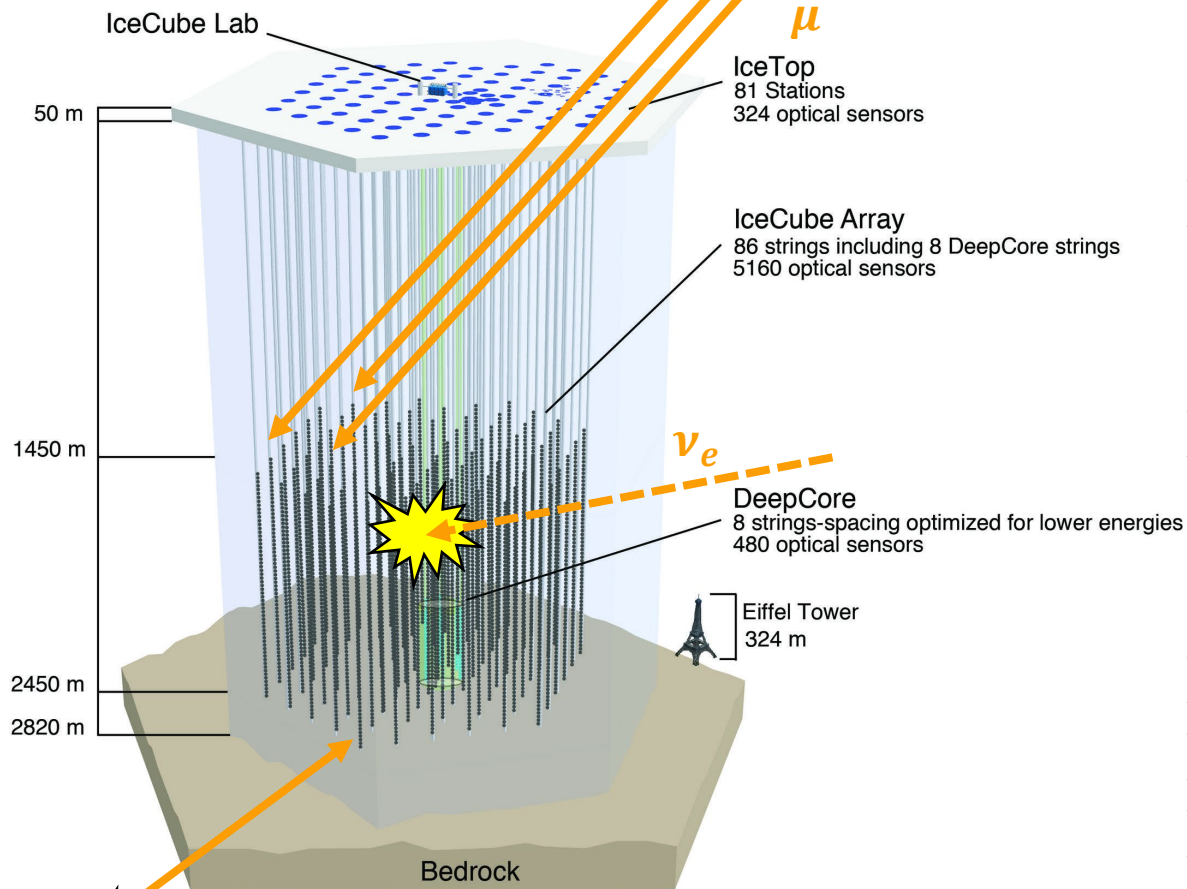




IceCube + Gen2

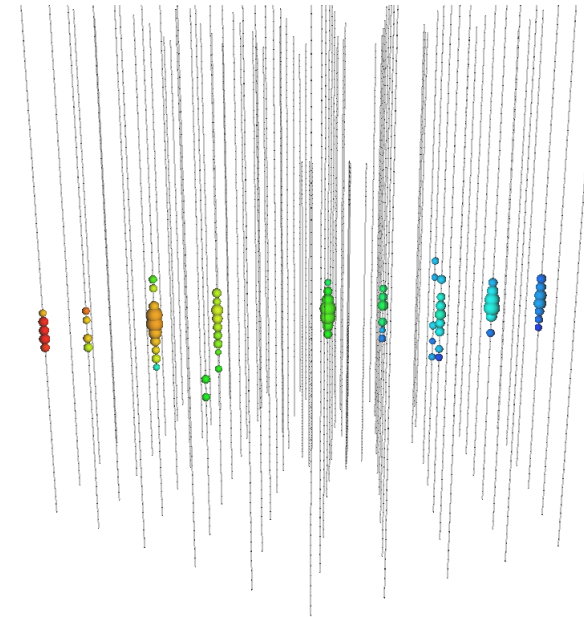
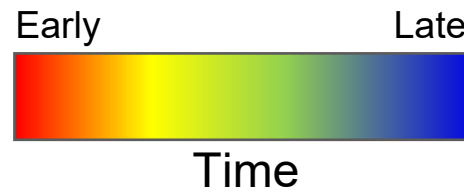
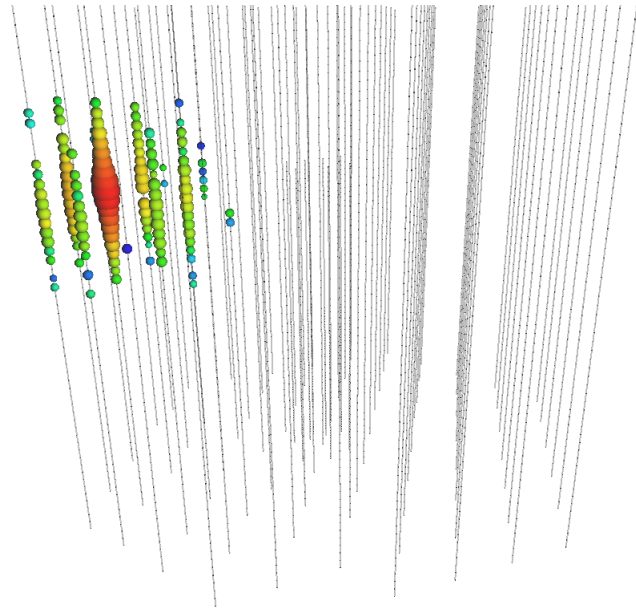
Christian Haack for the IceCube Collaboration
Lake Louise Winter Institute 2024

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

Event Channels



(EM / Hadronic) Cascades

Neutral Current (NC) & ν_e (ν_τ) Charged Current (CC)

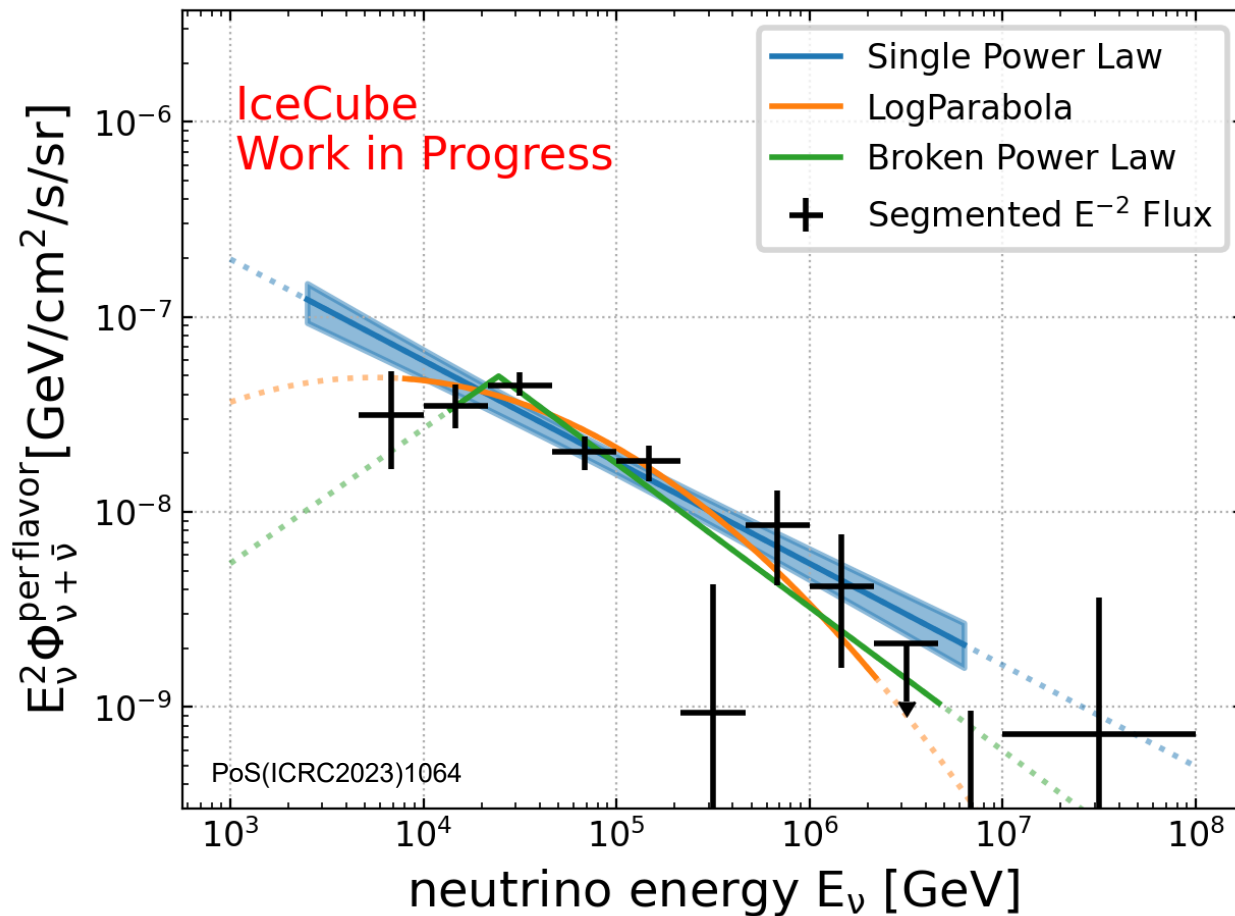
- + Energy resolution
- + High Purity

Throughgoing Tracks (muons)

ν_μ CC, atmospheric μ

- + Angular resolution
- + Large effective area

Cosmic Neutrino Spectrum



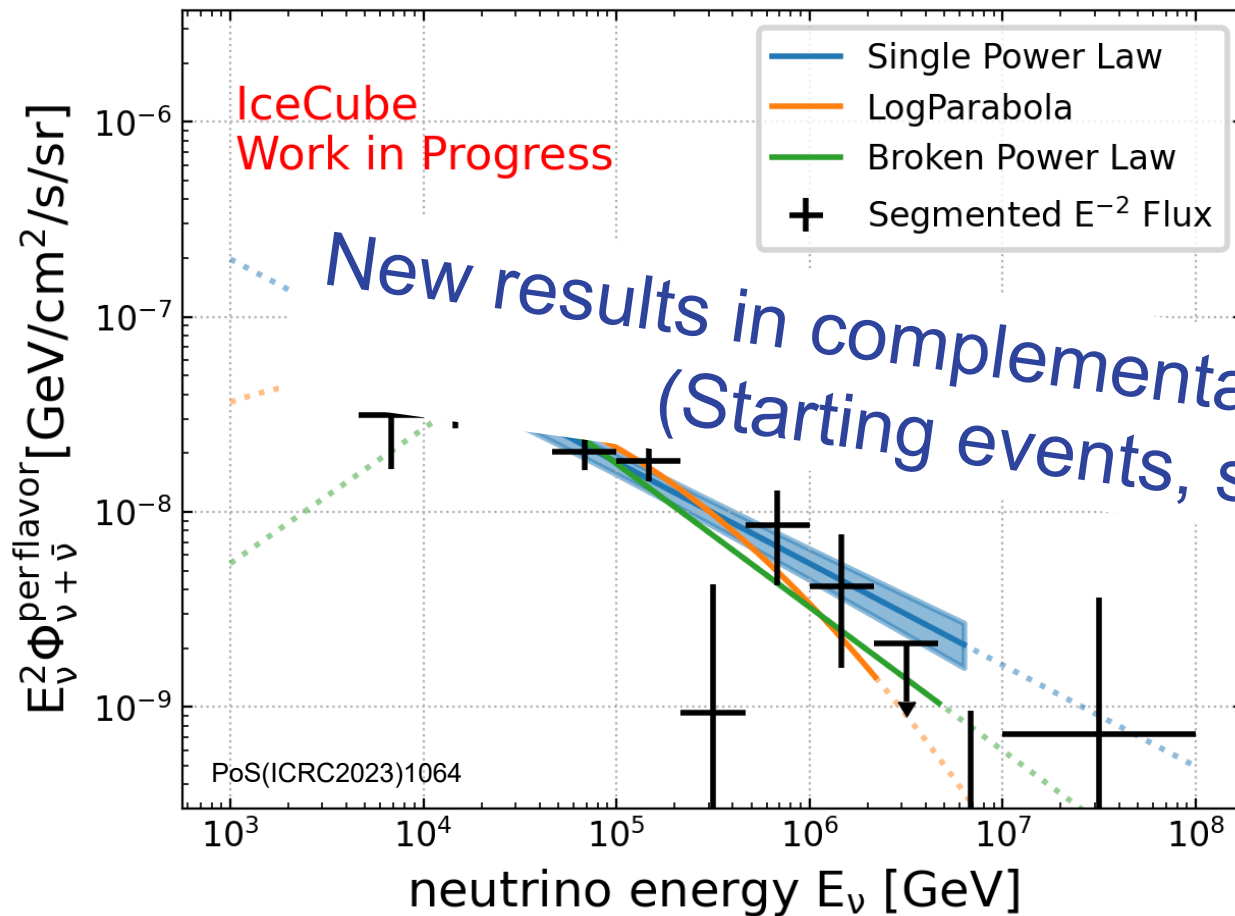
Combined fit of tracks / cascades with unified systematic uncertainty treatment

Indications for structure in energy spectrum

Work in Progress:

- Significance of BPL / LogParabola vs SPL
- Systematic Uncertainties

Cosmic Neutrino Spectrum

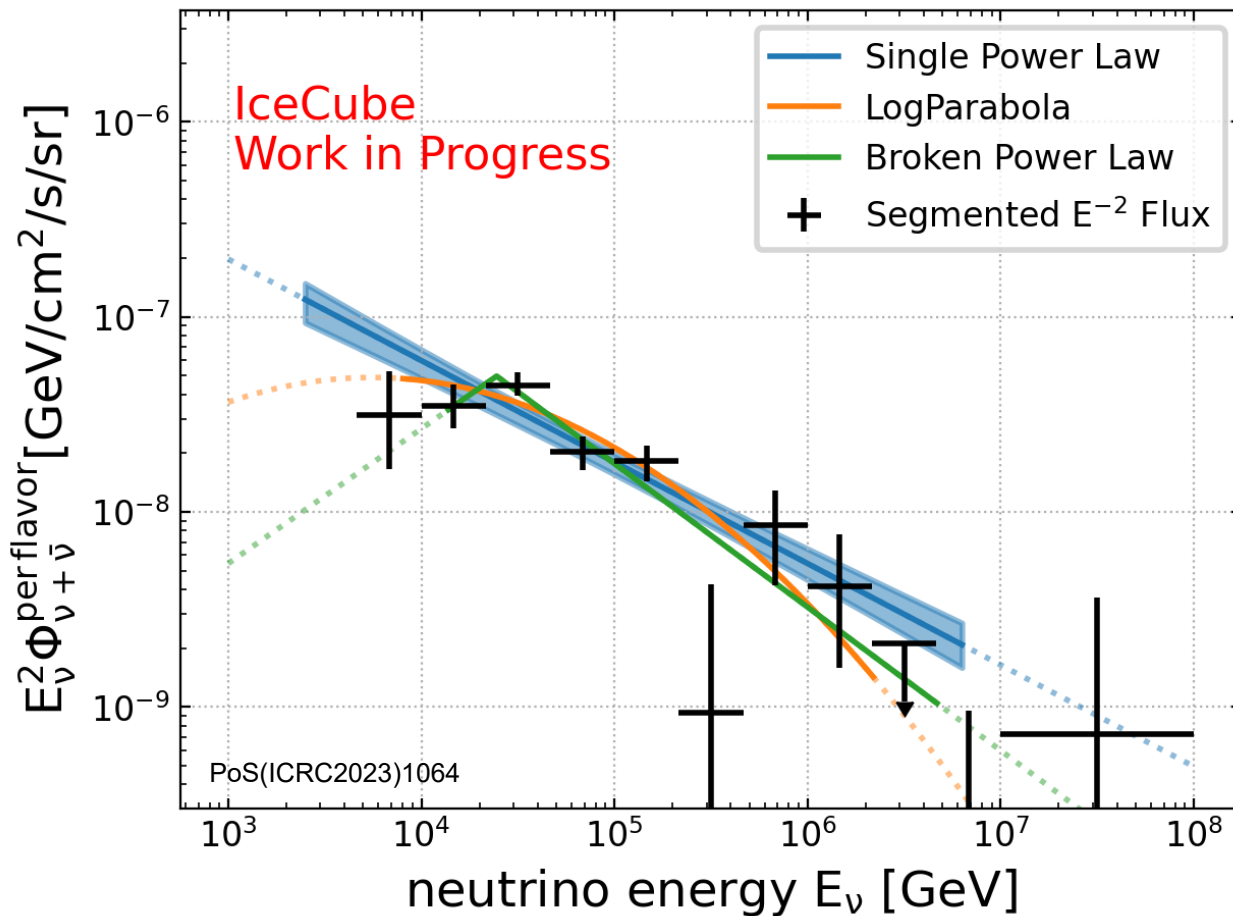


Combined fit of tracks / cascades with unified systematic uncertainty treatment

Indications for structure in energy spectrum

- LogParabola vs SPL
- Systematic Uncertainties

Cosmic Neutrino Spectrum



Combined fit of tracks / cascades with unified systematic uncertainty treatment

Indications for structure in energy spectrum

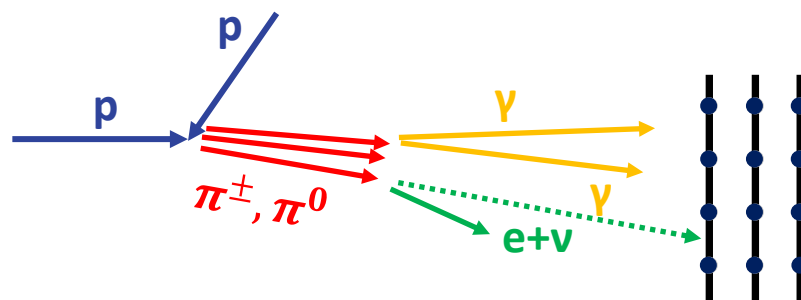
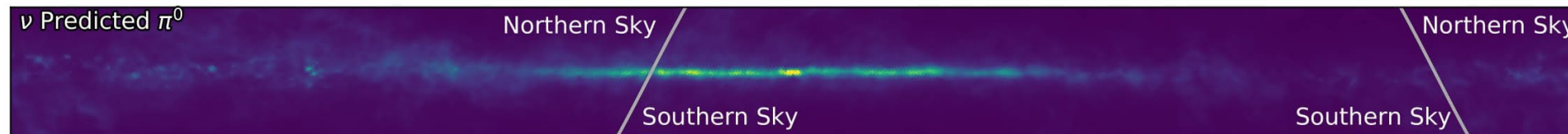
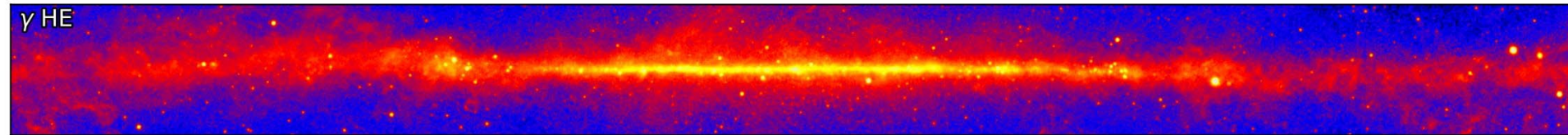
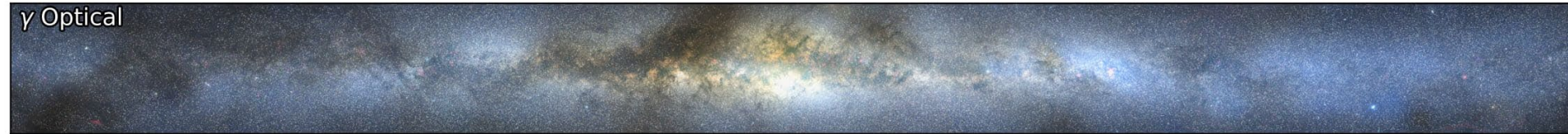
Work in Progress:

- Significance of BPL / LogParabola vs SPL
- Systematic Uncertainties

What are the sources of these neutrinos?

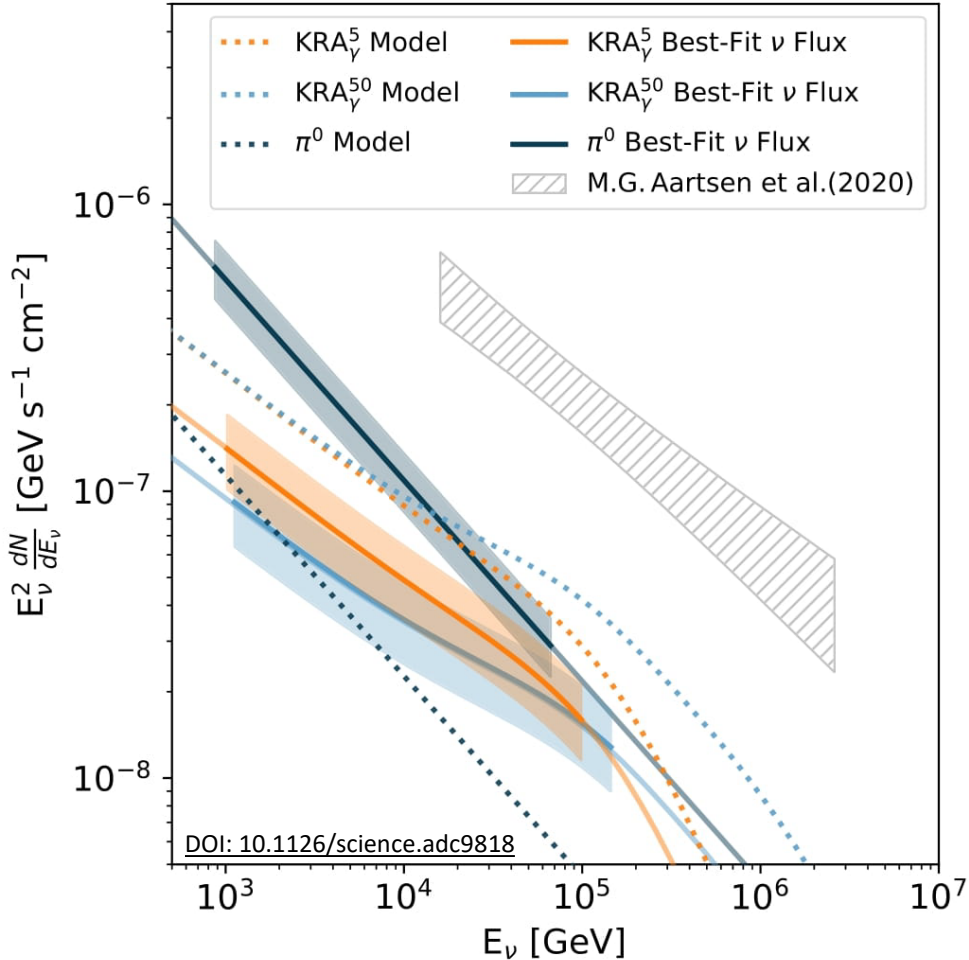
Neutrinos from the Galactic Plane

[DOI: 10.1126/science.adc9818](https://doi.org/10.1126/science.adc9818)

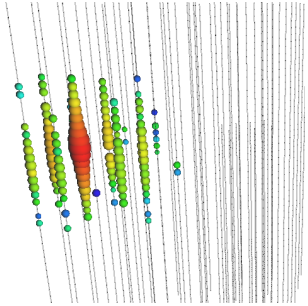


Galactic diffuse neutrino emission is a “guaranteed” flux

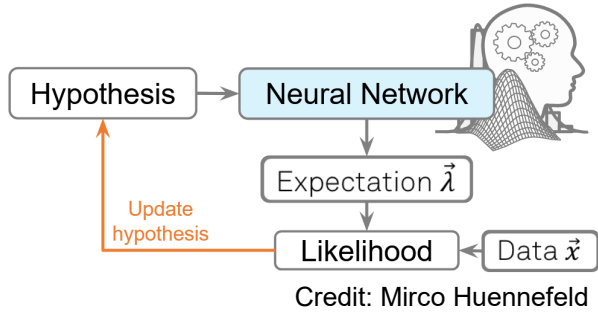
Evidence for Galactic Neutrino Emission



Cascade channel



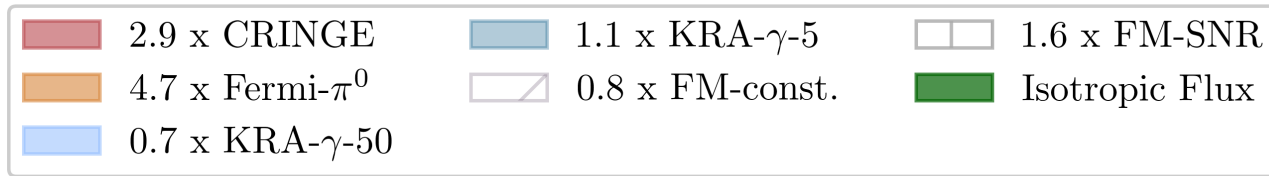
Deep Learning



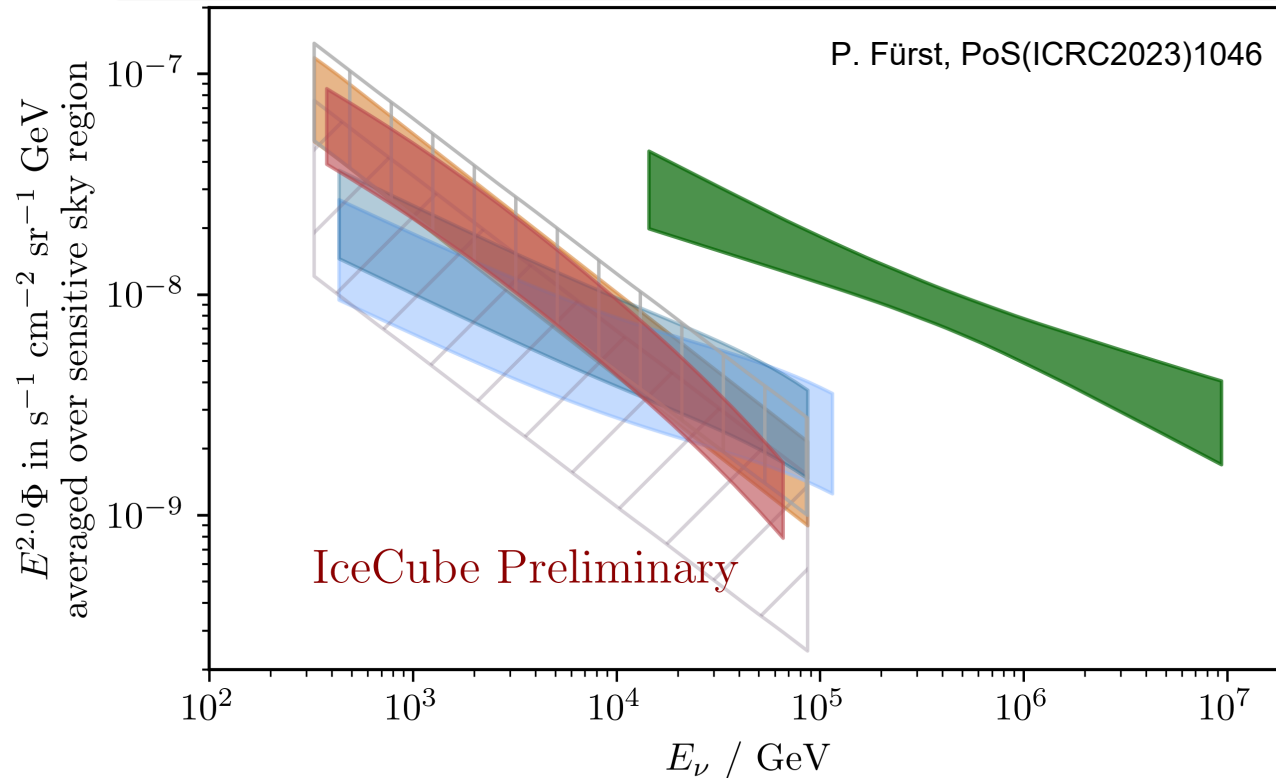
4.5 σ exclusion of pure isotropic hypothesis
6-13% of the total diffuse neutrino flux

Not yet enough statistical power to distinguish models or unresolved sources

New Result: Track Channel



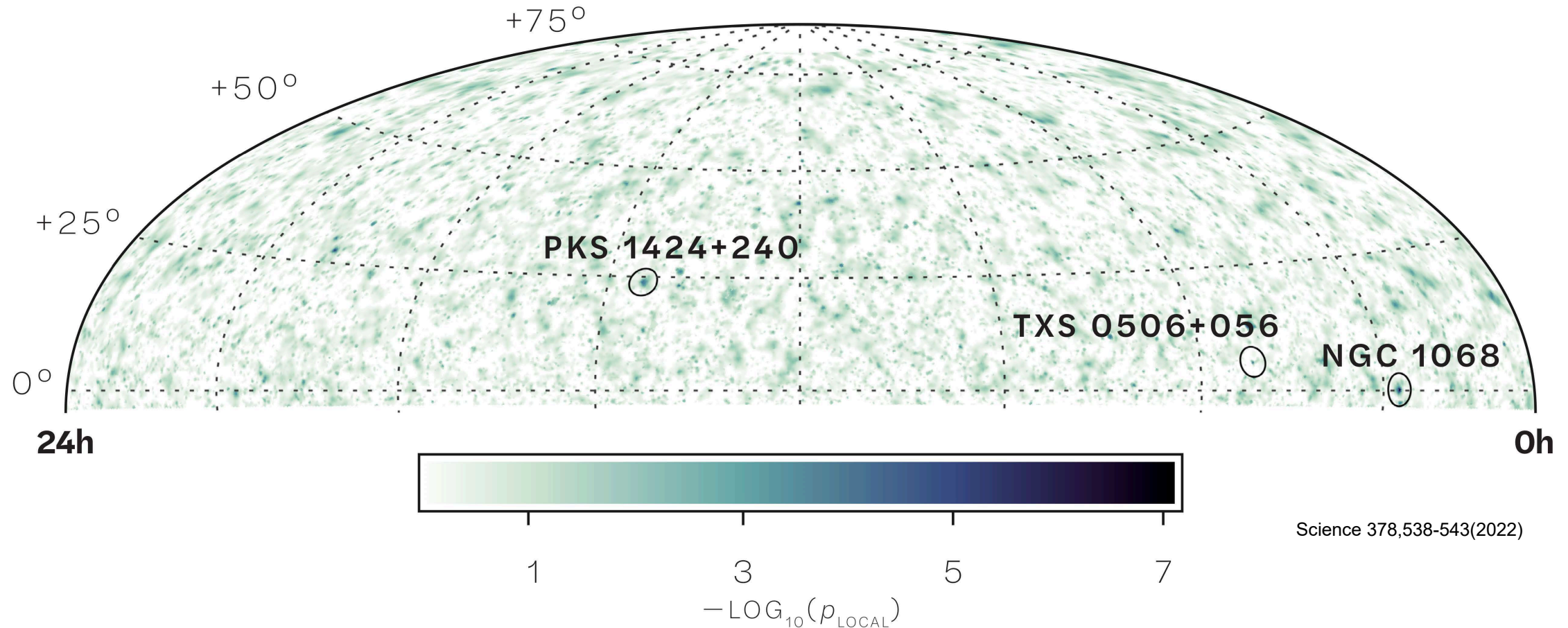
← Multiple diffuse emission models tested



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

The Muon-Neutrino Sky

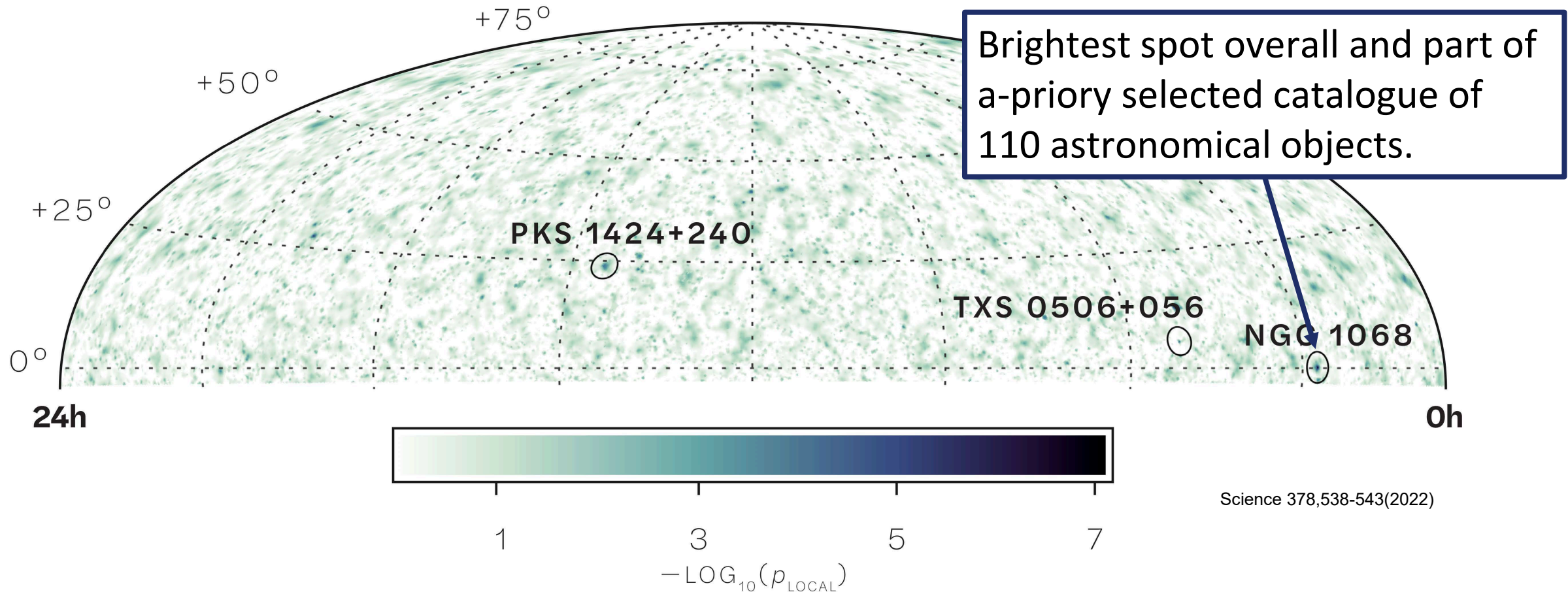
Searching for clustering and deviation from atmospheric ν spectrum at every point in the sky



Science 378,538-543(2022)

The Muon-Neutrino Sky

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



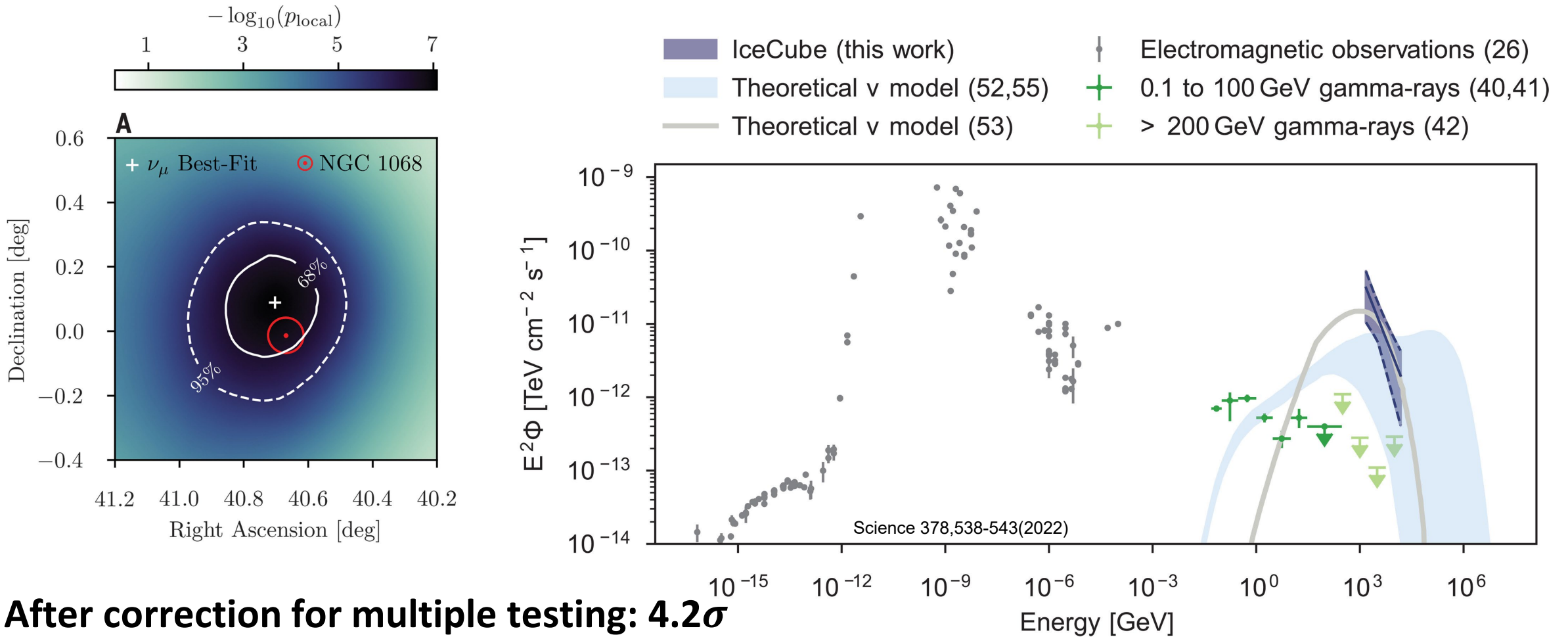
Science 378,538-543(2022)

NGC1068

- ❑ Type II Seyfert Galaxy
- ❑ $d=14.4\text{Mpc}$
- ❑ Compton-thick AGN
- ❑ Intrinsic X-ray photons in corona can provide target for ν production

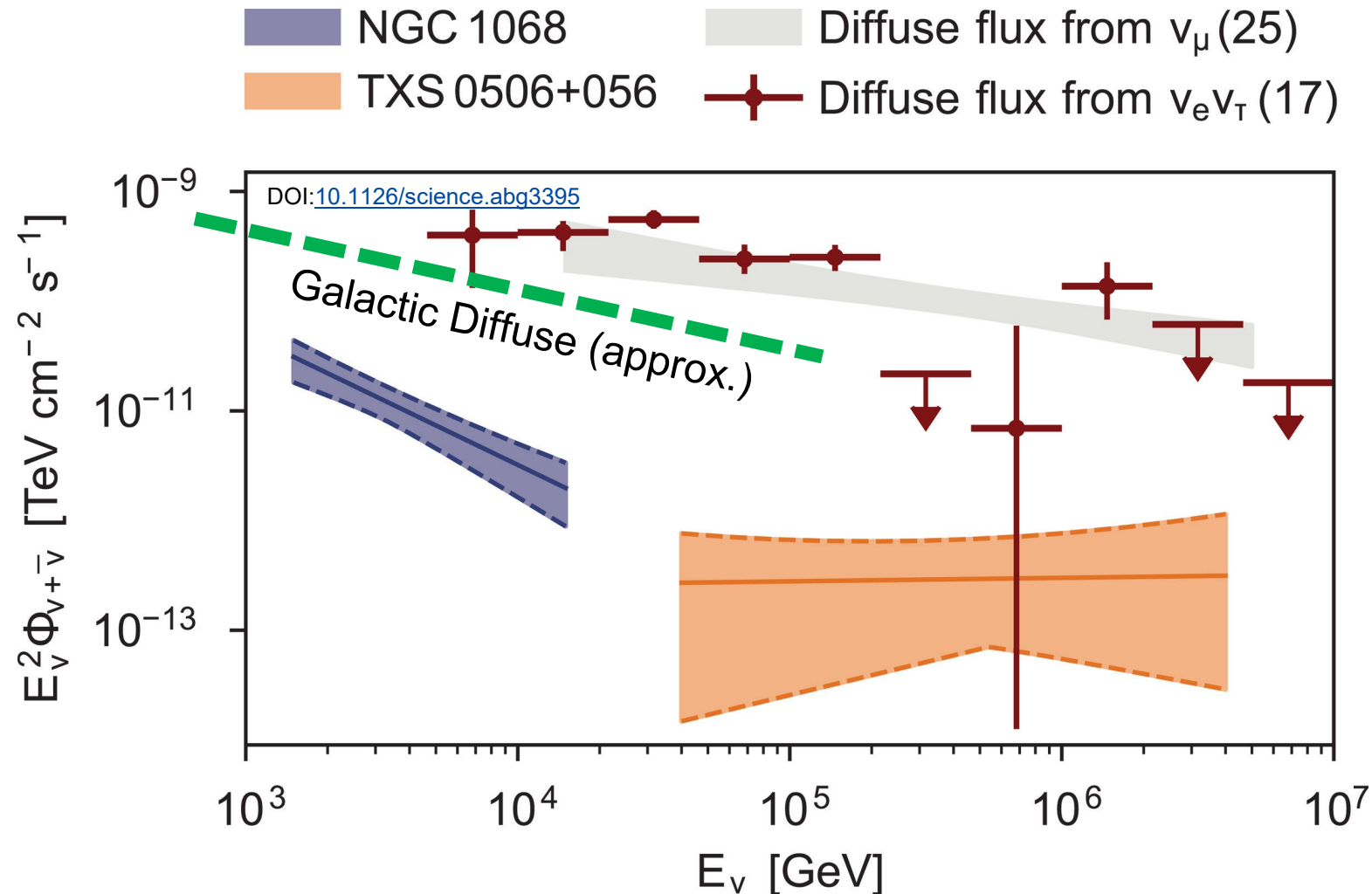


Neutrino Emission from NGC1068



After correction for multiple testing: 4.2σ

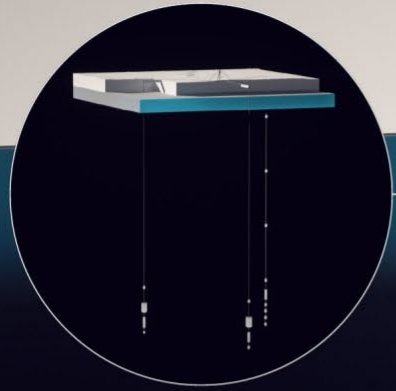
Neutrino Fluxes



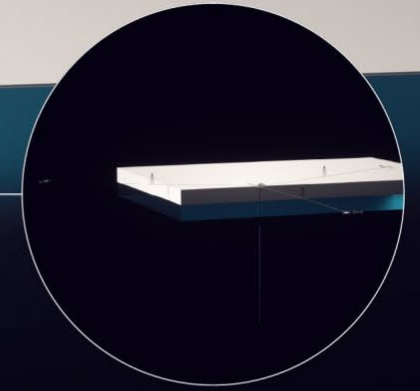
IceCube-Gen2 Neutrino Observatory

361 stations on a 550km² footprint

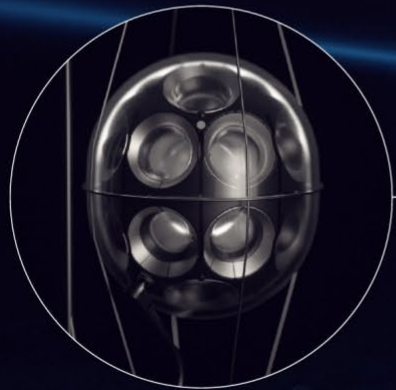
Covering the footprint of the optical array



Radio Array | Station

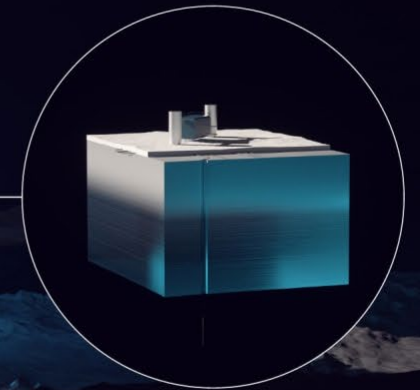


Surface Array | Station

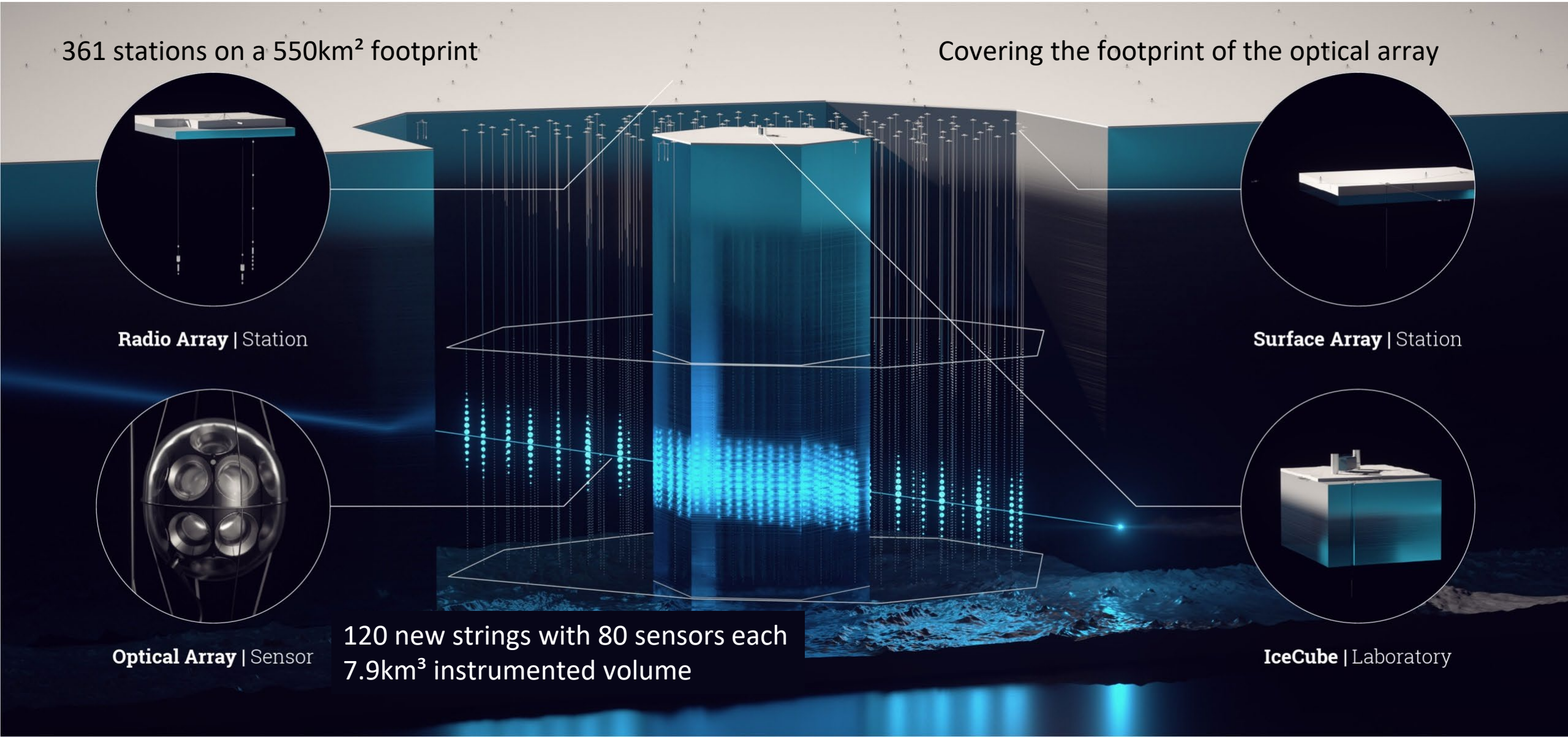


Optical Array | Sensor

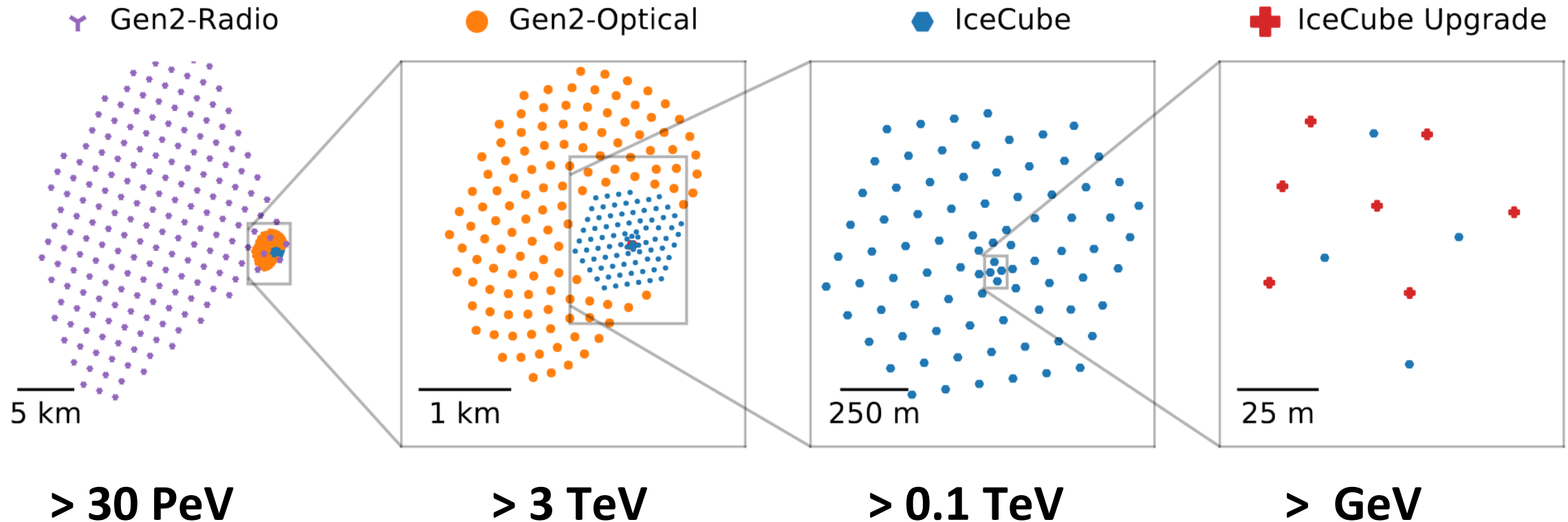
120 new strings with 80 sensors each
7.9km³ instrumented volume



IceCube | Laboratory

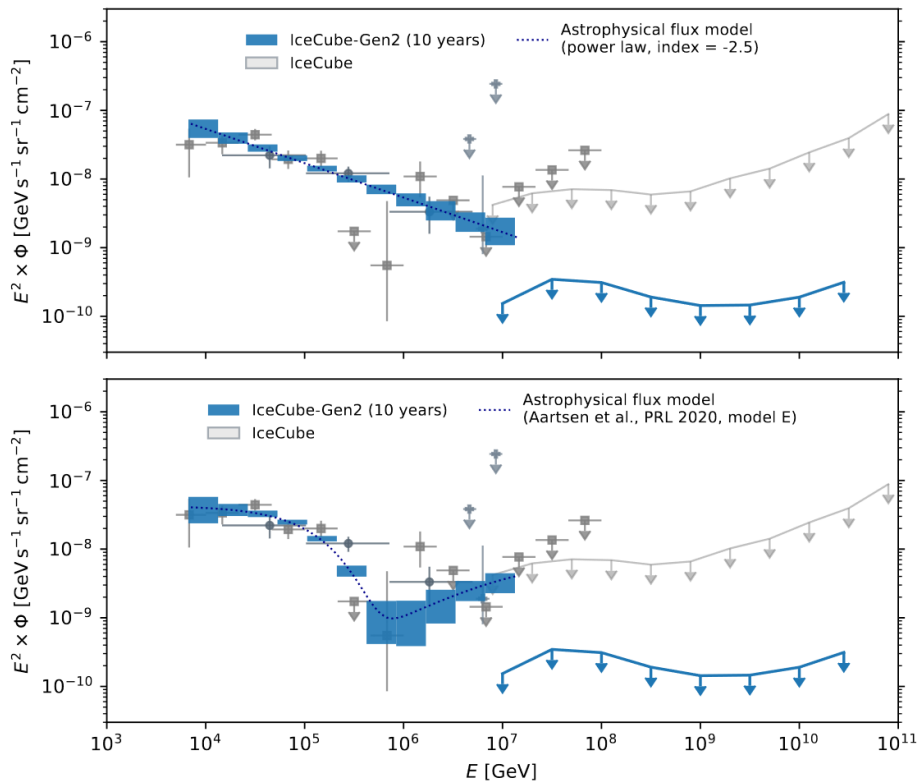


IceCube-Gen2

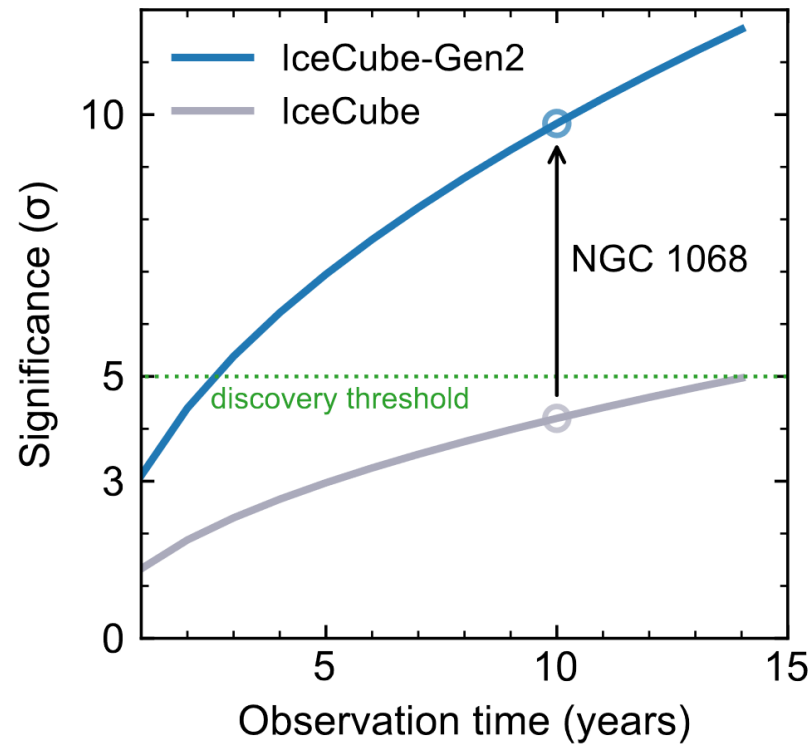


Gen2 Science Highlights

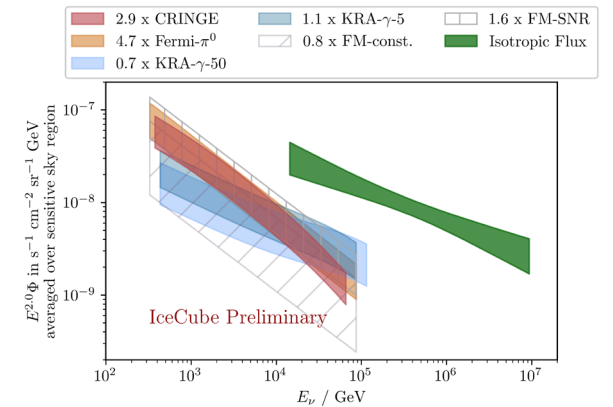
Precision measurement of the astrophysical neutrino spectrum



Resolving neutrino sources



8.7σ for diffuse galactic emission after 10 years.



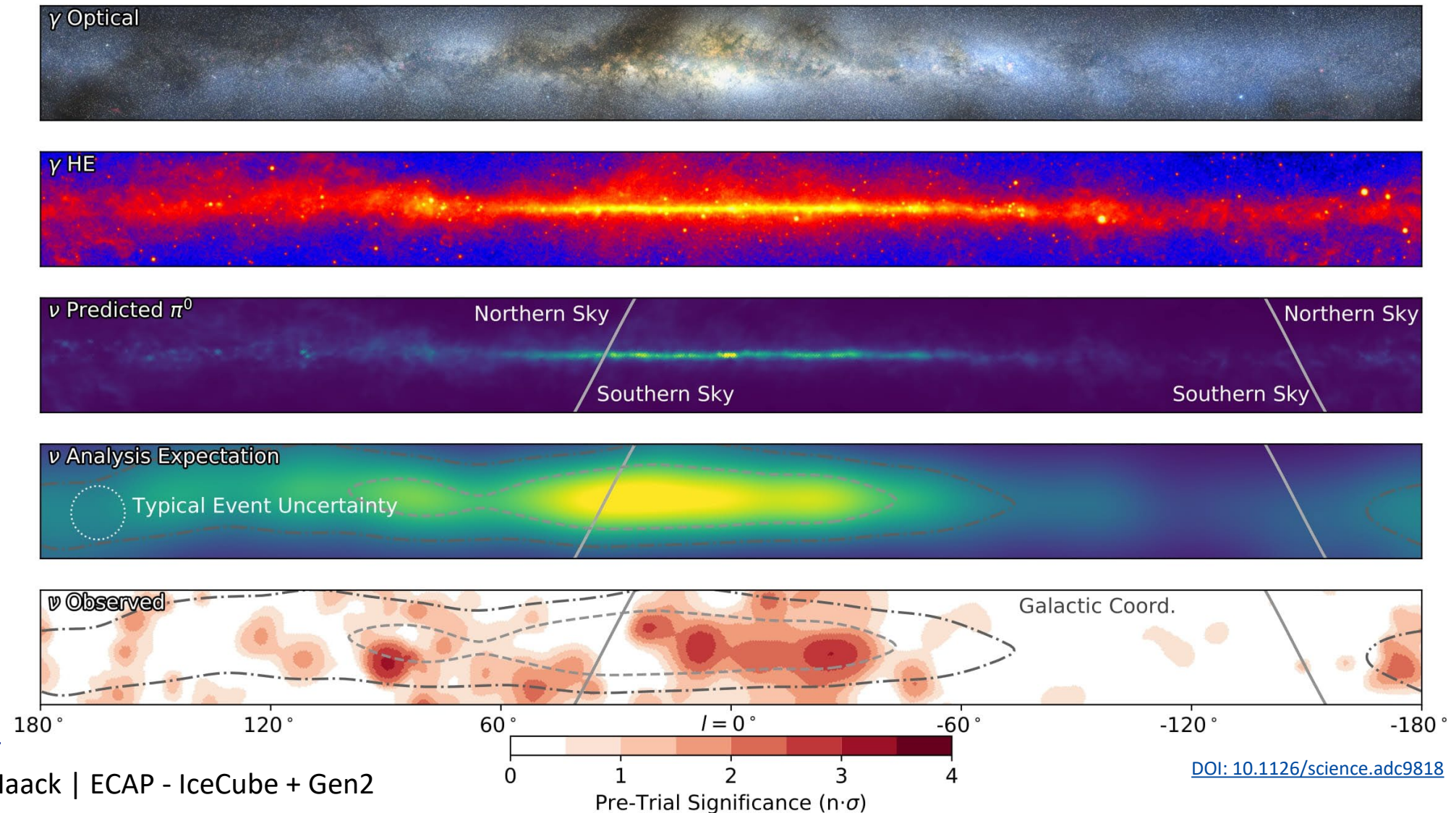
And much, much more.
Check out the [TDR](#)

Summary & Conclusions

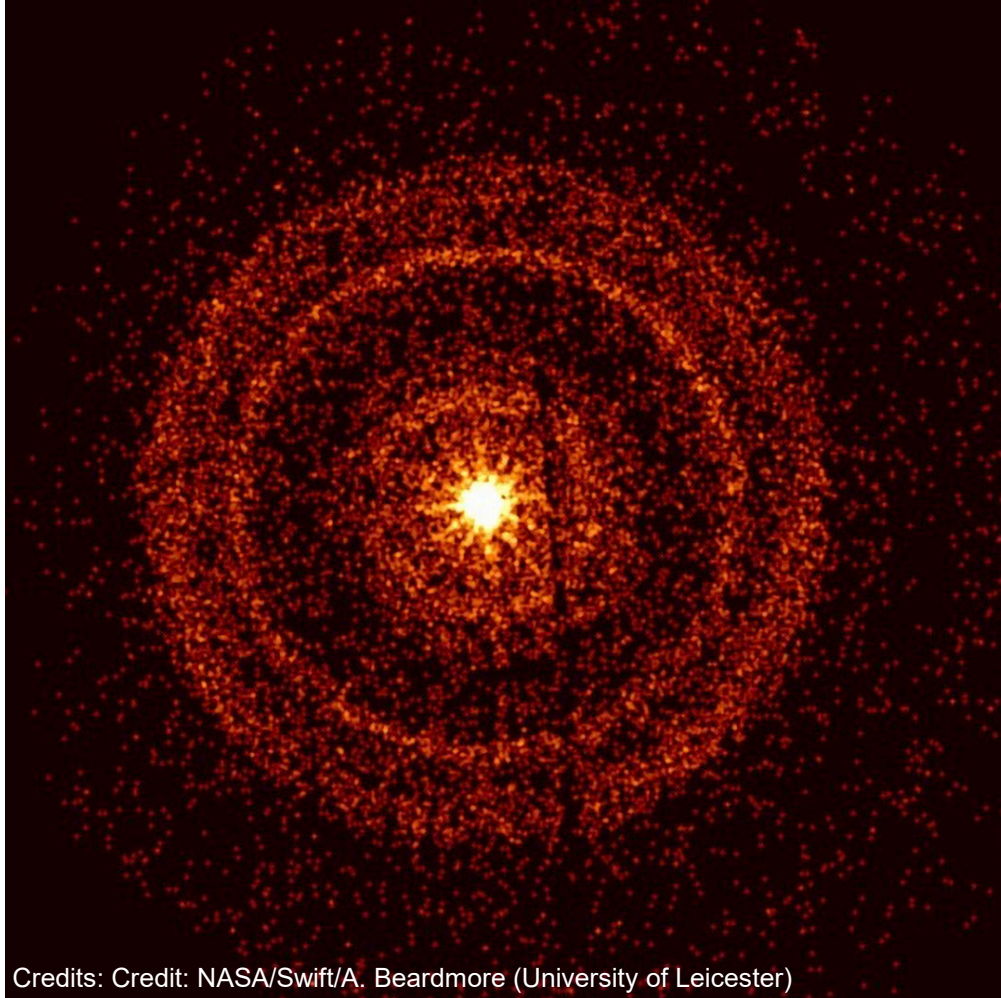
- After the discovery of the flaring blazar TXS 056+056 in 2017, IceCube has identified two additional sources of high-energy neutrinos
- Neutrino emission from the Galactic Plane has been found using the cascade channel (also seeing strong hints in track channel)
- NGC 1068 has been identified as a source of energetic neutrinos (4.2σ)
=> Searches for neutrino emission from other Seyfert Galaxies so far inconclusive
- Still a lot of room for more sources in the total diffuse neutrino flux
- IceCube-Gen2 will address the emerging questions raised by over ten years of IceCube measurements.

Backup

Neutrinos from the Galactic Plane

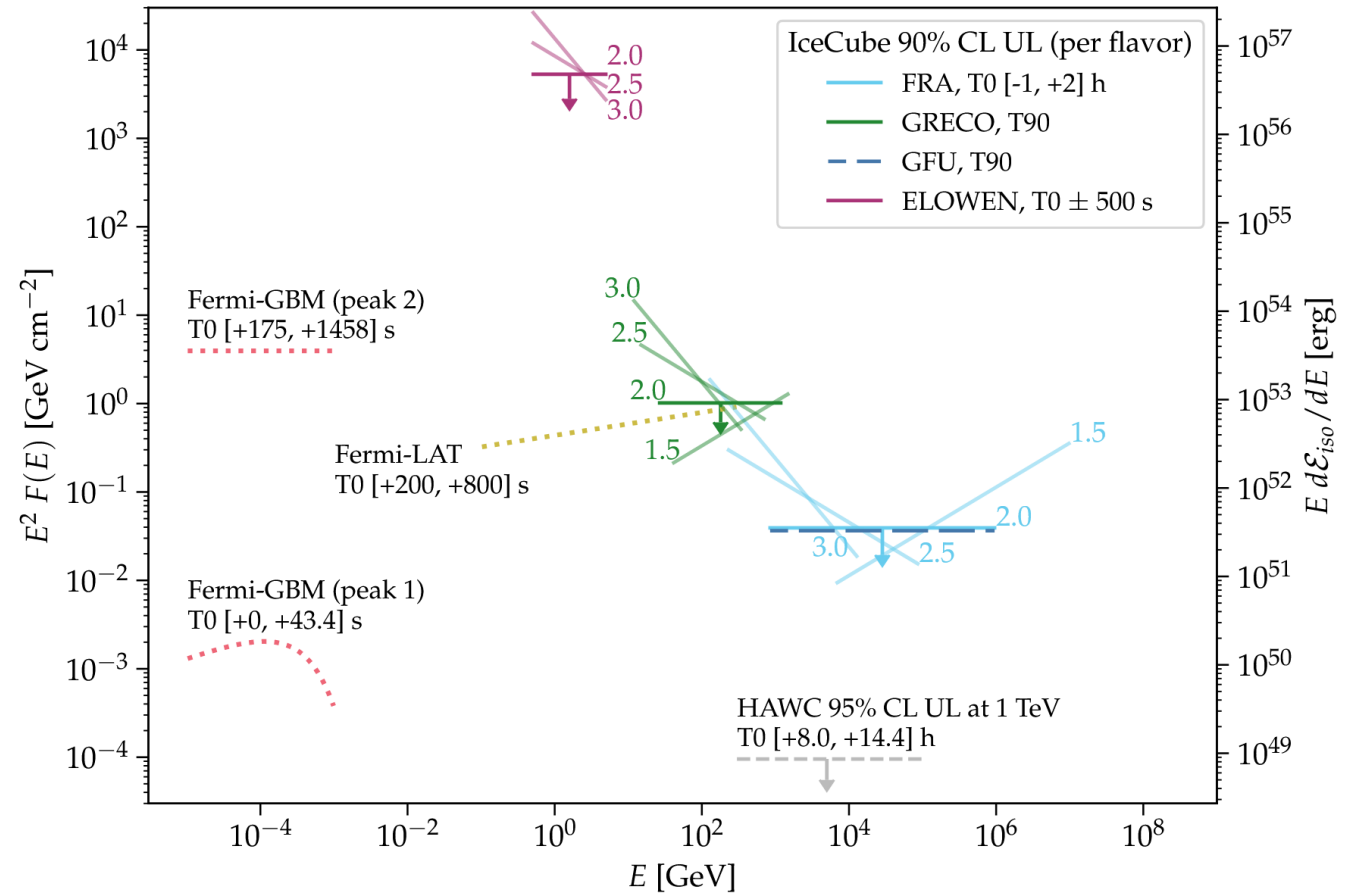


GRB221009A

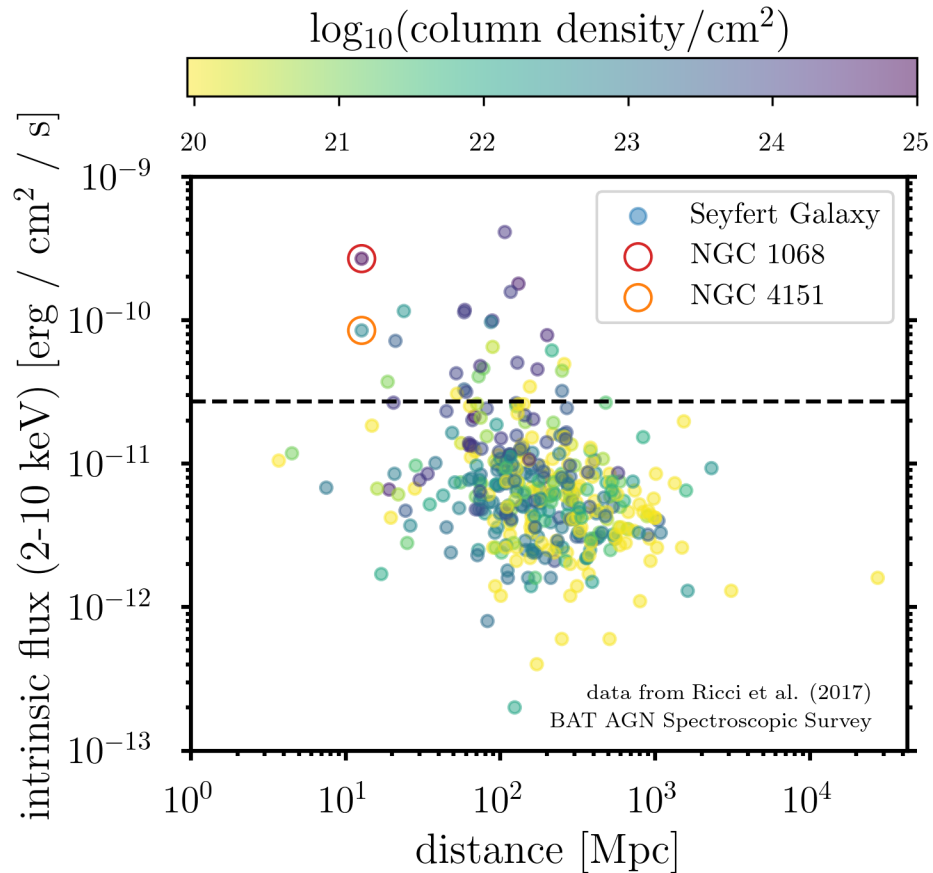


Credits: Credit: NASA/Swift/A. Beardmore (University of Leicester)

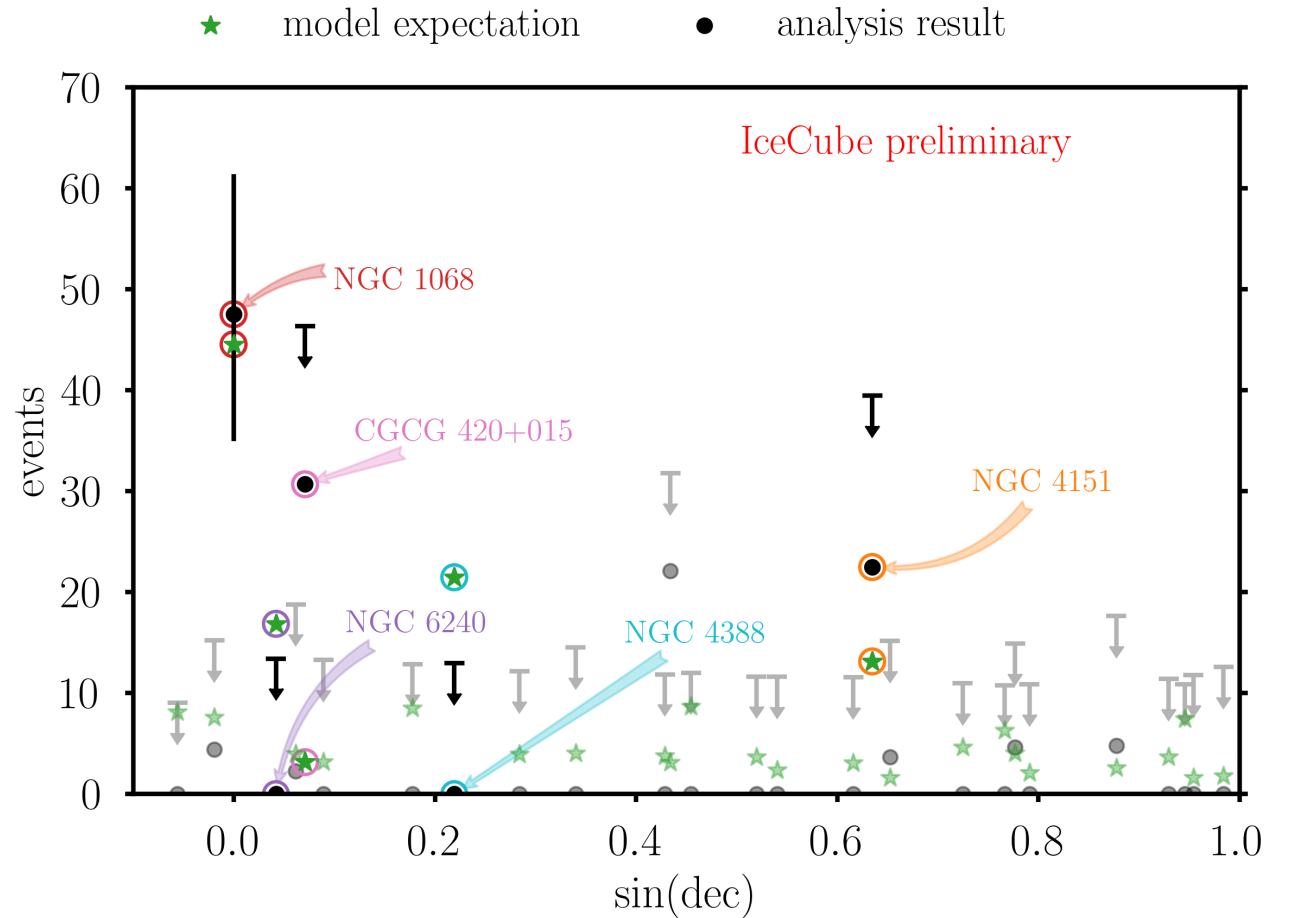
ICECUBE COLLABORATION



Seyfert Galaxies

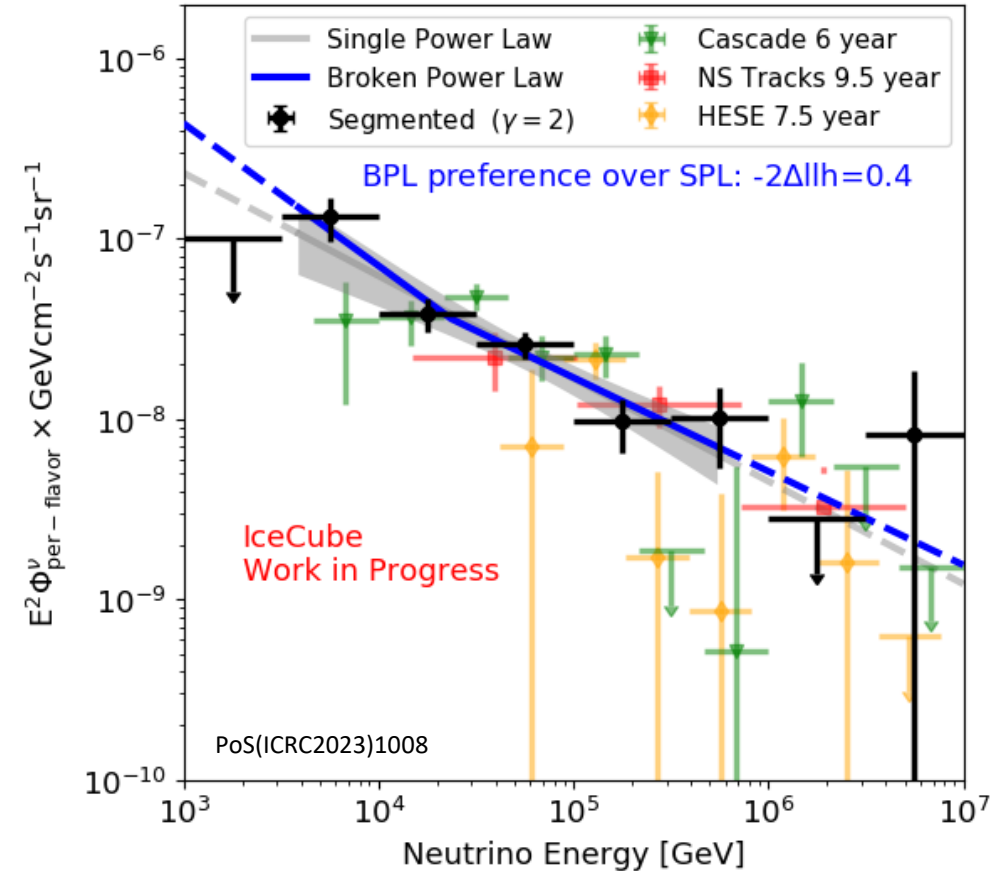
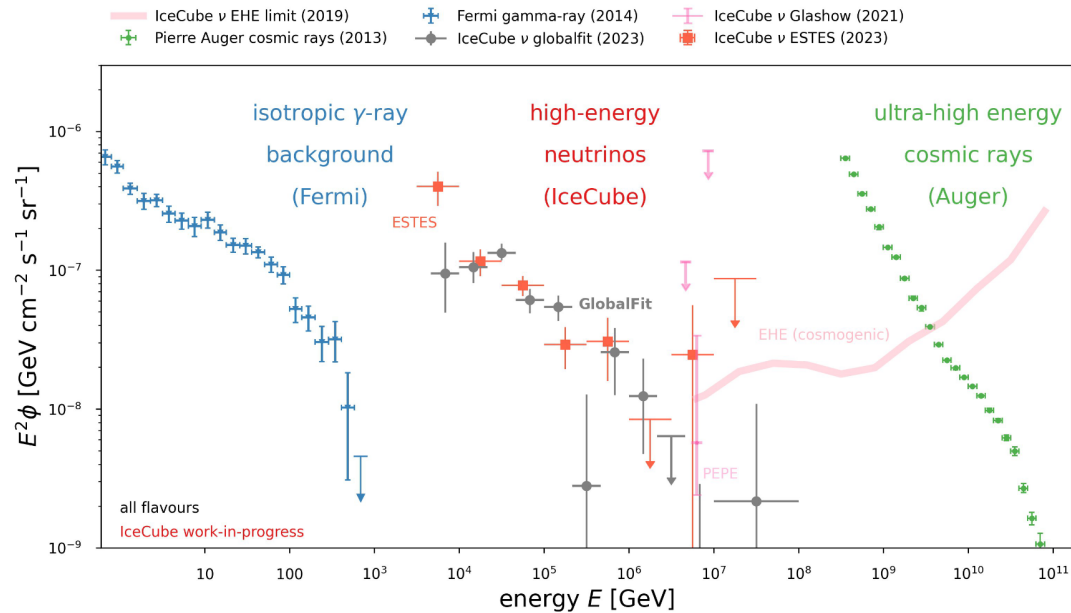


No significant excess found



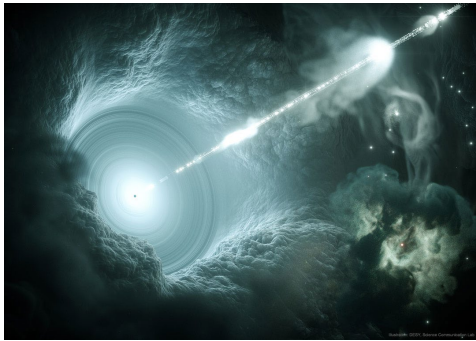
Cosmic Neutrino Spectrum

New measurements using starting tracks (ESTES)



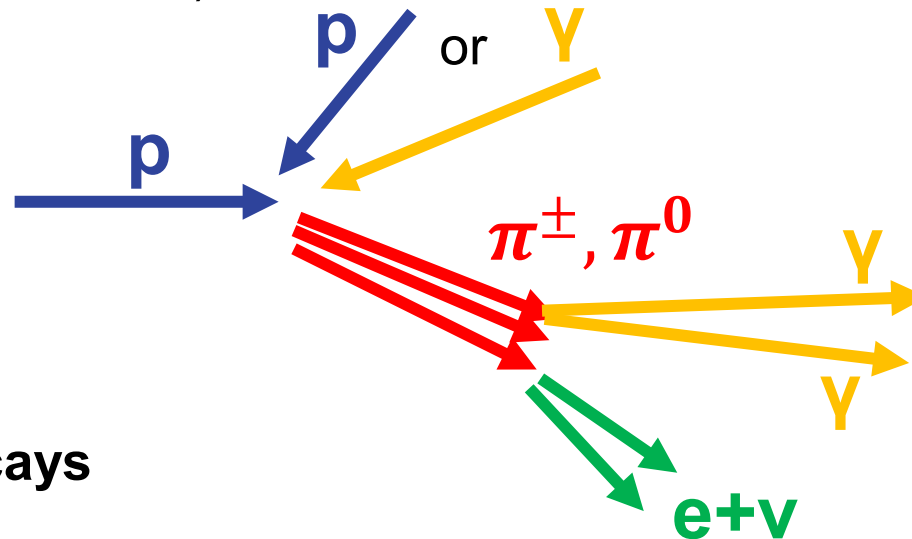
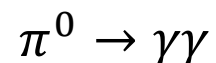
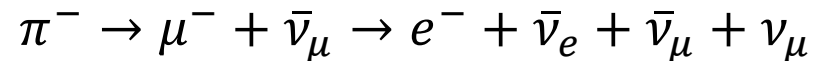
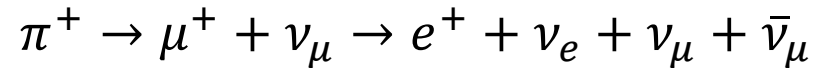
The Cosmic Ray Connection

Accelerator (AGN, SNR, GRB, ..)



DESY

Pion Decays



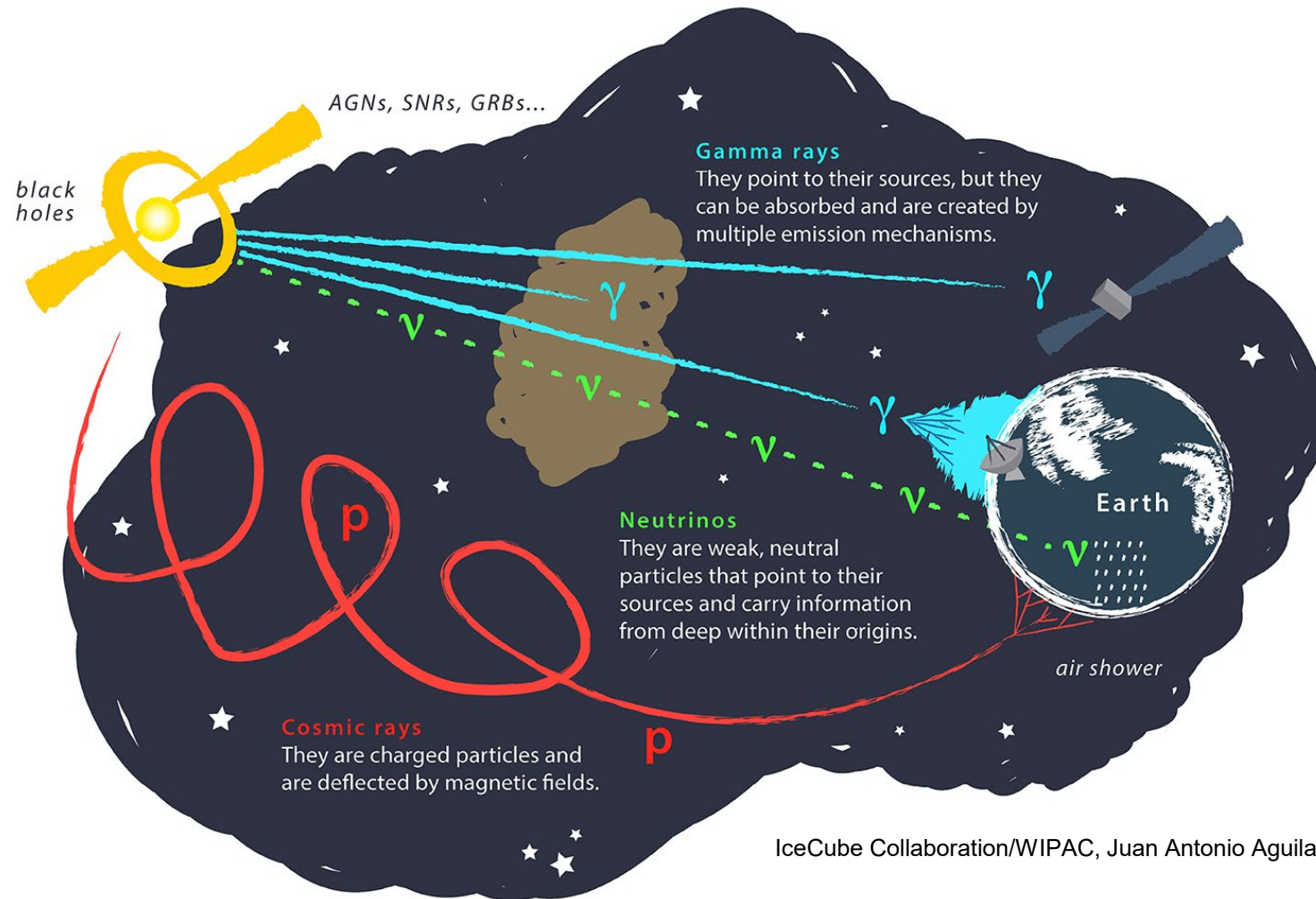
Idealized scenarios

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

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

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

Neutrinos are ideal messengers



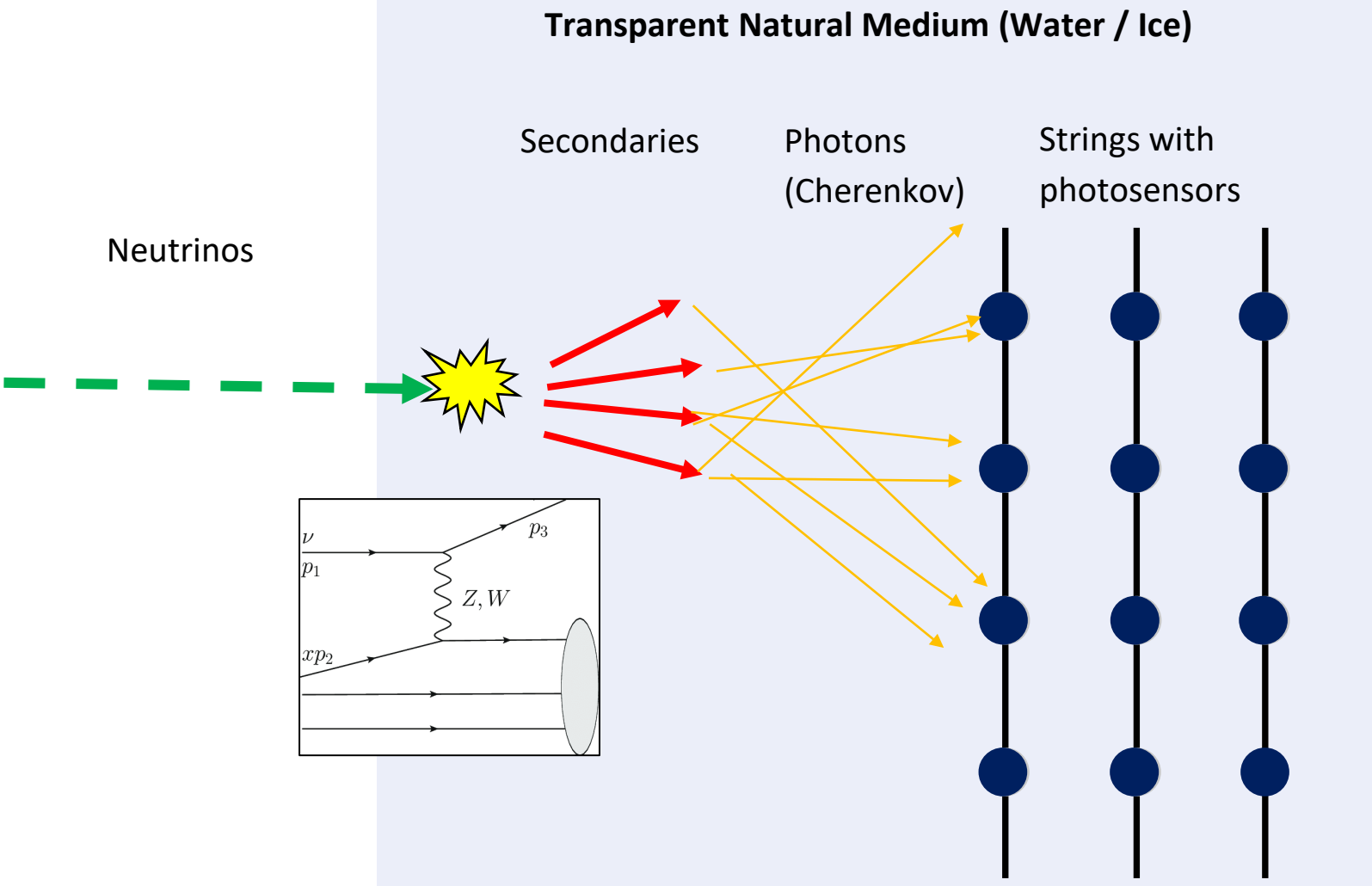
IceCube Collaboration/WIPAC, Juan Antonio Aguilar, and Jamie Yang

Detection Method

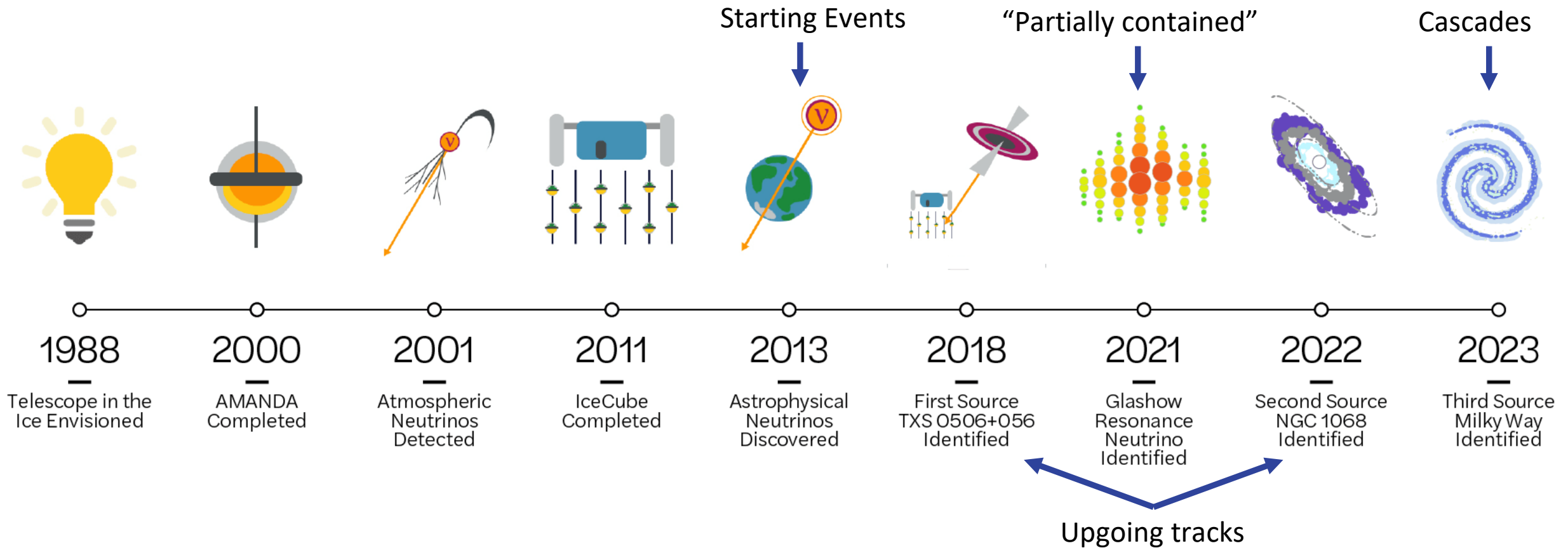
Astrophysical Accelerator



DESY



A History of Neutrino Astronomy in Antarctica

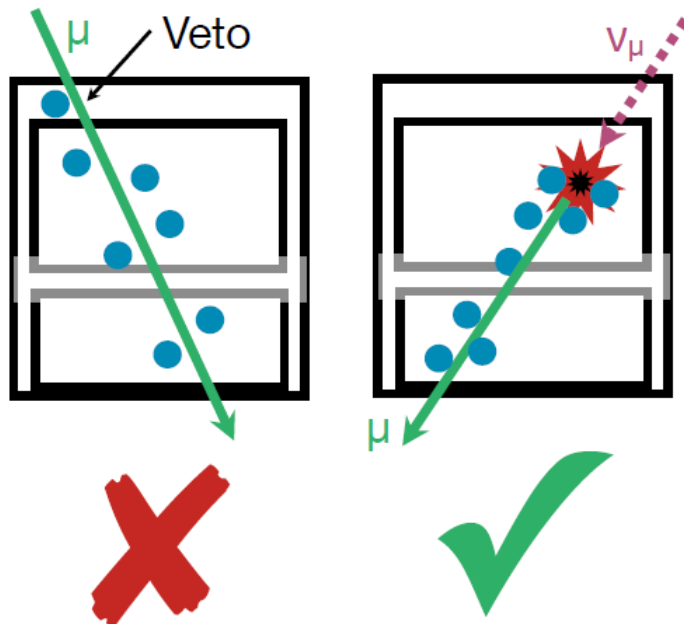


Event Selection Strategies

Fiducialization

Starting Tracks, Cascades

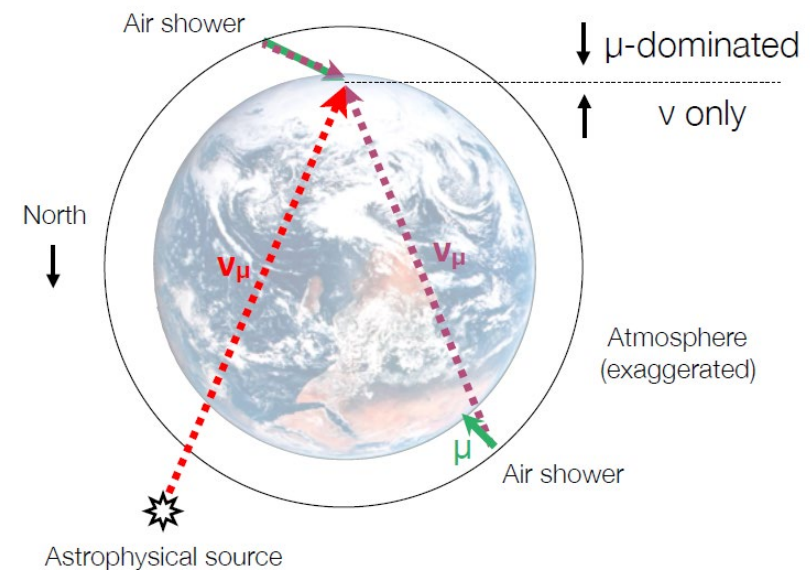
Morphology-based BG discrimination



Using Earth as shield

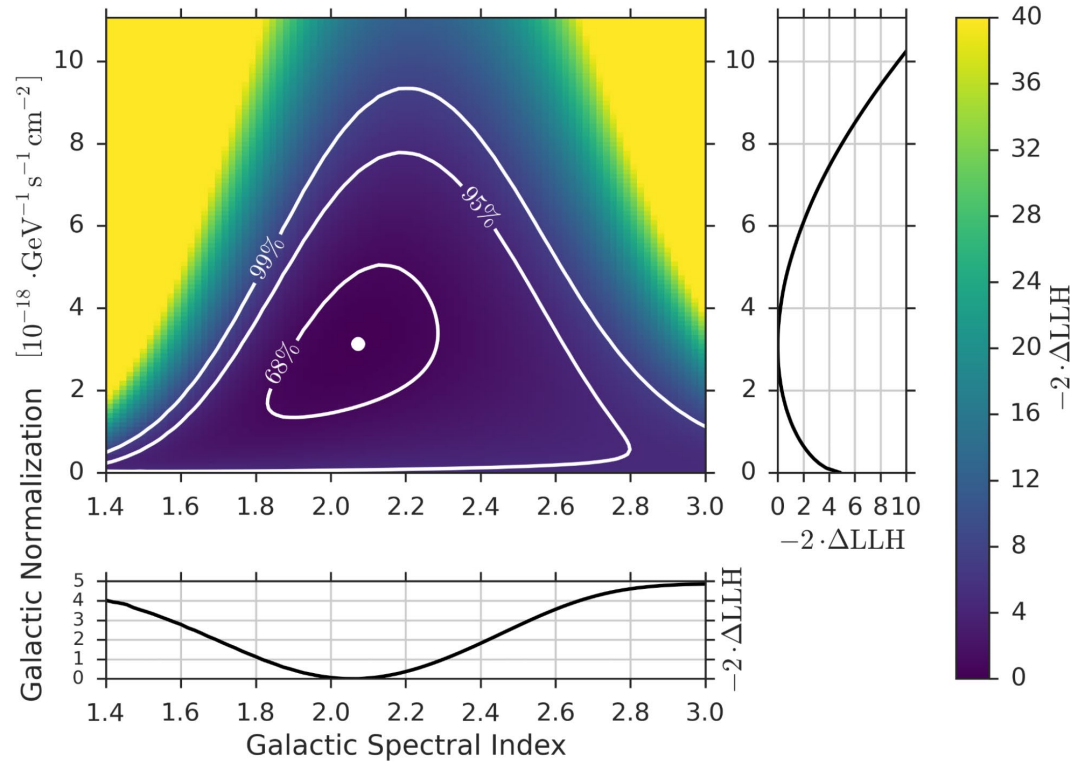
“Upgoing” tracks

Direction based BG discrimination

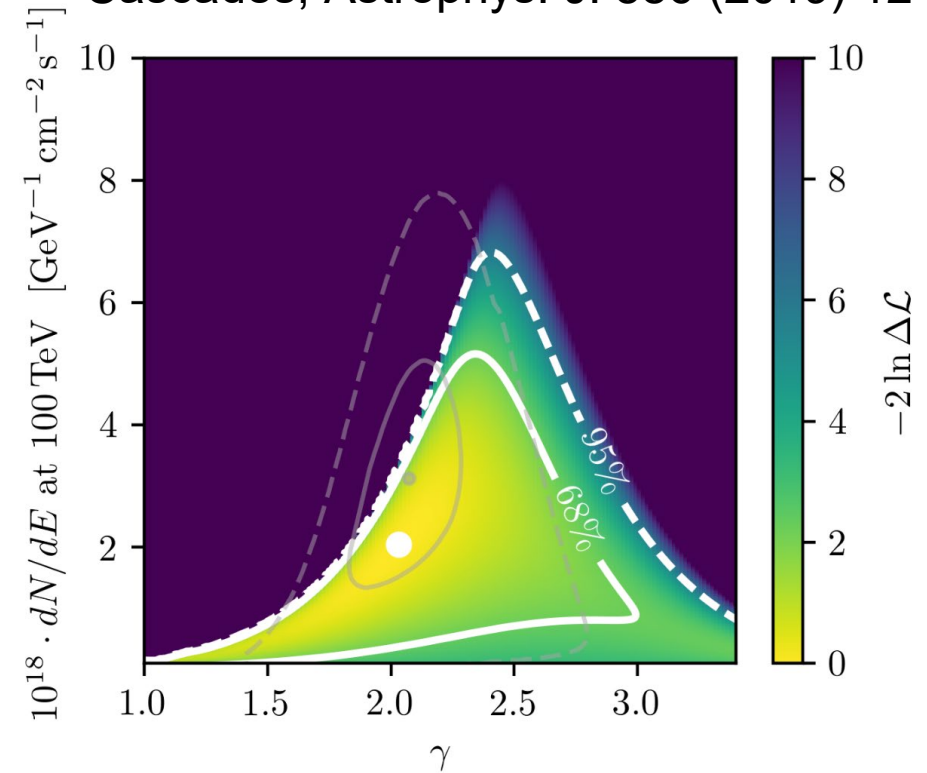


GP Searches in IceCube

Tracks, *Astrophys.J.* 849 (2017) 67



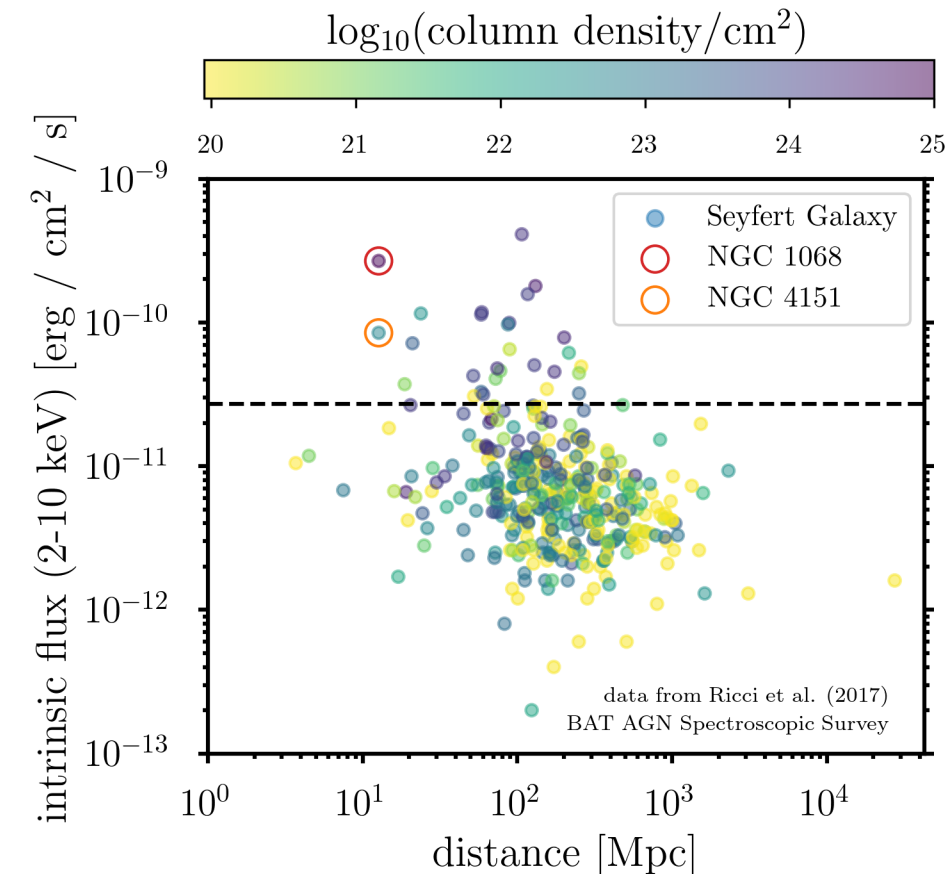
Cascades, *Astrophys. J.* 886 (2019) 12



Zero Galactic diffuse excluded @ 7% p-value

Zero Galactic diffuse excluded @ 2% p-value

Seyfert Galaxies



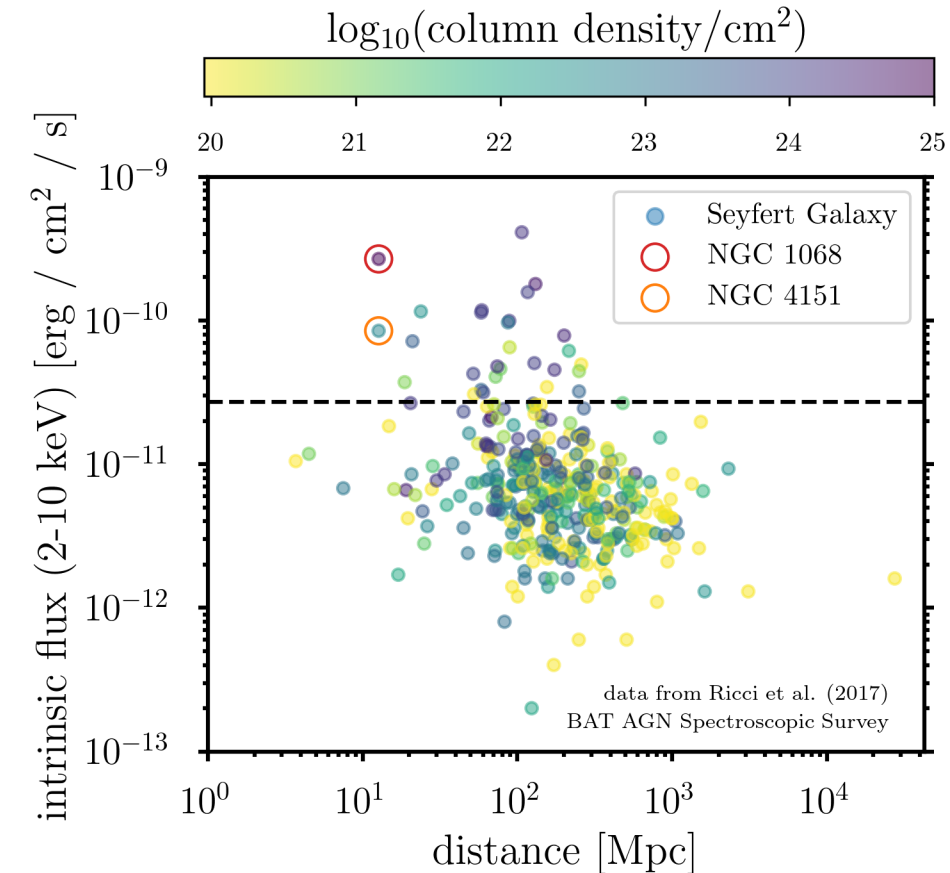
Searching for ν emission from Seyfert galaxies

Multiple tests:

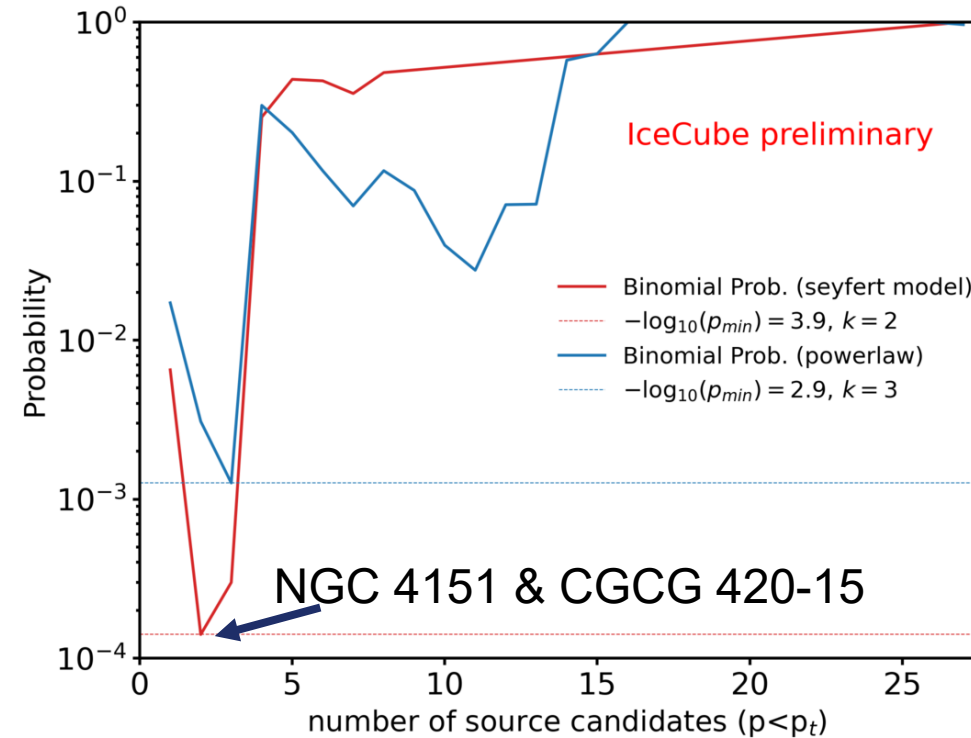
- Individual sources (significant emission from single source in catalogue)
- Stacking (combined emission of source catalogue)
- Binomial test: Prob. of finding k sources with $p < p_t$

NGC1068 not included in significance calculation!

Seyfert Galaxies

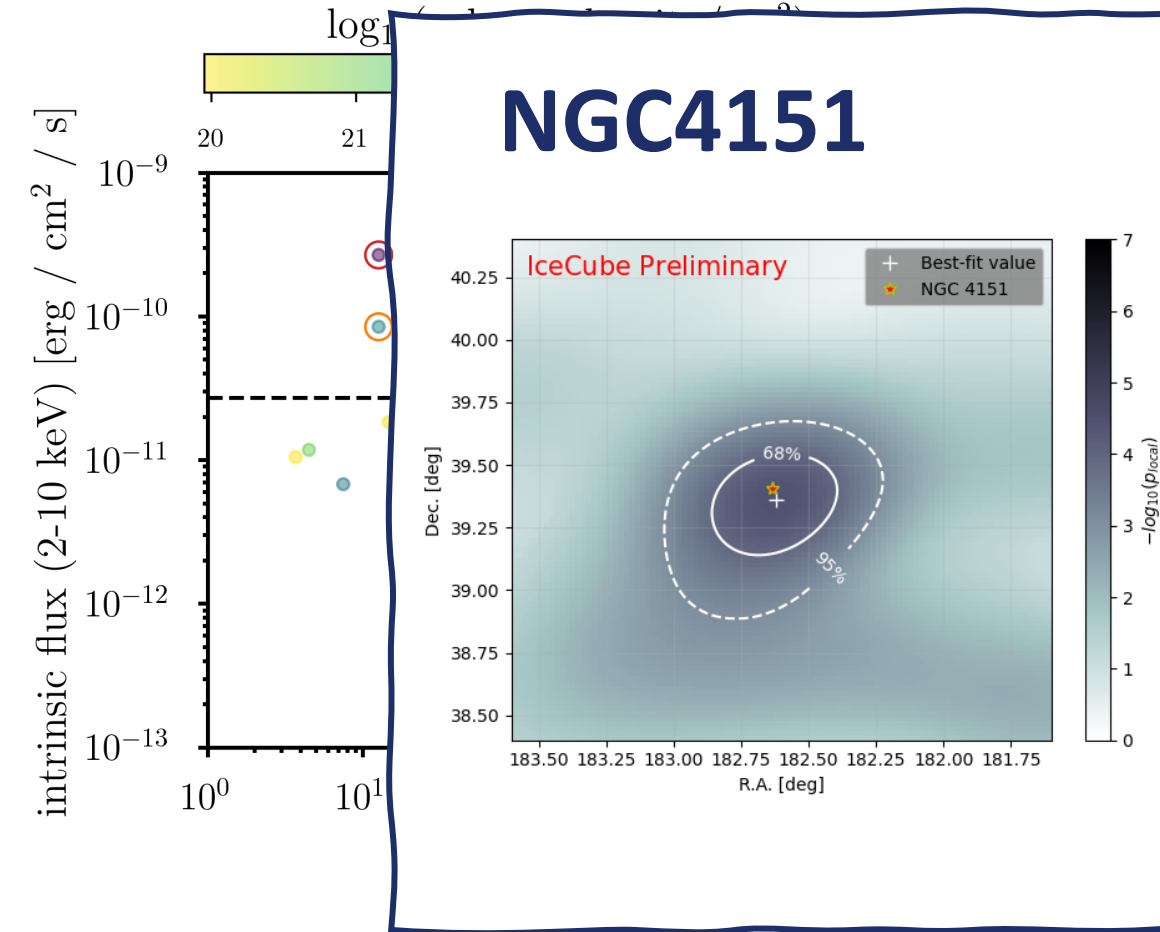


Binomial Test



After correcting for multiple testing: 2.7σ excess

Seyfert Galaxies



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

σ excess