



ICECUBE
NEUTRINO OBSERVATORY



THE
UNIVERSITY
OF UTAH®

Neutrino and multi-messenger astrophysics with IceCube

Vedant Basu

On behalf of
the IceCube Collaboration

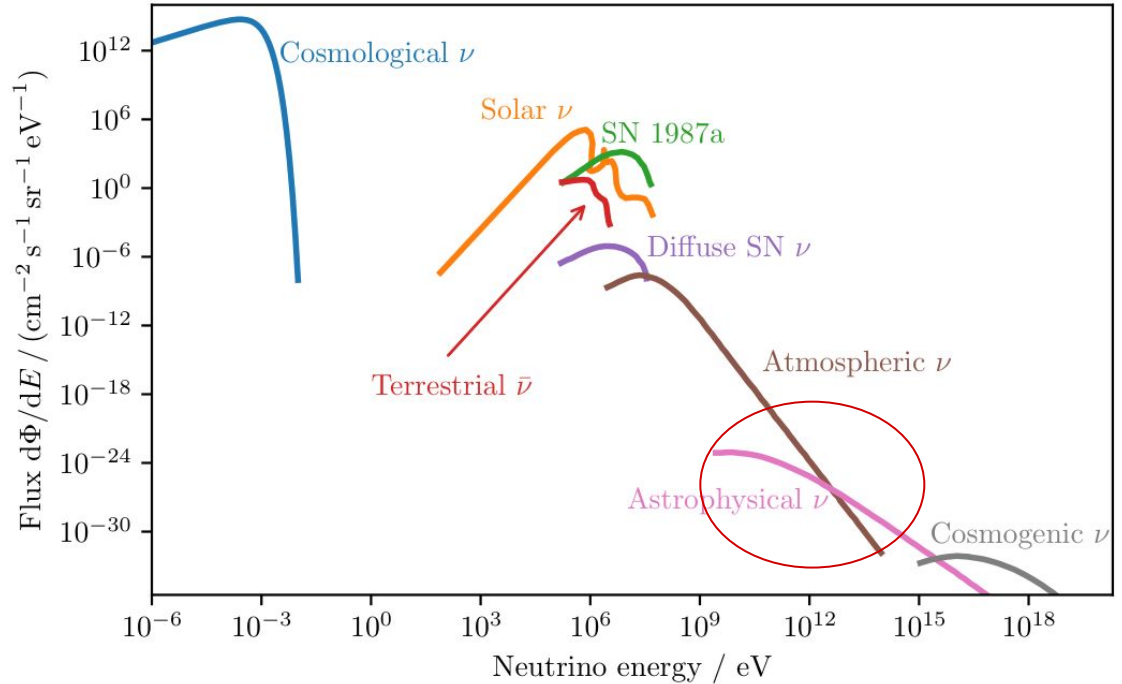


Outline

- **Multimessenger Astronomy at IceCube**
- Event Reconstructions with IceCube
- Measurements of the Diffuse Neutrino Spectrum
- Studies of Neutrino Sources
- Outlook

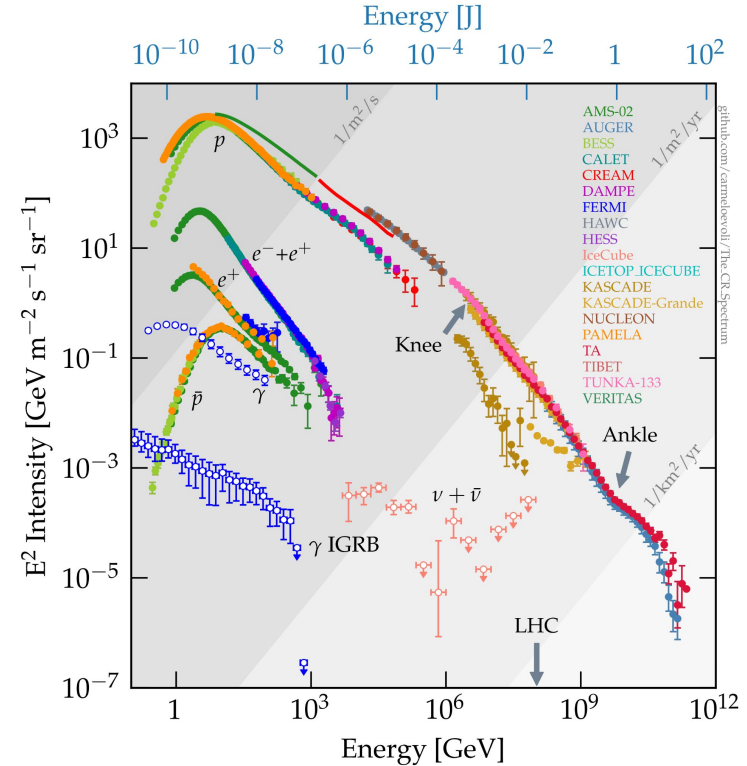
Neutrino Sources

- Neutrino spectra cover multiple orders of magnitude, from a plethora of sources
- Diffuse cosmic neutrino analyses focus on characteristics of astrophysical neutrino flux in the TeV-PeV range
- Isotropic nature indicates extragalactic origin, from sites of cosmic ray acceleration



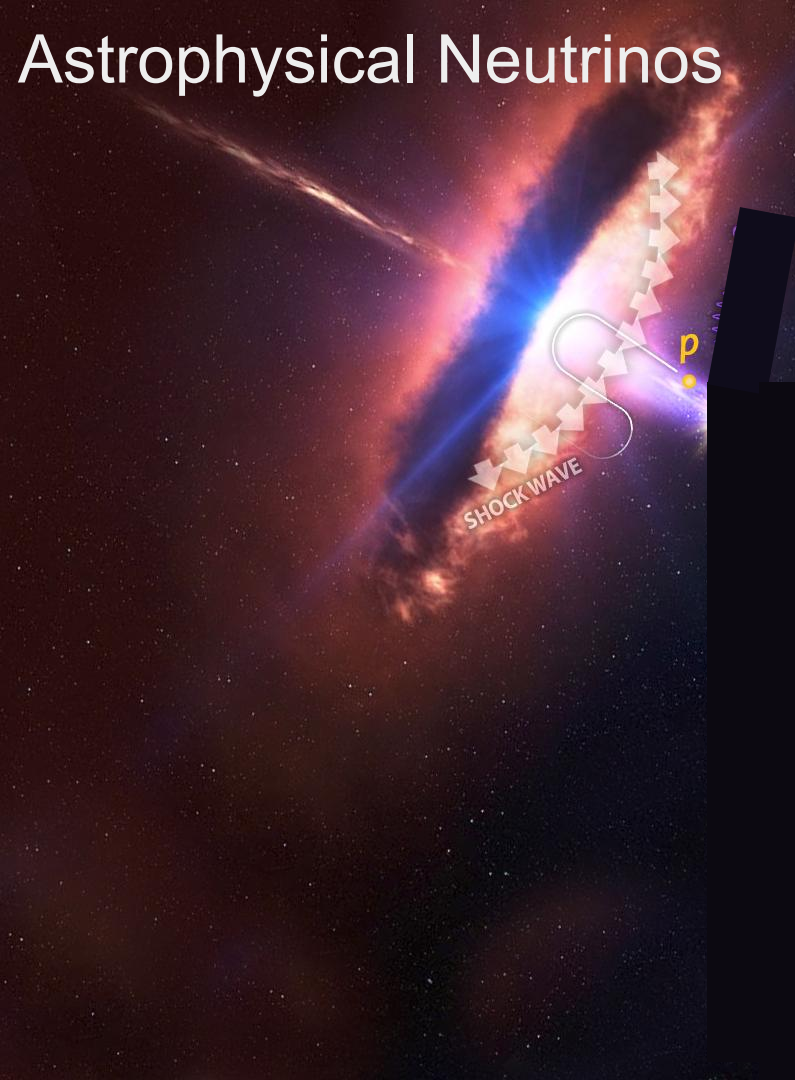
How are neutrinos produced from cosmic rays?

- Accelerated cosmic rays interact with photons in the ambient radiation field (p- γ interaction), or with protons in a gaseous environment (p-p interaction)
- In p-p interactions, pions are produced even at GeV proton energies, and inherit the power law spectrum of their parents.
- When the p- γ interaction is considered, the production of pions has a sharp resonance at the Δ^+ mass of 1232 MeV.



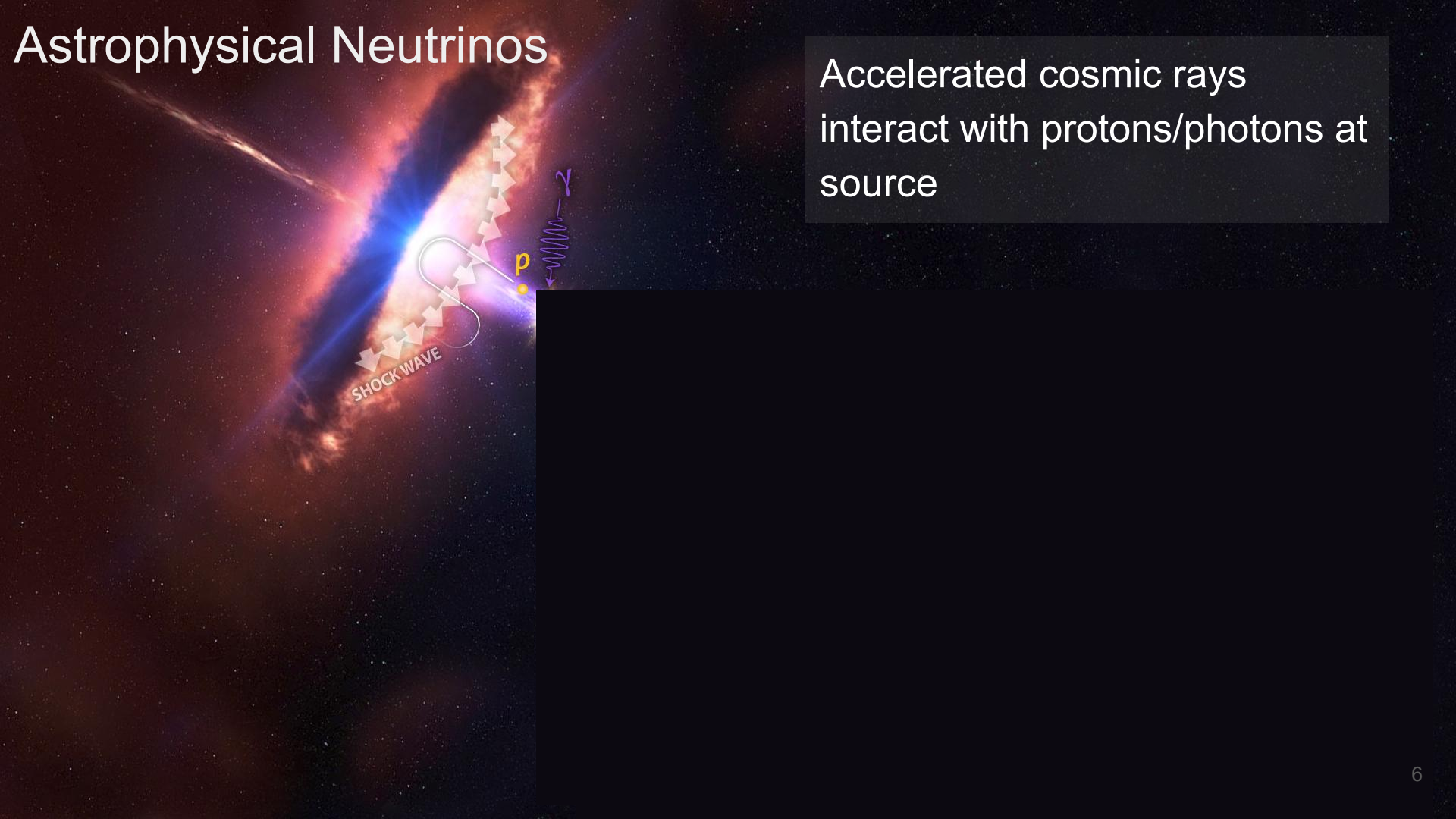
Astrophysical Neutrinos

Cosmic rays accelerated in
presence of strong magnetic fields
at source



Astrophysical Neutrinos

Accelerated cosmic rays
interact with protons/photons at
source

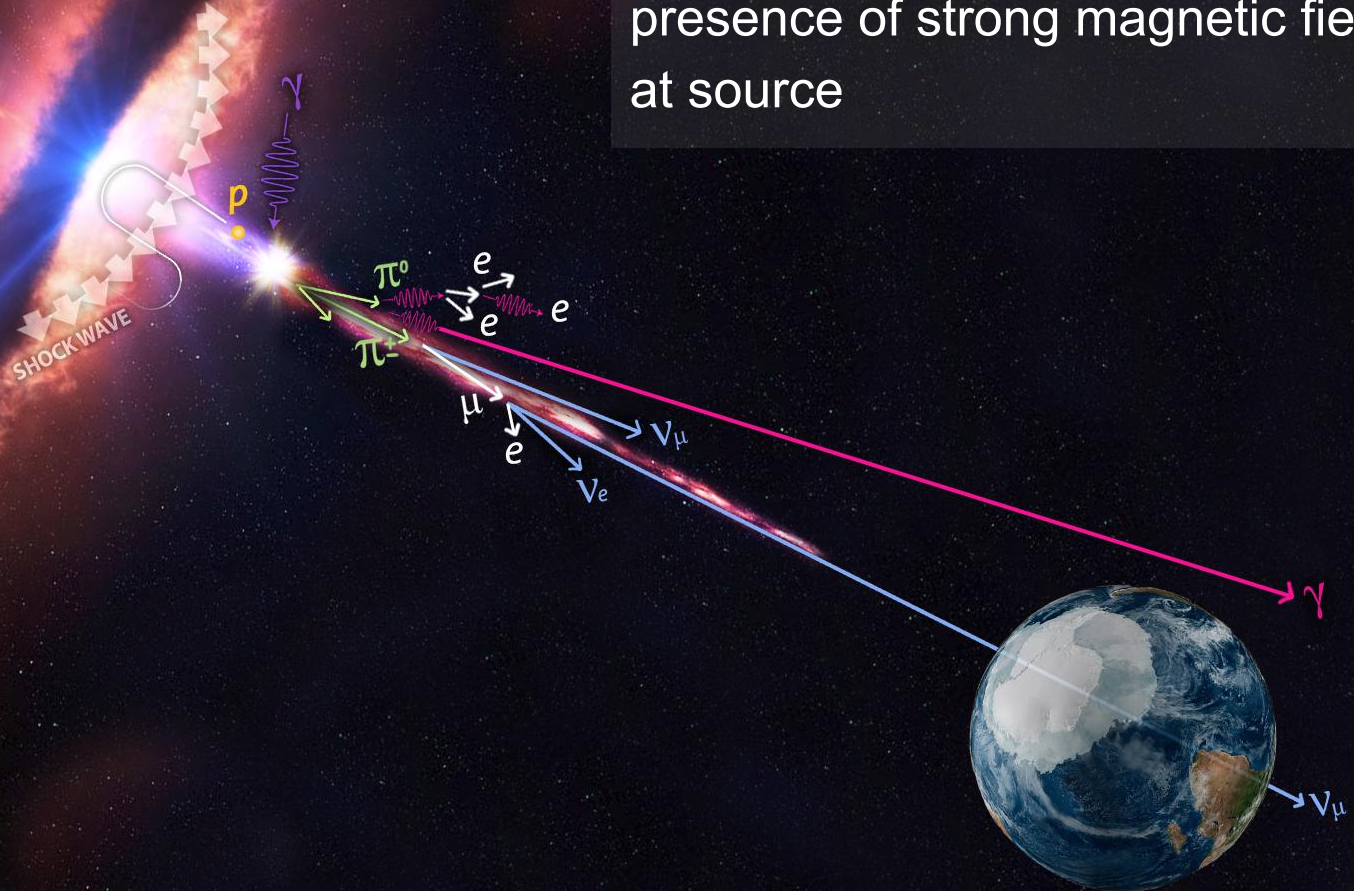


The diagram illustrates the acceleration of cosmic rays at an astrophysical source. A central, bright, multi-colored region (red, orange, blue) represents the source, with a prominent blue jet extending from it. A series of white arrows, labeled 'SHOCK WAVE', point towards the source from the left. A yellow dot labeled 'p' is located near the shock wave. A purple wavy line with a '2' at its end is also shown. The background is a dark, starry space.

SHOCK WAVE

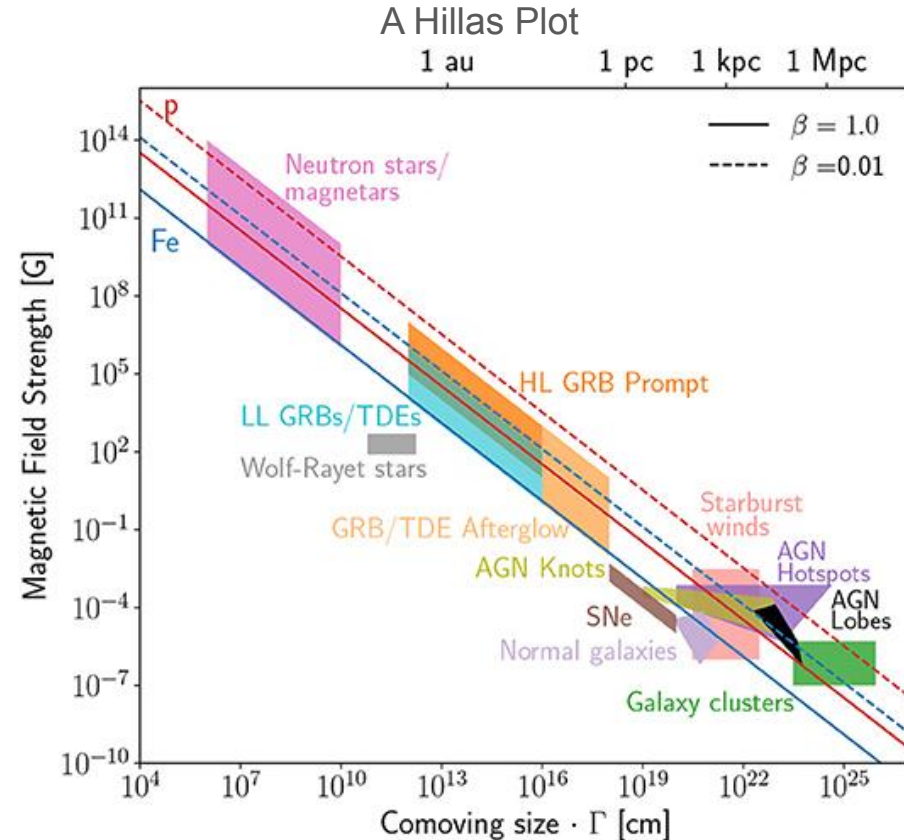
Astrophysical Neutrinos

Cosmic rays accelerated in presence of strong magnetic fields at source



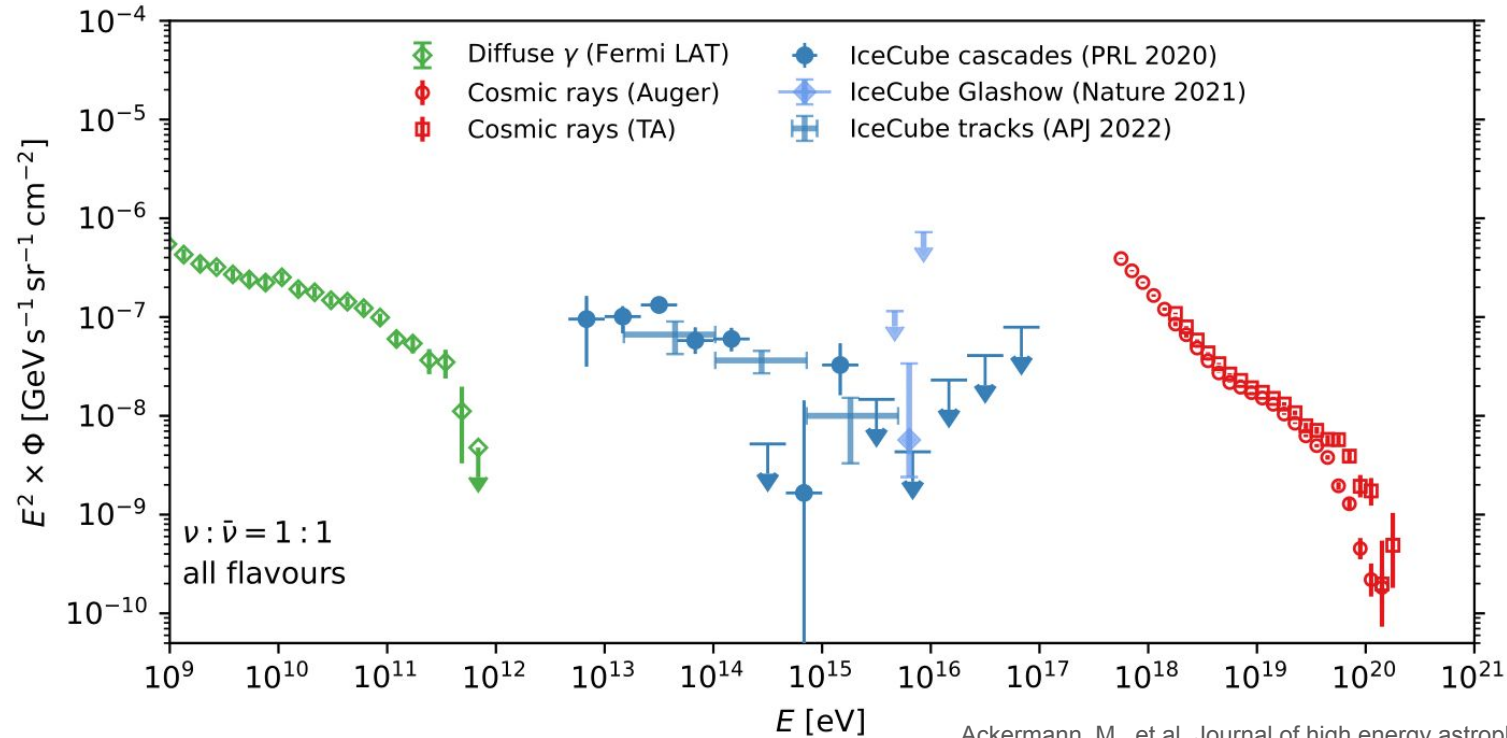
Characteristics of cosmic accelerators

- If we define the escape probability in terms of the characteristic periods of the acceleration and escape phenomena, T_{acc} and T_{esc} , we may define $P_{\text{esc}} = T_{\text{acc}}/T_{\text{esc}}$
- An accelerator with a certain characteristic T_{acc} must have an upper bound on the energy to which it can accelerate particles
- This also imposes a bound on the confinement volume of an accelerator. If the gyroradius of a particle exceeds the radius of the accelerator, it is no longer confined (**Hillas criterion**)



Multimessenger Astronomy

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



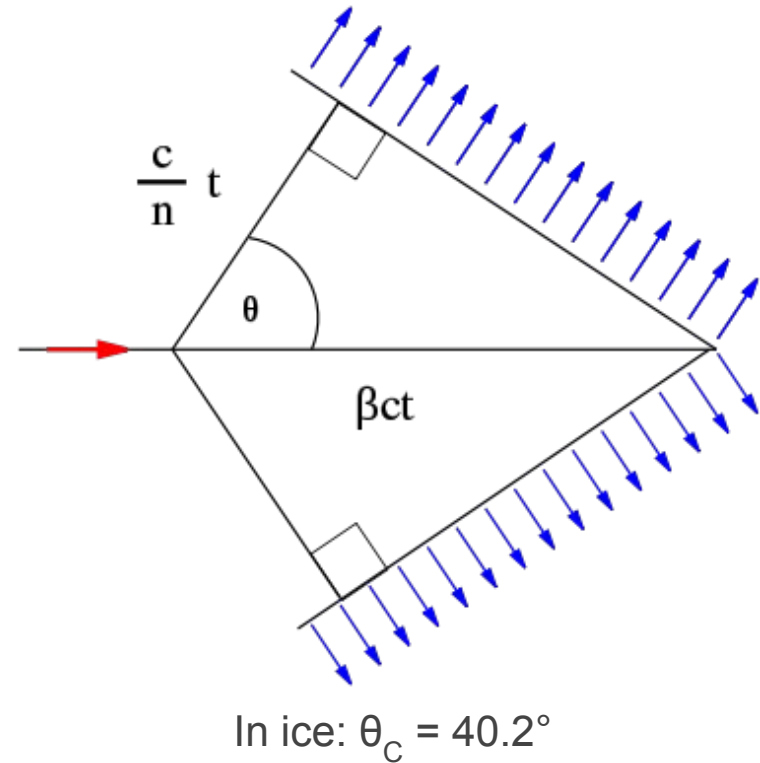
Ackermann, M., et al. Journal of high energy astrophysics 36 (2022)

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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





50 m

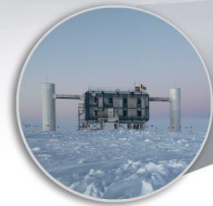
Ice Top

86 strings of DOMs,
set 125 meters apart

Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility



Digital Optical Module



IceCube Laboratory
Data is collected here and
sent by satellite to the data
warehouse at UW–Madison

1450 m



Digital Optical Module (DOM)
5,160 DOMs
deployed in the ice

2450 m

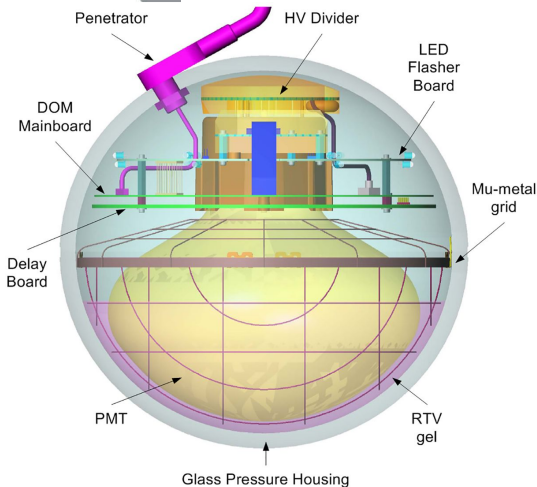
IceCube
detector

DeepCore

Antarctic bedrock

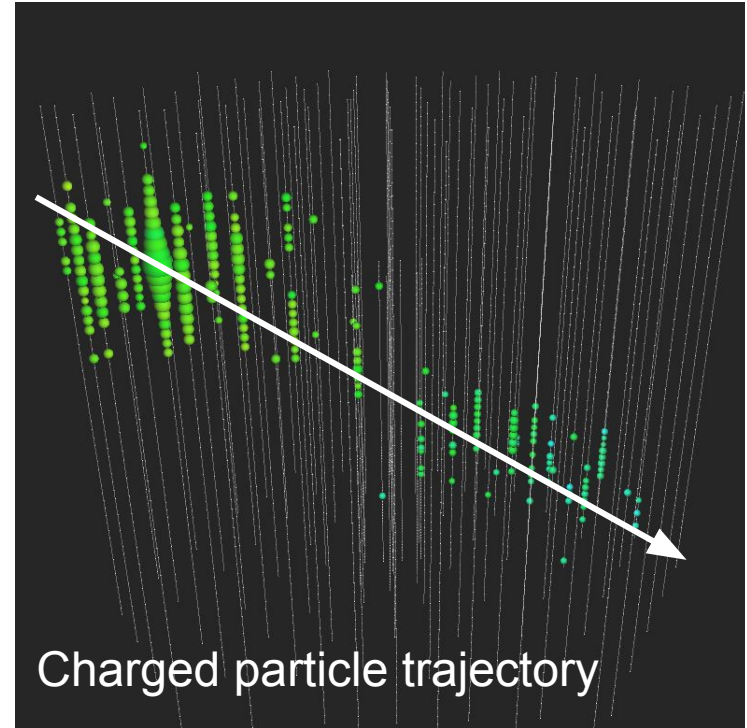
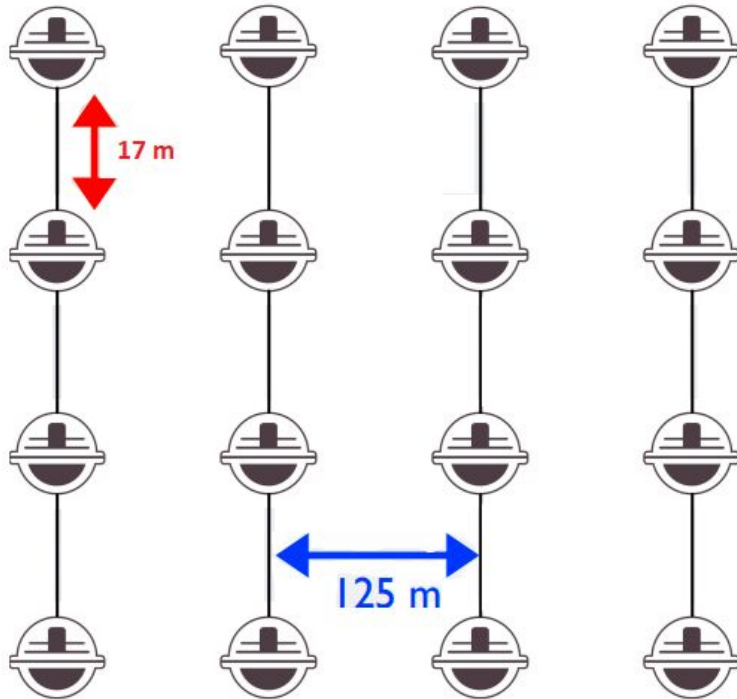
60 DOMs
on each string

DOMs
are 17 meters
apart



Event Reconstruction

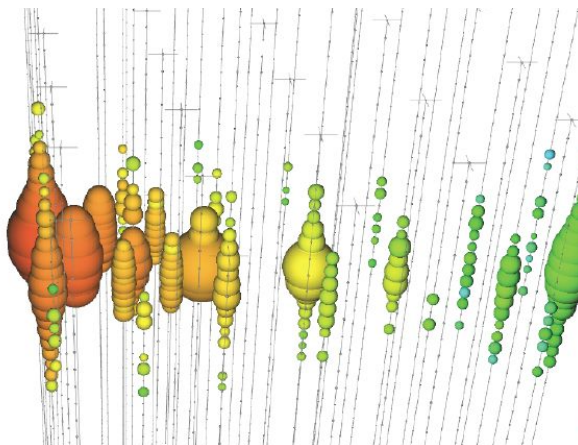
- Number of Cherenkov photons captured $\propto$ deposited energy.
- Photon arrival times at DOMs helps reconstruct particle trajectory.



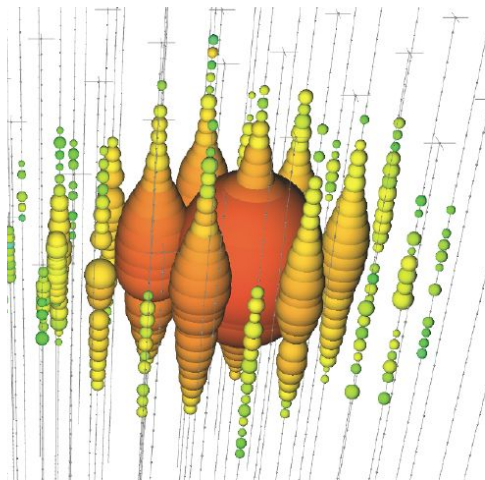
IceCube Event Morphologies



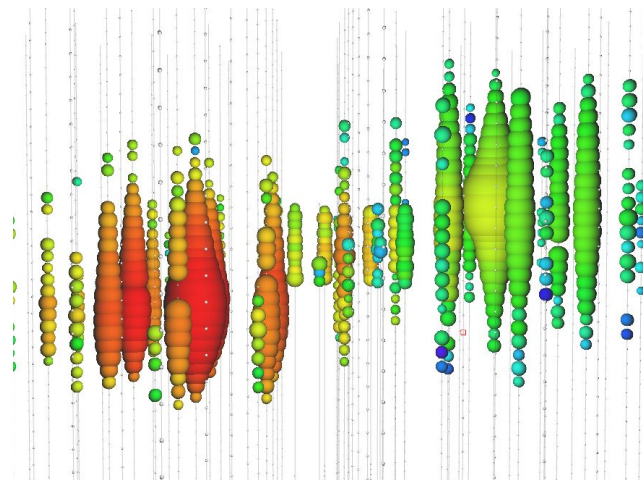
Tracks (Data)



Cascades (Data)



Double Cascade (Simulated)



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

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

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

$$\nu_l + X \rightarrow \nu_l + \text{Hadrons}$$

$$\tau^- \rightarrow \nu_\tau + \dots$$

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

Energy Res. : 8% @ 100 TeV

Decay Length : 50m/PeV

Angular Res. : 0.3°

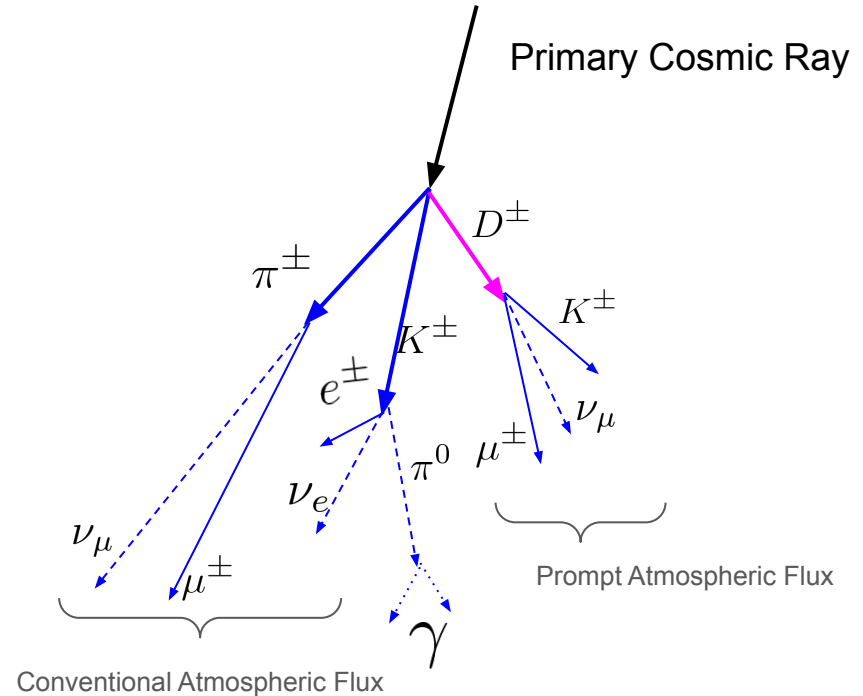
Angular Res. : 4°

Outline

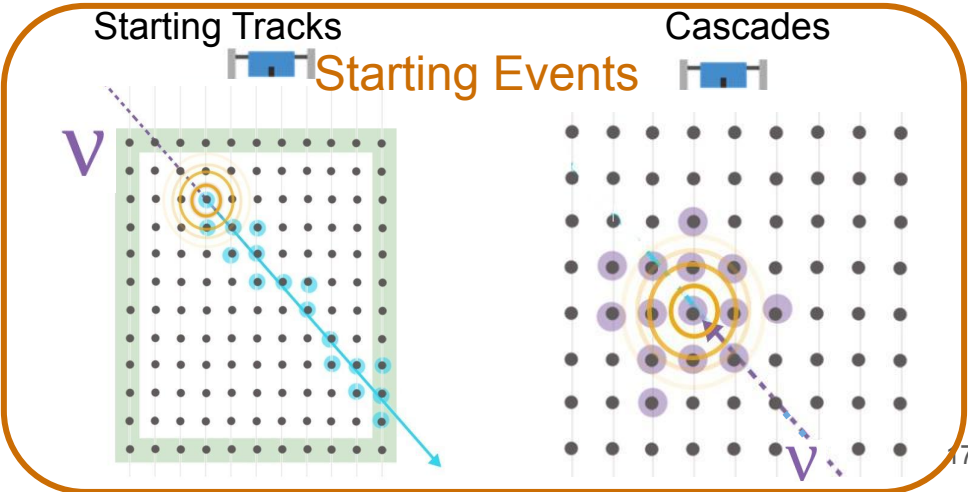
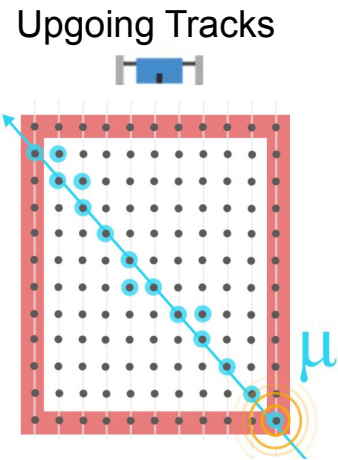
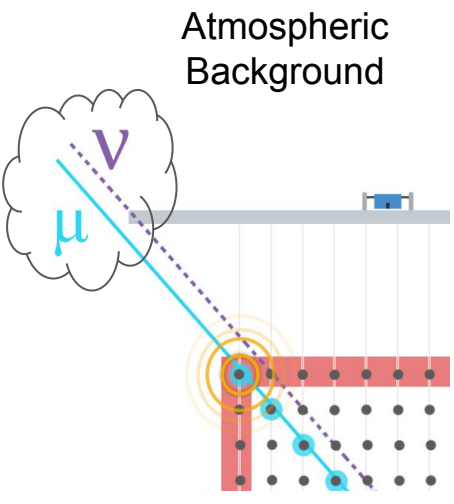
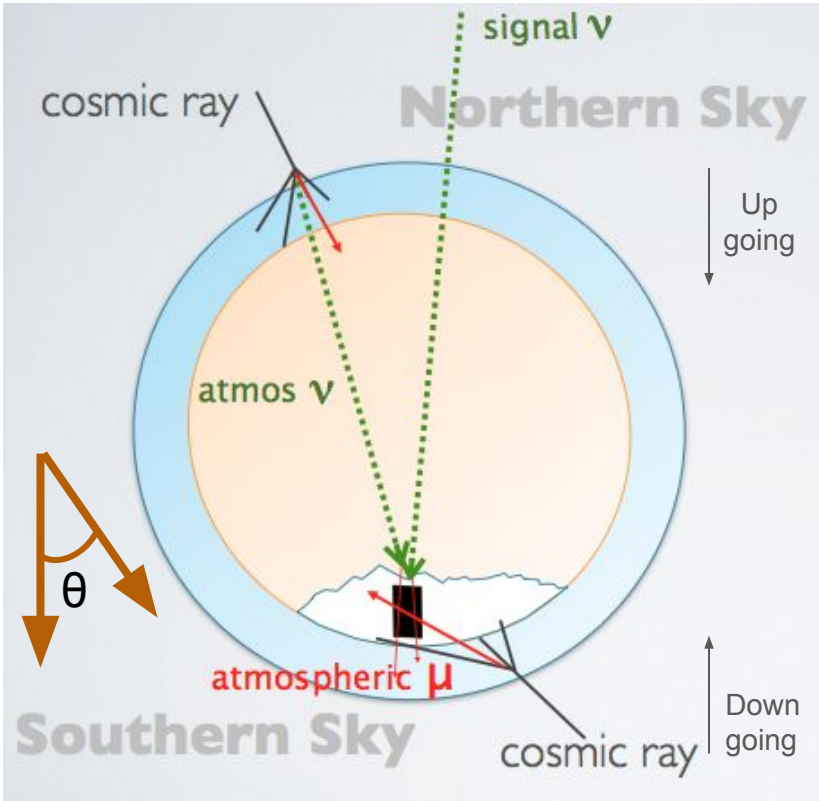
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Atmospheric Background

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



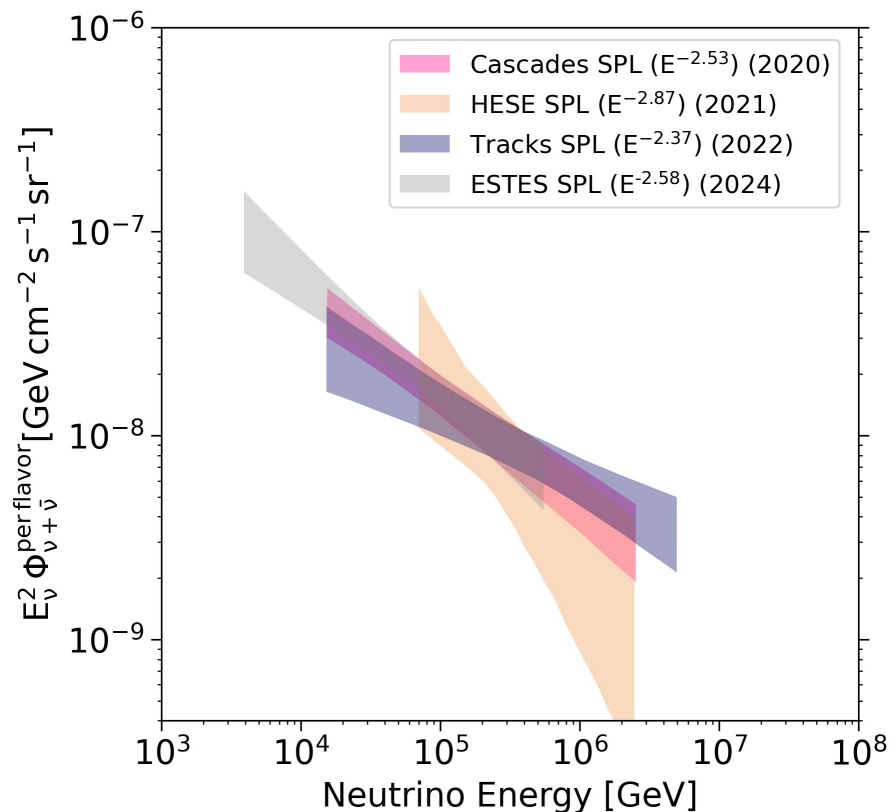
Identifying Cosmic Neutrinos



Diffuse Cosmic Neutrino Flux

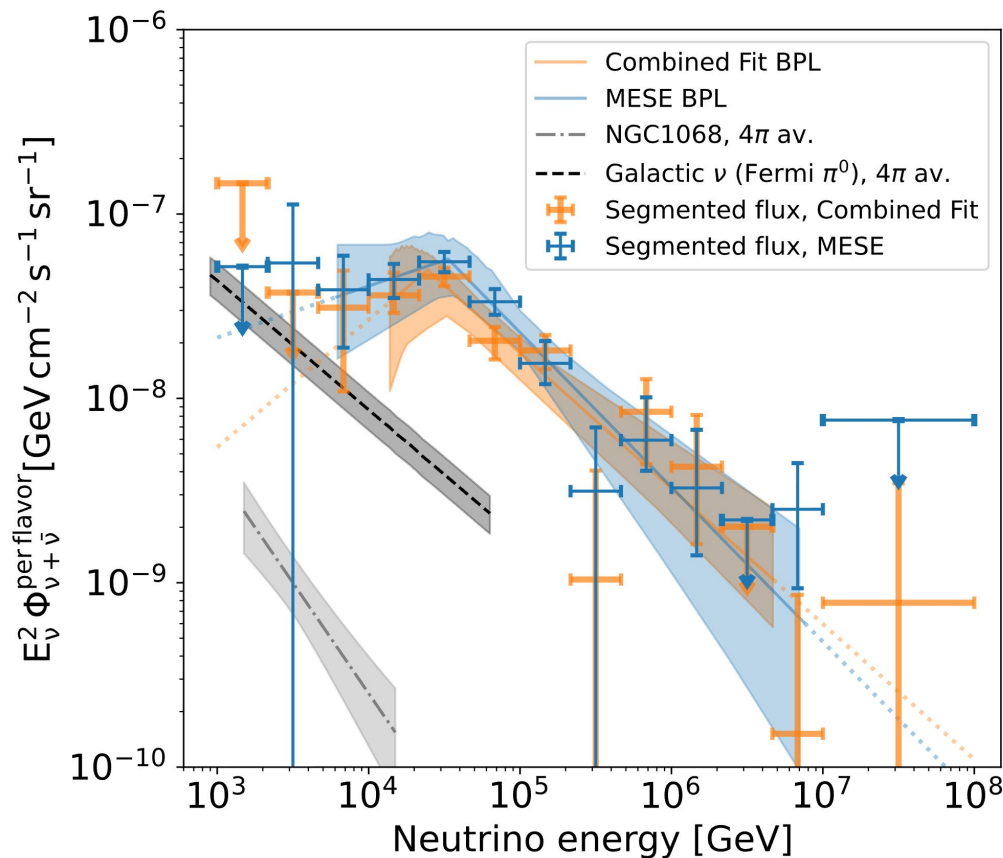
Previous IceCube measurements of the diffuse spectrum follow a single power law ($E^{-\gamma}$).

- 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



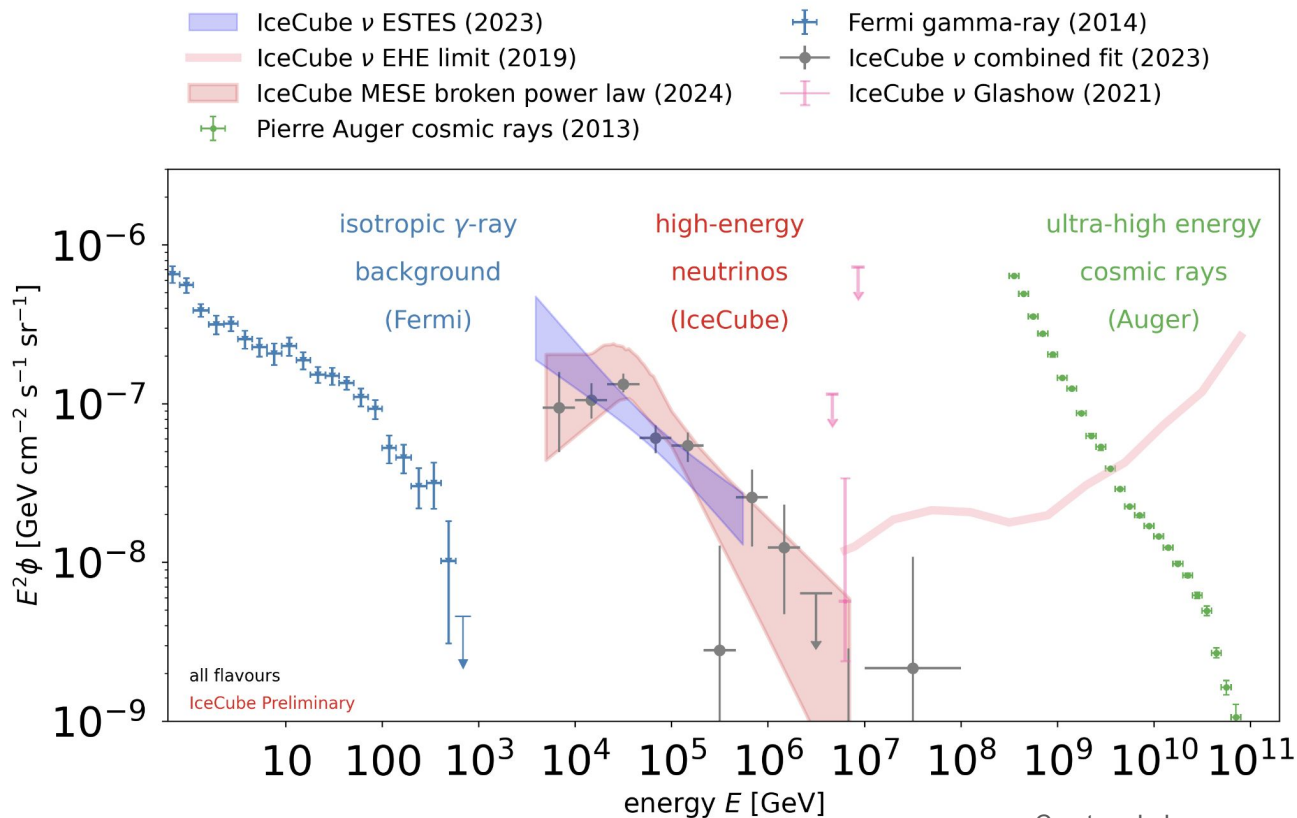
Evidence of spectral curvature

- Two analyses using both cascades and tracks reject SPL model for first time by $>4\sigma$
- “Combined Fit” analysis combining Cascades and Northern Tracks dataset
- “Medium Energy Starting Events (MESE)” selection using cascades and starting tracks
- Jointly published in [Phys. Rev. Lett.](#) and [Phys. Rev. D](#)



The multi-messenger sky

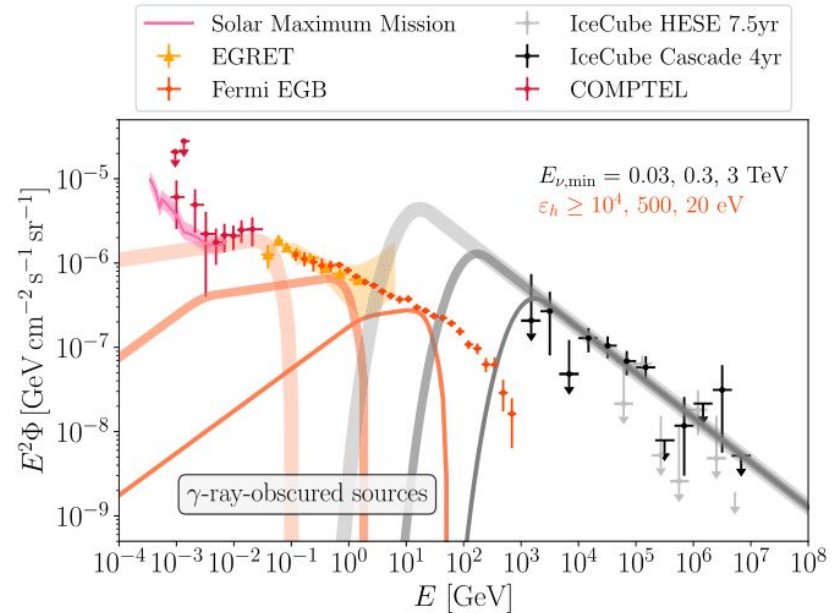
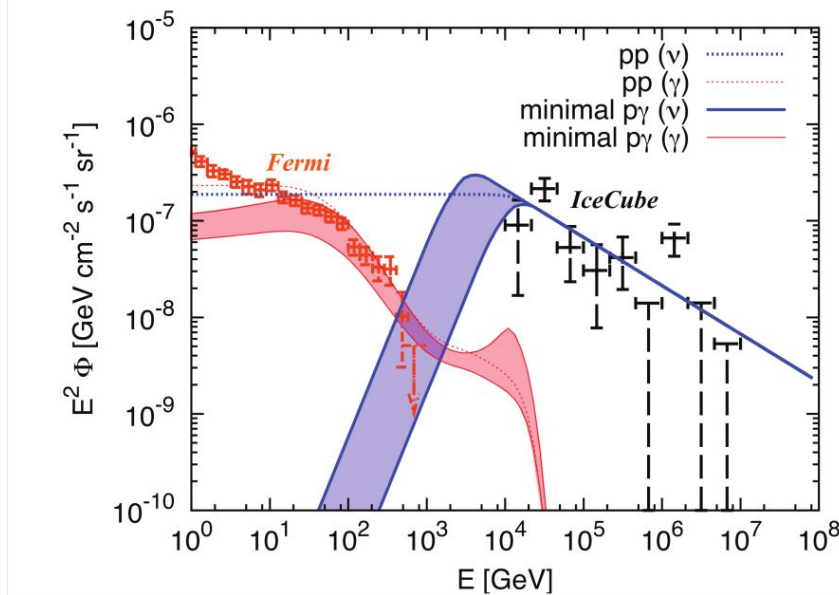
- Extrapolation of SPL model overestimates γ -ray flux
- Spectral curvature reduces potential tension with extragalactic γ -ray spectrum



Courtesy L. Lu

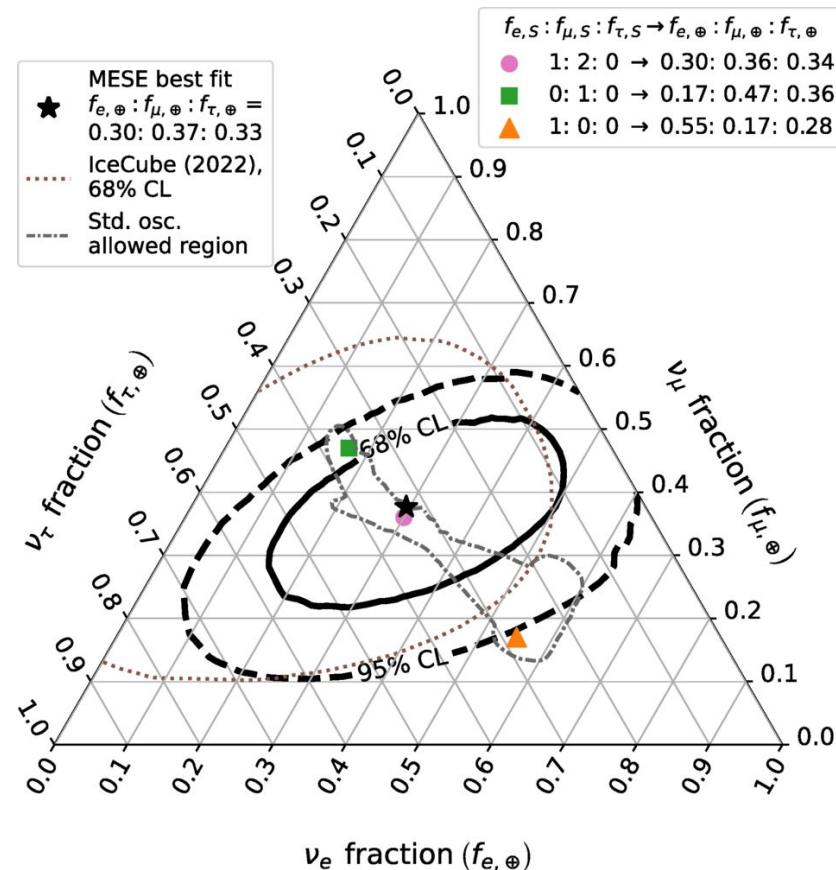
Cosmic ray accelerator dynamics

- Low-energy cutoff may indicate sensitivity to p-p vs p- γ neutrino emission
- Neutrino energy constrains photon field at source, could indicate correlation with MeV/X-ray bright objects



Neutrino flavor measurements

- Discovery of astrophysical tau neutrino flux, with 7 candidate events in PRL132, 151001, (2024).
- MESE dataset used to study ratio of neutrino 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

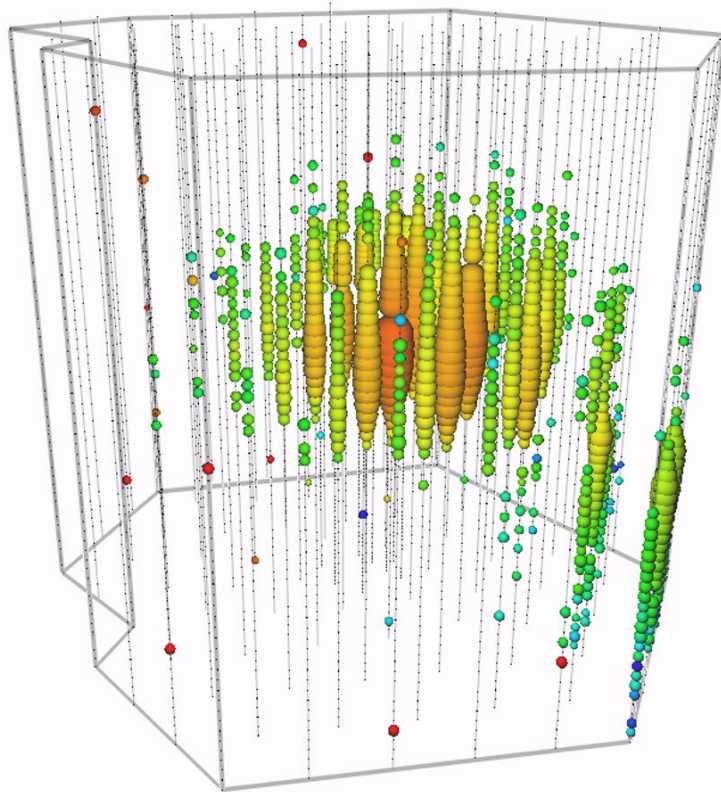


[Phys. Rev. Lett. 137, 081002](https://arxiv.org/abs/2405.08102)

IceCube's Highest Energy Event

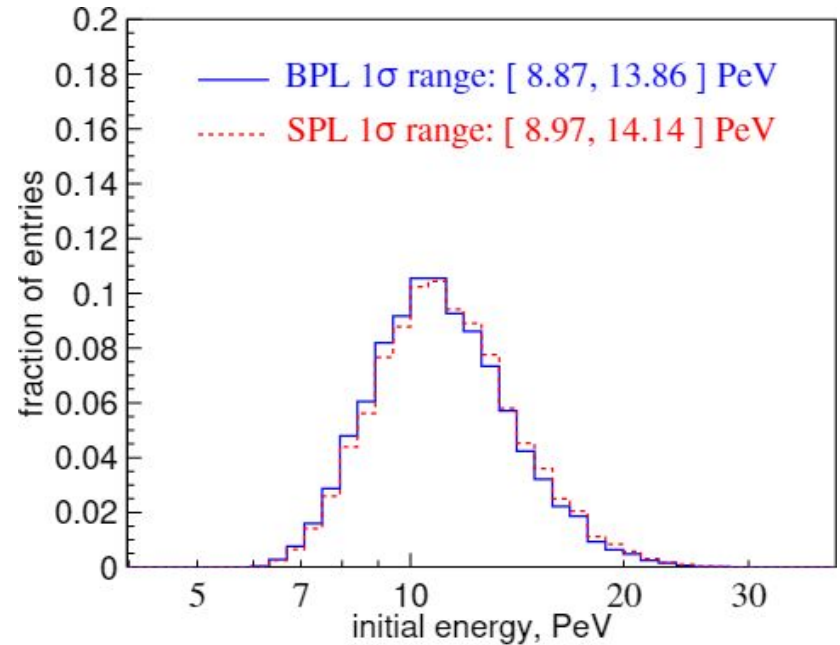
Event 132379/15947448-2
Time 2019-03-31 06:55:43 UTC

IceCube Preliminary



- IC190331A: Starting Track in HESE sample, reconstructed energy 4.8 PeV
- Primary neutrino energy*: 11.4 PeV

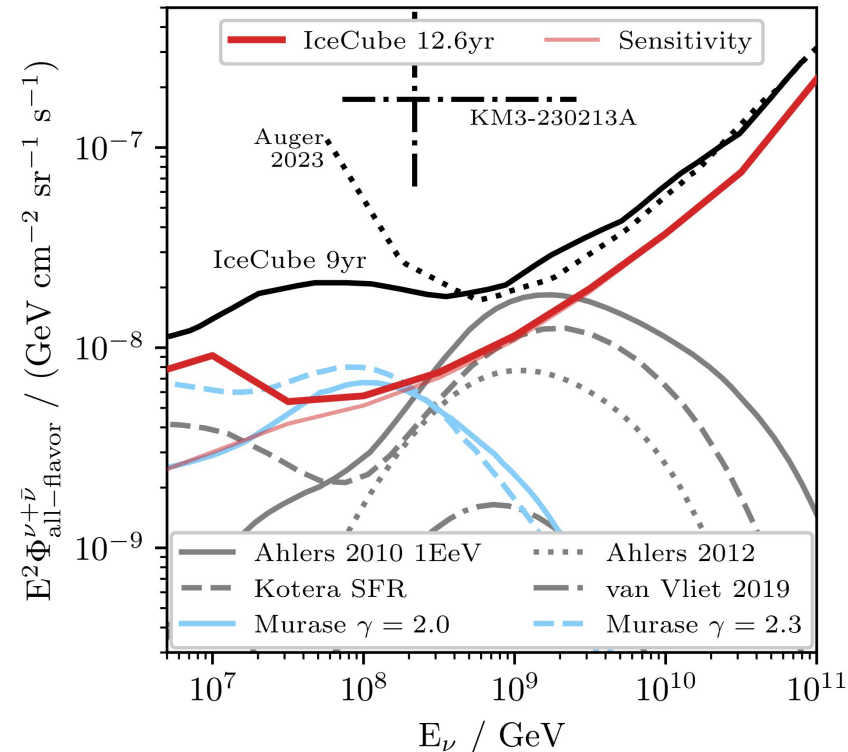
PoS ICRC2023, 1030 (2023)



*Most probable neutrino energy when assuming a BPL spectrum (γ_1, γ_2)=(1.72,2.84) [[Data Release](#)]²³

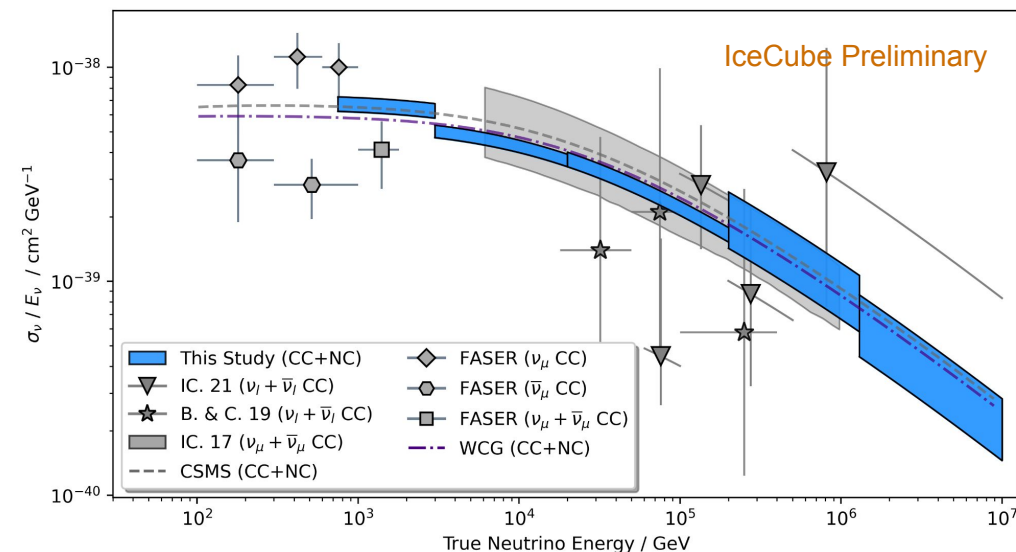
Spectral measurements at PeV energies and beyond

- 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
 $E^2\Phi_{\text{all-flavor}} \sim 10^{-8} \text{ GeV s}^{-1} \text{ sr}^{-1} \text{ cm}^{-2}$
- 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

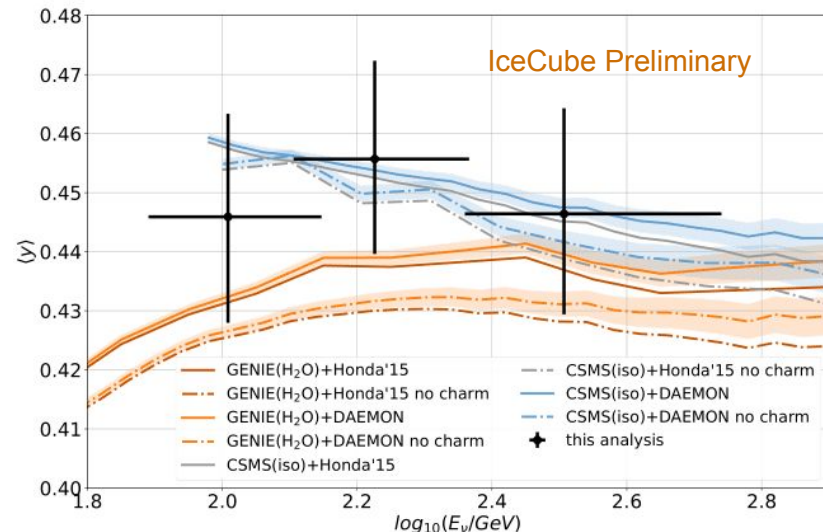


Deep Inelastic Scattering Inelasticity measurements

- Inelasticity measurements from energy ranges linking accelerator measurements to natural sources
- IceCube Upgrade expected to extend threshold below 80 GeV



[C. Hill, TEVPA 2026](#)



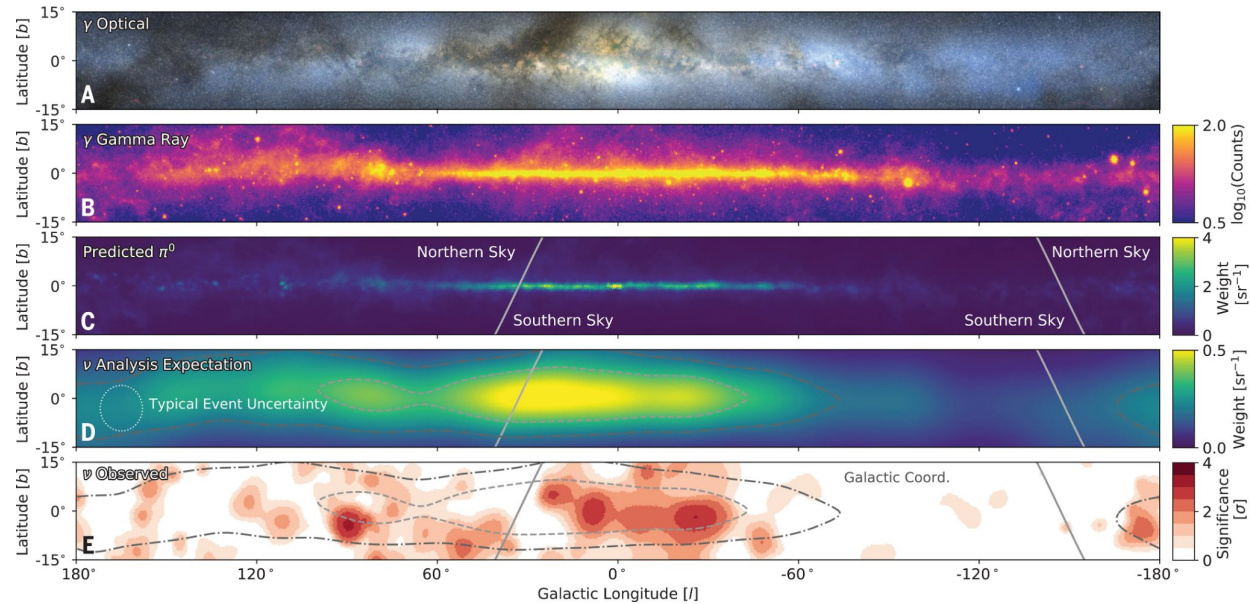
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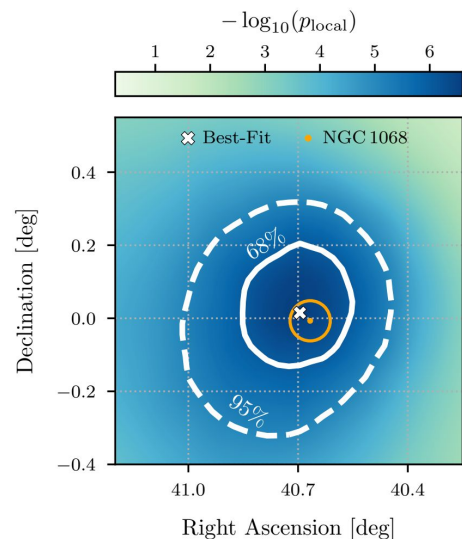
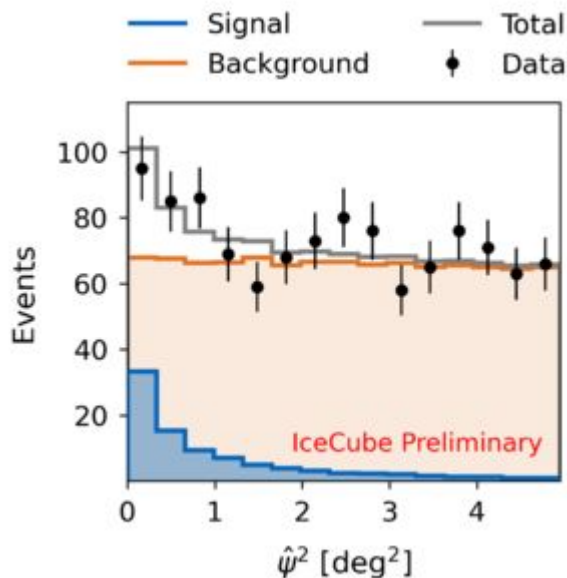
The Milky Way as a neutrino source

- A novel cascade event selection, created using deep learning techniques, was able to find evidence for galactic neutrino emission at 4.5σ
- Incorporation of track signatures and improved ice modelling leads to 5.7σ post trial significance: [Link](#)



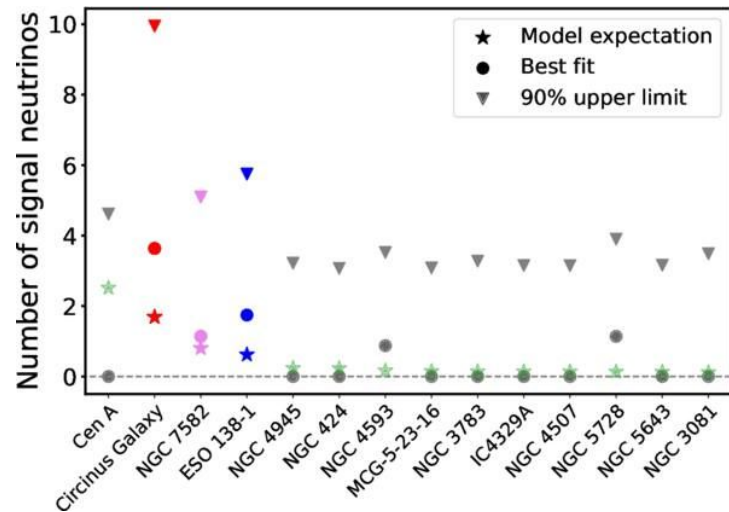
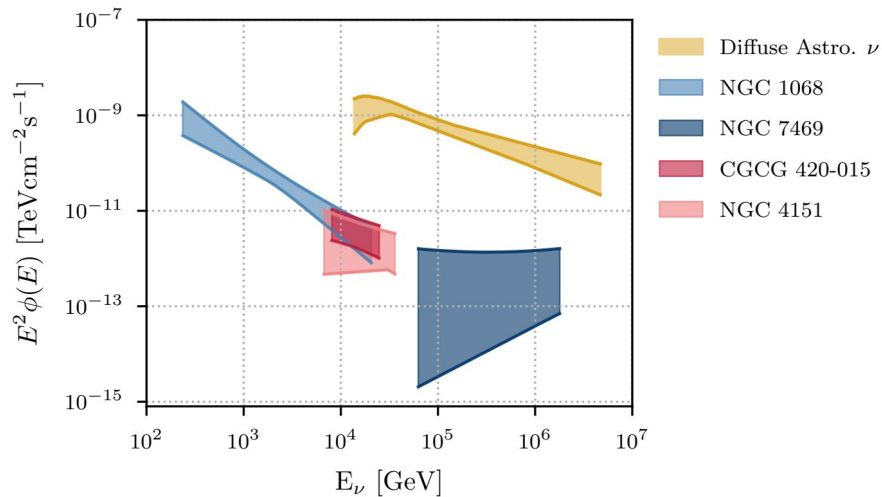
Neutrino emission from NGC 1068

- Neutrinos are observed from sources where ambient matter may occlude GeV gamma rays, but which may be bright in the MeV or X-ray regime.
- IceCube observed neutrinos from the galaxy NGC 1068 with a significance of 4.2σ , with the observed flux exceeding gamma-ray predictions by at least two orders of magnitude.



Neutrinos from X-ray bright Seyfert Galaxies

- Evidence for neutrino emission from X-ray bright AGN cores in northern sky, correlated with the intrinsic X-ray flux
- Study performed with sample of Seyfert galaxies in the Southern sky also finds an excess of events incompatible with background-only hypothesis at 3.0σ



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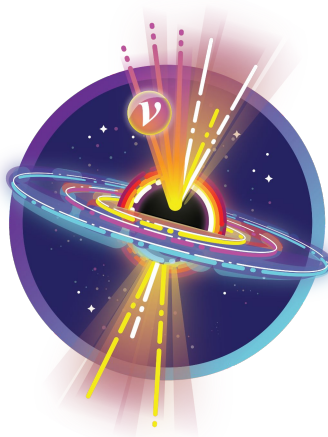
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Observations of astrophysical neutrinos



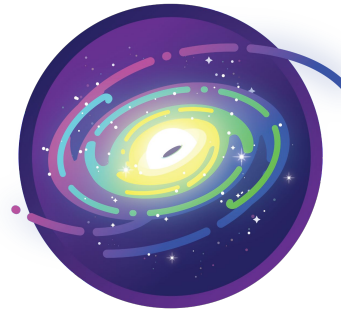
ASTROPHYSICAL NEUTRINOS
DISCOVERED

.....●.....
2013



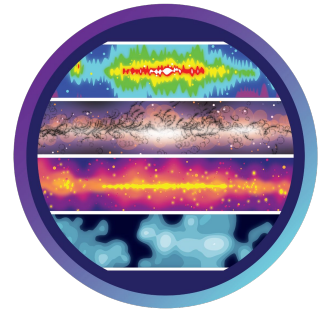
BLAZAR TXS 0506+056
NEUTRINO EMISSION IDENTIFIED

.....●.....
2018



ACTIVE GALAXY NGC 1068
NEUTRINO EMISSION IDENTIFIED

.....●.....
2022

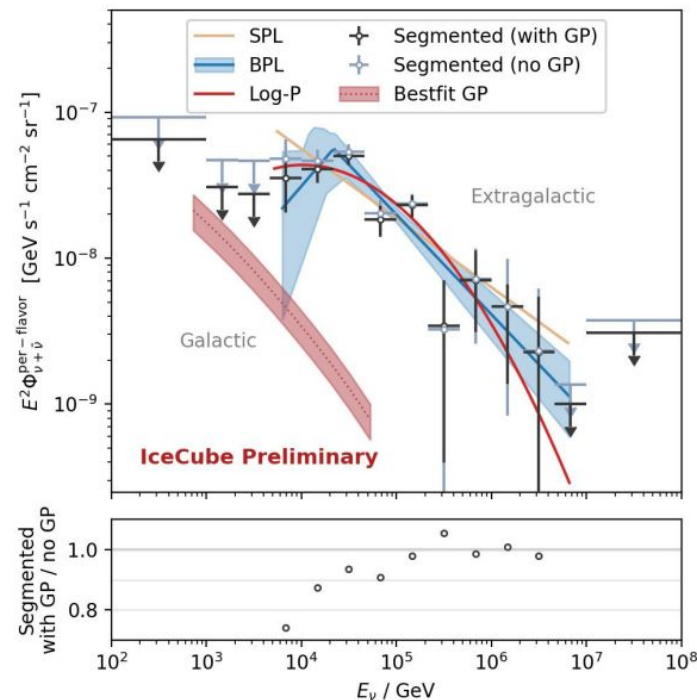


MILKY WAY
NEUTRINO EMISSION IDENTIFIED

.....●.....
2023

Combined picture

- Flux of neutrinos at Earth greater than contribution from Milky Way alone -> unresolved extragalactic sources account for the bulk of the TeV neutrino flux
- Extragalactic sources may be opaque to GeV gamma rays, but may show up in the MeV or keV range
- Sites of galactic neutrino emission are still unresolved, and need careful study to identify



[CRIS-MAC 2026](#)

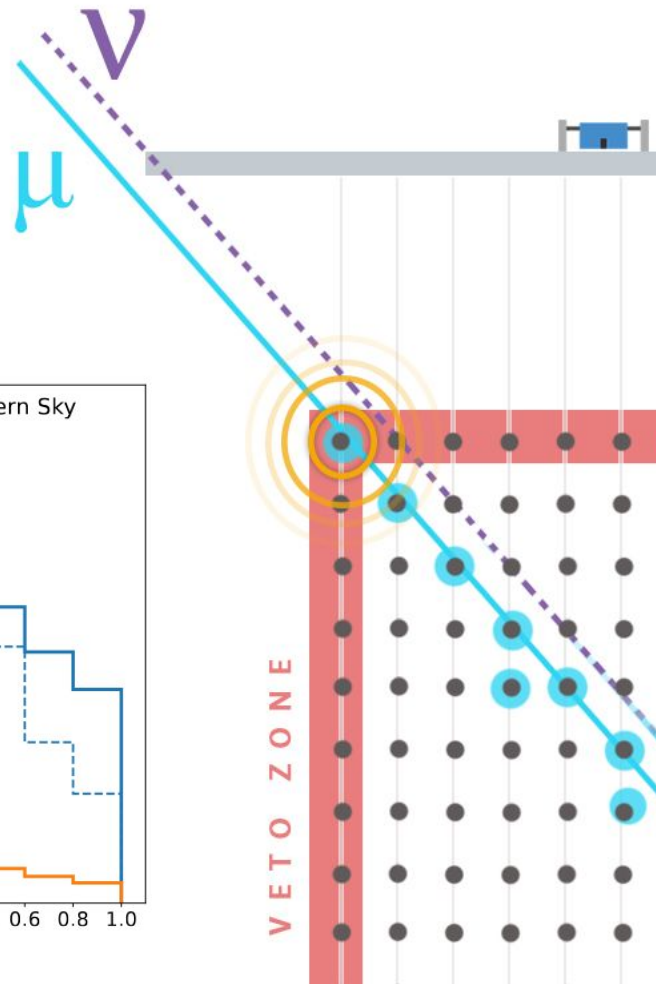
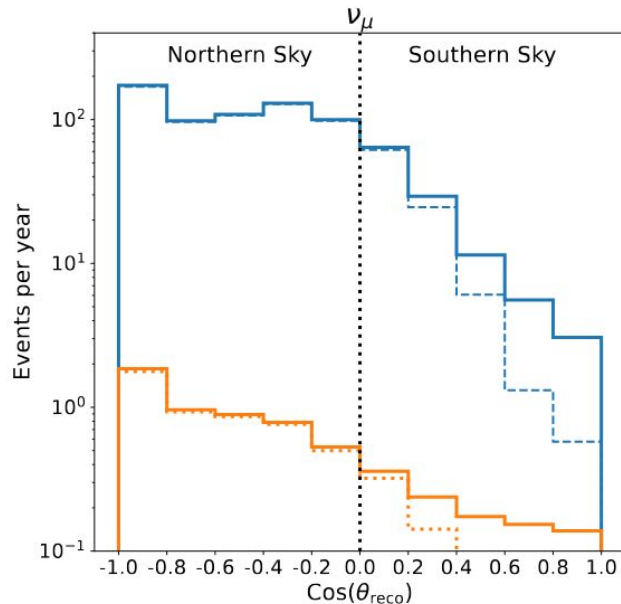
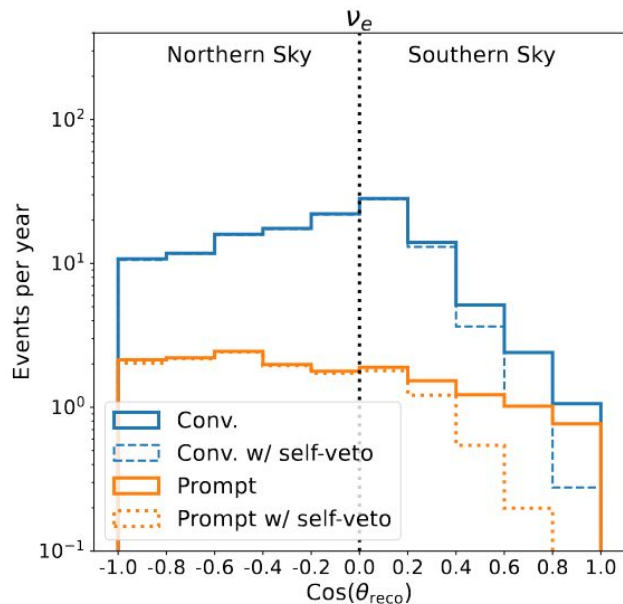
Outlook

- IceCube has been able to identify neutrino emission both from within our galaxy and from extragalactic sources
- Improvements in calibration, ice modelling, and machine-learning analysis techniques will push cosmic neutrino sensitivity lower into the TeV regime, enabling the testing of more detailed spectral models.
- Future analyses to study the dynamics and populations of neutrino emitters are underway. Expansions such as the IceCube Upgrade (see talk by D. Butterfield) and the planned IceCube-Gen2 aim to greatly boost the sensitivity of searches for neutrino sources across many decades in energy

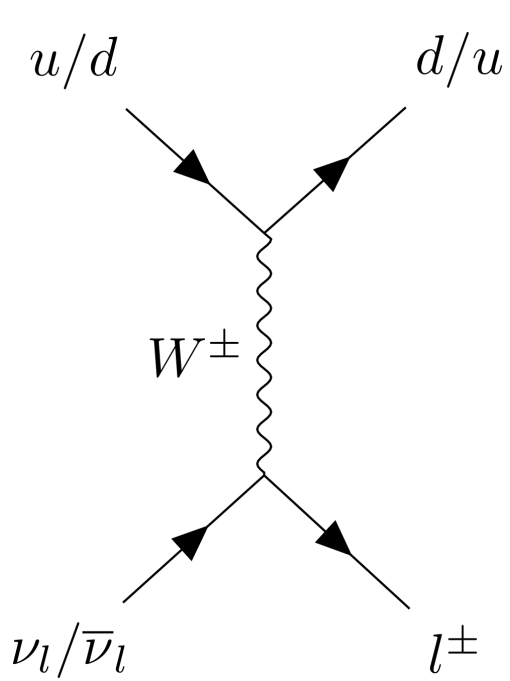
Backup

Neutrino self-veto

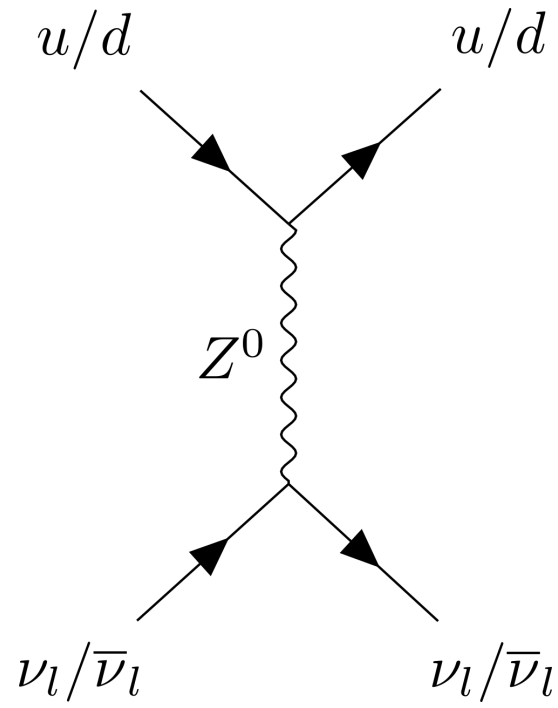
- Neutrinos from CR showers often accompanied by muons.
- Vetoing these muons suppresses atm. neutrino background
- Accurate modeling of the self-veto suppression via muon bundle injection.



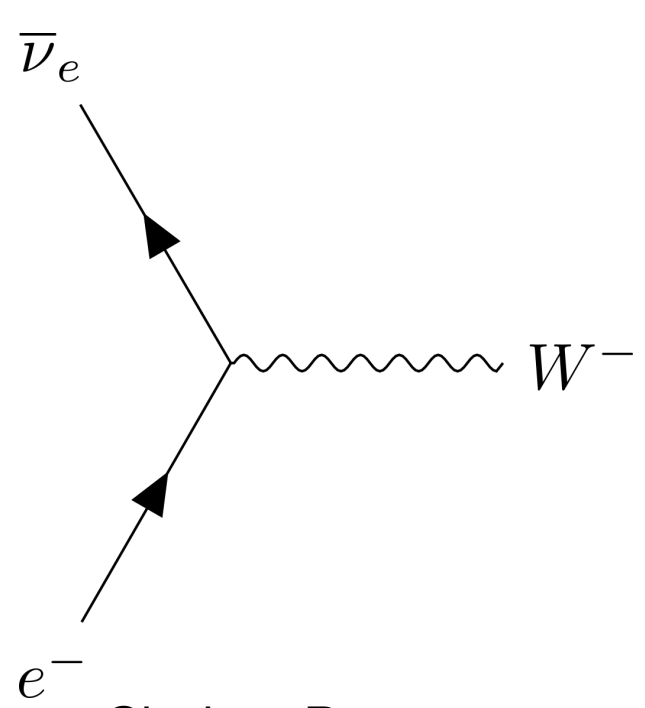
Neutrino Interaction Channels



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



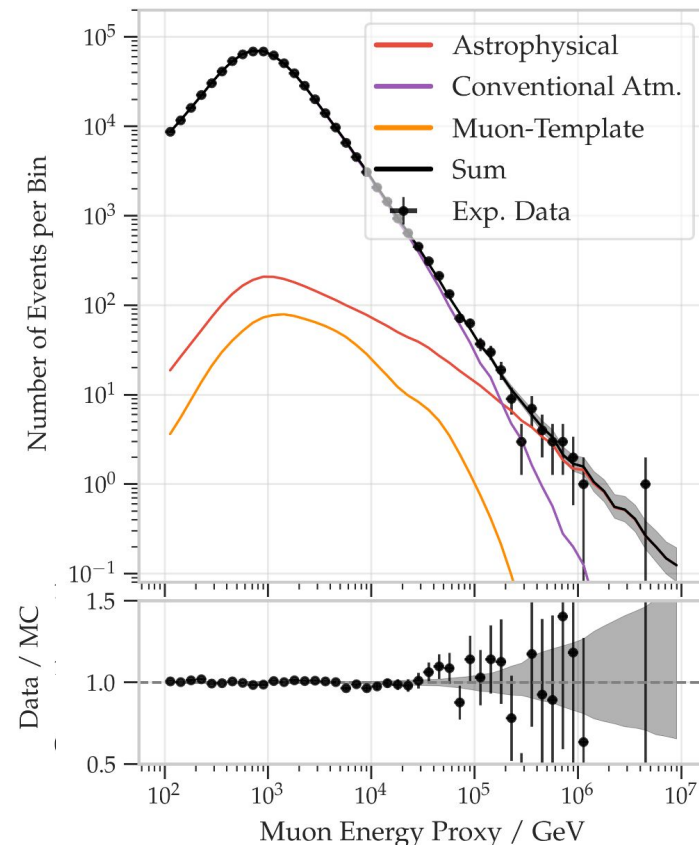
Neutral current interactions have an outgoing scattered hadron and neutrino



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

Atmospheric Neutrino Spectrum

- As conventional neutrinos are produced by the decay of pions produced in cosmic ray air showers, they follow a spectrum one unit steeper than the parent cosmic ray spectrum $\sim E^{-3.7}$
- The neutrino spectrum at Earth is therefore dominated by atmospheric neutrinos upto ~ 100 TeV, at which point astrophysical neutrinos predominate



The energy distribution of upgoing tracks for
the period 2010-18

The Astrophysical Journal 928.1 (2022): 50

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)

