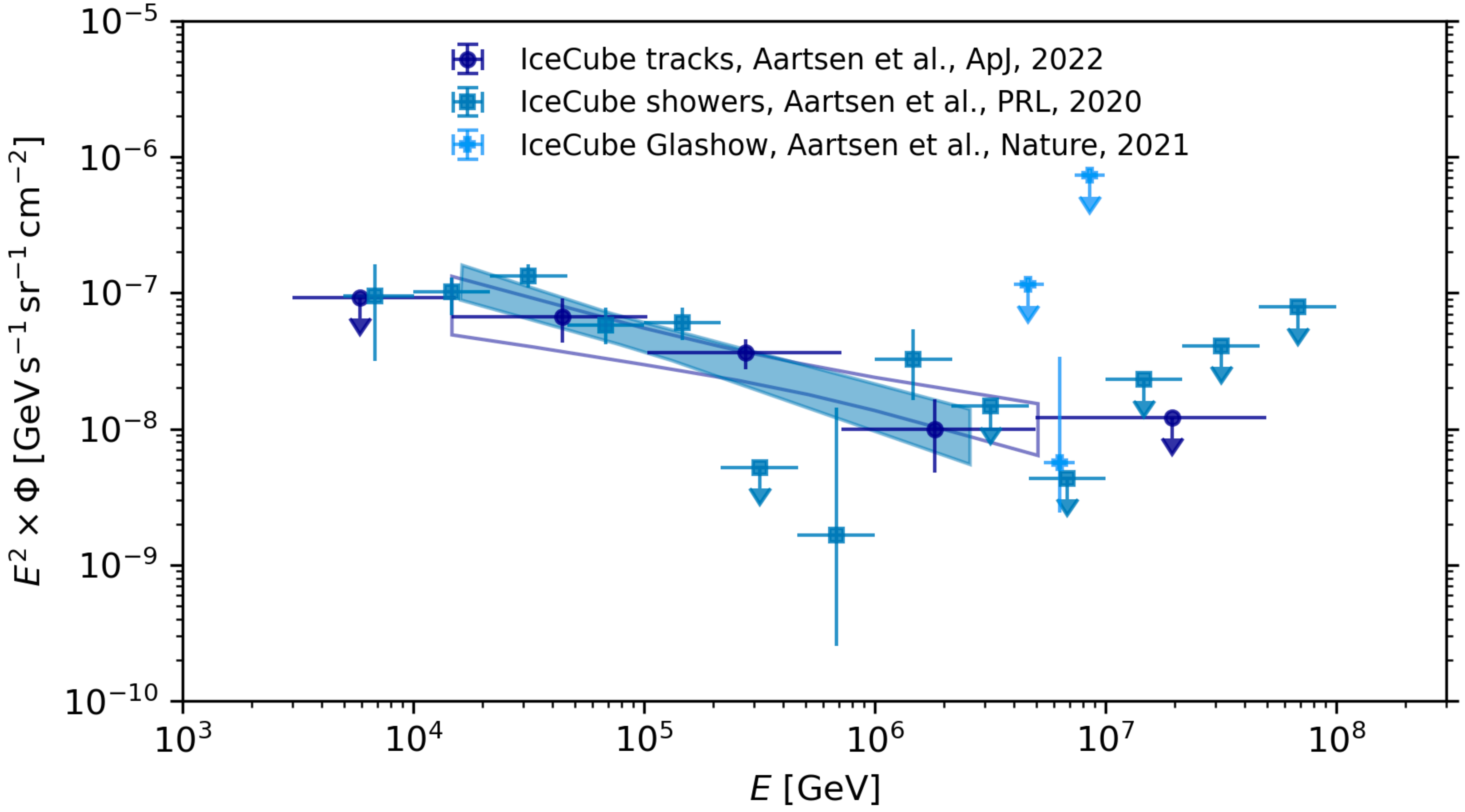
See backup slides: leading measurements of…

- **Atmospheric neutrino oscillations**
- **Searches for sterile neutrinos**
- **Indirect searches for dark matter**
- **Search for decoherence from quantum gravity**

Cosmic messengers

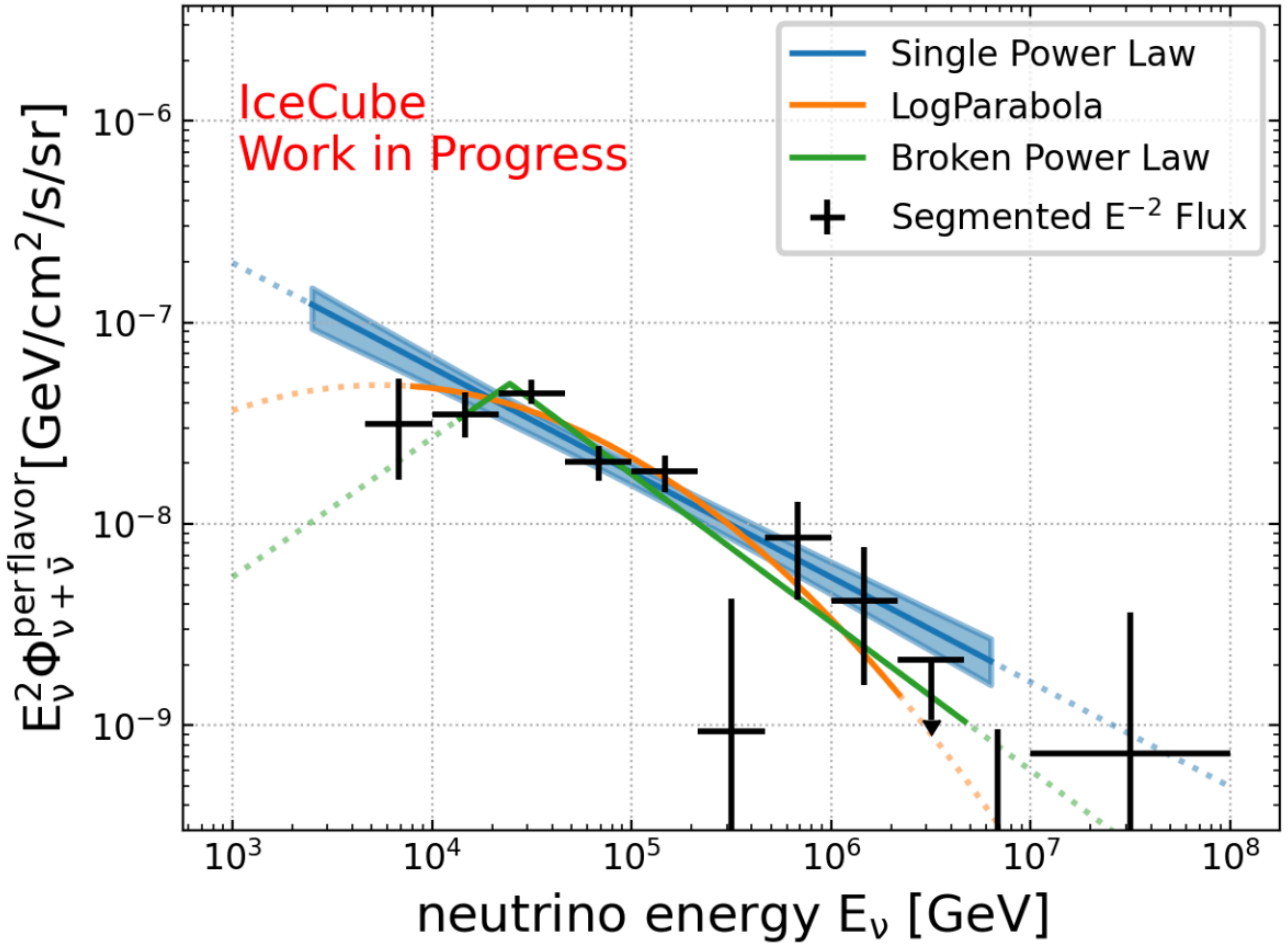


The high-energy astrophysical neutrino flux

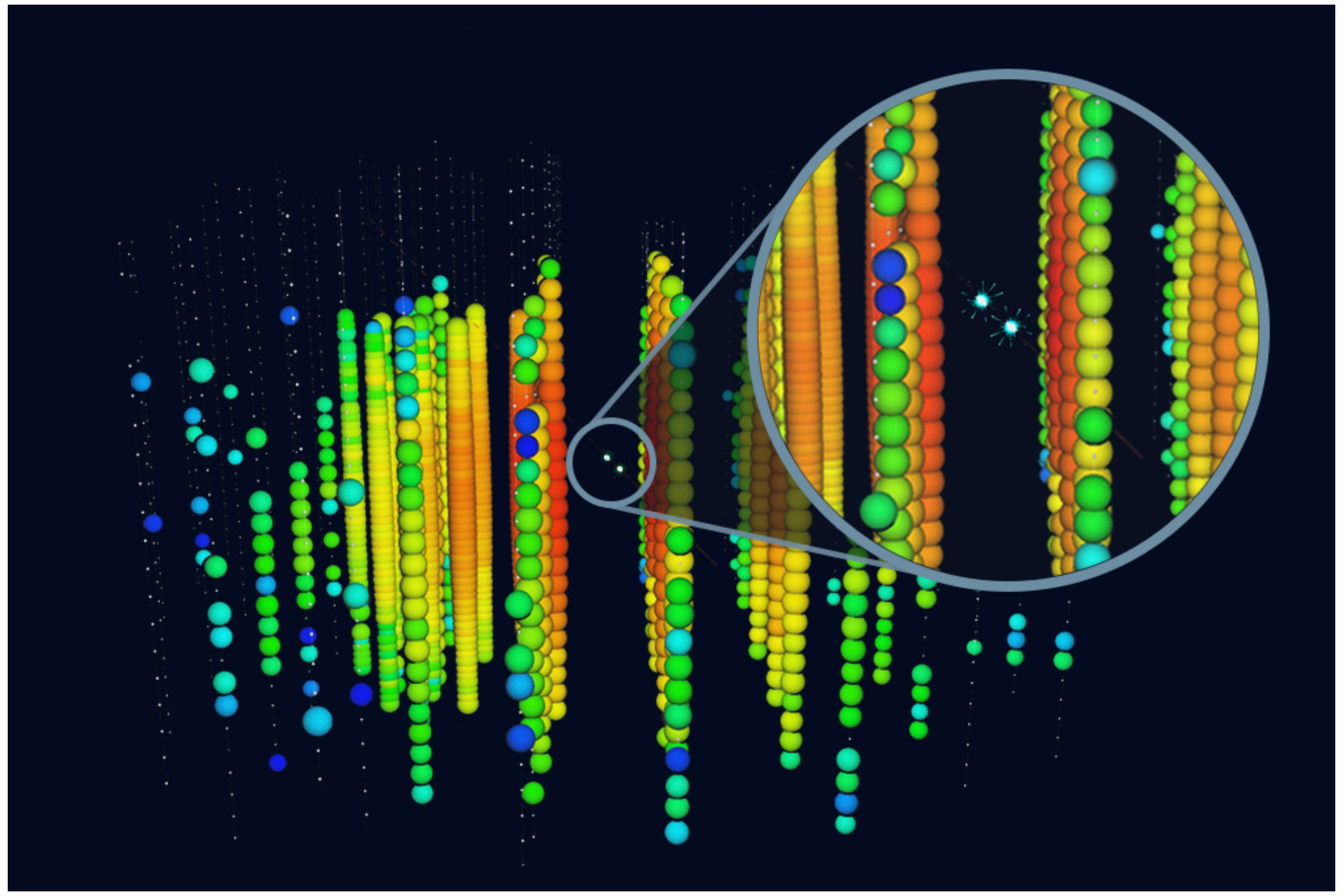


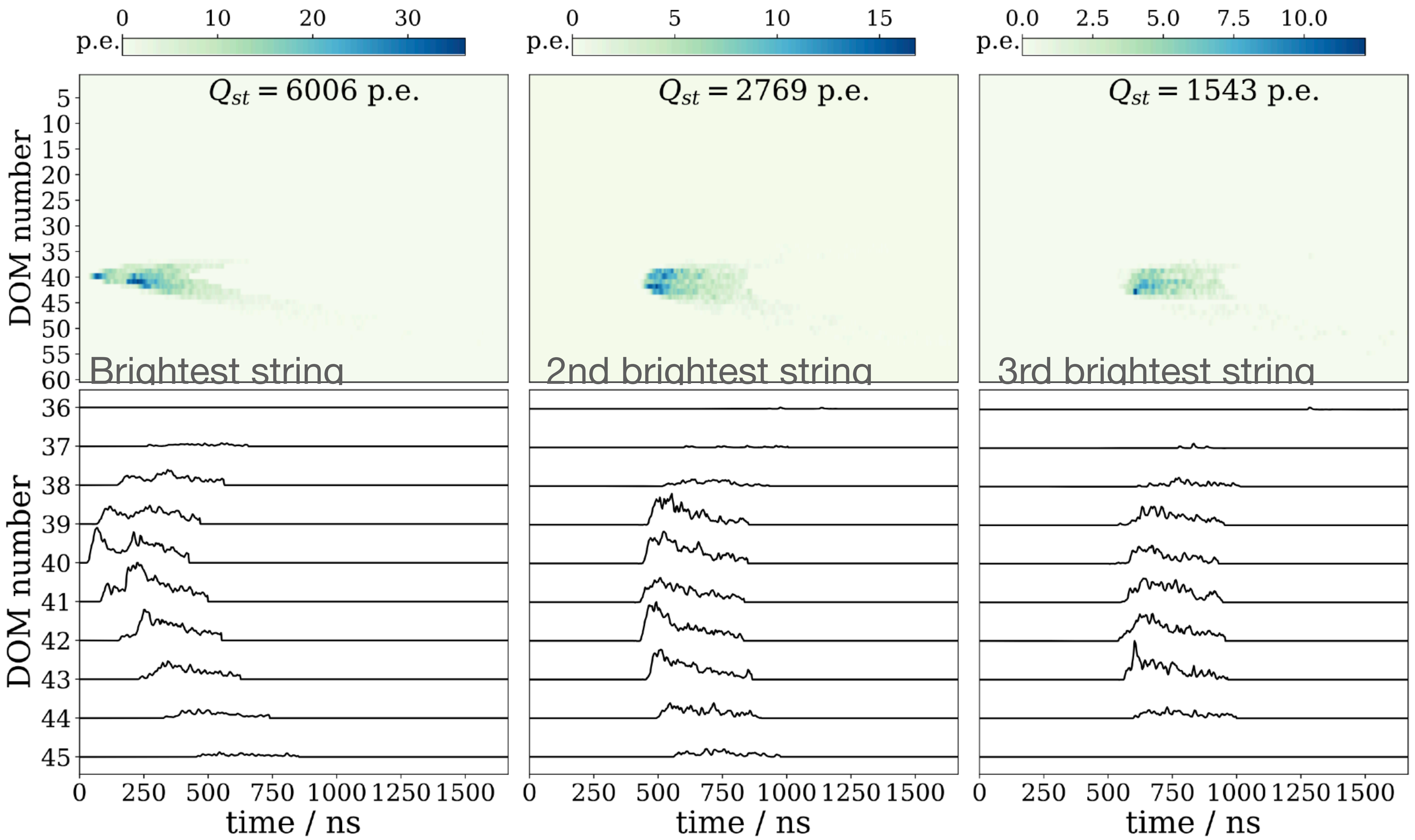
- Astrophysical neutrinos discovered by IceCube in 2013
- Spectrum now measured (multiple channels providing consistent picture) between few TeV - 10 PeV
- Primarily extragalactic origin of neutrinos

- Strong evidence for deviation from single power-law spectrum (disfavoured at >4 sigma)

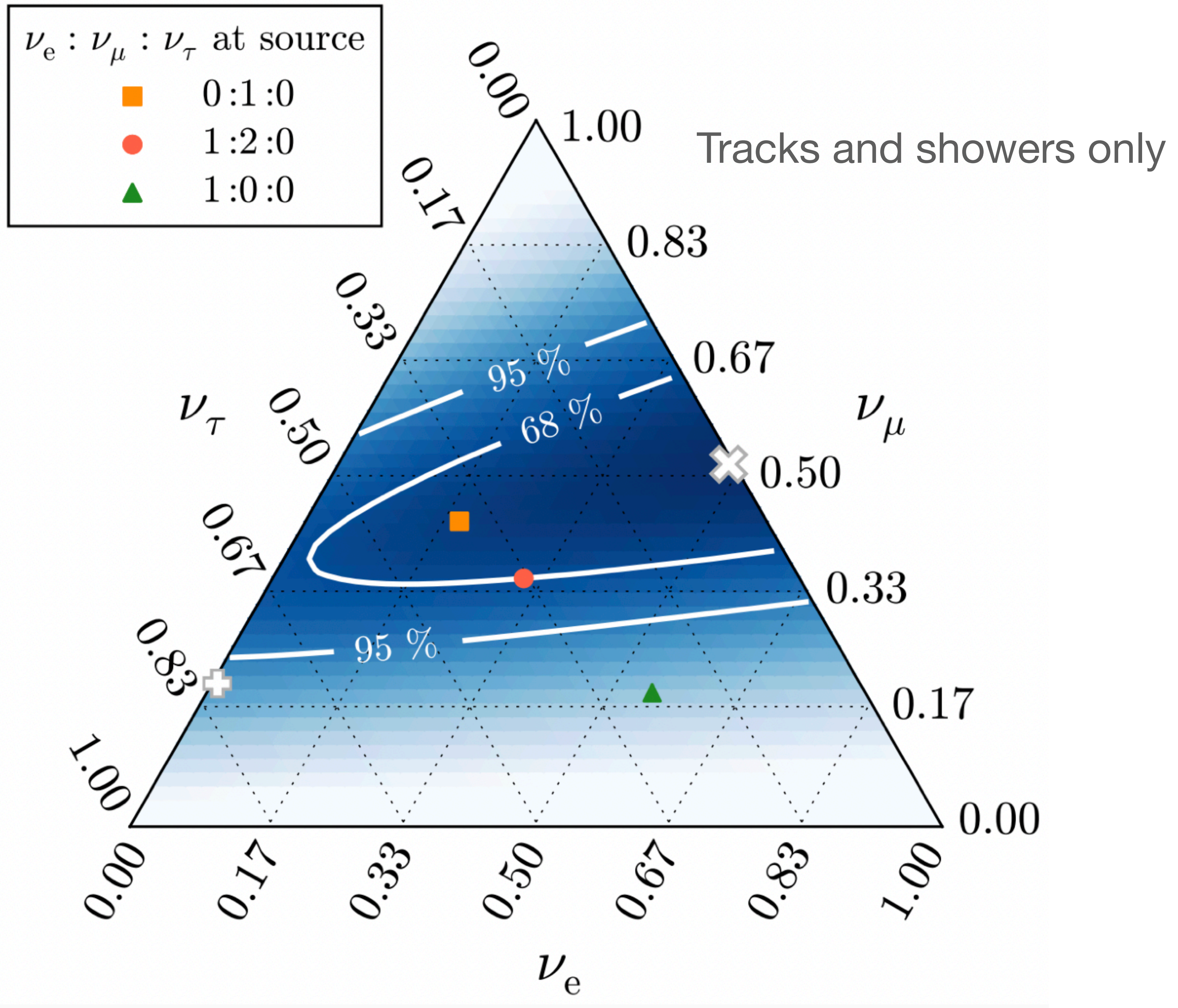


Evidence of astrophysical tau neutrinos

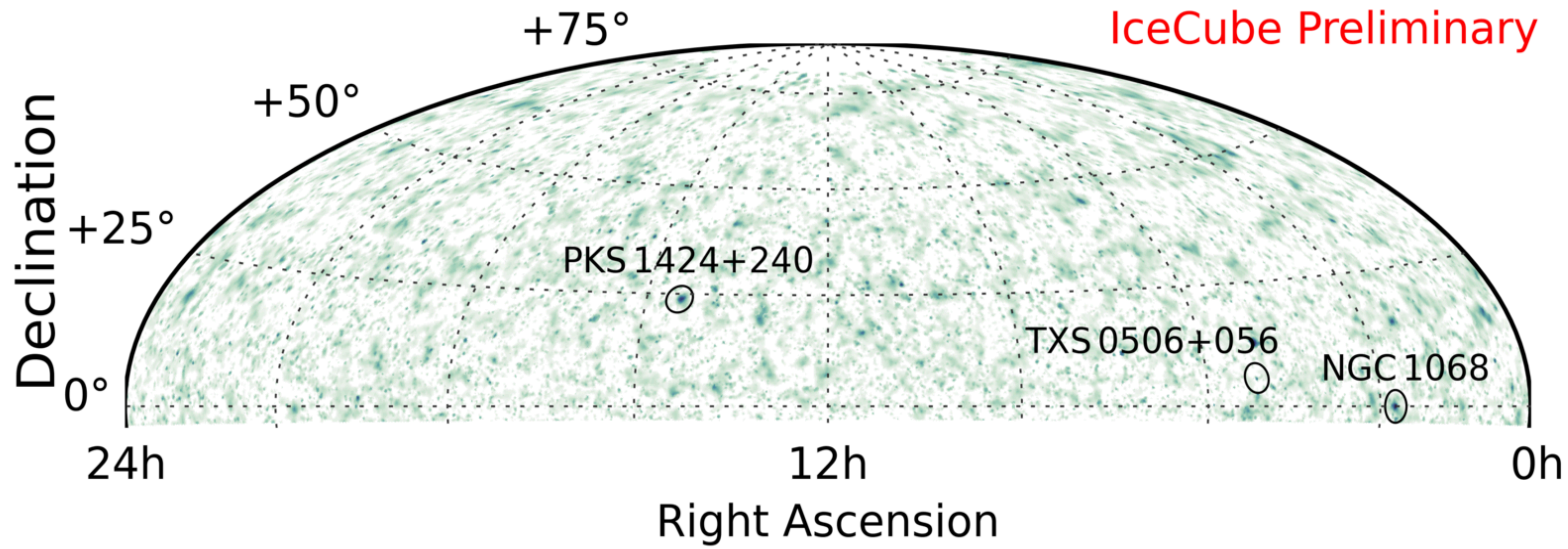


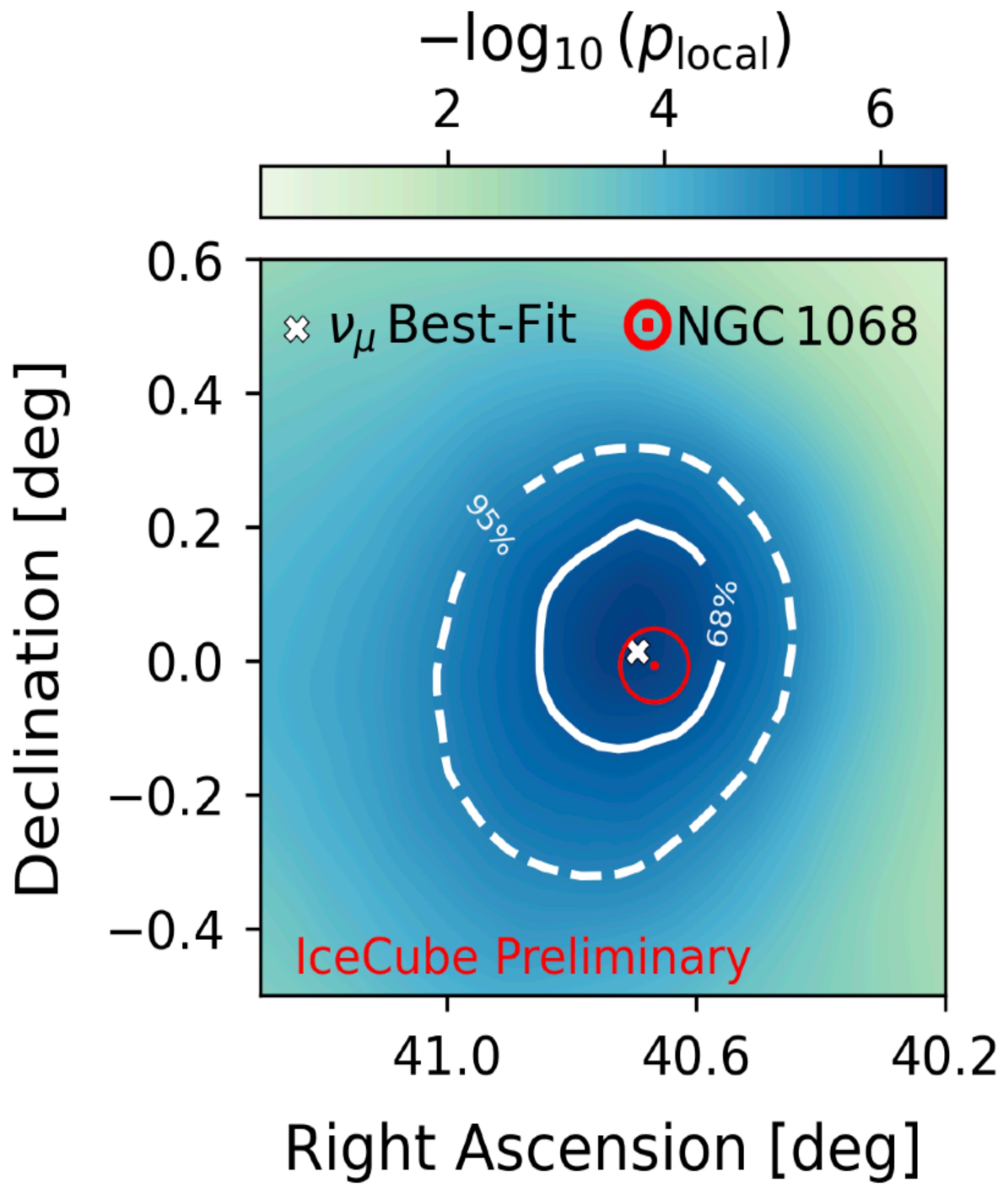


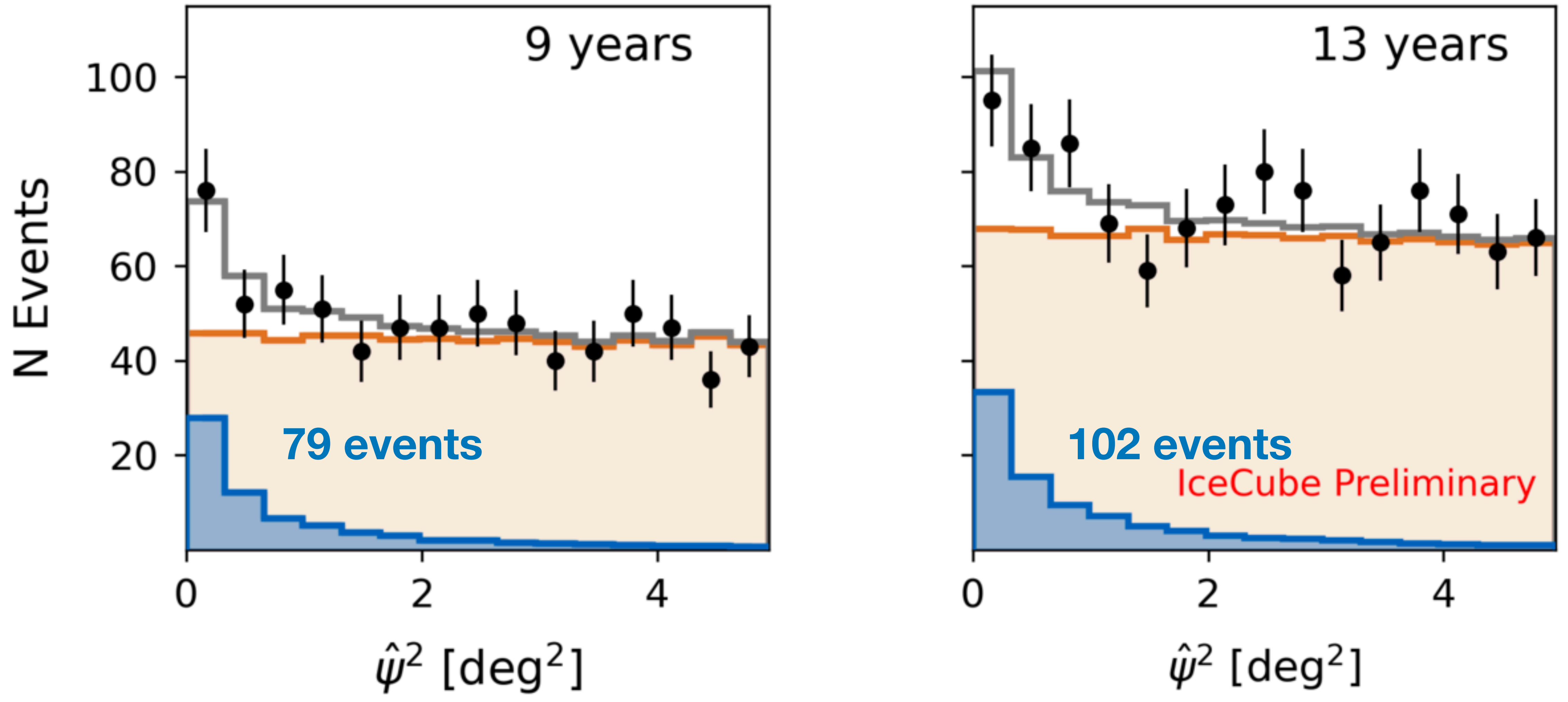
- Combined analysis of track and shower-type events provide strong constraints on the muon neutrino contribution
- 7 tau neutrino candidates identified using machine learning techniques
- Identification of tau neutrino events breaks degeneracy between electron neutrino and tau neutrino showers



Emerging extragalactic sources



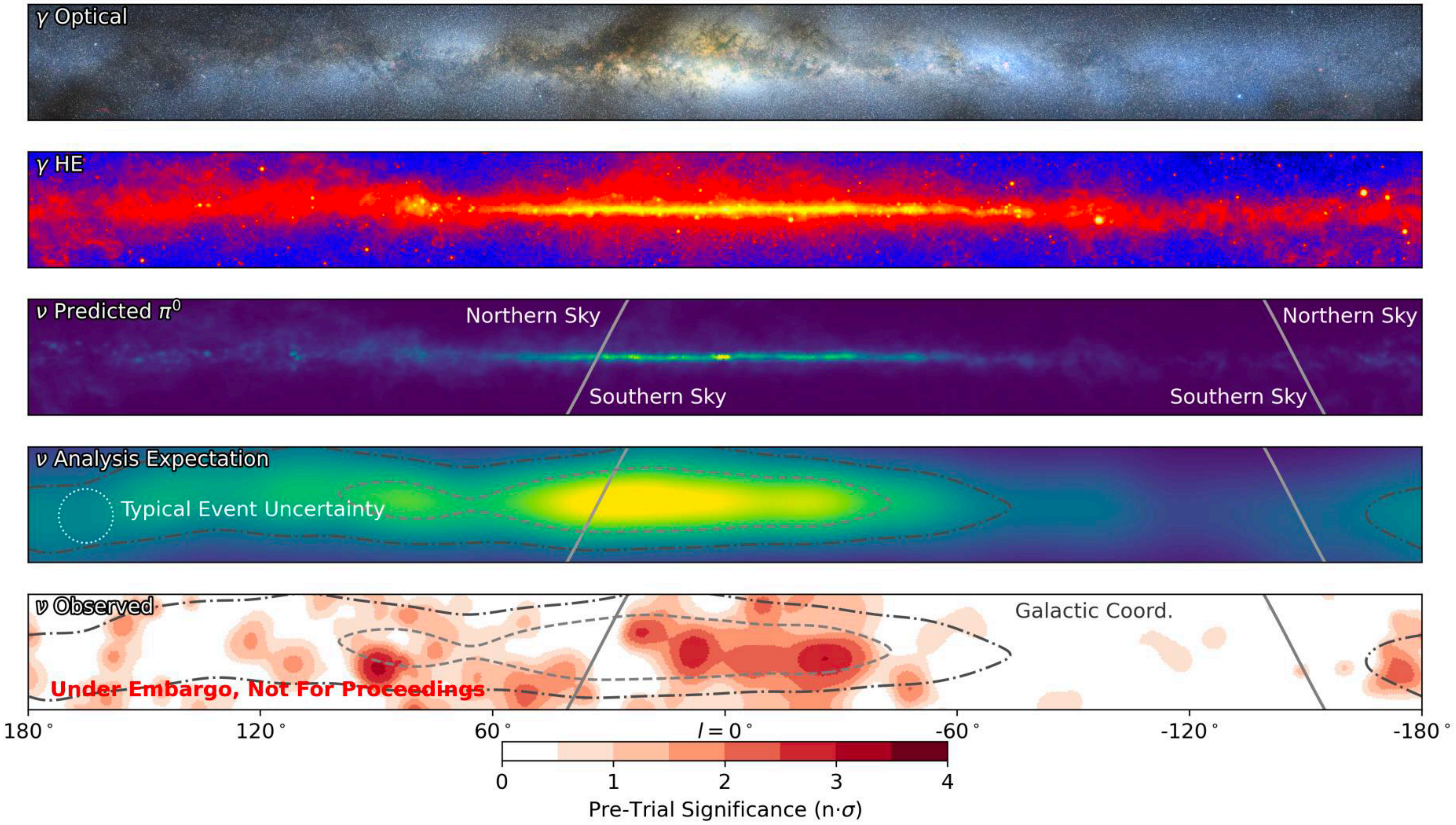




- Preliminary results of analysis with extended dataset (13 years); local NGC 1068 significant is 5 sigma; post trial corrected 4 sigma.
- Best fit spectral index -3.4 (9 year: -3.2)
- Represents a few percent of the overall diffuse astrophysical neutrino flux

A Galactic component

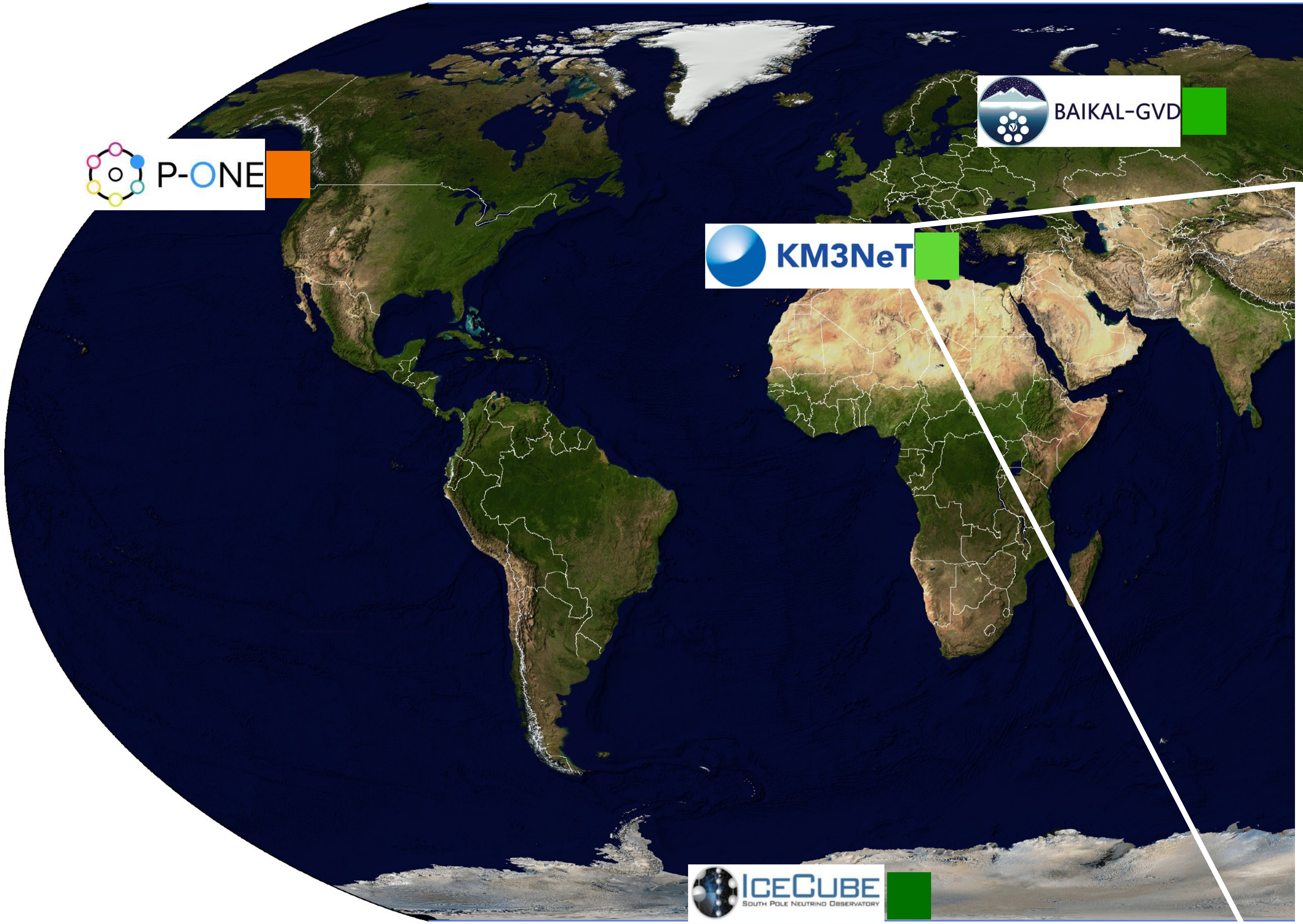
Science Vol 380, Issue 6652



Neutrinos from the Milky Way for the first time (4.5 sigma post trial); No individual sources yet observed at high significance due to current limits in angular resolution and statistics. Small fraction of the total observed diffuse flux.

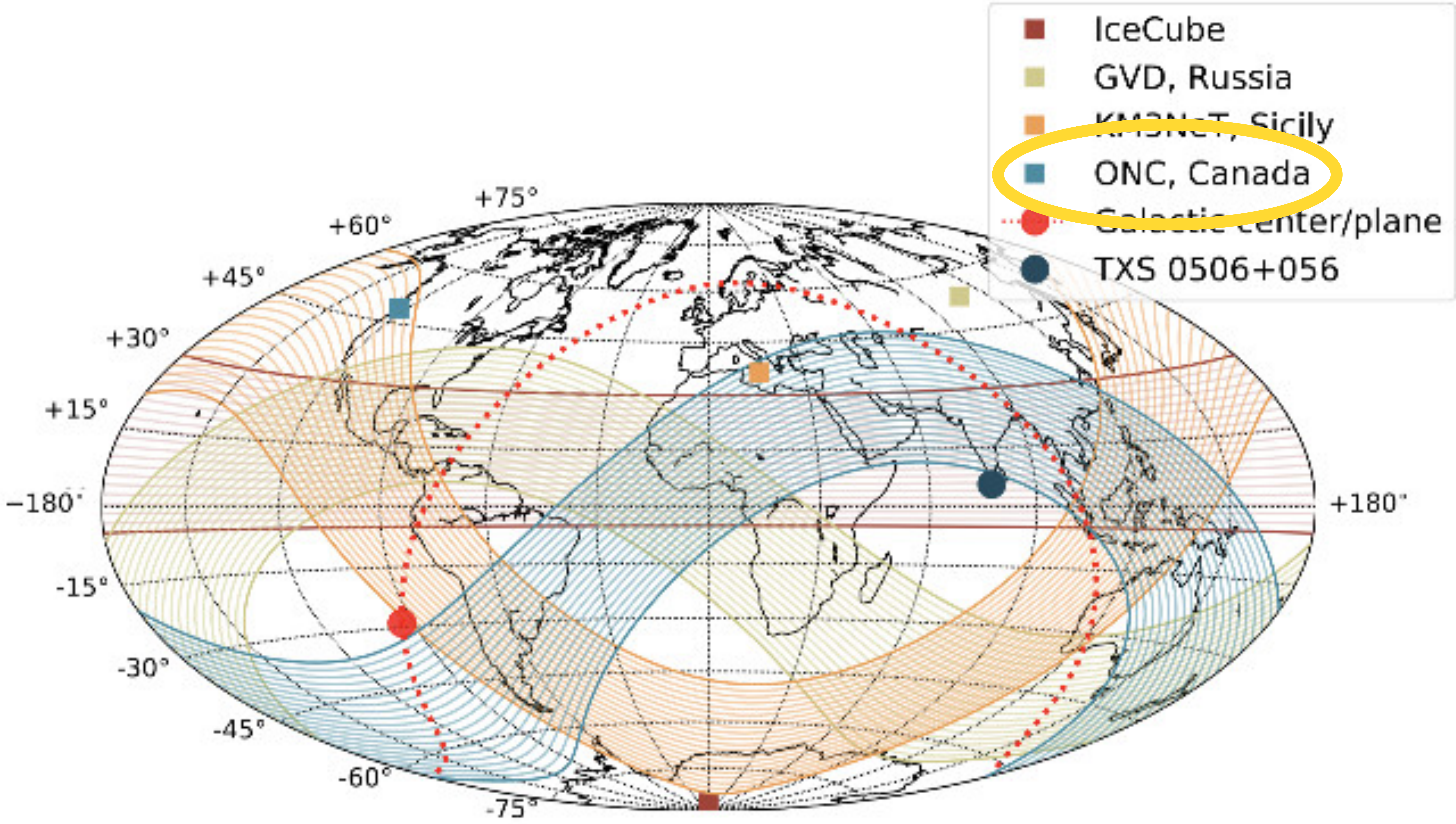
High-energy neutrino telescopes — global view

High-energy neutrino telescopes — global view

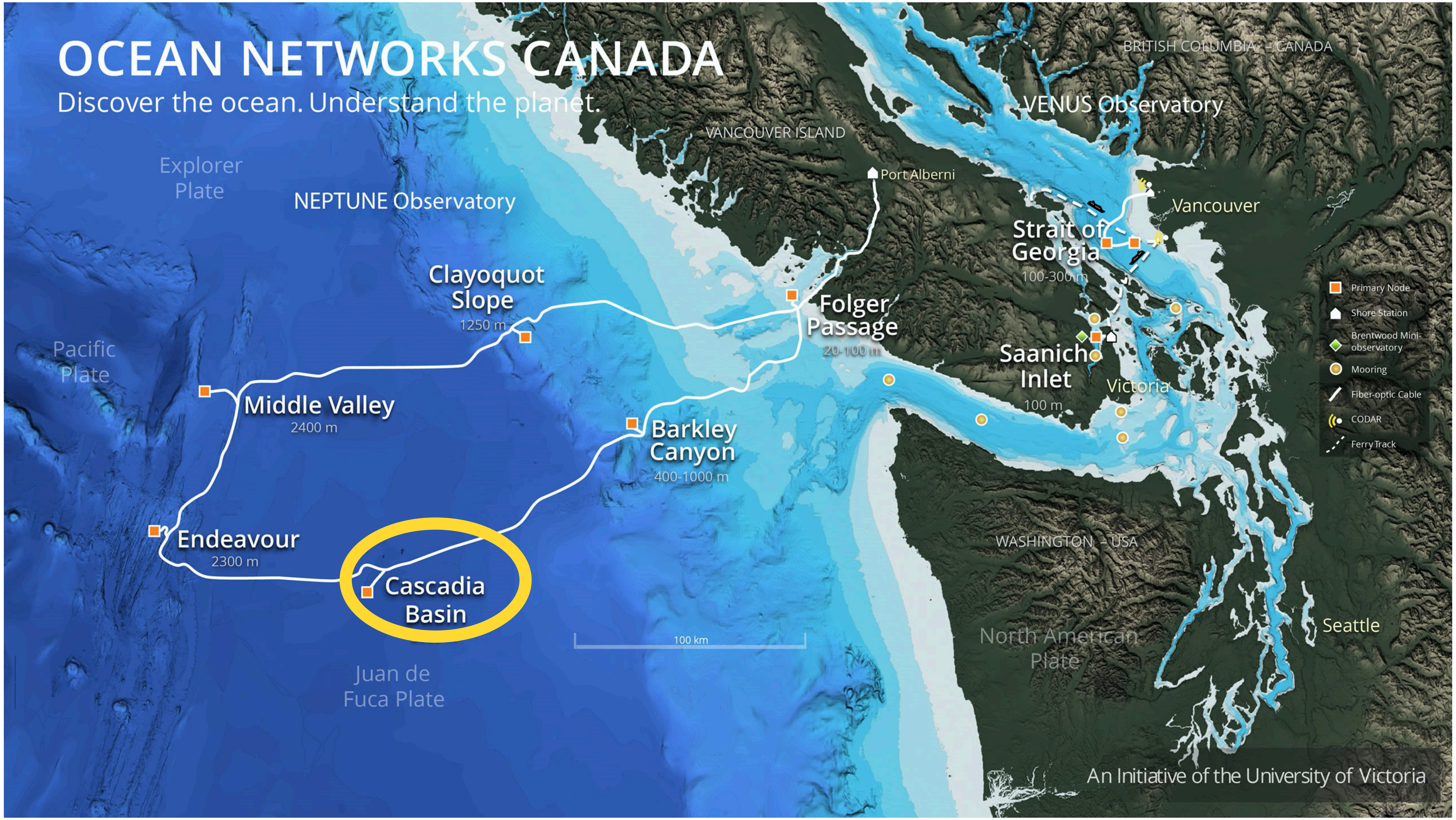


February 12, 2025

High-energy neutrino telescopes — global view

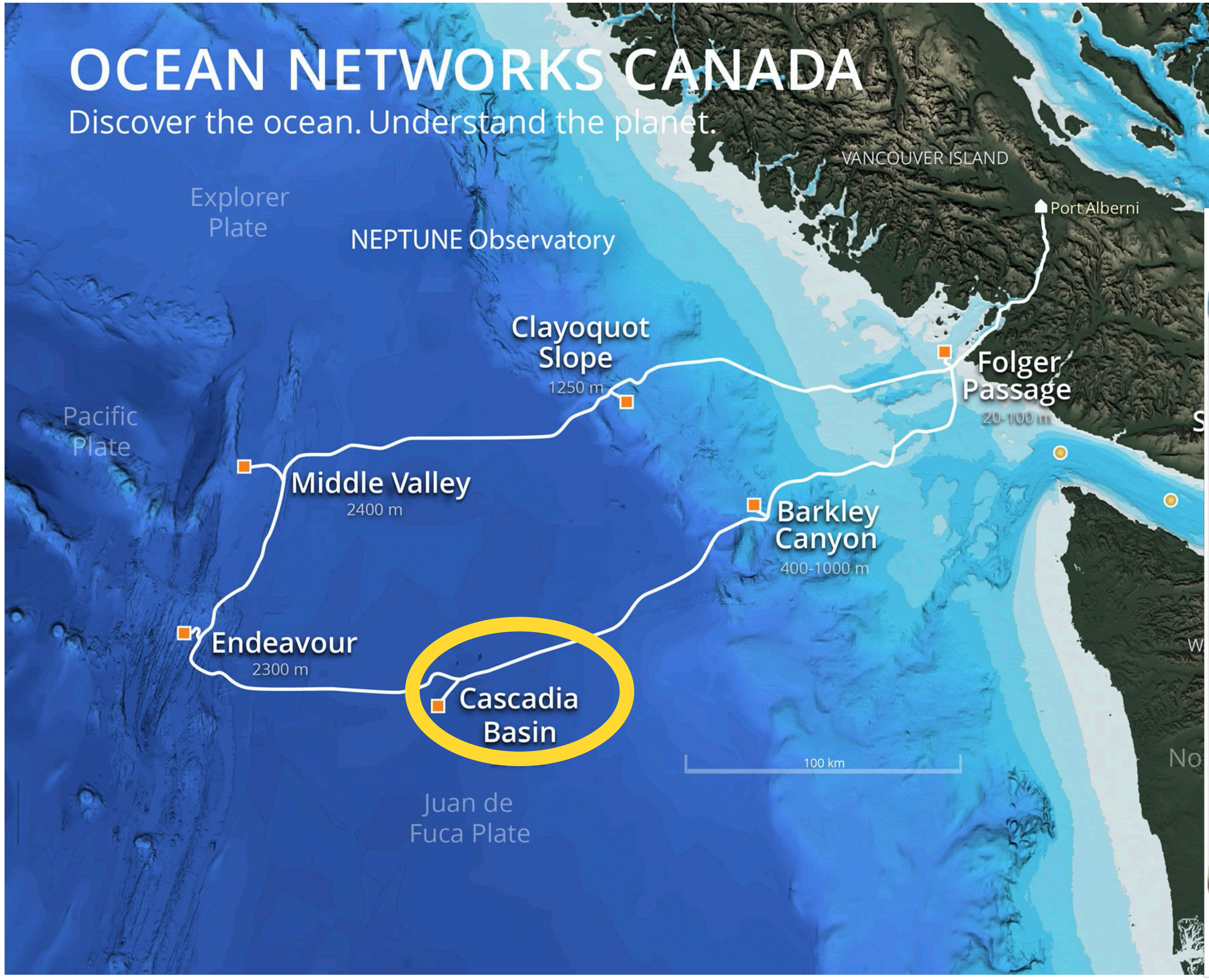


Leveraging Canada's investments in deep ocean science for particle astrophysics



- Neptune observatory instruments the Cascadia basin (2600m depth abyssal plane) with power and communications. Near constant temperature 2C year-round; currents ~0.1m/s

Leveraging Canada's investments in deep ocean science for particle astrophysics



P-ONE

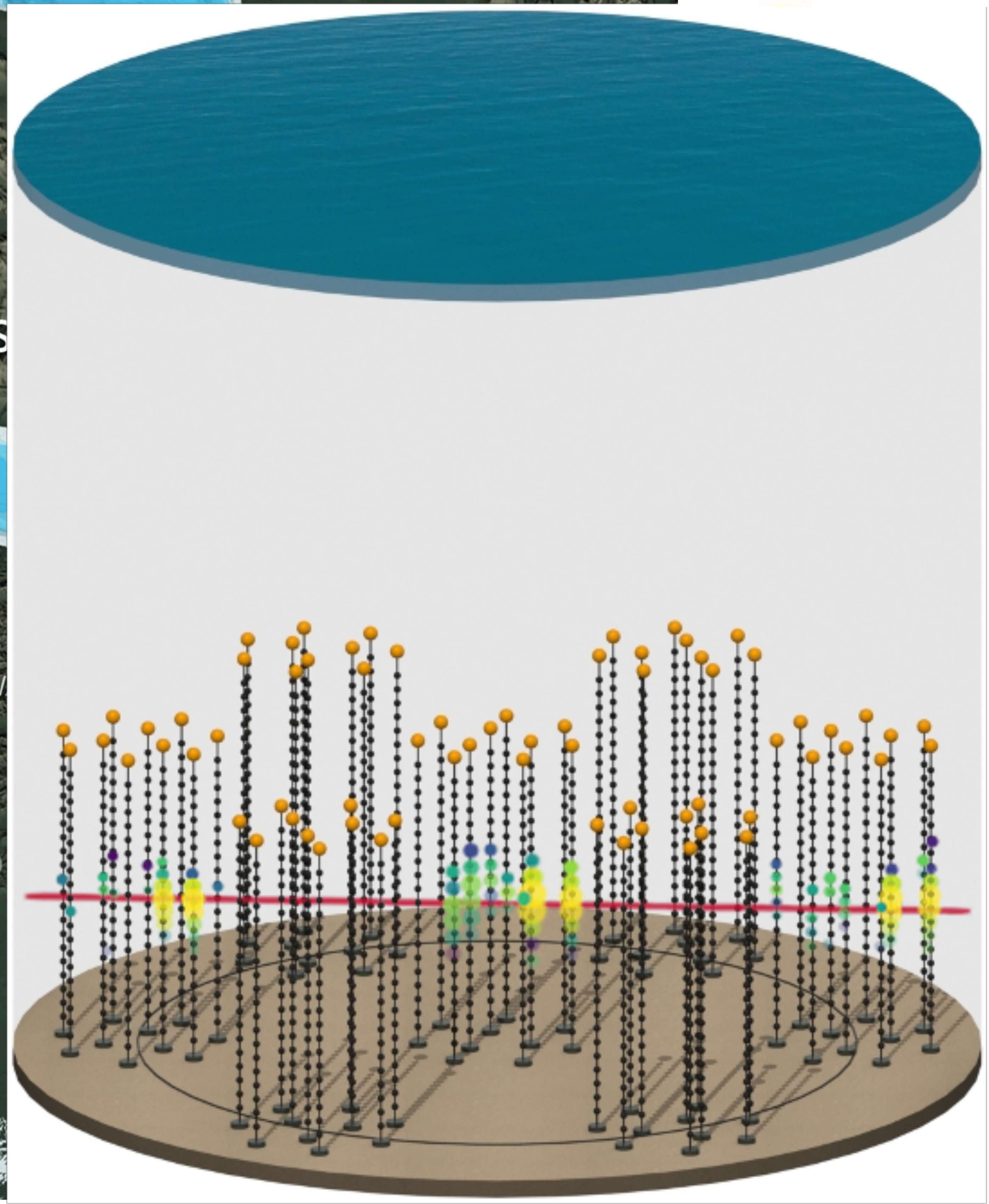
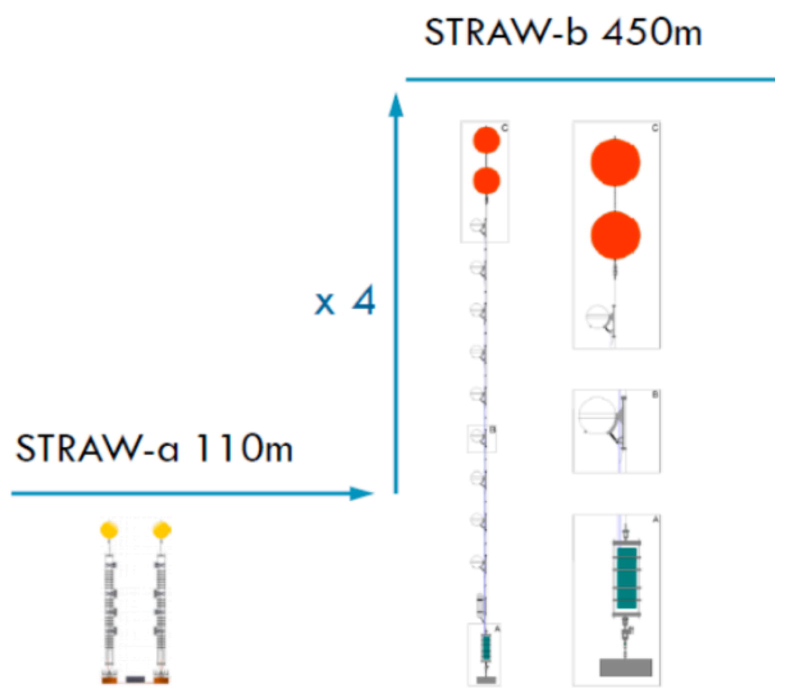


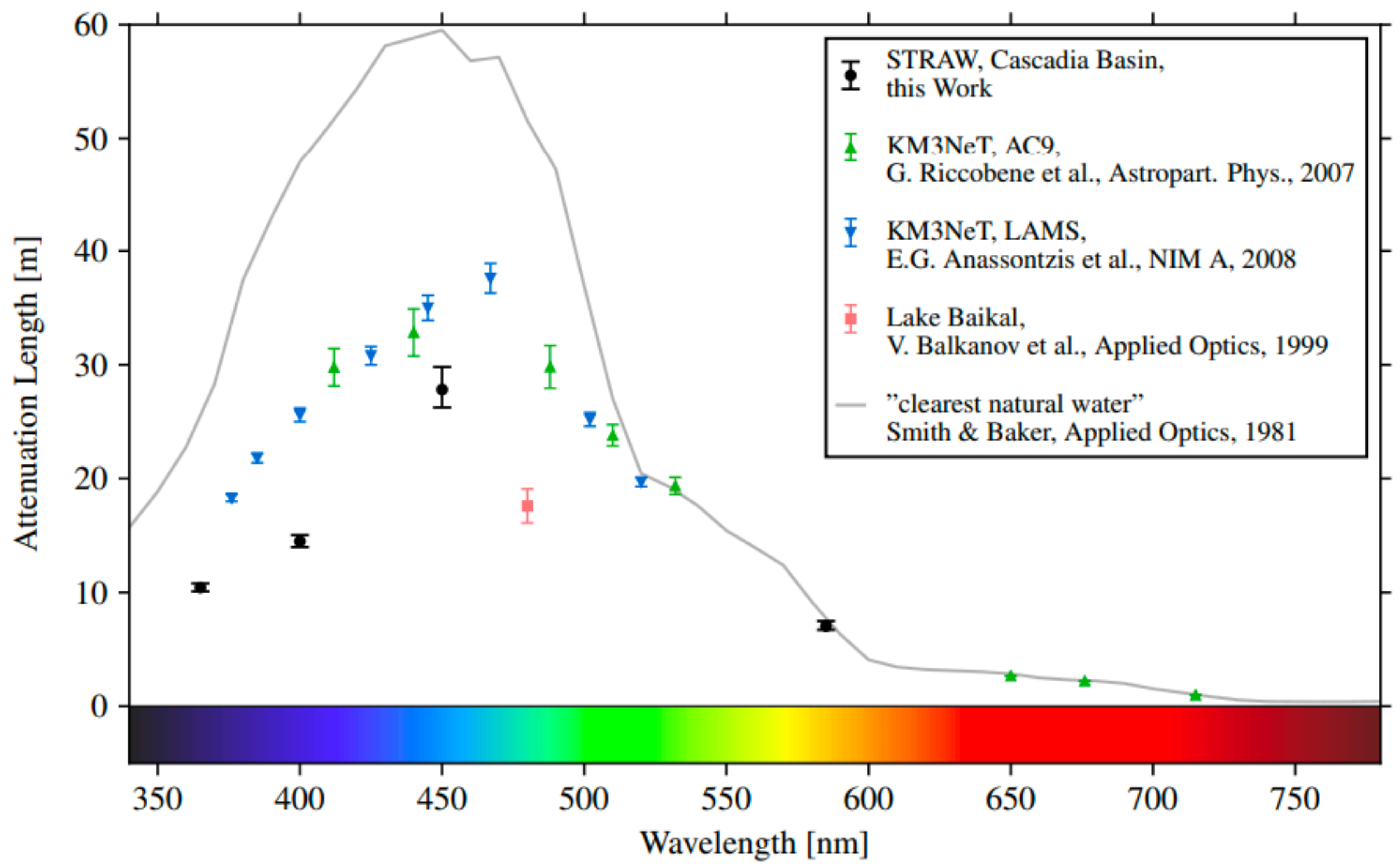
Image *Nat Astron* 4, 913–915 (2020)

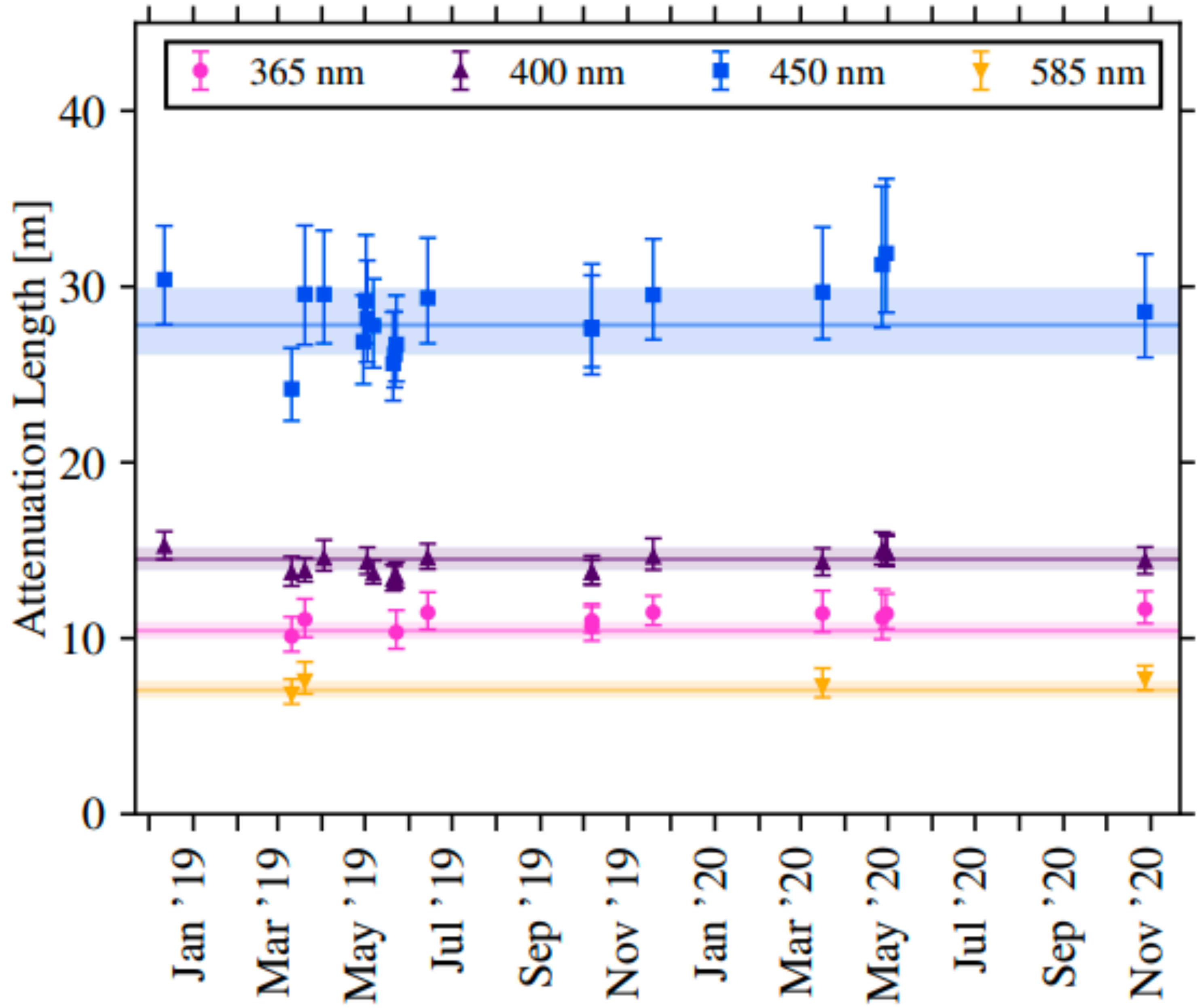
- Neptune observatory instruments the Cascadia basin (2600m depth abyssal plane) with power and communications. Near constant temperature 2C year-round; currents ~0.1m/s

P-ONE predecessor — site characterization

Eur. Phys. J. C 81, 1071 (2021)







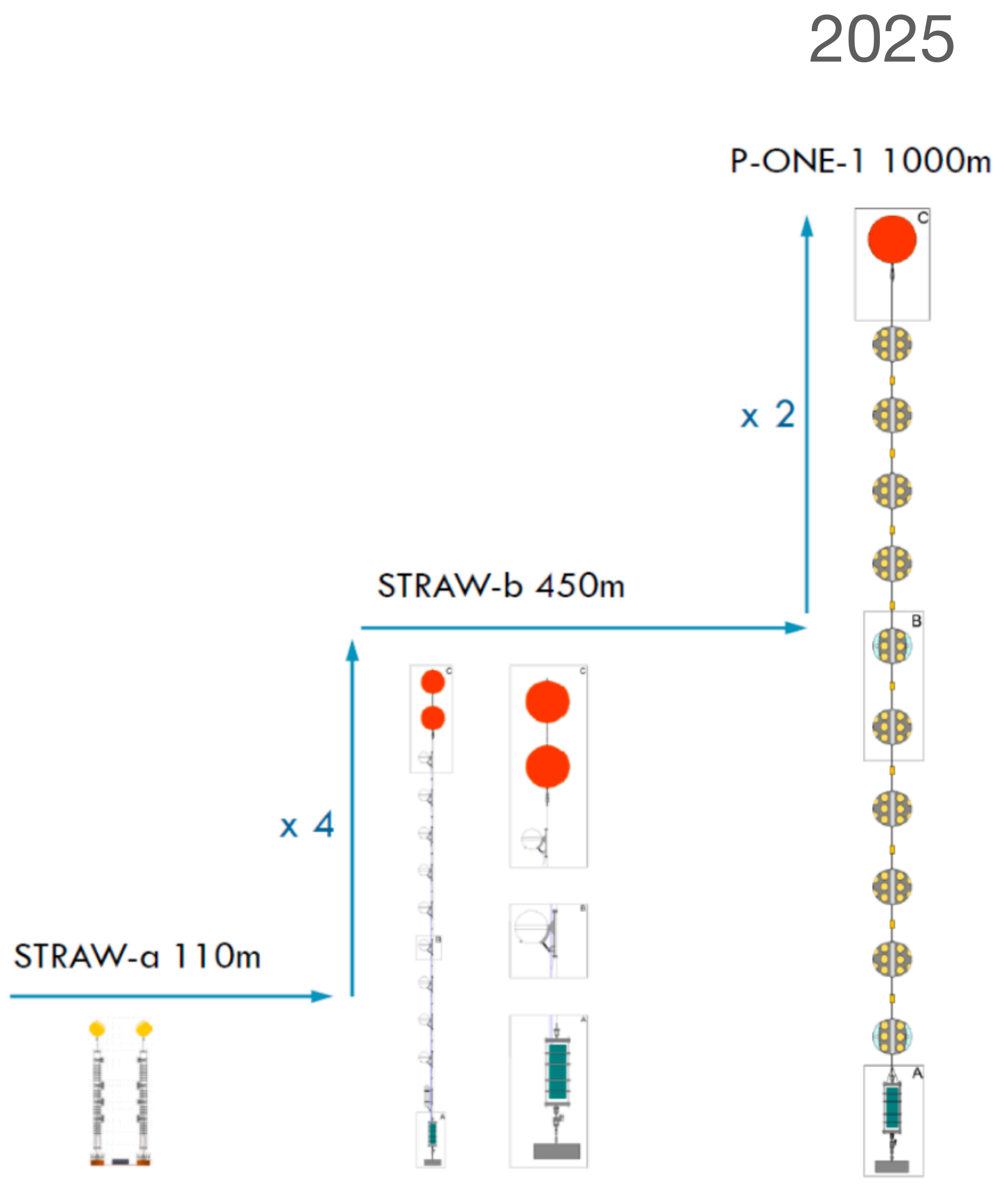
Pathfinder

Phase 1 (2018 — 2023)

- Measured attenuation after 2 years of monitoring = 27.7–1.3/+1.9m at 450nm
- Stable over the period of data collection
- Compatible with measurements at Mediterranean sites

P-ONE-1

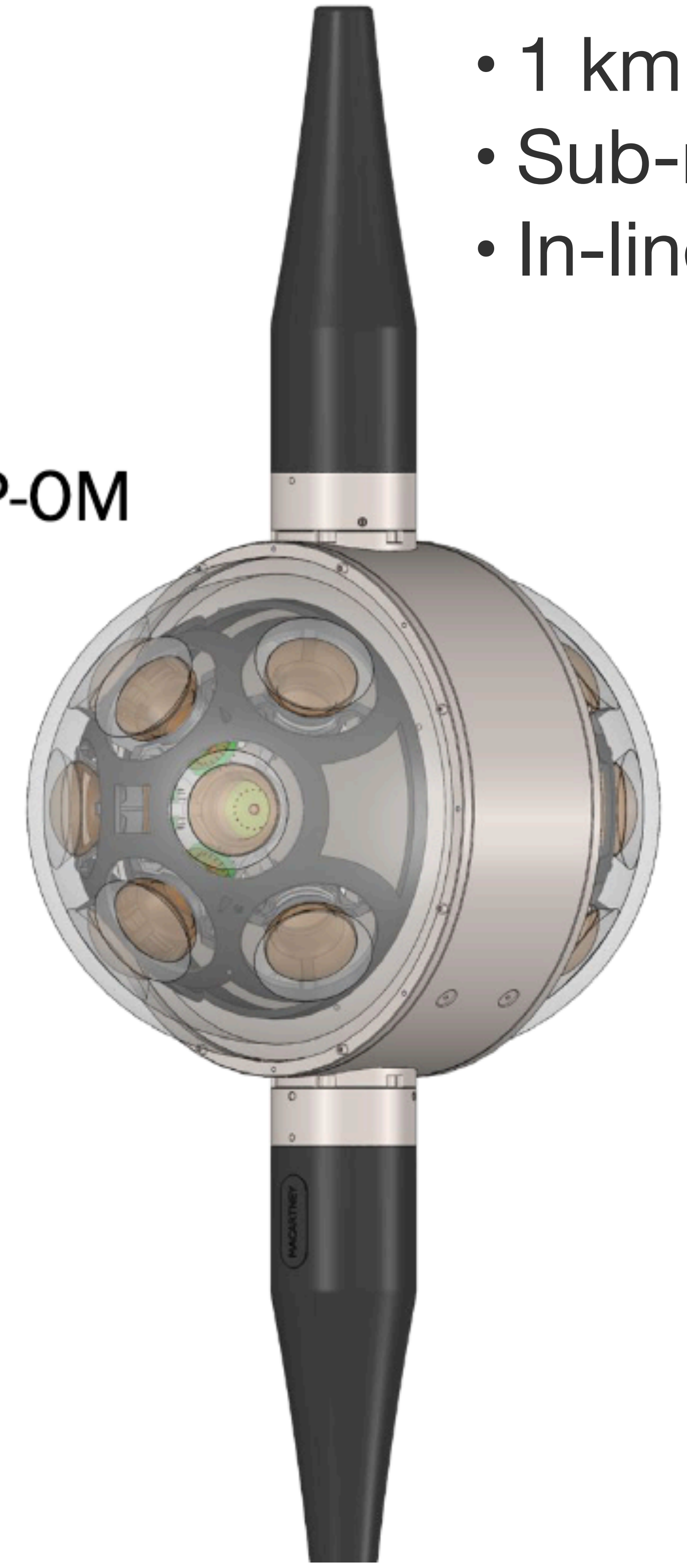
- 1 km mooring line with 20 modules employing a connector-less design
- Sub-ns synchronization
- In-line network infrastructure



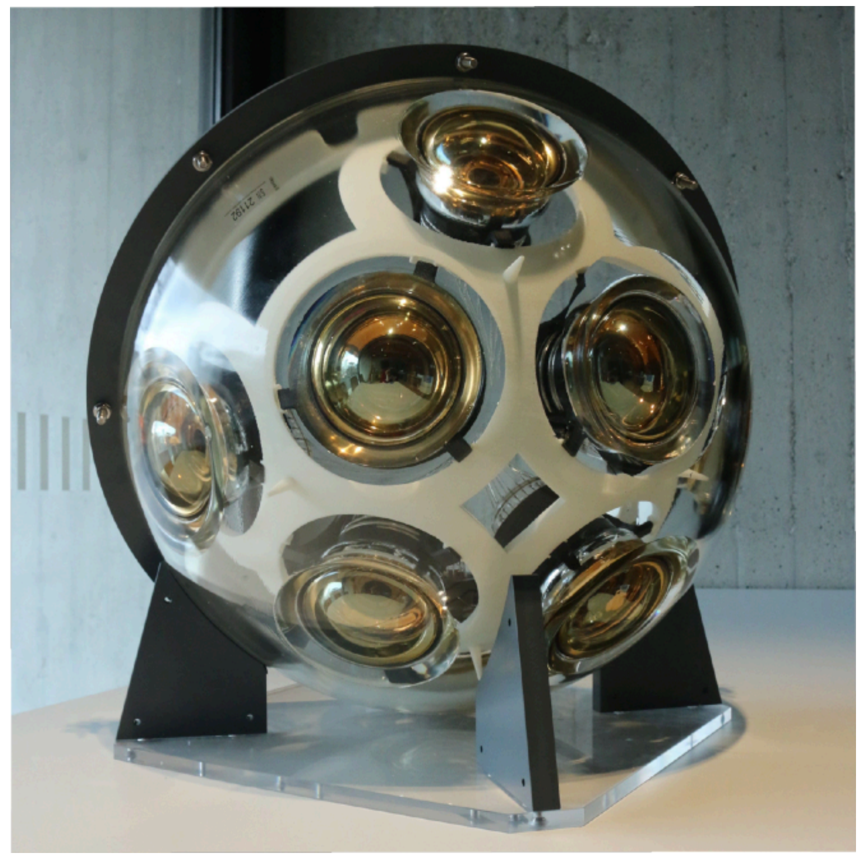
Pathfinder

Phase 1 (2018 — 2023)

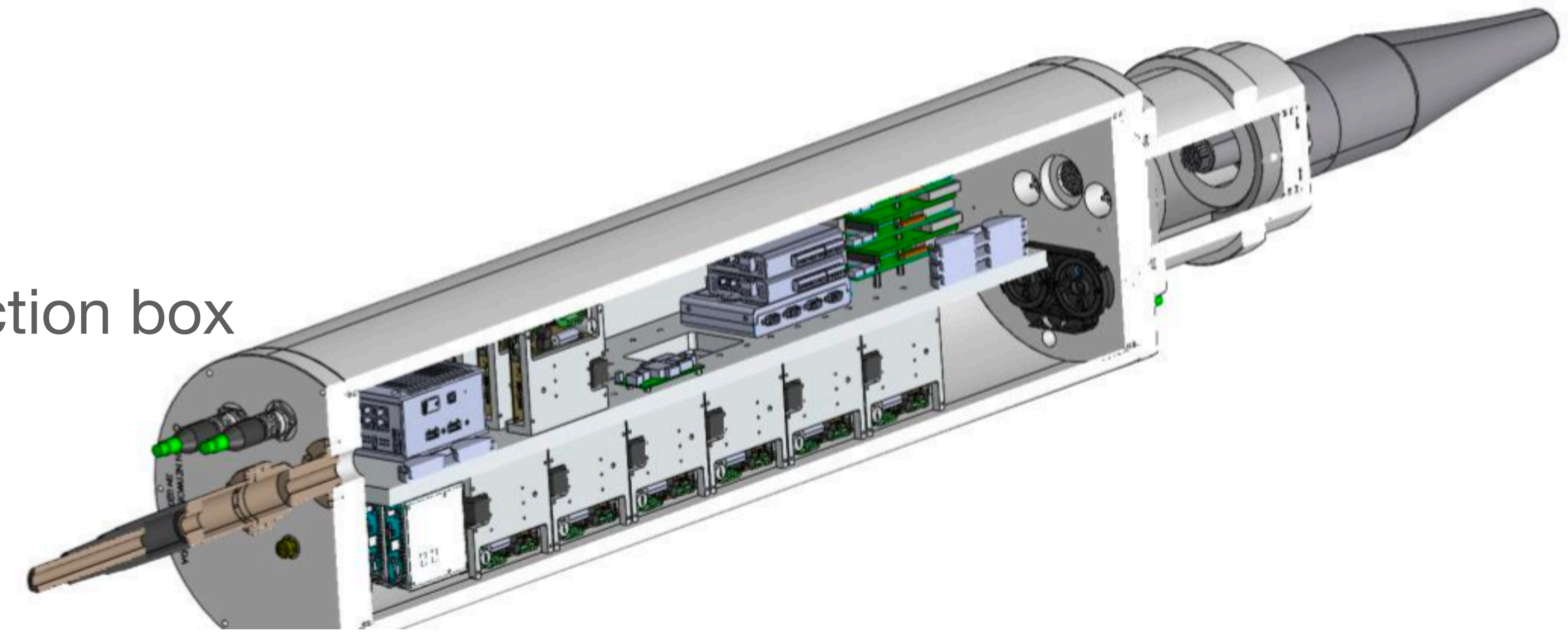
P-OM



For details PoS (ICRC2023) 1219

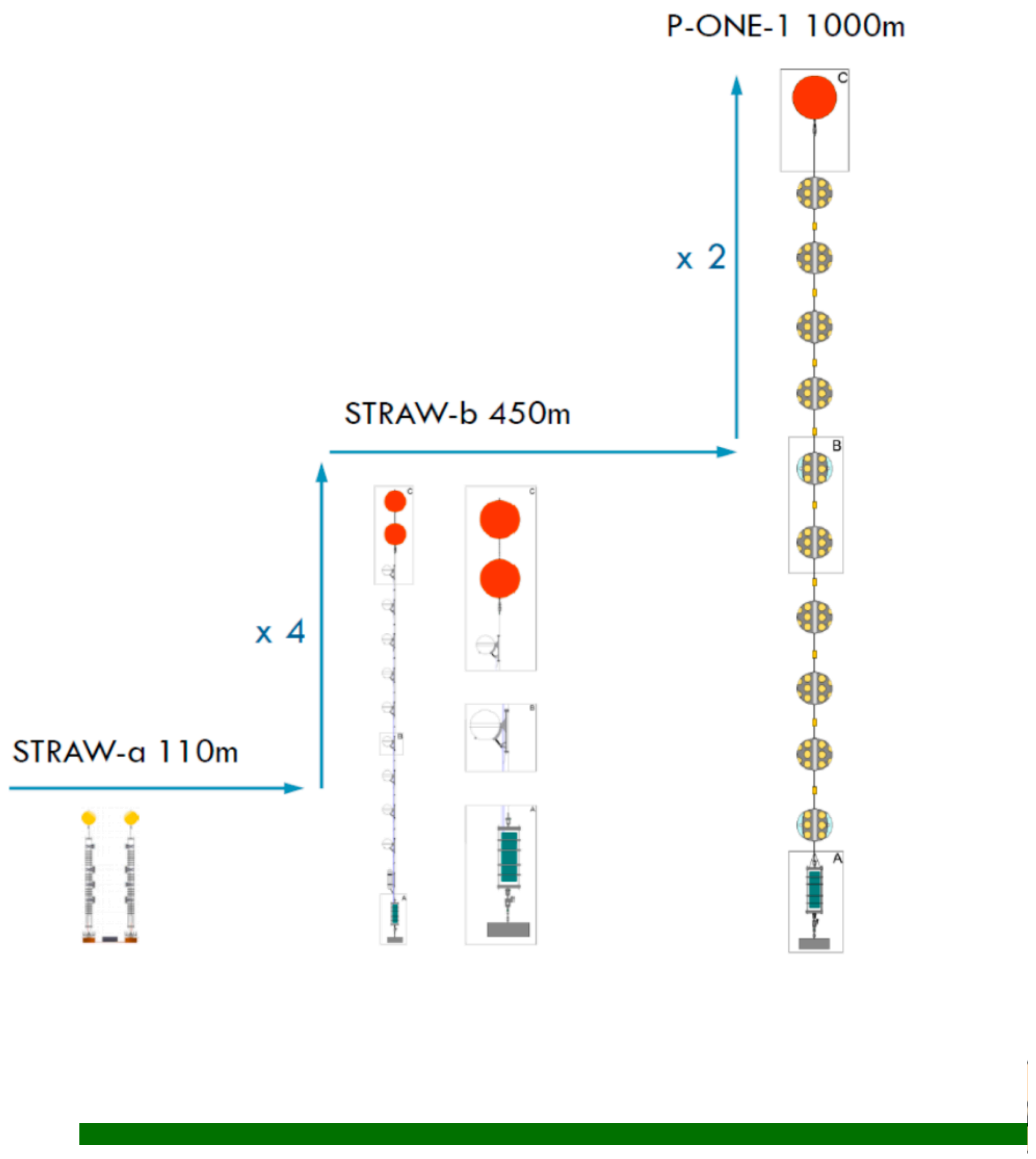


String junction box



P-ONE-1

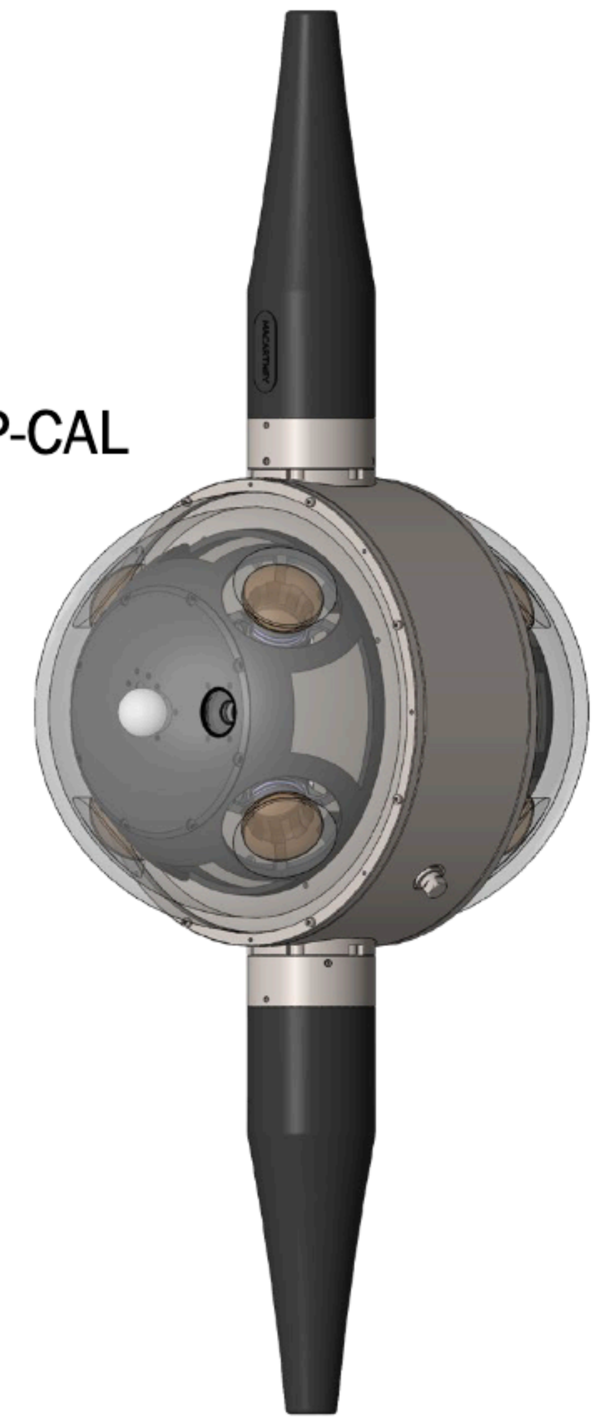
2025



Pathfinder

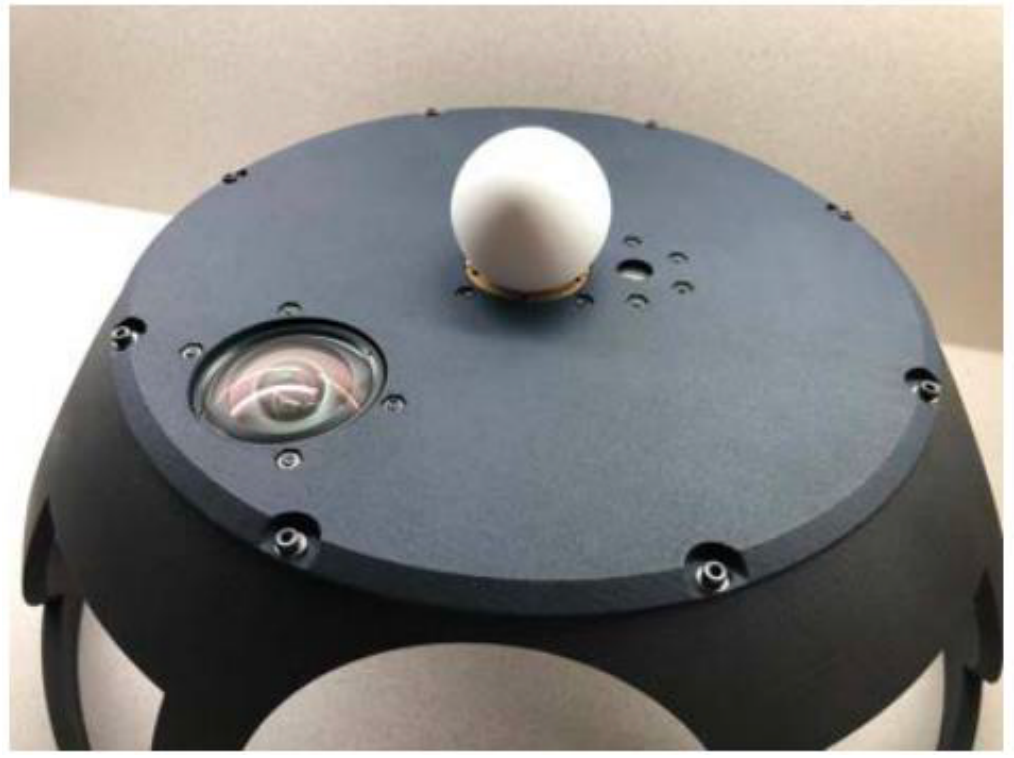
Phase 1 (2018 — 2025)

P-CAL

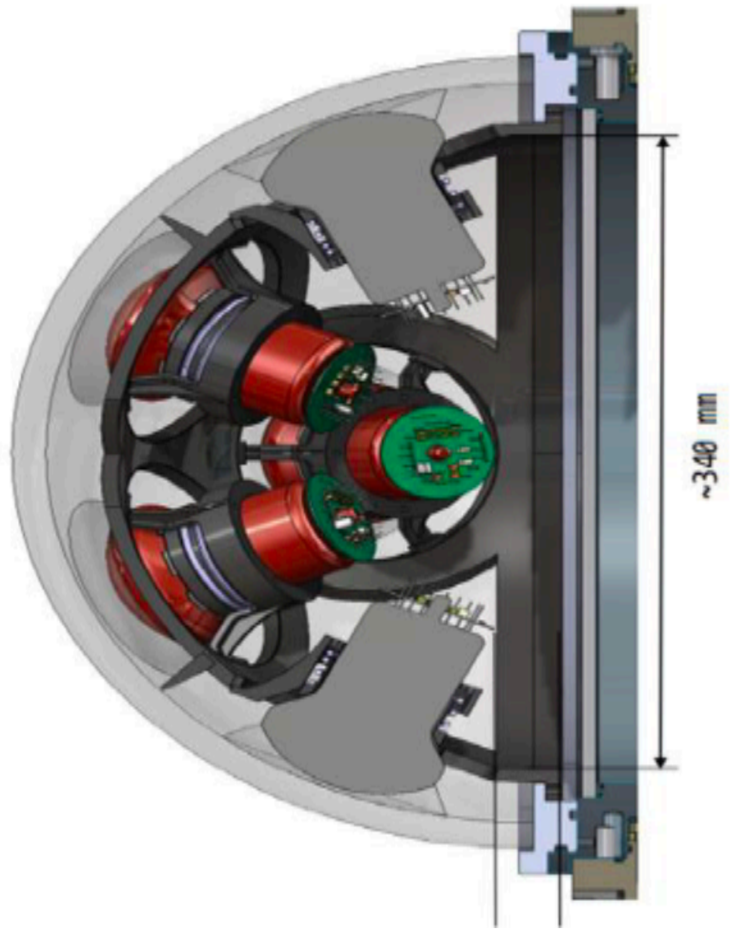


Calibration program

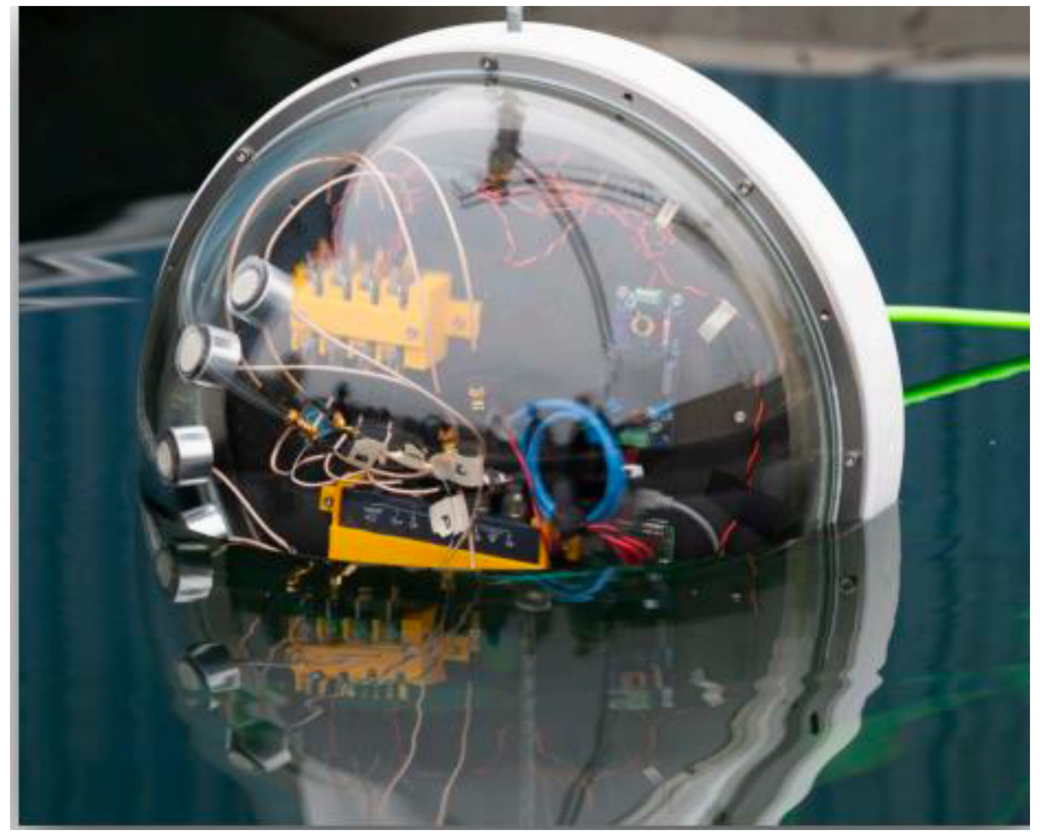
P-CAL optical diffusing sphere*

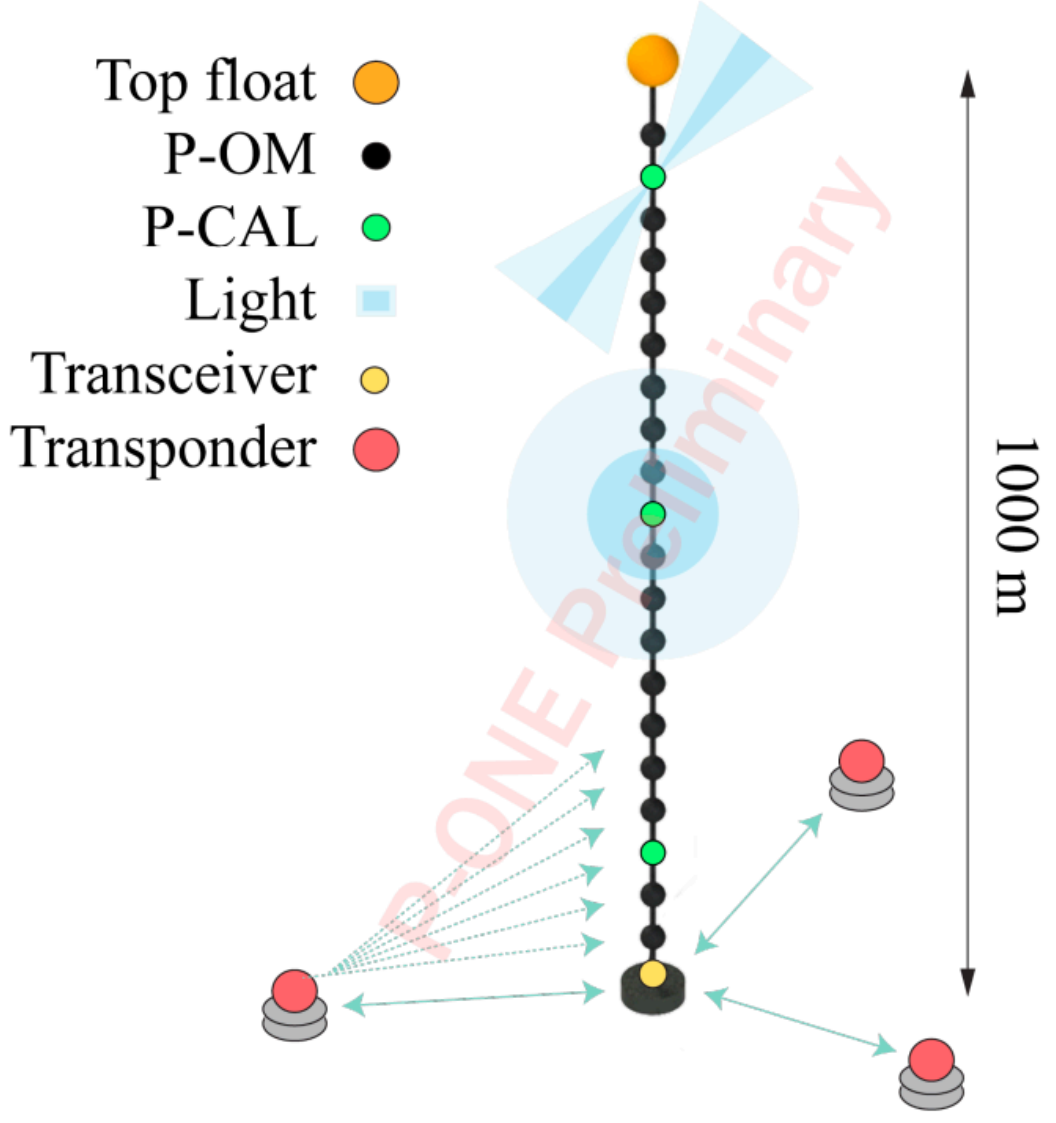


Muon scintillation tracker

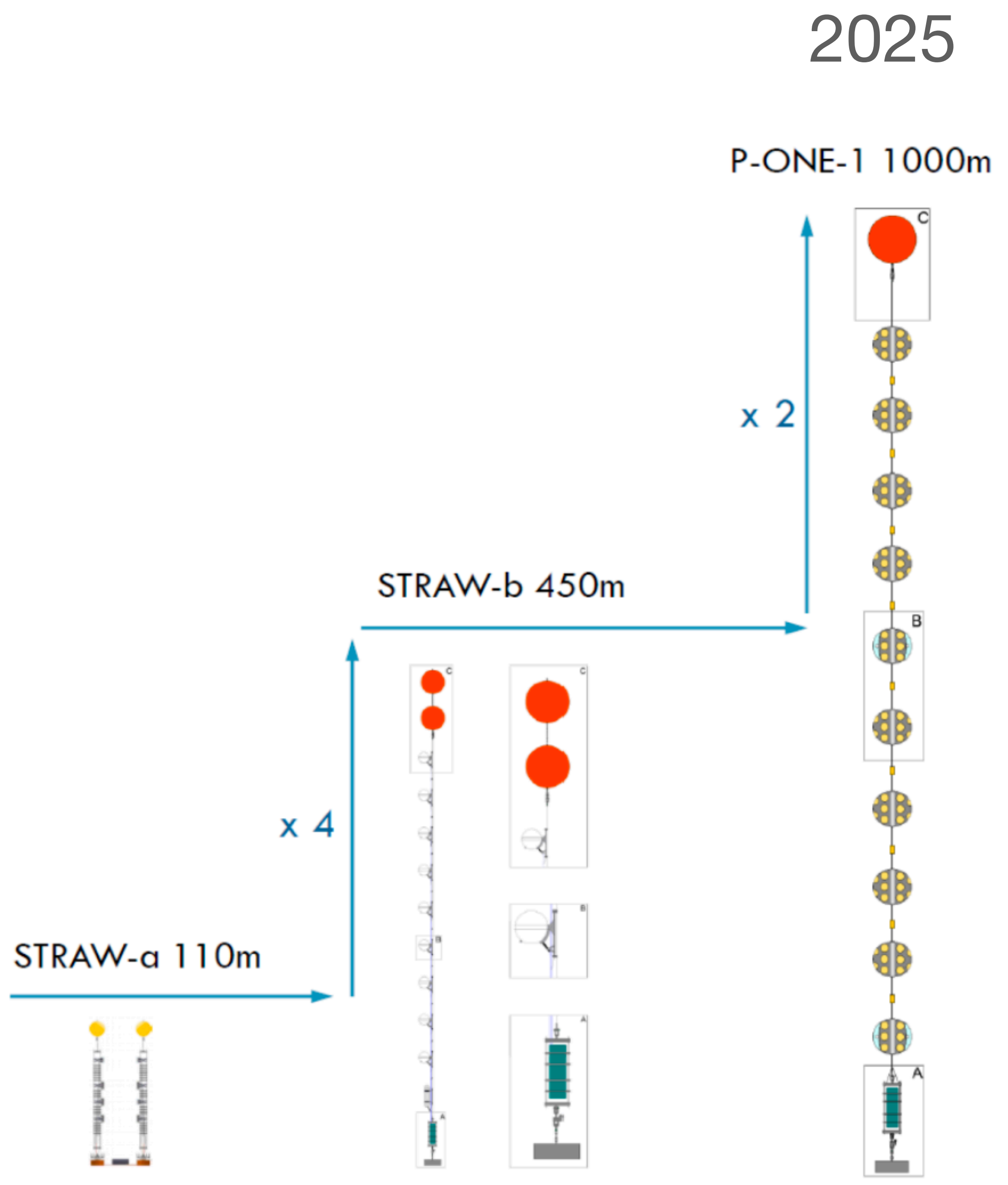


Acoustic position system

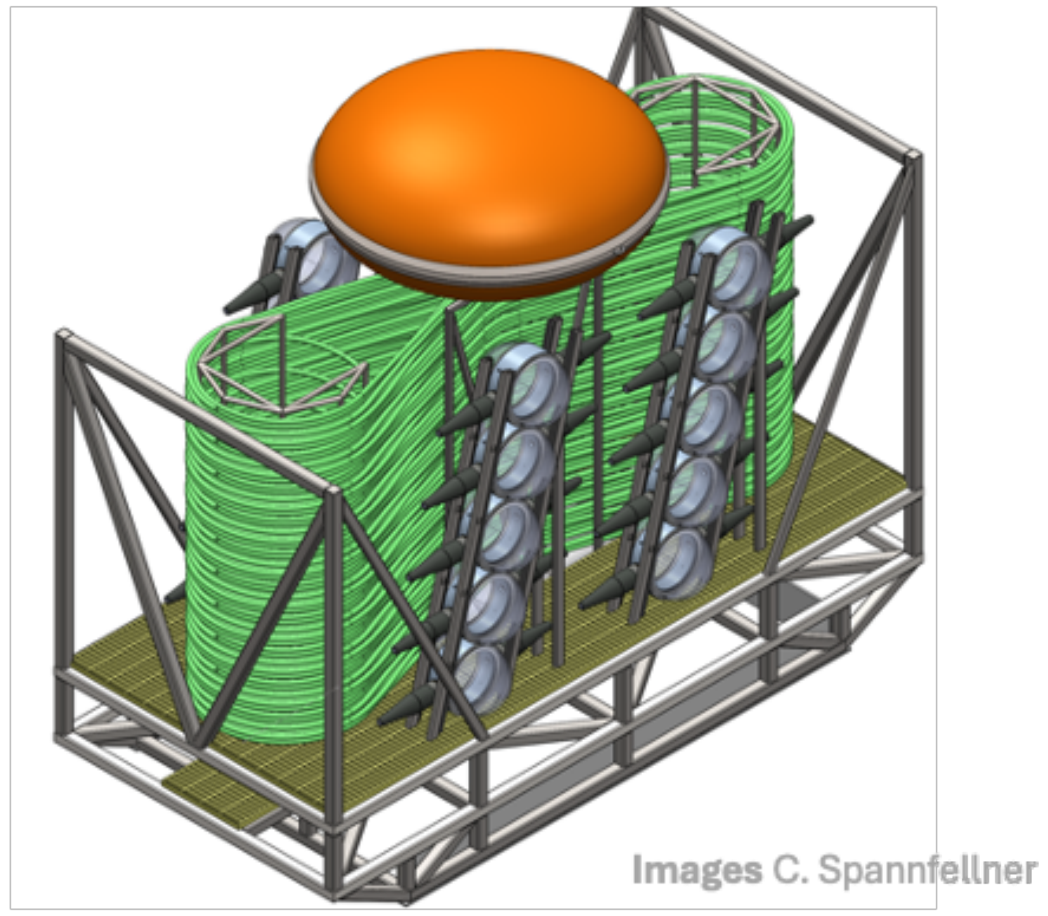


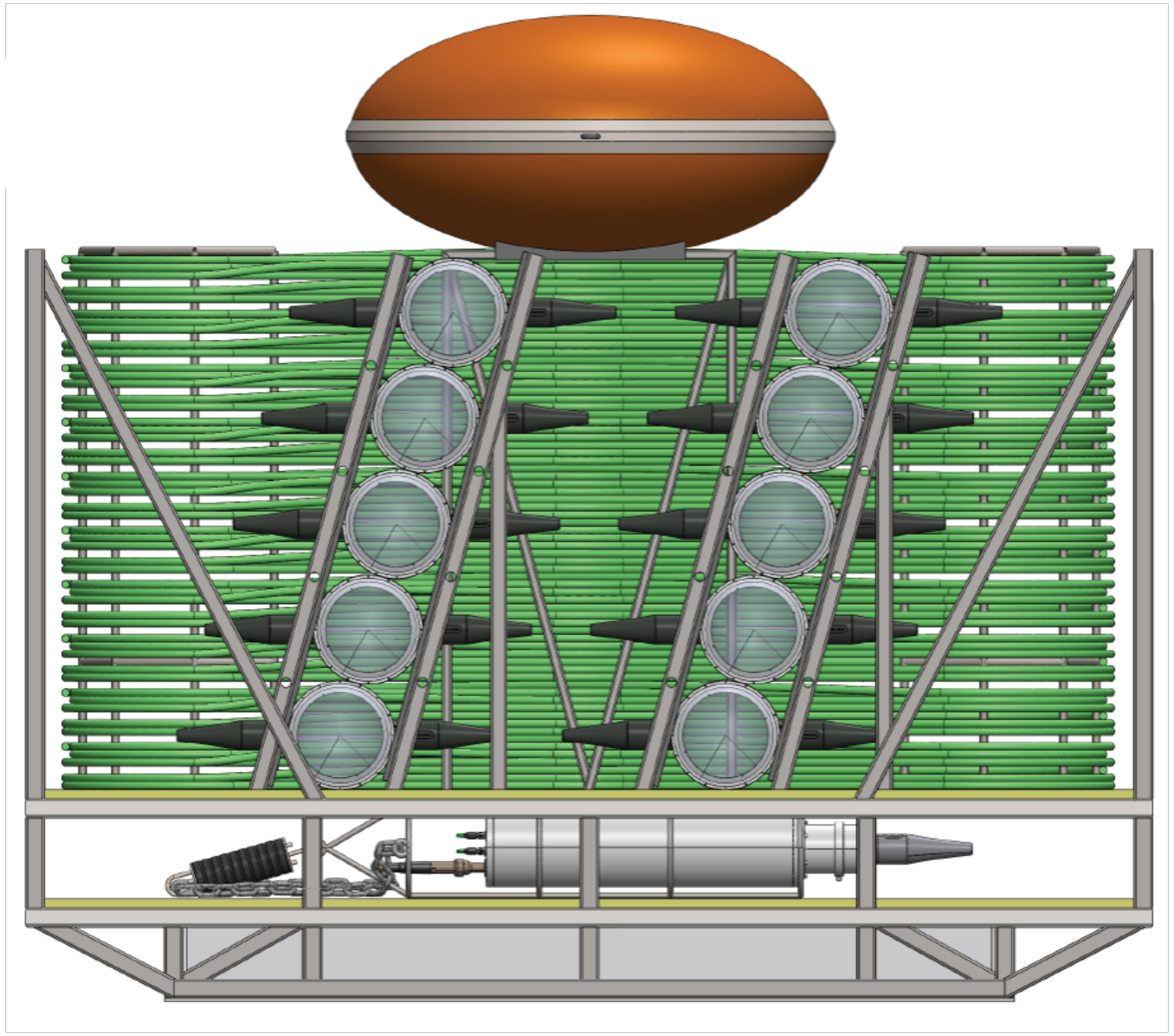


P-ONE-1



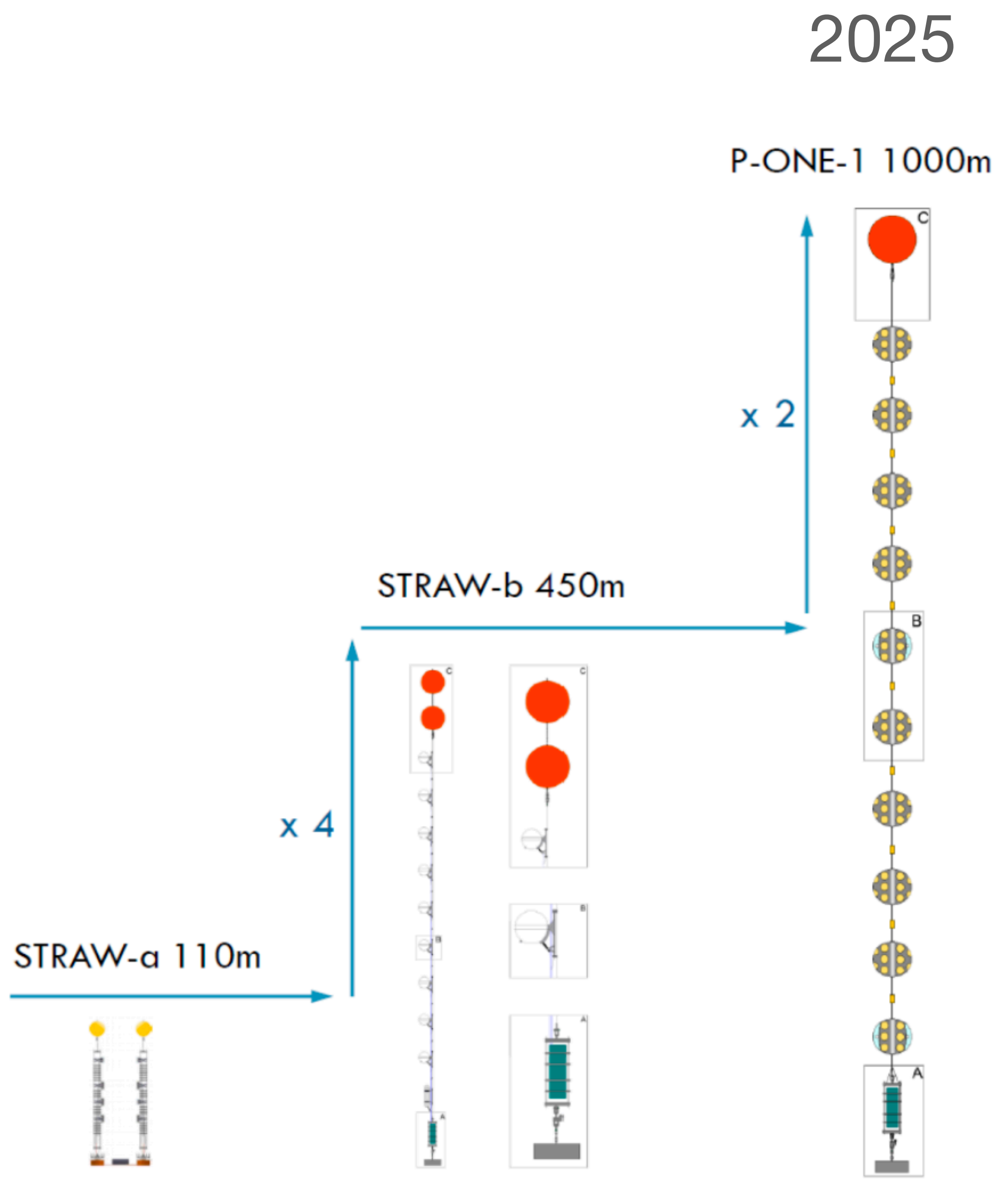
Pathfinder
Phase 1 (2018 — 2023)

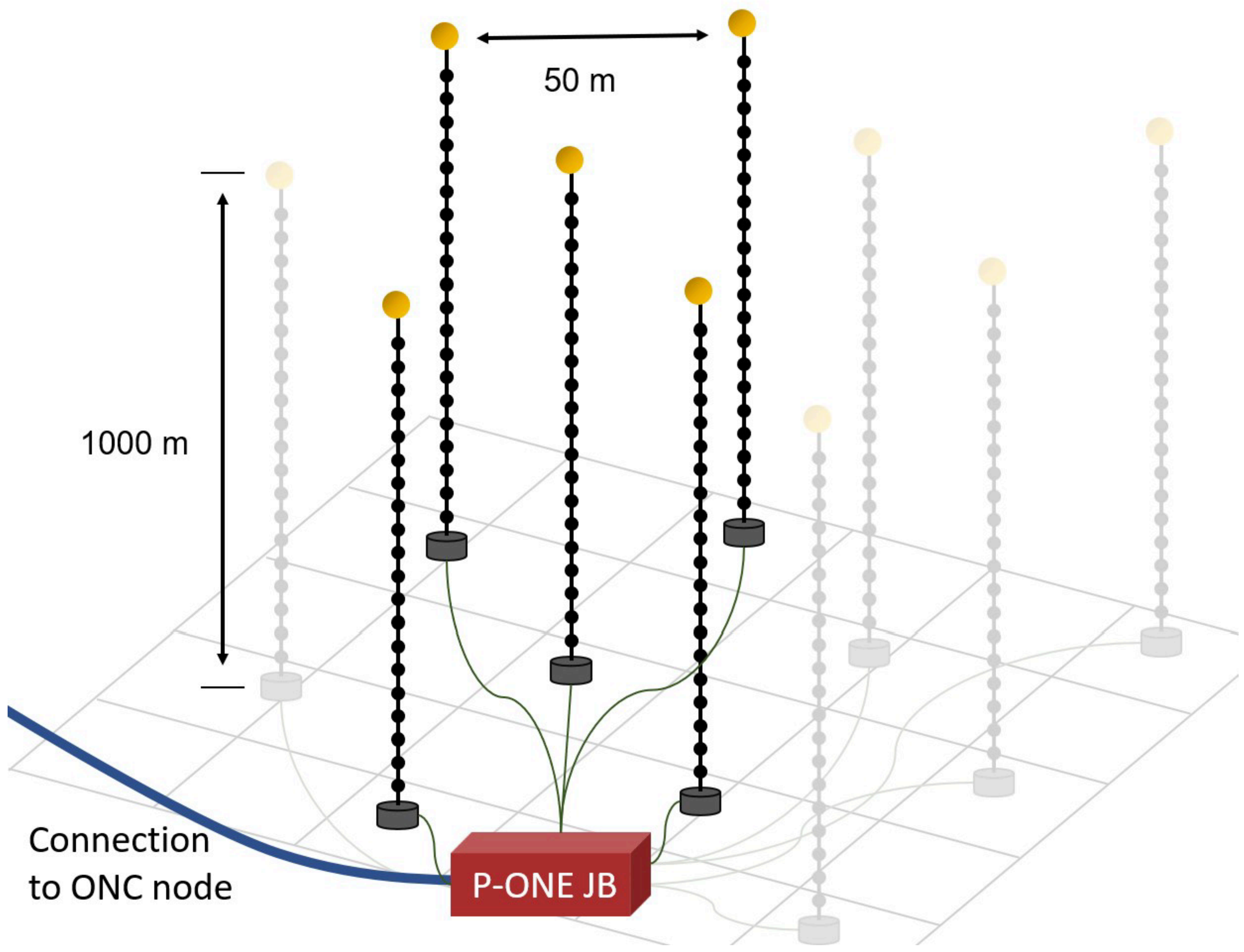




- 1 km mooring line with 20 modules employing a connector-less design
- Sub-ns synchronization
- In-line network infrastructure

P-ONE Demonstrator



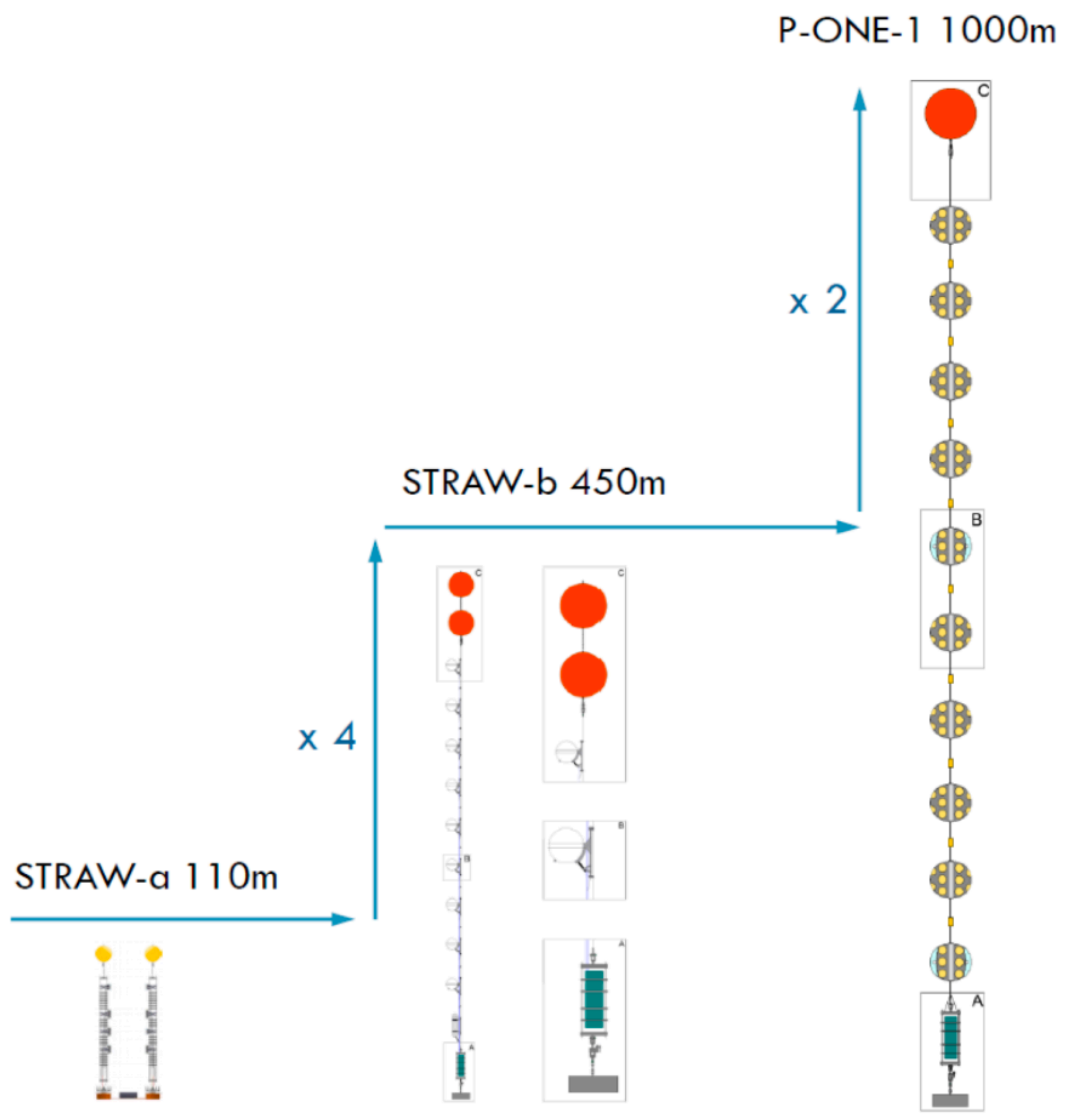


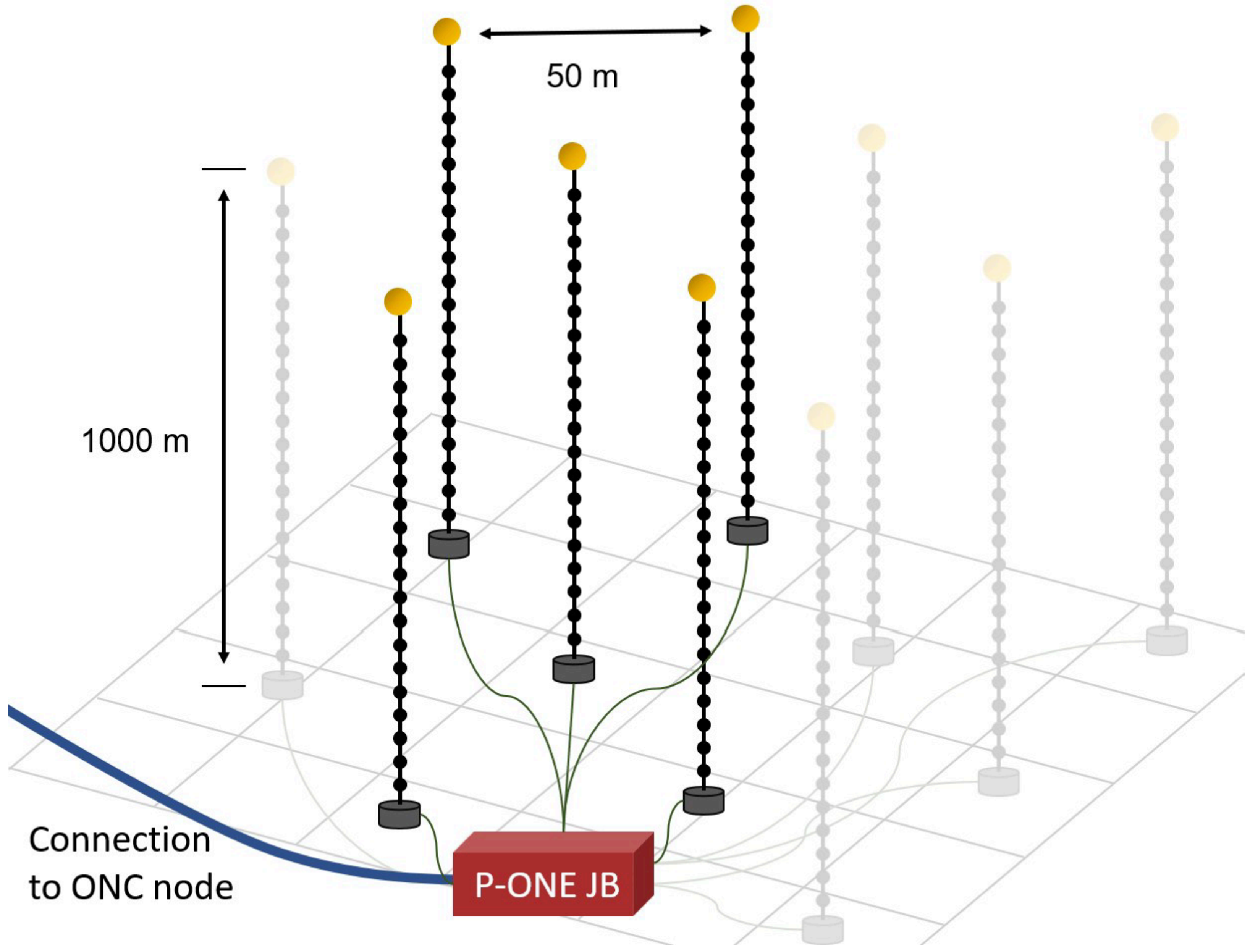
Pathfinder
Phase 1 (2018 — 2025)

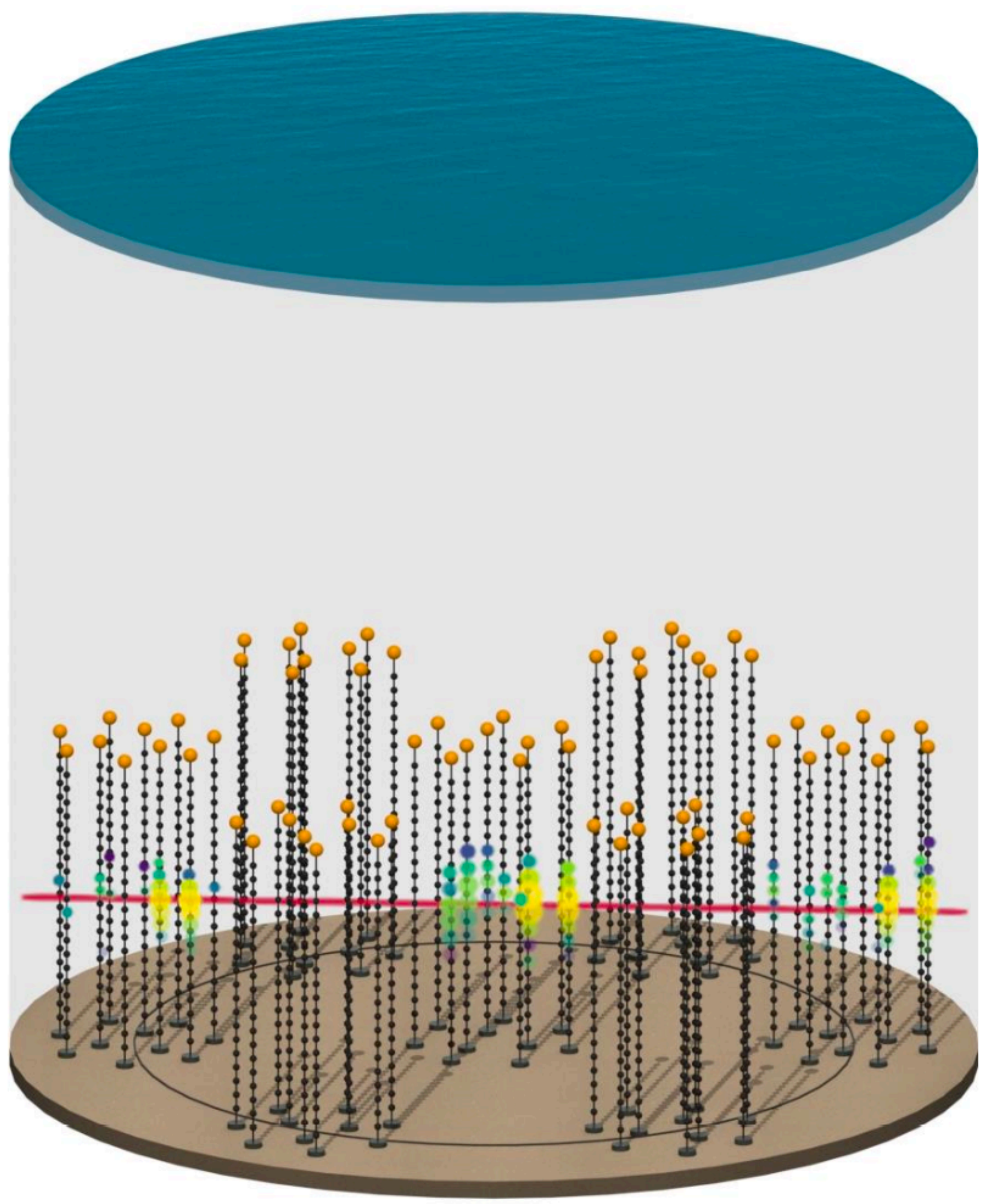
Demonstrator (first cluster)
Phase 2 (2025 — 2028)
~20M project **funding secured** (2023 CFI-IF/ERC/NSF)

P-ONE

2025







Pathfinder
Phase 1 (2018 — 2025)

Demonstrator (first cluster)
Phase 2 (2025 — 2028)
~20M project **funding secured** (2023 CFI-IF/ERC/NSF)

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

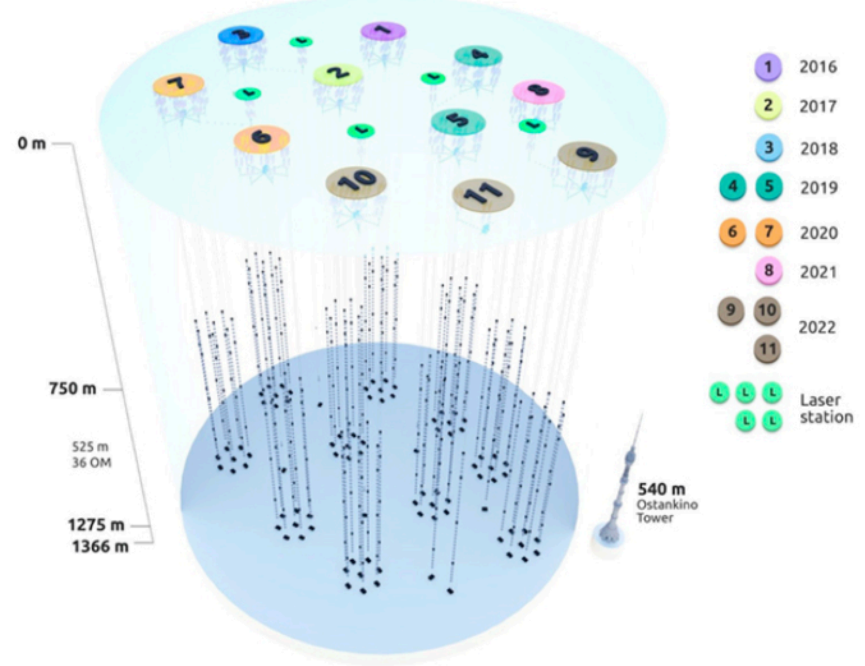
Summary

From discovery to the era of a new field in astroparticle physics…

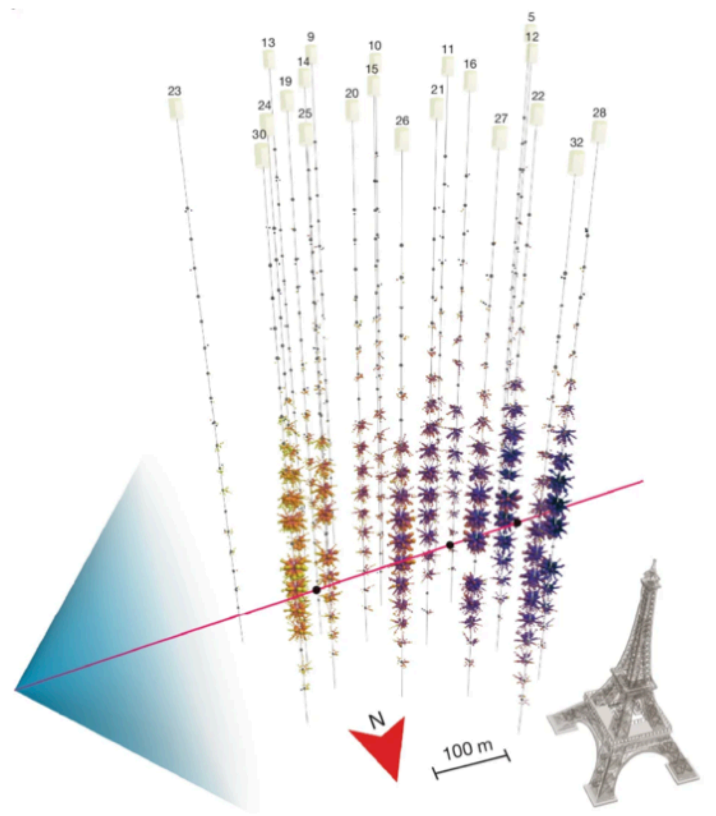
Discovered high-energy cosmic neutrino flux is robust
- energy density similar to that of gamma rays and cosmic rays
- mounting evidence emerging of the first extragalactic and Galactic sources

Global program underway to develop new and enhanced neutrino observatories
- a new window through which to study the extreme universe; from fundamental neutrino properties to cosmic accelerators

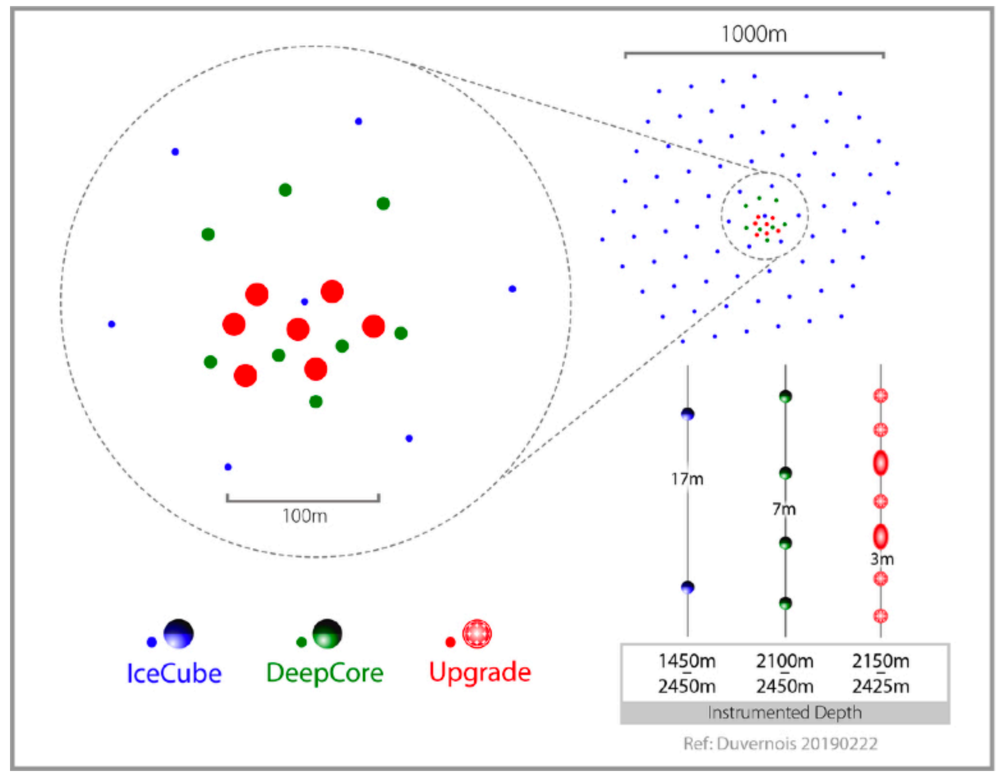
GVD

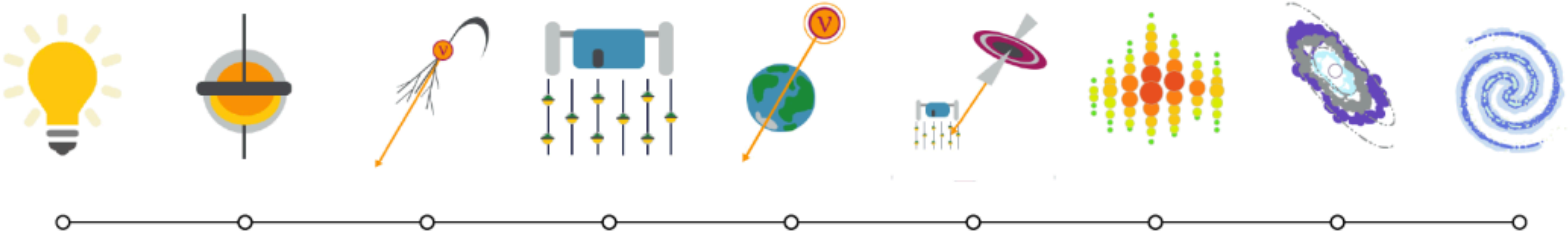


KM3NeT

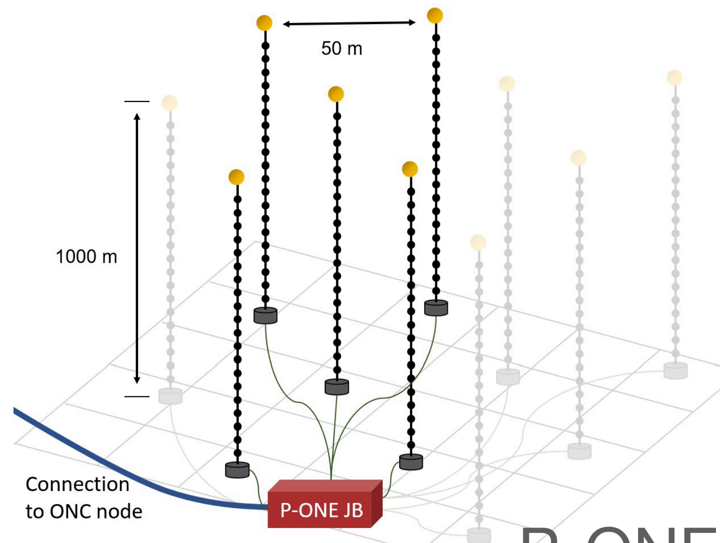


IceCube Upgrade/Gen2





1988	2000	2001	2011	2013	2018	2021	2022	2023
Telescope in the Ice Envisioned	AMANDA Completed	Atmospheric Neutrinos Detected	IceCube Completed	Astrophysical Neutrinos Discovered	First Source TXS 0506+056 Identified	Glashow Resonance Neutrino Identified	Second Source NGC 1068 Identified	Third Source Milky Way Identified

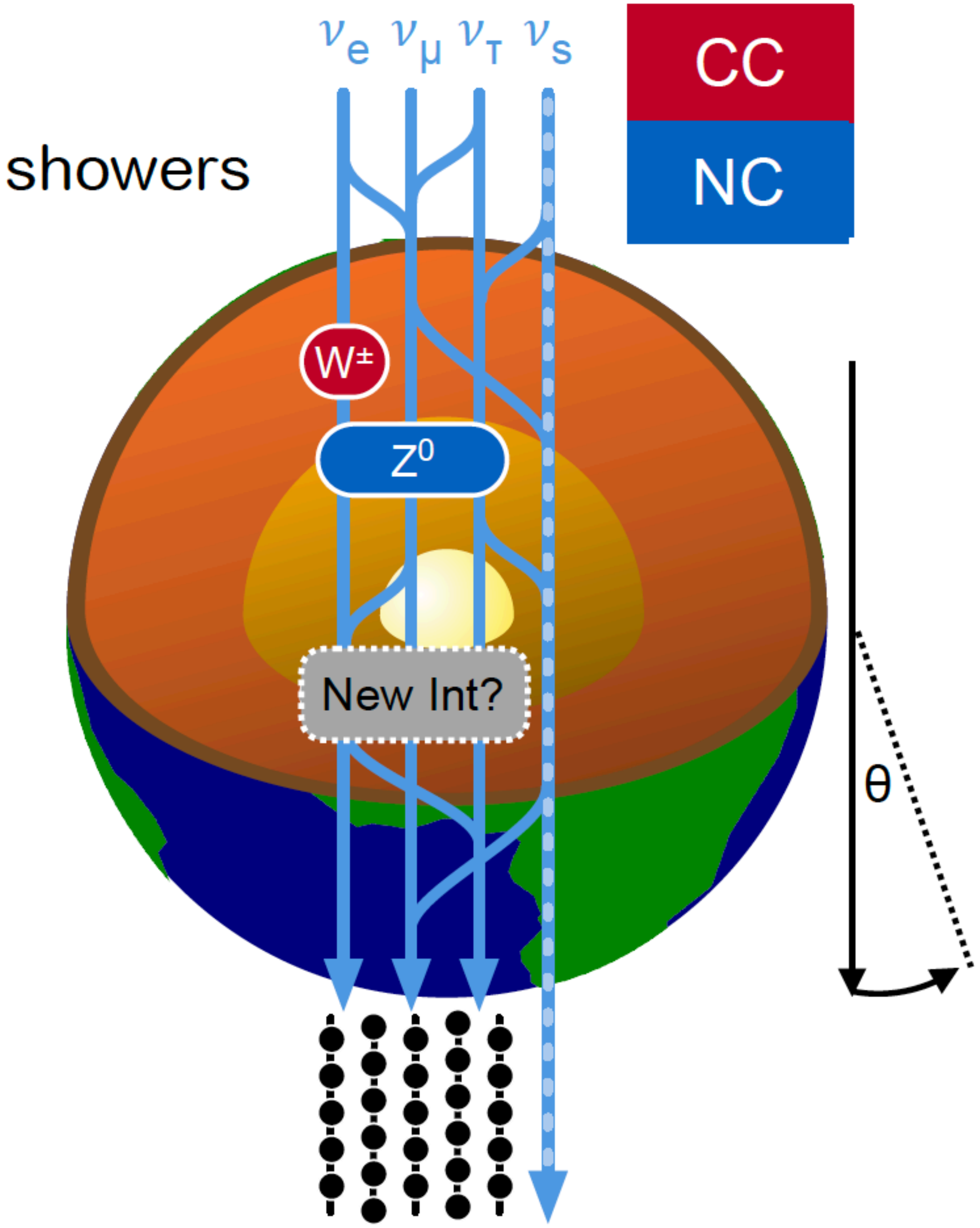


P-ONE

Backup slides

Atmospheric neutrino oscillations

- Natural beam of neutrinos generated in cosmic ray air showers
  - All flavors, neutrino + antineutrino
  - Broad energy band (GeV - TeV) and baselines (20 - 12,700 km) through variable Earth density profile



Flavour Mass

$$|\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle$$

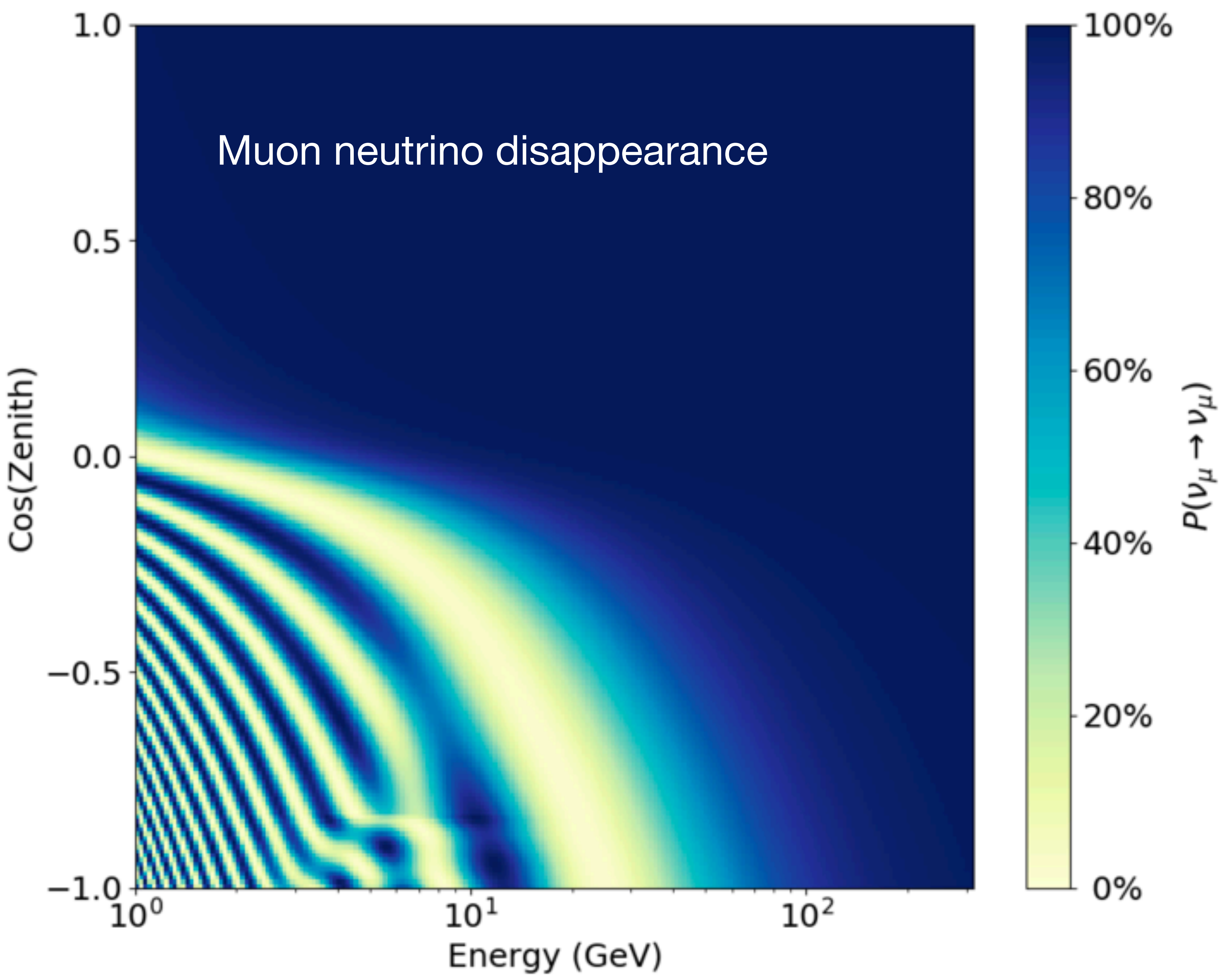
U_{PMNS} parameterised by…

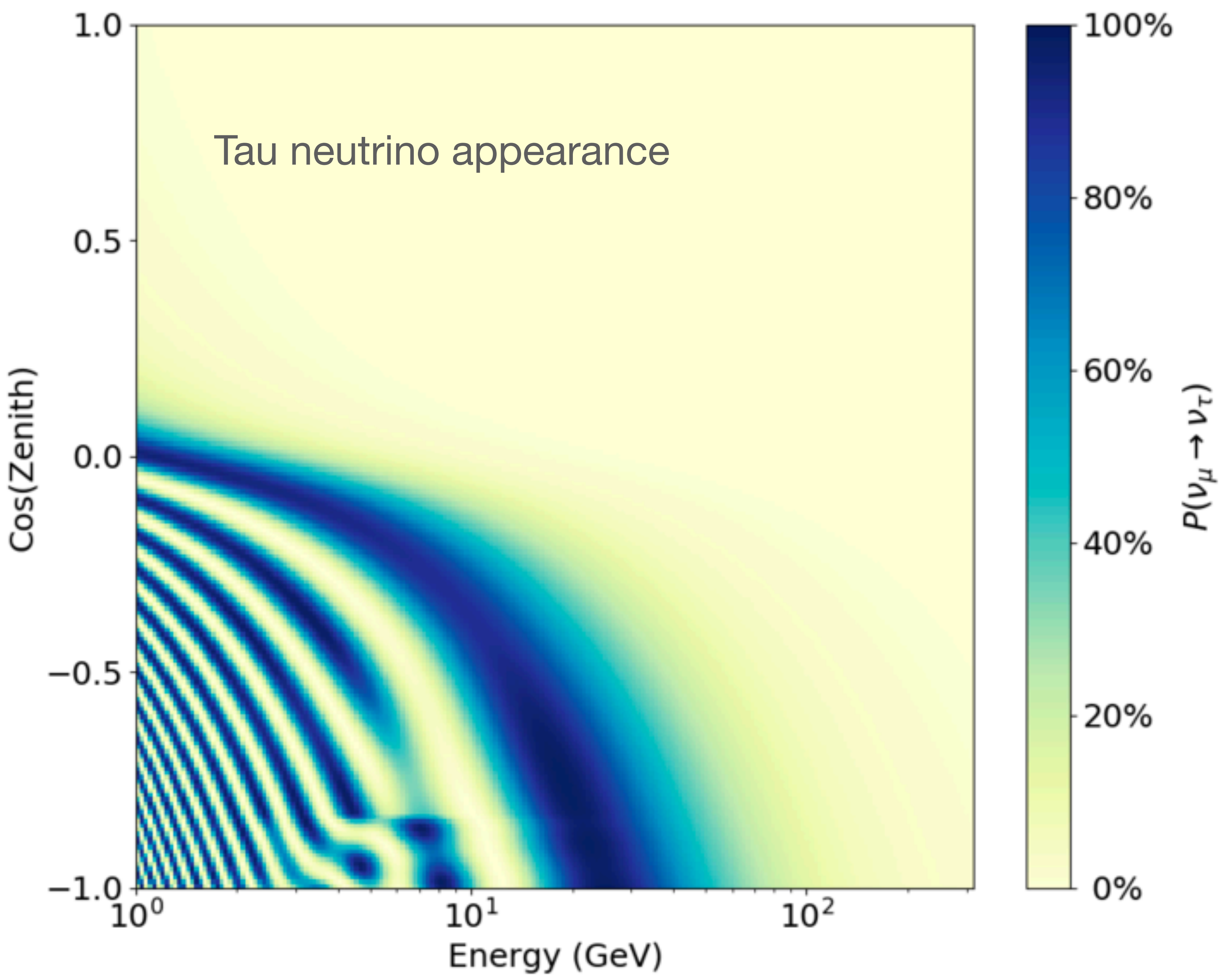
- Three mixing angles: θ_{12}, θ_{13}, θ_{23}
- δCP

Two mass splittings…

- $\Delta m^2_{21} \sim 10^{-5}$ eV^2
- $\Delta m^2_{32} \sim 10^{-3}$ eV^2

Atmospheric neutrino oscillations (3 x 3 mixing)





Atmospheric neutrino oscillations (3 x 3 mixing)

https://arxiv.org/pdf/2405.02163

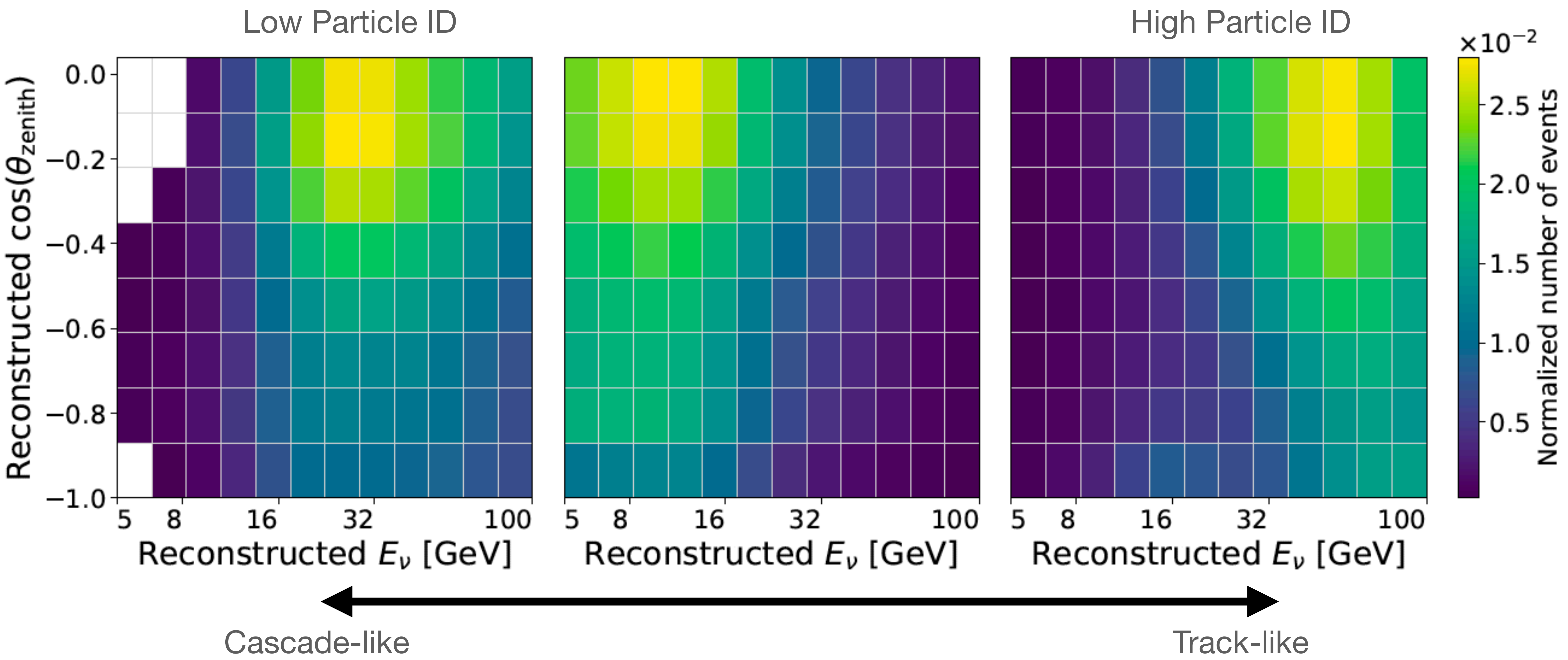
Summer Blot, LLWI 2024

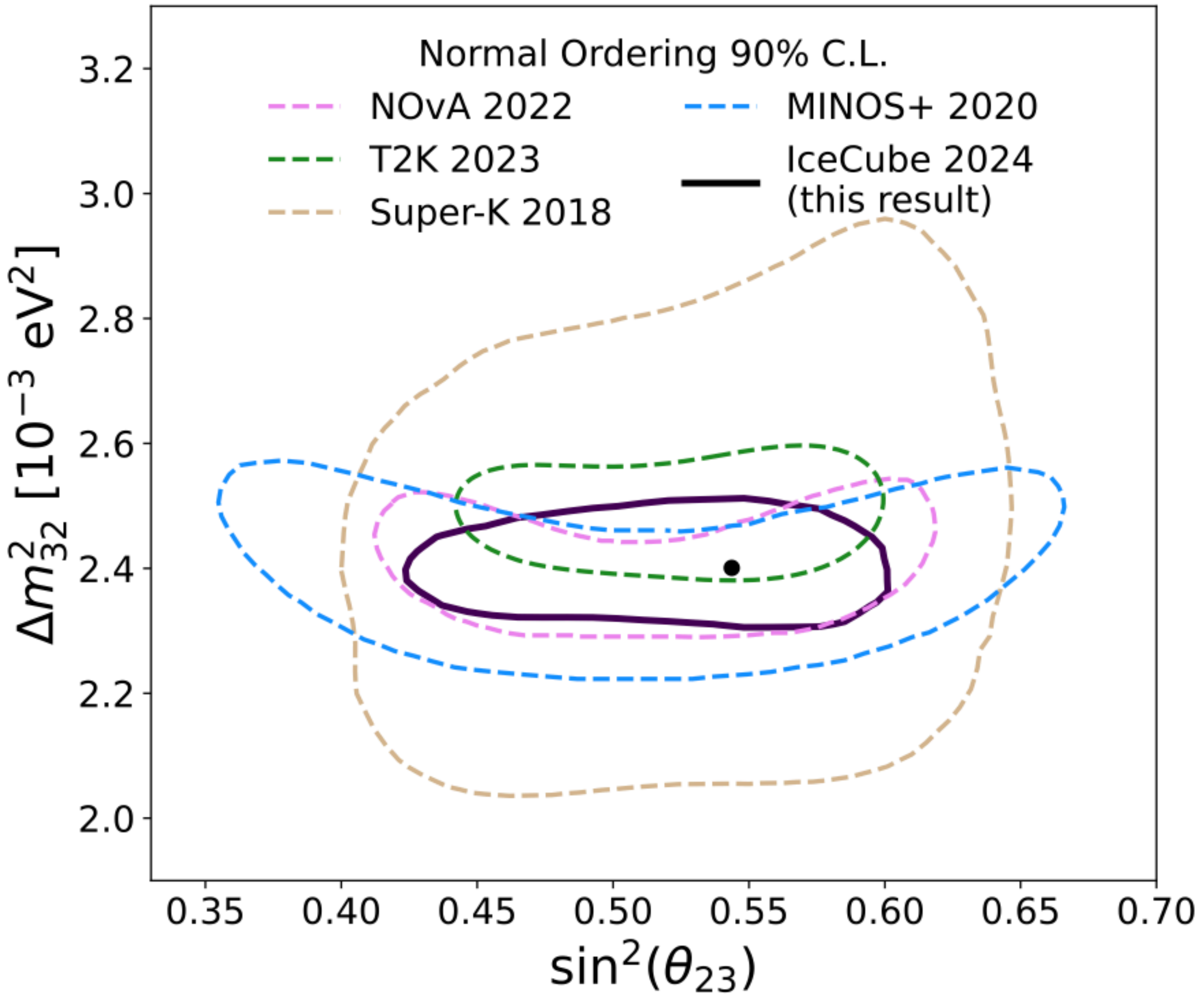
- High purity neutrino sample (9.3 years; less than 1% atmospheric muon contamination
- Applies convolutional neural networks reconstruction (factor 5000 speed-up with consistent resolutions)
- Incorporates latest detector systematics updates (calibration, flux, cross-section).

$$\sin^2\theta_{23} = 0.54^{+0.04}_{-0.03}$$

$$\Delta m^2_{32} = (2.40^{+0.05}_{-0.04}) \times 10^{-3}\ \mathrm{eV}^2$$

1σ errors include stat.+ syst. and F.C. corrections for accurate coverage

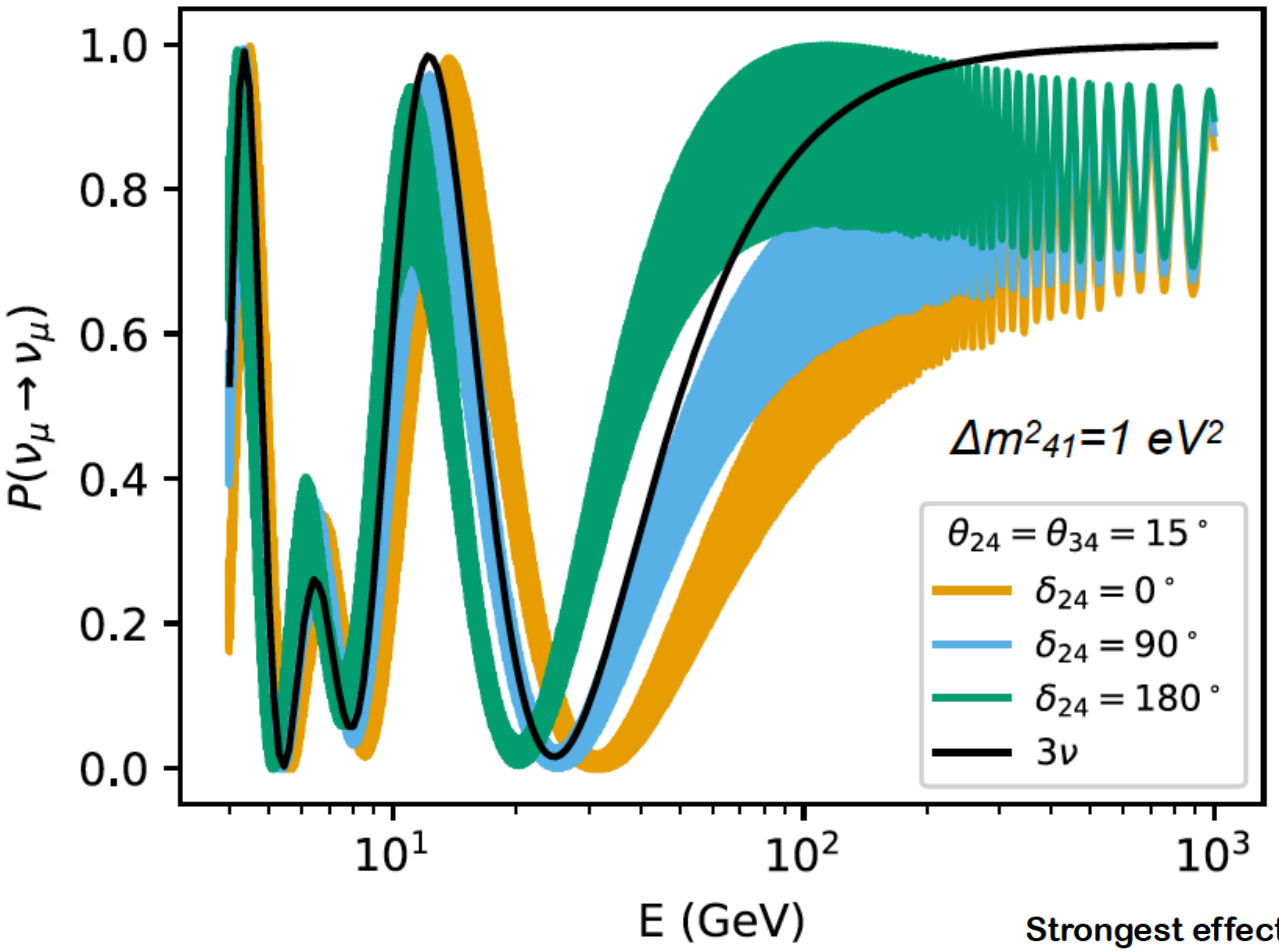




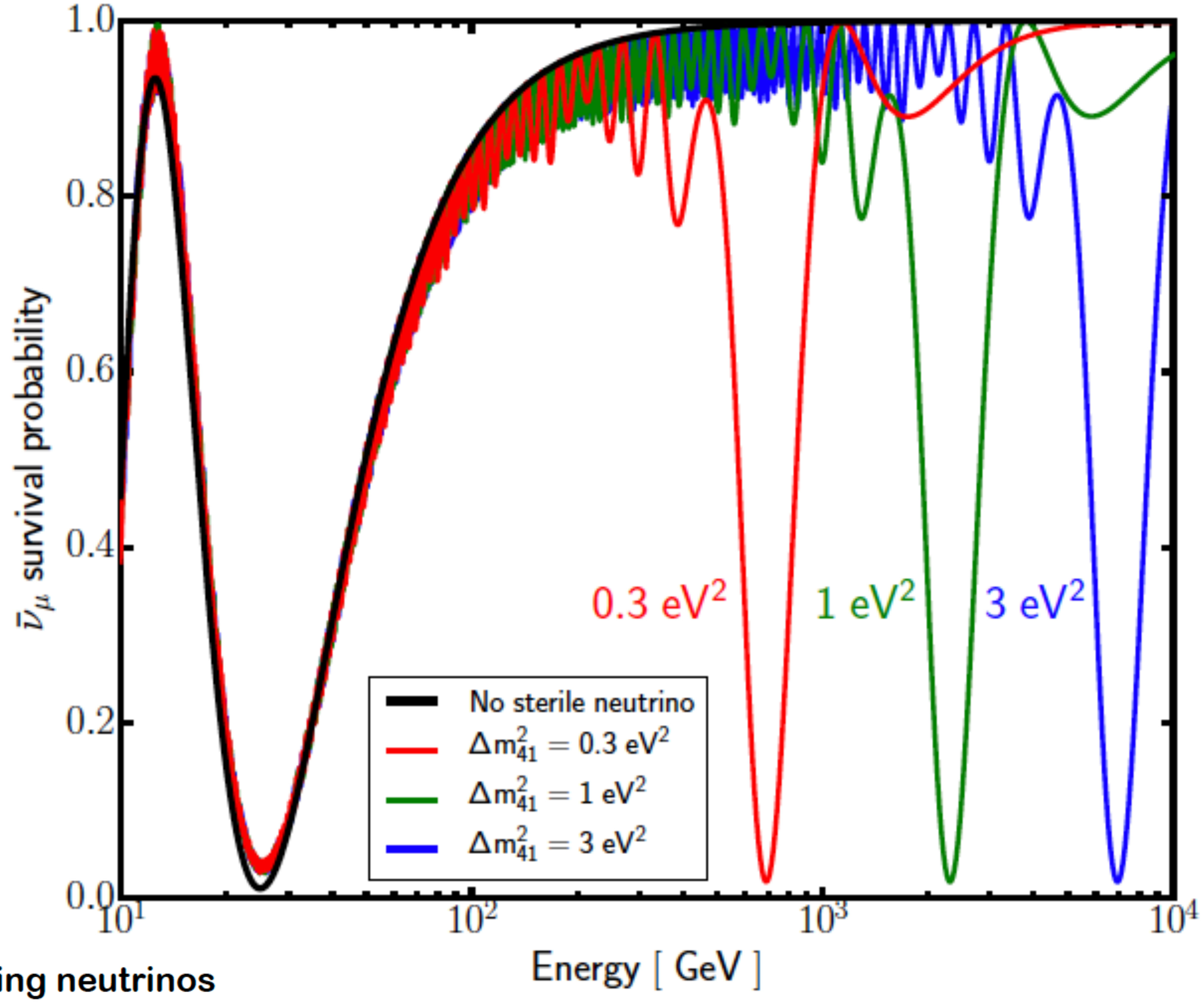
Atmospheric neutrino oscillations (3+1 sterile neutrino; 4 x 4 mixing)

- Individual analyses that focus on different energy regimes, leveraging differences in the potential signals and the impacts of systematics.

Low-energy: cannot resolve rapid oscillations; sensitivity to mixing angle for 2-4 and 3-4 mass eigenstates and phase 2-4



High-energy: MSW-like resonance effect; sensitivity to 4-1 mass splitting and mixing angle for 2-4 and 3-4 states



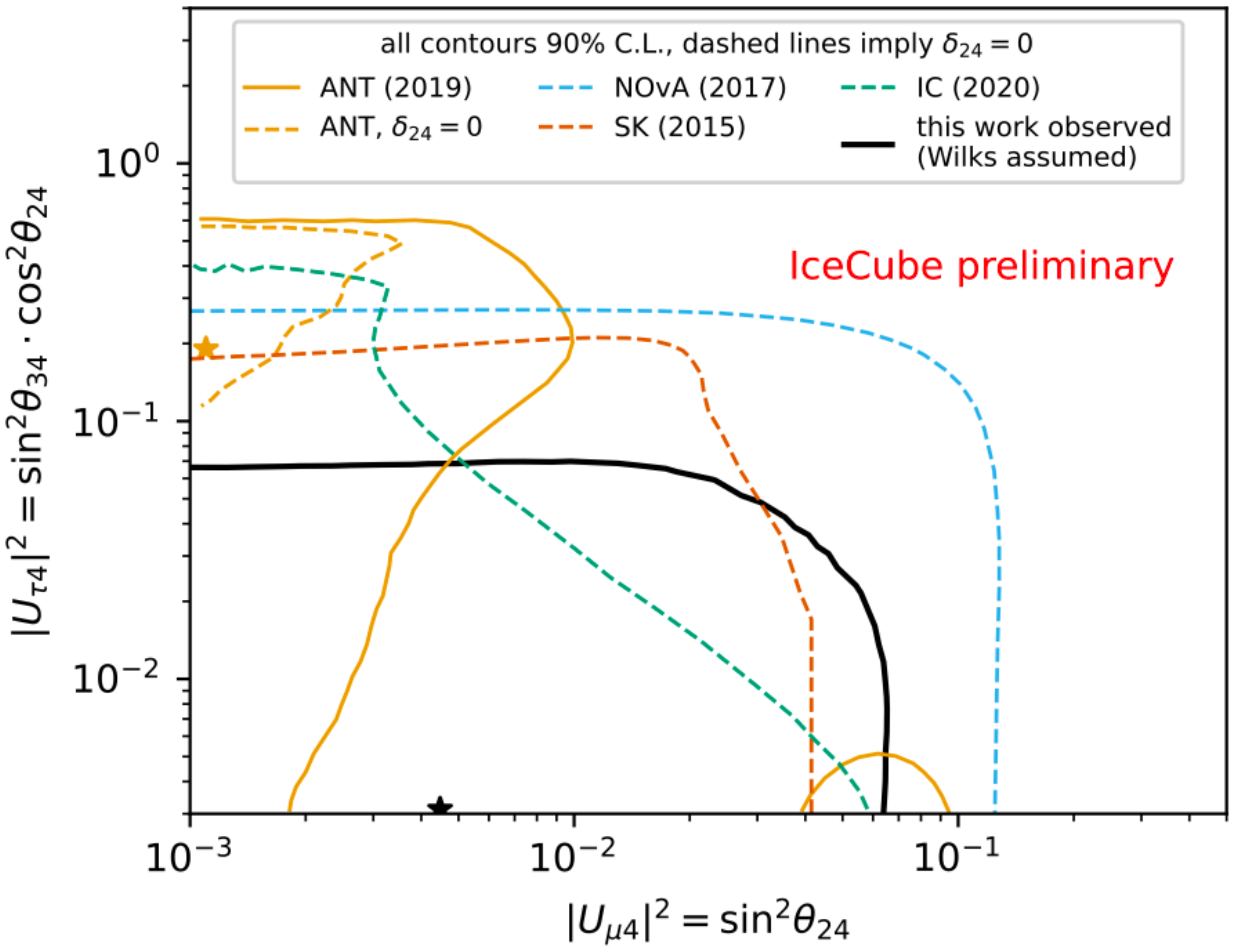
Strongest effects for core-crossing neutrinos

Atmospheric neutrino oscillations (3+1 sterile neutrino; 4 x 4 mixing)

- Individual analyses that focus on different energy regimes, leveraging differences in the potential signals and the impacts of systematics.

- Low-energy (5 - 150 GeV)
  - 7.5yr dataset
  - Fit compatible with the null hypothesis

$|U_{\mu 4}|^2 < 0.053$, $|U_{\tau 4}|^2 < 0.057$ @90%CL



Atmospheric neutrino oscillations (3+1 sterile neutrino; 4 x 4 mixing)

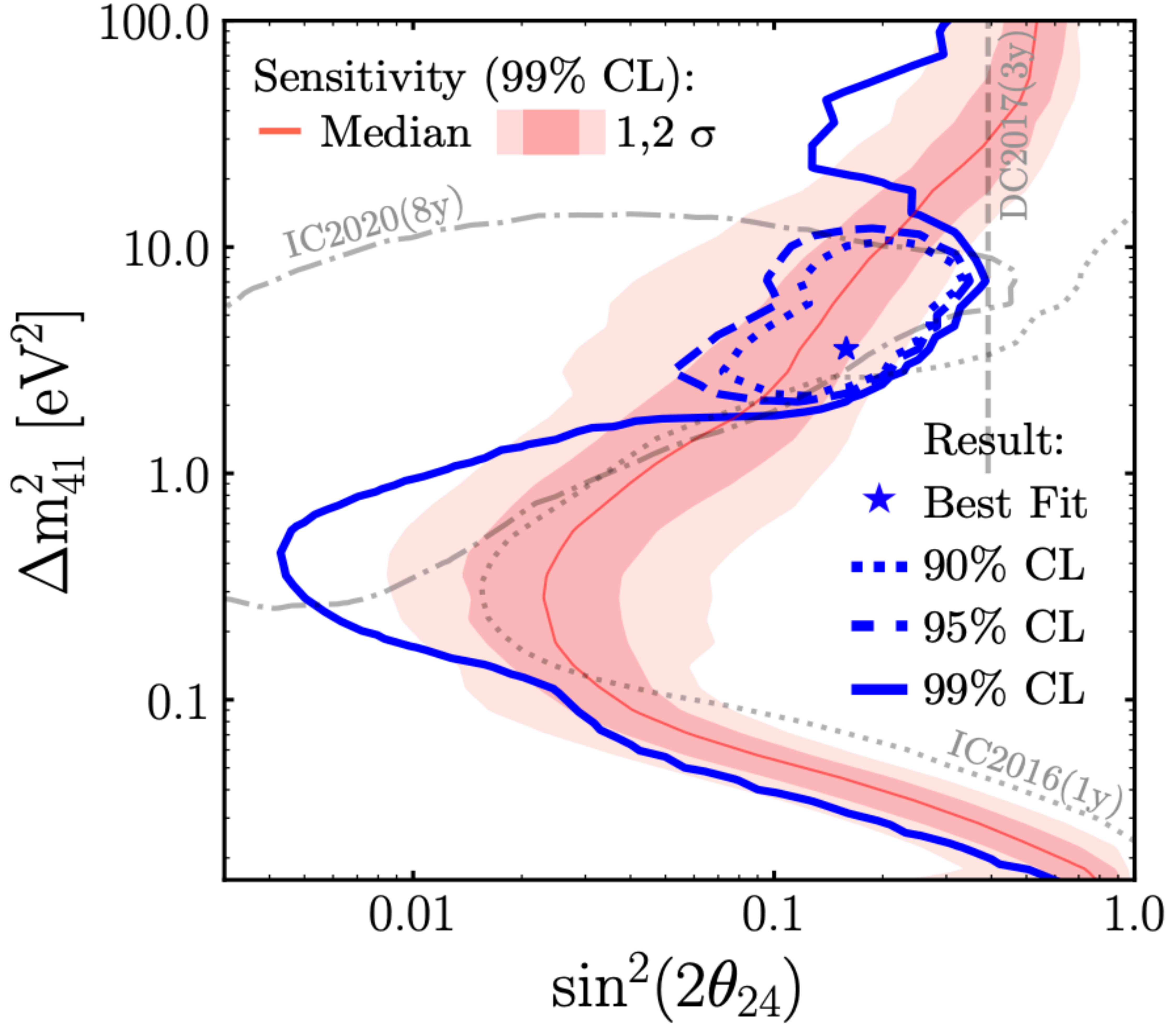
https://arxiv.org/pdf/2405.08070

- Individual analyses that focus on different energy regimes, leveraging differences in the potential signals and the impacts of systematics.

- Low-energy (5 - 150 GeV)
  - 7.5yr dataset
  - Fit compatible with the null hypothesis

- High-energy (500 GeV - 100 TeV)
  - 10.7 yr dataset
  - Improved muon neutrino fitter providing separation of starting and through-going events
  - Fit compatible with the null hypothesis (p-value 3.1%)

$\Delta m^2_{41} = 3.5\ eV^2$, $\sin^2(2\theta_{24}) = 0.16$

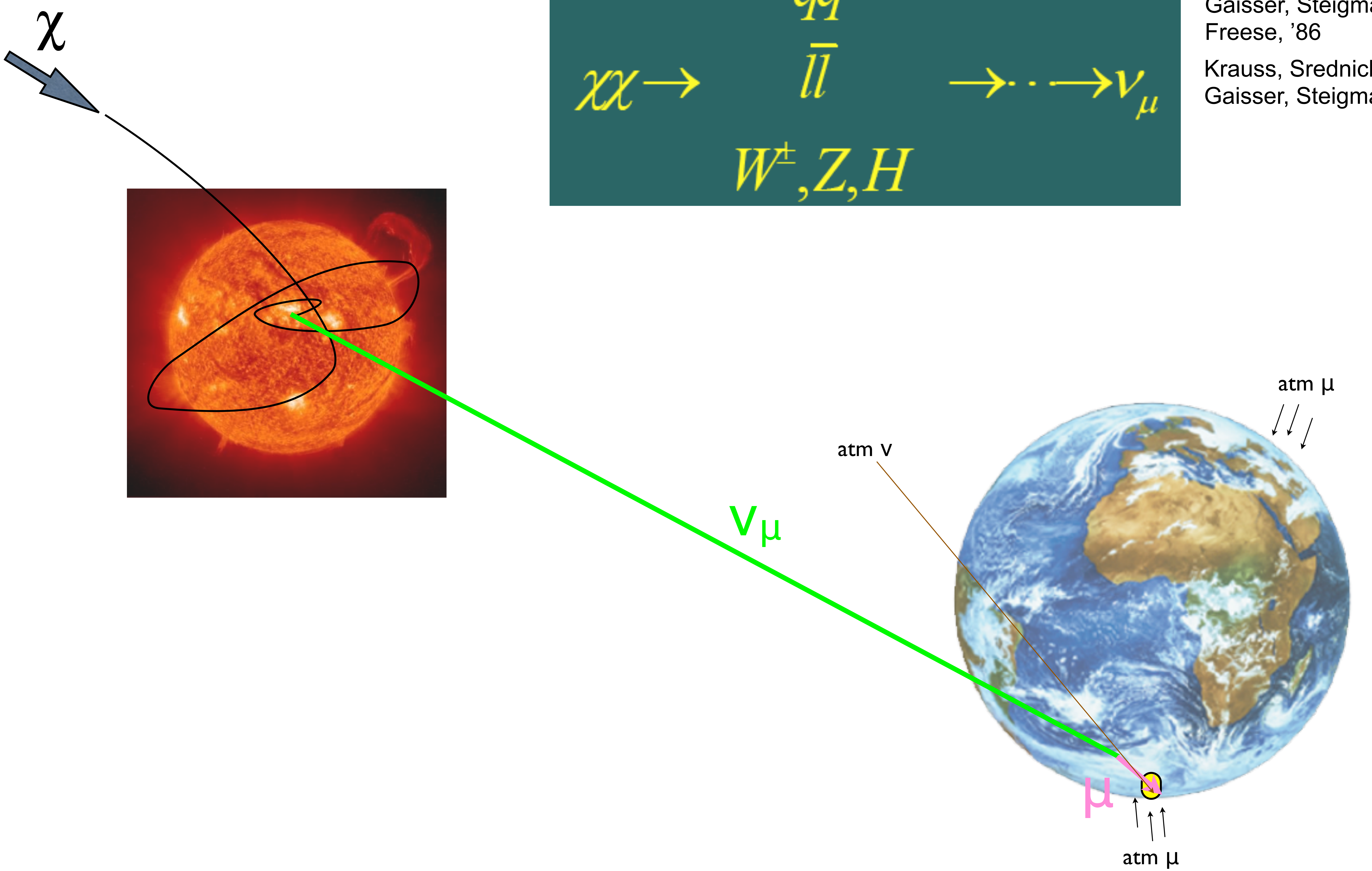


Dark matter search (indirect)

$$\chi\chi \rightarrow \begin{matrix} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{matrix} \rightarrow \cdots \rightarrow \nu_{\mu}$$

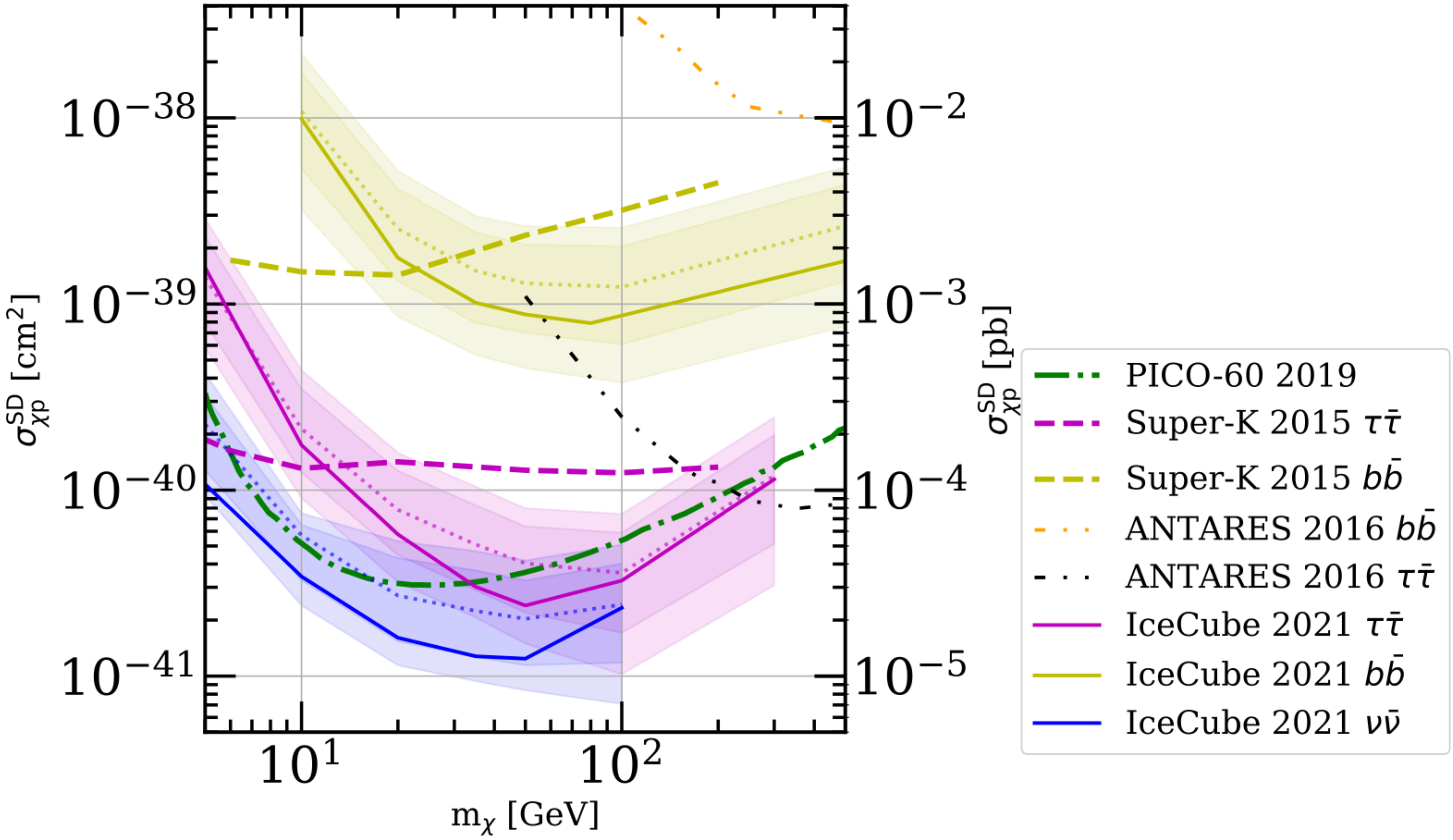
Silk, Olive and Srednicki, ’85
Gaisser, Steigman & Tilav, ’86
Freese, ’86

Krauss, Srednicki & Wilczek, ’86
Gaisser, Steigman & Tilav, ’86



Indirect dark matter search (Sun)

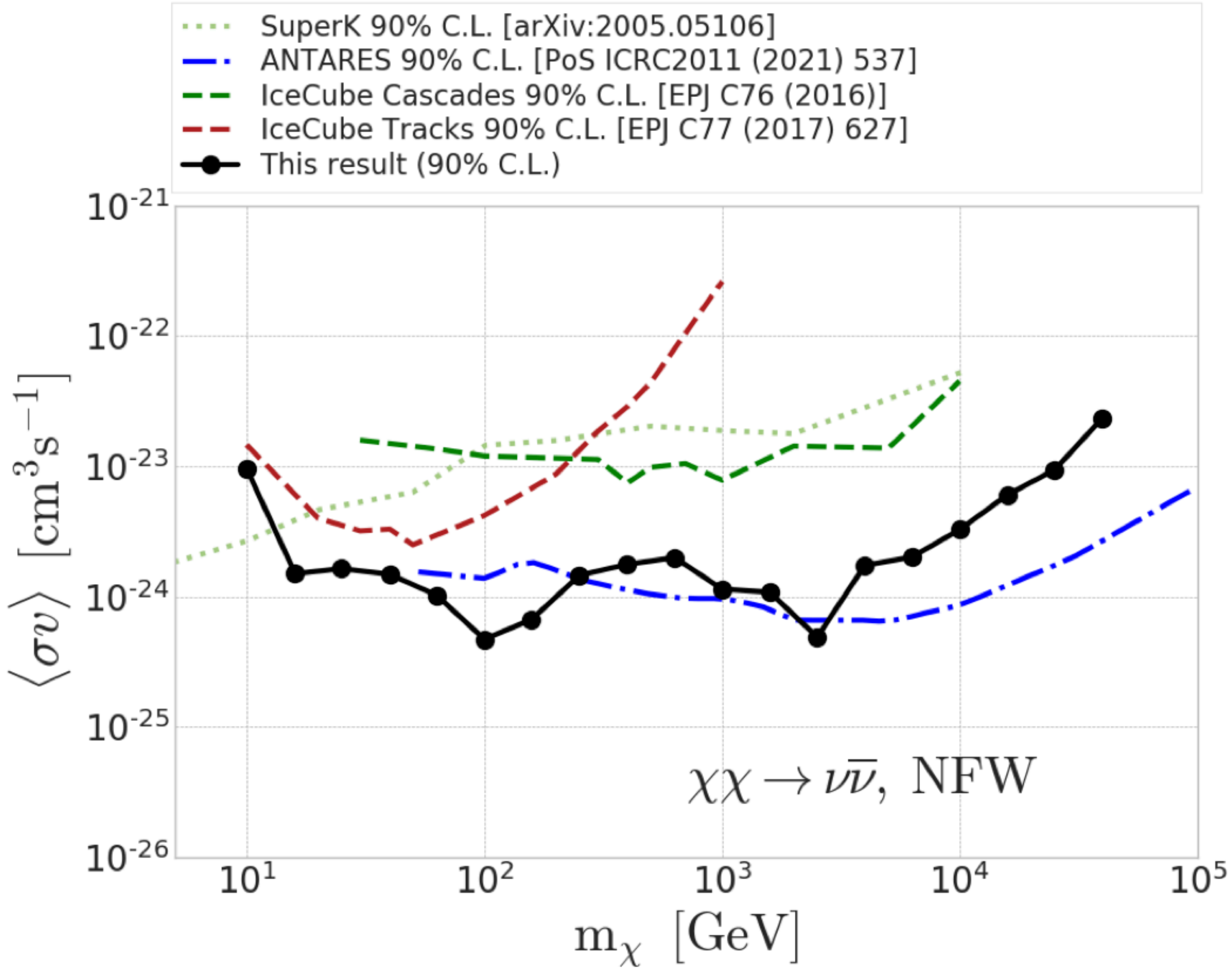
Phys. Rev. D 105, 062004

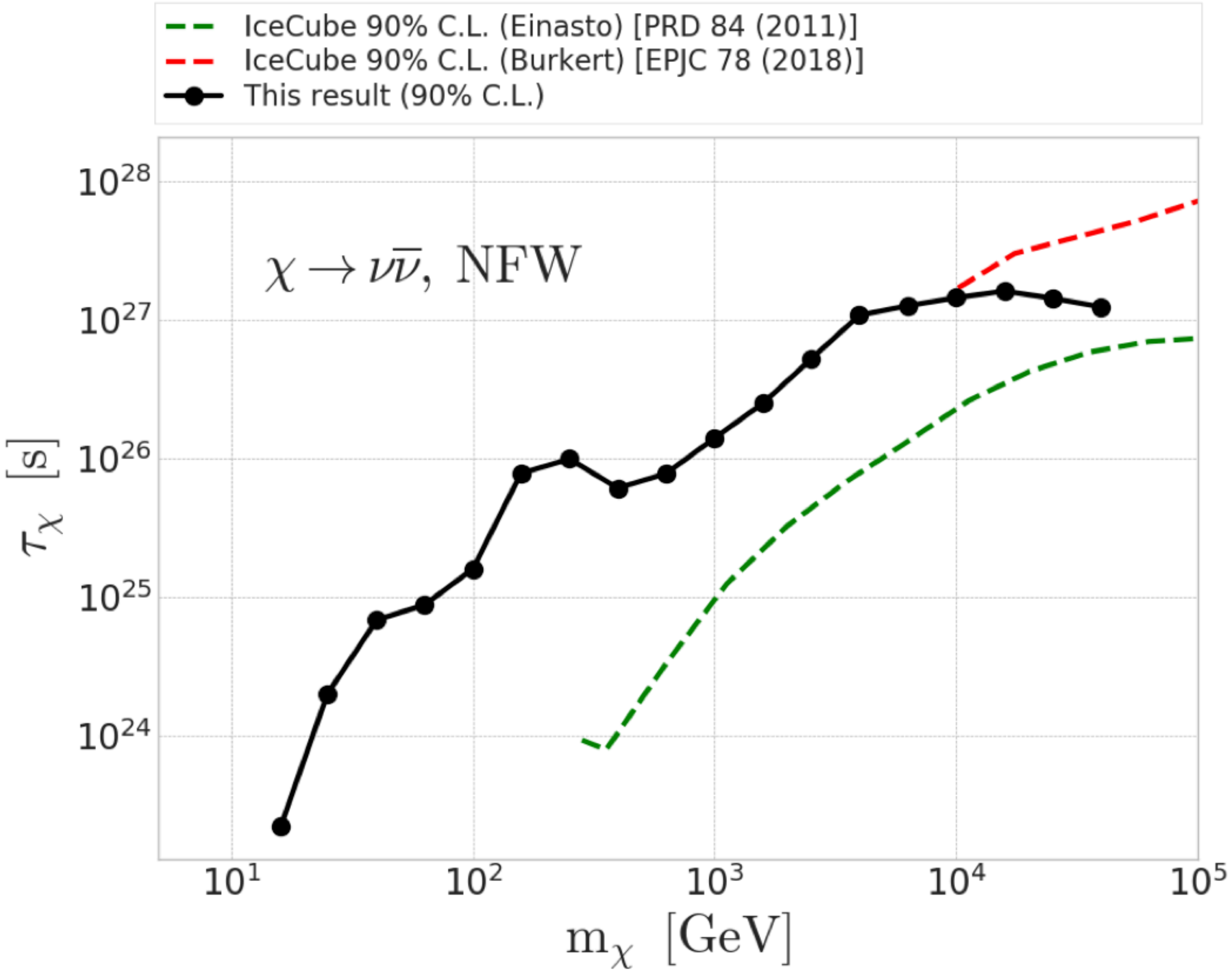


Indirect dark matter search (Milky Way Galactic Centre)

Phys. Rev. D108 102004

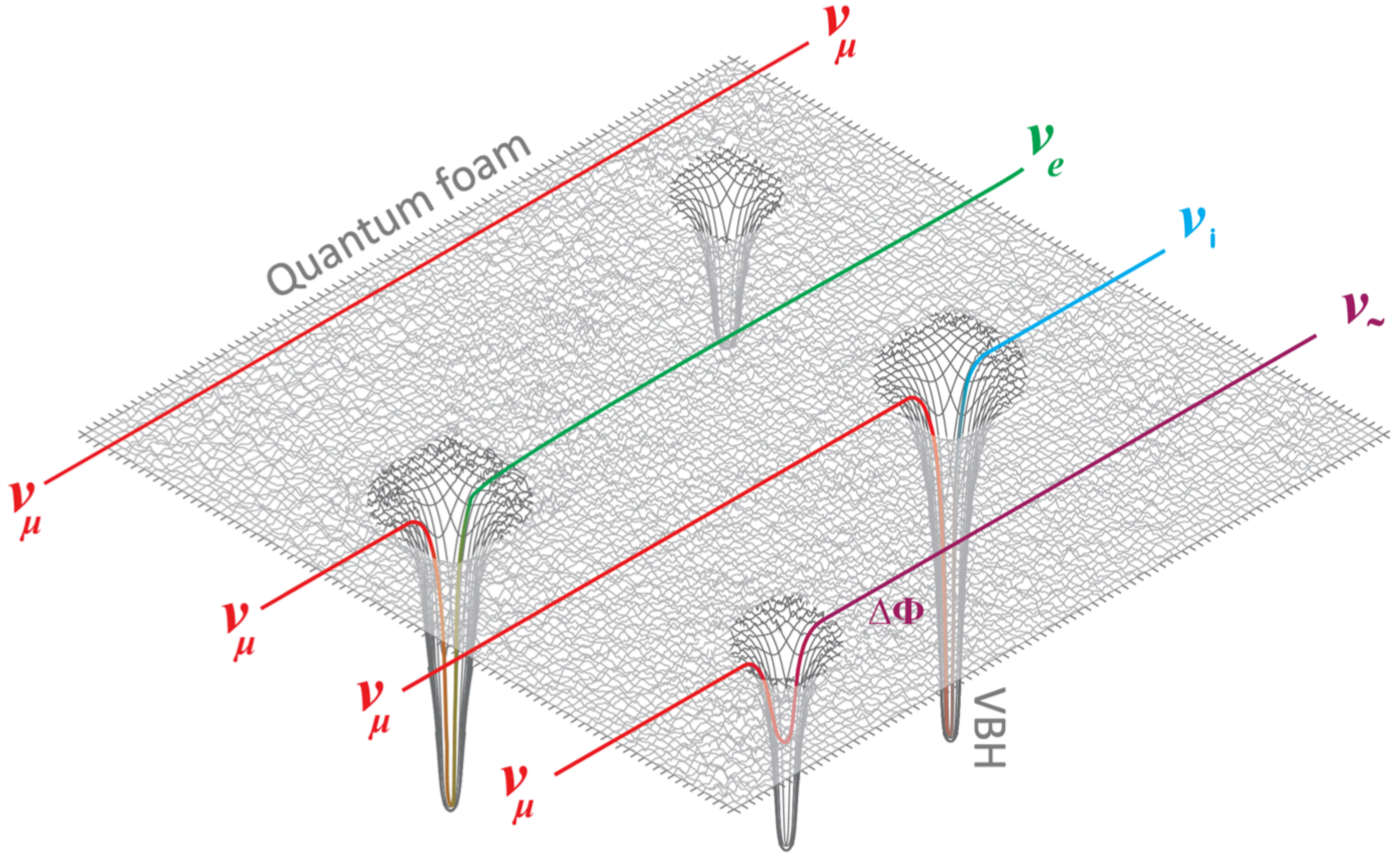
ICECUBE

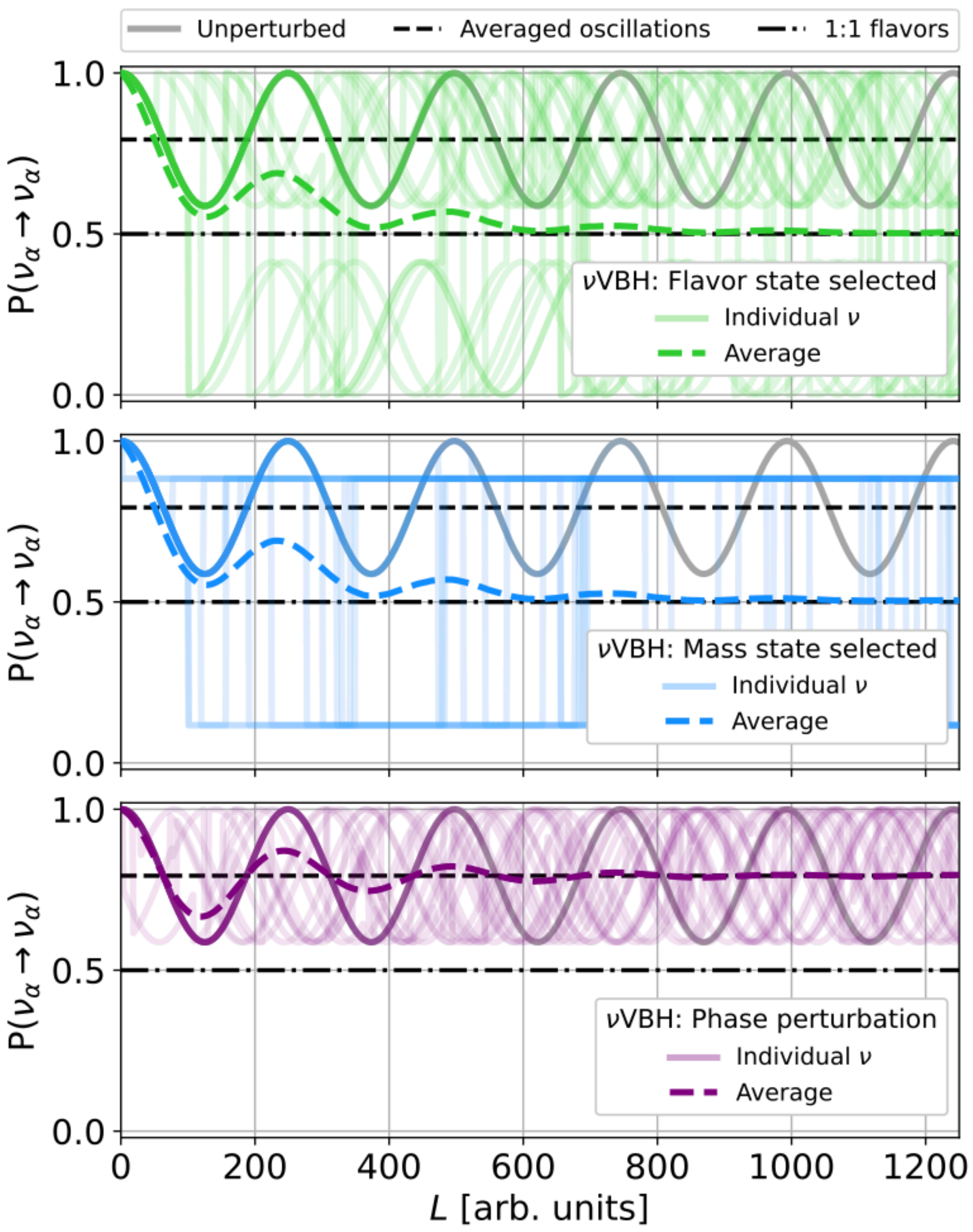




Atmospheric neutrino oscillations (decoherence from quantum gravity - νVBH)

Nat. Phys. (2024). https://doi.org/10.1038/s41567-024-02436-w





Atmospheric neutrino oscillations (decoherence from quantum gravity - νVBH)

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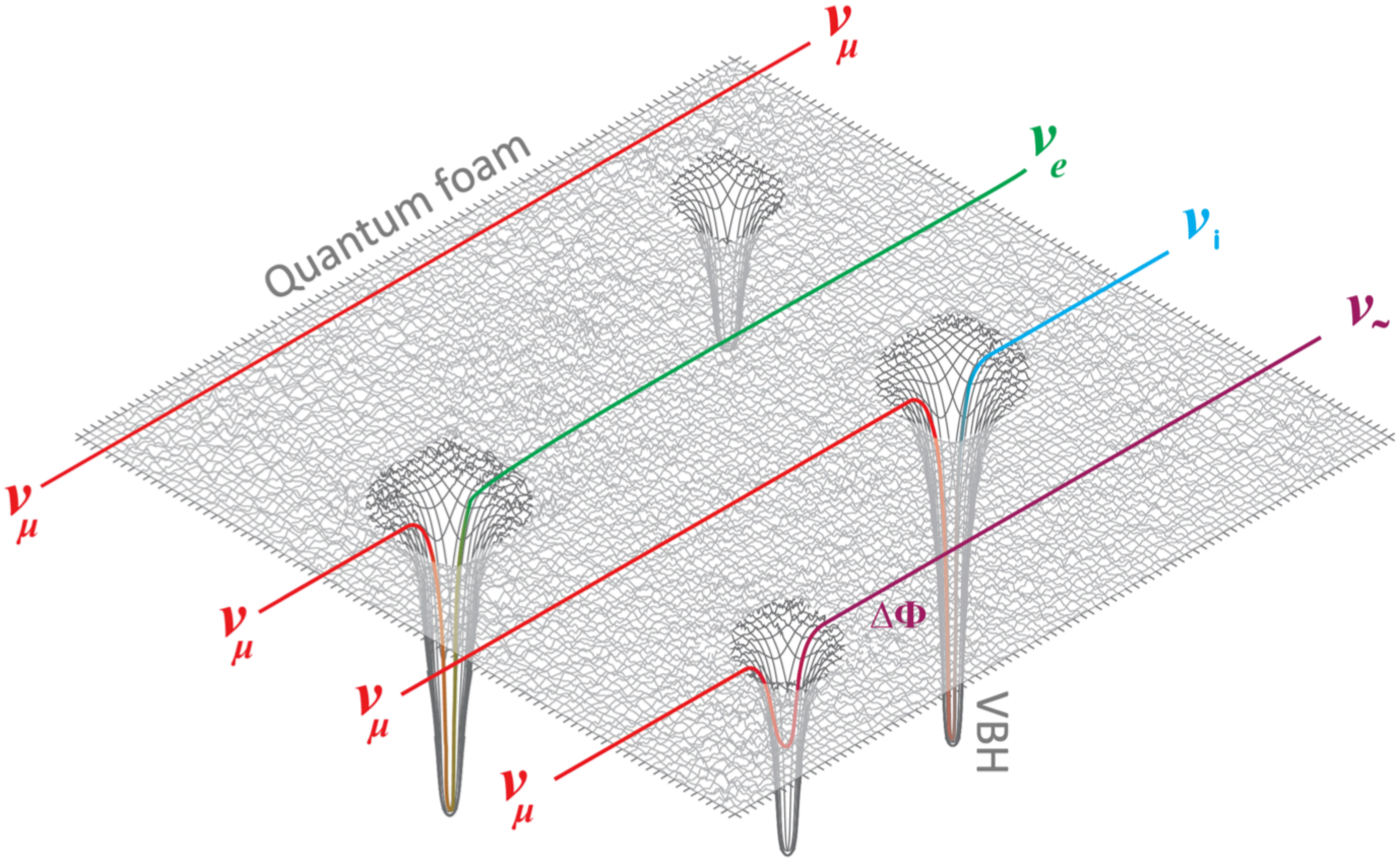
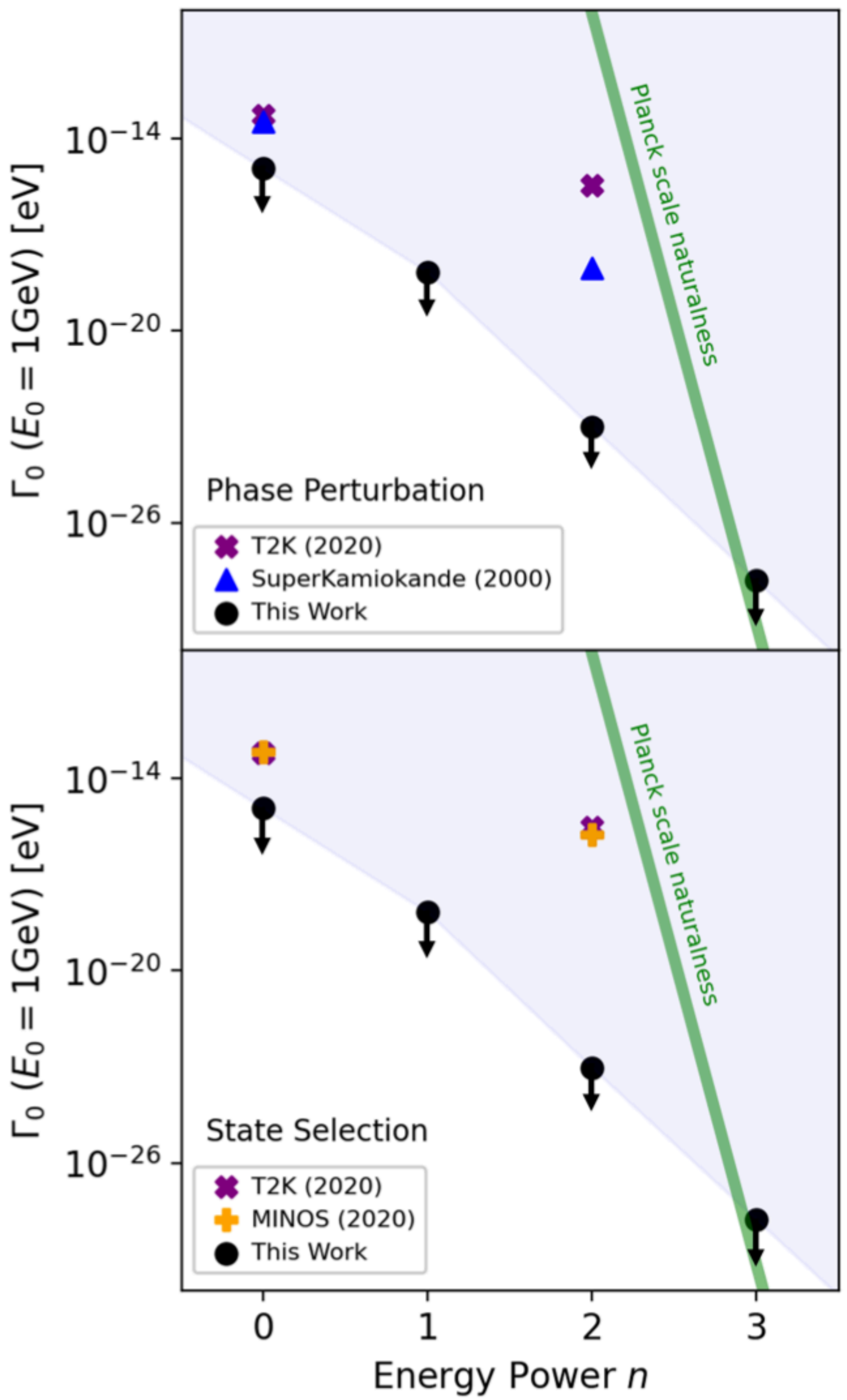
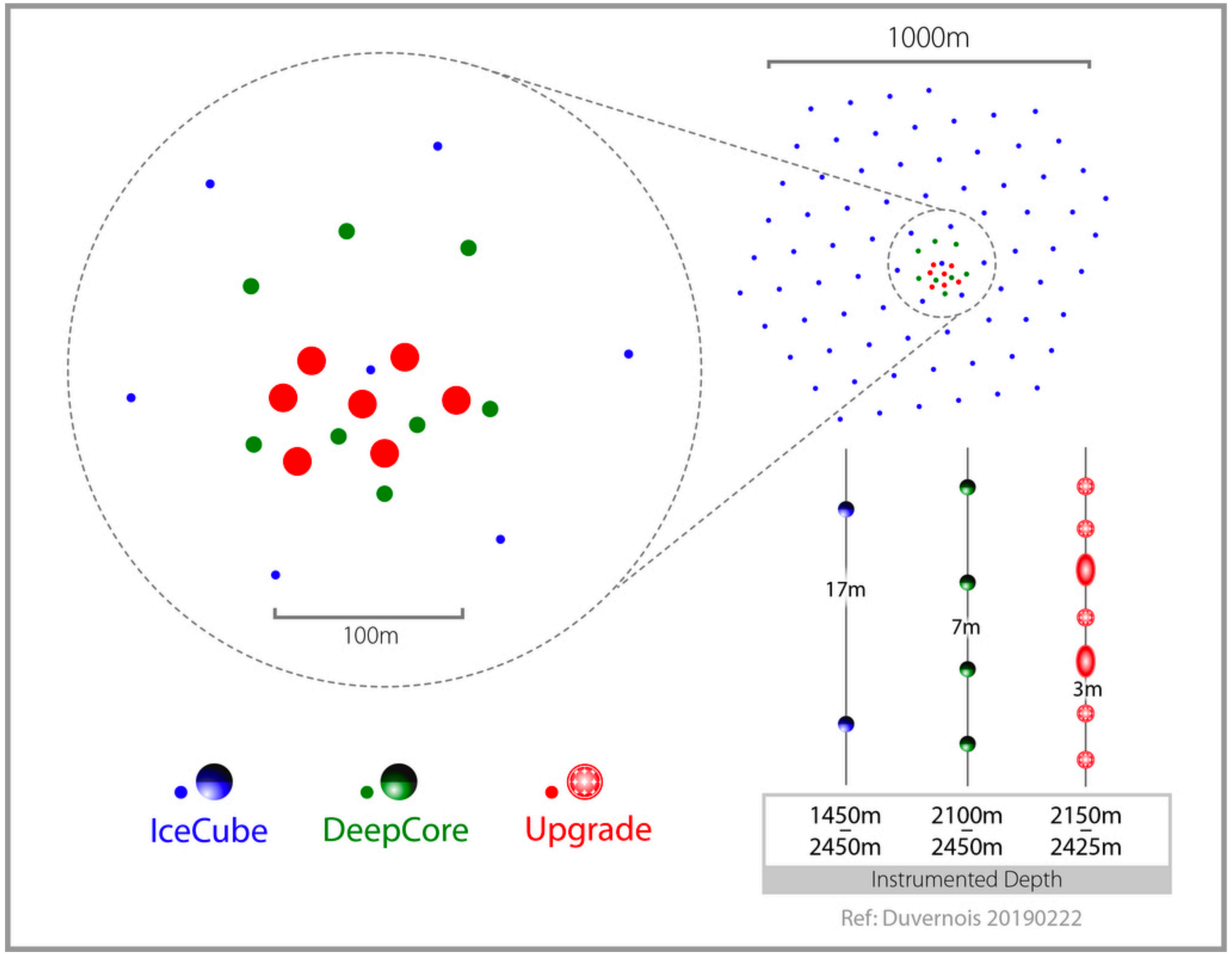


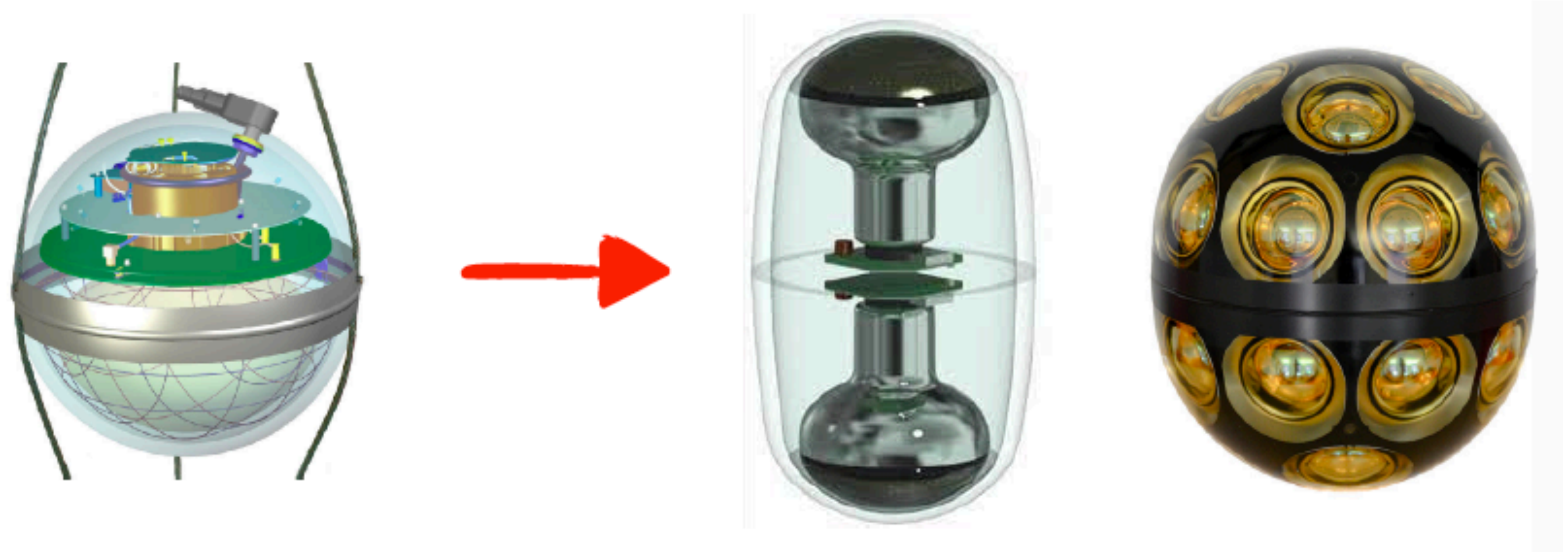


Future directions - IceCube Upgrade

- Construction underway, deployment December 2025
- Scientific reach:
  - Precision oscillation measurements
  - Recalibration of the complete IceCube dataset (including high-energy regime); improved angular and energy resolutions

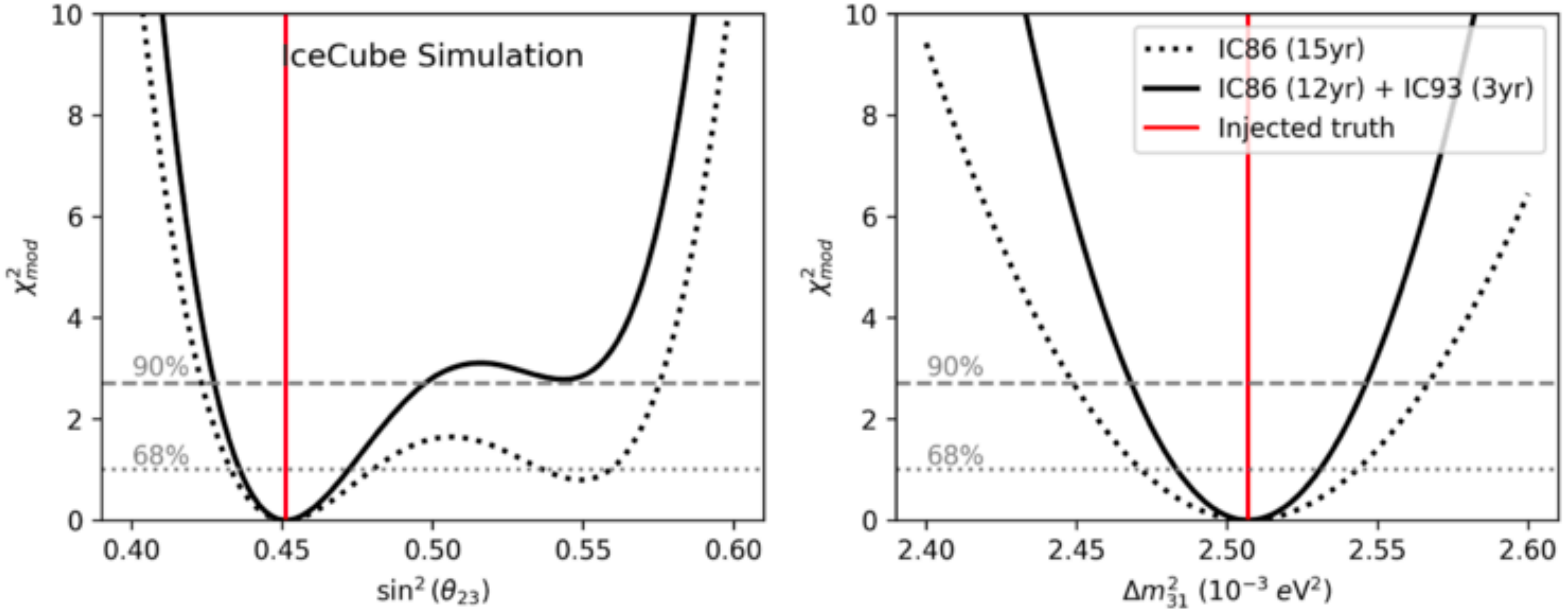
- More than 800 next generation modules and precision calibration devices
- Reduced inter-module spacing
- Deep-ice deployment to 2600 m

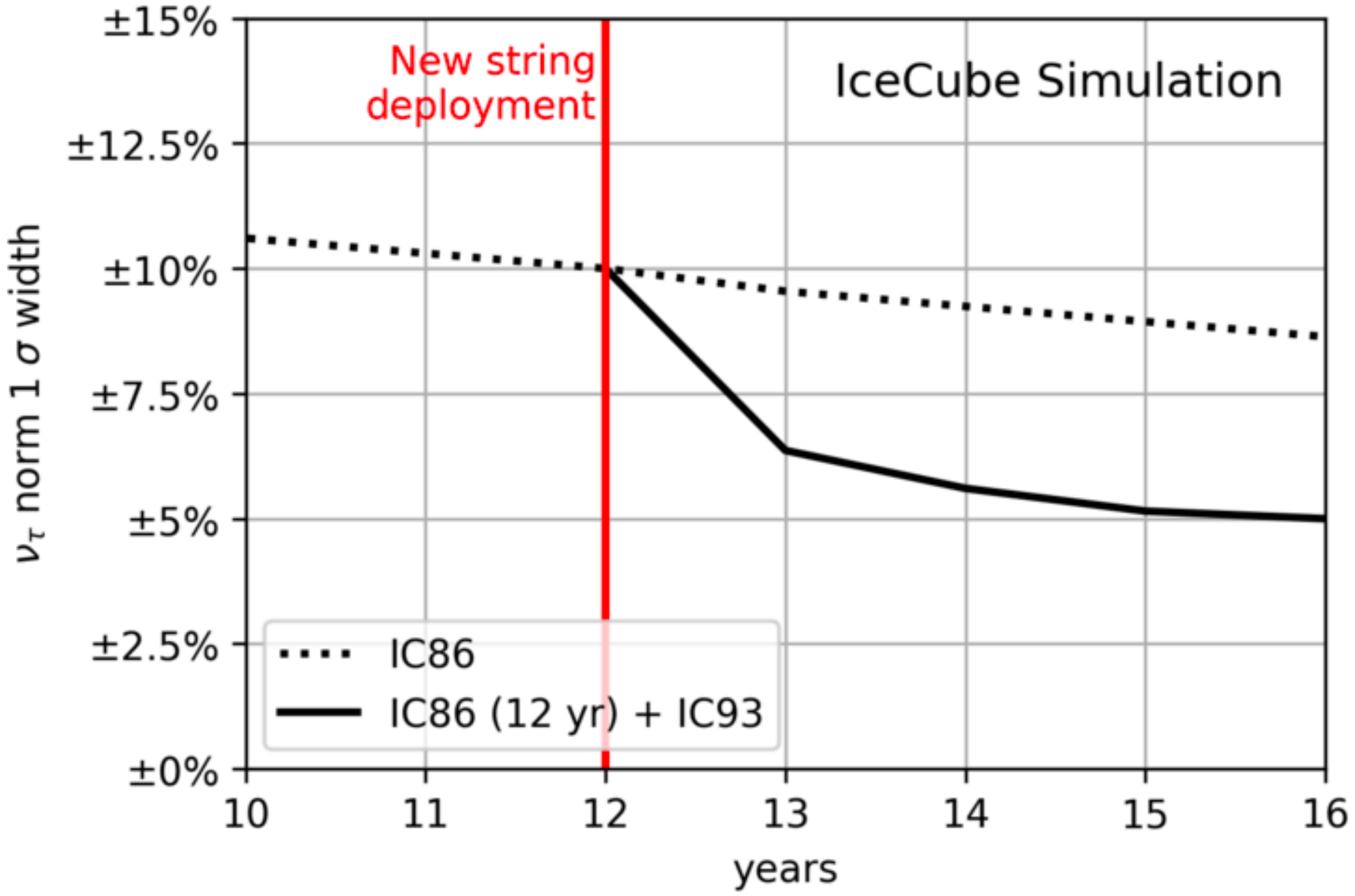


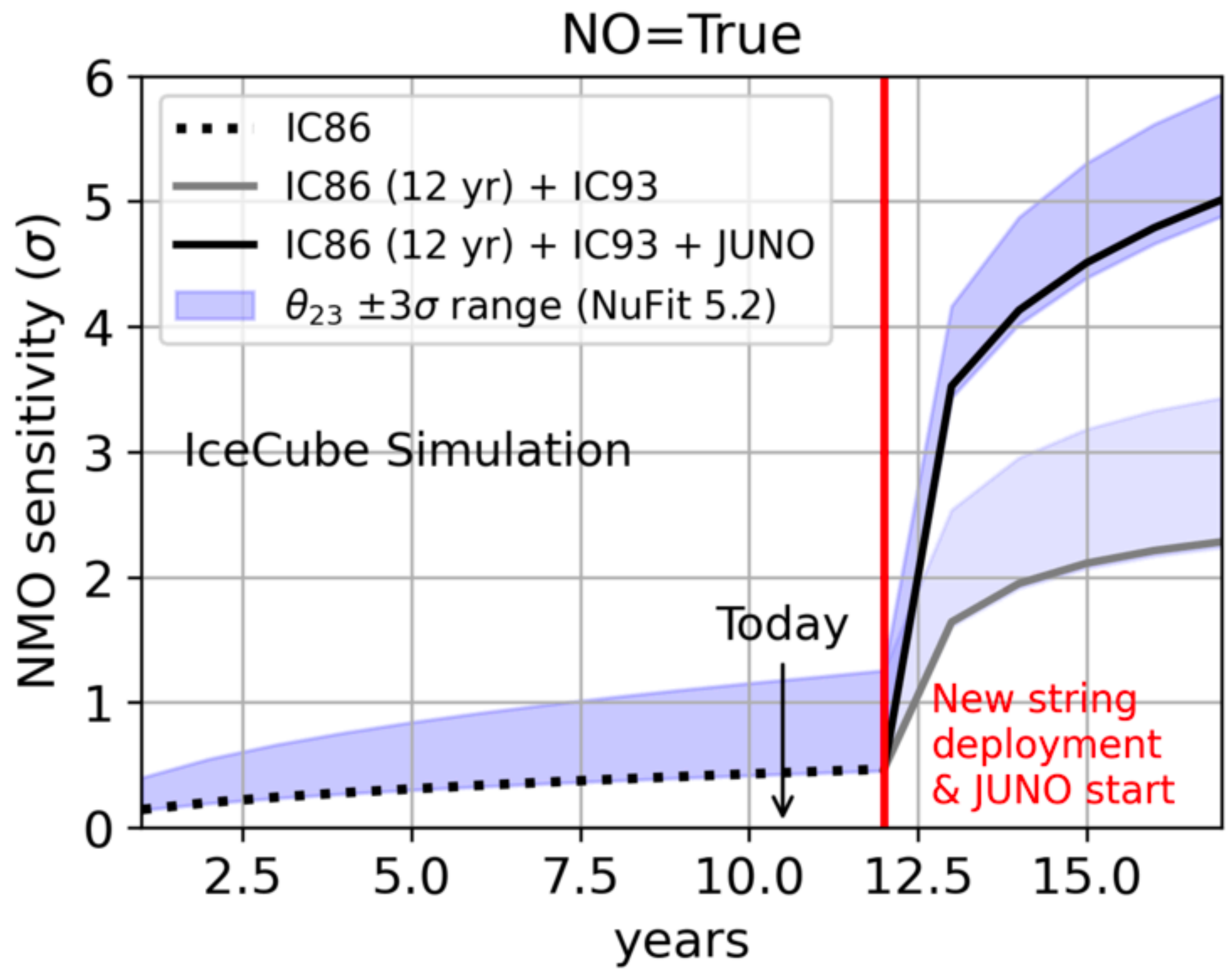


Future directions - IceCube Upgrade

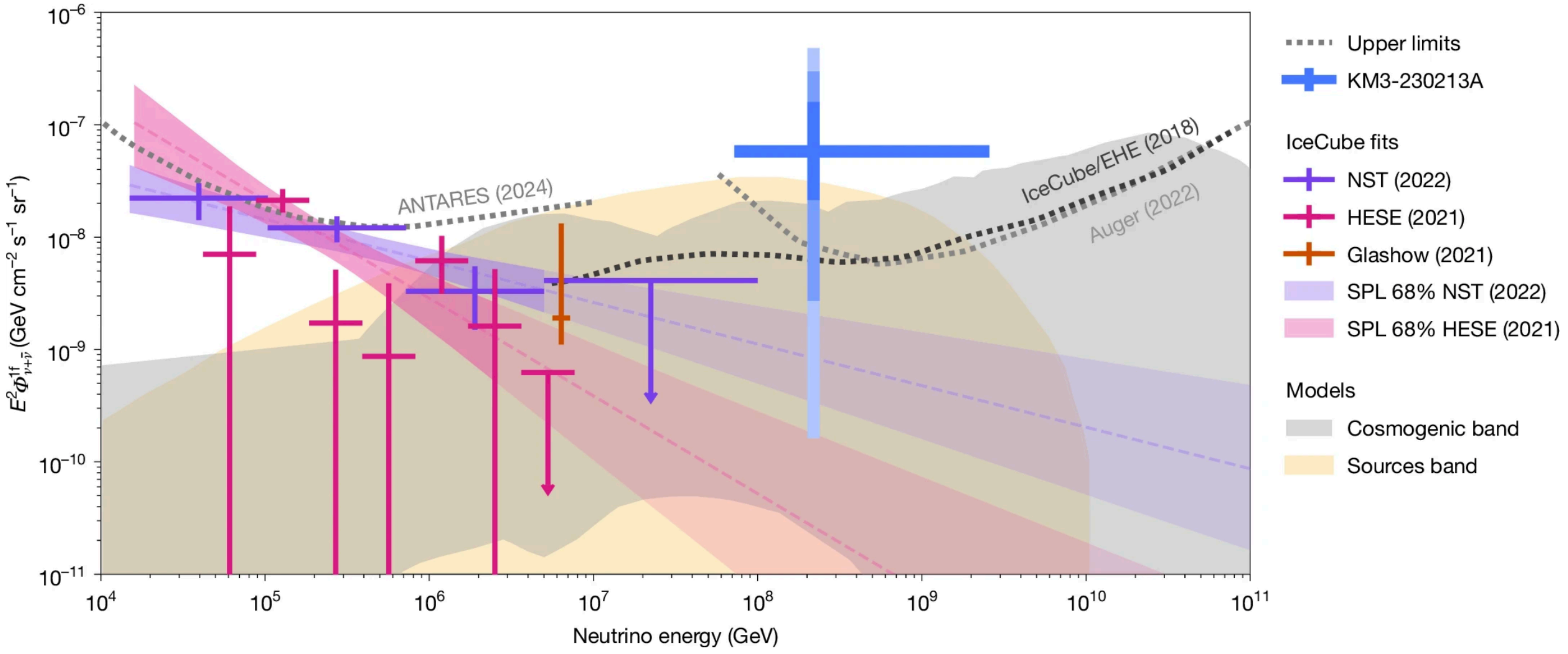
- 3-year sensitivity estimates
  - Improved sensitivity to the atmospheric mixing angle, including octant, and mass splitting
  - 5% uncertainty on the normalization of the tau neutrino normalization and test of PMNS unitarity
  - 3σ determination of the mass ordering (5σ with JUNO)

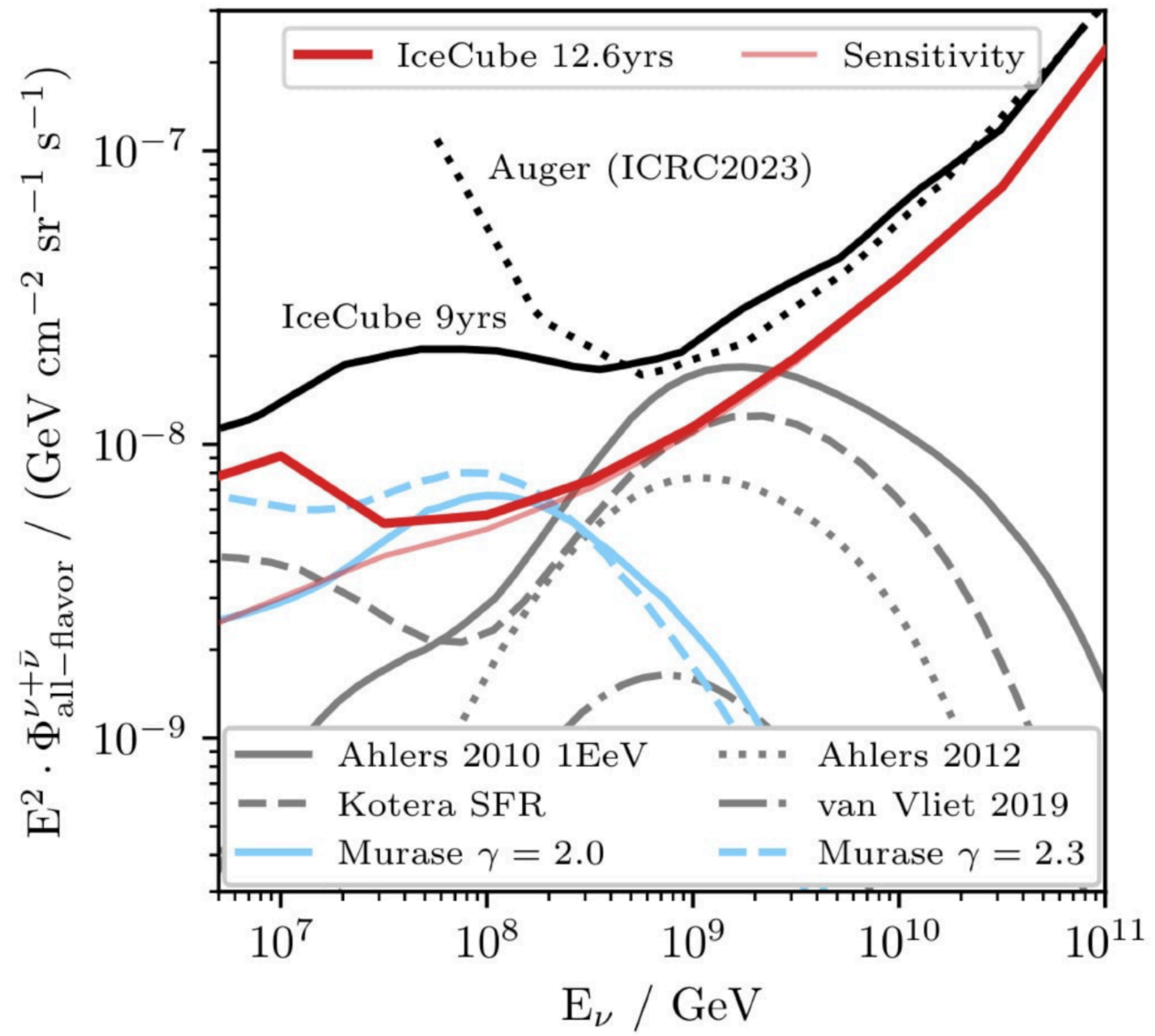




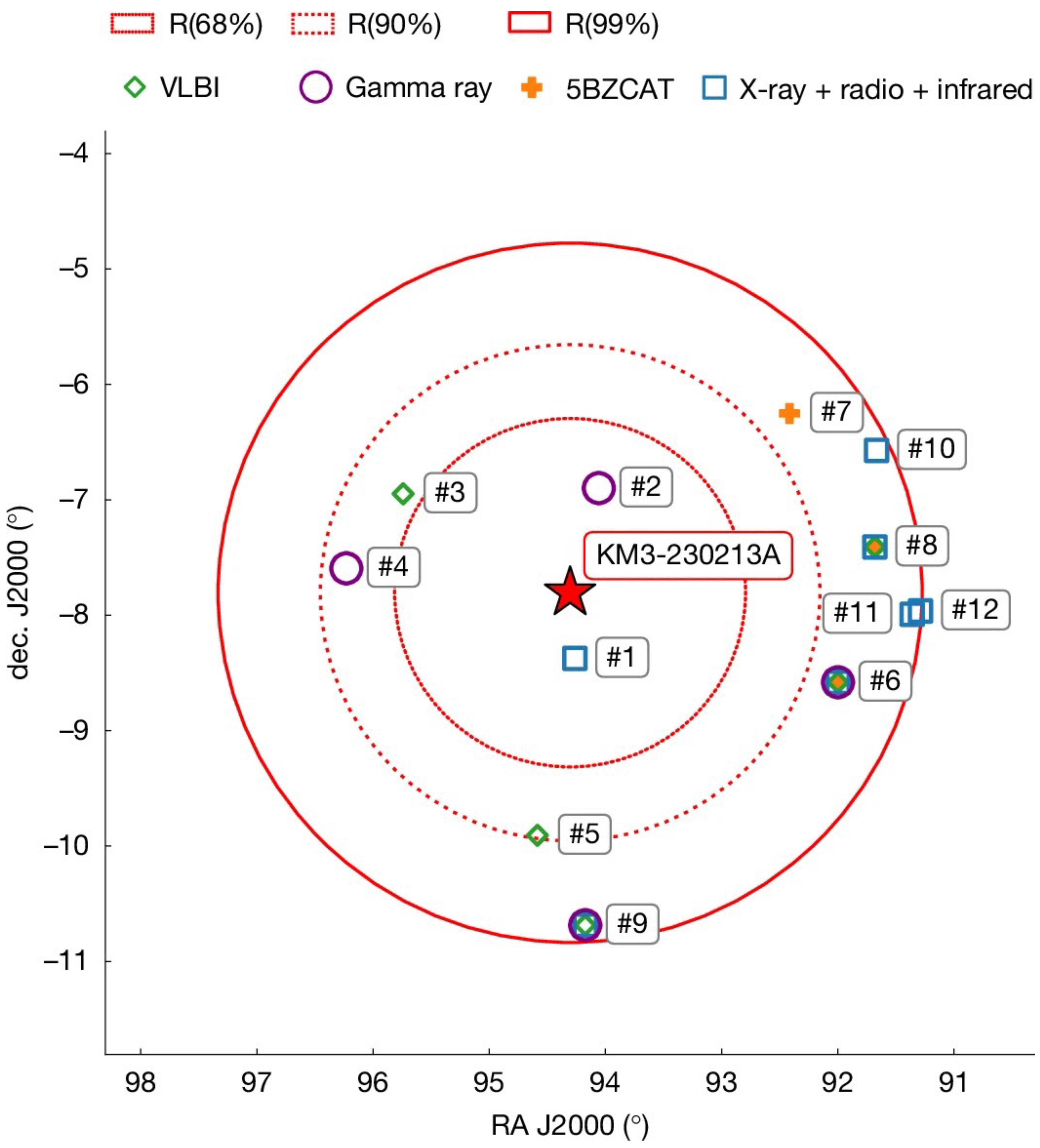


KM3NeT ultra high-energy event





KM3NeT ultra high-energy event



P-ONE Logistics Chain