Recent Results from the IceCube Neutrino Observatory

Jeff Lazar ***on behalf of the IceCube Collaboration***

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Invisibles 2024

Bologna, Italy

Intro to IceCube: What We See and What It Tells Us
Recent Results: Highlights across Energies
Future Directions and Opportunities

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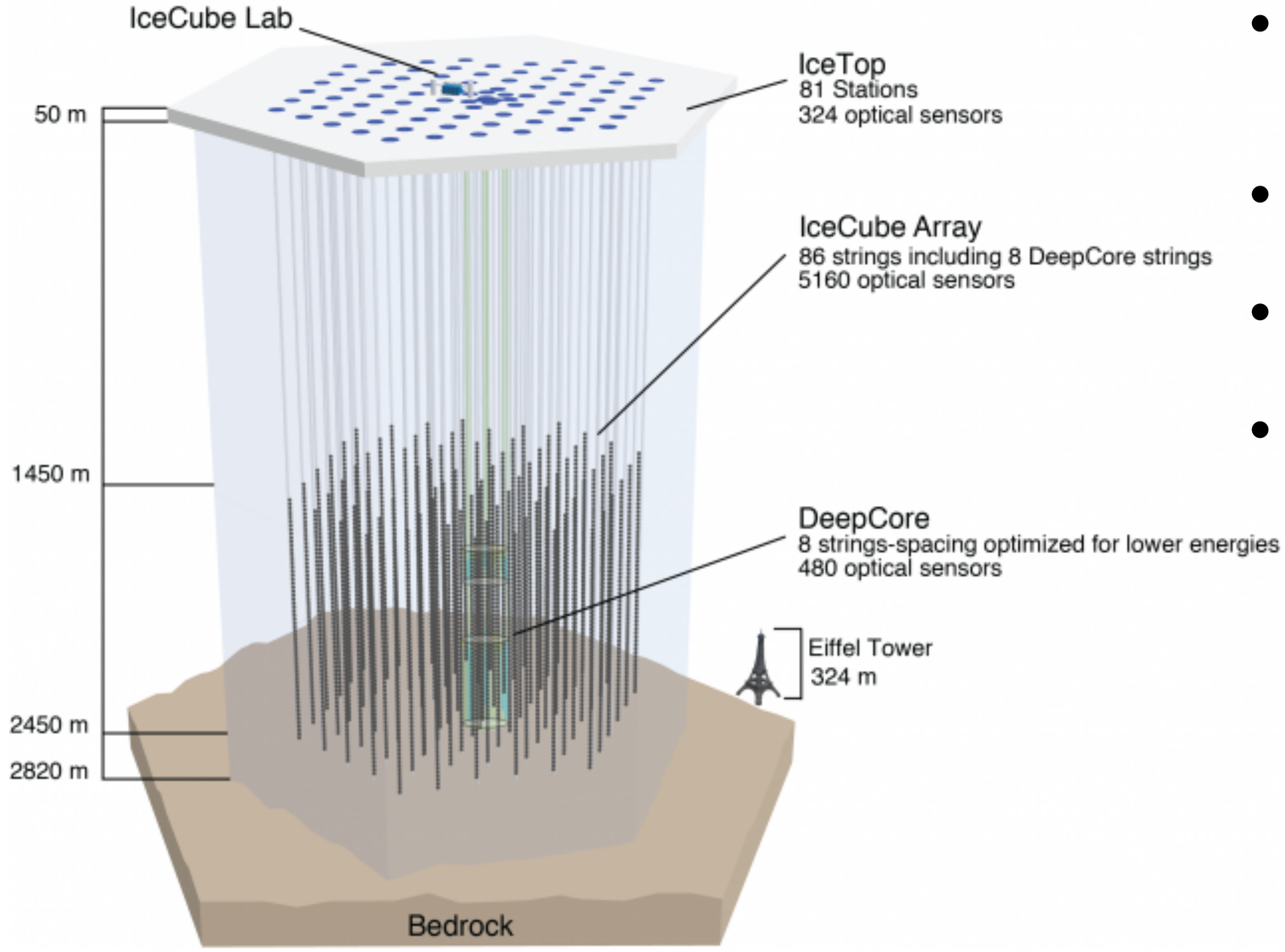
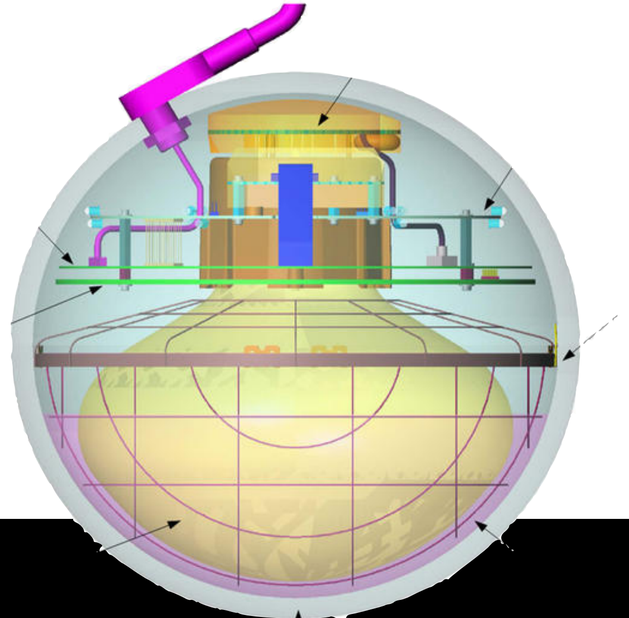
Recent Results: Highlights across Energies

Future Directions and Opportunities

The IceCube Neutrino Observatory



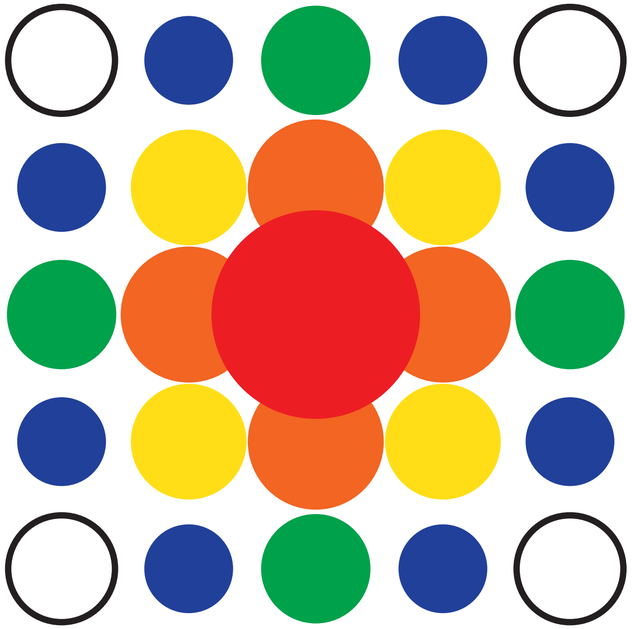
- 5,160 digital optical modules (DOMs) detect light from charged by-products of neutrino interactions
- 86 strings including 6 denser DeepCore strings
- In-ice array complemented by 86-station IceTop surface array
- Completed in December 2010 with near constant uptime since



In-Ice Signatures

Cascades

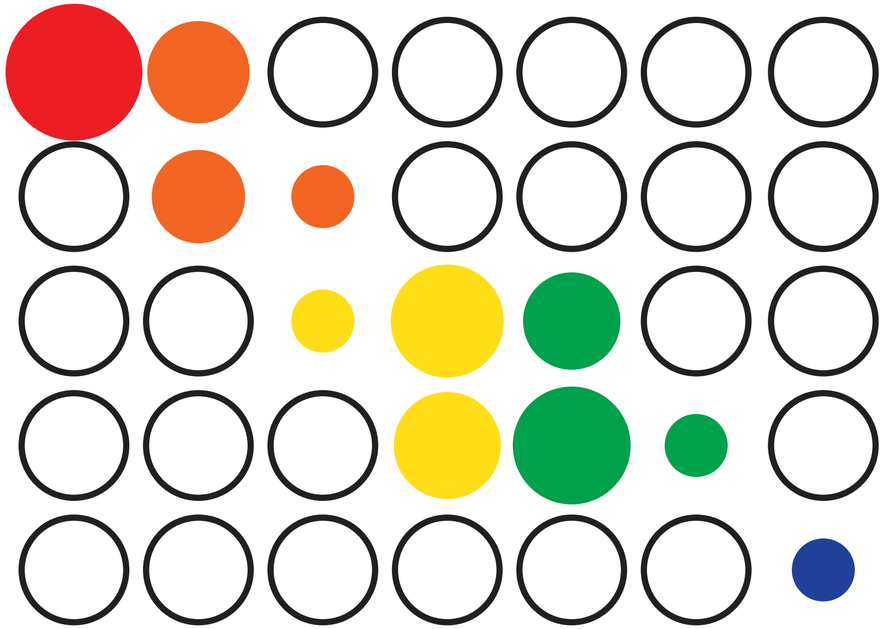
ν_e CC | ν_α NC



Great energy resolution, but angular reconstruction is challenging

Tracks

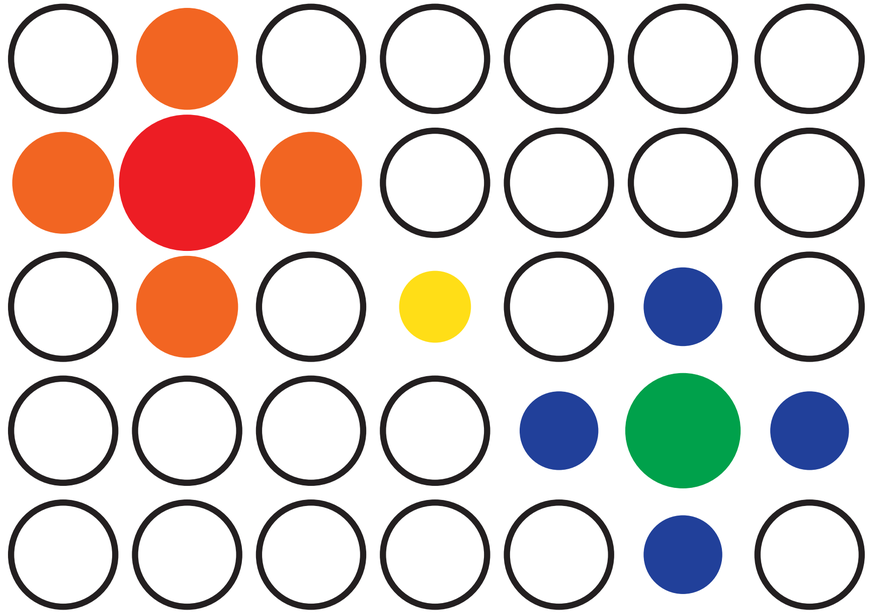
ν_μ CC



Great directional resolution, but deposited energy not proportional to E_ν

Double bangs

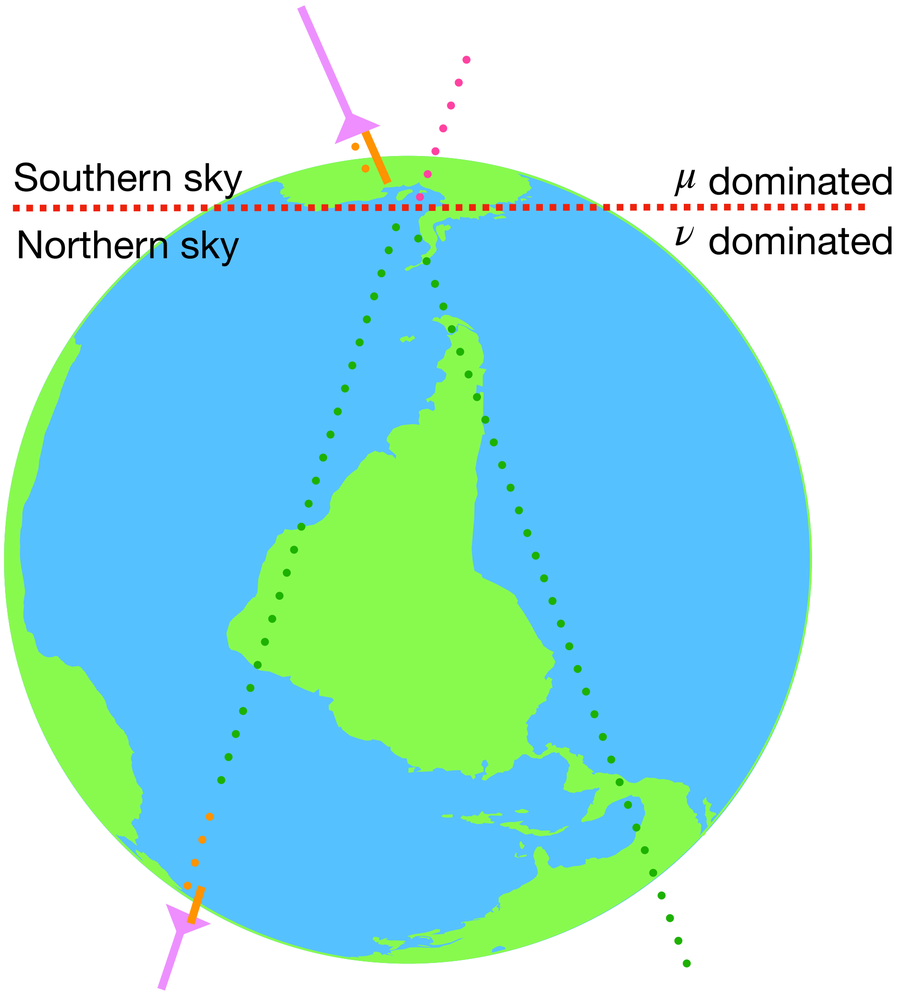
ν_τ CC



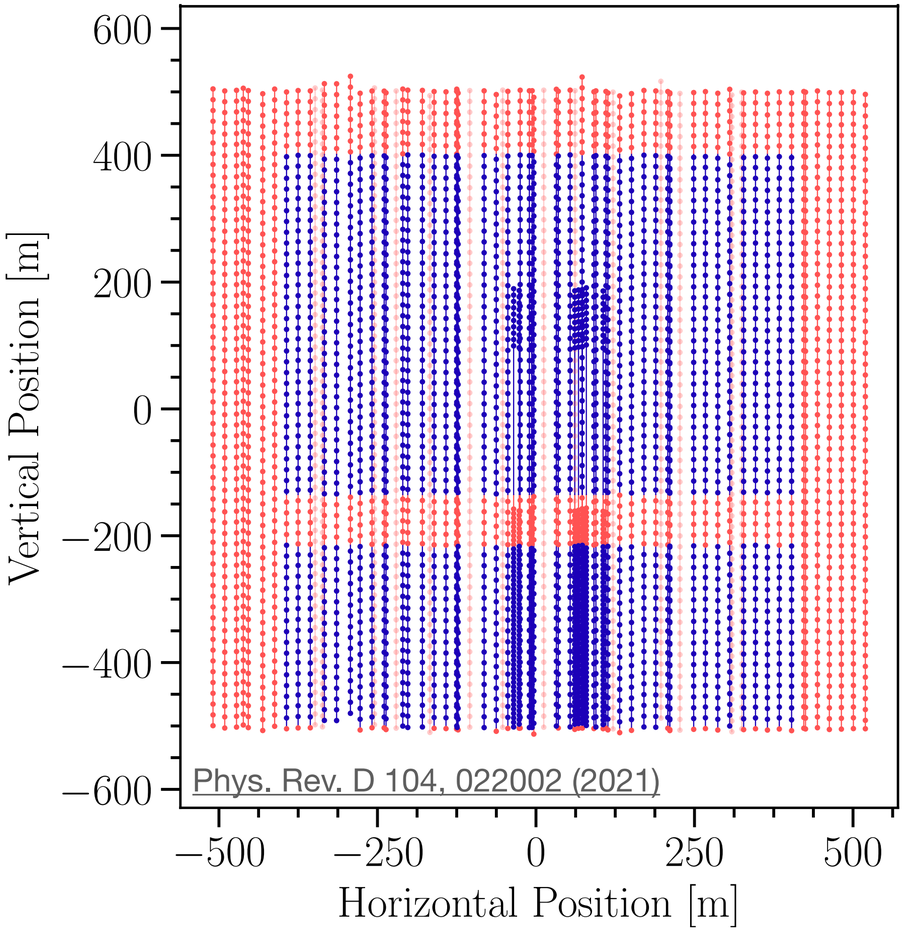
Signature of ν_τ CC events

Hunting for Needles in a Haystack

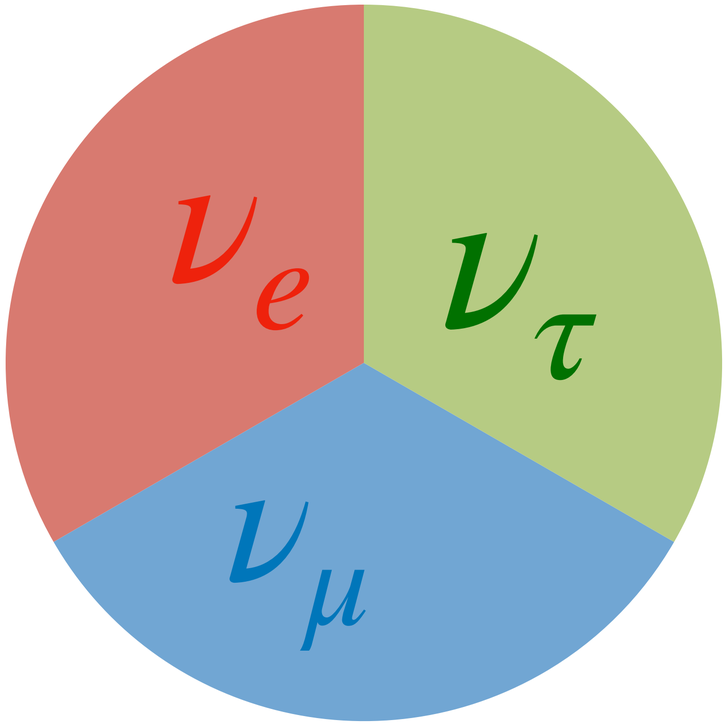
1. Look through the Earth to filter muons from the Southern sky

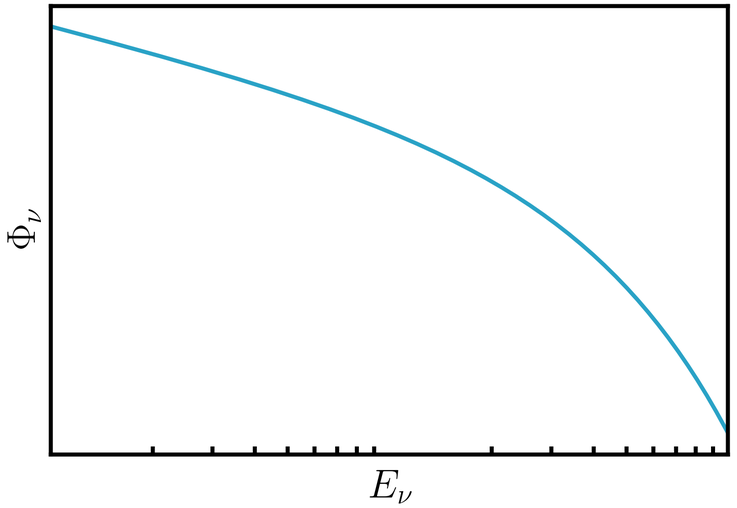


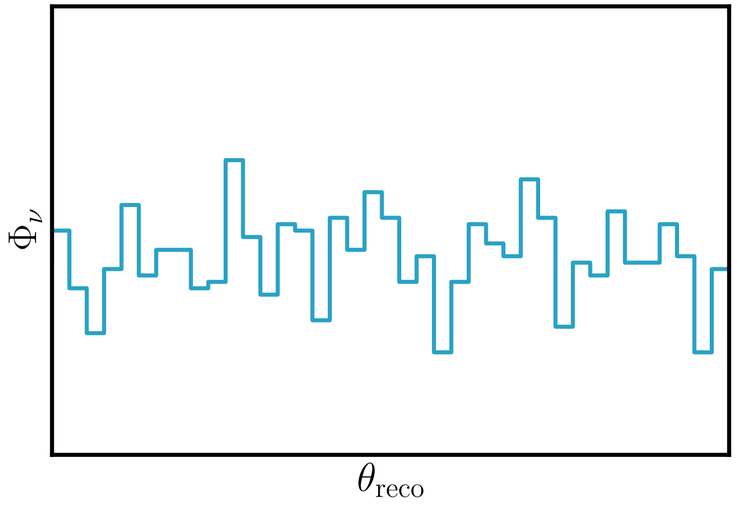
2. Use the outer layers of the detector as veto regions



Quantities of Interest







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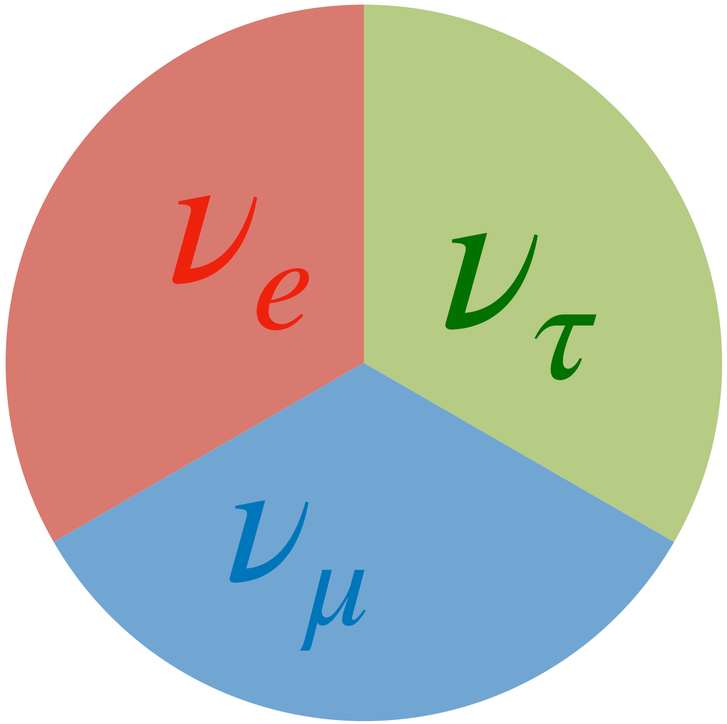

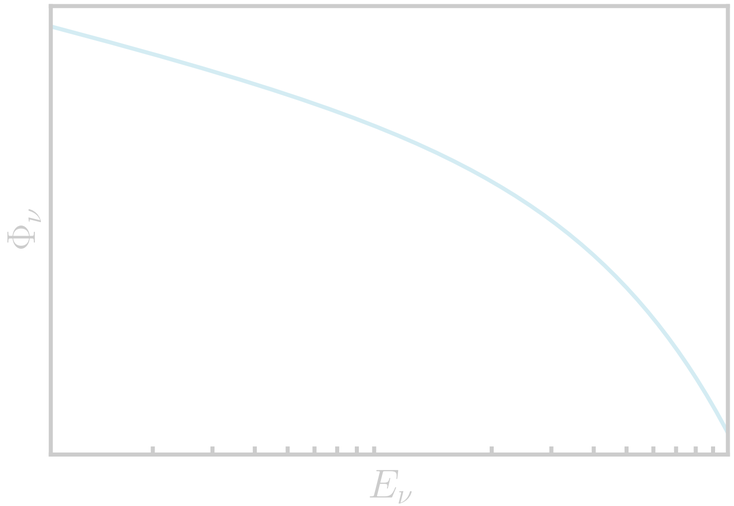

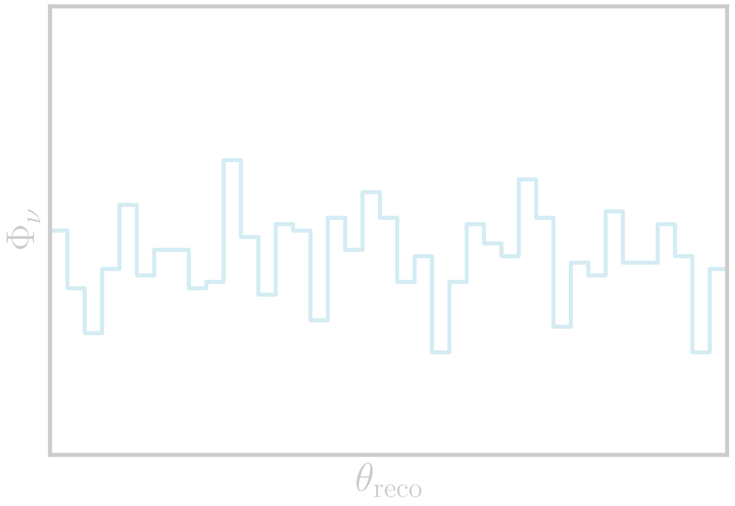

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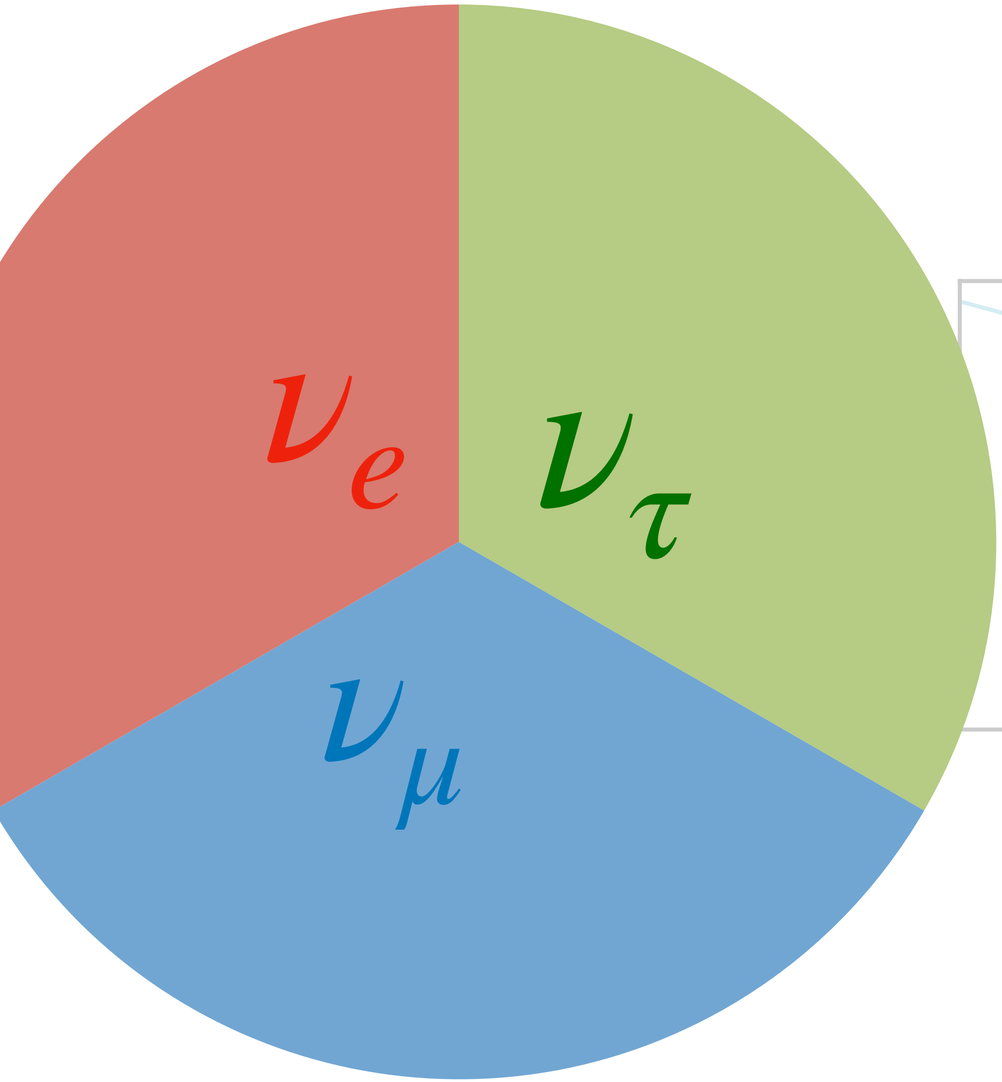

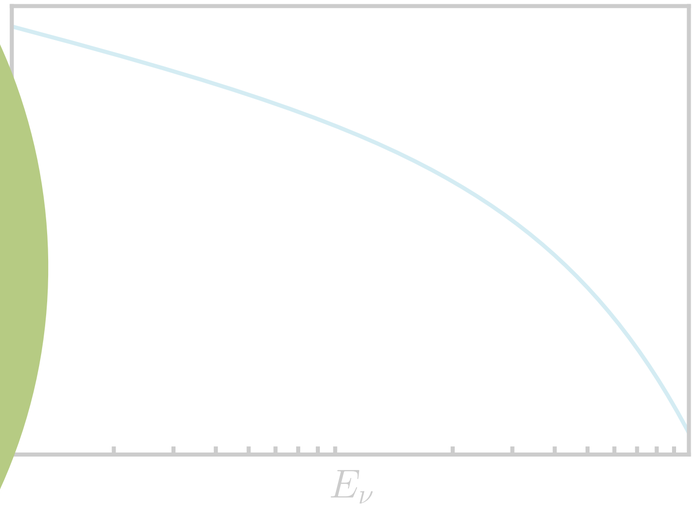

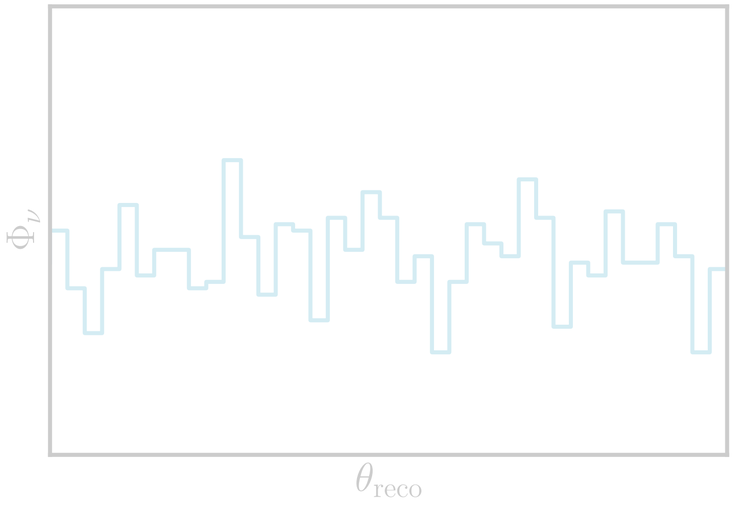

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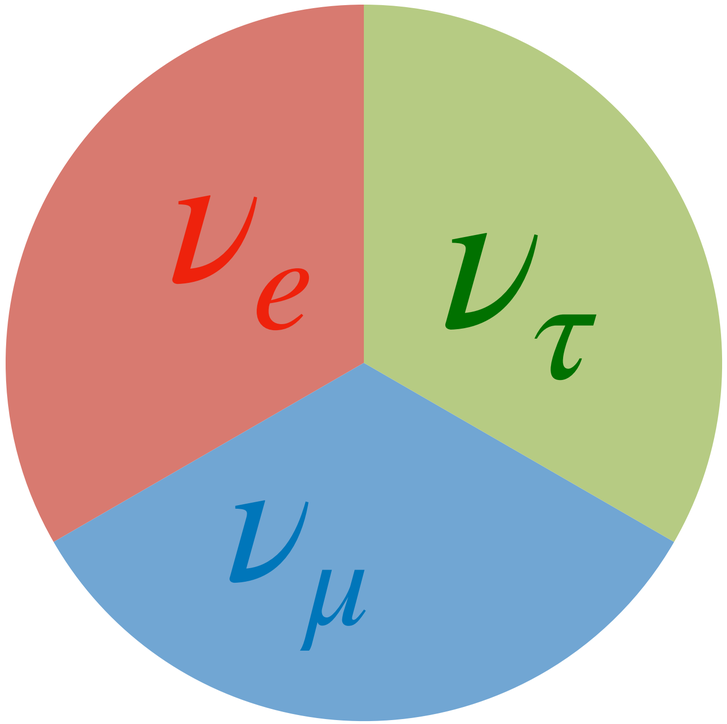

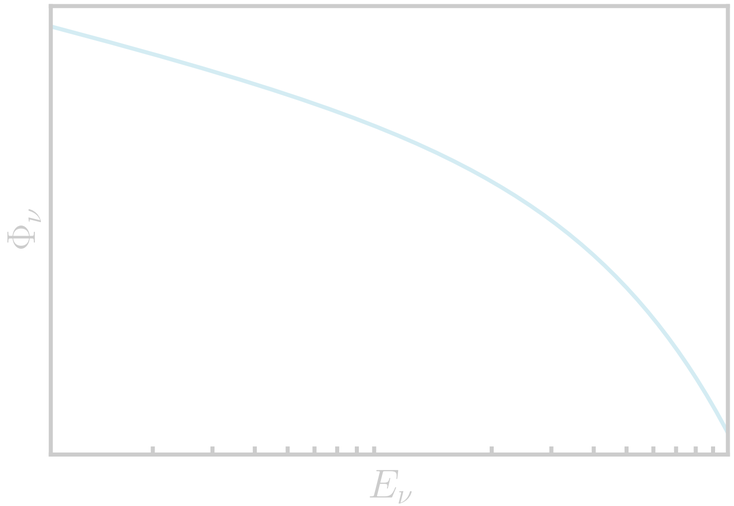

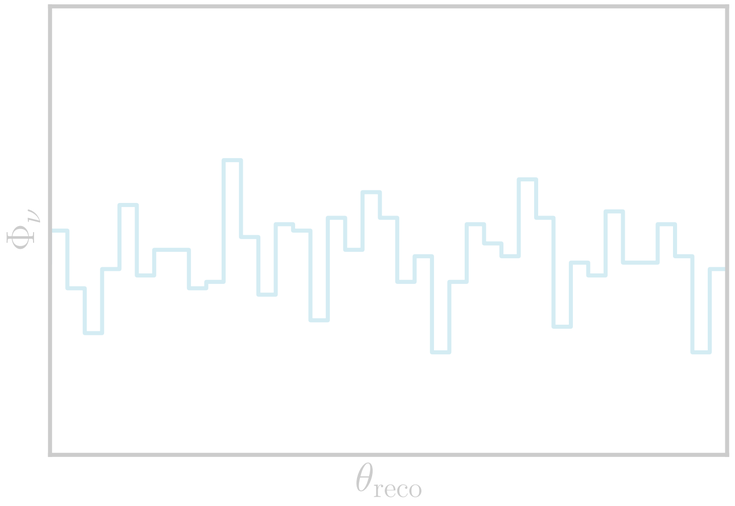

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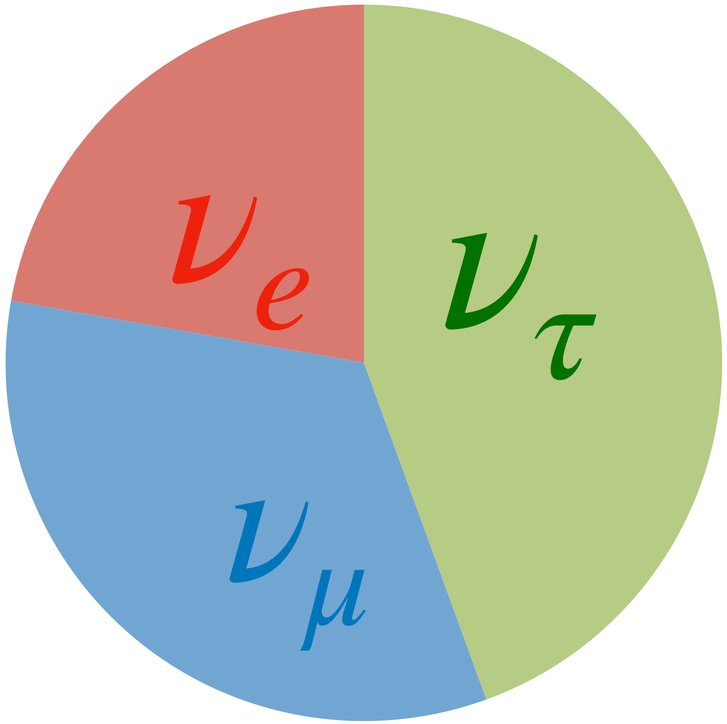

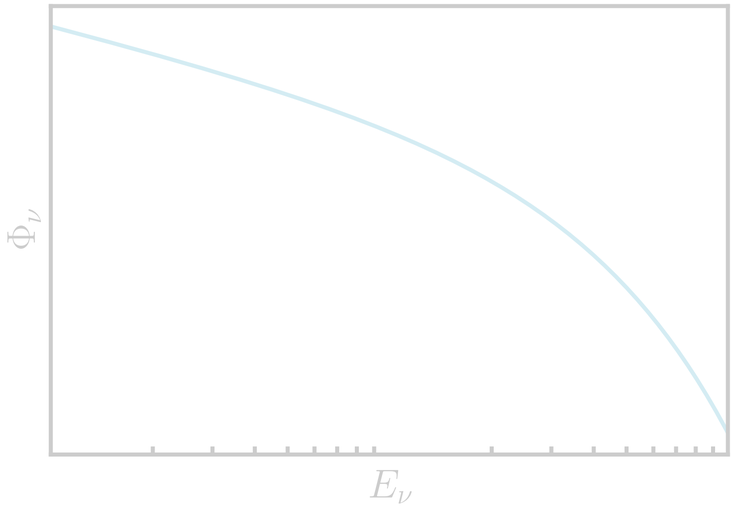

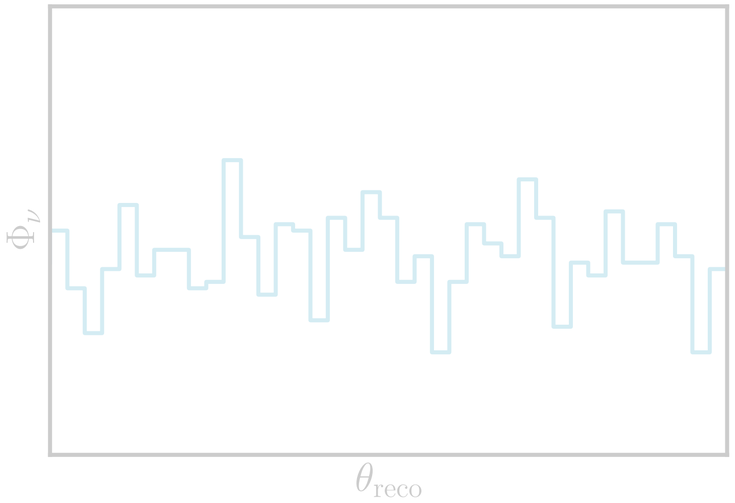

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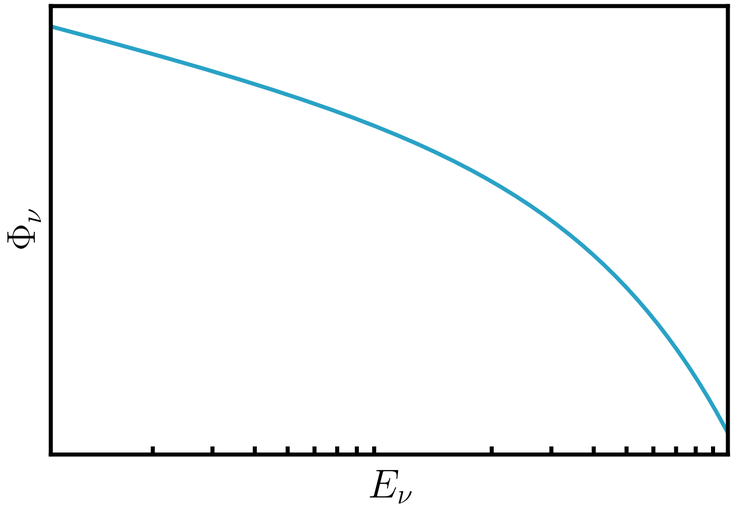

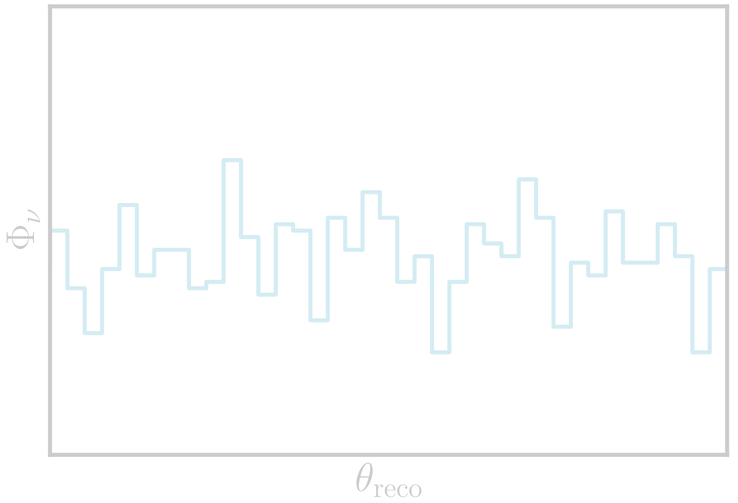

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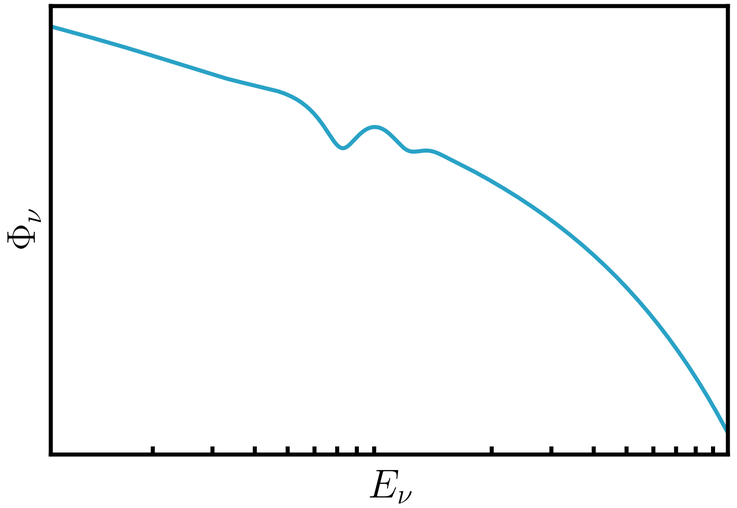

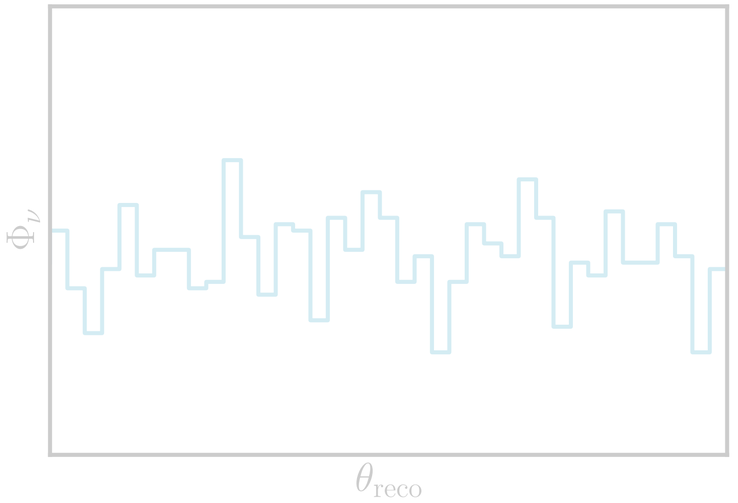

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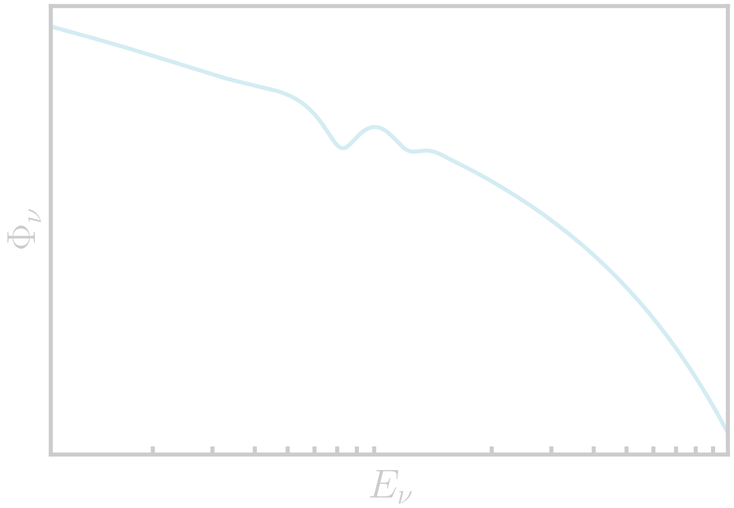

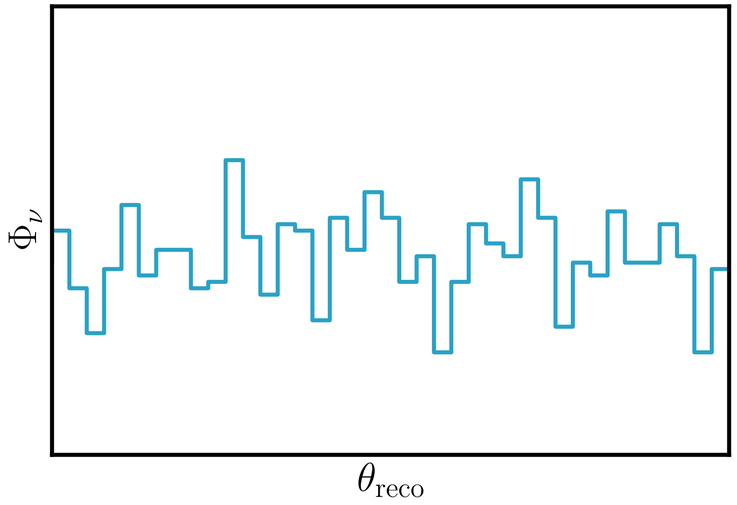

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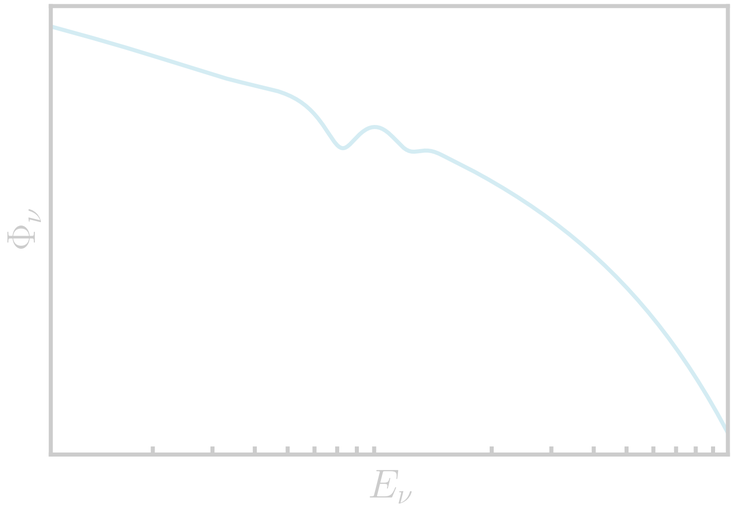

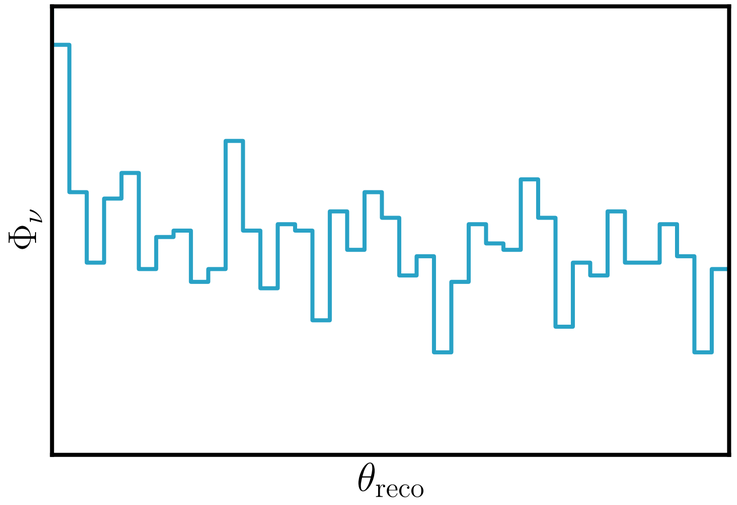

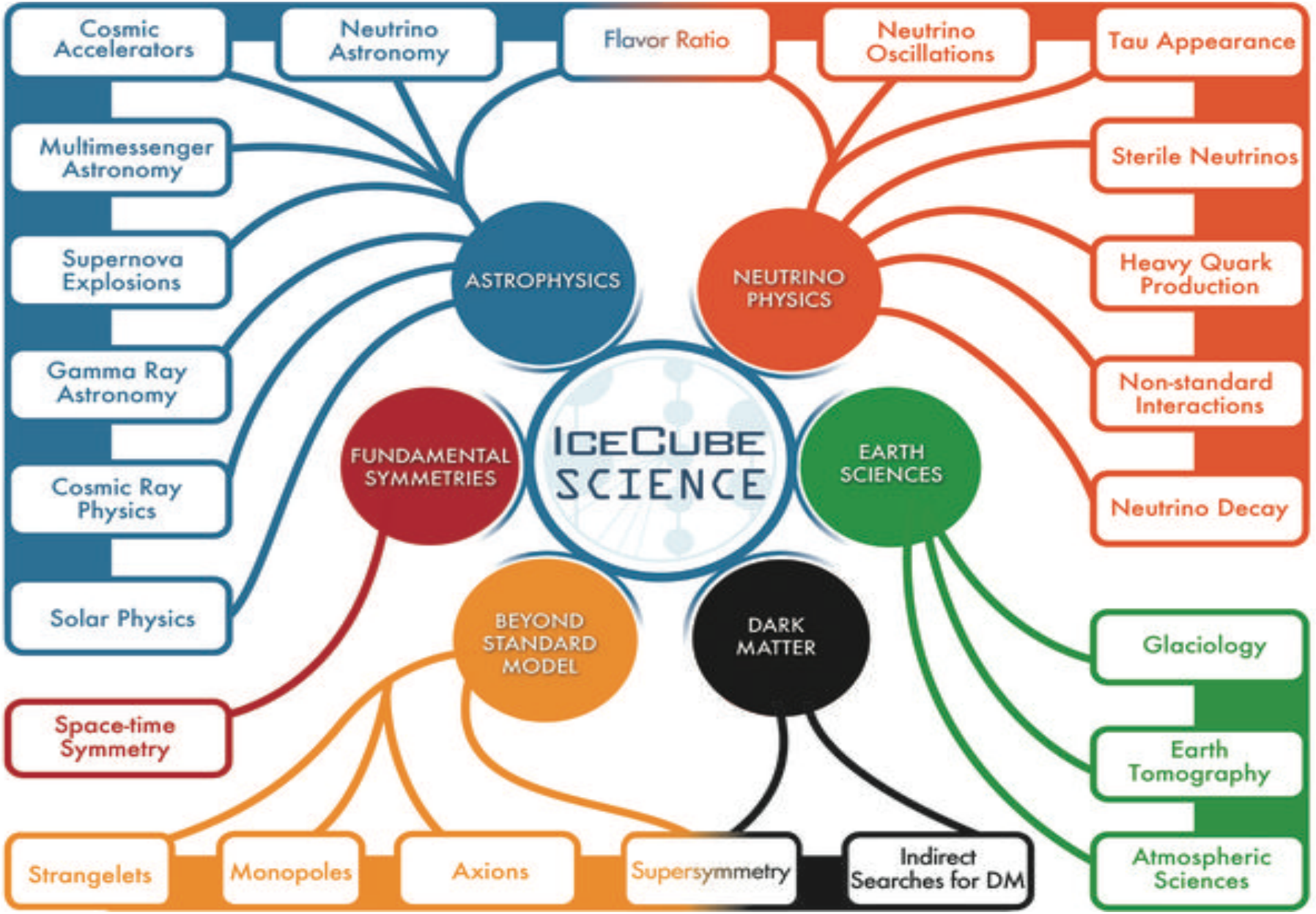

With these variables, IceCube can probe an extremely broad range of physics goals

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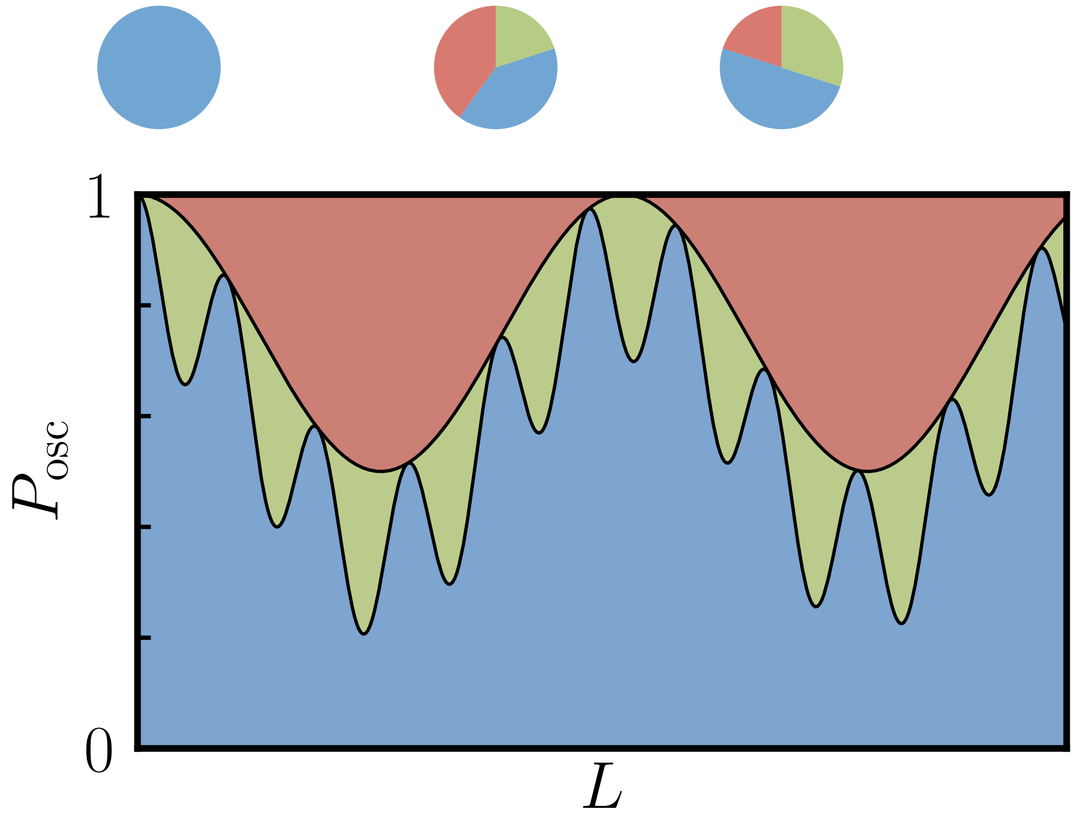
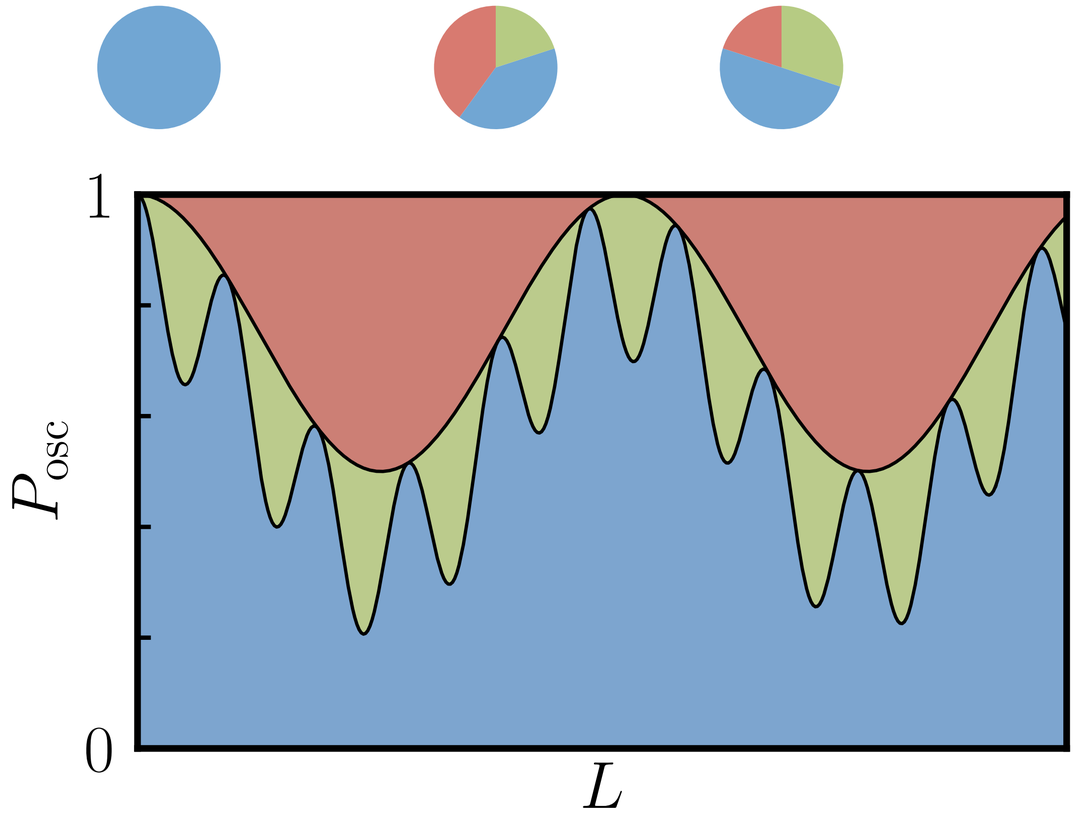
Oscillation Parameter Measurement

- As neutrinos propagate, they are able to change flavors



Oscillation Parameter Measurement

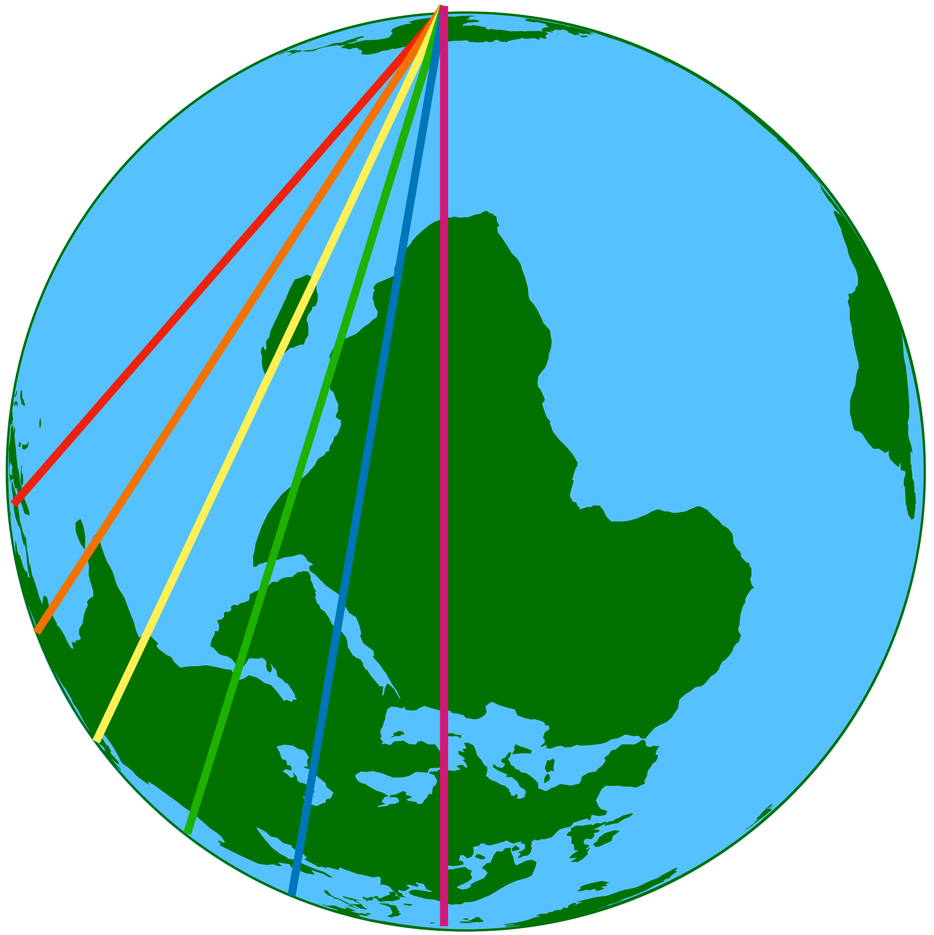
- As neutrinos propagate, they are able to change flavors
- The frequency of this is set by the mass splitting in conjunction with the neutrino energy and propagation distance



$$P_{\text{osc}} \sim \sin^2\left(\Delta m^2 \frac{L}{4E_\nu}\right)$$

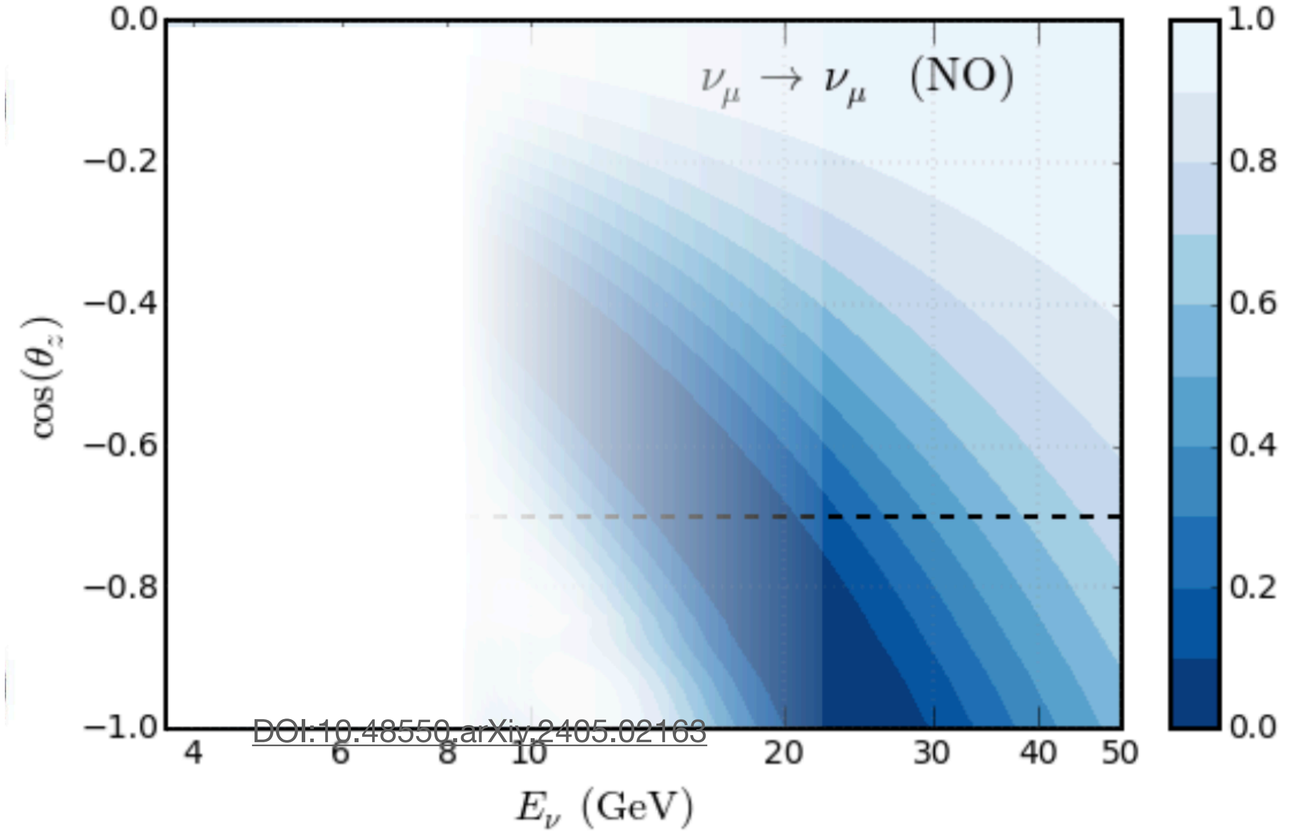
Oscillation Parameter Measurement

- As neutrinos propagate, they are able to change flavors
- The frequency of this is set by the mass splitting in conjunction with the neutrino energy and propagation distance
- IceCube can measure study different baselines by looking at different angles



Oscillation Parameter Measurement

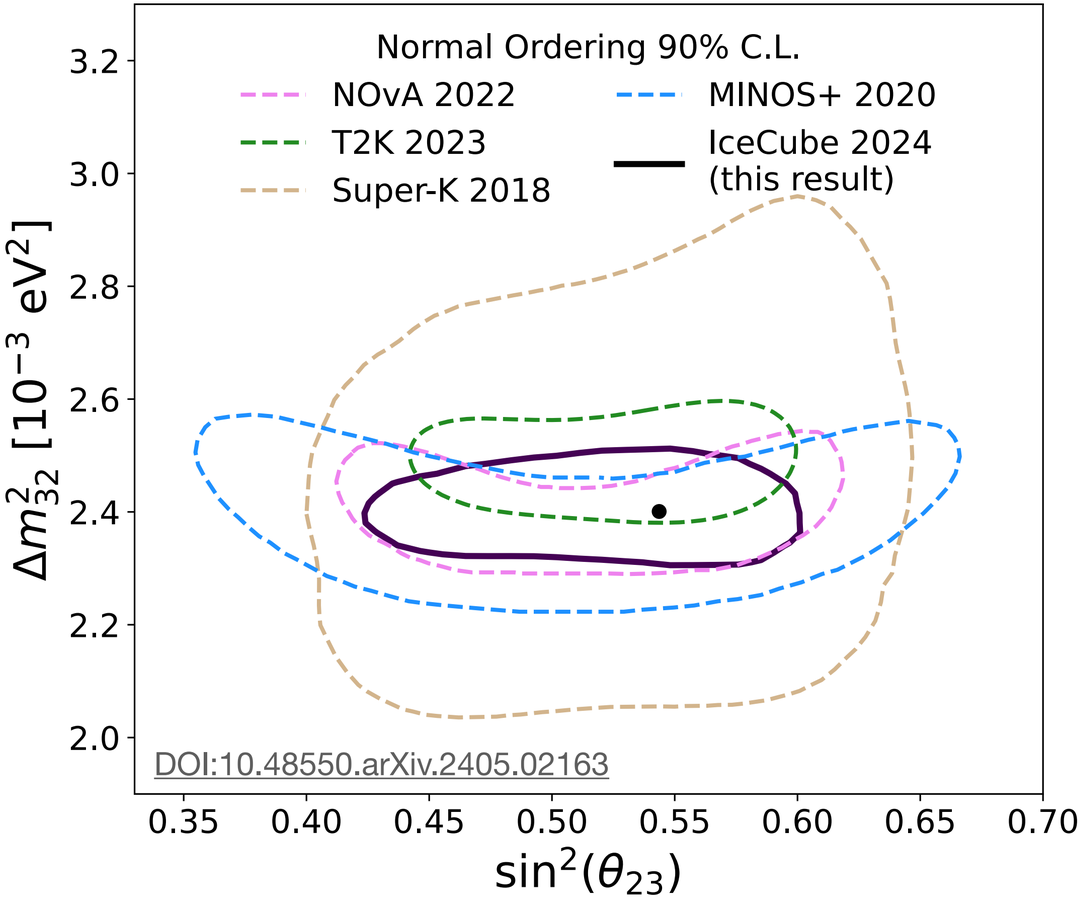
- Muon neutrinos created in cosmic ray showers oscillate to other flavors
- Deficit of these events at oscillation maximum



DOI:10.48550/arXiv.2405.02163

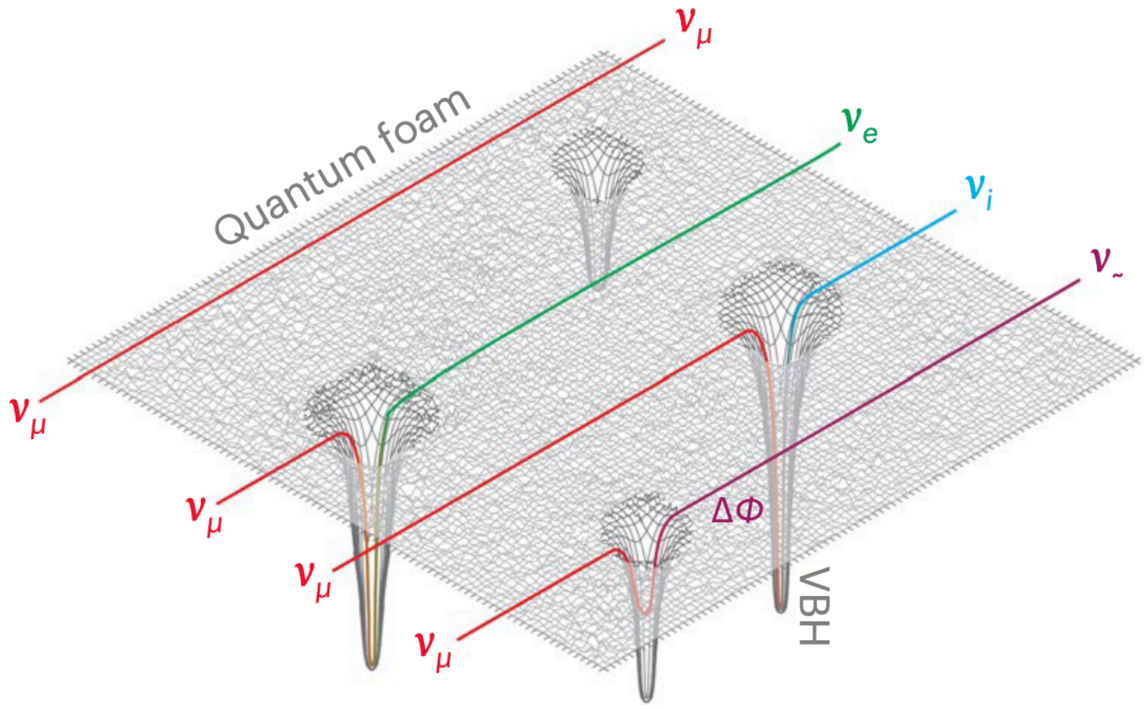
Oscillation Parameter Measurement

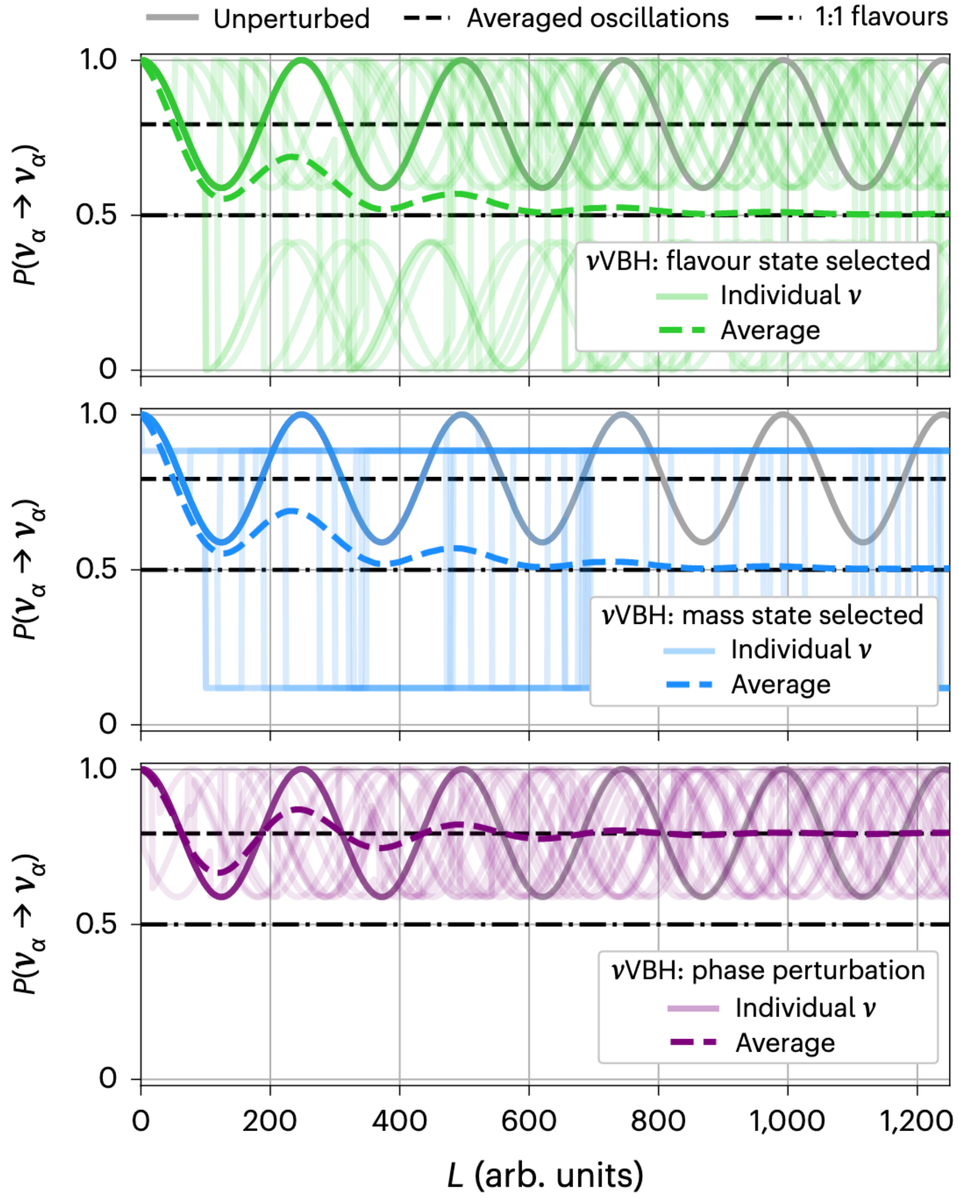
- Muon neutrinos created in cosmic ray showers oscillate to other flavors
- Deficit of these events at oscillation maximum
- Most recent measurement of oscillation parameters is very precise and prefers upper octant



Probing Quantum Gravity

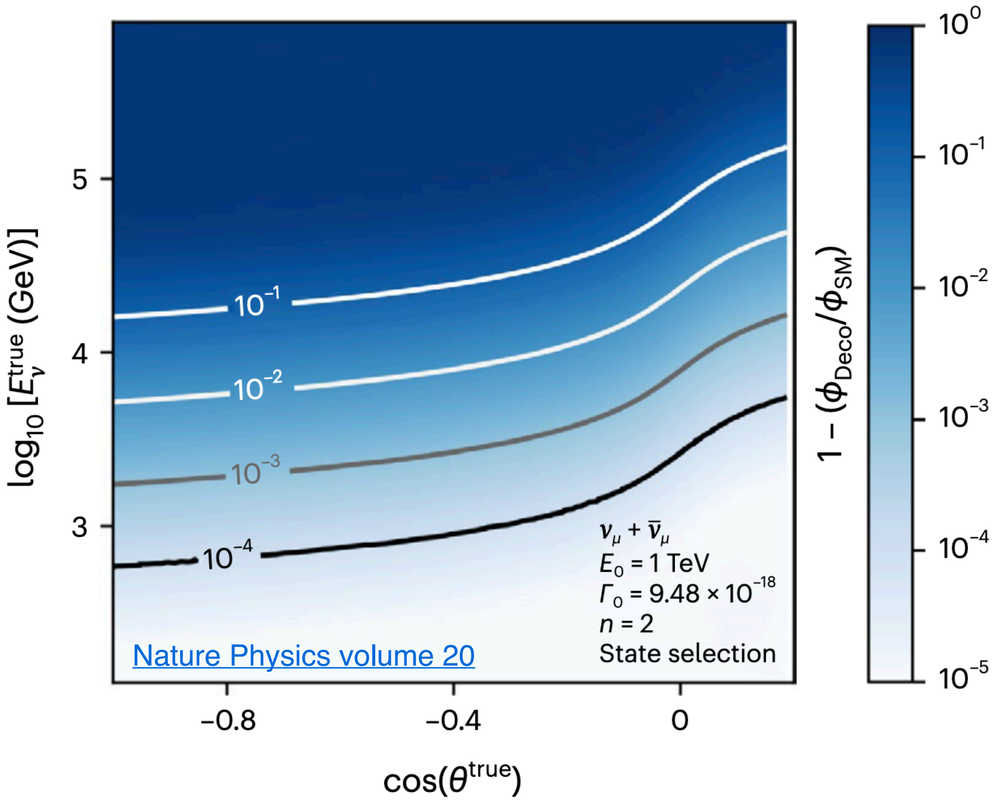
- Quantum gravity can induce virtual black holes along the neutrino trajectory
- These can alter the oscillation phenomenon

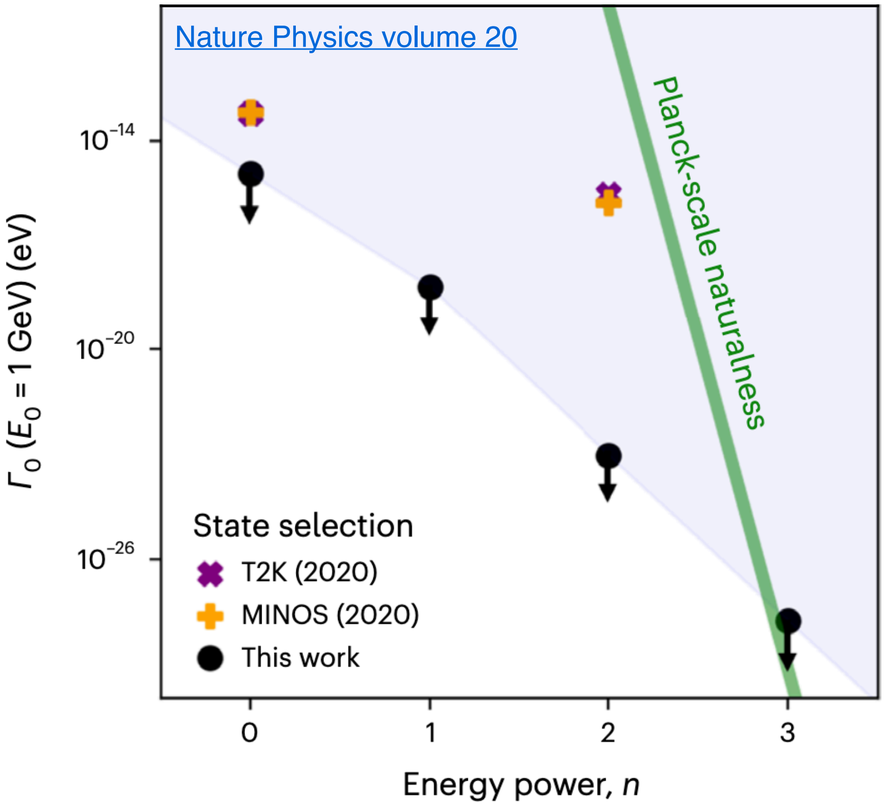




Probing Quantum Gravity

- Effects manifest in the angular and energy distributions of higher-energy atmospheric neutrinos
- IceCube recent set limits on the strength of decoherence cause by QG that reaches the Planck naturalness scale





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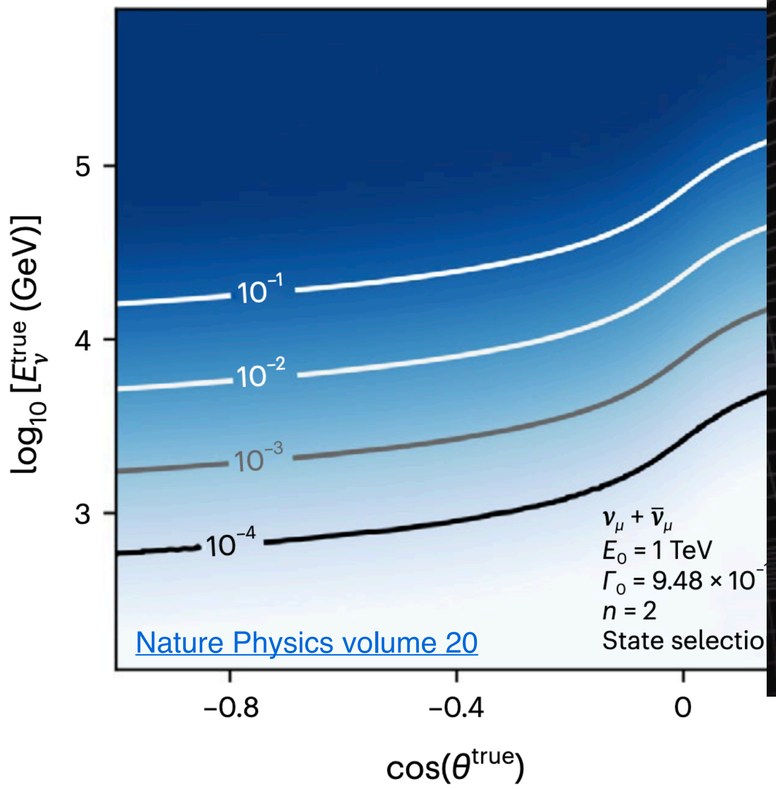
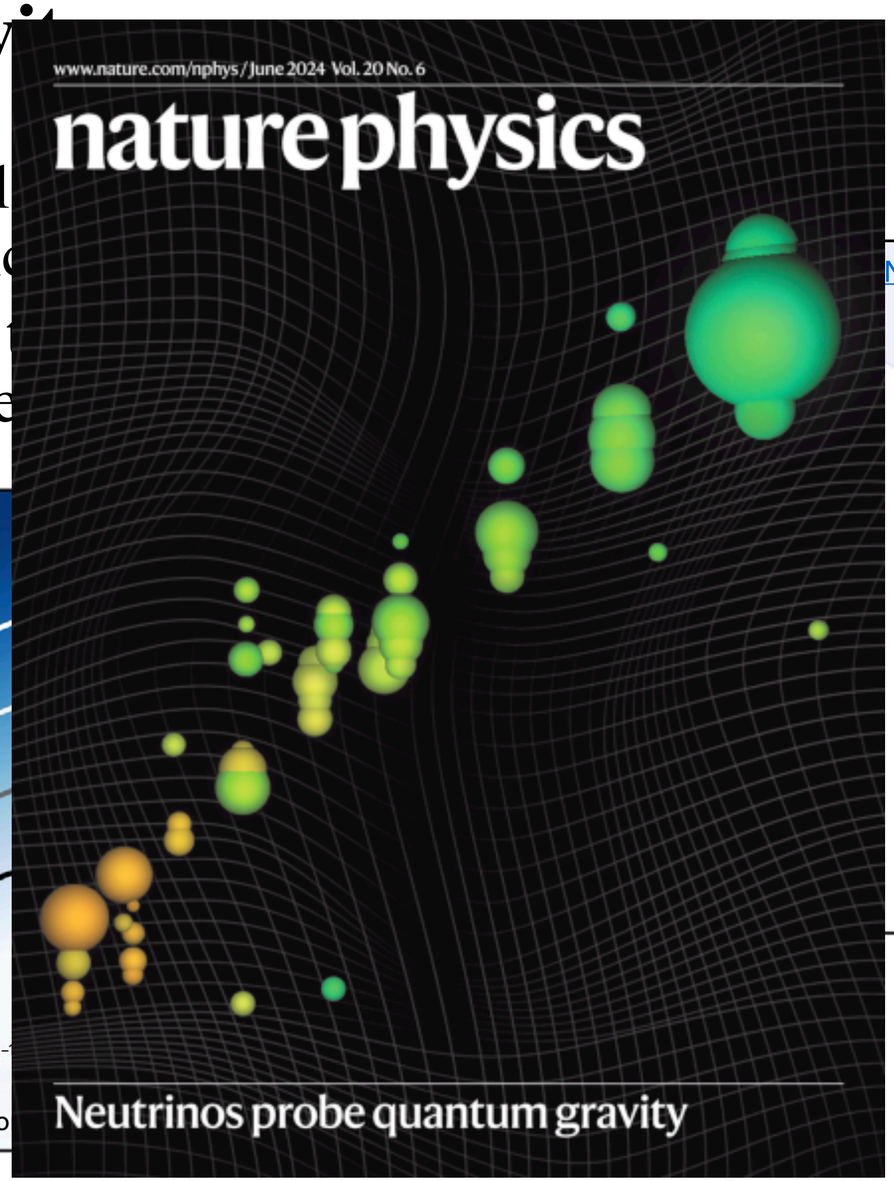
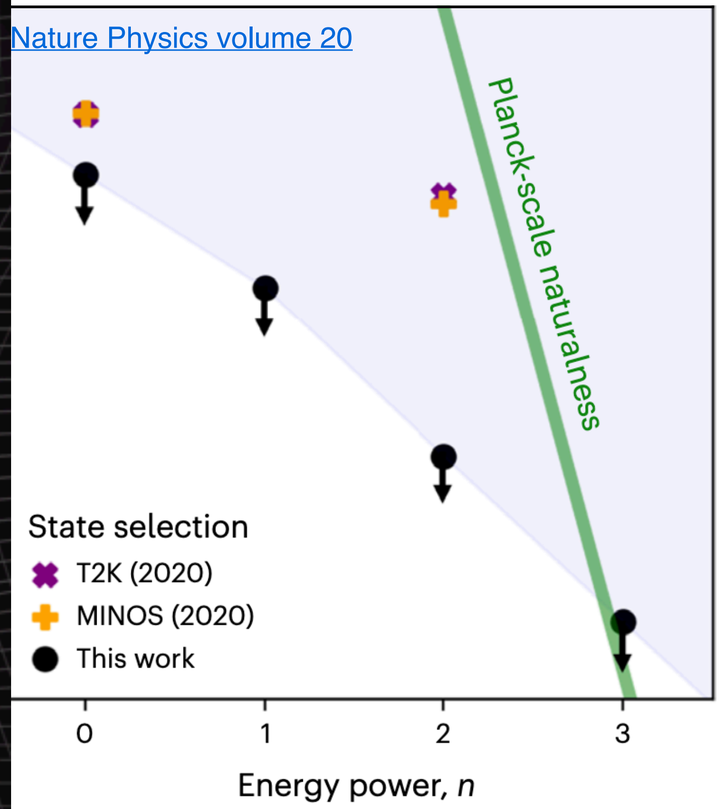
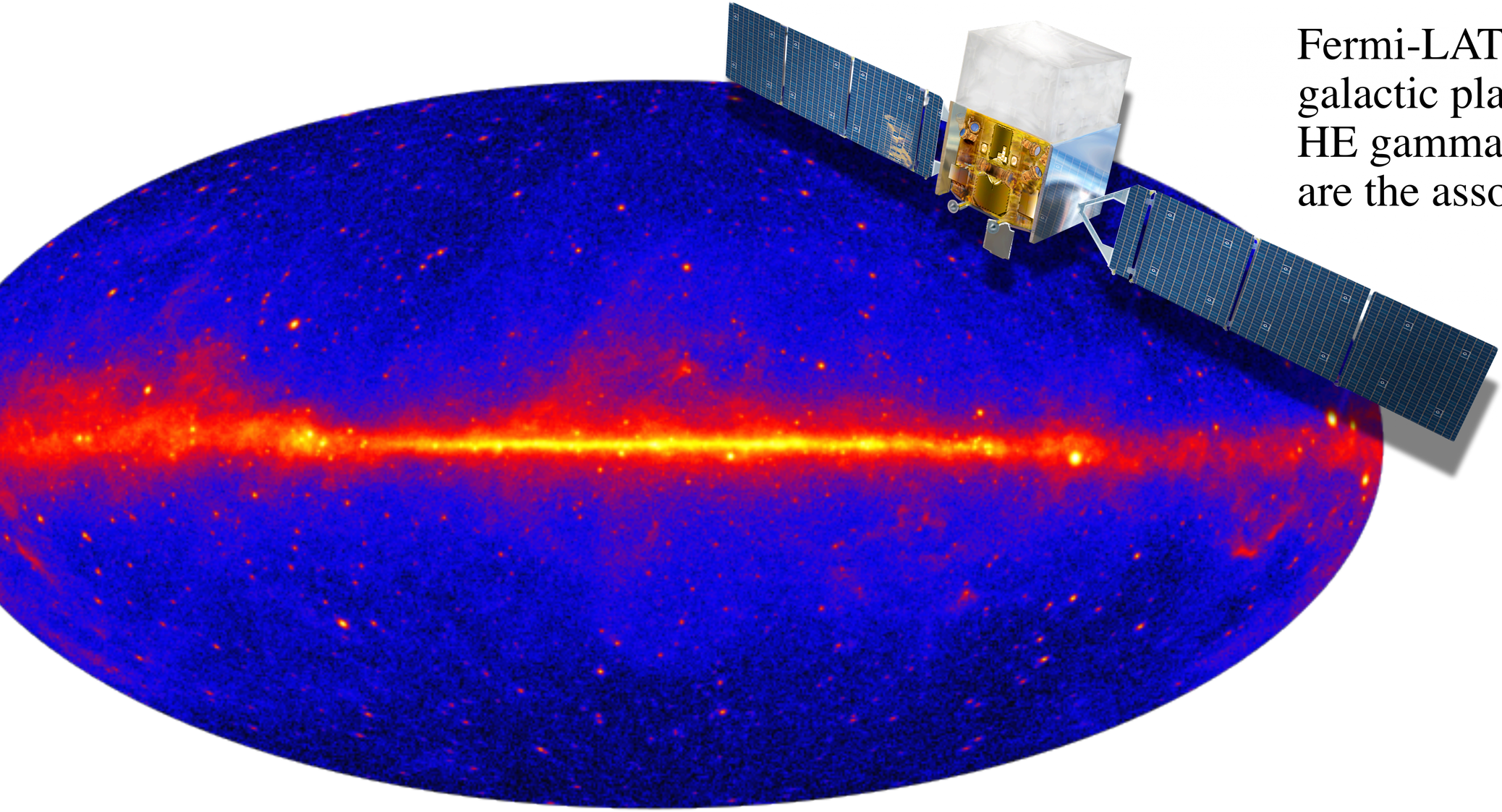






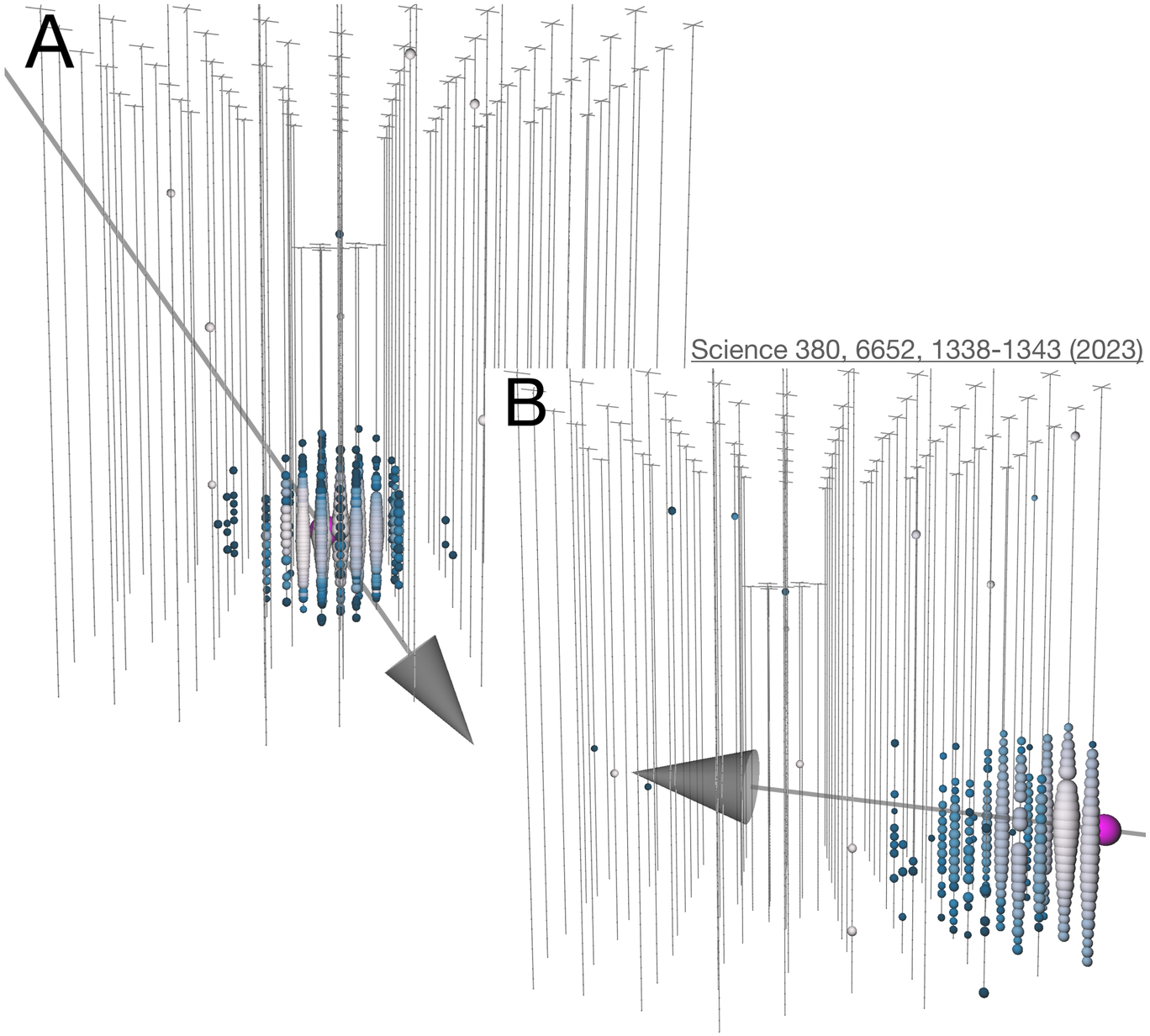
Does Our Galaxy Shine in Neutrinos ?



Fermi-LAT has seen our galactic plane shining in HE gamma rays, so where are the associated neutrinos

Swamped in the Southern Sky

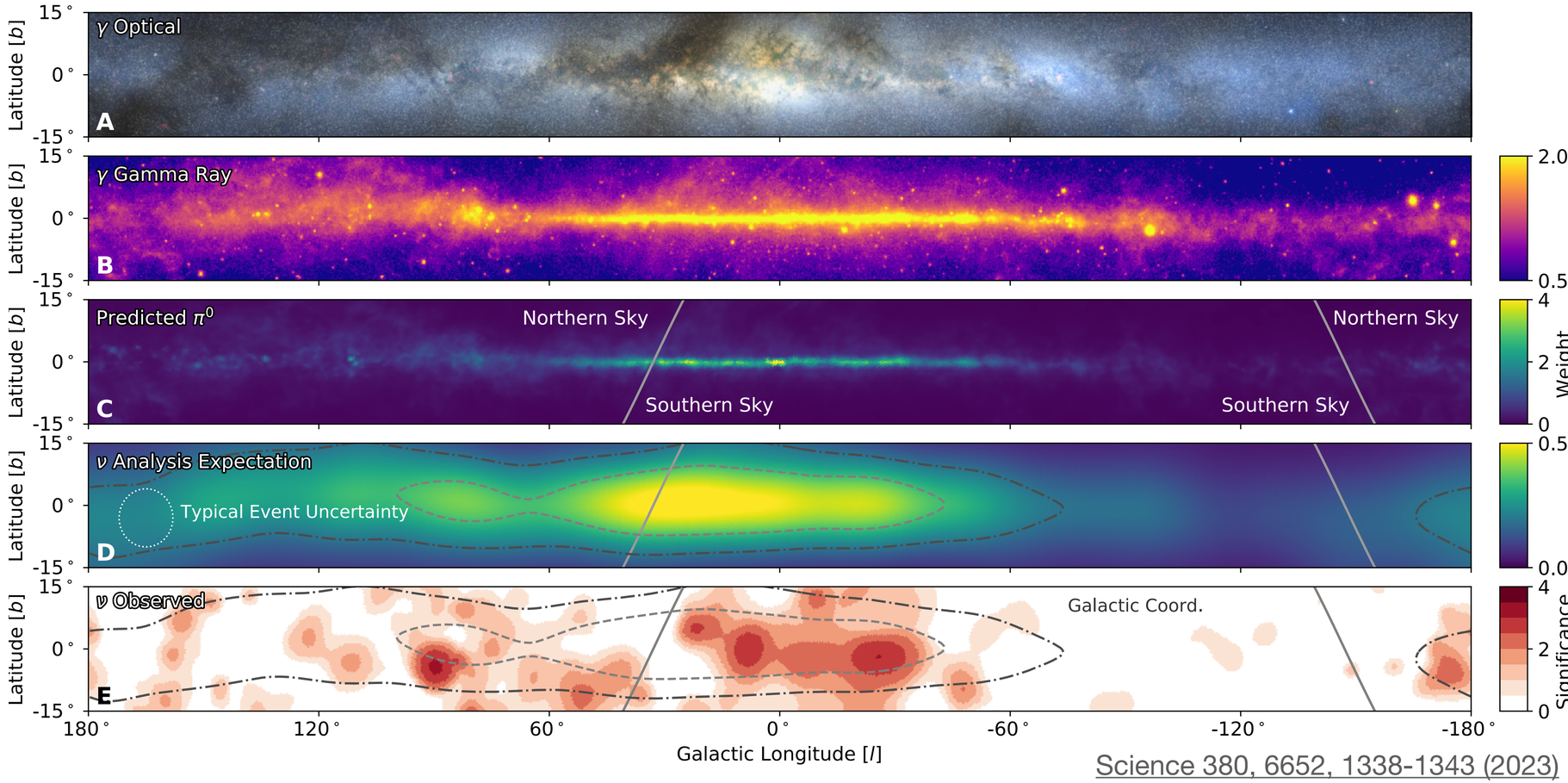
- Since much of the Galactic Plane, including the Galactic Center, we will be overwhelmed by atmospheric muons
- Restricting ourselves to cascades will allow us to filter more easily
  - Updated, ML-based reconstruction improved cascade pointing to ~7°
  - Order-of-magnitude improvement in acceptance by reconstructing partially contained events



Science 380, 6652, 1338-1343 (2023)

Strong Evidence of the Neutrinos from the Galactic Plane

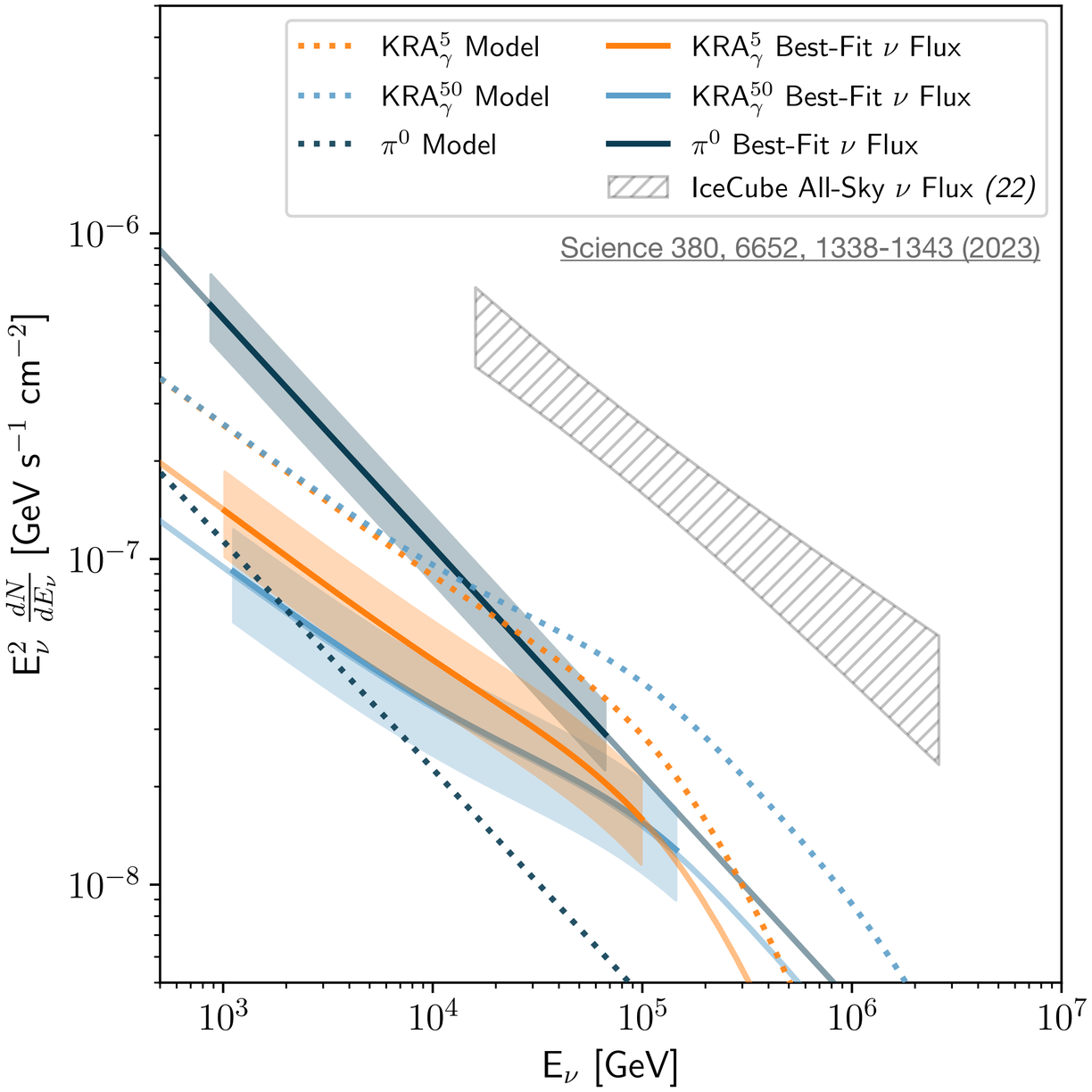
- Tested three different emission models
- Local significance between at 4.71σ, 4.37σ, and 3.96σ
- **Global significance > 4.5σ**



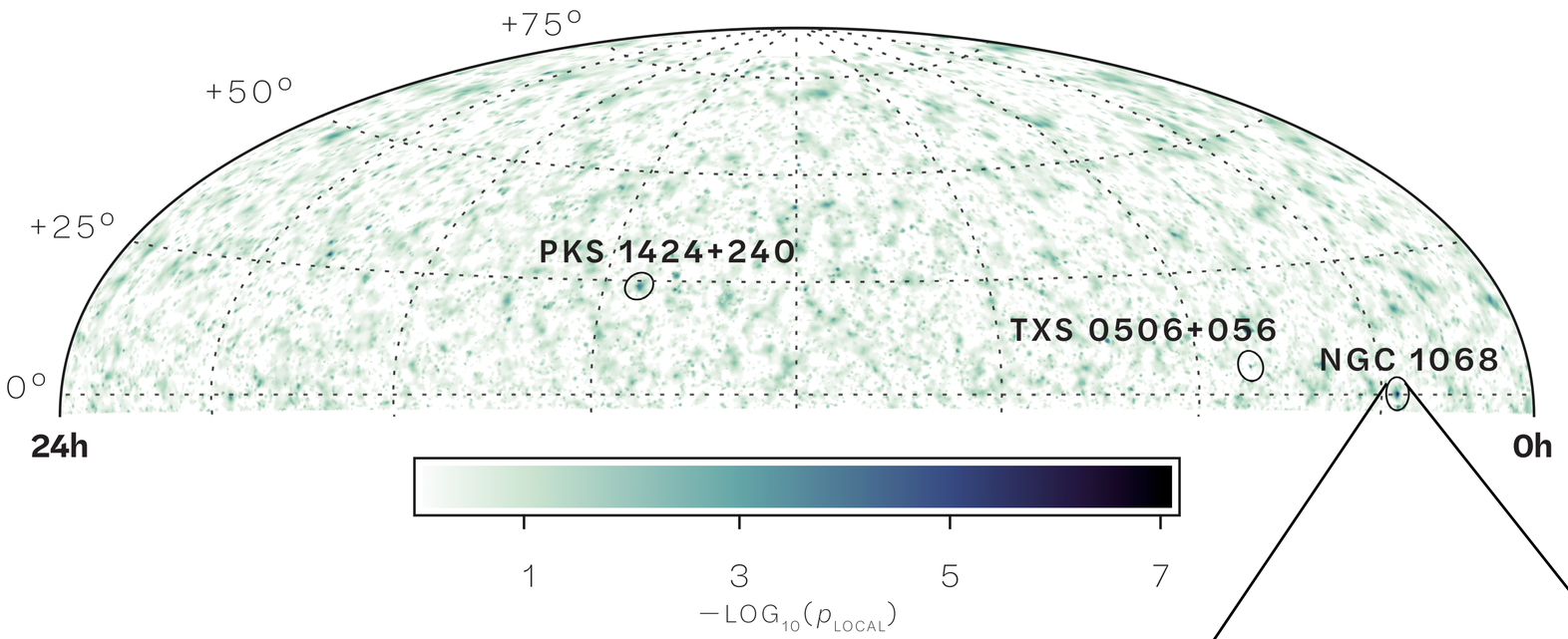
Science 380, 6652, 1338-1343 (2023)

Galactic Contribution to Diffuse Flux

- Galactic Plane emission contributes between 9% and 13% to the total
- There must be powerful accelerators outside the Milky Way



Northern-Sky Search



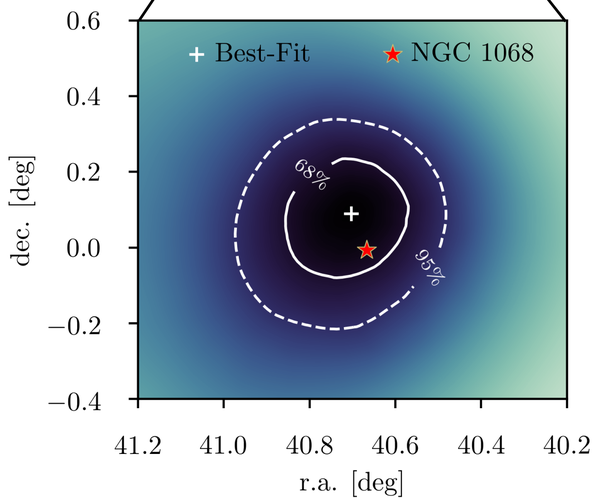
Science 378, 6619, 538-543 (2022)

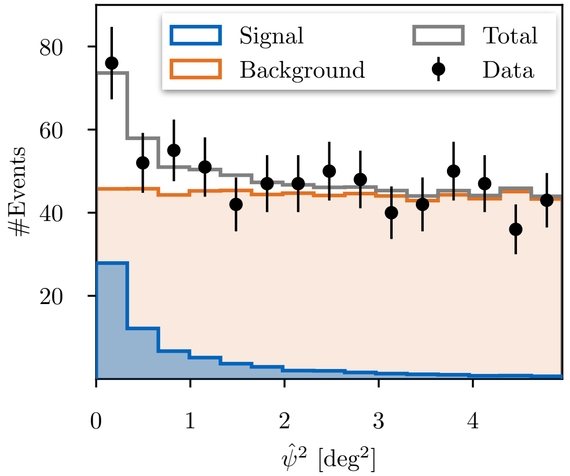
Most significant point in sky **0.11 degrees from NGC 1068**

81 events give 5.2σ pretrial significance

→4.2σ after trials

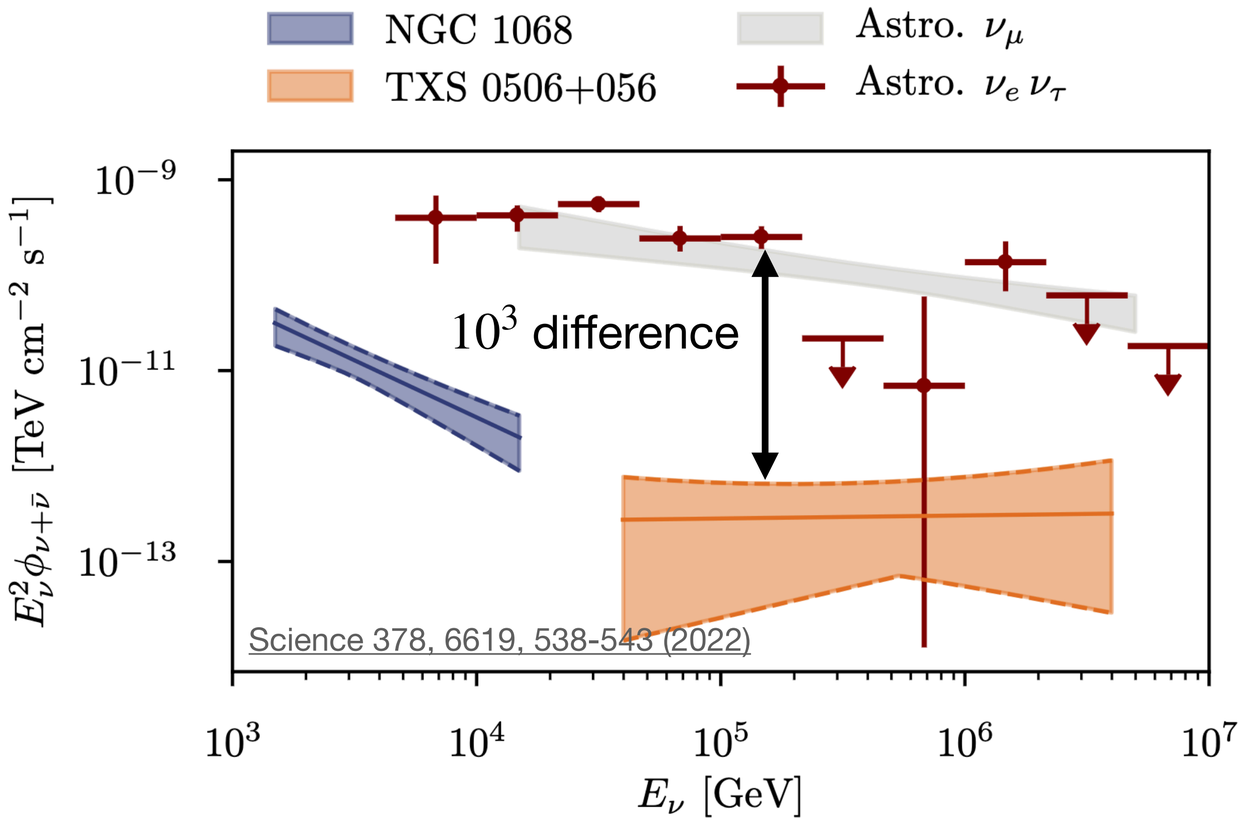
TXS 0506 and PKS 1424 also have pre-trial significances > 3.5σ





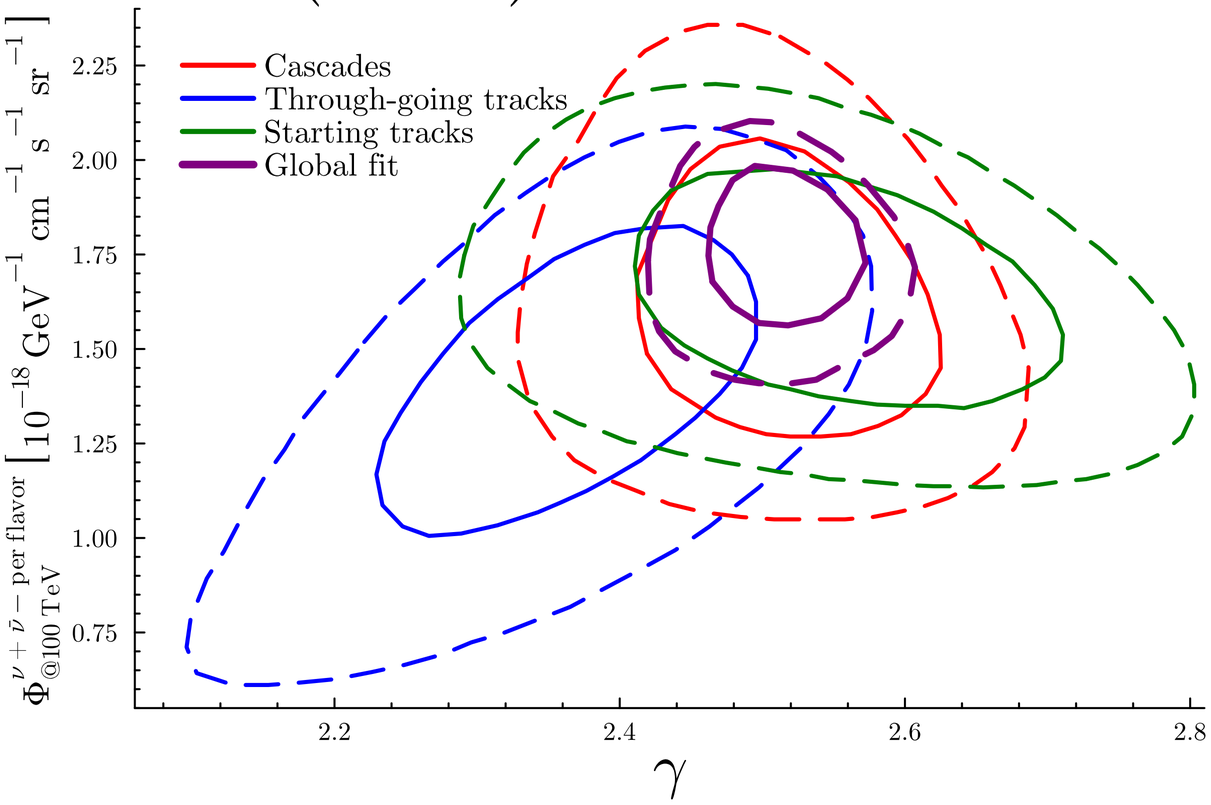
Point-Source Contribution to Diffuse Flux

- There are sufficient neutrinos to measure a spectrum for NGC 1068 and TXS 0506
- NGC brightest at low energies and can contribute 1%-5% at 10 TeV
- TXS is contributes ~0.1% to higher-energy flux



Precise Measurements of the Diffuse Flux

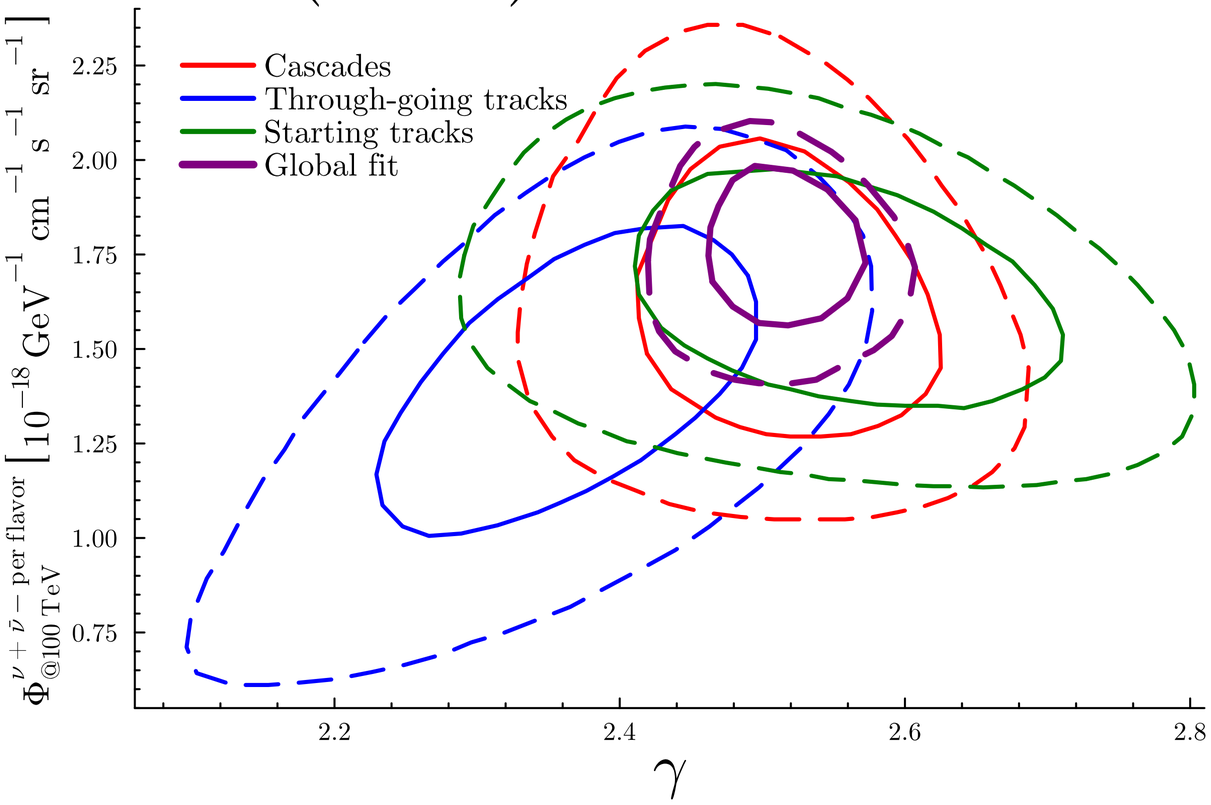
$$\Phi(E_\nu) = \Phi_0 \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-\gamma}$$

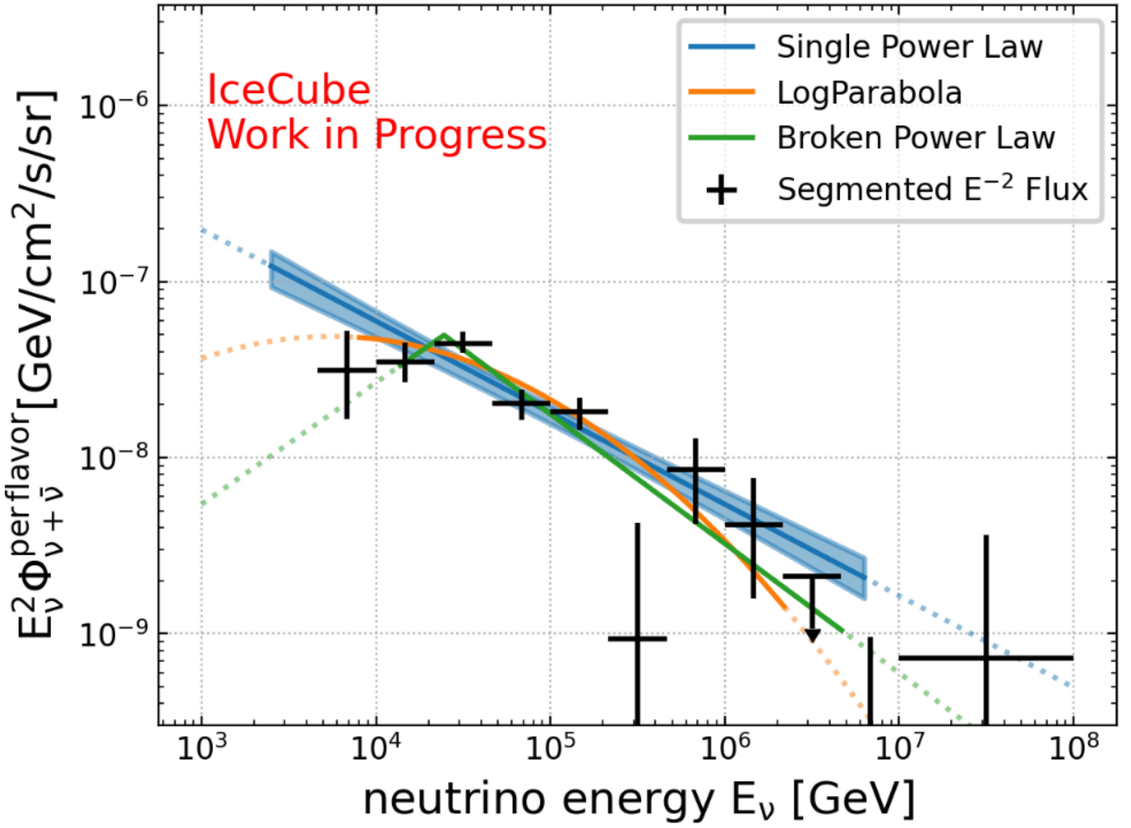


Global fits are consistent with a single power lower law with $\gamma = 2.5$.

Precise Measurements of the Diffuse Flux

$$\Phi(E_\nu) = \Phi_0 \left(\frac{E}{100\,\mathrm{TeV}} \right)^{-\gamma}$$





Global fits are consistent with a single power lower law with $\gamma = 2.5$. However, the data prefer more complex shapes at around 2σ significance

Intro to IceCube: What We See and What It Tells Us

Recent Results: Highlights across Energies

Future Directions and Opportunities

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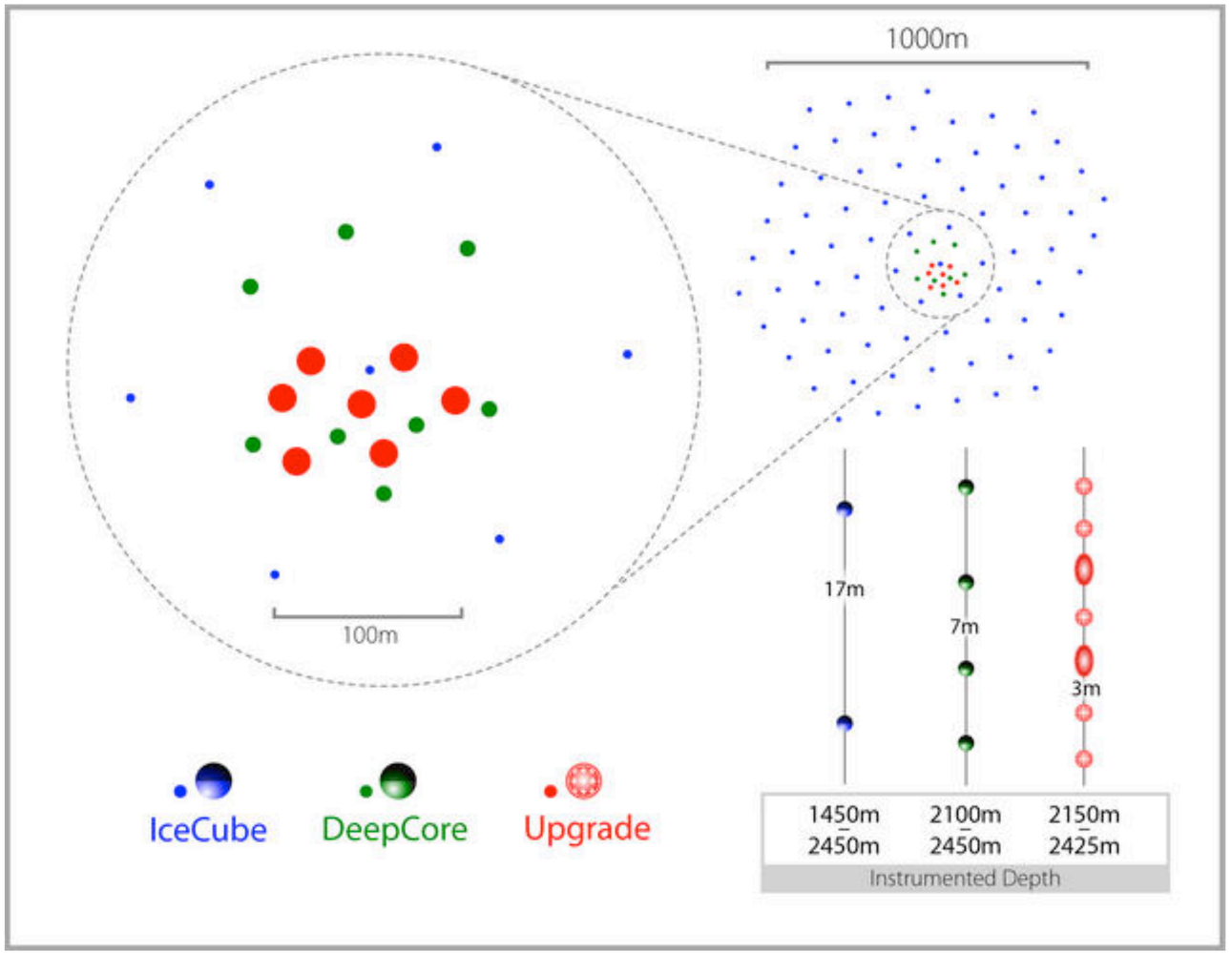
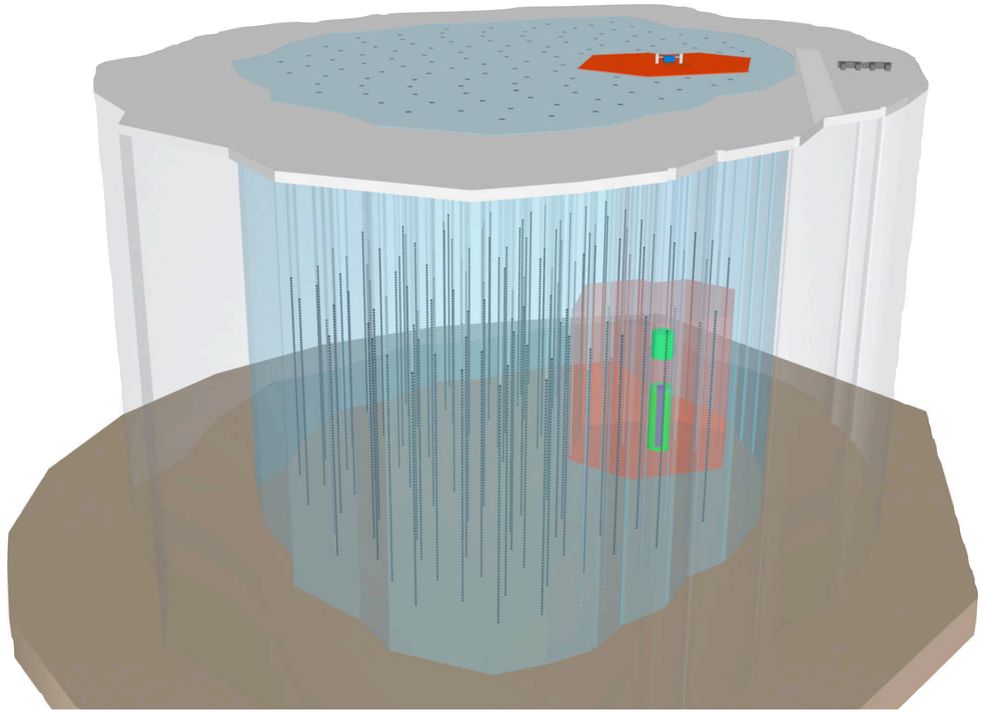
The IceCube Upgrade

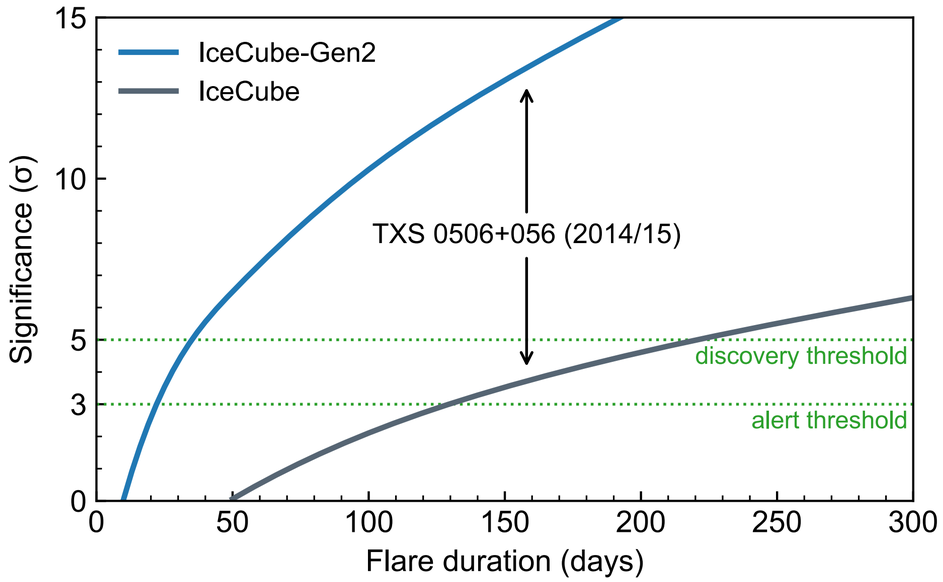


- Seven new, infilled strings
- Much improved efficiency and reconstructions at lowest energies to enable **high-precision measurement of oscillation parameters**
- Improved calibration and ice model to **improve reconstructions across all energies**
- Deployment scheduled for 2025-2026 Pole Season

IceCube Gen2

- Extension of in-ice array with surface radio array
- 5x and 2x improvements to effective area and angular resolution
- TXS 2014 flare detectable at ~13σ
- NGC-1068 detected at 10σ with 10 years of data





Summary and Outlook

- IceCube's measurement of atmospheric neutrinos have achieved similarly precise measurements of oscillation parameters and have probed QG at the Planck scale
- After one decade of observing the diffuse, high-energy neutrino flux, we are seeing the first hints of a deviation from a power law
- NGC 1068 and the Galactic Plane are neutrino sources at high significance
- IceCube has a rich science program that is at the forefront of many areas of study. Let's chat about it !
- There is a bright future ahead in neutrino astronomy