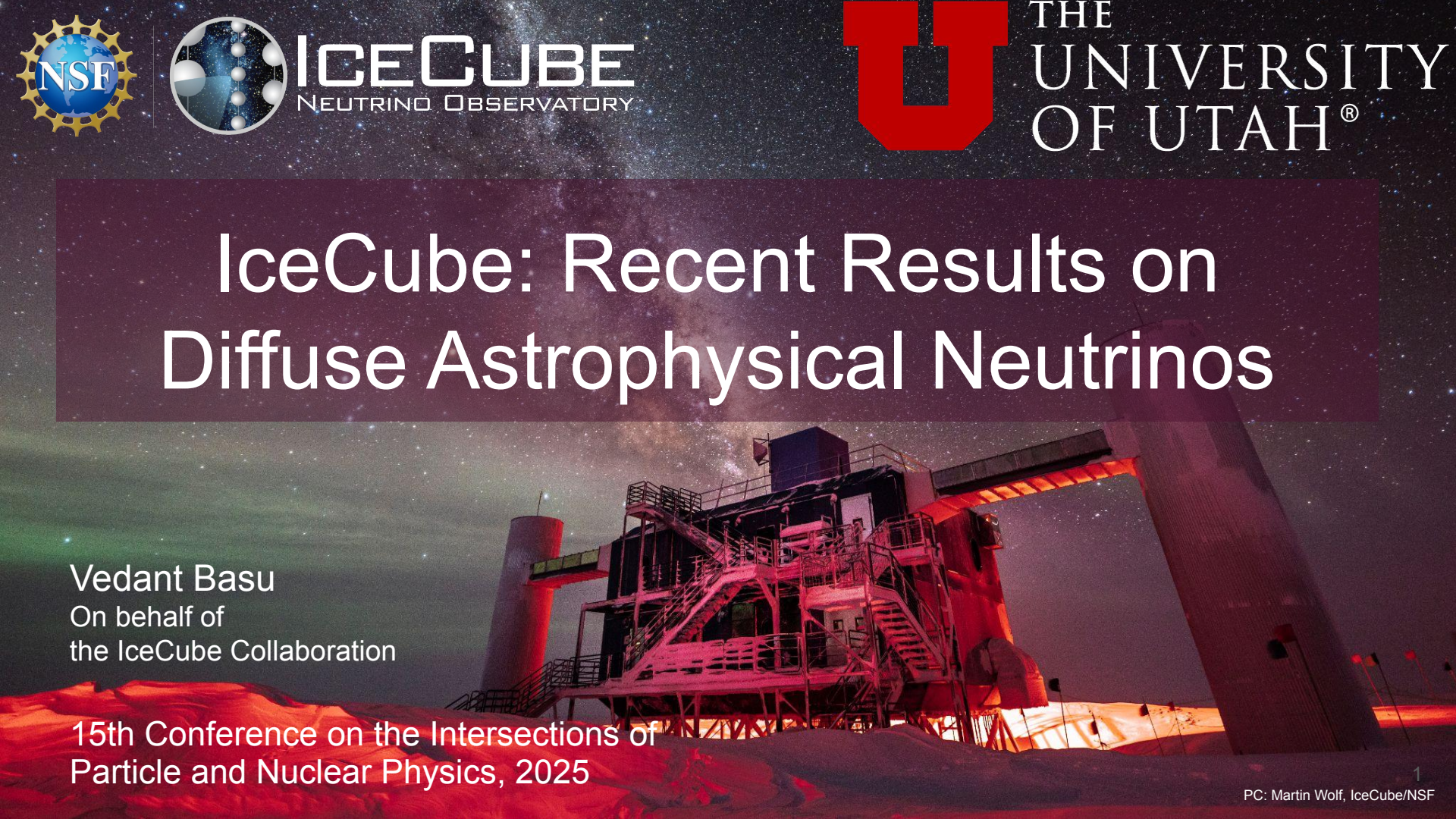
IceCube: Recent Results on Diffuse Astrophysical Neutrinos



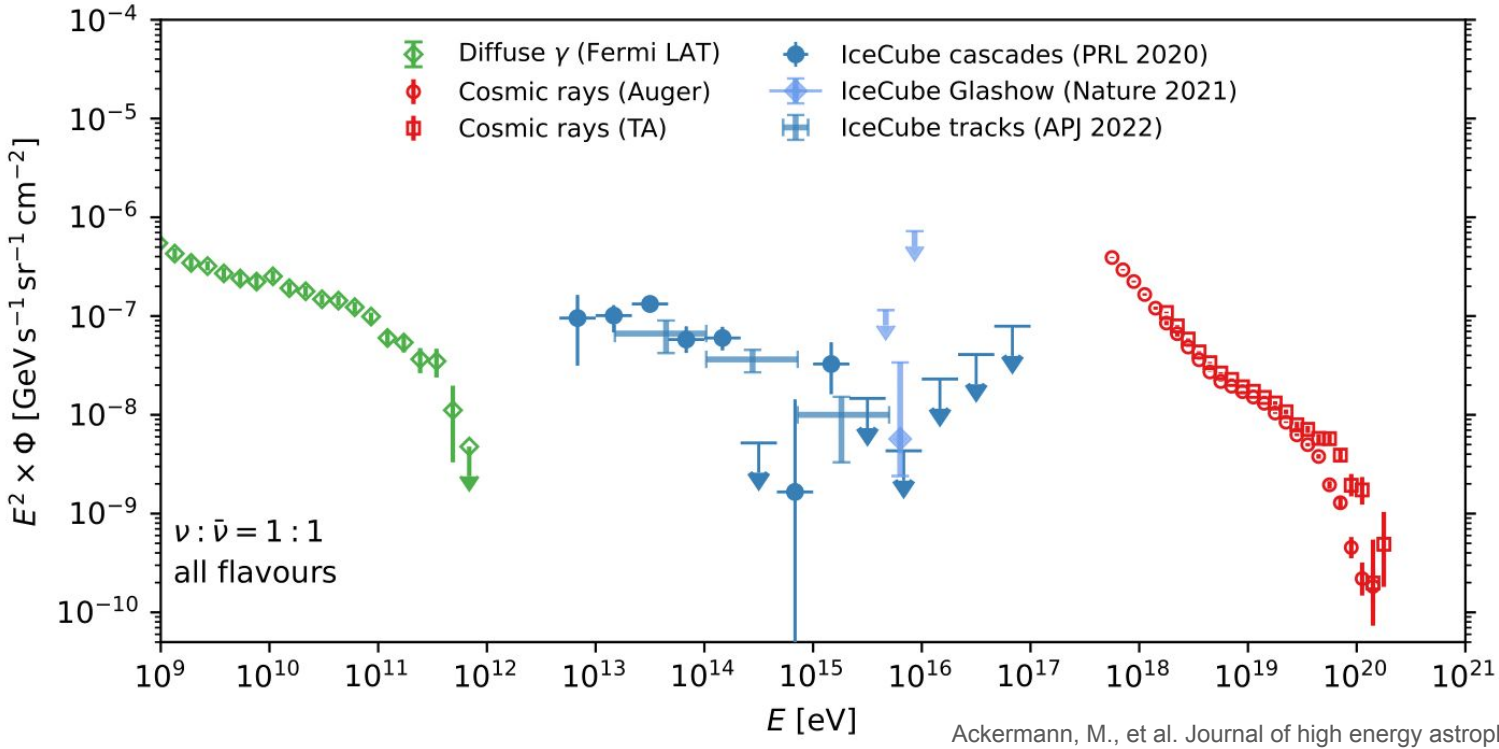
Vedant Basu
On behalf of
the IceCube Collaboration

15th Conference on the Intersections of Particle and Nuclear Physics, 2025

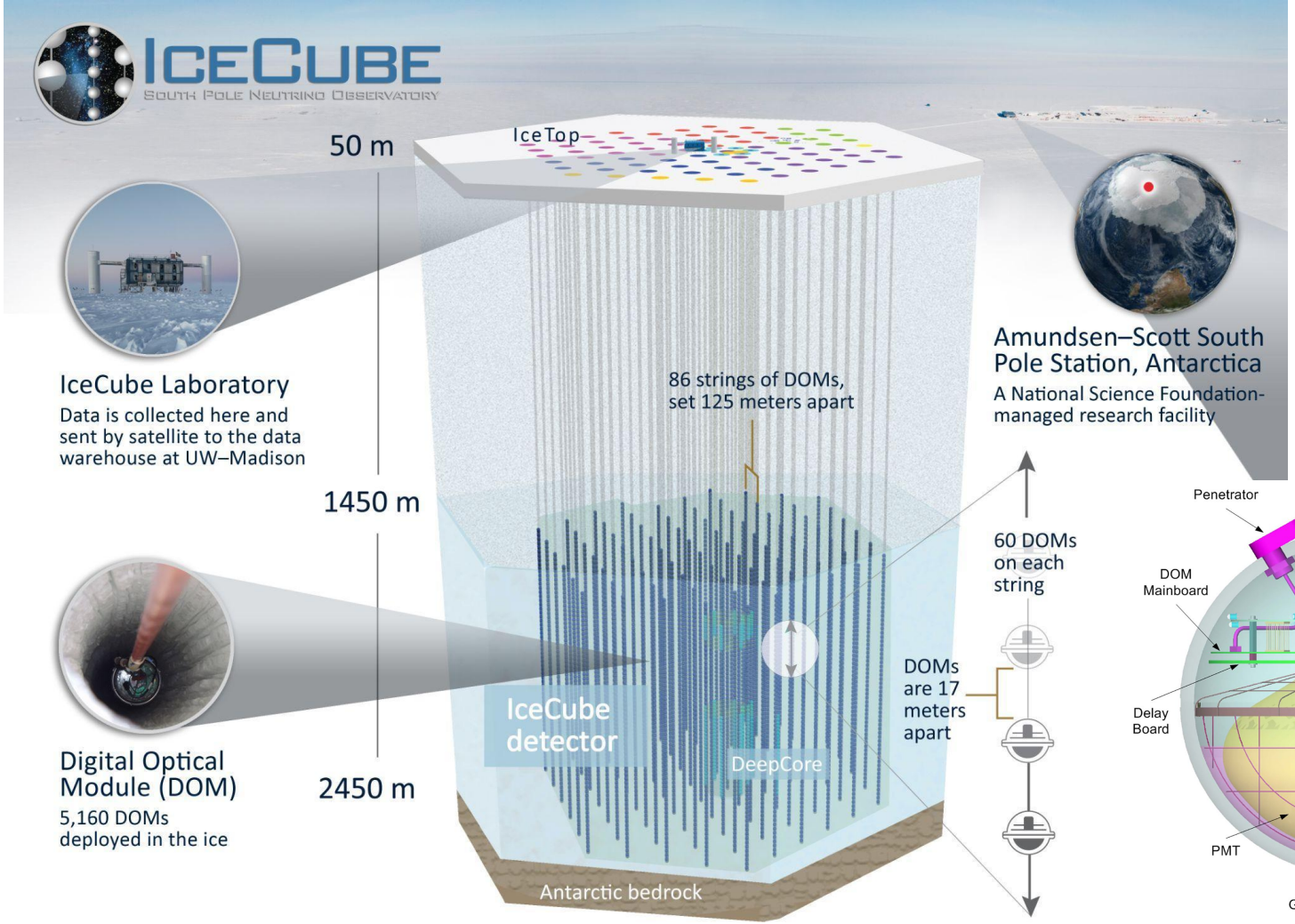
PC: Martin Wolf, IceCube/NSF

Multimessenger Astronomy

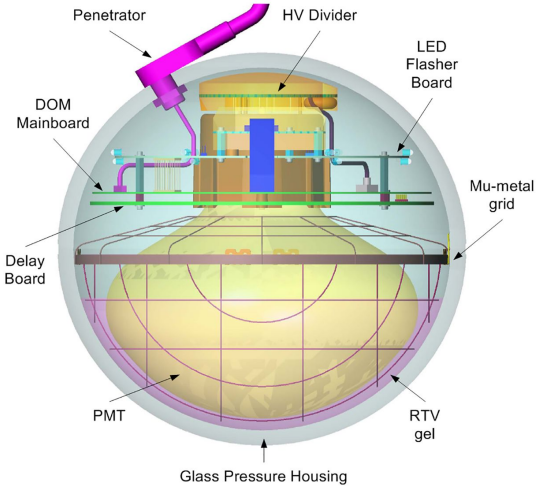
Energy density of high energy neutrinos similar to γ-ray flux, and Ultra High Energy Cosmic Rays (UHECRs)



Ackermann, M., et al. Journal of high energy astrophysics 36 (2022)

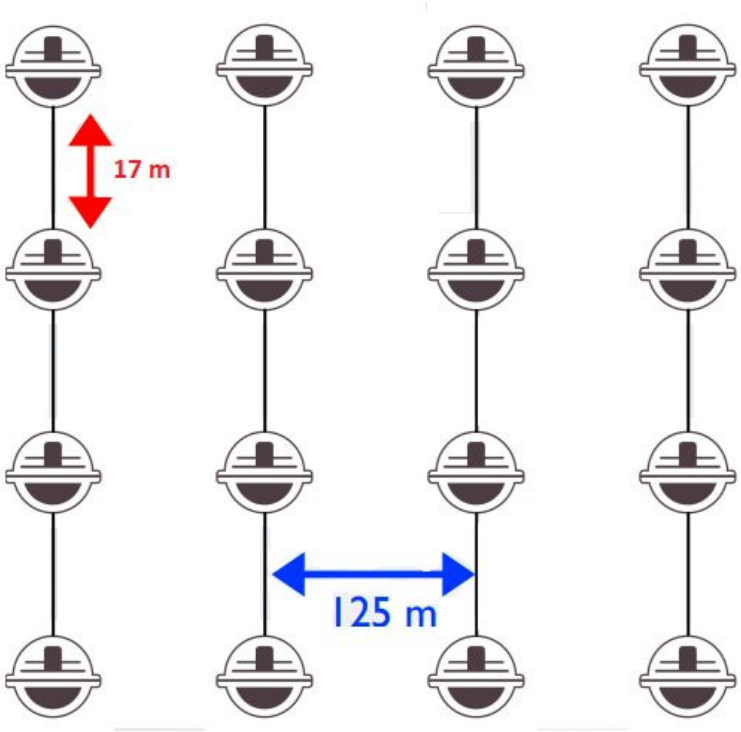


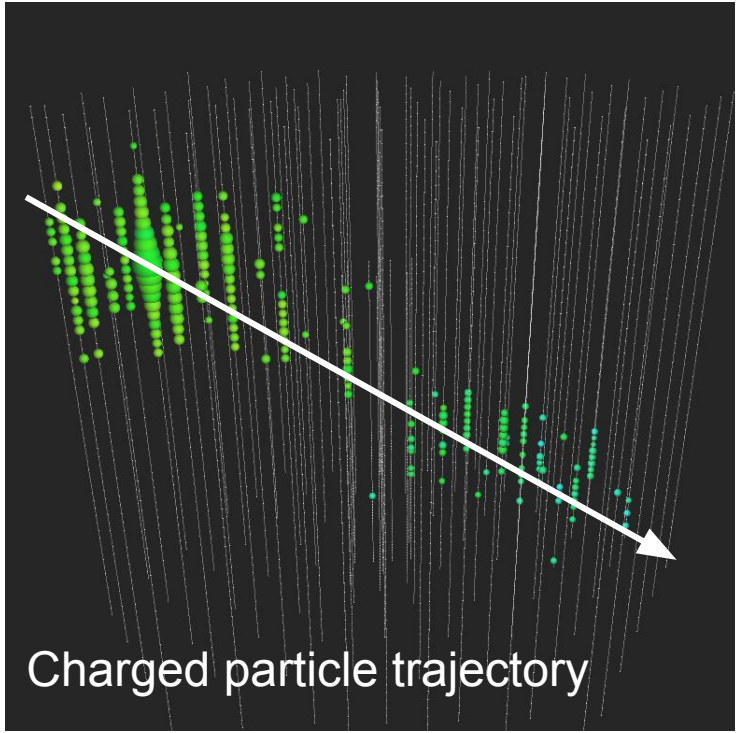
Digital **O**ptical **M**odule



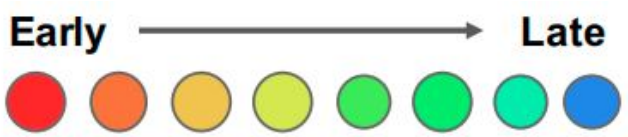
Event Reconstruction

- Number of Cherenkov photons captured $\propto$ deposited energy.
- Photon arrival times at DOMs helps reconstruct particle trajectory.

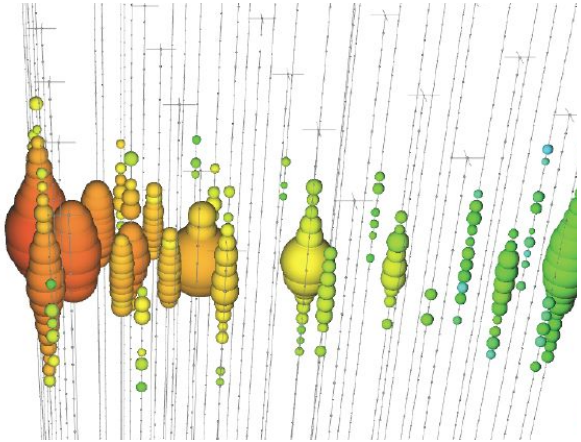




IceCube Event Morphologies



Tracks (Data)

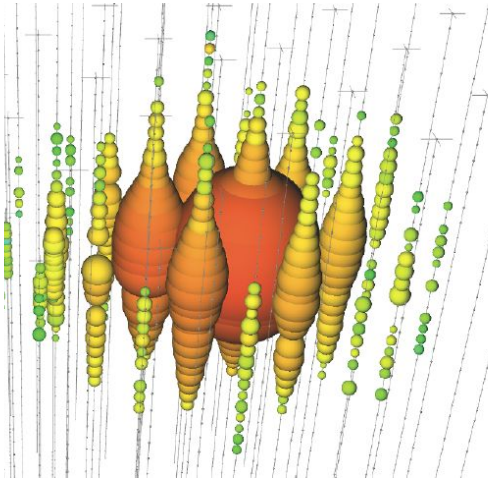


$$\nu_\mu + \mathrm{X} \rightarrow \mu^- + \mathrm{Hadrons}$$

Energy Res. : 0.3 in $\mathrm{Log}\frac{\mathrm{E}}{\mathrm{TeV}}$

Angular Res. : 0.3°

Cascades (Data)

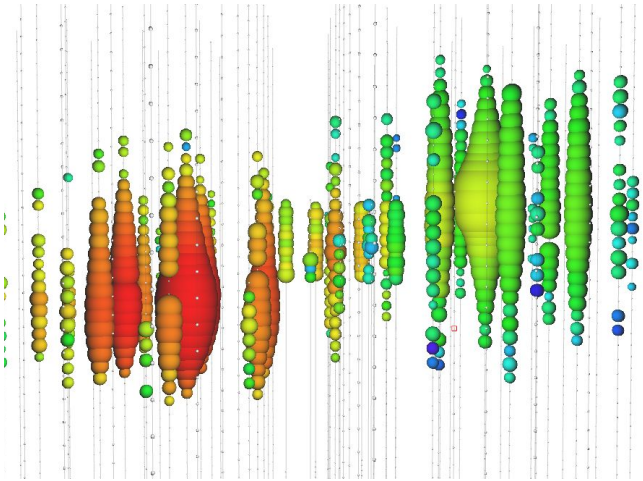


$$\nu_e + \mathrm{X} \rightarrow e^- + \mathrm{Hadrons}$$
$$\nu_l + \mathrm{X} \rightarrow \nu_l + \mathrm{Hadrons}$$

Energy Res. : 8%@100TeV

Angular Res. : 4°

Double Cascade (Simulated)



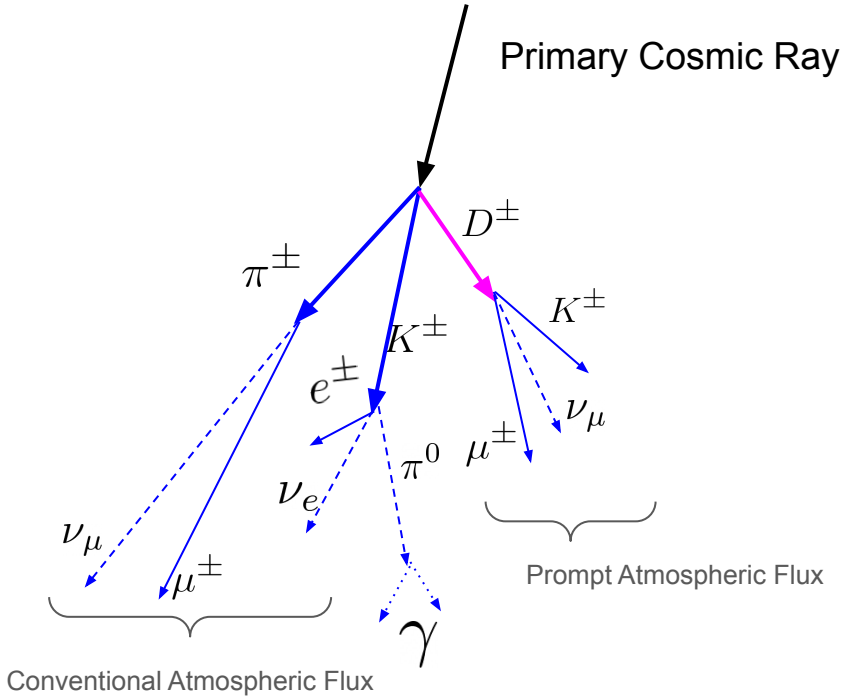
$$\nu_\tau + \mathrm{X} \rightarrow \tau^- + \mathrm{Hadrons}$$
$$\tau^- \rightarrow \nu_\tau + \ldots$$

Decay Length : 50m/PeV

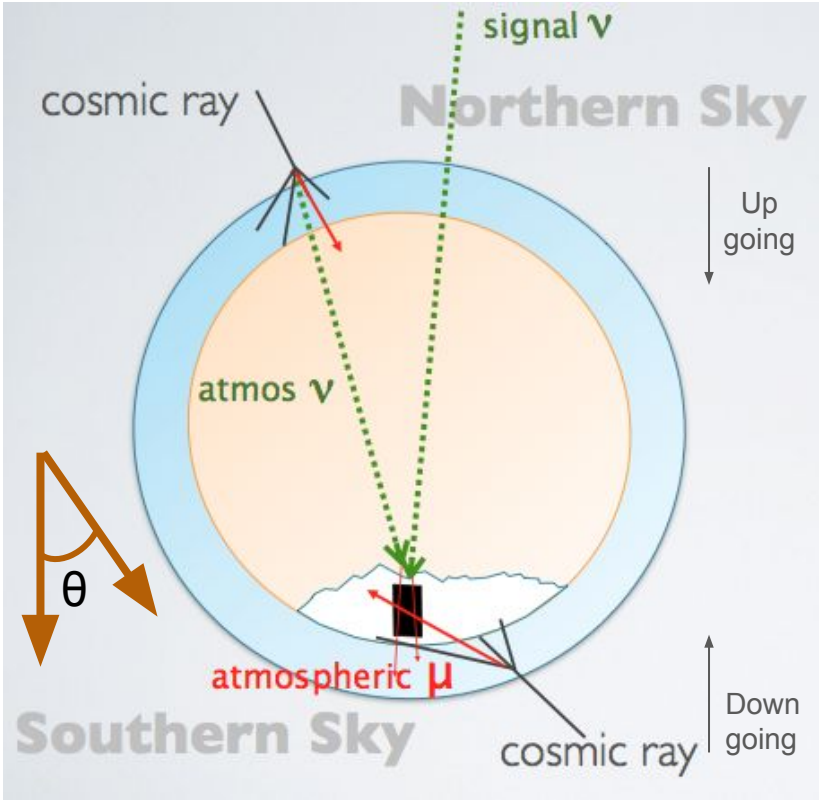
Ref.

Atmospheric Background

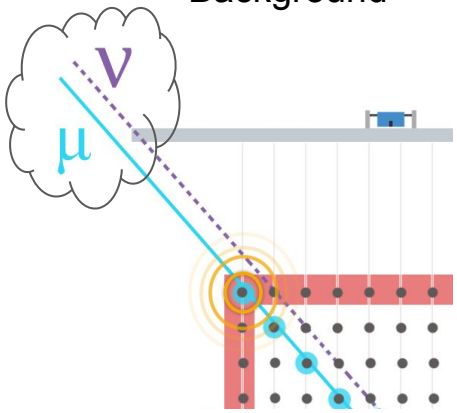
- Main background from atmospheric muons
- Neutrinos also produced in atmospheric cosmic rays interactions. Flux from pion/kaon decay follows ~$E^{-3.7}$
- Prompt contribution from charmed meson decay- follows ~$E^{-2.7}$



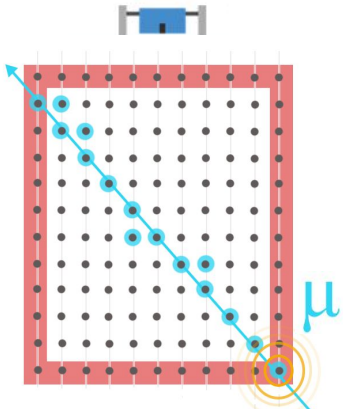
Event Selections



Atmospheric Background

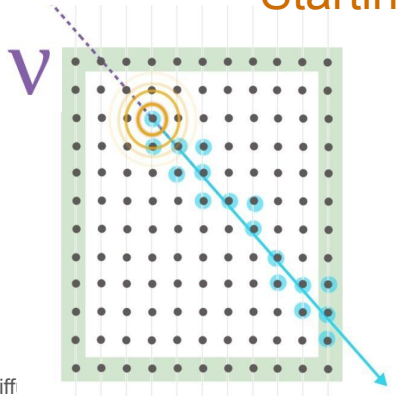


Upgoing Tracks

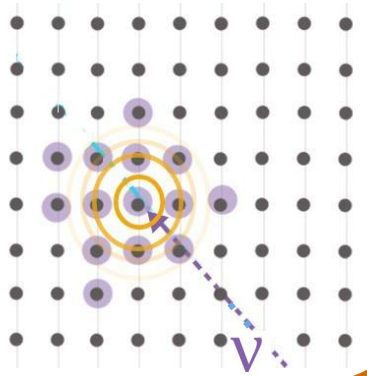


Starting Events

Starting Tracks



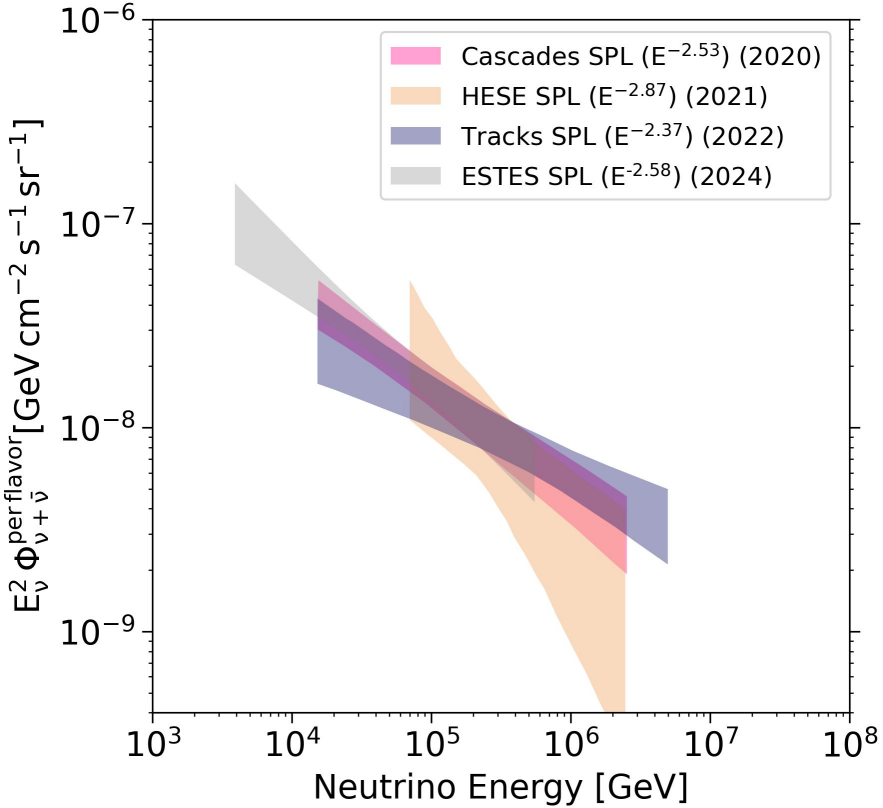
Cascades



Diffuse Cosmic Neutrino Flux

Previous IceCube measurements of the diffuse spectrum follow a single power law ($E^{-\gamma}$).

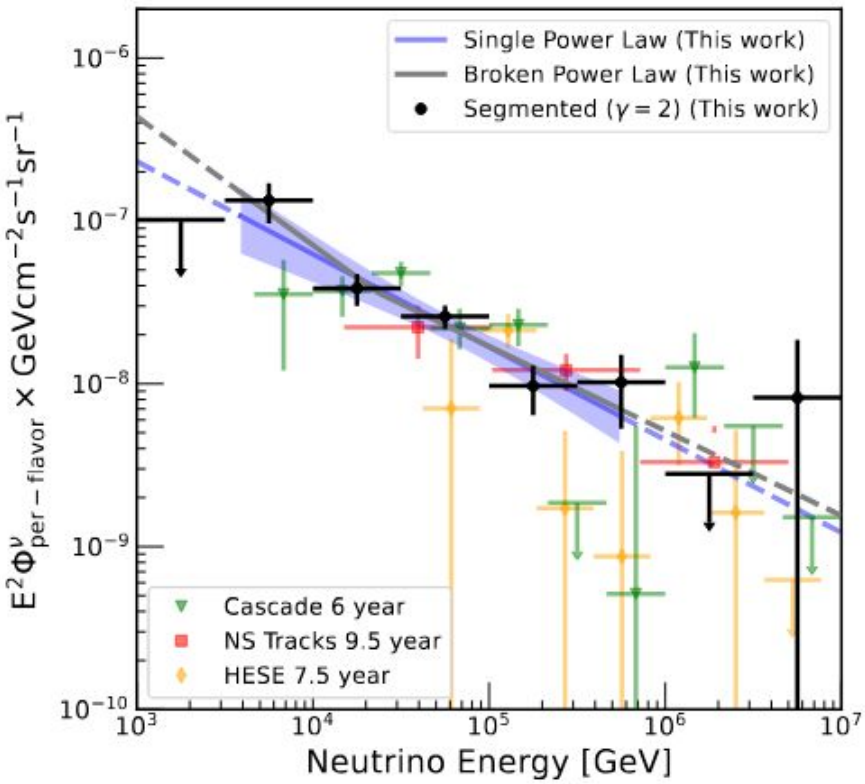
- High Energy Starting Event (HESE):
  all flavours & all sky, above 60 TeV
- Through-going tracks:
  muon neutrinos from the Northern sky
- Cascades:
  All sky electron and tau neutrinos, and muon neutrino NC interactions
- Enhanced Starting Track Event Selection (ESTES):
  All sky muon neutrinos



Enhanced Starting Track Event Selection

The ESTES analysis is the most recently published IceCube result

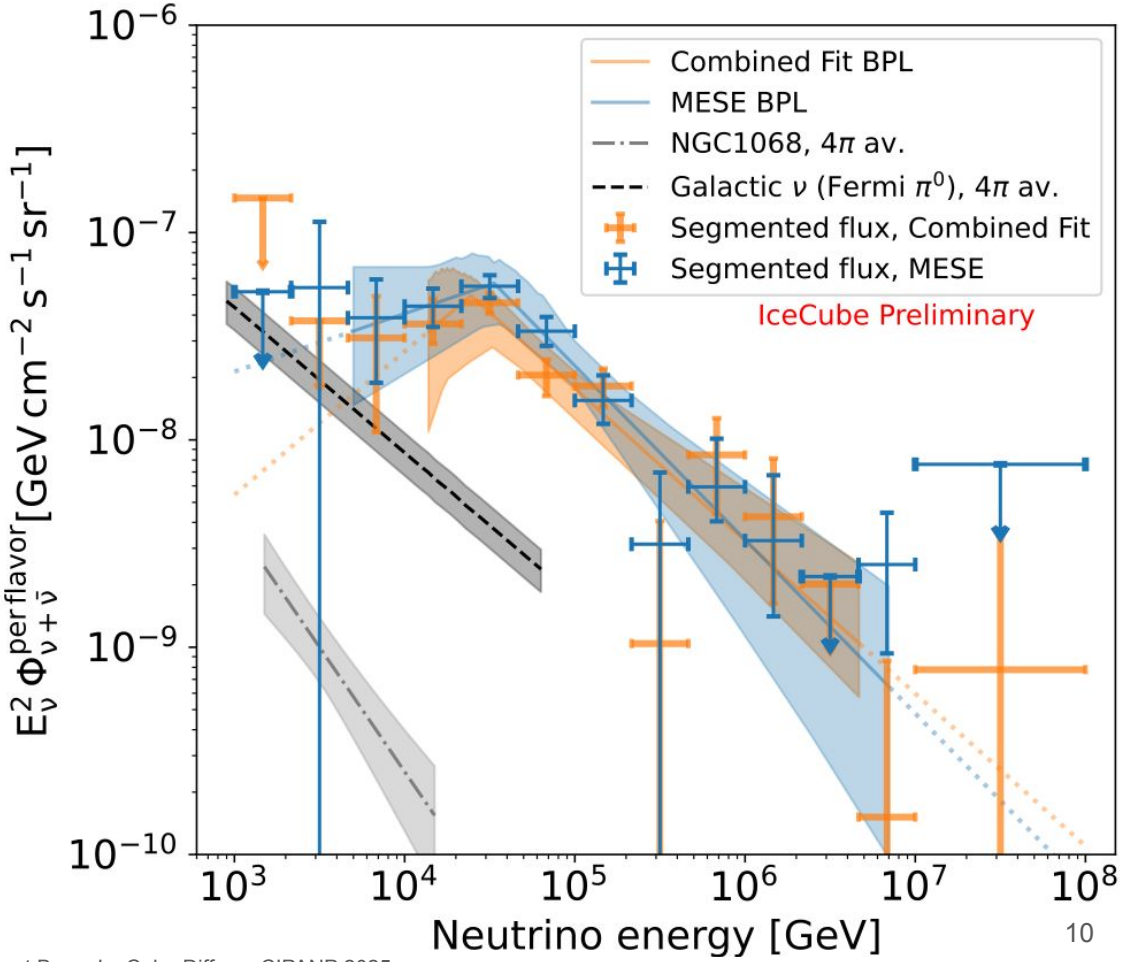
- Focuses on starting tracks (all-sky muon neutrinos)
- Excellent energy resolution (25 - 30%)
- High sample purity of astrophysical neutrinos
- Measurement consistent with single power law



Phys. Rev. D 110, 022001

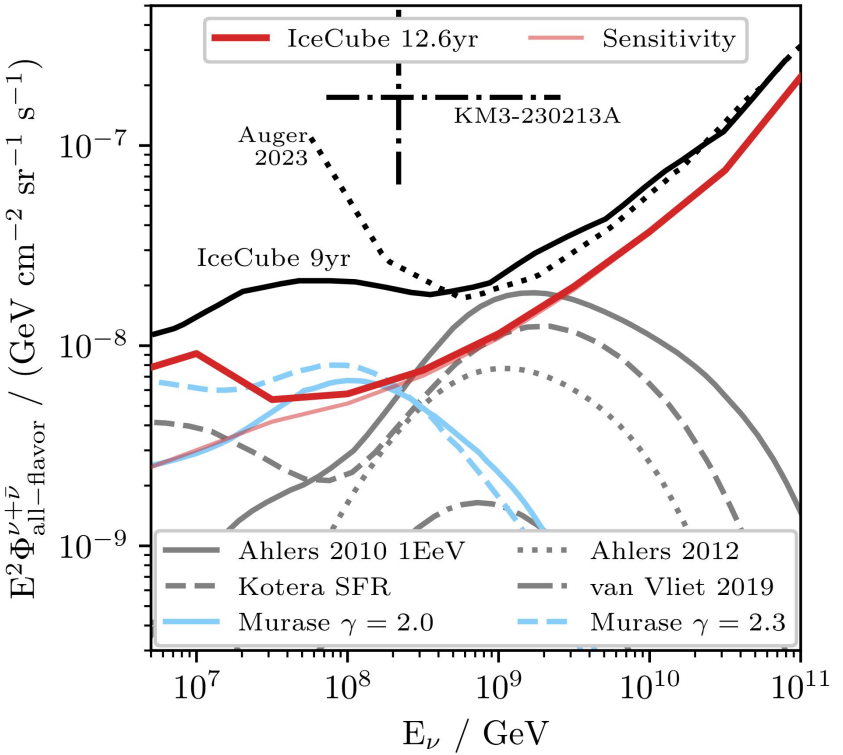
Evidence of spectral curvature

- Two analyses using both cascades and tracks reject SPL model for first time by >4σ
- "Combined Fit" analysis combining Cascades and Northern Tracks dataset
- "Medium Energy Starting Events (MESE)" selection using cascades and starting tracks
- Joint publication underway!



Spectral measurements at PeV energies and beyond

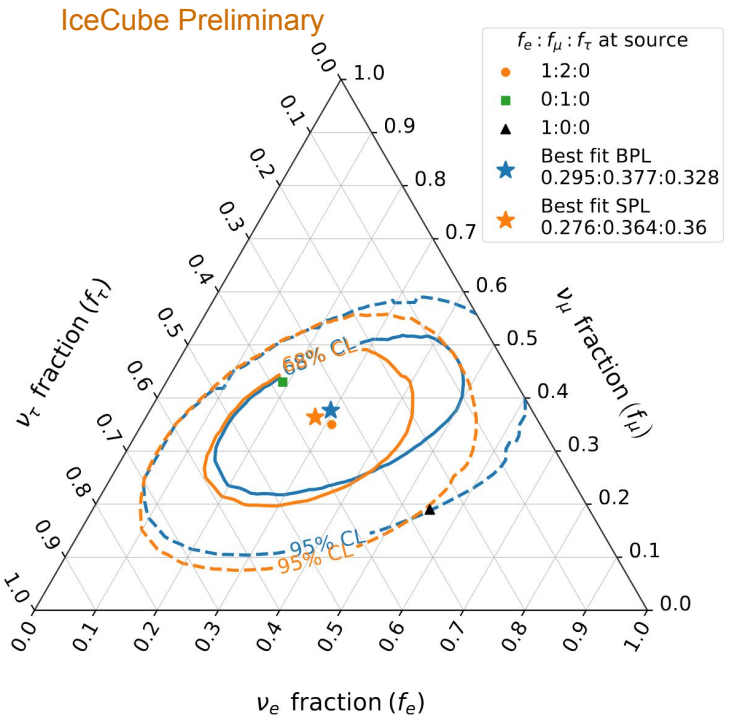
- Gap between 1-10 PeV also probed with downgoing muon neutrino sample, finding no significant preference for a cutoff.
- EHE neutrino flux measured at 1 EeV $E^2\phi_{\text{all-flavor}} \sim 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}
- Constraints on UHECR source conditions, disfavoring 100% proton fraction from CR measurements, in agreement with Auger, TA
- KM3NeT observation of 220 PeV neutrino at 2.9σ tension with IceCube EHE measurements



arXiv:2502.01963

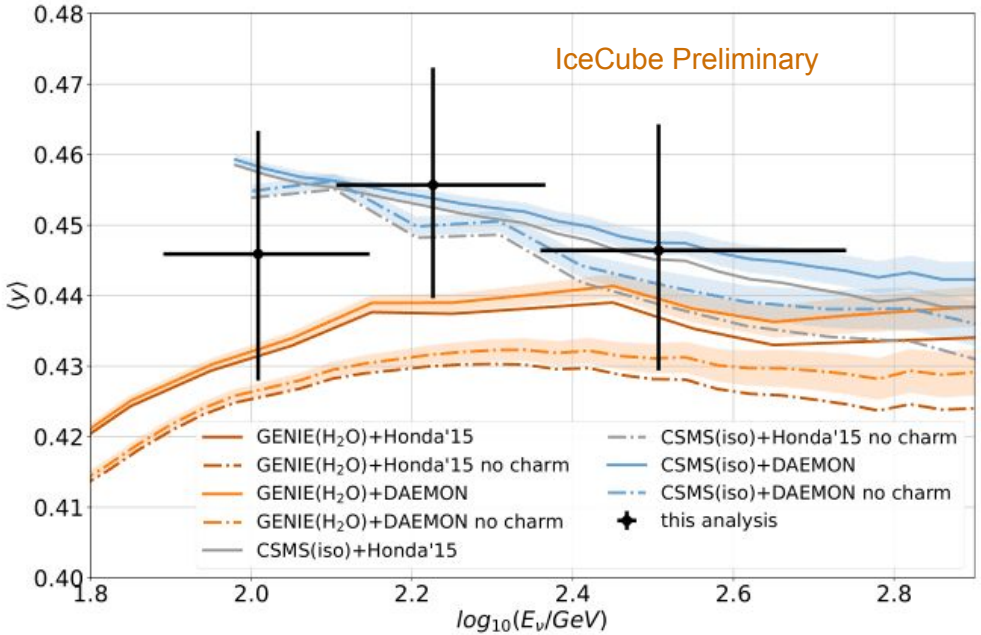
Neutrino flavor measurements

- Discovery of astrophysical tau neutrino flux, with 7 candidate events in PRL132, 151001 (2024).
- MESE dataset used to study ratio of neutrin flavors at Earth
- Consistent with models assuming neutrino production via pion decay, and oscillation over cosmic distances
- No evidence for interactions beyond Standard Model predictions



Deep Inelastic Scattering Inelasticity measurements

- Inelasticity measurements from 80-560 GeV
- Use atmospheric muon neutrinos from IceCube DeepCore sub-detector
- Upcoming IceCube Upgrade expected to extend threshold below 80 GeV



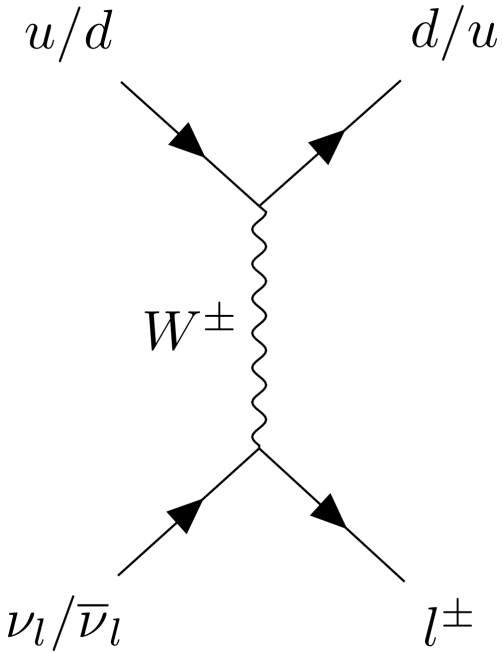
arxiv

Summary

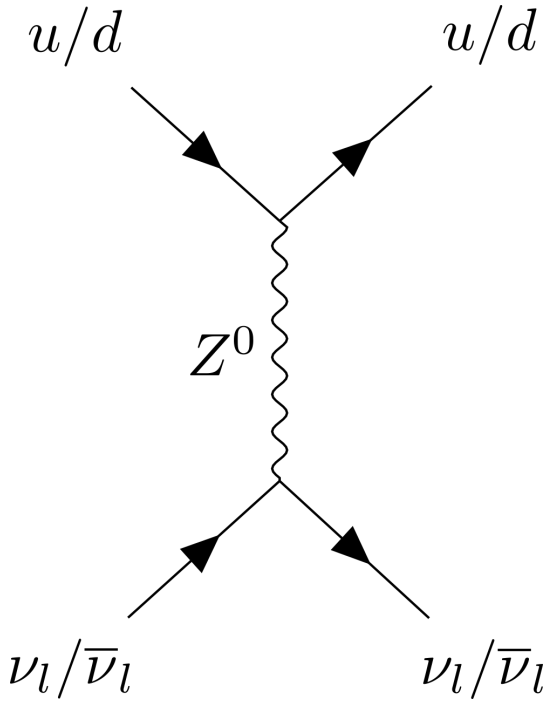
- IceCube has performed various measurements on diffuse neutrinos which shed light on dynamics of cosmic particle accelerators
- Some analyses evidence for deviation from single power law astrophysical spectrum. Further investigations planned to unify different samples into a joint fit.
- New limits obtained on the EHE neutrino flux, which constrain UHECR source conditions
- Models of neutrino production and propagation tested with measurements of unfolded spectra and neutrino flavor compositions
- Next generation of analyses underway to improve sensitivity to astrophysical neutrinos at TeV energies, and better test models of prompt neutrino production and neutrino interactions

Backup

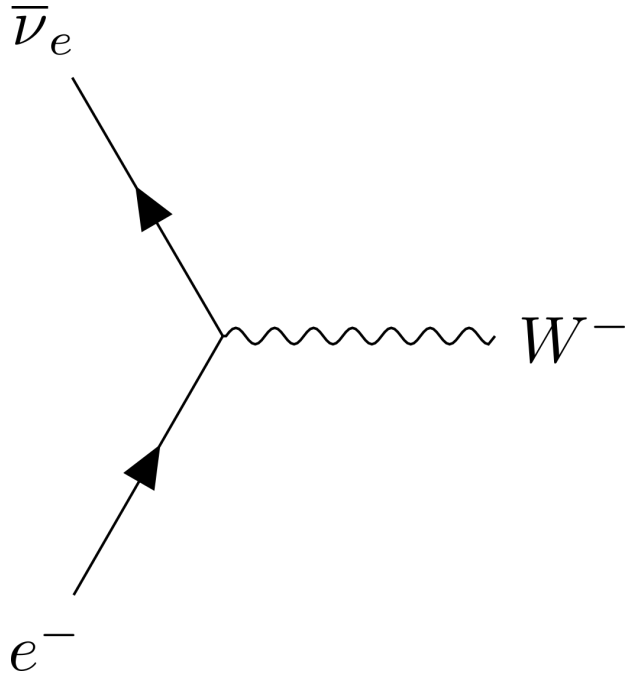
Neutrino Interaction Channels



Charged current interactions yield an outgoing charged lepton and a hadronic shower



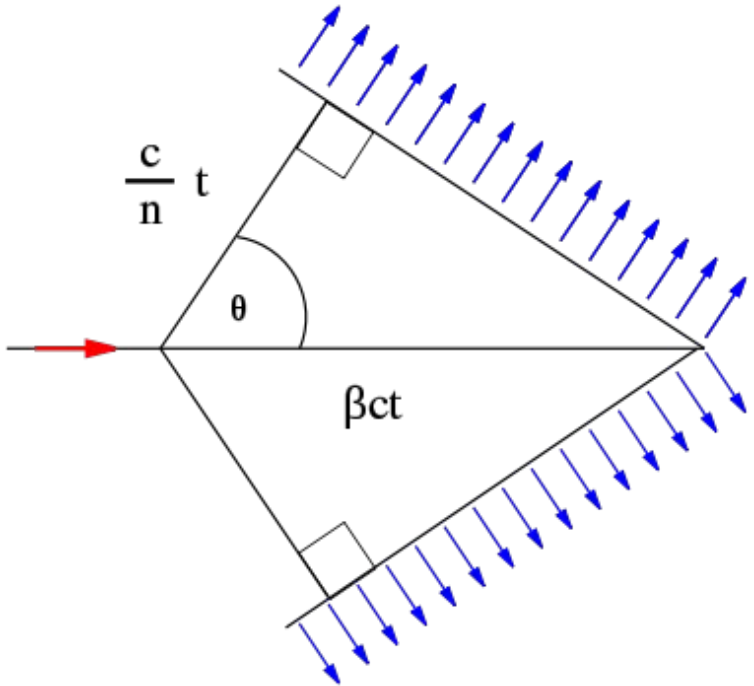
Neutral current interactions have an outgoing scattered hadron and neutrino



Glashow Resonance interactions yield an on-shell W^- boson, which subsequently decays

Observing neutrino interactions via the Cherenkov effect

- **Charged particles deposit energy** as they travel through matter
- When charged particles travel faster than the speed of light in a medium, they emit Cherenkov radiation
- A **cone of light is formed** determined by Cherenkov angle, θ_C
- Cherenkov light collected by DOM photomultiplier tubes (PMTs), which convert the optical signal to an amplified electrical signal

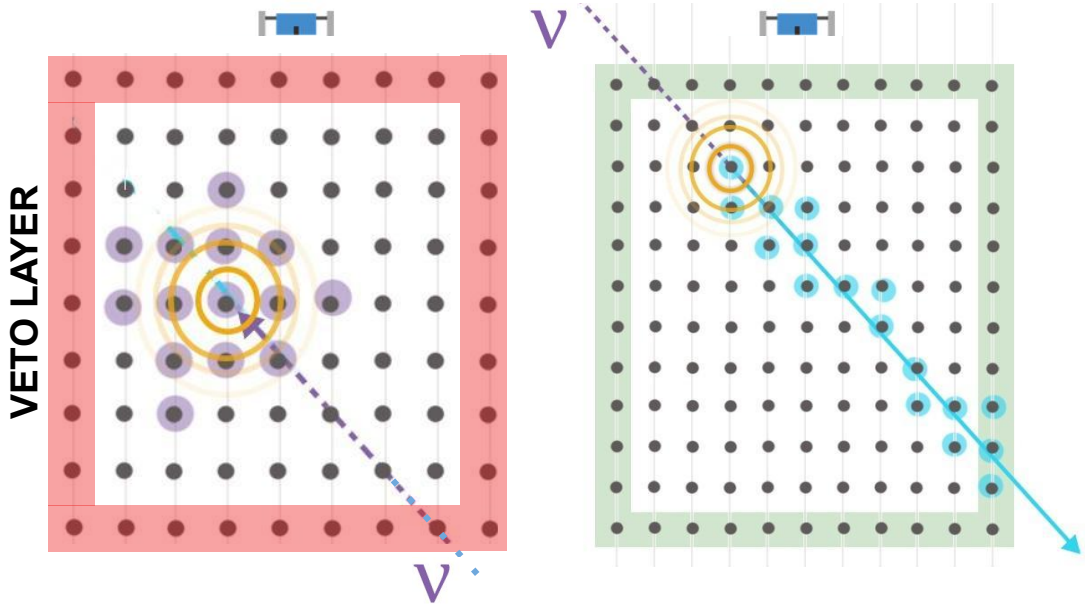


In ice: $\theta_C = 40.2°$

Wikimedia Commons

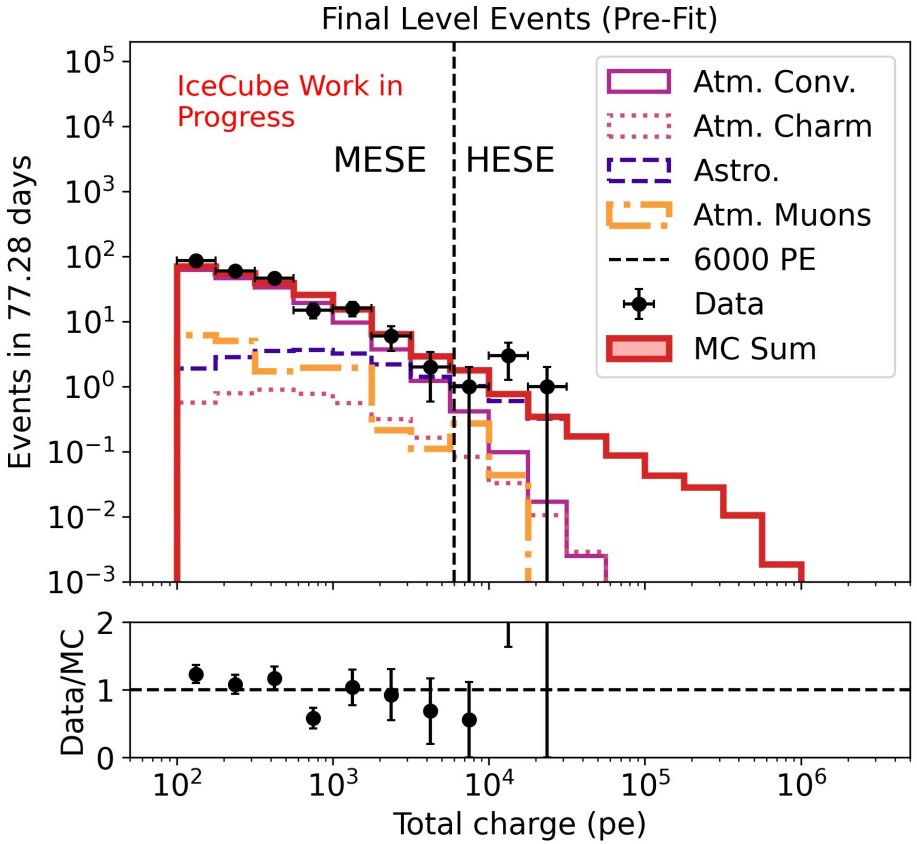
IceCube Starting Events

- Identify neutrinos with interaction vertex contained within the detector (Starting Events)
- Sensitive to all neutrino flavours with different event morphologies, from the entire sky



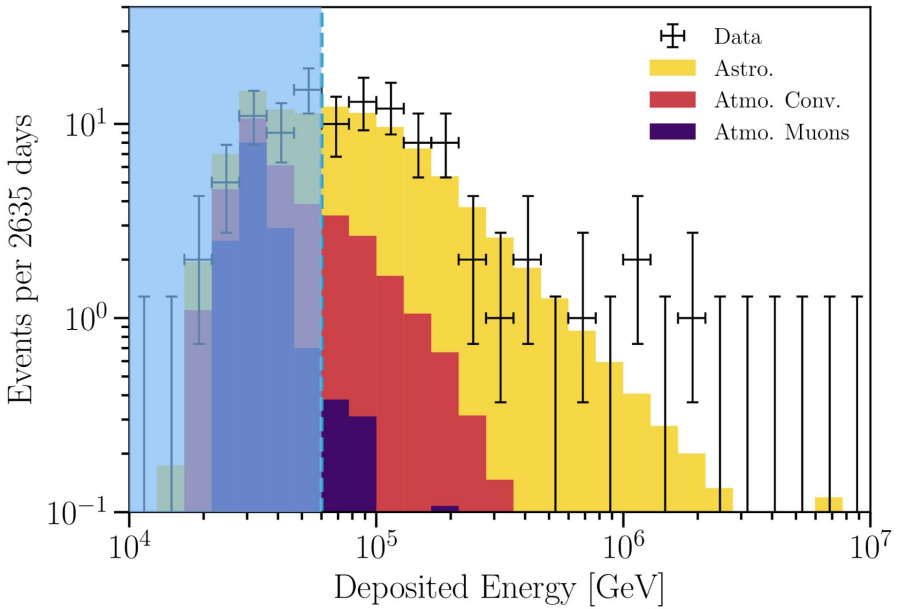
Medium Energy Starting Events (MESE)

- Extend starting event sample to lower energies, while retaining high signal purity, with additional veto steps
- Neutrinos with energy > 1 TeV of all flavors from the whole sky included in this dataset
- Use the dataset to measure astrophysical neutrino spectrum

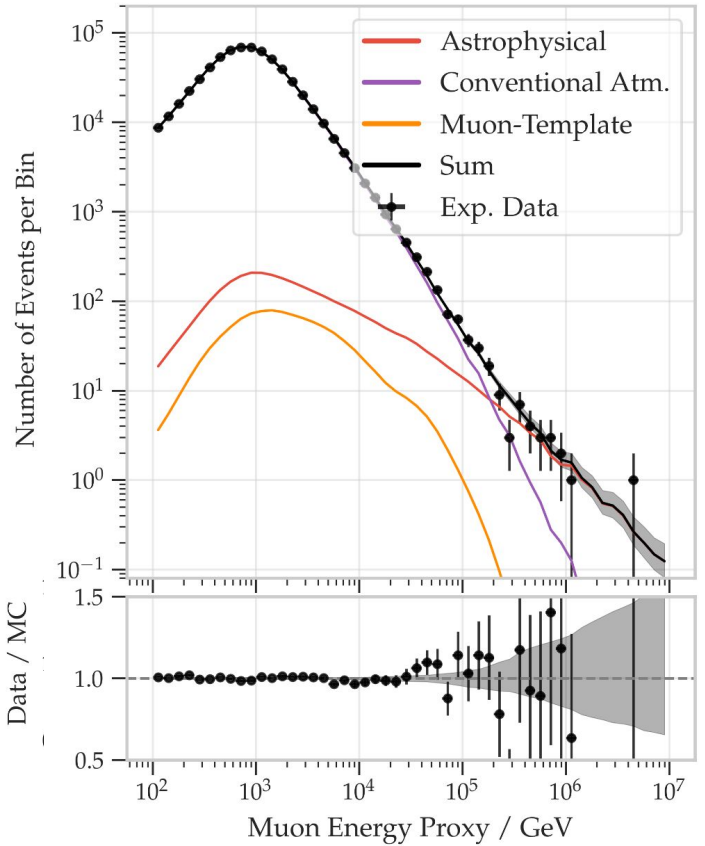


Motivation: Low energy sensitivity

- Energy range probed by MESE permits study of events below threshold of other studies

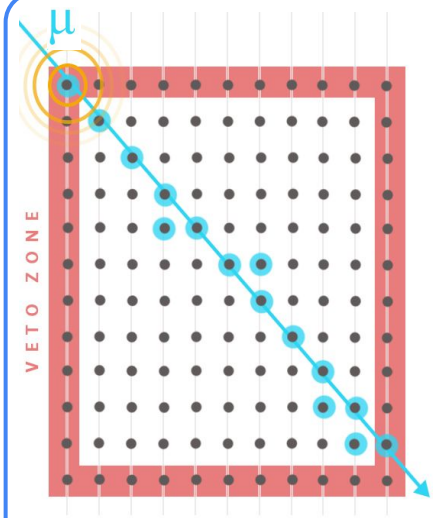


HESE flux characterization, 7.5 years of data
(events below 60 TeV (shaded) ignored in fit)
IceCube HESE: PRD 104.2 (2021): 022002.



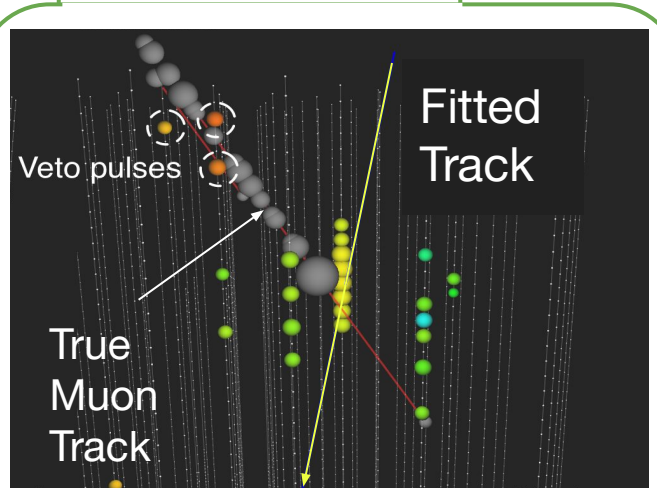
The energy distribution of upgoing tracks for the period 2010-18
The Astrophysical Journal 928.1 (2022): 50

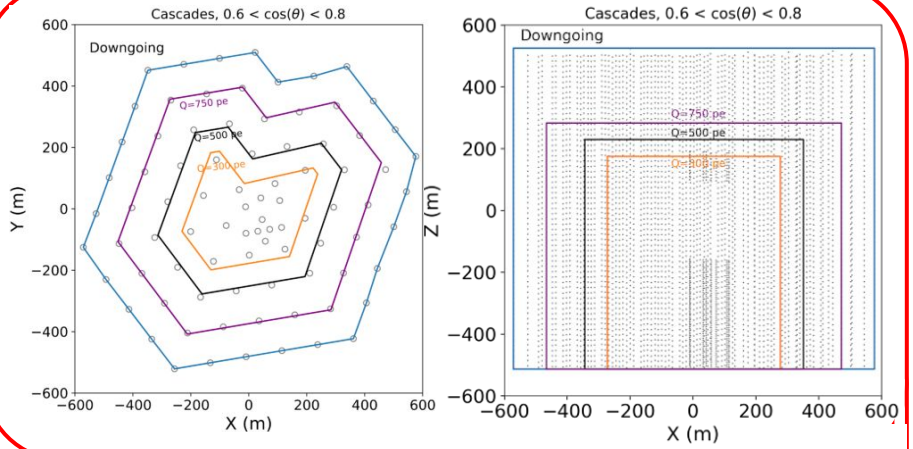
Event Selection



Outer Layer Veto, reject atmospheric muons starting outside detector

Downgoing Track Veto, link isolated hits with muon hypotheses

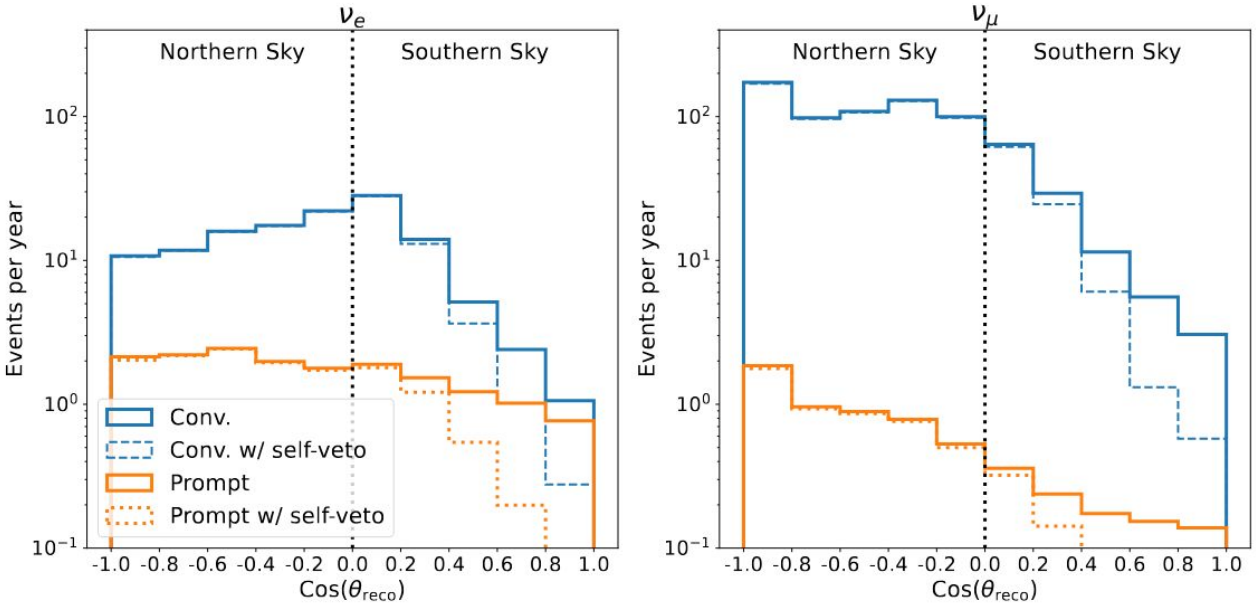


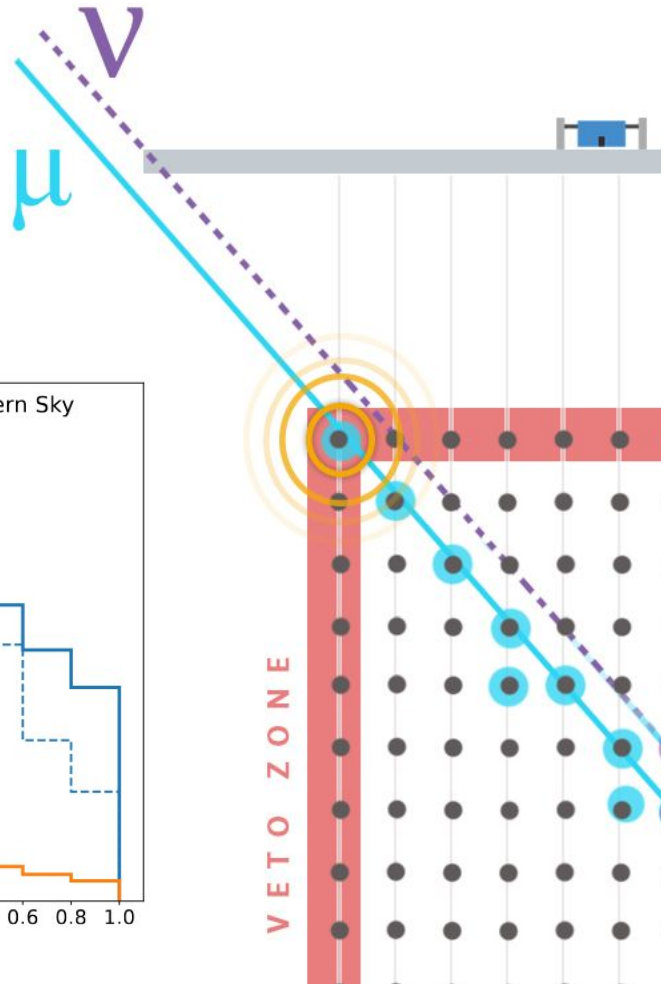


Fiducial Volume Scaling for dim events, veto hits closer to the reconstructed vertex.

Neutrino self-veto

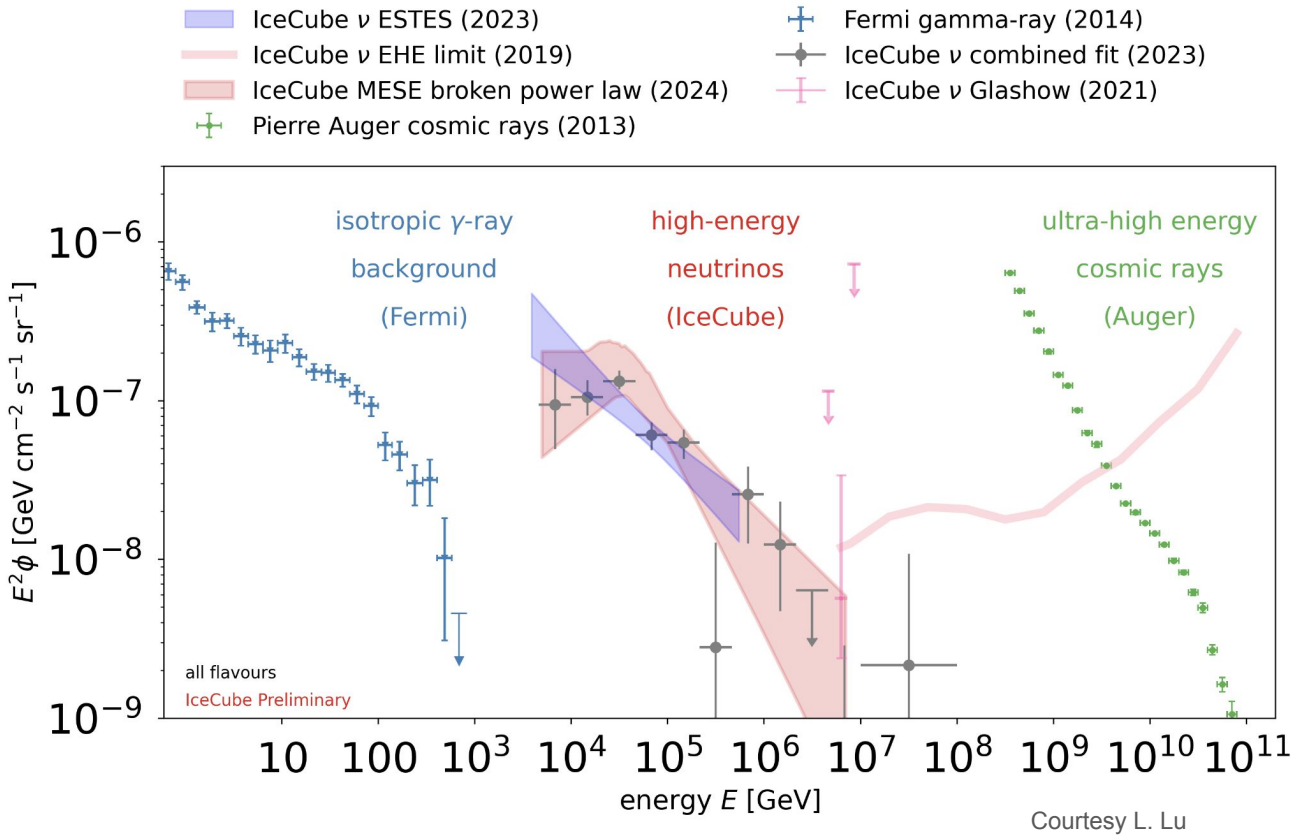
- Neutrinos from CR showers often accompanied by muons.
- Vetoing these muons suppresses atm. neutrino background
- Accurate modeling of the self-veto suppression via muon bundle injection.





The multi-messenger sky

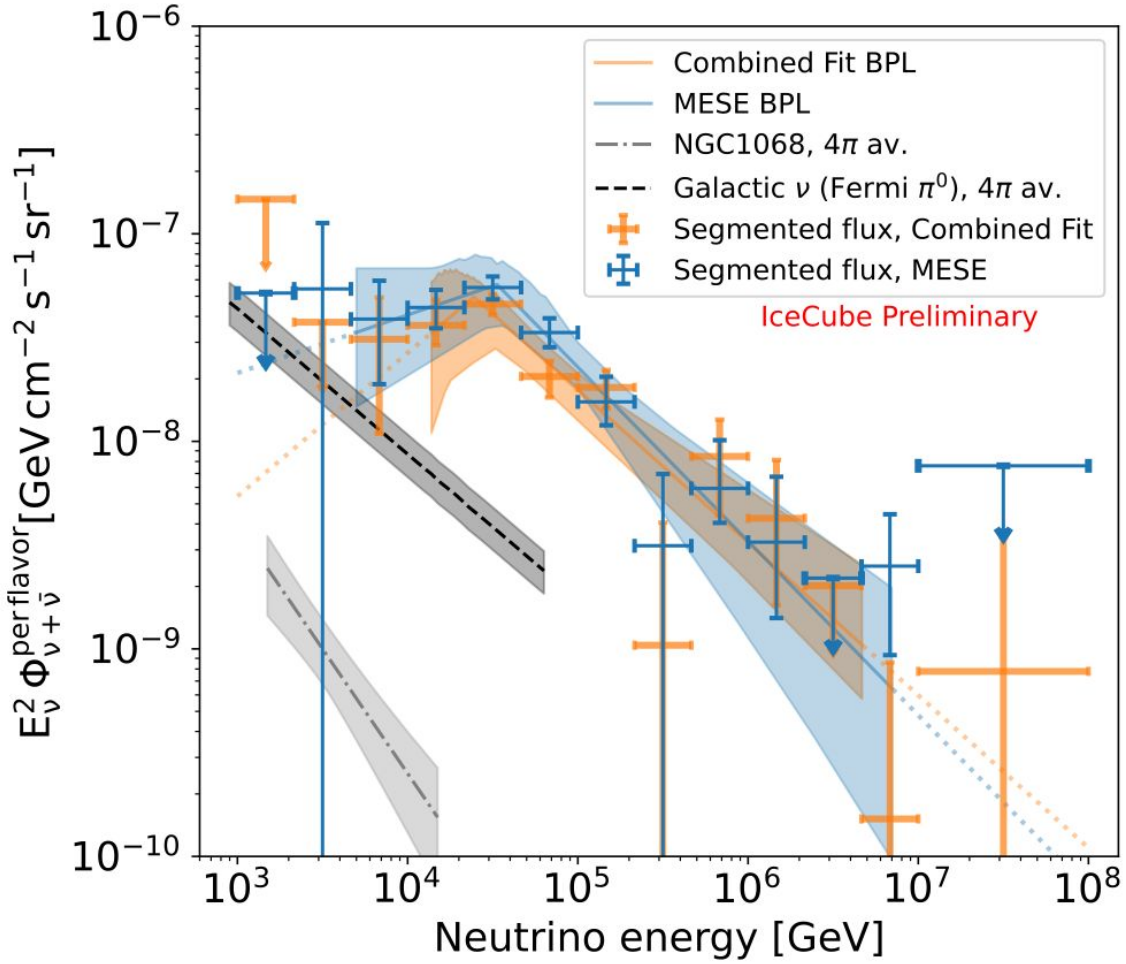
- Extrapolation of SPL model overestimates γ-ray flux
- MESE and Combined Fit results may reduce potential tension with extragalactic γ-ray spectrum



Courtesy L. Lu

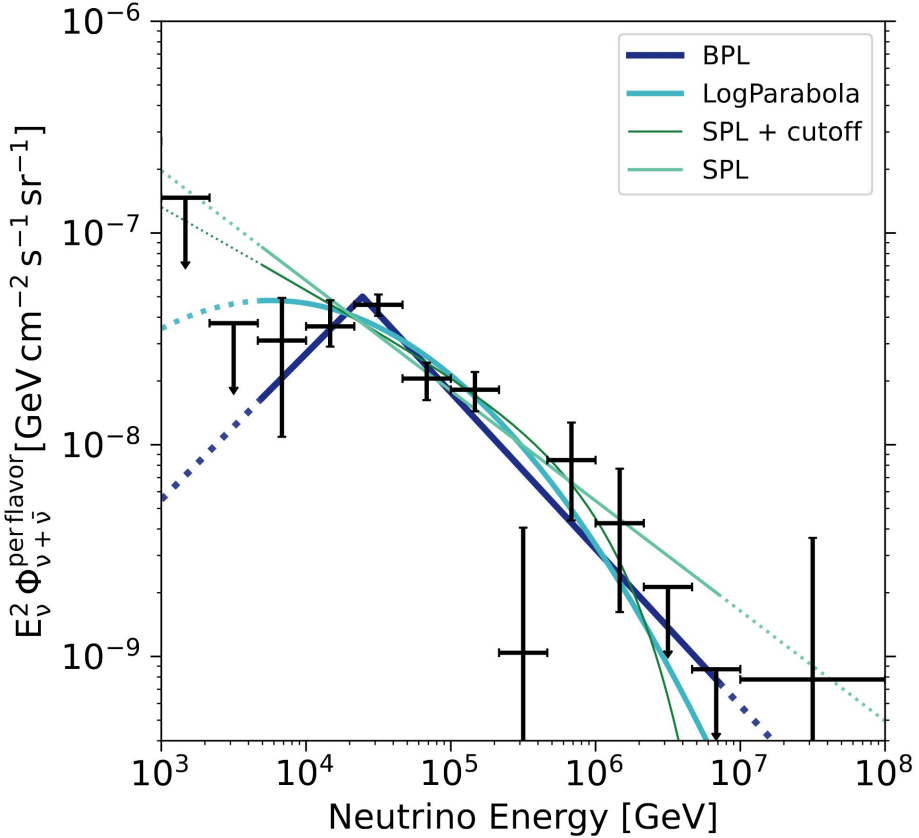
Implications for the Diffuse Neutrino Spectrum

- Reject SPL model for first time by >4σ
- Fit parameters robust against bias from mismodelled atmospheric fluxes, contribution from galactic plane.
- Minimal contribution from brightest individual source NGC1068

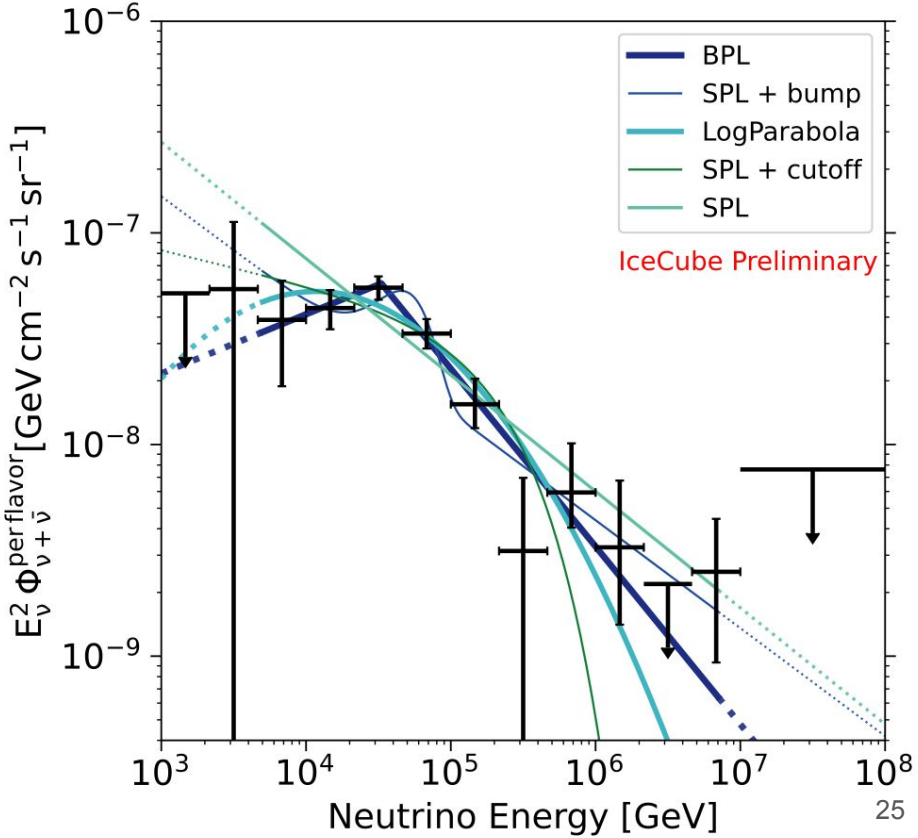


Evidence of spectral break?

We reject SPL wrt BPL with 4.4σ with Combined Fit



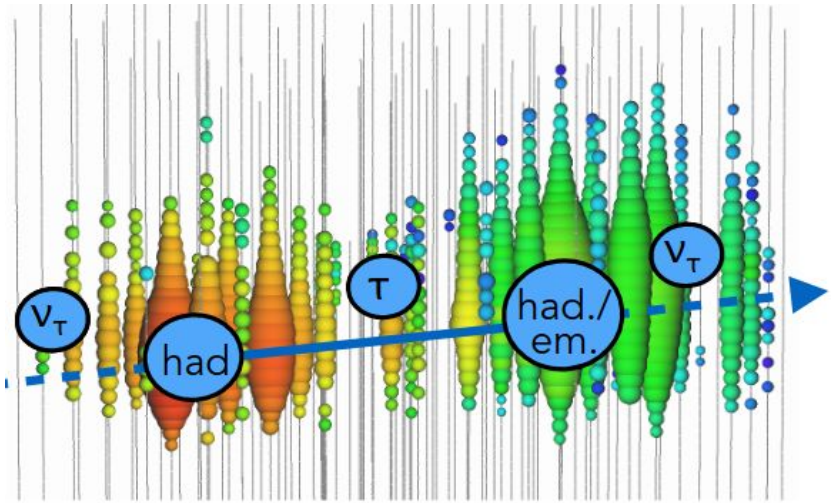
We reject SPL wrt BPL with 4.7σ with MESE



Tau neutrino identification

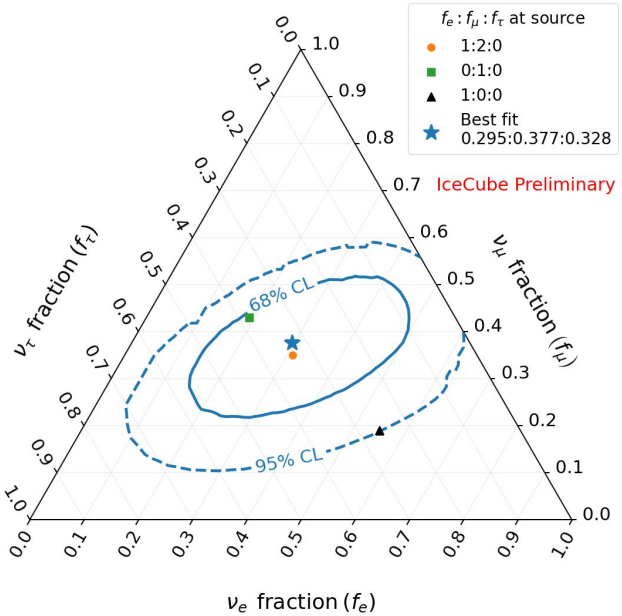
Selection strategy focused on double-cascade identification

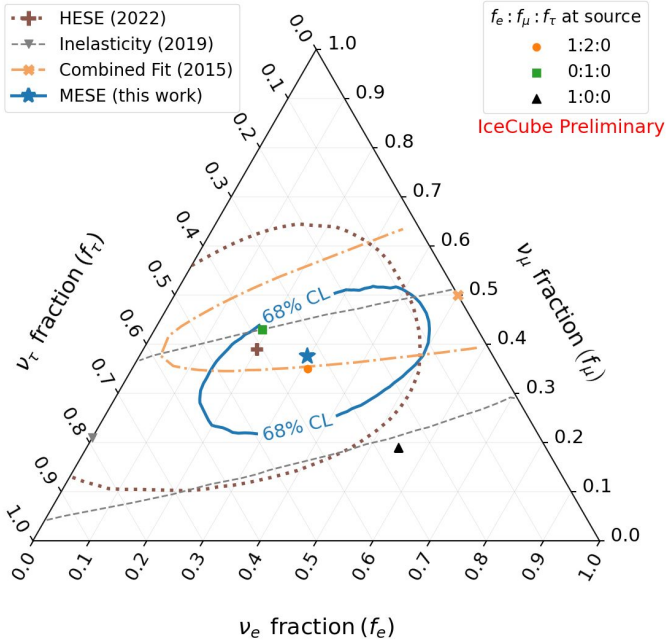
- Perform likelihood-based reconstruction
- Additional cuts to select double cascades based on reconstructed energy in both cascades and their relative magnitudes
- Retain events that pass the cuts with tau-decay length > 10 m and energy > 30 TeV as double cascades
- Remaining events are cascades or tracks (based on a DNN)



Measurement of the flavor ratio

- BPL assumed as the flux model for the measurement of the flavor ratio
- IceCube obtains a closed 1σ contour for the first time
- ν_e-only at source (neutron decay) excluded with 94.8% CL

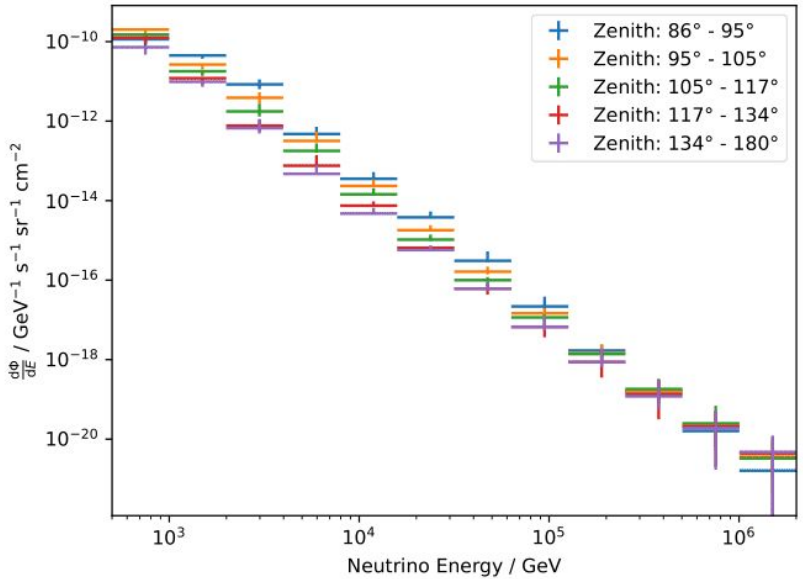




Comparison of MESE results with previous IC results

Muon neutrino unfolded spectrum

- Analysis of the total muon neutrino spectrum from 500 GeV- 4 PeV
- Helps constrain neutrino production from decay of heavy charmed mesons (‘prompt’ neutrino flux) produced in CR air showers



Spectral fit across five zenith bins

arXiv:2502.01963