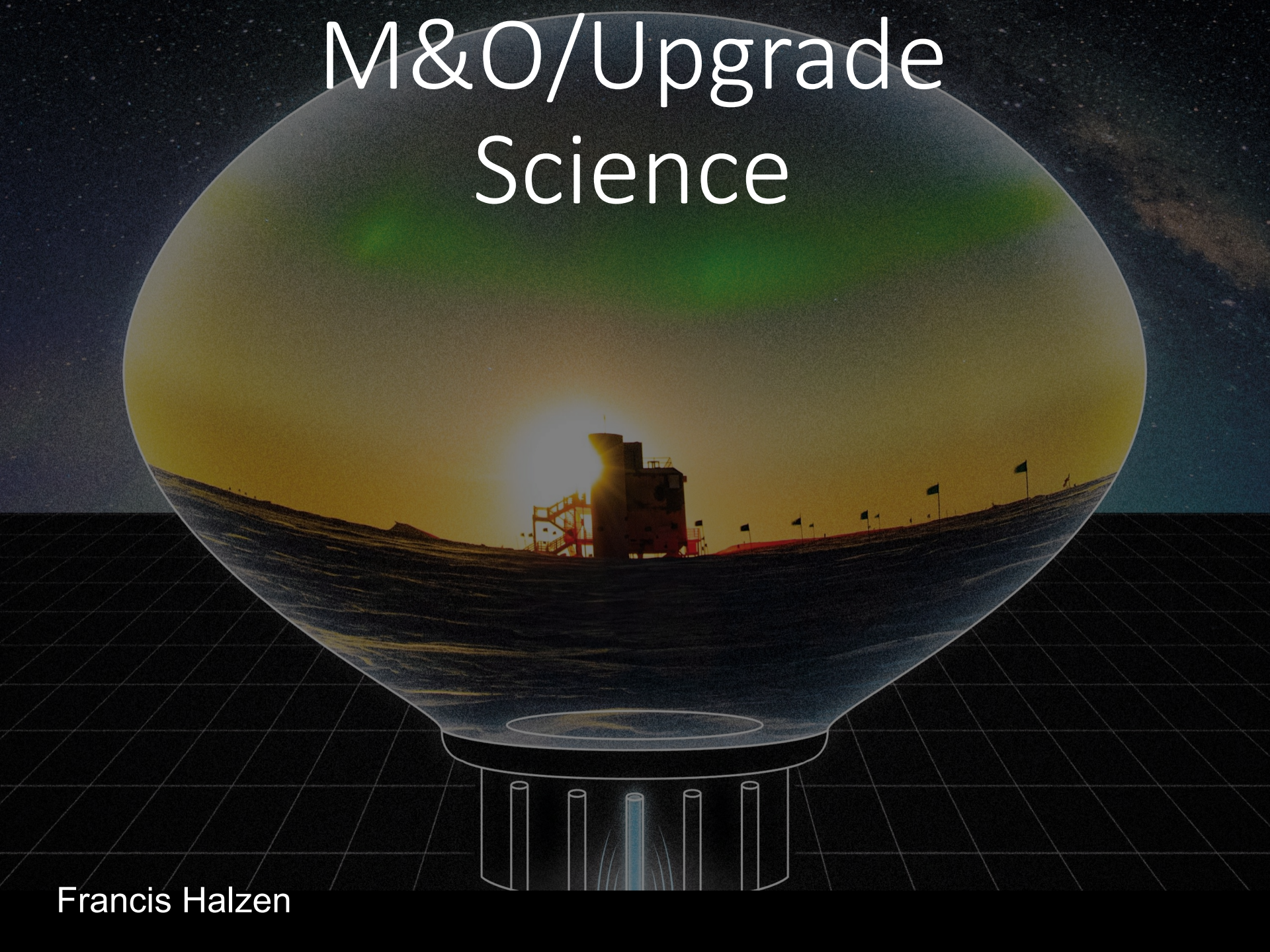
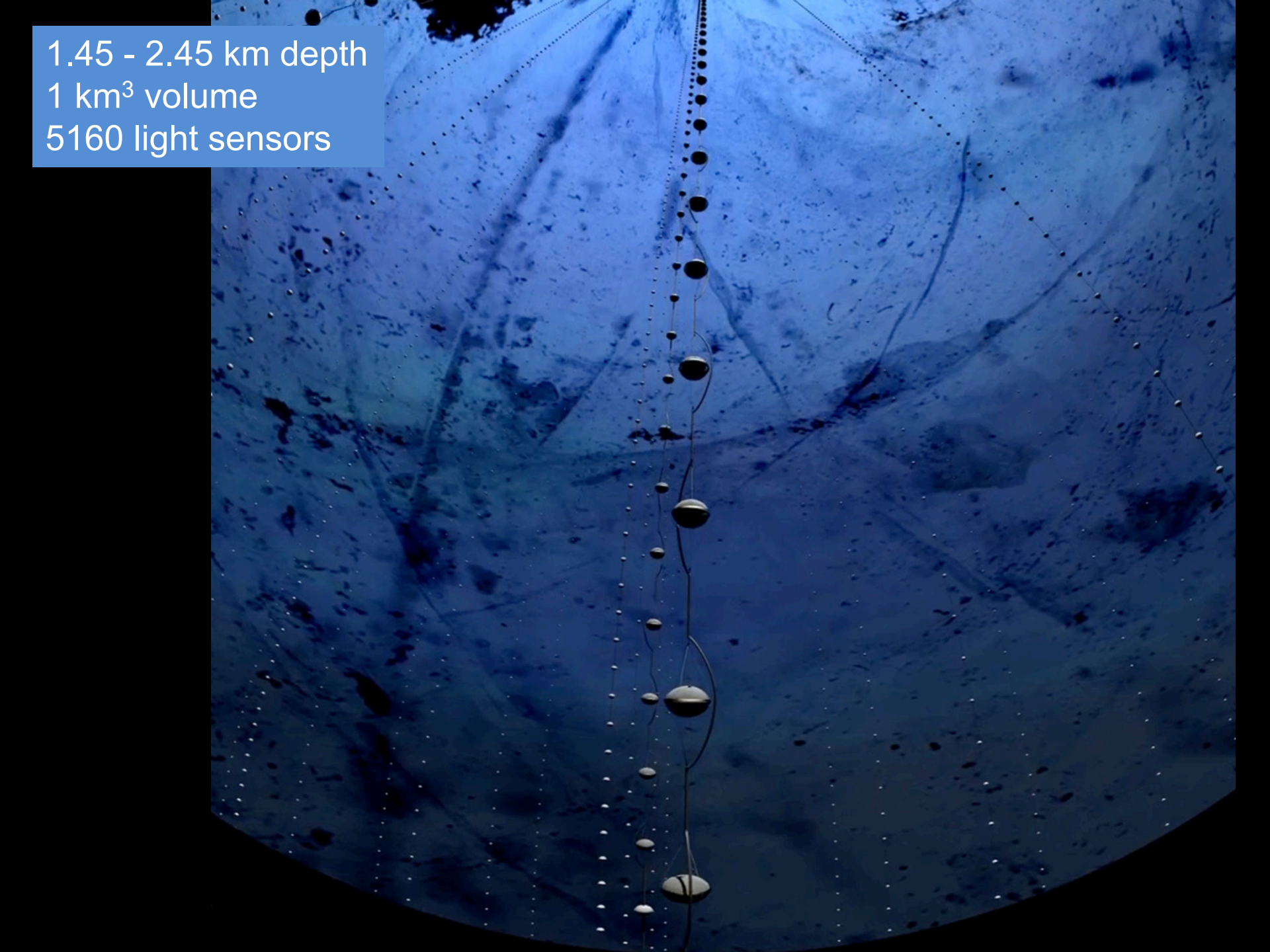
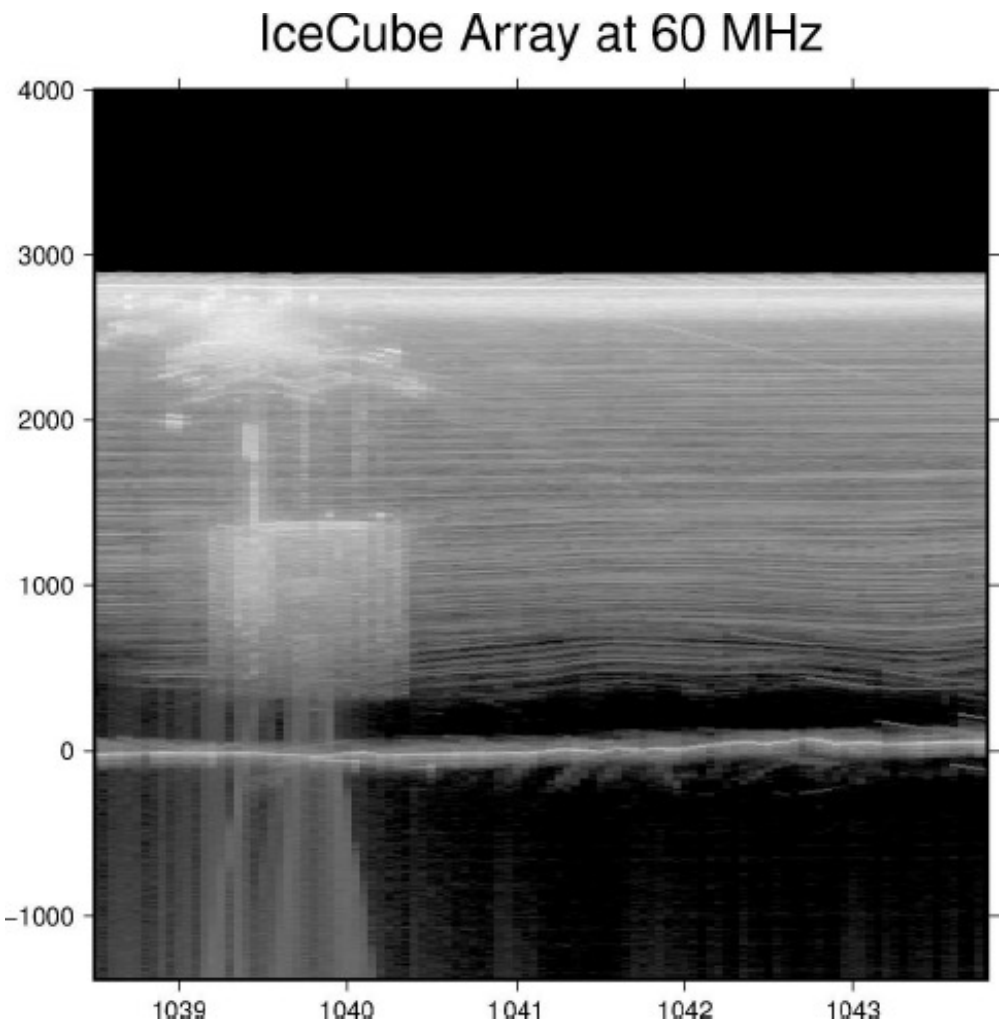
M&O/Upgrade Science



Francis Halzen


1.45 - 2.45 km depth
1 km^3 volume
5160 light sensors

ground-penetrating radar from airplane



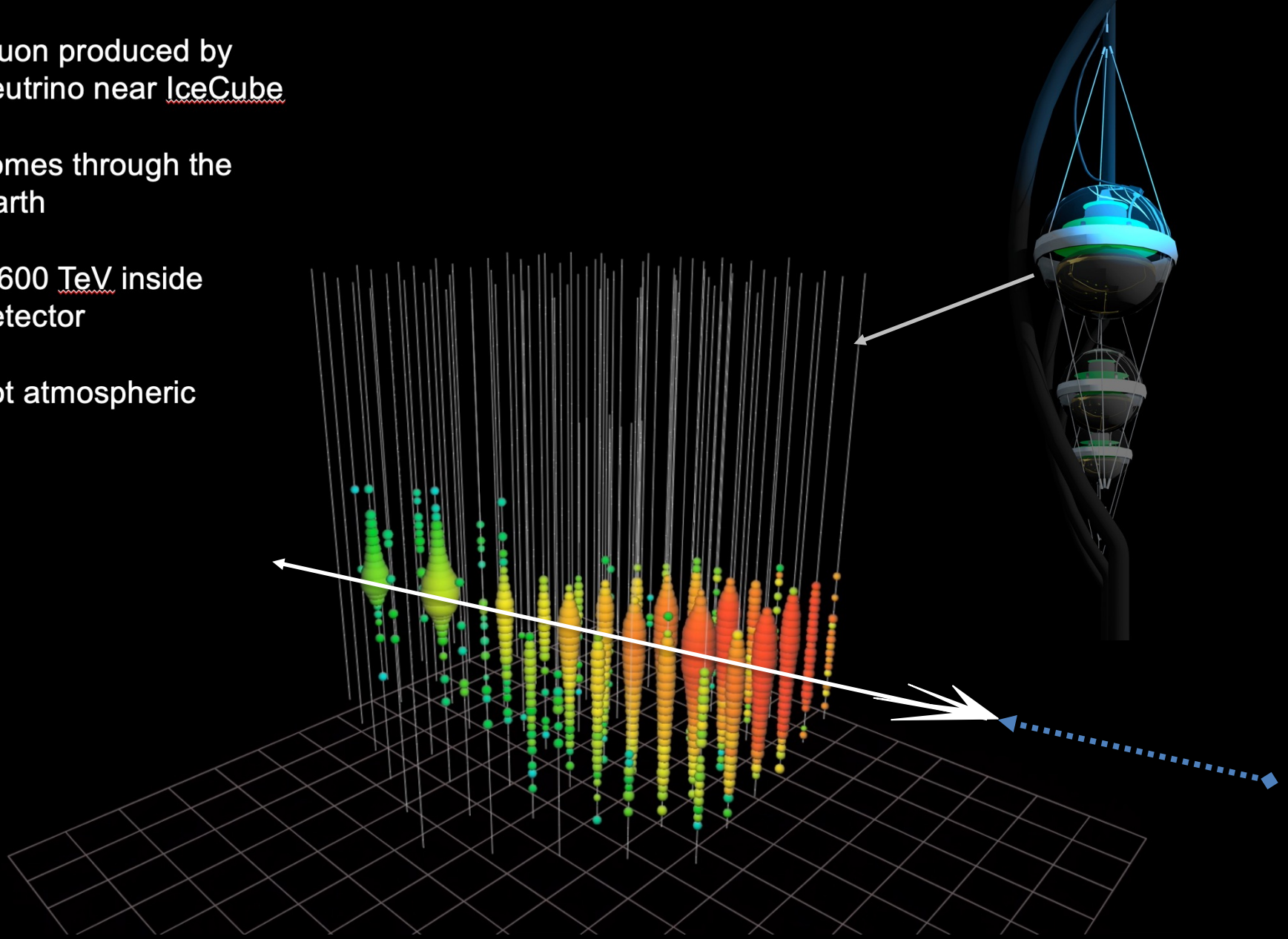
South Pole surface

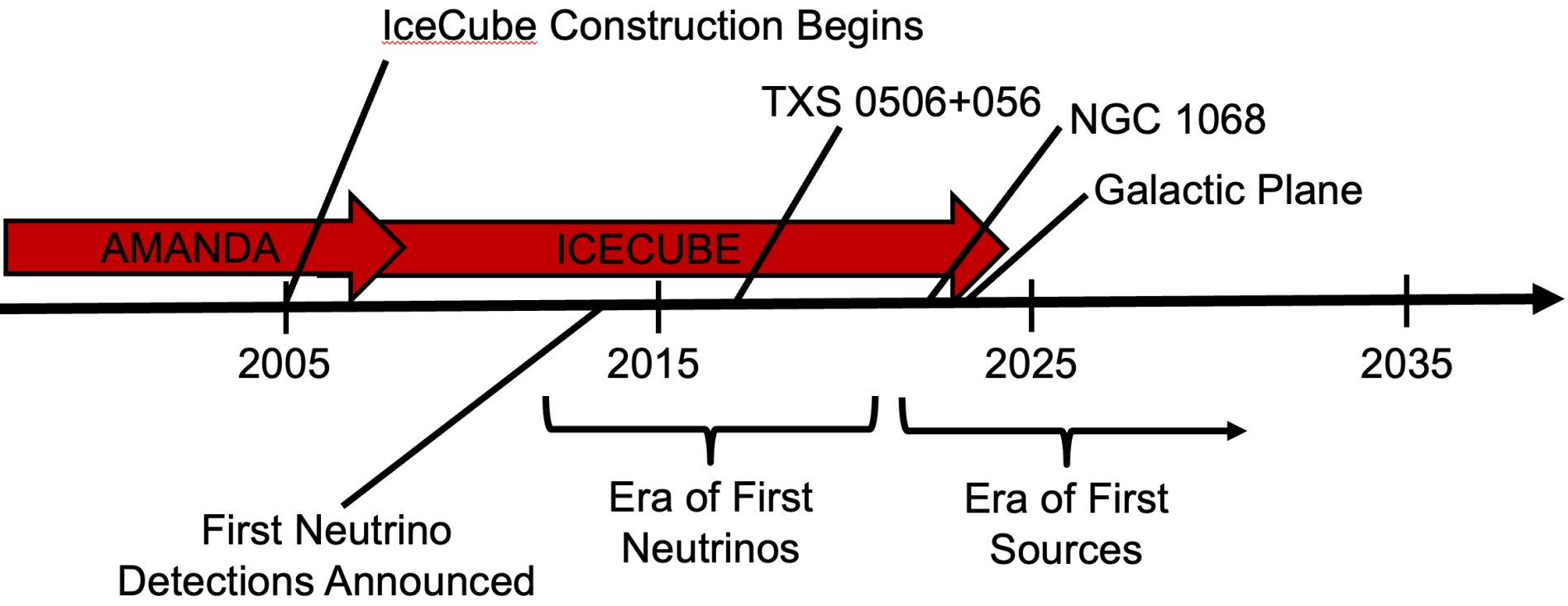
1450 m

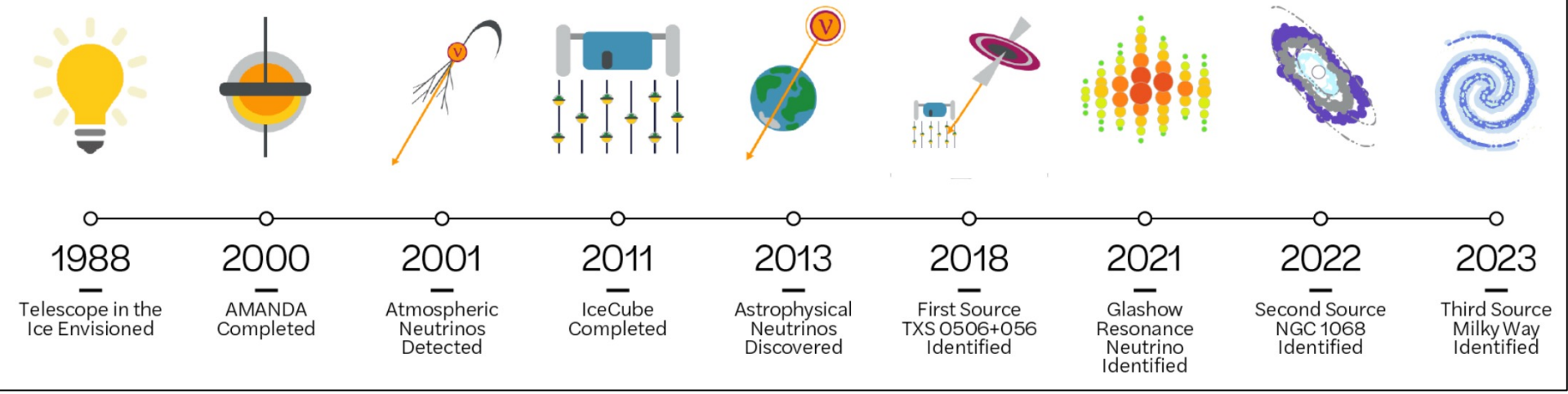
2450 m

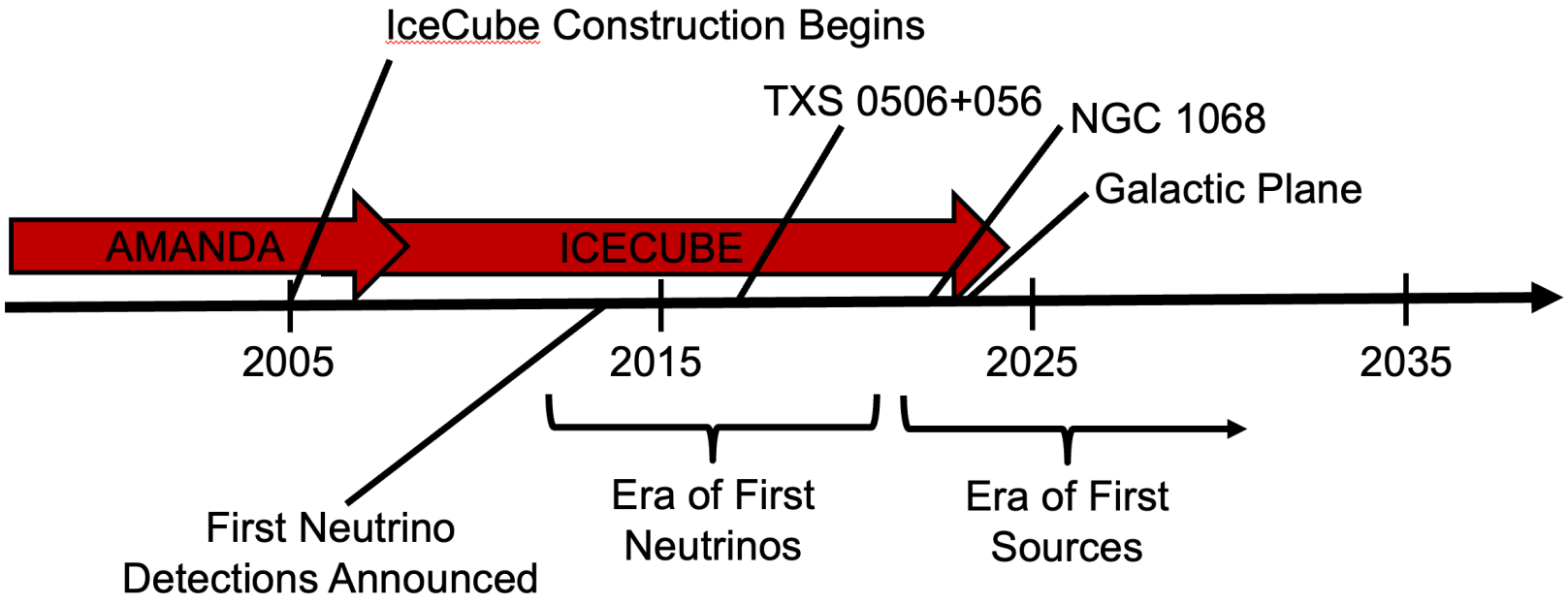
bedrock

- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric




IceCube Construction Begins
TXS 0506+056
NGC 1068
Galactic Plane
AMANDA
ICECUBE
2005
2015
2025
2035
First Neutrino Detections Announced
Era of First Neutrinos
Era of First Sources


1988
Telescope in the Ice Envisioned
2000
AMANDA Completed
2001
Atmospheric Neutrinos Detected
2011
IceCube Completed
2013
Astrophysical Neutrinos Discovered
2018
First Source TXS 0506+056 Identified
2021
Glashow Resonance Neutrino Identified
2022
Second Source NGC 1068 Identified
2023
Third Source Milky Way Identified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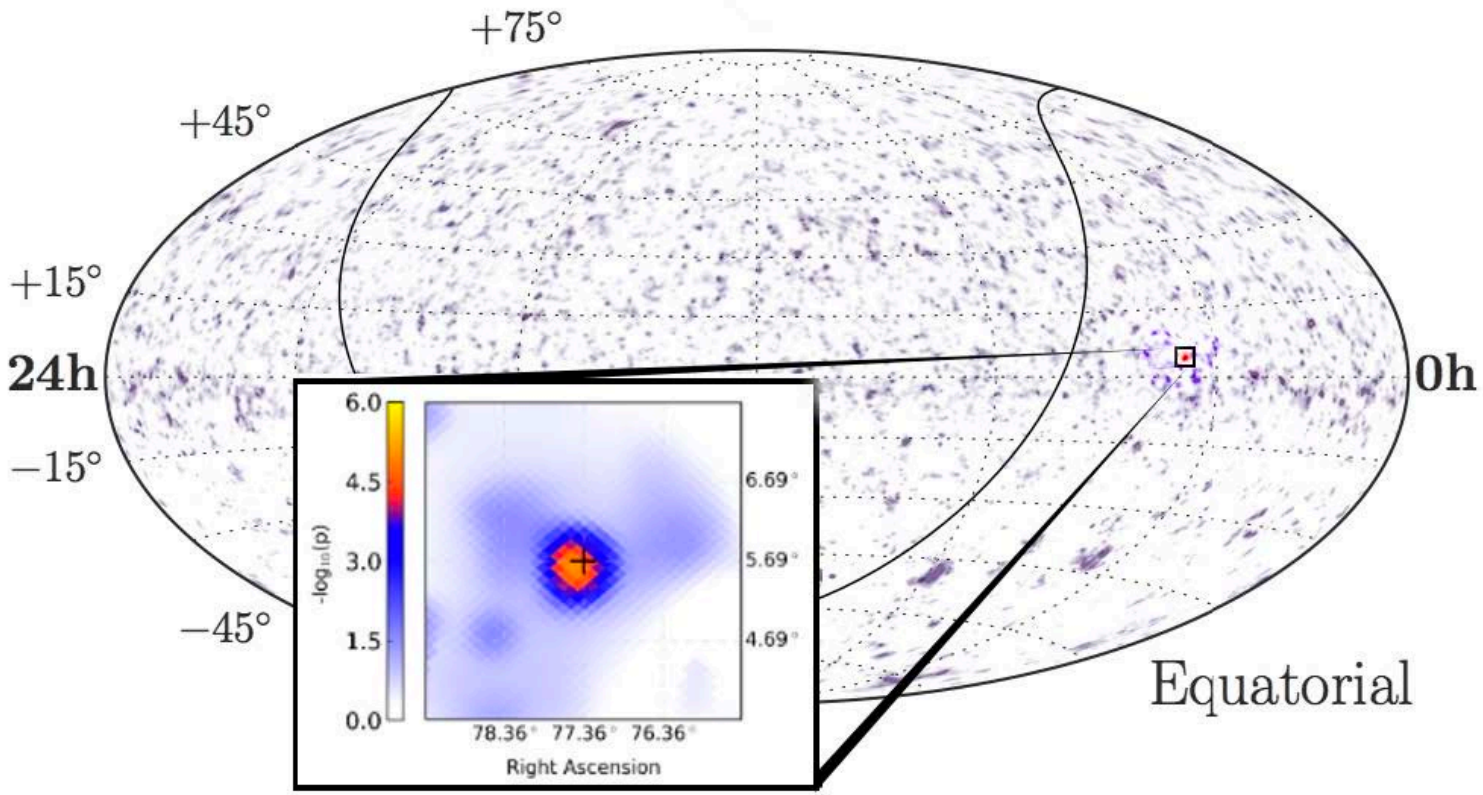
pre-trial p-value for clustering of high energy neutrinos



- hottest spot coincident with NGC 1068
- also hottest spot in the sources list (2.9σ)

evidence for non-uniform skymap in 10 years of IceCube data : mostly resulting from 4 extragalactic source candidates

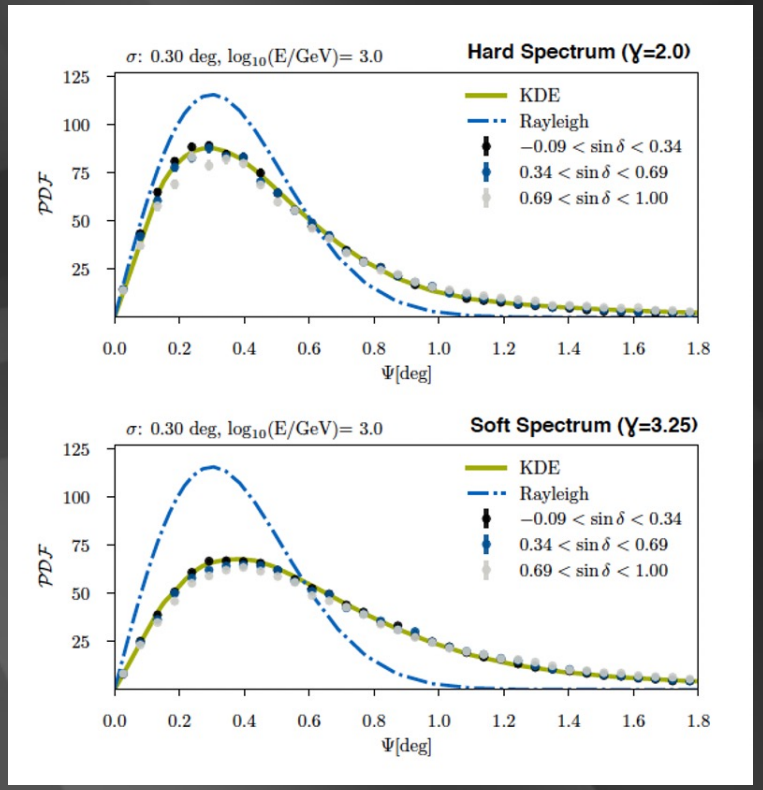
statistical fluctuations or neutrino sources?

ongoing program to upgrade the performance of IceCube

- improved detector geometry
- each photomultiplier calibrated individually
- improved characterization of the optics of the ice

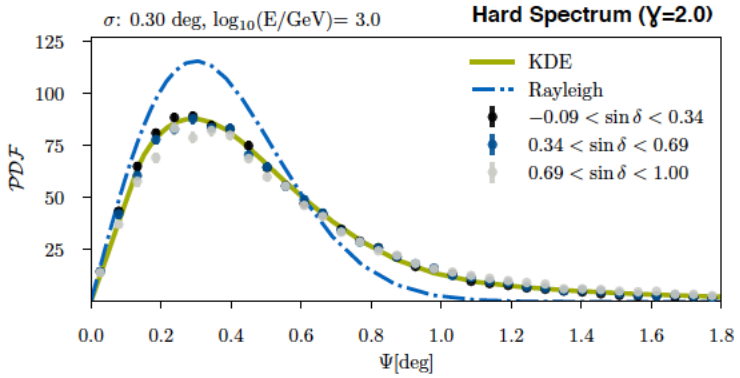
→ pass 2 data

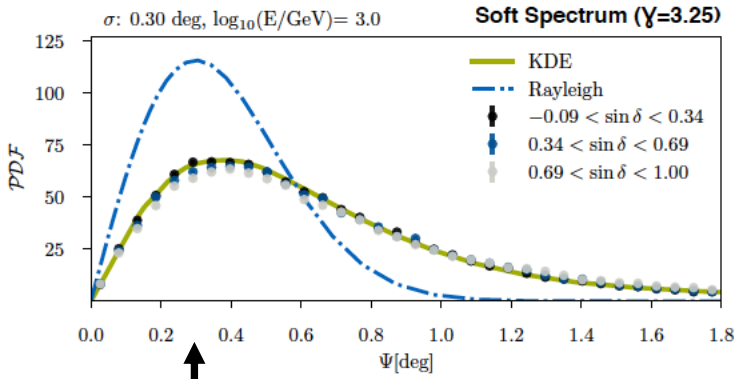
- improved muon angular resolution and energy reconstruction using machine learning
- point spread function consistent with simulation…



applied to 10 years of archival data

- point spread function consistent with simulation
- insensitive to systematics





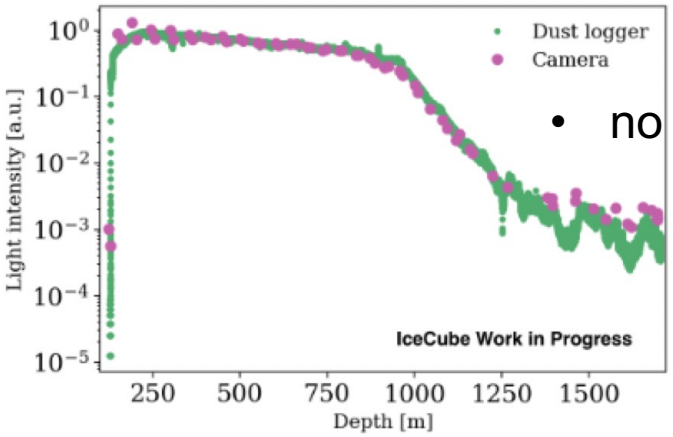
muon direction

- Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- The distribution depends on the spectral index!
- Effect mainly visible at < 10 TeV energies where the kinematic angle between neutrino and muon matters
- **Solution:** Obtain a numerical representation of the γ-dependent spatial term from MC simulation (for example using KDEs)

$$\frac{1}{2\pi\sigma^2} e^{-\frac{\psi^2}{2\sigma^2}} \rightarrow \mathcal{S}\left(\psi \,|\, \sigma,\, E_\mu,\, \gamma\right)$$

ice: step by step
next step: Upgrade

- hole ice ?

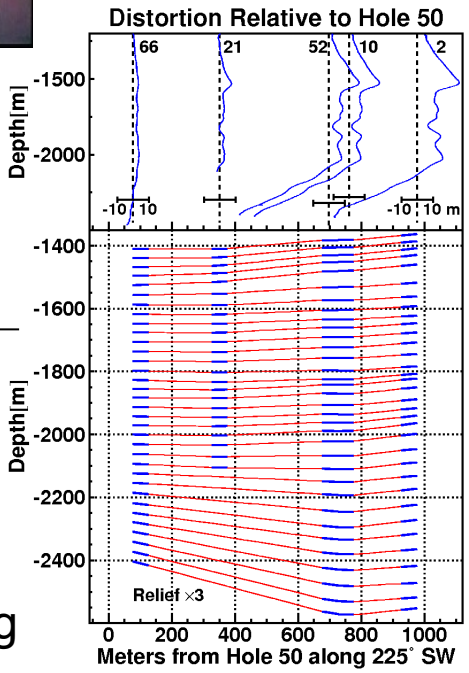


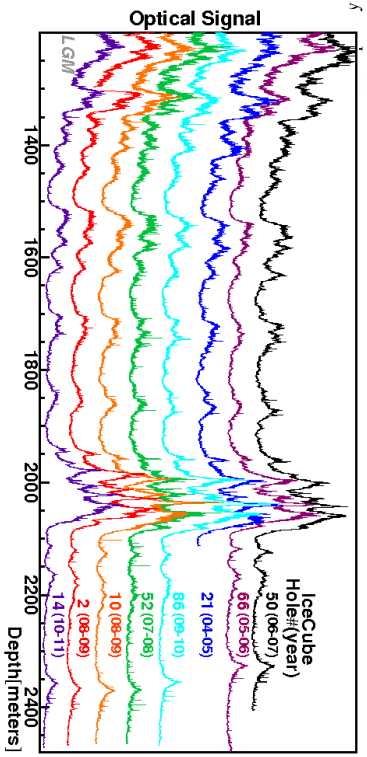
- no air bubbles/hydrates below 1350 m

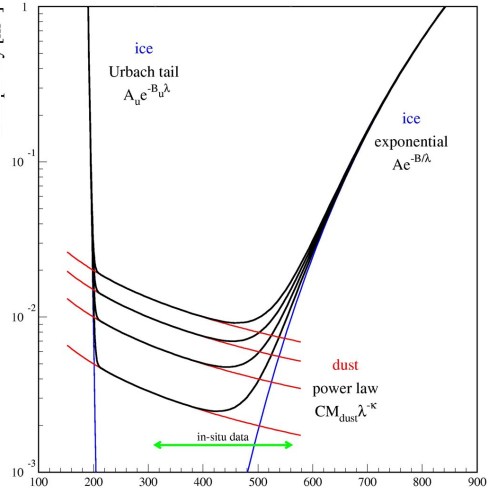
- > 100 m absorption length limited by dust

- ice layers

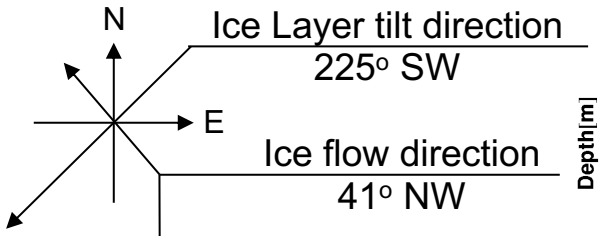
- tilted ice layers





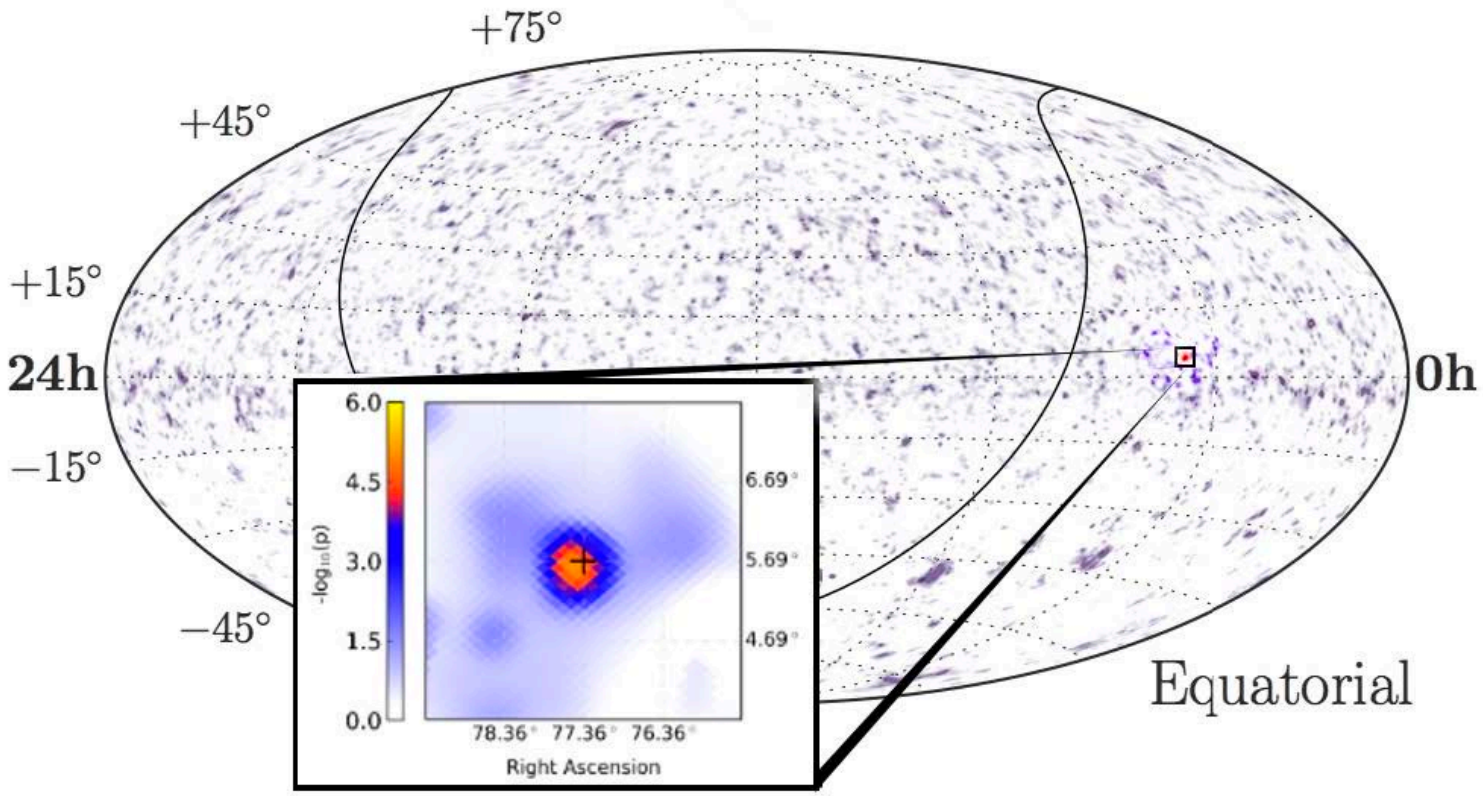


- birefringence



- anisotropy
~8% less scattering
41° NW

pre-trial p-value for clustering of high energy neutrinos



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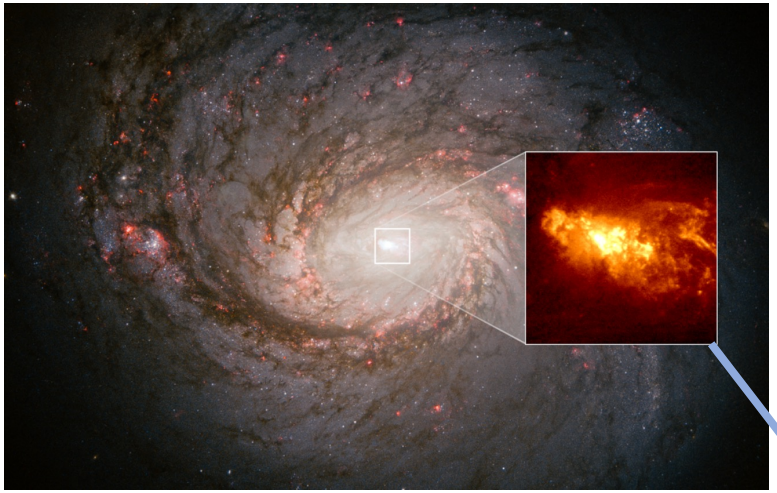
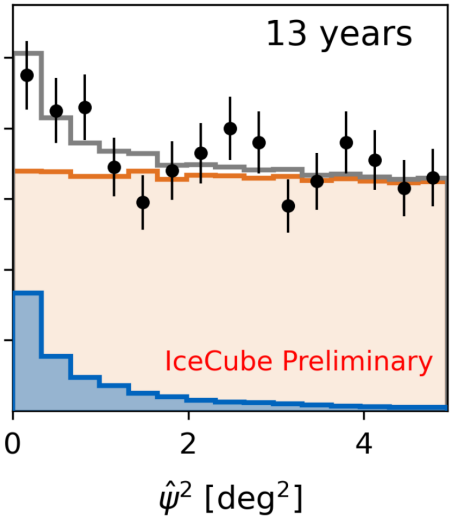
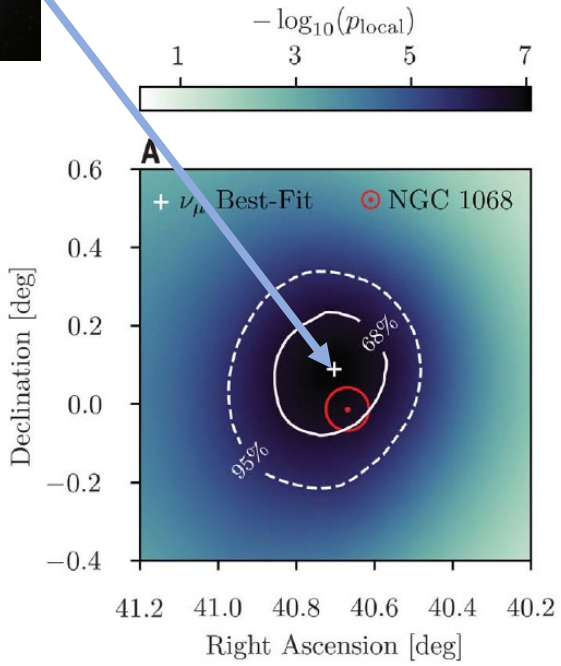
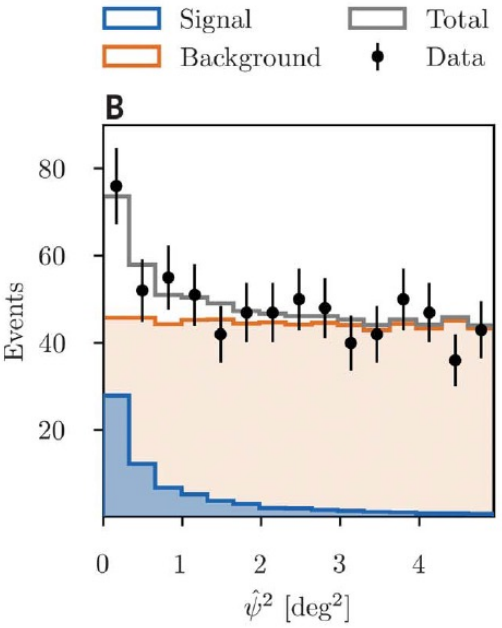
statistical fluctuations or neutrino sources?



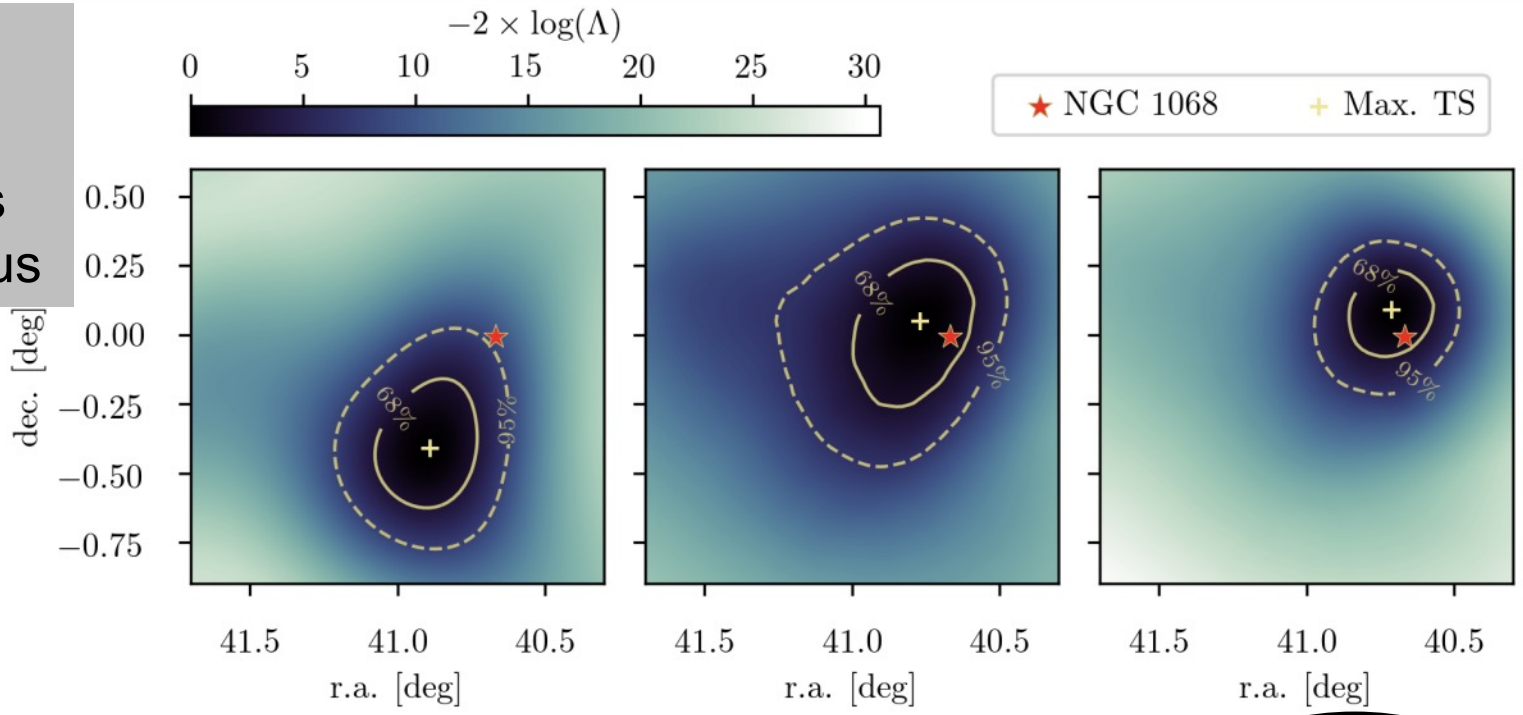
80 high-energy neutrinos from the direction of the active galaxy NGC 1068







NGC 1068 comes into focus

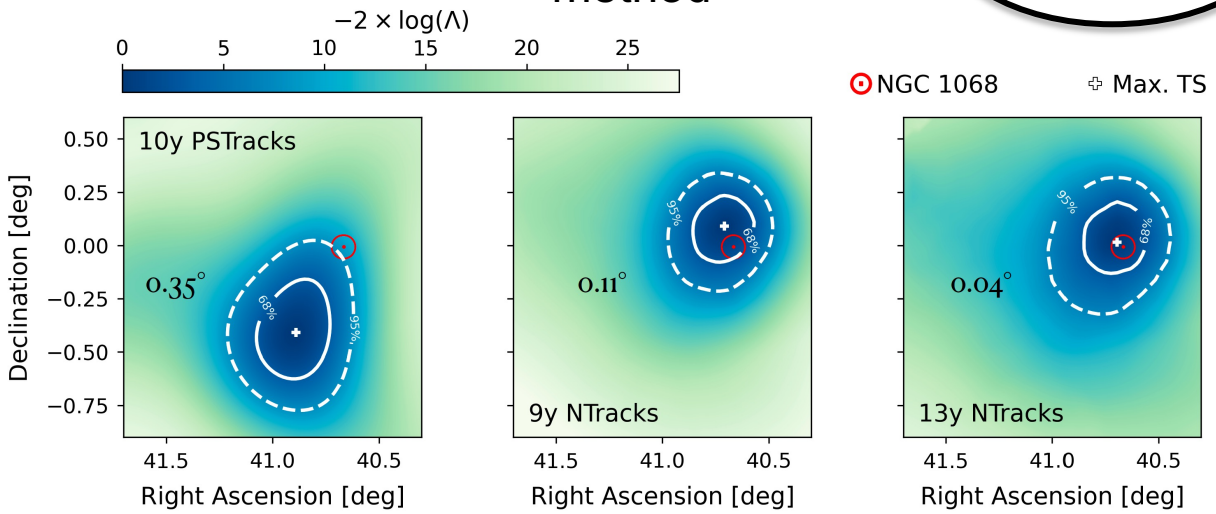


5σ local significance

2.9σ
- 10-year analysis

3.3σ
- new likelihood method

4.2σ
- pass 2



- accelerator(s): electrons and protons are accelerated in the turbulent magnetic fields associated with the accretion disk, in the infall onto the black hole,…
- target: the neutrinos are produced in the optically thick corona with a high density in gas (protons) and radiation (X-rays)

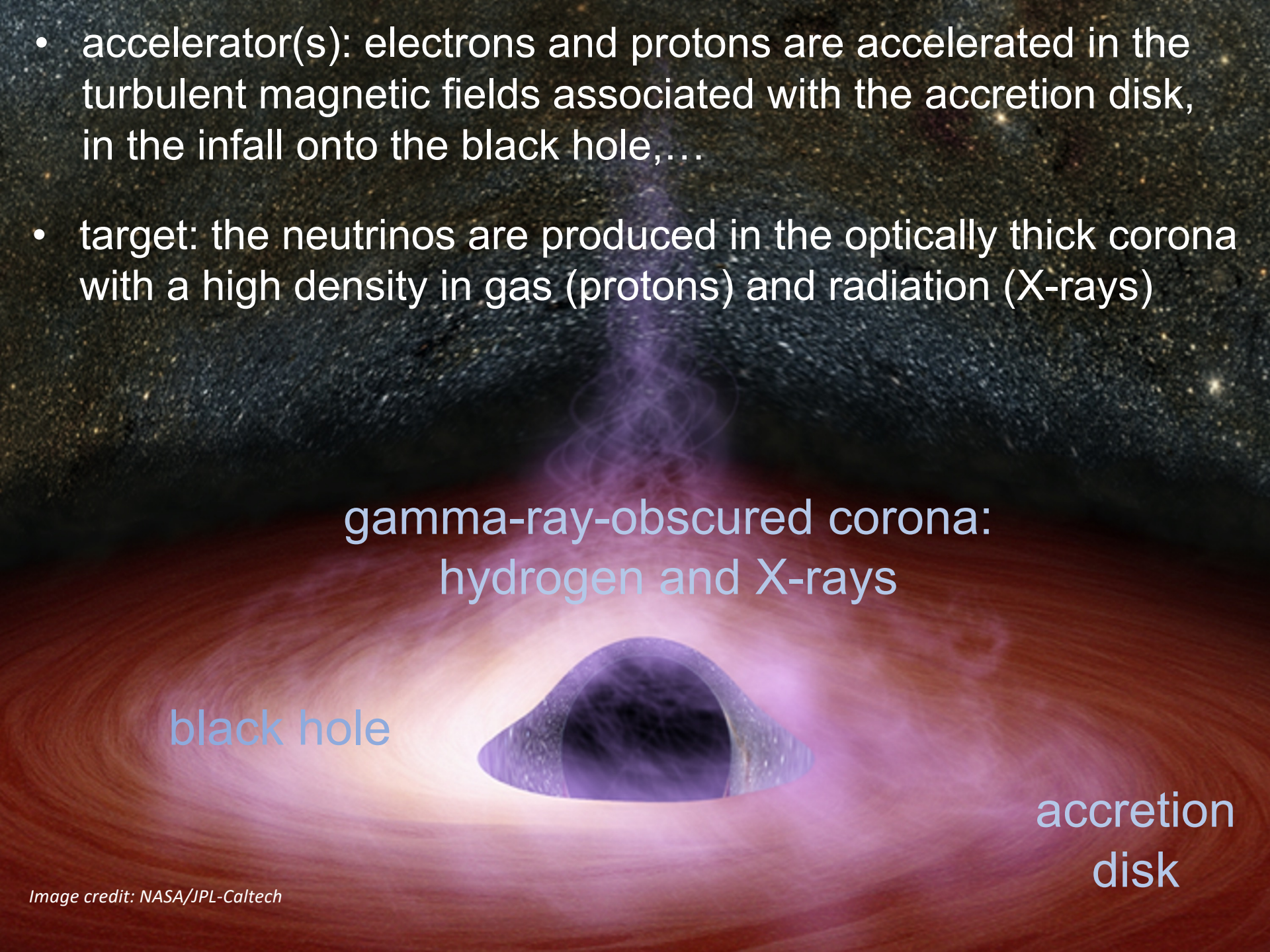


Image credit: NASA/JPL-Caltech

accumulating evidence for X-ray bright active galaxies as neutrino sources

- multimessenger (2017) and IceCube source (2014)
  TXS 0506
- IceCube source
  NGC 1068
- binomial analysis all sky
- NGC 1068+TXS 0506+PKS 1424
  NGC 1068+NGC 4151+NGC 7469+CGCG 420 (?) +….
- active galacties with high X-ray flux (Seyferts or not)
  NGC 4151
  CGCG 420 (?)
  NGC 1068+NGC 4151+NGC 3079 IceCube public data (Neronov et al.)
- Galaxy
- Circinus

binomial test of X-ray bright Seyfert galaxies

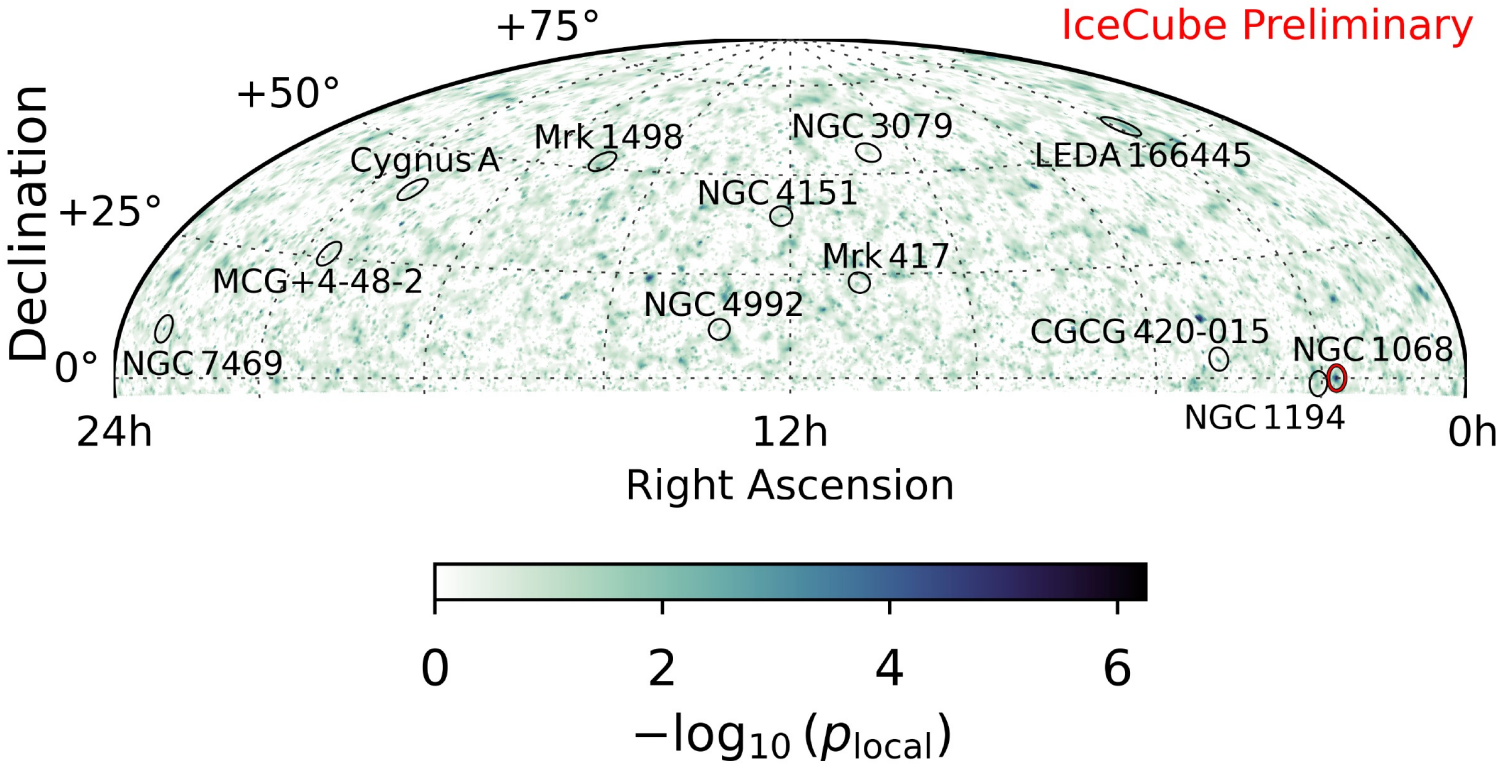
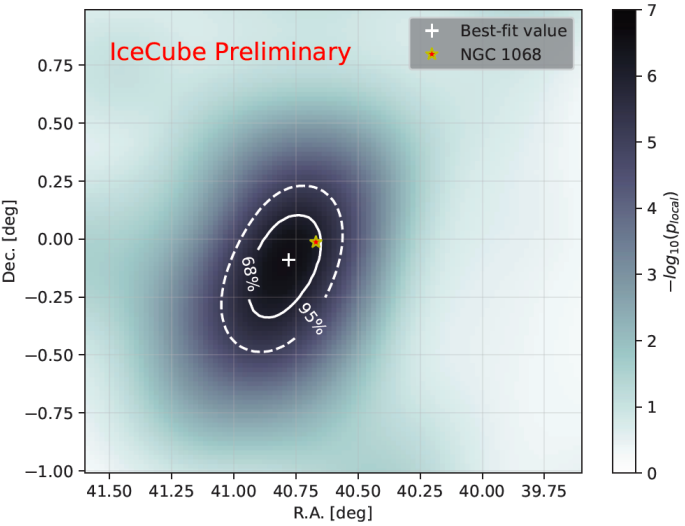
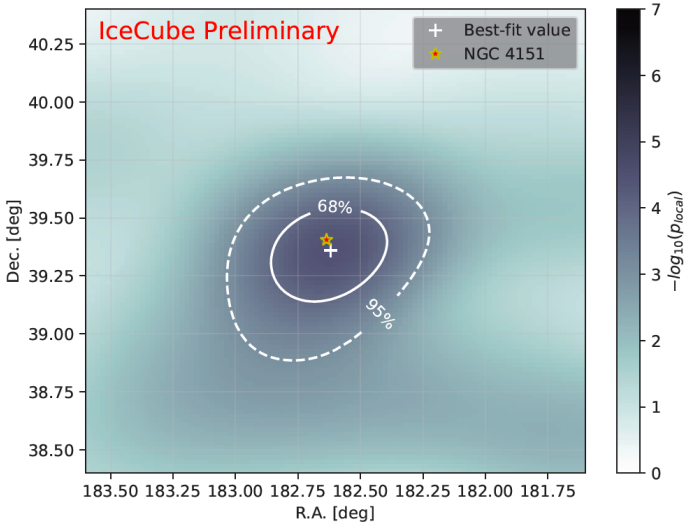


Figure 2: Northern Sky p-value map under the floating gamma assumption. We highlight the 11 sources which contribute to the excess found for the binomial test for the Seyfert Catalog in the power-law model case.

more sources …





- two brightest active galaxies discovered by Seyfert in 1943

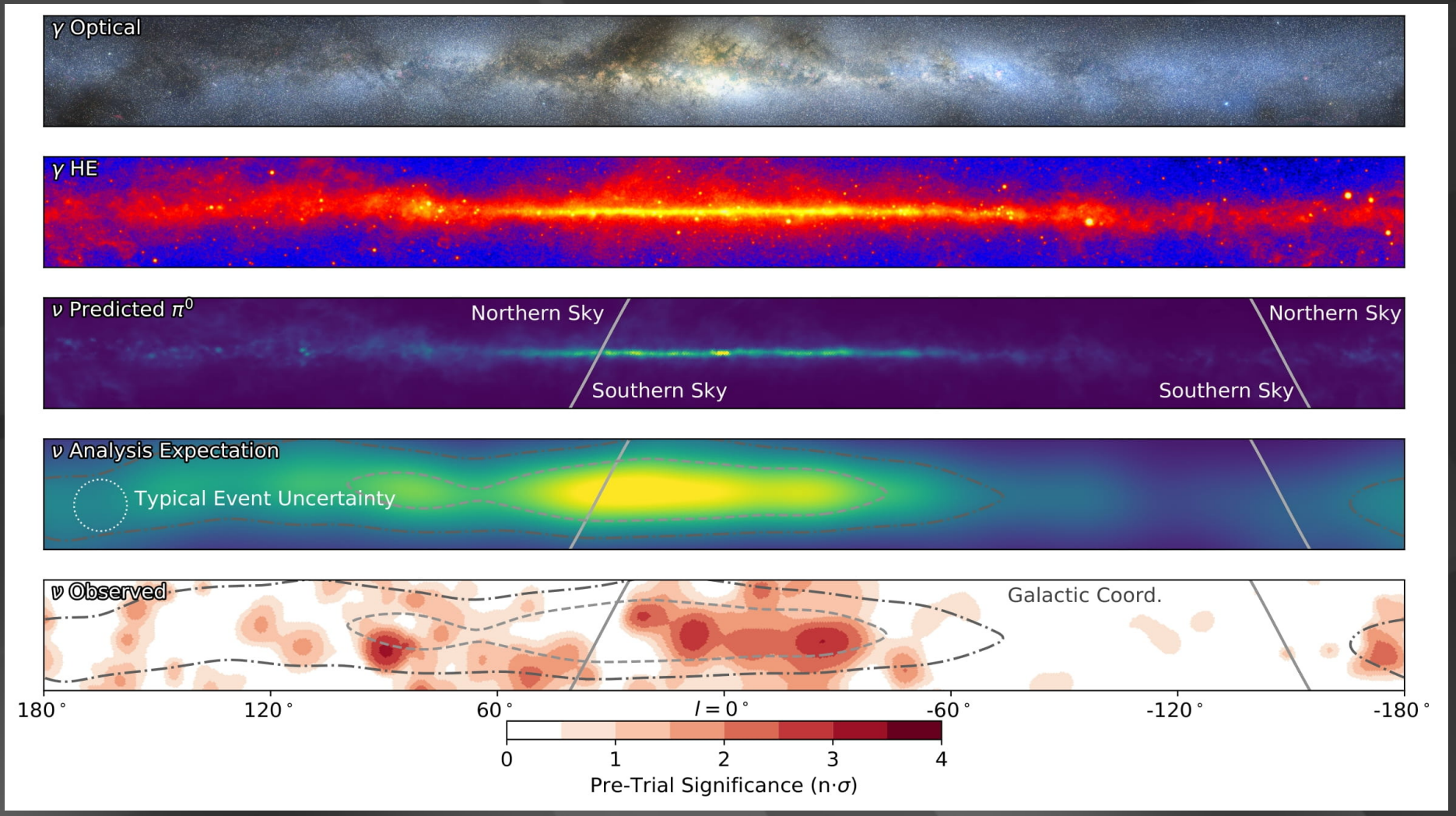
NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT† **1943**

ABSTRACT

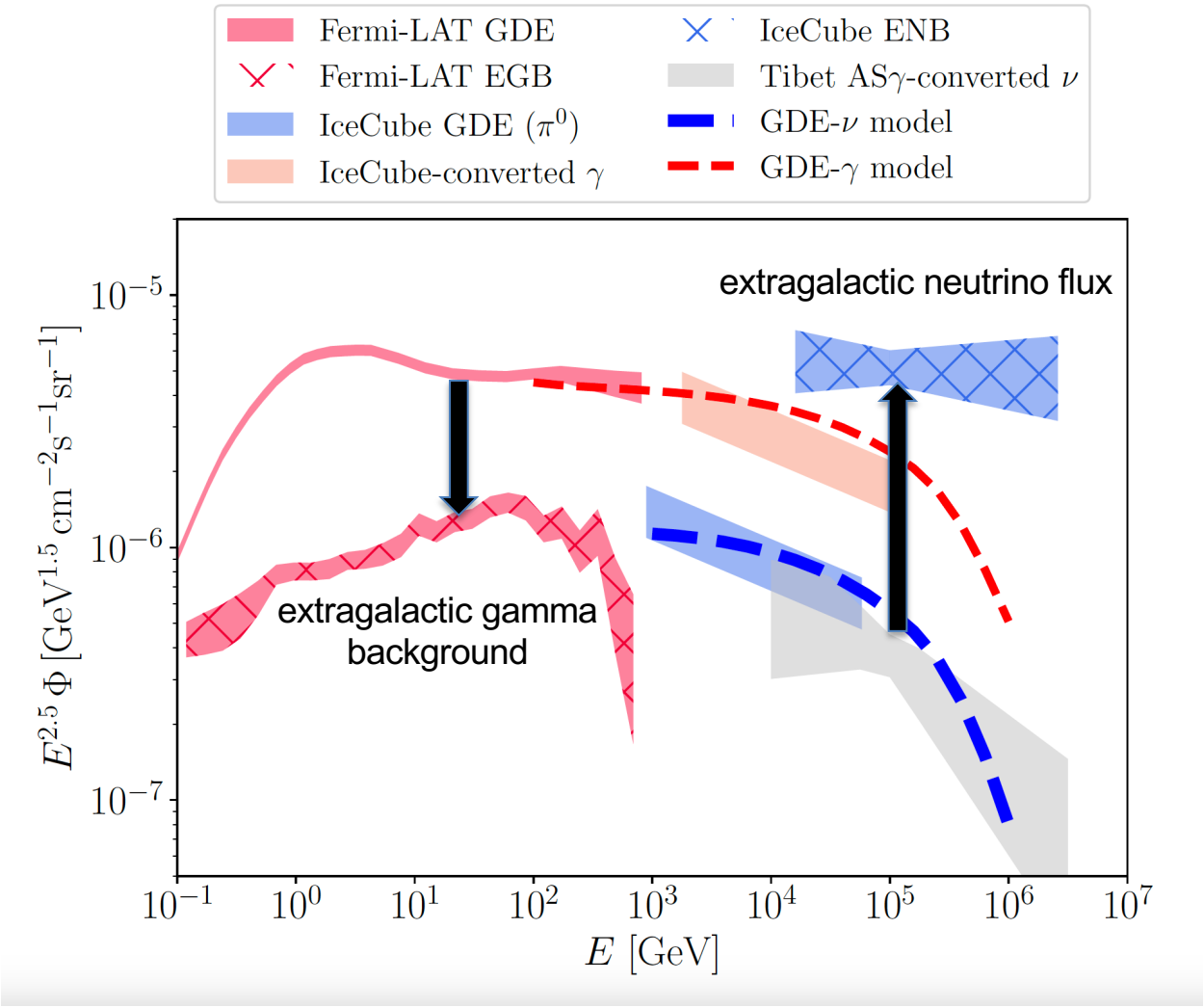
Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

Carl K. Seyfert (VANDERBILT SPECIAL COLLECTIONS AND UNIVERSITY ARCHIVES)



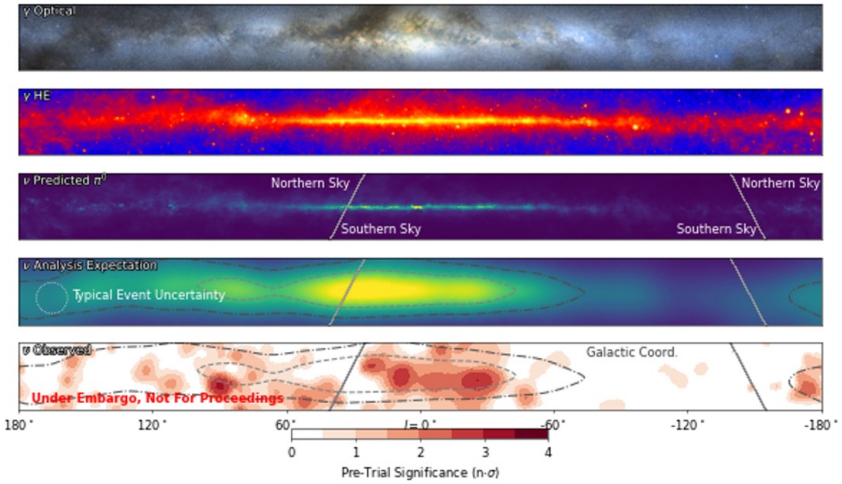
Fermi (GeV gamma rays) and IceCube (TeV neutrinos)
see the same Galactic plane

new opportunity to find the Galactic cosmic ray sources



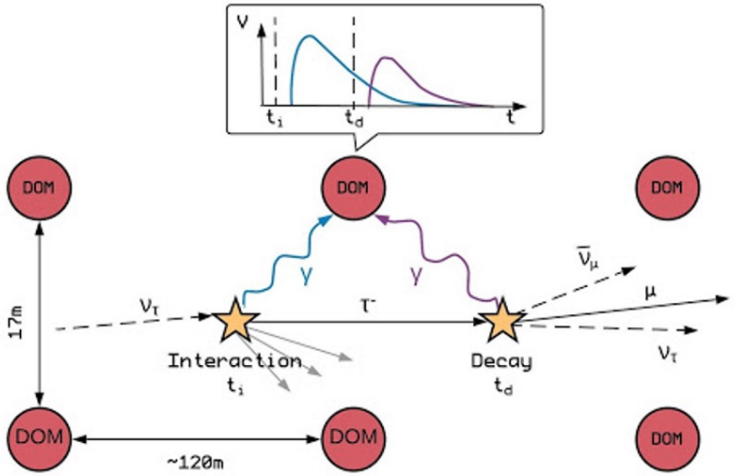
ML Driven Science Results

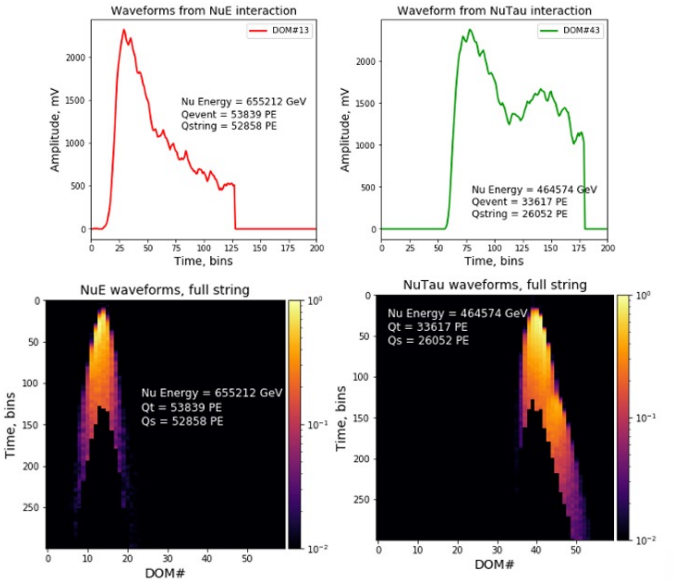
Galactic plane search



- Using Cascade events for “large” (e.g. Milky Way) or isolated sources a good option for Southern Sky point source search – Clear differentiation from background
- Maximum-Likelihood method for cascade pointing insufficient to find a source – Using BDT and CNN to find and reconstruct cascade events

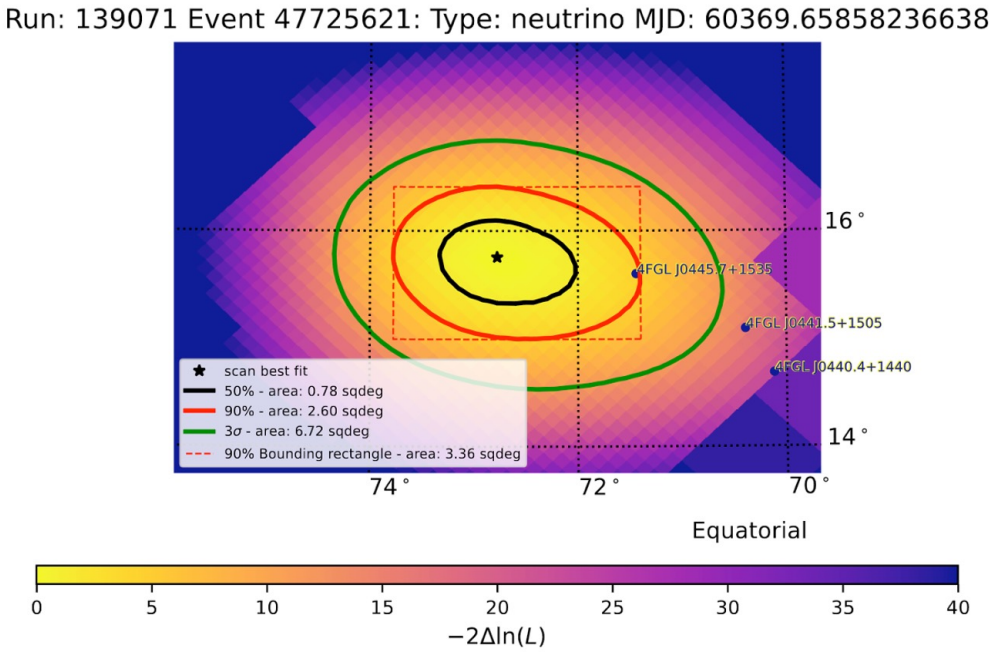
nutau search





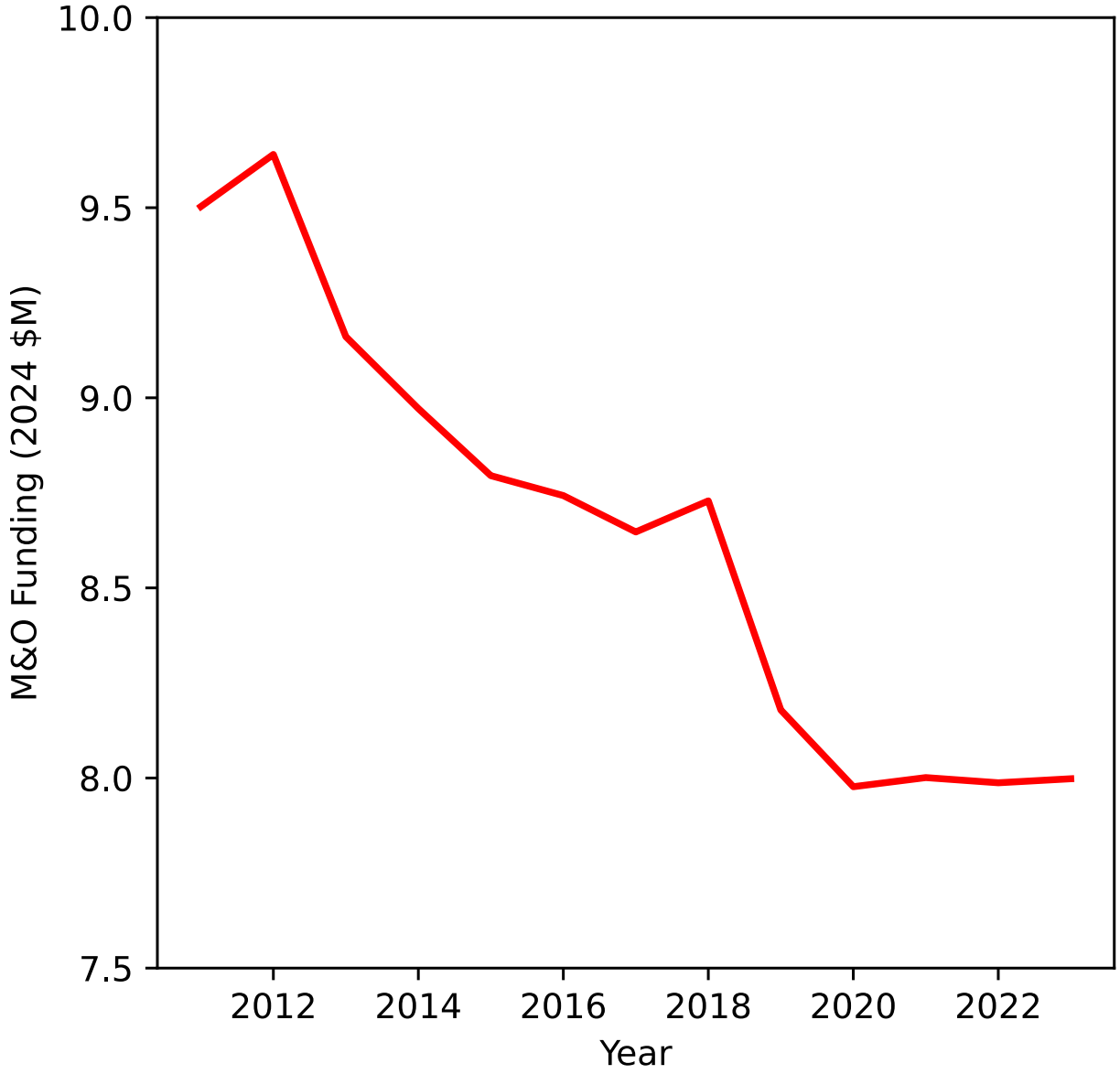
SkyDriver – Reconstruction-a-a-S

- SkyDriver – Now in production for realtime scans!
  - Replacement for Skymap Scanner – Original scanner
  - Development funded through a separate grant – NSF #2103963
- Uses PATh's Open Science Pool and ACCESS CPU resources
- Reduced time to result



- Pass3 is coming within the next couple years
  - Bring better science
  - Reduce storage footprint for Upgrade, etc.
- Testing Pass3 on NSF leadership-class HPC (TACC's Frontera) as part of the NSF #2139536
  - Next NSF leadership-class HPC system (Vista and Horizon) will be ARM64
  - IceCube codes run on ARM64

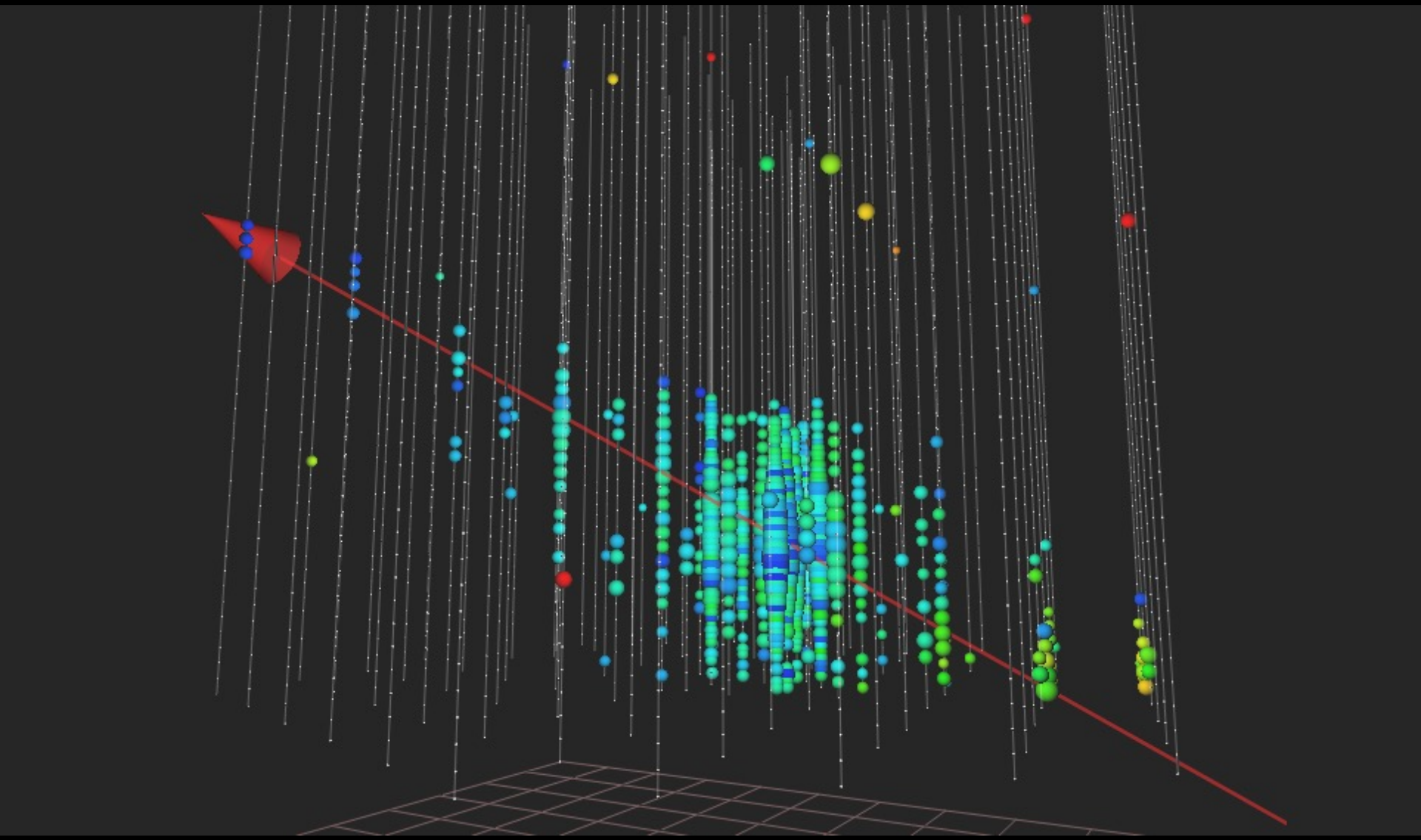
M&O funding in 2024 $M



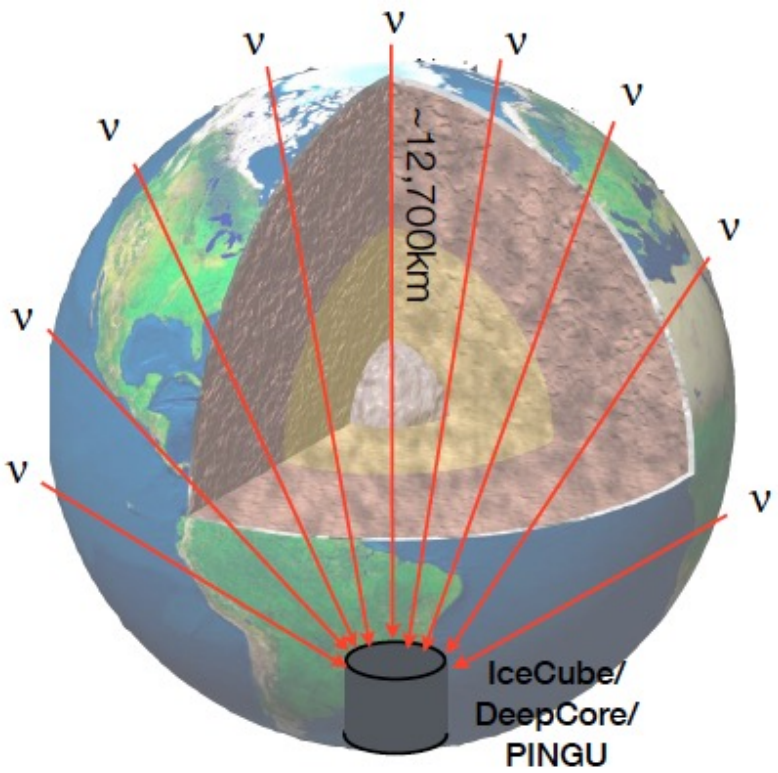
Next step: the IceCube upgrade

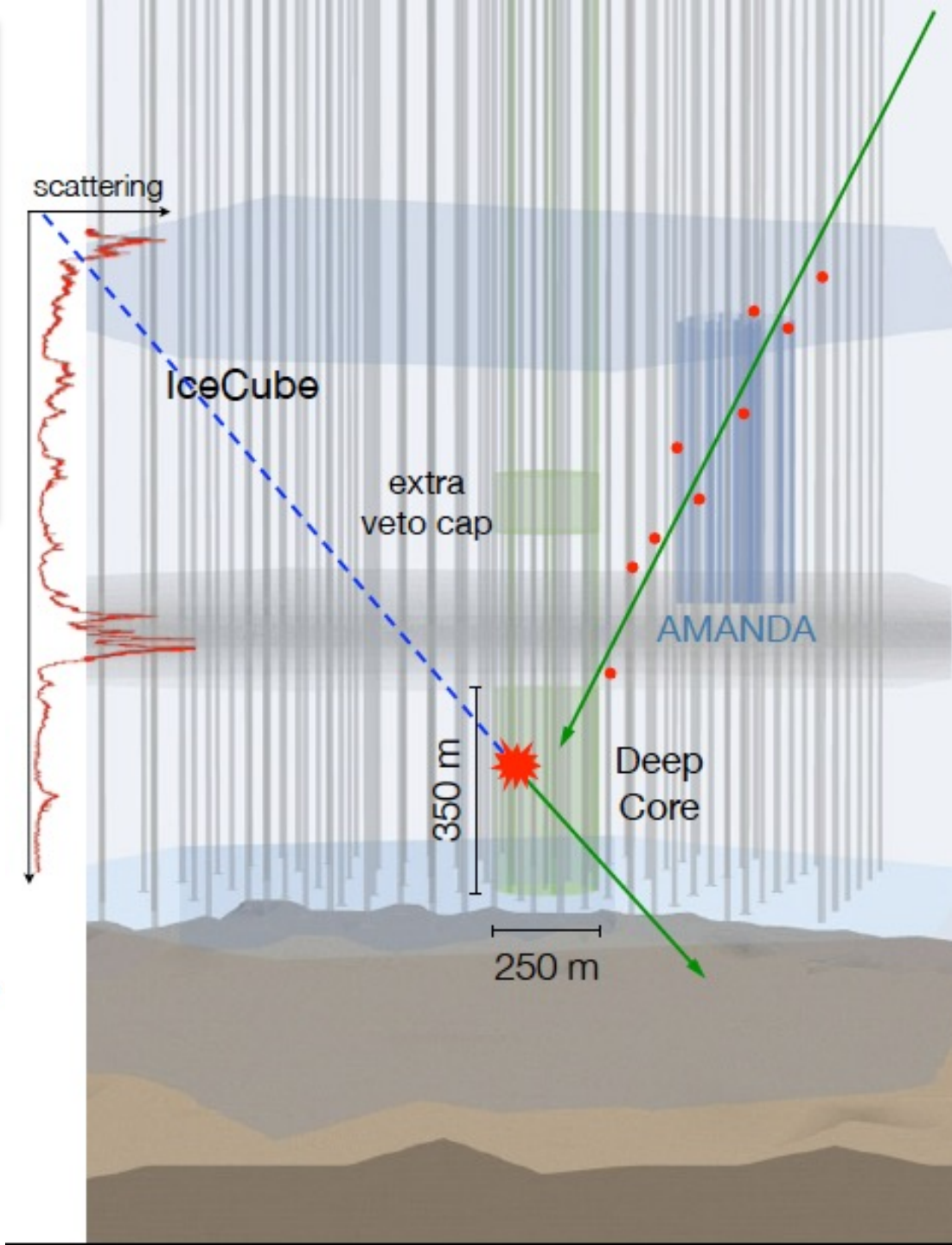
- improve the scientific capabilities of IceCube at low energies
- improve the scientific capabilities of IceCube at high energies with improved optics of the ice using the information obtained with the Upgrade’s small string spacings and novel calibration devices

IceCube and DeepCore



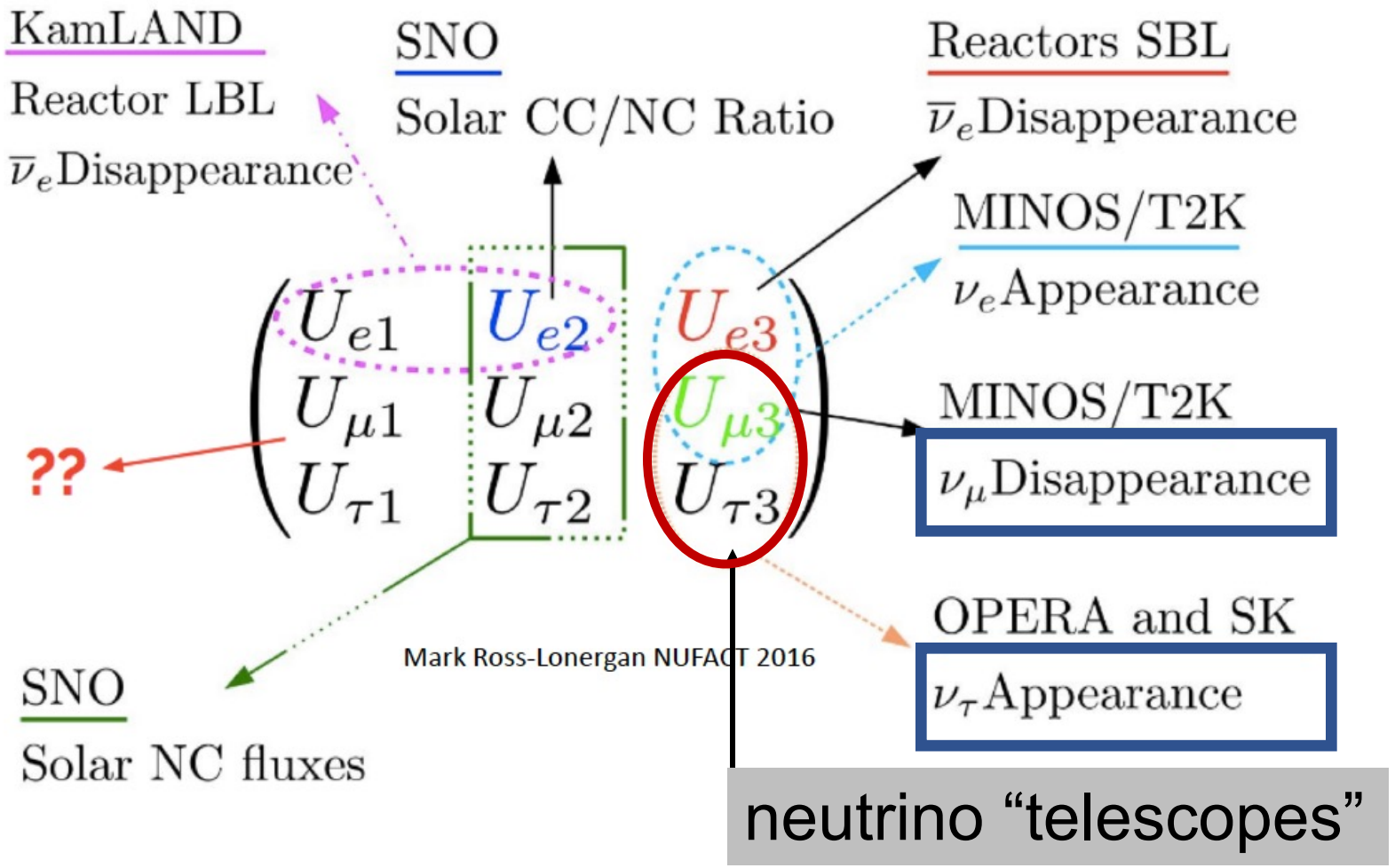
- one million atmospheric ν's
- 10 megaton instrumented ice
- at analysis level in DeepCore one every 15 min and with Upgrade one every 4 min
- near 25 GeV energy nearly all muon neutrinos reappear as tau neutrinos. We measure both!





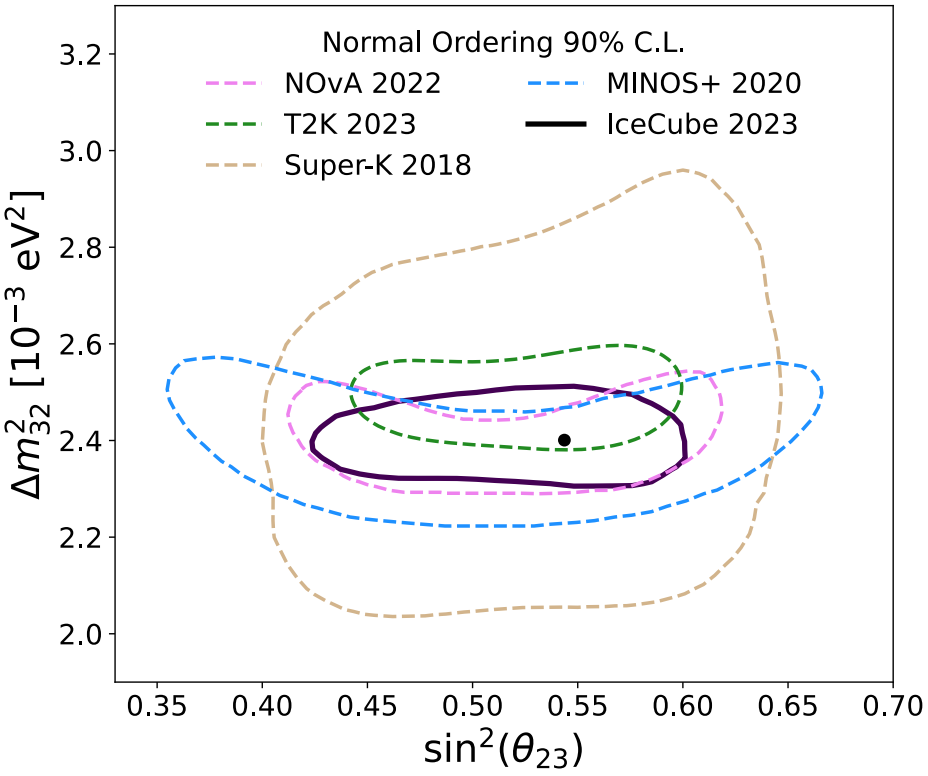
neutrino oscillations with a neutrino telescope:
access to tau neutrinos in the atmospheric (and cosmic) beam

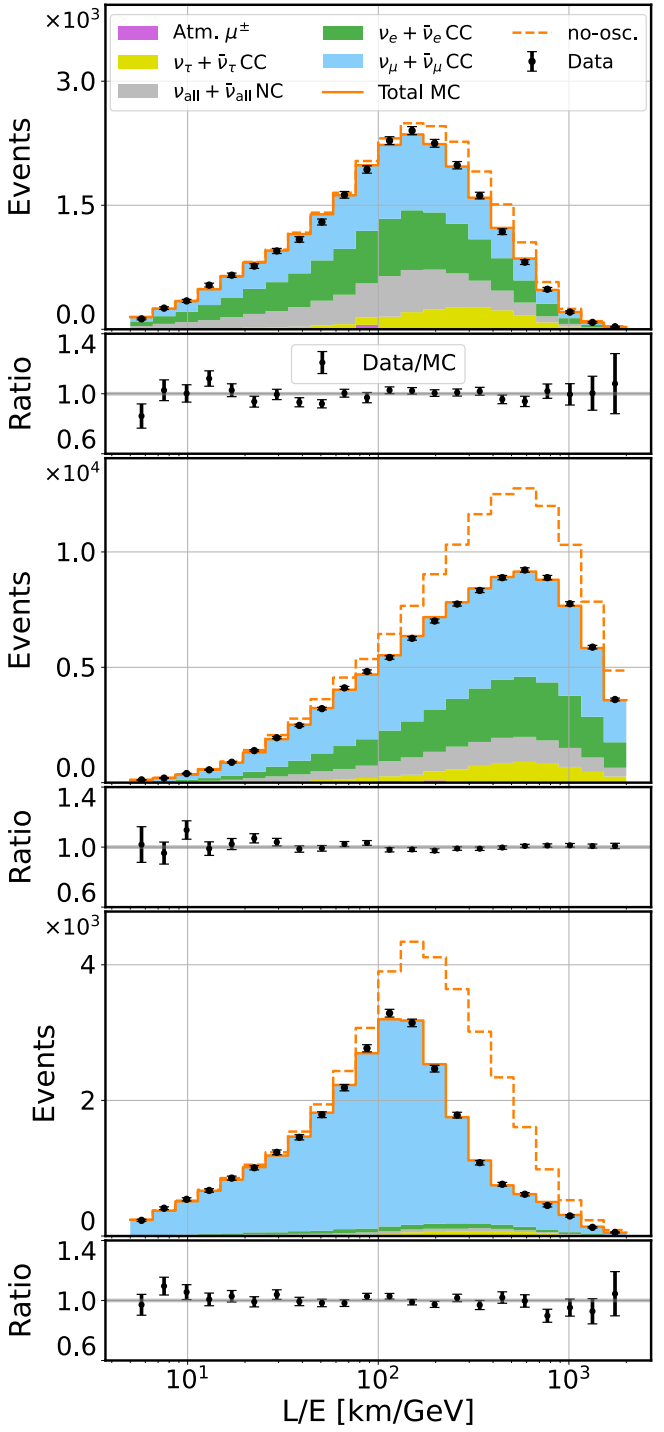
The PMNS mixing matrix



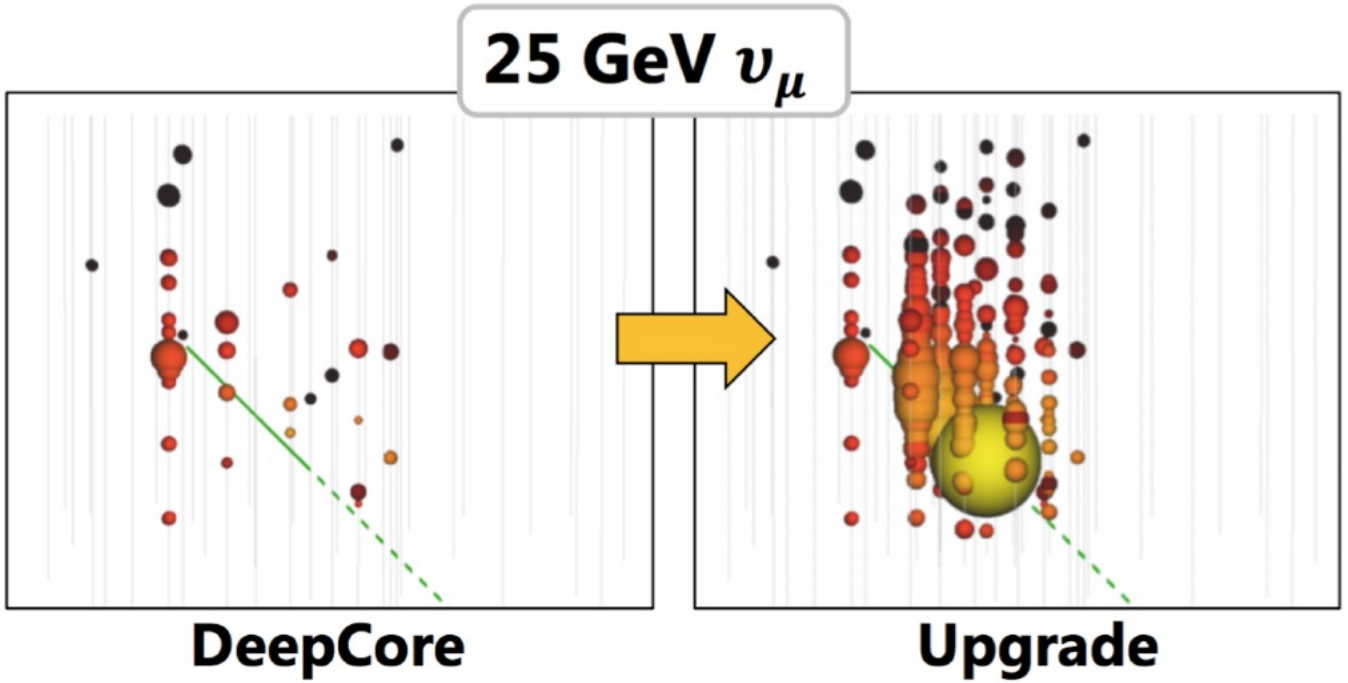
imminent unblinding:

- analysis with a sample of 210,000 neutrinos (9.3 years and 97.3% purity)
- higher energy than accelerator experiments and SuperK (5~55 GeV)
- 6900 tau neutrinos
- improved calibration of the data, event reconstruction using machine learning and new treatment of systematics





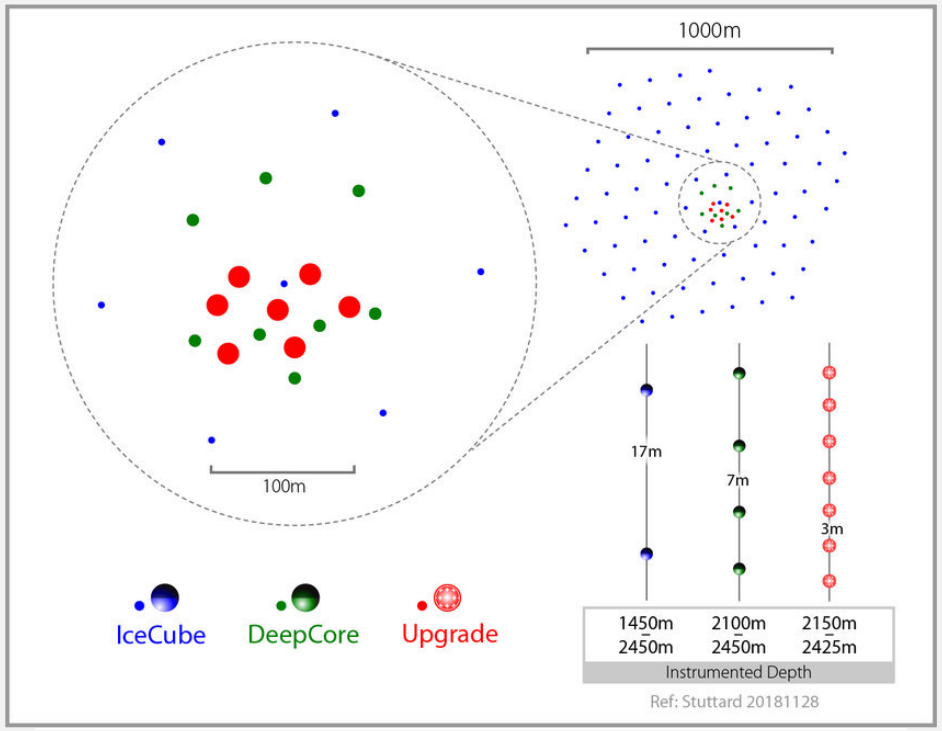
Low energy neutrinos in the Upgrade



IceCube Overview

- IceCube
  - DeepCore
  - IceTop

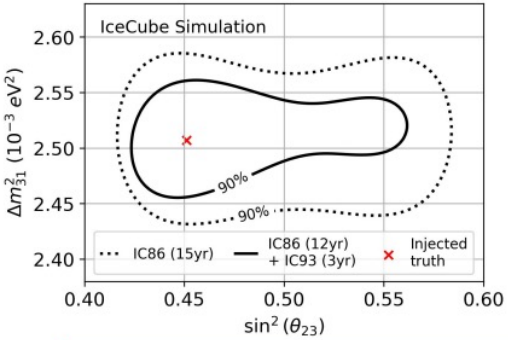
  } Done & Delivering
- Upgrade } Underway
- IceCube-Gen2
  - Full } Astro2020 Review Preliminary Design in Preparation

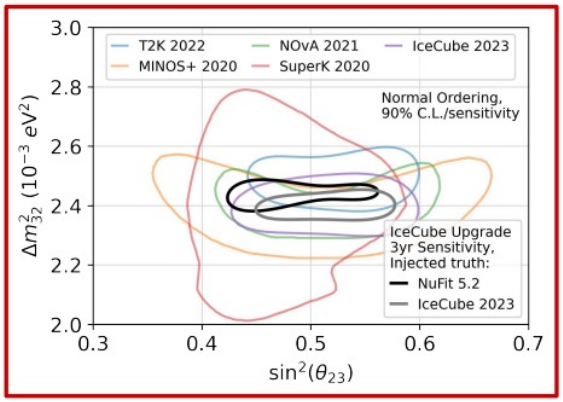


- 10 megaton volume
- string spacing : 125m → 35m → 22m
- module spacing: 17m → 7m → 3 m

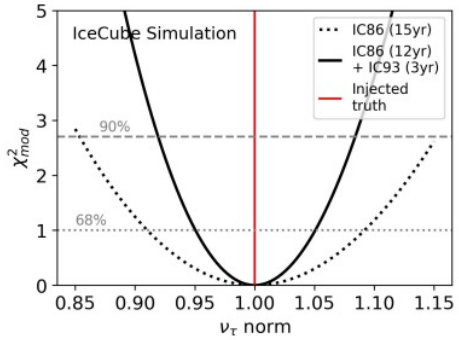
and with the Upgrade strings in 2025…

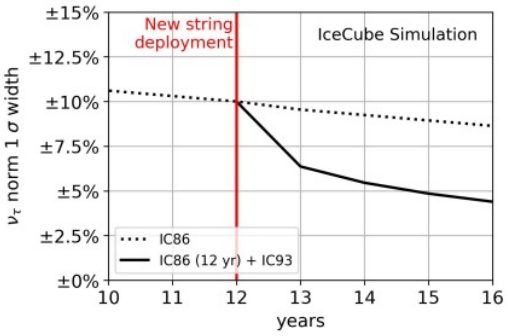
Sensitivities - Atm. Osc. Params



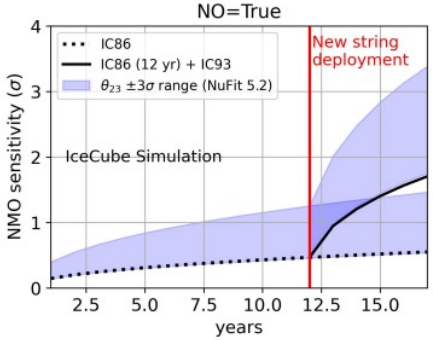


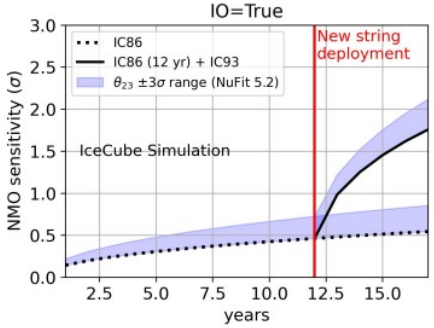
Tau Neutrino Norm





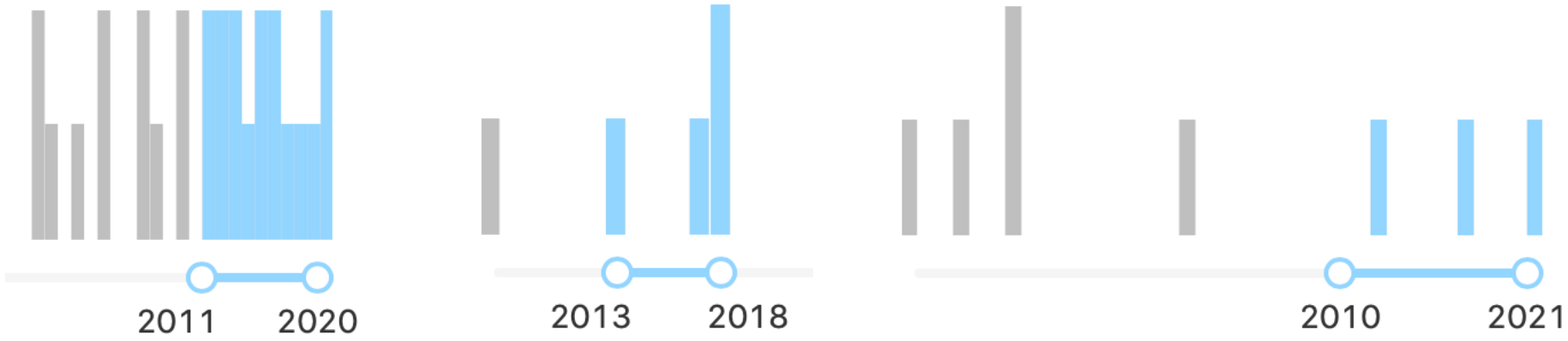
NMO





leading atmospheric beam detector until the advent of HyperK in 2028

IceCube high profile papers

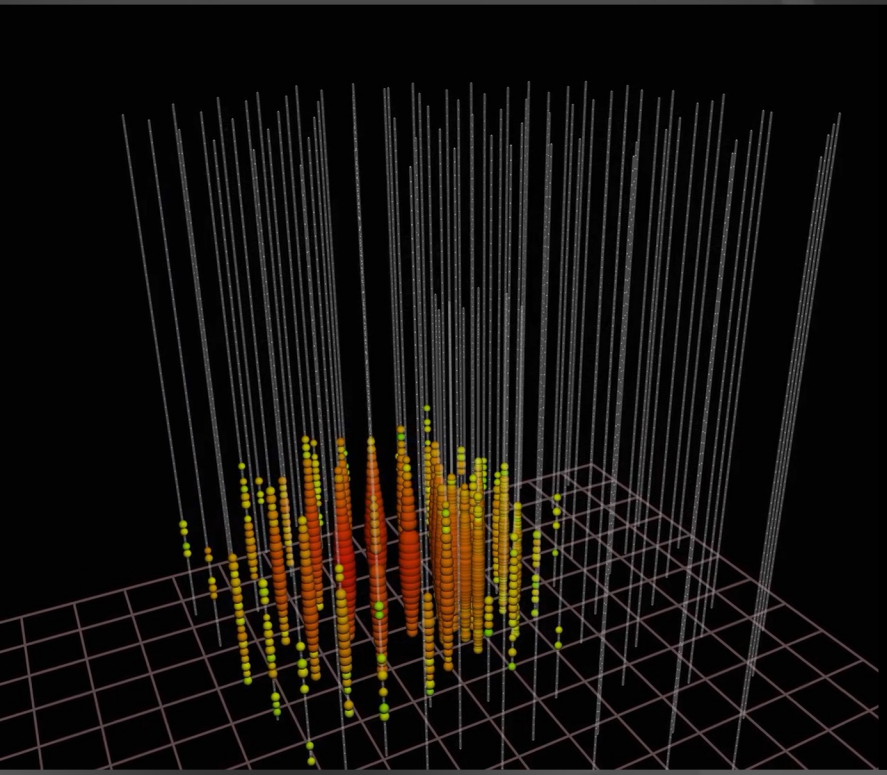


Phys. Rev. Lett. (16+4+…) Science (4+2) Nature (3)

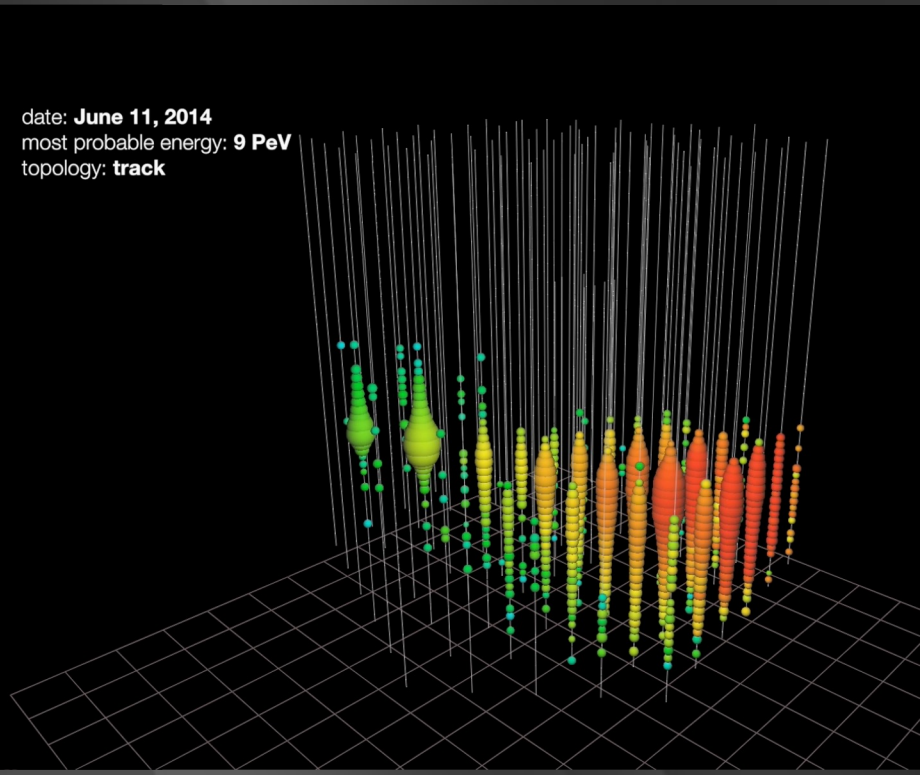
no evidence of decline of new results in 10 years

overflow slides

neutrinos interacting inside the detector



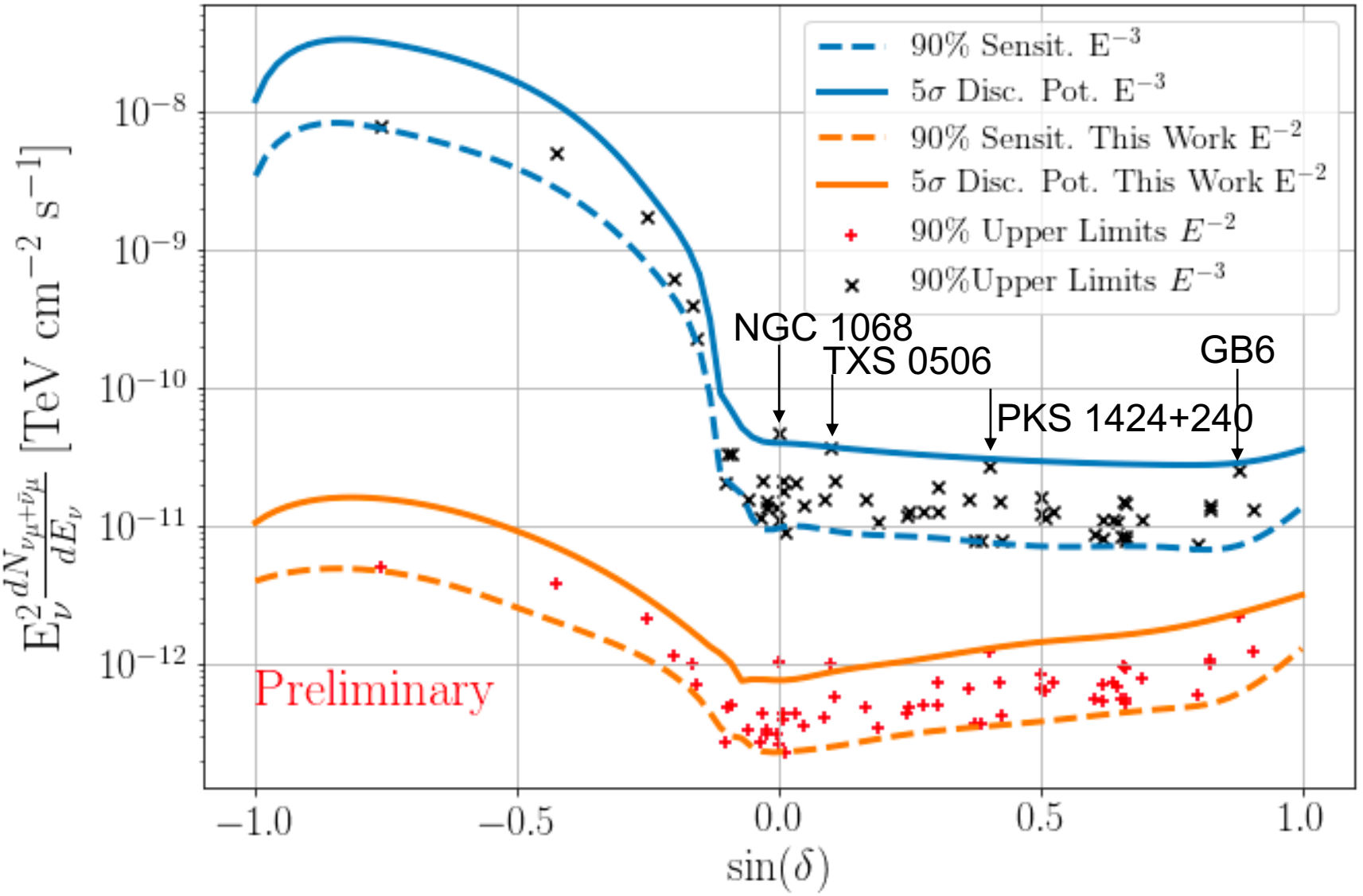
muon neutrinos filtered by the Earth



superior total energy measurement
to 10%, all flavors, all sky

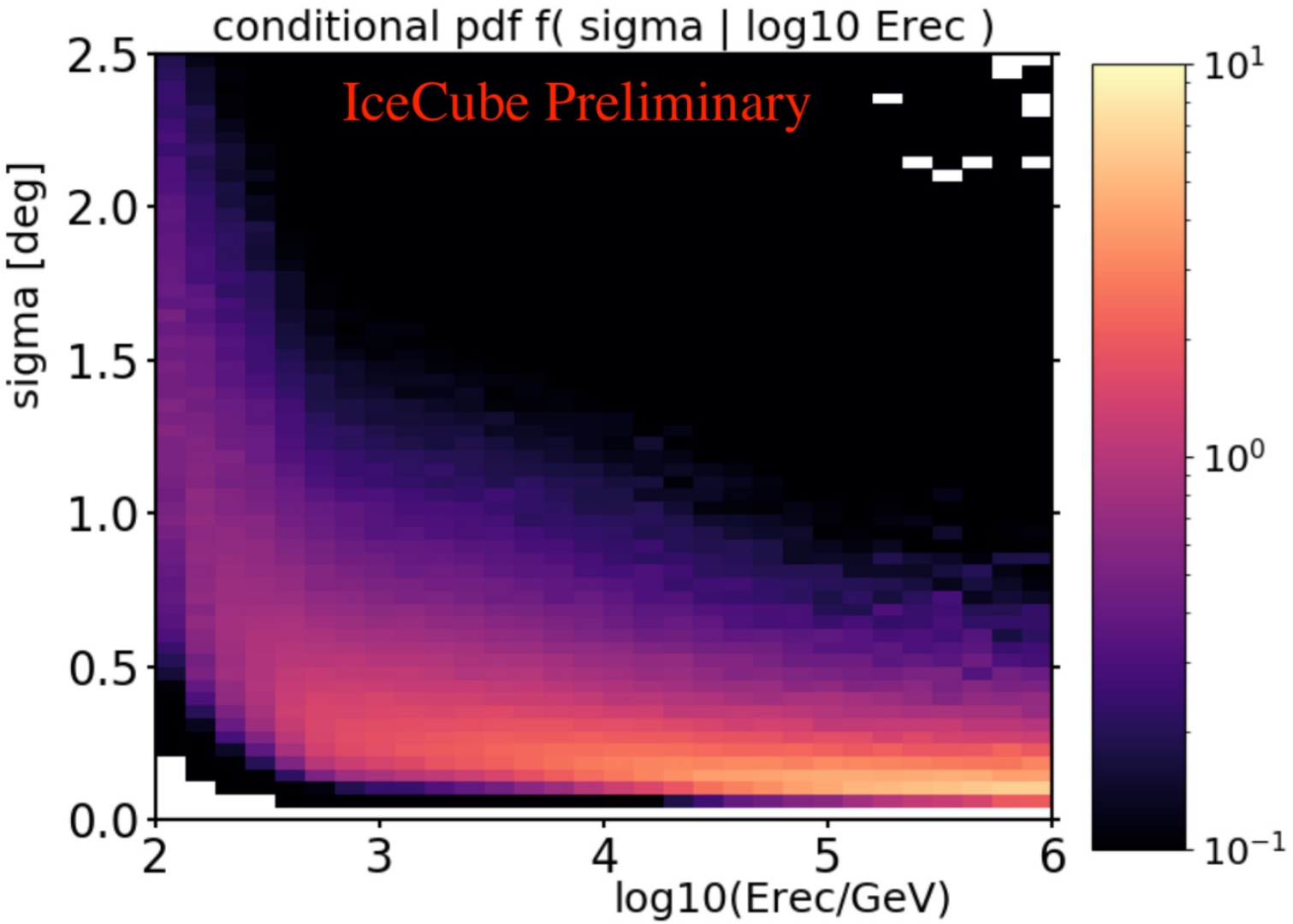
astronomy: superior angular resolution
superior (< 0.3º)

limits and interesting fluctuations (?)



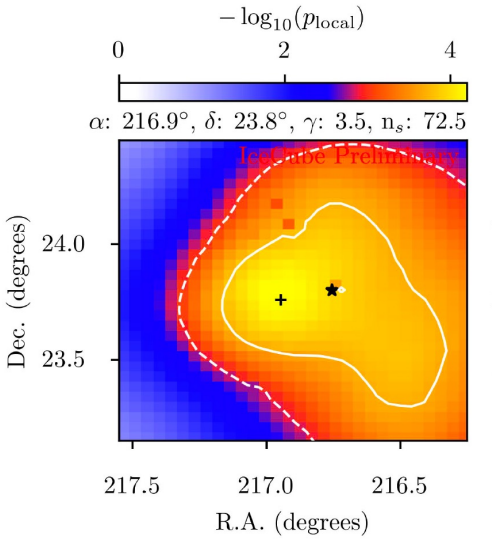
improve calibration, event selection and reconstruction

sources come into focus: angular resolution < 0.3°



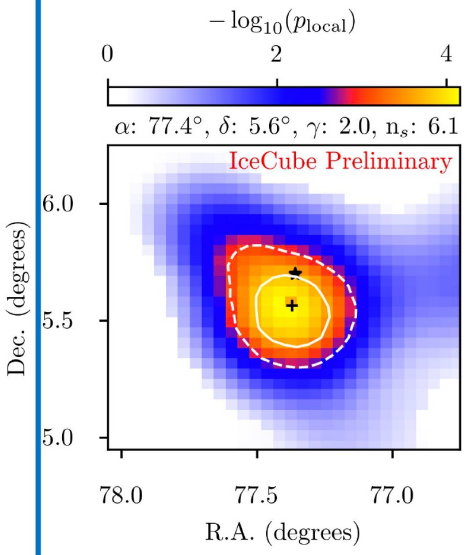
what about the other sources?

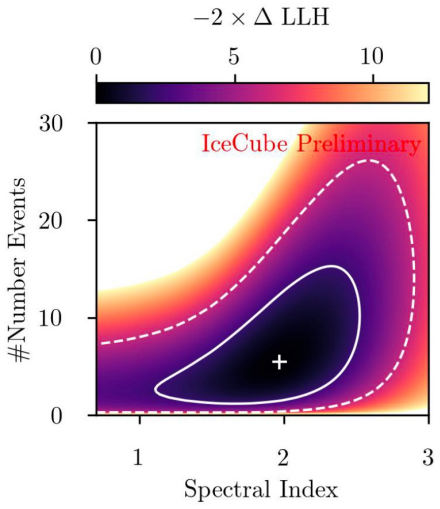
- TXS 0506+056: 3.6σ → 3.7σ
- PKS1424+240 : 3.0σ → 3.7σ

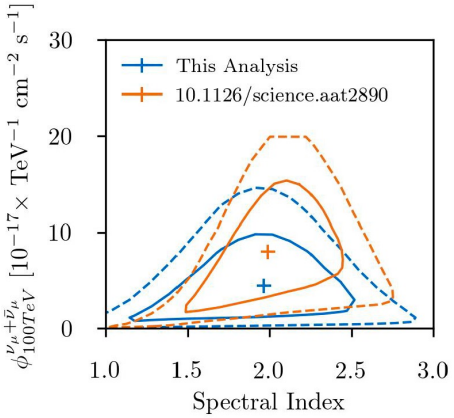


PKS 1424+240

3.0σ -> 3.7σ



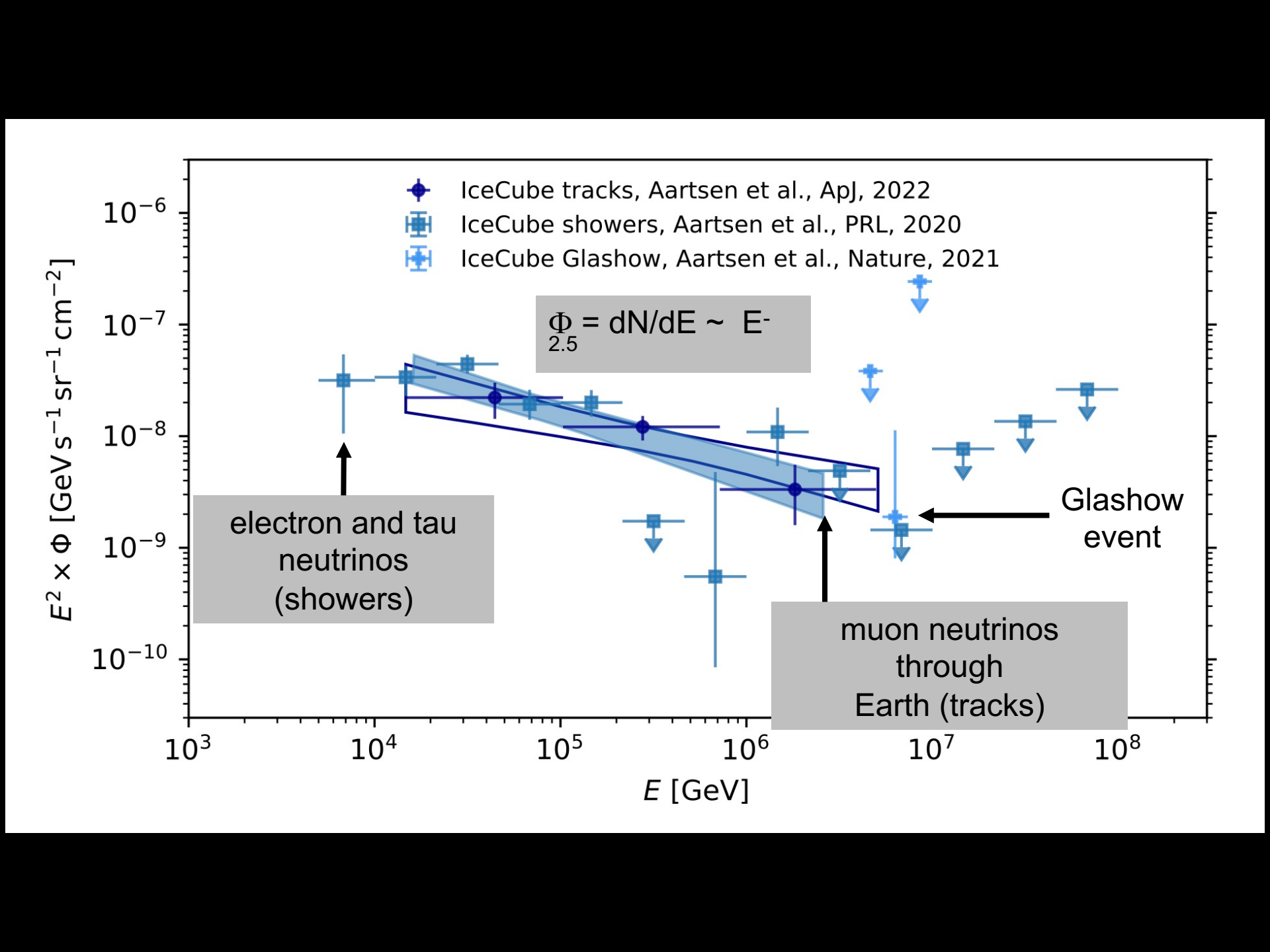




results broadly consistent with previous work.

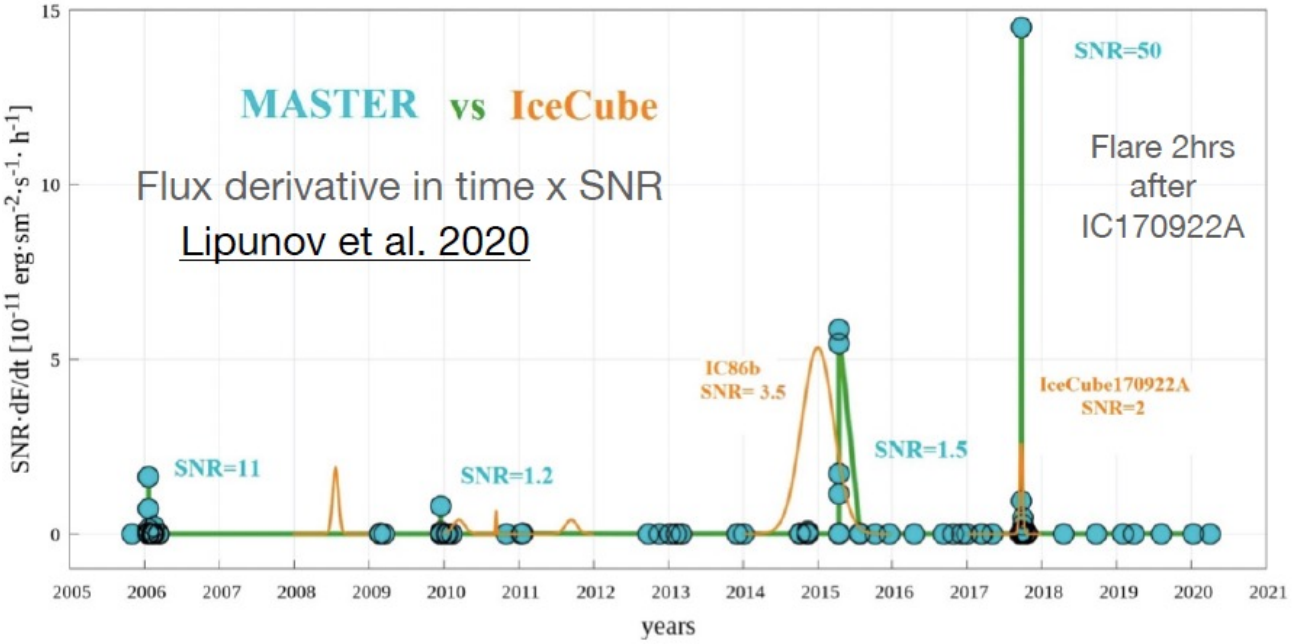
TXS 0506+056

ongoing program to improve the focus of the neutrino telescope will receive another boost with the information on the ice obtained with the Upgrade's small string spacings and the new calibration devices

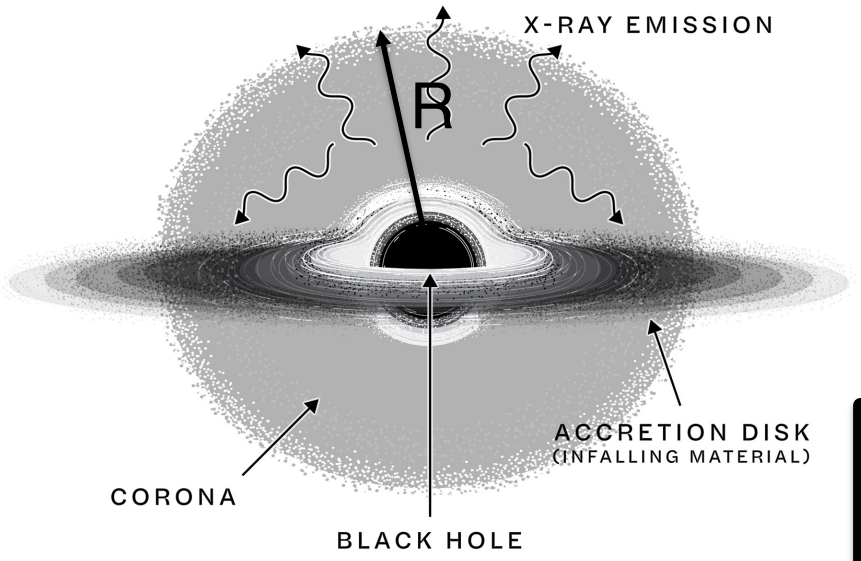

IceCube tracks, Aartsen et al., ApJ, 2022
IceCube showers, Aartsen et al., PRL, 2020
IceCube Glashow, Aartsen et al., Nature, 2021
$\Phi_{2.5}$ = dN/dE ~ E^{-}
electron and tau neutrinos (showers)
Glashow event
muon neutrinos through Earth (tracks)
$E^2 \times \Phi$ [GeV s^{-1} sr^{-1} cm^{-2}]
E [GeV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}

"MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level"

optical flashes often originate from magnetohydrodynamical instabilities triggered by processes modulated by the magnetic field of the accretion disk



NGC 1068 core: large optical depth in photons (X-ray) and matter



$$\tau_{p\gamma} \sim \sigma_{p\gamma} \left[\frac{1}{\mathrm{R}} \frac{L_X}{E_X}\right]$$

cross section x target density

= optical depth τ

$$\tau_{p\gamma} \sim 0.1 \rightarrow \mathrm{PeV\ neutrinos}$$
$$\tau_{pp} \sim 1 \rightarrow 1 \sim 100\,\mathrm{TeV\ neutrinos}$$

$$E_X = 1\,\mathrm{keV}\,;\ \mathrm{L_X} \sim 10^{43}\,\mathrm{ergs}^{-1}$$

neutrinos originate within 10~10^2 Schwarzschild radii from the BH

we finally found our own Galaxy