Current results and future outlook

very large neutrino telescopes

IceCube

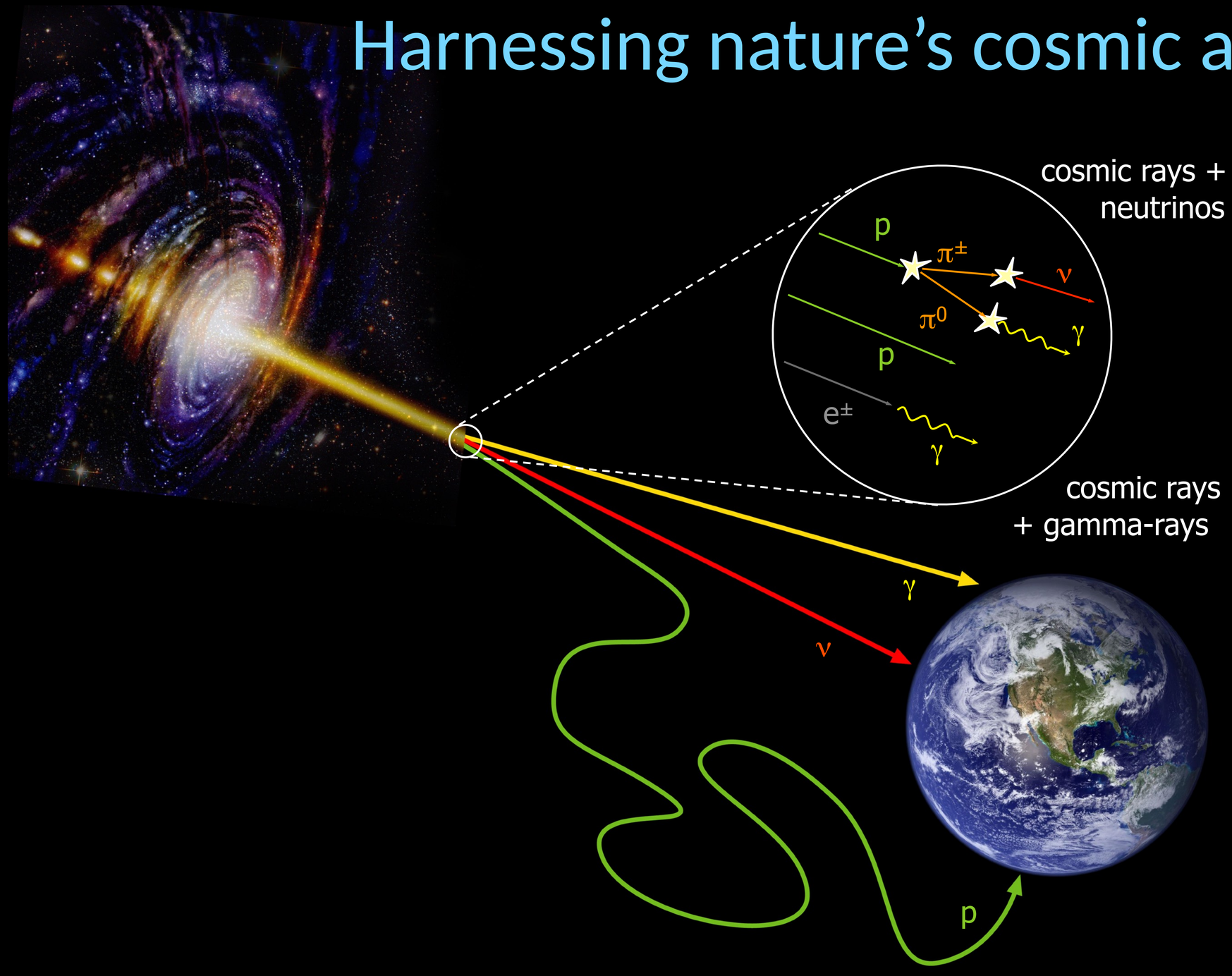
P-ONE

Darren R Grant — CAP 2024 Symposium Day — May 29, 2024

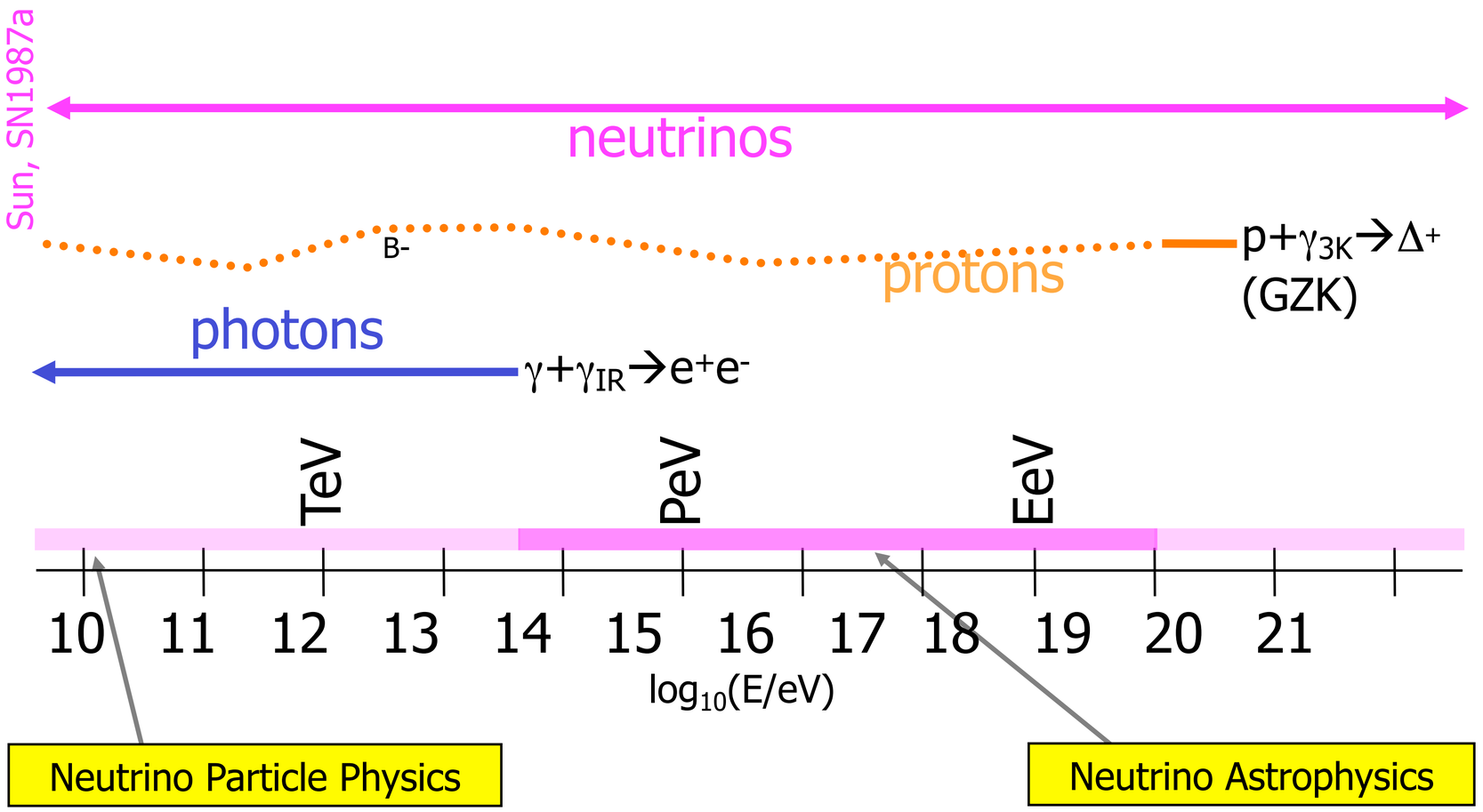
Canada Excellence Research Chairs
Chaires d'excellence en recherche du Canada

SFU SIMON FRASER UNIVERSITY

Harnessing nature's cosmic accelerators



Cosmic messengers



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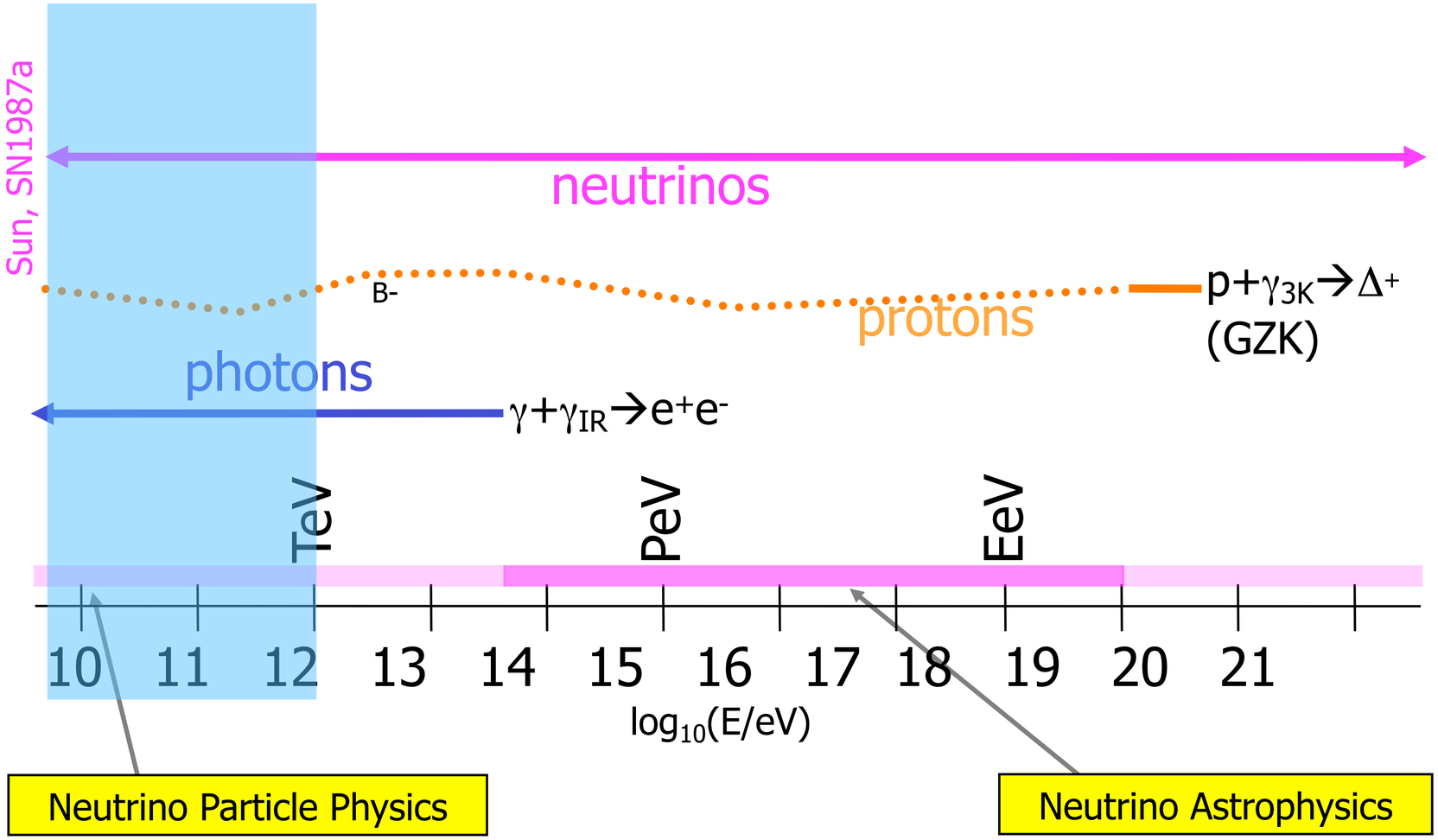
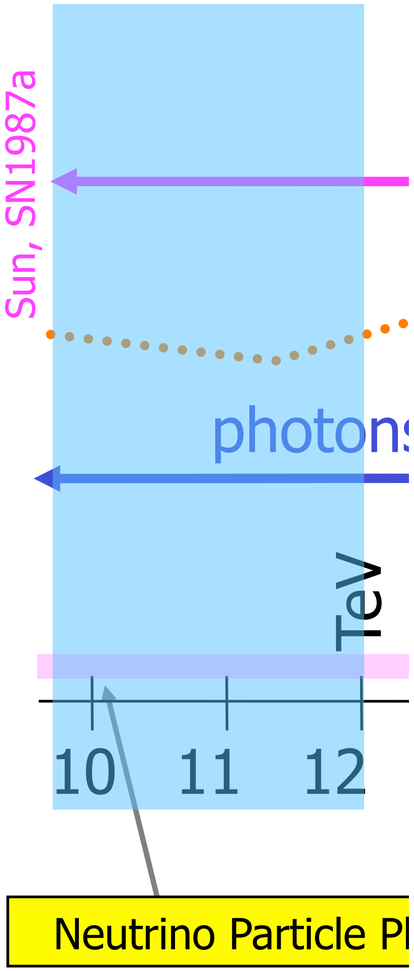
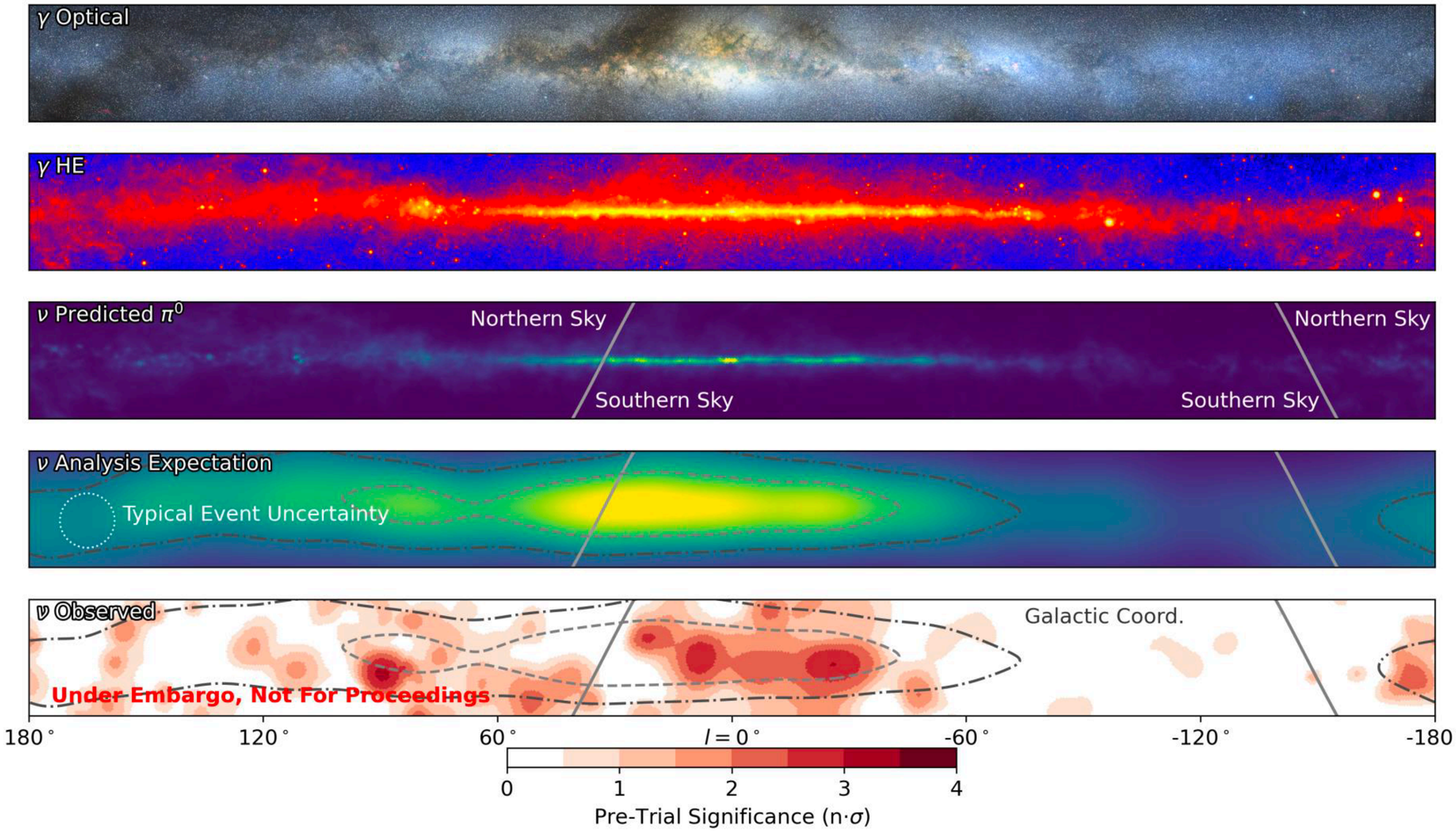


Cosmic messengers

Science Vol 380, Issue 6652



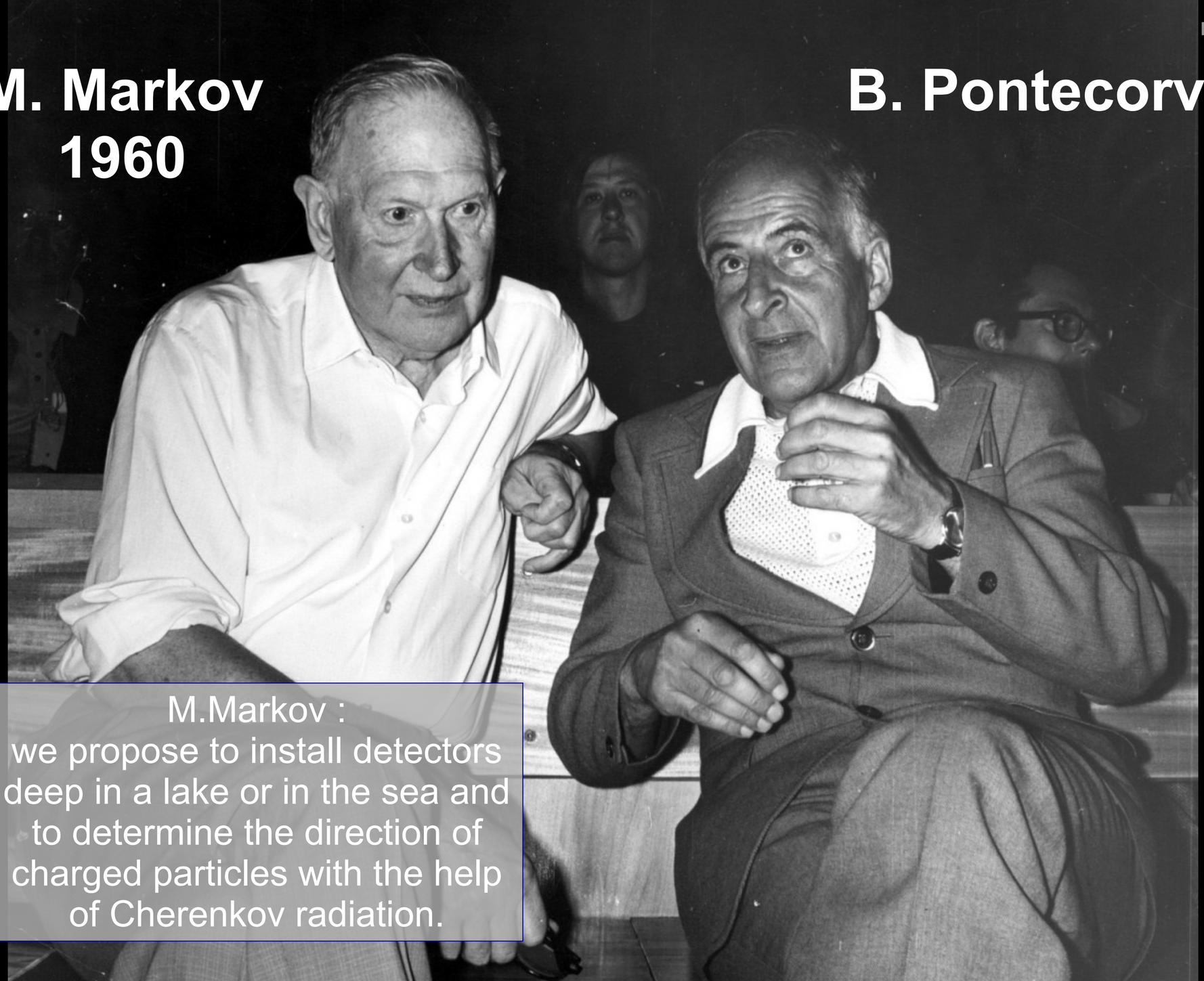
Observation of the Milky Way Galactic Plane w/IceCube cascade events



Neutrinos from the Milky Way for the first time (4.5 sigma post trial); No individual sources yet observed at high significance… but that is a different talk.

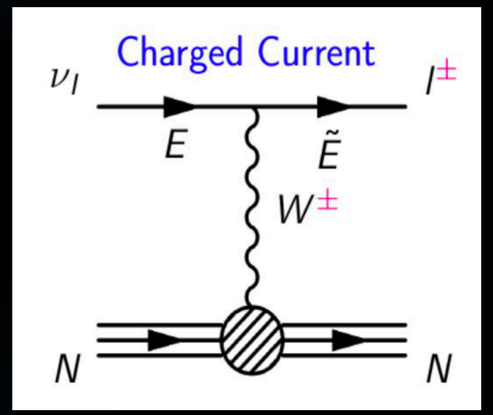
M. Markov 1960

B. Pontecorvo

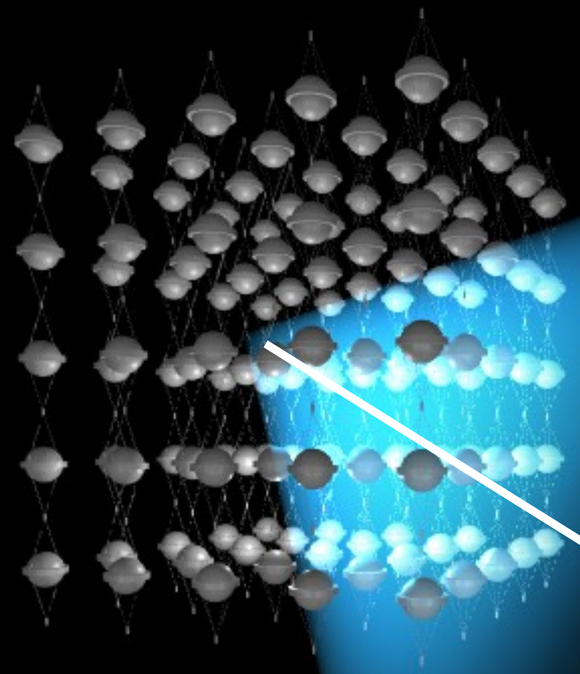


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

charged secondary particles produced as the neutrino disappears



nuclear interaction



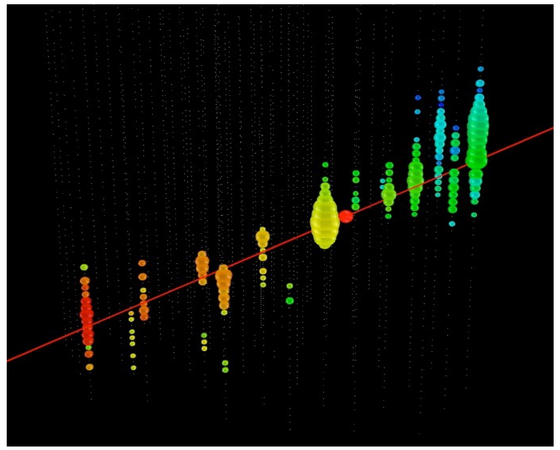
- lattice of photomultipliers

neutrino

Principles of high-energy neutrino detection - water Cherenkov

TeV-scale+

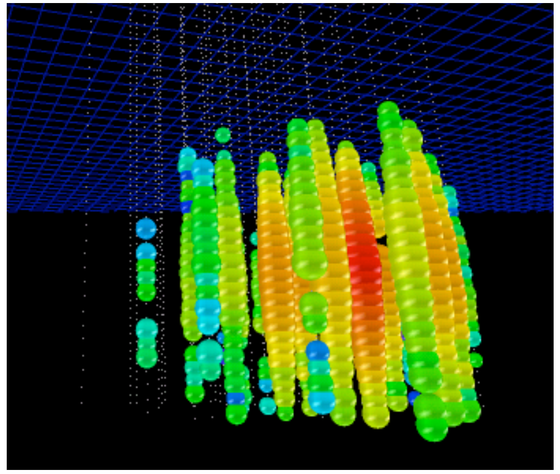
CC Muon Neutrino



track

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

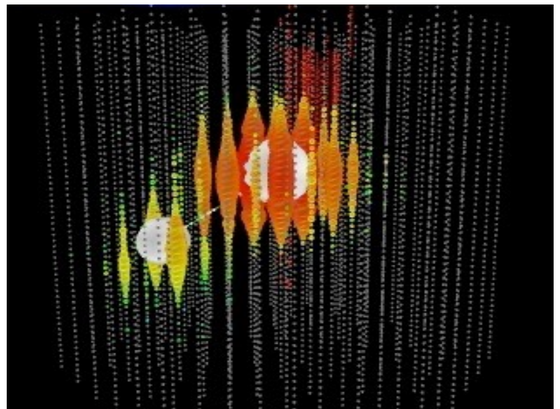
Neutral Current / Electron Neutrino



cascade

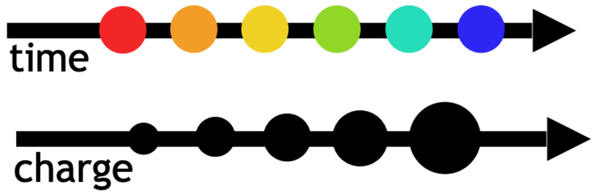
≈ ±15% deposited energy resolution
≈ 10° angular resolution (at energies ≳ 100 TeV)

CC Tau Neutrino



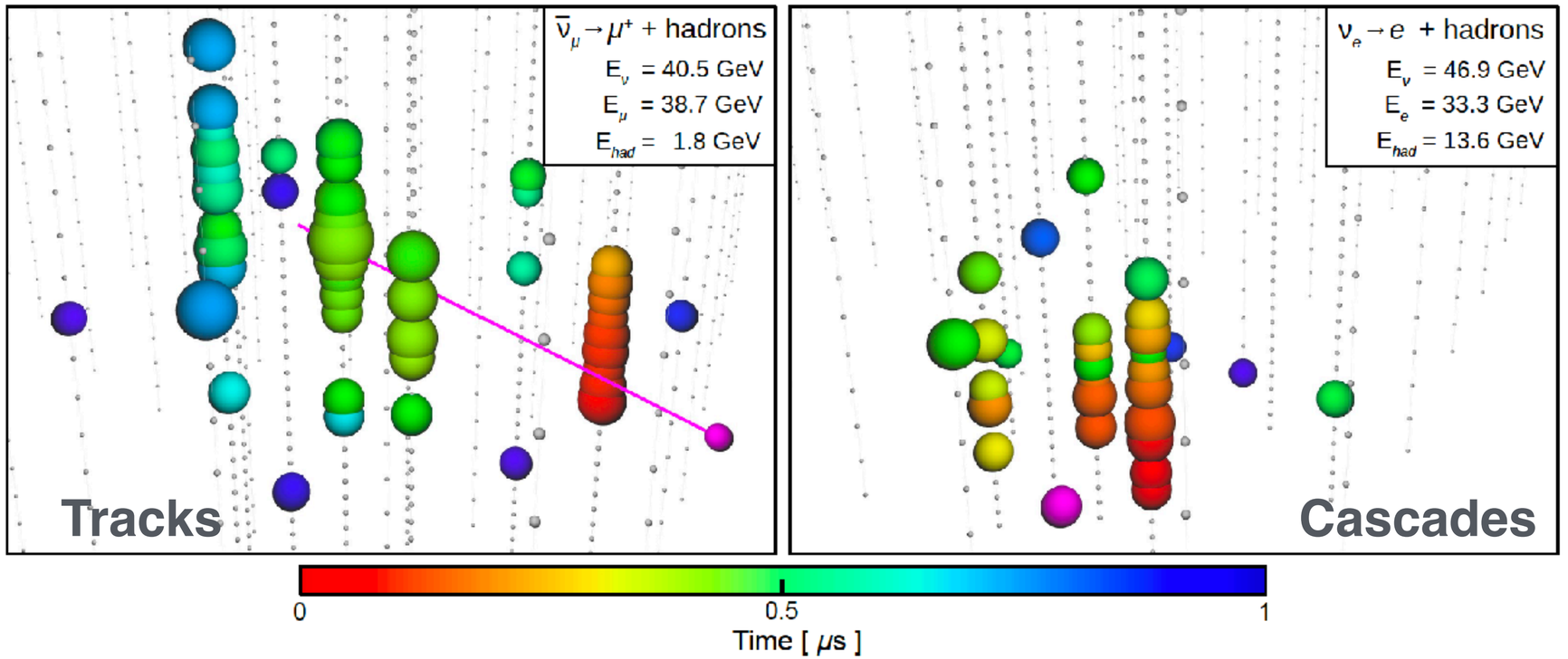
“double-bang” and other signatures

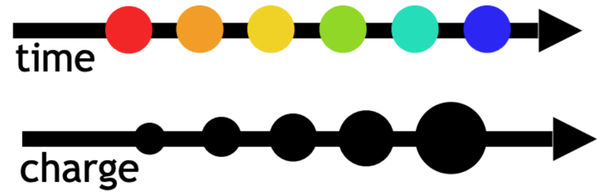
(τ decay length is 50 m/ PeV)



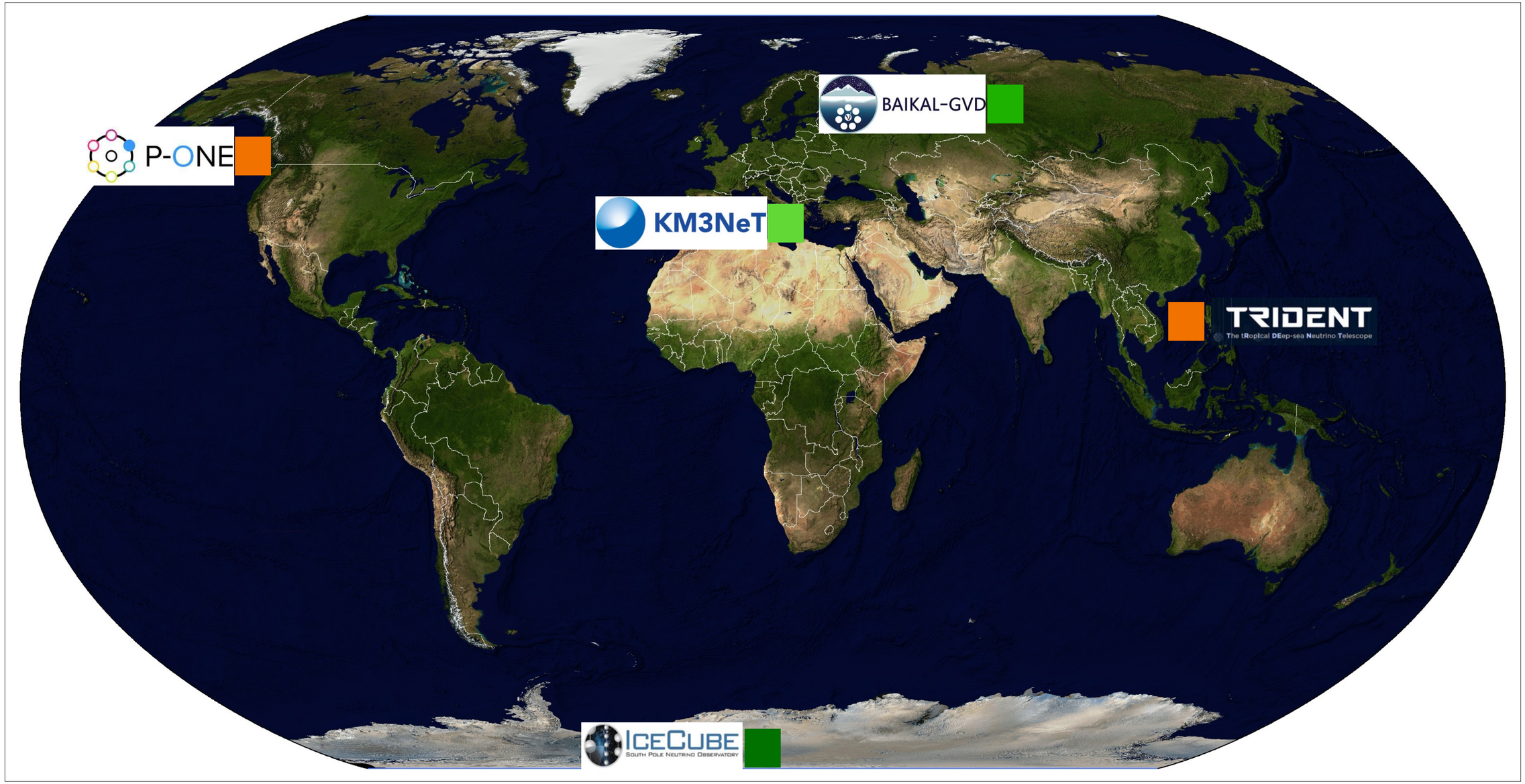
Principles of high-energy neutrino detection - water Cherenkov

GeV-scale





High-energy neutrino telescopes — global view



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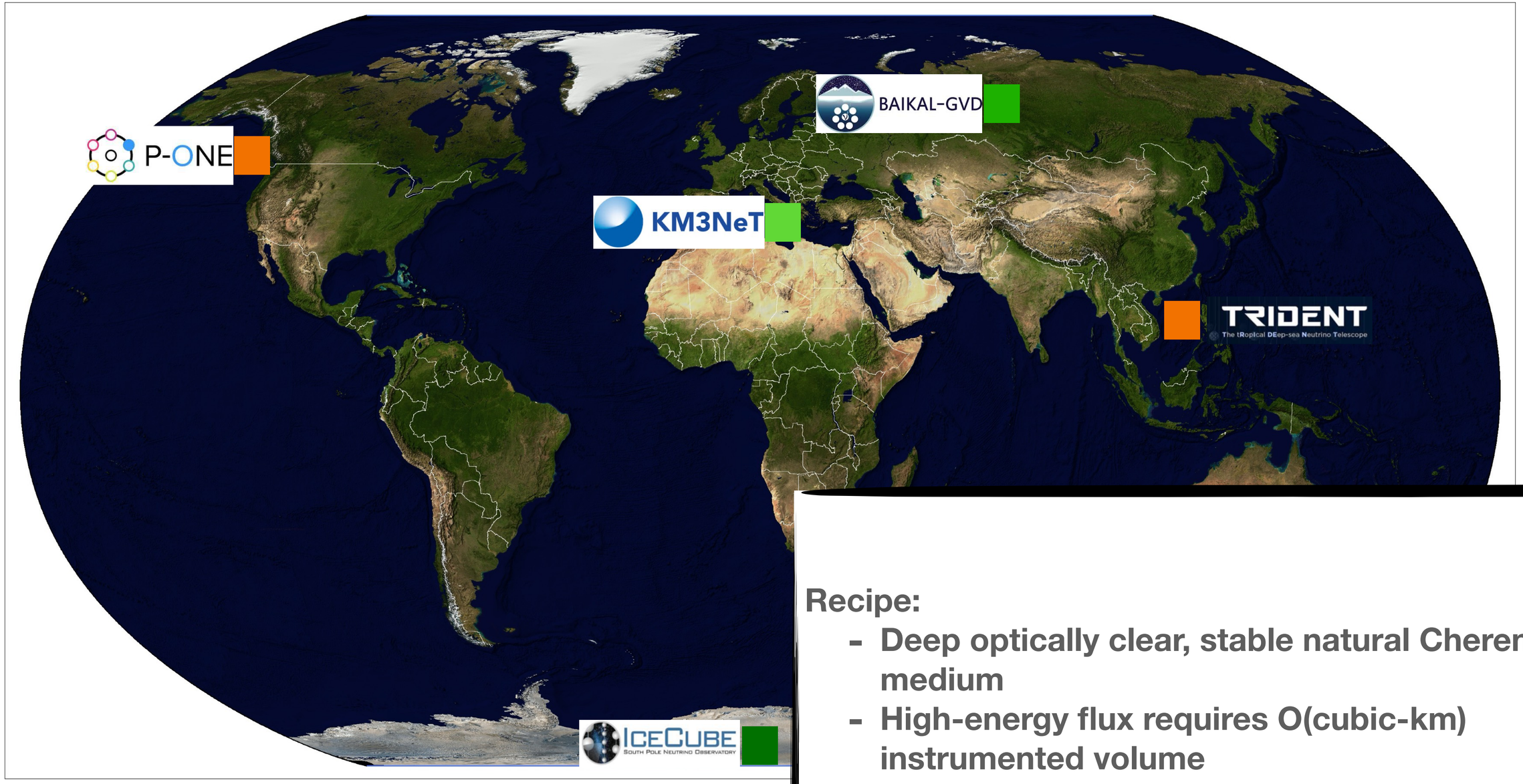


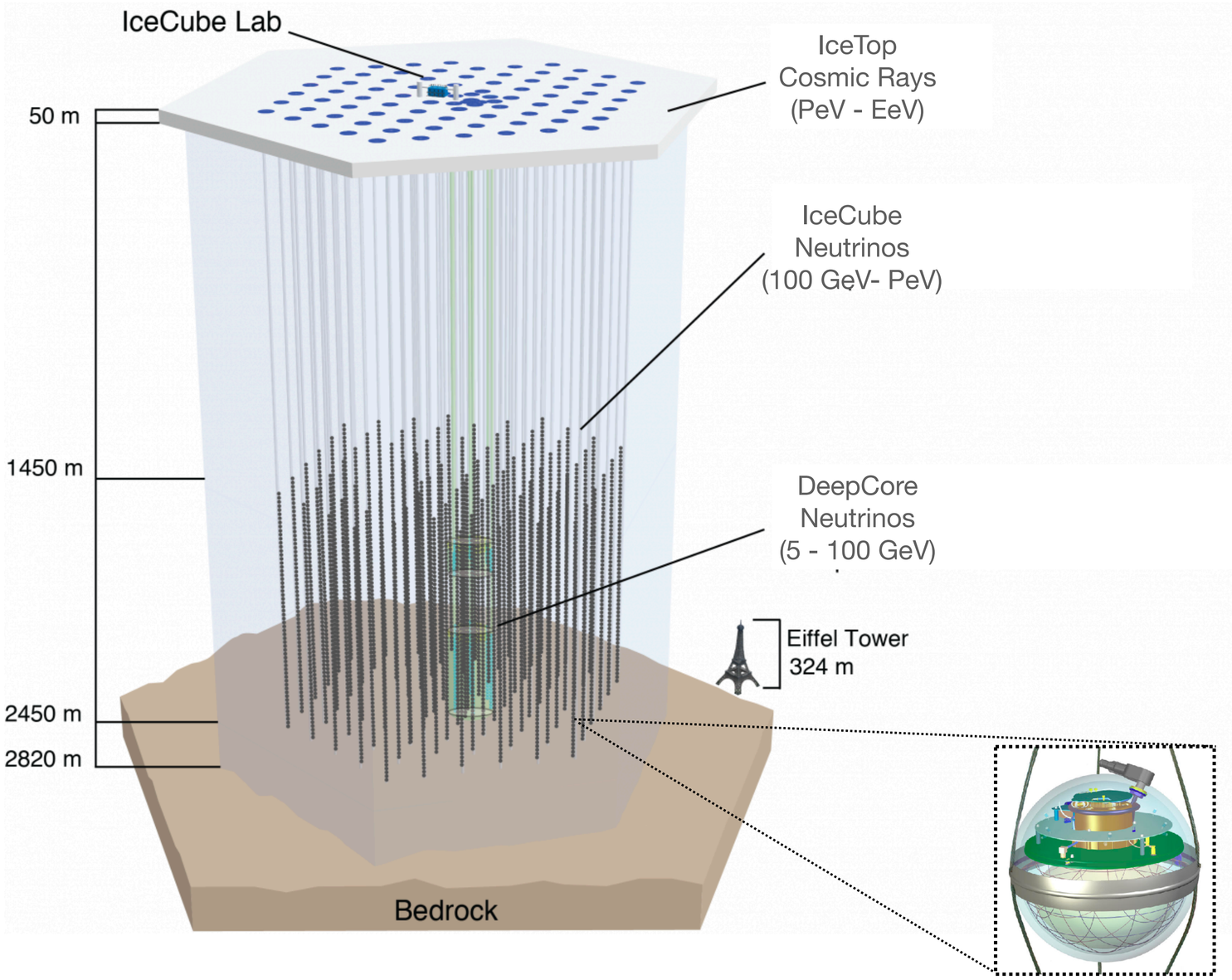
Recipe:

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

IceCube Neutrino Observatory

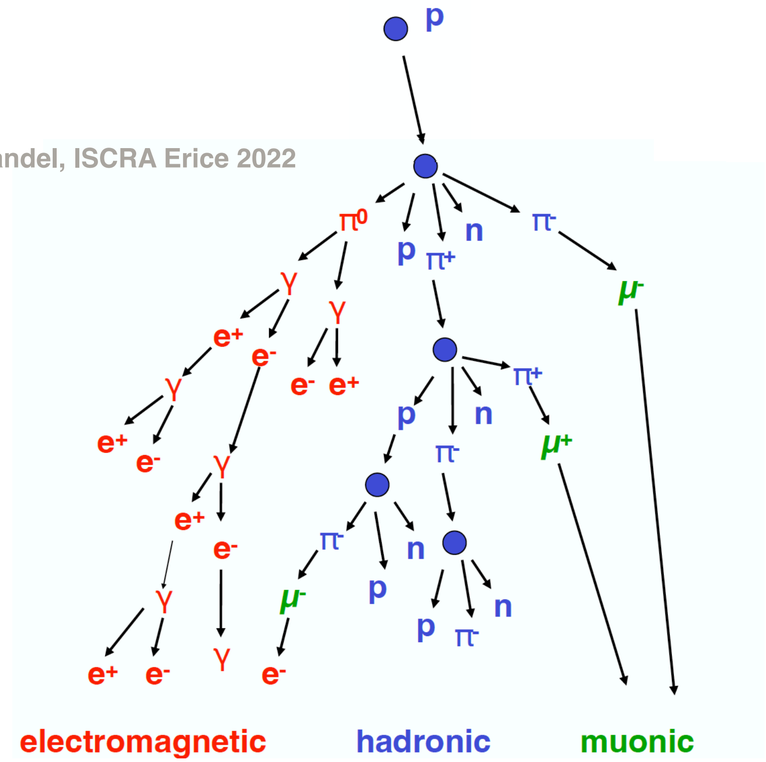
- Approximate cubic-km-scale hybrid observatory
  - Detection of Cherenkov photons with over 5000 digital optical modules (DOMs) deployed on a hexagonal grid of 86 ‘strings’
  - DOM and string spacing defines the energy response and thus physics of each detector region

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



Atmospheric neutrino flux from cosmic ray air showers

Jörg R. Hörandel, ISCRA Erice 2022



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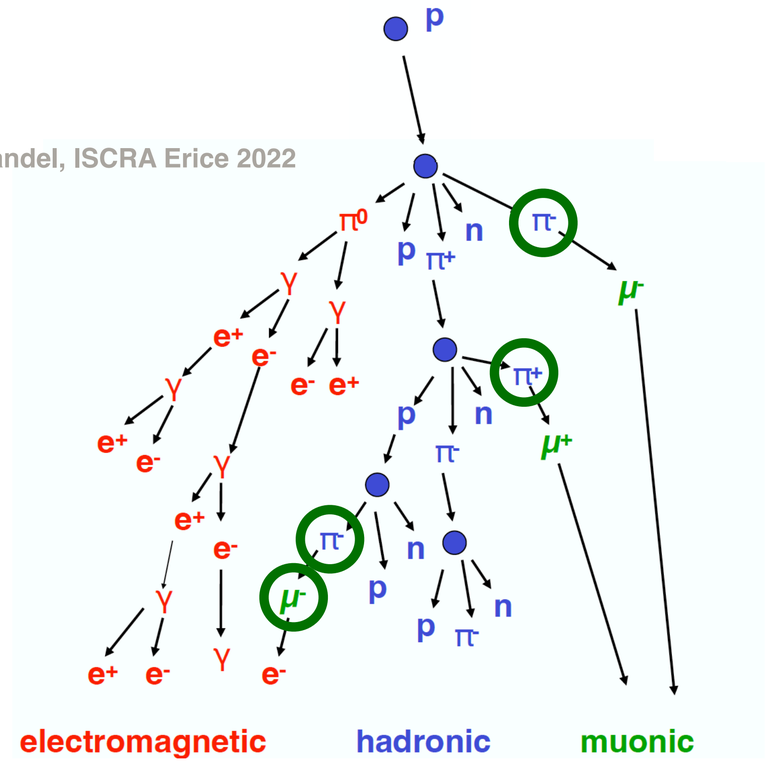
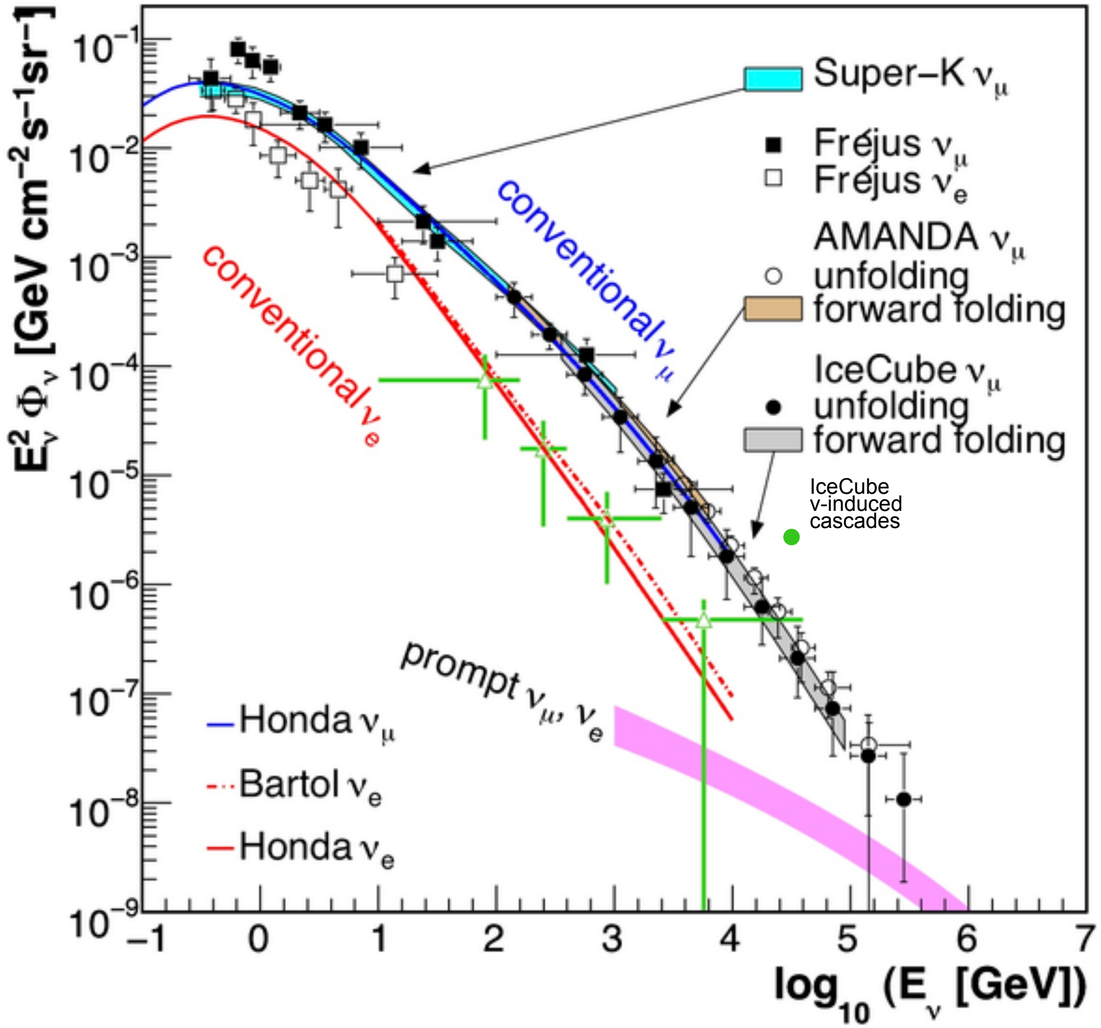




Atmospheric neutrino oscillations

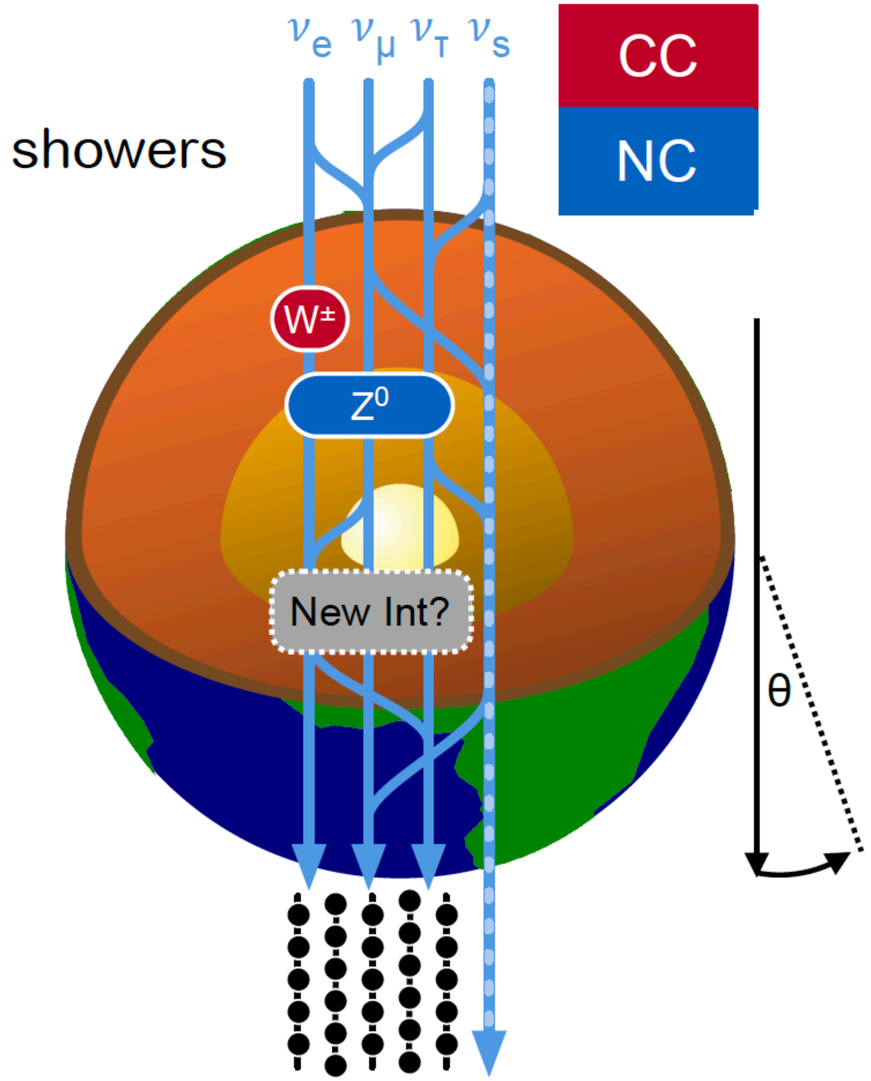
- Natural beam of neutrinos generated in cosmic ray air showers
  - All flavors, neutrino + antineutrino
  - Broad energy band (GeV - TeV) and baselines (20 - 12,700 km) through variable Earth density profile

Flavour Mass

$$|\nu_a\rangle = \sum U^*_{ak} |\nu_k\rangle$$

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



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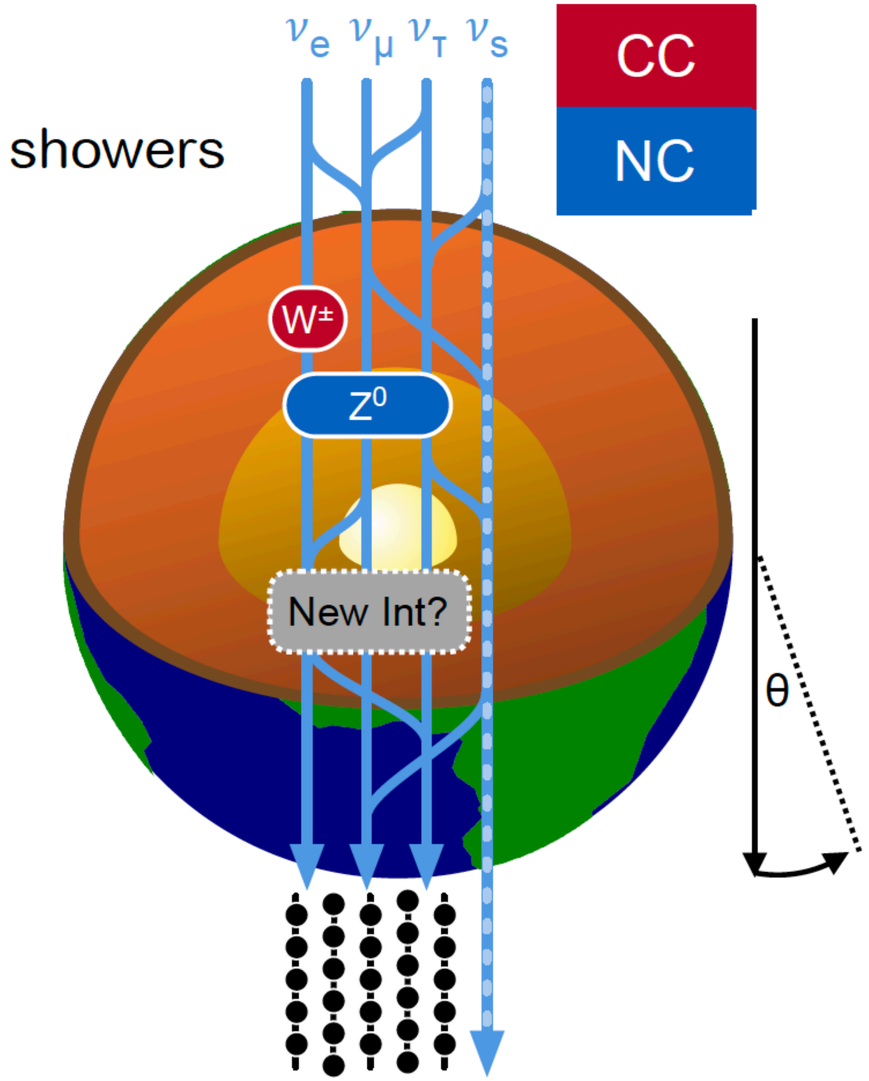

Flavour Mass

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

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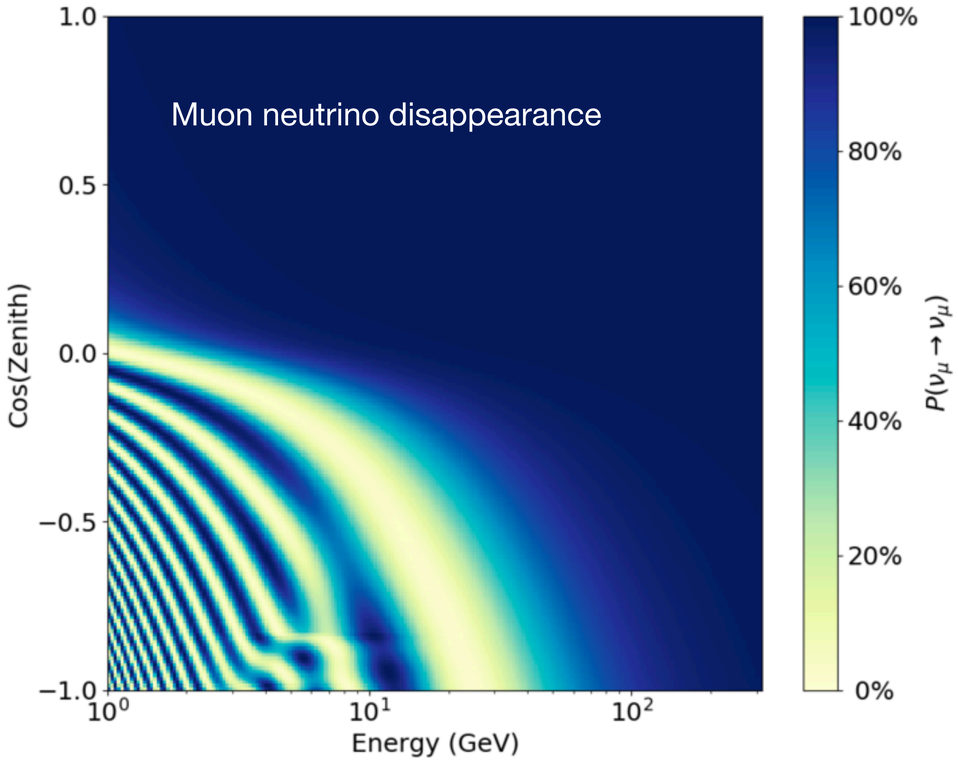
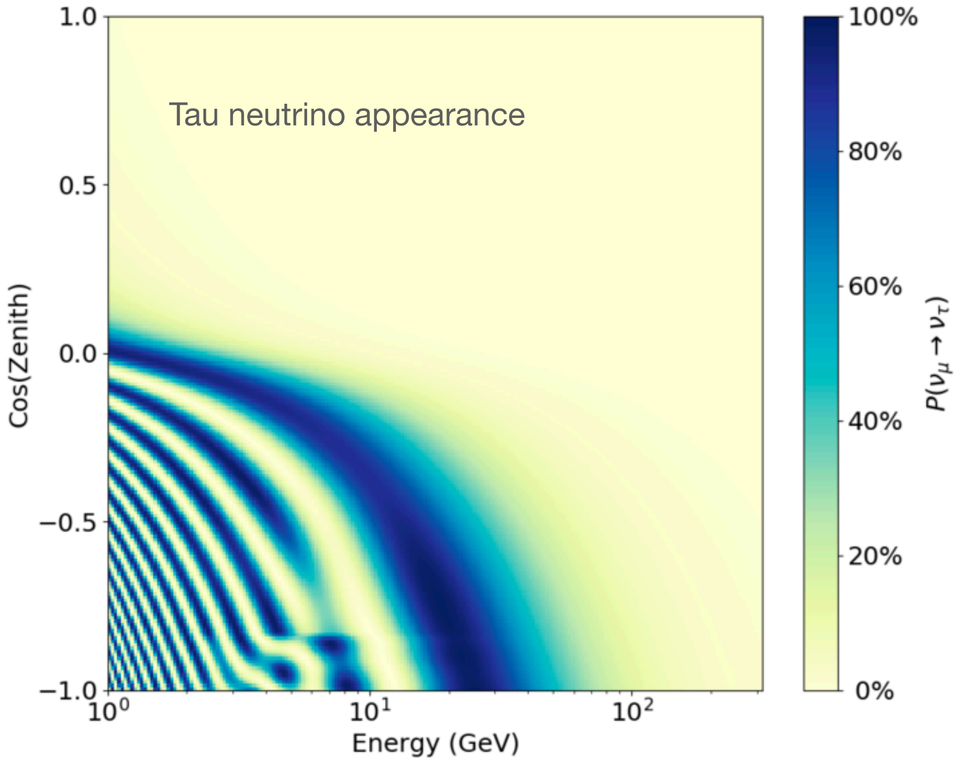
Atmospheric neutrino oscillations (3 x 3 mixing)





Atmospheric neutrino oscillations (3 x 3 mixing)

https://arxiv.org/pdf/2405.02163

- High purity neutrino sample (9.3 years; less than 1% atmospheric muon contamination

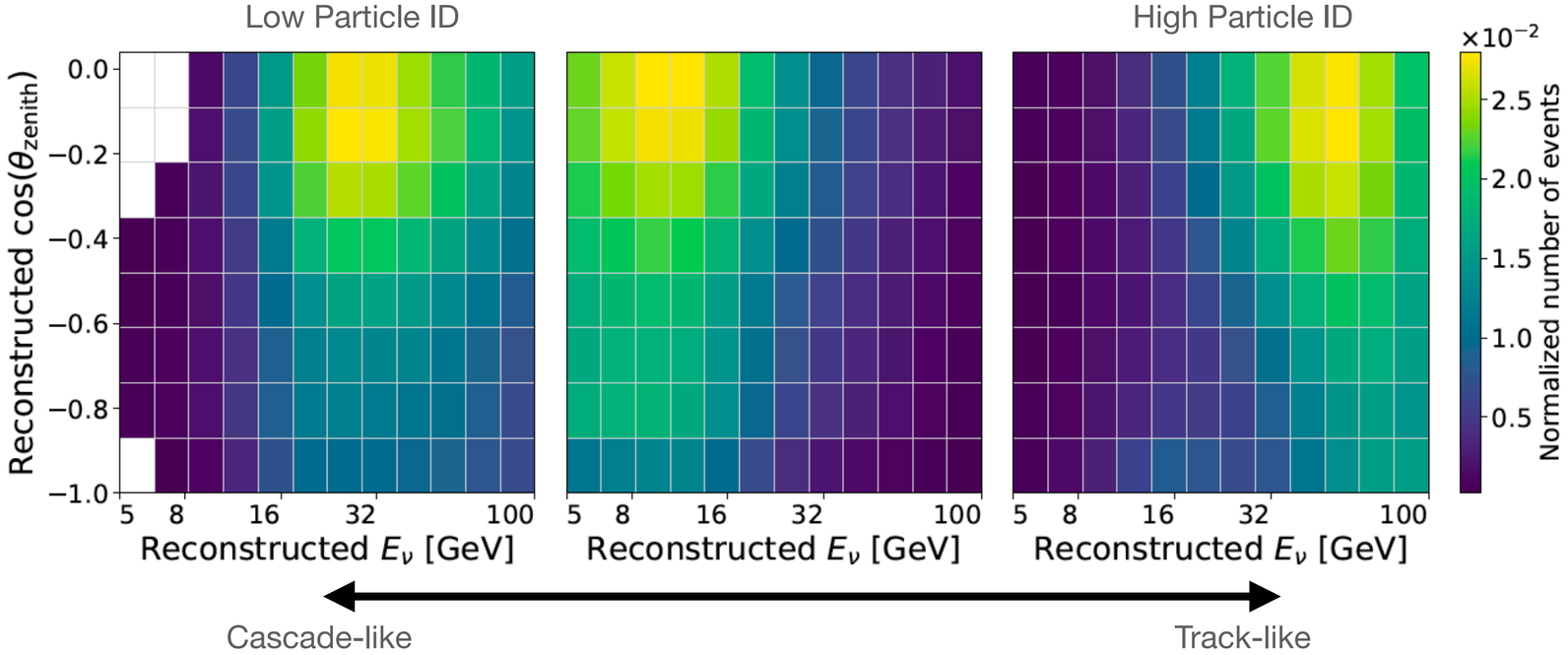
- Applies convolutional neural networks reconstruction (factor 5000 speed-up with consistent resolutions)

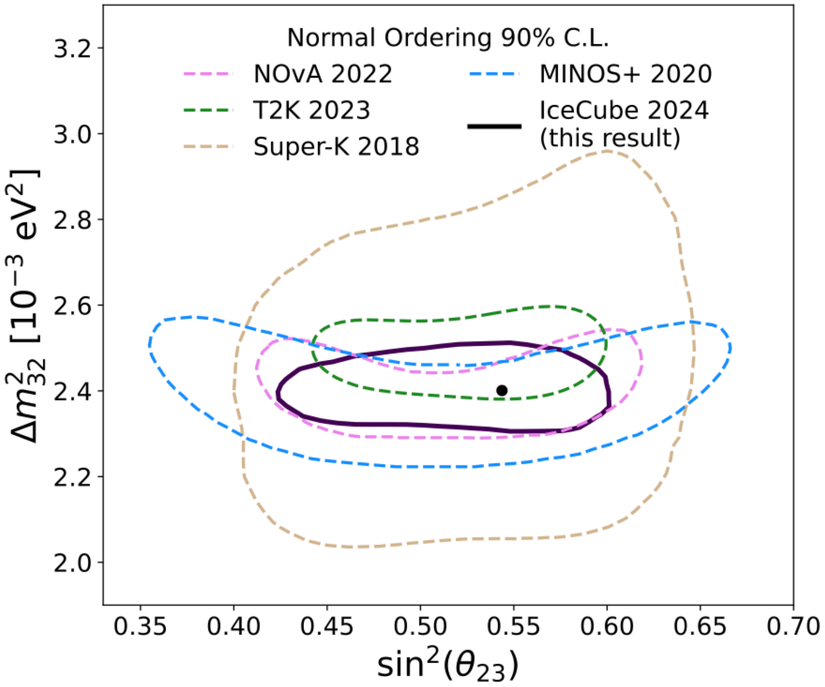
- Incorporates latest detector systematics updates (calibration, flux, cross-section).

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

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

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

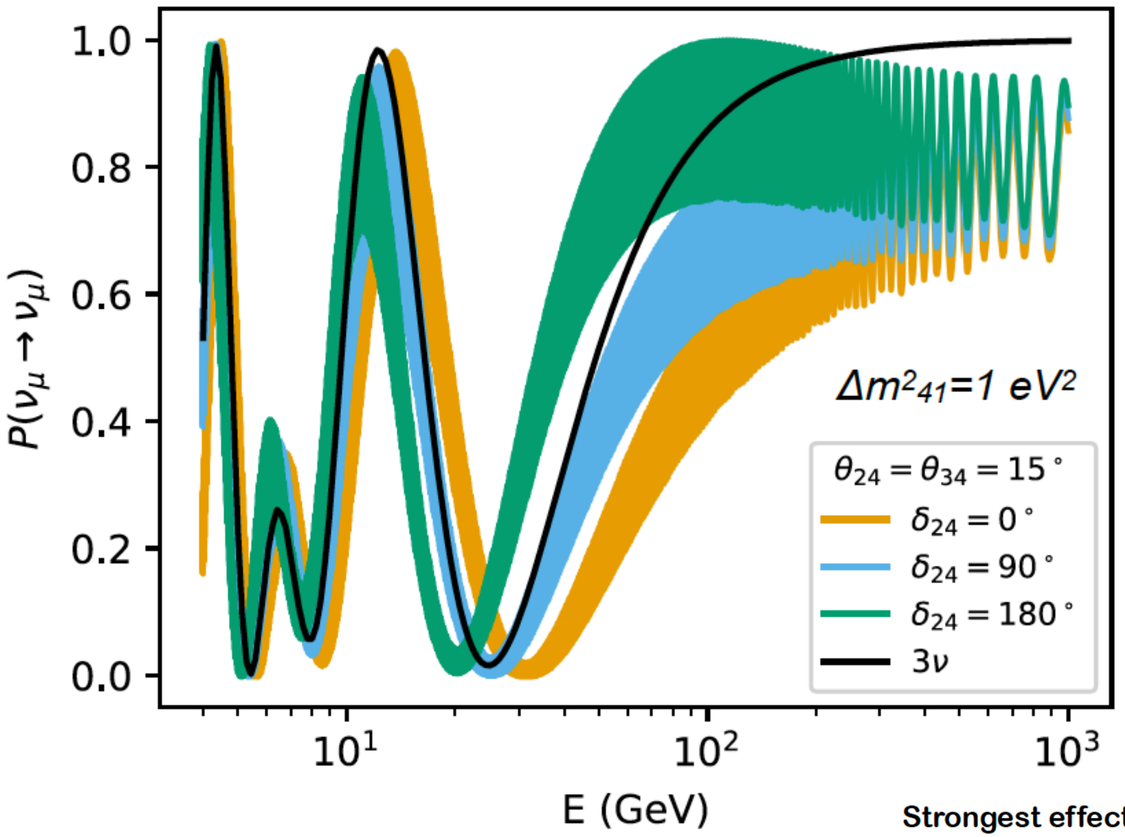




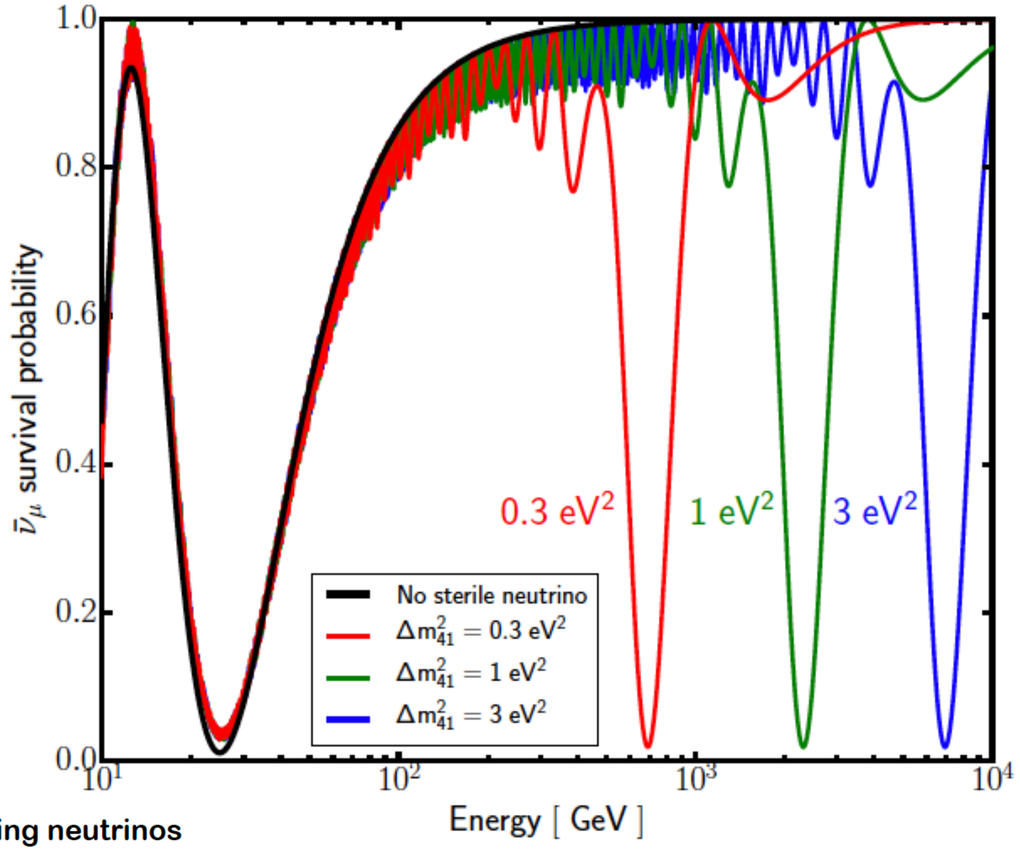
Atmospheric neutrino oscillations (3+1 sterile neutrino; 4 x 4 mixing)

- 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



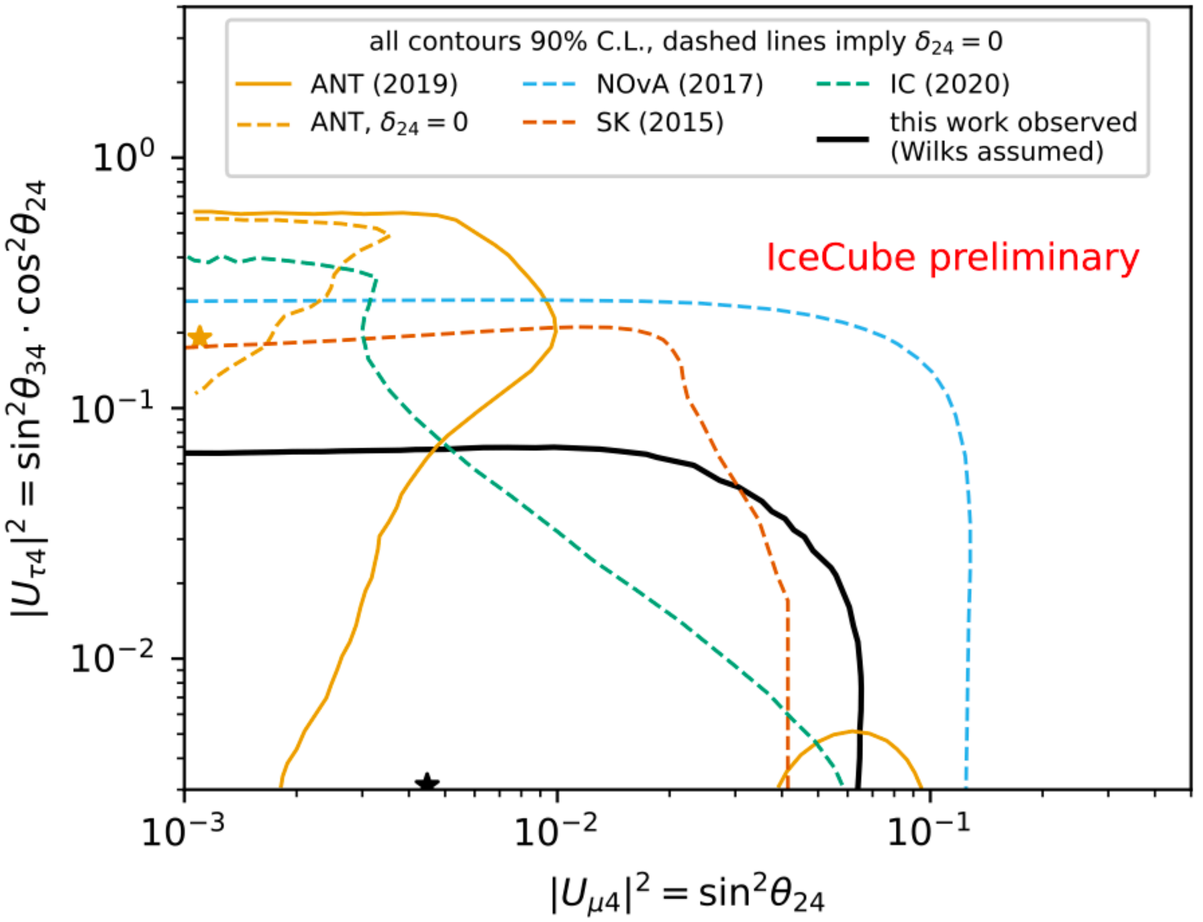
Strongest effects for core-crossing neutrinos

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



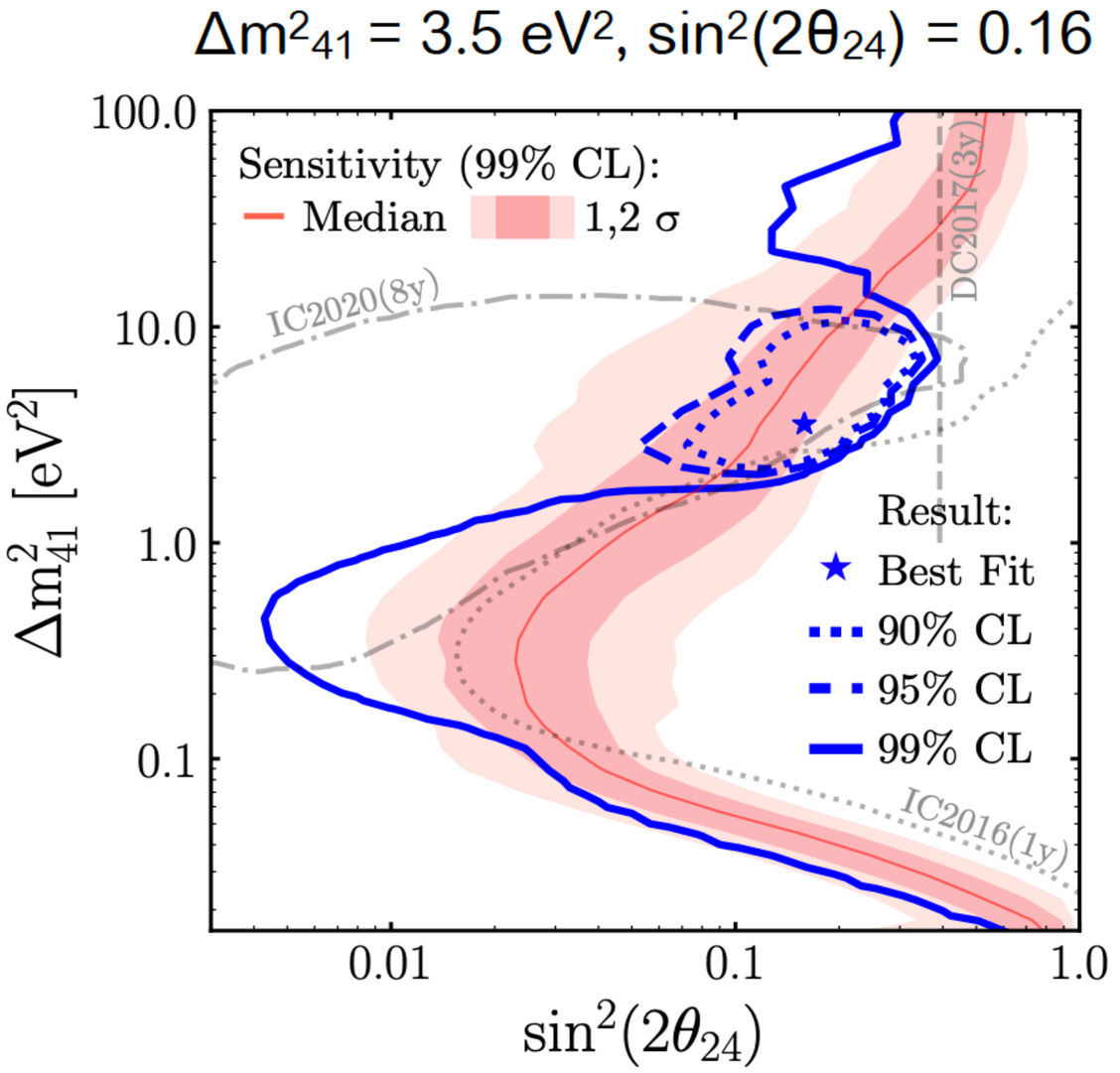
Atmospheric neutrino oscillations (3+1 sterile neutrino; 4 x 4 mixing)

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%)

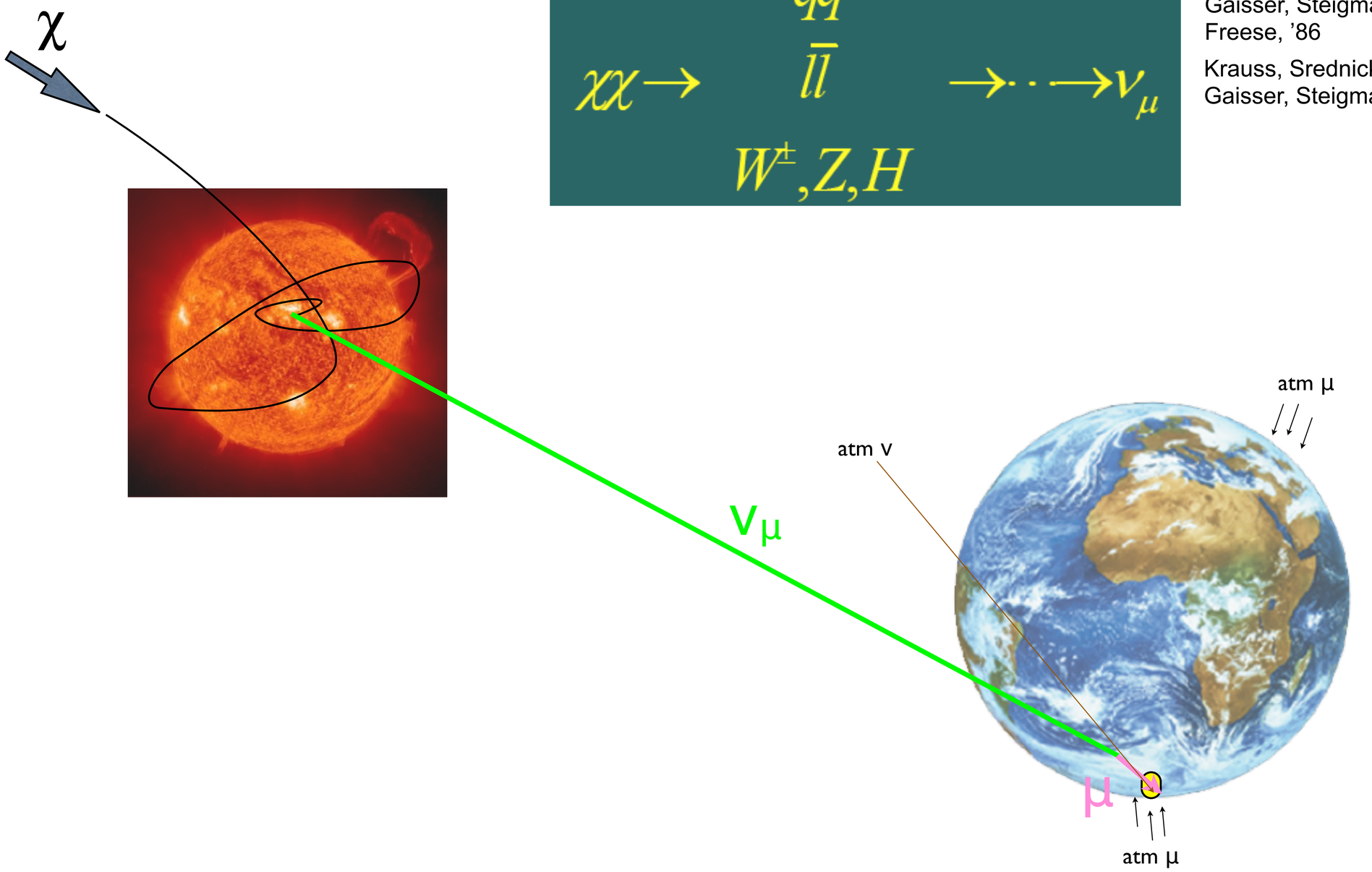


Dark matter search (indirect)

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

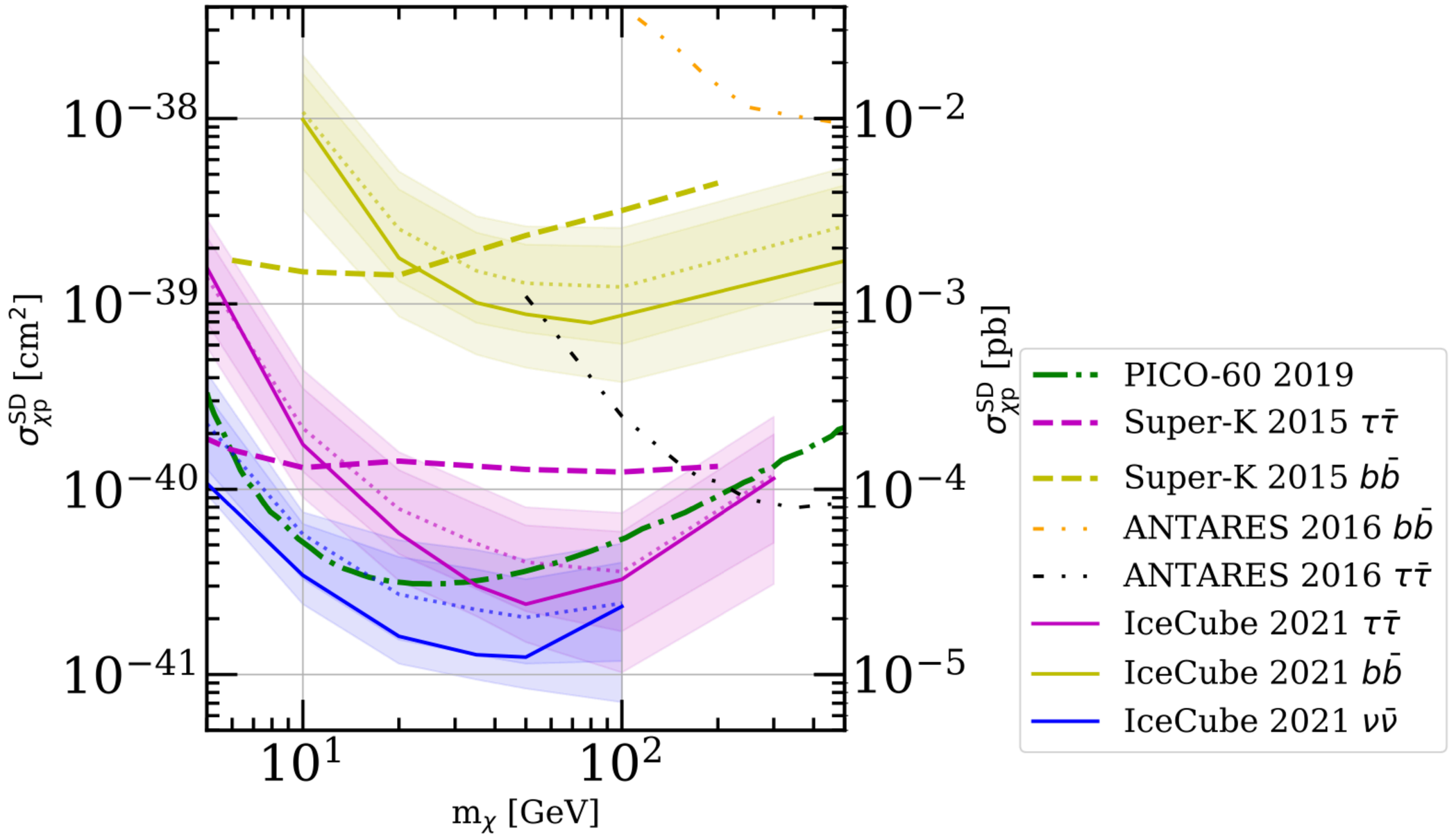
Silk, Olive and Srednicki, ’85
Gaisser, Steigman & Tilav, ’86
Freese, ’86

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



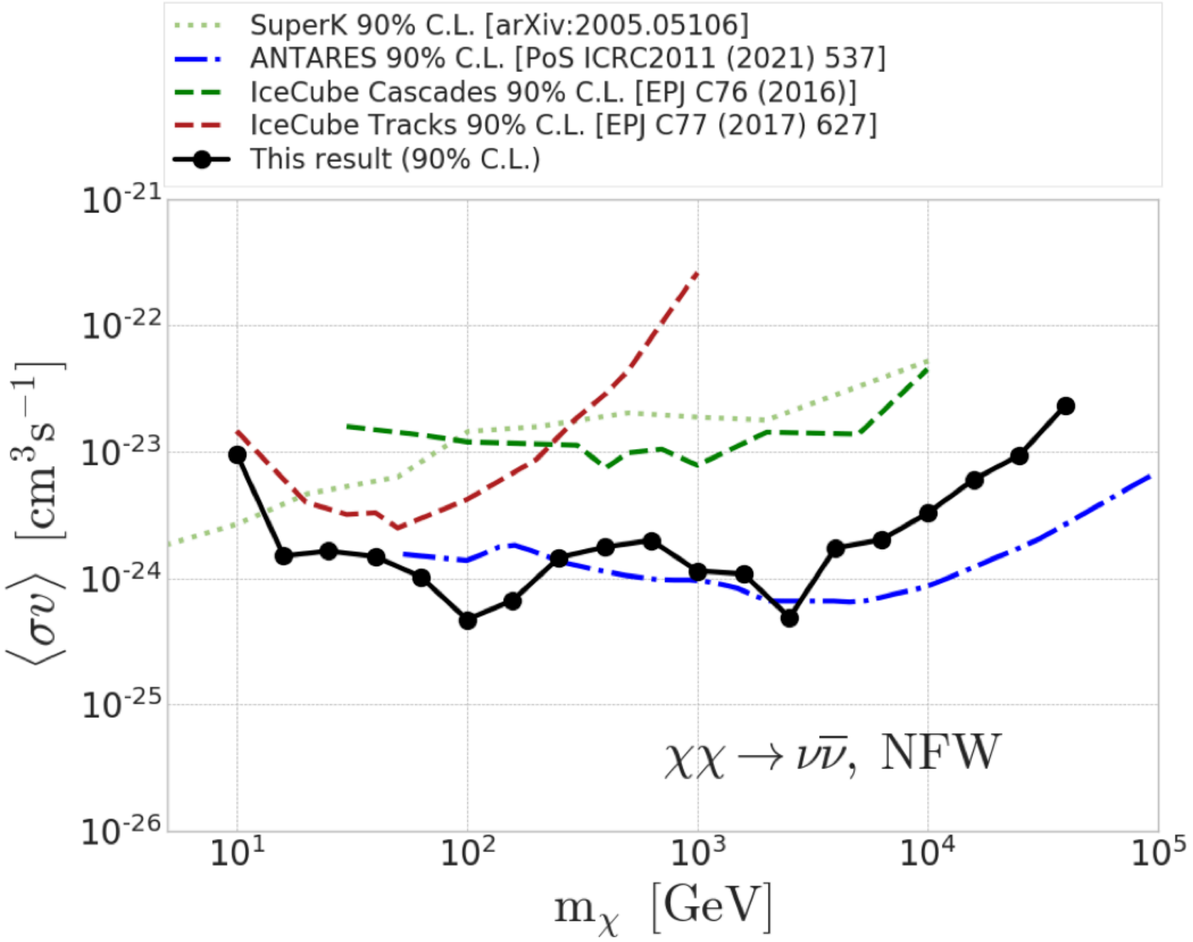
Indirect dark matter search (Sun)

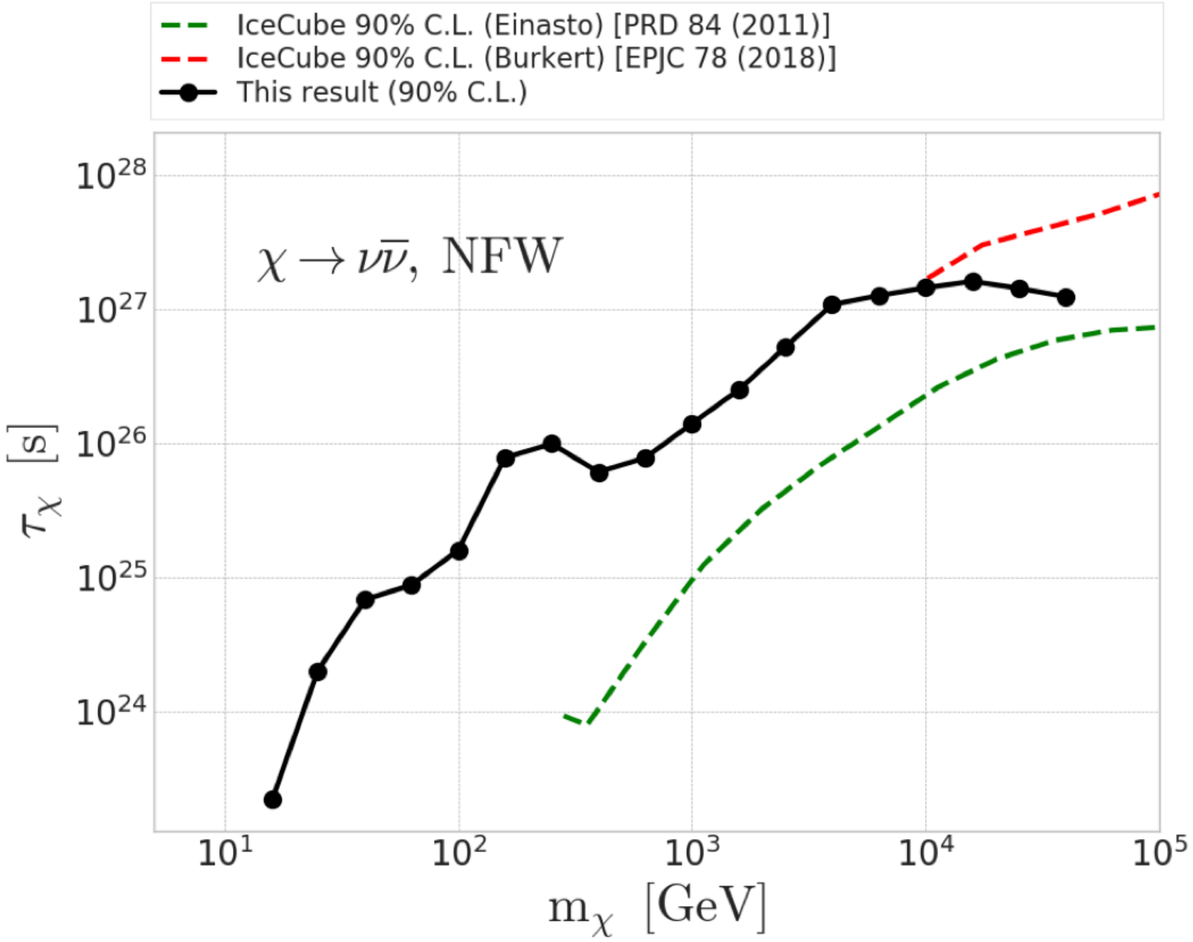
Phys. Rev. D 105, 062004



Indirect dark matter search (Milky Way Galactic Centre)

Phys. Rev. D108 102004

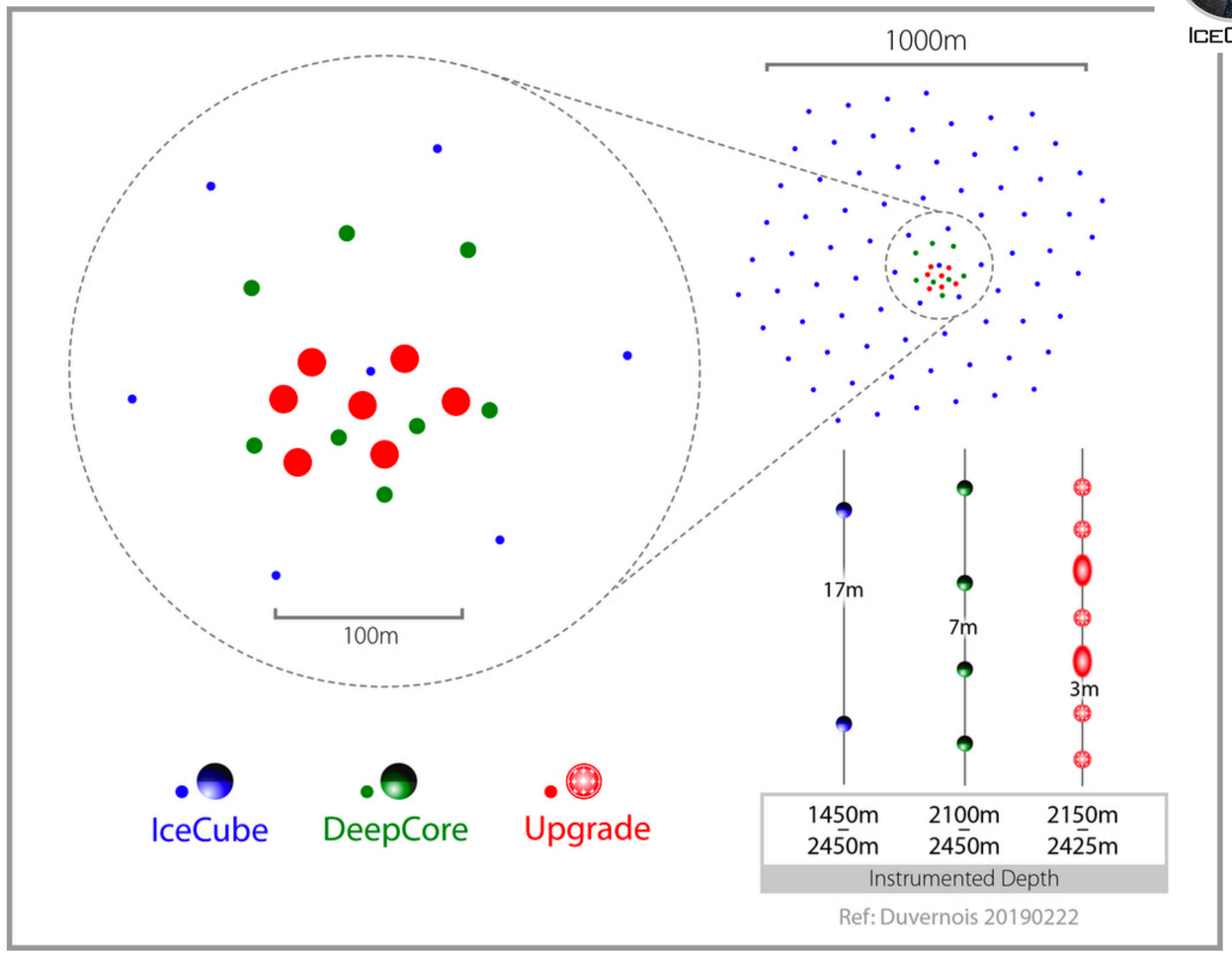


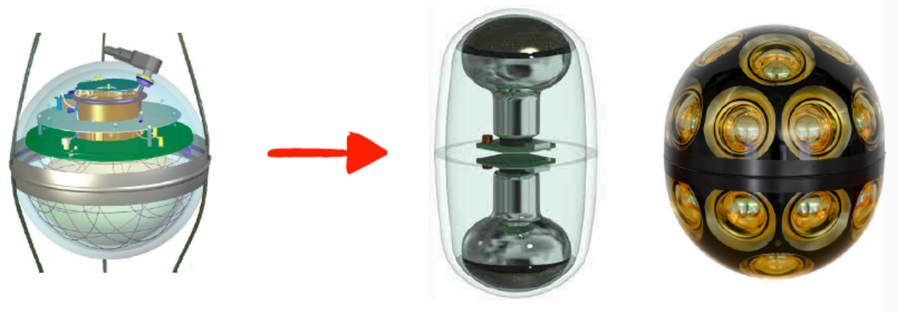


Future directions - IceCube Upgrade

- 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

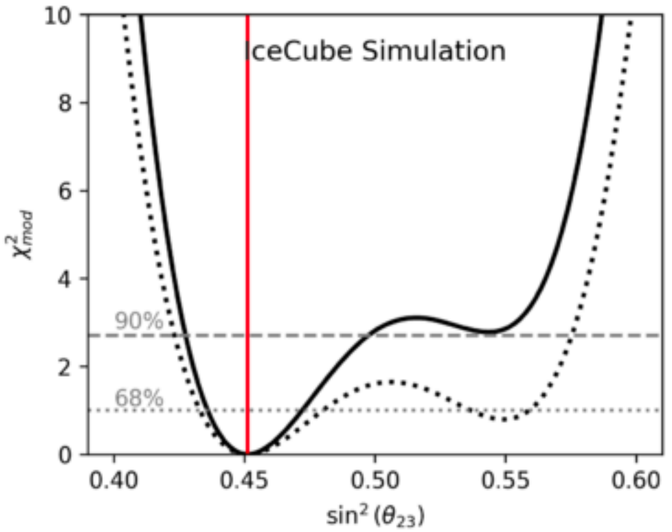
- More than 800 next generation modules and precision calibration devices
- Reduced inter-module spacing
- Deep-ice deployment to 2600 m

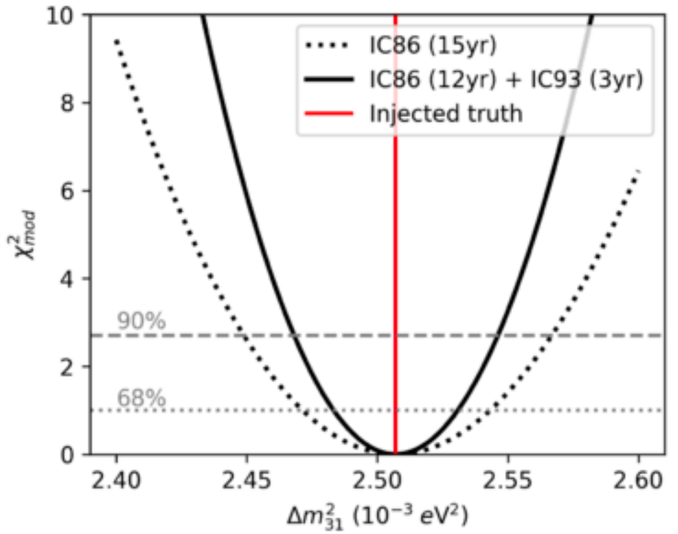


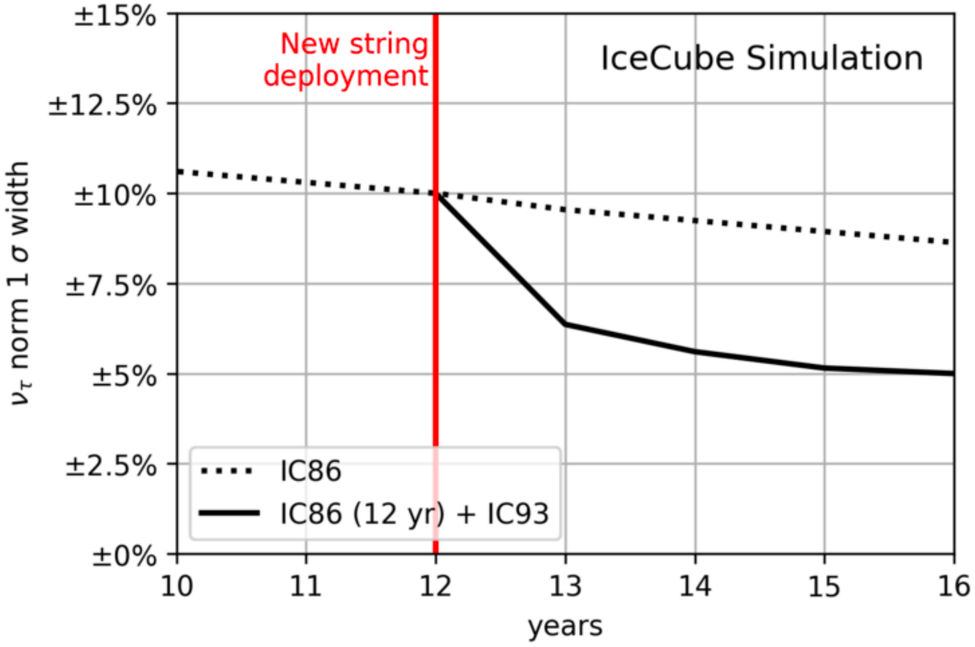


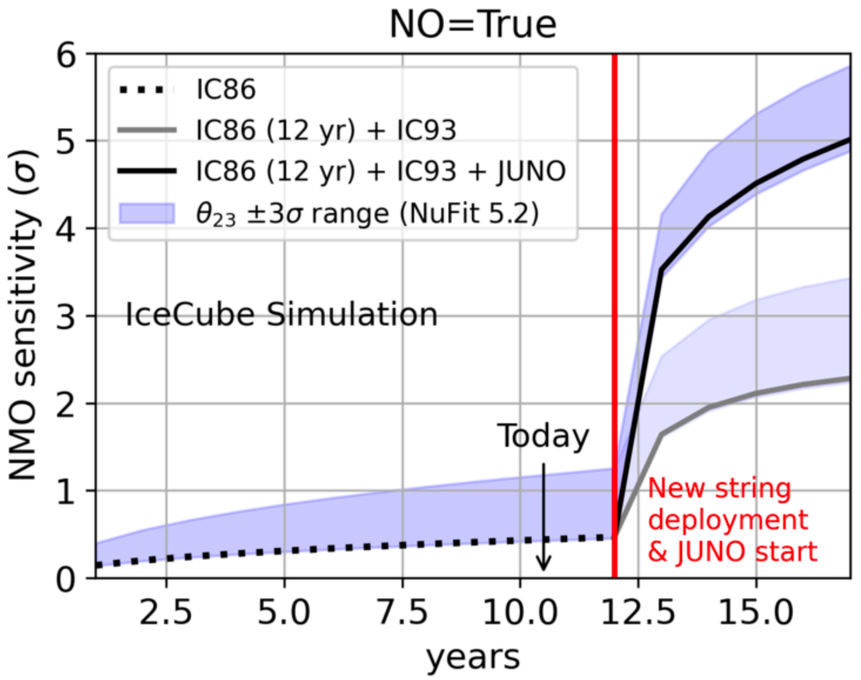
Future directions - IceCube Upgrade

- 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)



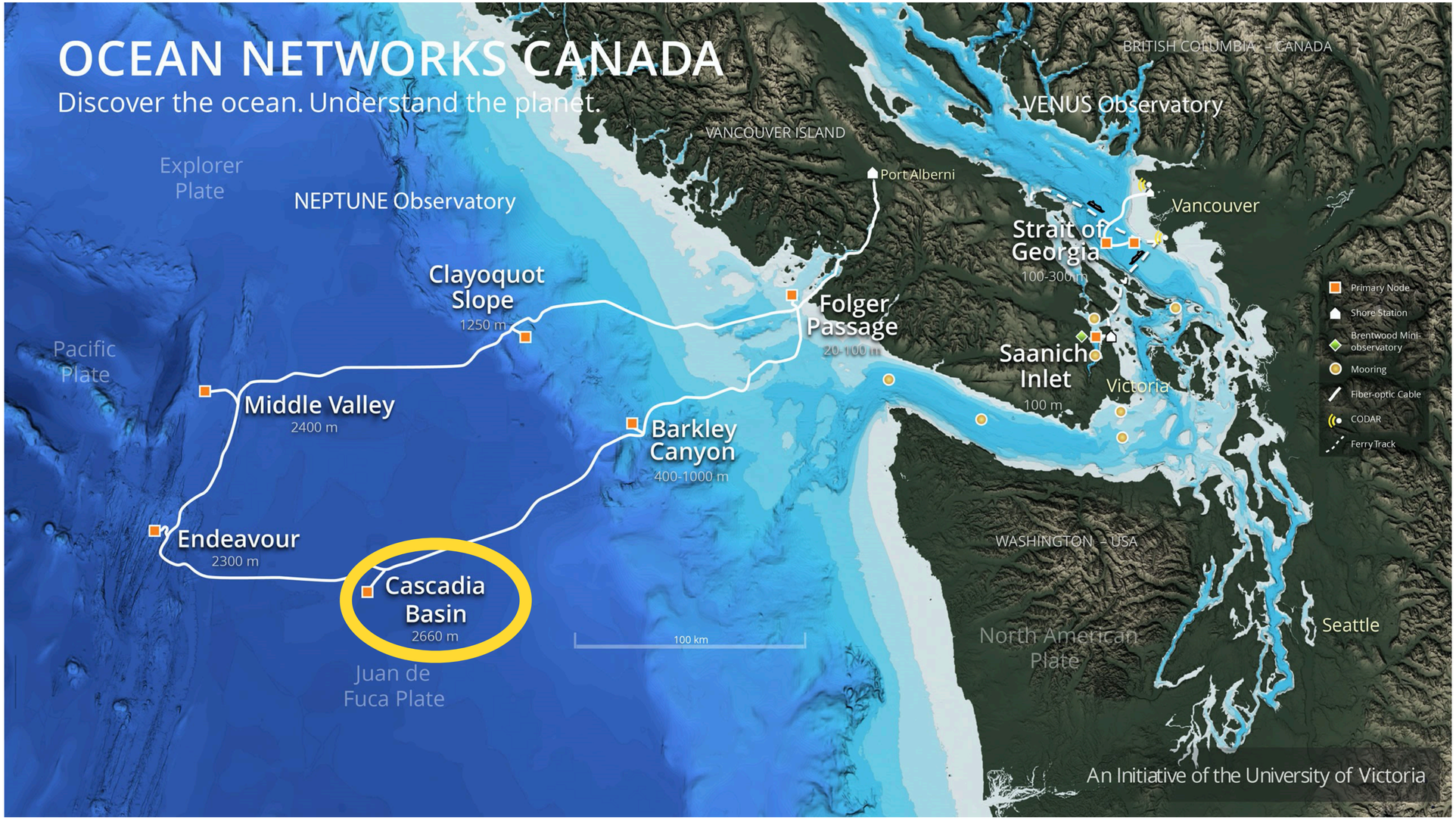






IceCube

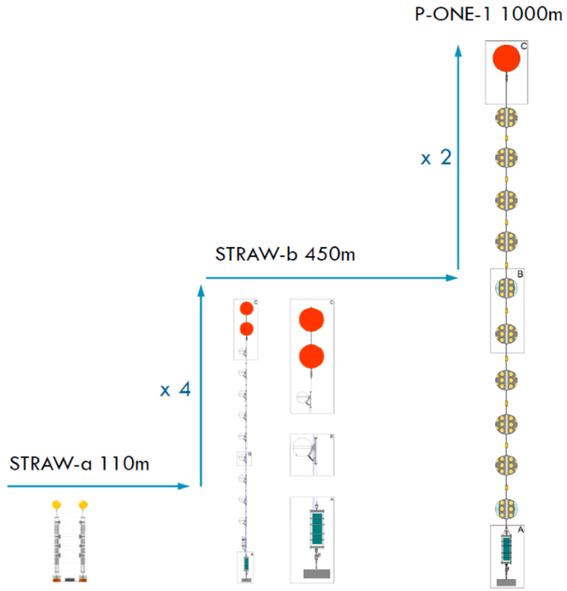
Future directions - Pacific Ocean Neutrino Experiment (P-ONE)

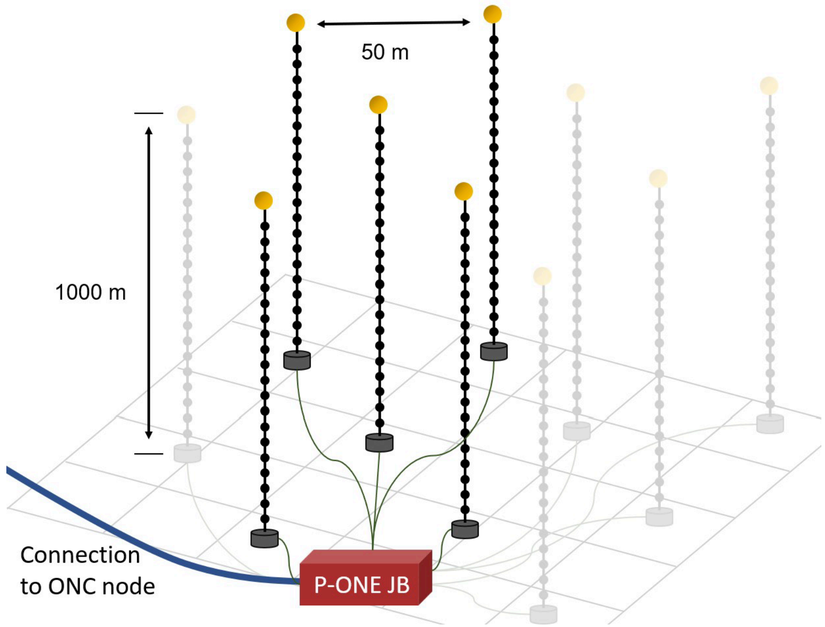


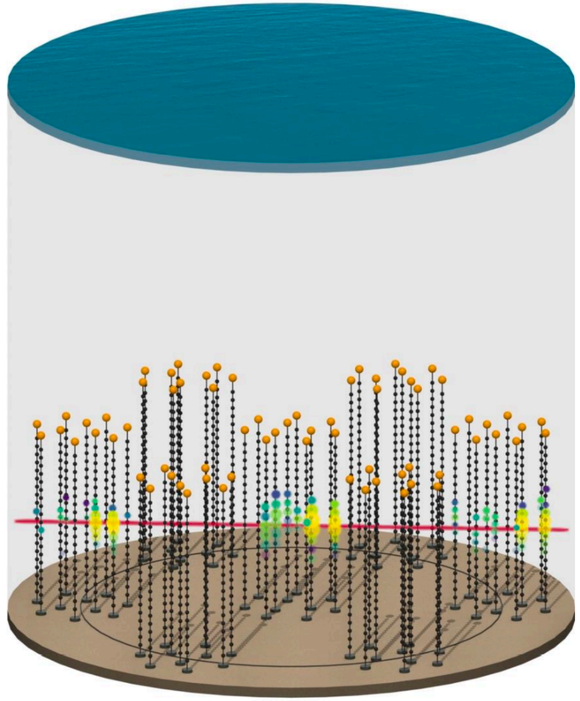
Leverages Canada's investments in deep ocean

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

Future directions - Pacific Ocean Neutrino Experiment (P-ONE)





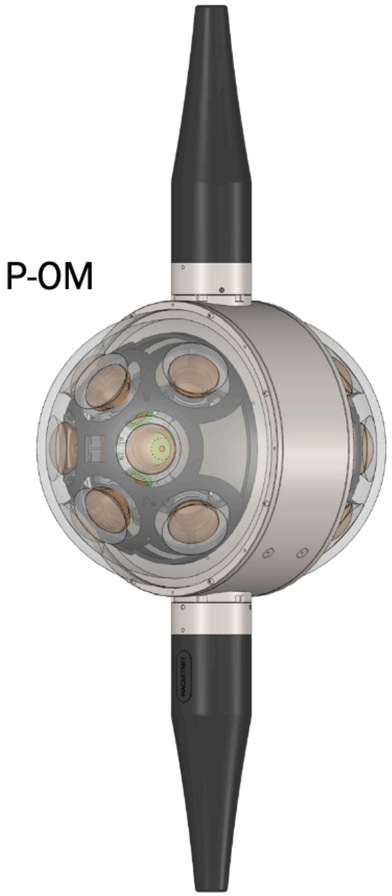


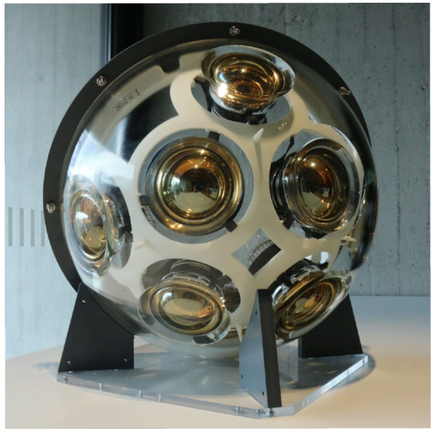
Pathfinder
Phase 1 (2018 — 2025)

Demonstrator (first cluster)
Phase 1 (2025 — 2028)

P-ONE
Phase 1 (2028+)

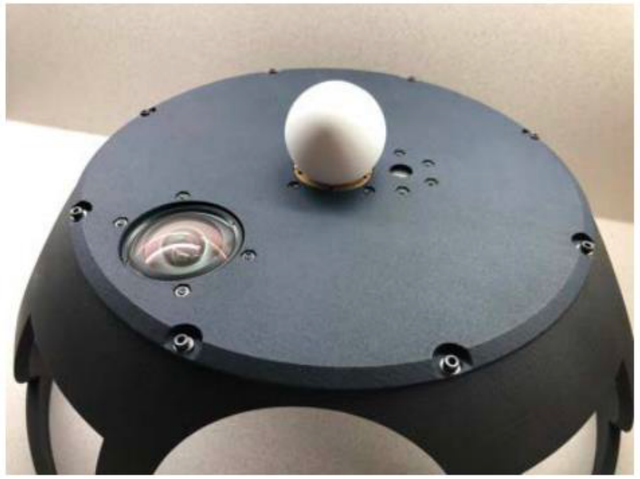
Future directions - Pacific Ocean Neutrino Experiment (P-ONE)



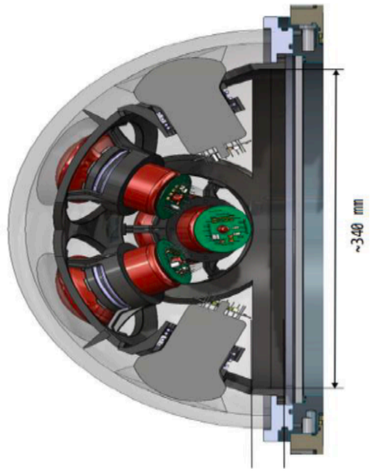


Calibration program

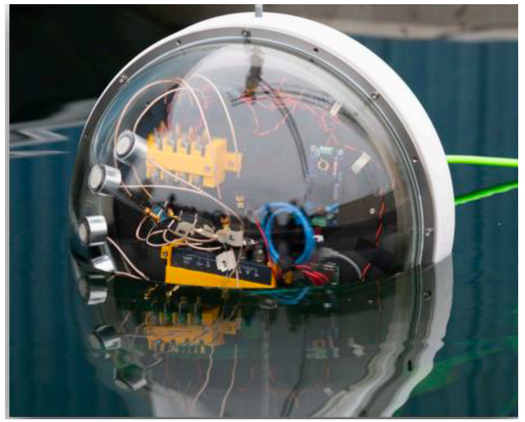
P-cal optical diffusing sphere

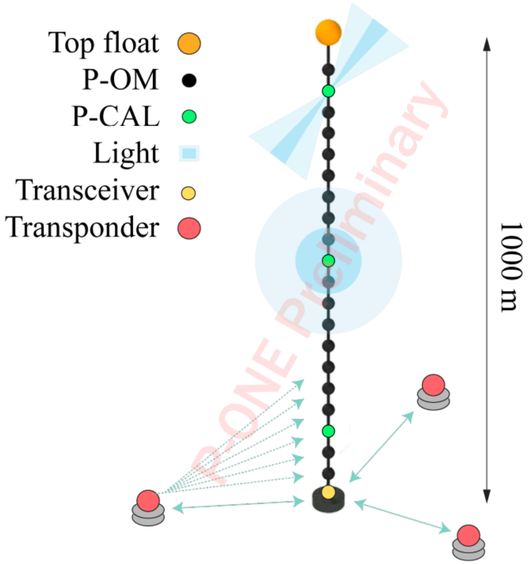


Muon scintillation tracker



Acoustic position system

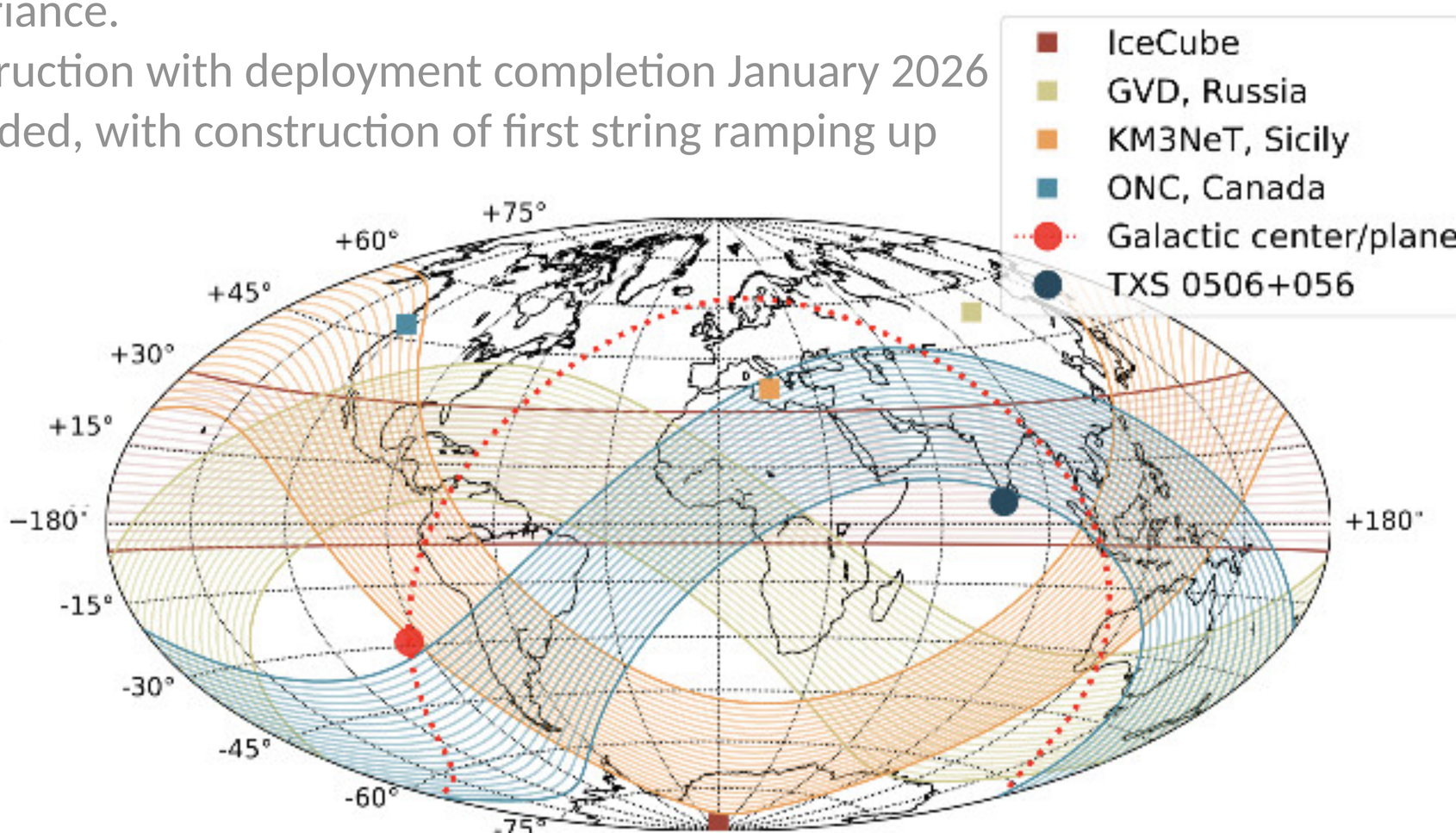




Summary

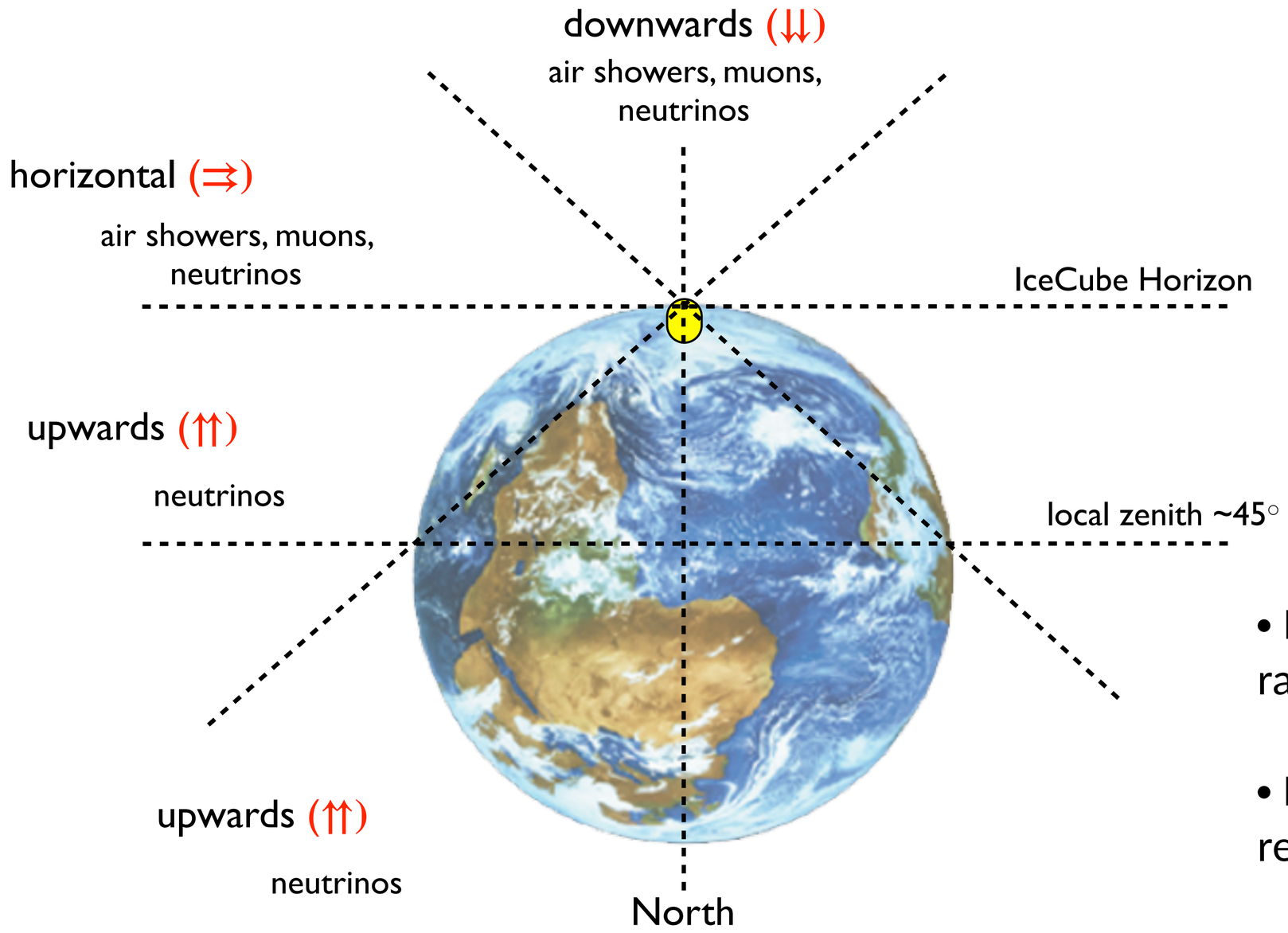
- High-energy neutrinos are an excellent probe of new physics beyond the Standard Model
  - IceCube's (nearly 15-year) dataset continues to provide leading sensitivity to standard and non-standard neutrino oscillations, as indirect dark matter searches
    - Not covered today are recent results in quantum gravity decoherence, neutrino decay, and tests of Lorentz invariance.
  - IceCube Upgrade is under construction with deployment completion January 2026
  - P-ONE Demonstrator is now funded, with construction of first string ramping up towards 2025 deployment.

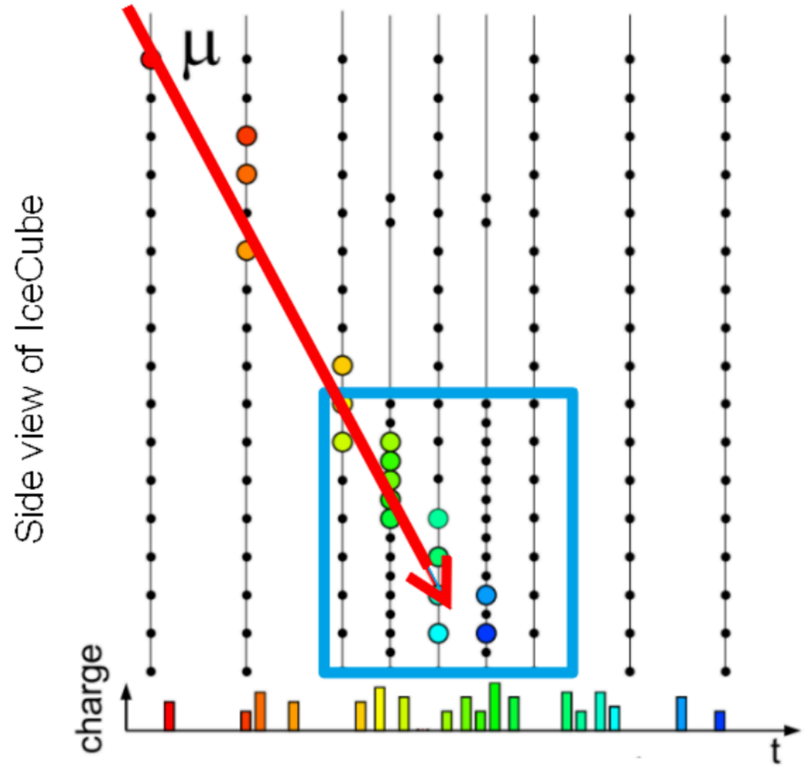
A suite of next generation large-scale neutrino telescopes will continue to help shape the measurements in this rapidly evolving field.



Backup slides

Signal and backgrounds…



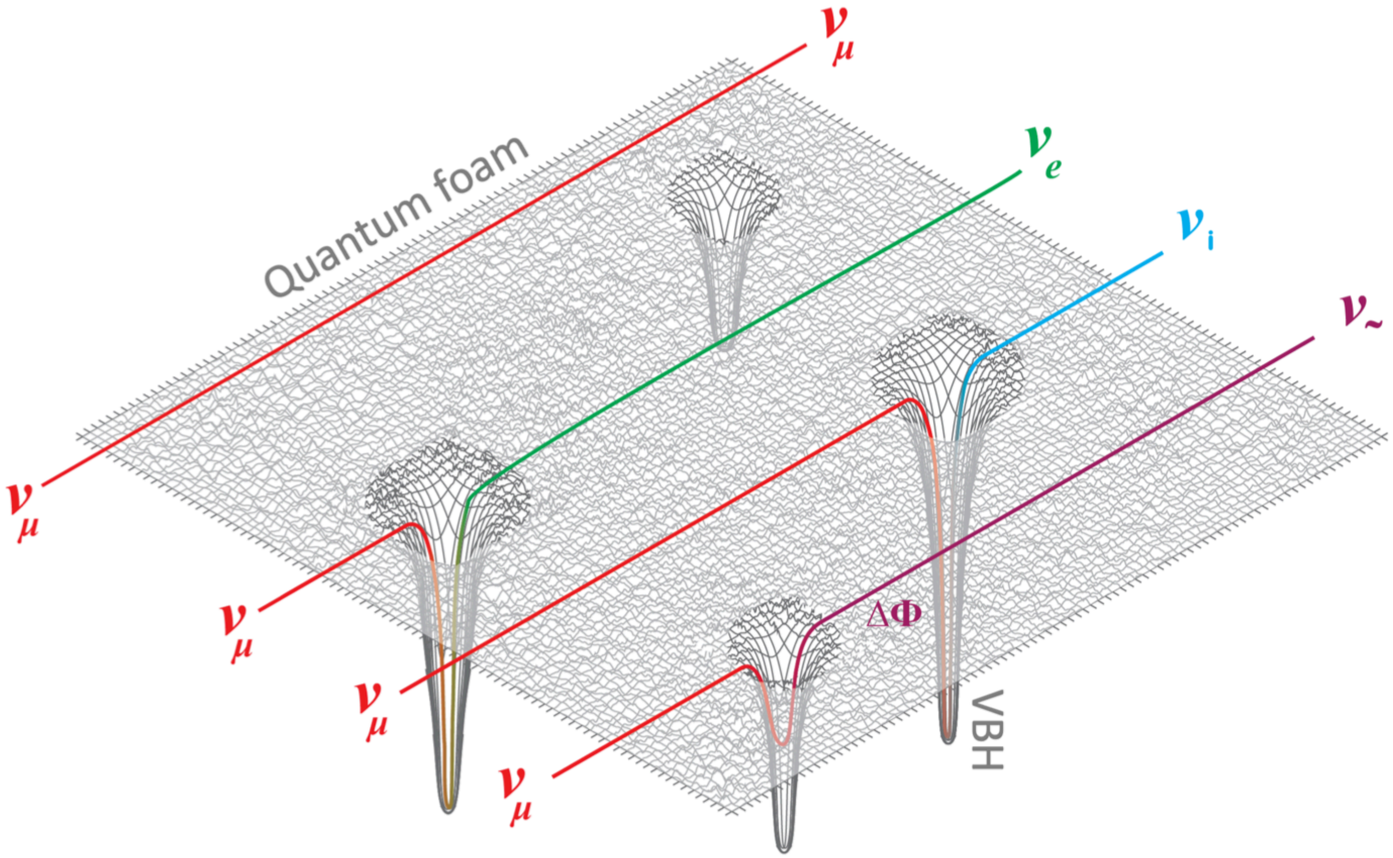


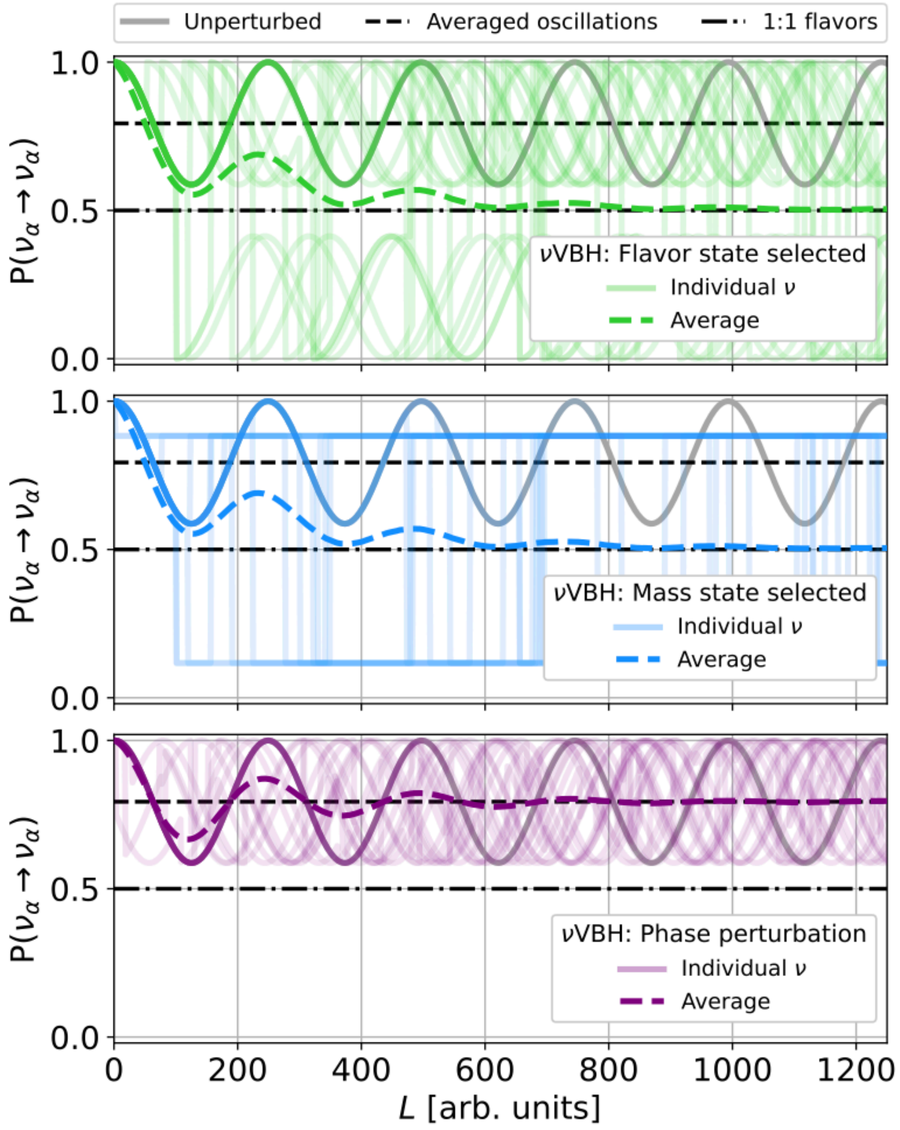
- Random coincidence hits from intrinsic radioactivity removed via causal triggering

- Dominate atmospheric muon signature reduced via
  - Earth shielding
  - Active detector veto

Atmospheric neutrino oscillations (decoherence from quantum gravity - νVBH)

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





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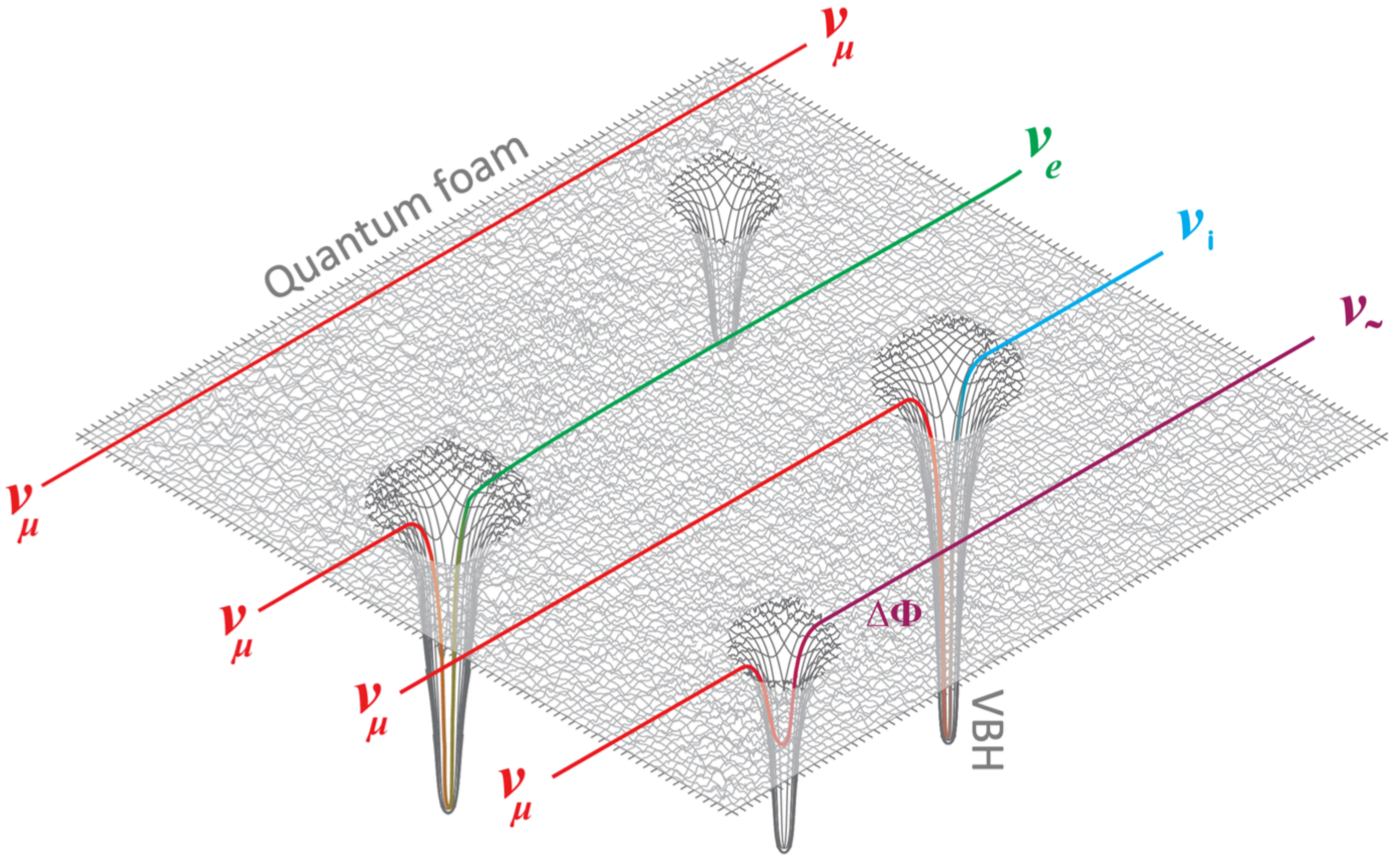

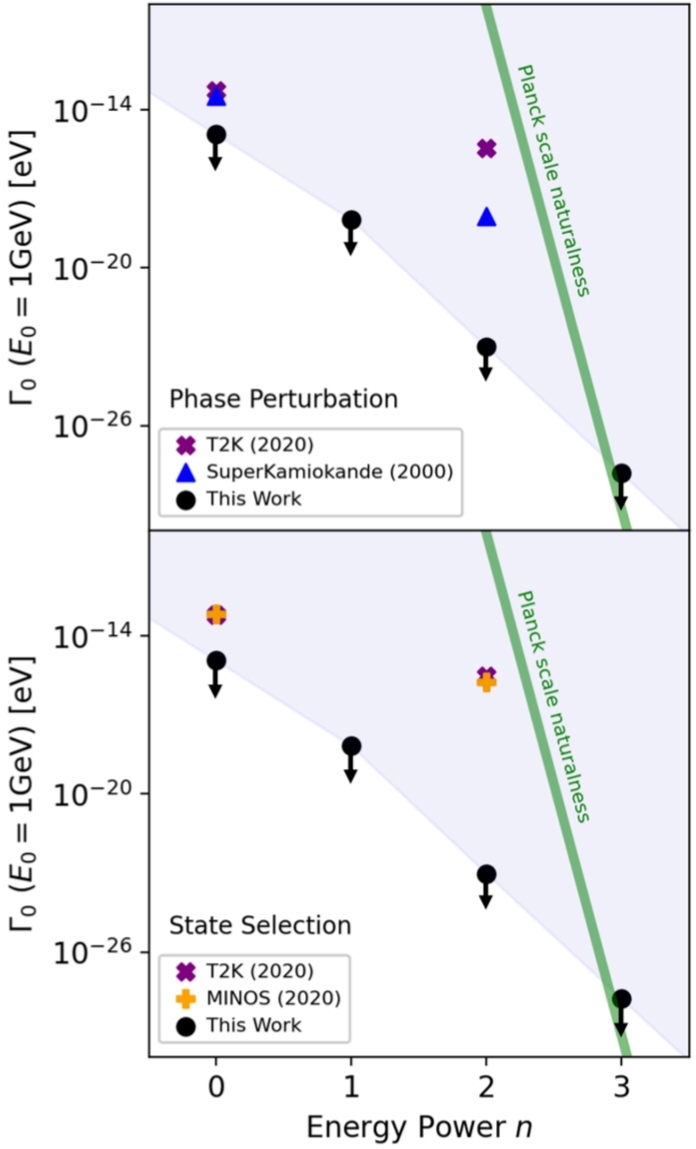

Future directions - Pacific Ocean Neutrino Experiment (P-ONE)