Recent Results and Highlights from the IceCube Neutrino Observatory

LTP/PSI Thursday Colloquium
11 November 2024

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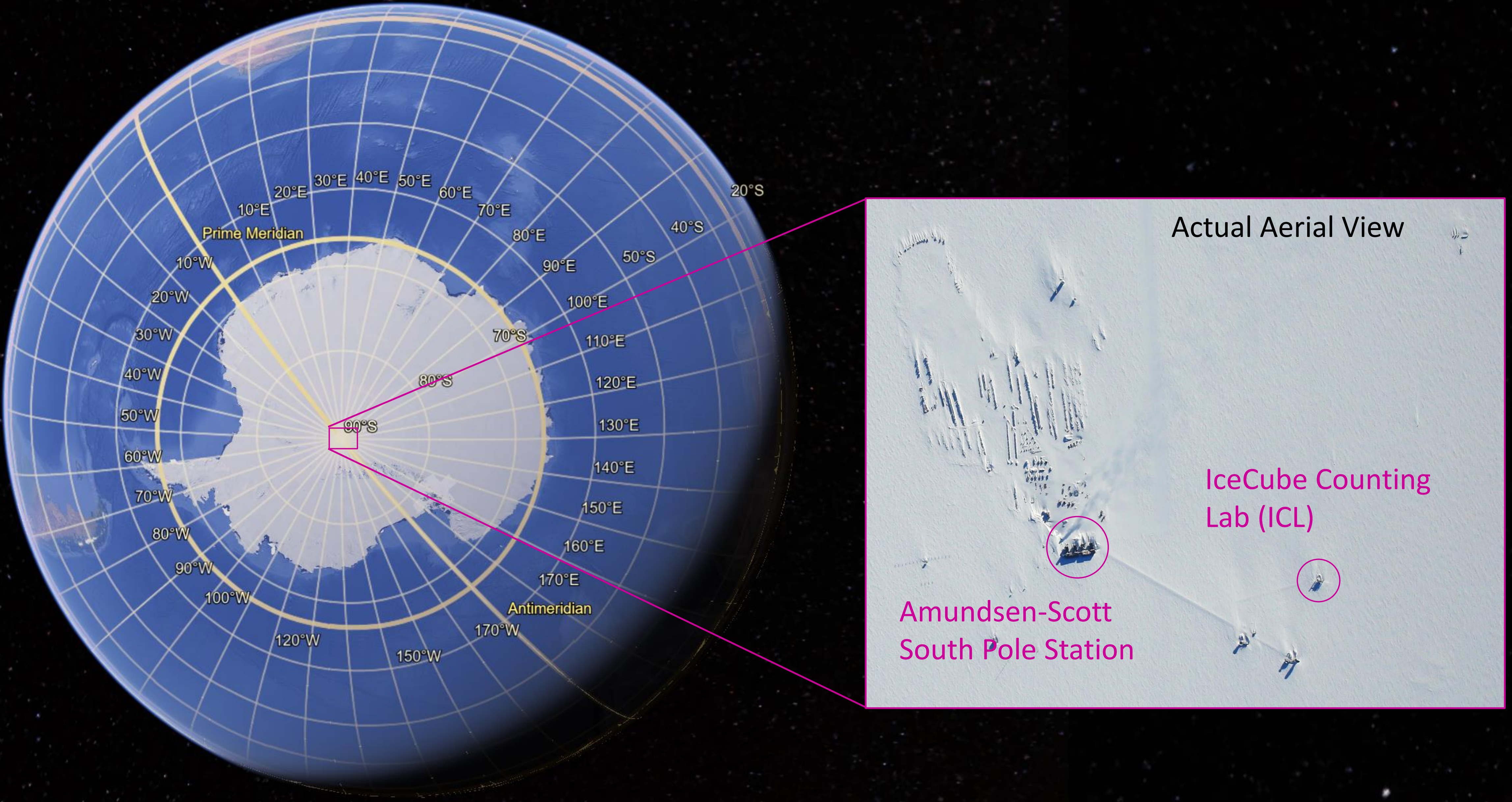
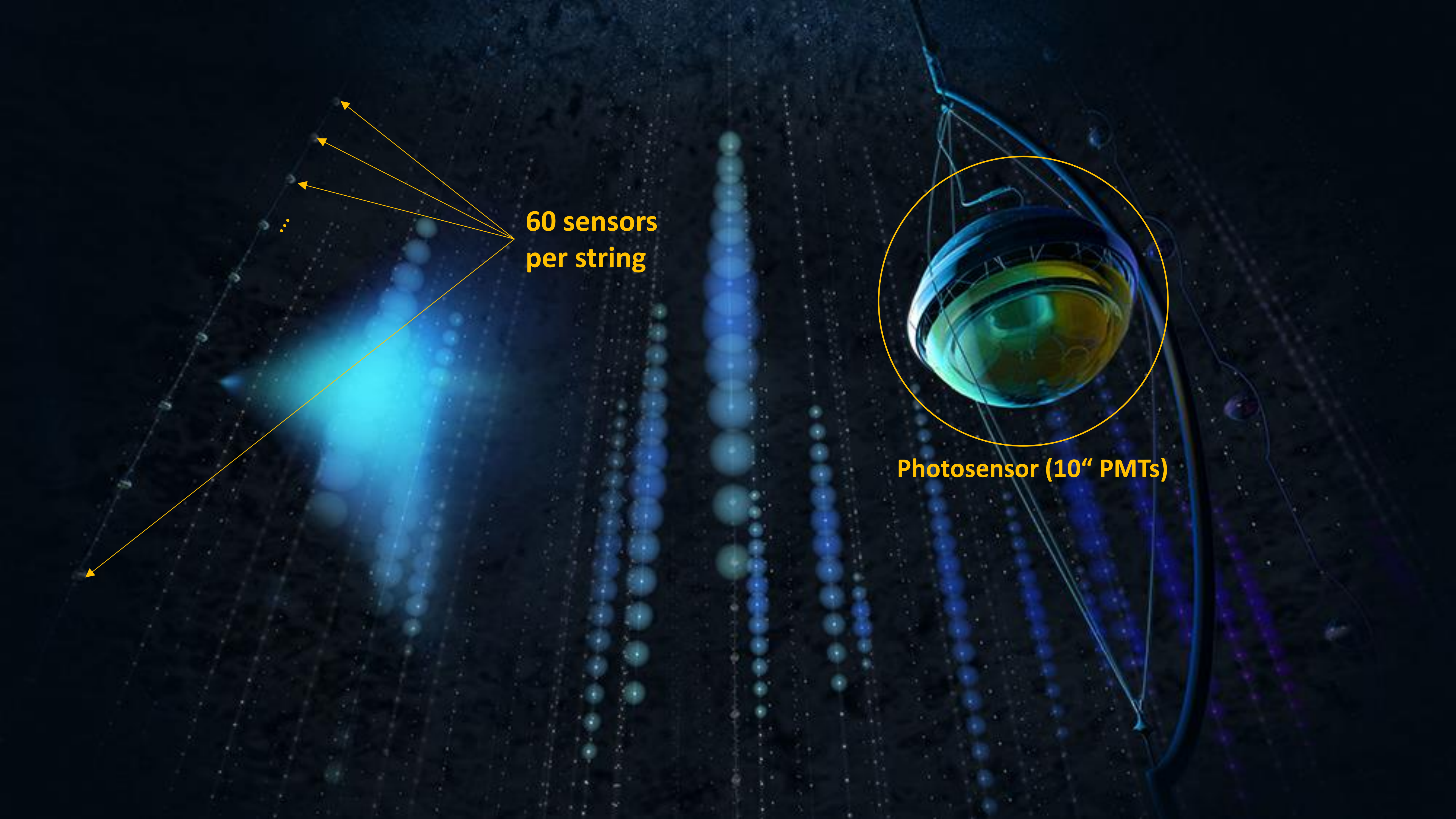


Google Earth

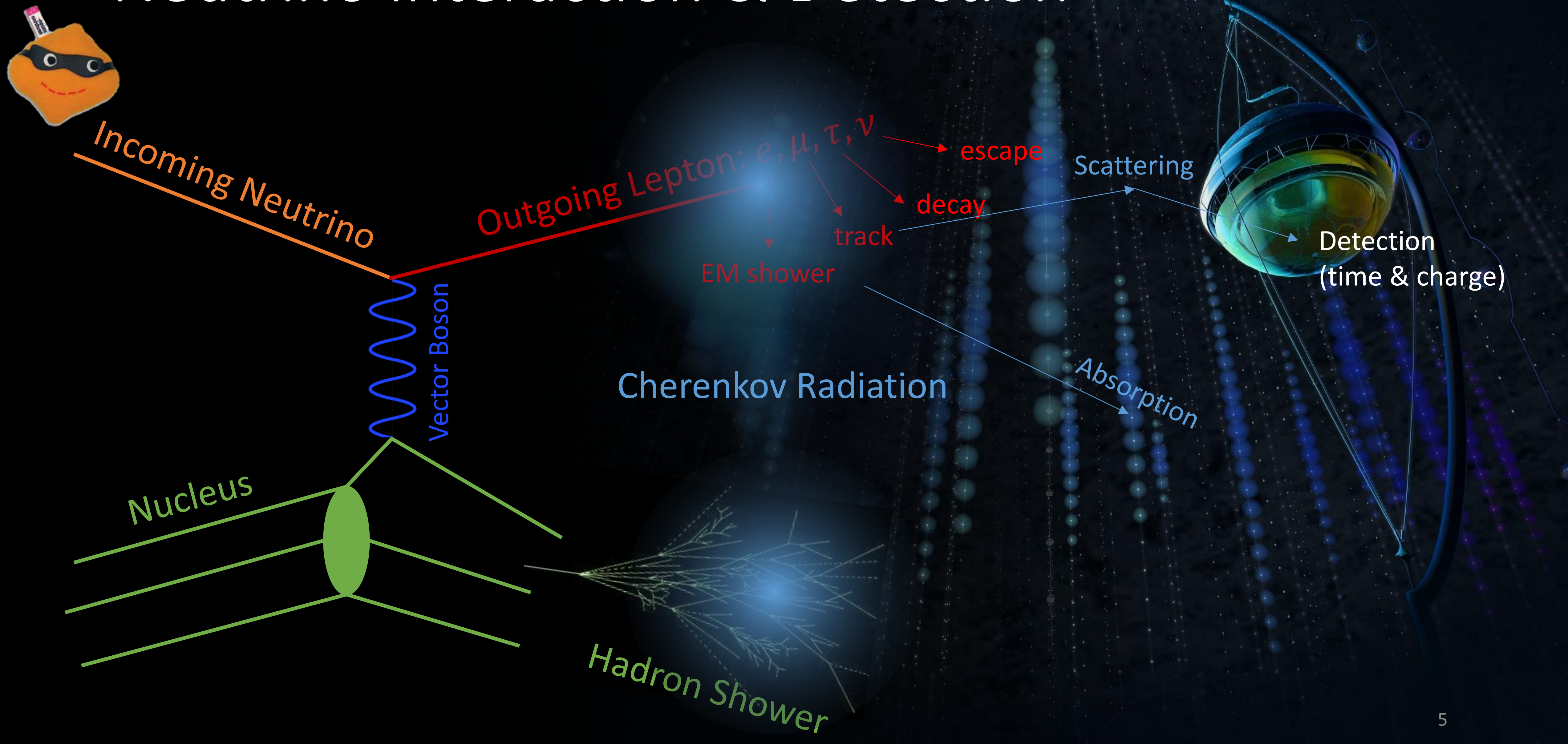
IceCube Counting Lab (ICL)

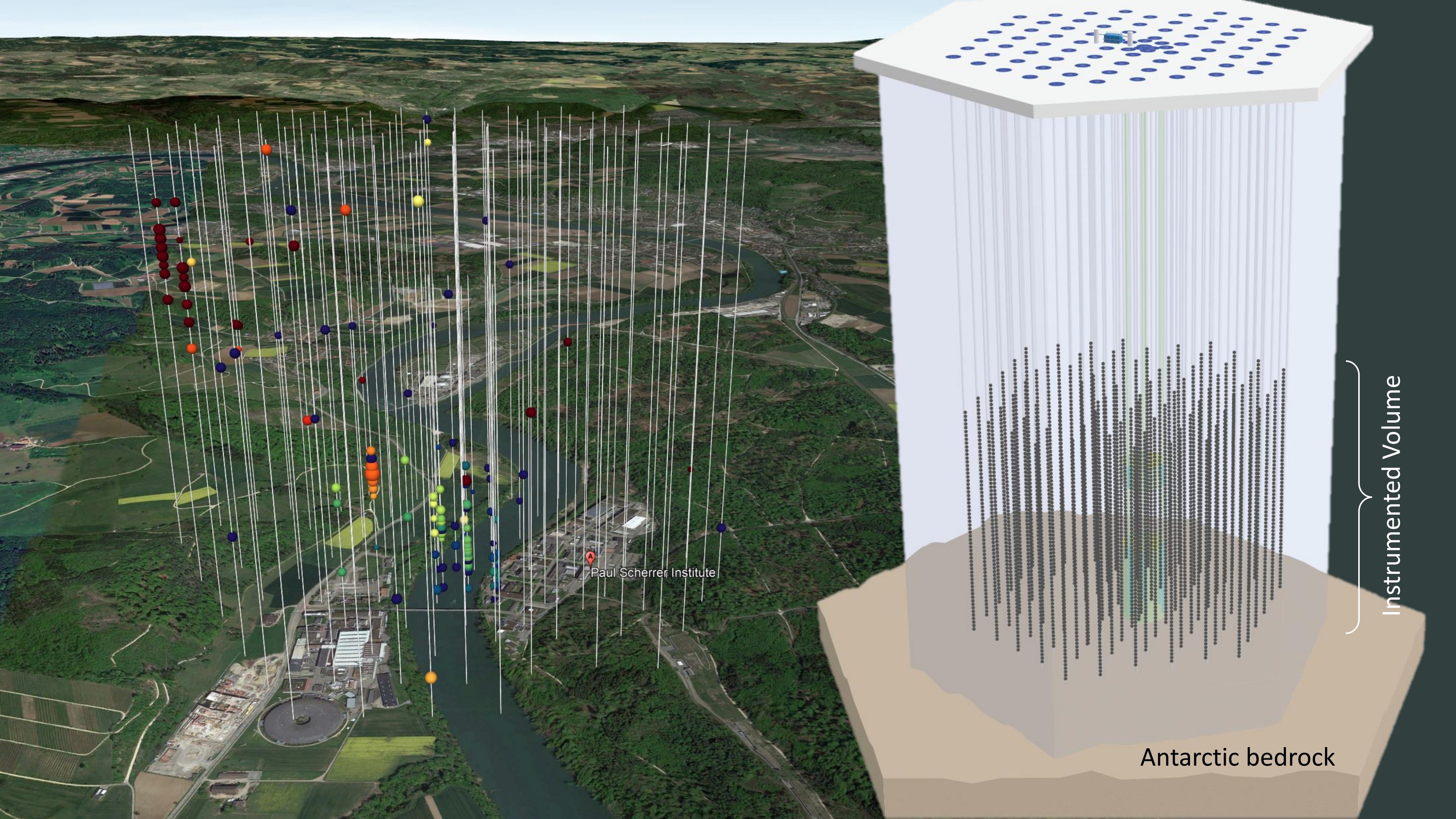
The more interesting is hidden underneath!

86 Cables, 2.5 km long each, go down into the glacier…


60 sensors
per string
Photosensor (10“ PMTs)

Neutrino Interaction & Detection




Paul Scherrer Institute
Instrumented Volume
Antarctic bedrock

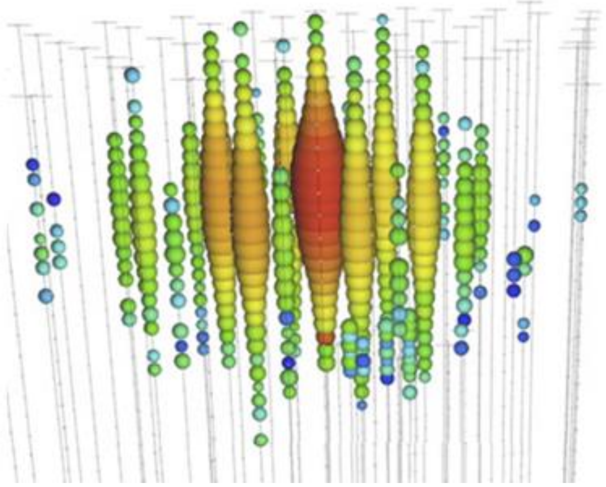
Event classes & Reconstruction

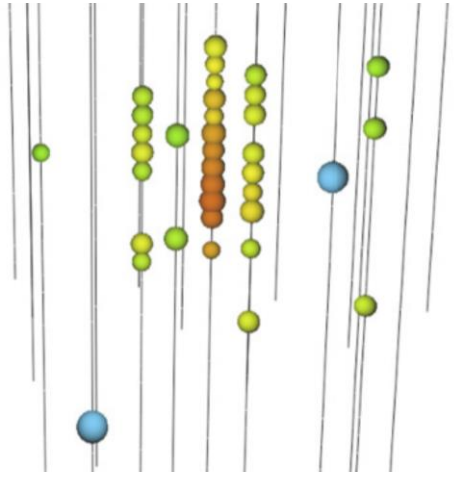
Early Late

Energy

High Low

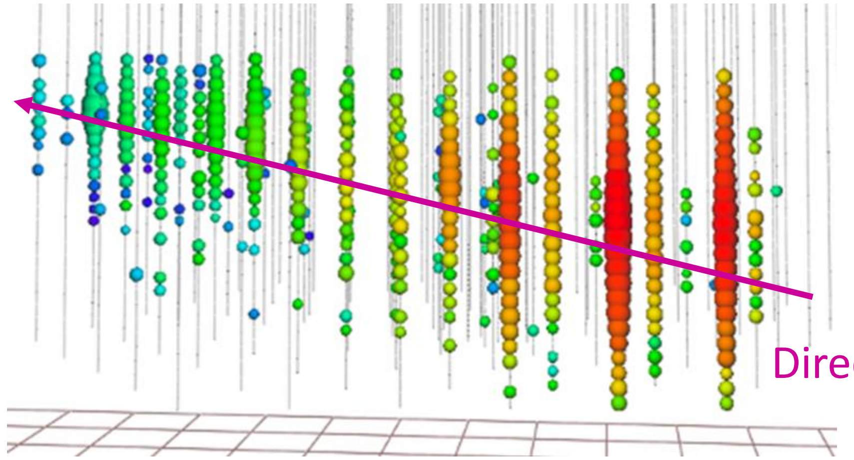
Cascade Events:
EM/Had shower
Mostly ν_e CC and ν NC



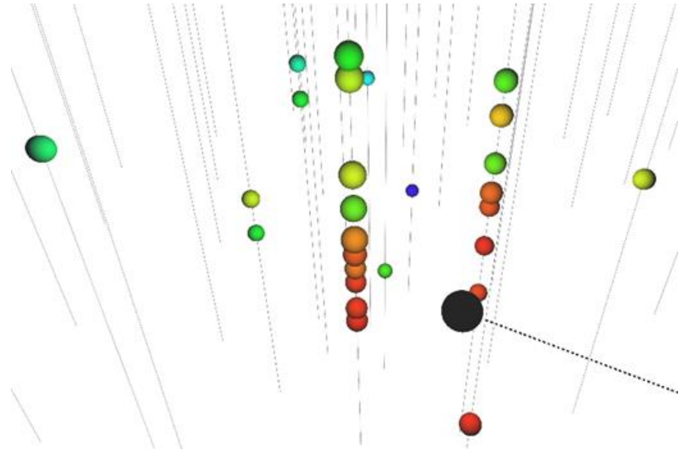


Signature

Track Events:
Long Muon signature
Mostly μ, ν_μ CC



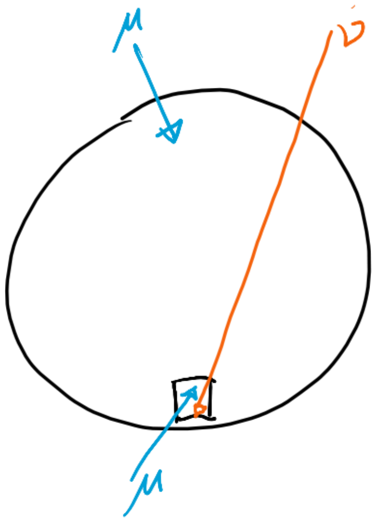
Direction



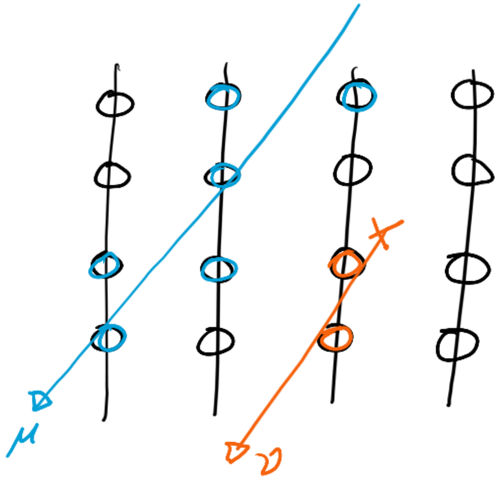
Muons vs. Neutrinos

- Most events we see in IceCube are **atmospheric muons**
  - From meson decays in cosmic ray induced air showers
  - We have around $O(10^{10})$ per year
  - Those are for most purposes an unwanted background
    → How can we single out **neutrinos** from these **muons**?

Earth as shield:



Starting events:



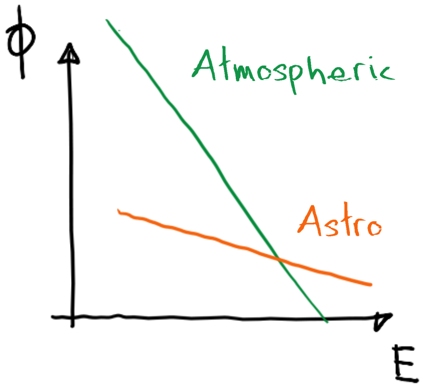
Atmospheric vs. Astrophysical Neutrinos

- Most neutrinos we observe with IceCube are **atmospheric neutrinos**
  - From meson decays in cosmic ray induced air showers
  - IceCube records O(100'000) atmospheric neutrinos per year

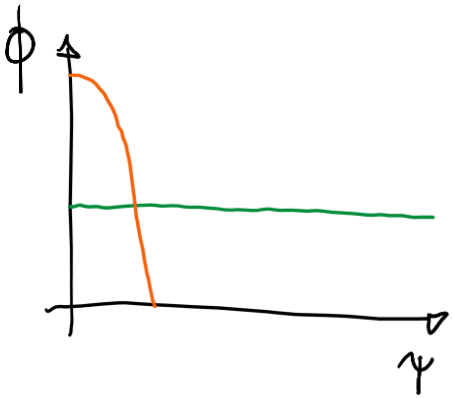
- How can we fish out **astrophysical neutrinos**?
  - Neutrinos that were produced outside Earth, potentially quite far away

  → Can gives us insight into possible sources / production mechanisms, and maybe shed light onto the origin of high-energy cosmic rays

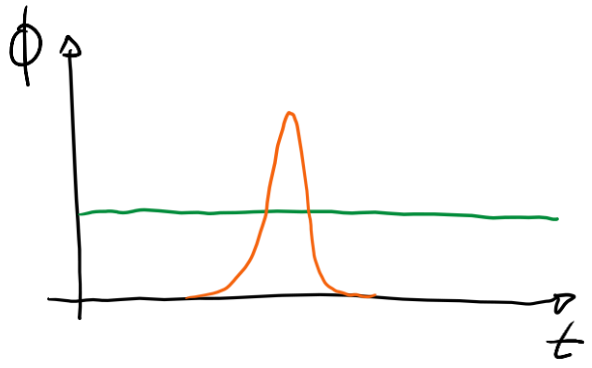
Harder energy spectrum:

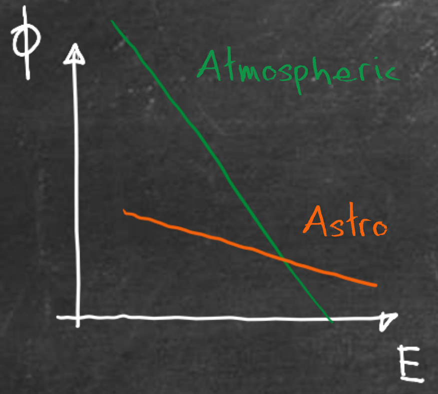


Clustering in Direction:



Clustering in Time:



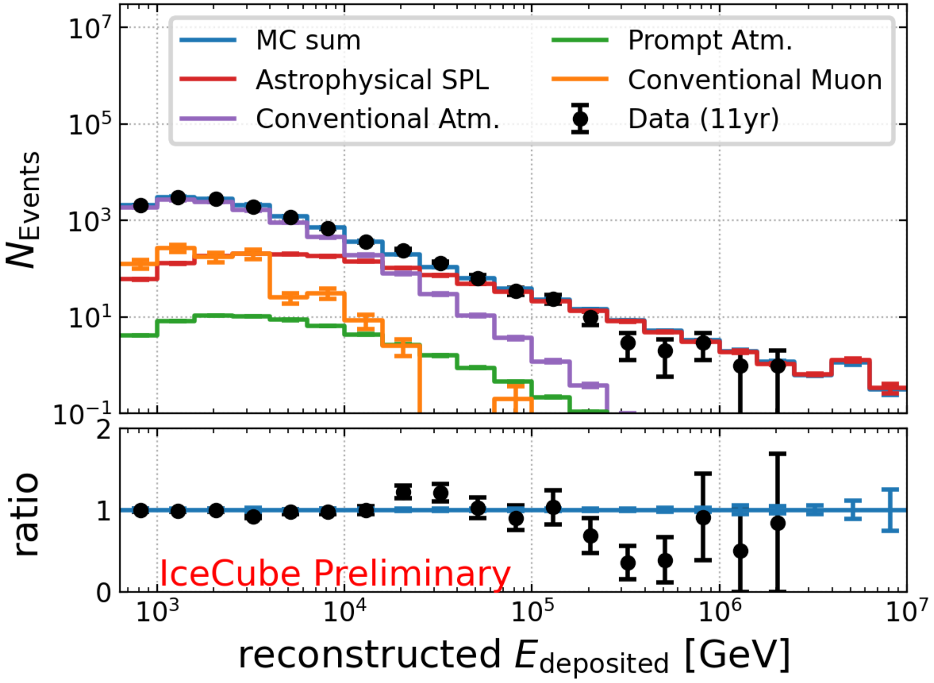


Diffuse Astrophysical Flux

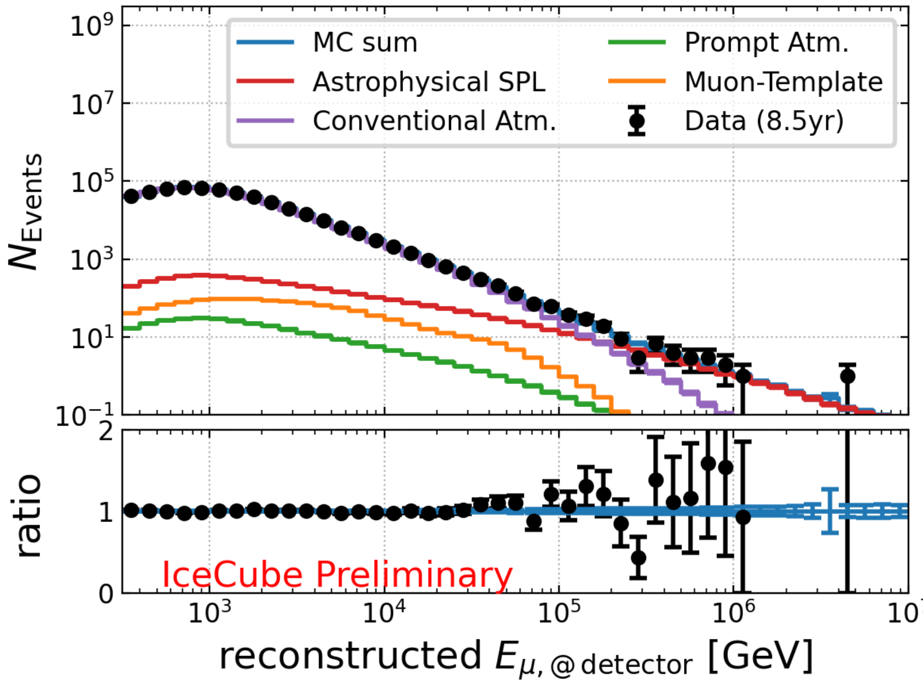
Diffuse Astrophysical Flux

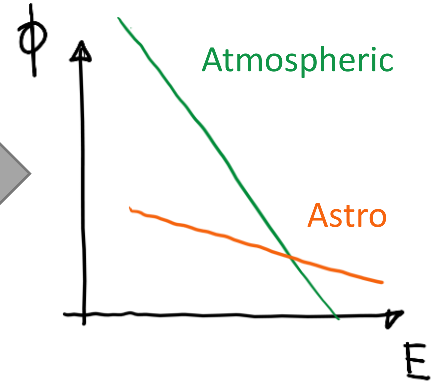
New analysis using both, cascades and tracks, jointly

Cascades:
great energy resolution & low background
12641 events



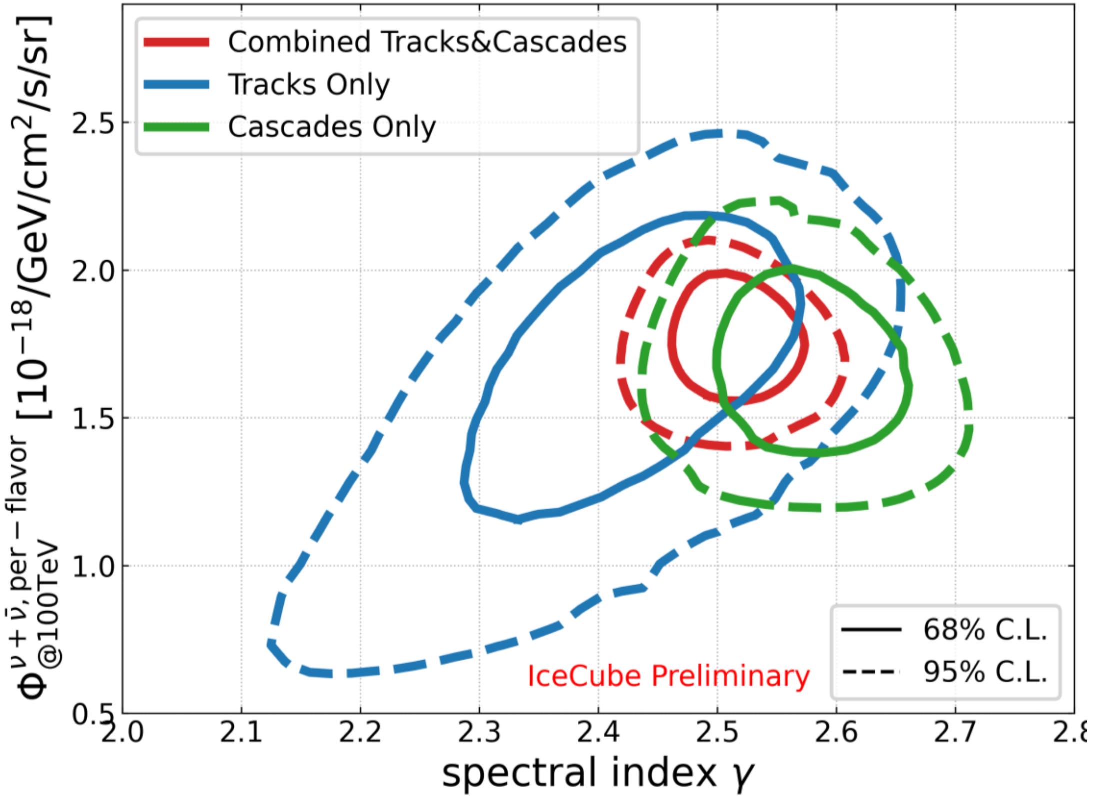
Tracks:
large statistics
542066 events

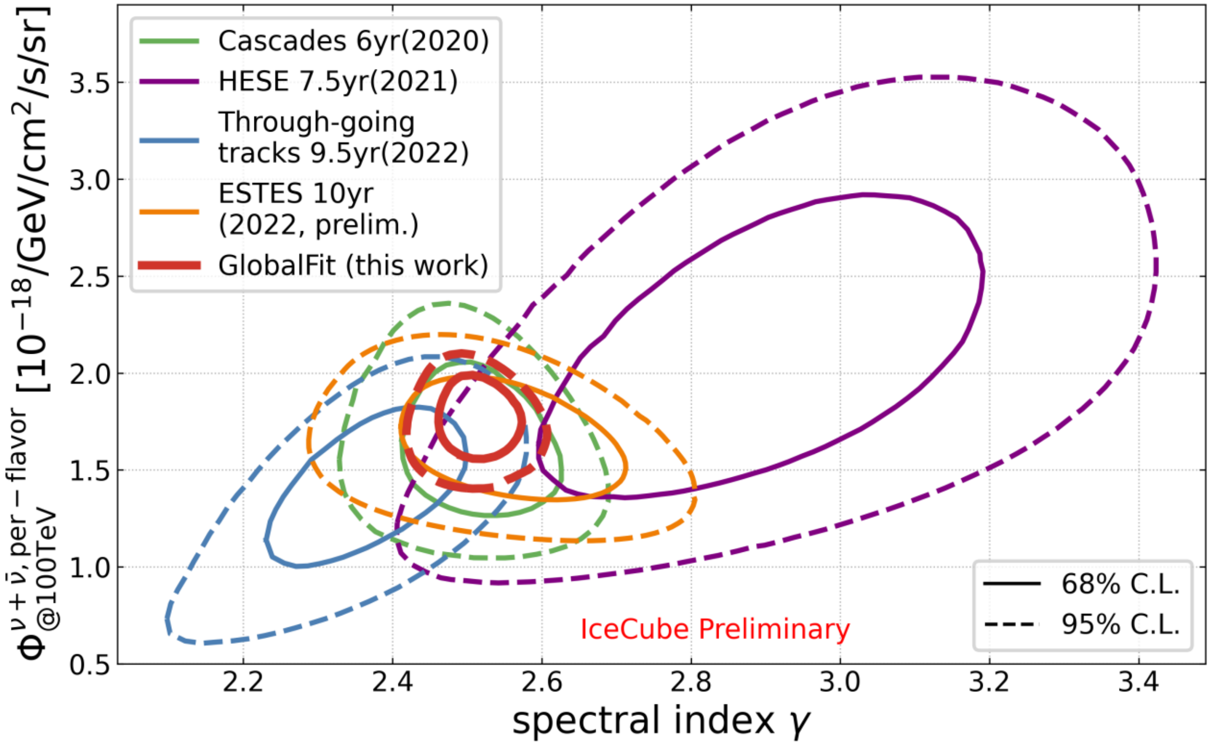




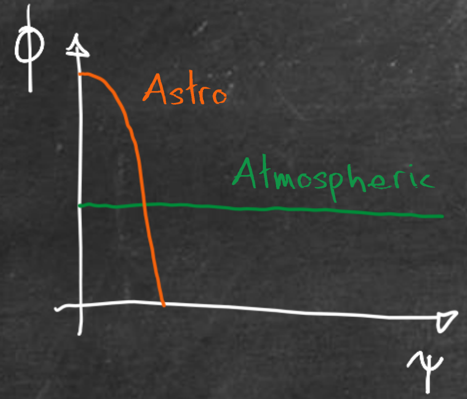
2308.00191

Results



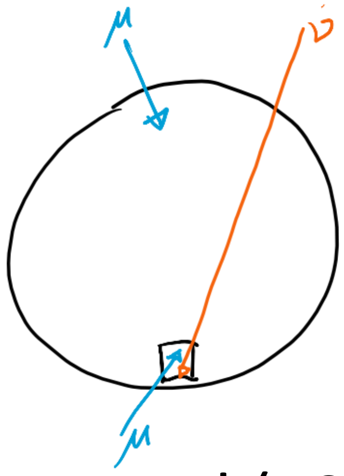


assuming single power law (SPL)



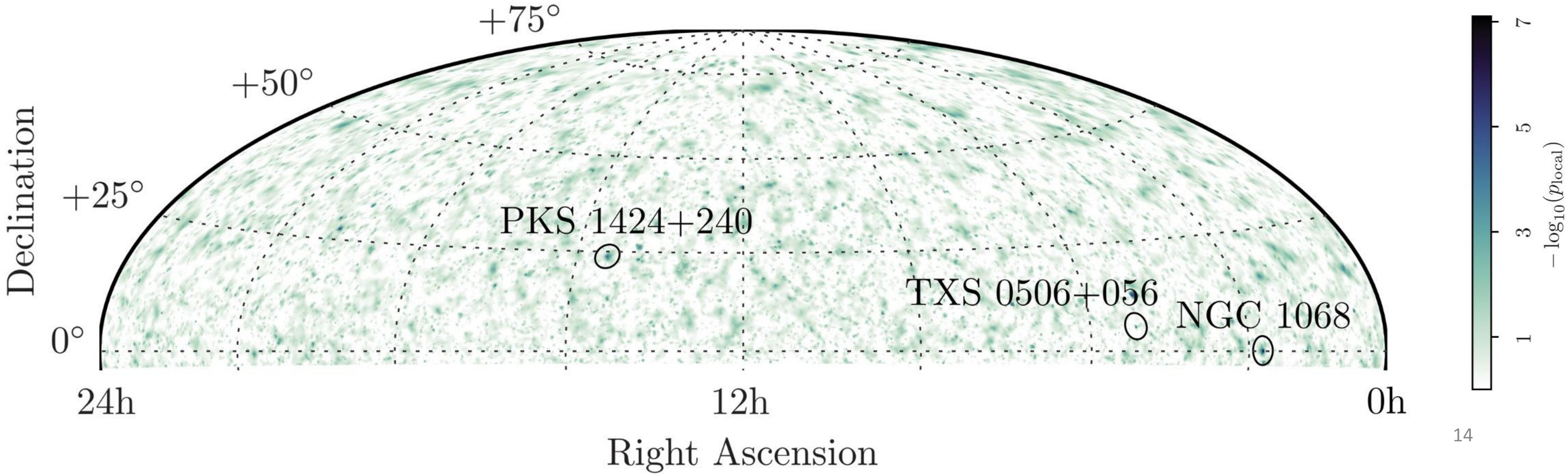
Neutrino Sources

Neutrino Point Sources



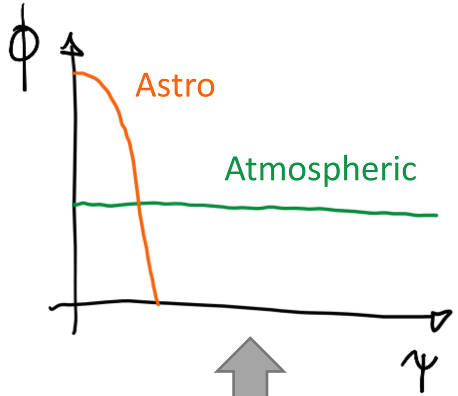
2211.09972

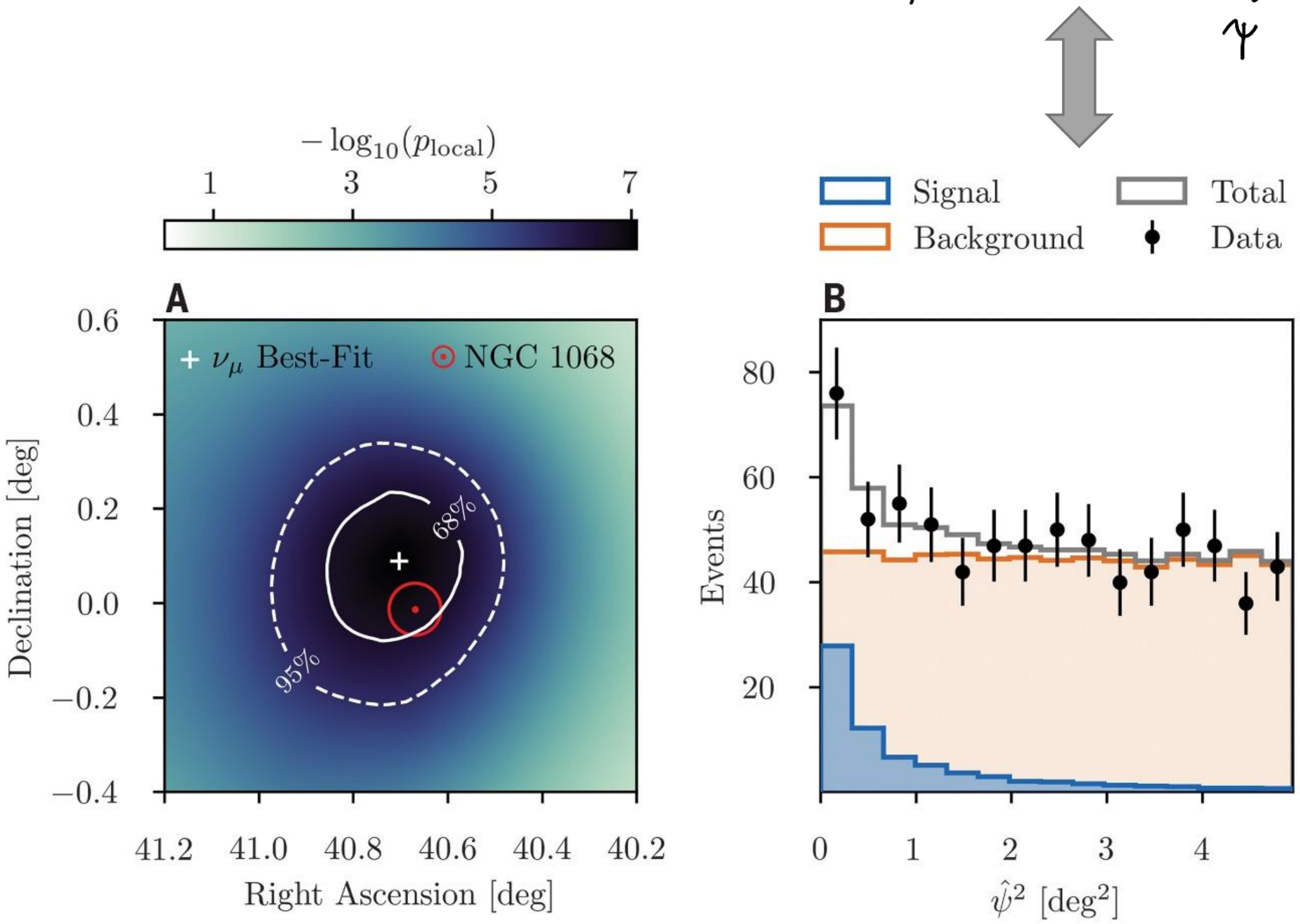
- Using tracks→ excellent pointing resolution ($\lesssim 1°$)
- Northern sky ($-3° - +81°$) → avoiding muon background (<0.3%)
- New event sample containing 670,000 neutrinos



NGC 1068

- Position of NGC1068 (nearby AGN) revealed an excess of 79^{+29}_{-22} neutrinos above background
- Based on an a priori defined catalog of 110 know gamma ray point sources
  → 4.2σ significance above background

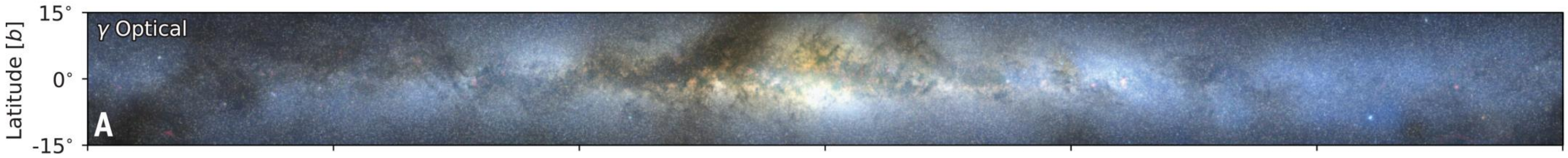




2211.09972

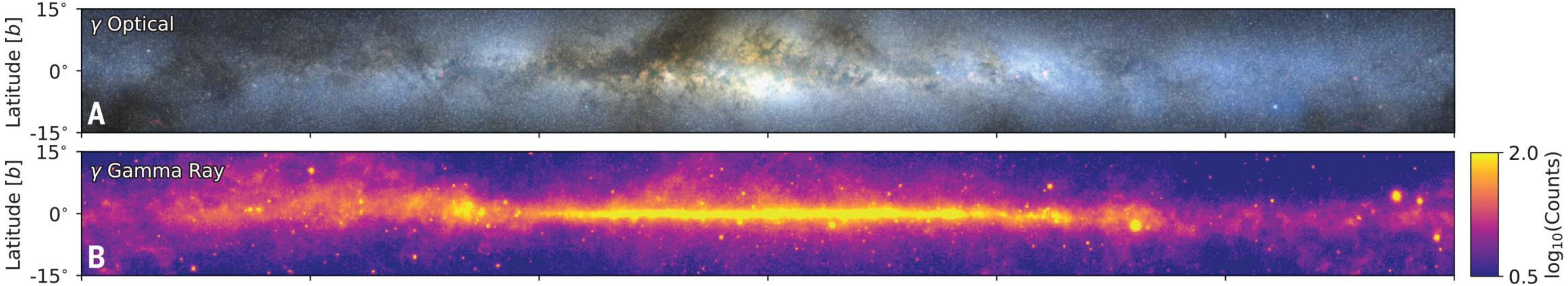
[2307.04427](2307.04427)

Extended Source: Galactic Plane



- Optical Image of the plane of our Milky Way
- Image is in galactic coordinates, showing $\pm 15°$ latitude and $\pm 180°$ longitude

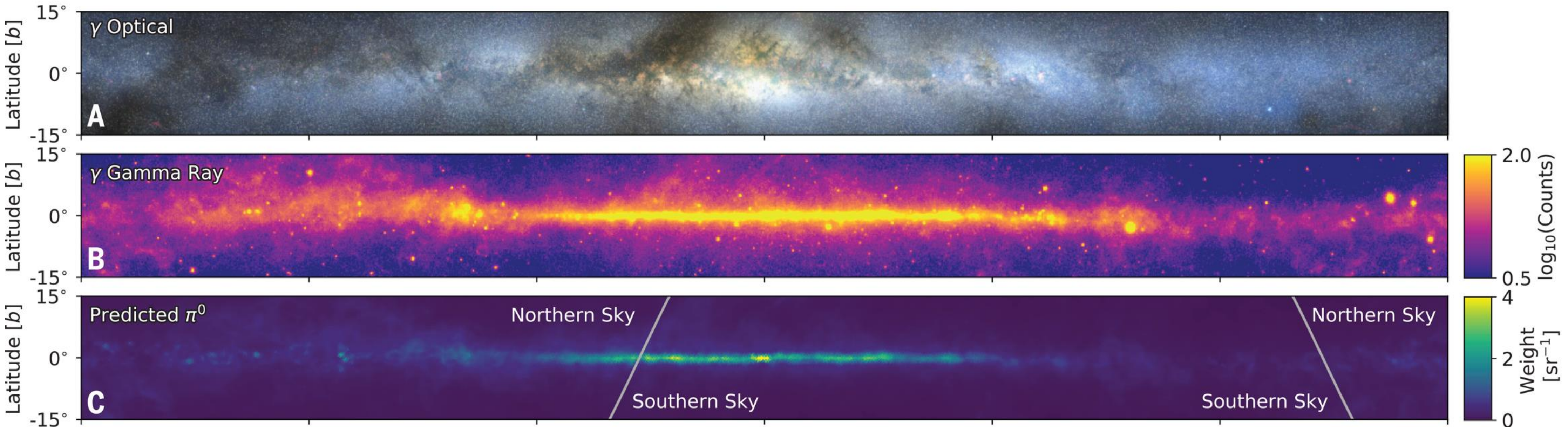
Extended Source: Galactic Plane



- Gamma Ray Flux (> 1 GeV) from Fermi-LAT
- Prime candidate for neutrino emission

2307.04427

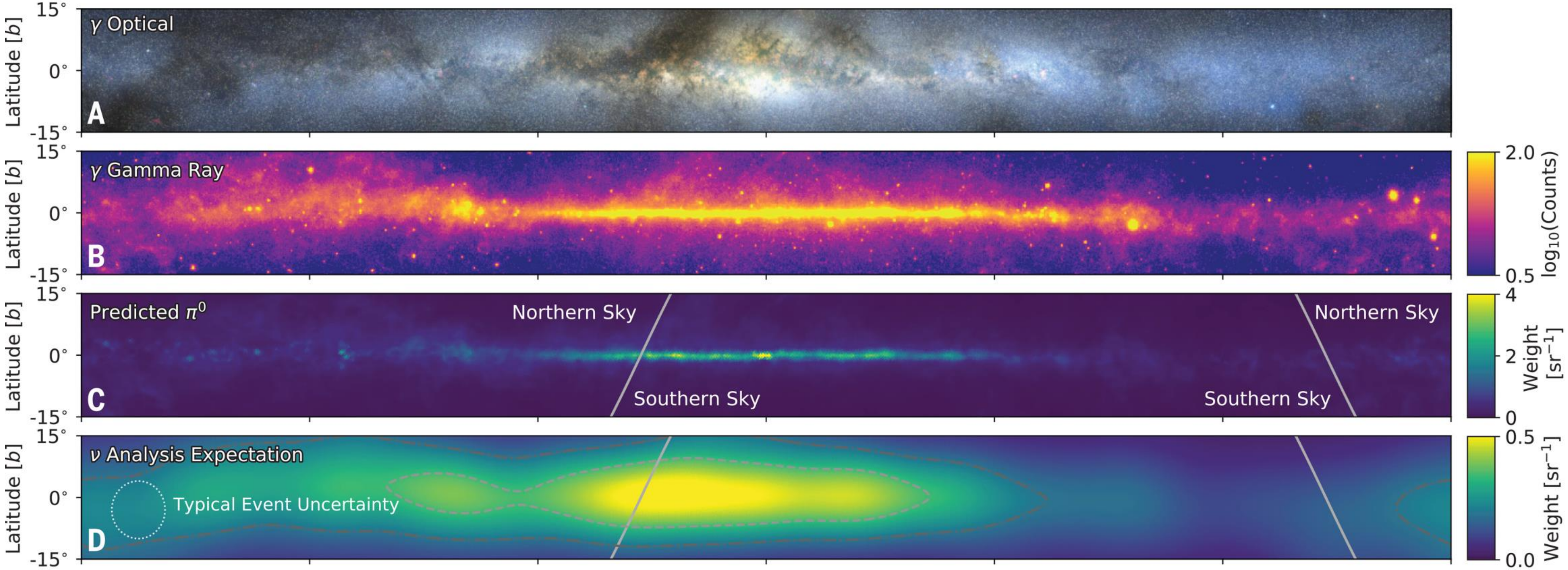
Extended Source: Galactic Plane



- Predicted template for neutrino emission from pions, that matches the observed gamma rays
- Most emissions are expected in southern sky → cannot use Northern tracks!

2307.04427

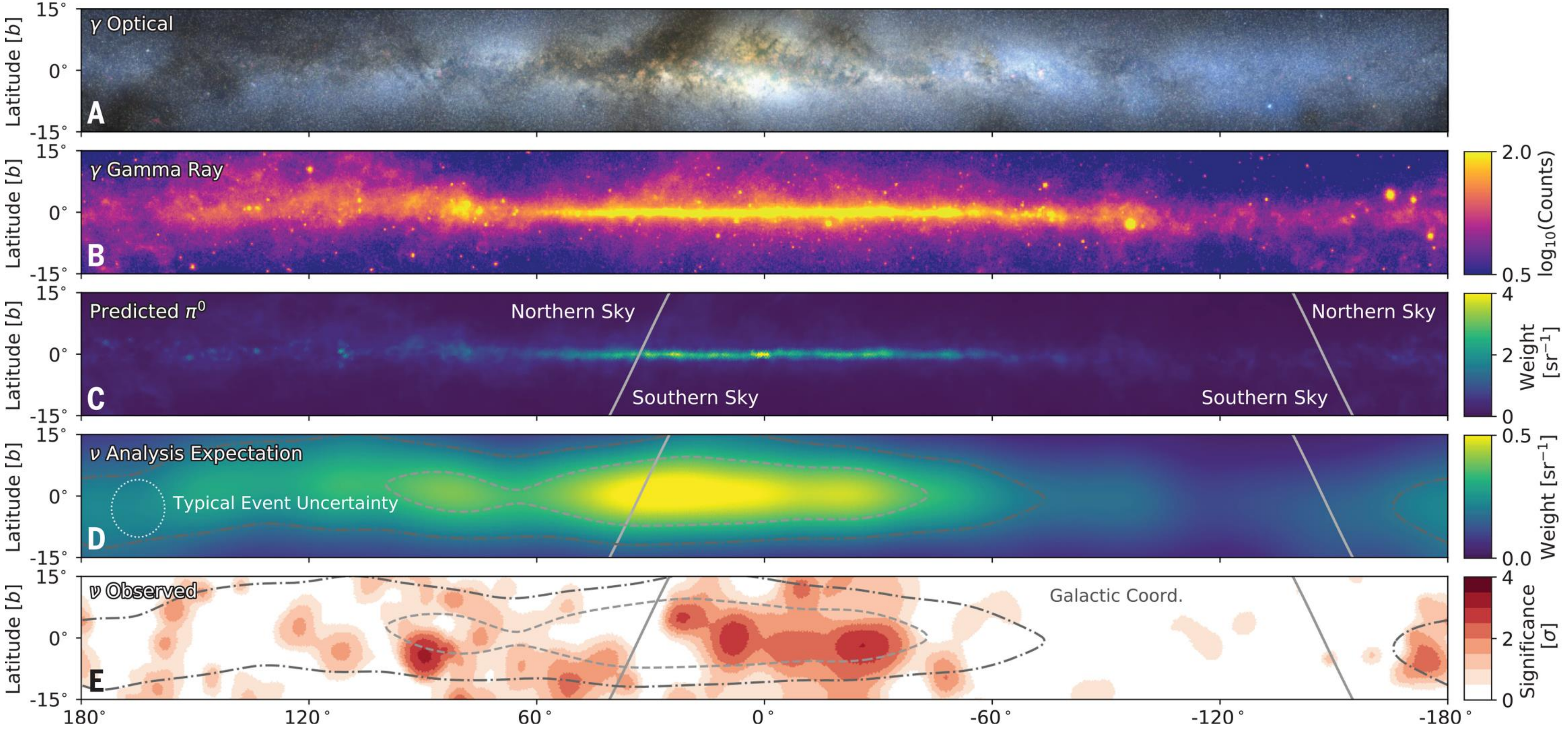
Extended Source: Galactic Plane



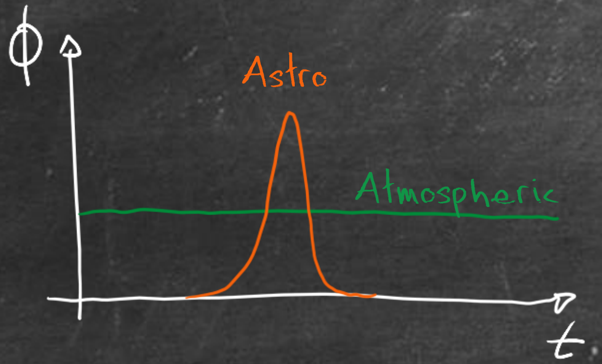
- Same template after applying selection and detector effects (cascades with angular resolution $\sim 5 - 10°$)

2307.04427

Extended Source: Galactic Plane



- Observed neutrinos in IceCube, 4.5σ significance above background

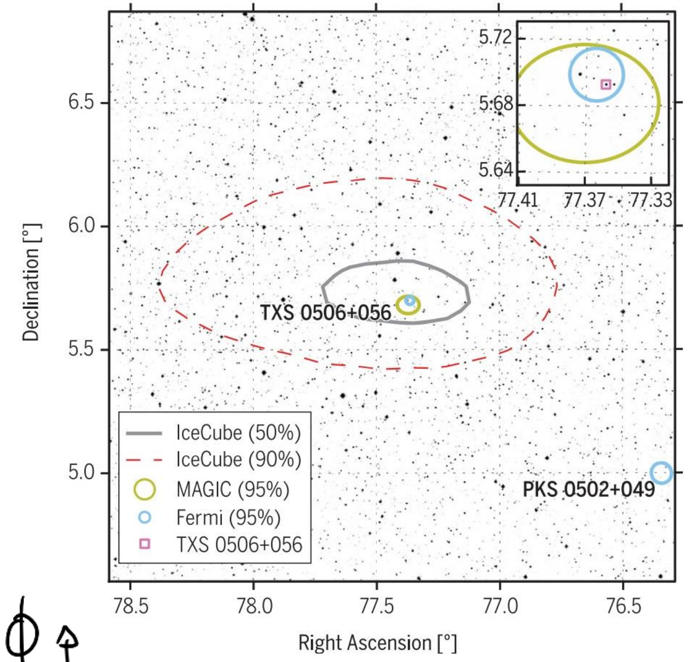


Transient Sources

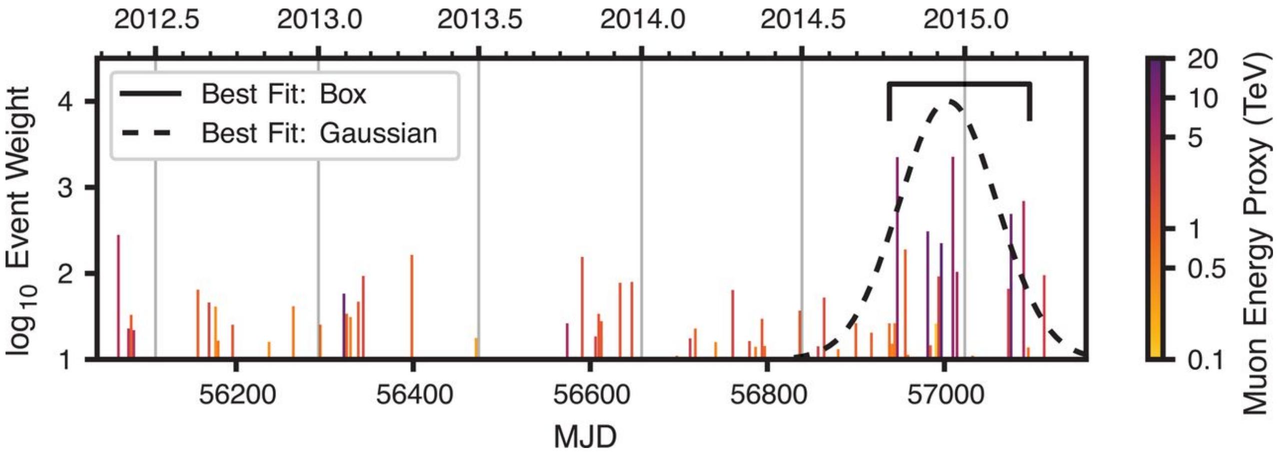
Transient Sources

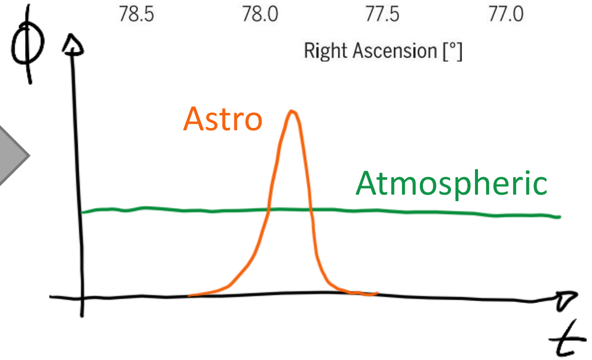
High energy neutrino alert from 2017:

- Follow-up studies (Fermi-LAT and MAGIC) identified the blazar TXS 0506+056 in a flaring state
- Analyzing all (previous) IceCube data, found a clustering of 13 ± 5 events around December 13 2014 from the same location



This blazar is situated in the night sky just off the left shoulder of the constellation Orion and is about 4 billion light years from Earth.



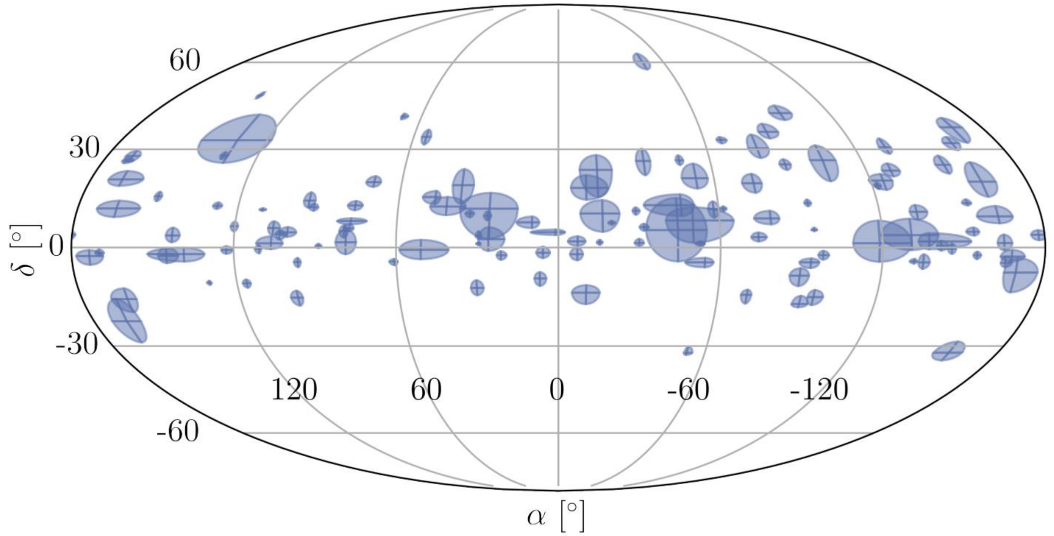


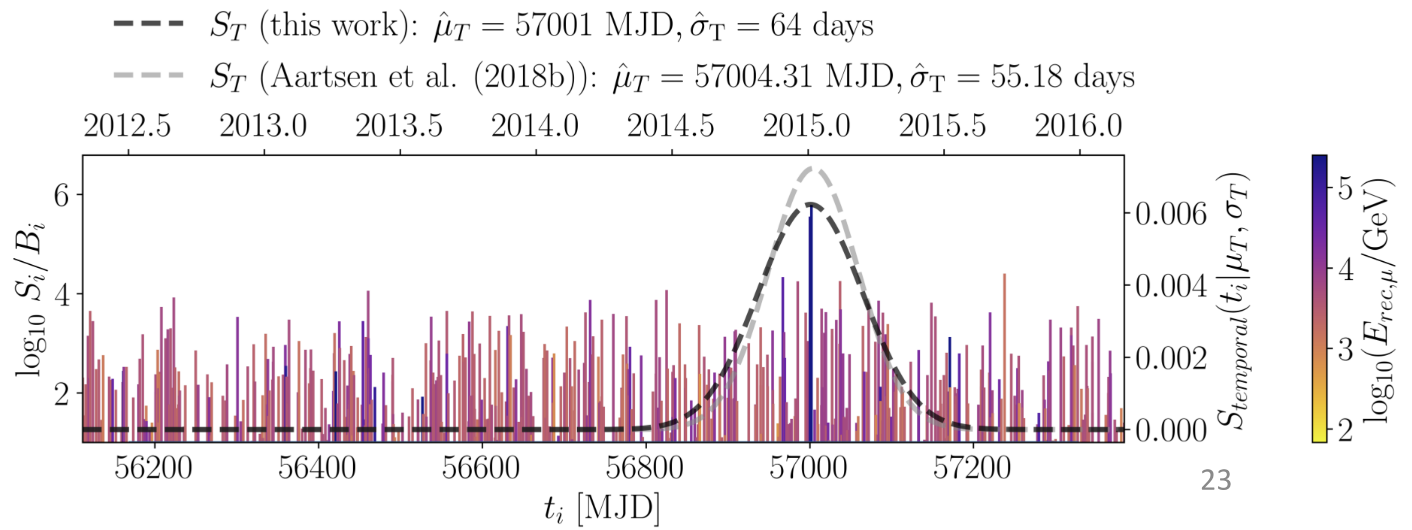
1807.08816 & 1807.08794

2309.12130

Search for more Transient Sources

- Since the TXS discovery, we have checked IceCube’s 122 highest-quality alert positions
- Only significant excess is still at TXS position (re-discovery)
- No other alerts could be associated with any contin-uous or transient emission





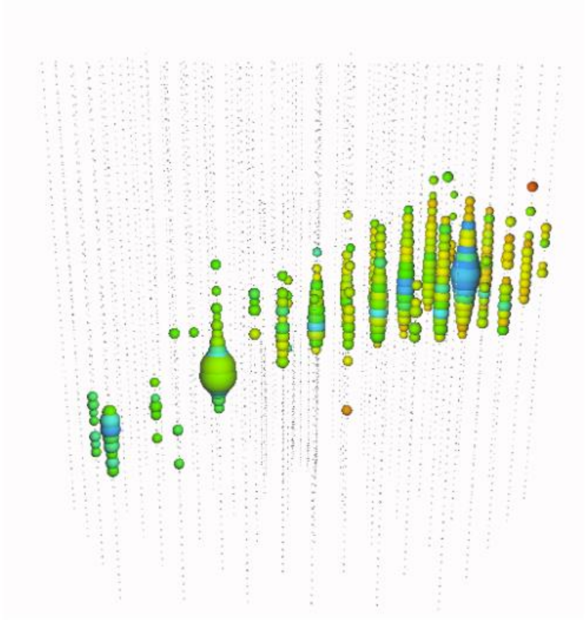
...what about tau neutrinos?

Tau Neutrinos

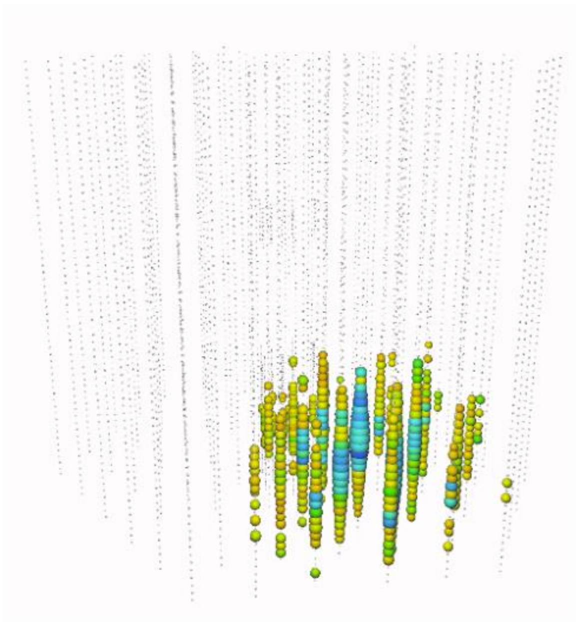
- We have seen:
  - **Tracks** (muon neutrinos)
    - → Diffuse Flux
    - → NGC1068 source
    - → TXS0506+056 blazar
  - **Cascades** (electron neutrinos)
    - → Diffuse Flux
    - → Galactic Plane

What about tau neutrinos?

"Tracks"
induced by ν_μ



"Casacdes"
induced by ν_e or NC interactions

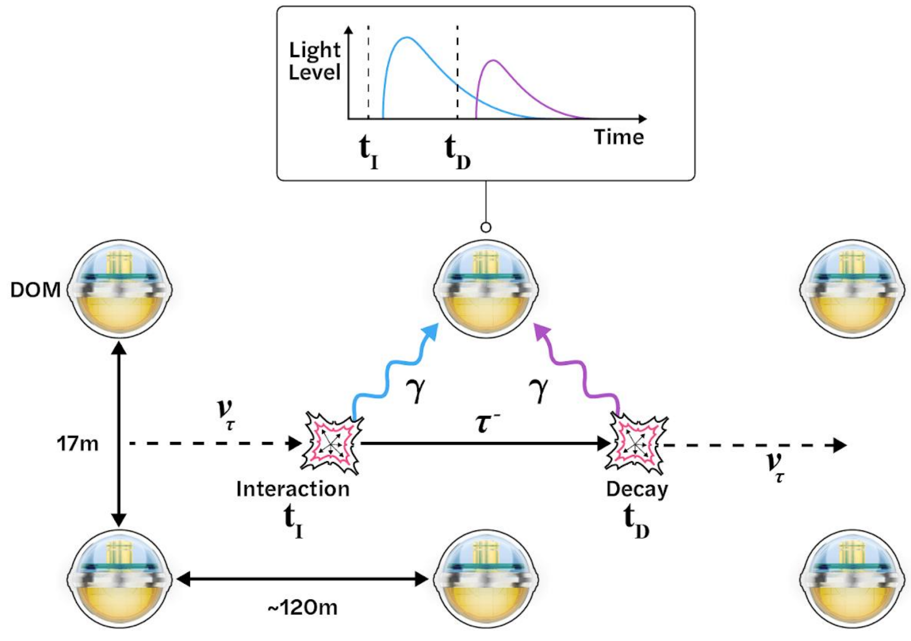


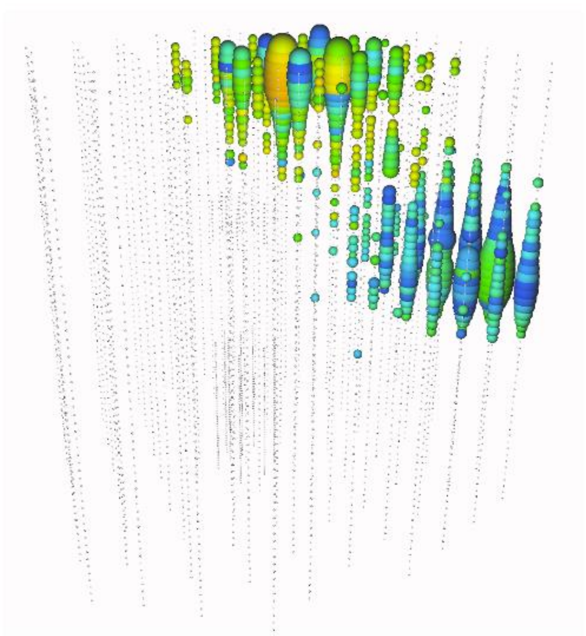
Tau Neutrinos

- A ν_τ **CC** interaction creates a τ lepton
  - Lifetime of 2.9×10^{-13} s
- If sufficiently energetic, it will travel several meters before decay (~50m / PeV)

→ Two separate vertices:
  - First: Initial **ν_τ interaction**
  - Later: **τ decay**

→ Double pulse signature

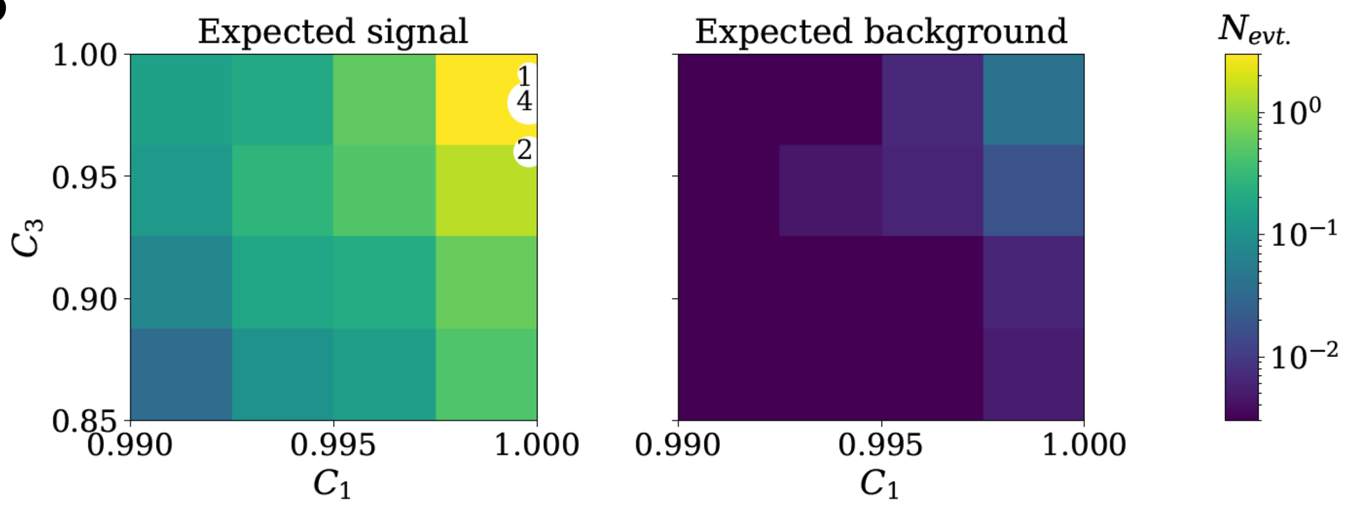


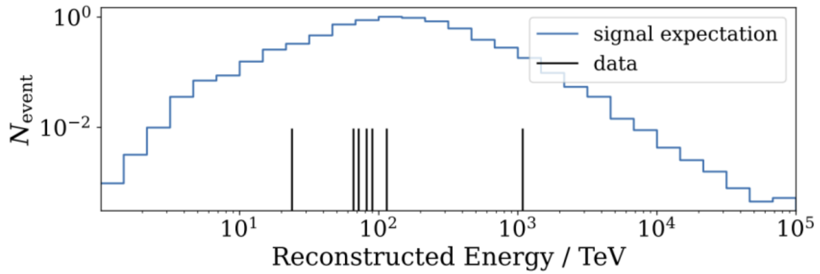


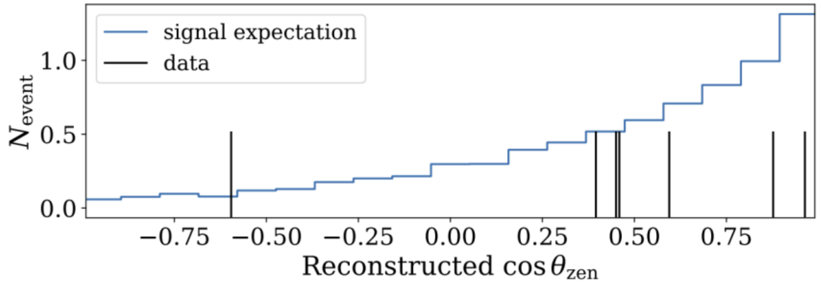
"Double Cascades"
induced by ν_τ

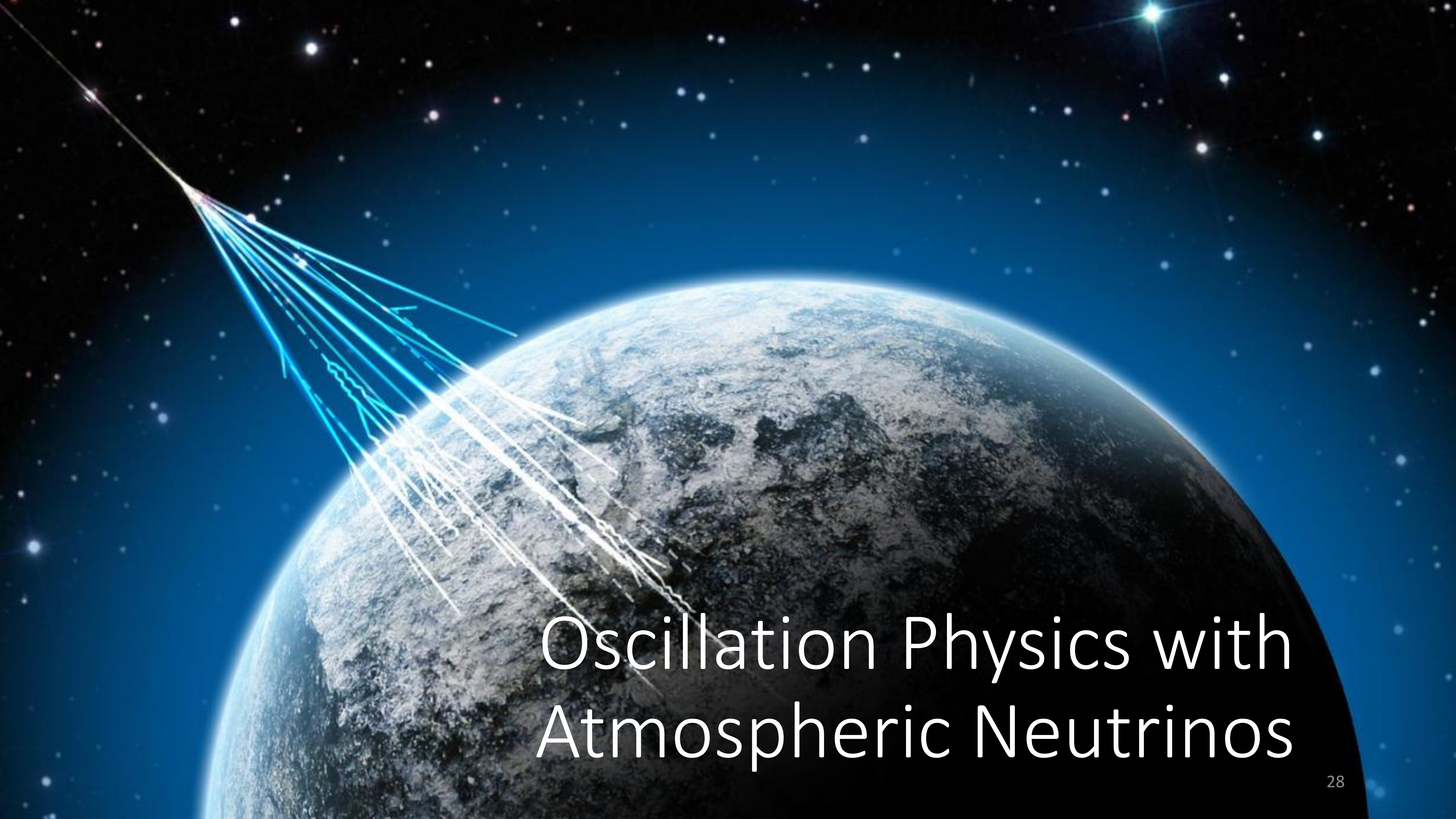
Tau Neutrino Results

- Using a new ML driven approach, in 9.7 years of data we expected:
  - 6.4 tau neutrinos
  - 0.5 background events
- We found 7 events in the signal region
  - One of these seven was also identified in a previous tau analysis
  - 5 sigma p-value for this being a background fluctuation









Oscillation Physics with Atmospheric Neutrinos

Neutrino Oscillations

Difference of mass eigenstates squared

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$

Length

Initial flavour

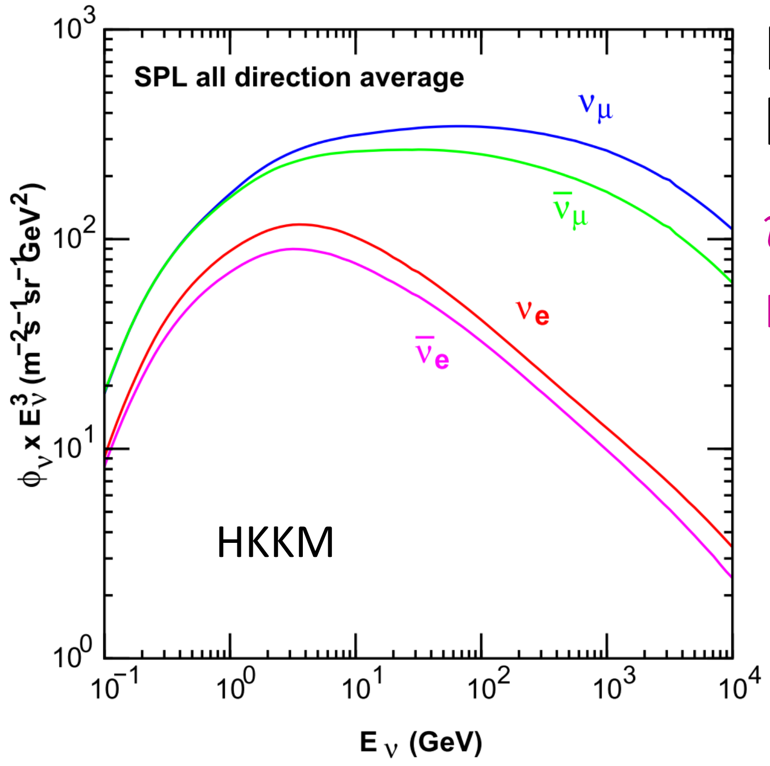
final flavour

Mixing Angle (PMNS)

Energy

Atmospheric Neutrinos

Oscillations are a function of $\boldsymbol{L/E}$ → what ***L***s and ***E***s do we have?



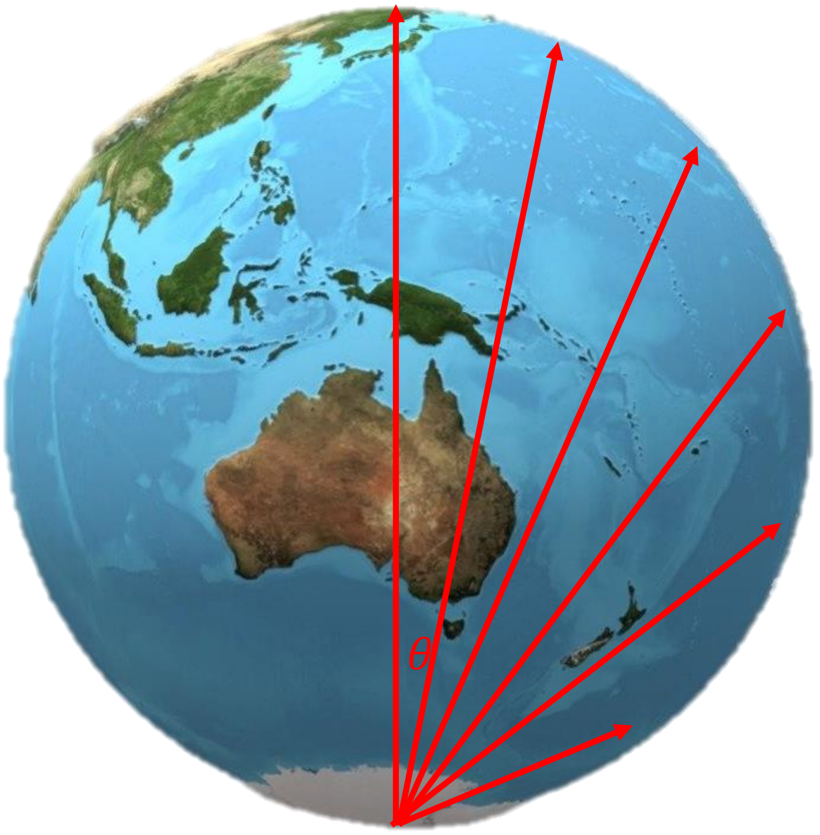
Flux from conventional pion / kaon decay

ν_μ / $\bar{\nu}_\mu$ and ν_e / $\bar{\nu}_e$ at Energies ranging from GeV to TeV

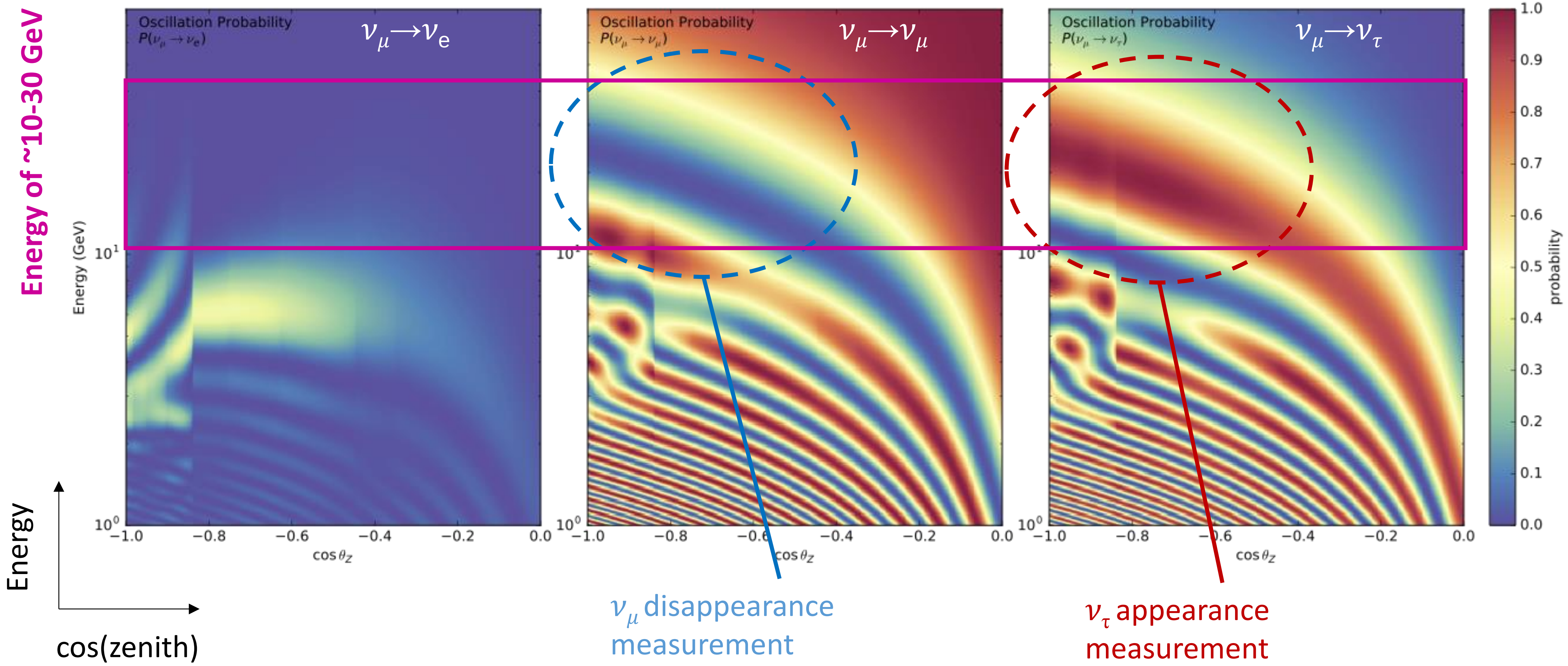
Distance L depending on zenith

$$L \approx 12700\ km \cdot \cos\theta$$

→ Baselines ranging from ~20 km to 12700 km



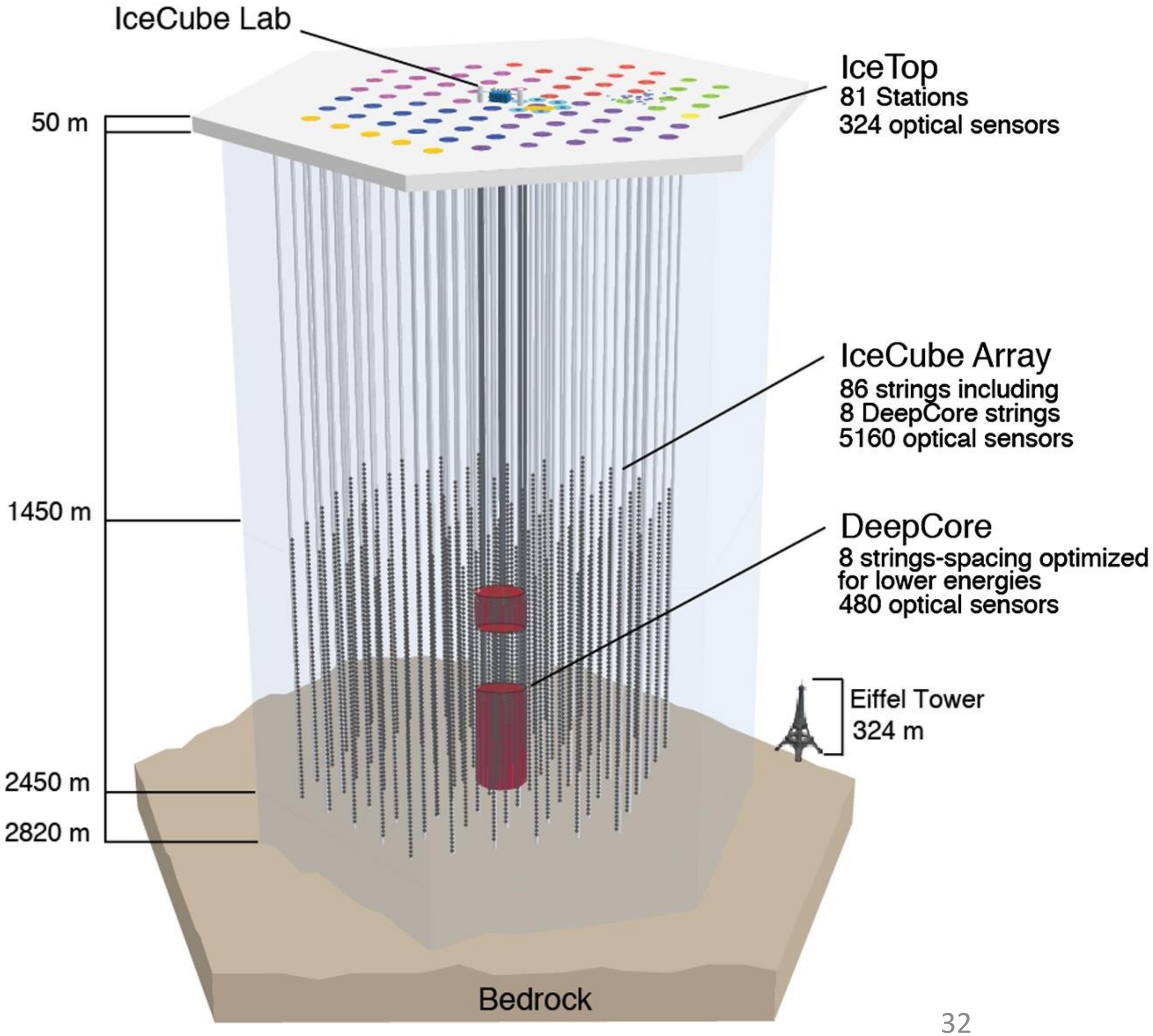
Atmospheric Oscillations



Need to go lower in Energy!

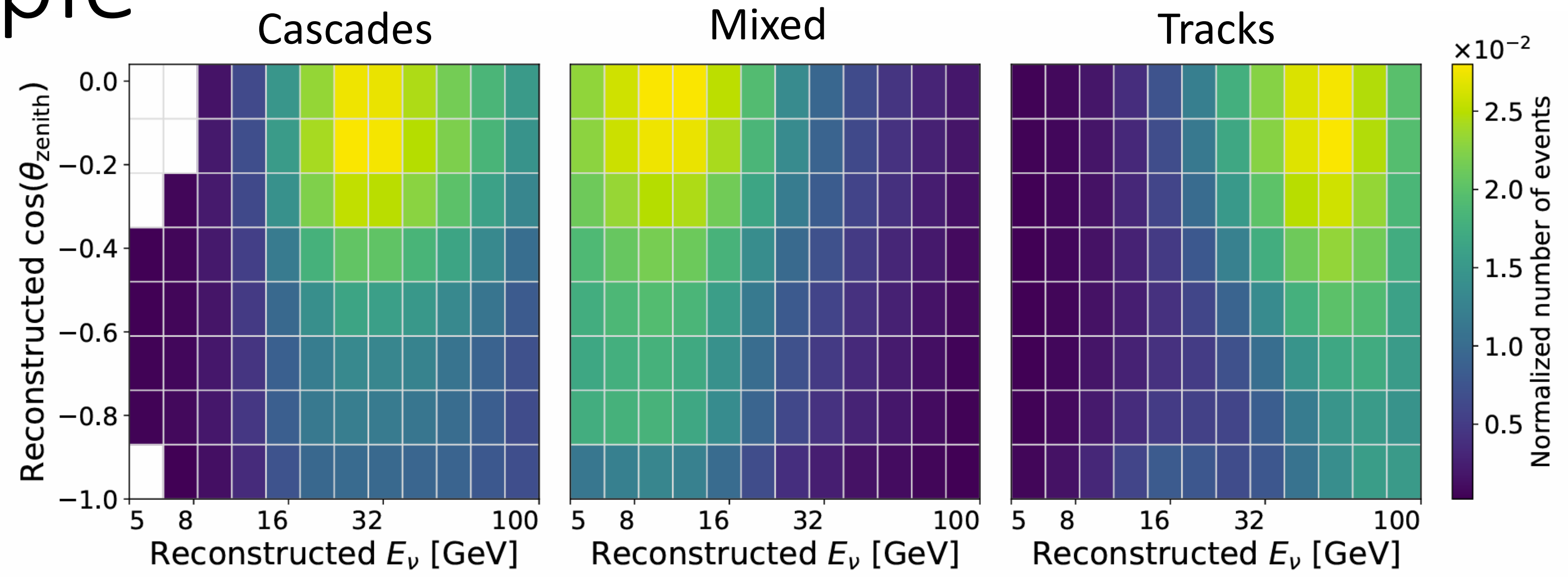
- IceCube's detector spacing is too wide
  - →Energy threshold ~100 GeV

- We **need the DeepCore** sub-array
  - 8 innermost detector strings with HQE PMTs
  - and denser instrumentation
  - → Energy threshold ~5 GeV

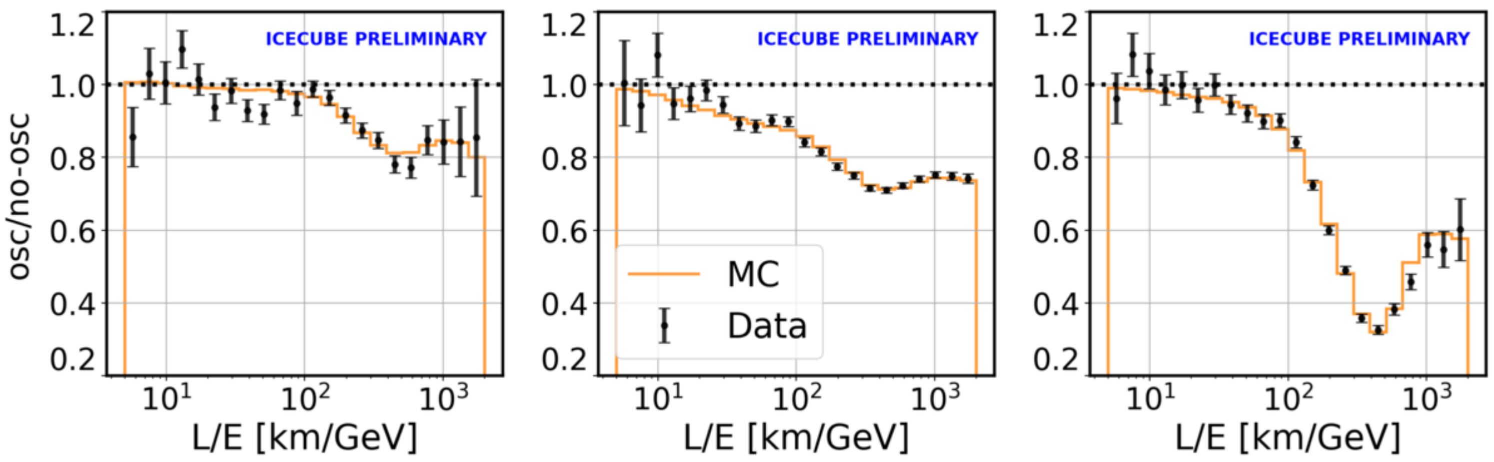


DeepCore Sample

- Using 9.3 years of data
- Using both, cascades and tracks
- New ML-based selection and reconstruction
- Total sample consiting of ~150k Neutrinos

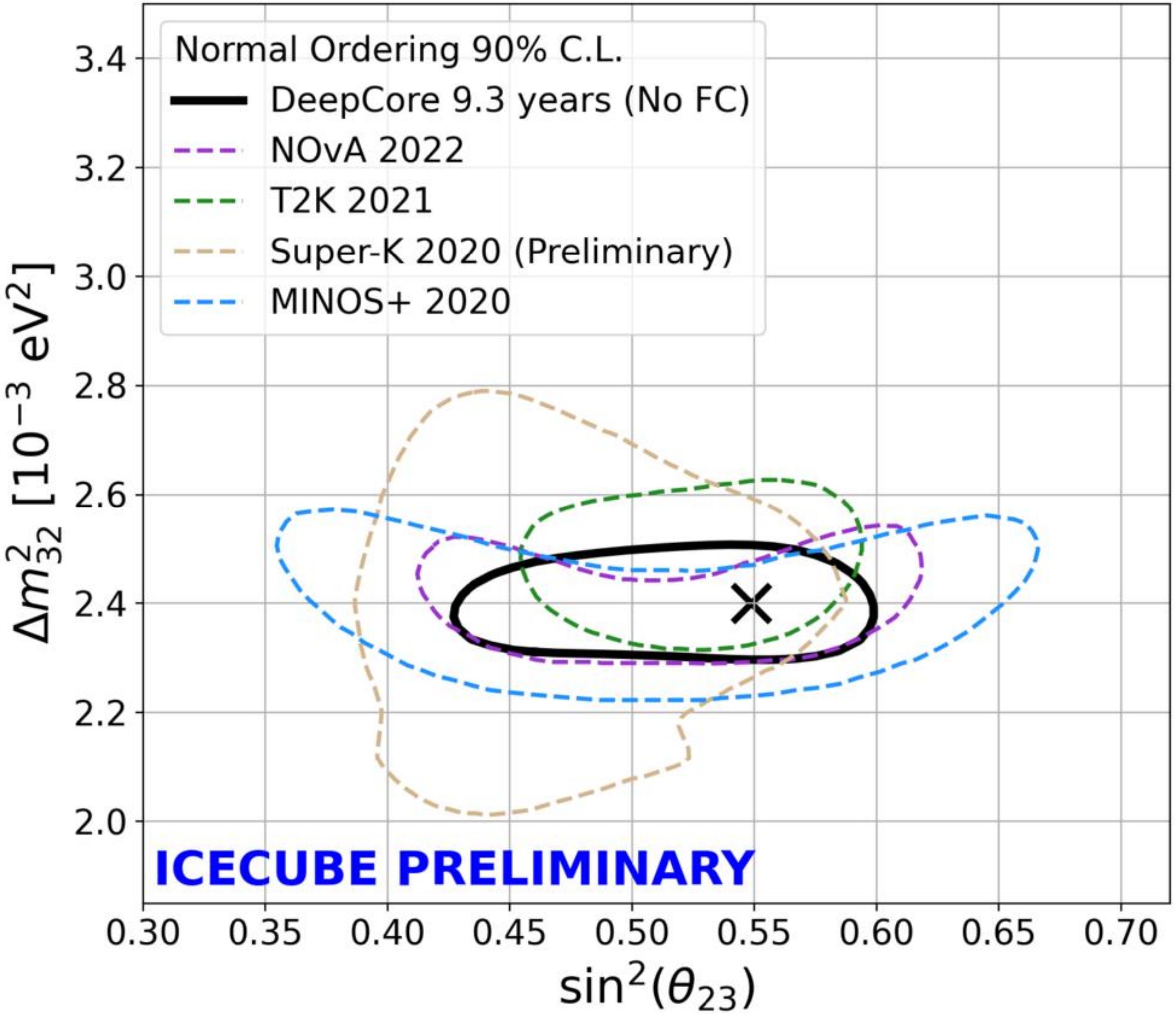


↓ L/E projection to better visualize oscillation pattern ↓



DeepCore Results

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \frac{\Delta m^2}{4E} L$$



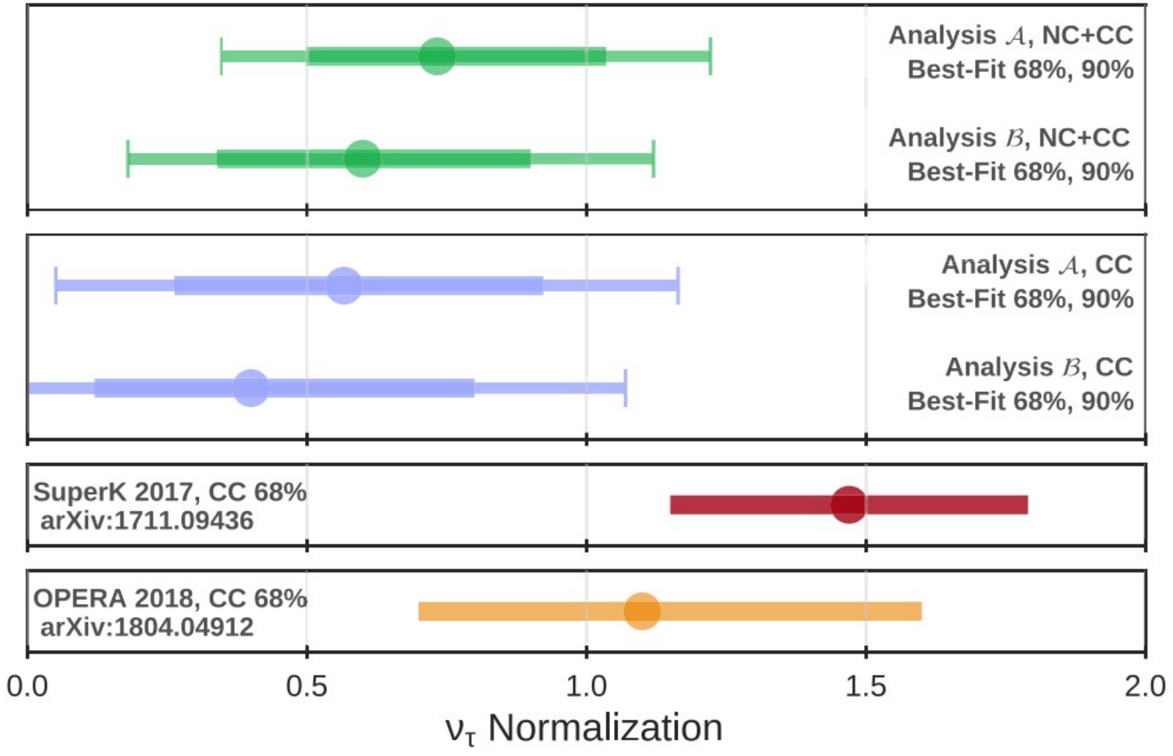
- Competitive measurement of atmospheric mixing parameters
  - Rivaling precision of dedicated long-baseline accelerator experiments (T2K, NOvA, MINOS)
  - Best measurement using atmospheric neutrinos
  - PRL coming out soon (https://arxiv.org/abs/2405.02163)

What about tau neutrinos, again?

- Challenging measurement
  - ν_τ CC threshold energy ~3.5 GeV
  → Out of reach for most LBL experiments (e.g. T2K, NOvA)
  - Suppressed cross section
  - Appearance in cascade channel (more difficult to reconstruct)

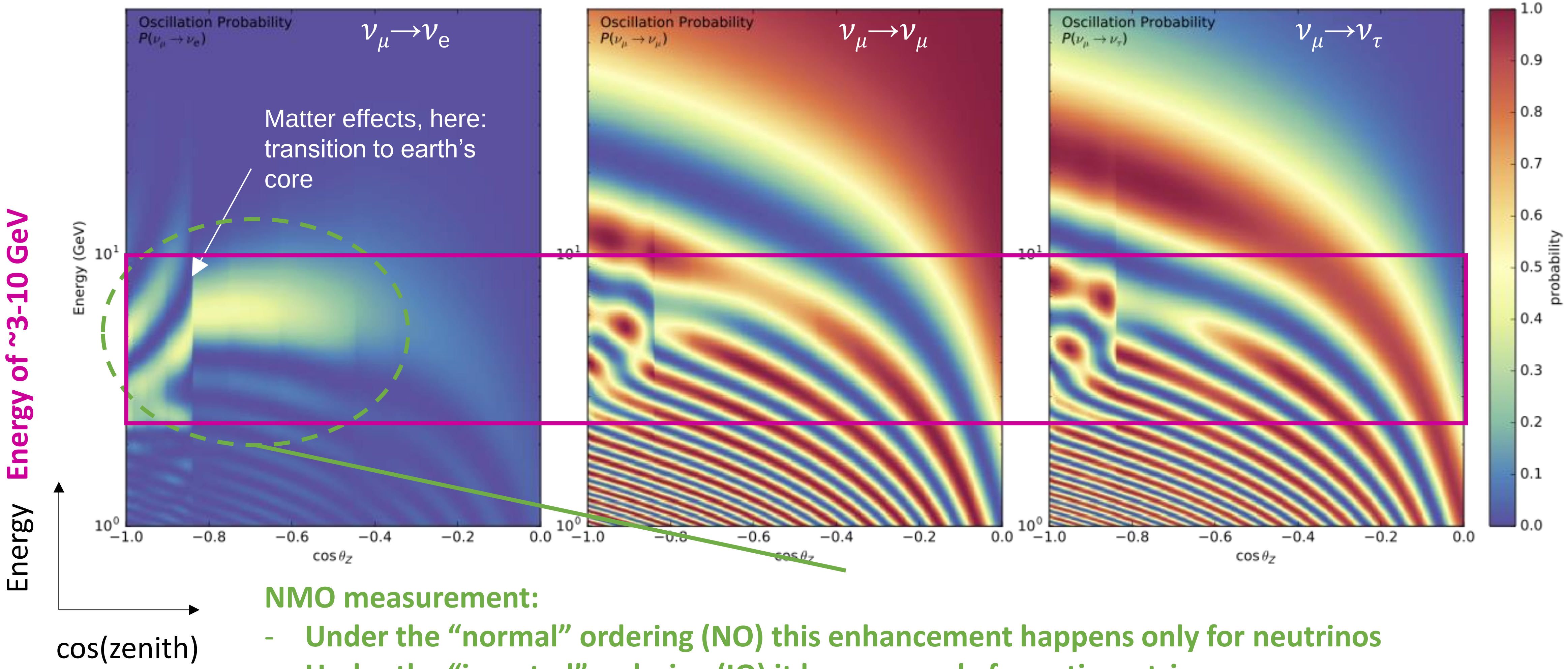
- So far, results consistent with expectations (=1.0)

DeepCore 3 years



IceCube 1901.05366

Atmospheric Oscillations

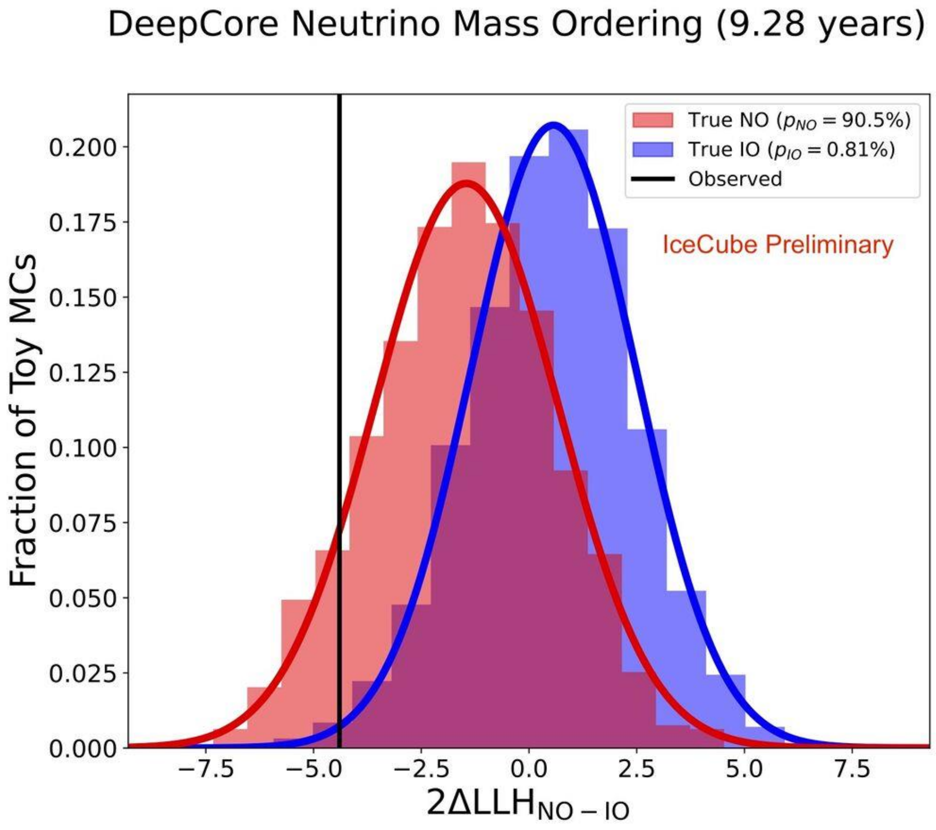


NMO measurement:
- Under the "normal" ordering (NO) this enhancement happens only for neutrinos
- Under the "inverted" ordering (IO) it happens only for anti-neutrinos

Neutrino Mass Ordering with DeepCore

- First result with 9.3 years of DeepCore data
- Slight preference for NO:
  → 1.72 sigma to reject IO in favour of NO using CLs method
- Analysis not sensitive enough to expect large gains in the near future
- Real issue is accessing neutrinos with low enough (<10 GeV) energy

→ Need to go lower in energy, again!



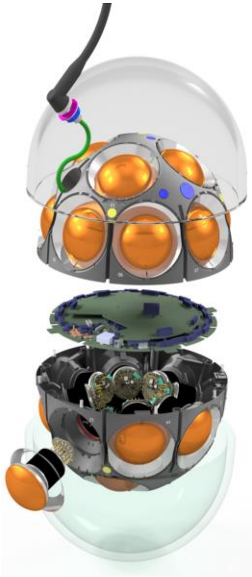
IceCube Upgrade

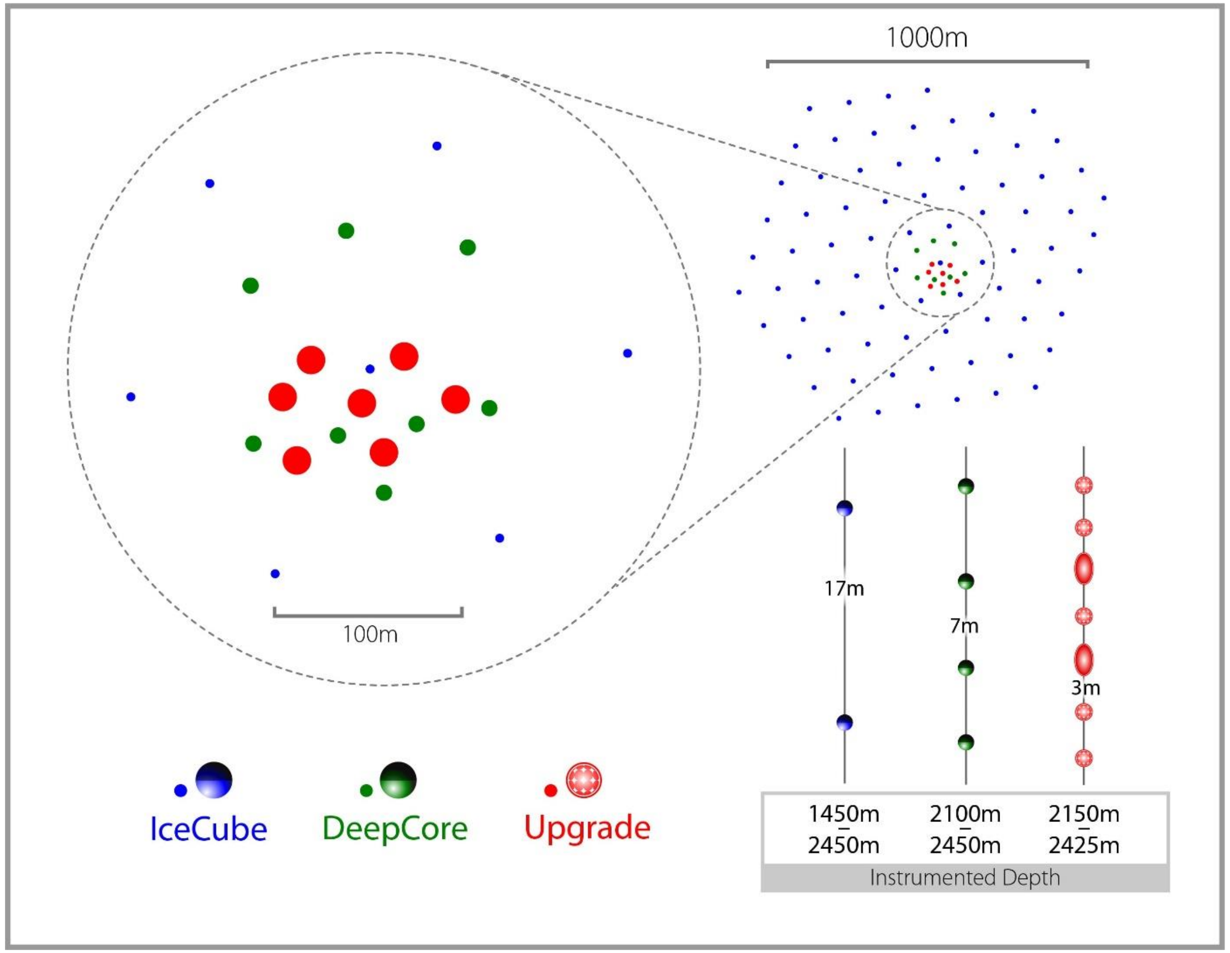
→ we are going back to Pole next Winter to drill!

IceCube Upgrade

- 7 new detector strings in center of IceCube
- Total of 680 multi-PMT modules
  - mDOMs: 24x 3” PMTs
  - dEggs: 2x 8” PMTs

  → **over 10’000 additional PMTs**, more than tripling the number of channels of the existing IceCube!





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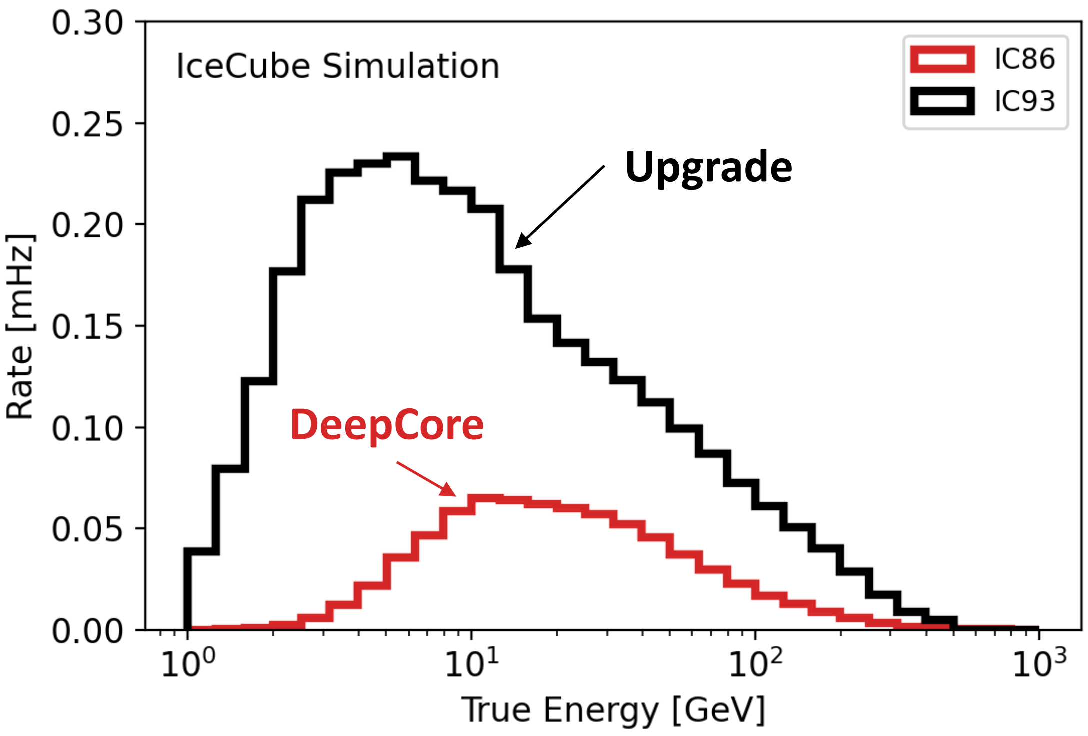
IceCube Upgrade

- Much increased event rates in the oscillation regime
- Even denser instrumentation than DeepCore
  →Energy threshold of ~2 GeV
- Additional calibration devices and R&D modules
- Scheduled to be installed in field season 2025/26

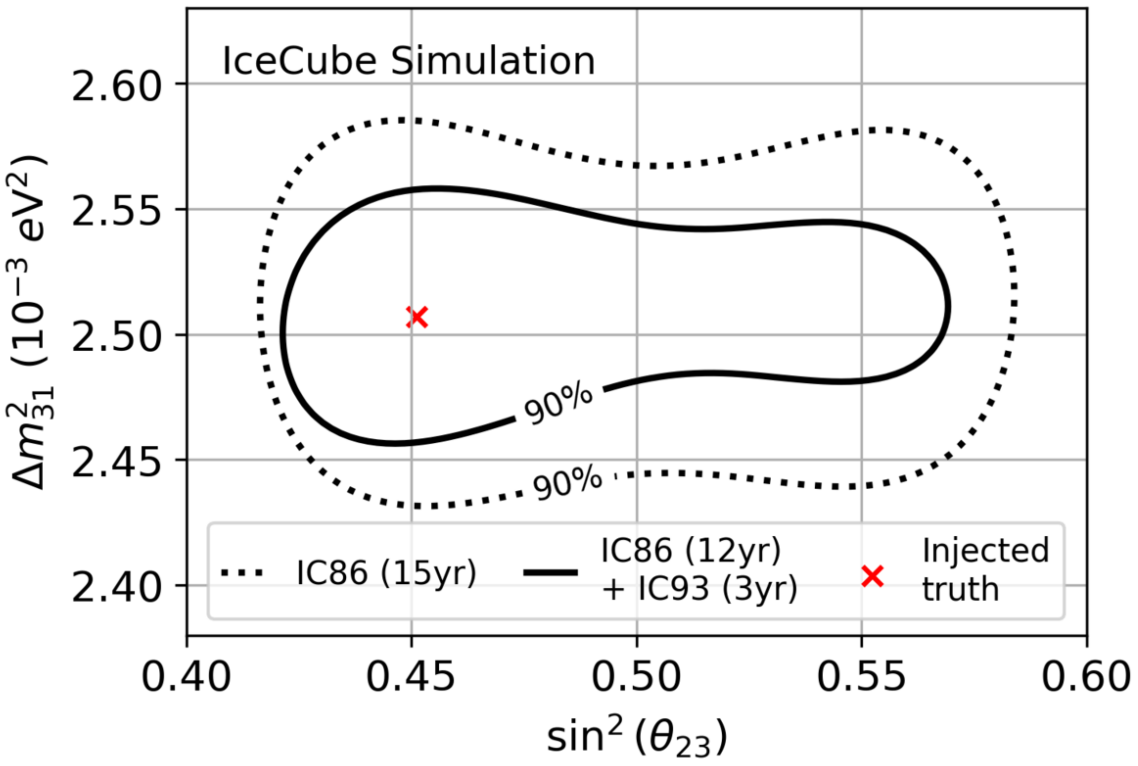


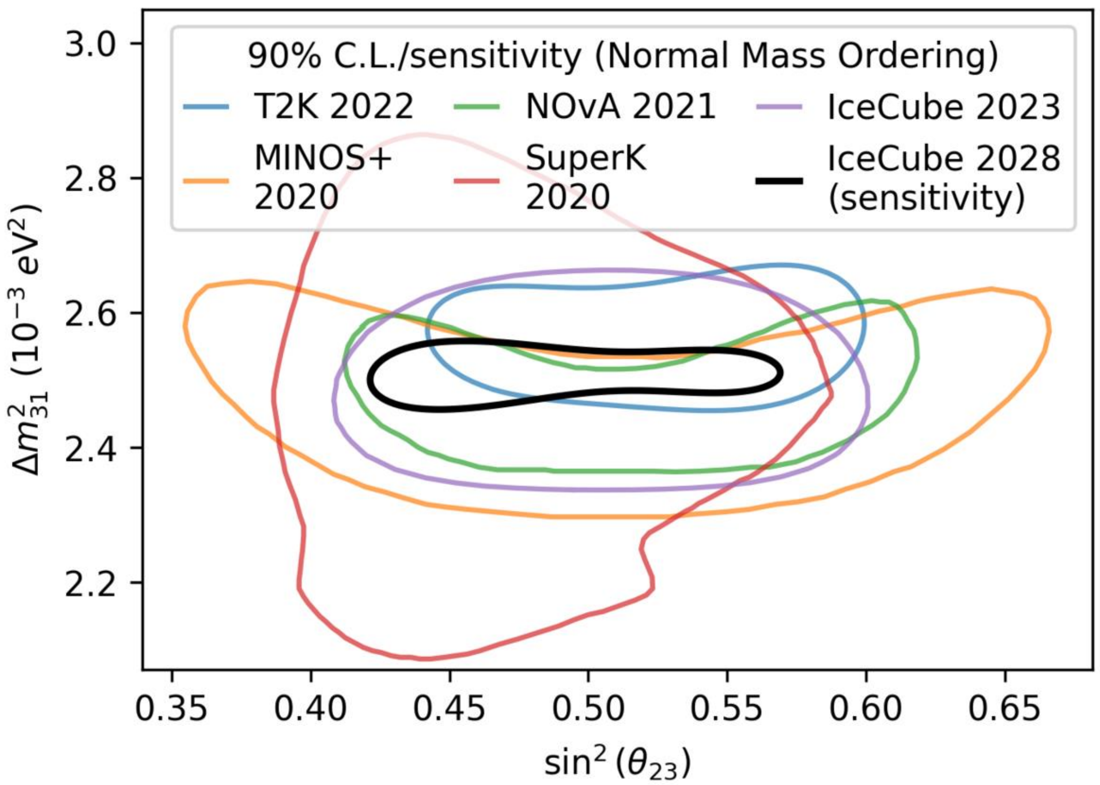
Precision **O**ptical **C**alibration **M**odule (**POCAM**)

2307.15295

Upgrade Oscillation Sensitivities

- Upgrade will deliver sensitivities ~2 × better than DeepCore alone





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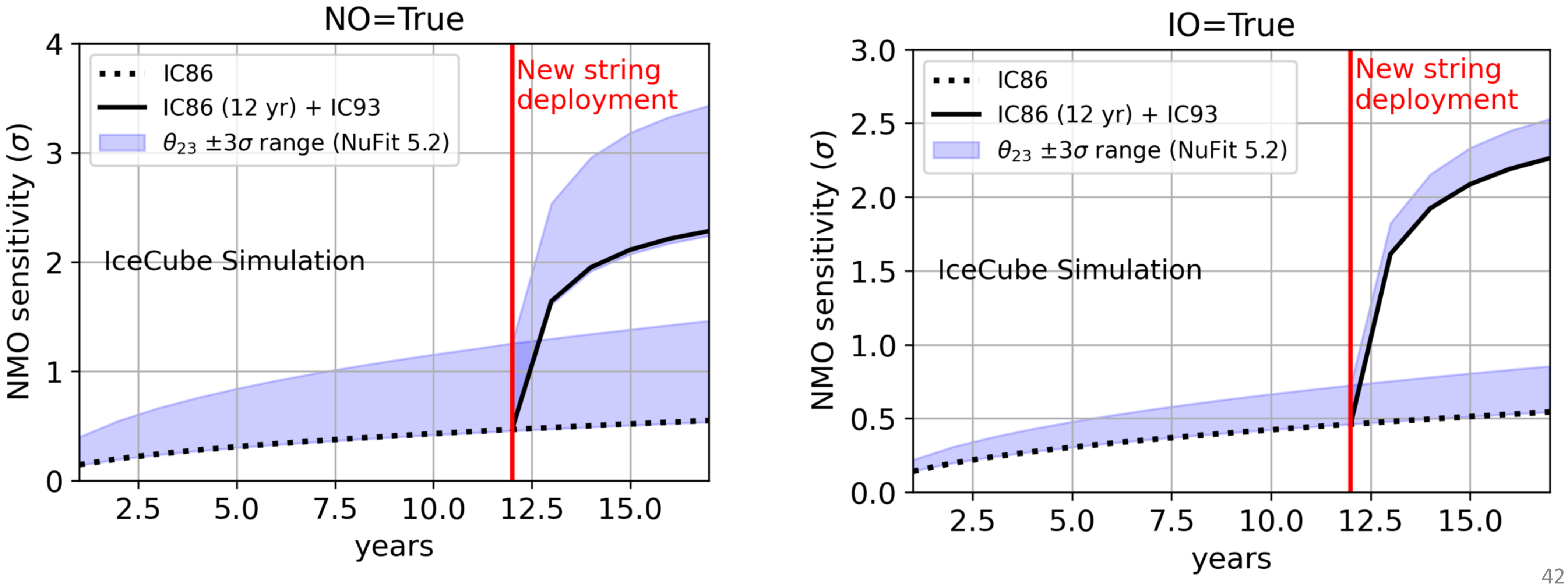
Neutrino Mass Ordering with IC Upgrade

Upgrade strongly enhances sensitivity to the Neutrino Mass Ordering

→ 3σ significance in reach with few years of data



Summary

- Several astrophysical neutrino sources detected:
  - Steady emission from NGC 1068
  - Neutrinos from Galactic plane
  - Transient emission from TXS 0506+056
  - Still, ~90% of diffuse flux yet unaccounted for

  → Much more to discover
- Oscillation physics with Atmospheric Neutrinos:
  - Using DeepCore allows us to measure neutrino oscillations

  → Competitive with dedicated oscillation experiments
- IceCube Upgrade Detector:
  - New detector hardware and calibration devices
  - To be installed in Winter 2025/26
  - Enhancing IceCube's low-energy capabilities

  → Exciting new data for oscillation physics, and recalibration of the entire IceCube detector

THANK YOU!