Probing the Transition from Atmospheric to Astrophysical Neutrinos in IceCube

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ISVHECRI

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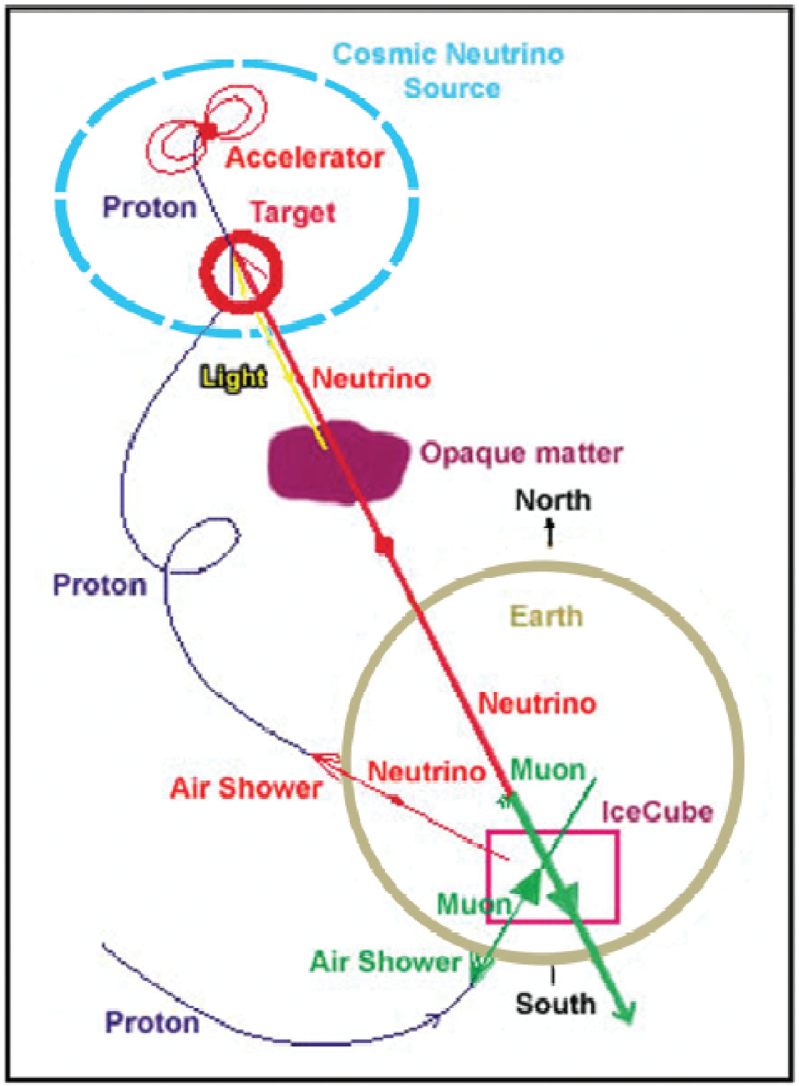
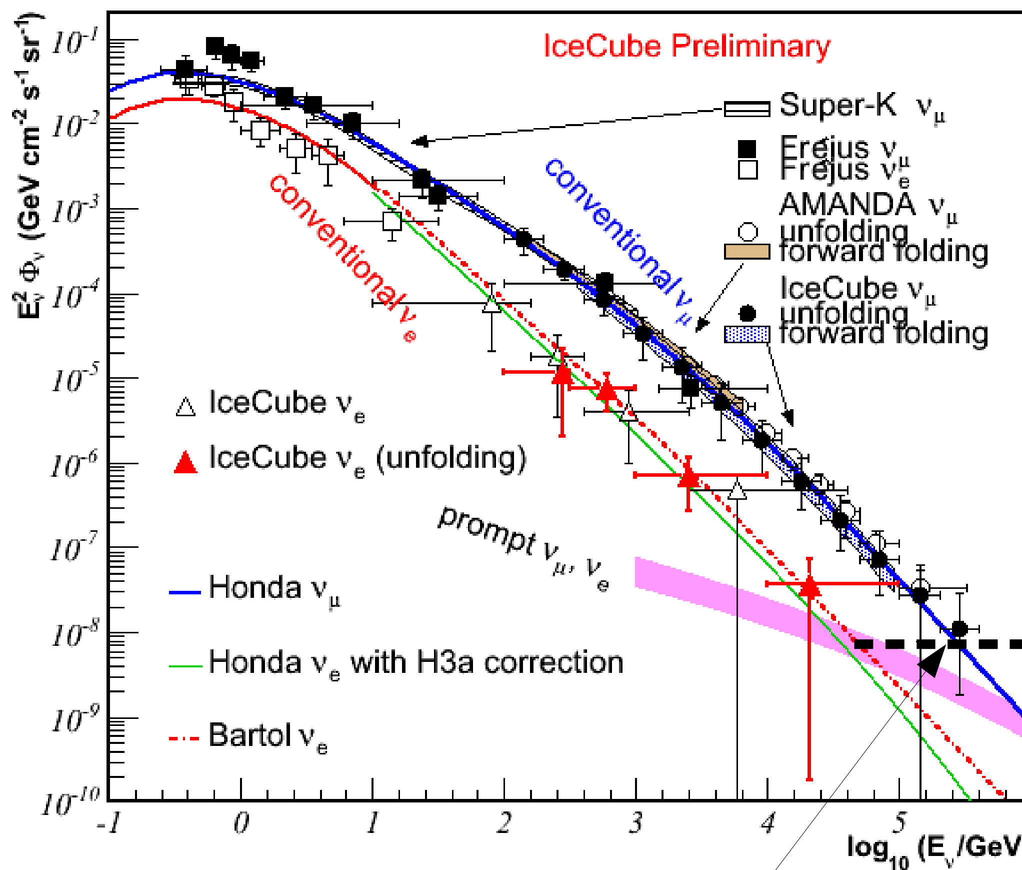
Astrophysical Neutrinos



- Neutrinos are ideal tracers of cosmic ray acceleration
- Generic models of shock acceleration predict an ~E^{-2} spectrum and 1:1:1 flavor ratio at Earth
- IceCube was built to find them
- Detect Cherenkov light from neutrino interactions in ~1 km^3 of clear glacial ice at the South Pole
- New measurements above ~10 TeV:
  - 2-year multi-flavor search: J. van Santen's talk
  - Here: 3-year results with cascade events

Atmospheric Neutrinos

- Neutrinos also produced by cosmic rays in the atmosphere
- “Conventional”
  - Pion/kaon decay
  - ~$E^{-3.7}$, enhanced flux near horizon
- “Prompt”
  - Charm meson decay
  - ~$E^{-2.7}$, isotropic
  - Unobserved so far
- IceCube has found strong evidence for an excess of astrophysical origin above ~60 TeV

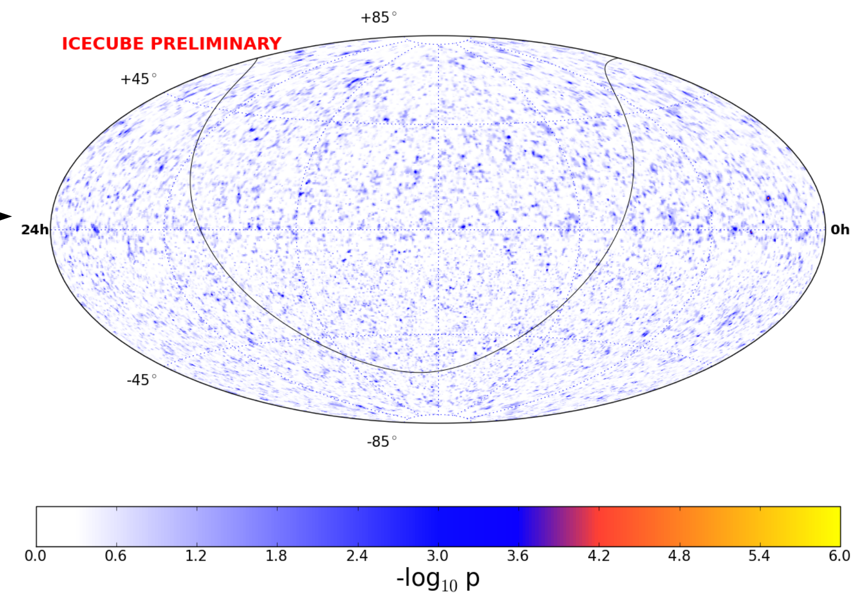


Red: Latest IceCube ν_e measurement

Current best estimate of E^{-2} flux

Finding Neutrinos in IceCube

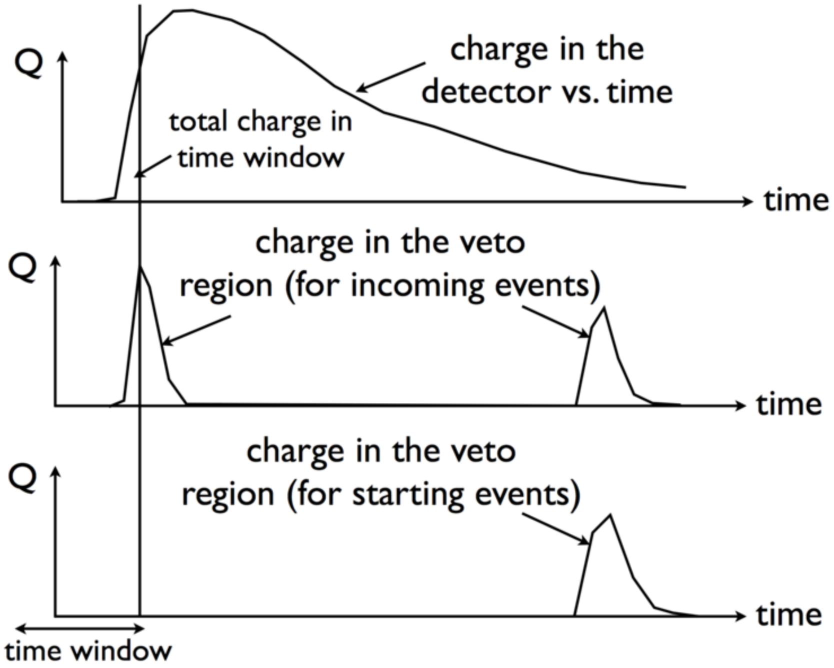
- Cosmic ray muons are the largest background
- Several approaches (see J. van Santen's talk):
  - **Point source** ⟶
    - Look for clustering of events in the sky
    - None found yet
  - **Up-going ν_μ**
    - Use the Earth to shield muons, half-sky
    - Look for high energy excess
  - **Veto-based** (focus of this talk)
    - Reject events with signs of an incoming muon
    - Full-sky
    - High energy atmospheric neutrinos are likely accompanied by muons

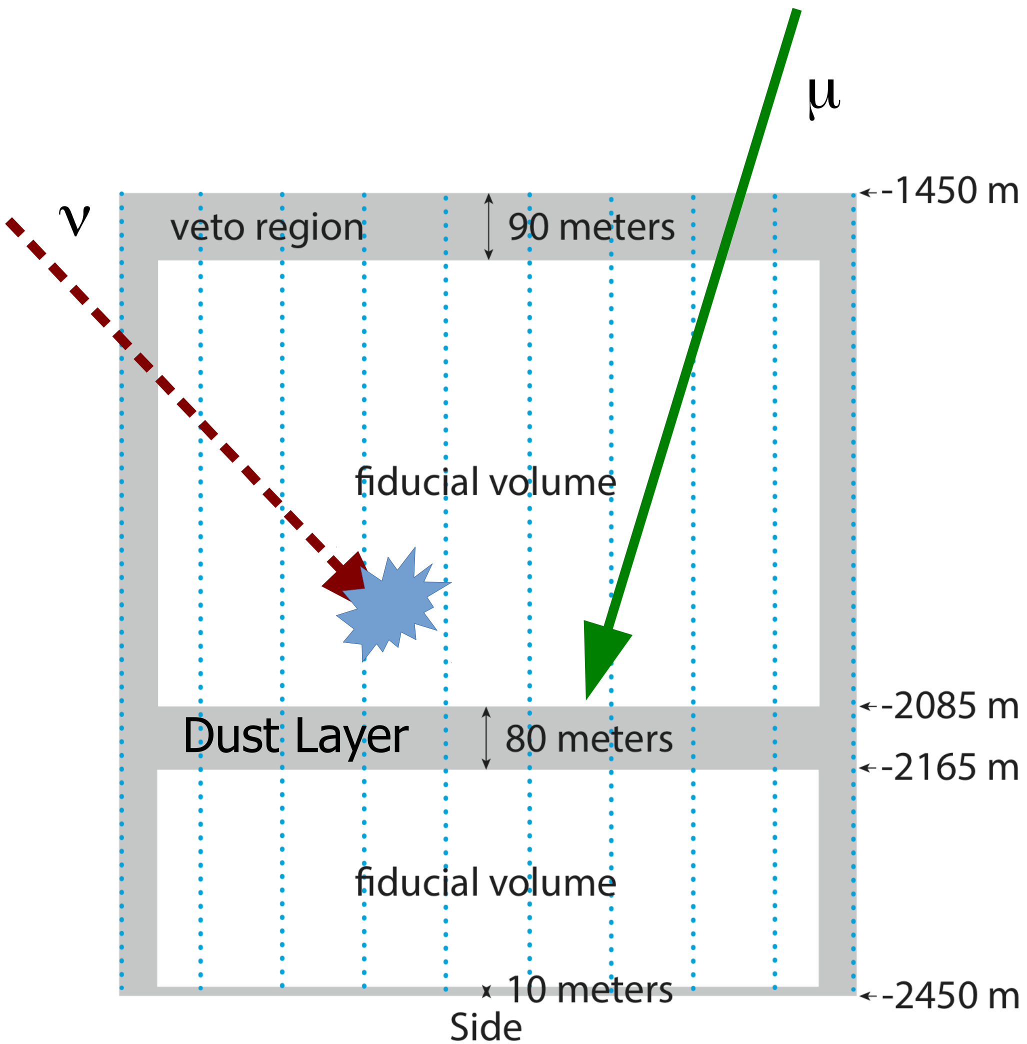


arXiv:1406.6757
(submitted to ApJ)

Vetoing Muons

- Photomultipliers record photoelectrons (charge) vs time
- Charge in an outer veto layer as an event starts indicates a penetrating muon
- Lack of charge in the veto layer is a sign of a neutrino interacting in the fiducial volume

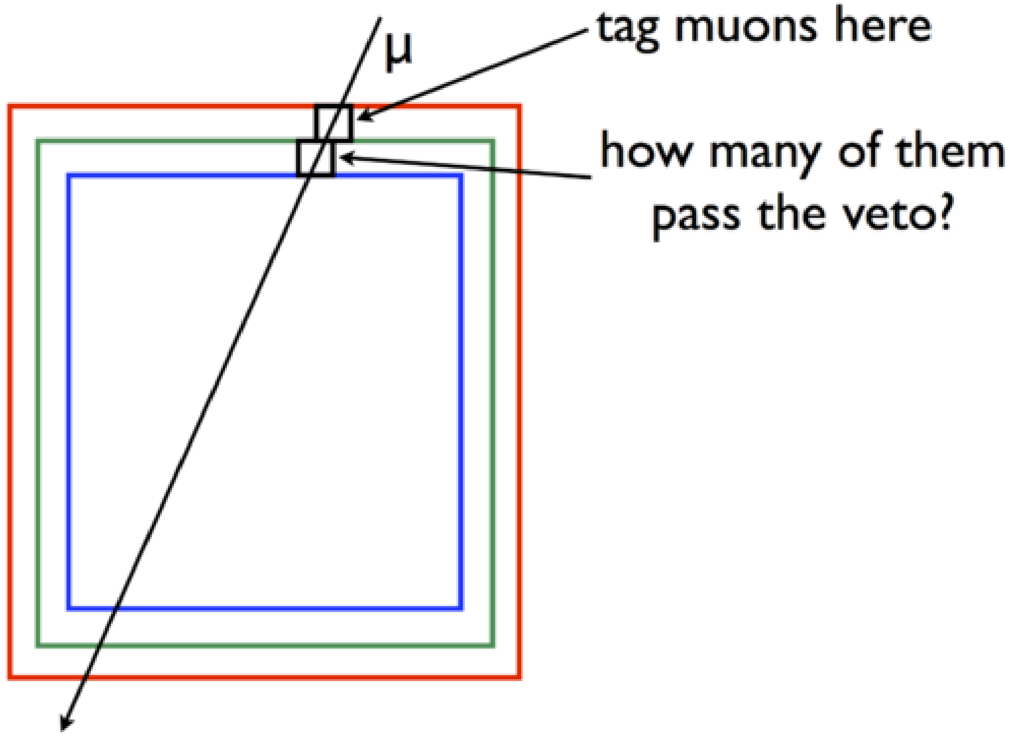




Science 342, 1242856 (2013)

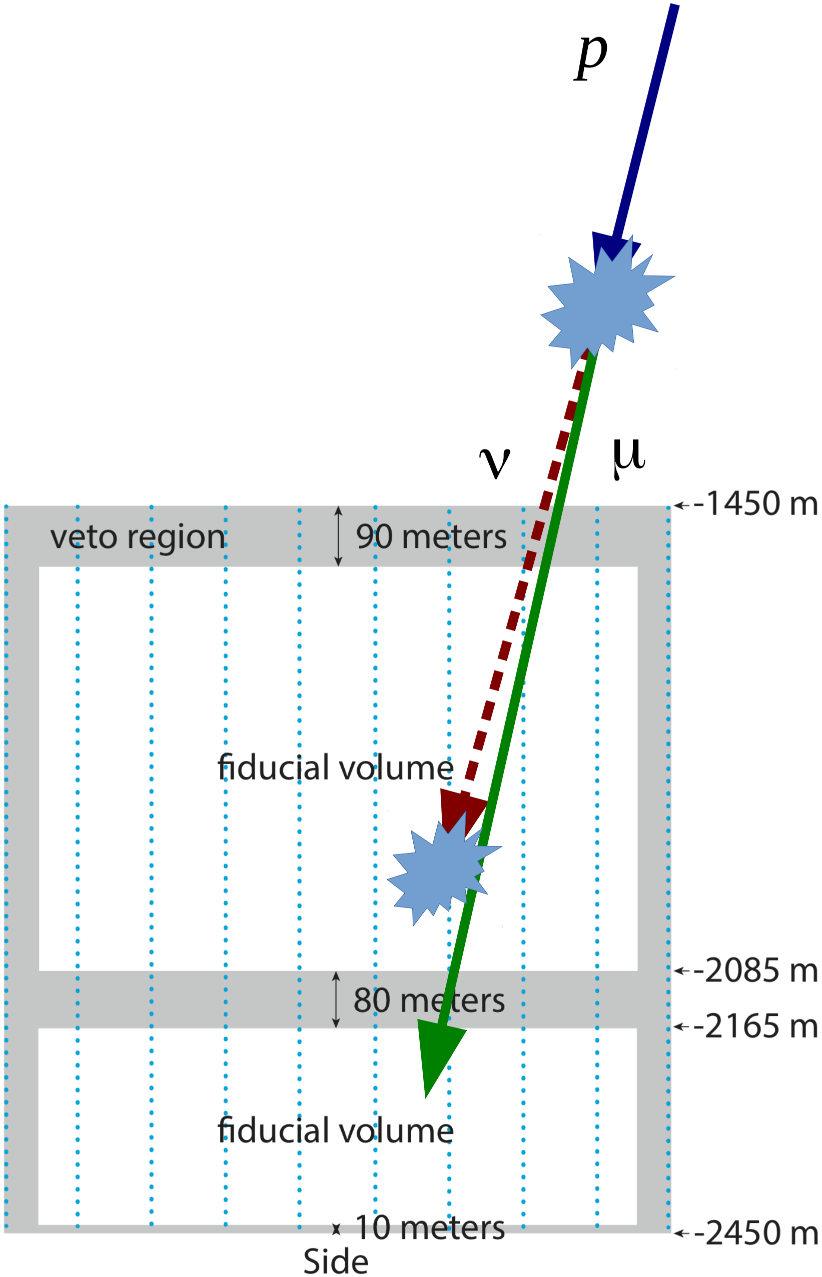
Muon Background Estimation

- Muons still slip through
- Data-driven approach
- Define an inner detector with its own veto layer
- Tag incoming muons with the outer layer
- Control sample of pure veto-passing muons
- Scale up the rate by 2 to account for the smaller volume of the inner detector



Vetoing Atmospheric Neutrinos

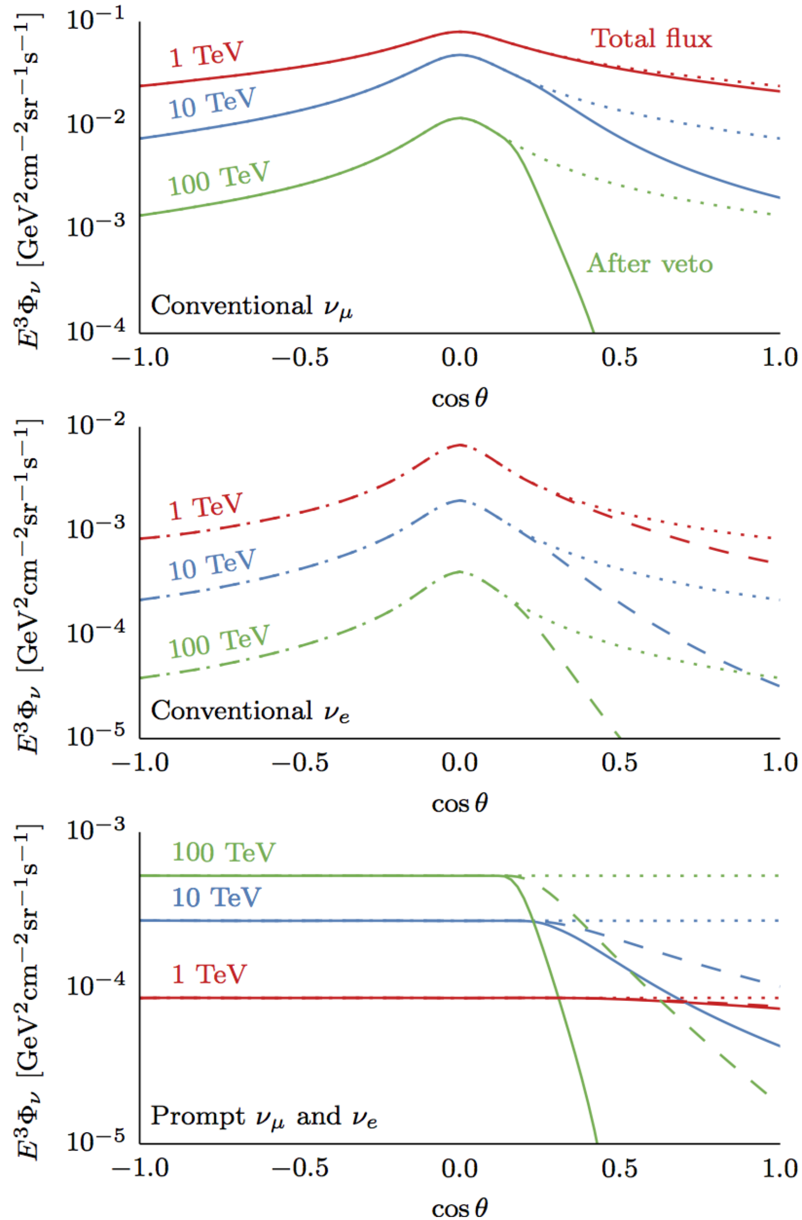
- At high energies, a muon from the same air shower is likely to survive to the detector and trigger the veto
- “Self-veto probability”
  - Fraction of the atmospheric flux accompanied by vetoing muons



Science 342, 1242856 (2013)

Self-veto Probability

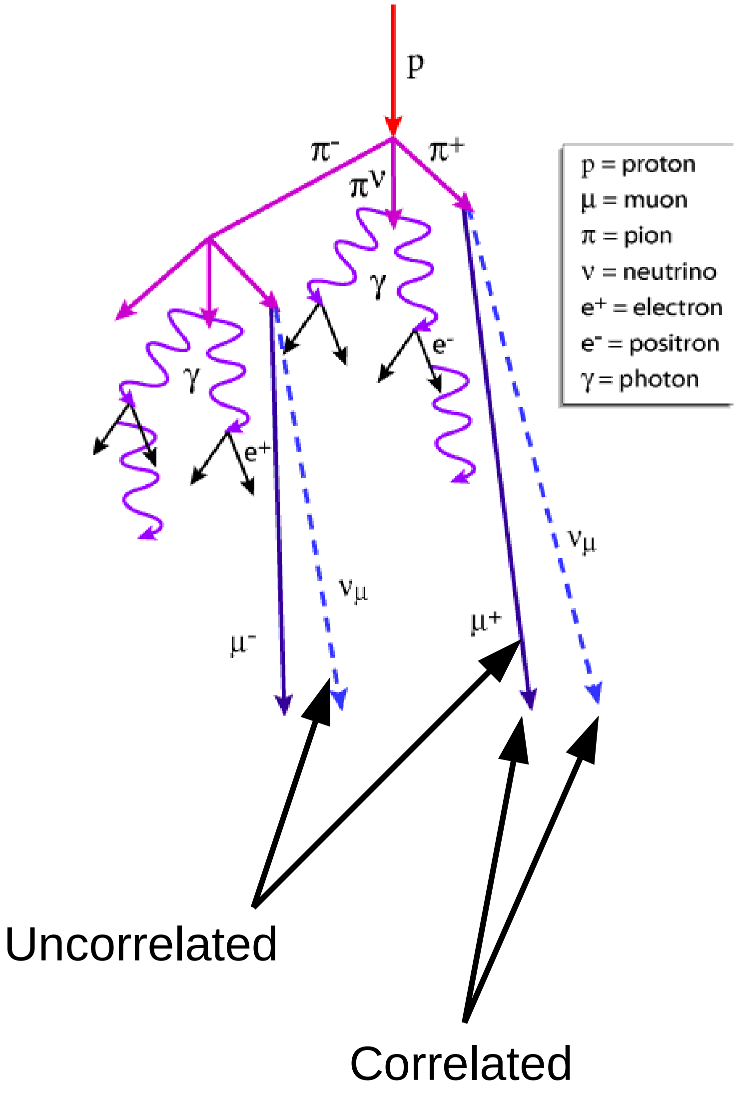
- An effective suppression of atmospheric neutrino flux
- Highest self-veto probability:
  - High energy
  - Near vertical
- Accurate calculation vital to distinguish atmospheric from astrophysical neutrinos



PRD 90, 023009 (2014)

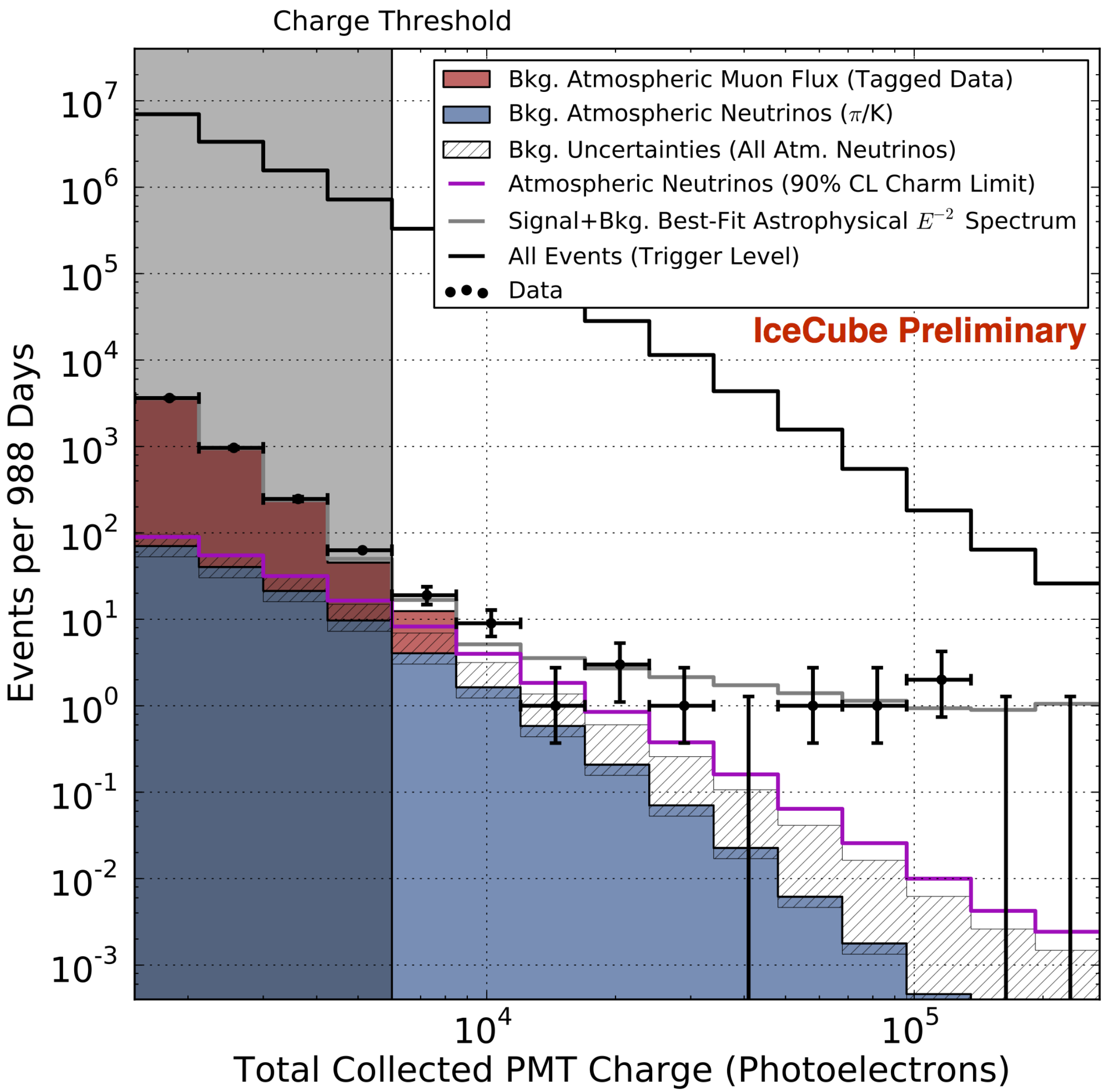
Calculating Self-Veto Probability

- Analytic calculations available
- First considered by Schönert et al.
  - Correlated muons only
  - PRD 79, 043009 (2009)
- Improved calculation by Gaisser et al.
  - Includes uncorrelated muons
  - PRD 90, 023009 (2014)
- Typically require > 1 TeV muon energy at 1950 m depth is required to veto an event
- Compares favorably to direct Monte Carlo simulation



Results

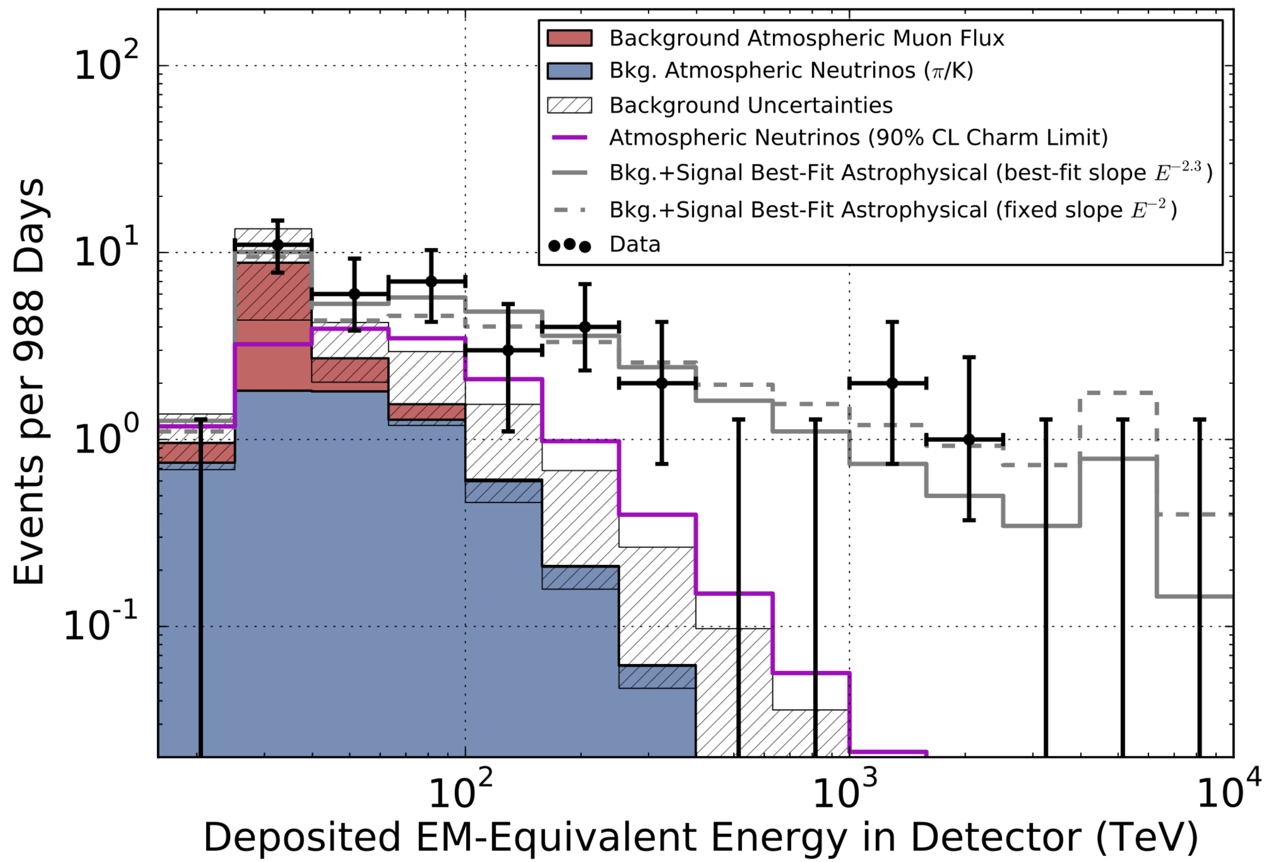
What Was Found



arXiv:1405.5303 (accepted for PRL)

- 37 events in 3 years
- Tagged sample describes muon background well below 6000 PE
- Clear excess above atmospheric backgrounds (hatched/pink)
- New ~2 PeV event found

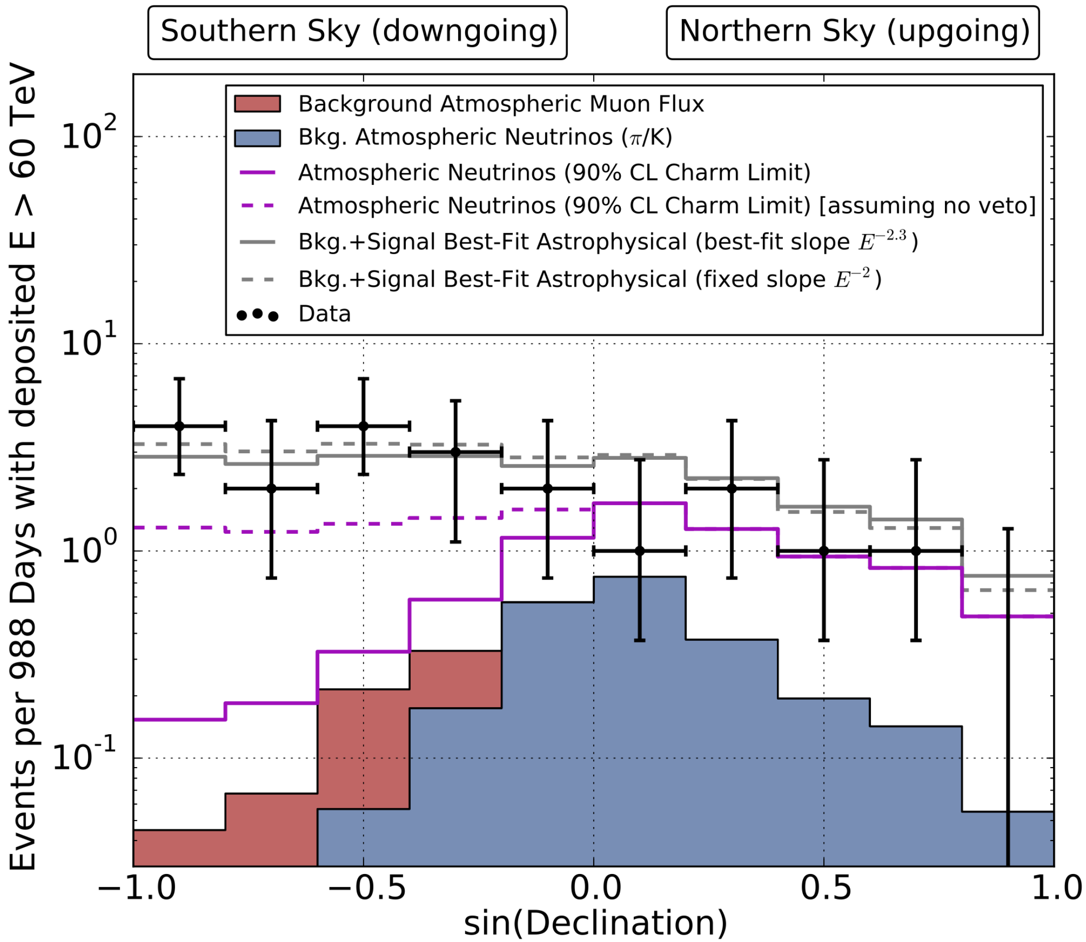
Properties of the Excess



arXiv:1405.5303 (accepted for PRL)

- 5.7σ significance above background only, no evidence for sources or anisotropy
- Best fit E^{-2} flux (per flavor): $0.95 \pm 0.3 \times 10^{-8} E^{-2}\ \mathrm{GeV\ s^{-1}\ cm^{-2}\ sr^{-1}}$
- Some evidence for a cutoff or softer spectral index
  - Unbroken E^{-2} predicts 3.1 events above 2 PeV
  - Best-fit index: 2.3 ± 0.3

Declination Distribution

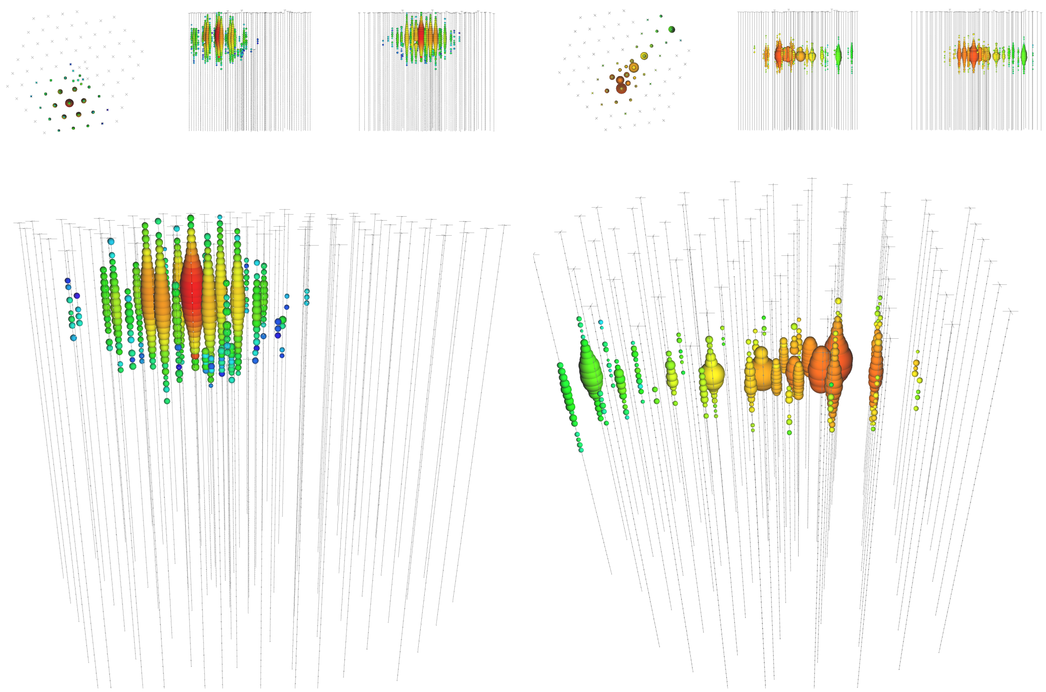


arXiv:1405.5303 (accepted for PRL)

- Self-veto probability is a key distinguishing feature between astrophysical and charm fluxes

Extending to Lower Energies

- Remaining questions:
  - What happens below ~60 TeV?
  - What is the shape of the astrophysical energy spectrum?
  - Can the charm flux be identified?
- Further reduction of backgrounds needed
- Events in IceCube are generally classified into tracks or cascades
- Solution: focus on cascades



Cascade
“Big Bird”
~ 2 PeV

Track
“Dr. Strangepork”
~ 70 TeV
ν_μ charged-current

Neutrino Interactions in IceCube

	ν_e	ν_μ	ν_τ
Neutral-Current	Cascade	Cascade	Cascade
Charged-Current	Cascade	Track/Cascade	Cascade/Track

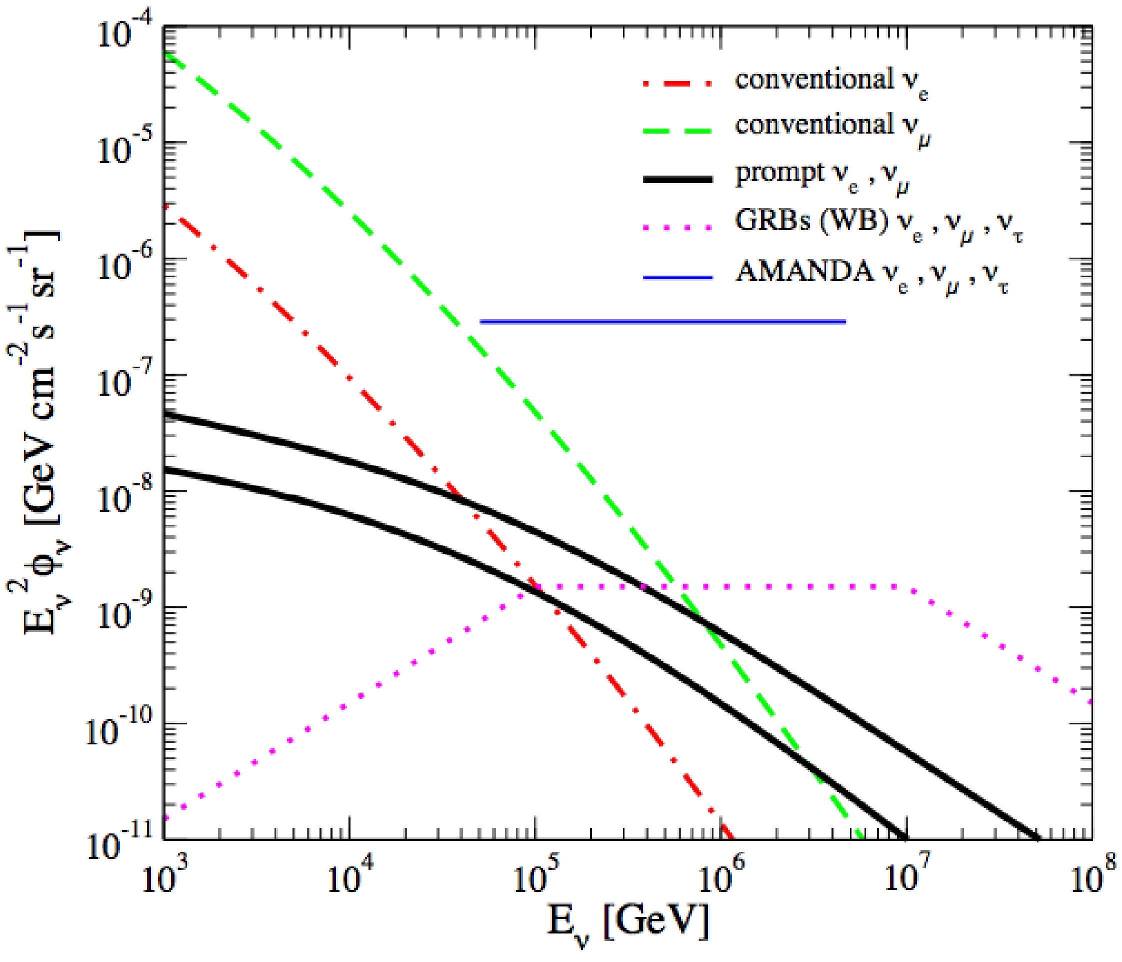
- Neutral current interactions produce hadronic cascades
  - Inelasticity: $y \sim 0.3 - 0.4$
  - Smaller cross section: $\frac{\sigma_{NC}}{\sigma_{CC}} \sim 0.4$
- Charged-current interactions produce more variety:
  - ν_e produces electromagnetic shower, indistinguishable from hadronic shower
  - ν_μ mostly produces a long outgoing muon track
    - Sometimes a cascade if the track is too faint or leaves the detector
  - If ν_τ is >~ 1 PeV, the τ track can be resolved
    - Not observed yet
    - Also muonic τ decay (18% branching ratio)
- <u>For 1:1:1 flavor ratio, ~80% of events are cascades</u>

Advantages of Cascades

- Muon background is mostly track-like
- Conventional is mostly ν_μ
  - Mostly ν_μ NC events left
  - Reduction in rate by a factor:

$$\sim y^{\gamma-1}\frac{\sigma_{NC}}{\sigma_{CC}}\sim 0.1$$

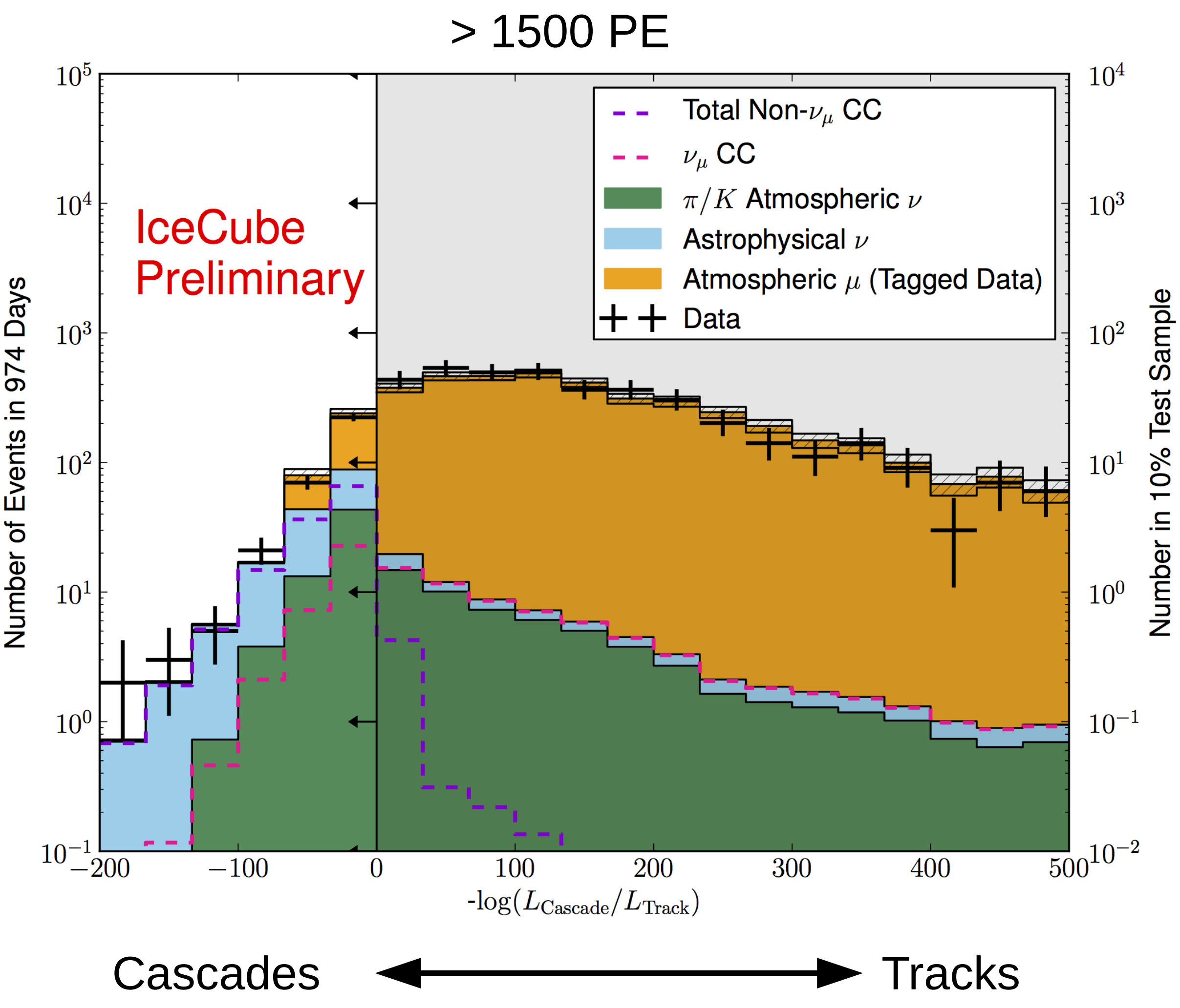
- Can largely reduce two backgrounds with small loss (~20%) in astrophysical signal
- Charm flux also more visible



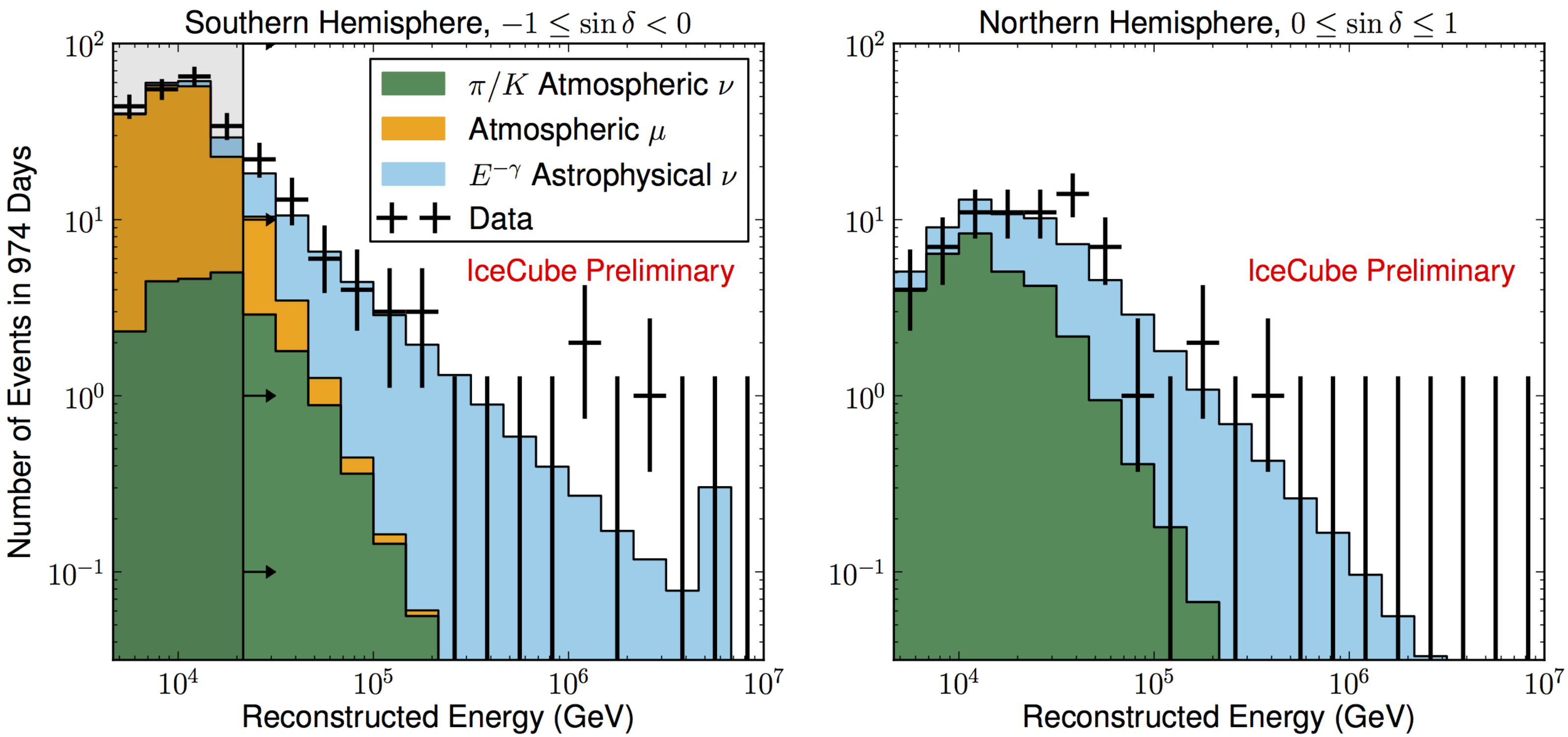
JCAP 0411 (2004) 009

Cascade Identification

- Construct a likelihood ratio for a track and cascade using the times of the first hits in each photomultiplier
- Clear separation of muons
- Tagged control sample describes muon background very well
- Separation of ν_μ CC events as well
  - Not all ν_μ CC events are tracks
  - ~30% classified as cascades
- Can lower charge threshold to 1500 PE for cascades

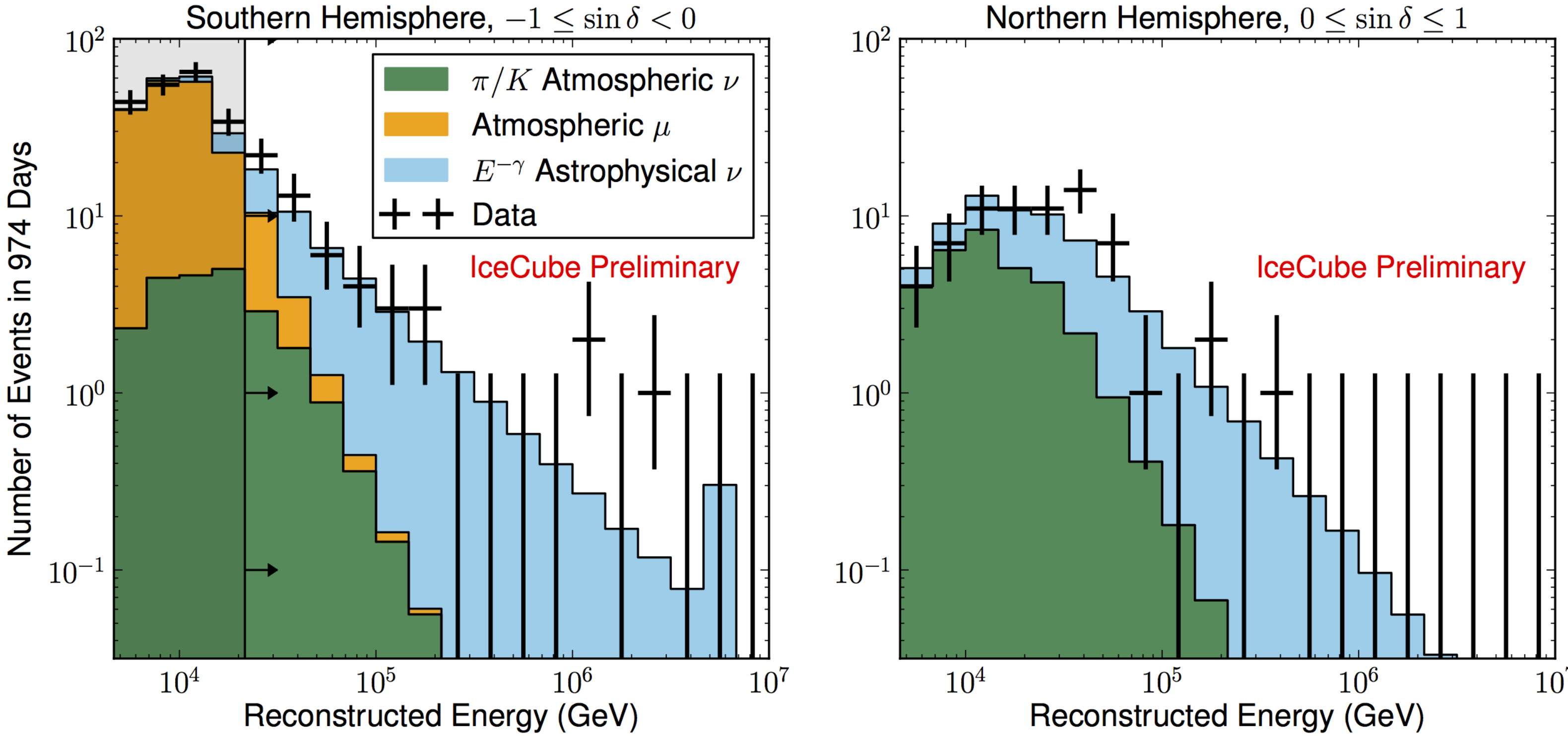


Results



- 123 events in 3 years
- Muon background described by tagged control sample below 20 TeV
  - Power-law extrapolation above 20 TeV
- Conventional neutrinos seen in accordance with expectations
- Astrophysical excess down to ~10 TeV
- Best-fit power-law astrophysical spectrum shown

Fit Results



- Data is well-described by a power-law astrophysical spectrum (p-value = 0.31):

$$\Phi(E) = \Phi_0 \left(\frac{E}{100 \text{ TeV}}\right)^{-\gamma}$$

$$\Phi_0 = 2.32^{+0.42}_{-0.57} \times 10^{-18} \text{ GeV}^{-1}\text{s}^{-1}\text{cm}^{-2}\text{sr}^{-1}$$

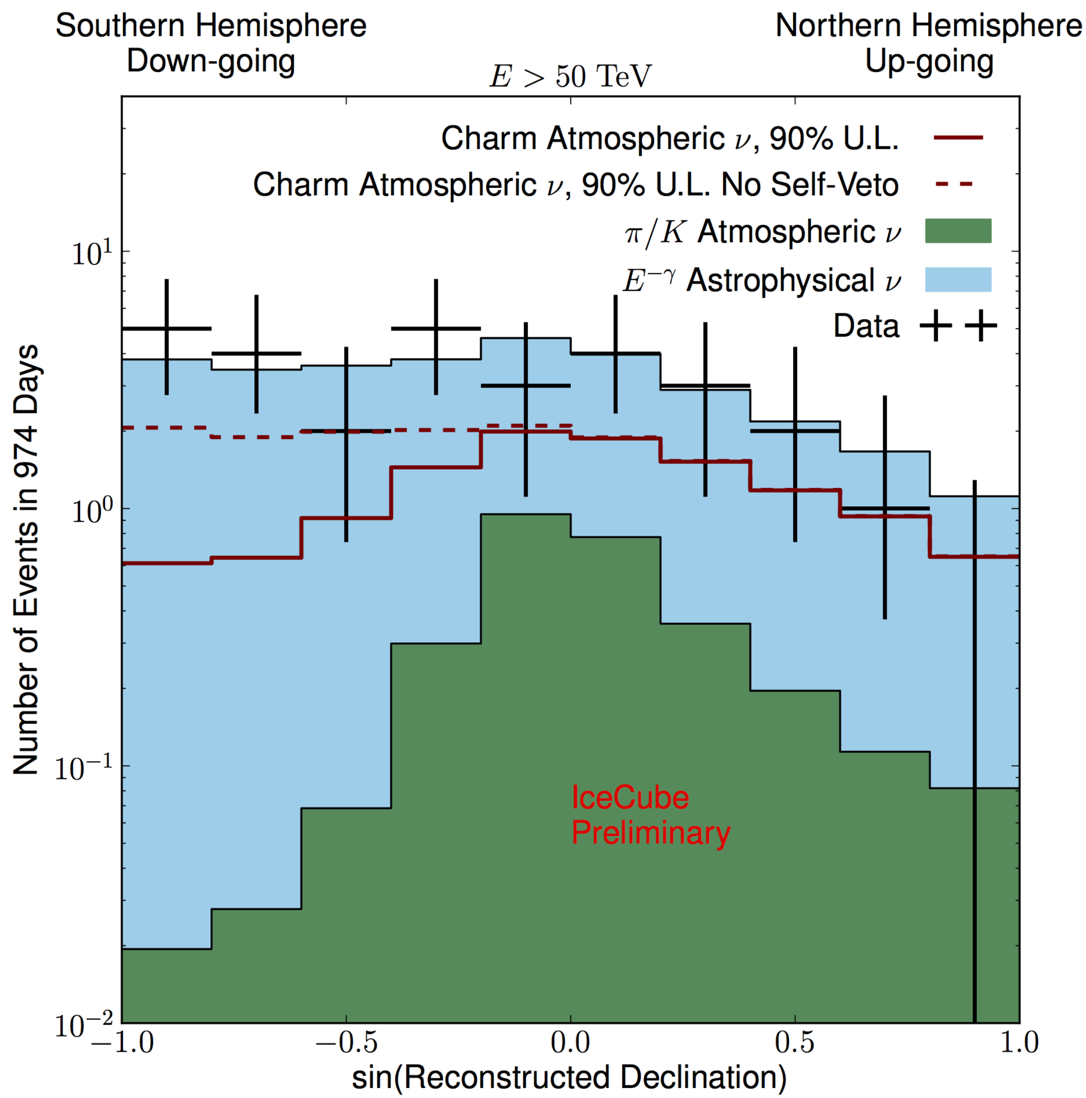
$$\gamma = 2.64^{+0.15}_{-0.17}$$

- Favored by 2.3σ over E^{-2}
- Best-fit charm flux is 0 x ERS* model
- Limits on charm depend on assumptions on the shape of the astrophysical spectrum

IceCube Preliminary

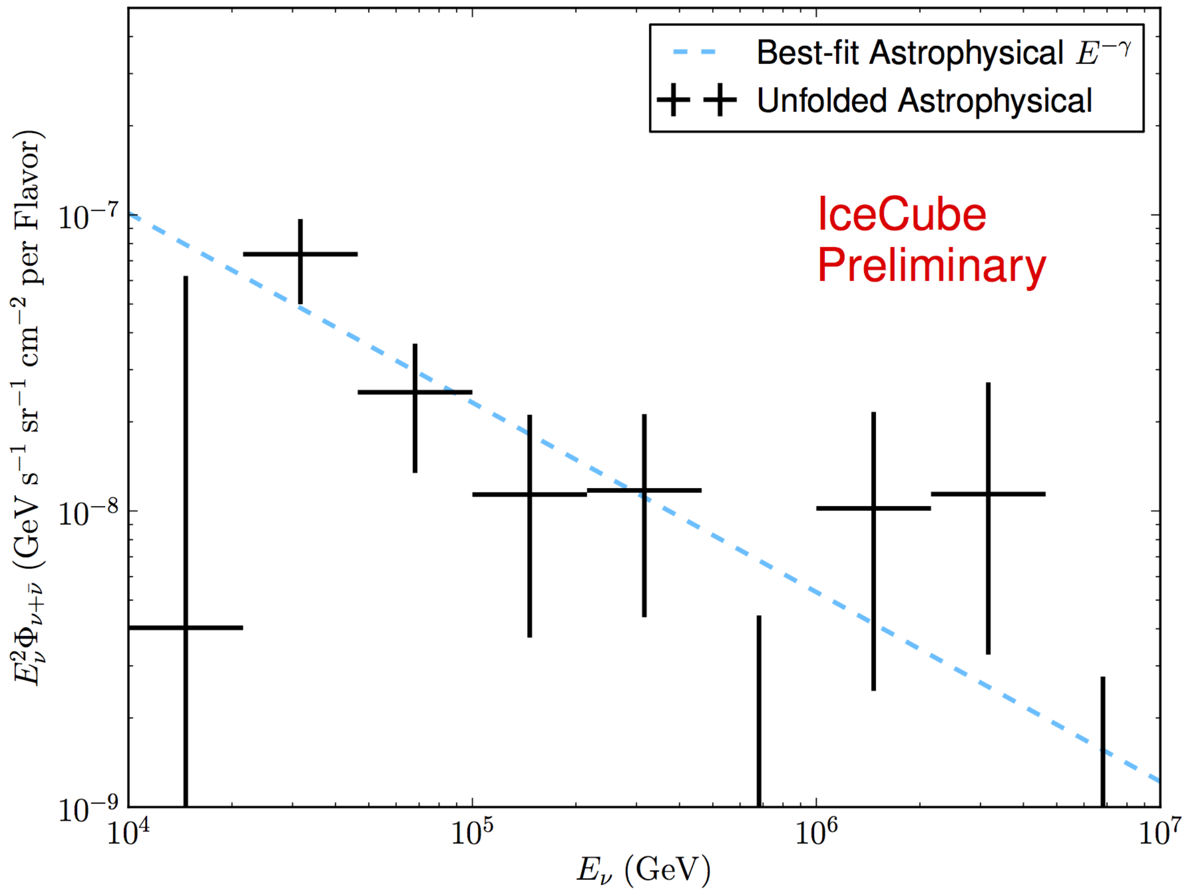
*ERS: Enberg, Reno, Sarcevic, Phys. Rev. D 78: 043005

Declination Distribution



- Self-veto probability distinguishes the charm flux from astrophysical when their spectral index is similar

Unfolded Spectrum



- What if the astrophysical spectrum isn't well-described by a power law?
- Unfold the astrophysical spectrum into true neutrino energy while also fitting for atmospheric backgrounds
- More data is needed to look for possible deviations from the power-law, isotropic paradigm

Conclusions

- Veto techniques are a powerful tool to probe the astrophysical neutrino flux in IceCube
- Self-veto probability distinguishes atmospheric from astrophysical fluxes
- Selecting cascades allows lower energies to be probed
  - Better rejection of muons and conventional neutrinos
- Astrophysical excess observed down to ~10 TeV
- The observed astrophysical flux is consistent with an isotropic, power-law
- Spectral index > 2 is favored
  - Best-fit: $2.64^{+0.15}_{-0.17}$
- Charm flux not identified yet
- One of several IceCube studies on the astrophysical fllux
  - See J. van Santen's talk
  - Improved veto techniques
  - Even lower energies
  - Up-going ν_μ
  - Global analysis

Thanks


The IceCube Collaboration
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Lawrence Berkeley National Laboratory
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Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
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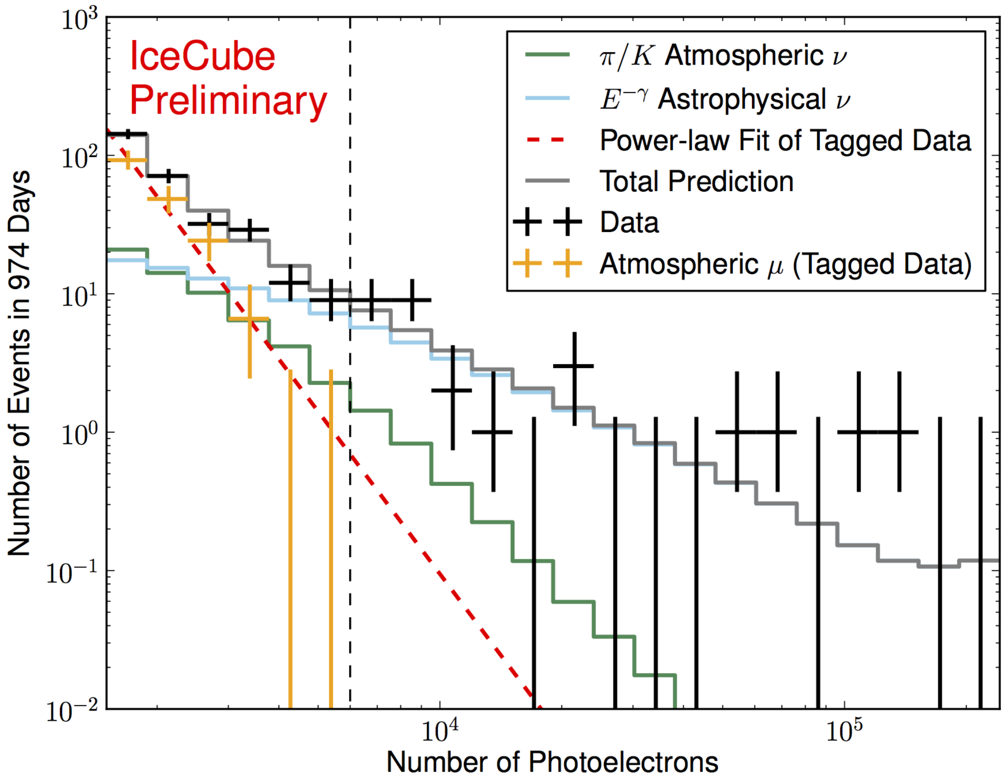
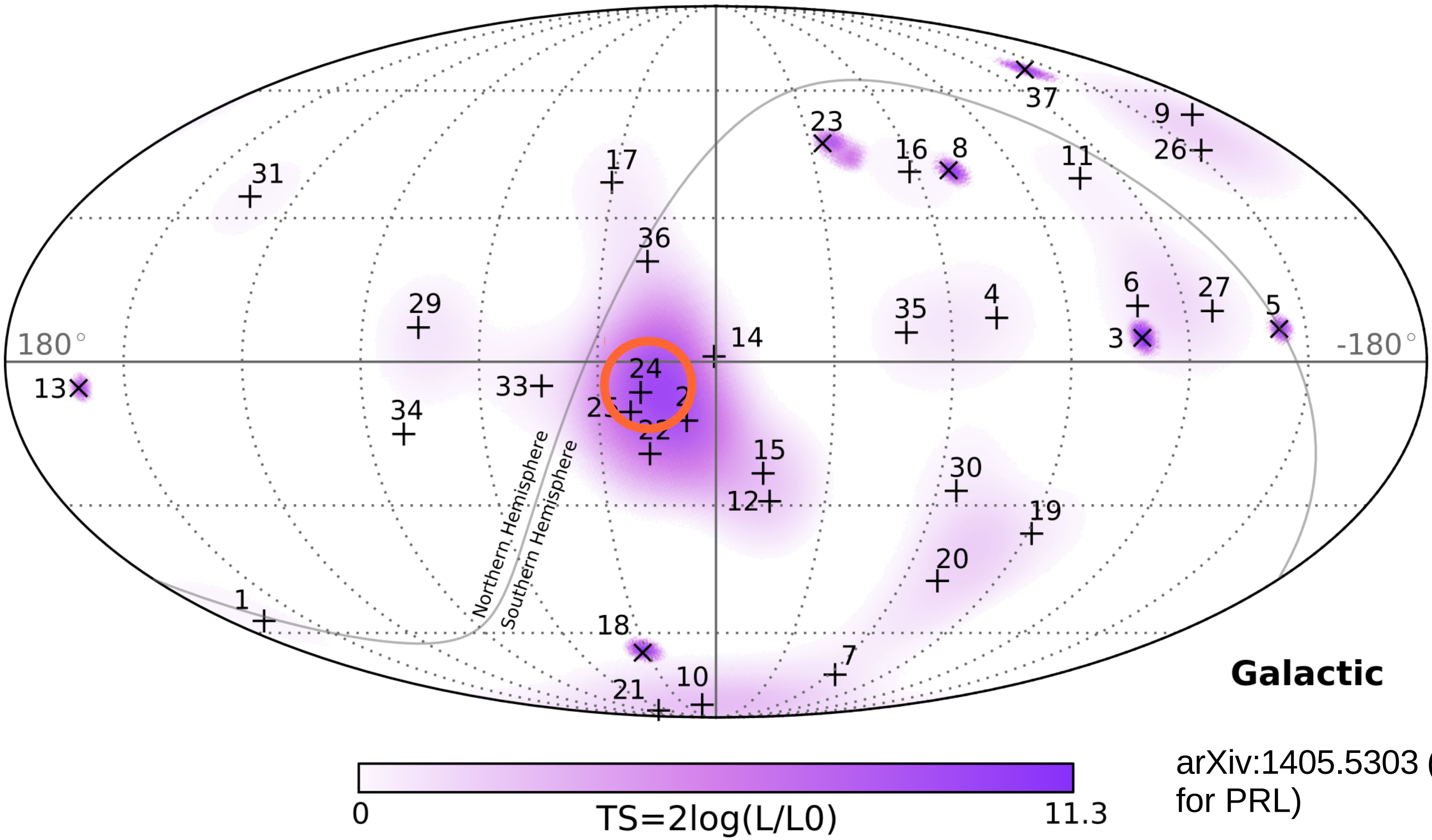
Charge distribution



- A power-law extrapolation of the tagged control sample is used to estimate the muon background at high energy

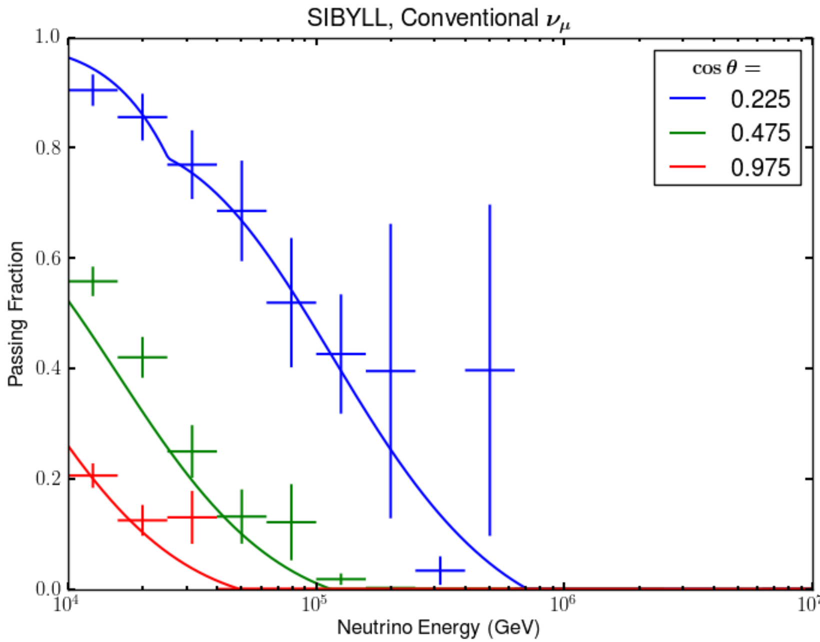
Sources?

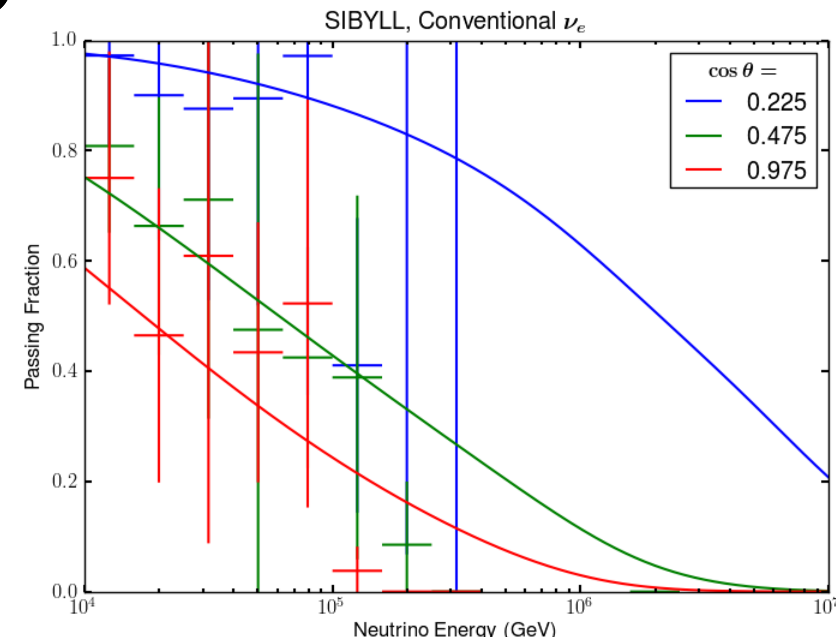


arXiv:1405.5303 (accepted for PRL)

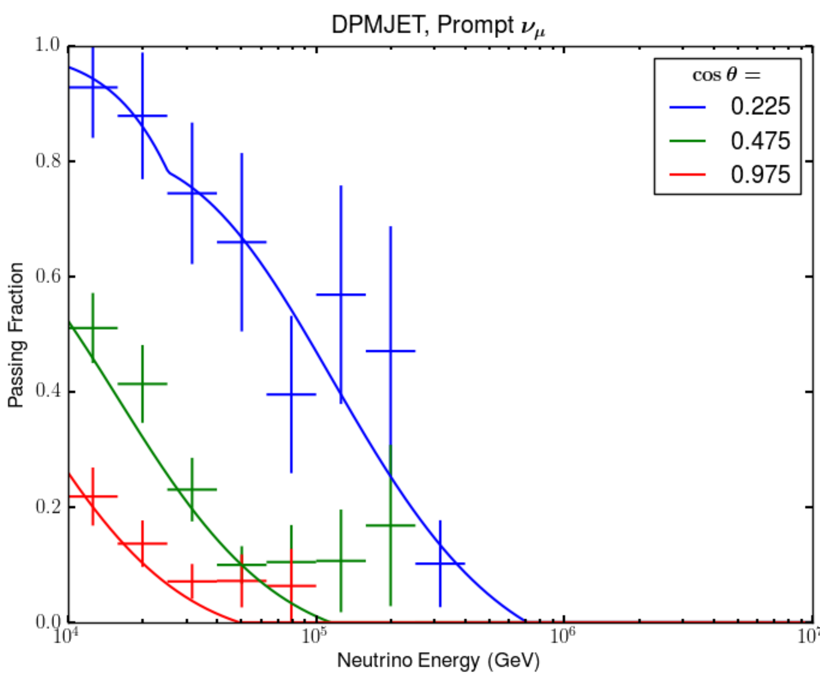
- 7.2% p-value for most significant cluster (had no new events in 3rd year)
- No correlation with galactic plane or other objects, no time clustering
- Consistent with isotropy

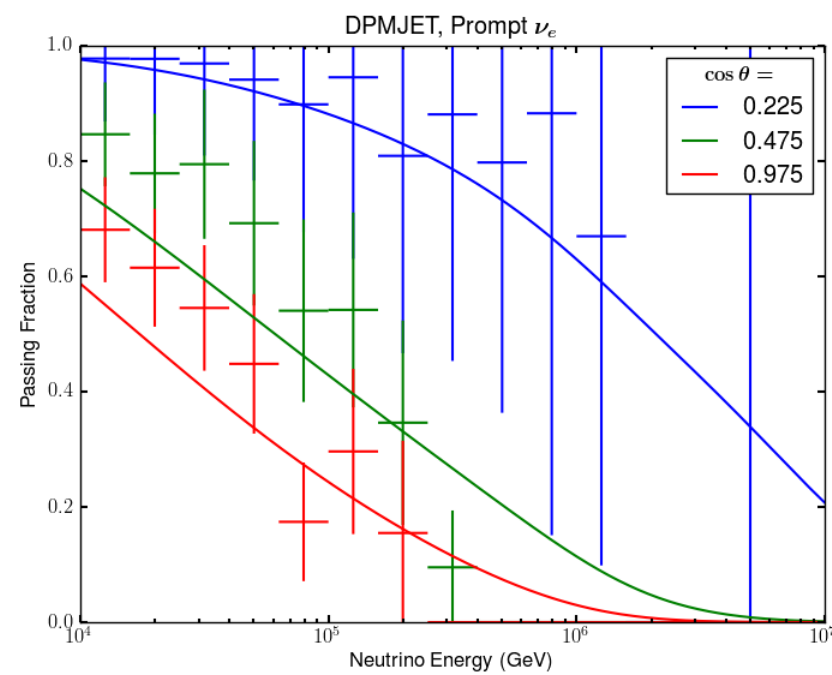
Self-Veto Probability Verification





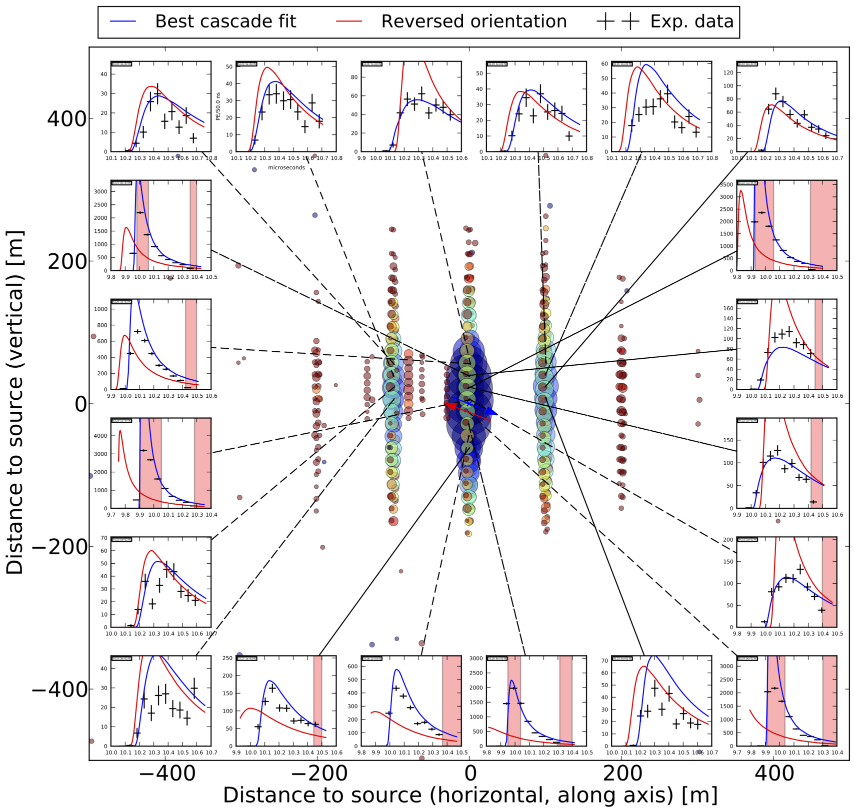
- CORSIKA-generated air showers
- MC muon propagation
- Direct simulation of light and detector response



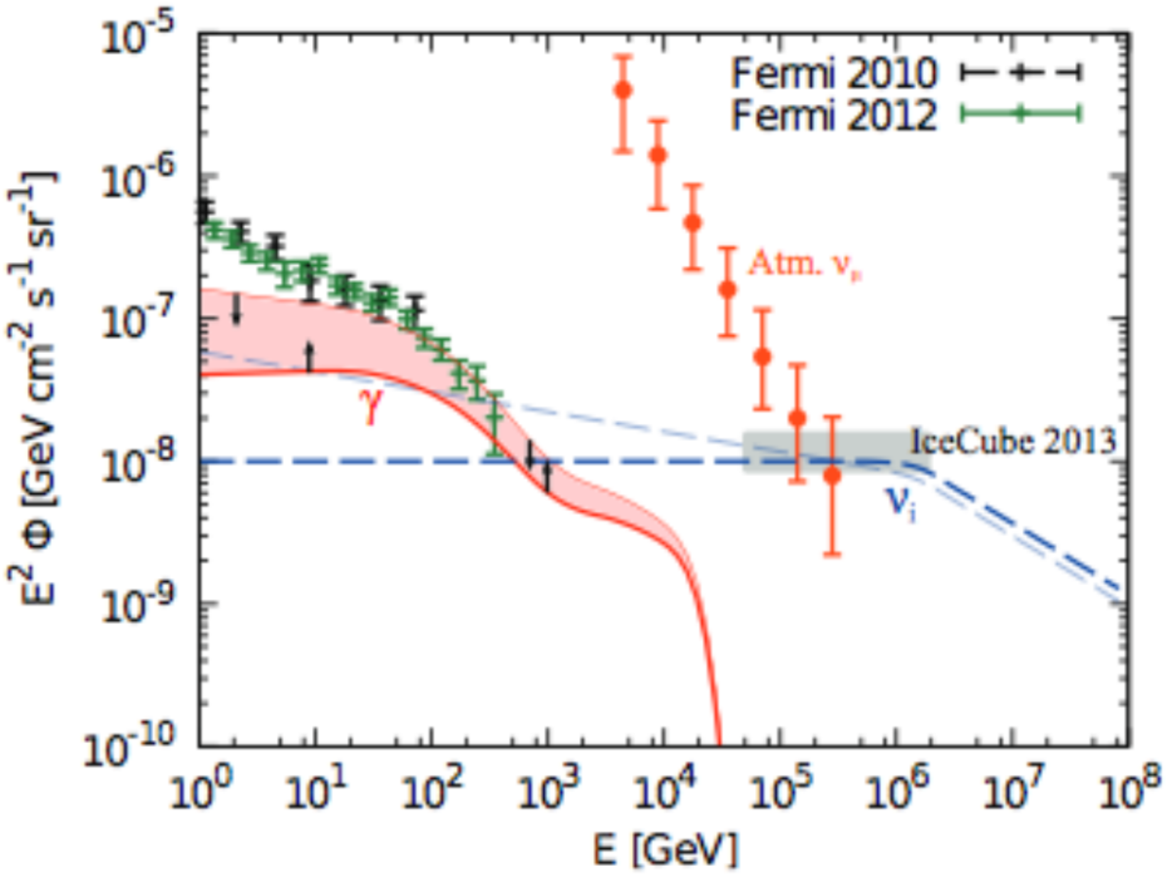


Event Reconstruction

- Compare observed charge and timing with templates depending on orientation, position, scaling linearly with energy
- Templates evaluated using Monte Carlo propagation of photons in inhomogeneous ice
- Deposited energy resolution ~ 15%
- Angular resolution:
  - < 1 degree for tracks
  - ~15 degrees for cascades



Relation to Fermi Results



Phys.Rev.D 88 (2013) 121301(R)

- Possible tension with Fermi results if power-law flux is extrapolated to lower energies is being investigated

Likelihood Contours