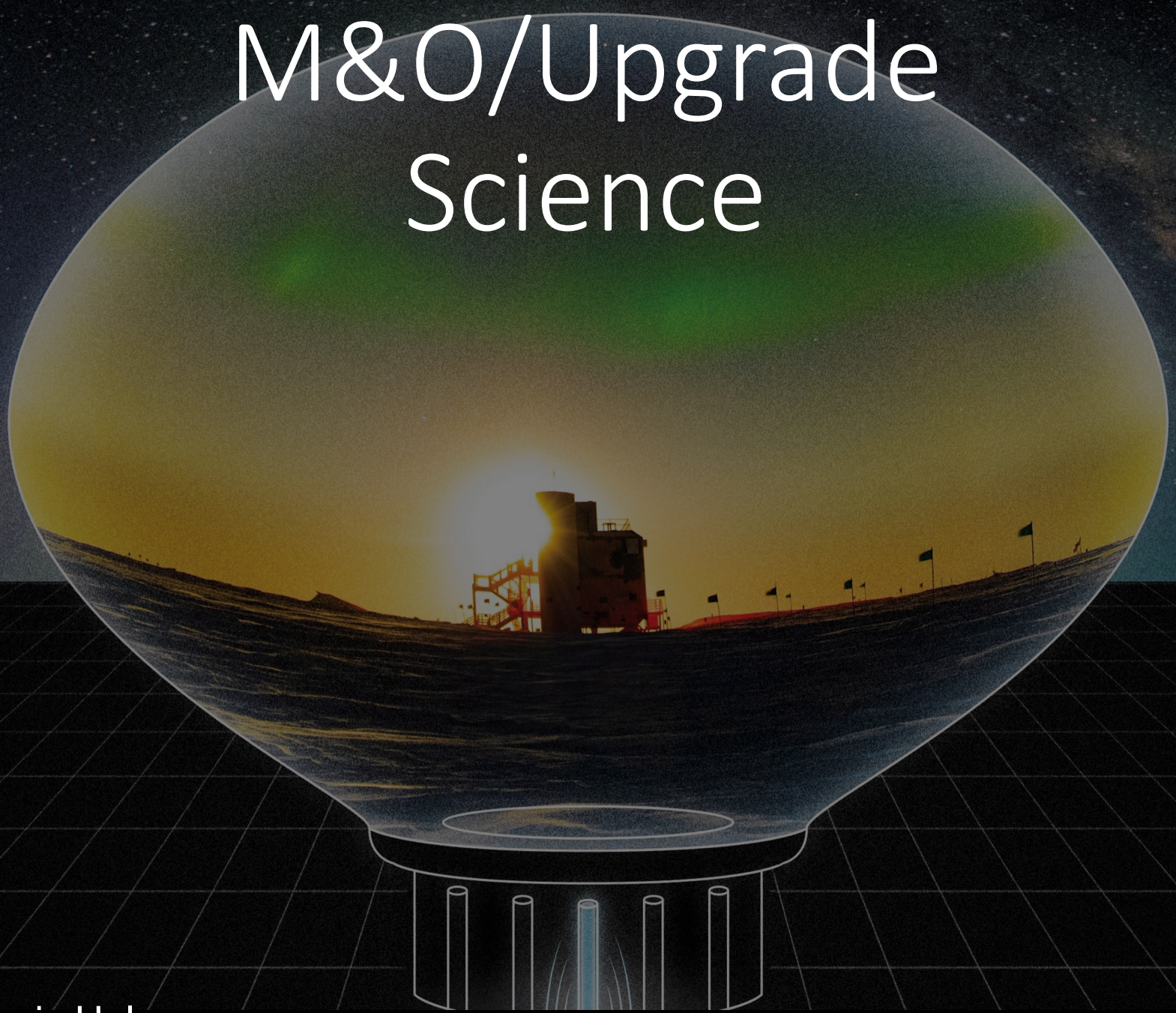
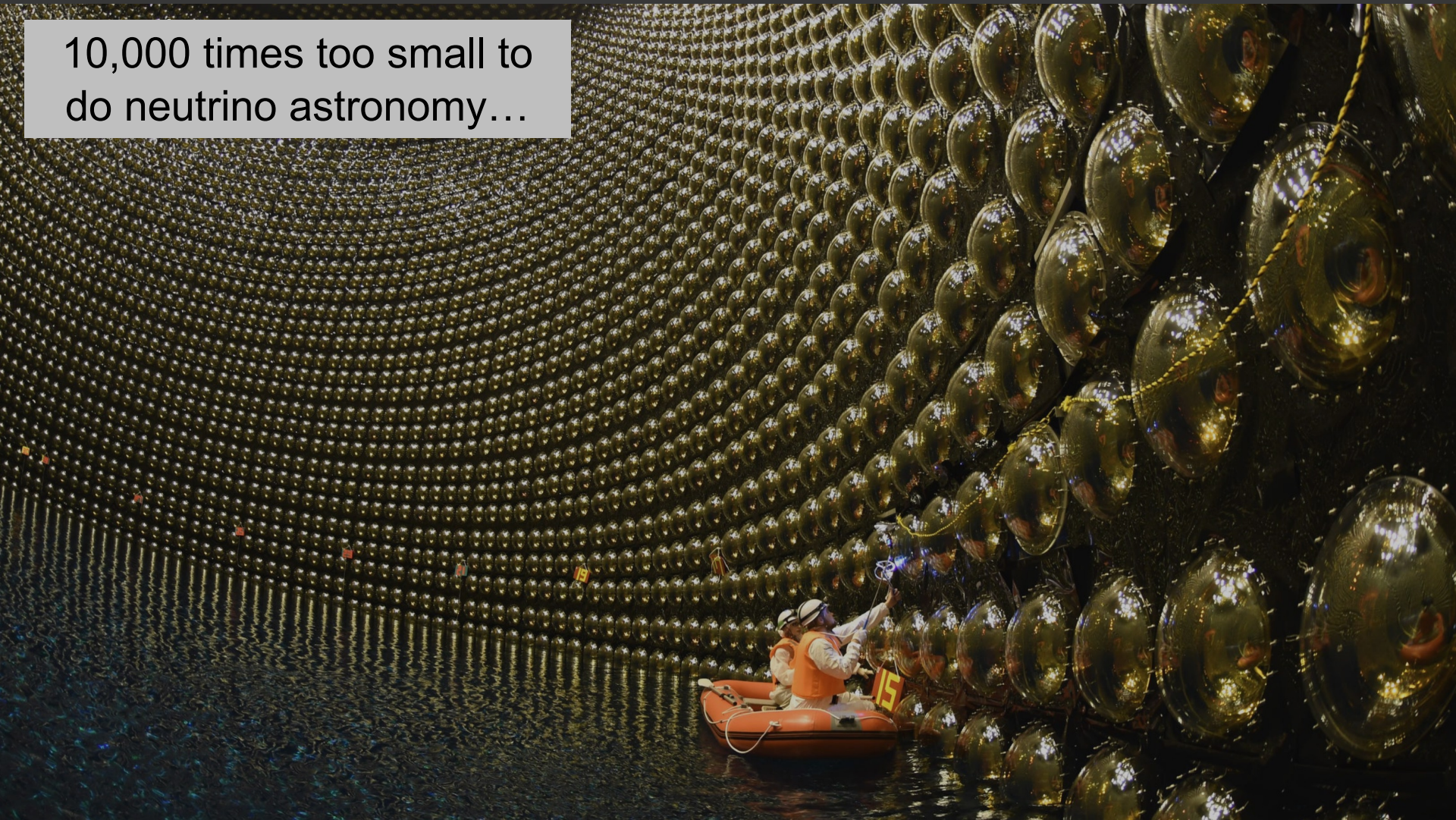


# M&O/Upgrade Science

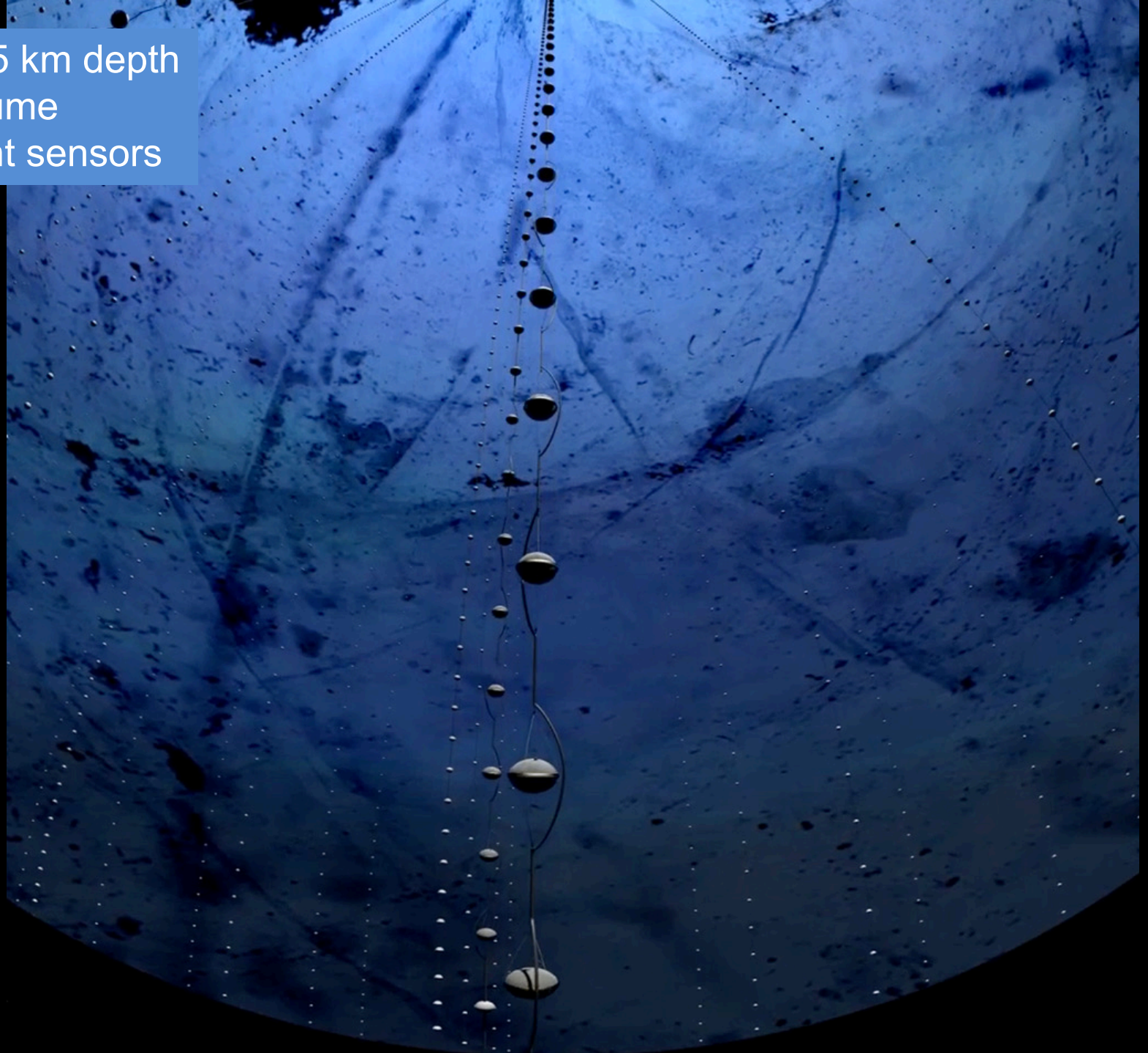


Francis Halzen

10,000 times too small to  
do neutrino astronomy...

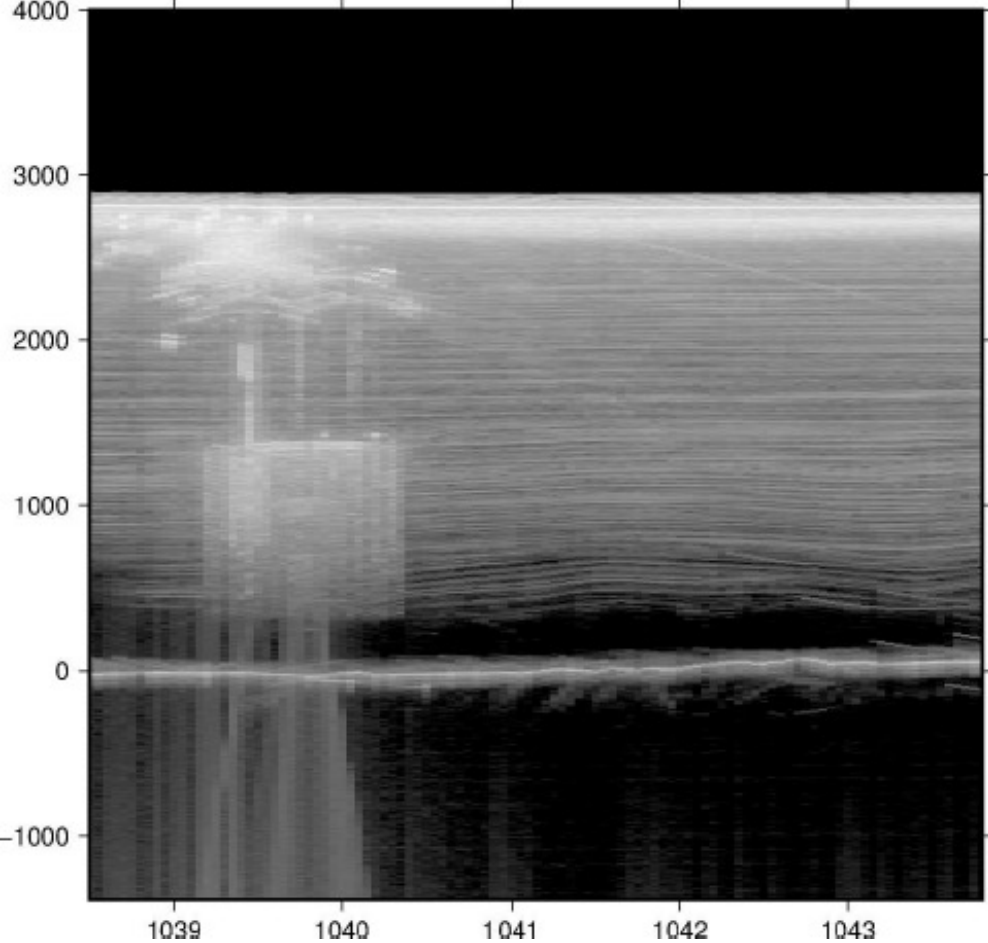


1.45 - 2.45 km depth  
1 km<sup>3</sup> volume  
5000+ light sensors



ground-penetrating  
radar from airplane

### IceCube Array at 60 MHz



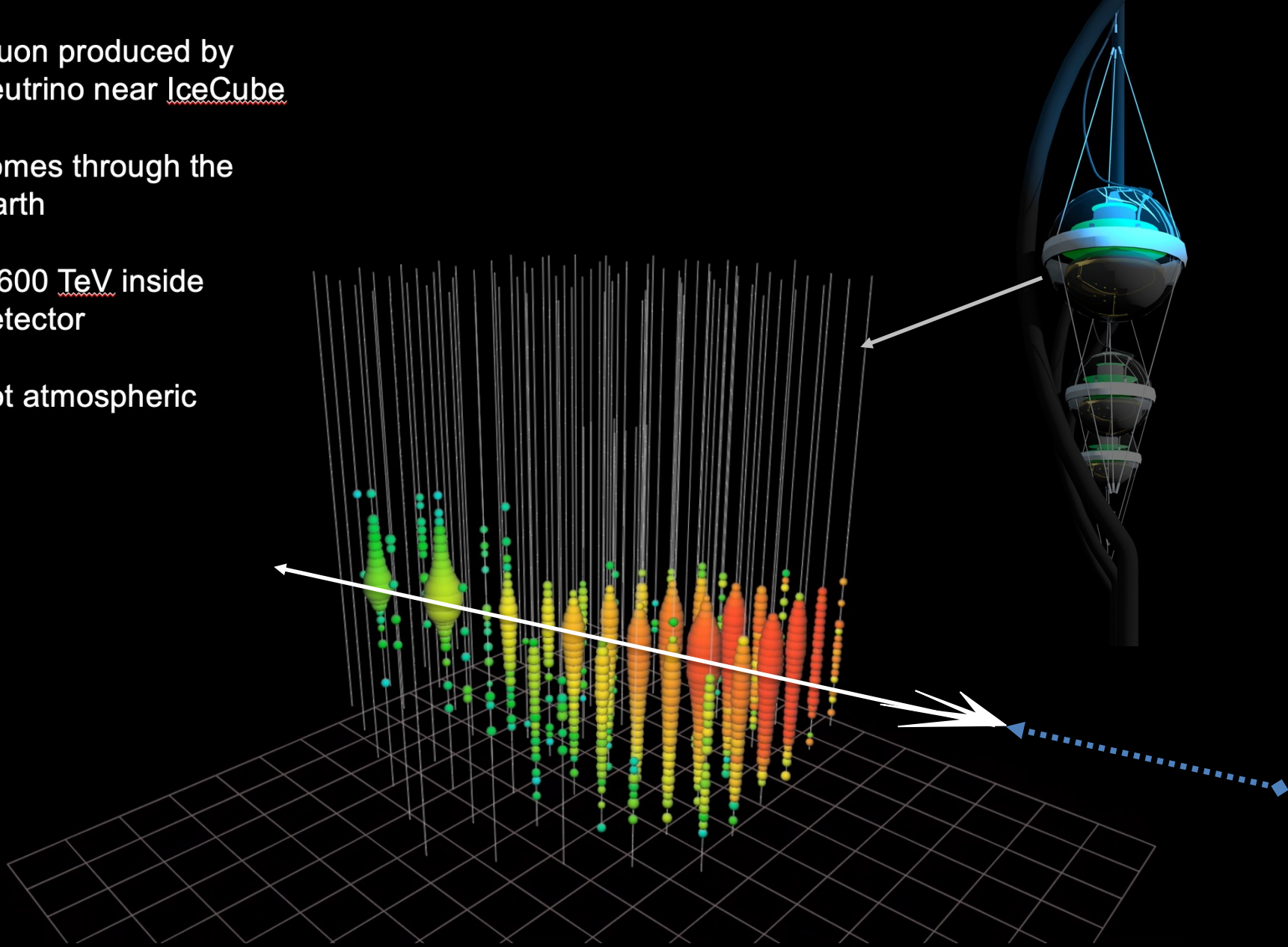
← South Pole surface

← 1450 m

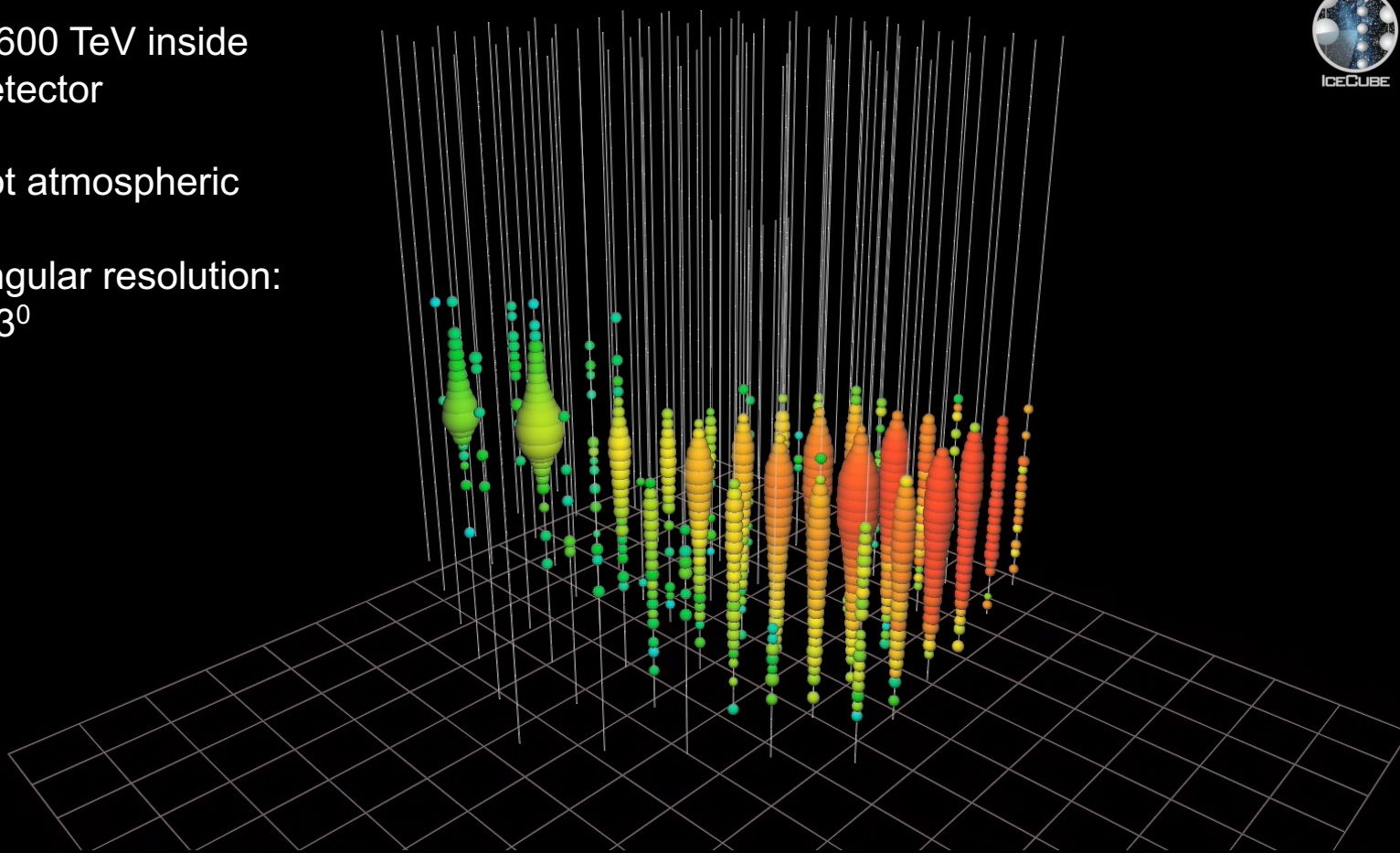
← 2450 m

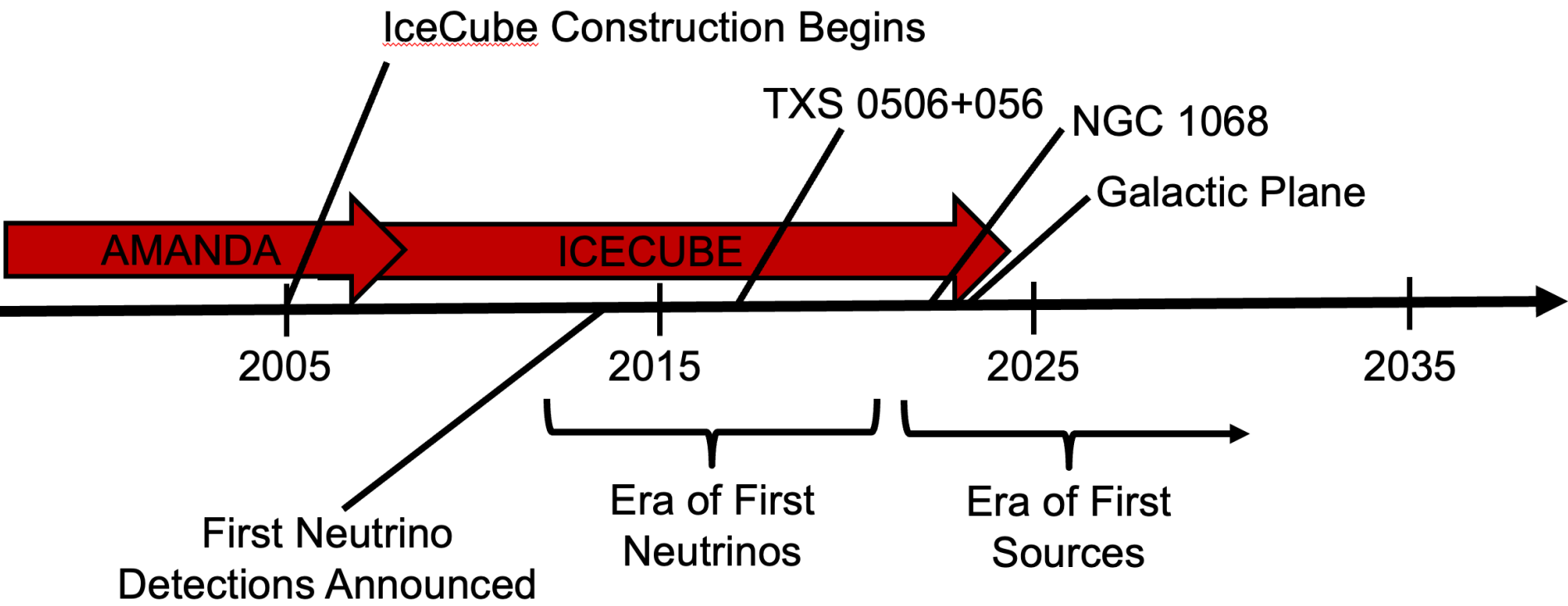
← bedrock

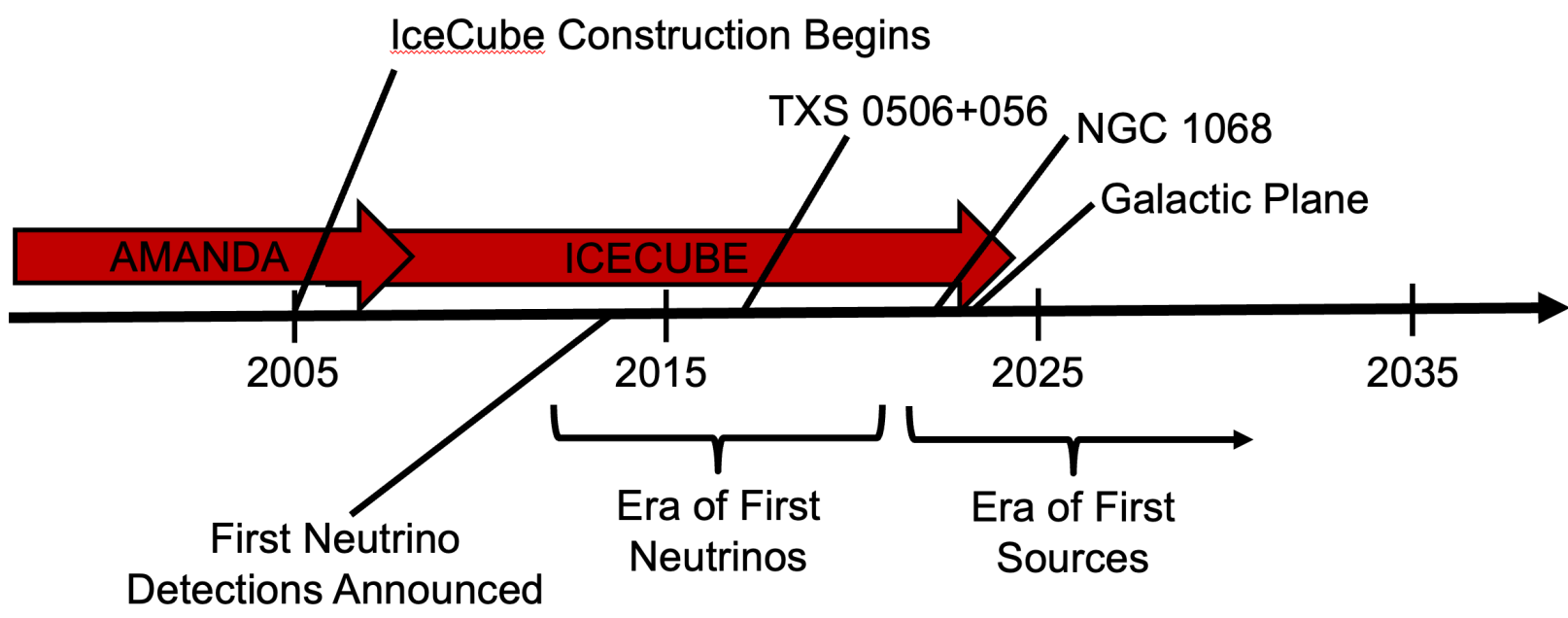
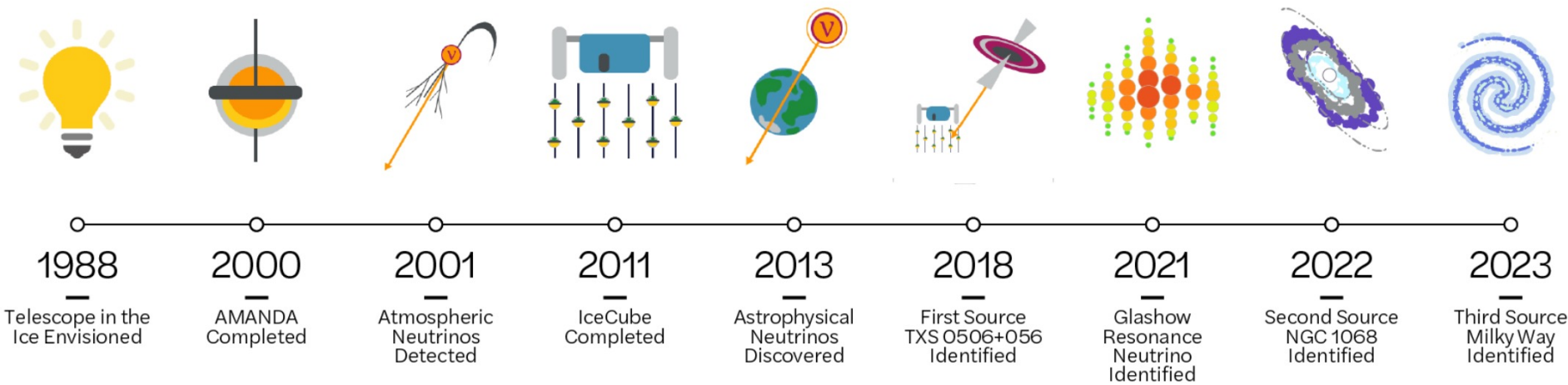
- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric



- muon produced by neutrino near IceCube
- comes through the Earth
- 2,600 TeV inside detector
- not atmospheric
- angular resolution:  $0.3^\circ$

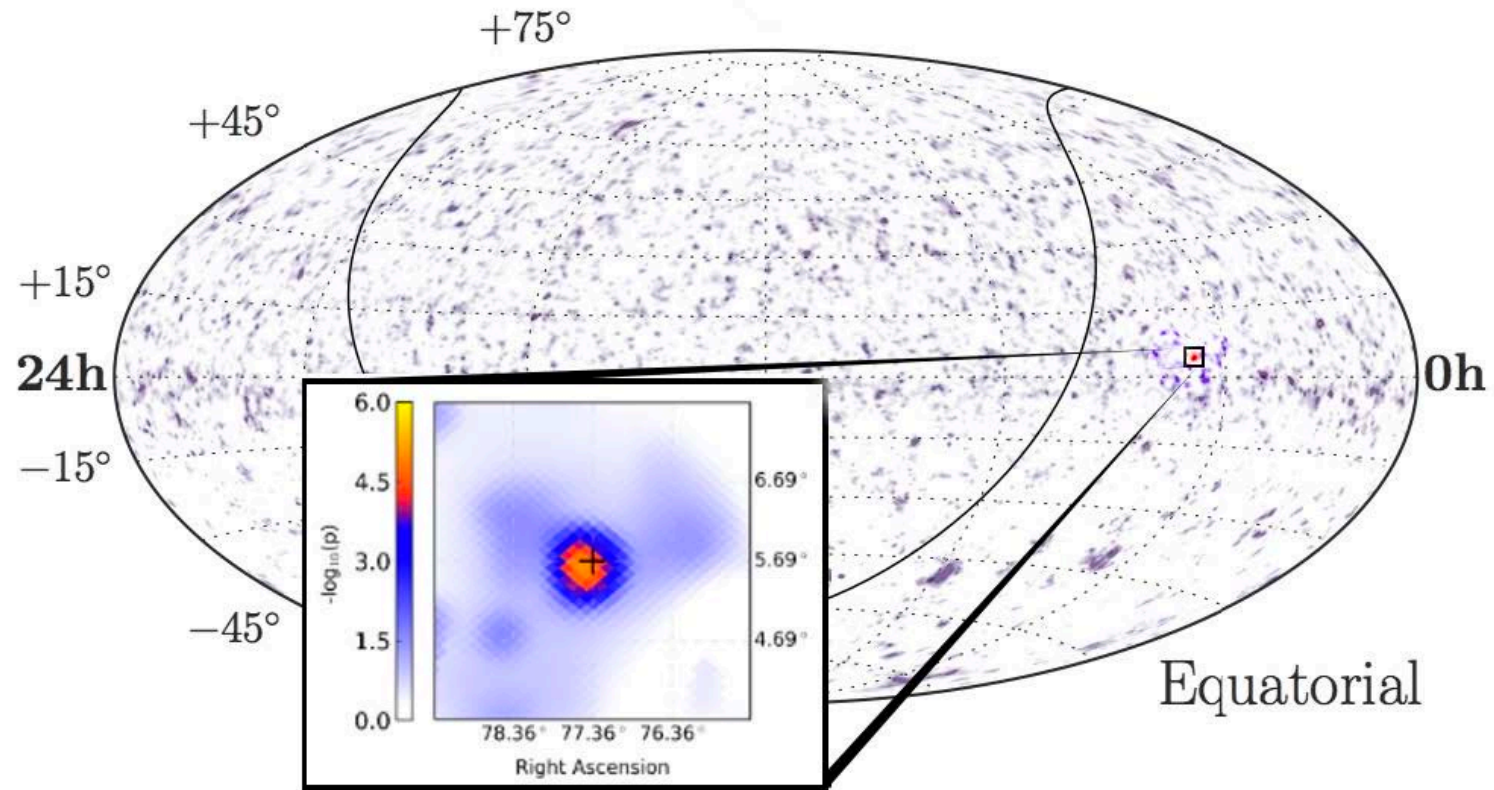








# pre-trial p-value for clustering of high energy neutrinos



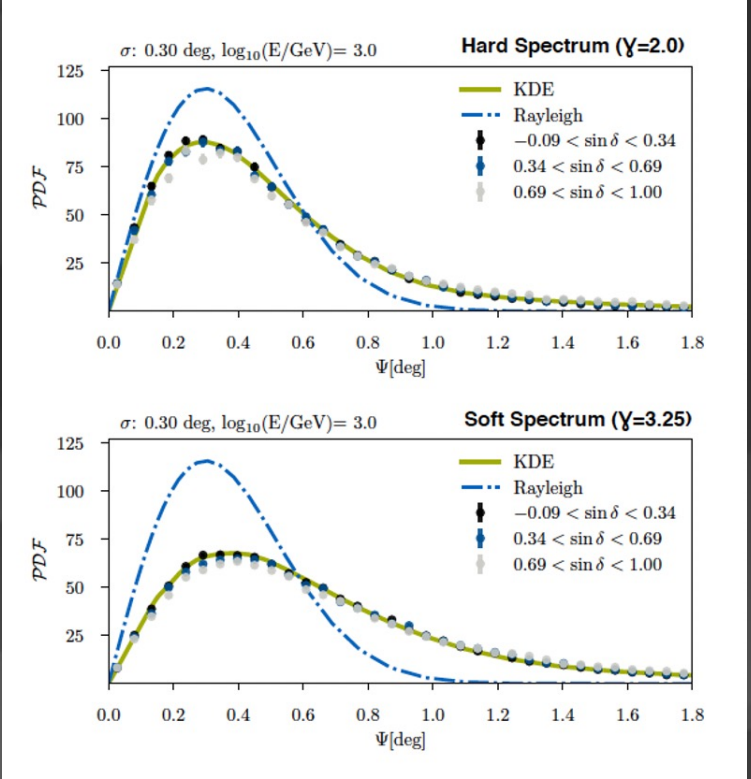
- hottest spot coincident with NGC 1068
- also hottest spot in the sources list ( $2.9\sigma$ )

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

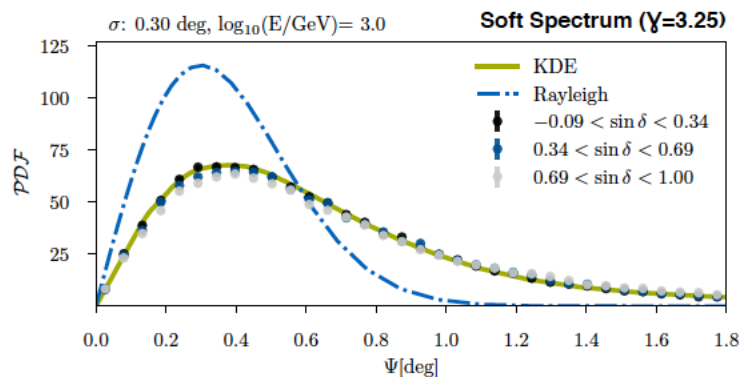
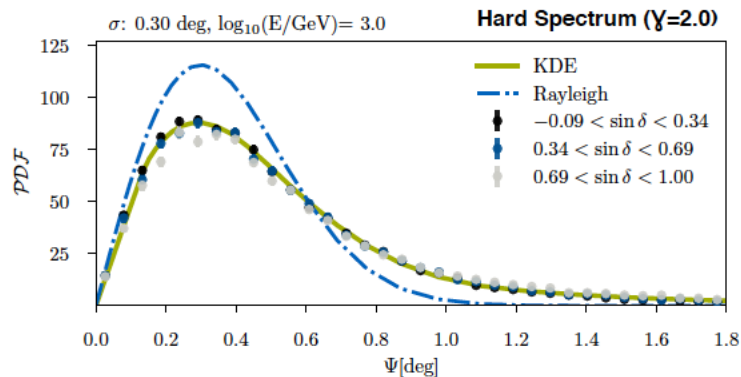
interesting fluctuations or neutrino sources?

ongoing program to upgrade the performance of IceCube

- improved detector geometry
- each photomultiplier calibrated individually
- improved characterization of the optics of the ice
- improved muon angular resolution and energy reconstruction using **machine learning**
- *point spread function consistent with simulation or, we were partially blind*
- ...
- applied to 10 years of archival data (pass 2), data unblinded, result ...



- improved detector calibration (pass 2)
- improved modeling of the optics of the ice
- DNN (energy) and BDT (pointing) reconstruction
- point spread function consistent with simulation
- insensitive to systematics

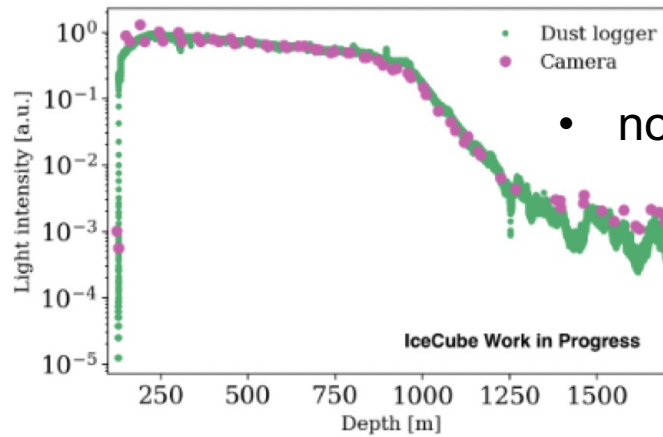


- ▶ Rayleigh (1D-projection of 2D Gauss) doesn't describe our Monte Carlo accurately → Tails are suppressed
- ▶ The distribution depends on the spectral index!
- ▶ Effect mainly visible at  $< 10 \text{ TeV}$  energies where the kinematic angle between neutrino and muon matters
- ▶ **Solution:** Obtain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

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

# ice: step by step

- hole ice ?

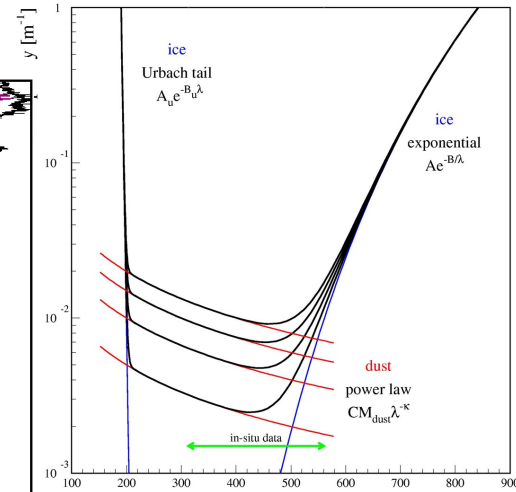
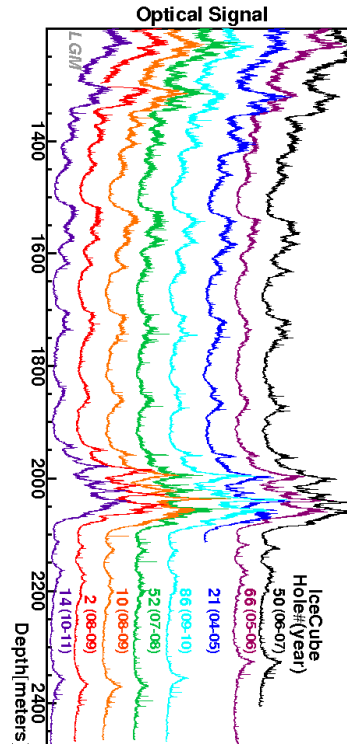
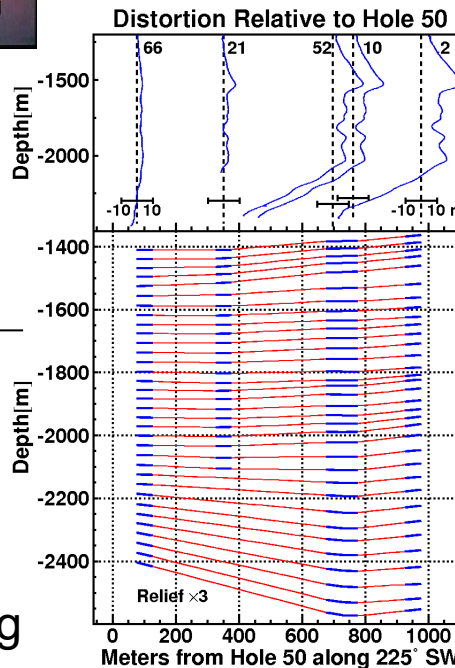


- no air bubbles/hydrates below 1350 m

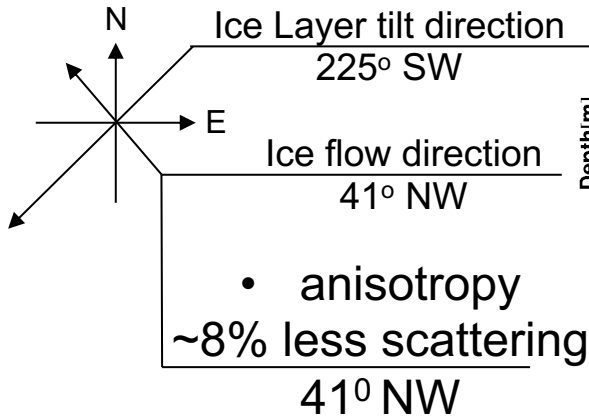
- > 100 m absorption length limited by dust

- ice layers

- tilted ice layers



- birefringence

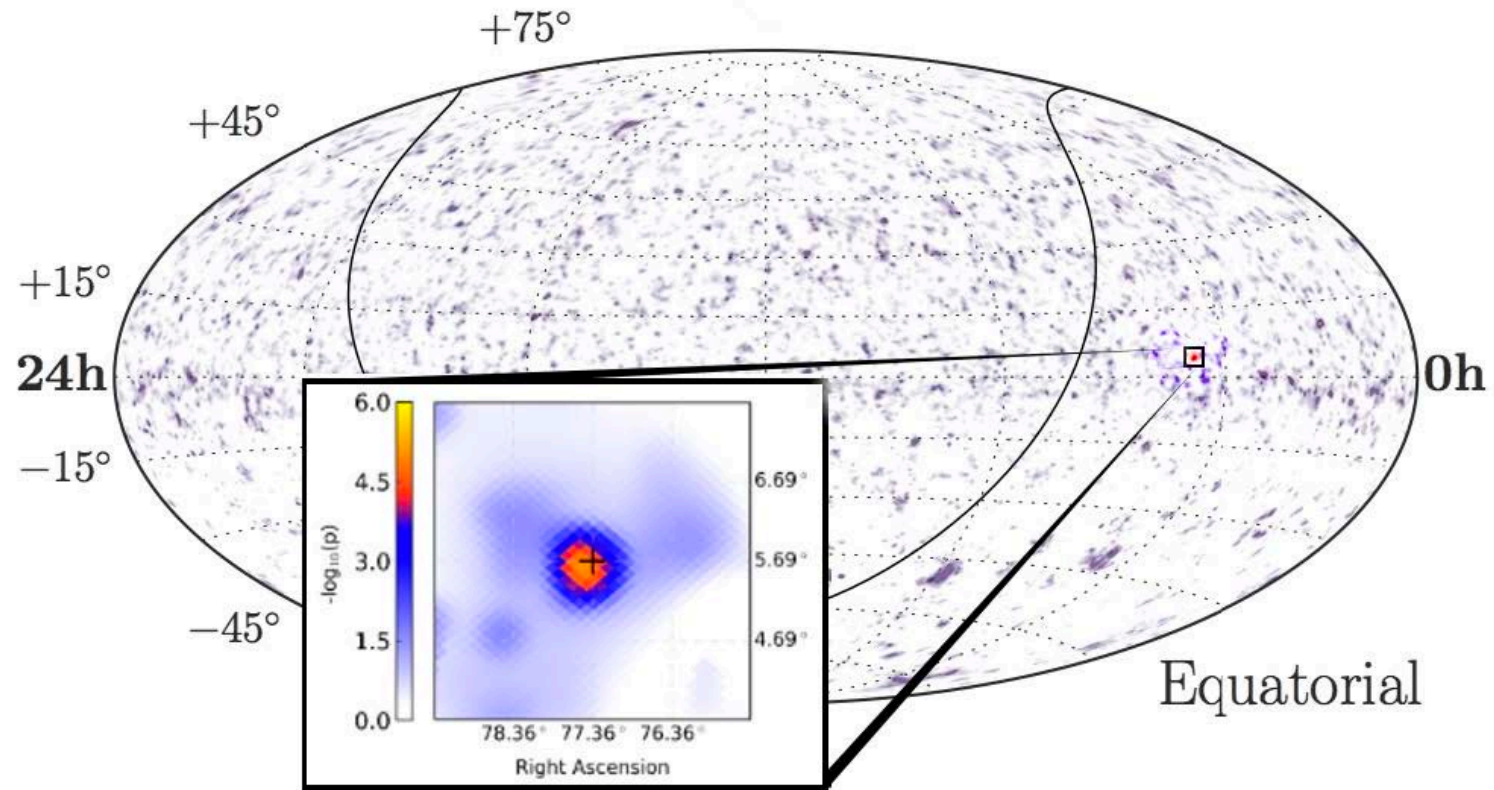


- anisotropy  
~8% less scattering  
41° NW

# Next step: the IceCube upgrade

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

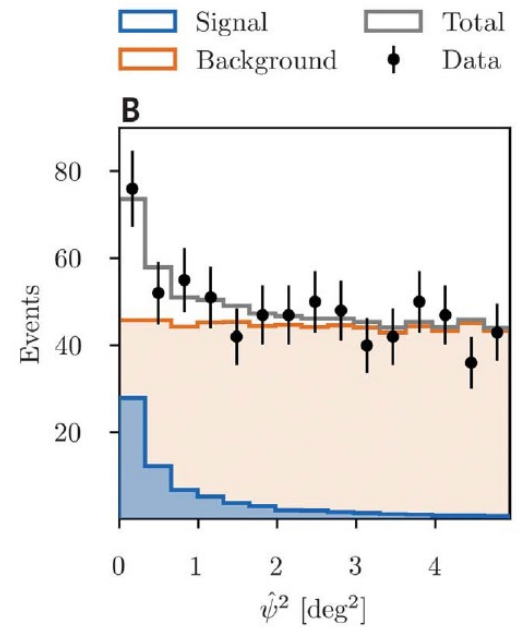
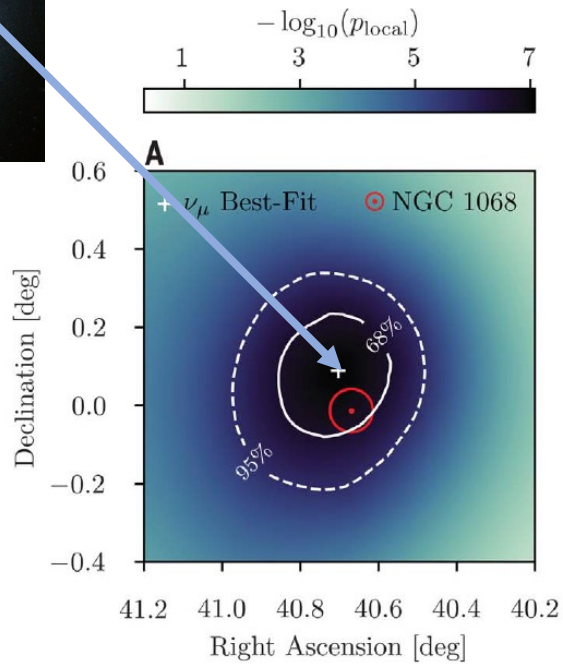
# pre-trial p-value for clustering of high energy neutrinos



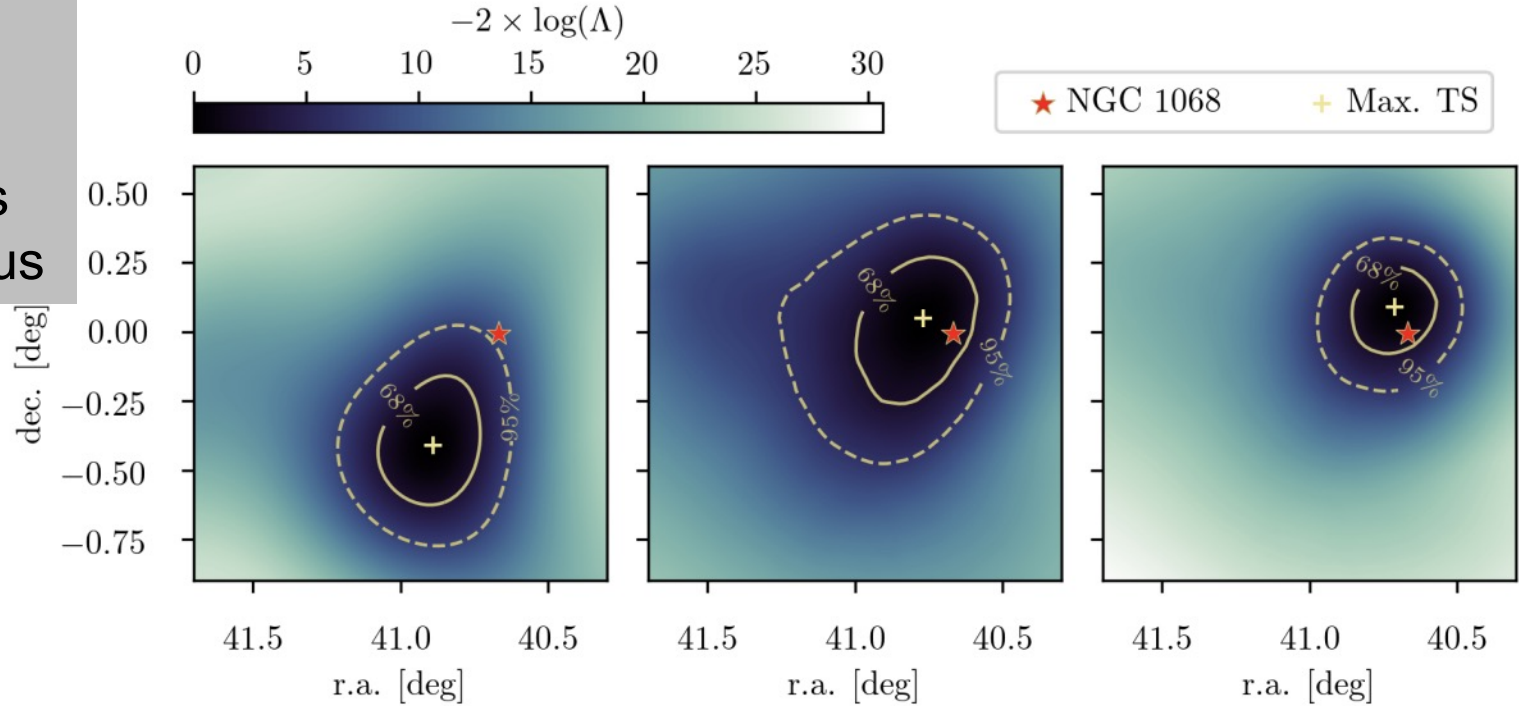
- hottest spot coincident with NGC 1068
- also hottest spot in the sources list ( $2.9\sigma$ )

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

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



NGC 1068 comes into focus

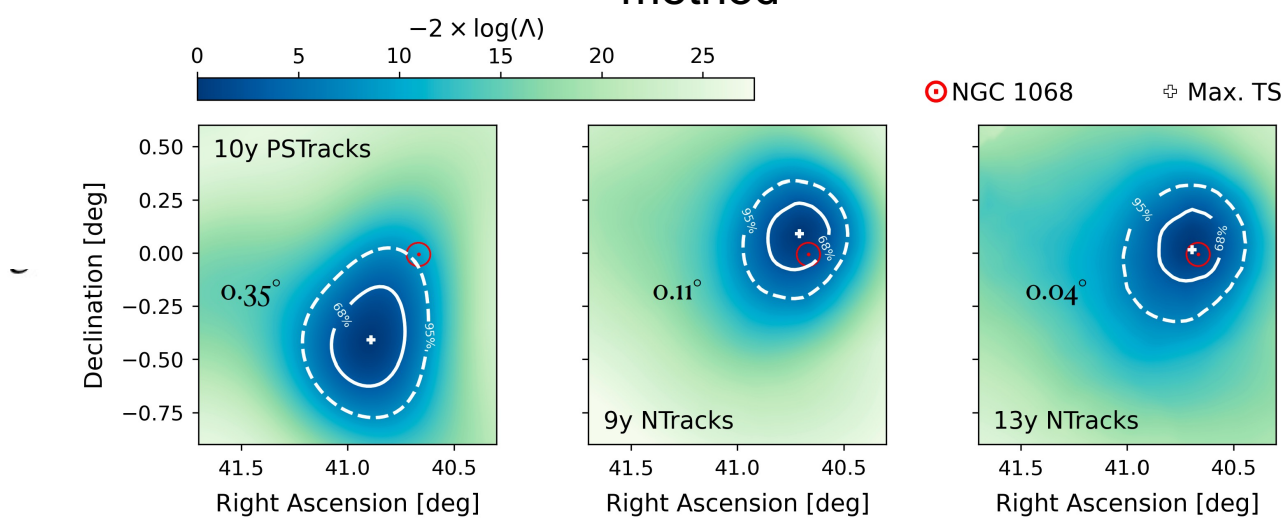


$5\sigma$  local significance

$2.9\sigma$   
• 10-year analysis

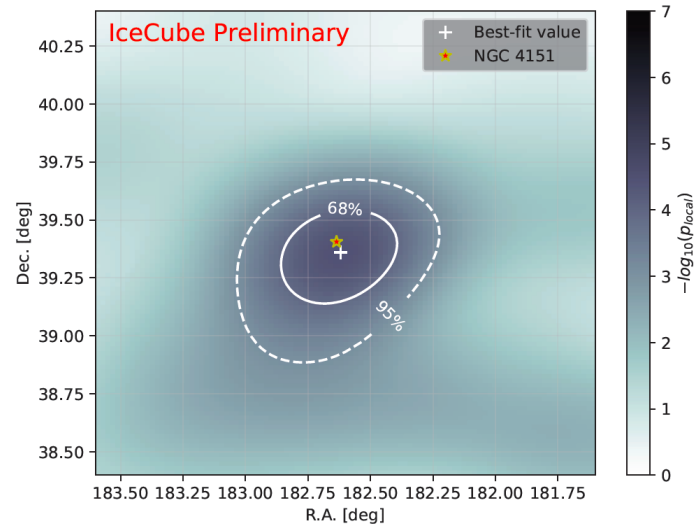
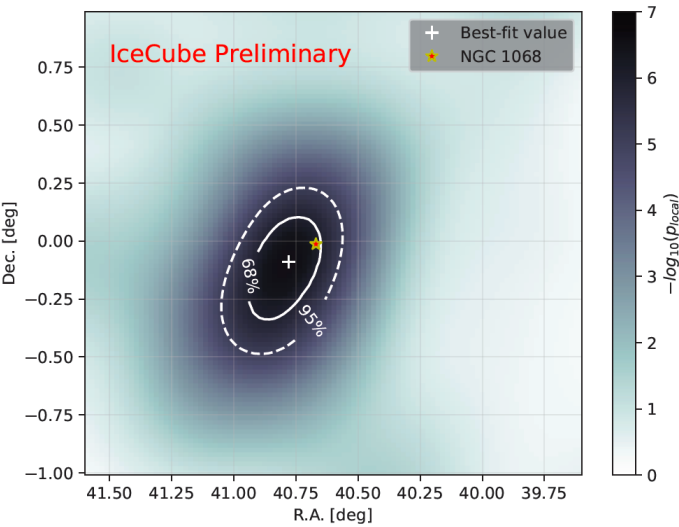
$3.3\sigma$   
• new likelihood method

$4.2\sigma$   
• pass 2





more sources ...



- two brightest active galaxies discovered by Seyfert in 1943

## NUCLEAR EMISSION IN SPIRAL NEBULAE\*

CARL K. SEYFERT†

1943

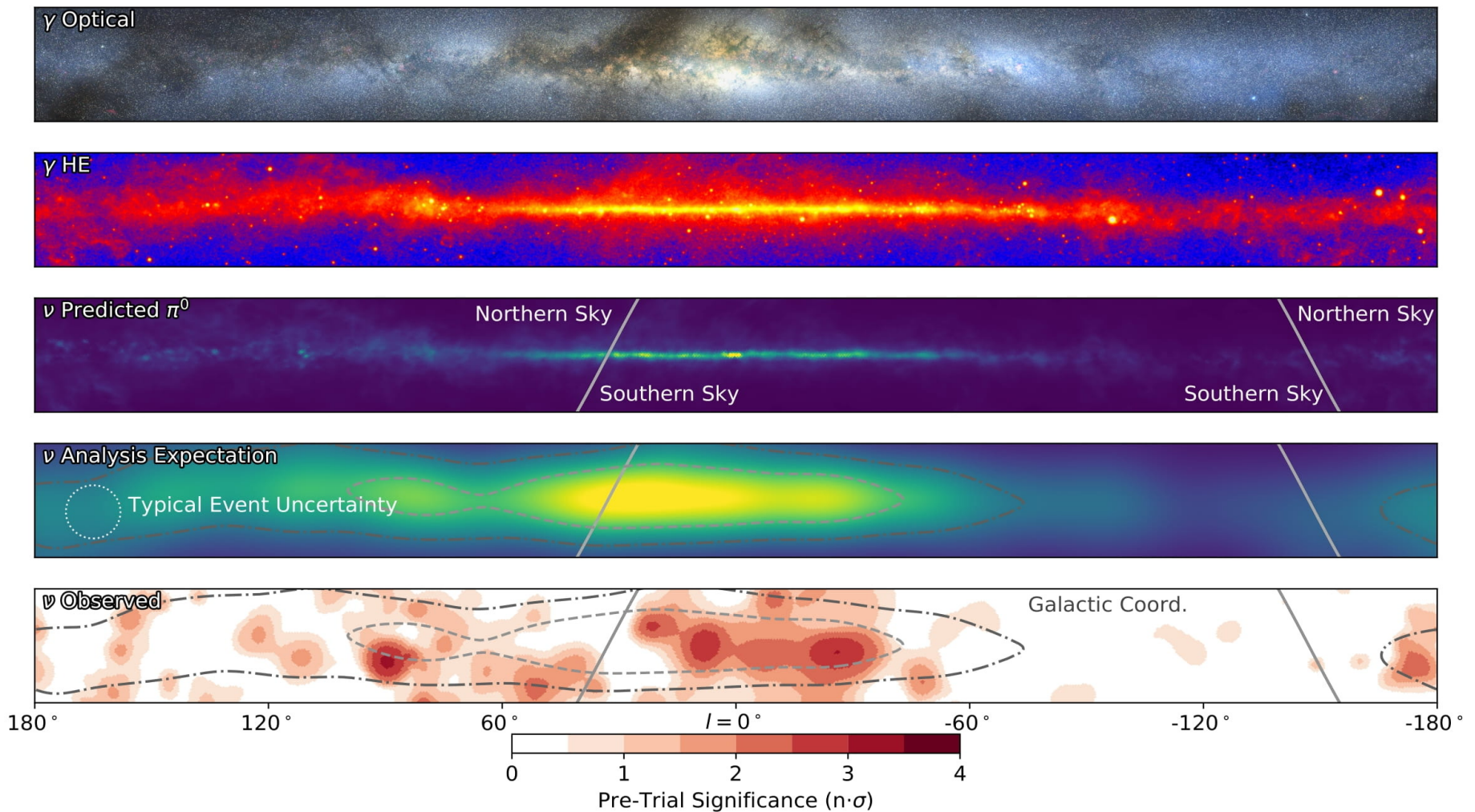
### ABSTRACT

Spectrograms of dispersion 37–200 Å/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  $\lambda$  3727 to  $\lambda$  6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

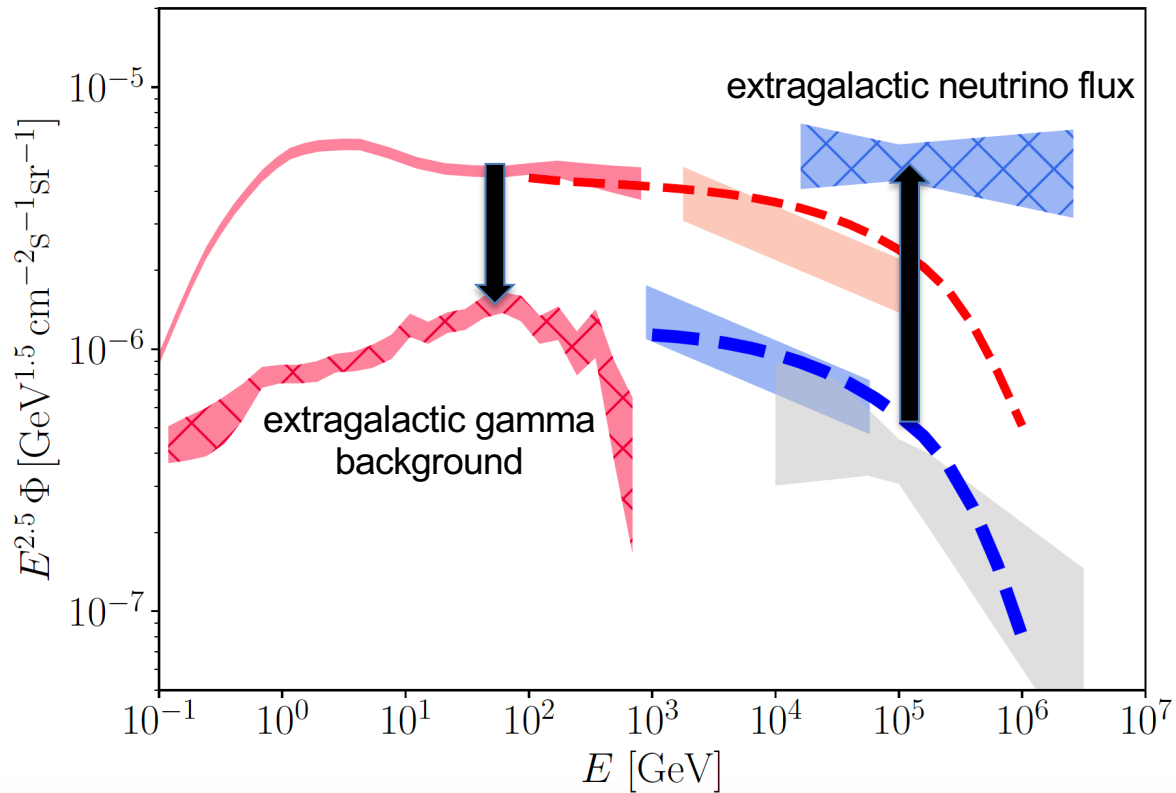
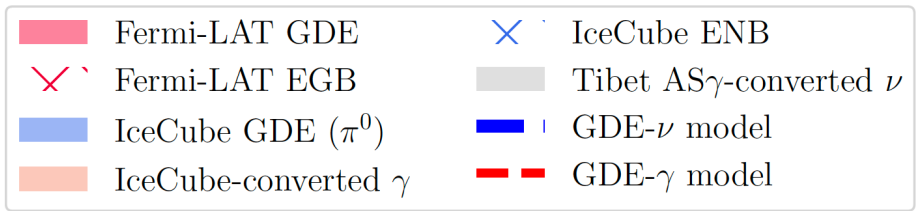


## accumulating evidence for active galaxies

- ~~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 galaxies 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

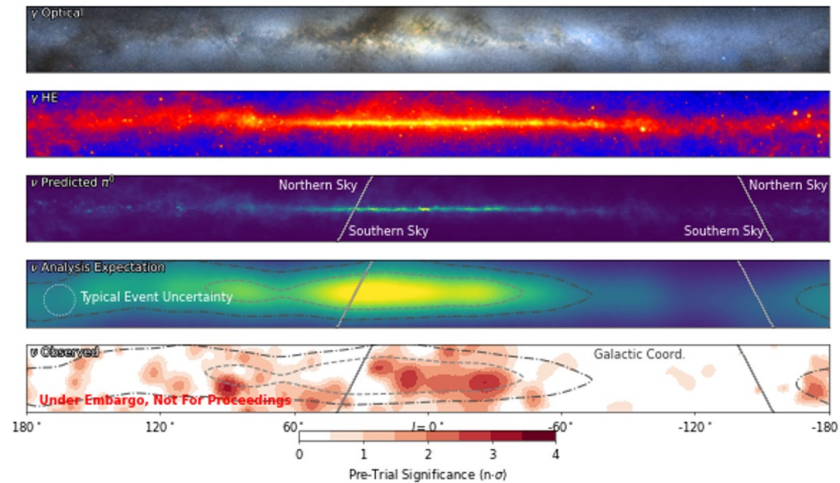


Fermi (GeV gamma rays) and IceCube (TeV neutrinos) see the same Galactic plane



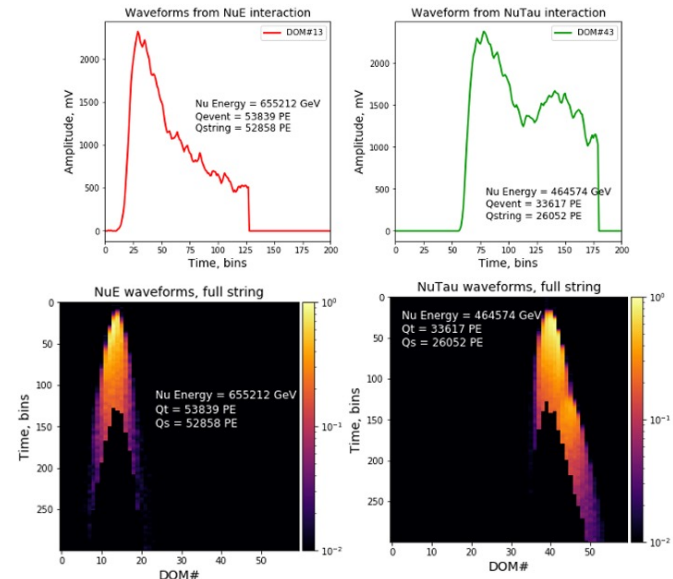
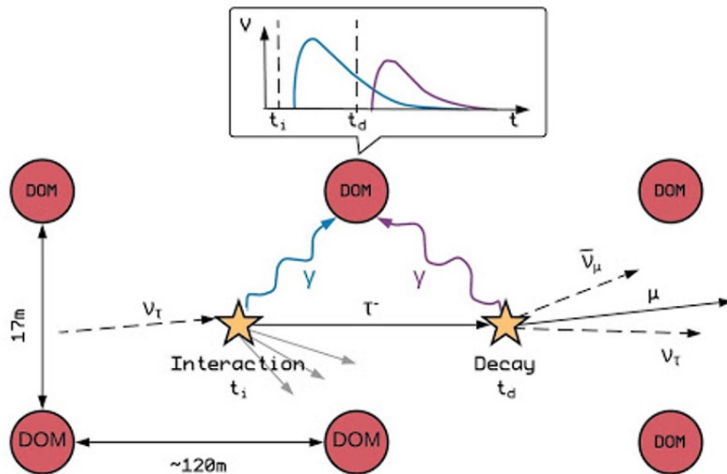
# ML Driven Science Results

## 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

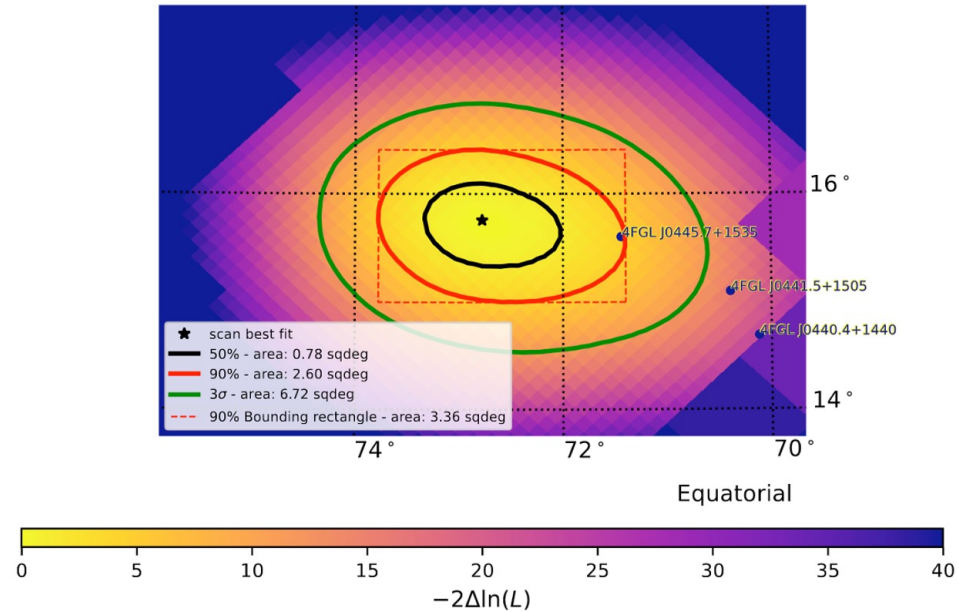
## nutau search



# SkyDriver – Reconstruction-a-a-S

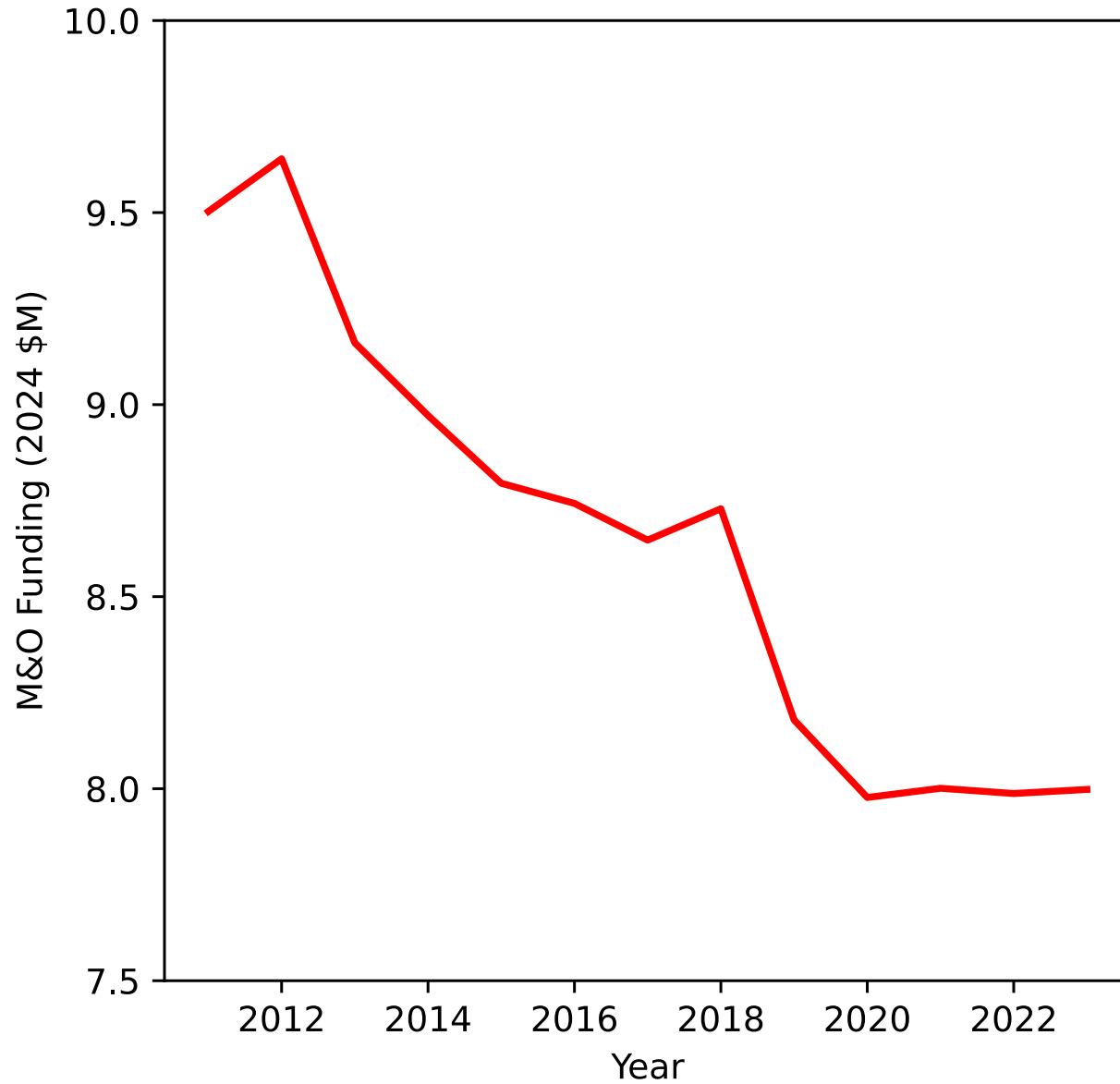
Run: 139071 Event 47725621: Type: neutrino MJD: 60369.65858236638

- 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

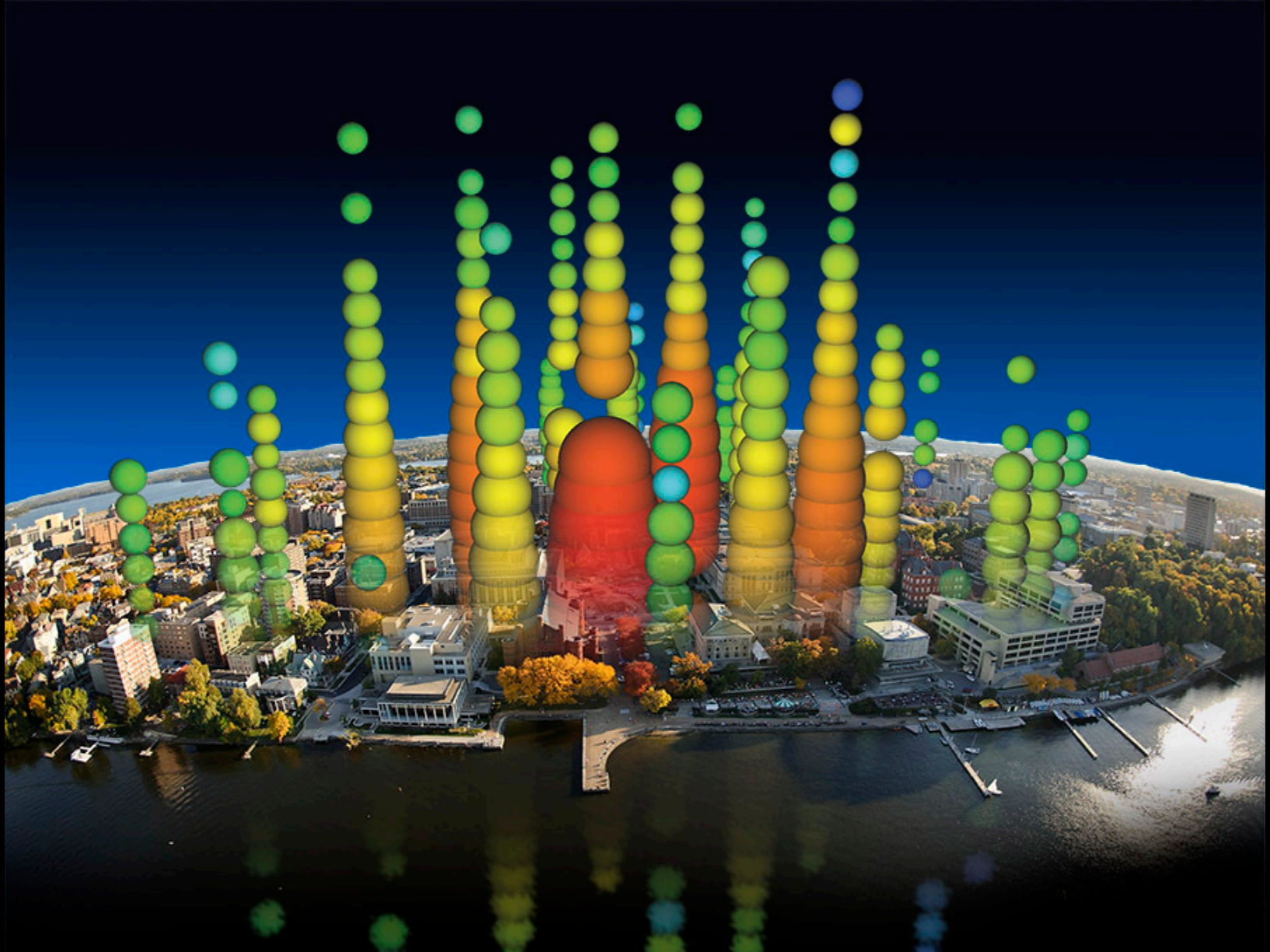
# M&O funding in 2024 \$M



# Next step: the IceCube upgrade

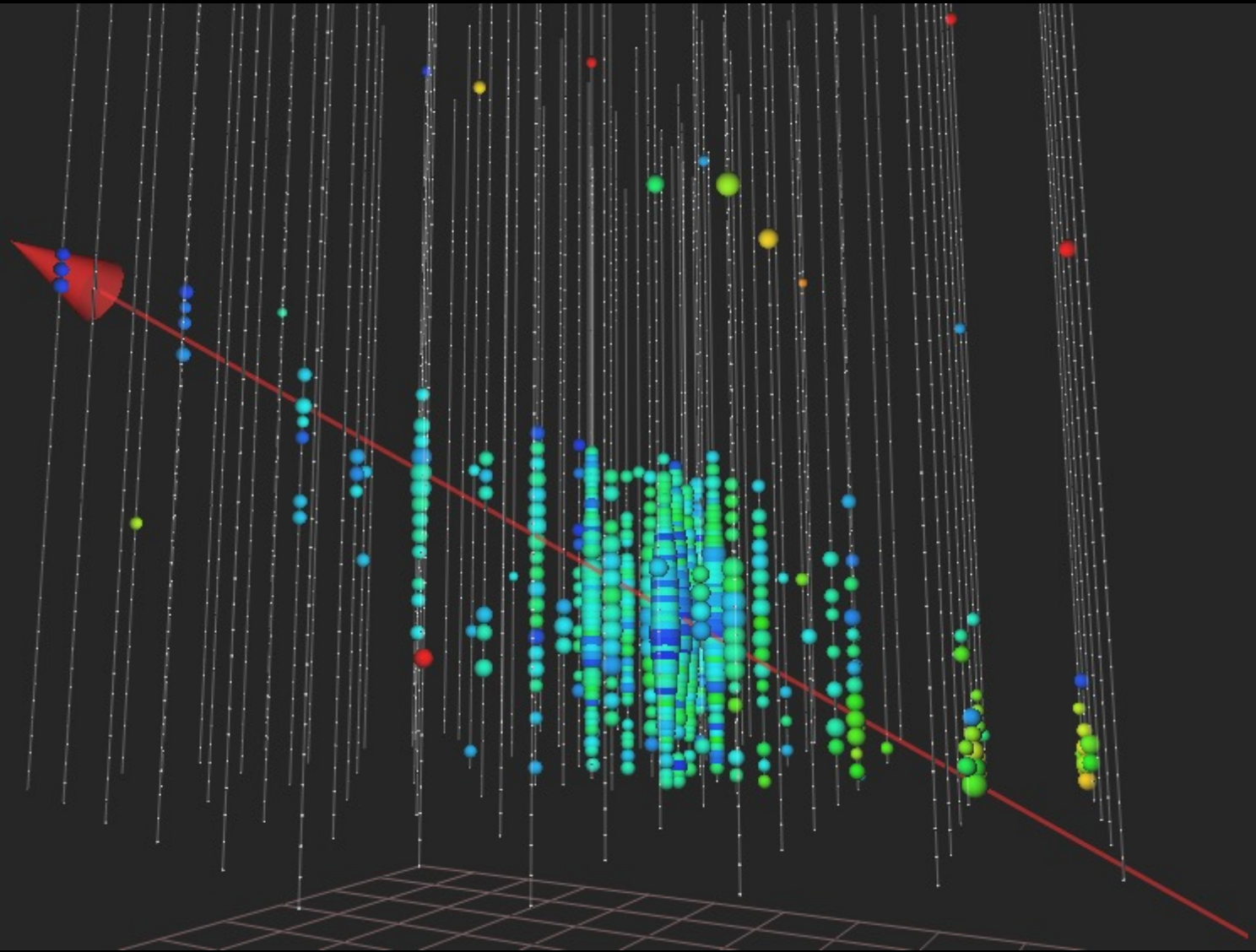
- improve the scientific capabilities of IceCube at low energies
- improve the scientific capabilities of IceCube at high energies with improved optics of the ice using the information obtained with the Upgrade's small string spacings and novel calibration devices



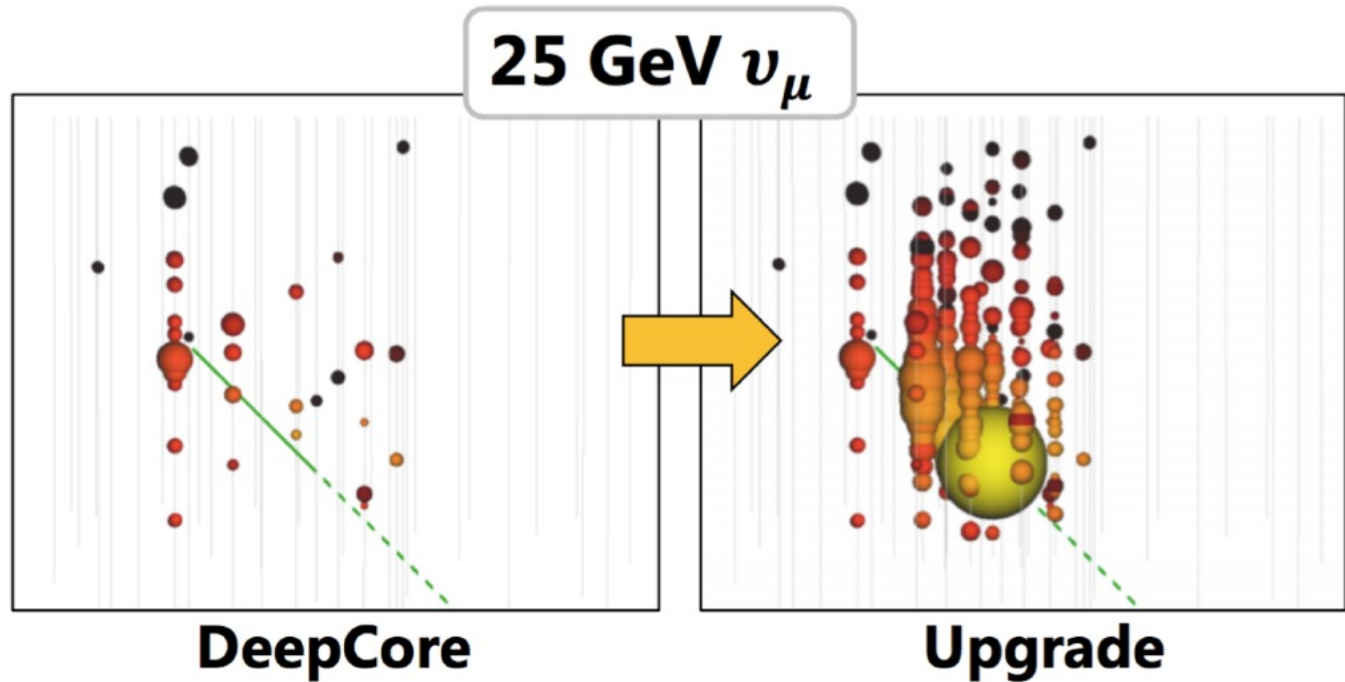


Cherenkov radiation from PeV electron (tau) shower  
we detect all 3 flavors of neutrinos

# IceCube and DeepCore

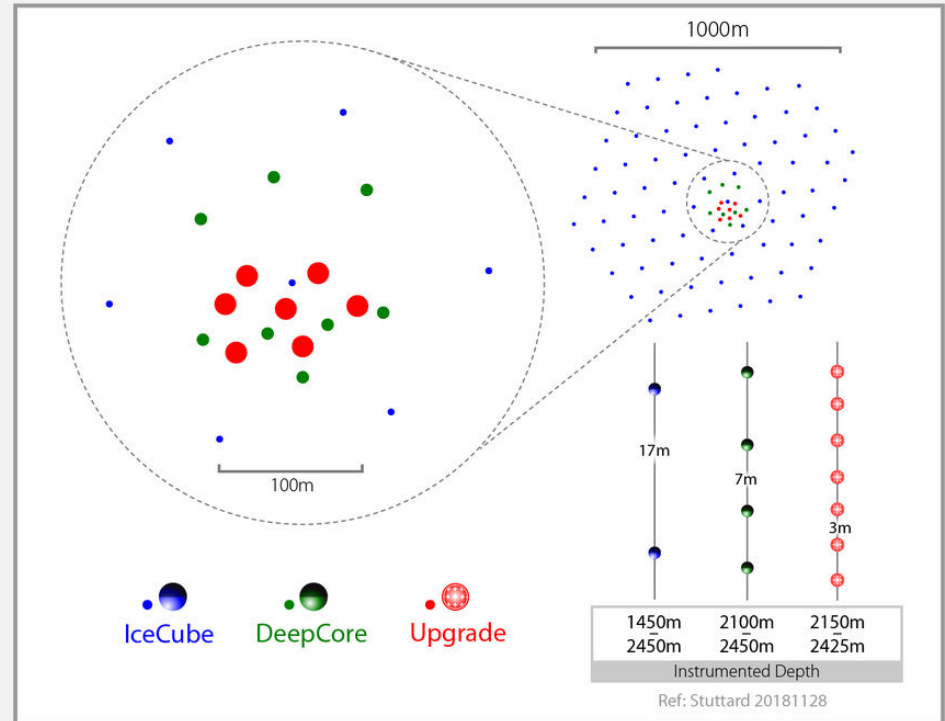


# Low energy neutrinos in the Upgrade



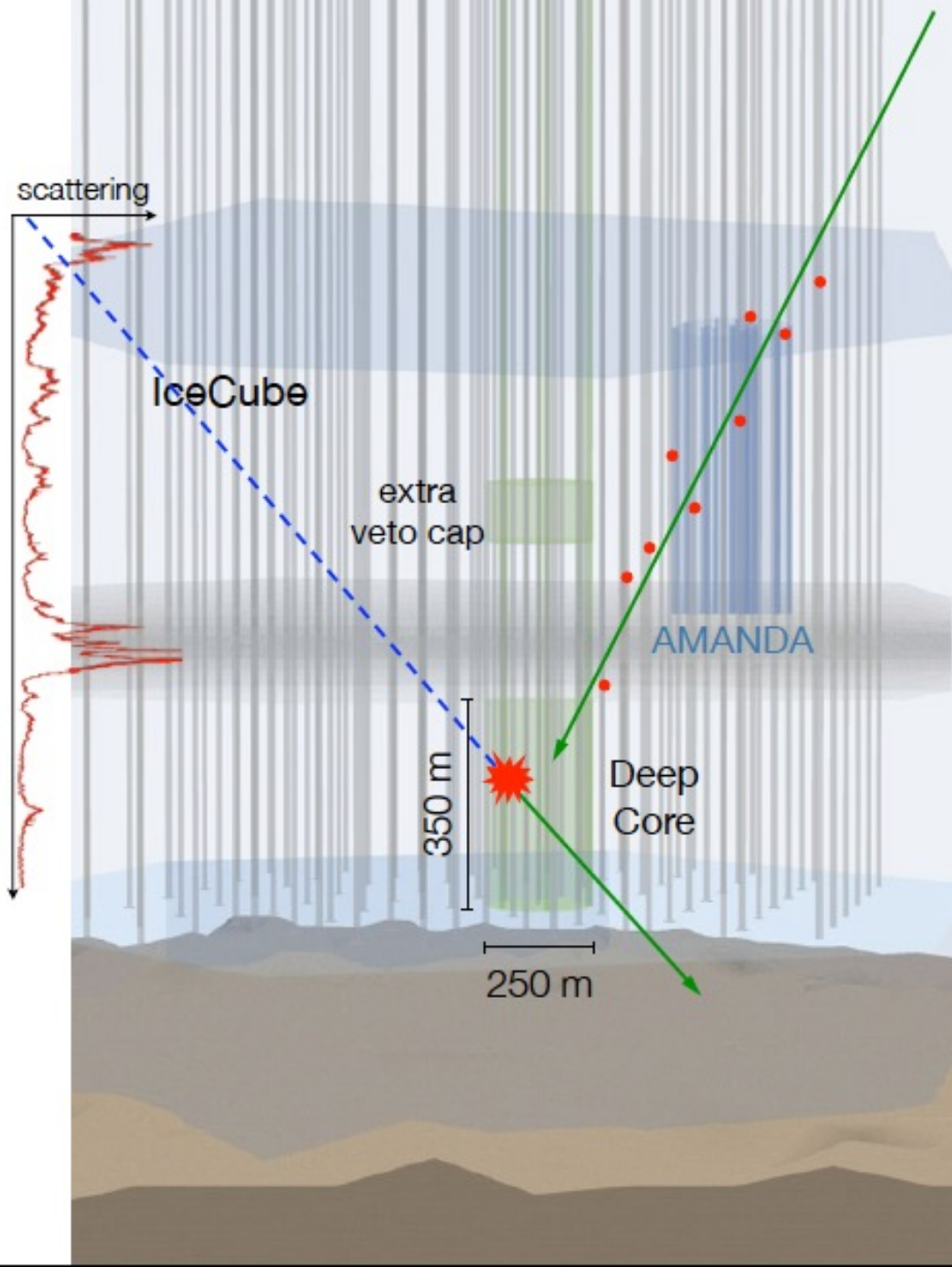
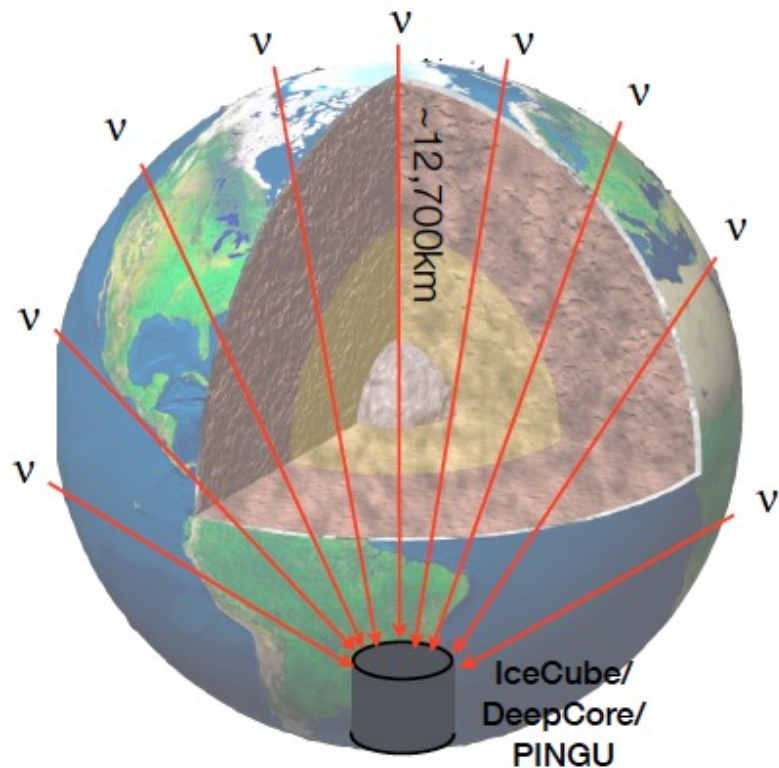
# IceCube Overview

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



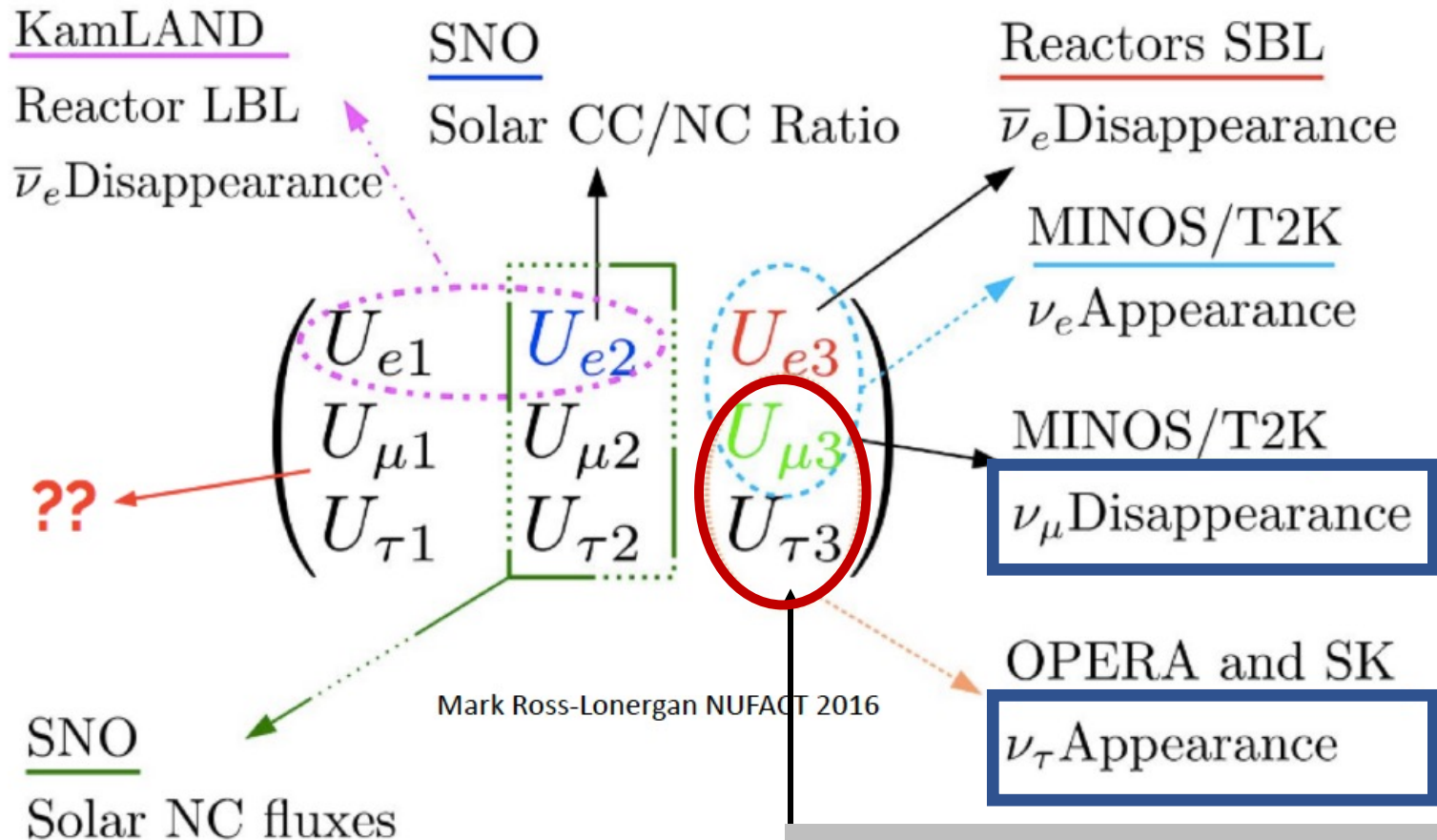
- 10 megaton volume
- string spacing : 125m → 35m → 22m
- module spacing: 17m → 7m → 3 m

- one million atmospheric  $\nu$ '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

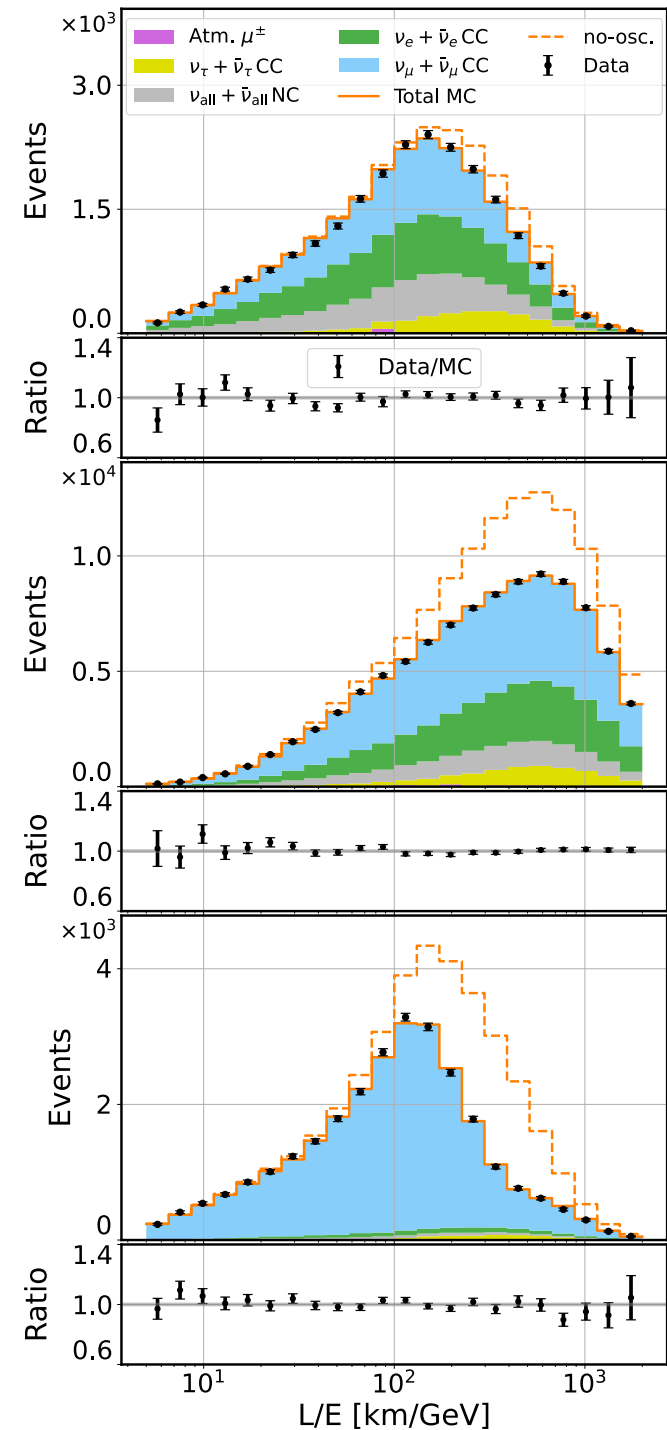
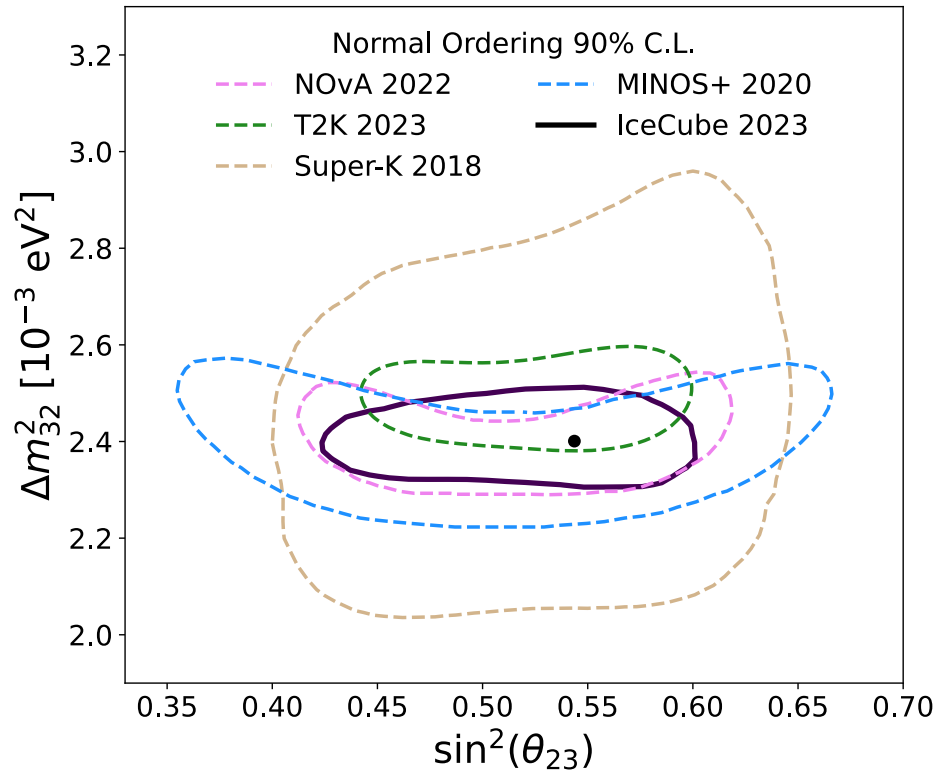
## The PMNS mixing matrix



neutrino “telescopes”

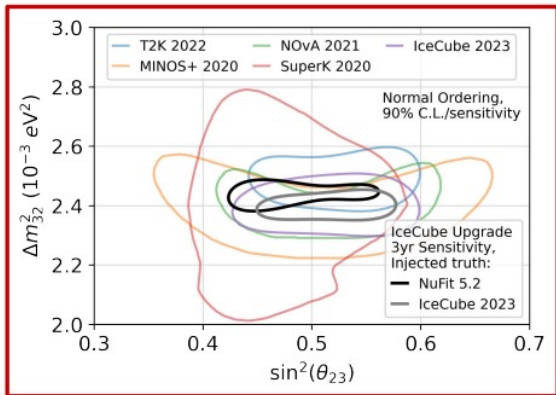
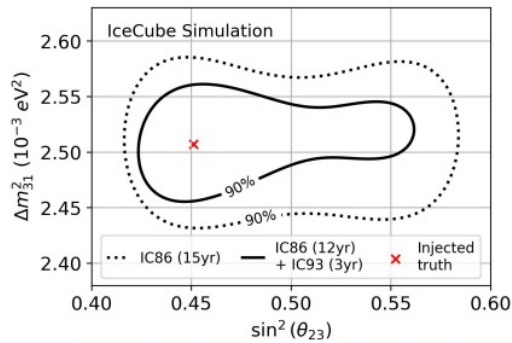
## imminent unblinding:

- 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

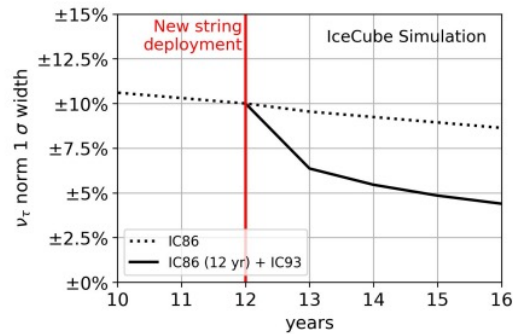
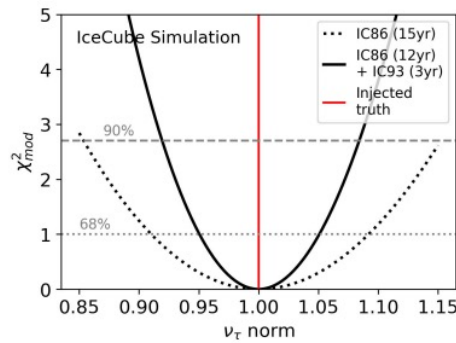


and with the Upgrade strings in 2025...

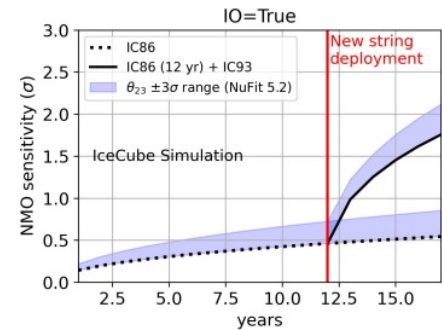
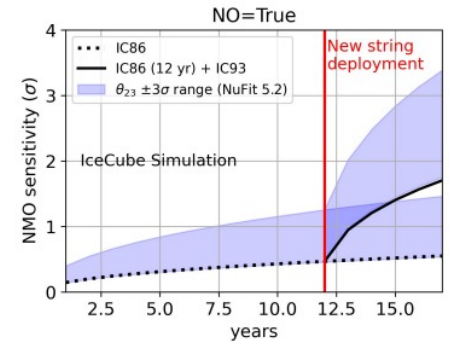
### Sensitivities - Atm. Osc. Params



### Tau Neutrino Norm



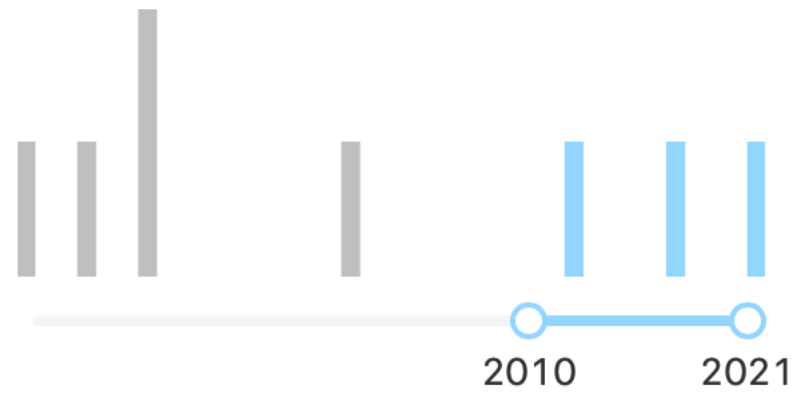
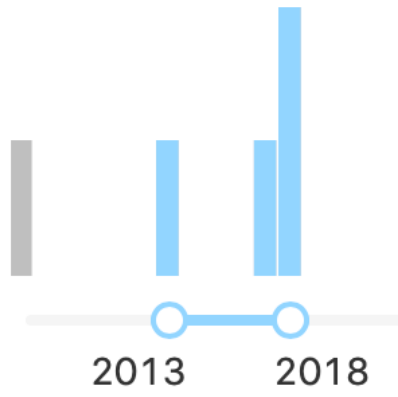
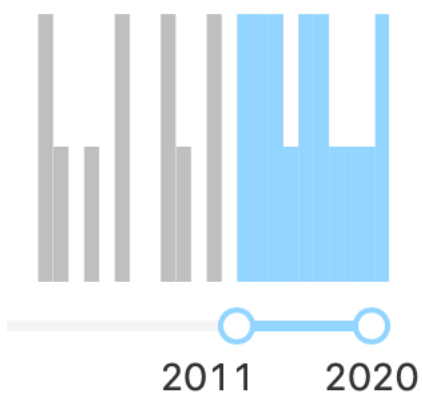
### NMO



leading atmospheric beam detector until the advent of HyperK in 2028



# IceCube high profile papers



Phys. Rev. Lett. (16+4+...)

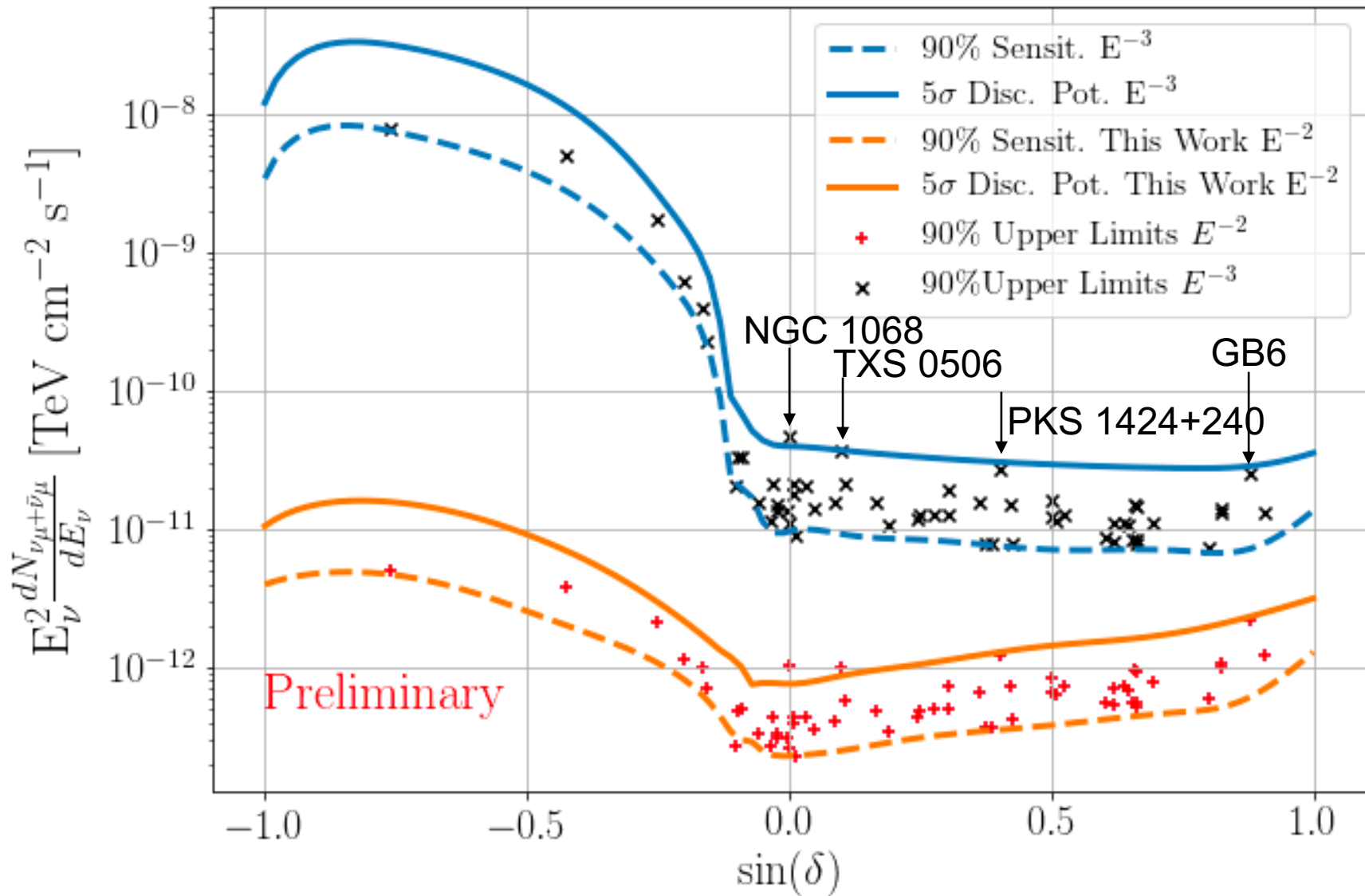
Science (4+2)

Nature (3)

no evidence of decline of new results in 10 years

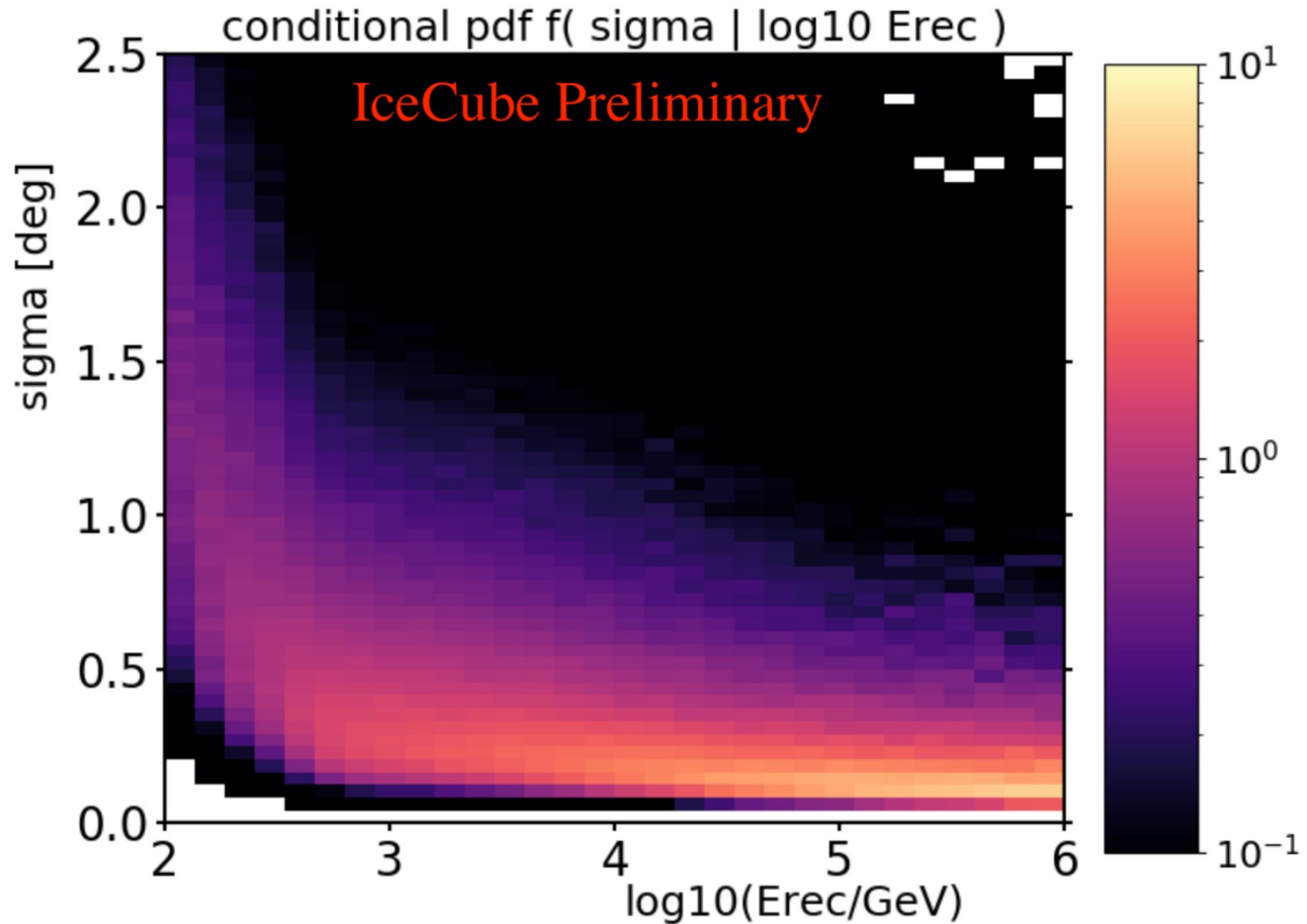
overflow slides

# limits and interesting fluctuations (?)



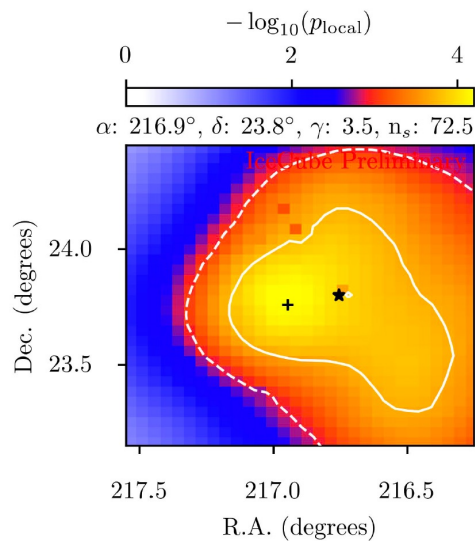
improve calibration, event selection and reconstruction

sources come into focus: angular resolution  $< 0.3^\circ$



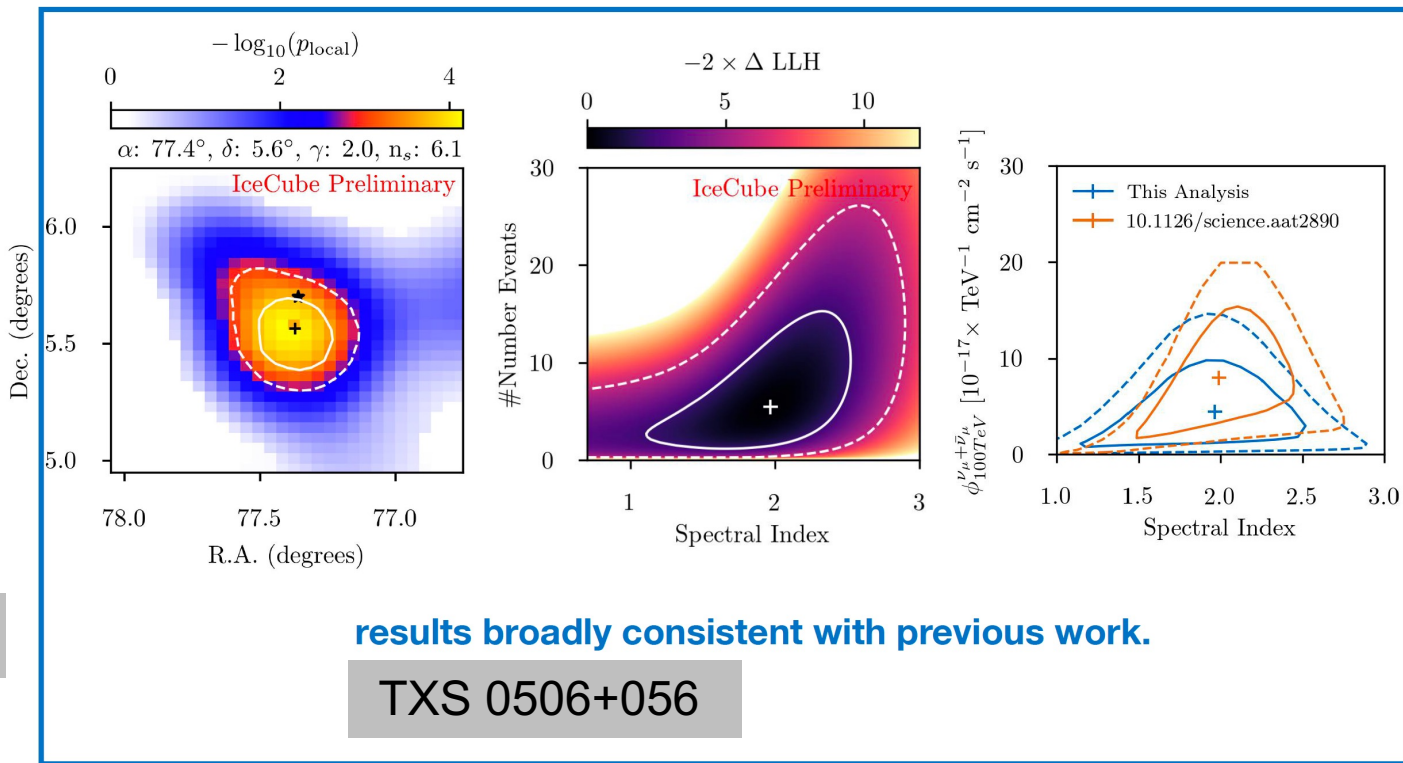
# what about the other sources?

- TXS 0506+056:  $3.6\sigma \rightarrow 3.7\sigma$
- PKS1424+240 :  $3.0\sigma \rightarrow 3.7\sigma$



PKS 1424+240

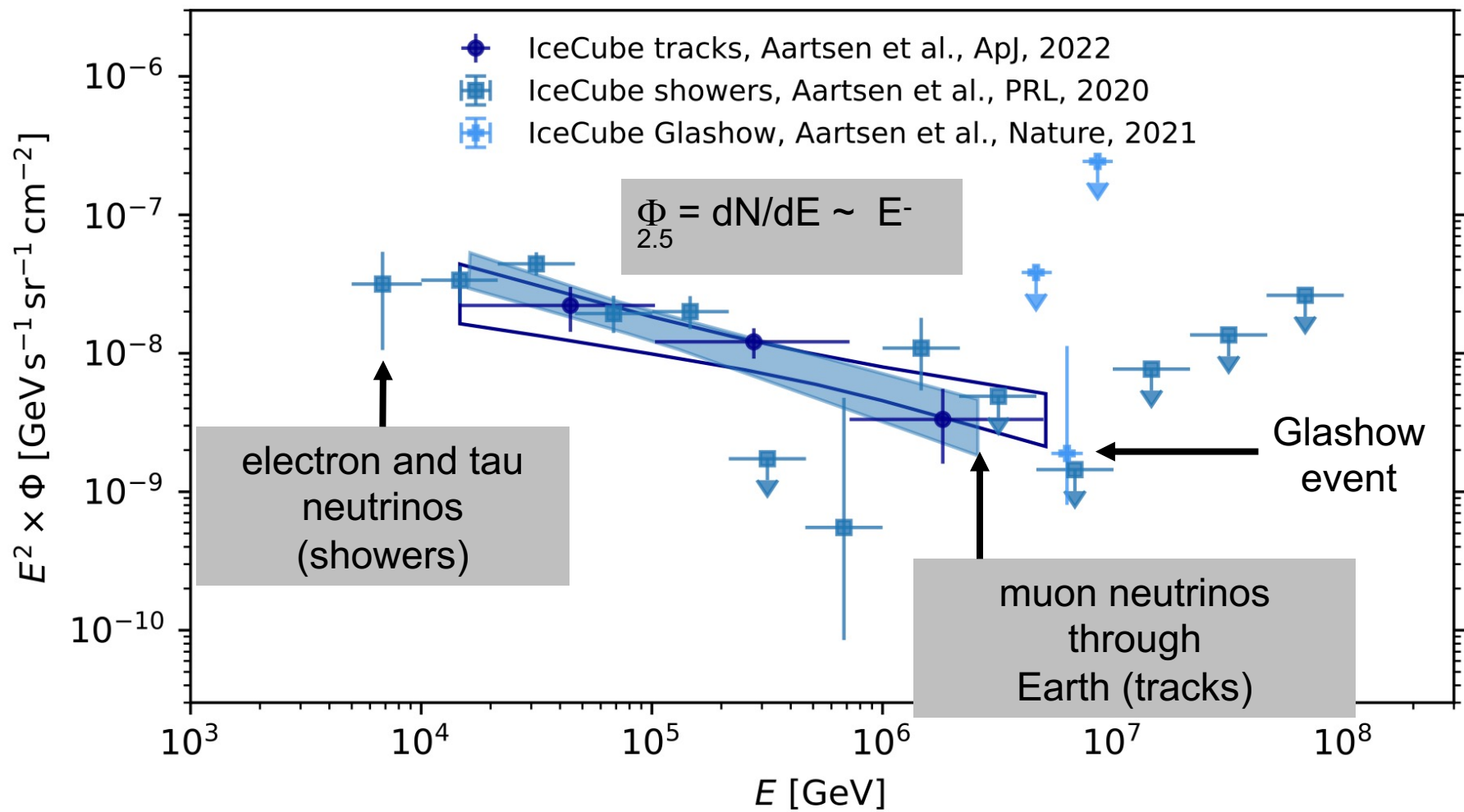
$3.0\sigma \rightarrow 3.7\sigma$



results broadly consistent with previous work.

TXS 0506+056

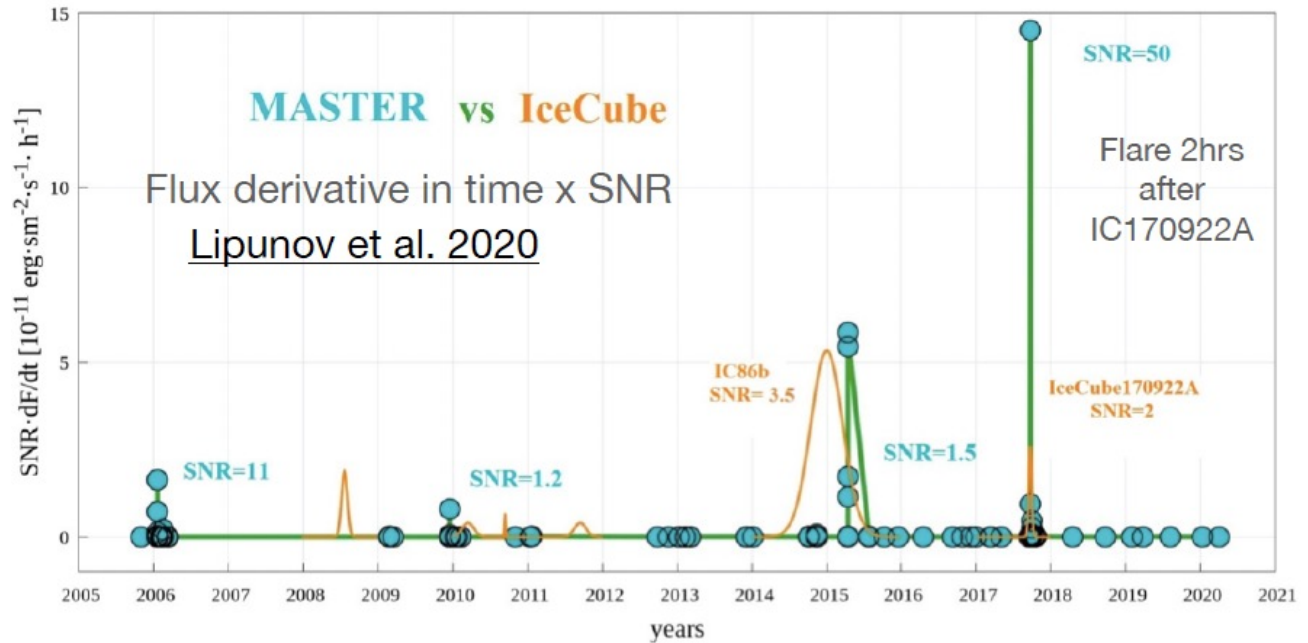
ongoing program to improve the focus of the neutrino telescope will receive another boost with the information on the ice obtained with the Upgrade's small string spacings and the new calibration devices



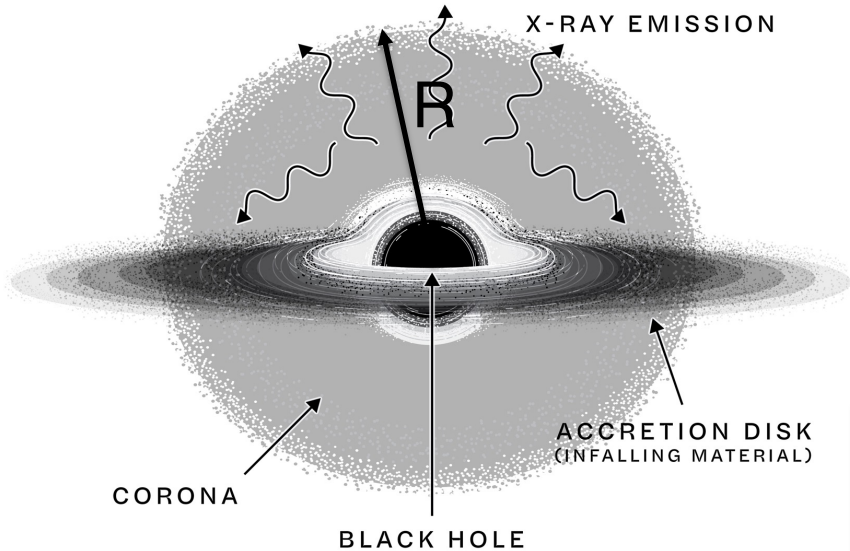


“MASTER found the blazar in the off-state *after one minute* and then switched to on-state two hours after the event. The effect is observed at a 50-sigma significance level”

optical flashes often originate from magnetohydrodynamic 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



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

cross section x target density  
= optical depth  $\tau$

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

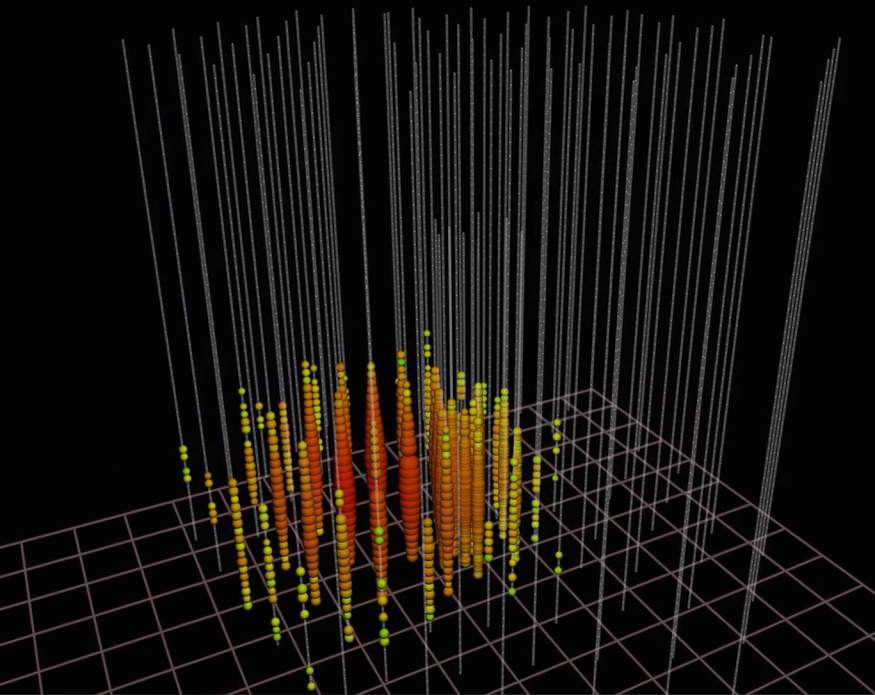
$$E_X = 1 \text{ keV}; L_X \sim 10^{43} \text{ ergs}^{-1}$$

neutrinos originate within  $10 \sim 10^2$  Schwarzschild radii from the BH

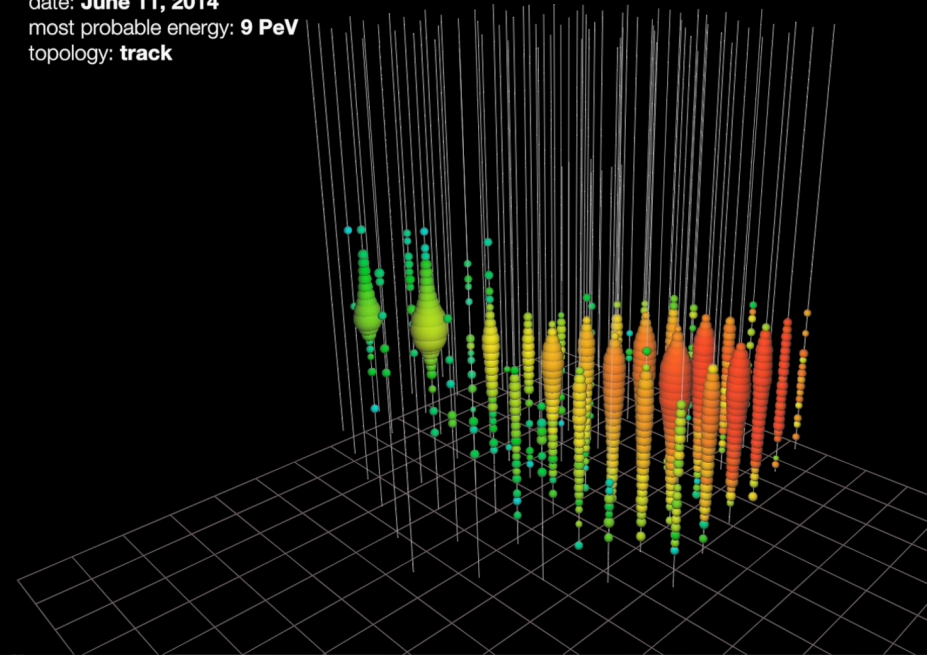


neutrinos interacting  
inside the detector

muon neutrinos  
filtered by the Earth



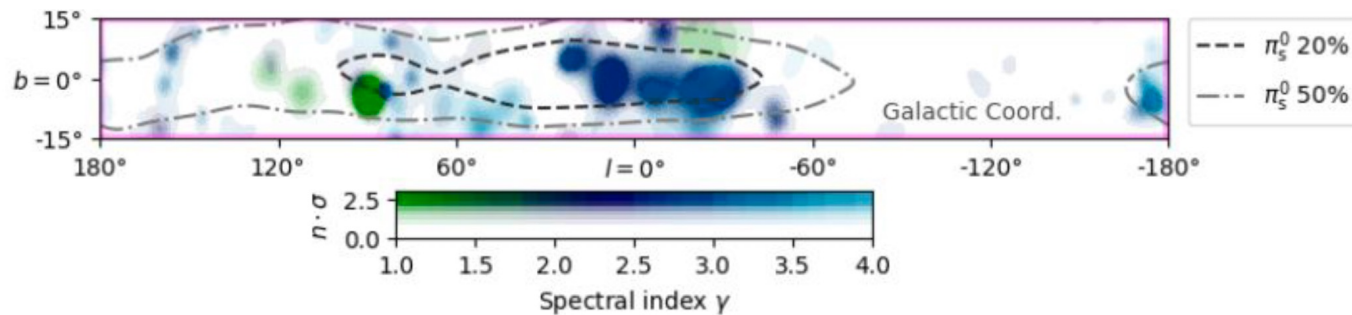
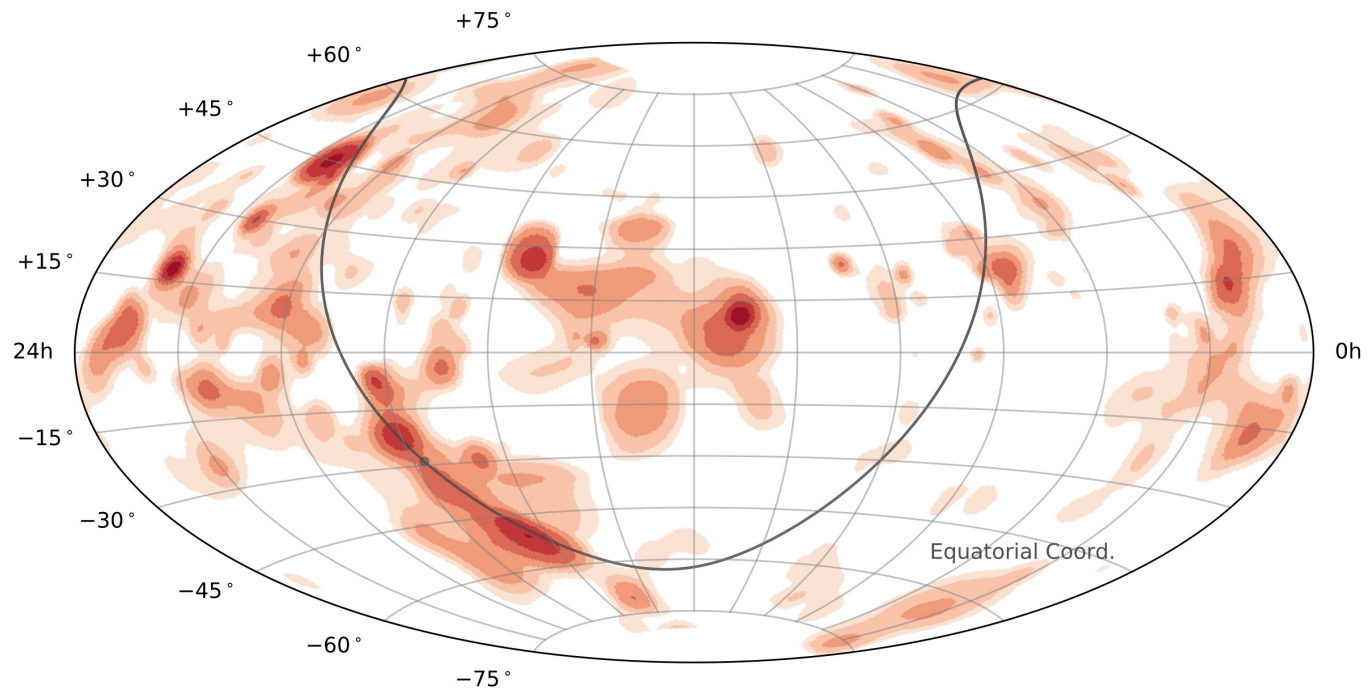
date: **June 11, 2014**  
most probable energy: **9 PeV**  
topology: **track**

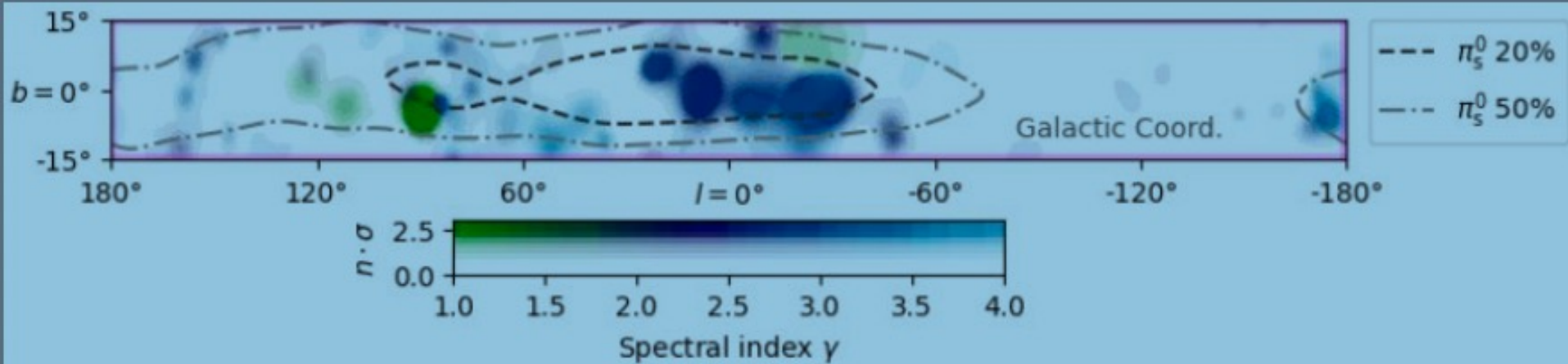
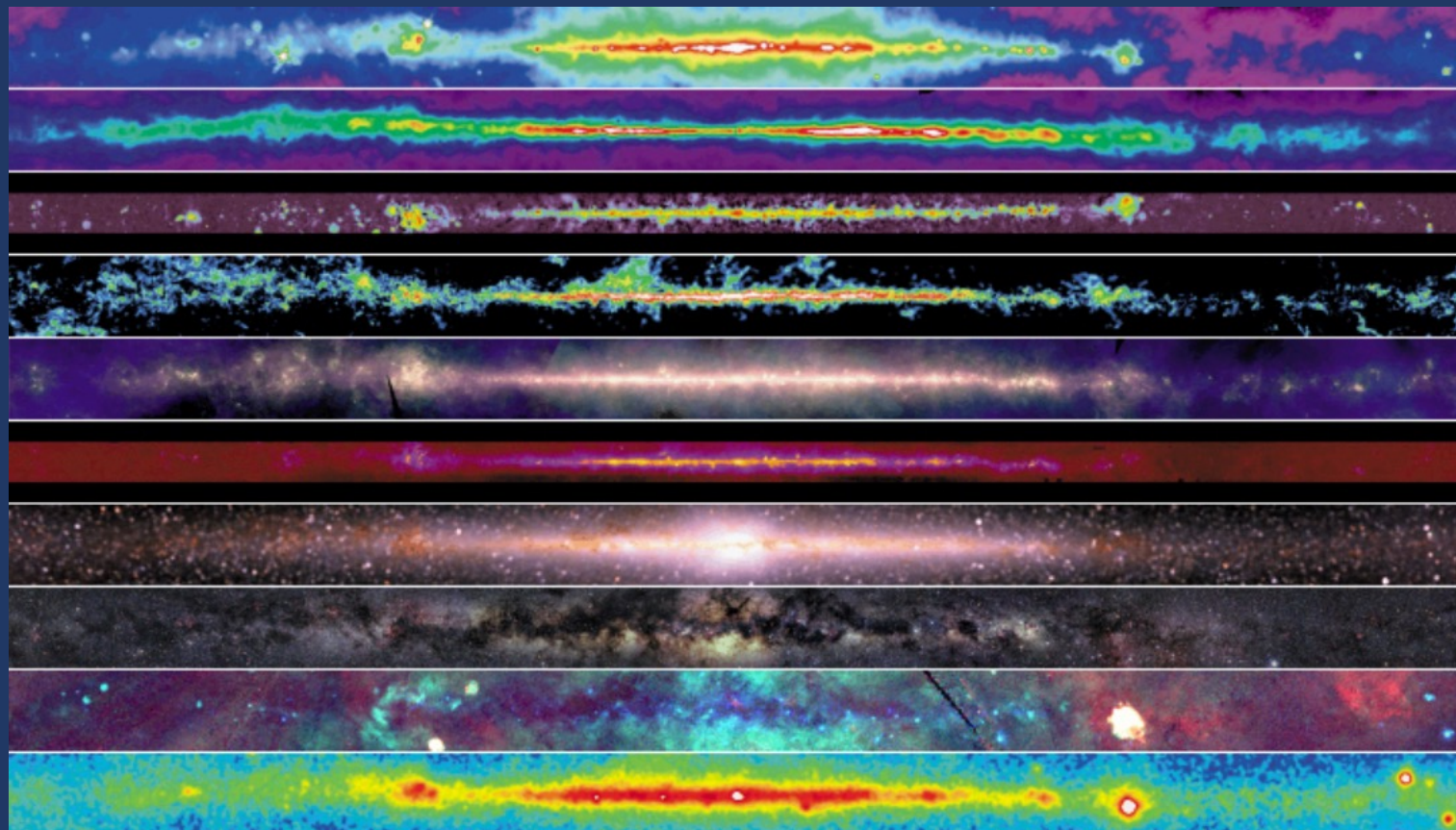


superior total energy  
measurement  
to 10%, all flavors, all sky

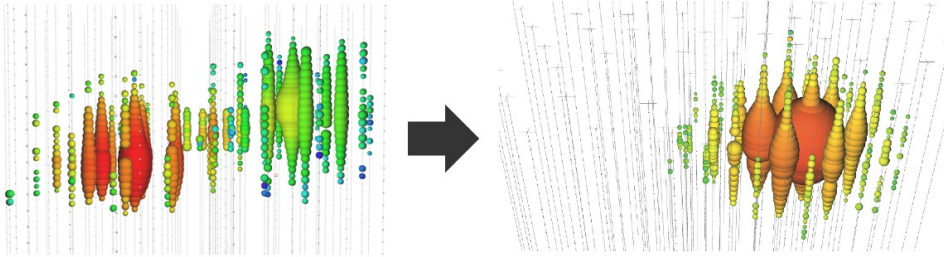
astronomy: superior  
angular resolution  
superior ( $< 0.3^\circ$ )

# we finally found our own Galaxy

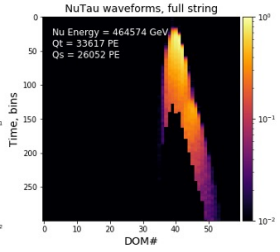
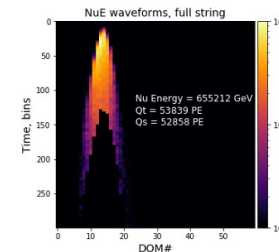
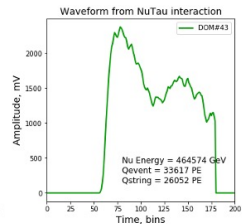
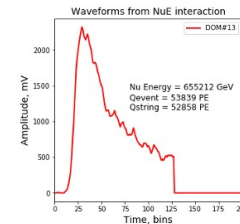
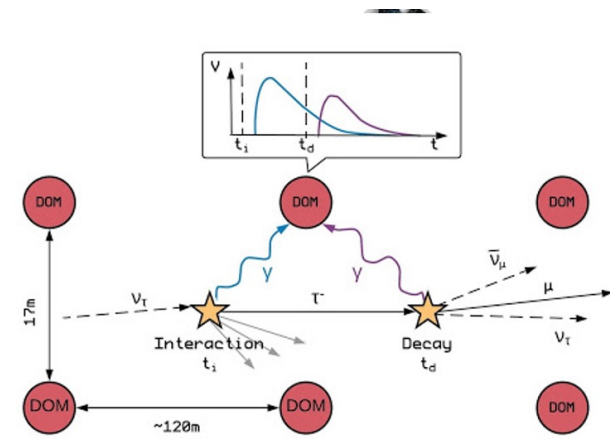




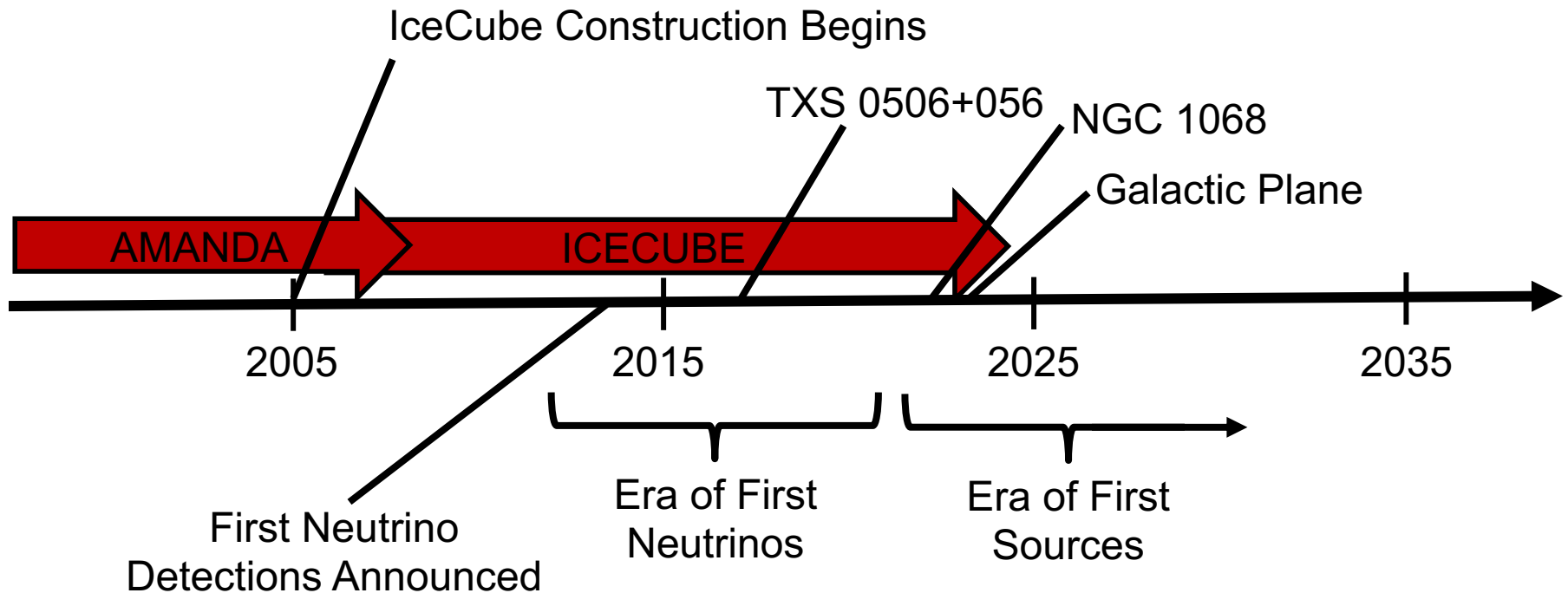
# Astrophysical Tau Neutrino Search



- TeV – O(1) PeV Tau neutrinos look like Electron neutrinos due to sparse instrumentation
- Differentiation by shape of waveform in a given module, i.e. two waveforms in the same module offset by a certain quantity
- Create an image (2D histogram) of the of the charge distribution in time along a string
- CNN used to find the subtle difference in waveform shapes



# The Past, Present, and Future of High-Energy Neutrino Astronomy



# The Past, Present, and Future of High-Energy Neutrino Astronomy

