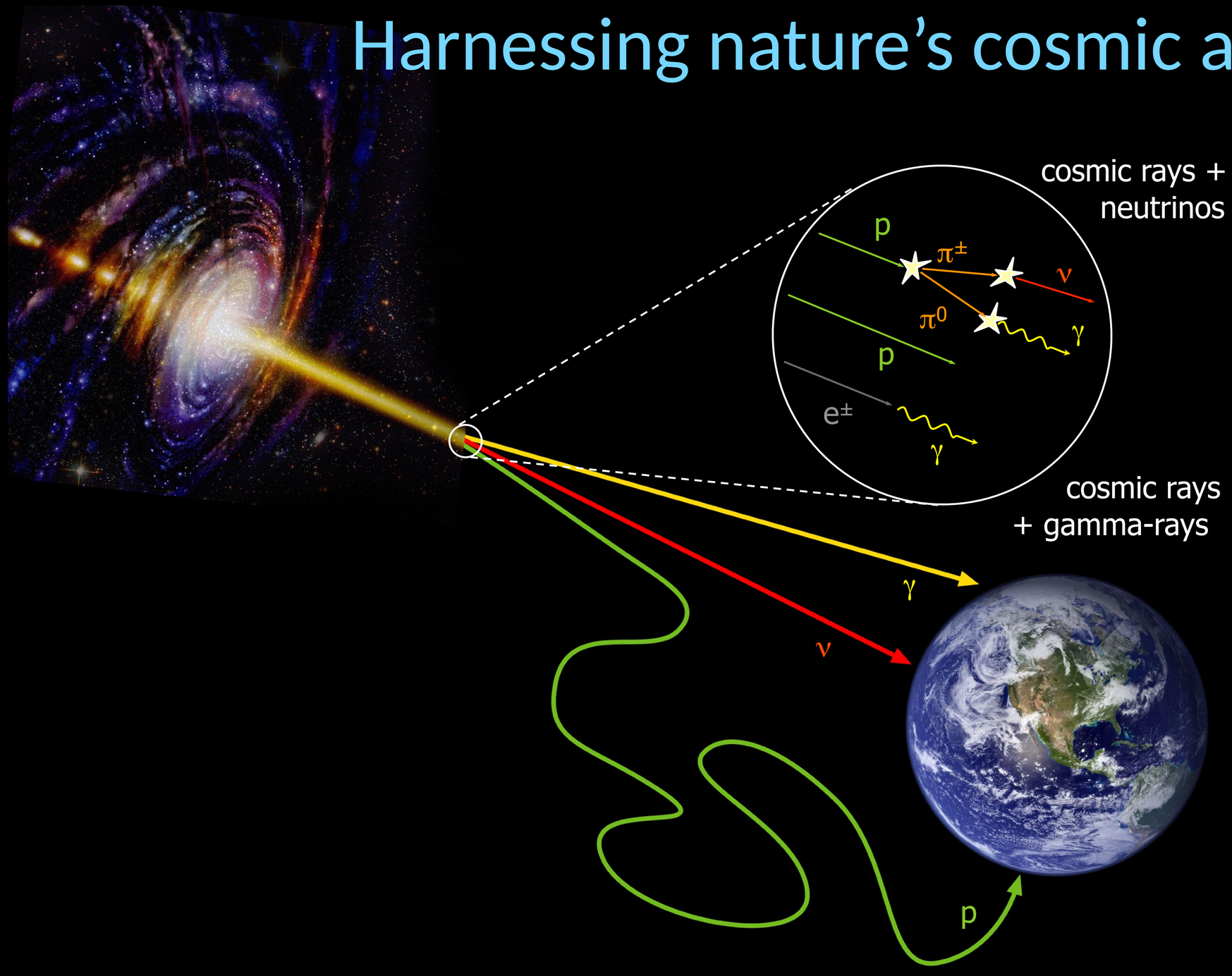
Current results and future outlook

IceCube Neutrino Observatory

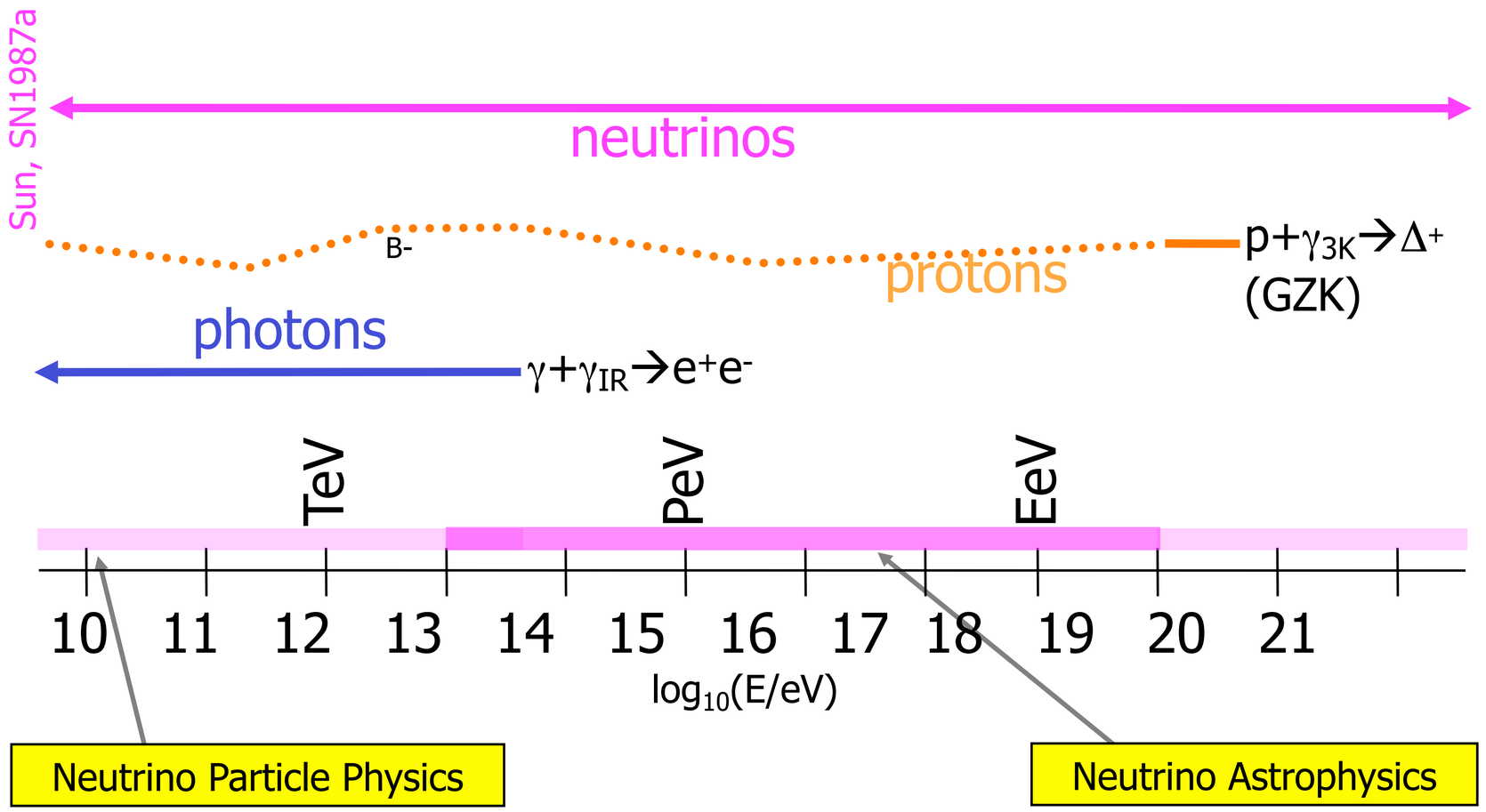
Darren R Grant — McDonald Institute ANM — August 2024

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

Harnessing nature's cosmic accelerators

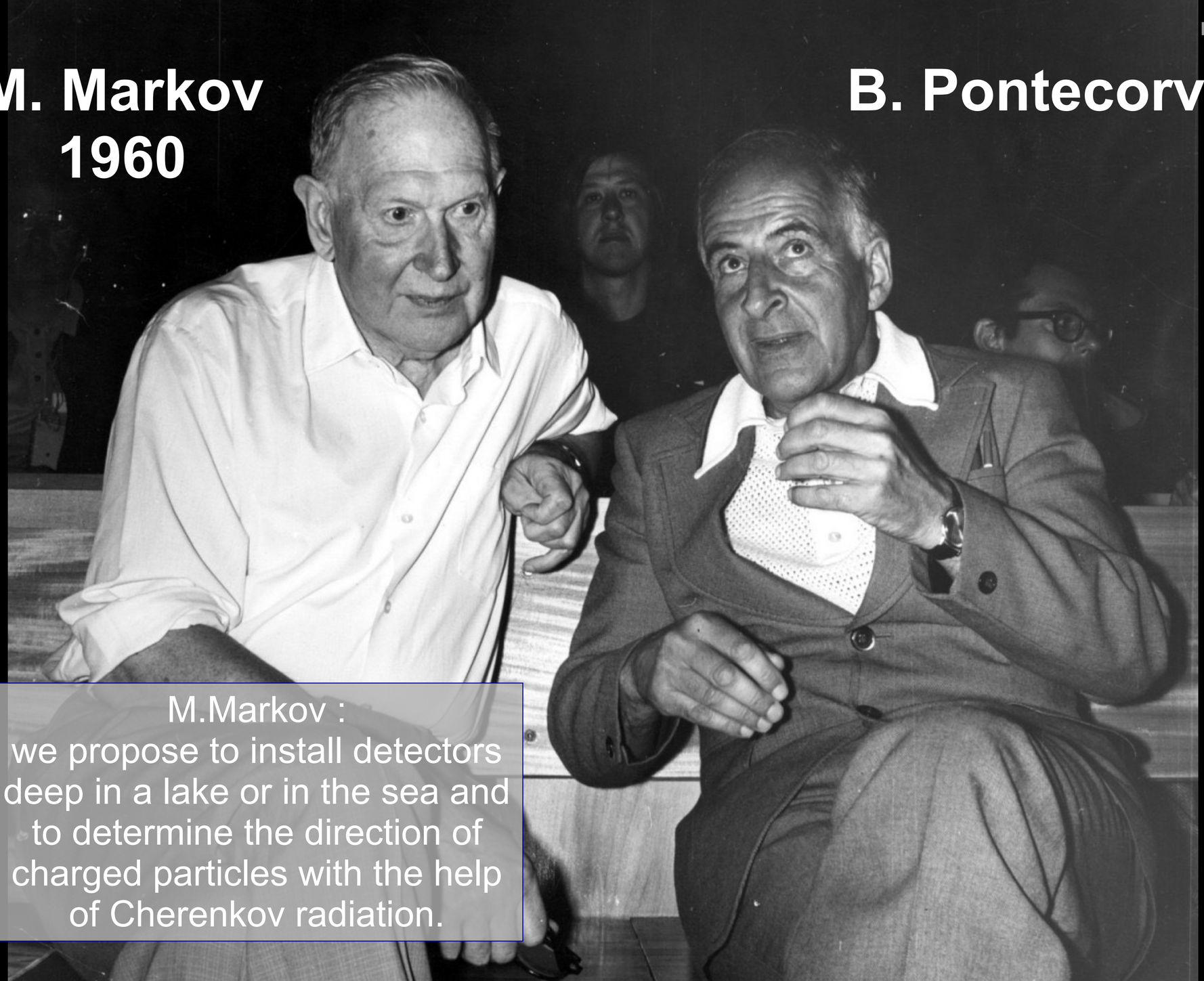


Cosmic messengers



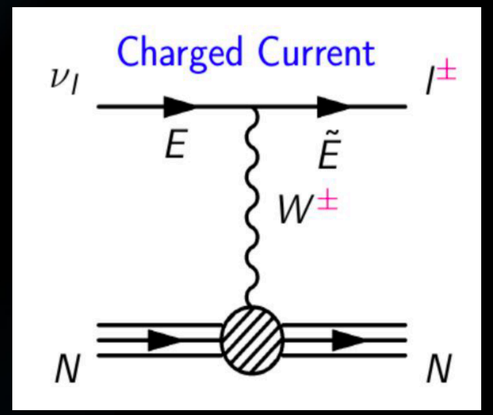
M. Markov 1960

B. Pontecorvo

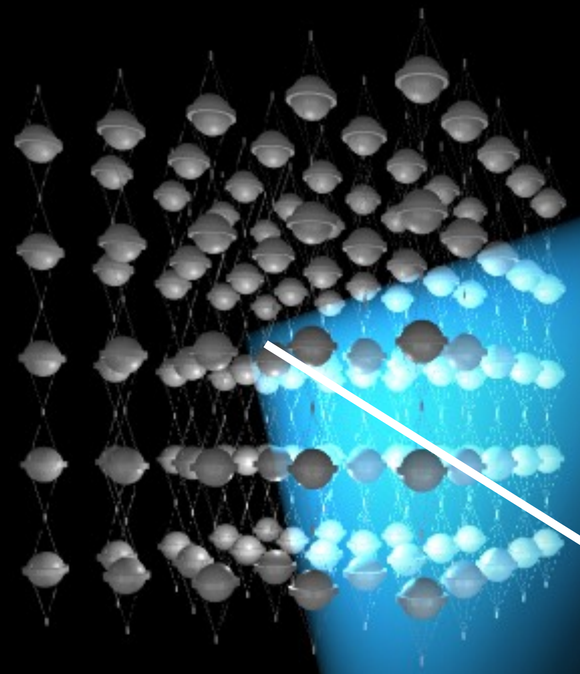


M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

charged secondary particles produced as the neutrino disappears



nuclear interaction



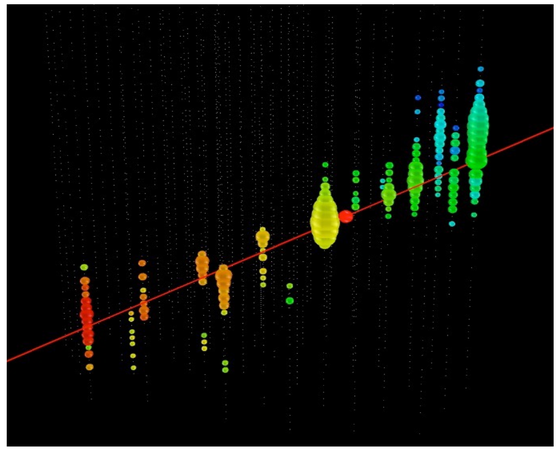
- lattice of photomultipliers

neutrino

Principles of high-energy neutrino detection - water Cherenkov

TeV-scale+

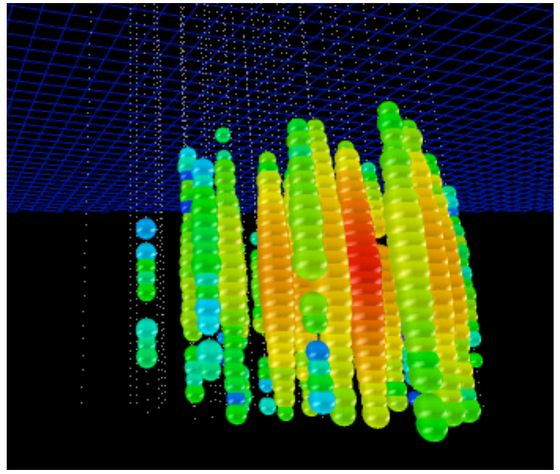
CC Muon Neutrino



track

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

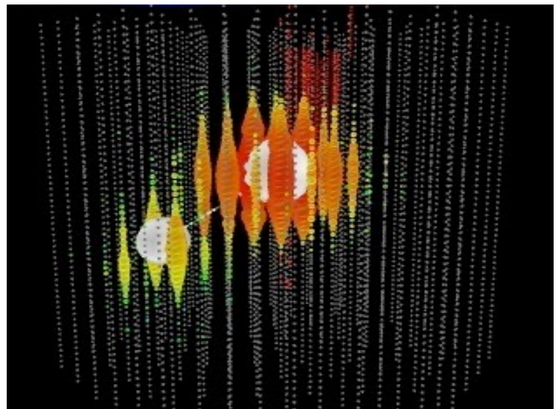
Neutral Current / Electron Neutrino



cascade

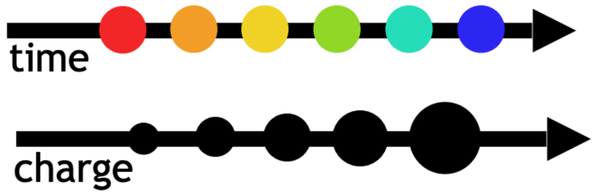
≈ ±15% deposited energy resolution
≈ 10° angular resolution (at energies ≳ 100 TeV)

CC Tau Neutrino

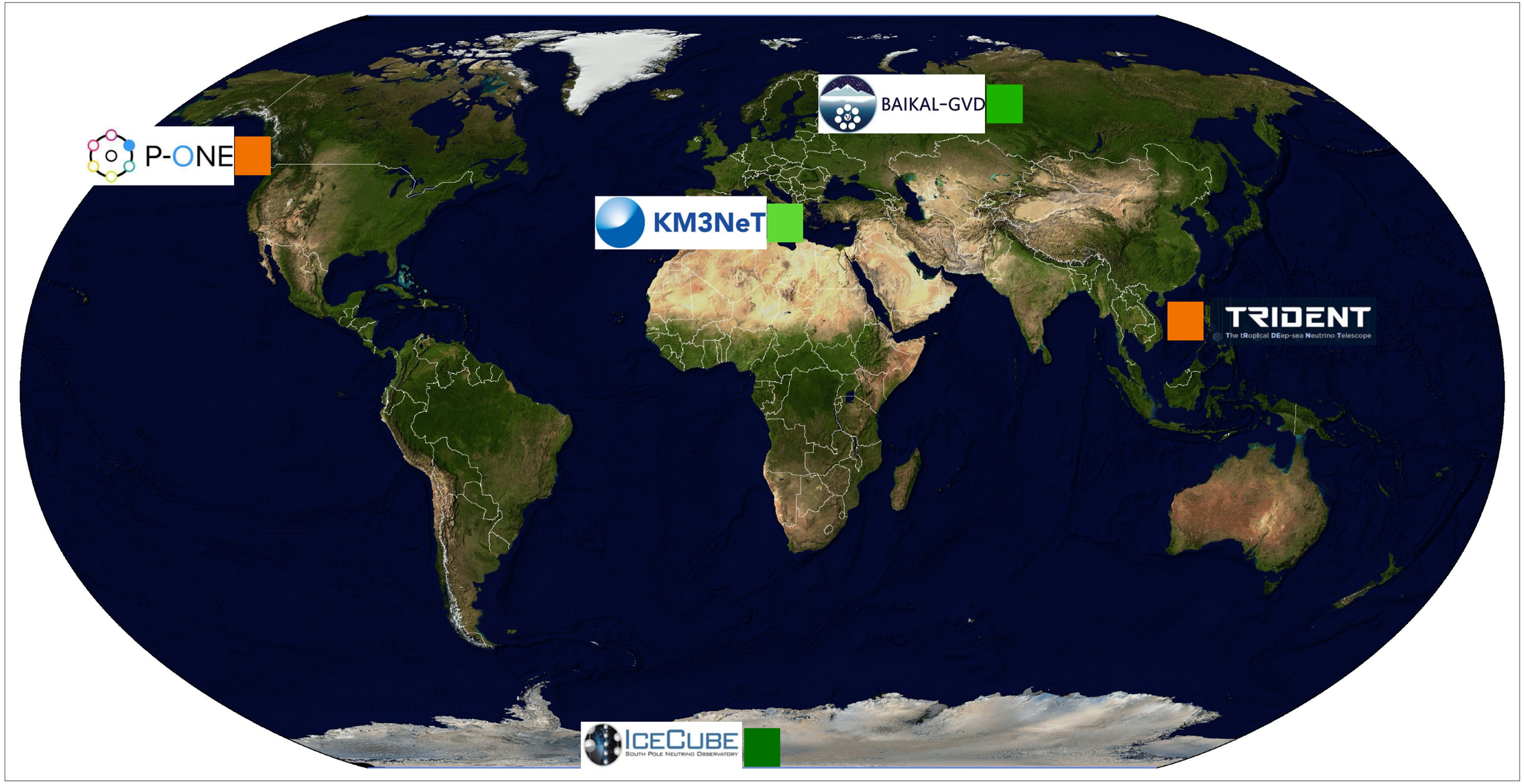


“double-bang” and other signatures

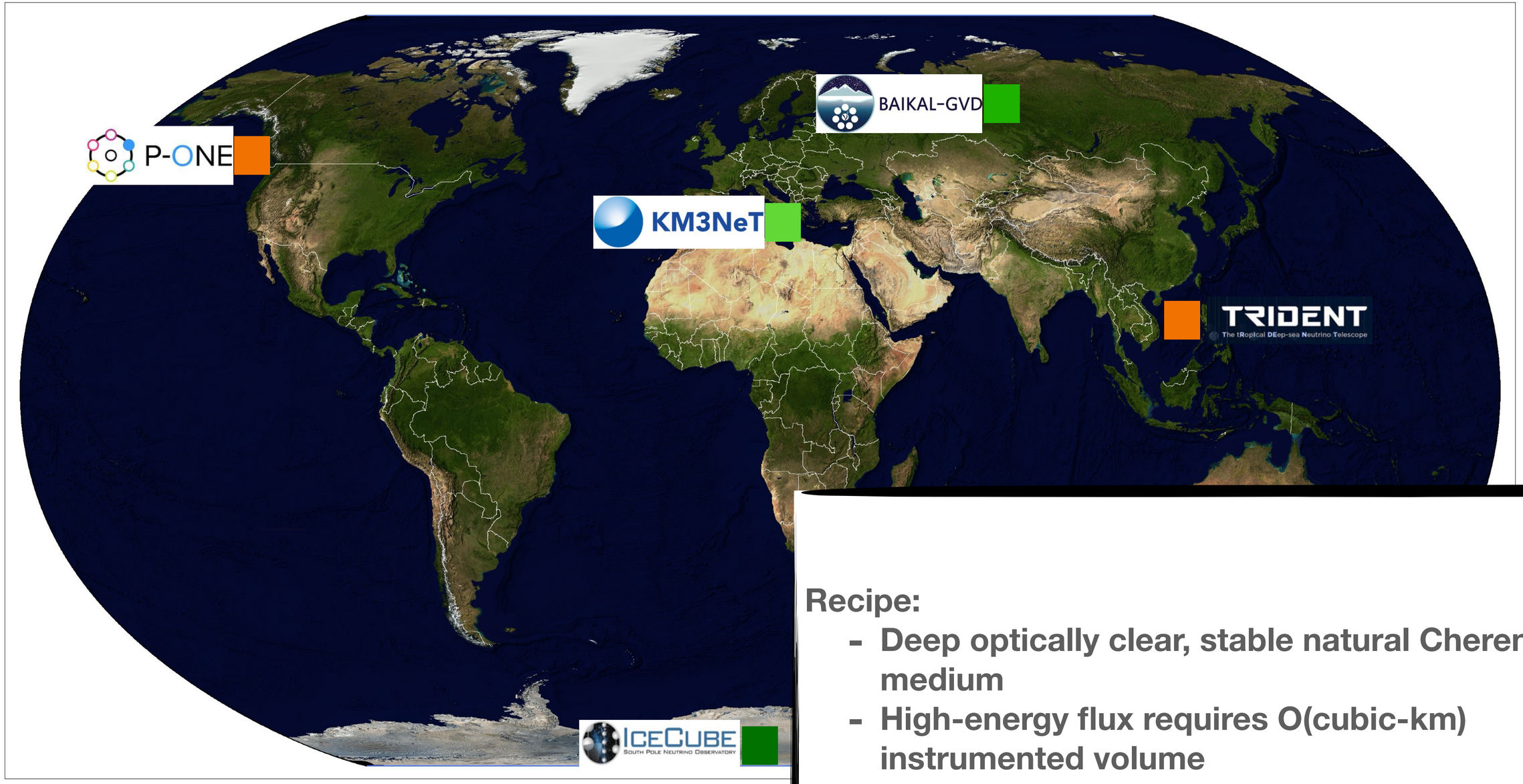
(τ decay length is 50 m/ PeV)



High-energy neutrino telescopes — global view



High-energy neutrino telescopes — global view



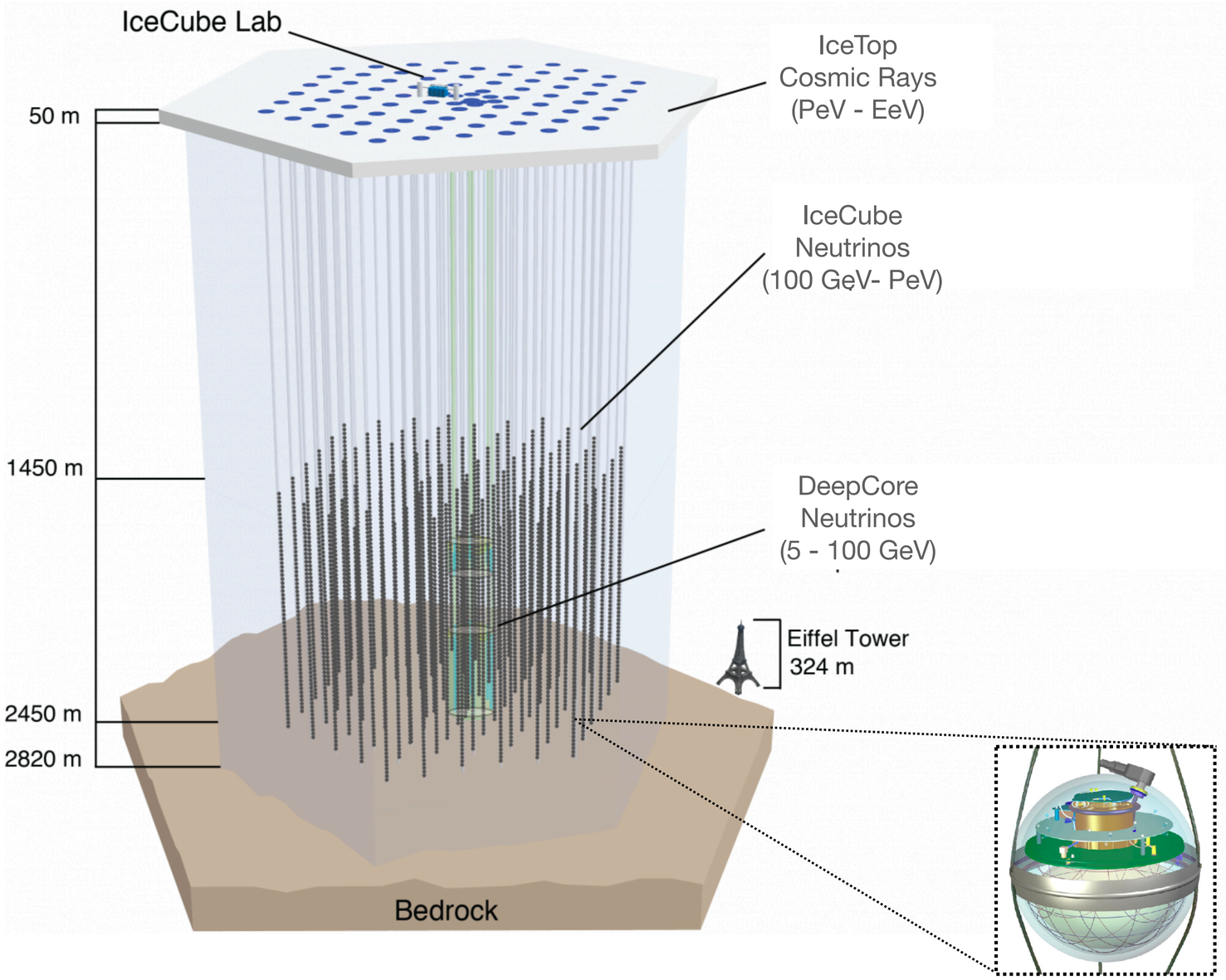
Recipe:

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

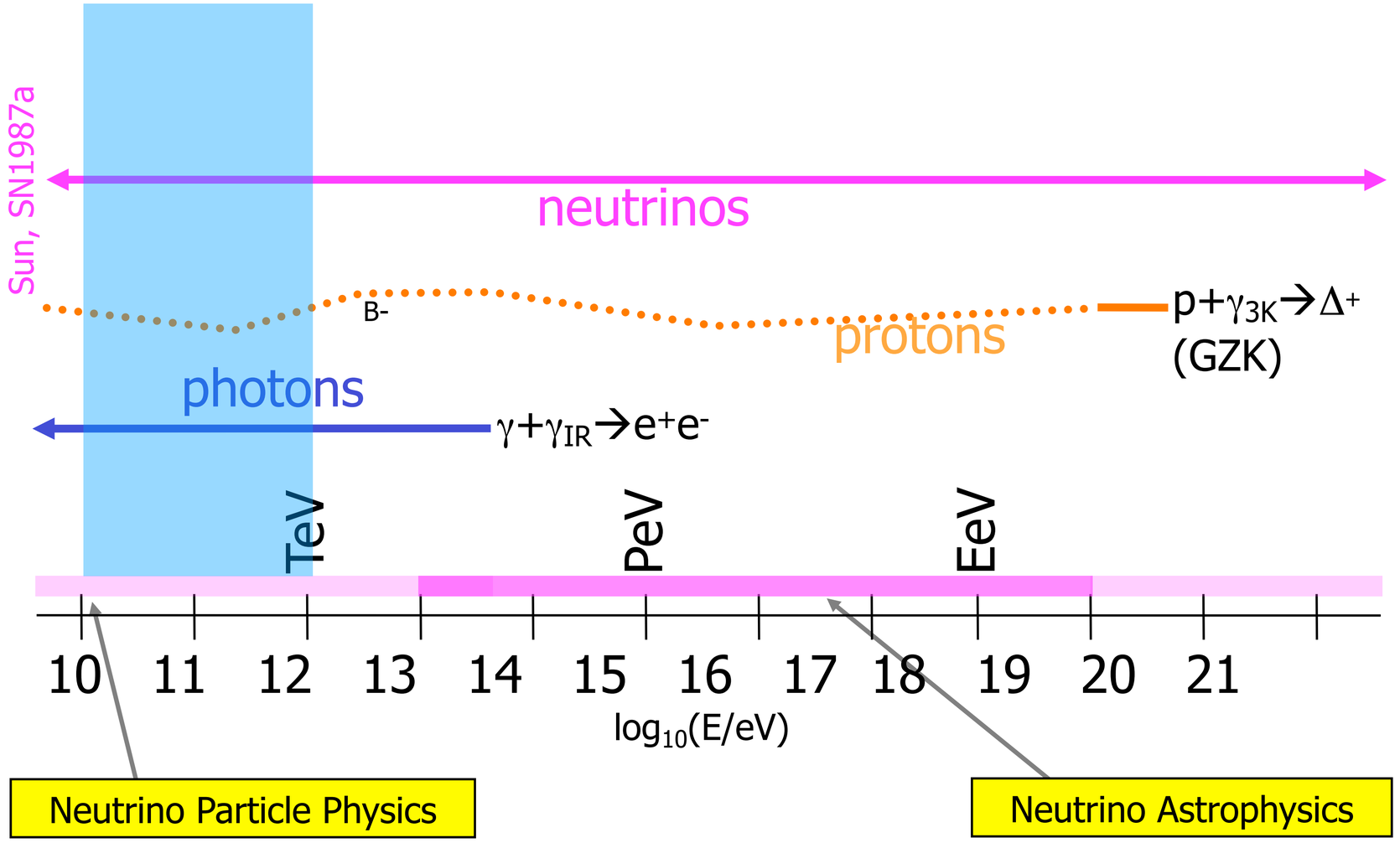
IceCube Neutrino Observatory

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



Cosmic messengers



Atmospheric neutrino oscillations

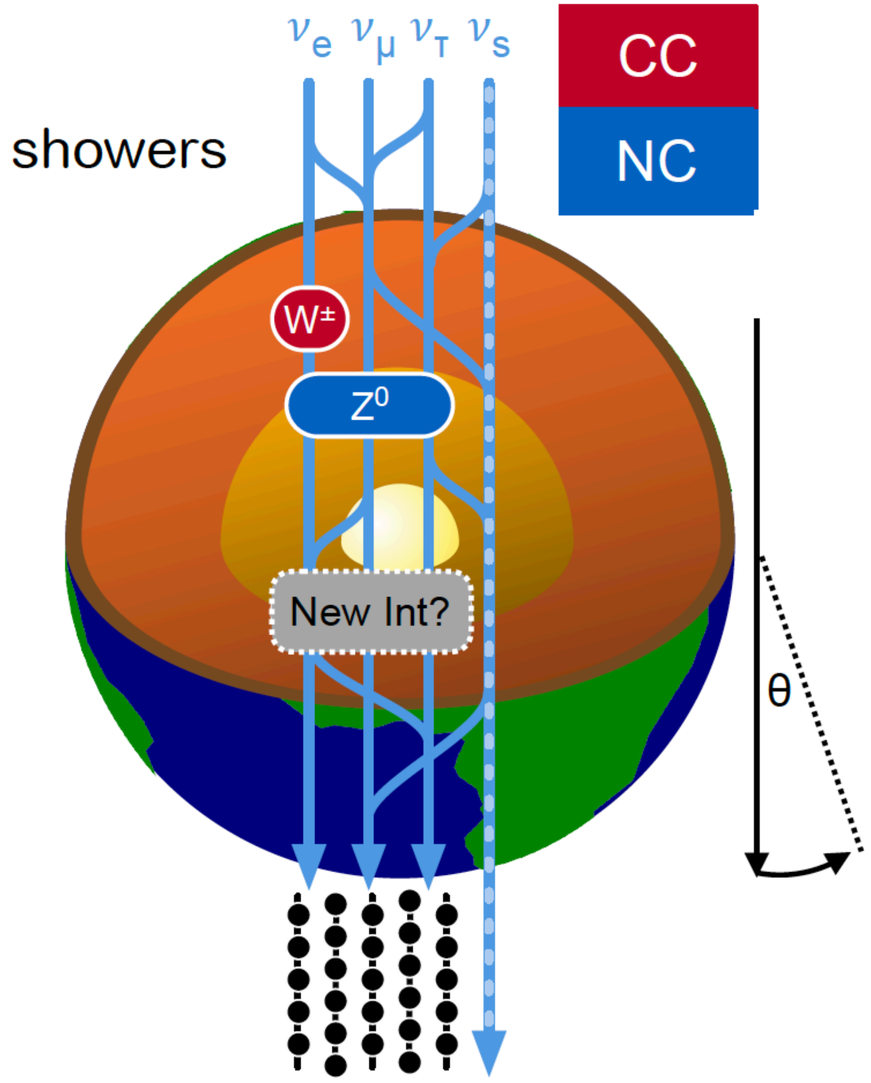
- Natural beam of neutrinos generated in cosmic ray air showers
  - All flavors, neutrino + antineutrino
  - Broad energy band (GeV - TeV) and baselines (20 - 12,700 km) through variable Earth density profile

Flavour Mass

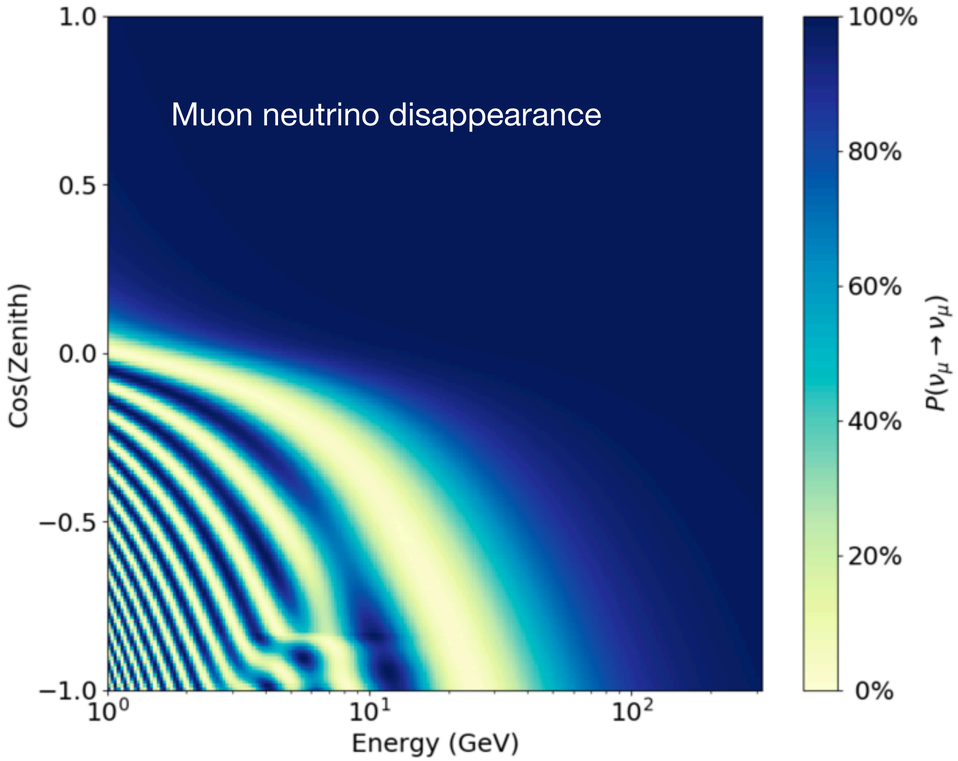
$|\nu_\alpha\rangle = \sum U^*_{\alpha k} |\nu_k\rangle$

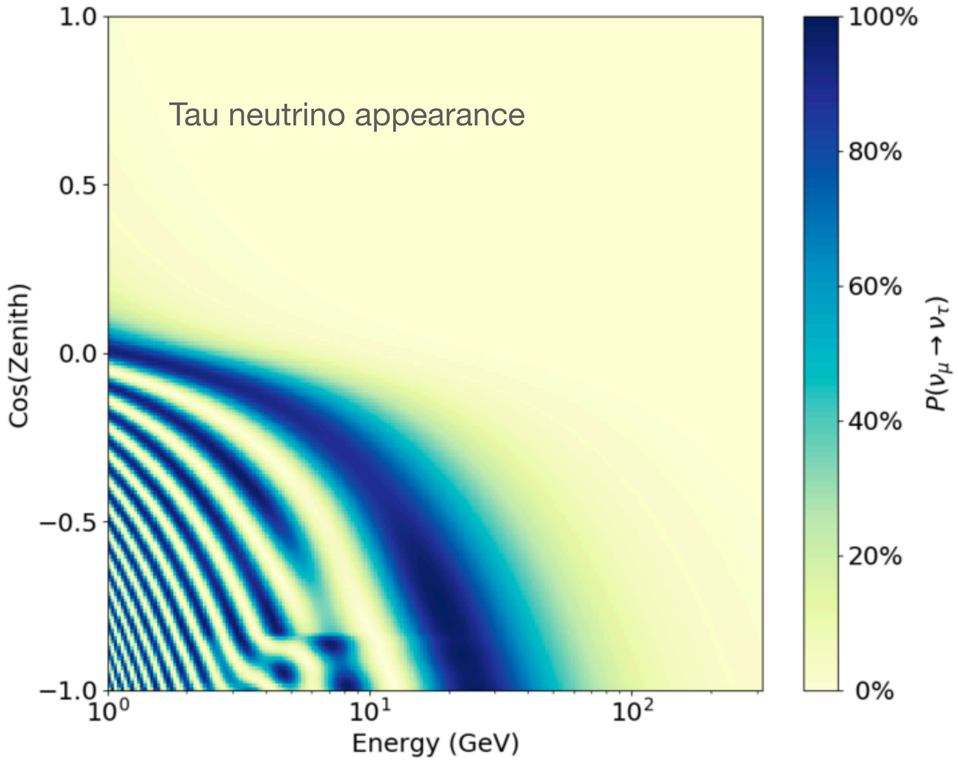
U_{PMNS} parameterised by…
- Three mixing angles: θ_{12}, θ_{13}, θ_{23}
- δCP

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

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

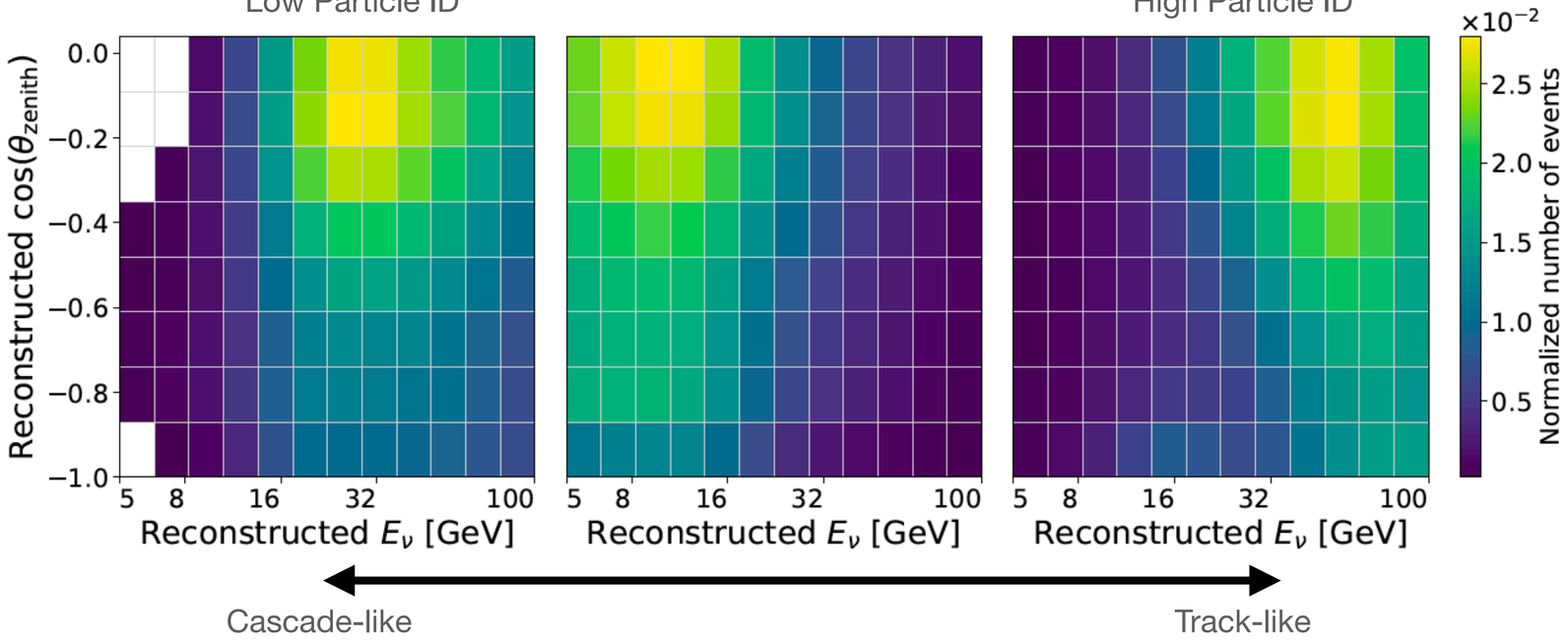
- Applies convolutional neural networks reconstruction (factor 5000 speed-up with consistent resolutions)

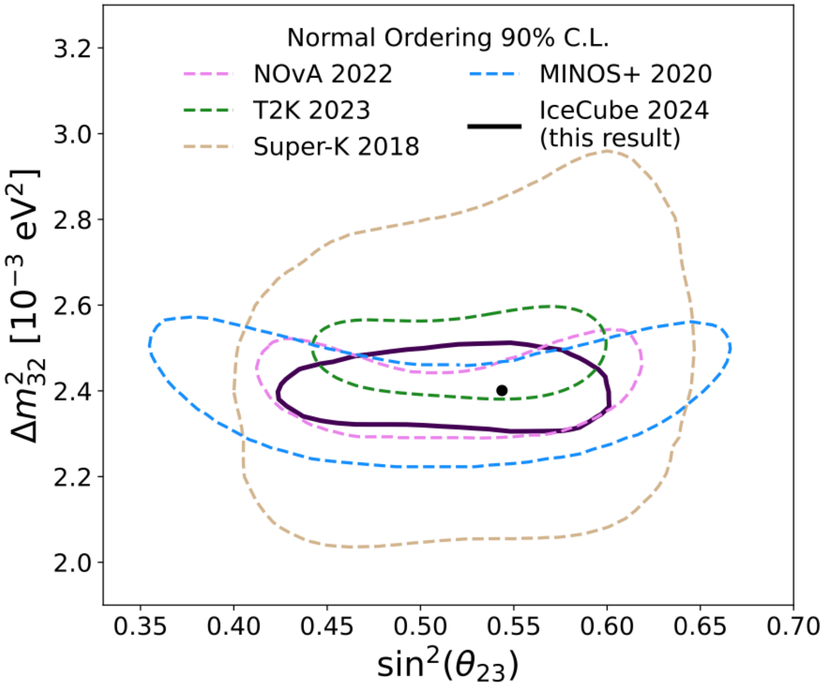
- Incorporates latest detector systematics updates (calibration, flux, cross-section).

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

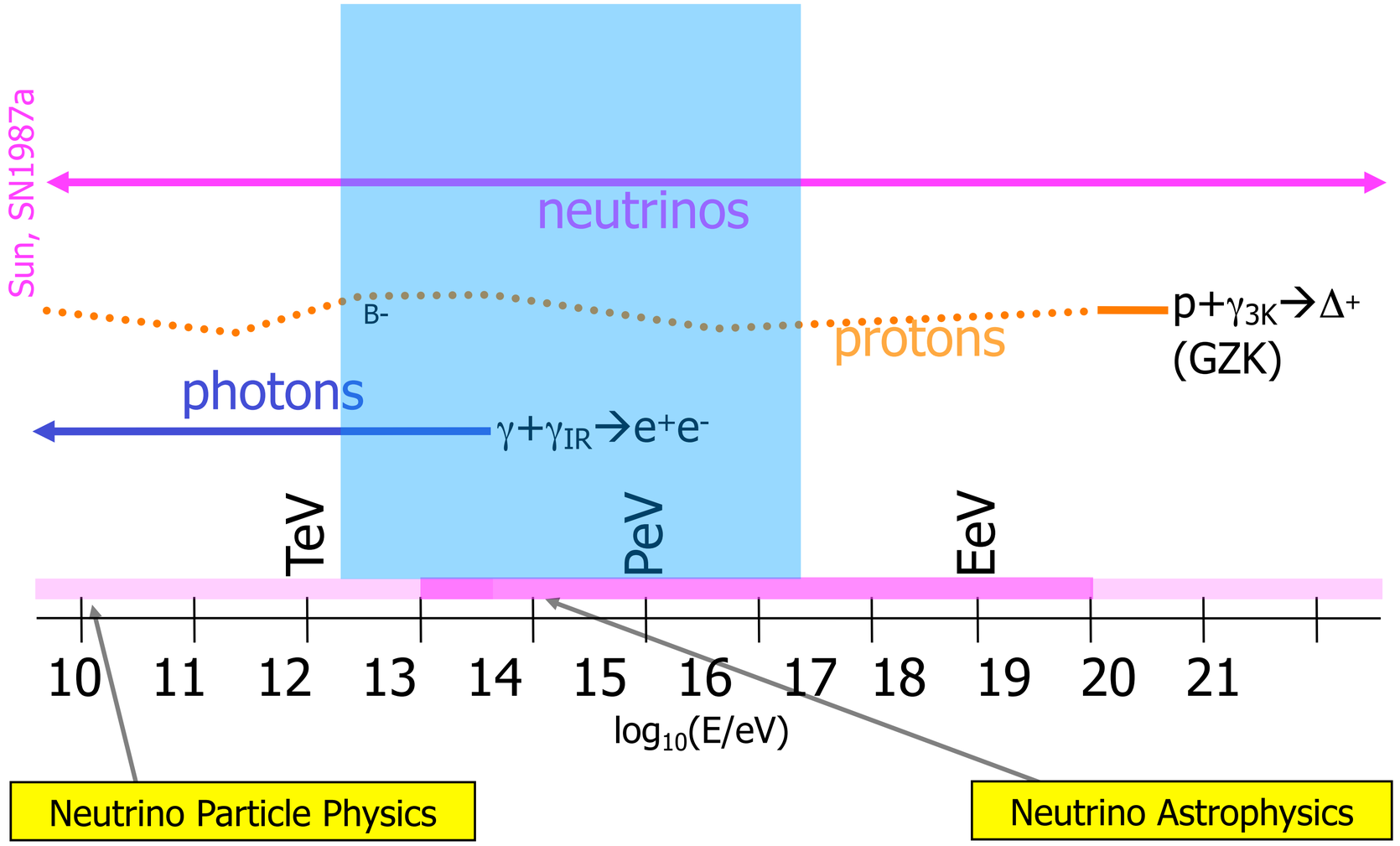
$$\Delta m^2_{32} = (2.40^{+0.05}_{-0.04}) \times 10^{-3}\ \text{eV}^2$$

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

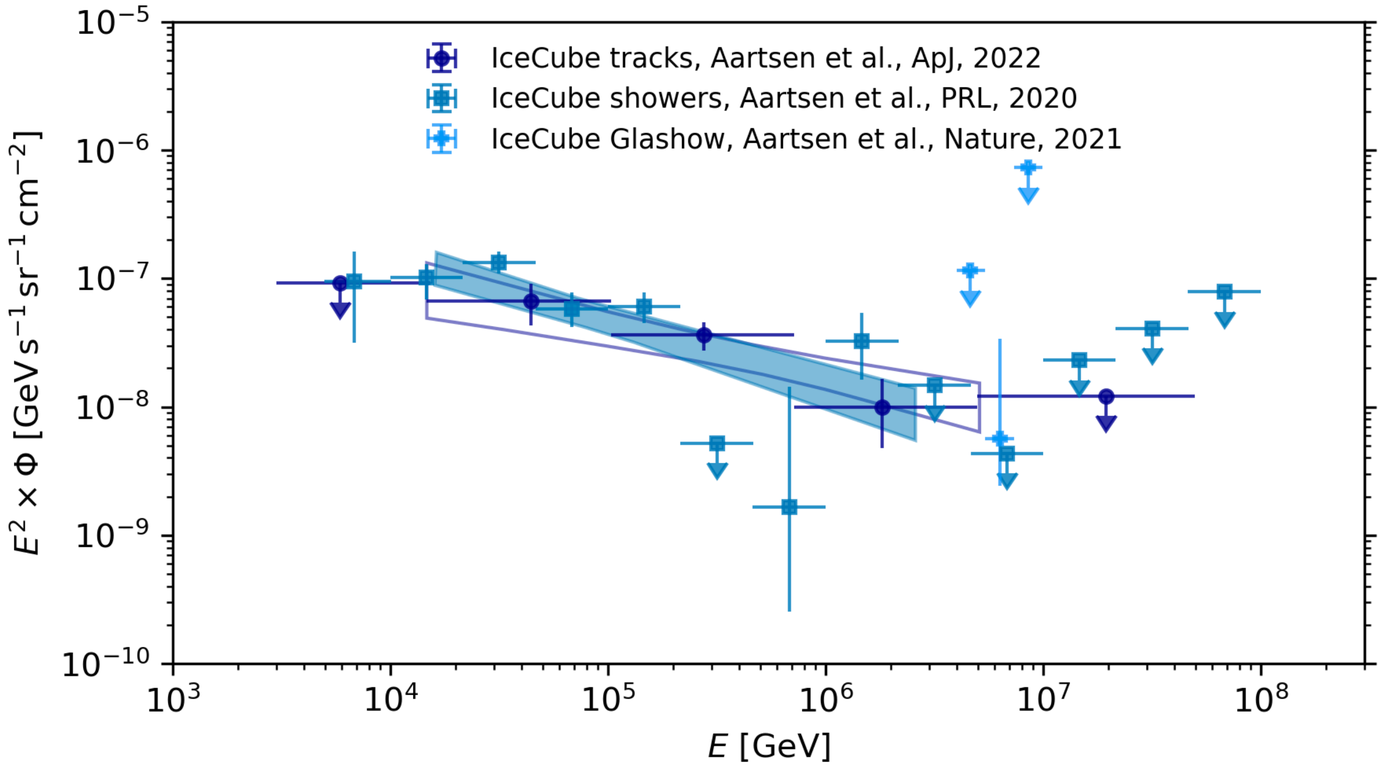




Cosmic messengers

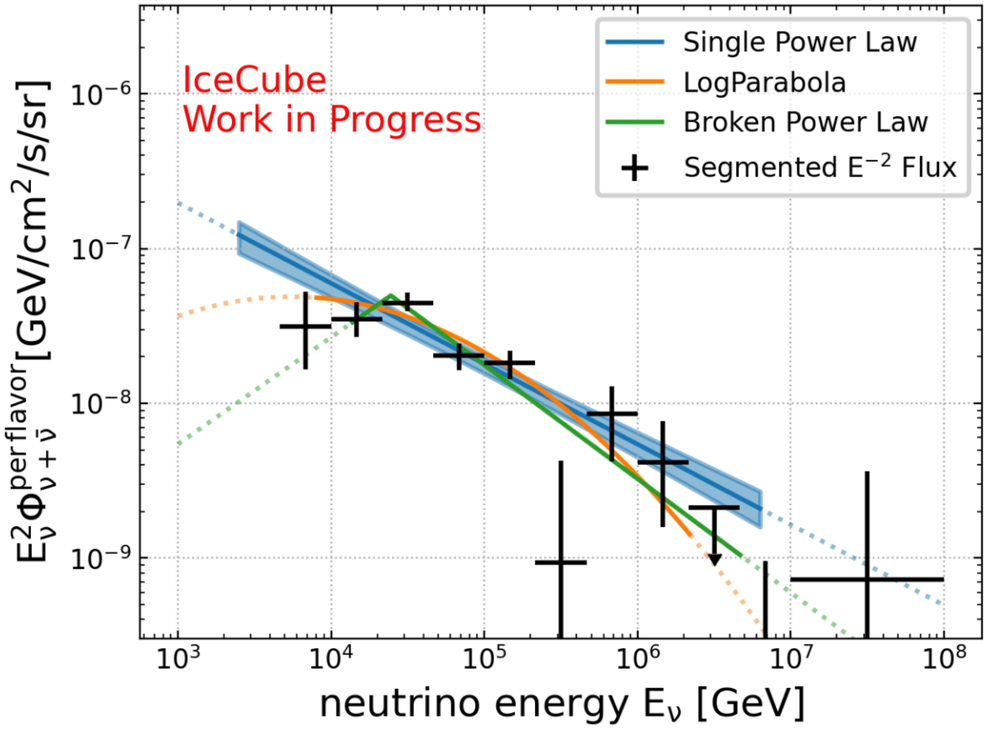


The high-energy astrophysical neutrino flux

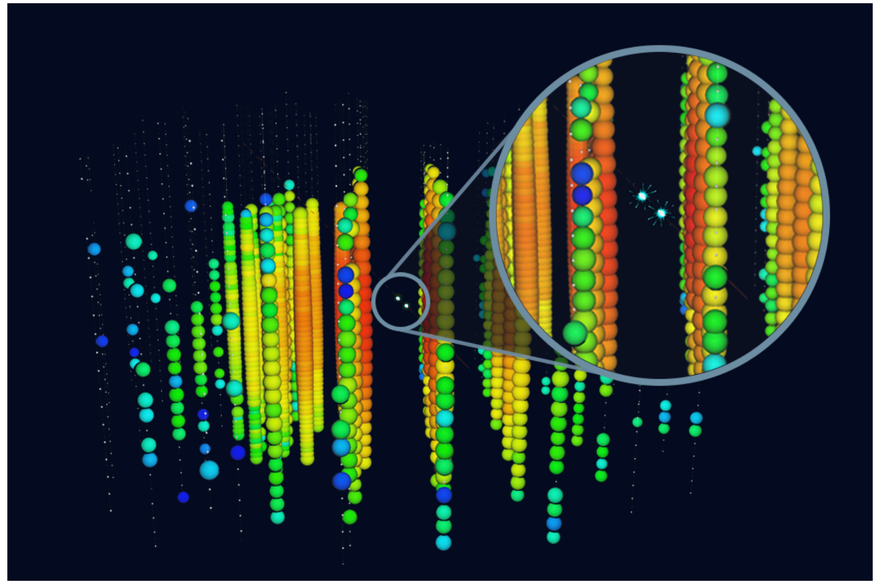


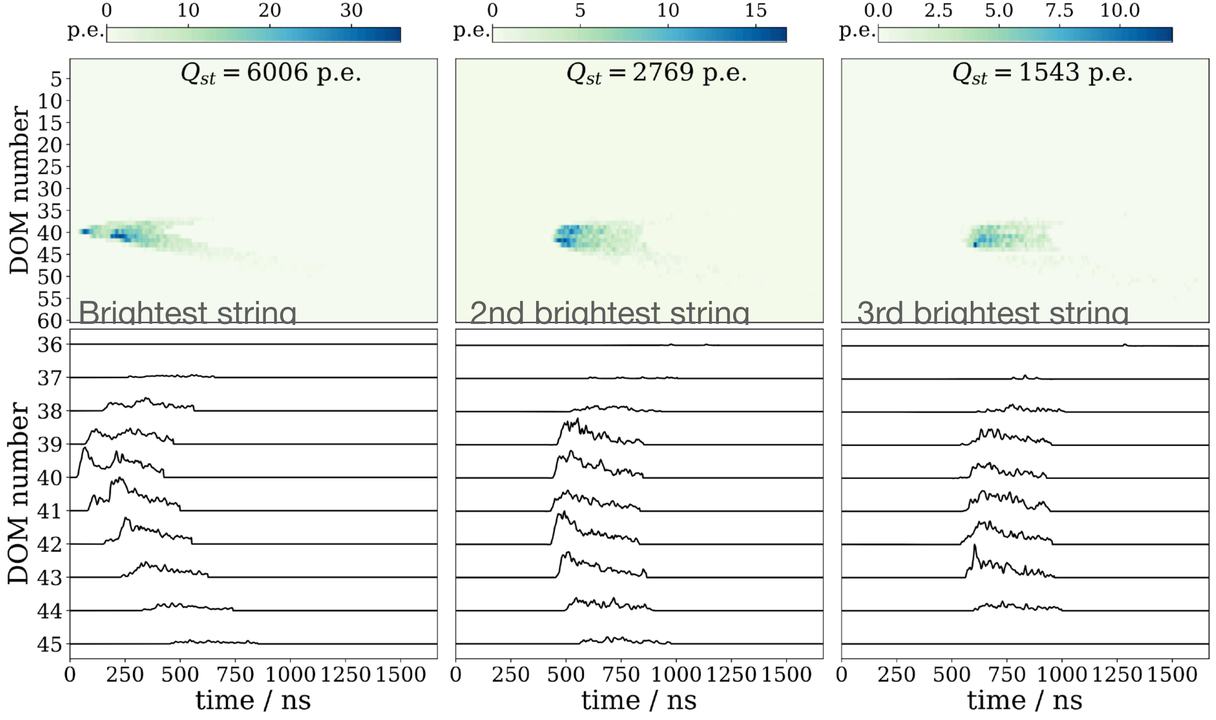
- Astrophysical neutrinos discovered by IceCube in 2013
- Spectrum now measured (multiple channels providing consistent picture) between few TeV - 10 PeV
- Primarily extragalactic origin of neutrinos

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



Evidence of astrophysical tau neutrinos

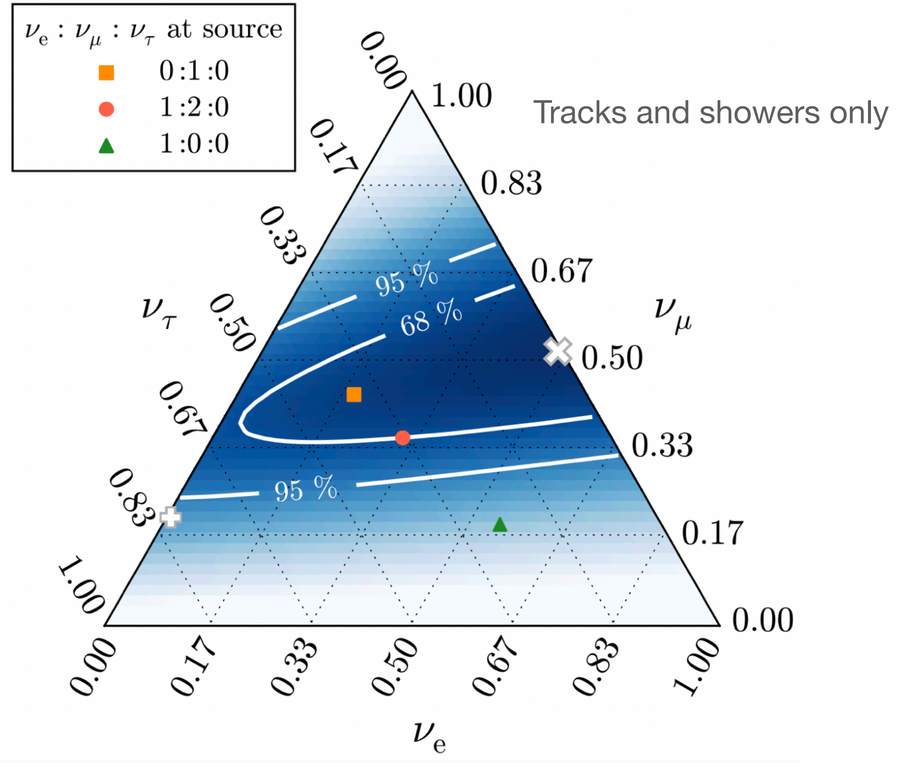




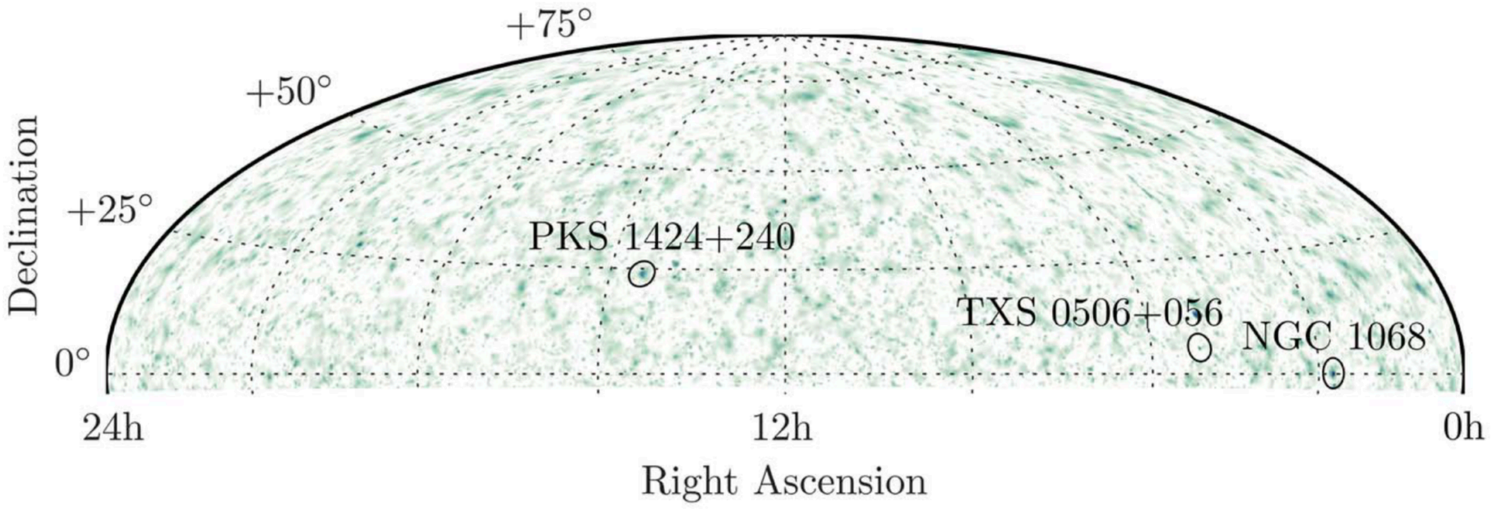
- Combined analysis of track and shower-type events provide strong constraints on the muon neutrino contribution

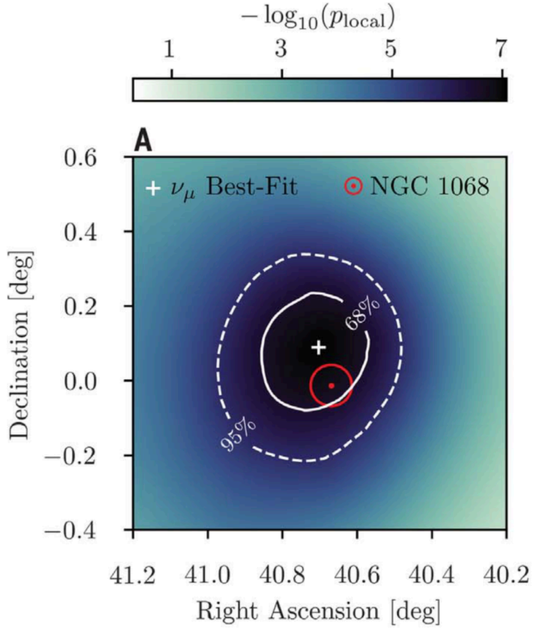
- 7 tau neutrino candidates identified using machine learning techniques

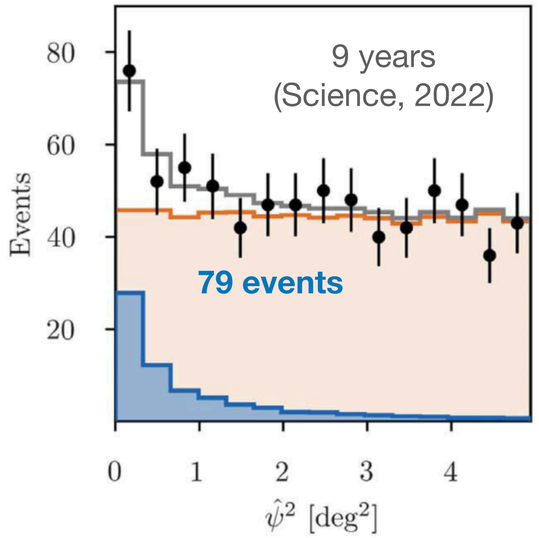
- Identification of tau neutrino events breaks degeneracy between electron neutrino and tau neutrino showers



Emerging extragalactic sources



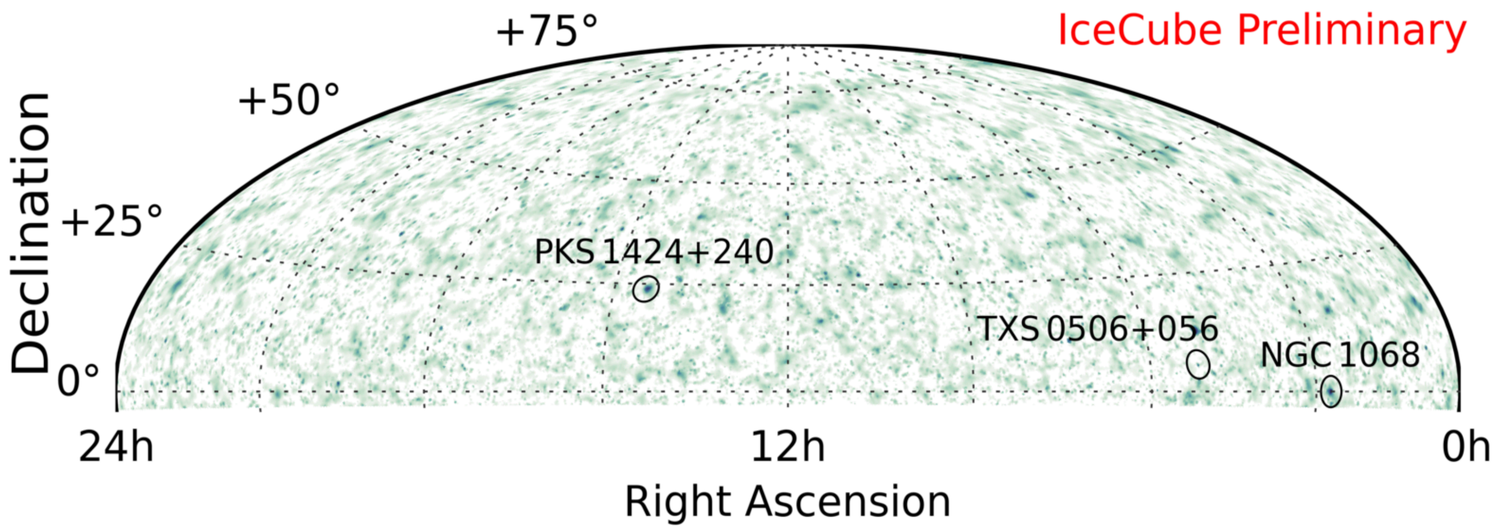


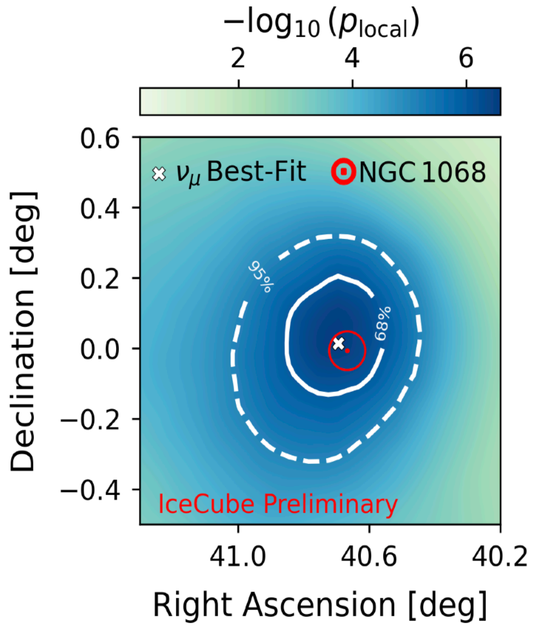


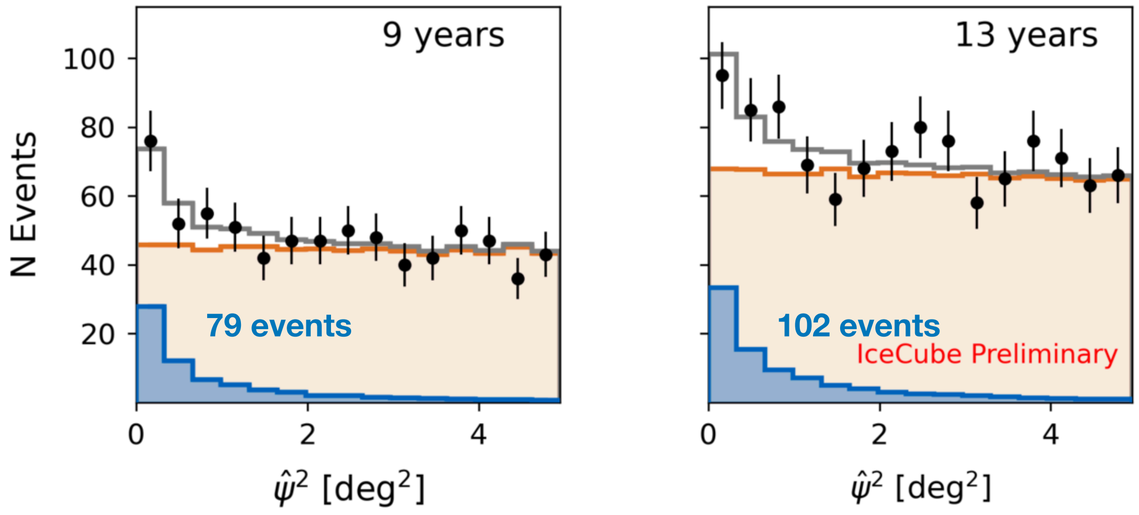
- Largest excess of events on the northern hemisphere consistent with position of NGC 1068; local significant 5.2 sigma and post trial correction for look-elsewhere (110 pre-defined candidates) 4.2 sigma.

- Two other blazers observed at greater than 3 sigma

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

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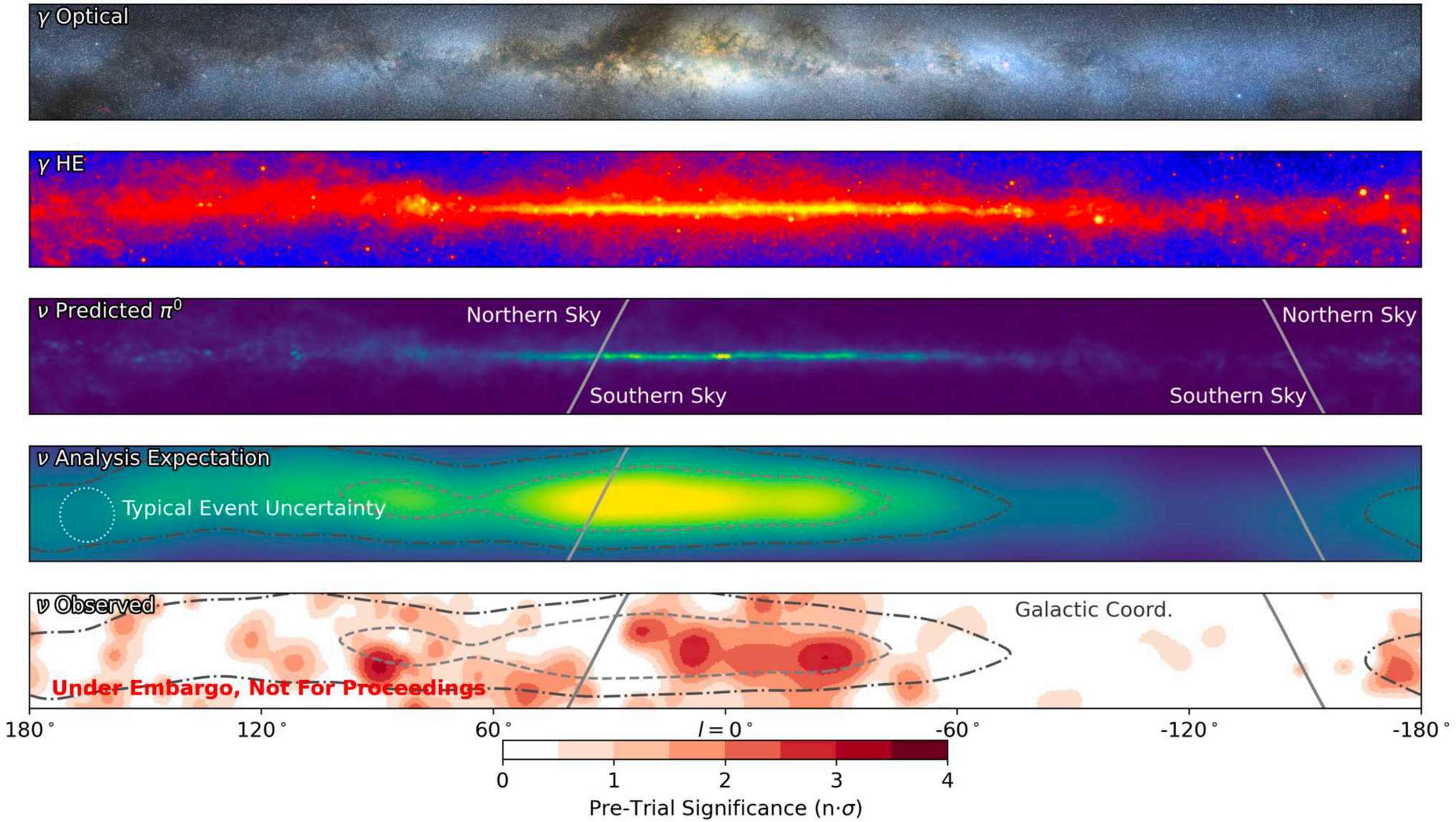
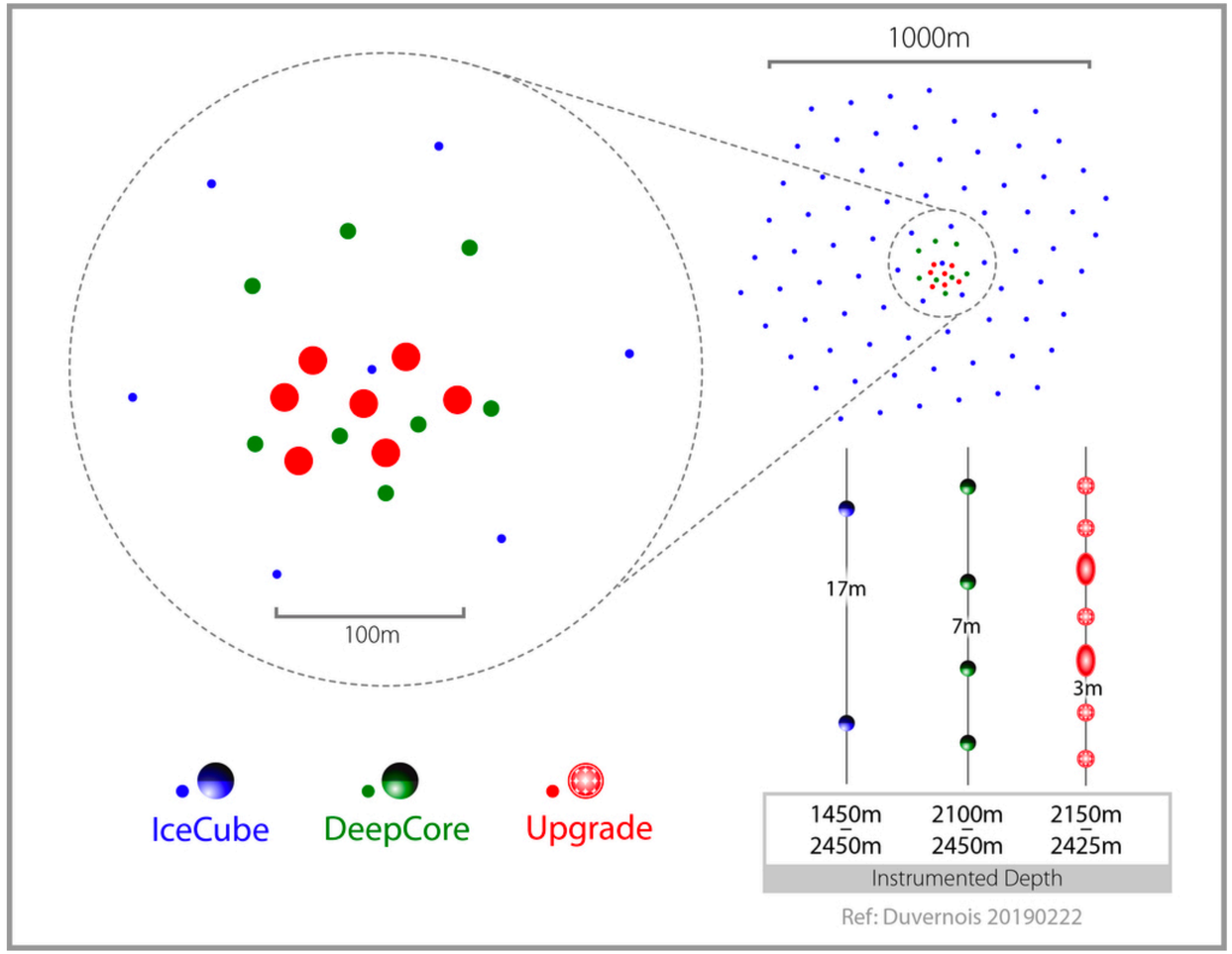


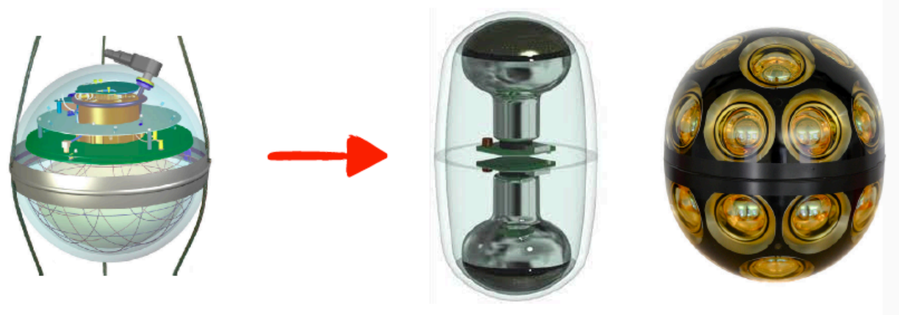
Neutrinos from the Milky Way for the first time (4.5 sigma post trial); No individual sources yet observed at high significance due to current limits in angular resolution and statistics. Small fraction of the total observed diffuse flux.

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

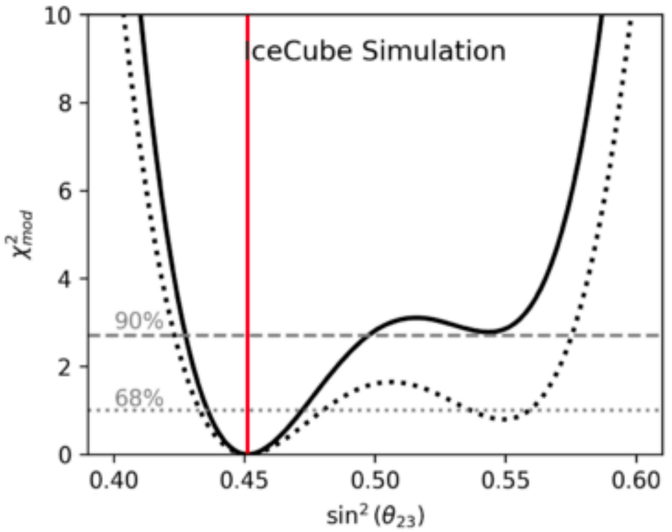
- More than 800 next generation modules and precision calibration devices
- Reduced inter-module spacing
- Deep-ice deployment to 2600 m

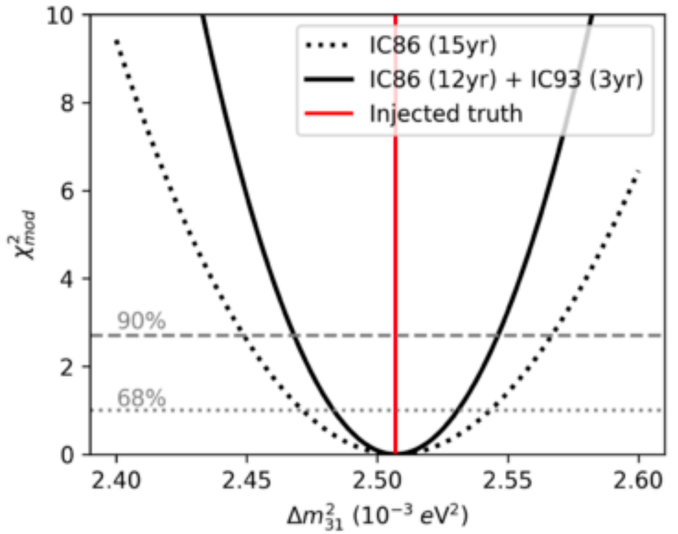


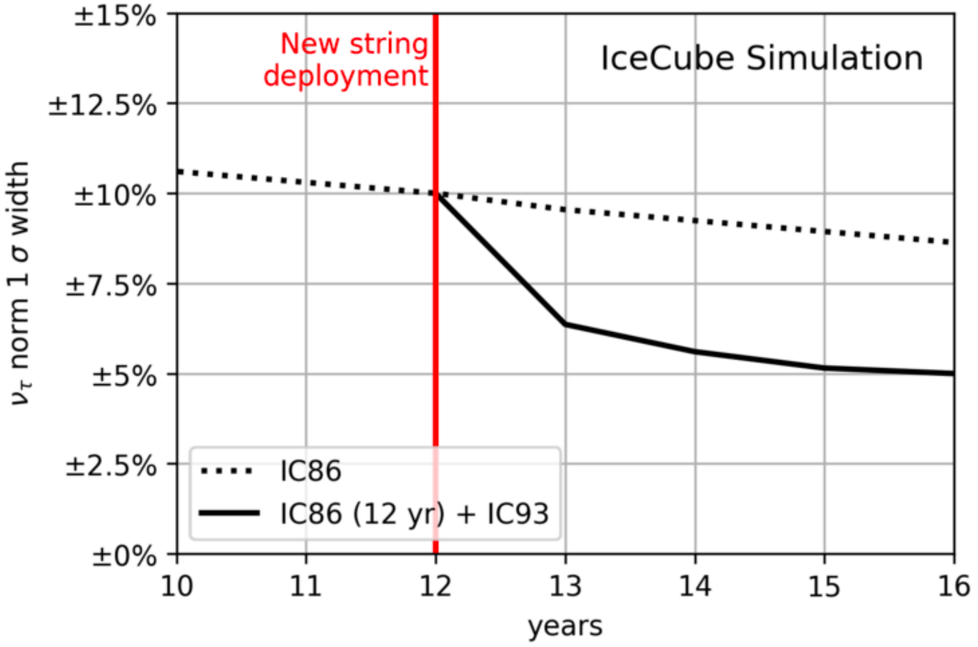


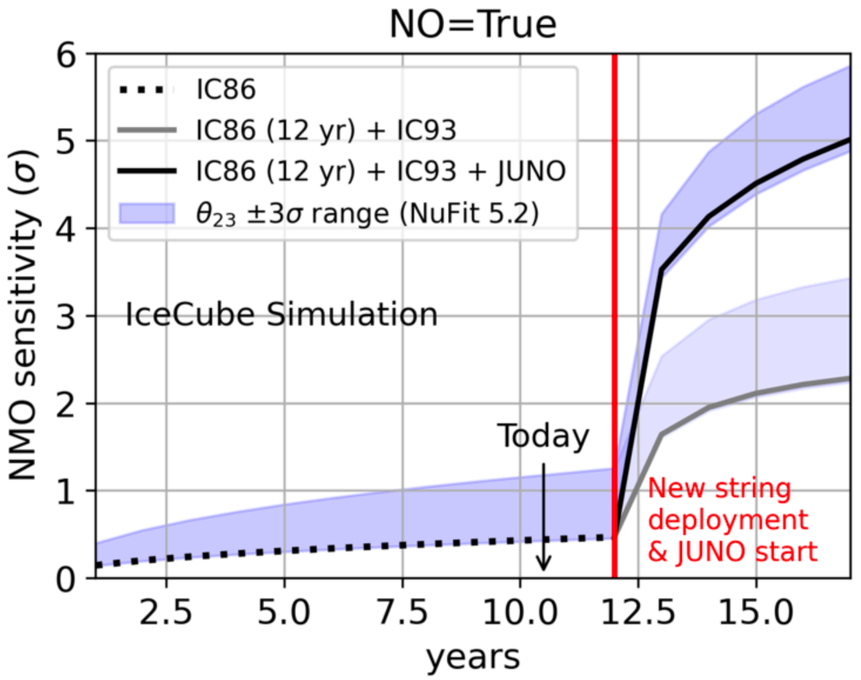
Future directions - IceCube Upgrade

- 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)

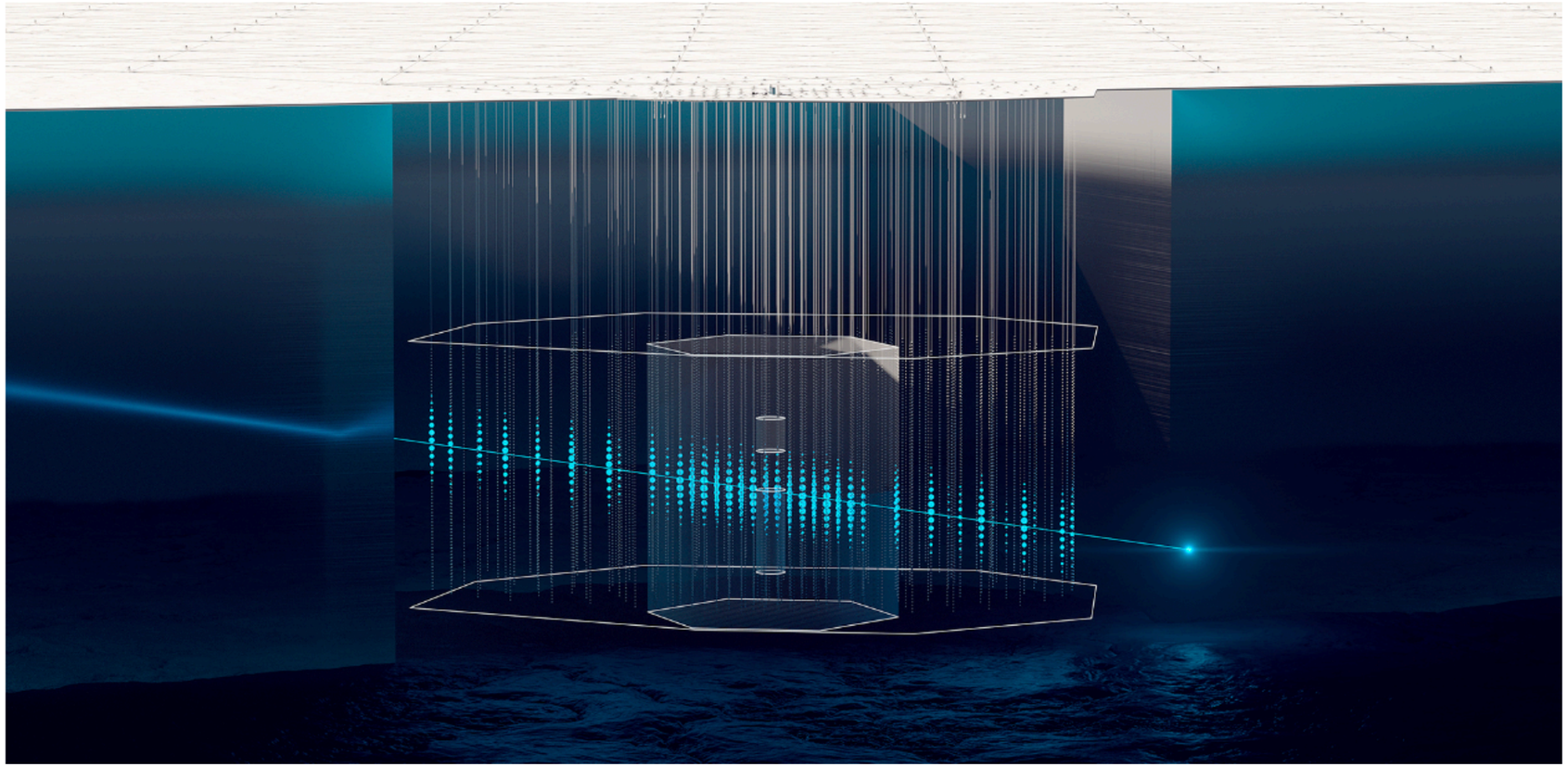




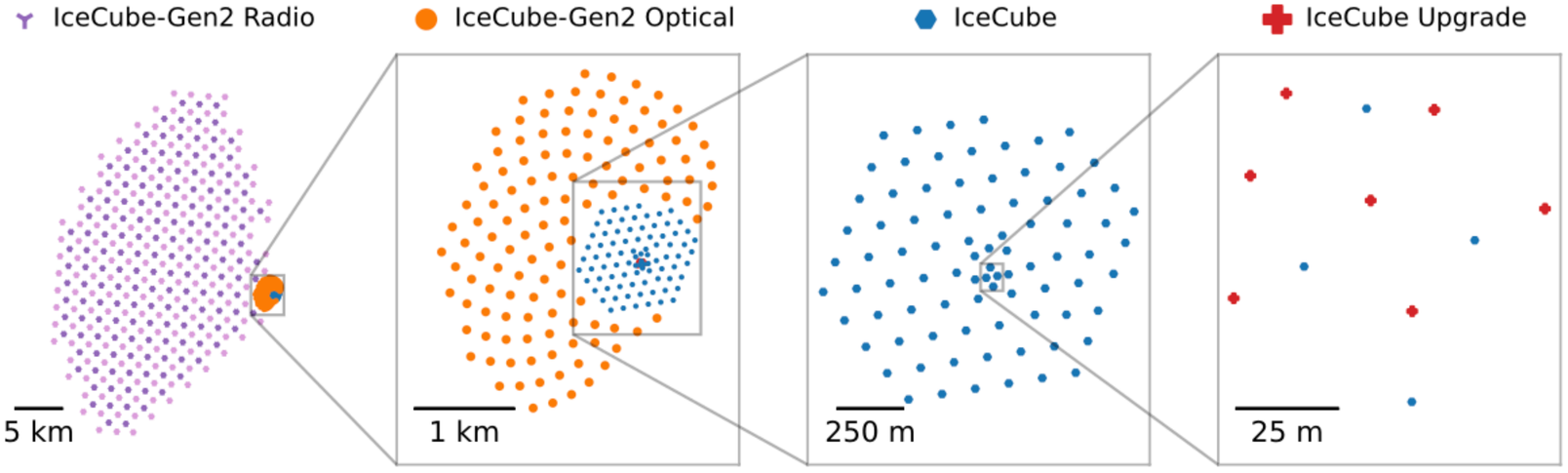


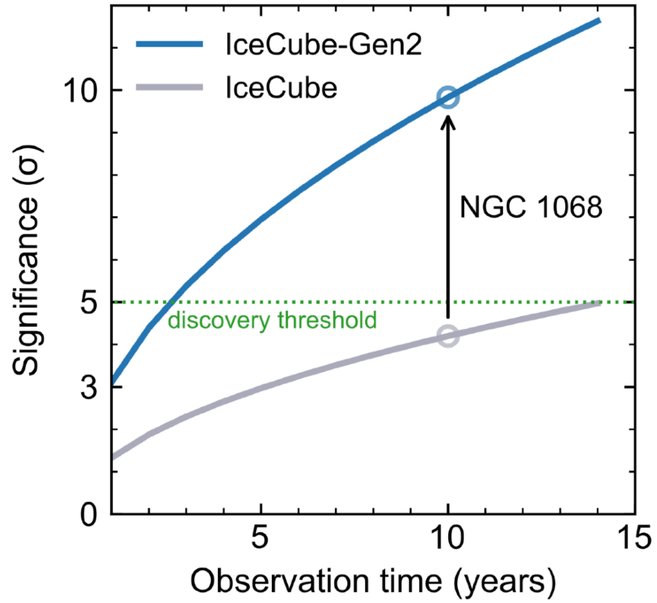


Future directions - IceCube Gen2



- 8x increased instrumented volume
- 5x increased sensitivity to neutrino sources compared to current IceCube
- 500 square-km array designed for radio detection of > 100 PeV neutrinos
- Surface array above optical array footprint designed for cosmic ray science





Summary

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

High-energy neutrinos continue to be an excellent probe of physics beyond the Standard Model

the nearly 15-years of dataset provides the world's largest sample of atmospheric neutrinos, providing leading sensitivity to standard and non-standard neutrino oscillations, indirect dark matter searches, …

Discovered high-energy cosmic neutrino flux is robust

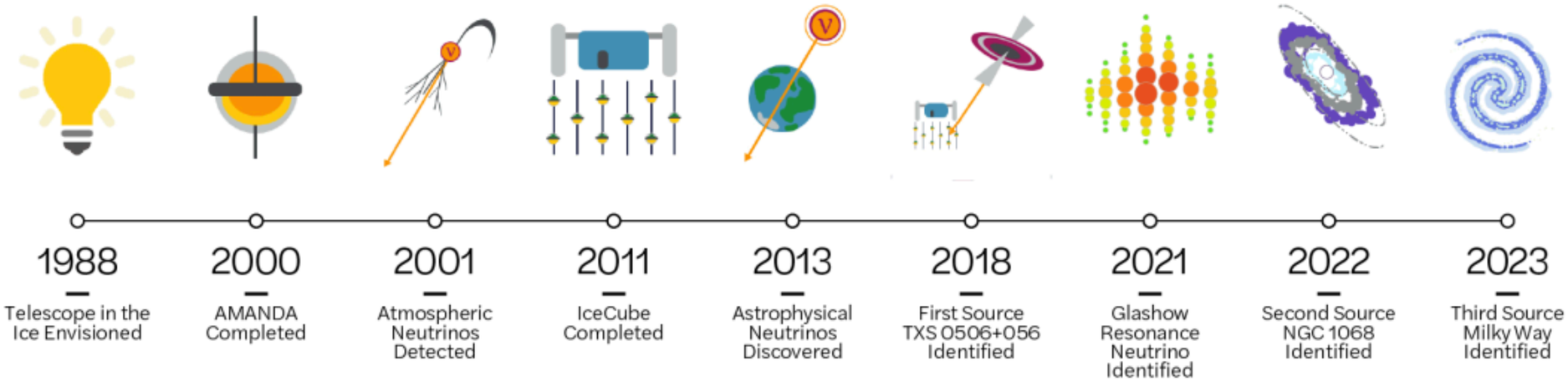
energy density similar to that of gamma rays and cosmic rays

mounting evidence emerging of the first extragalactic and Galactic sources

Mature EDI and Outreach programs continue to evolve and grow

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



Backup slides