Next Generation Diffuse Neutrino Combined Fit: Inclusion of Multi Flavor Neutrinos Partially Contained in IceCube

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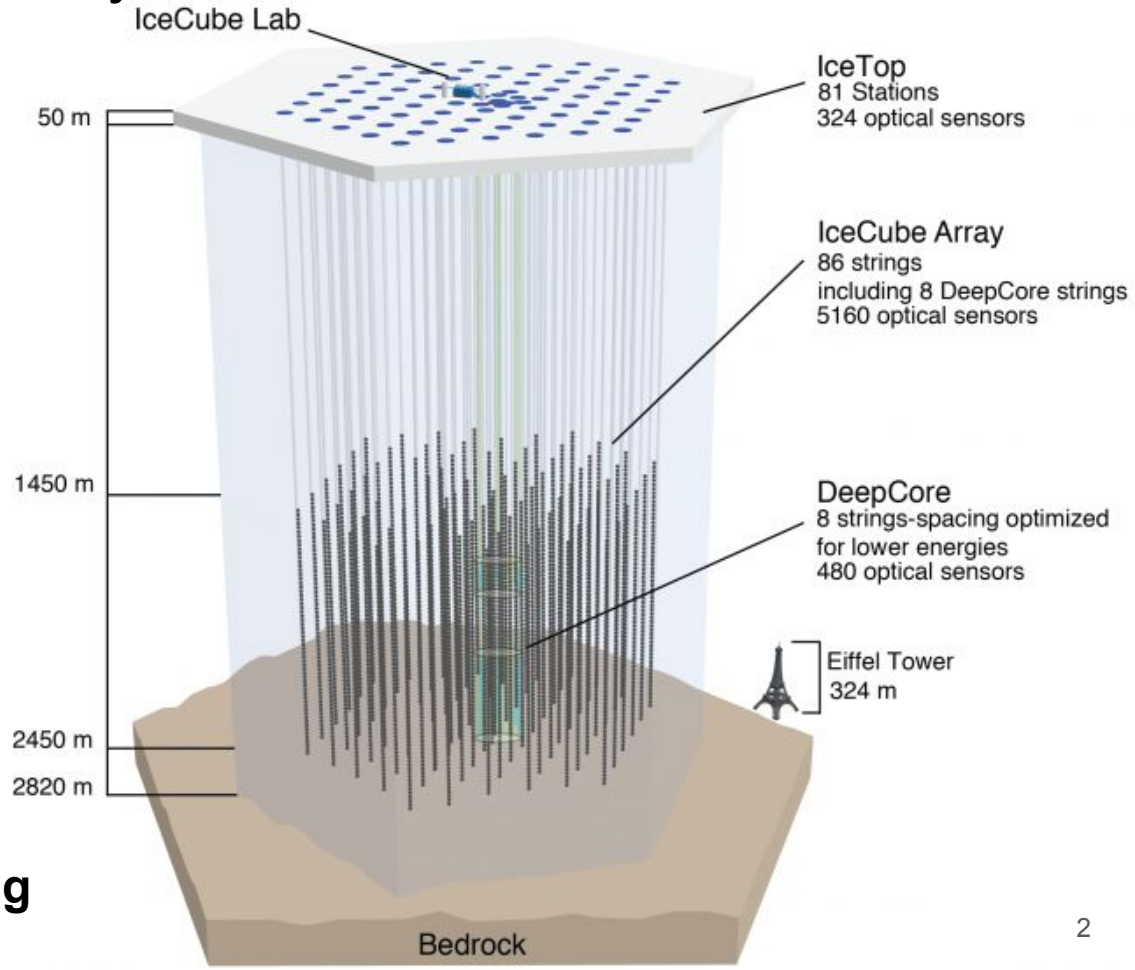
IceCube Neutrino Observatory

- Array of 5160 Digital Optical Modules (DOMs) arranged 1400m to 2500m from ice surface at South Pole

- Cherenkov light emitted by neutrino interactions, seen by DOMS

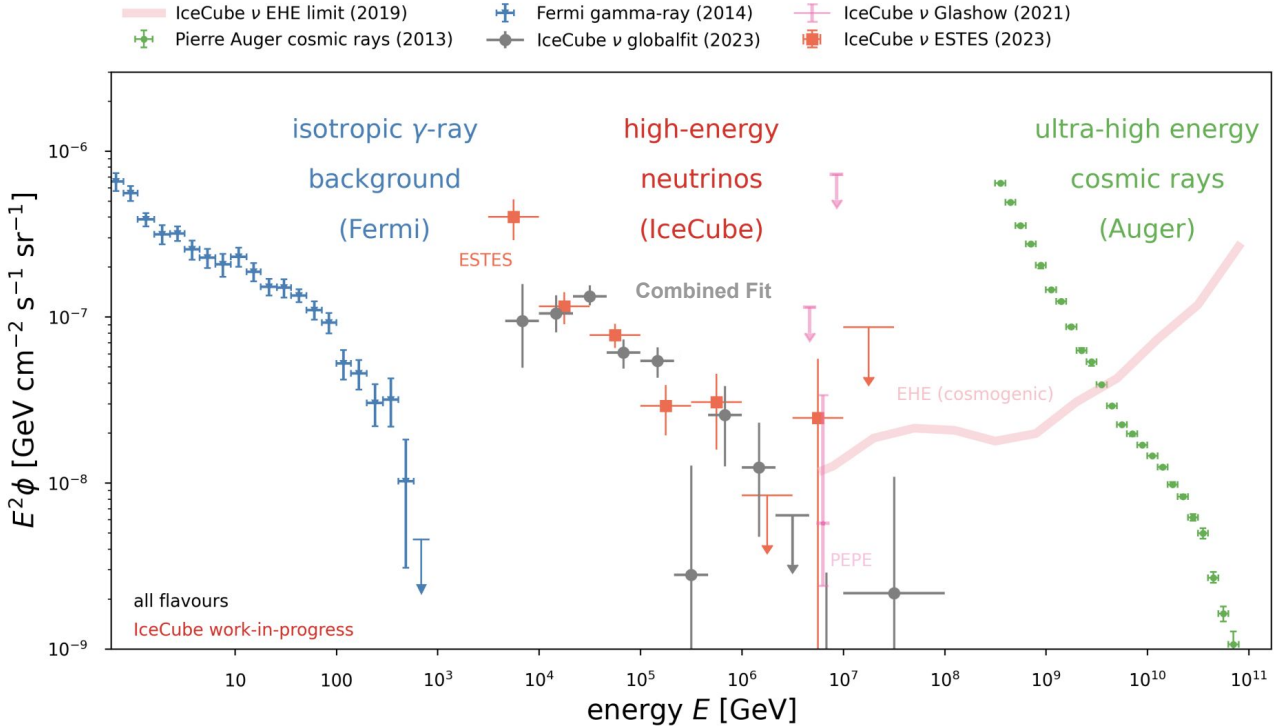
- Interacting particle direction, energy, and other observables used for analyses

One analysis type→ characterizing the astrophysical diffuse flux



The Diffuse Astrophysical Neutrino Flux

Neutrinos are products of hadronic interactions, and their flux can tell us about their production mechanisms



Characterize flux in most sensitive energy range possible

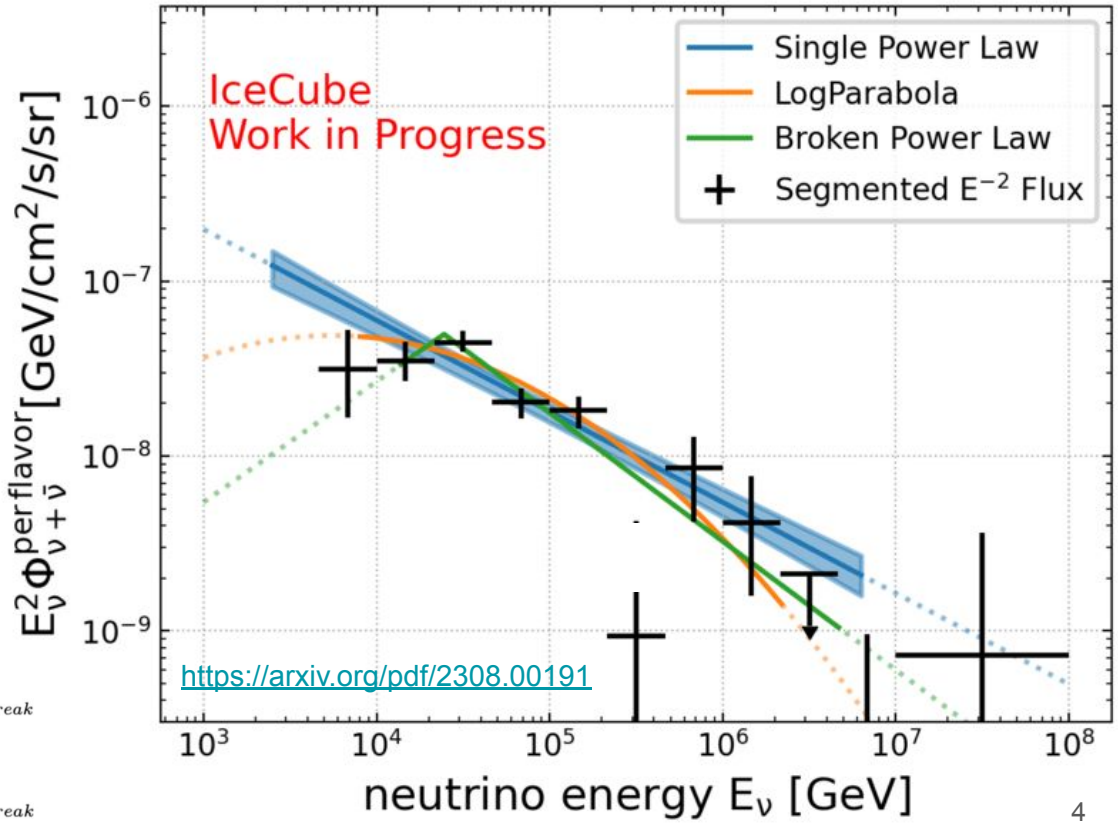
Characterizing the Astrophysical Diffuse Spectrum

What does the fit say about the spectrum?
Neutrino production mechanisms

How to characterize something like this →

- Physics parameters
- Systematic parameters
- Atmospheric parameters

Combined Fit



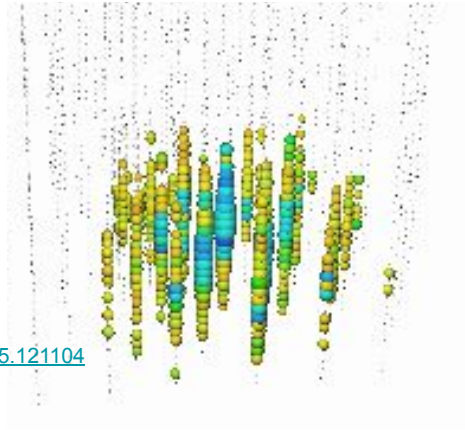
$$\Phi = \Phi_0 \left(\frac{E}{E_{break}} \right)^{-\gamma_x} \qquad \gamma_x = \gamma_1 \quad E < E_{break} \qquad \gamma_x = \gamma_2 \quad E > E_{break}$$

Merging Event Selections in Ice Cube → The Combined Fit

Cascades

High energy resolution increases sensitivity to constrain energy spectrum

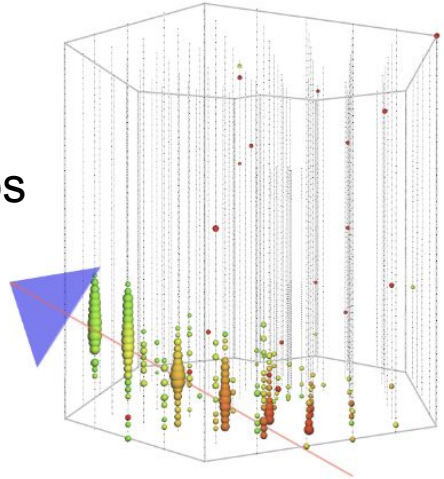
https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.125.121104



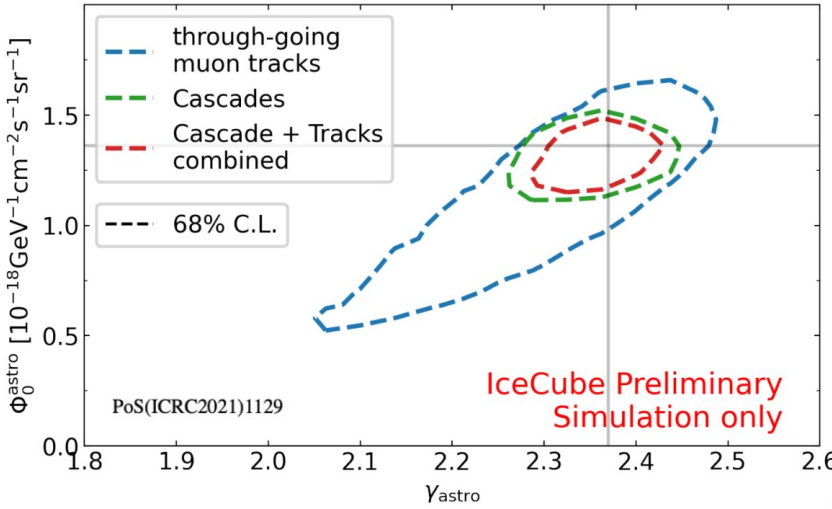
Northern Tracks

High statistics and angular resolution helps contain atmospheric fluxes and detector systematics

https://arxiv.org/abs/2111.10299

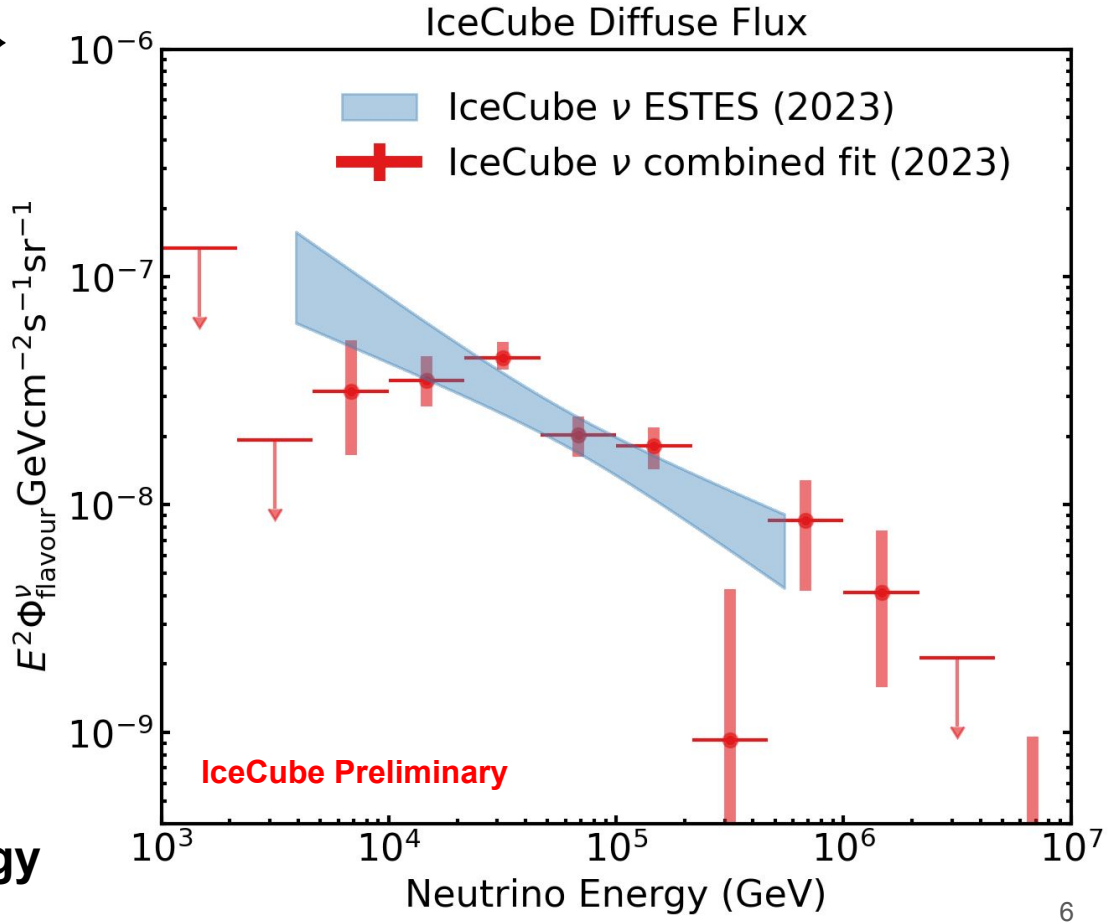


Single power law sensitivity (10 years data)



Recent Diffuse Characterization using Combined Fit

- Statistical deviation from SPL → BPL favored
- Primarily due to flux hardening below 30 TeV
- Unresolved Features across energy spectrum
  - neutrino flux < 30 TeV
  - bump at ~30 TeV
  - dip near ~500 TeV
  - neutrino flux > 10 PeV

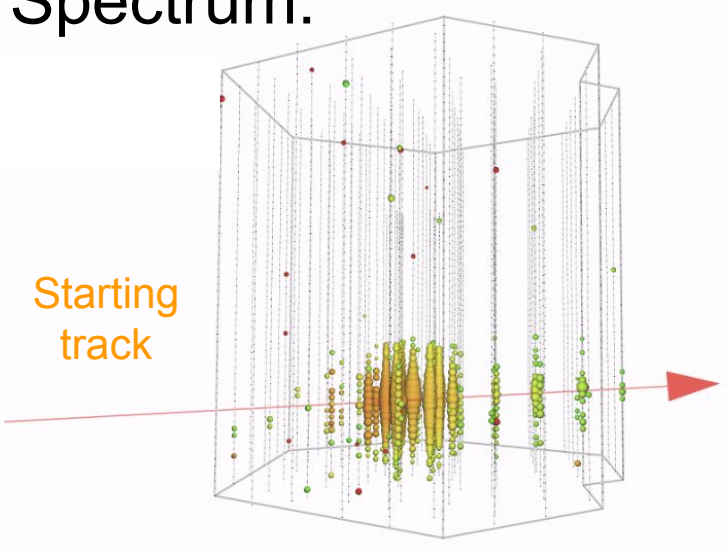


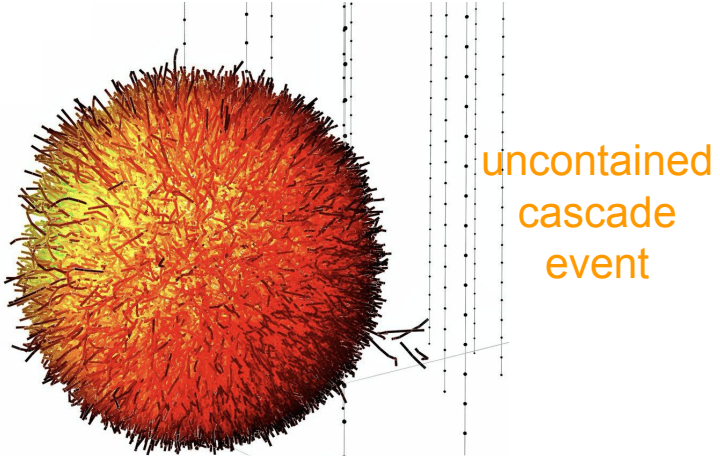
Need stronger constraint on energy spectrum to resolve features

Resolving Features Across the Energy Spectrum: Next Generation Combined Fit

- New Combination of Event Selections
  - Northern Tracks sample from previous existing combined fit
  - **High energy starting tracks** https://arxiv.org/abs/2011.03545
    - Full sky sample
    - Energy and Angular resolution
    - Astrophysical purity in southern sky at high energies > 60 TeV
  - **New cascades sample**
    - All flavor, full sky sample
    - Contained and **Uncontained**
    - High statistics energy resolution across energy spectrum (1 TeV to 100 PeV)

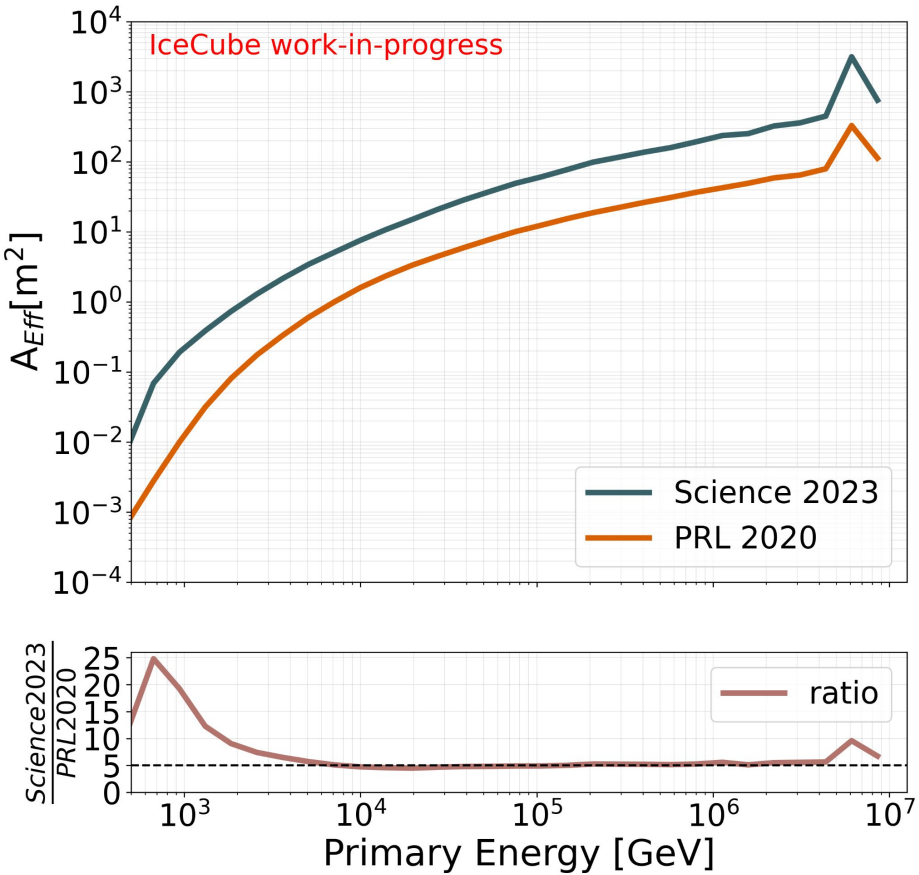
- Systematic Uncertainties
  - Antarctic Ice
  - Atmospheric Neutrino Flux



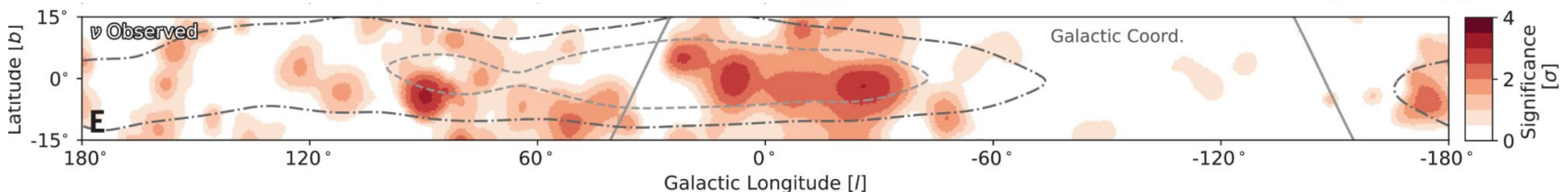


New Cascades Sample

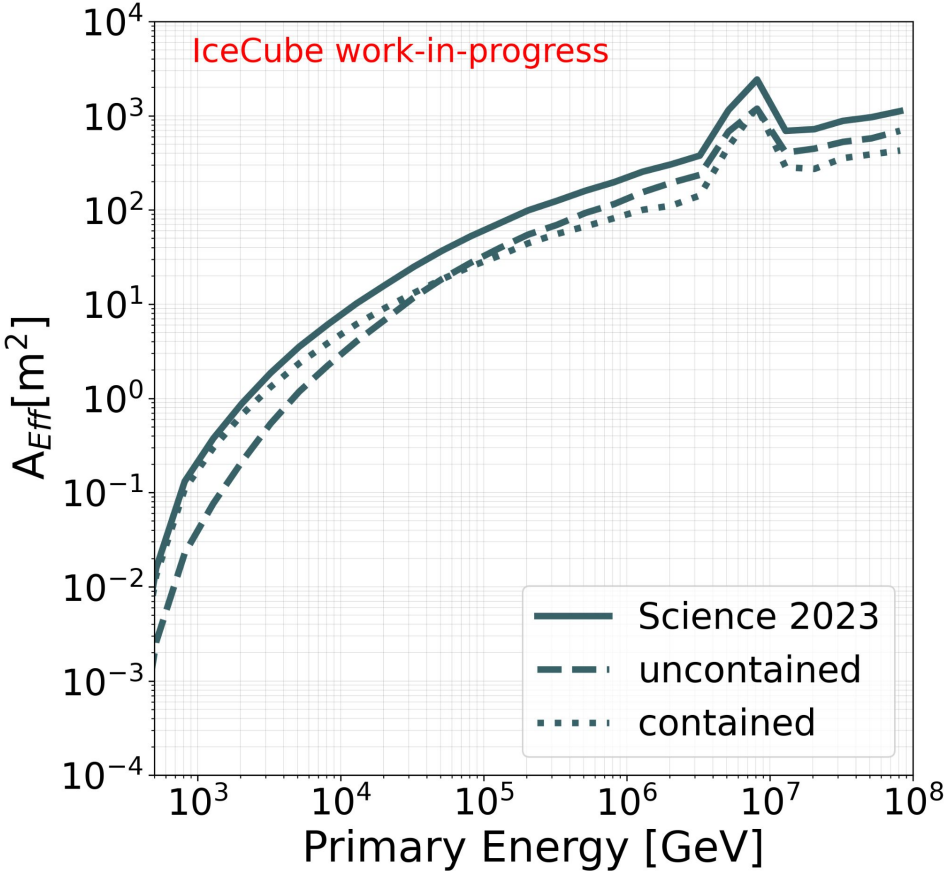
- **Deep Neural Networking Cascades event selection (DNNCascades)**
- Discovery of high energy neutrinos in Galactic Plane
- ~5x effective area across energy spectrum
- Undergoing optimization for an independent diffuse analysis

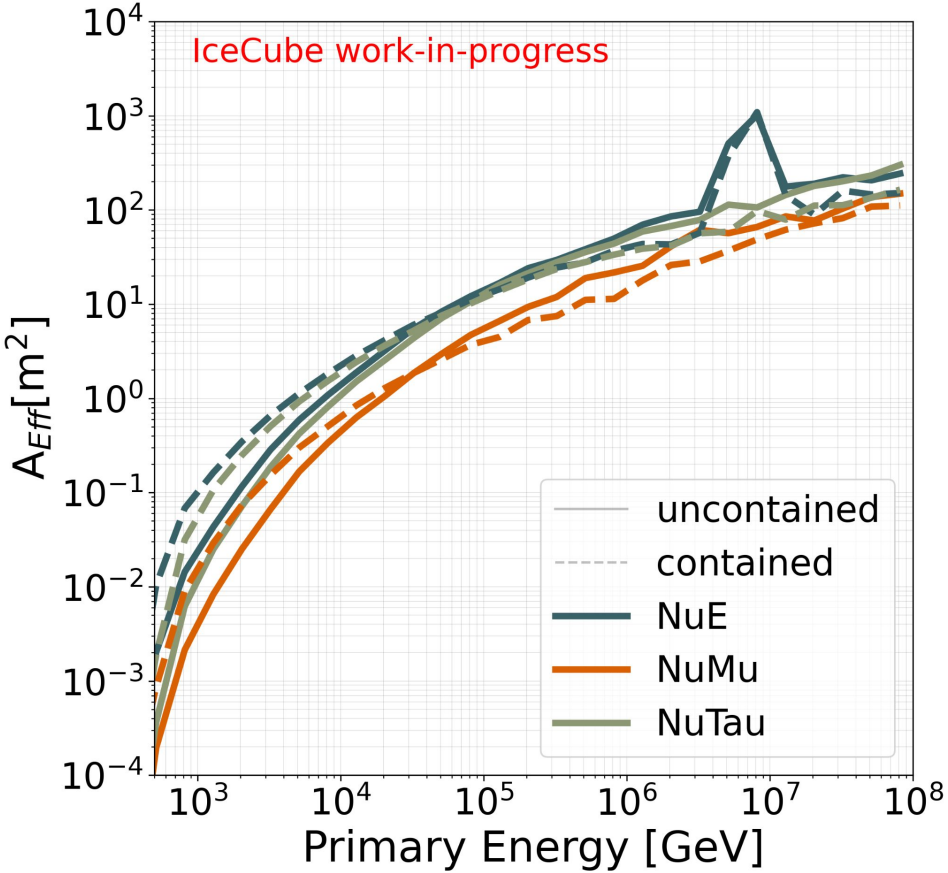


https://www.science.org/doi/10.1126/science.adc9818



DNNCascades – A Closer Look





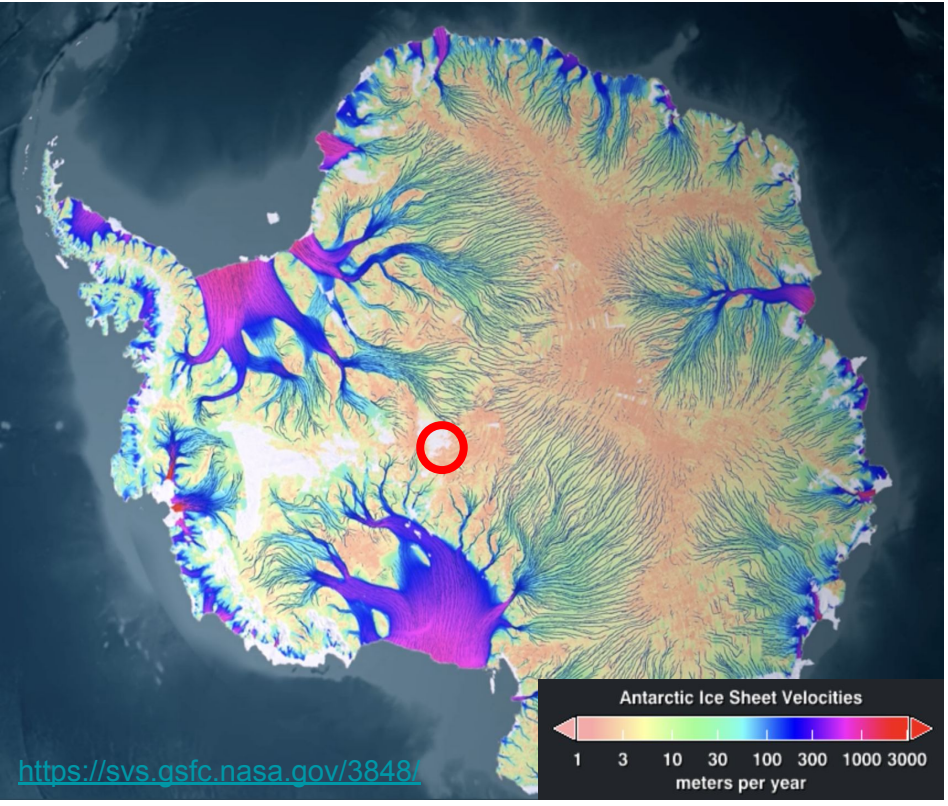
Transition at 100 TeV contained (~75%) → uncontained (~60%)

Dominated by electron and tau neutrinos at low energy

Improved Understanding of Anisotropic Antarctic Ice

- Absorption
- Scattering

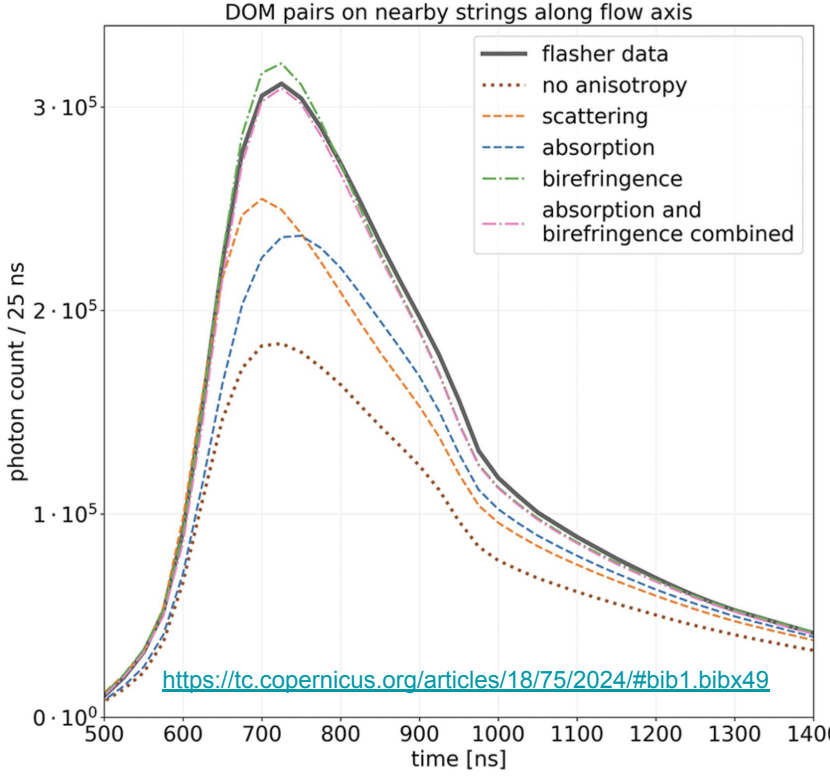
→ Previously modeled



https://svs.gsfc.nasa.gov/3848/

Birefringent Light Propagation in the Ice

- Macrostructure: sheet movement
- Microstructure: ice crystals



https://tc.copernicus.org/articles/18/75/2024/#bib1.bibx49

Updated Modeling of Atmospheric Neutrino Correlations

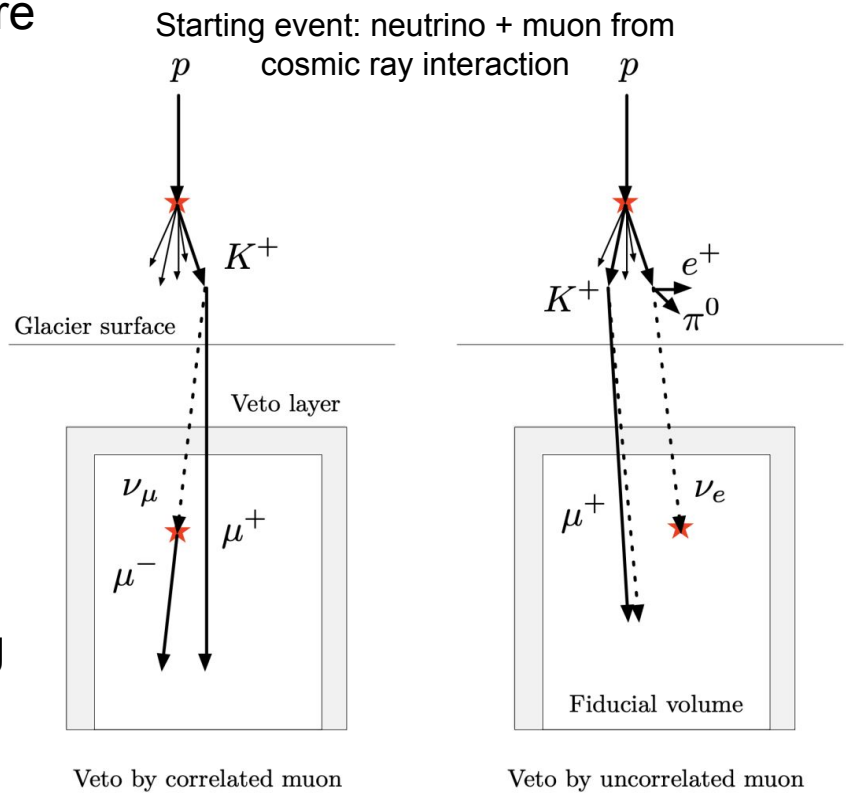
Cosmic rays collide with particles in atmosphere

Pion/Kaon decay → Accompanying
- Neutrino
- Muons

Close in time to each other

Updated correlation method between neutrino and its muons
- Single random muon from predetermined energy spectrum
- **direct sampling of muon bundles using cosmic air shower simulations** (CORSIKA, MESE and DNNCascades)

Detector response to these events → important part of modeling atmospheric neutrino flux



Likely atmospheric

Jakob van Santen PhD thesis

In Summary

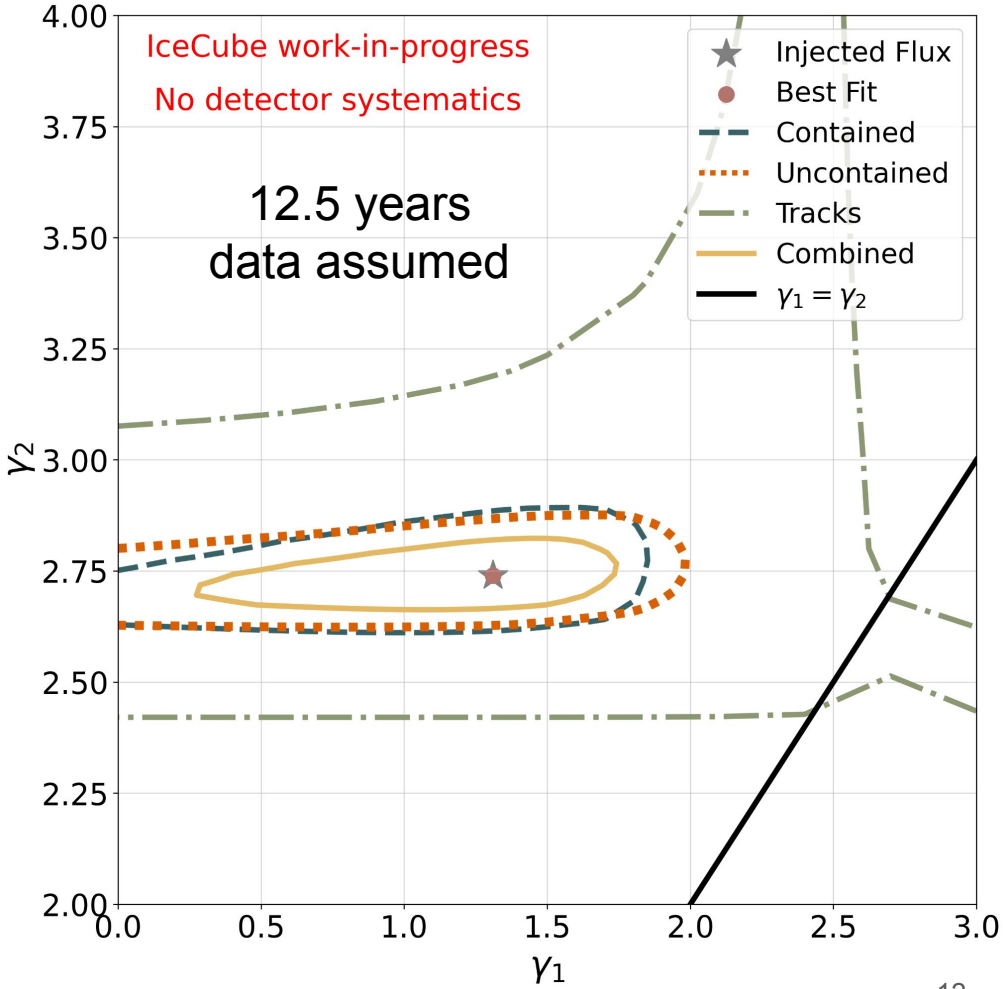
Next Generation Combined Fit
(constraint on energy spectrum, more statistics at low and high energies)

High Energy Starting Events
(sensitivity at high E)

DNNCascades
(Uncontained, statistics)

Northern Tracks
(atmospheric modeling)

Understanding and Implementing
Birefringence in Ice
Direct muon bundle sampling using air showers



Addition of uncontained cascades → increases potential sensitivity

Future Work

- Implement updated Antarctic ice and atmospheric correlation modeling in atmospheric neutrino flux calculation

- Unblind the pieces with updated systematic uncertainties and modeling
  - High Energy Starting Events (HESE)
  - Tracks from the Northern Sky (Northern Tracks)
  - Deep Neural Network Cascades (DNNCascades)
    - Astrophysical diffuse flux measurement
    - Galactic plane diffuse measurement
    - Potential beyond standard model physics tests

- Combine the pieces: unblind next generation combined fit
  - Flavor measurement
  - Beyond 10 PeV astrophysical diffuse flux

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Supporting Information

Contained vs. Uncontained Identification