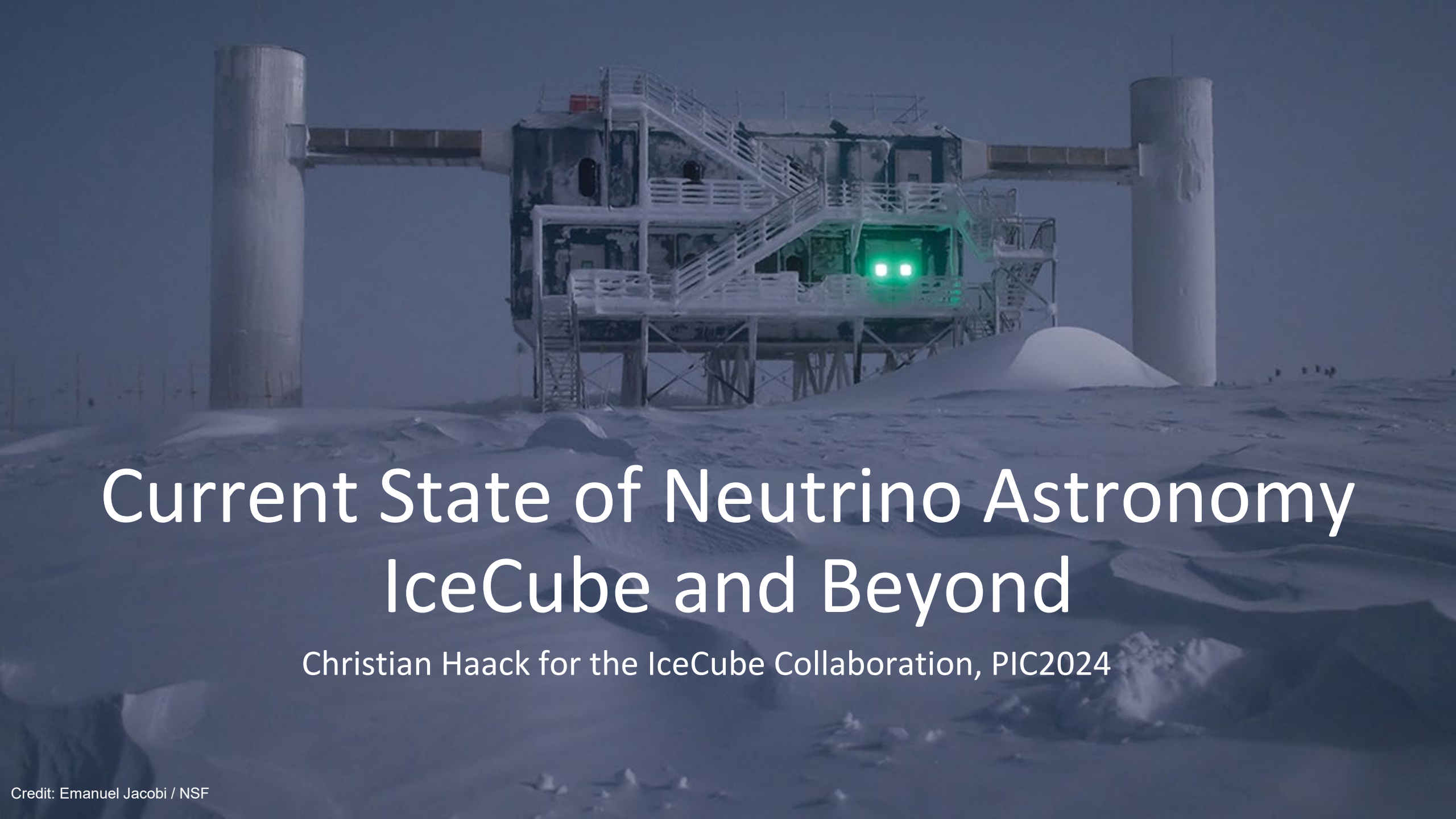
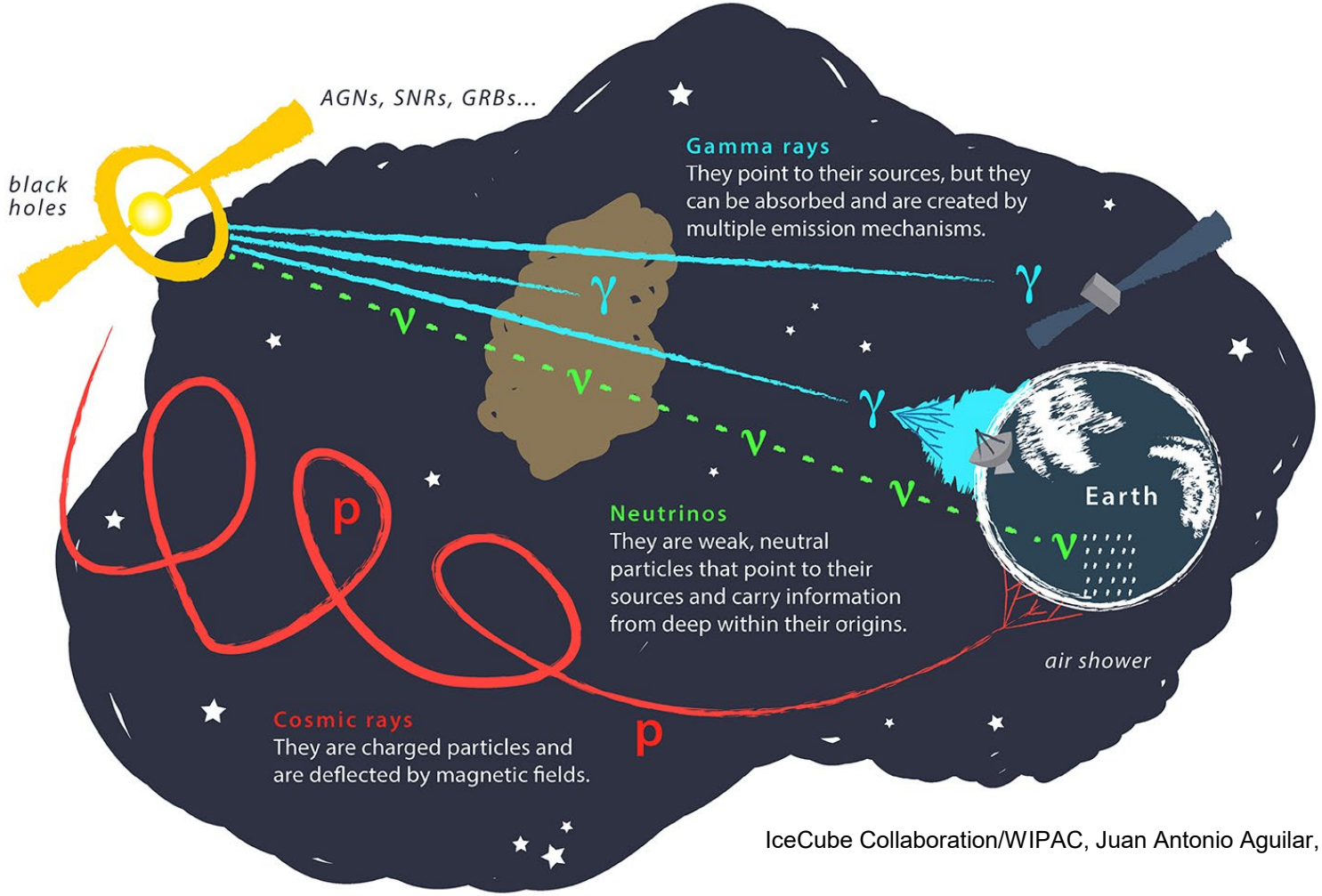


Current State of Neutrino Astronomy IceCube and Beyond

Christian Haack for the IceCube Collaboration, PIC2024

Credit: Emanuel Jacobi / NSF

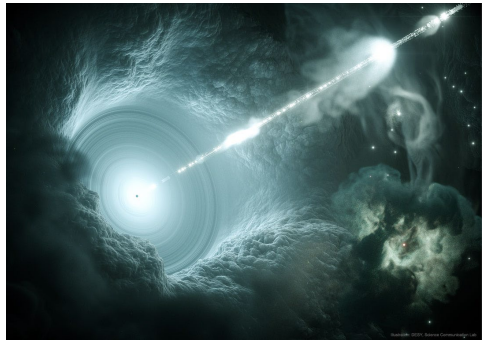
Multimessenger Astronomy



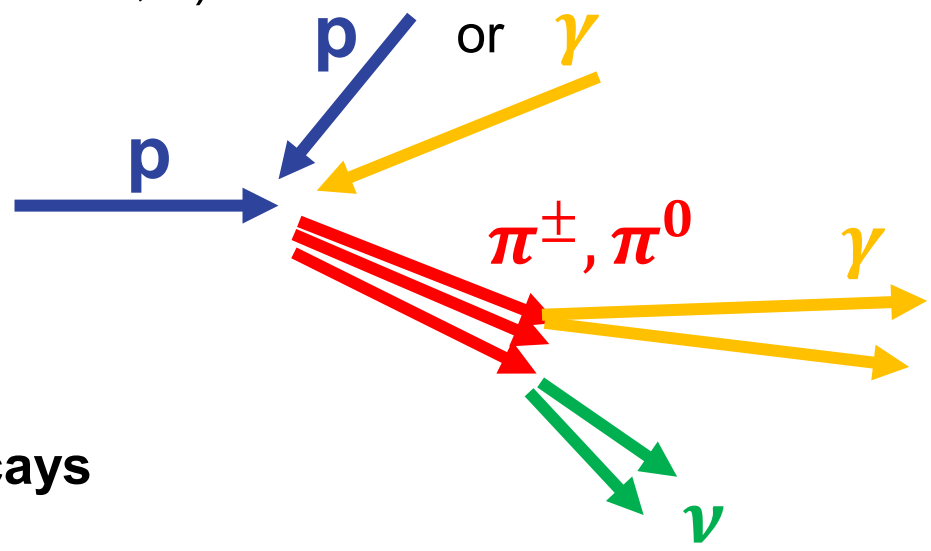
IceCube Collaboration/WIPAC, Juan Antonio Aguilar, and Jamie Yang

The Cosmic Ray Connection

Accelerator (AGN, SNR, GRB, ..)



DESY



Idealized scenarios

$$p + p \rightarrow X + \begin{cases} \pi^+ & 1/3 \\ \pi^- & 1/3 \\ \pi^0 & 1/3 \end{cases}$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 & 1/3 \\ n + \pi^+ & 2/3 \end{cases}$$

Pion Decays

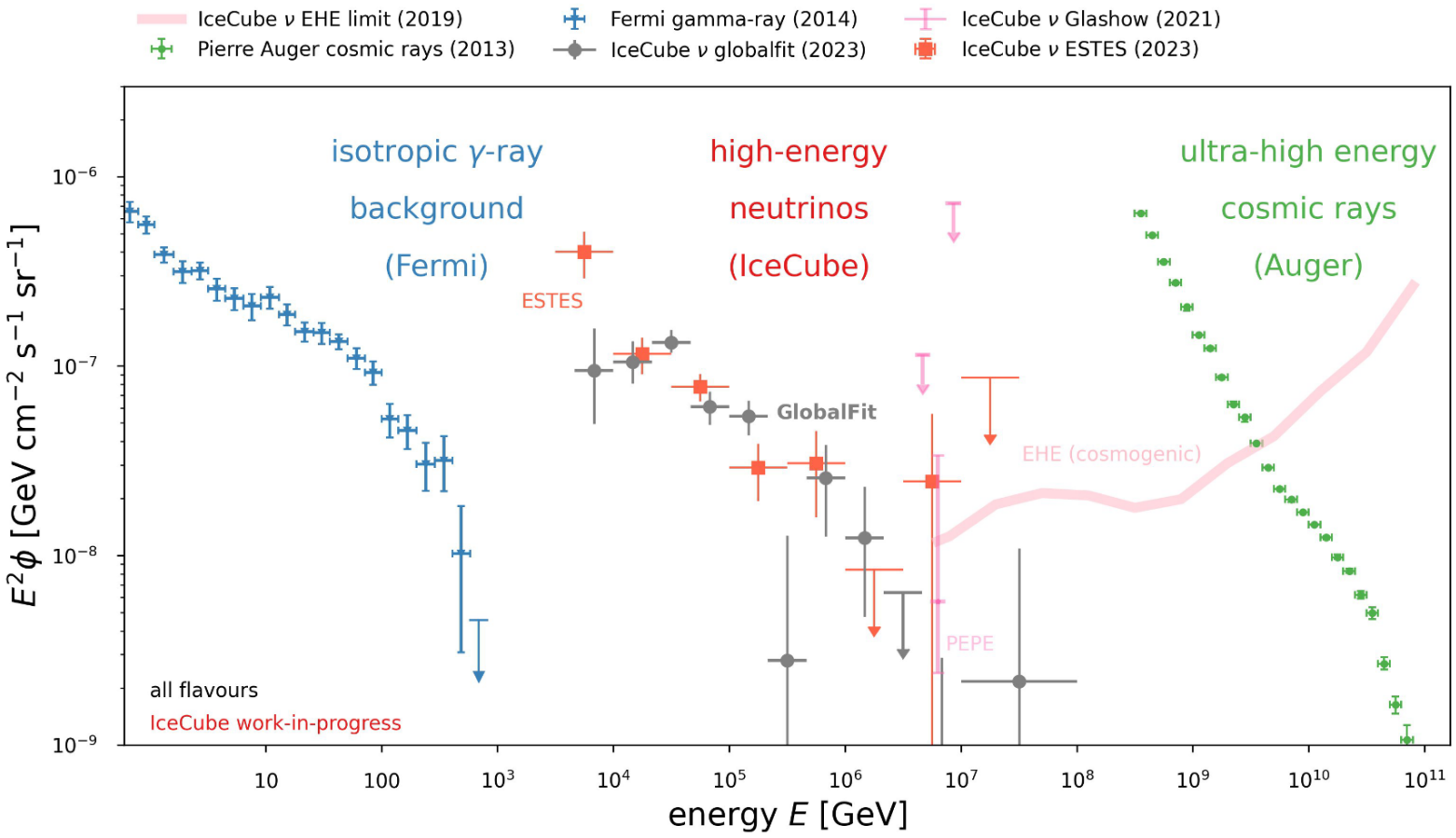
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \bar{\nu}_\mu + \nu_\mu$$

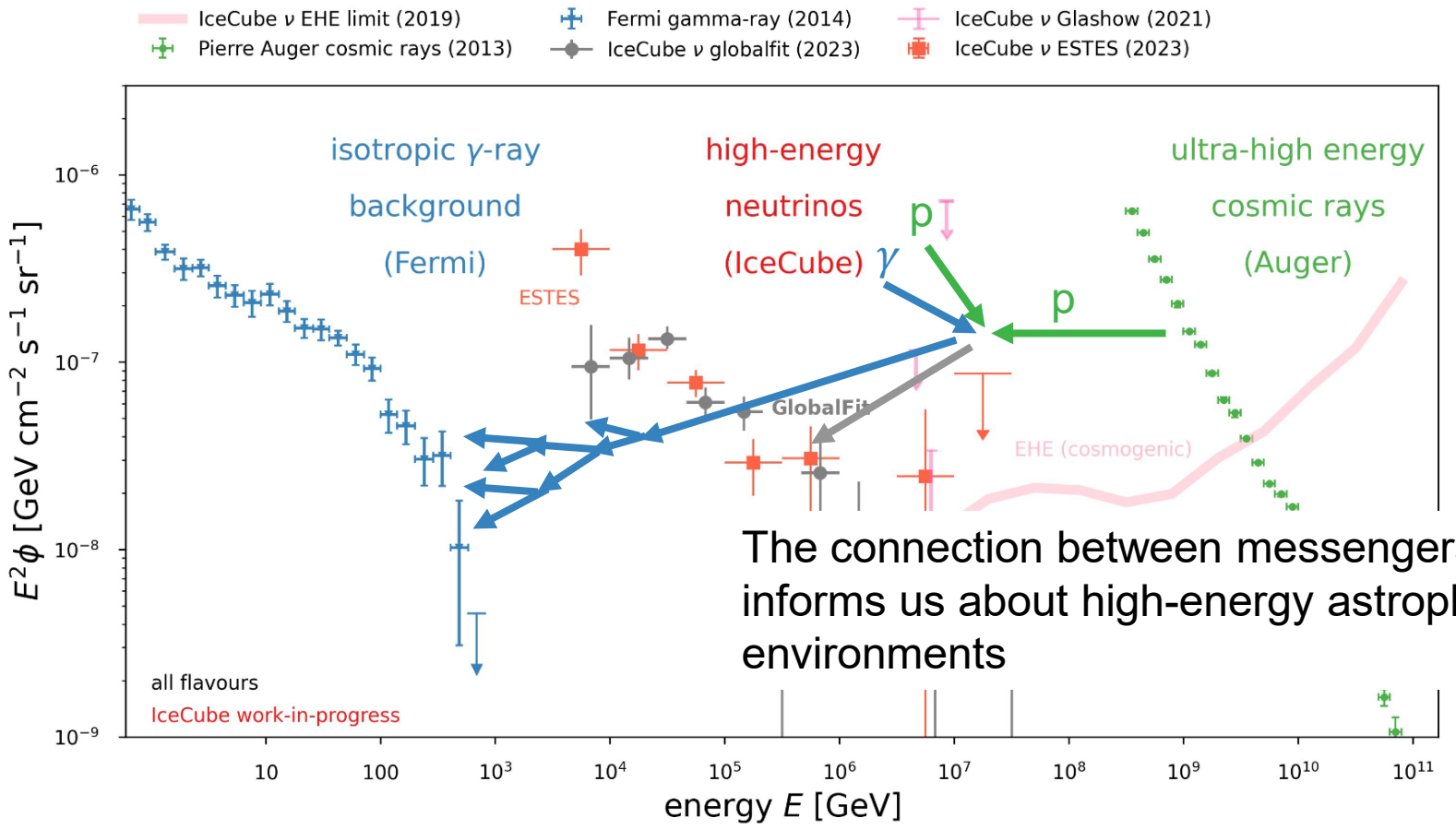
$$\pi^0 \rightarrow \gamma\gamma$$

Interaction of accelerated CR naturally leads to production of neutrinos and gamma rays

Energy Density of Cosmic Particles



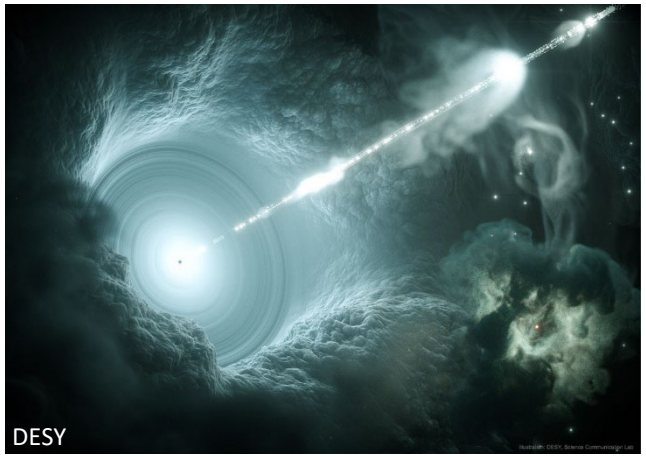
Energy Density of Cosmic Particles



The connection between messengers informs us about high-energy astrophysical environments

Detection Method

Astrophysical Accelerator



Neutrinos

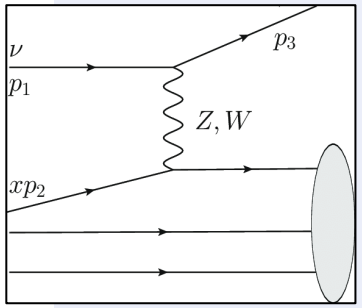
Transparent Natural Medium (Water / Ice)

Secondaries

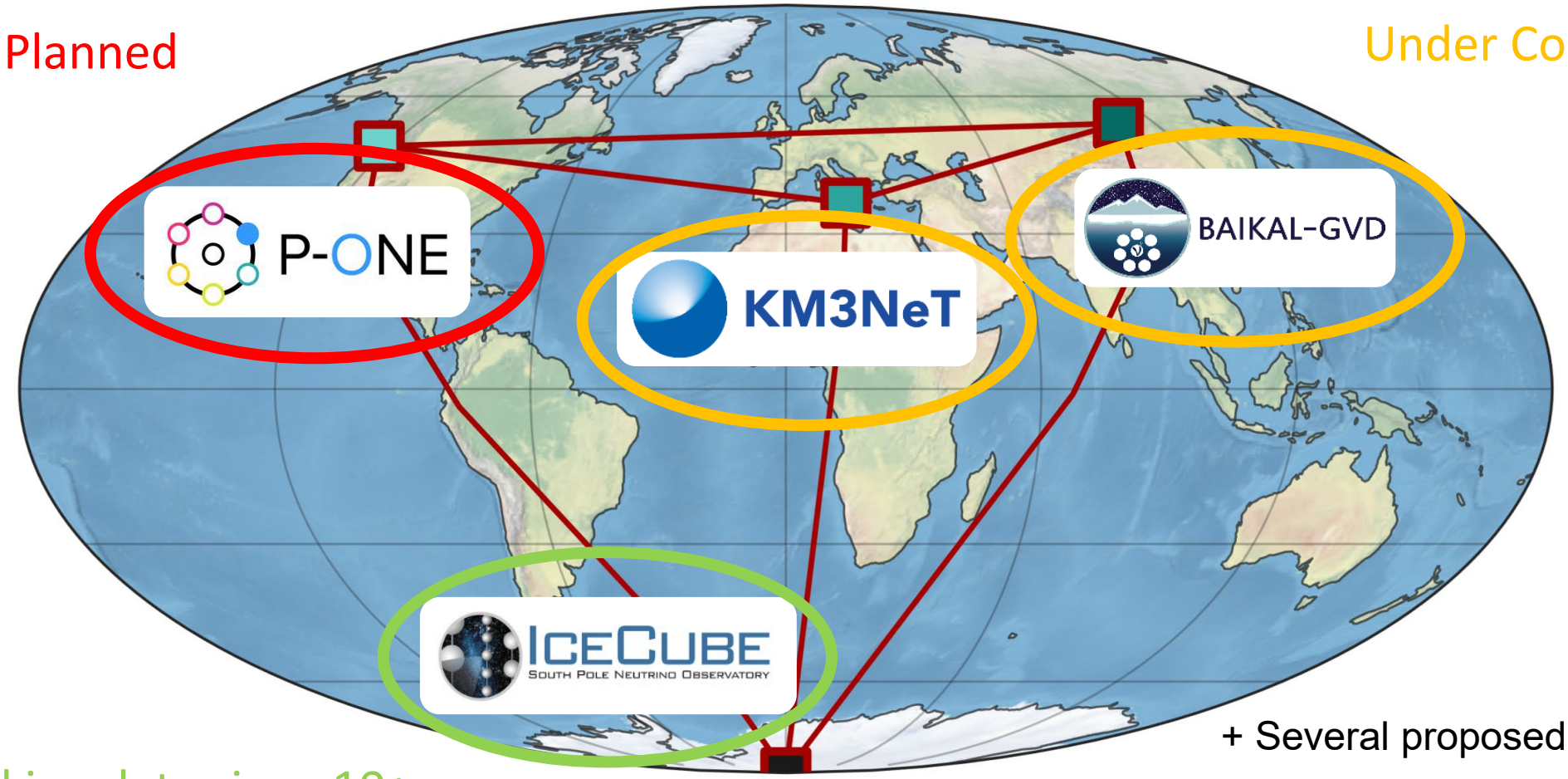
Photons (Cherenkov)

Strings with photosensors

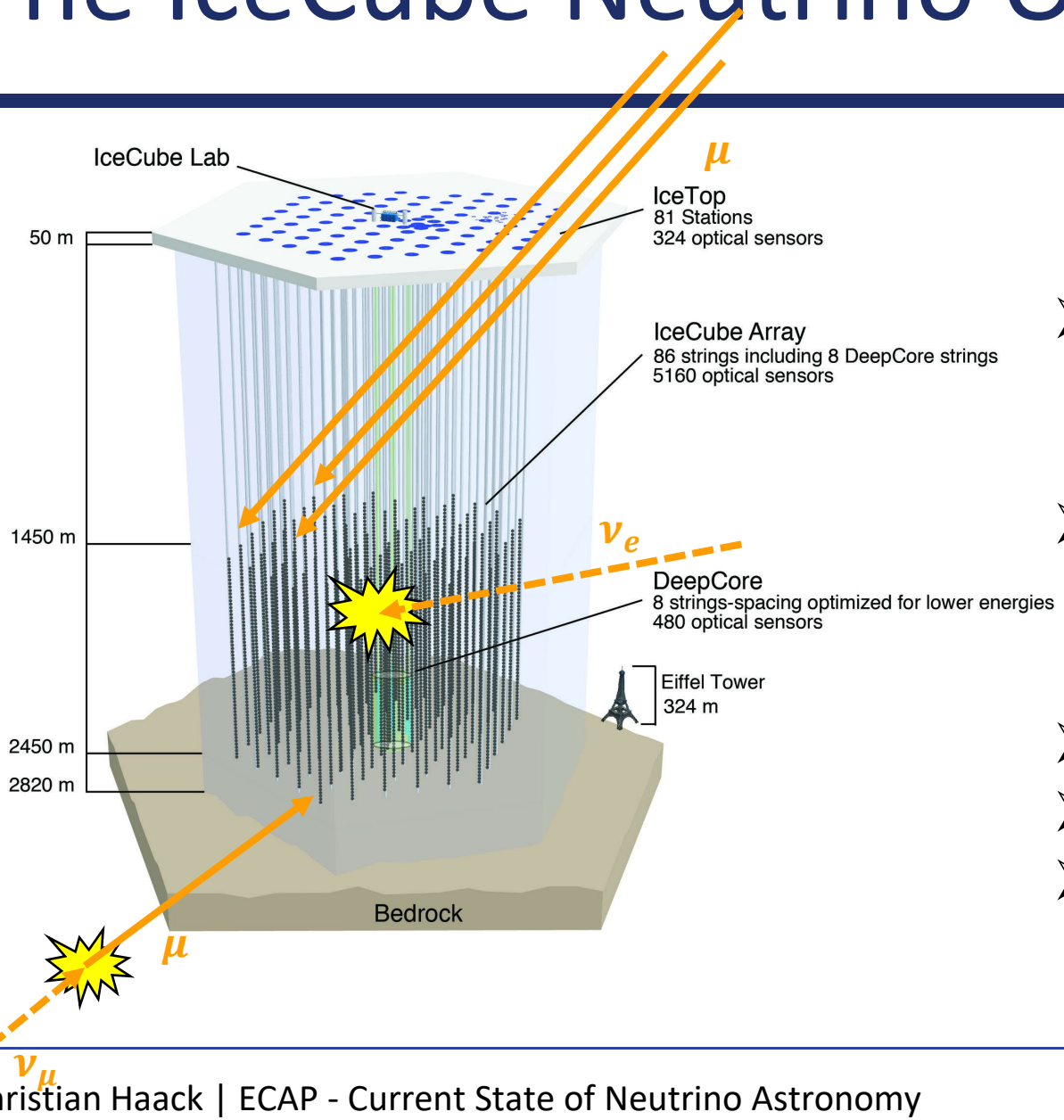
DIS



Neutrino Telescopes

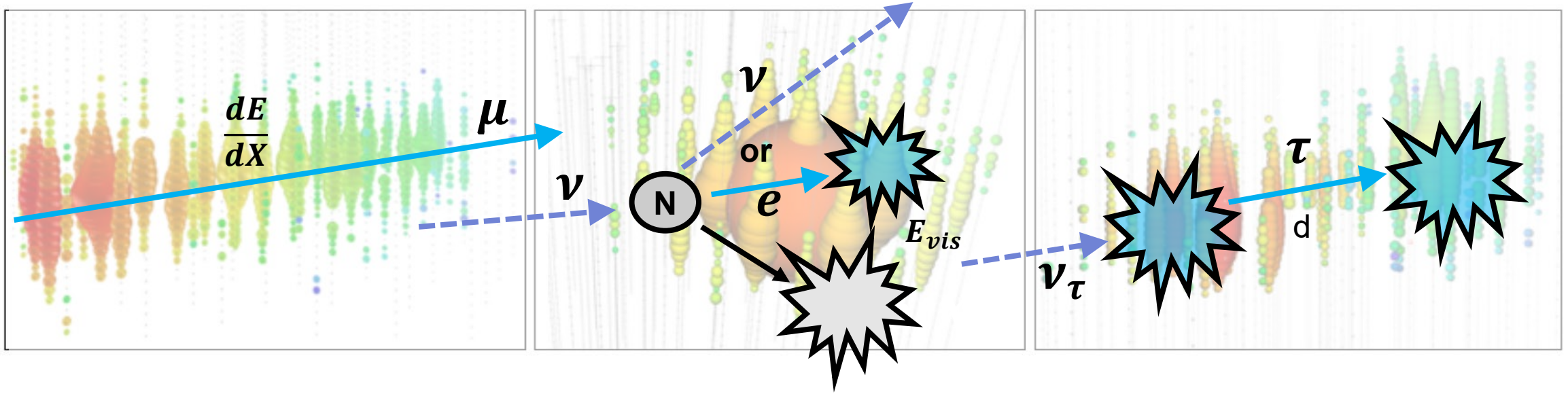


The IceCube Neutrino Observatory



- 86 Strings with 60 Digital Optical Modules (DOMs)
- Full configuration running with > 99% uptime since 2011
- 3000 atmospheric μ per second
- 1 atmospheric ν per minute
- 1 astrophysical ν per day

Neutrino signatures



IceCube-Gen2
arXiv:2008.04323v1

"**Tracks**":
- Good directional resolution $< 1°$
- Poor energy resolution via $\frac{dE}{dX}$ of muon

"**Cascades**":
- CC ν_e & ν_τ interactions + NC all-flavor
- Directional resolution $\sim 5 - 15°$
- Good resolution of visible energy: $\sim 10\%$ for CC ν_e

"**Double Bang**":
- CC ν_τ interactions + τ decay
- Atmospheric ν_τ production strongly surpressed
- τ decay length:

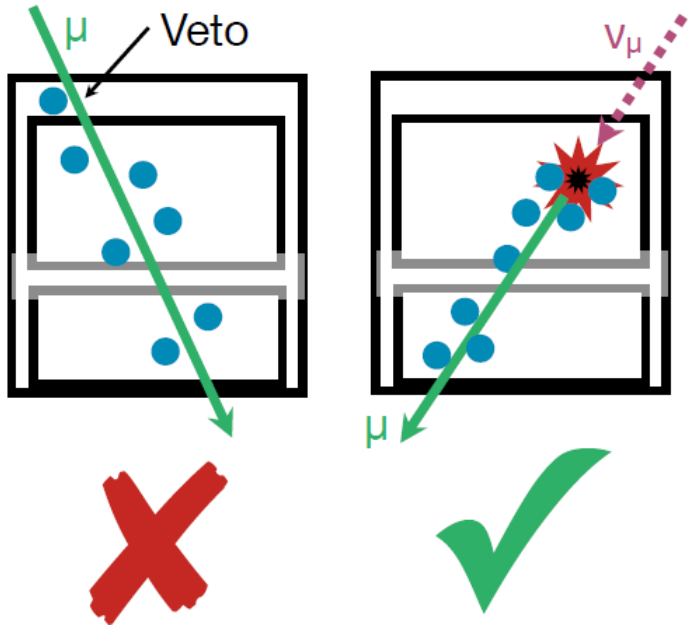
$$\mathrm{d} \sim 50\mathrm{m} \cdot \left(\frac{E}{\mathrm{PeV}}\right)$$

Event Selection Strategies

Fiducialisation

Morphology-based BG discrimination

All* flavors

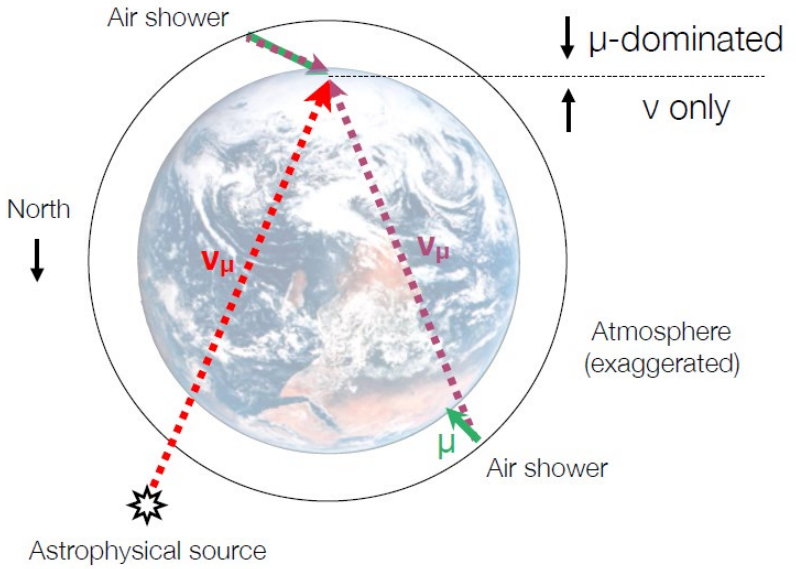


“Starting Events”

Using Earth as shield

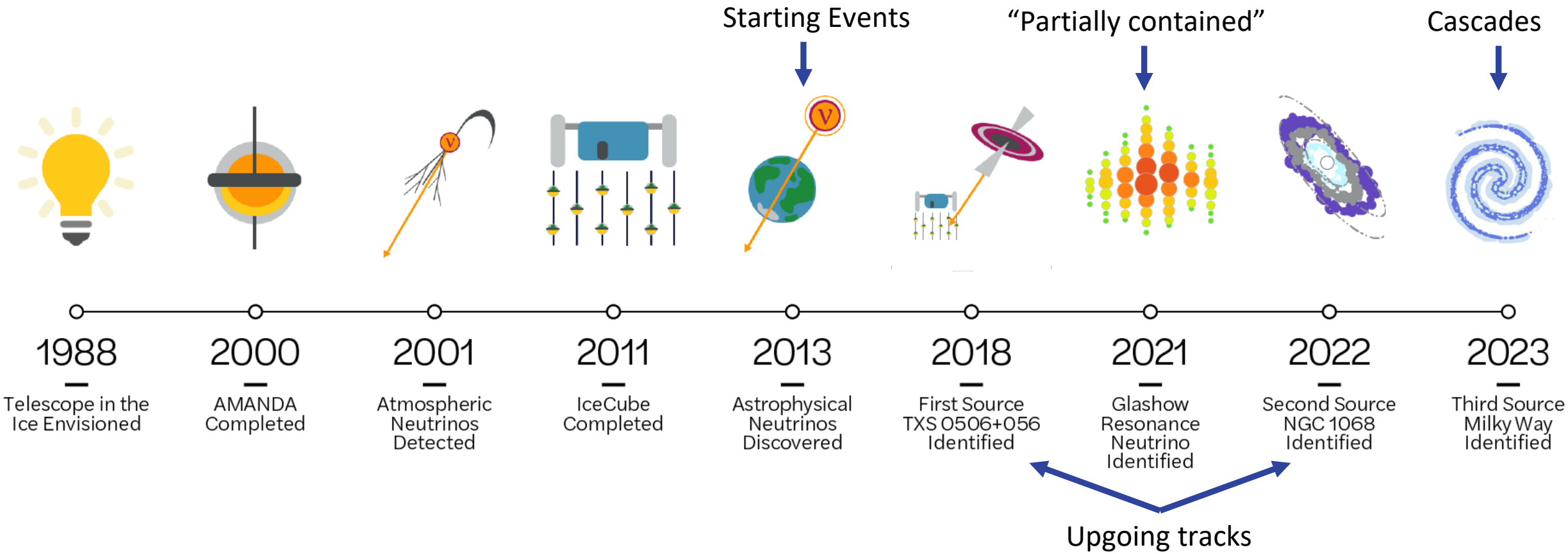
Direction based BG discrimination

Only ν_μ

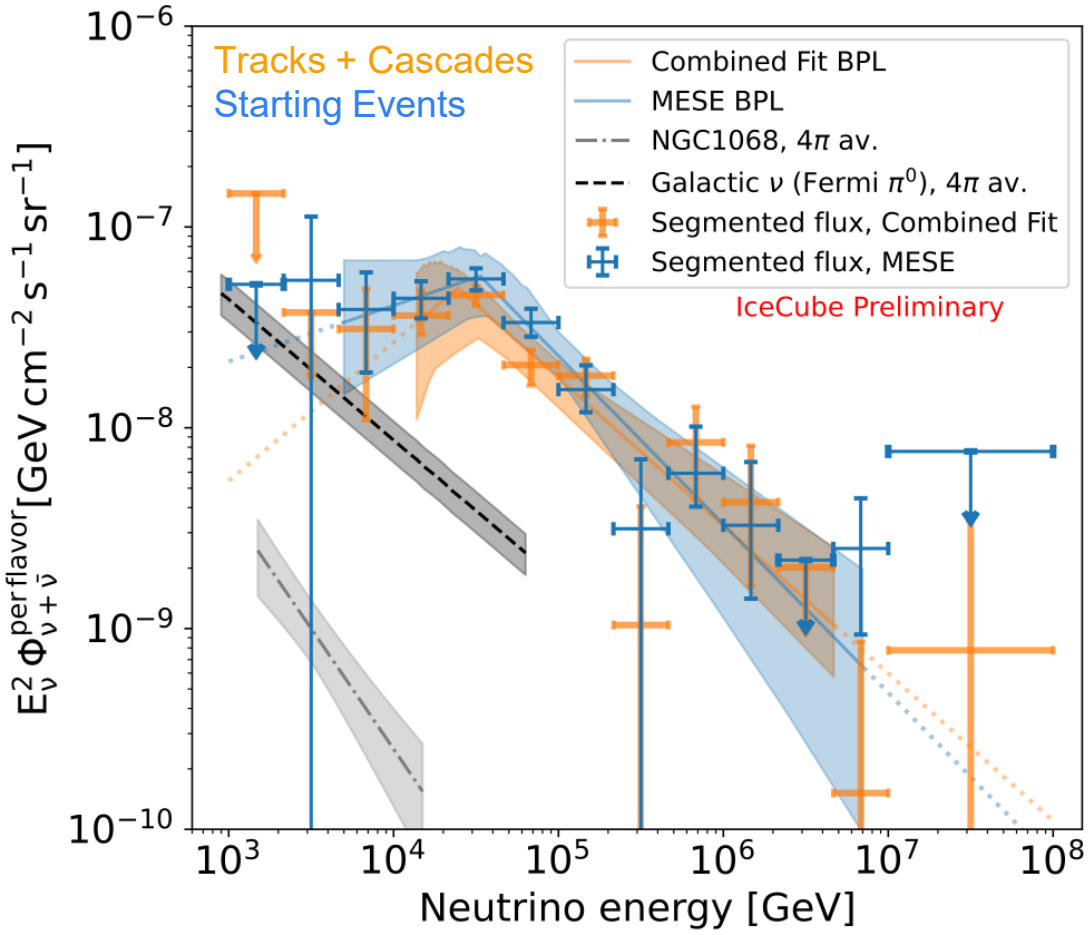


“Upgoing Tracks”

A History of Neutrino Astronomy in Antarctica

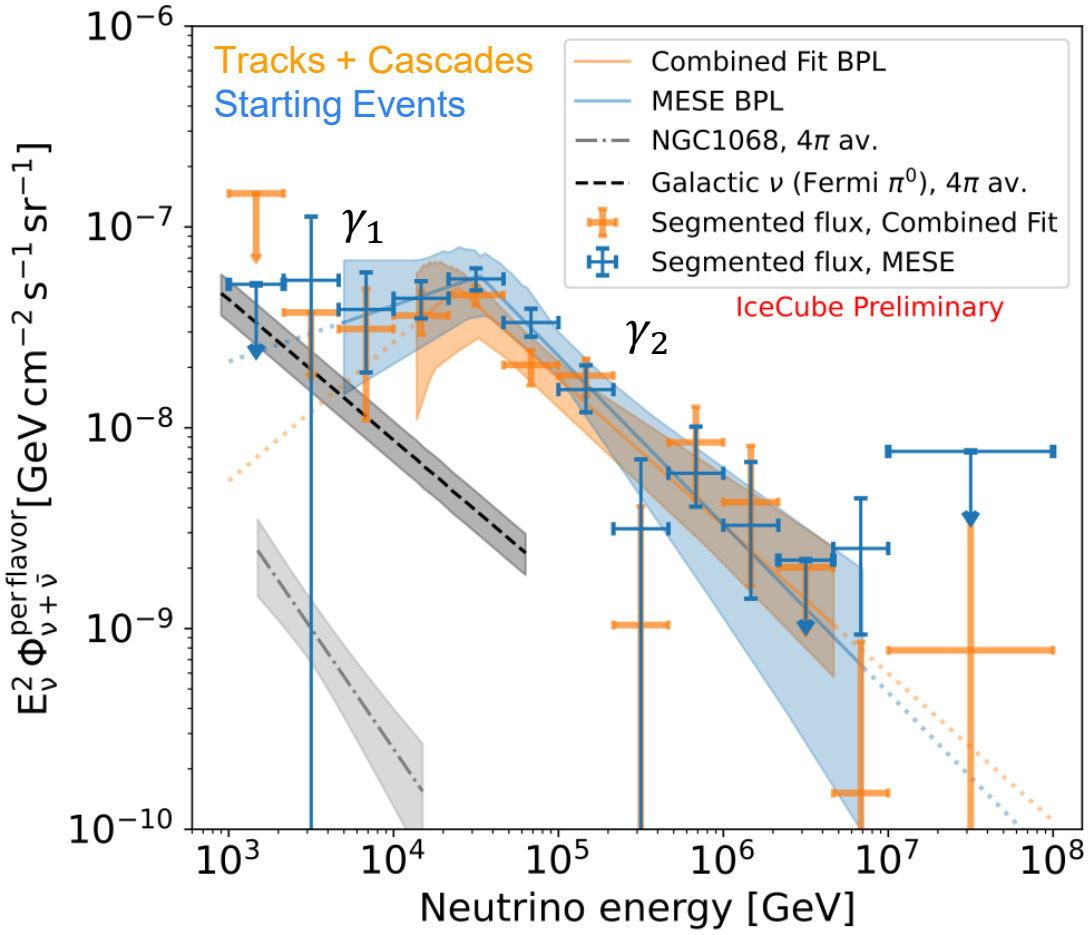


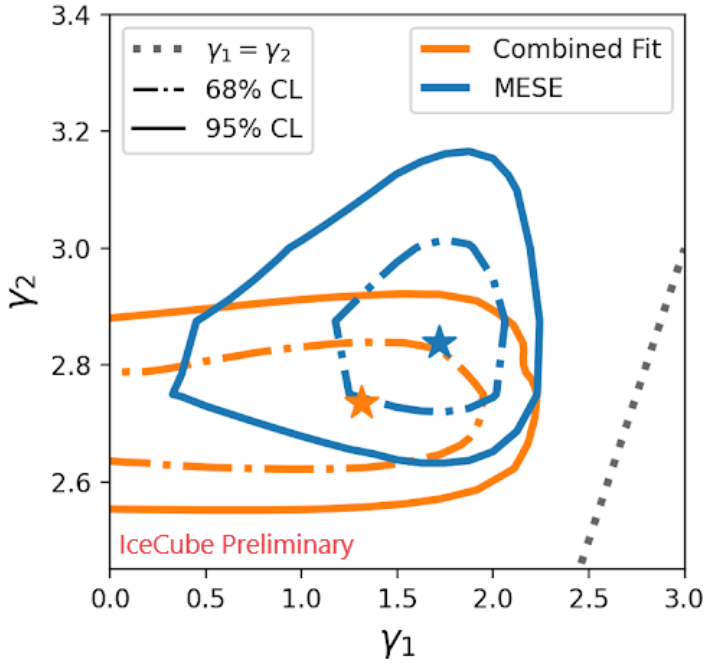
Beyond the Single Powerlaw



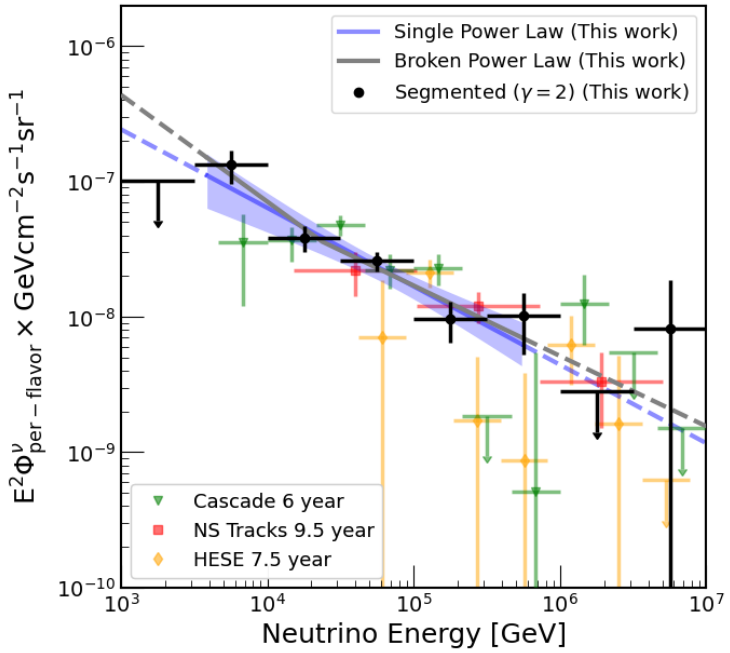
- Two recent analyses on different (but correlated) event samples see deviation from a single powerlaw spectrum.
- Spectrum is better described by a broken-powerlaw (or log-parabola) than a single power law.
- Puzzling: Starting Track sample prefers a SPL

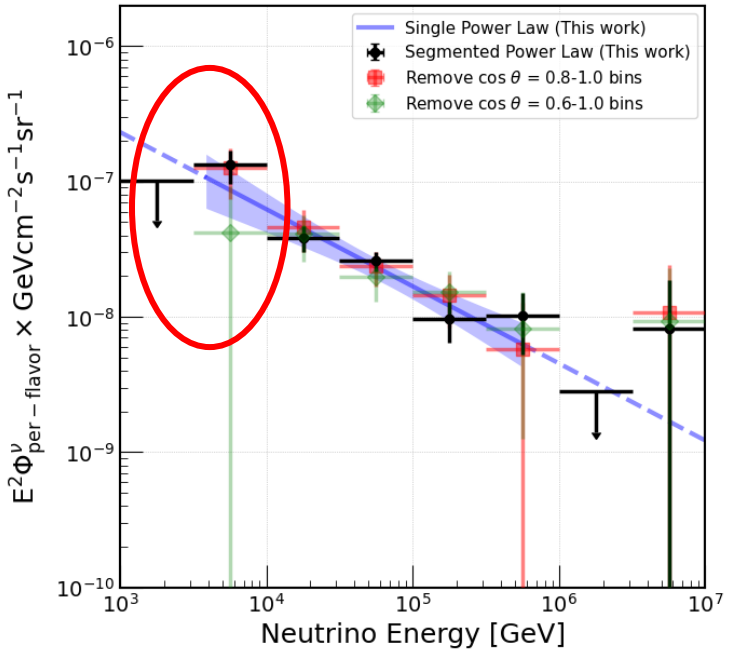
Beyond the Single Powerlaw





Enhanced Starting Track Selection

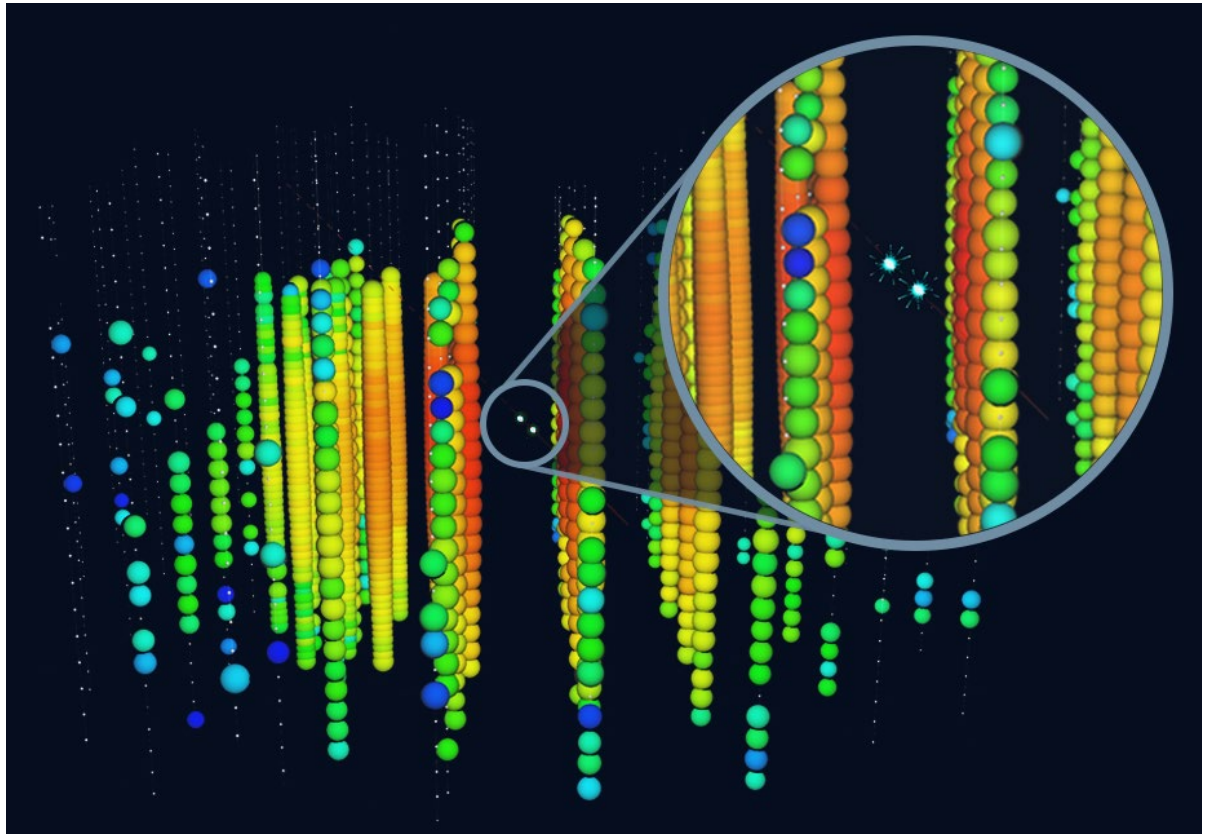




- Sample dominated by starting tracks (ν_μ interacting inside the detector)
- High purity & good energy resolution
- Does not see spectral hardening at lower energies
- Prefers single-power law ($\gamma = 2.58$)

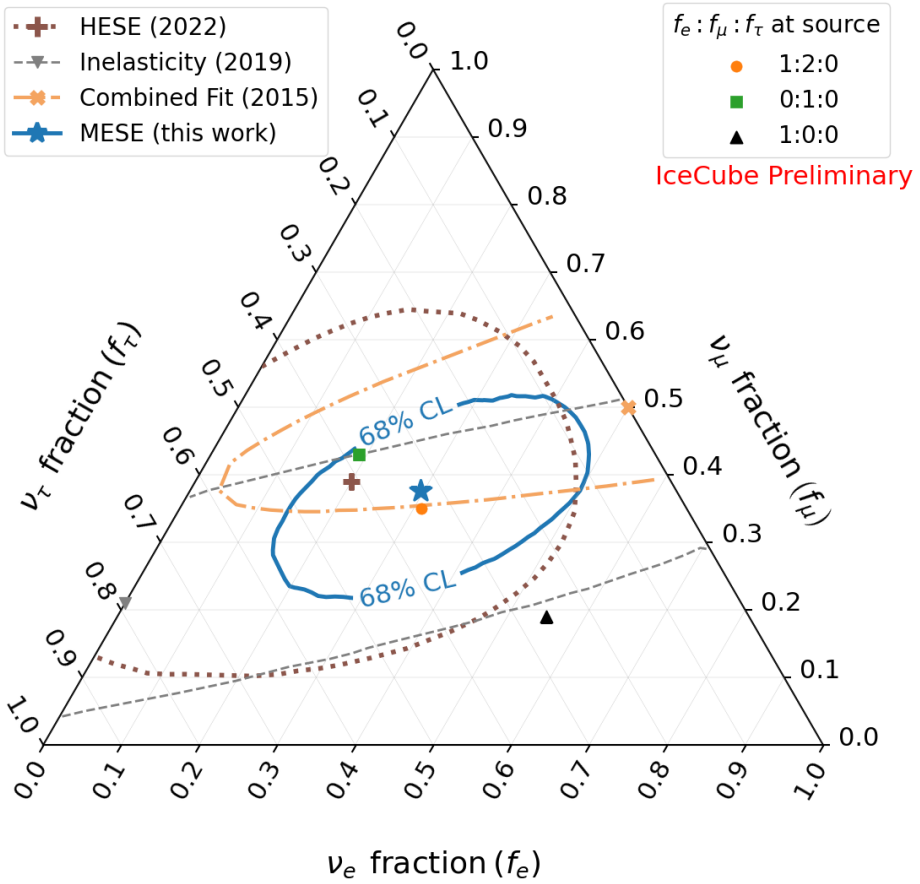
Tau Neutrinos

https://doi.org/10.1103/PhysRevLett.132.151001



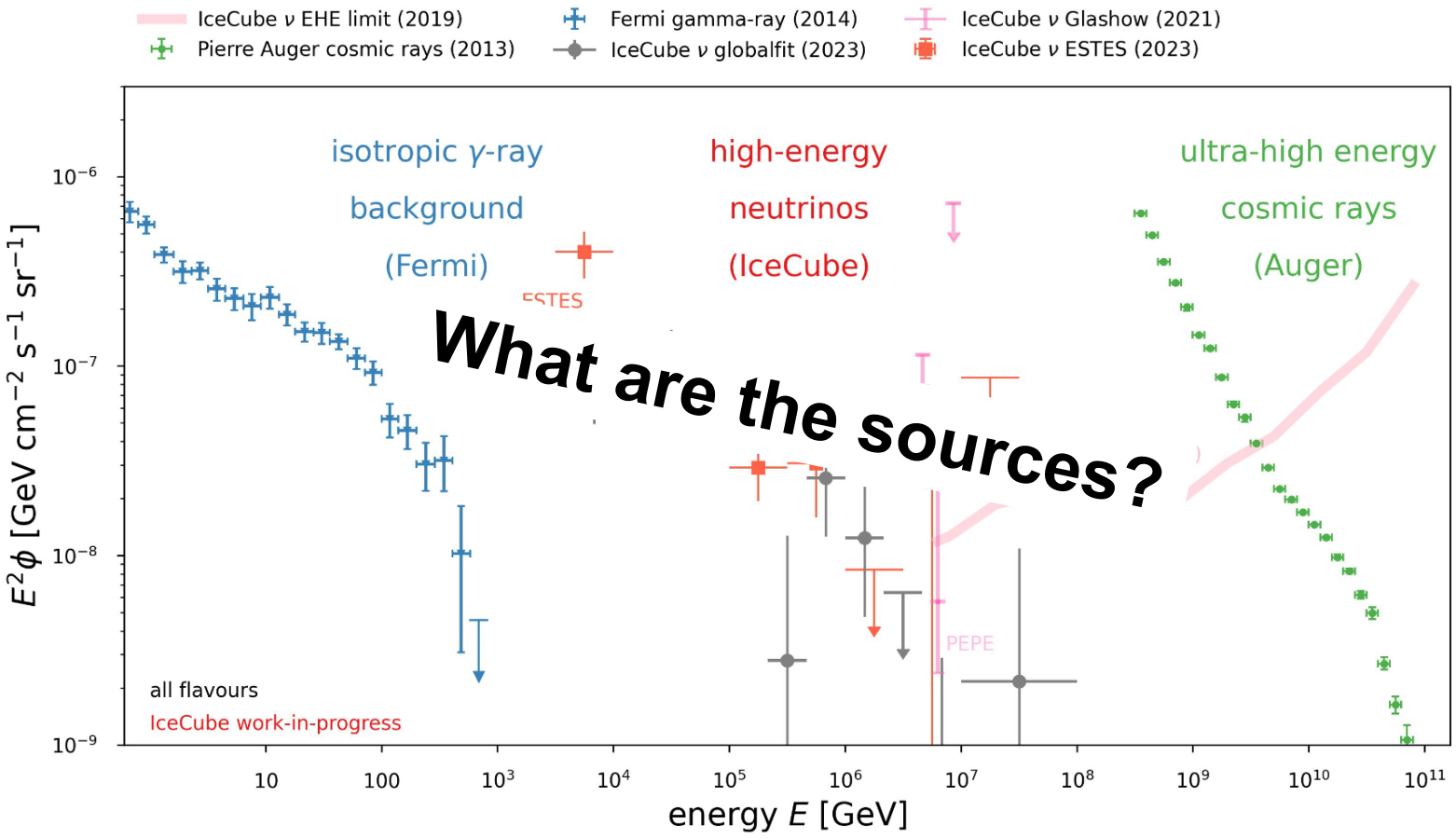
- Seven tau neutrino candidates with novel image recognition methods based on CNNs (background expectation of 0.5 events, only considering light-meson decays)
- Combined significance $> 5\sigma$
- Independent confirmation of astrophysical neutrino flux

Neutrino Flavor Ratio



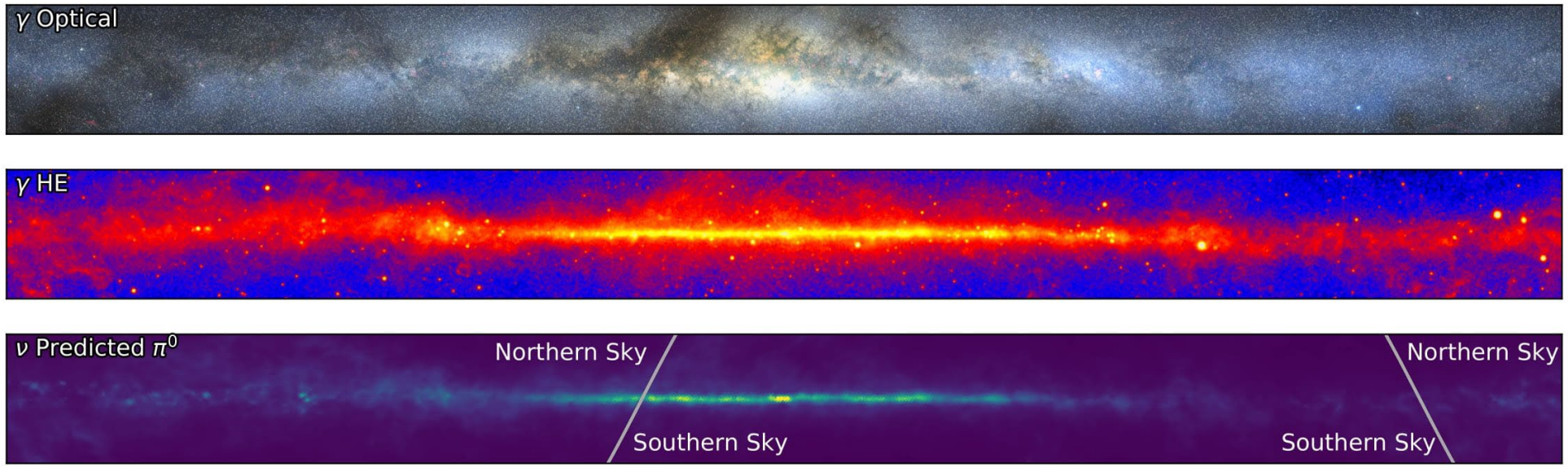
- Measurement of the ratio of $\nu_e : \nu_\mu : \nu_\tau$ -fluxes
- Consistent with expectation of ν-production via π-decay
- Important input for BSM / LIV searches (see backup)

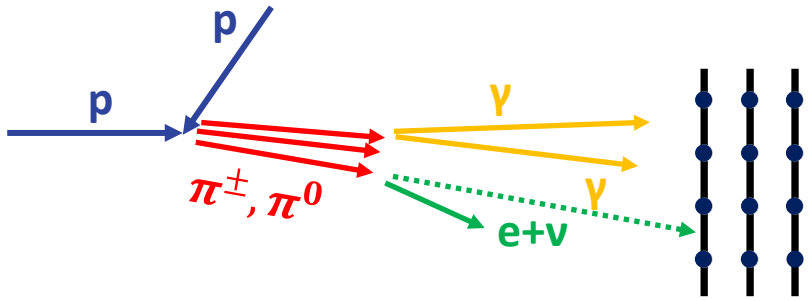
Energy Density of Cosmic Particles



Neutrinos from the Galactic Plane

DOI: 10.1126/science.adc9818

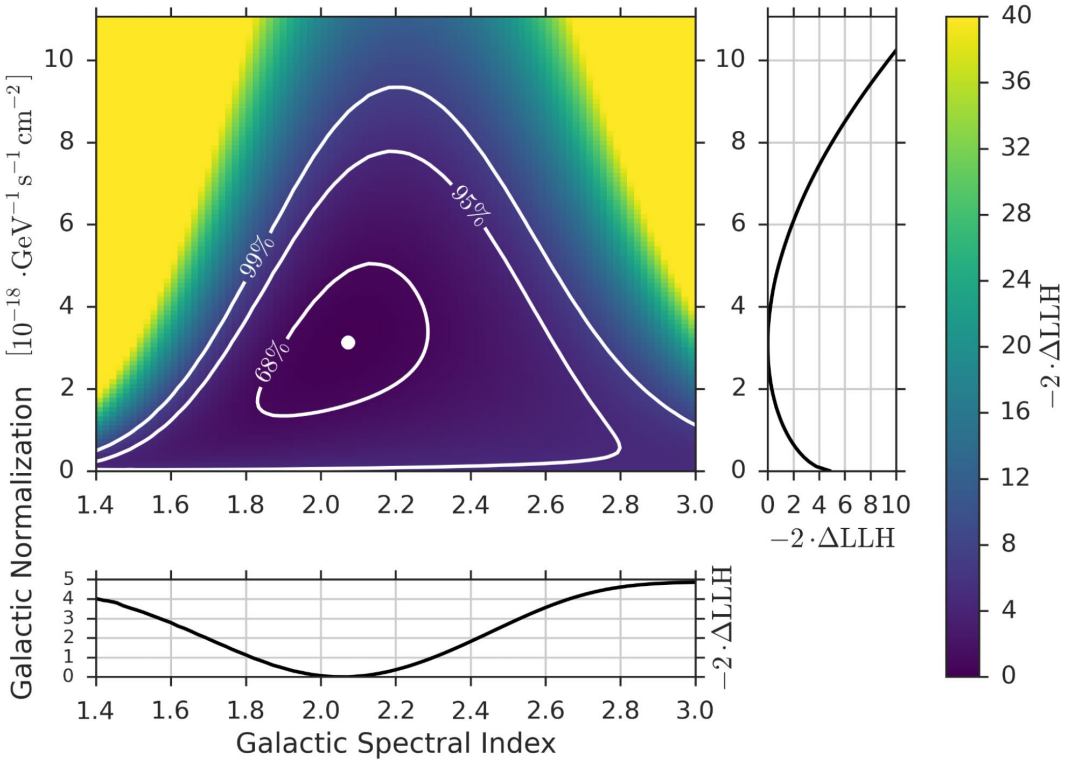




Galactic diffuse neutrino emission is a guaranteed flux

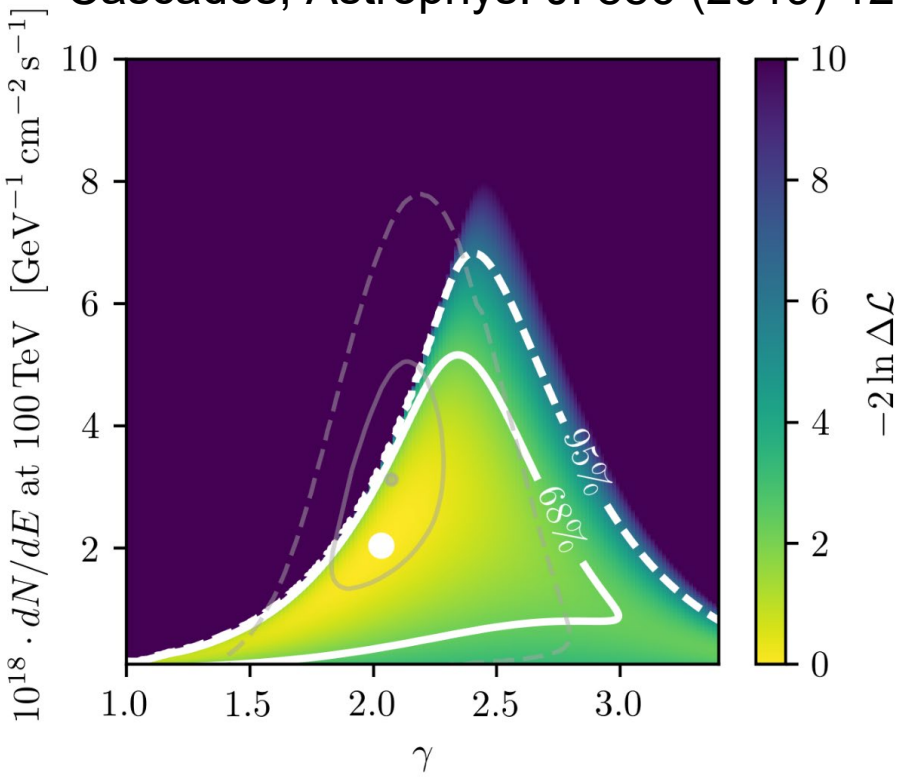
GP Searches in IceCube

Tracks, Astrophys.J. 849 (2017) 67



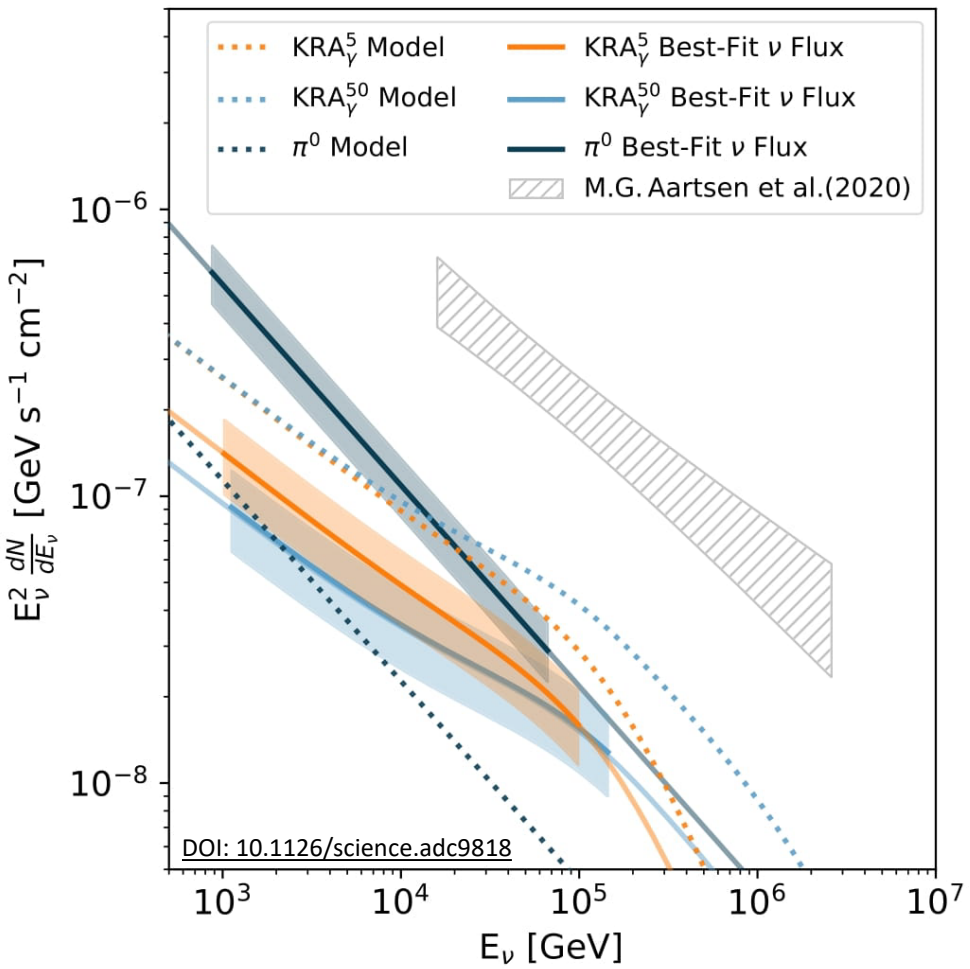
Zero Galactic diffuse excluded @ 7% p-value

Cascades, Astrophys. J. 886 (2019) 12

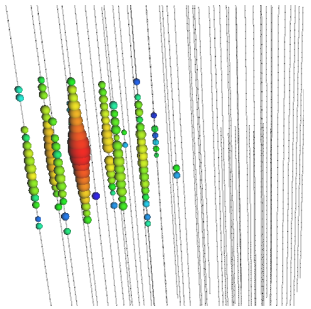


Zero Galactic diffuse excluded @ 2% p-value

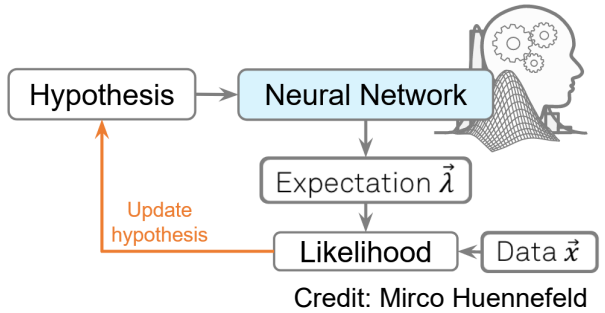
Evidence for Galactic Neutrino Emission



Cascade channel



Deep Learning

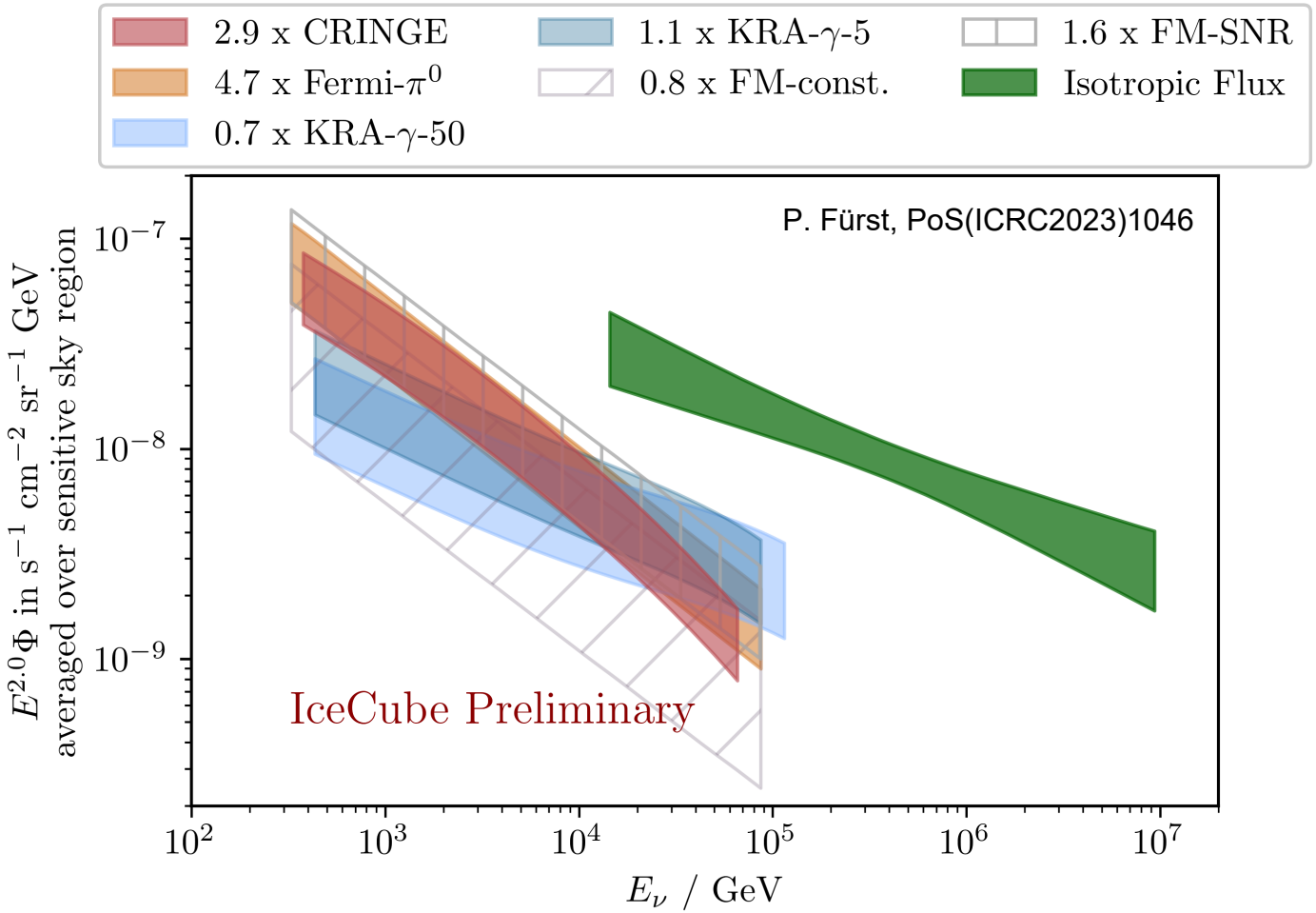


Credit: Mirco Huennefeld

4.5σ exclusion of pure isotropic hypothesis
6-13% of the total diffuse neutrino flux

Not yet enough statistical power to distinguish models or unresolved sources

New Result: Track Channel

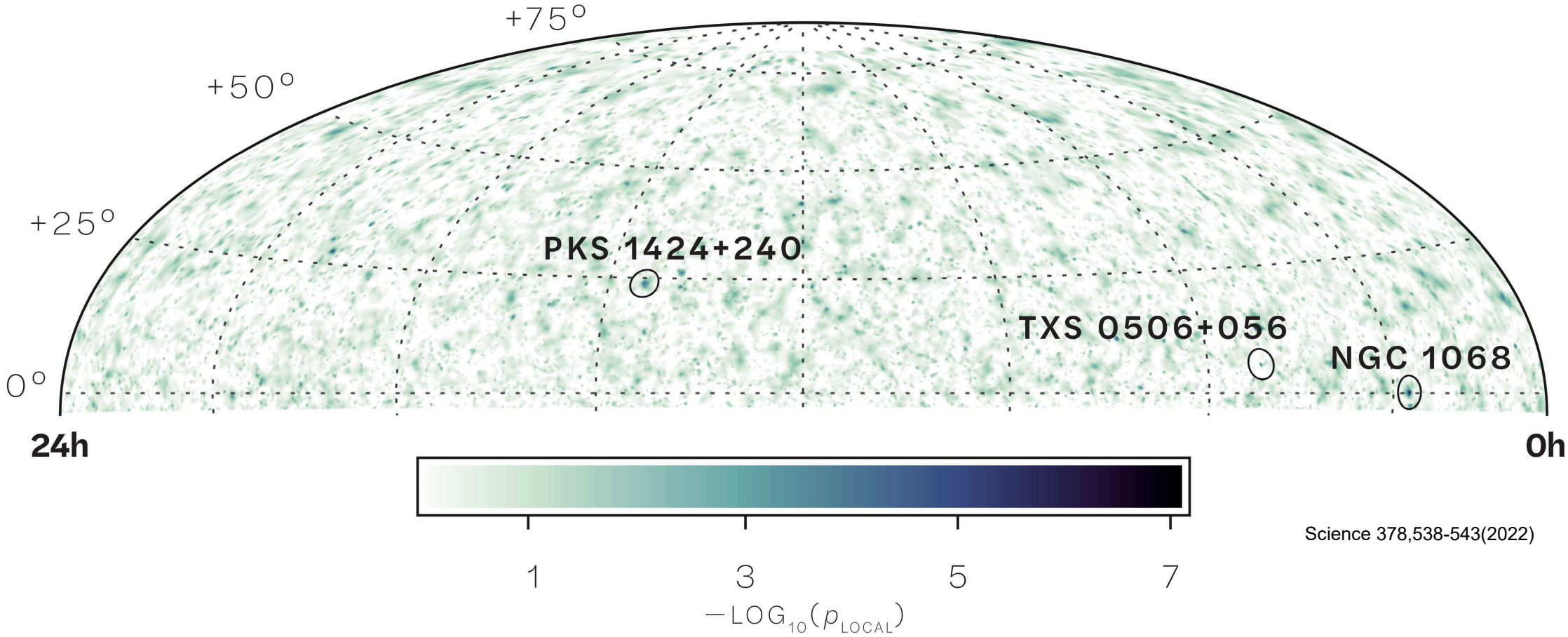


Multiple diffuse emission models tested

Supporting result by independent analysis using track channel (2.7σ)

The Muon-Neutrino Sky

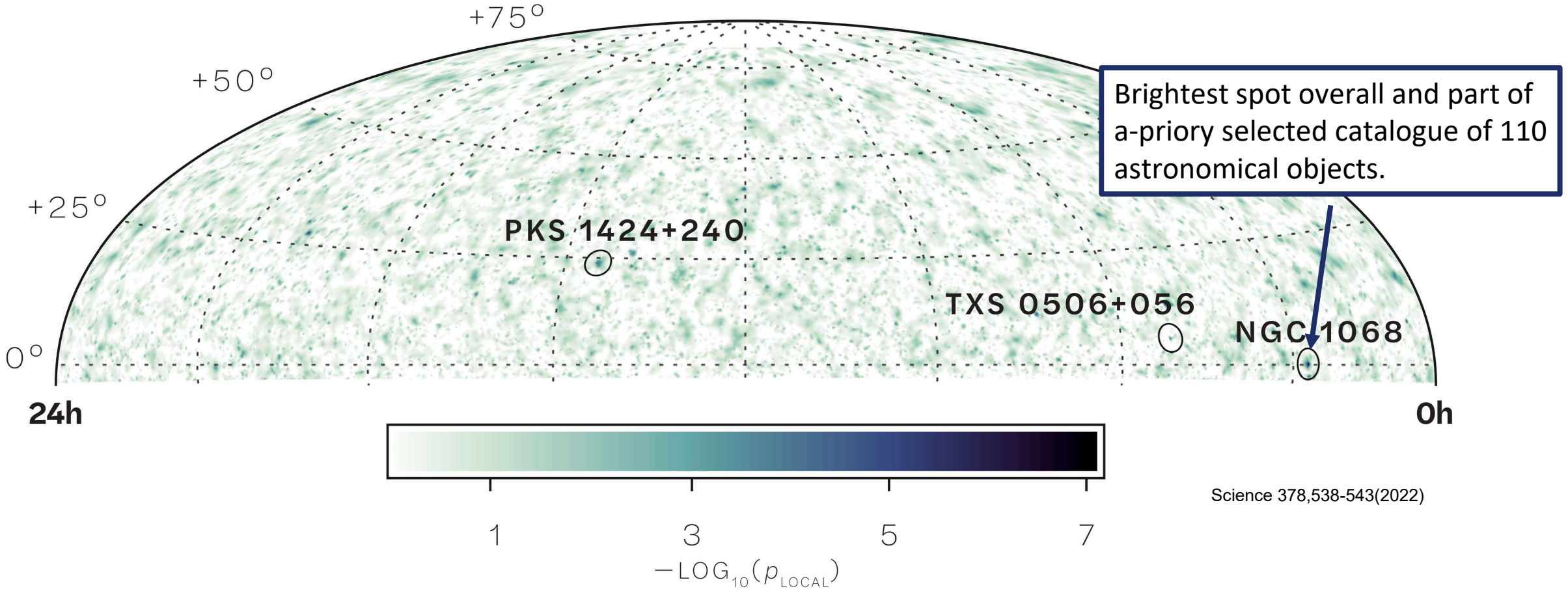
Searching for clustering and deviation from atmospheric ν spectrum at every point in the sky



Science 378,538-543(2022)

The Muon-Neutrino Sky

Searching for clustering and deviation from atmospheric ν spectrum at every point in the sky

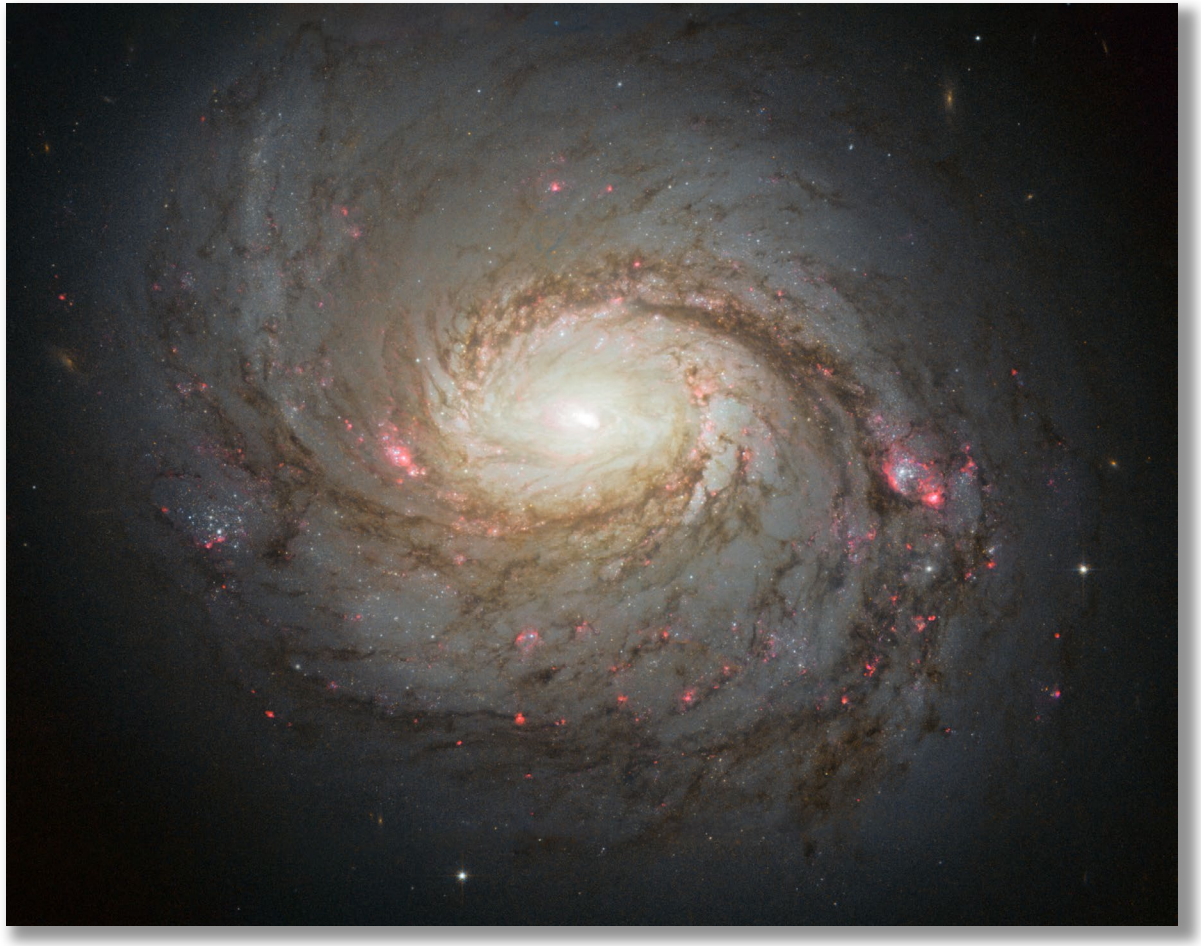


Brightest spot overall and part of a-priory selected catalogue of 110 astronomical objects.

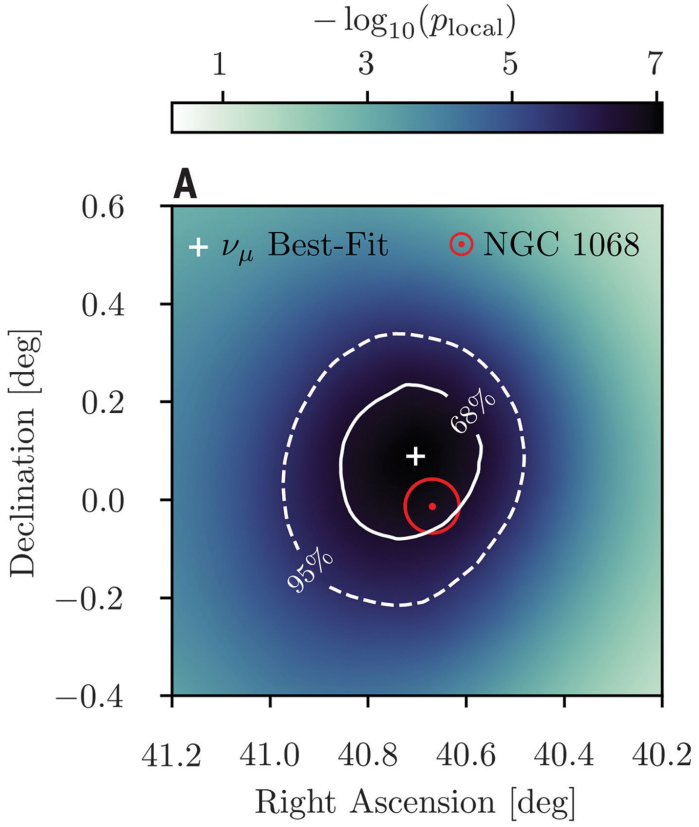
Science 378,538-543(2022)

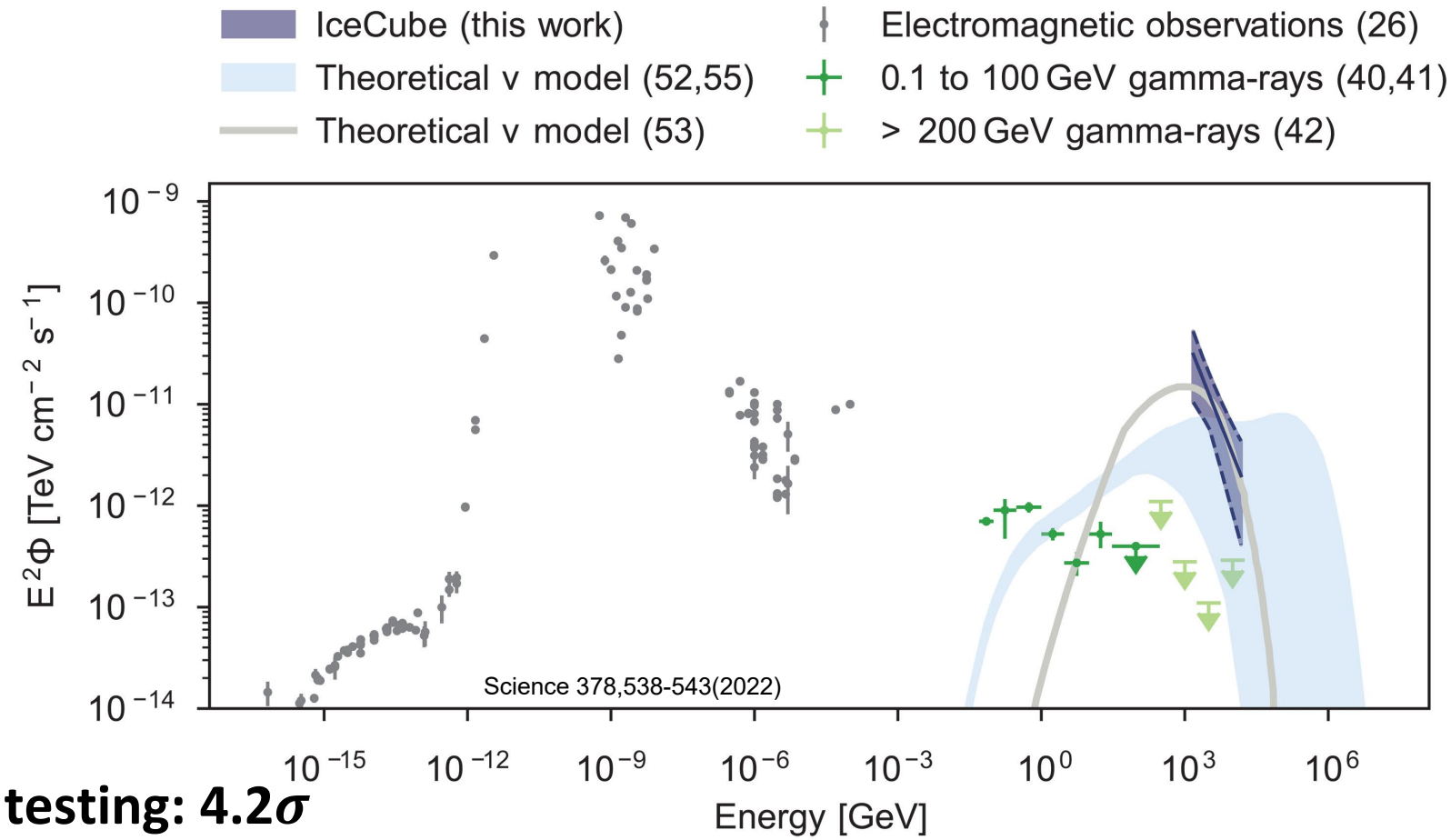
NGC1068

- Type II Seyfert Galaxy
- d=14.4Mpc
- Compton-thick AGN
- **Intrinsic X-ray photons in corona can provide target for ν production**



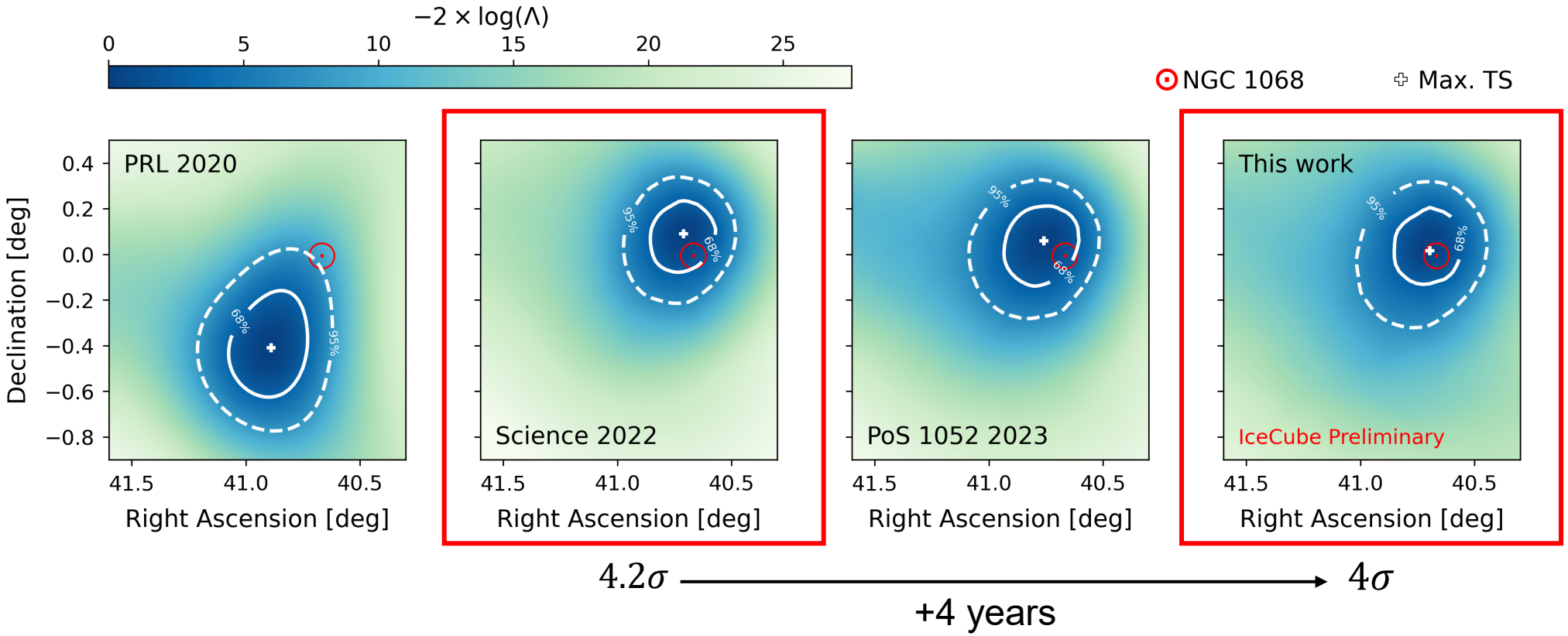
Neutrino Emission from NGC1068



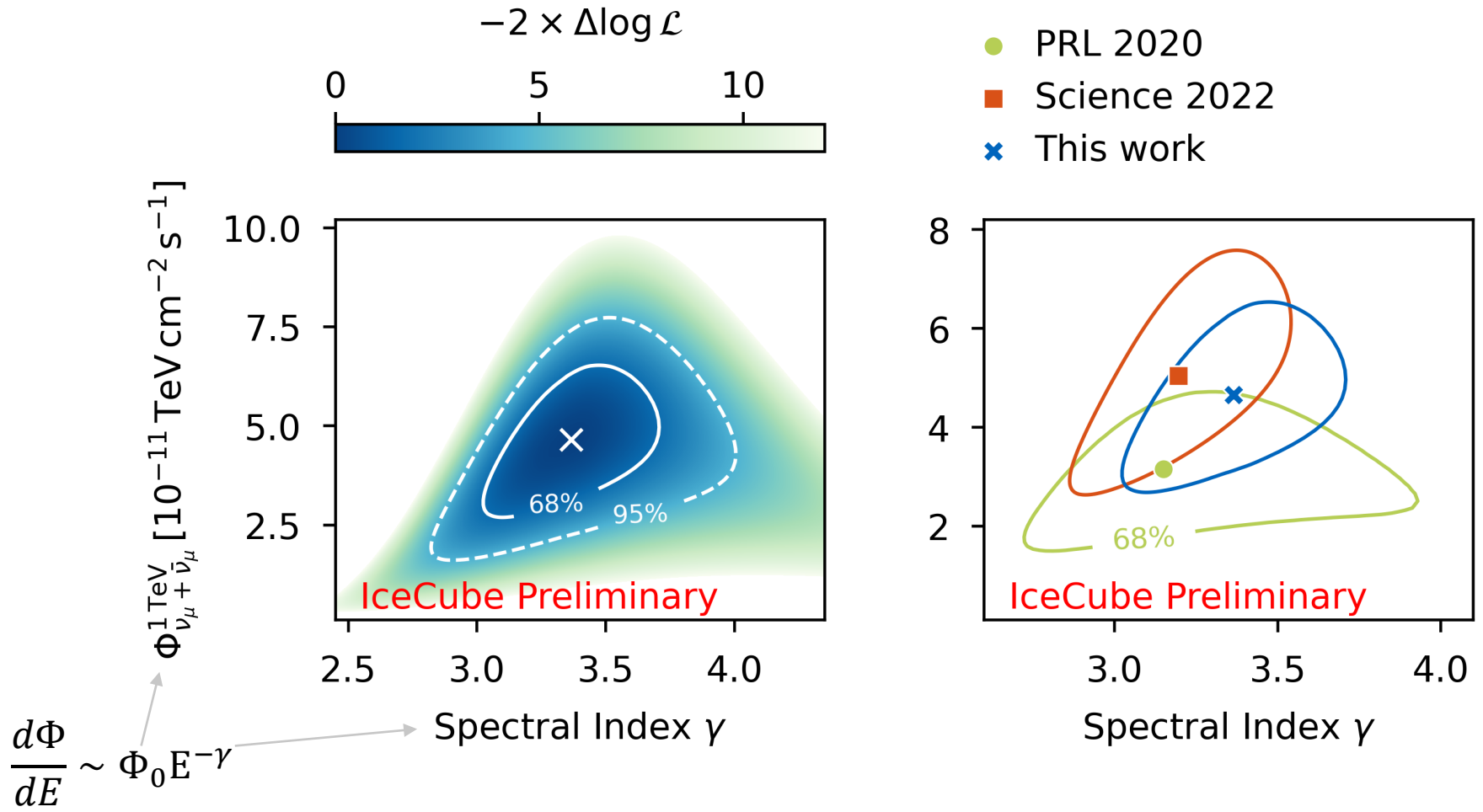


After correction for multiple testing: 4.2σ

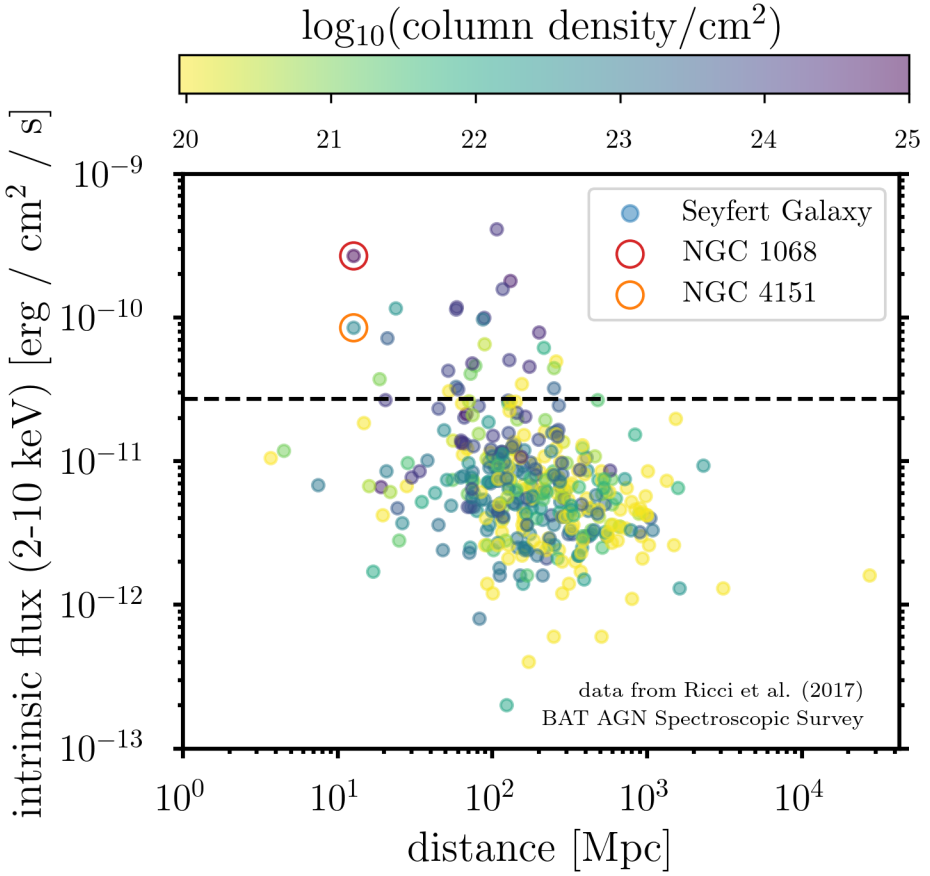
Four Extra Years of Data



Source Spectrum



Exploring Seyfert Galaxies



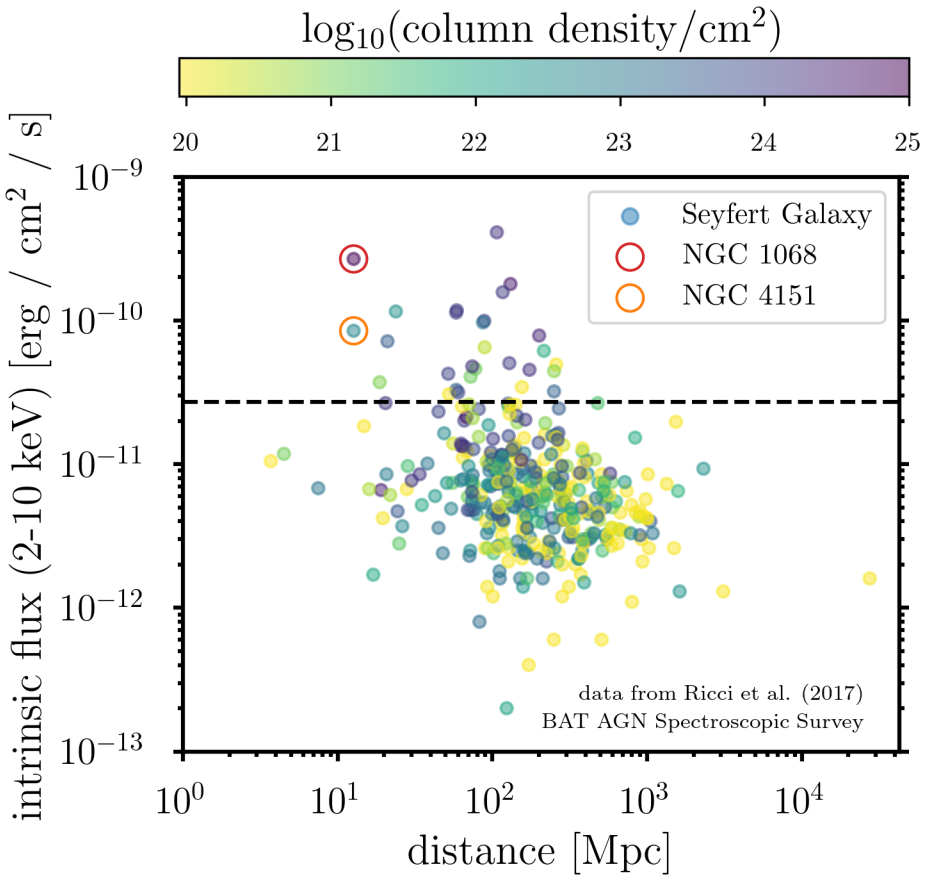
Searching for ν emission from Seyfert galaxies

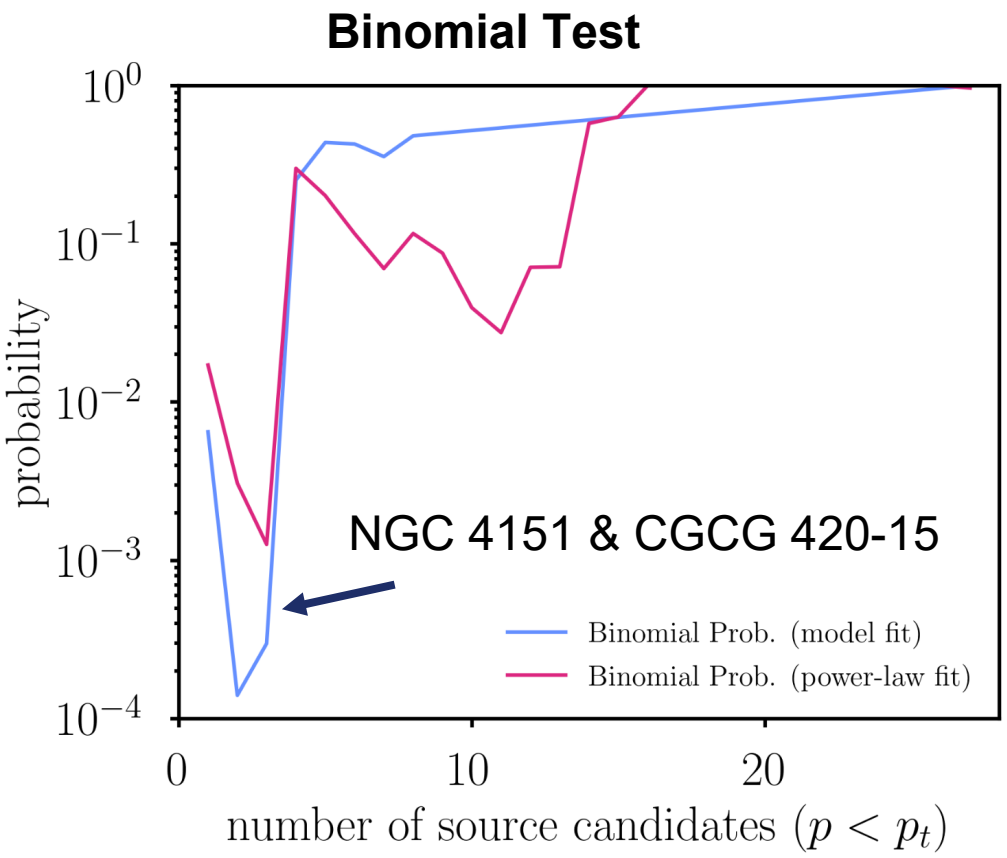
Multiple tests:

- Individual sources (significant emission from single source in catalogue)
- Stacking (combined emission of source catalogue)
- Binomial test: Prob. of finding k sources with $p < p_t$

NGC1068 not included in significance calculation!

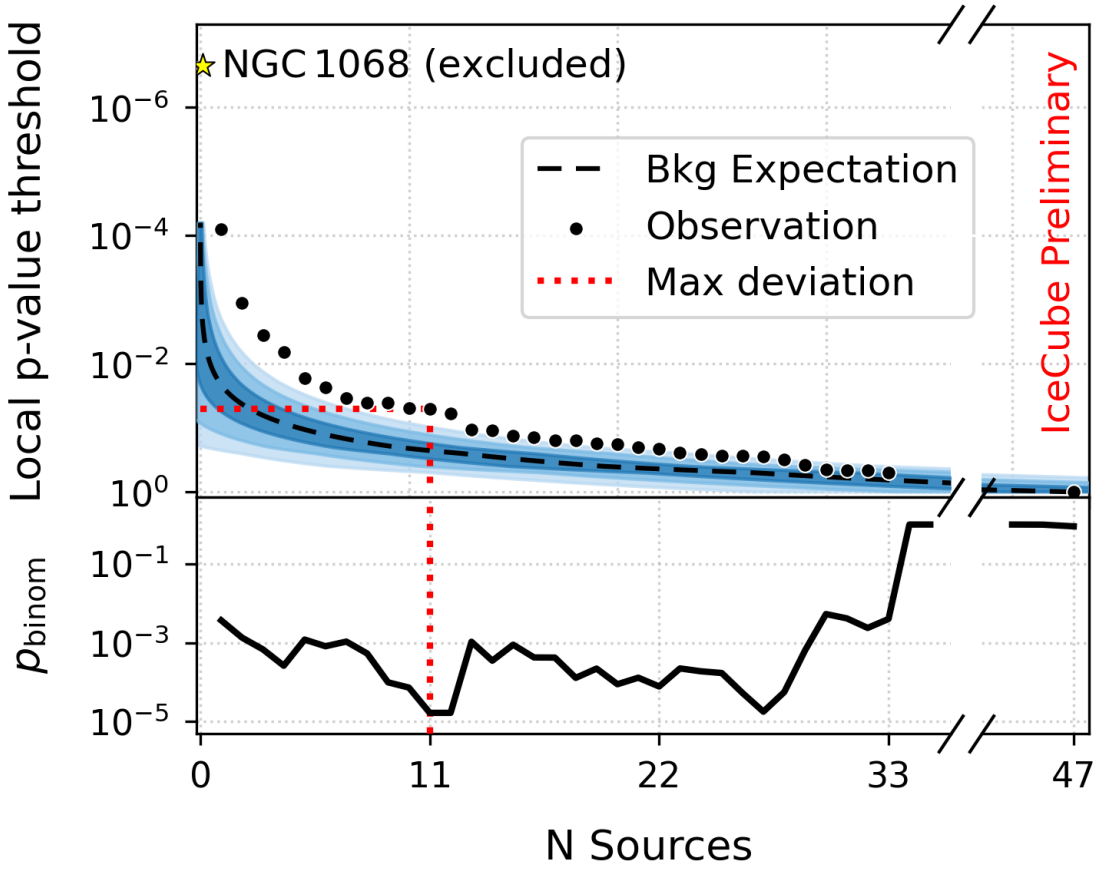
Exploring Seyfert Galaxies





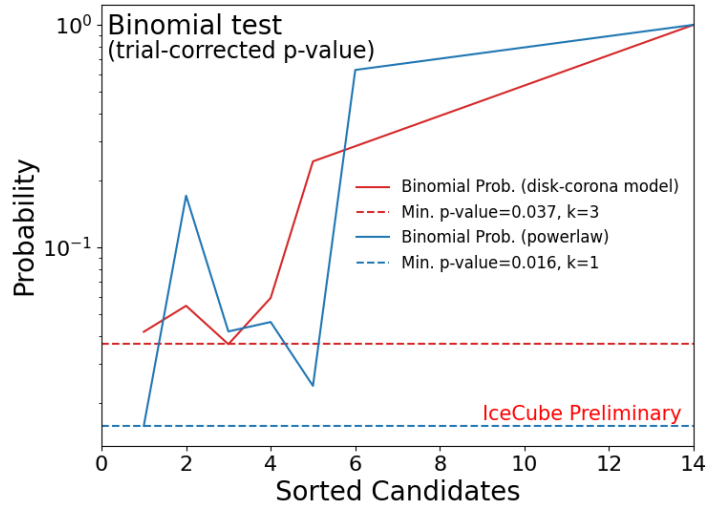
After correcting for multiple testing: 2.7σ excess

Four additional years of data

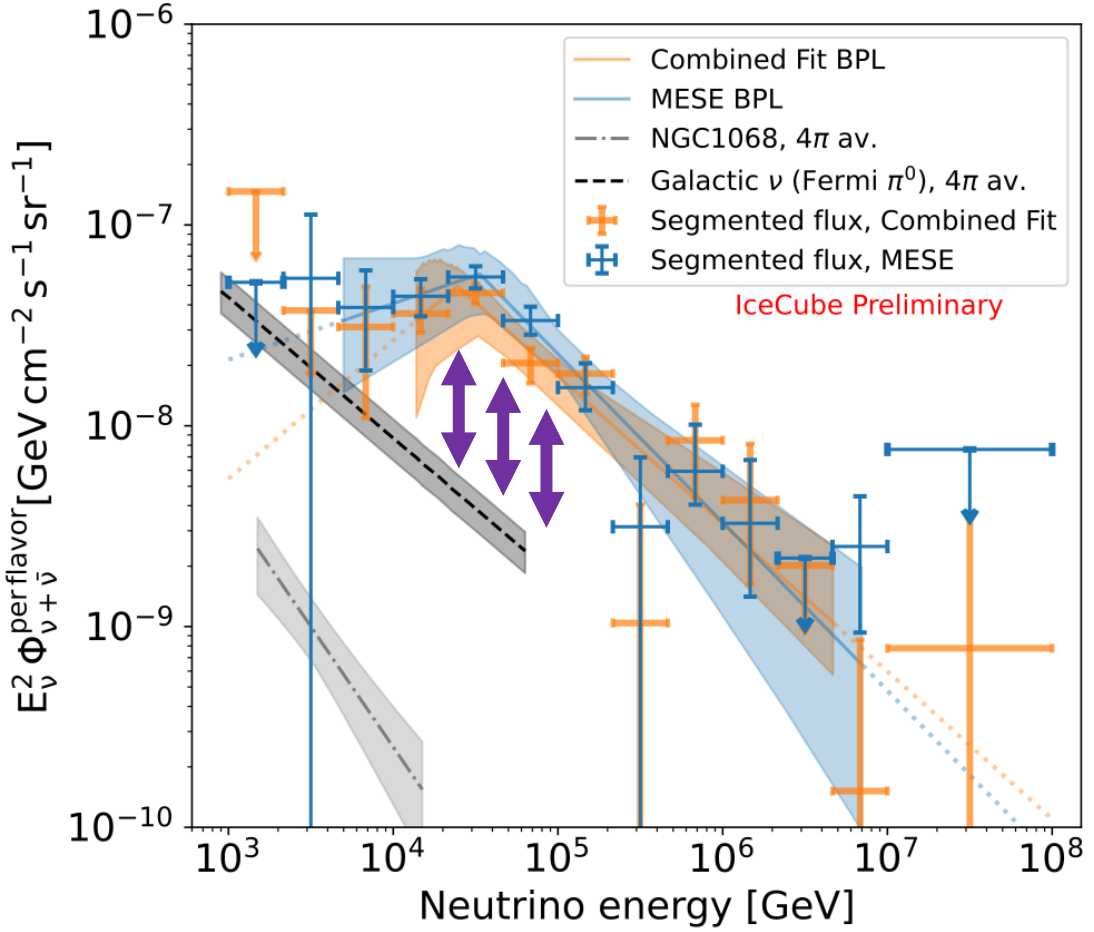


3.3σ after trial correction (4.5σ with NGC1068)

Also $< 5\%$ p-values in the Sourthern Sky



Neutrino Fluxes

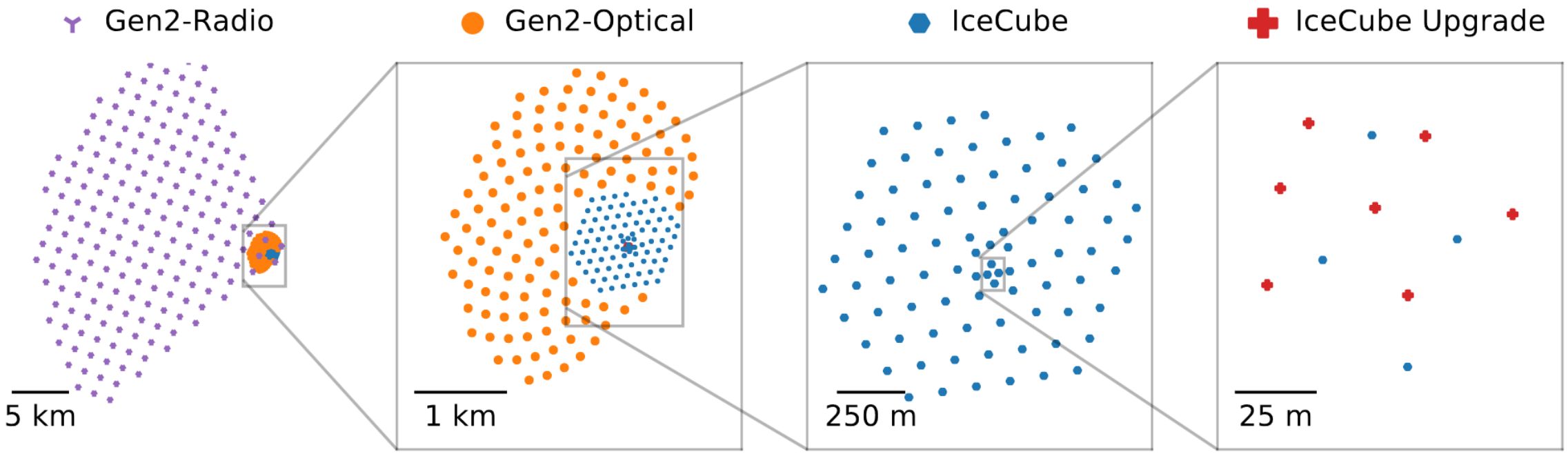


Still a lot of room for additional sources!

What’s Next?

Credit: Emanuel Jacobi / NSF

IceCube Upgrade + Gen2

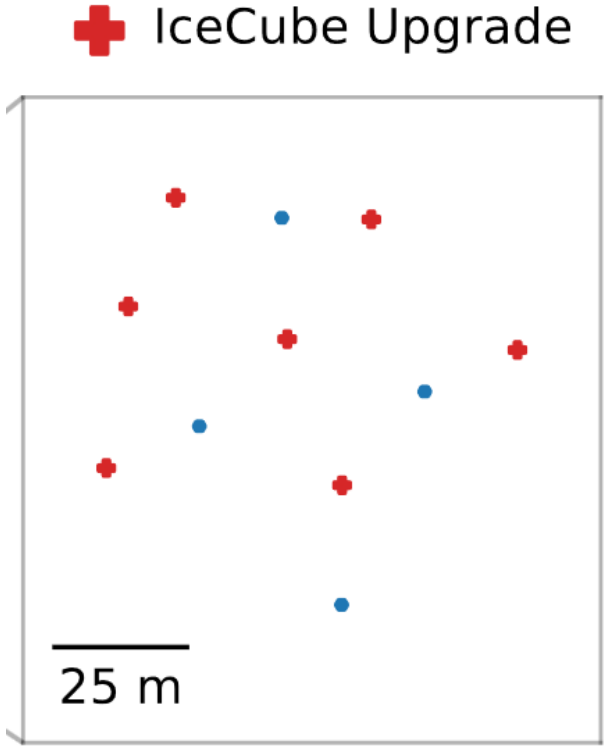


> 30 PeV **> 3 TeV** **> 0.1 TeV** **> GeV**

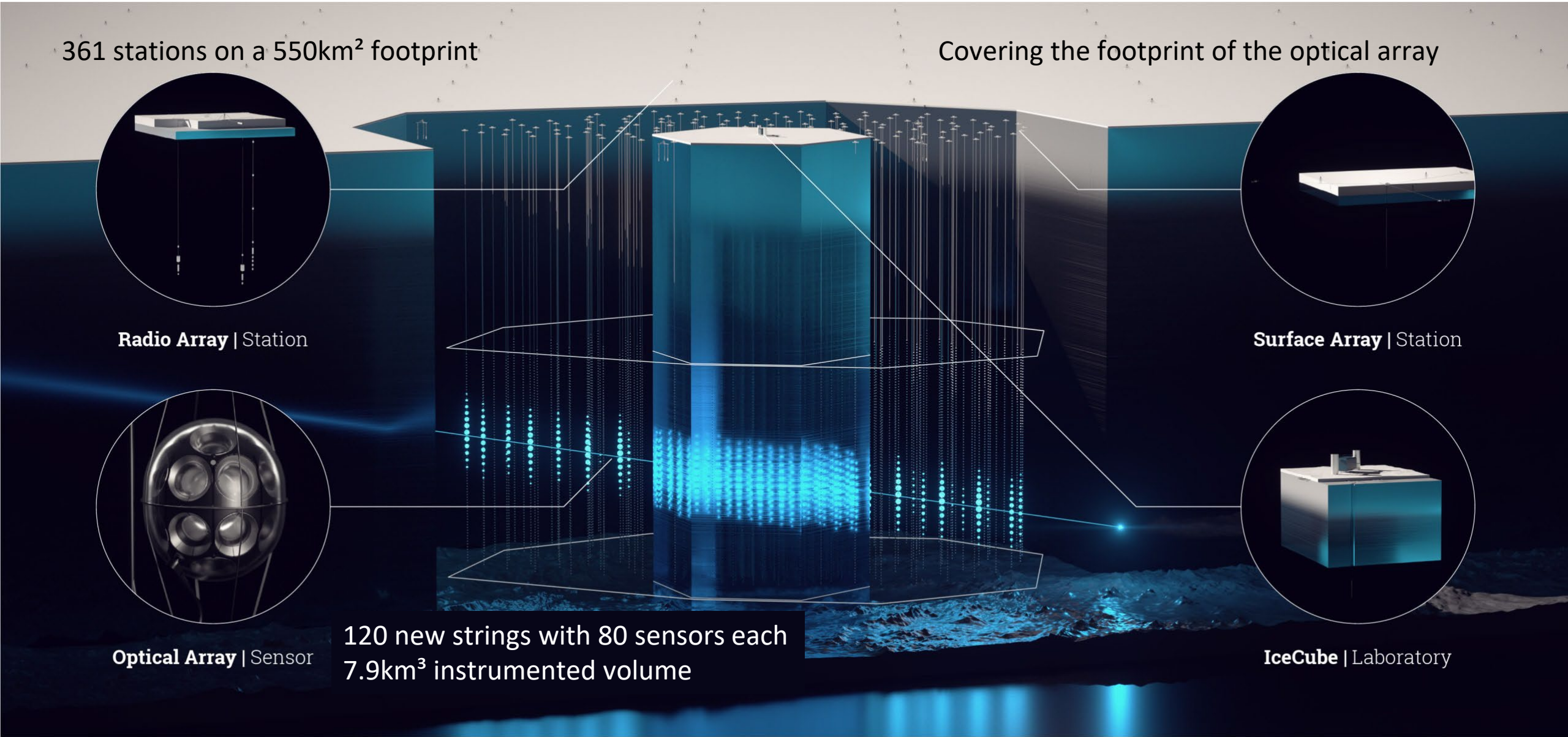
IceCube Upgrade + Gen2

IceCube Upgrade

- Extending sensitivity at lower energies for calibration & atmospheric neutrino oscillations
- Re-processing of >TeV data to include new calibration
- Deployment of new photosensors in winter 2025/26

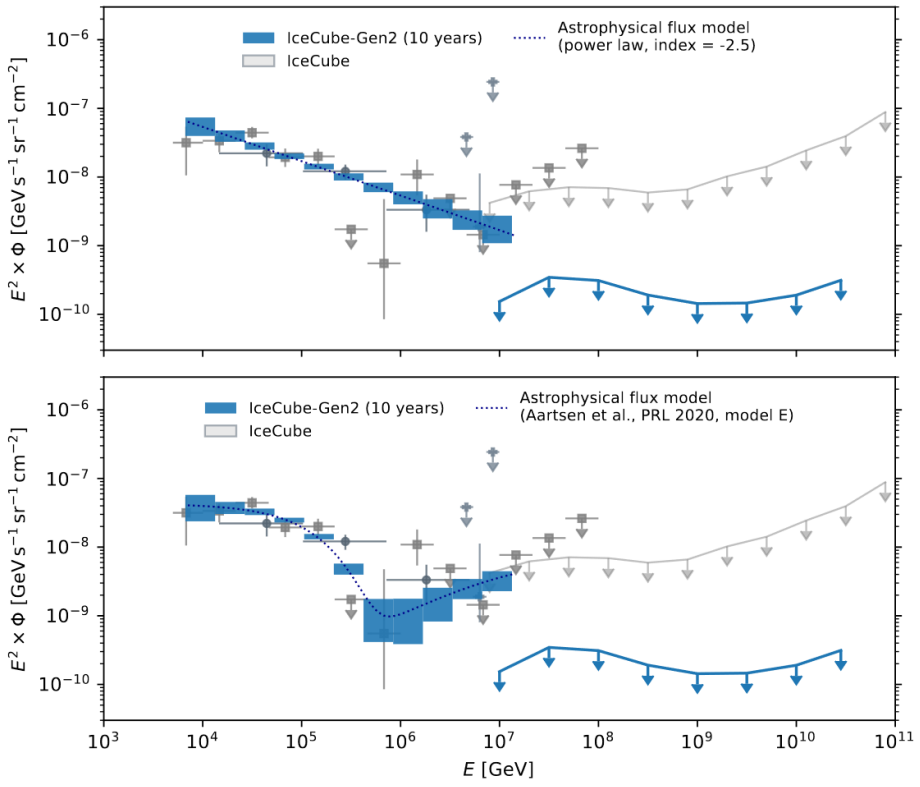


IceCube-Gen2 Neutrino Observatory

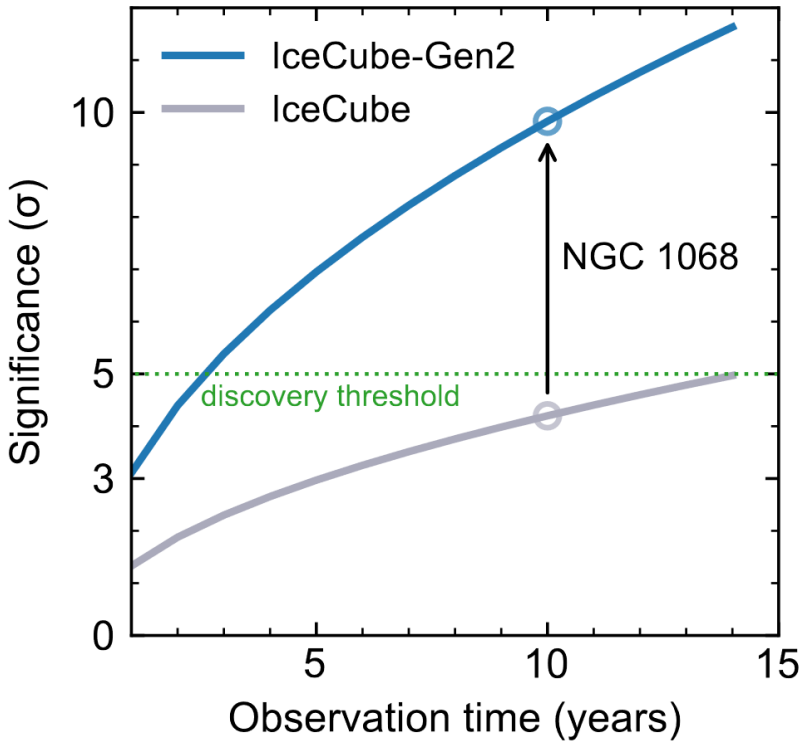


Gen2 Science Highlights

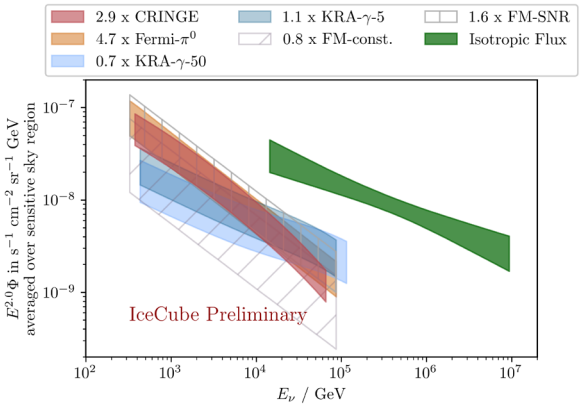
Precision measurement of the astrophysical neutrino spectrum



Resolving neutrino sources

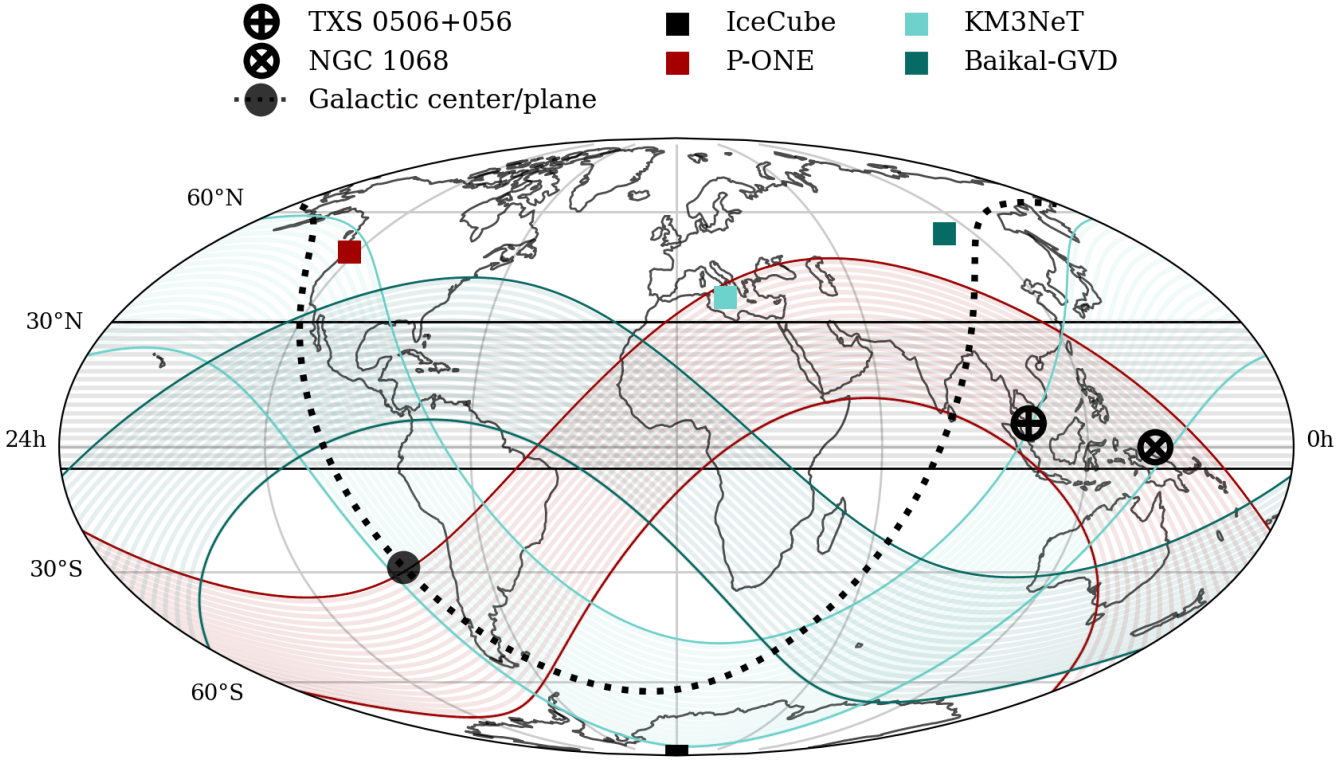


8.7σ for diffuse galactic emission after 10years.



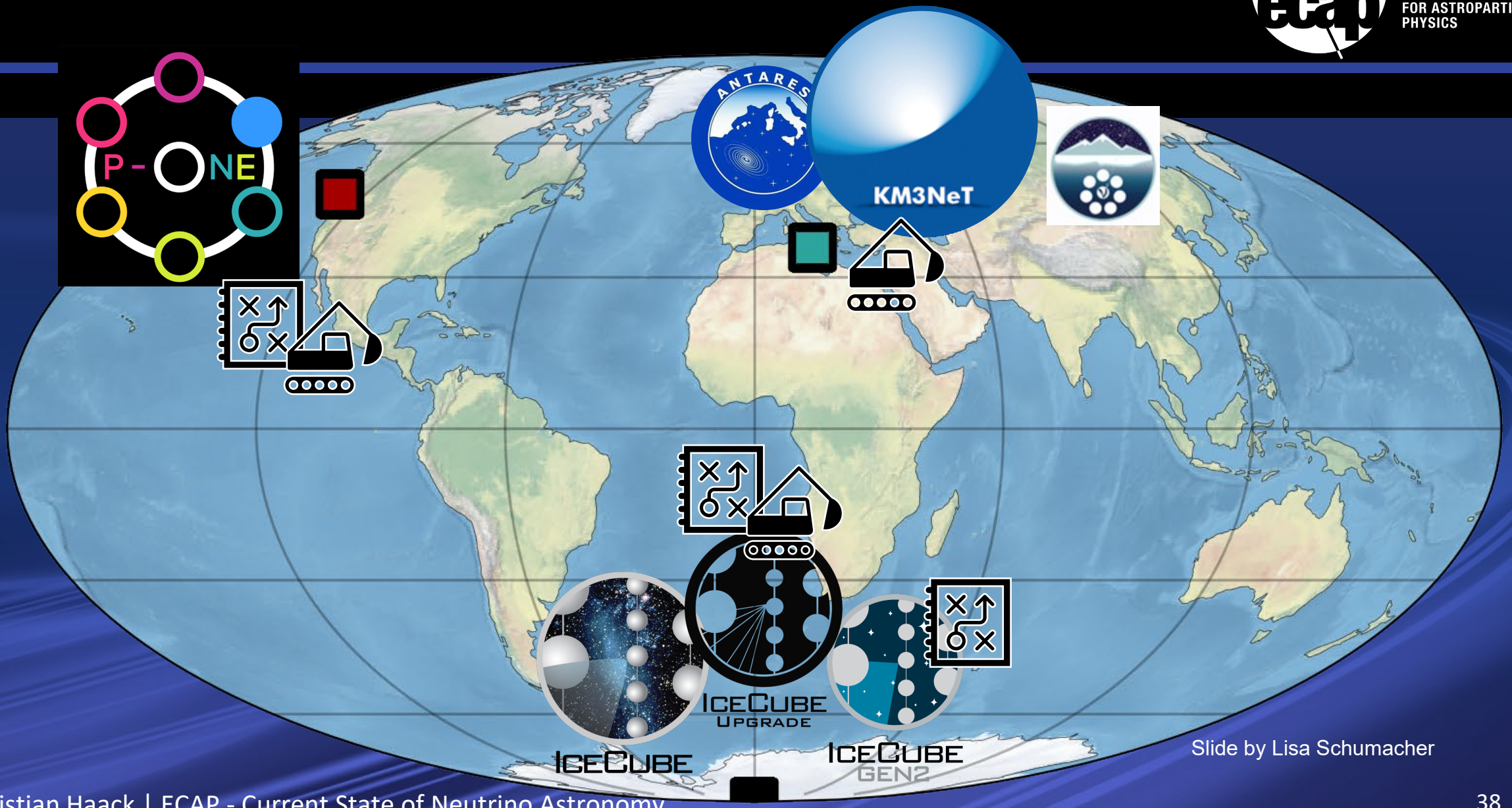
And much, much more.
Check out the TDR

Telescope Complementarity



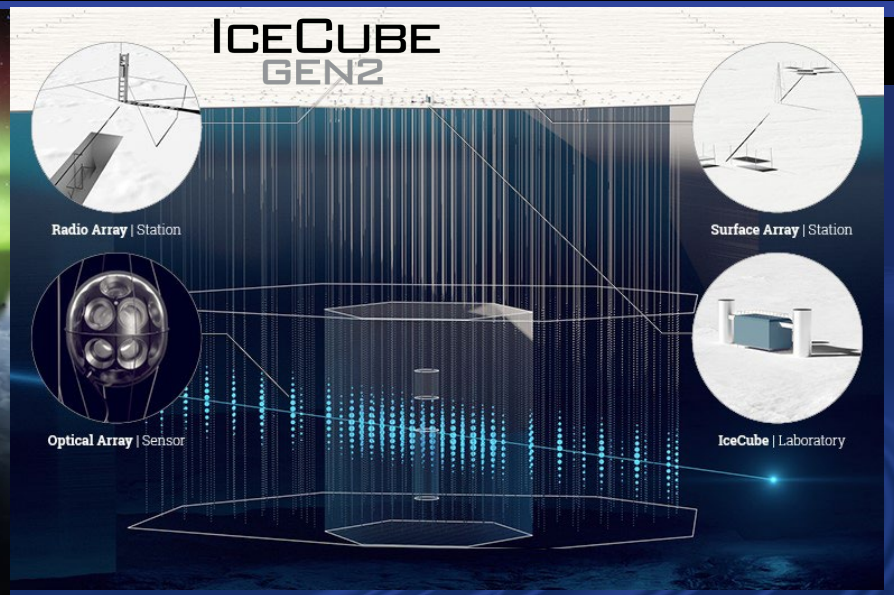
Lisa Schumacher

The global picture

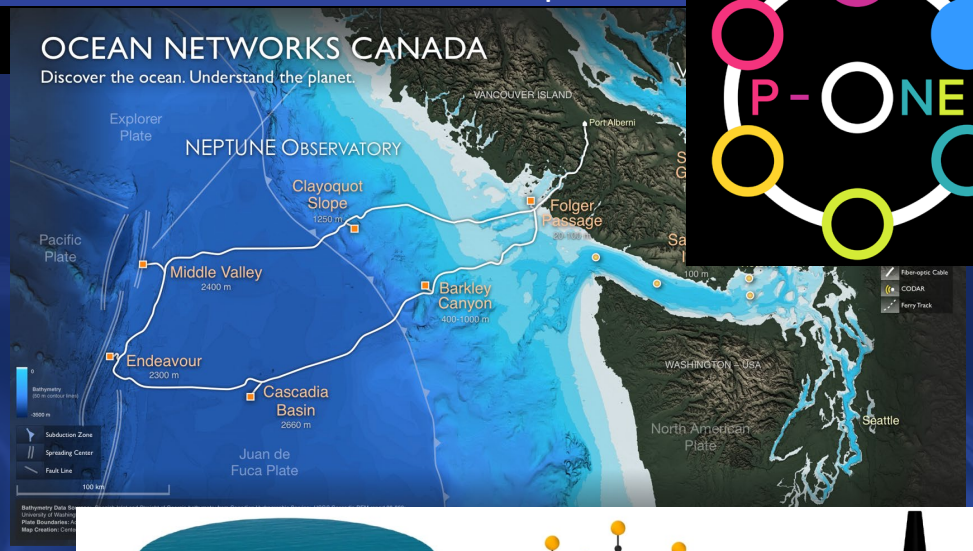


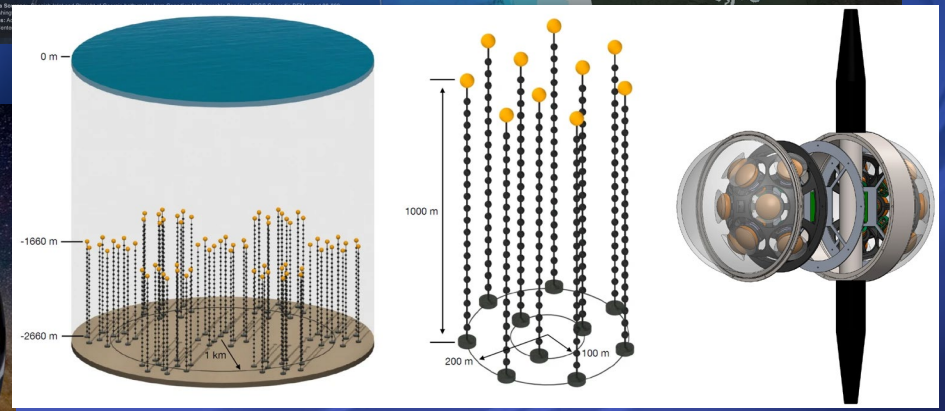
Slide by Lisa Schumacher

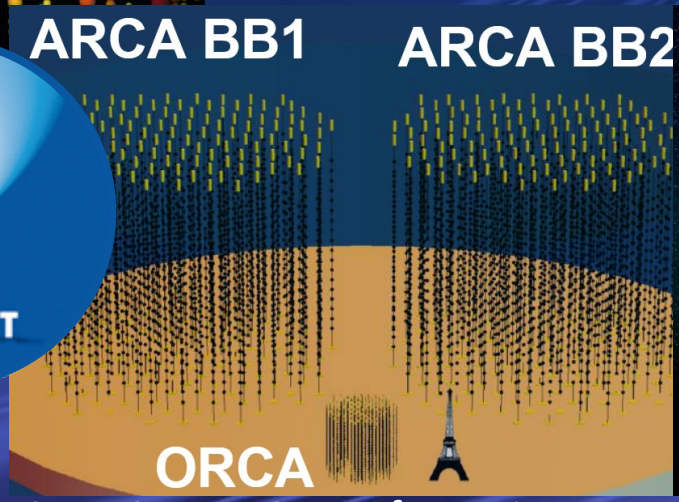
The global picture



Pacific Ocean Neutrino Experiment







João Coelho – Neutrino 2024

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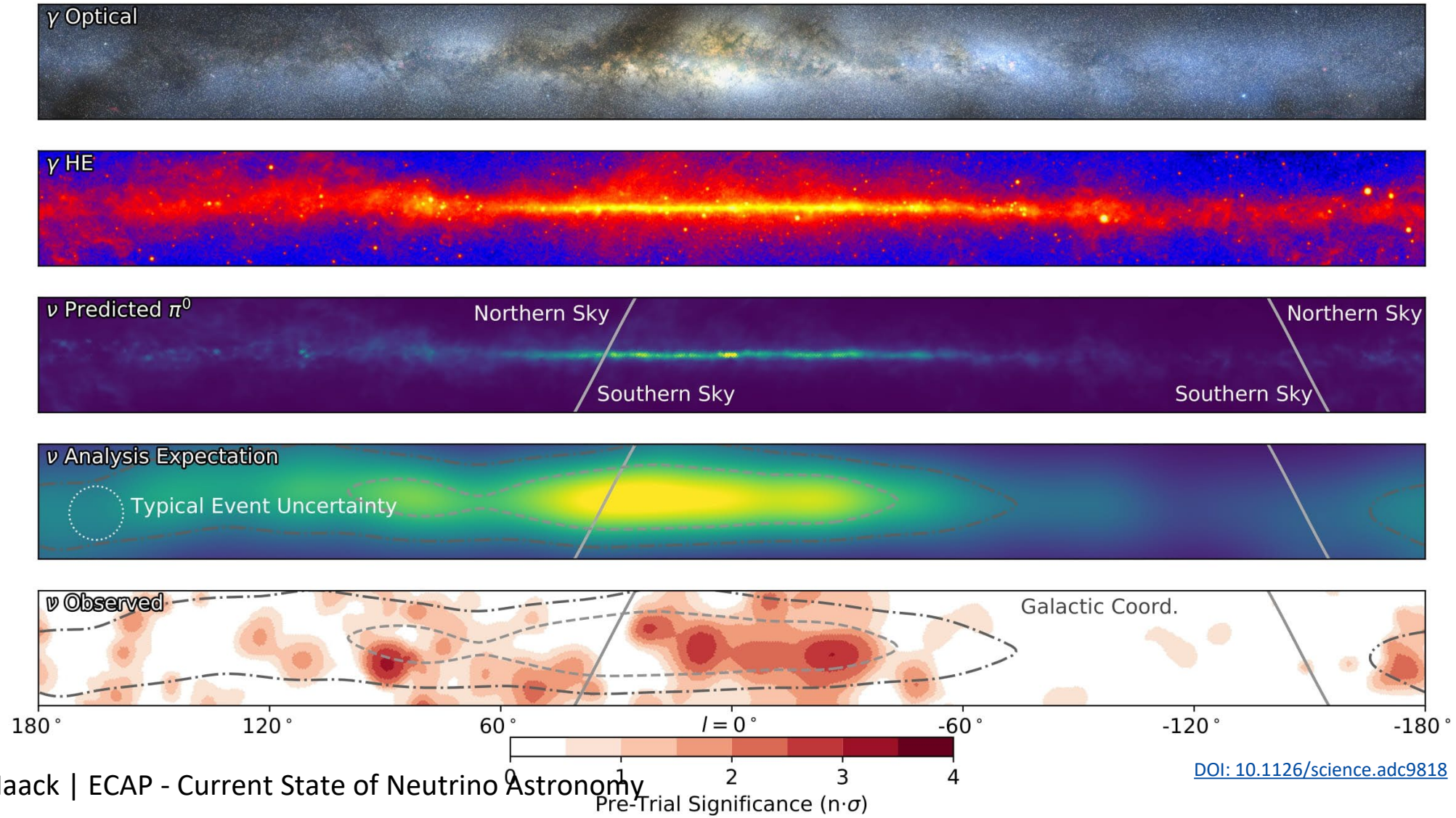
+ TRIDENT, HUNT, Baikal-GVD, TAMBO, …

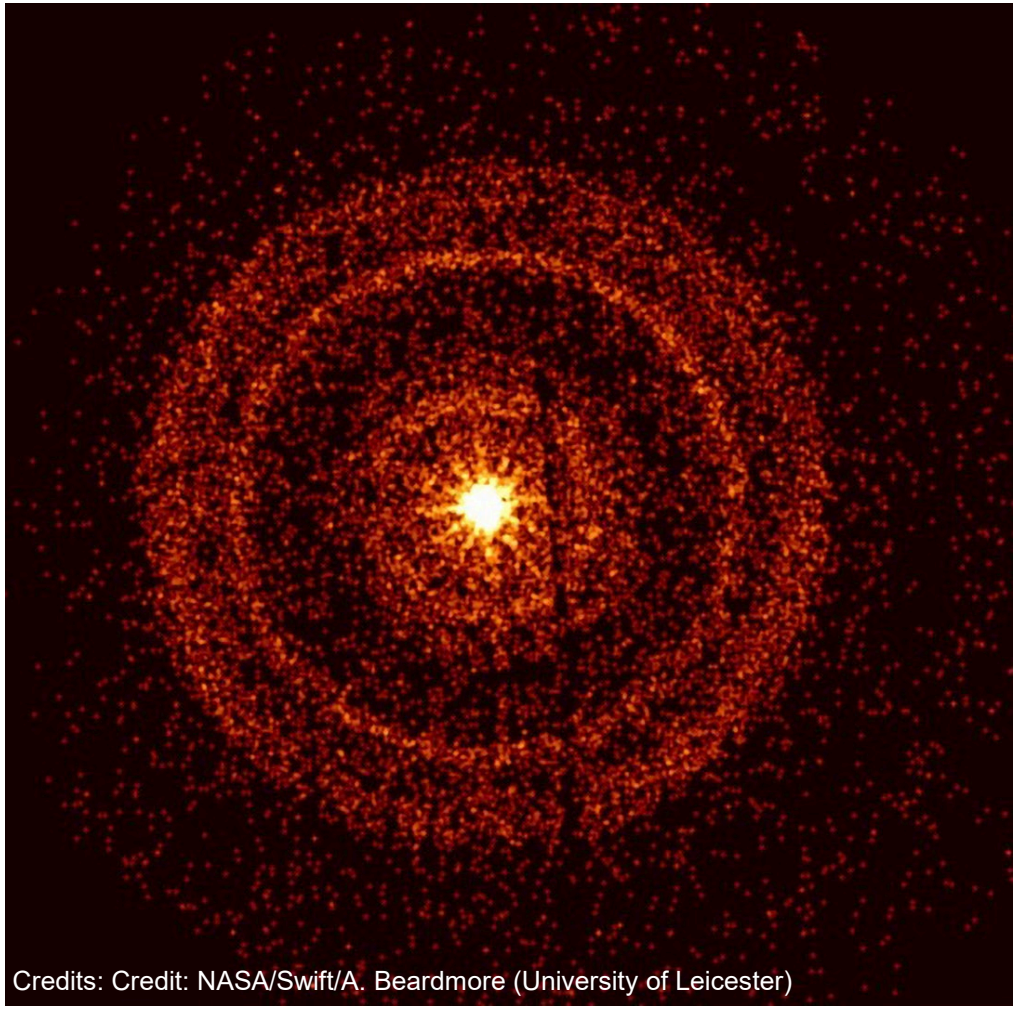
Backup

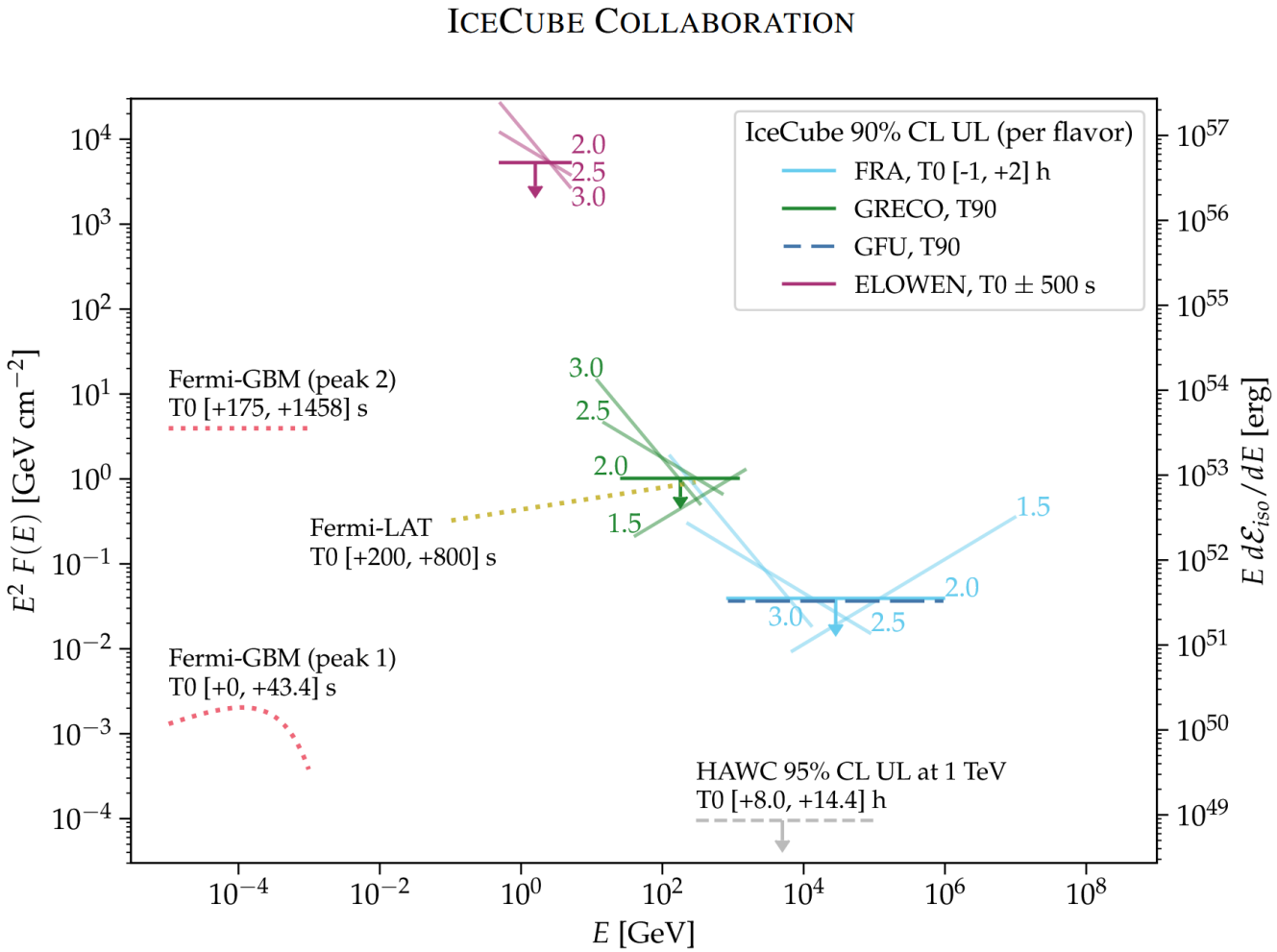
Neutrinos from the Galactic Plane



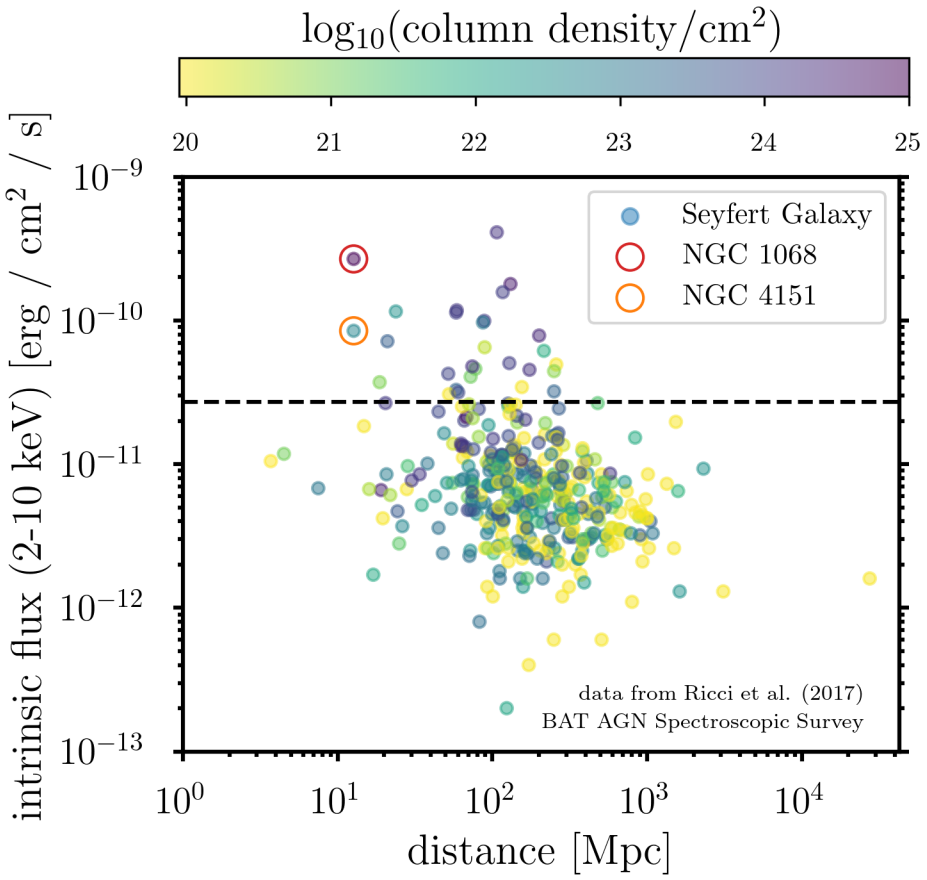
DOI: 10.1126/science.adc9818

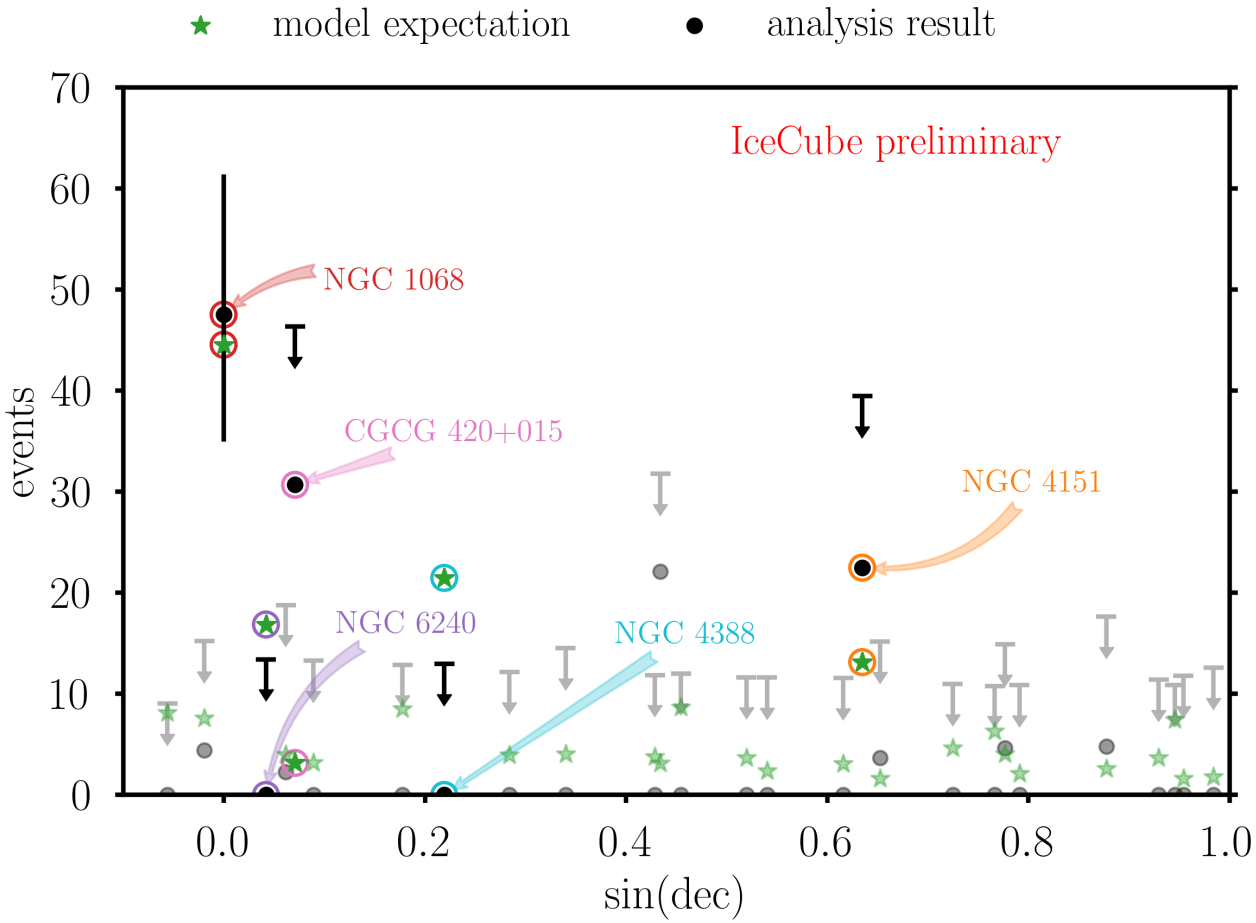
GRB221009A


Credits: Credit: NASA/Swift/A. Beardmore (University of Leicester)



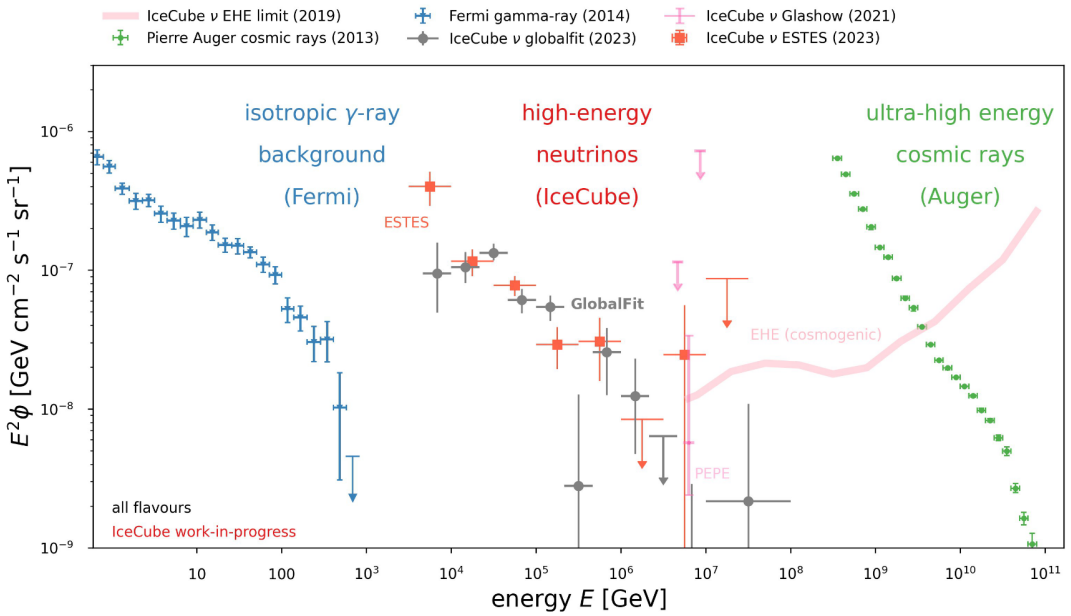
Seyfert Galaxies



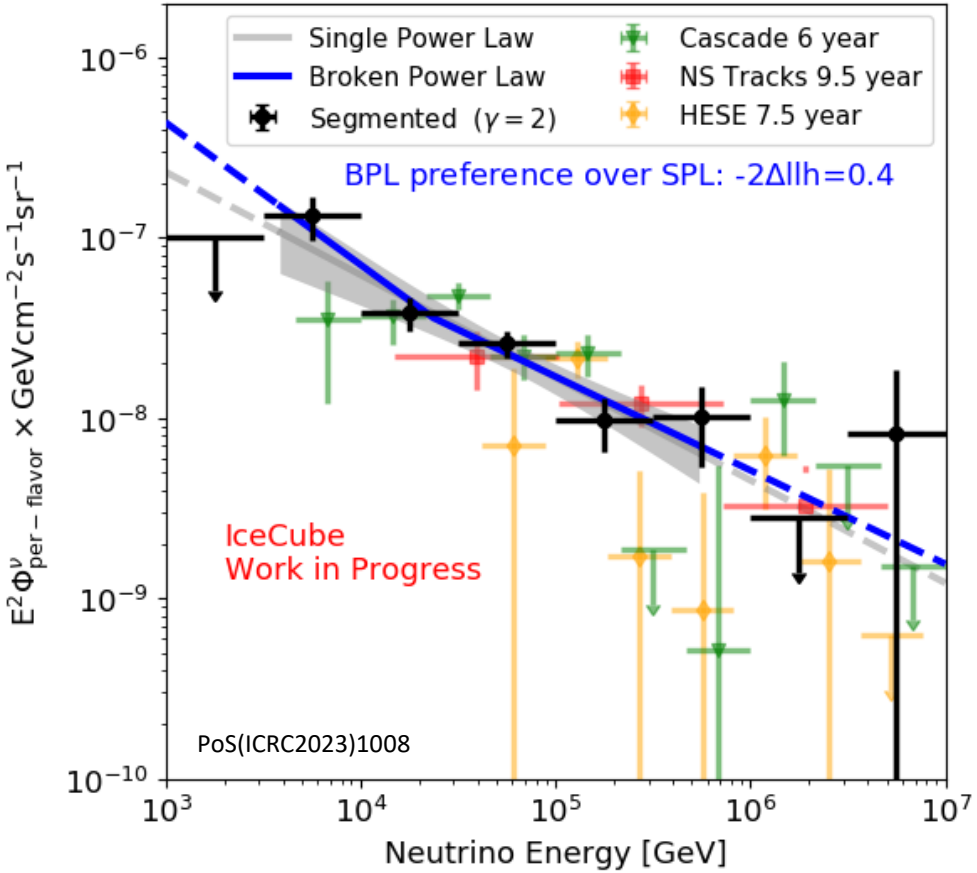


No significant excess found

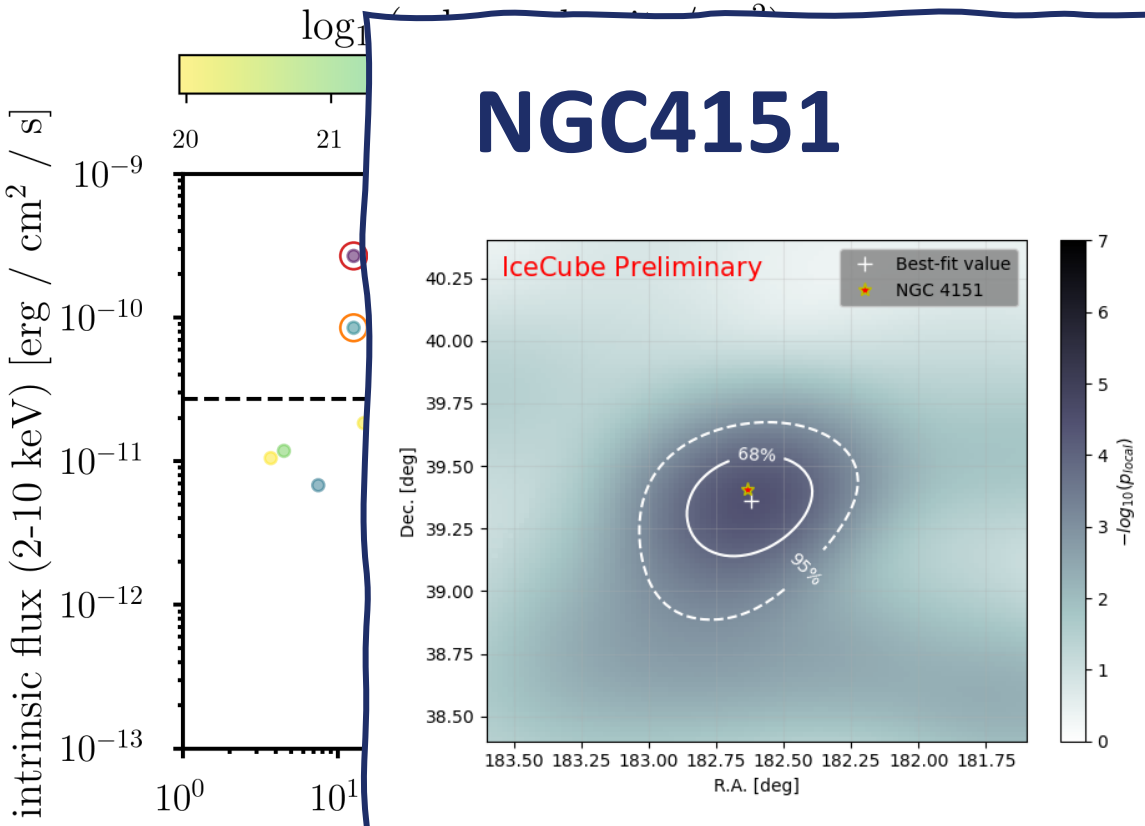
Cosmic Neutrino Spectrum



New measurements using starting tracks (ESTES)



Seyfert Galaxies

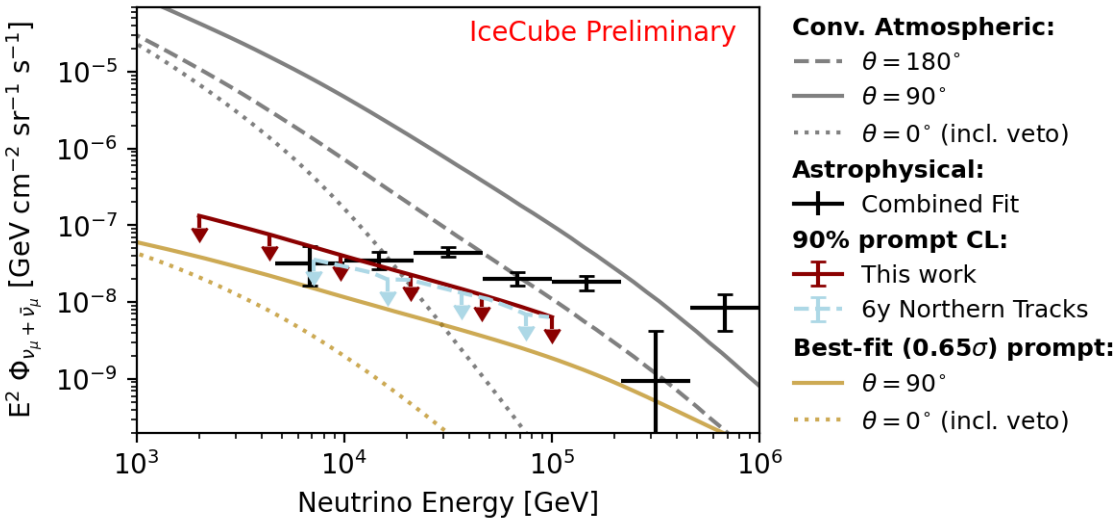


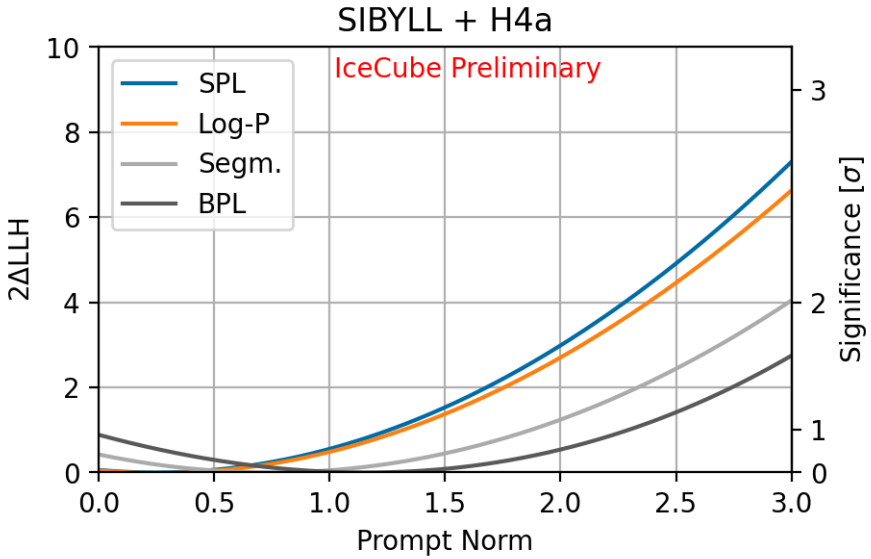
NGC4151

Independent (but overlapping) analysis searching for ν emission from hard X-ray sources: **2.9σ**

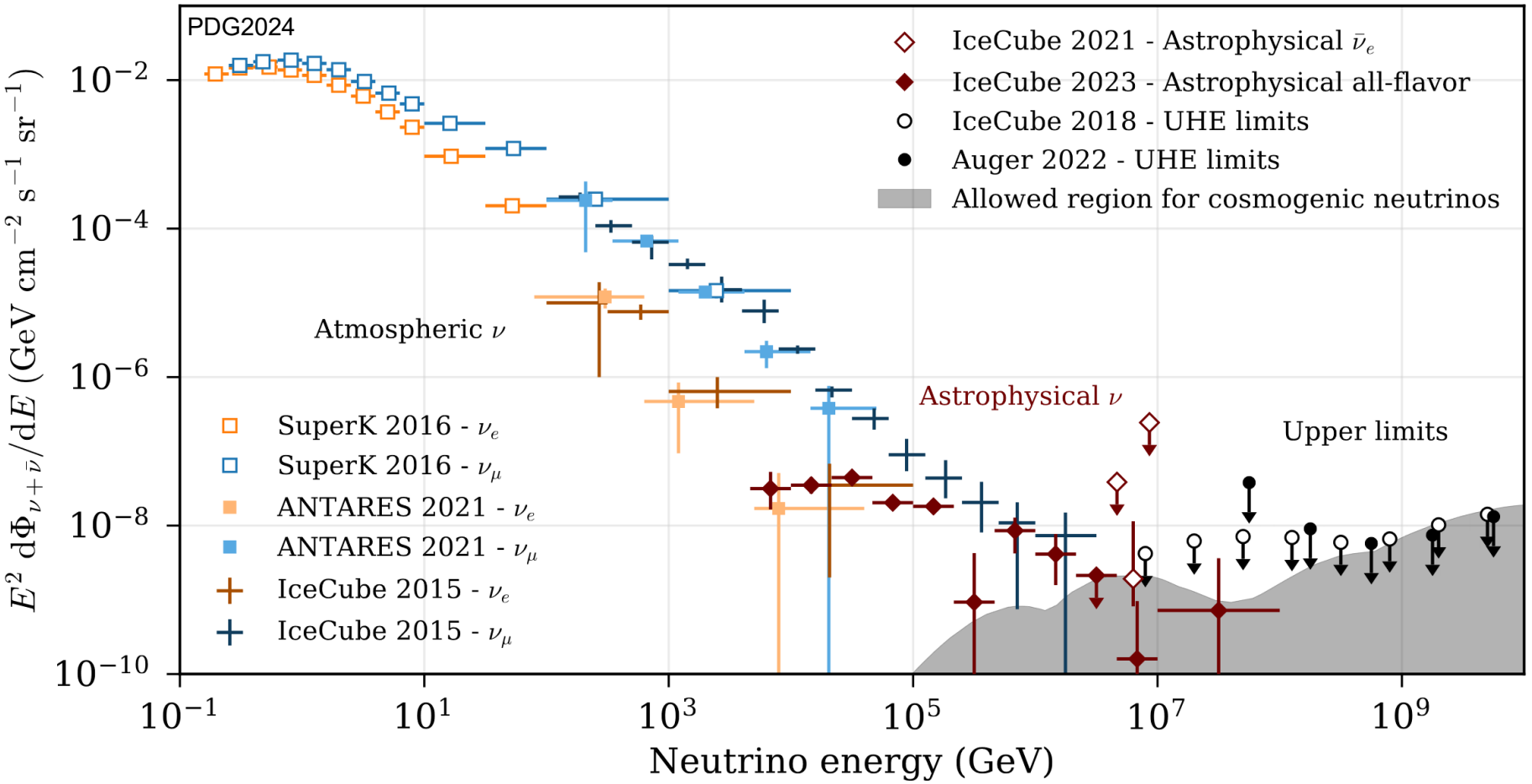
σ excess

Prompt Atmospheric Neutrinos

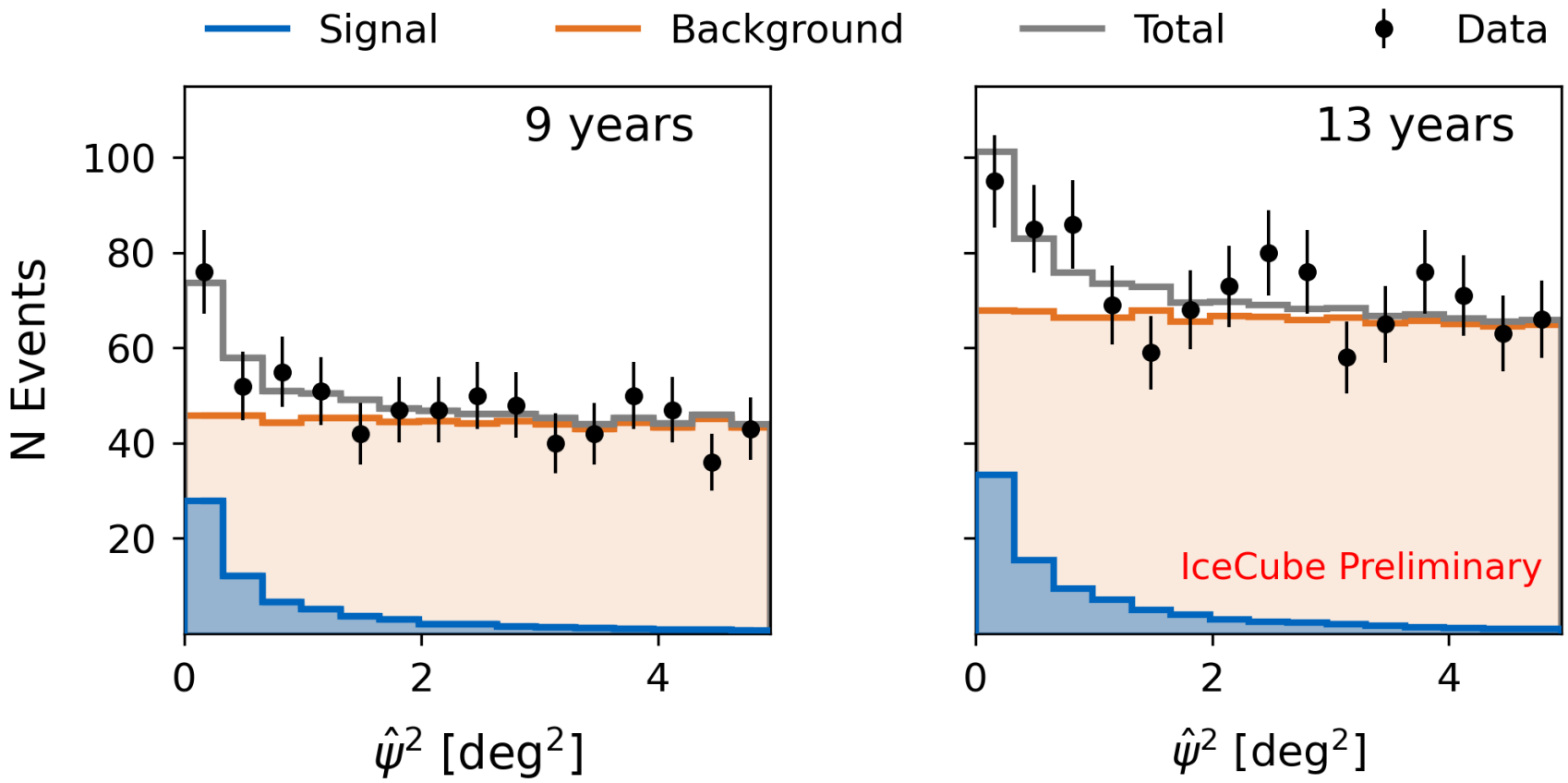




Neutrino Fluxes

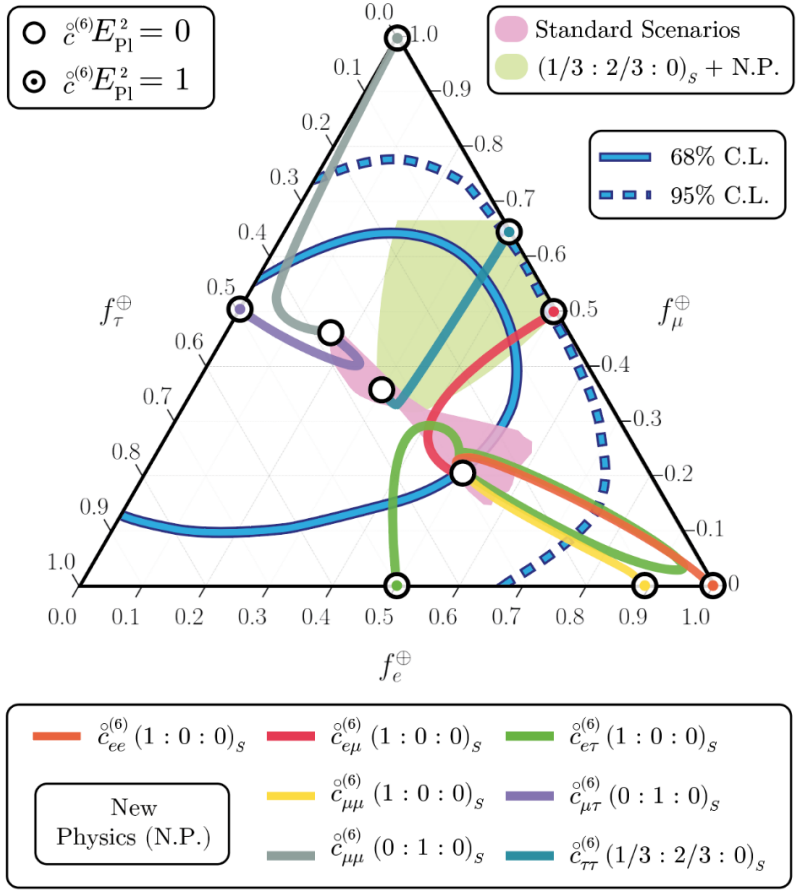


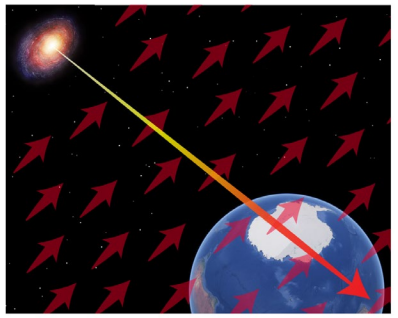
NGC1068 Data/MC



Quantum Gravity

https://doi.org/10.1038/s41567-022-01762-1





Idea: Neutrino propagation over cosmic distance scales is influenced by space-time defects

Modelled as effective operators in vacuum Hamiltonian

$$H \sim \frac{m^2}{2E} + \mathring{a}^{(3)} - E \cdot \mathring{c}^{(4)} + E^2 \cdot \mathring{a}^{(5)} - E^3 \cdot \mathring{c}^{(6)} \cdots .$$

Quantum Gravity

https://doi.org/10.1038/s41567-022-01762-1