Recent Results from the IceCube Neutrino Observatory

Jeff Lazar, *on behalf of the IceCube Collaboration*

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CRIS-MAC

Trapani, Italy

IceCube: What We See and What It Tells Us
Characterizing the Diffuse Astrophysical Flux
Sources of Astrophysical Neutrinos
Future Directions

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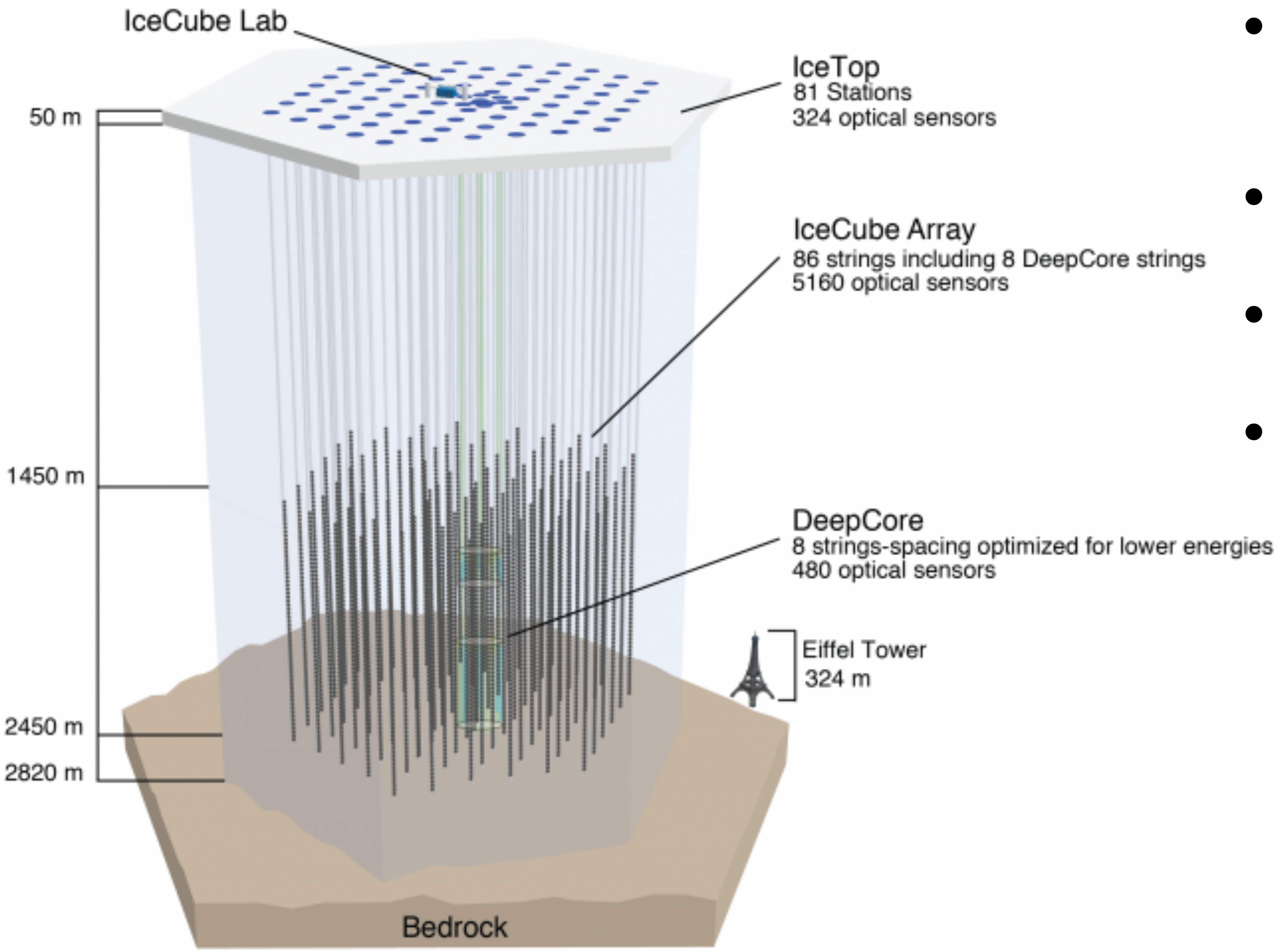
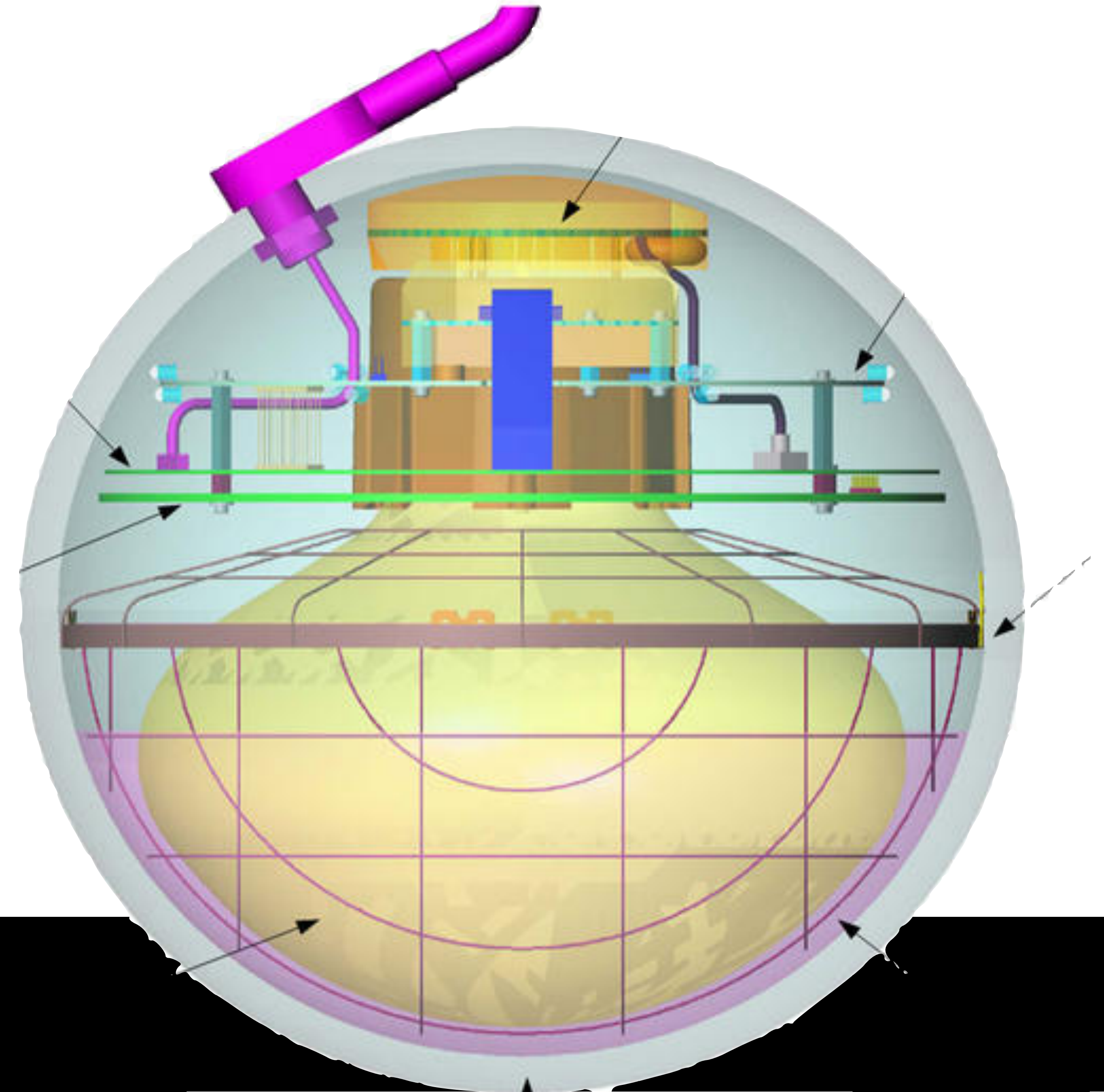
The IceCube Neutrino Observatory

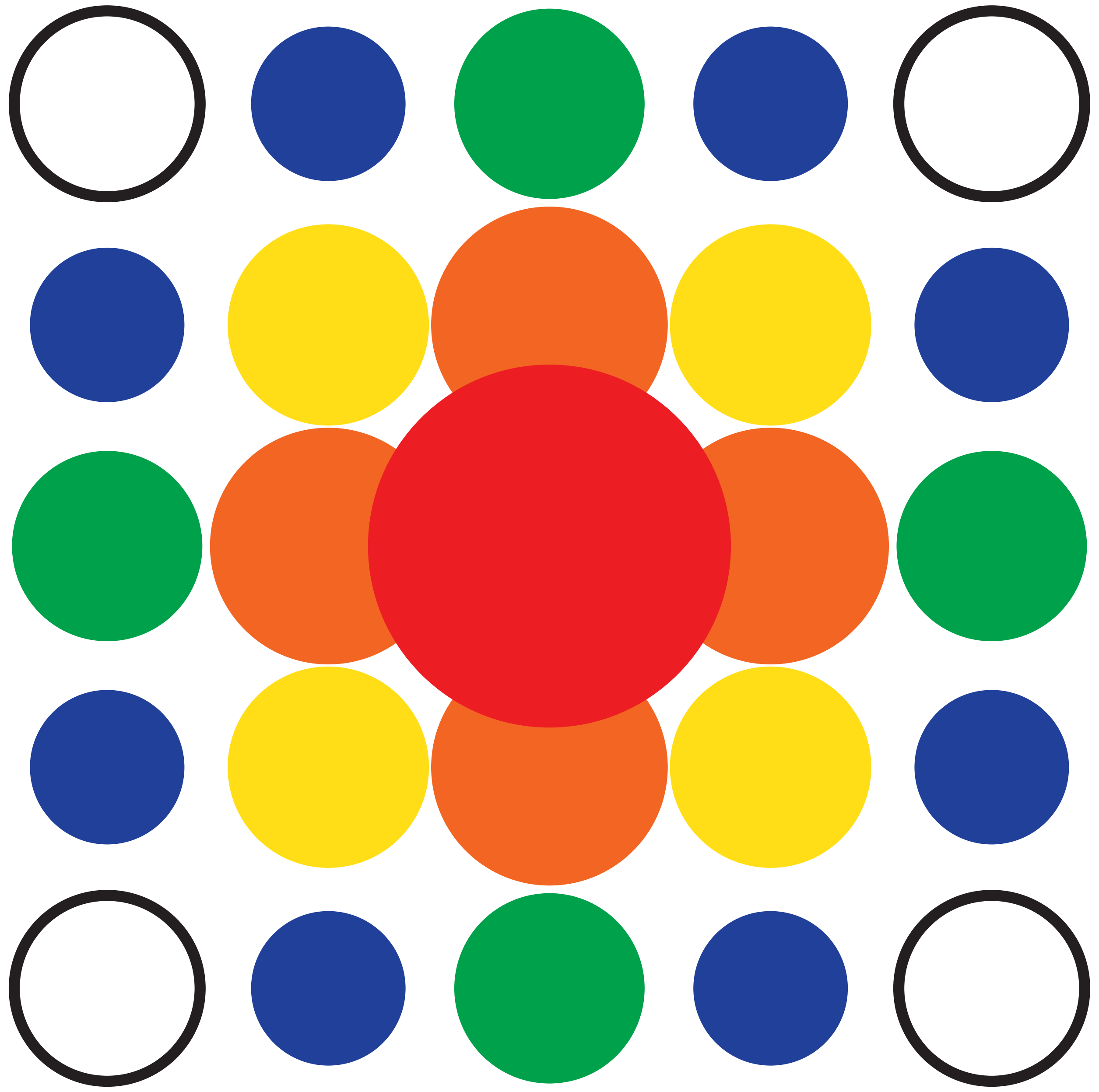


- 5,160 digital optical modules (DOMs) detect light from charged by-products of neutrino interactions
- 86 strings including 6 denser DeepCore strings
- In-ice array complemented by 86-station IceTop surface array
- Completed in December 2010 with near constant uptime since



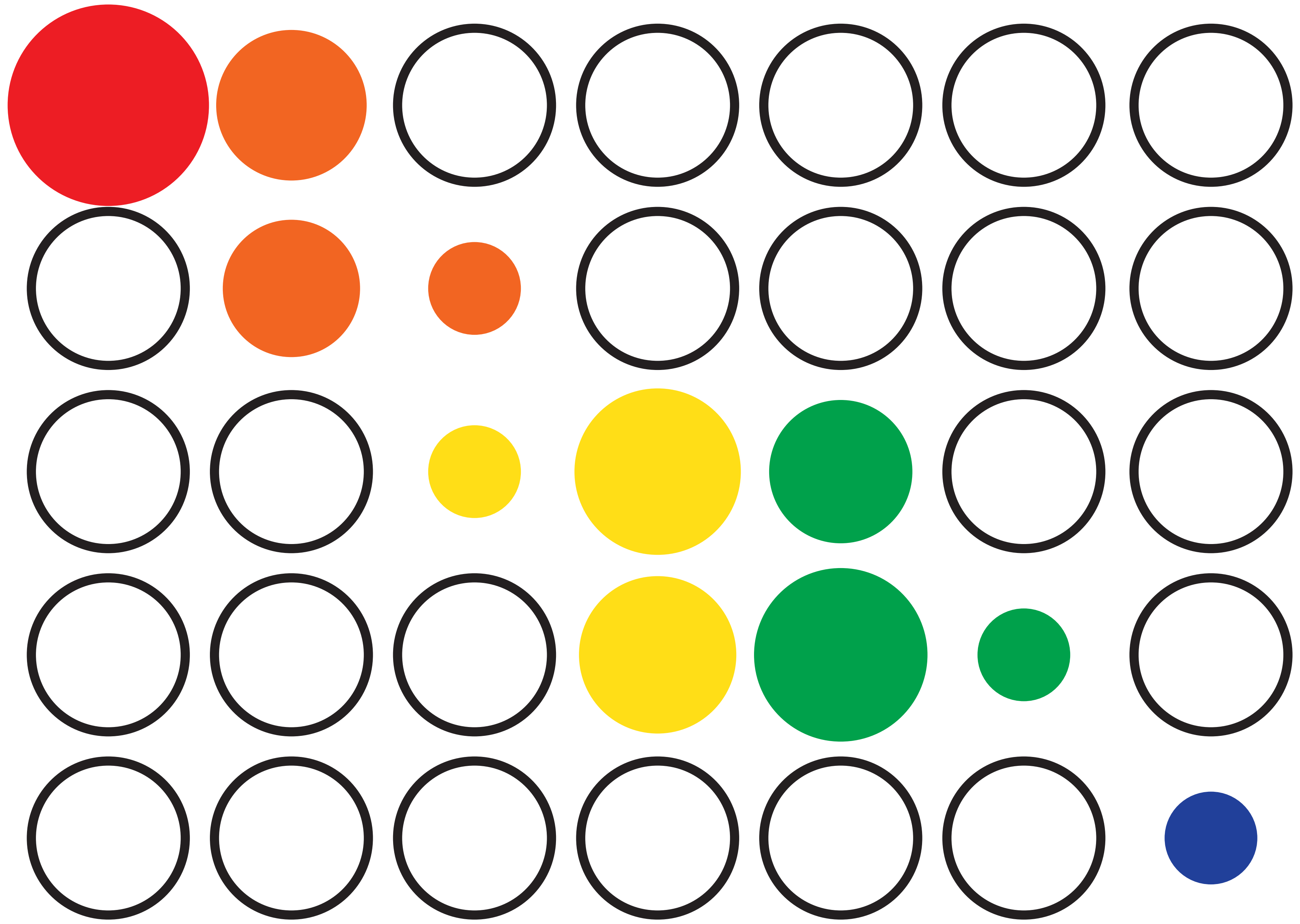
In-Ice Signatures

Cascades ν_e CC | ν_α NC



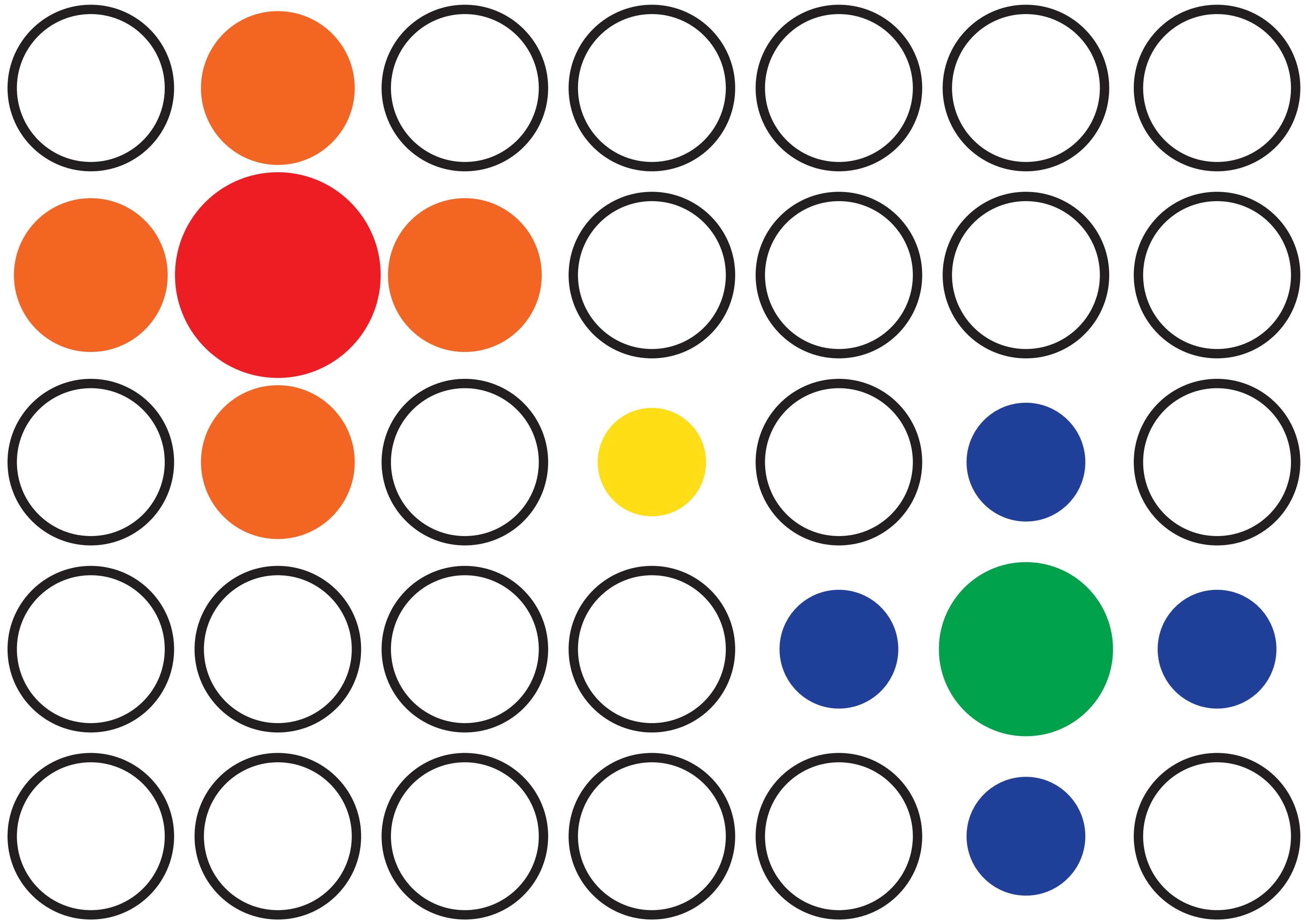
Great energy resolution, but angular reconstruction is challenging

Tracks ν_μ CC



Great directional resolution, but deposited energy not proportional to E_ν

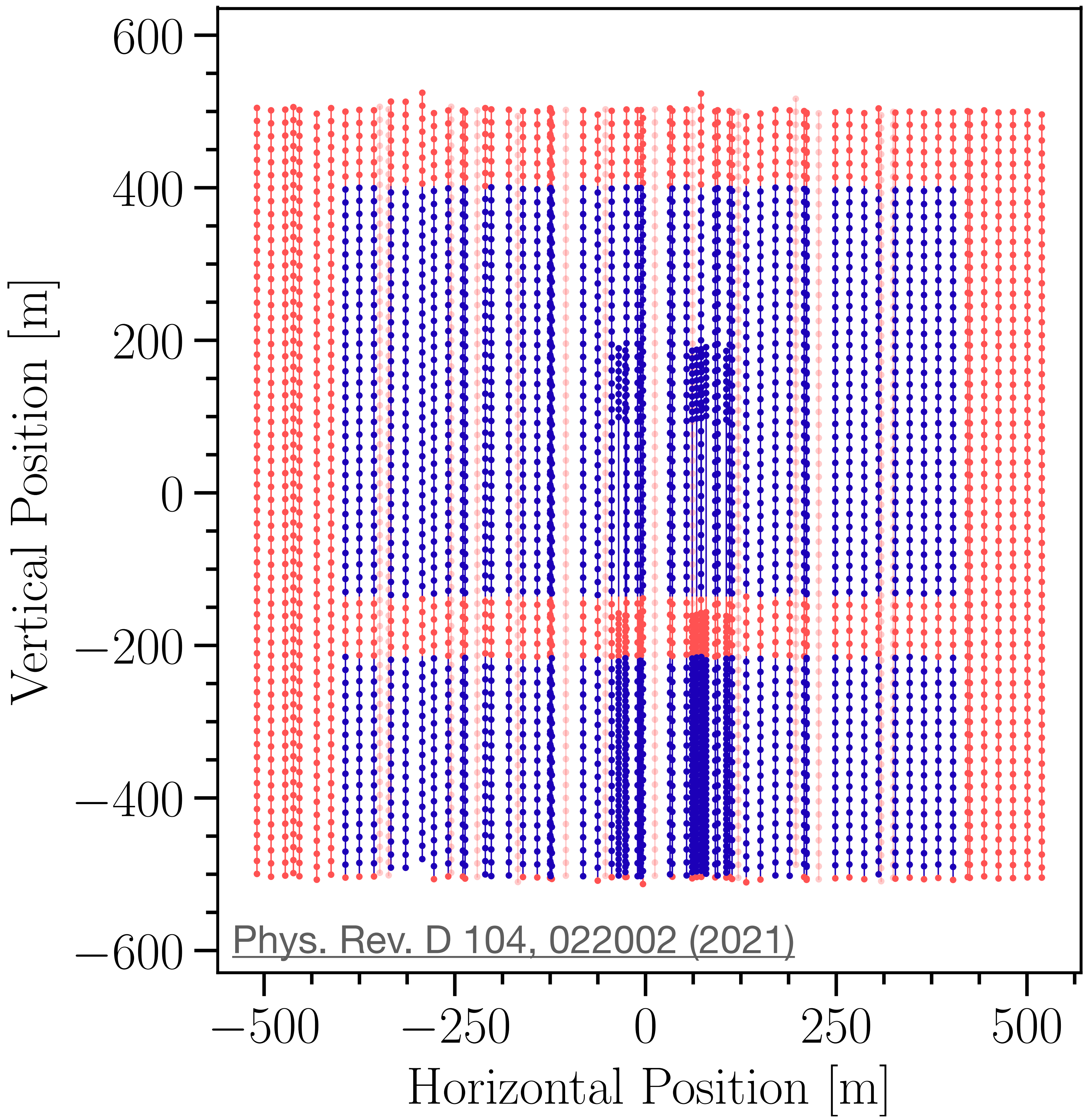
Double bangs ν_τ CC



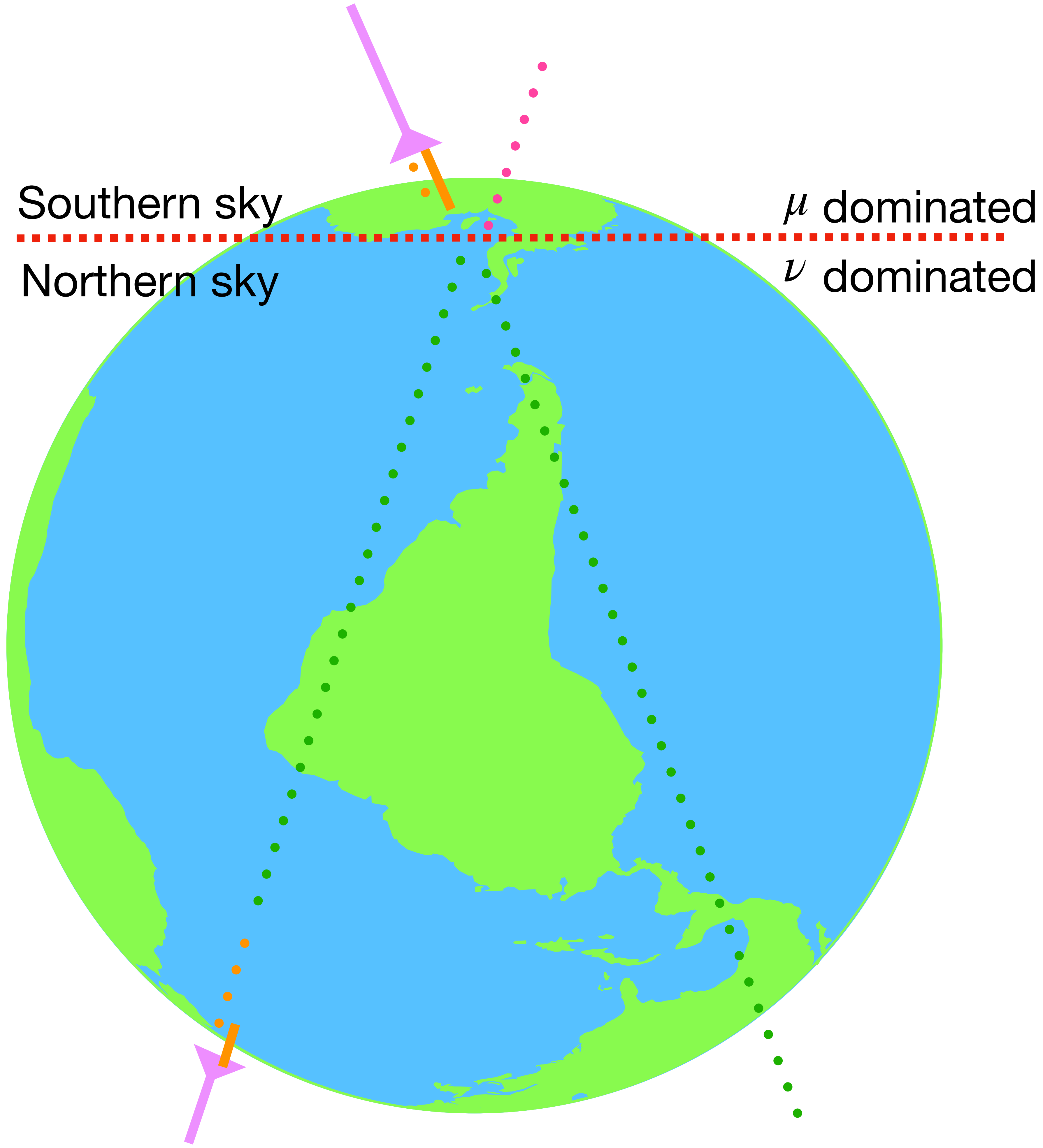
Signature of ν_τ CC events

Hunting for Needles in a Haystack

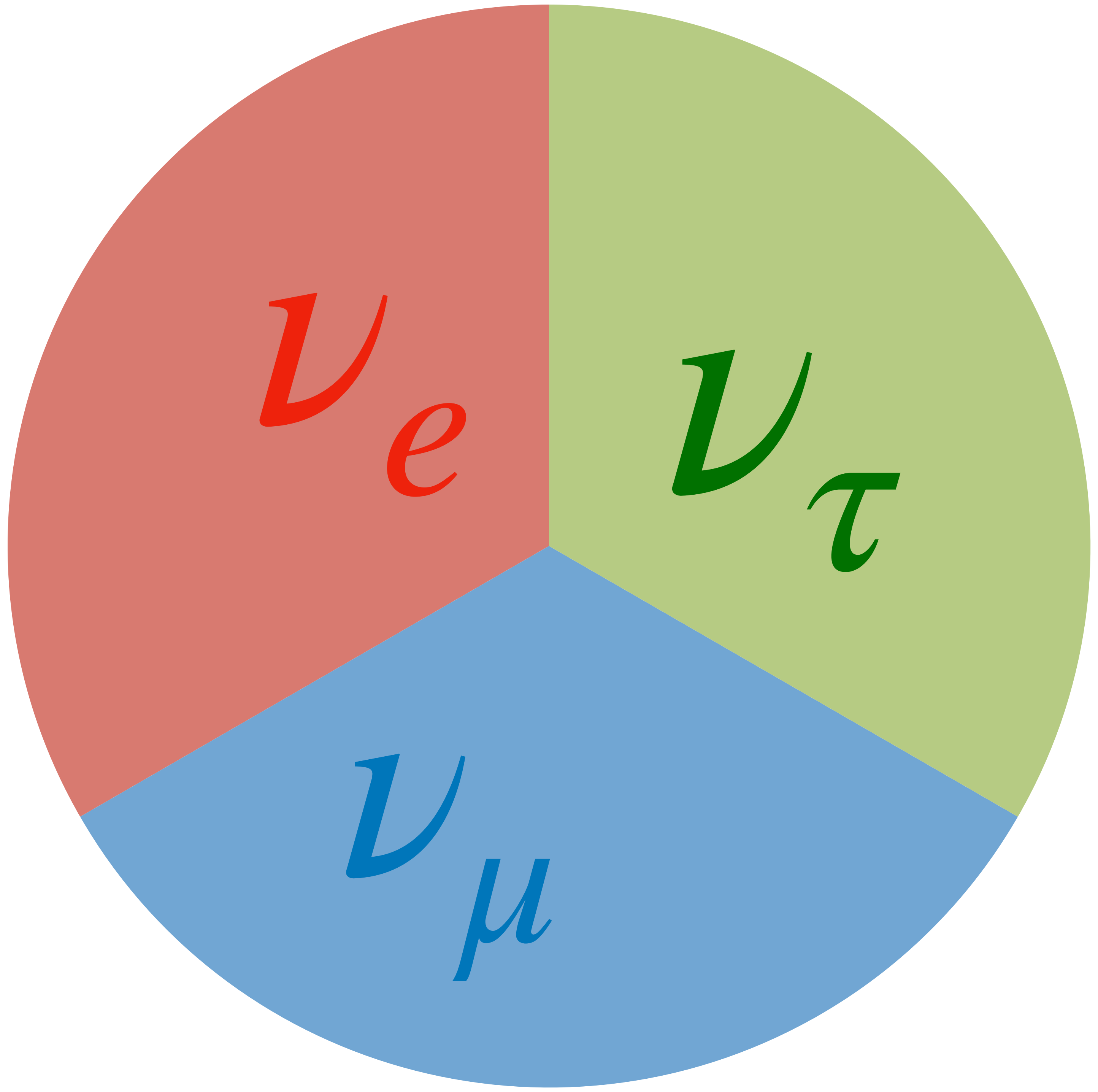
1. Use the outer layers of the detector as veto regions

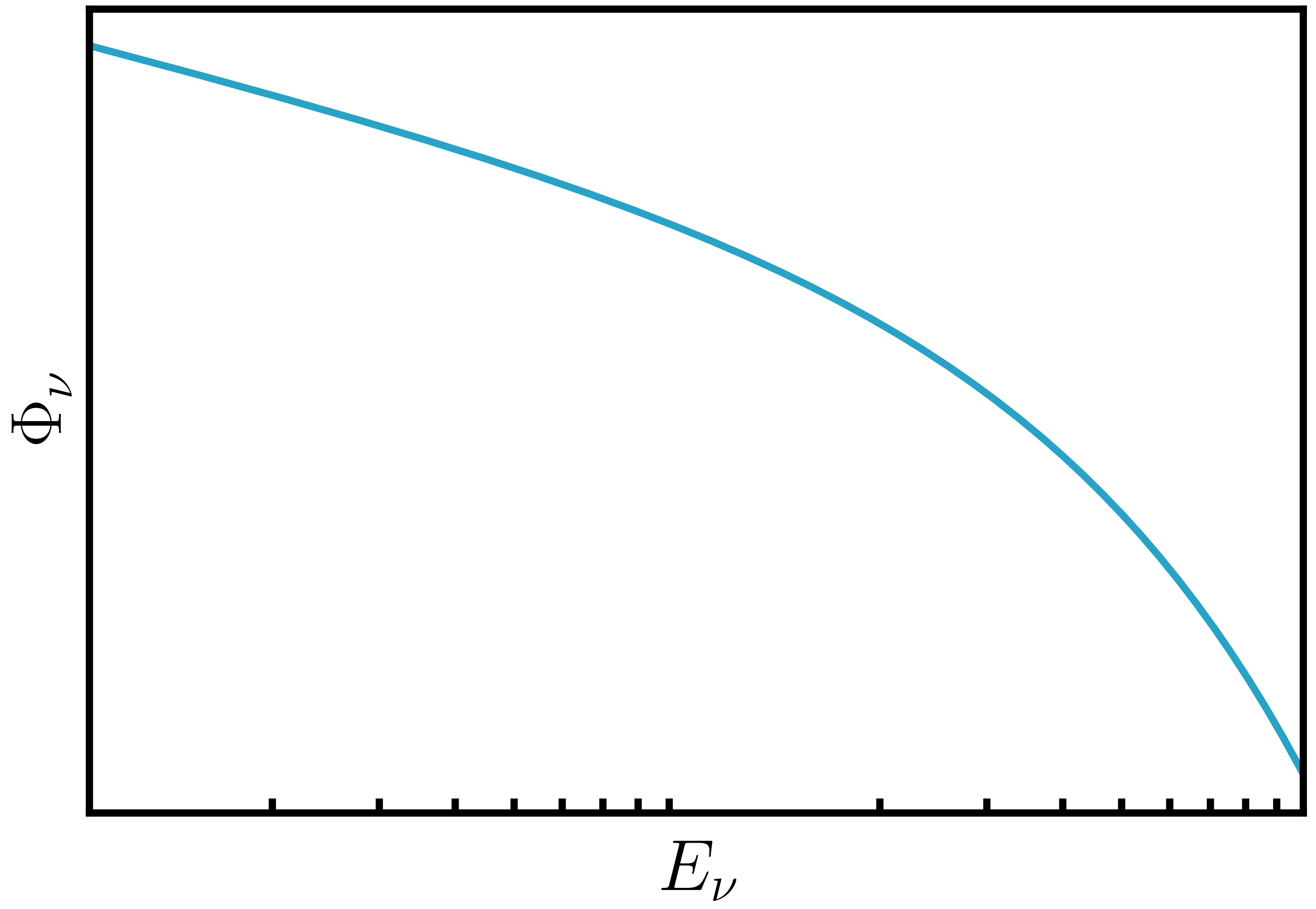


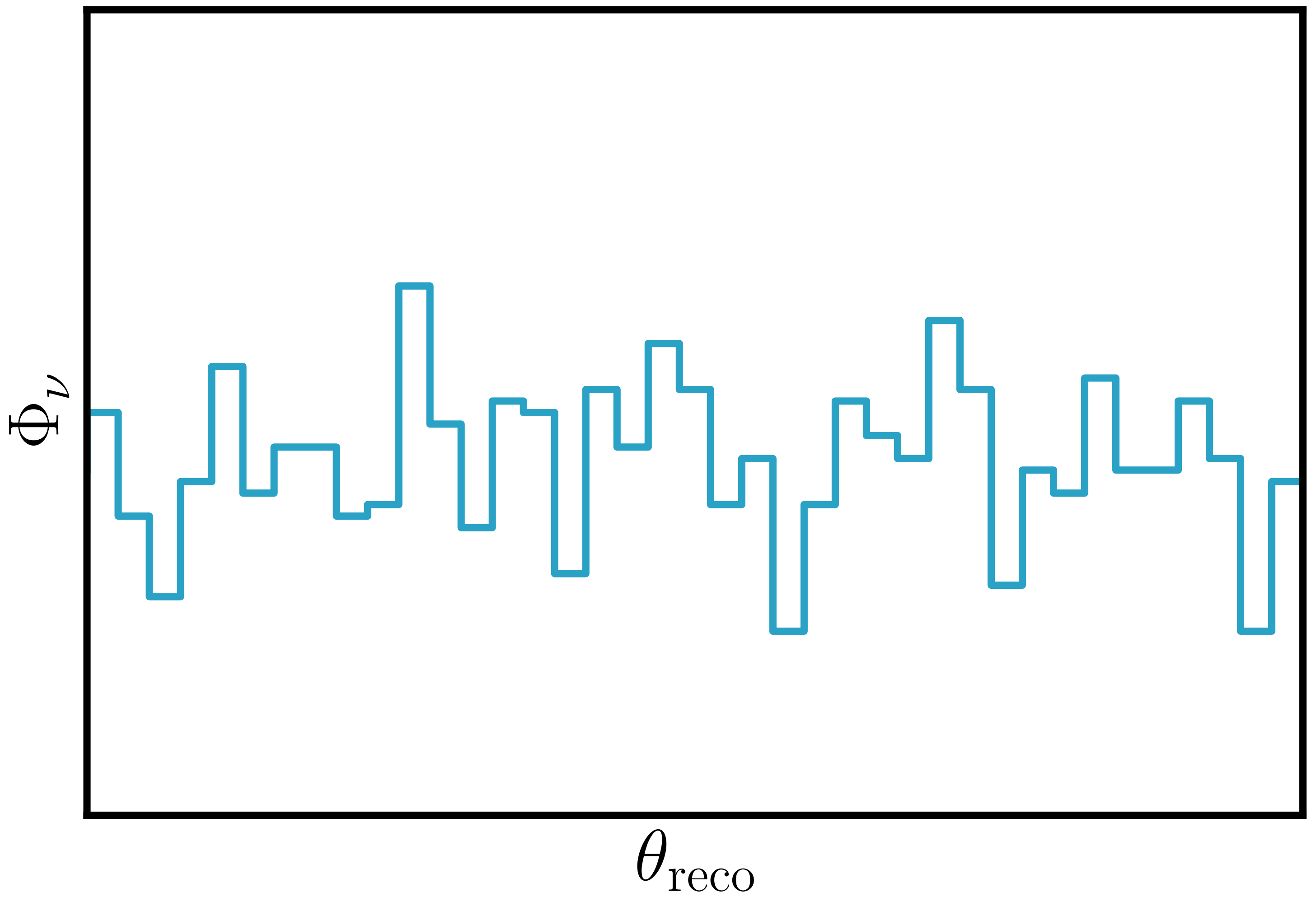
2. Look into the northern sky, using the Earth to filter cosmic-ray muons



Quantities of Interest







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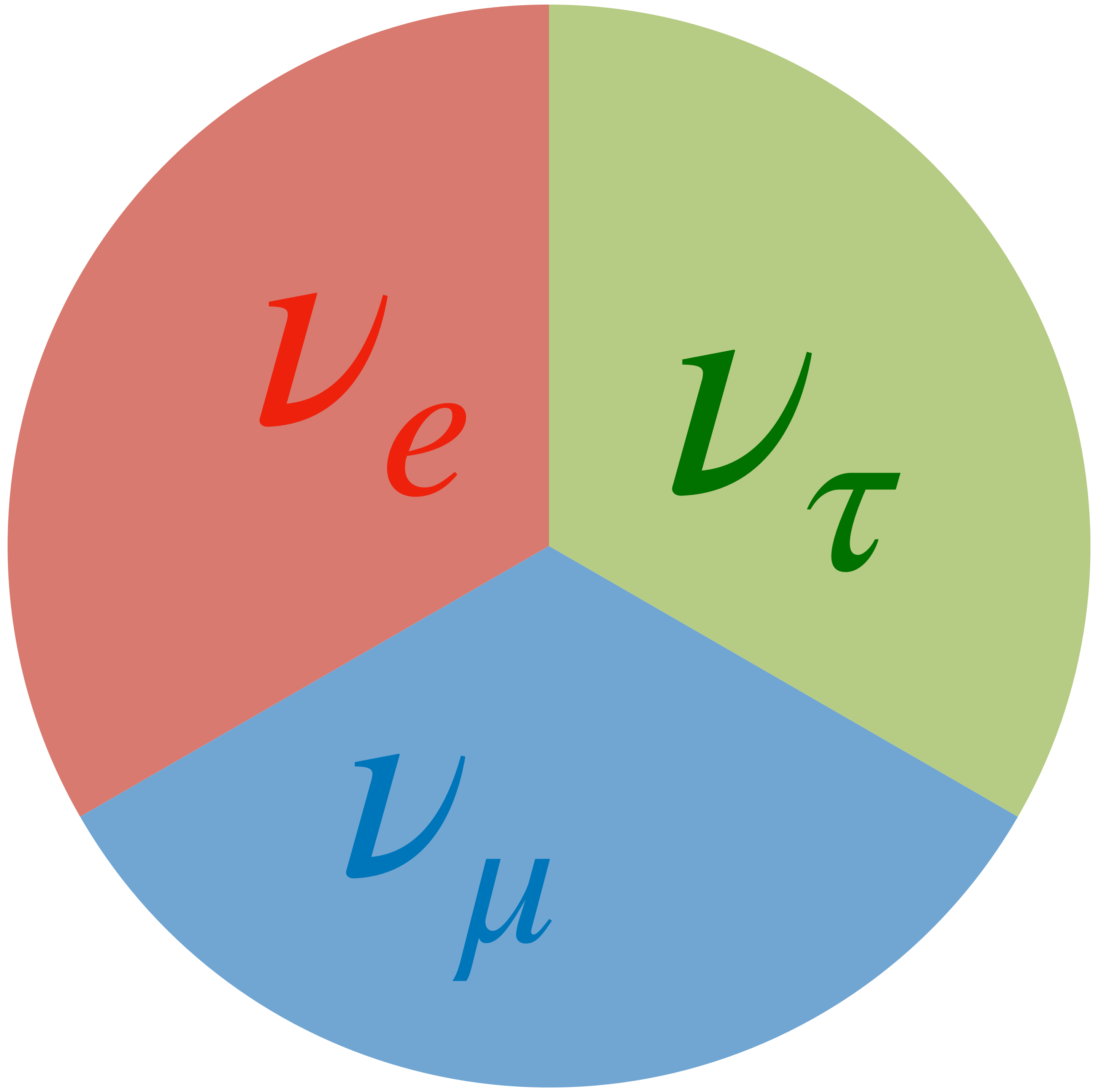

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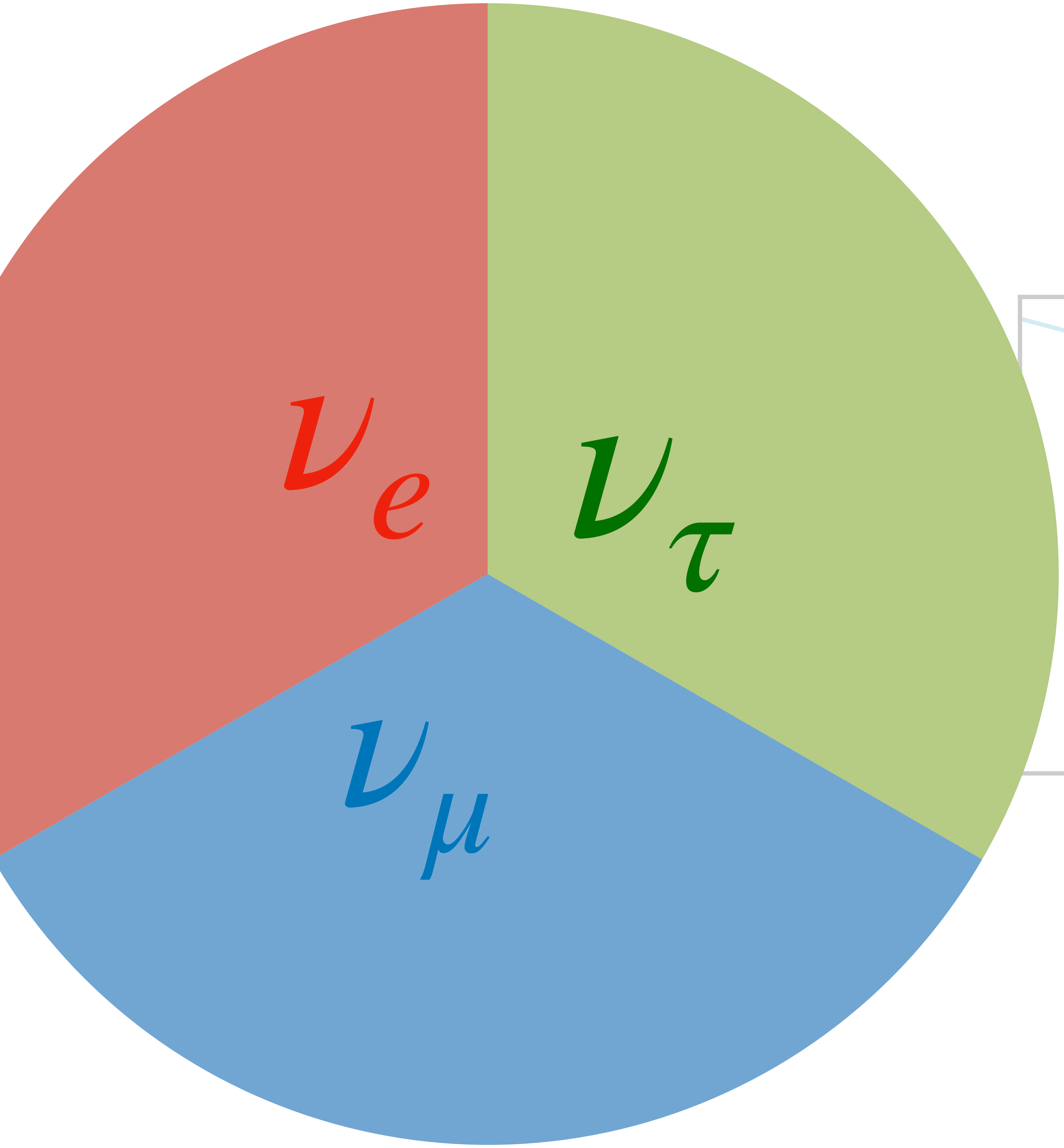

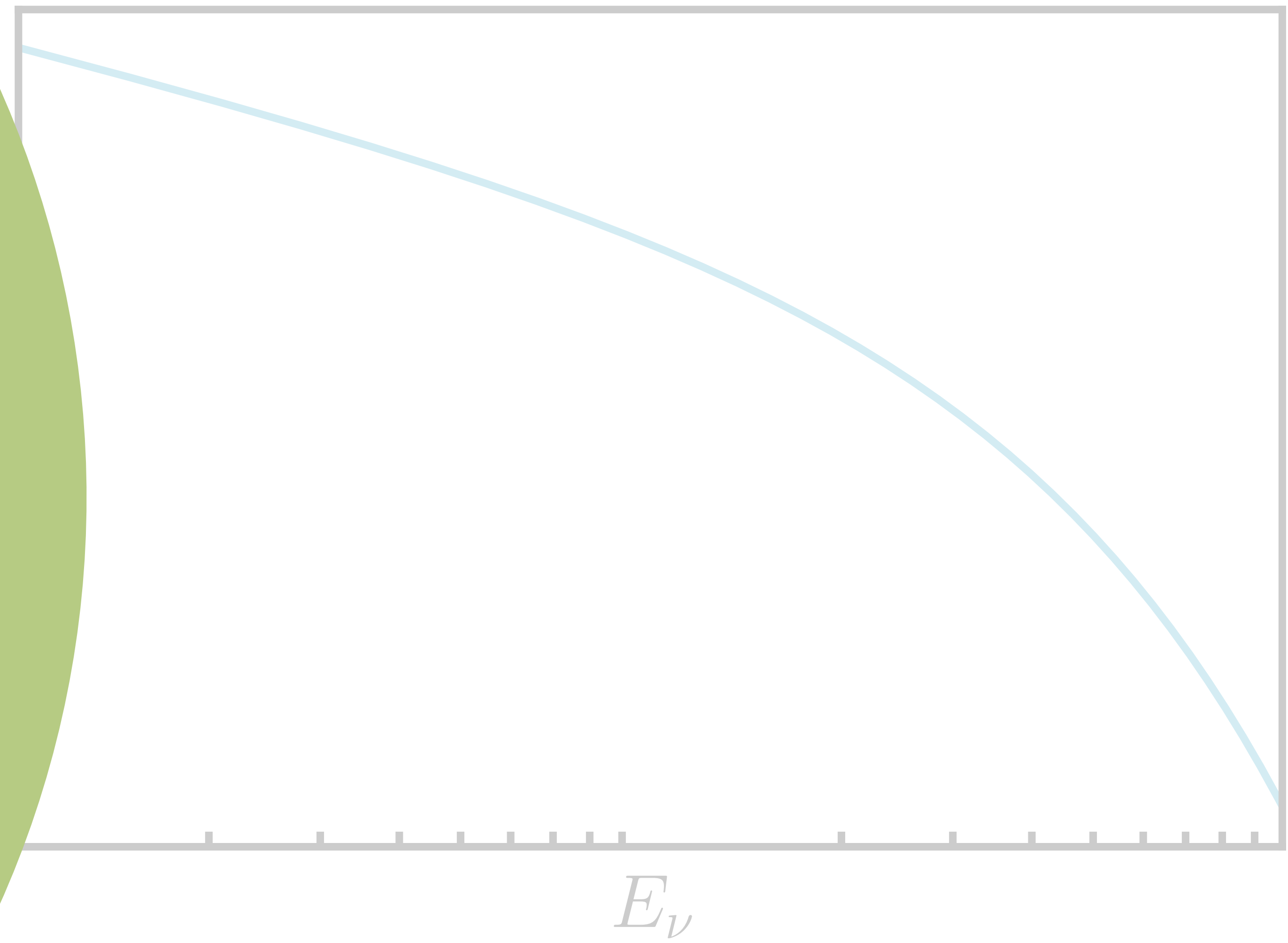

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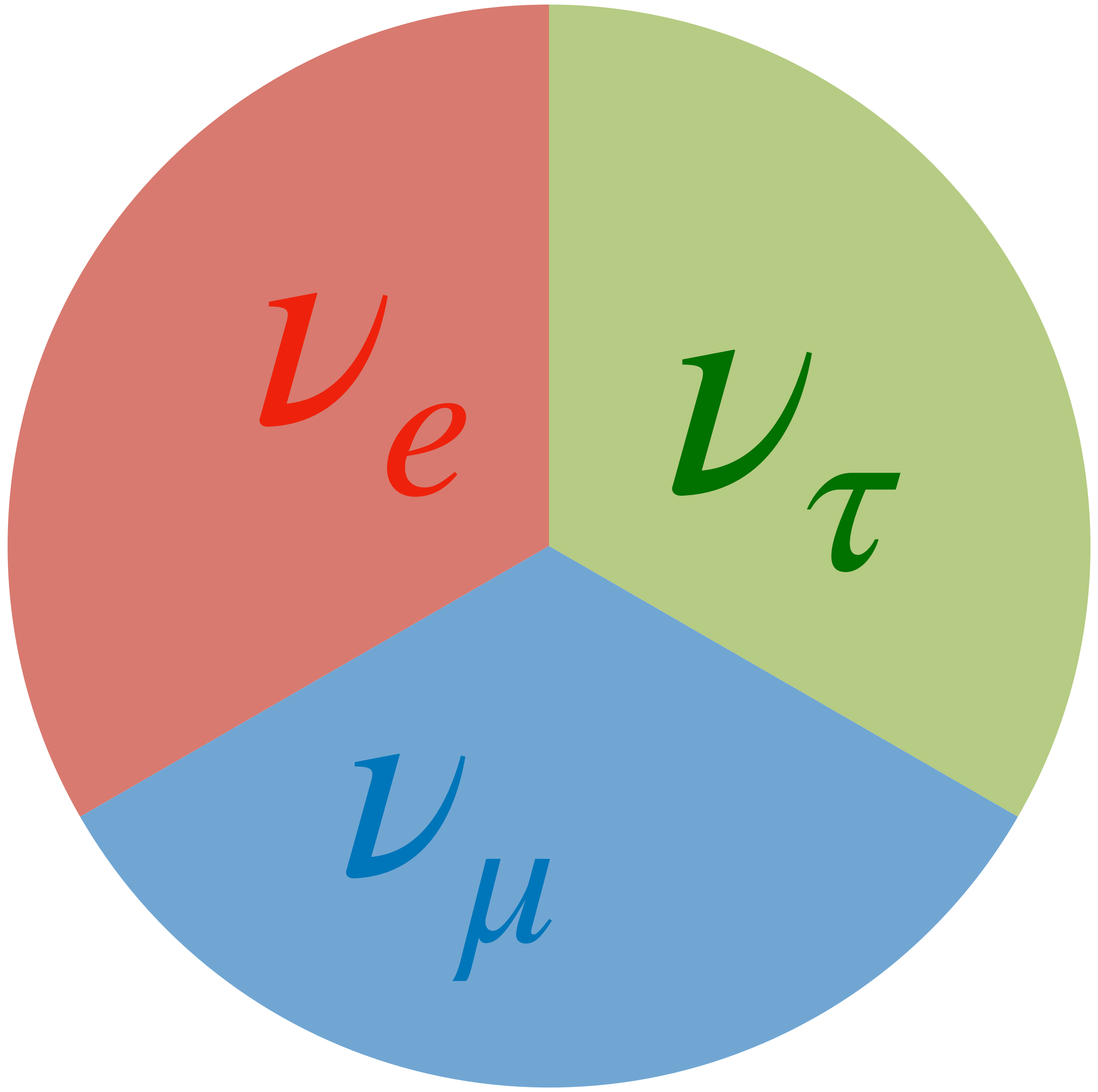

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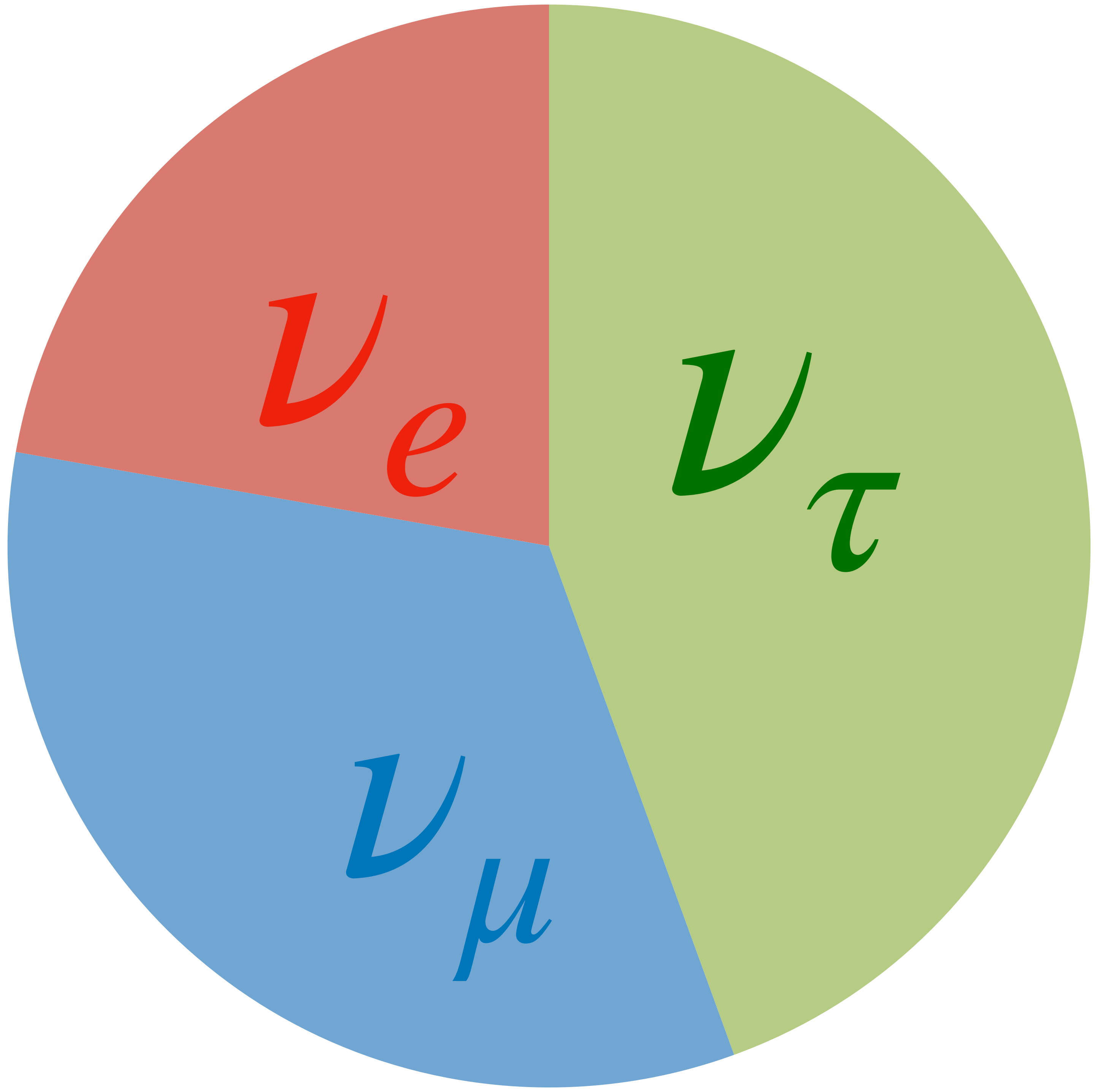

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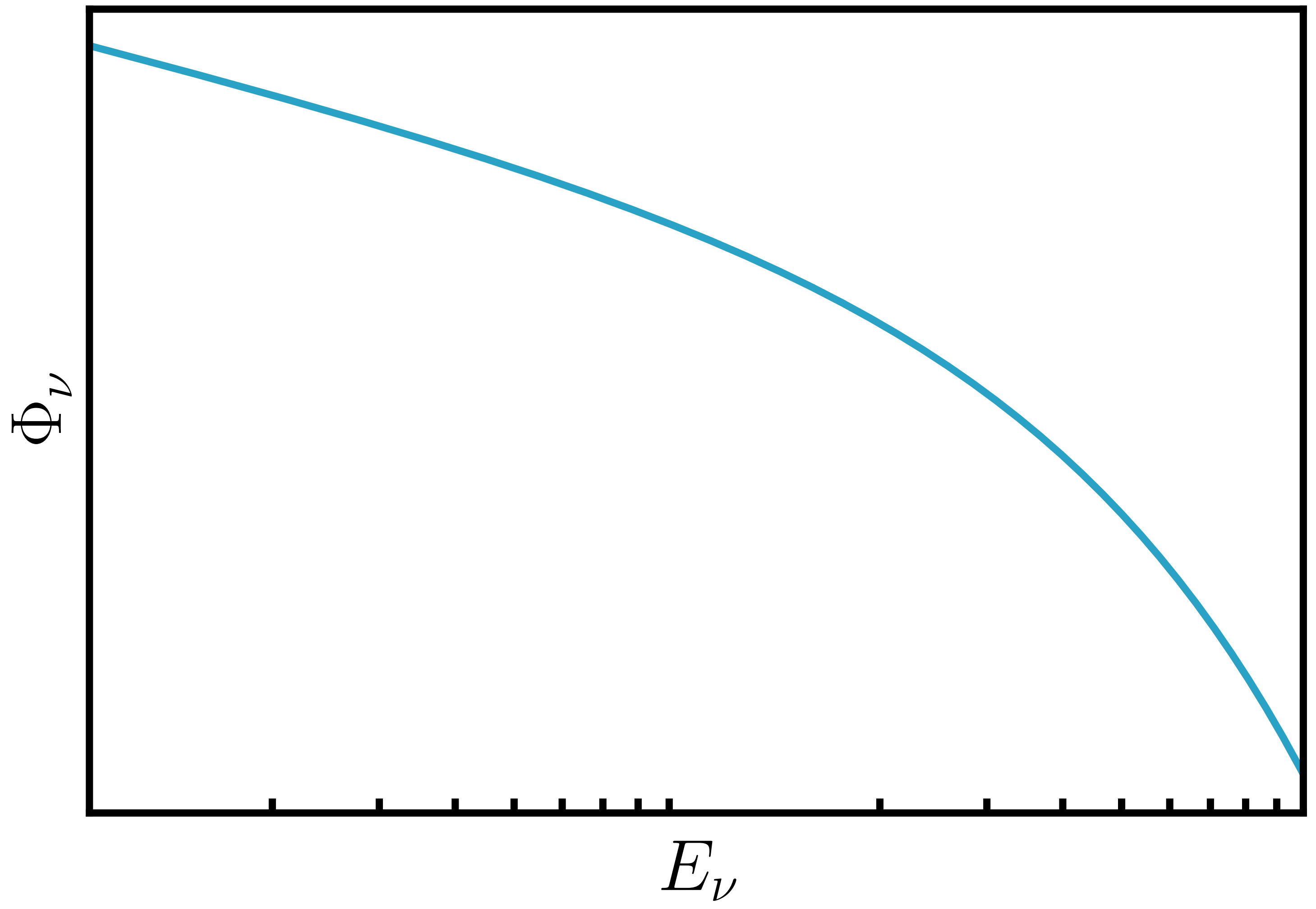

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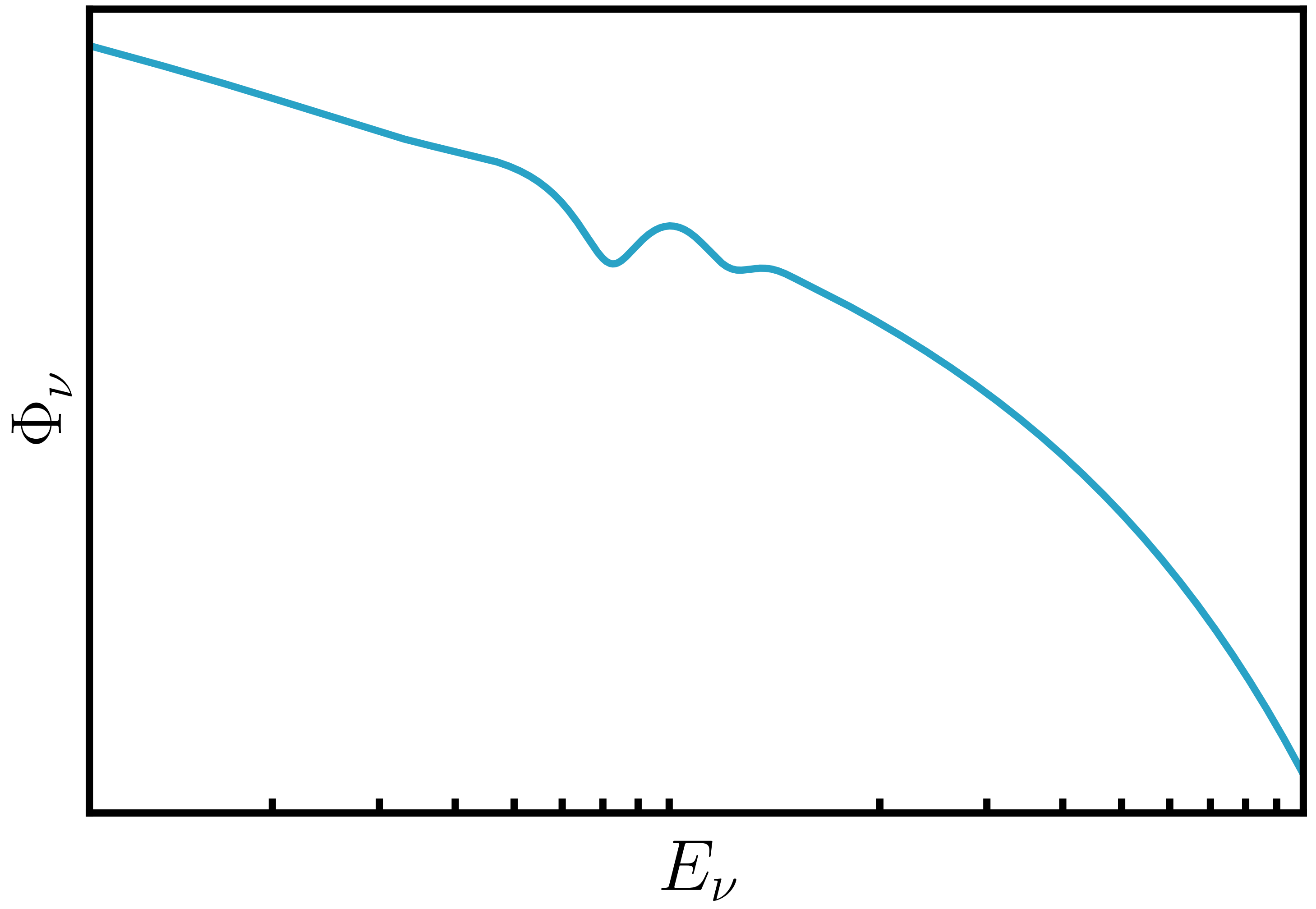

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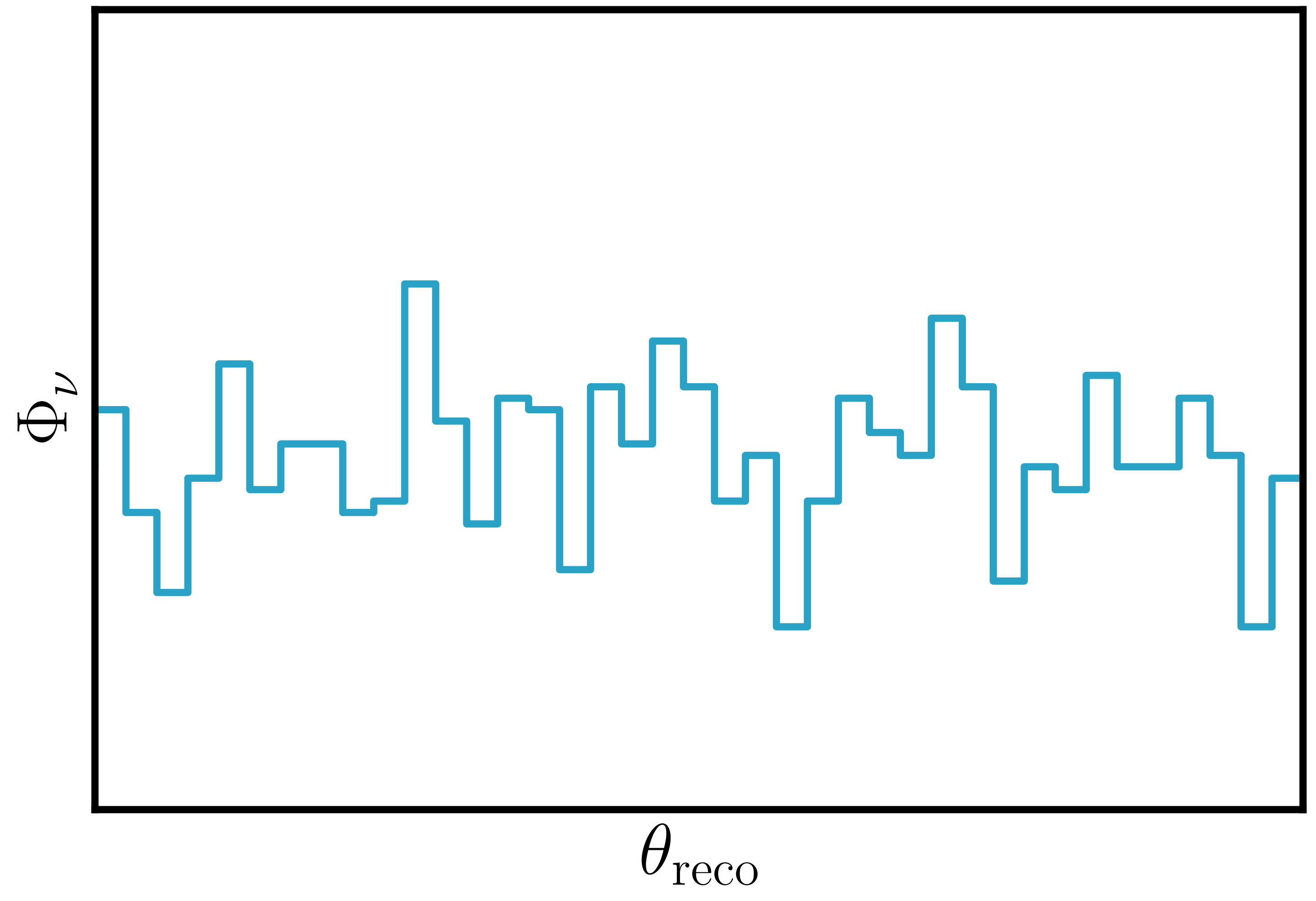

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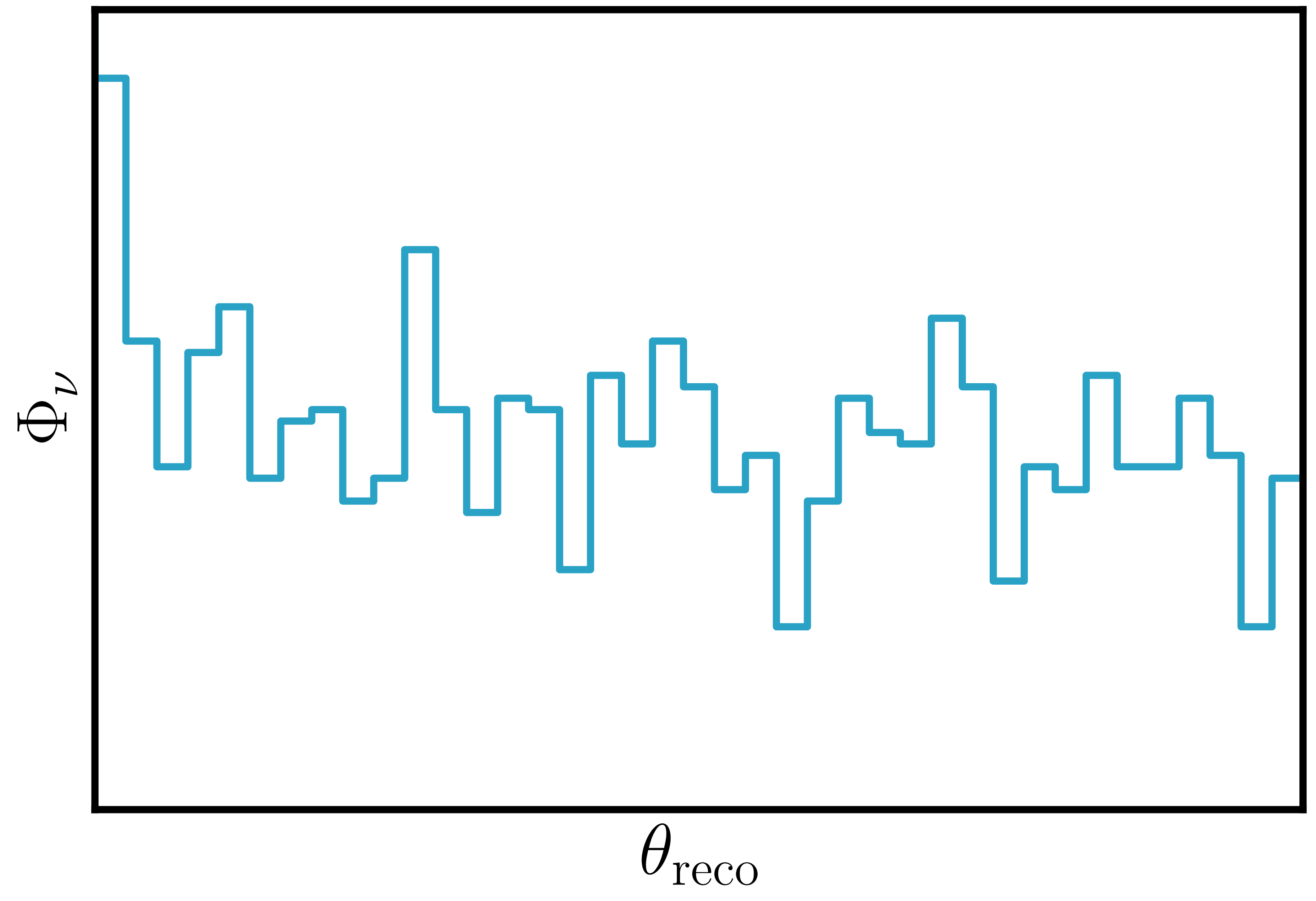

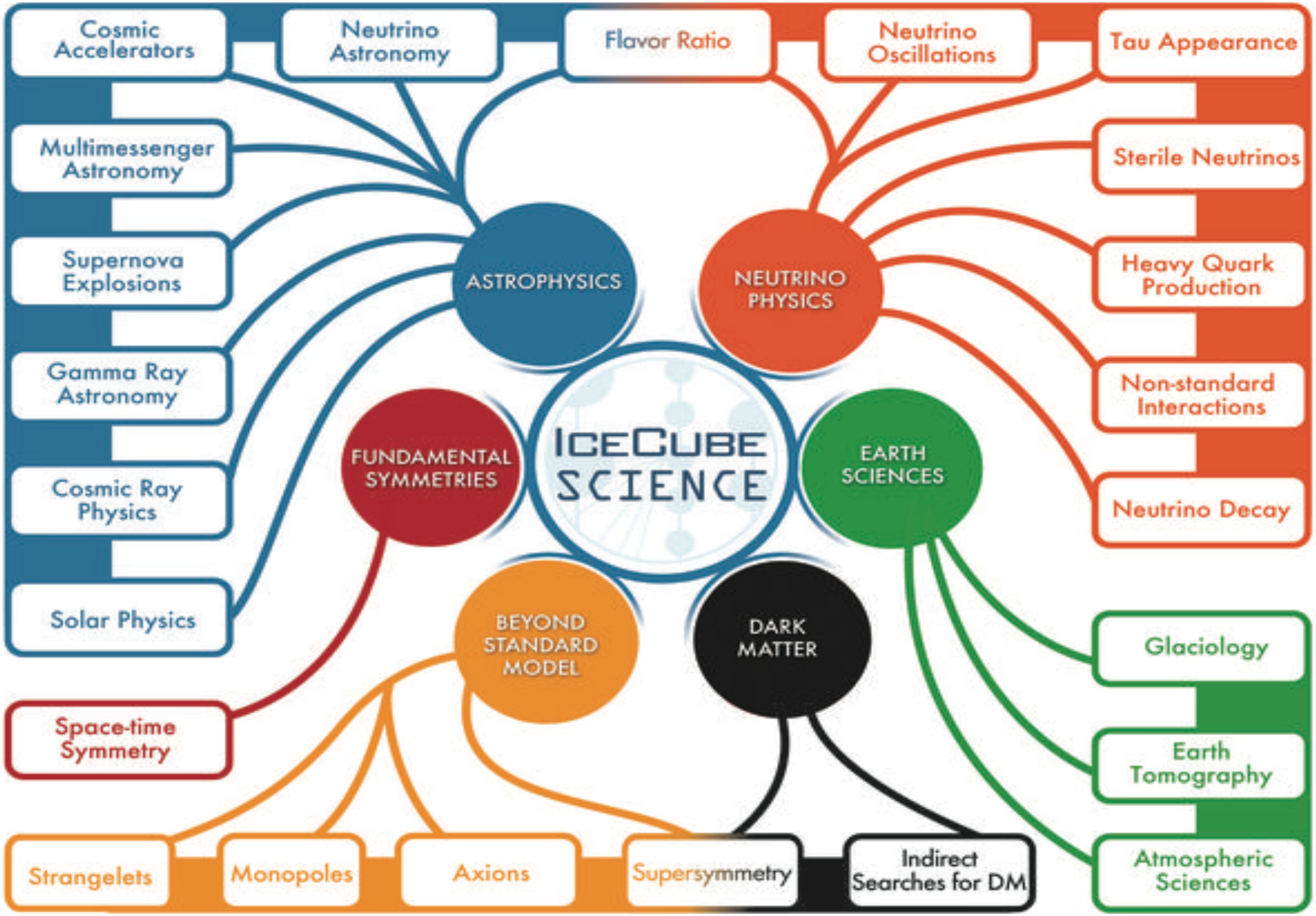

With these variables, IceCube can probe an extremely broad range of physics goals

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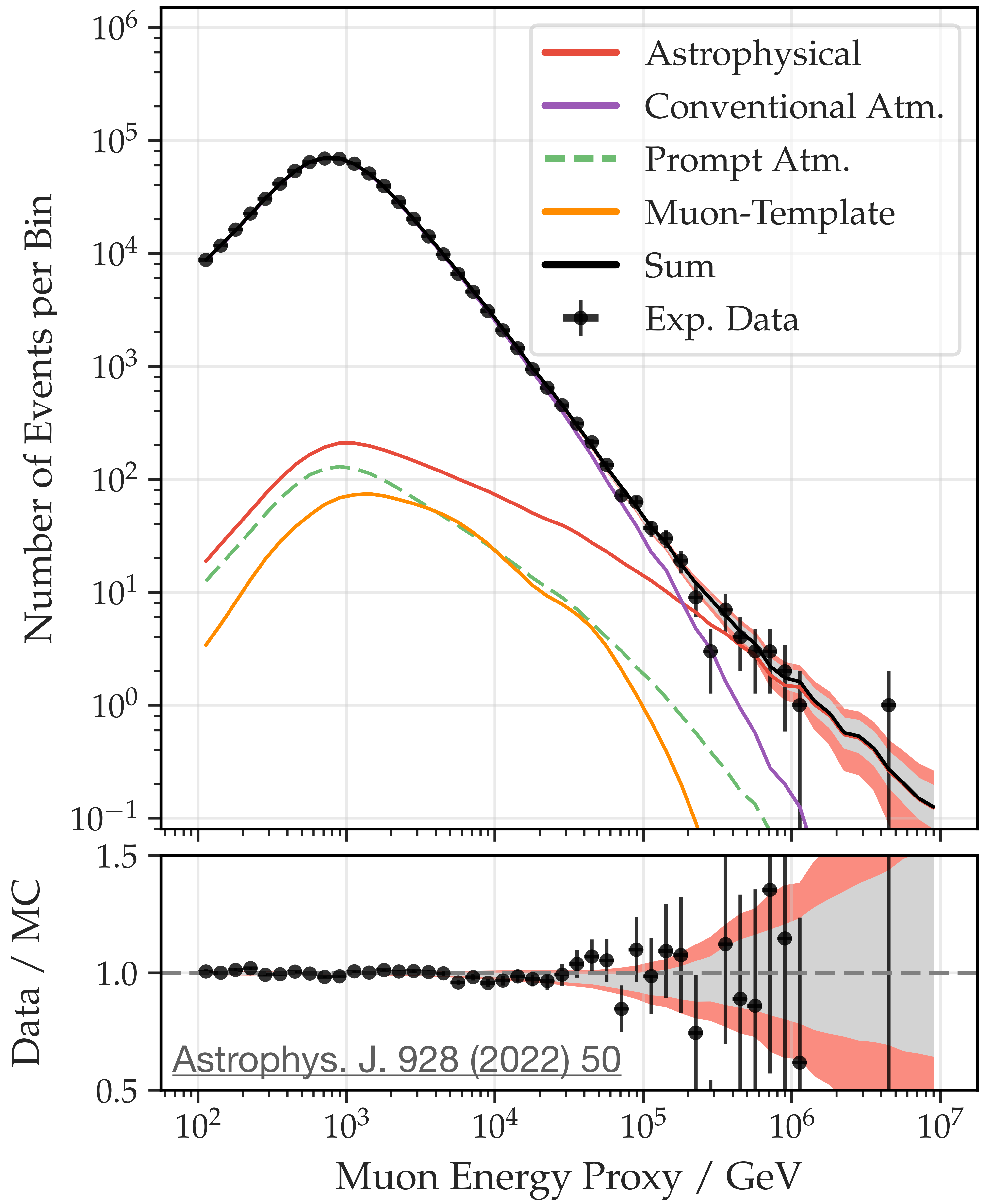
Through-Going Tracks

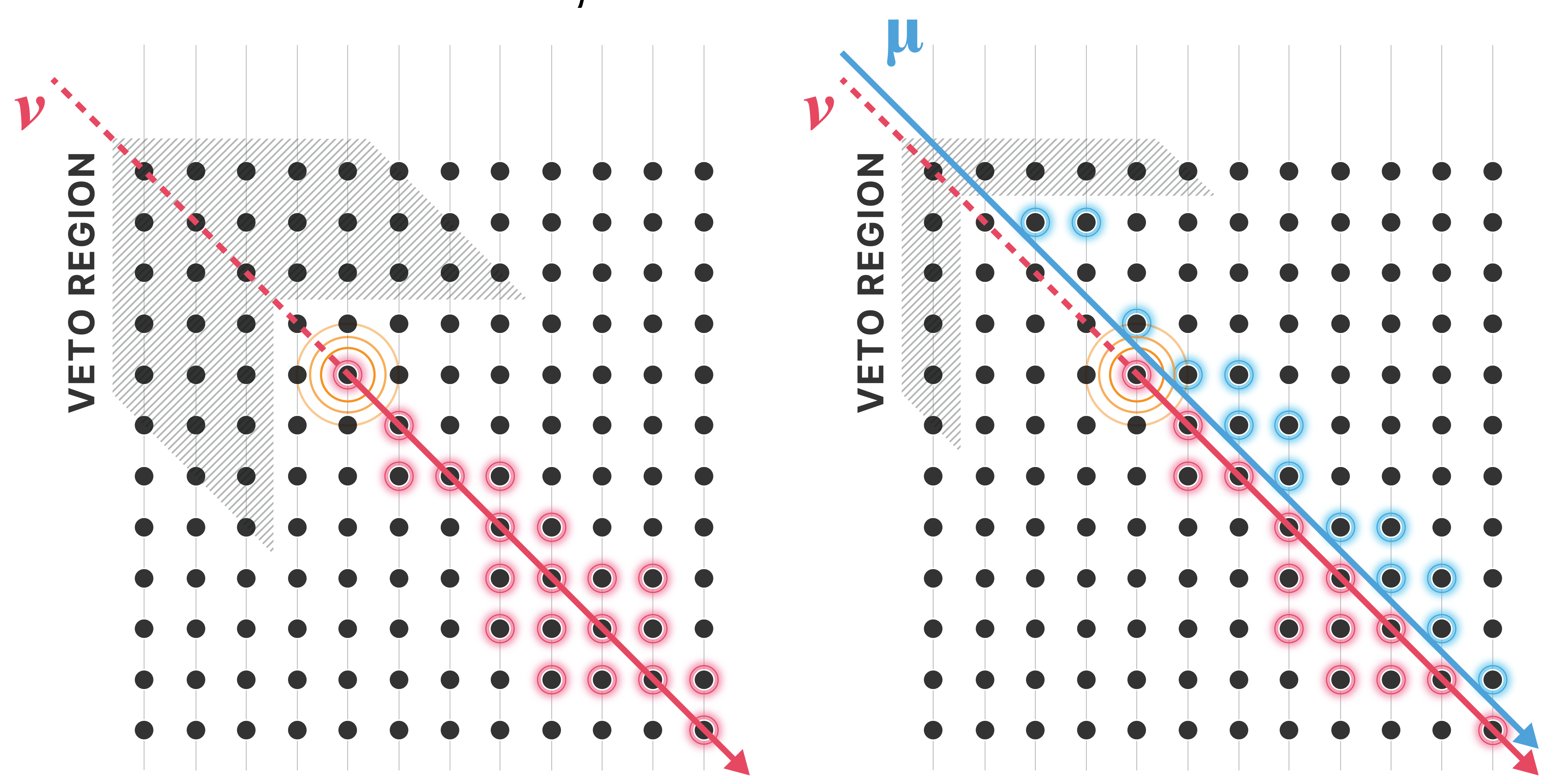
The Northern-Sky ν_μ

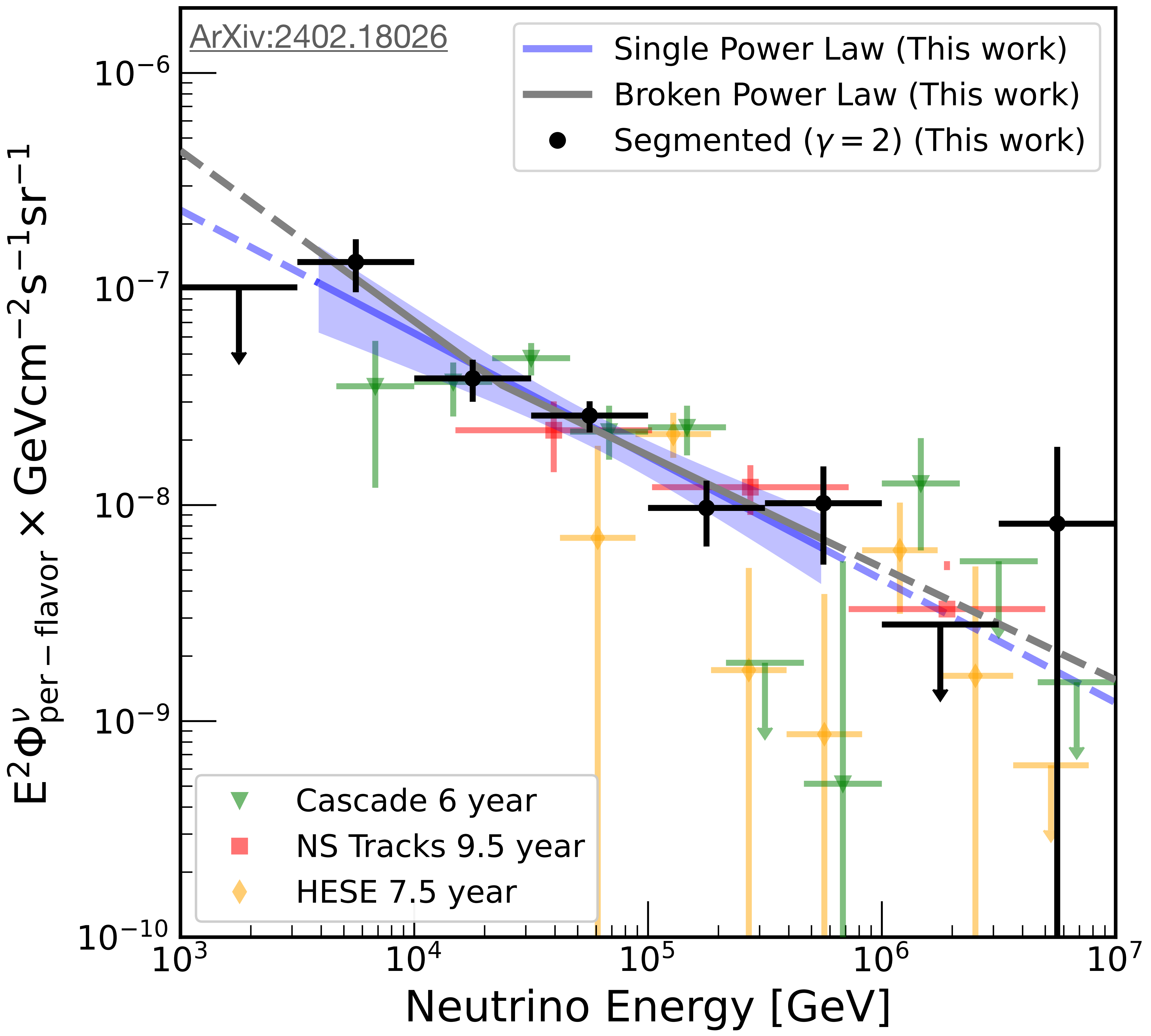
- Track-like events in the Northern Sky where neutrino events are dominant
- Excess of neutrinos above atmospheric background 80 TeV
- This analysis favors a harder energy spectrum, with $\gamma = 2.28$



Enhanced Starting Tracks

The Southern-Sky ν_μ

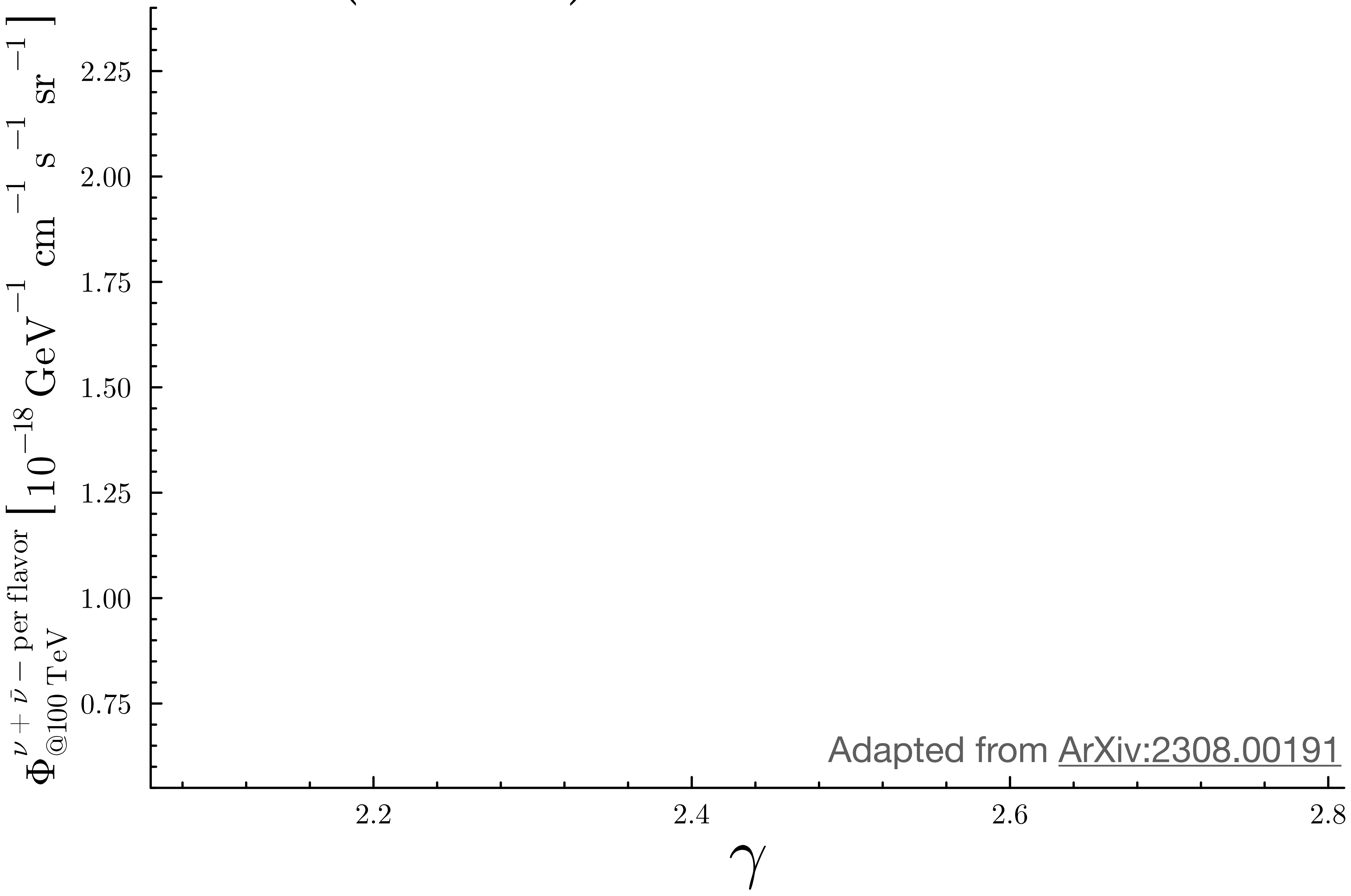




- Dynamic veto region allows atmospheric muons and neutrinos to be efficiently filtered
- Best selection of tracks in the Southern Sky
- Best fit spectral index at $\gamma = 2.58$

Characterizing the Diffuse Flux

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



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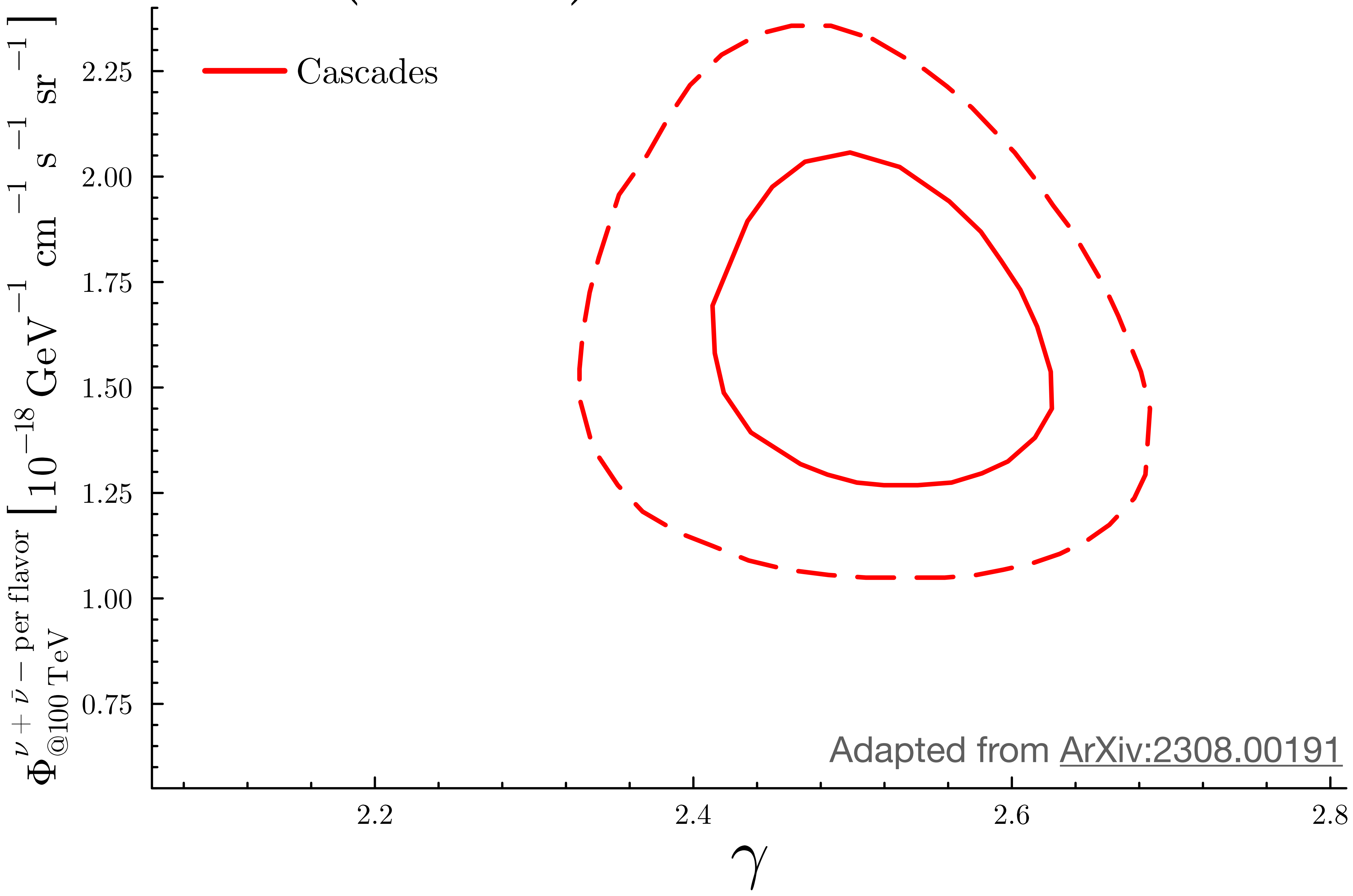

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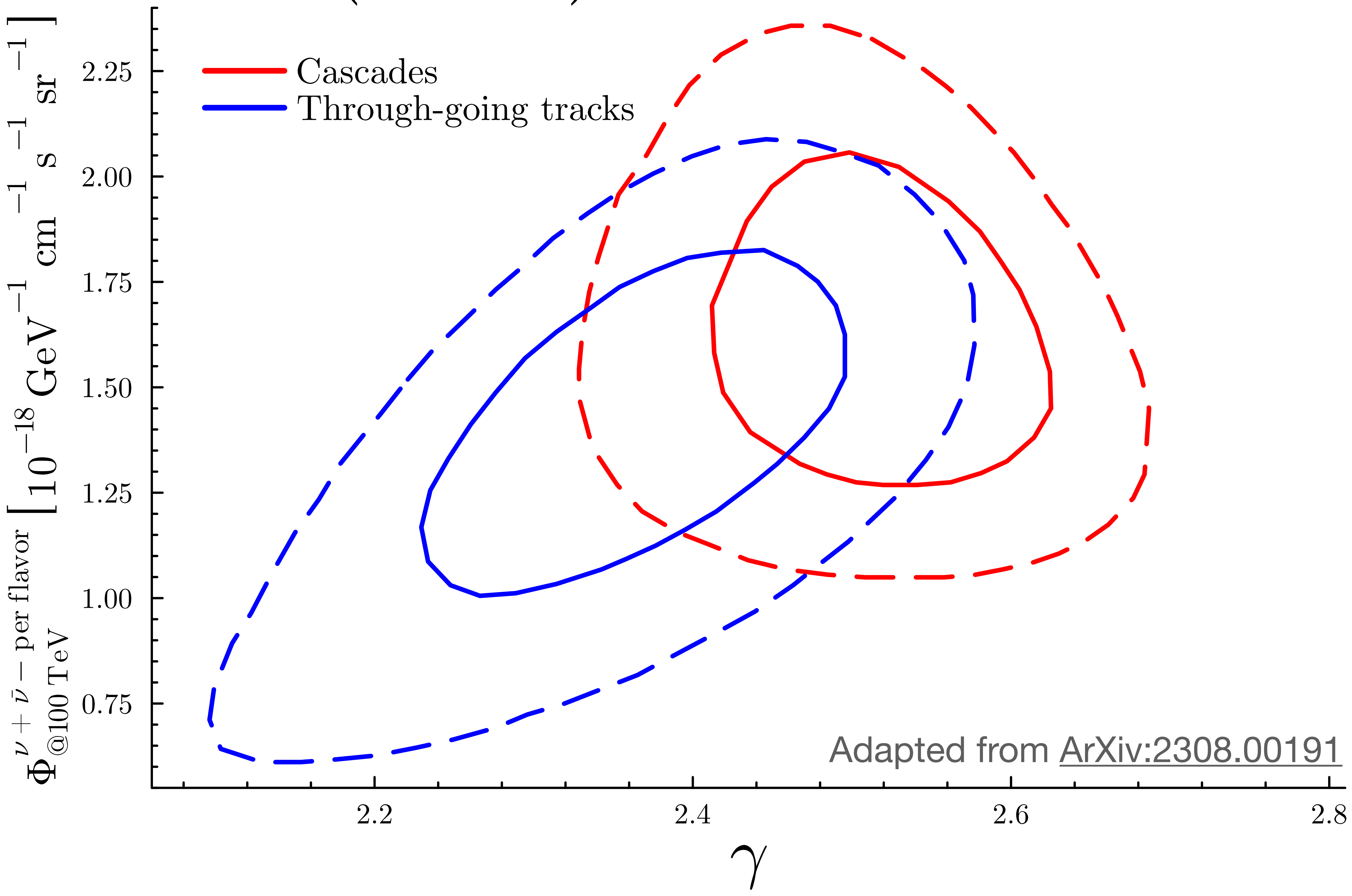

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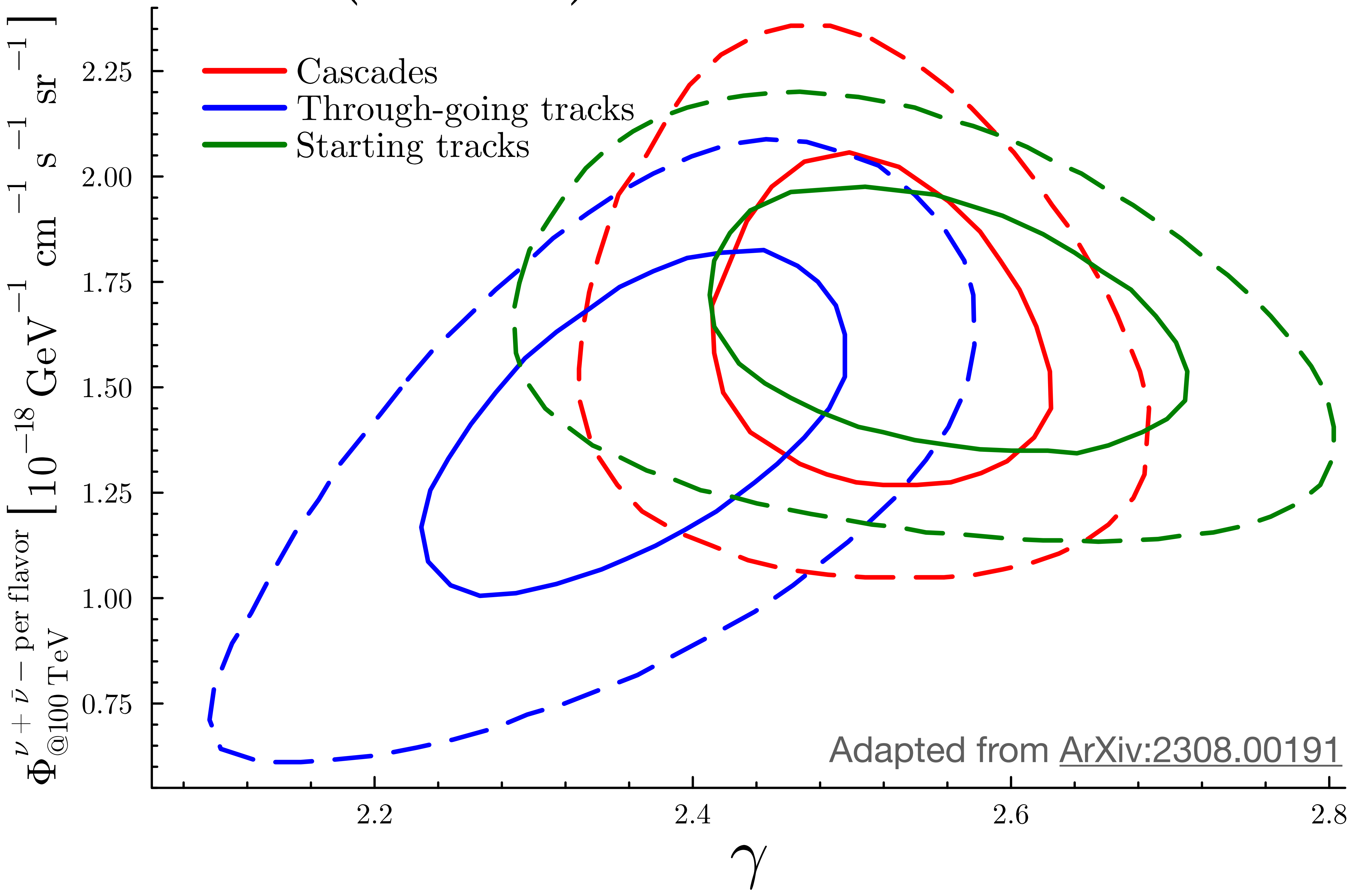

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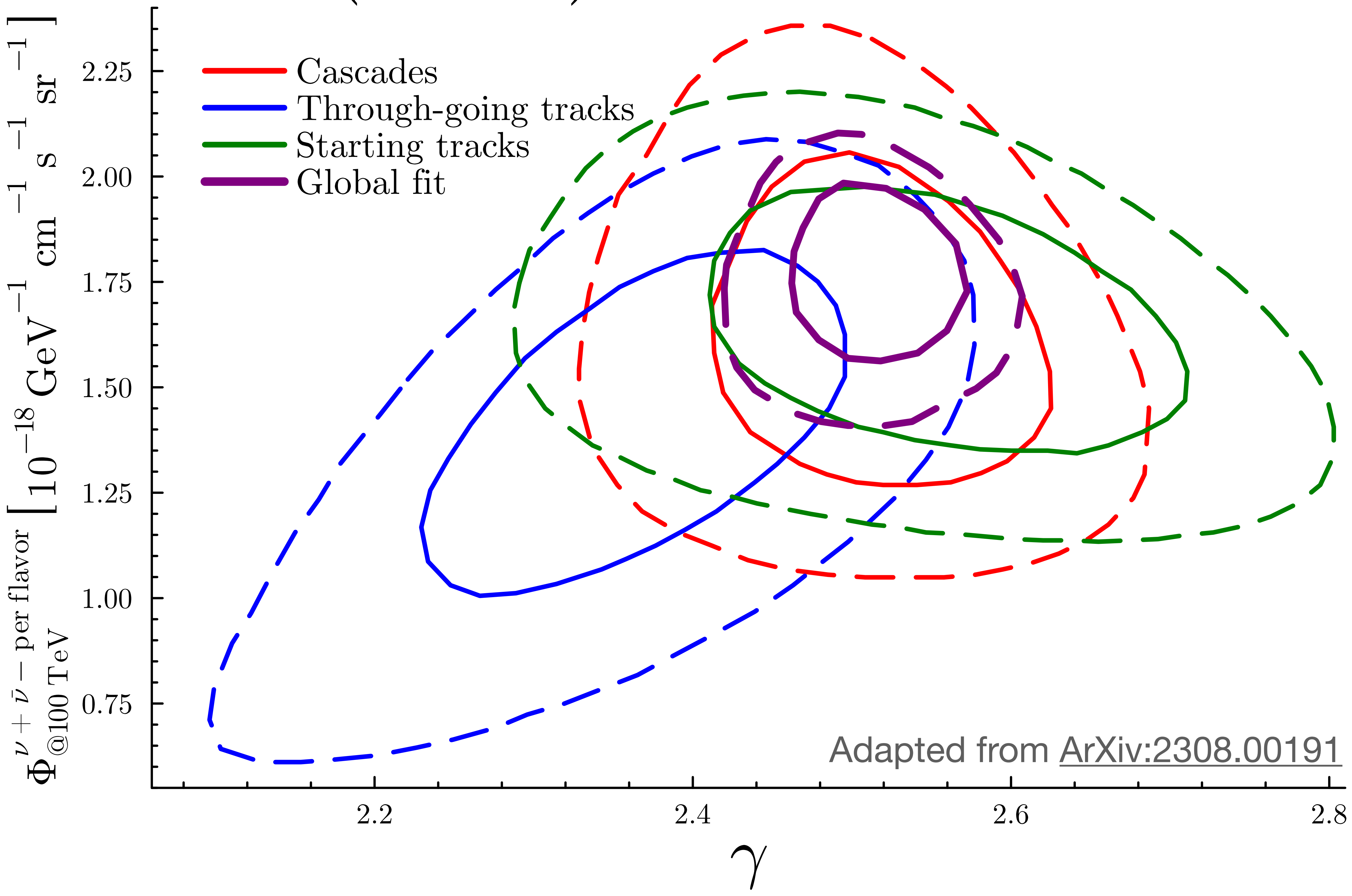

Global fits are consistent with a single power lower law with $\gamma = 2.5$.

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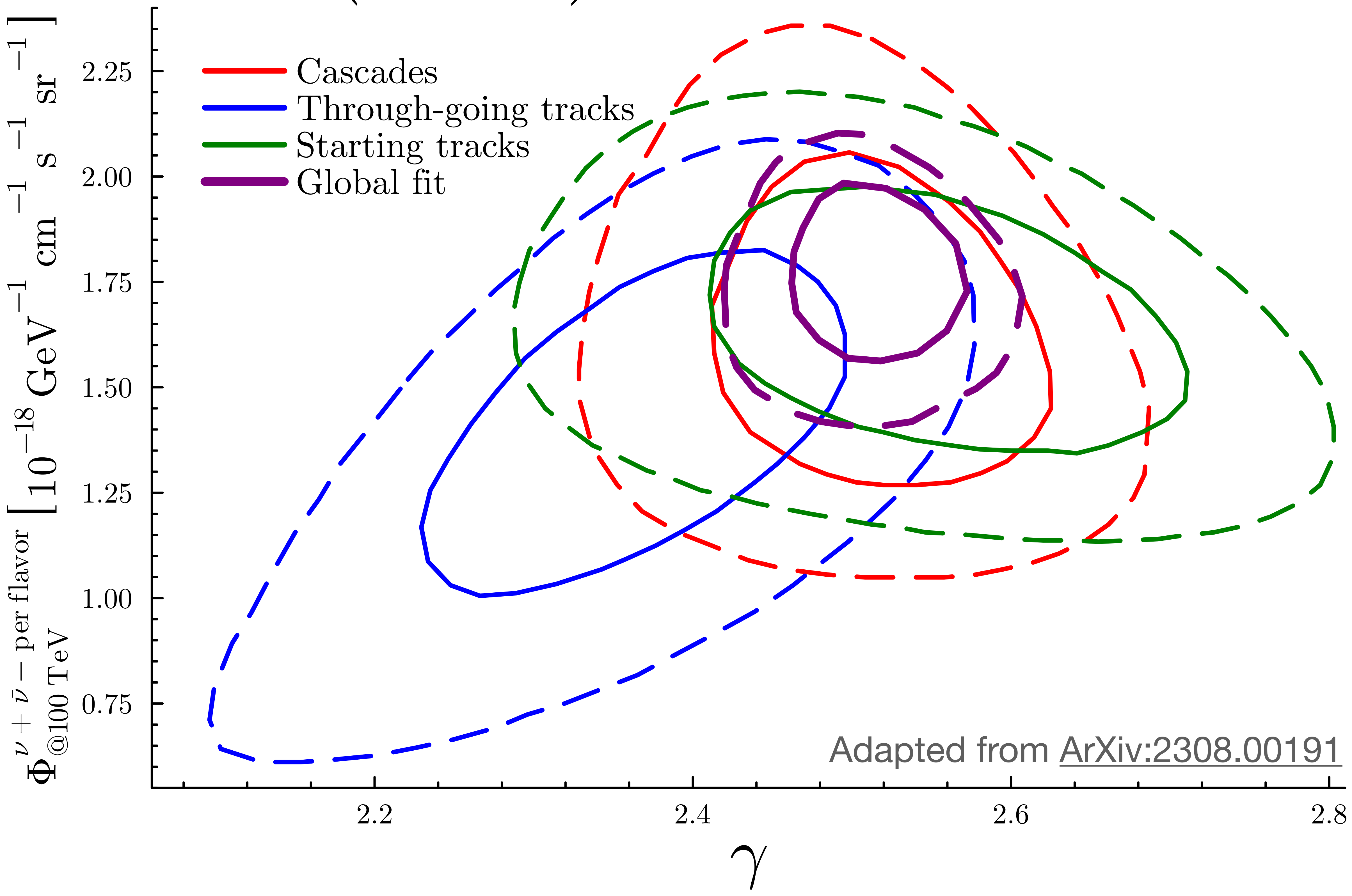

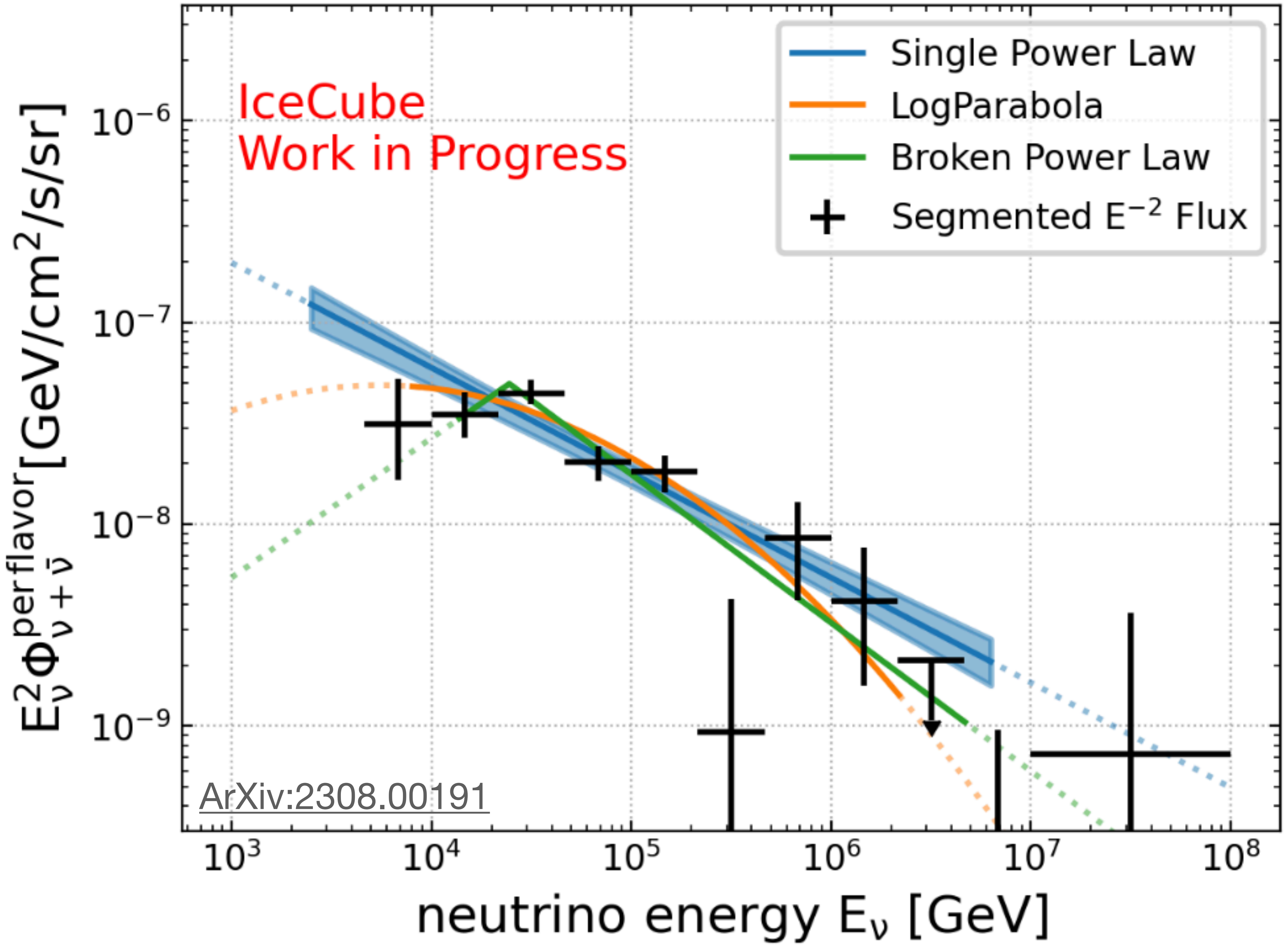

Global fits are consistent with a single power lower law with $\gamma = 2.5$. However, the data prefer more complex shapes at around 2σ significance

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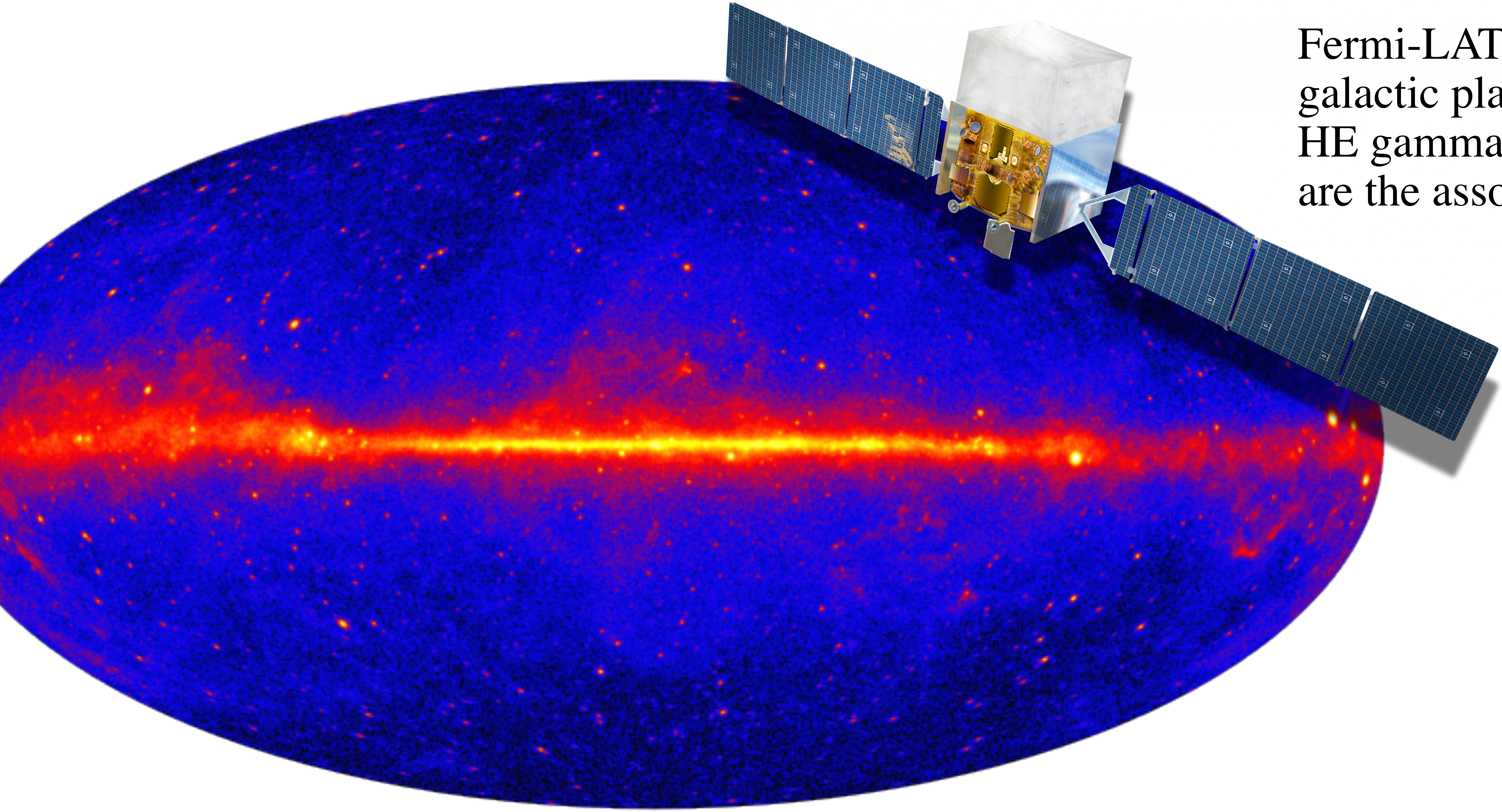
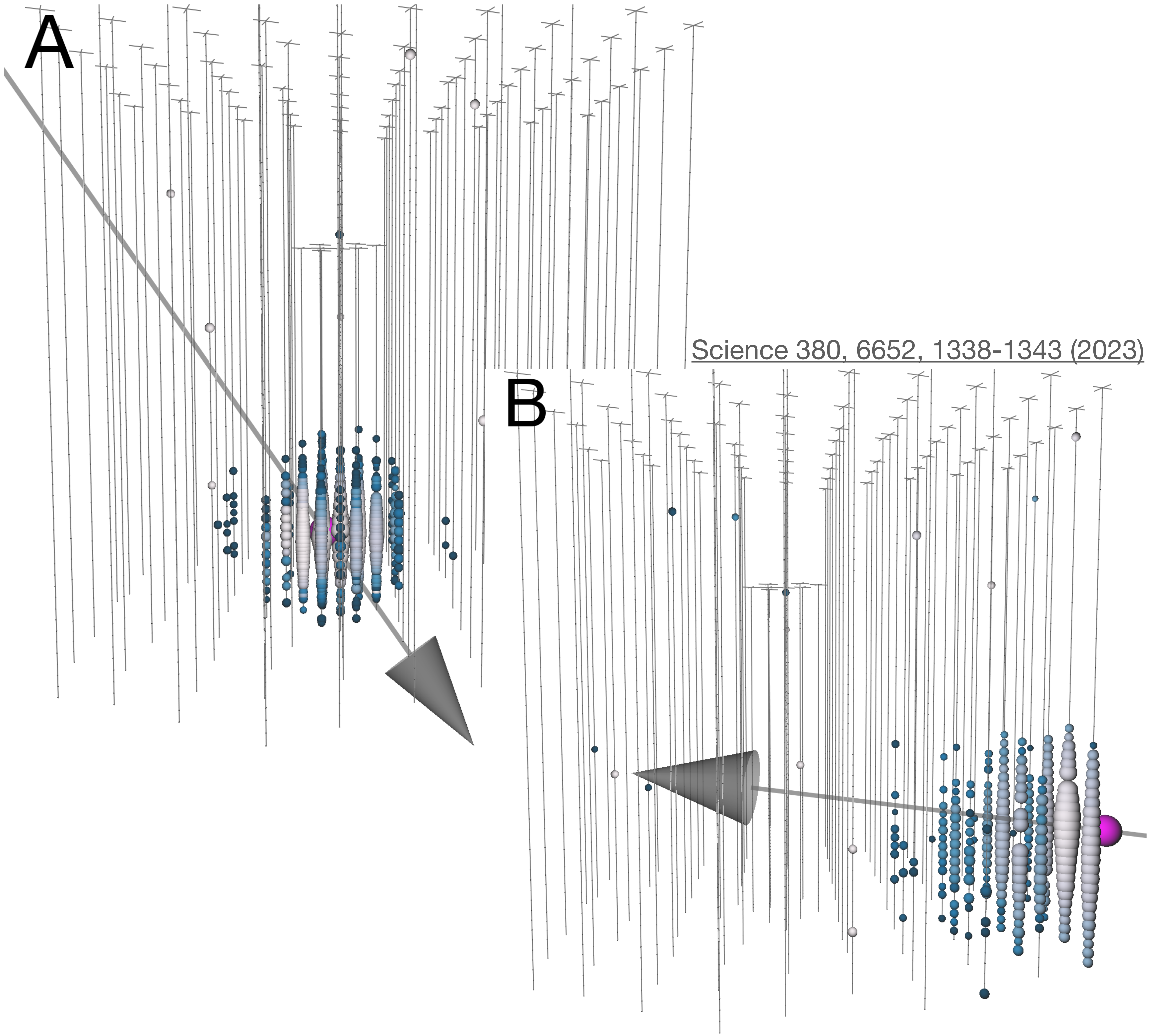
Does Our Galaxy Shine in Neutrinos ?



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

Swamped in the Southern Sky

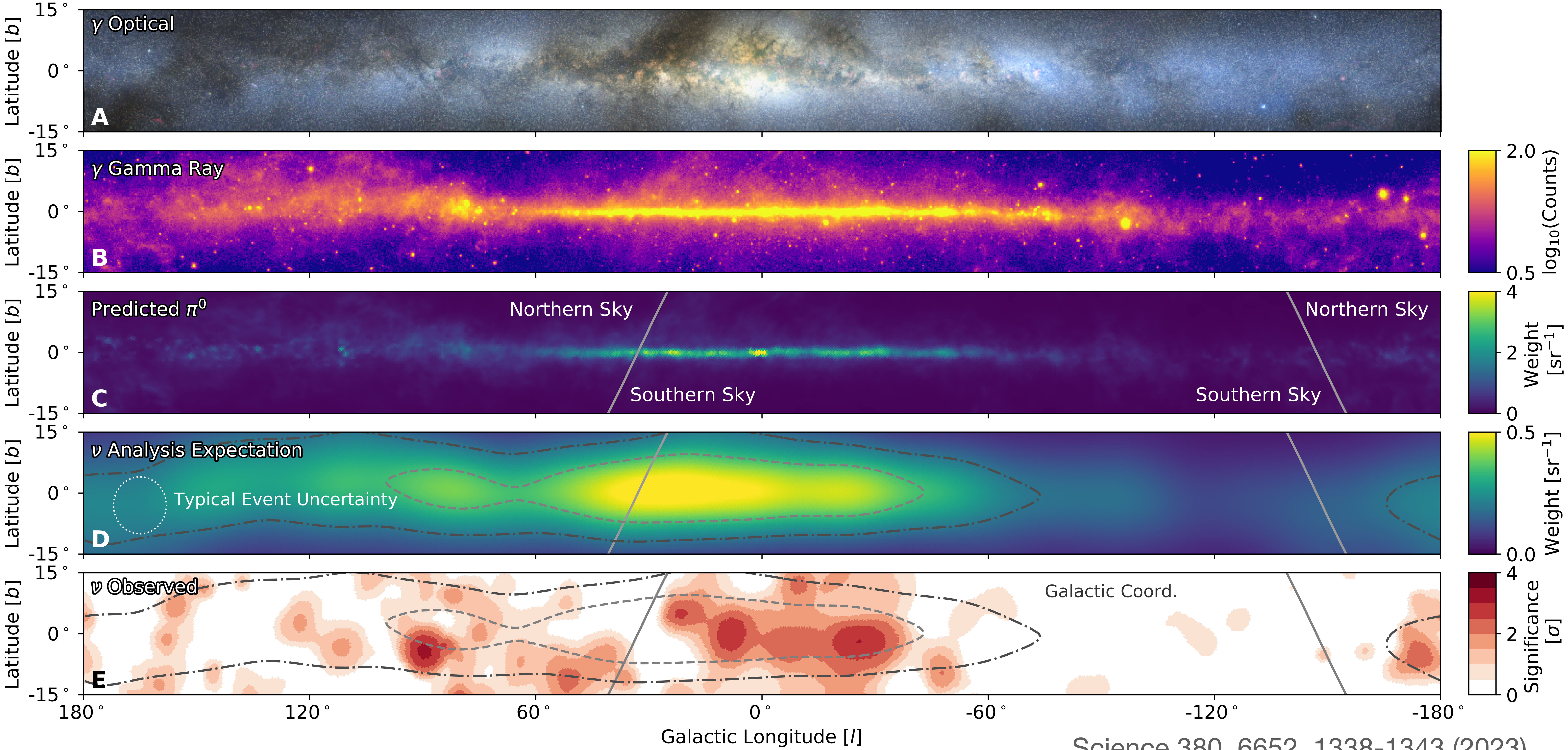
- Since much of the Galactic Plane, including the Galactic Center, we will be overwhelmed by atmospheric muons
- Restricting ourselves to cascades will allow us to filter more easily
  - Updated, ML-based reconstruction improved cascade pointing to ~7°
  - Order-of-magnitude improvement in acceptance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



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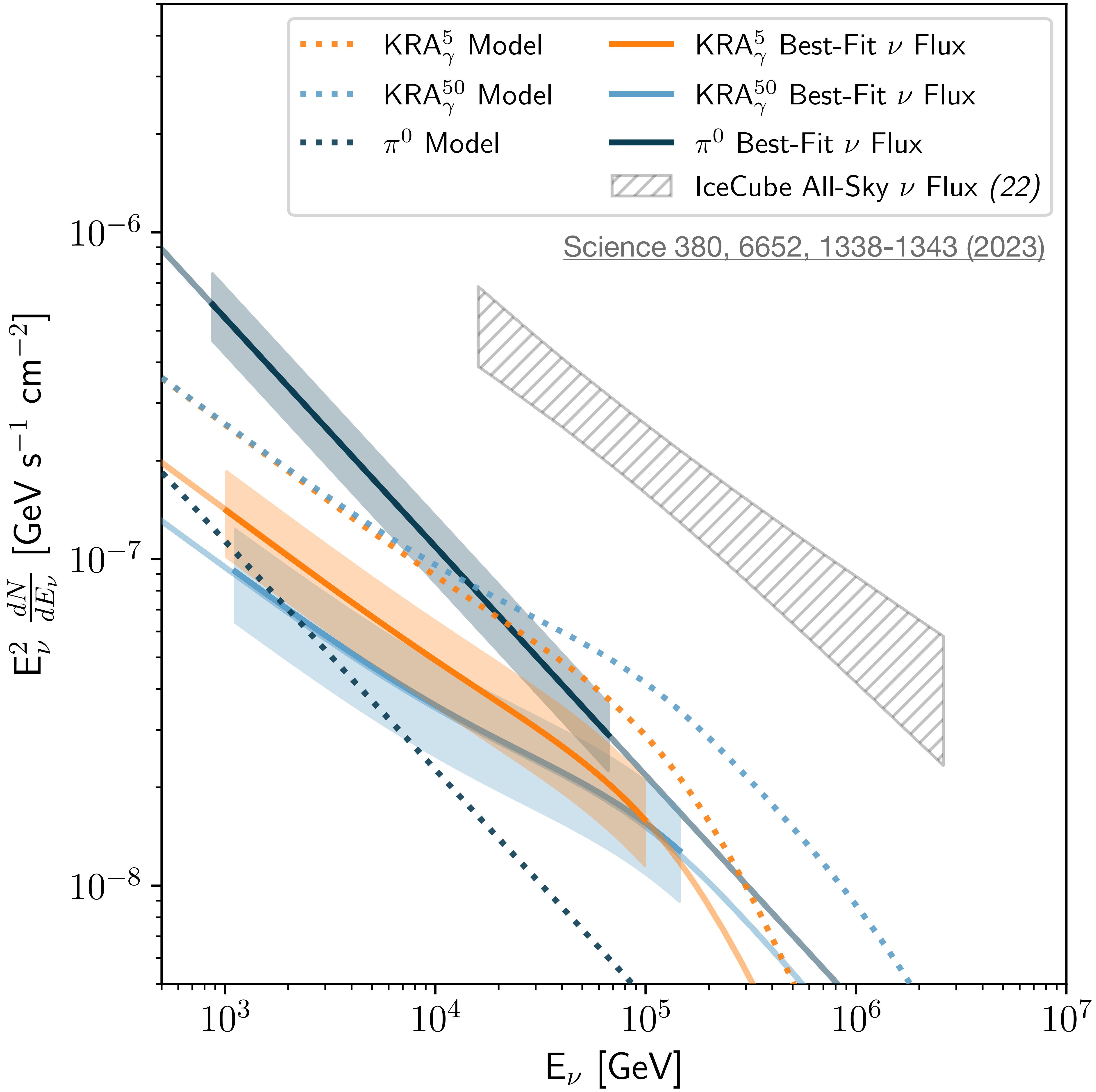
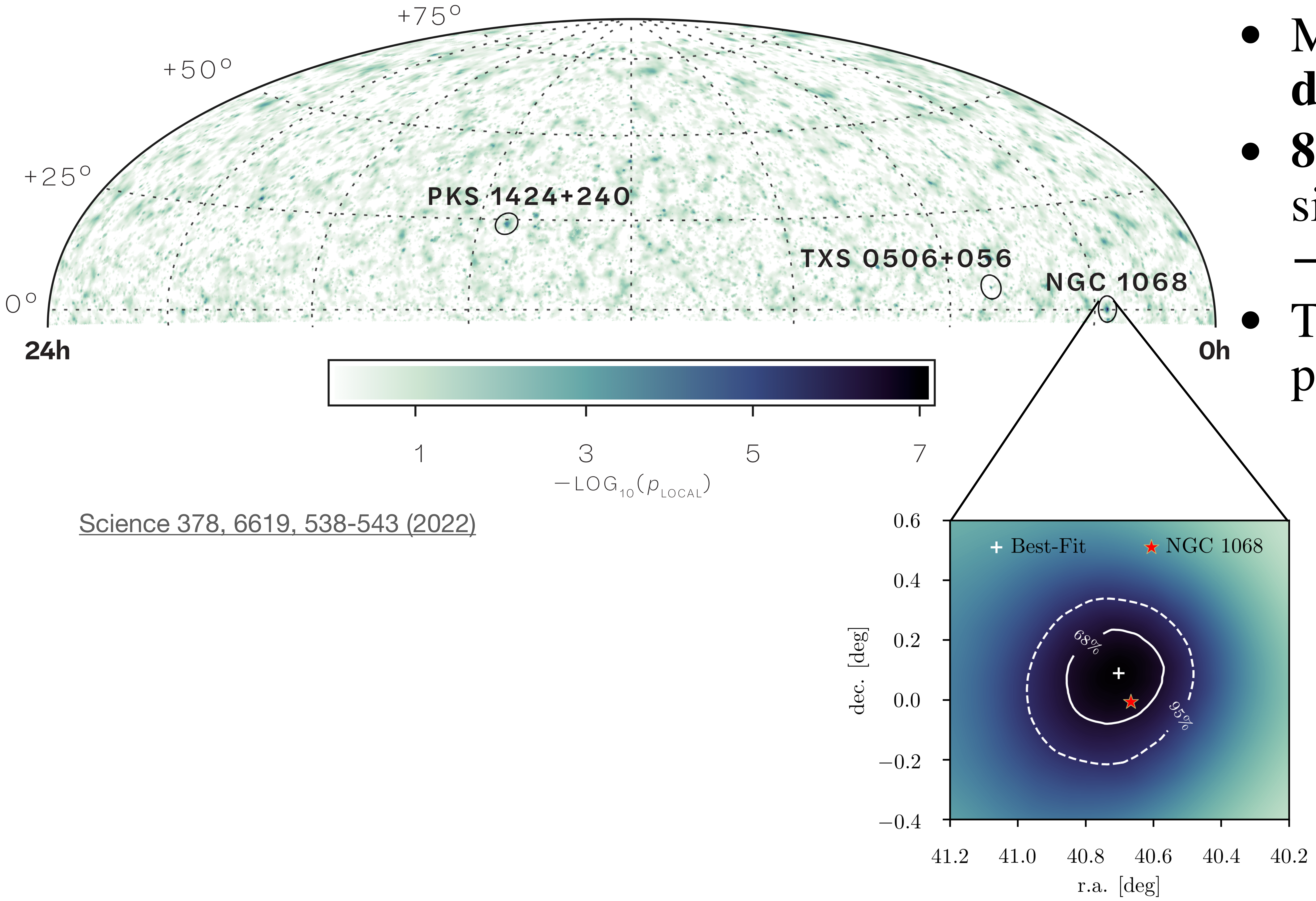
Galactic Contribution to Diffuse Flux

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

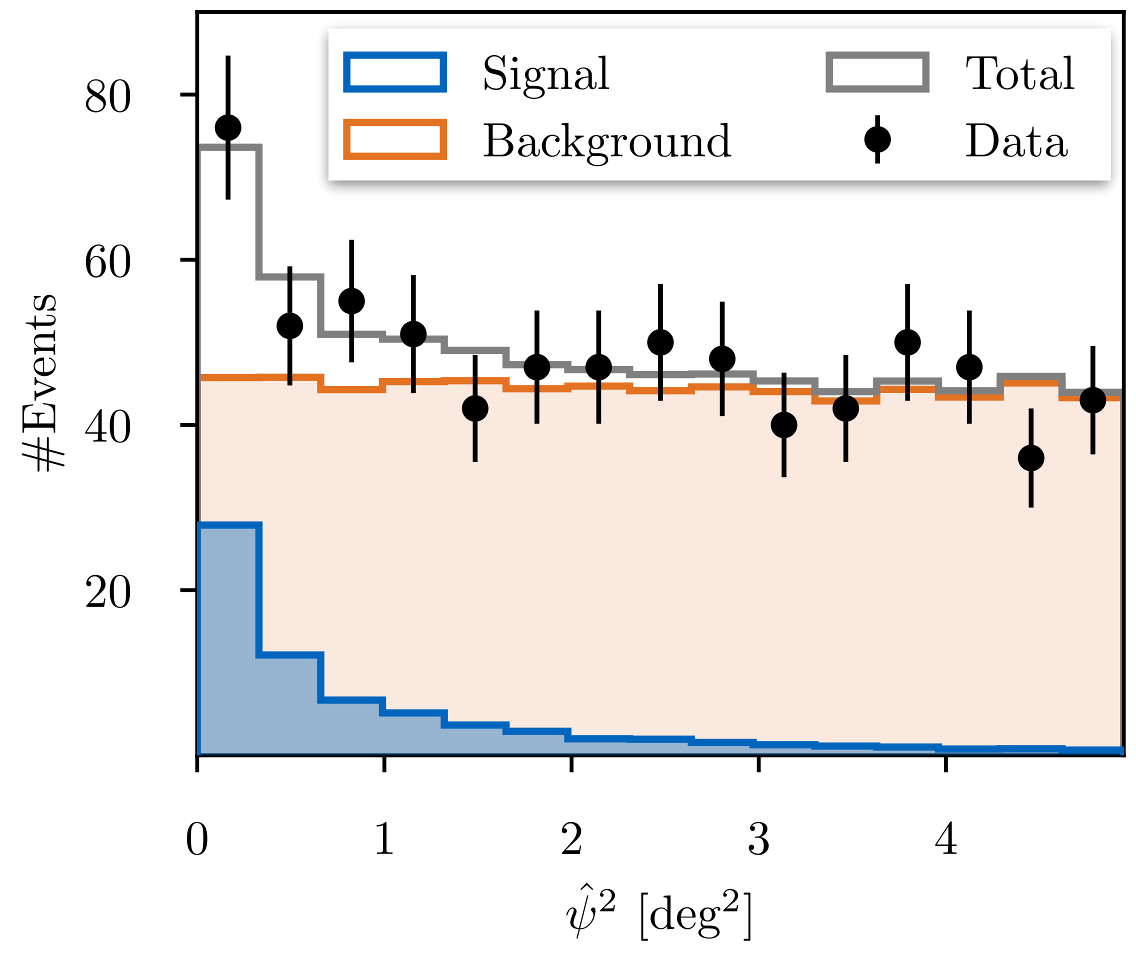


Northern-Sky Search



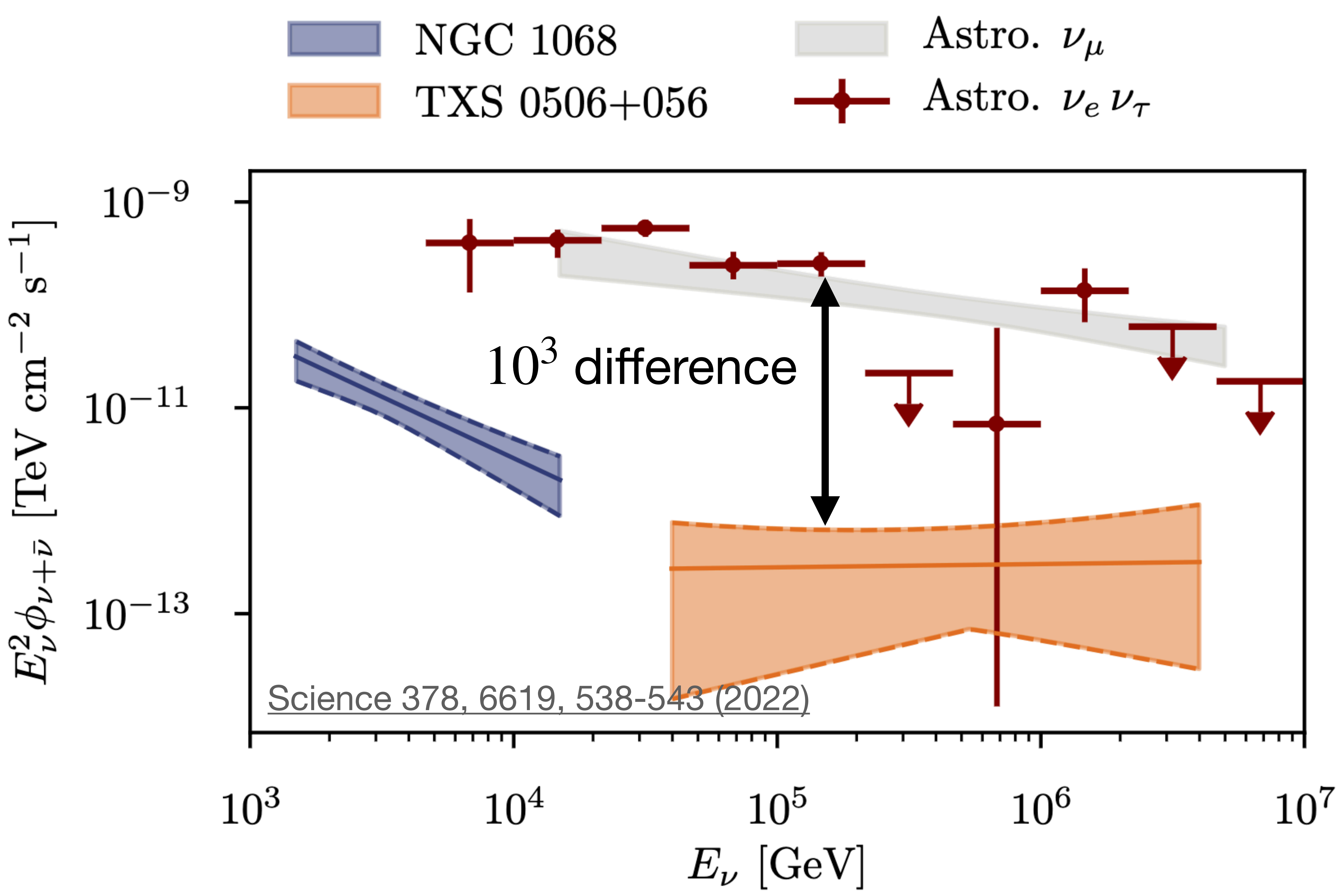
Science 378, 6619, 538-543 (2022)

- 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



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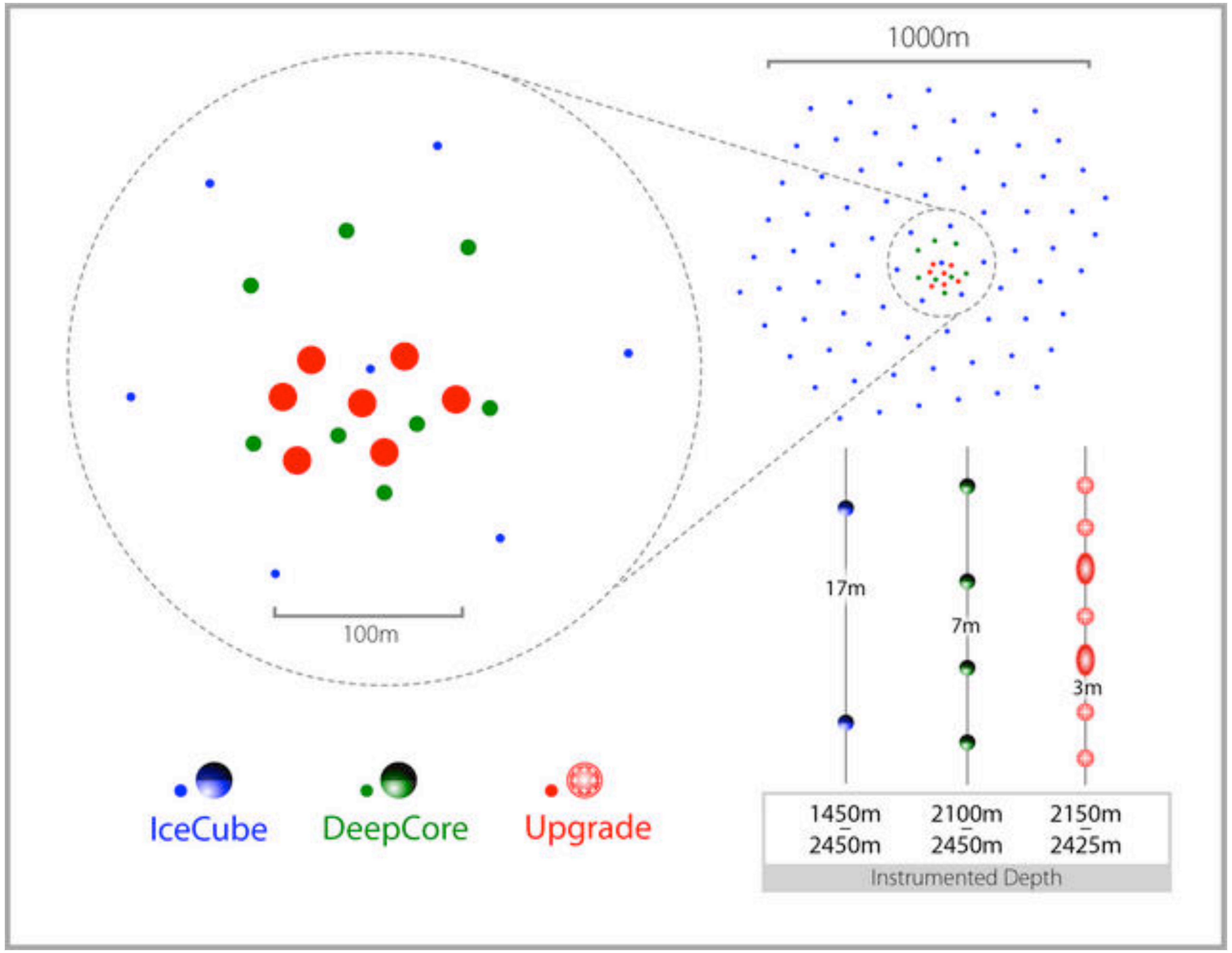
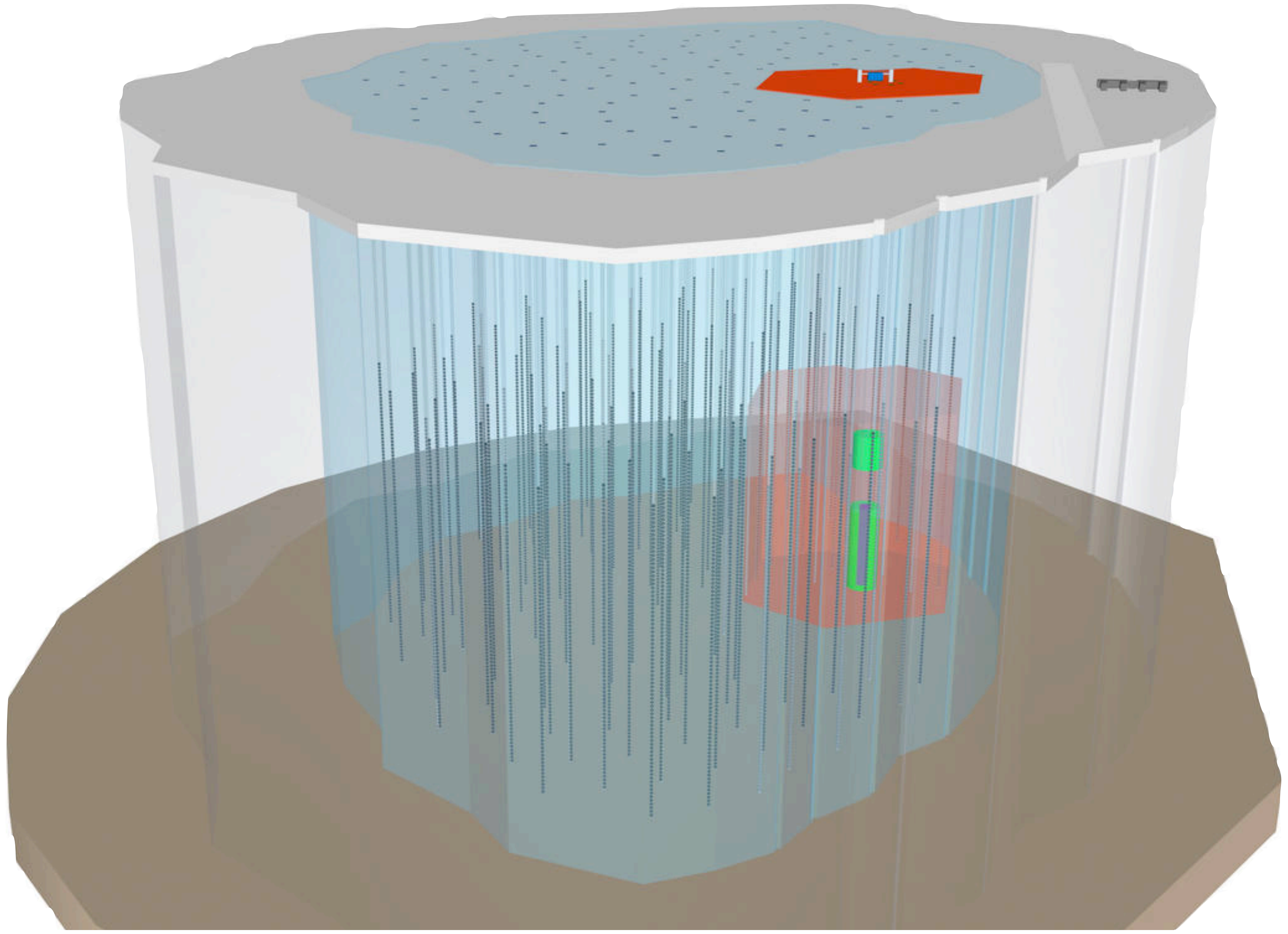
The IceCube Upgrade

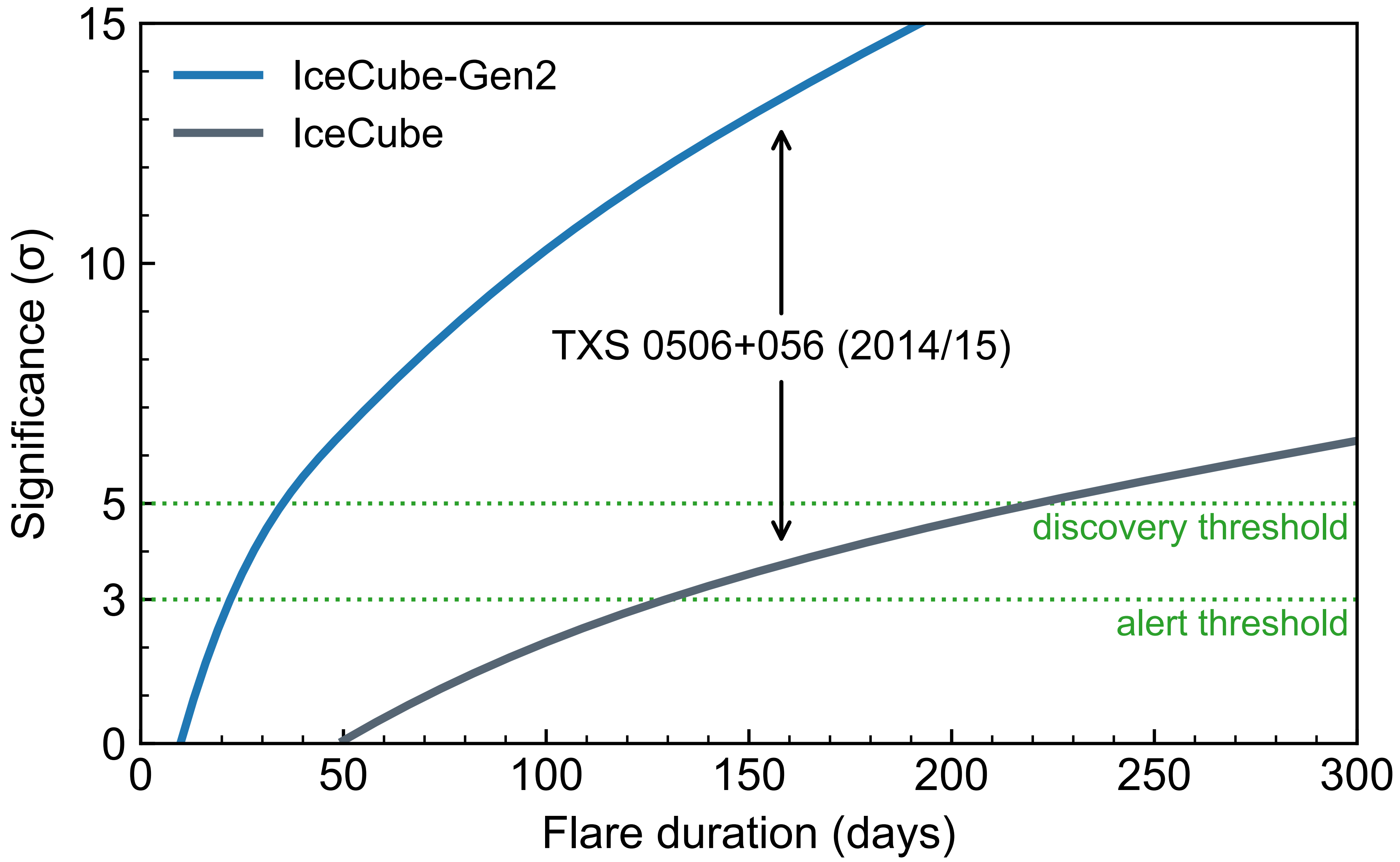


- Seven new, infilled strings
- Much improved efficiency and reconstructions at lowest energies to enable **high-precision measurement of oscillation parameters**
- Improved calibration and ice model to **improve reconstructions across all energies**
- Deployment scheduled for 2025-2026 Pole Season

IceCube Gen2

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



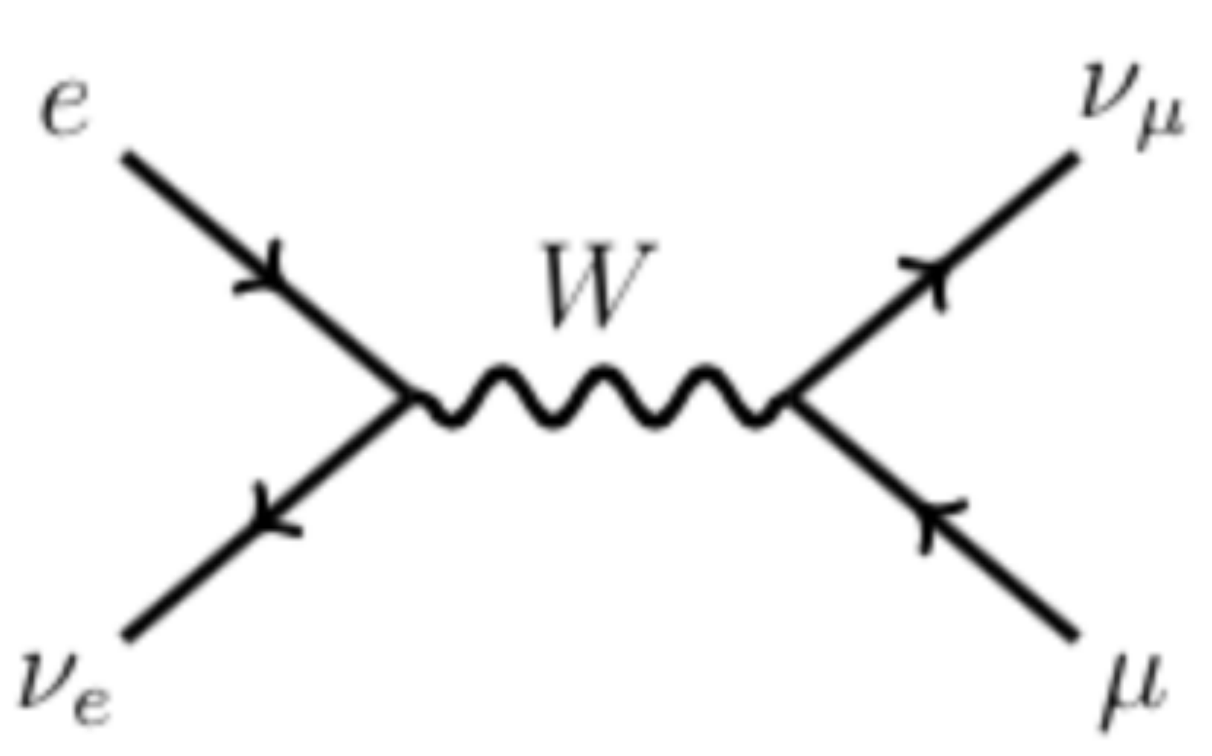


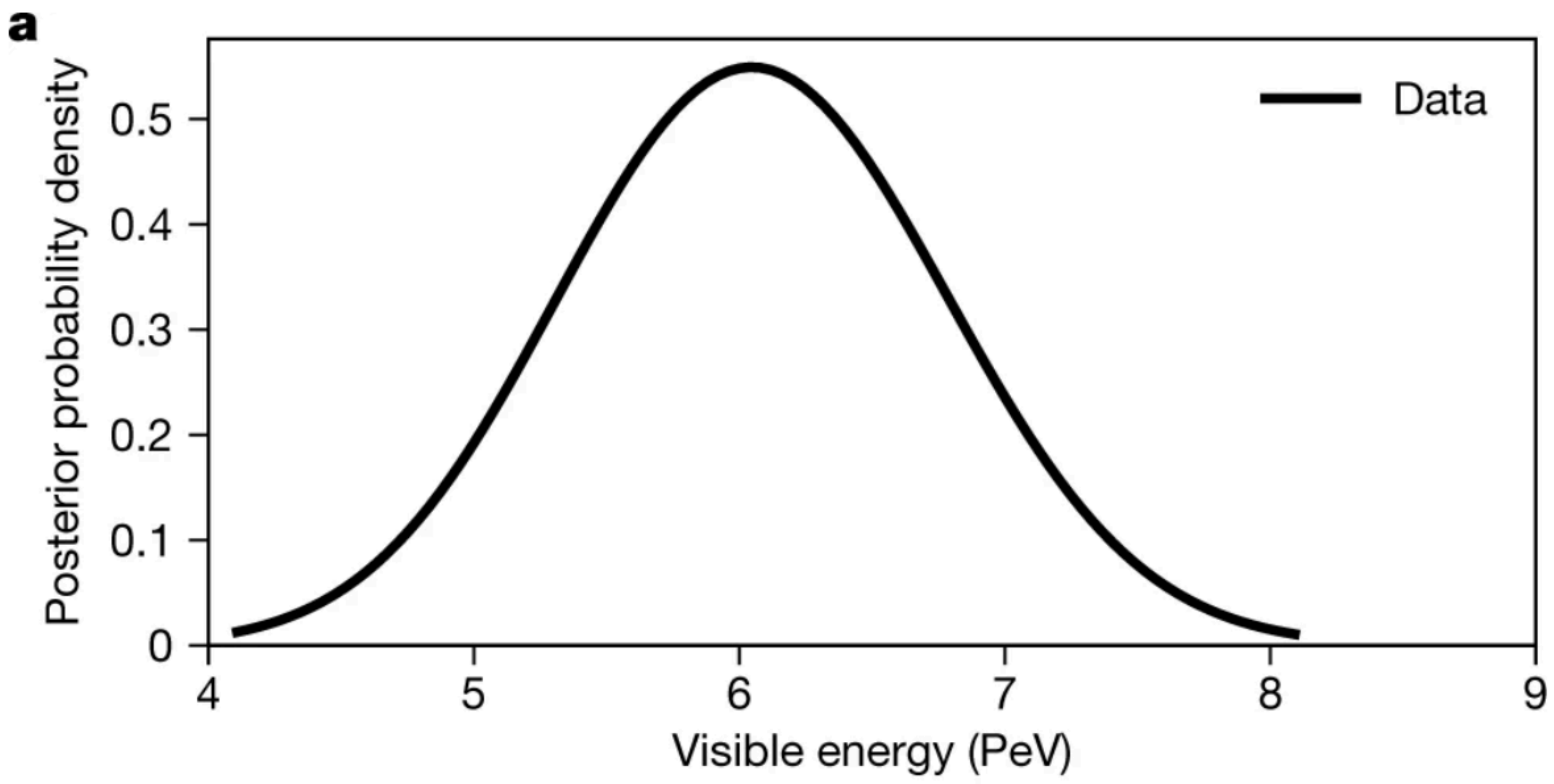
Summary and Conclusion

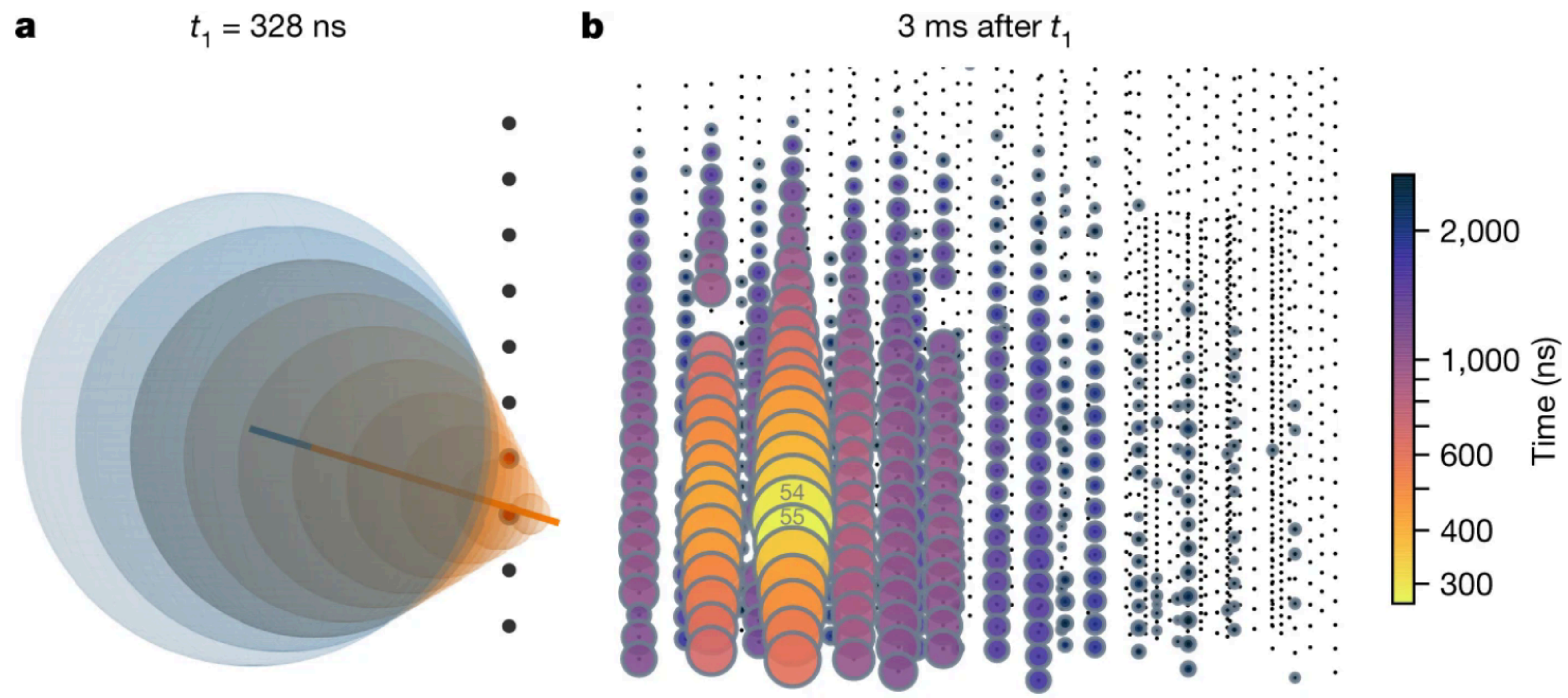
- After one decade of observing the diffuse, high-energy neutrino flux, we are seeing the first hints of a deviation from a power law
- NGC 1068 and the Galactic Plane are neutrino sources at high significance
- IceCube has a rich science program that is at the forefront of many areas of study. Let's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

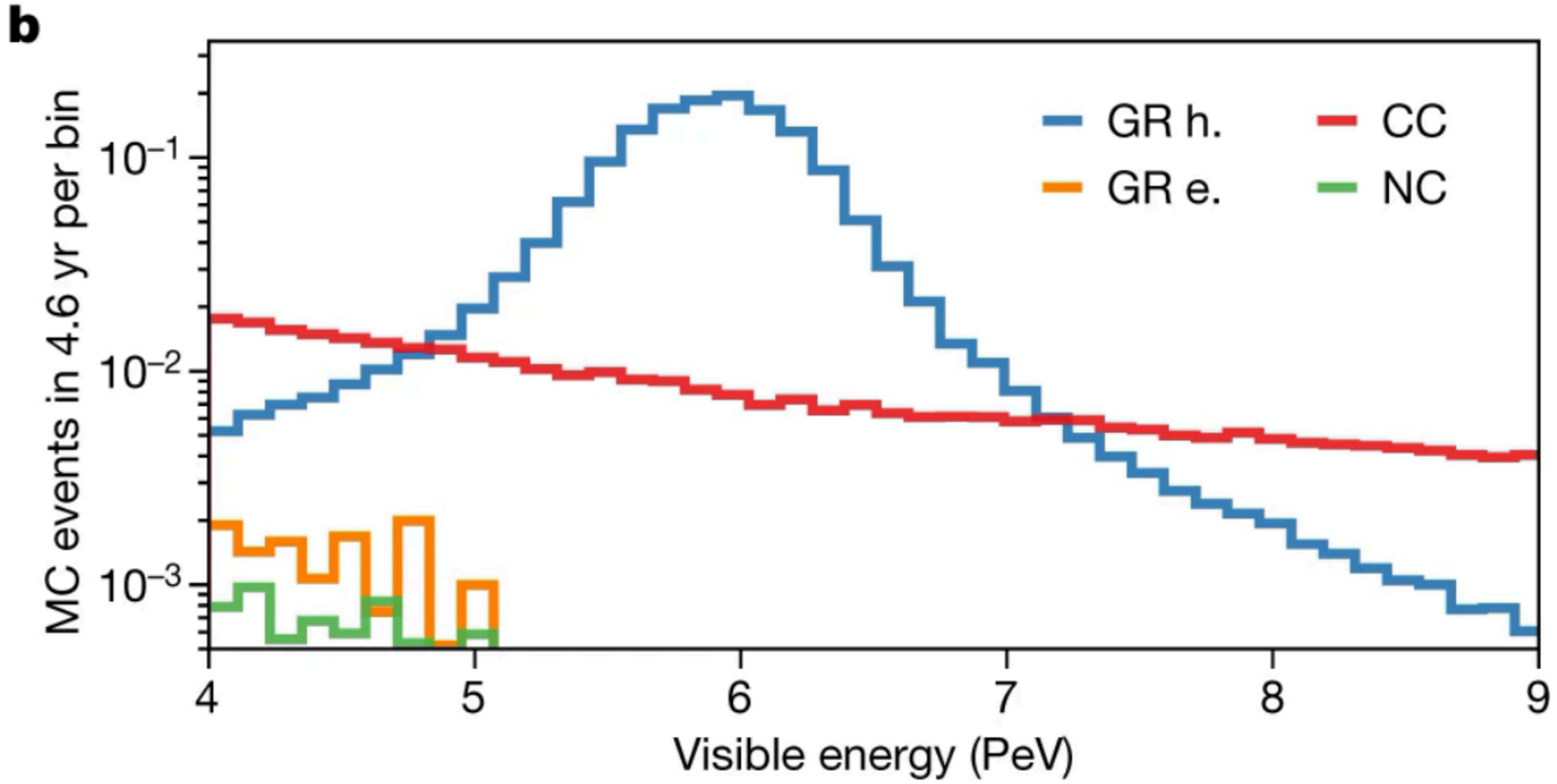
Backups

Glashow Event









Double Cascade Events

	$\nu^{astro}_{\tau,CC}$ [59]	ν^{astro}_{other} [59]	$\nu^{atm}_{conv.}$ [60–63]	ν^{atm}_{prompt} [56, 64–66]	$\mu^{atm}_{conv.}$ [67–70]	all background
initial	160 ± 0.2 (190 ± 0.3)	400 ± 0.7 (490 ± 0.8)	580 ± 7	72 ± 0.1	8400 ± 110	9450 ± 110 (9540 ± 110)
final	6.4 ± 0.02 (4.0 ± 0.02)	0.3 ± 0.02 (0.2 ± 0.01)	0.1 ± 0.008	0.1 ± 0.001	0.01 ± 0.008	0.5 ± 0.02 (0.4 ± 0.02)