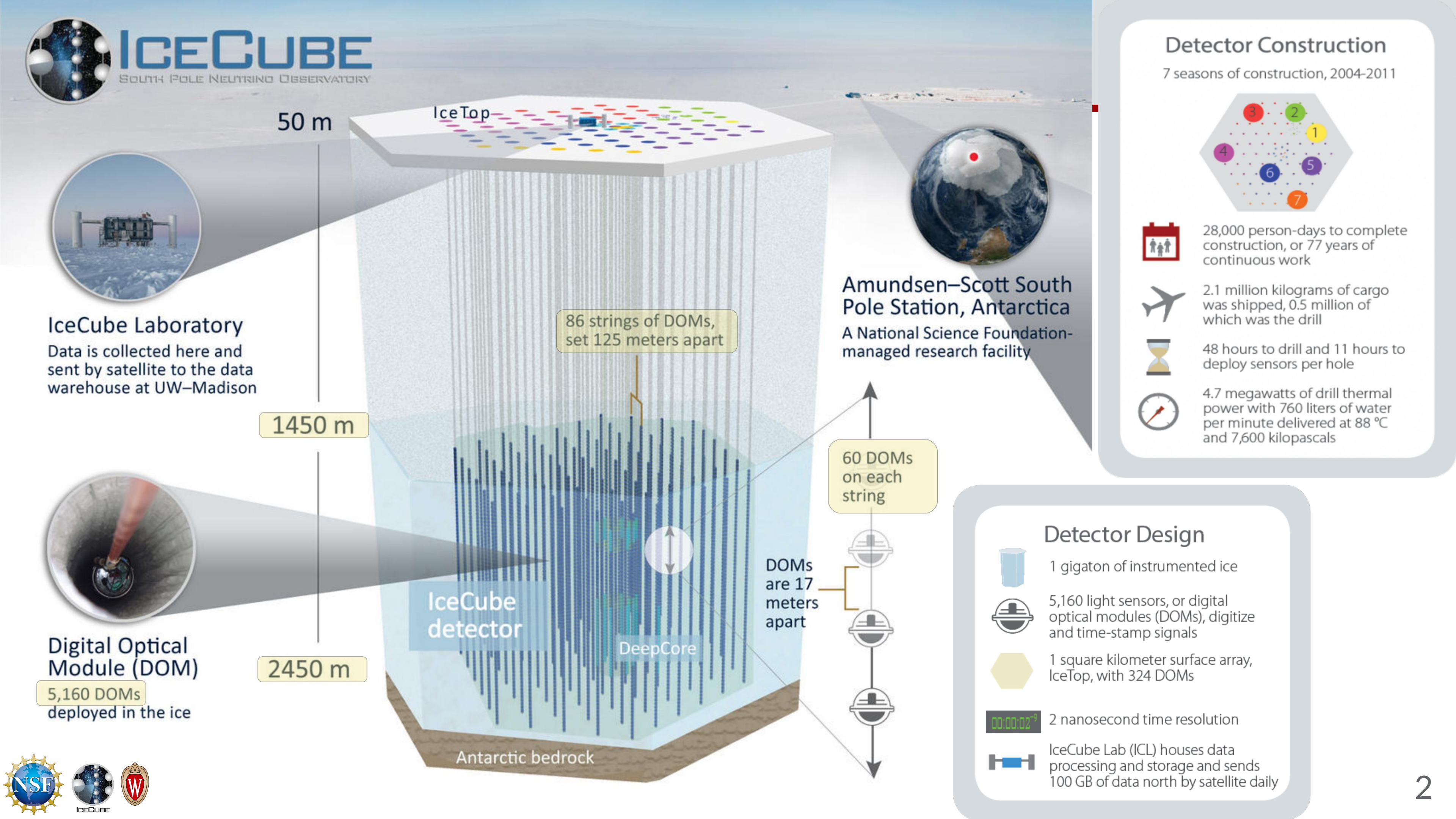
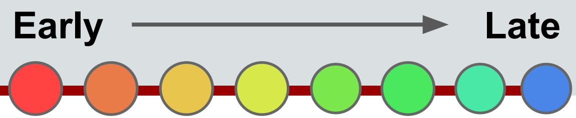
Characterization of the Astrophysical Diffuse Neutrino Flux

Austin Schneider
For The IceCube Collaboration

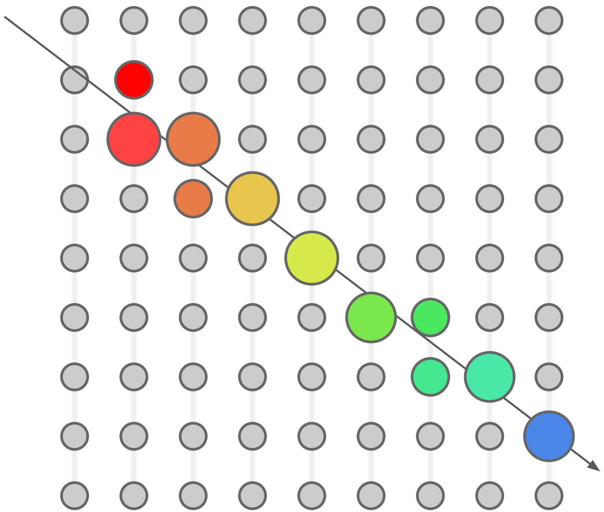
ICRC 2019


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
Detector Construction
7 seasons of construction, 2004-2011
3
2
1
4
5
6
7
28,000 person-days to complete construction, or 77 years of continuous work
2.1 million kilograms of cargo was shipped, 0.5 million of which was the drill
48 hours to drill and 11 hours to deploy sensors per hole
4.7 megawatts of drill thermal power with 760 liters of water per minute delivered at 88 °C and 7,600 kilopascals
Detector Design
1 gigaton of instrumented ice
5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
1 square kilometer surface array, IceTop, with 324 DOMs
2 nanosecond time resolution
IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily
NSF
ICECUBE

Event Morphologies

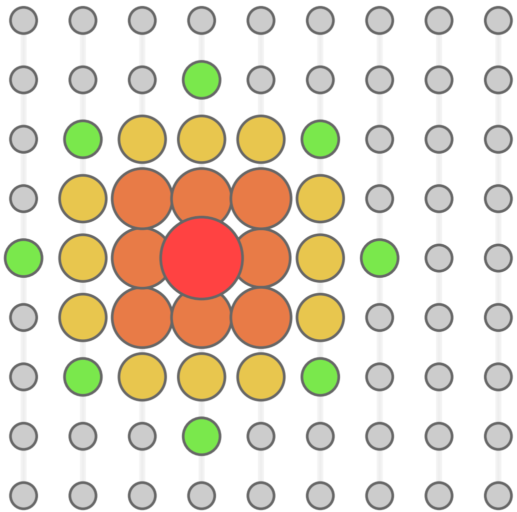


Track
Muon Neutrino CC



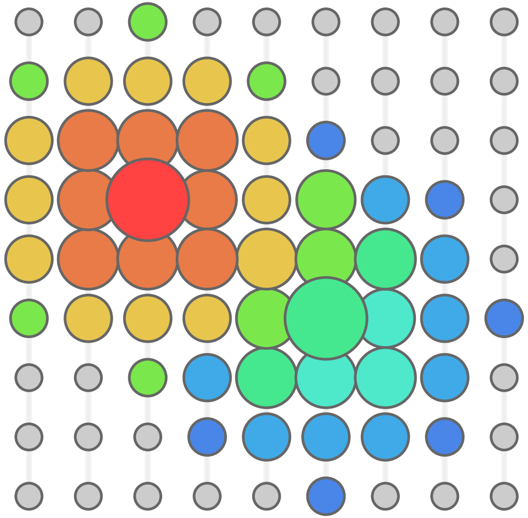
Factor of ~2 energy resolution
0.3° angular resolution at 100TeV

Cascade
Electron Neutrino CC
Tau Neutrino CC
Neutrino NC



15% deposited energy resolution
10° angular resolution above 100 TeV

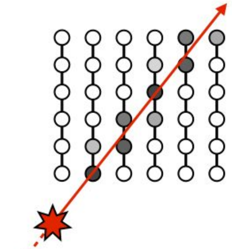
Double Cascade
High Energy Tau Neutrino CC



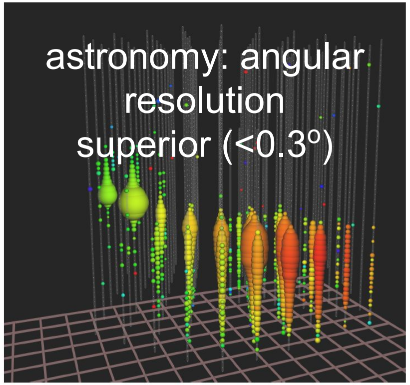
Angular and energy resolution comparable to cascades
First candidate observed!
See talk: J. Stachurska NU8f for details!

Astrophysical Neutrinos - Two Methods

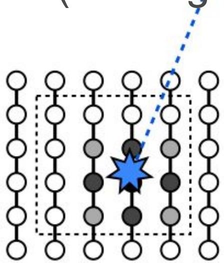
1. Upgoing muon neutrino tracks

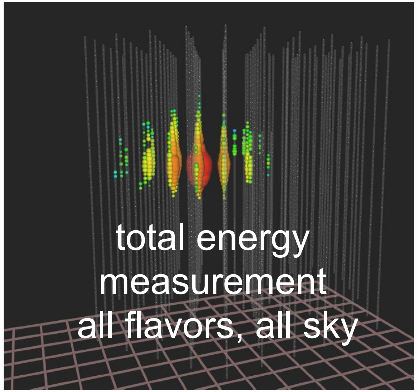


J. Stettner NU4a



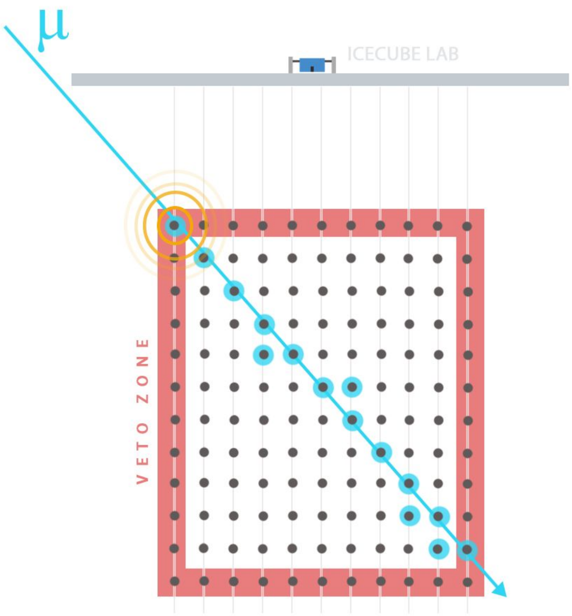
2. Isolated neutrinos interacting inside the detector (starting events)



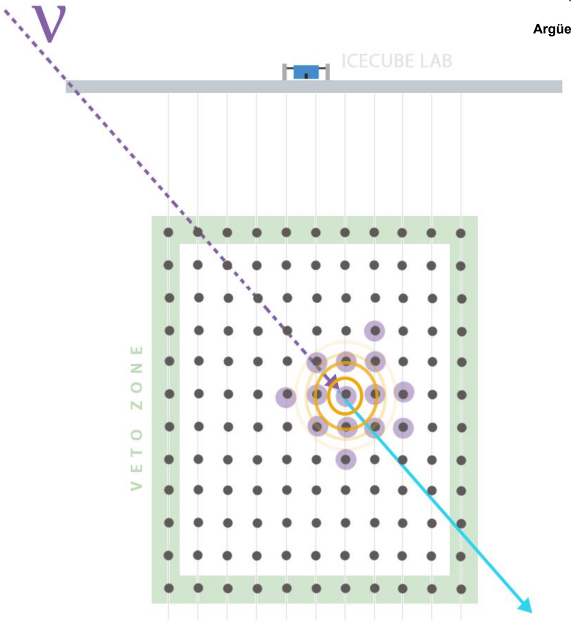


Events with Contained Vertex (the veto technique)

Schönert, Gaisser, Resconi, Schulz
Phys. Rev. D 79; 043009(2009)
Gaisser, Jero, Karle, van Santen
Phys. Rev. D 90; 023009(2014)
**Argüelles, Palomares-Ruiz, AS, Wille, Yuan
JCAP 1807 (2018) no.07, 047**



Veto region rejects atmospheric muons and neutrinos



High neutrino signal purity at high energy

More on the veto

Schönert, Gaisser, Resconi, Schulz
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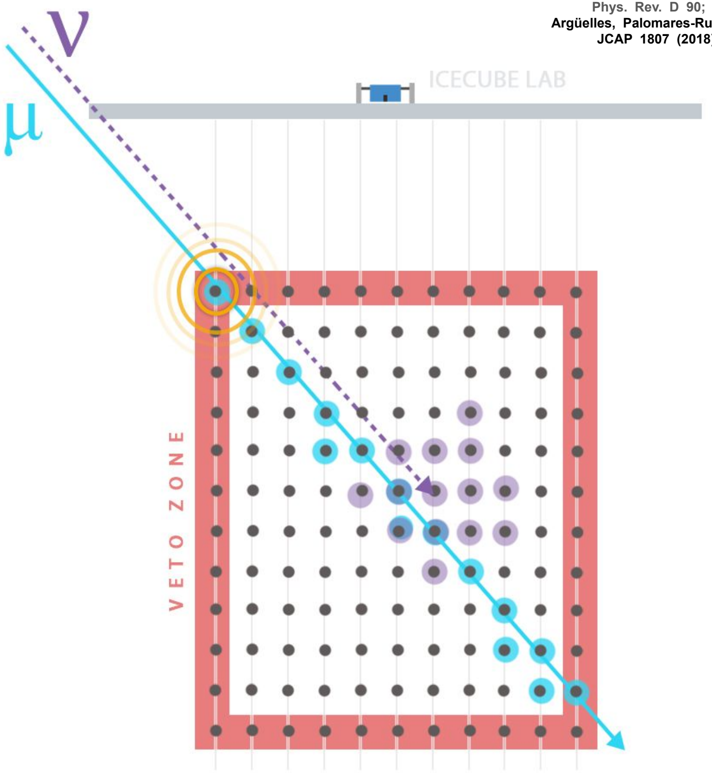
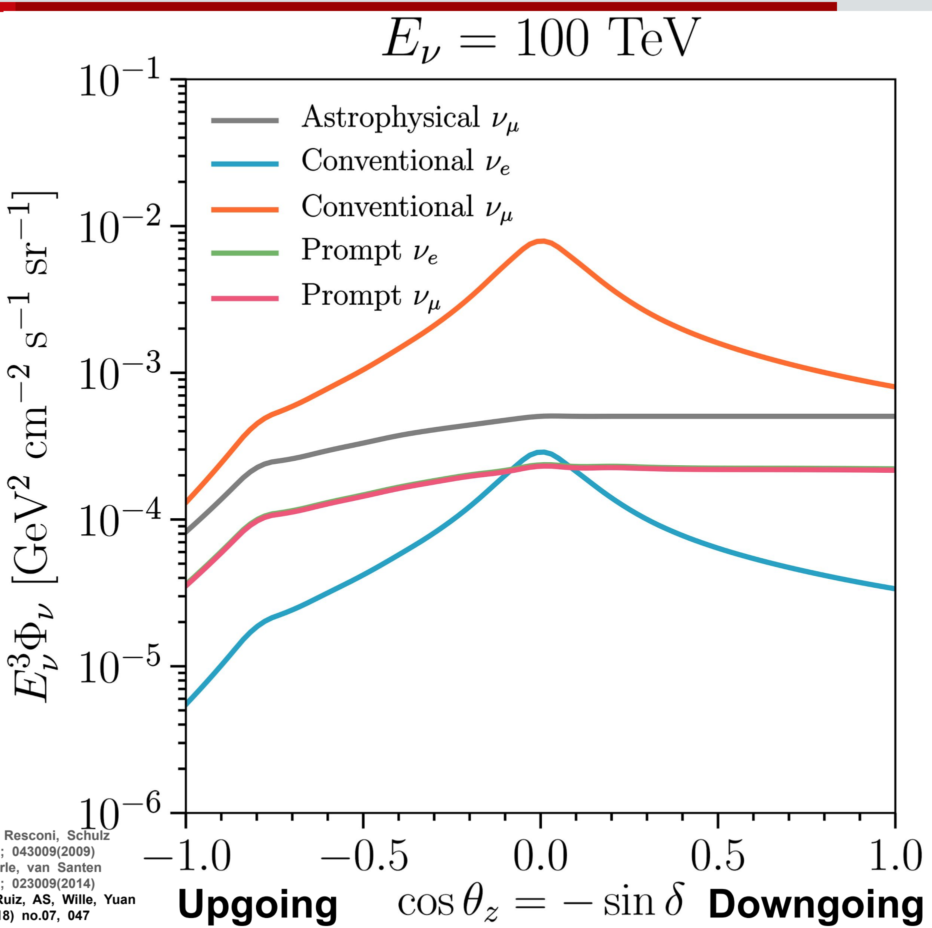
- Muons accompany neutrinos from CR air showers
- High-energy muons reach the detector
- Veto suppresses atmospheric neutrino background
- Allows us to look at downgoing neutrino events!



Modelling the Data

Three Neutrino Flux Components

1. Astrophysical **ν**
   a. Mostly flat
   b. Suppression at Earth's core
2. Atmospheric **ν** from K/π (Conventional **ν_e** **ν_μ**)
   a. Neutrino production peaked at horizon
3. Atmospheric **ν** from charmed hadrons (Prompt **ν_e** **ν_μ**)
   a. Mostly flat
   b. Suppression at Earth's core



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ICECUBE

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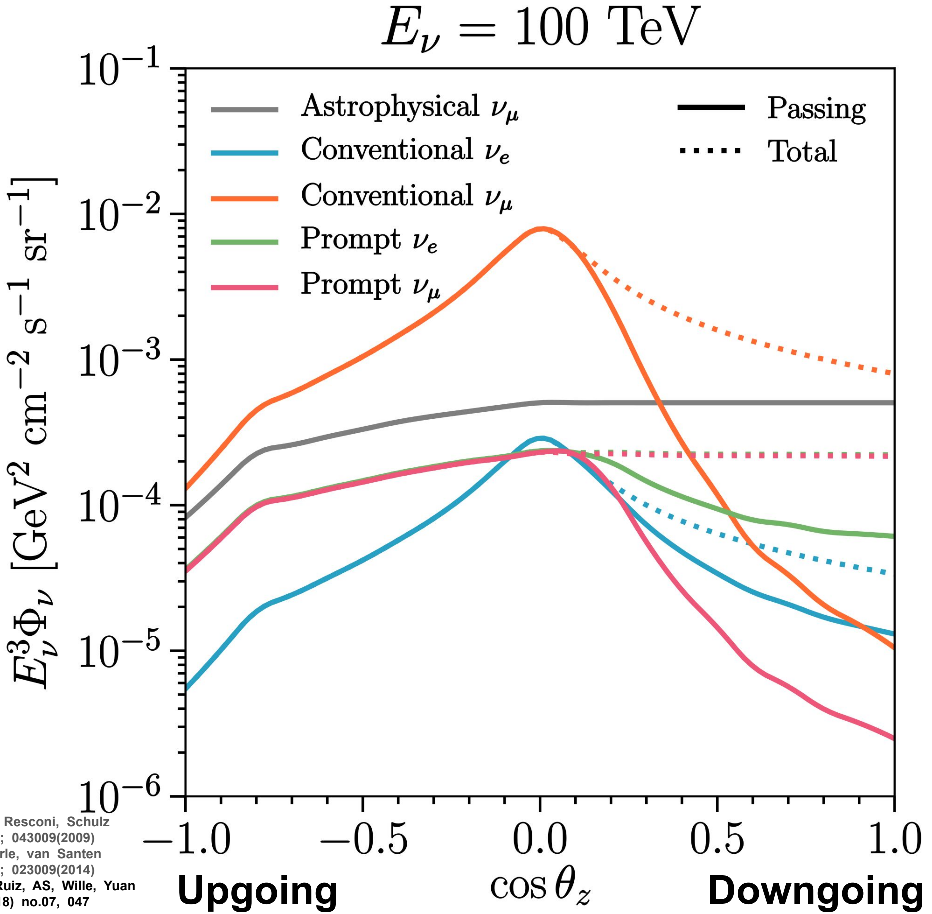
   b. Down-going suppressed by veto
3. Atmospheric **ν** from charmed hadrons (Prompt **ν_e ν_μ**)
   a. Mostly flat
   b. Suppression at Earth's core
   c. Downgoing suppressed by veto



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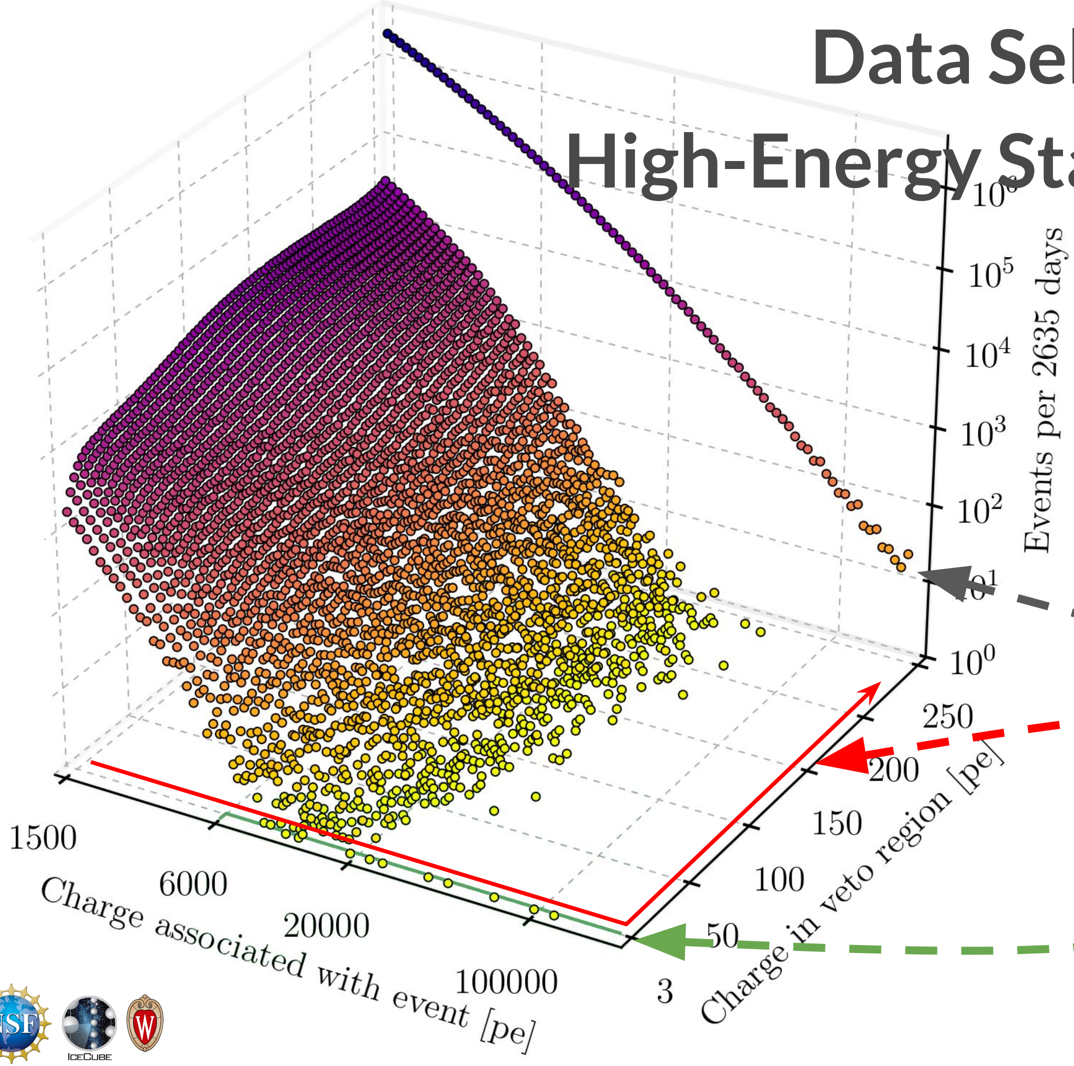
Data Selection With The Veto

High-Energy Starting Event Selection



Atmospheric events above 250PE in the veto region

Two distinct populations!

Backgrounds

Astrophysical candidates

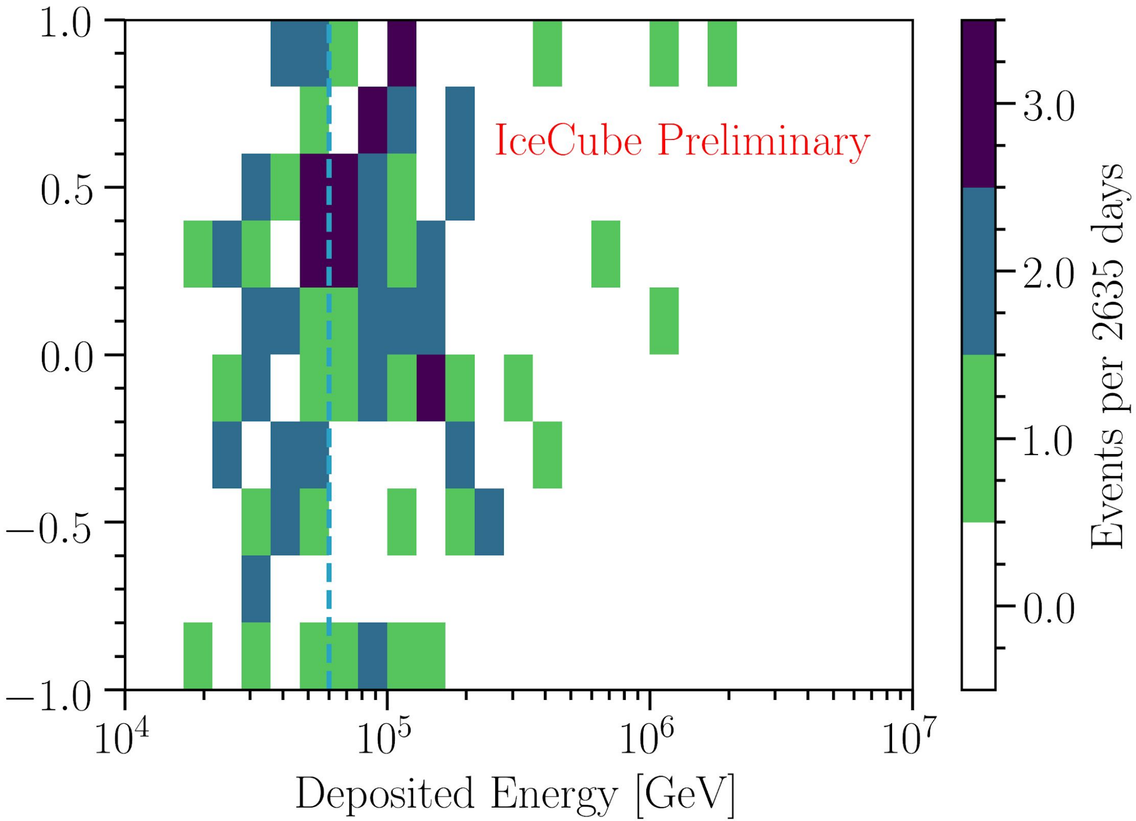
A Closer Look At The Data

Reconstruct: deposited energy, direction, morphology

Ternary morphology ID

Above 60TeV:
60 events

All energies:
102 events



Diffuse Astrophysical Neutrino Flux

$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma_{\mathrm{astro}}} \cdot 10^{-18}\ [\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$$

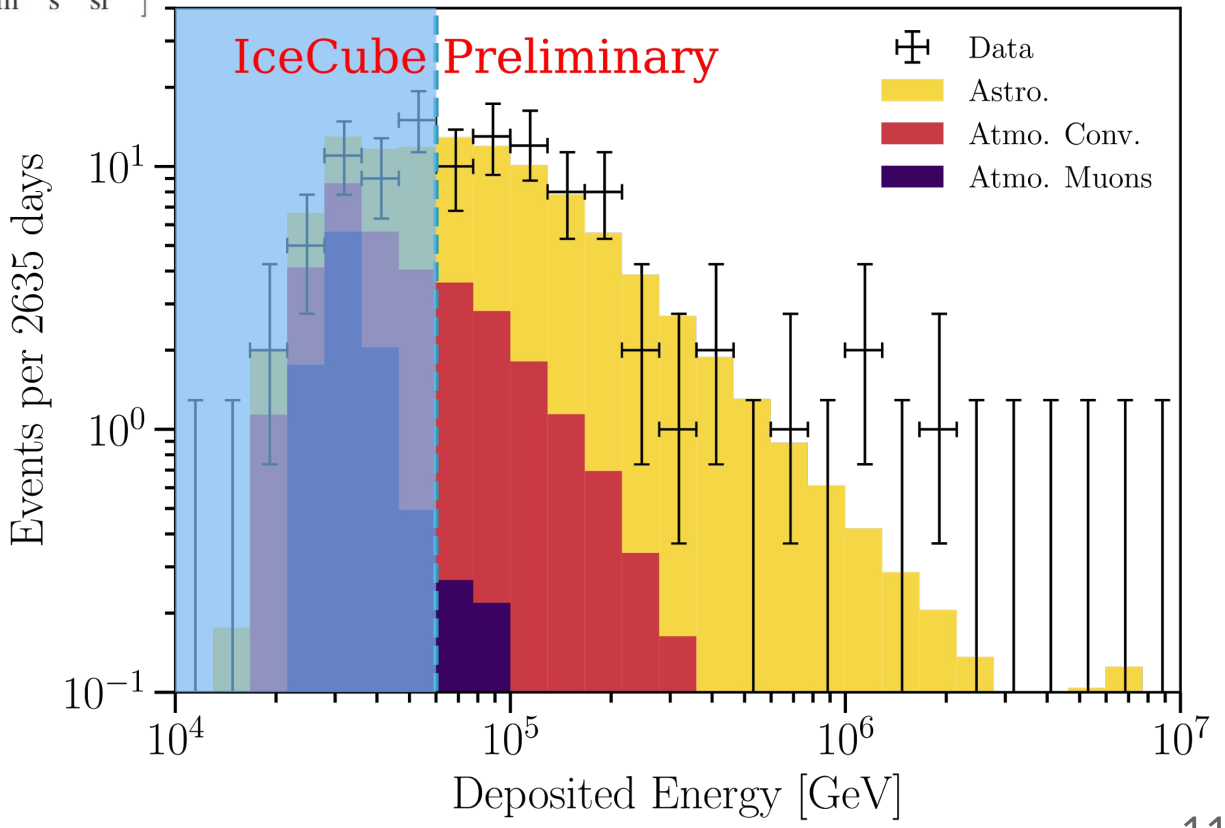
Best-fit spectral index 2.89 ±0.2

Prompt best fit ⇒ zero

Prompt 90% upper limit 9.65*BERSS

Fit performed for events above 60TeV

Compatible with results from 6 year analysis



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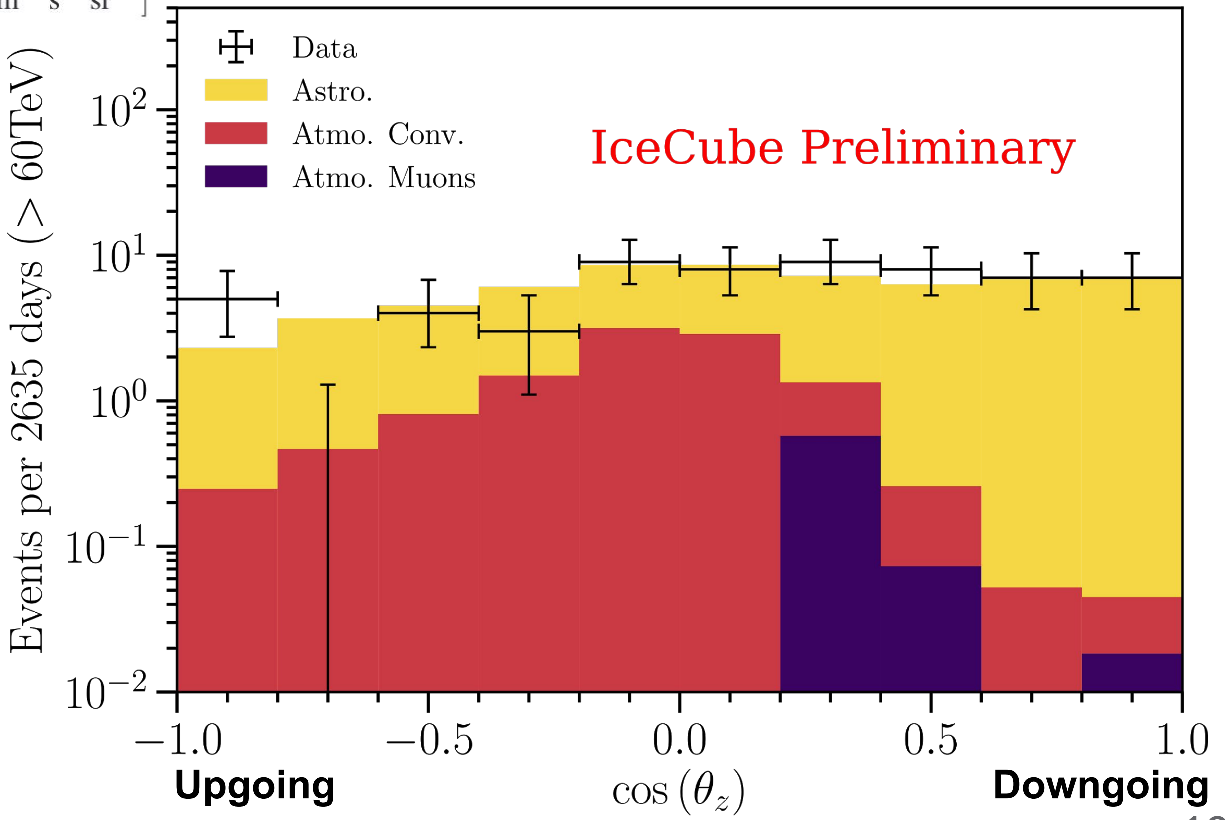
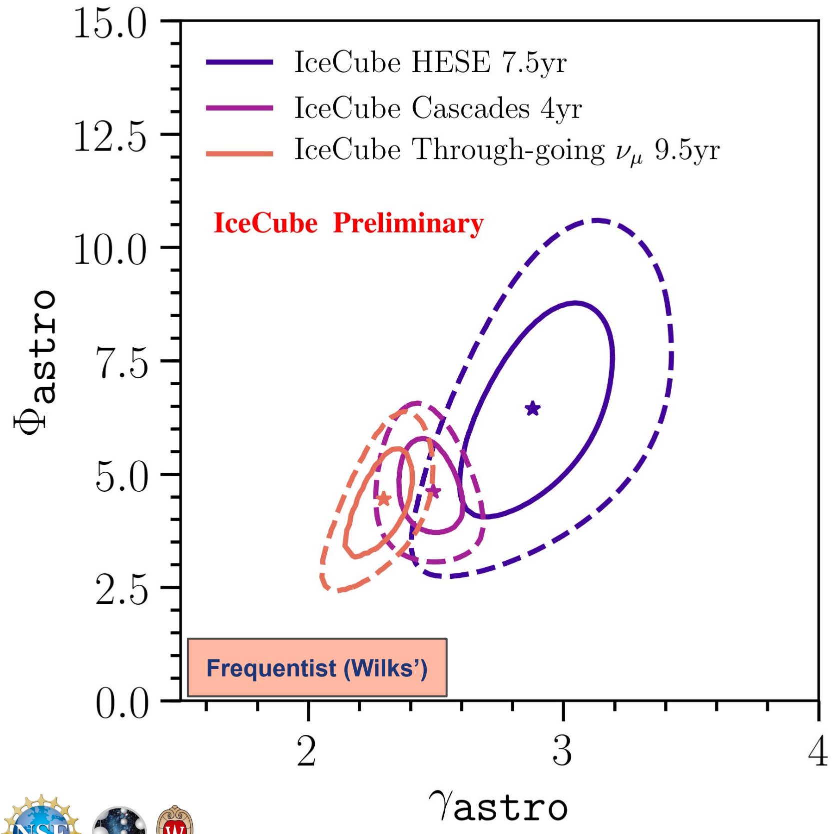


Comparison with Other Samples



Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

Tests of Models

- Many possibilities for high energy astrophysical neutrino production
- Test just a few: AGN, low-luminosity AGN BLLacs, choked jets in core-collapse SN, star burst galaxies, low-luminosity BLLacs, and GRBs
- Compare to single power law as a baseline
- Test Model only (no free parameters)
- Test Model + SPL (only SPL parameters)
- Mostly SPL preferred
- Data in this sample is compatible with an unbroken single power law its sensitive energy range

$$\mathcal{L}(\vec{\theta},\vec{\eta}) = \left[\prod_i^n \mathcal{L}_{\texttt{Eff}}(\mu_i(\vec{\theta},\vec{\eta}),\sigma_i(\vec{\theta},\vec{\eta});d_i)\right]\prod_s^m \Pi_s(\eta_s) \quad (1)$$

$$\mathcal{B}_{10} = \frac{\int d\vec{\eta}'\ \mathcal{L}_1(\vec{\eta}')}{\int d\vec{\eta}\ \mathcal{L}_0(\vec{\eta})} \quad (2)$$

Model	Model only Bayes factor	Model + SPL Bayes factor	Most-likely SPL $\gamma_{\texttt{astro}}$	Most-likely SPL $\Phi_{\texttt{astro}}$
Stecker [26]	4.32×10^{-13}	1.45×10^{-10}	$3.97^{+0.54}_{-0.47}$	$4.08^{+1.8}_{-1.13}$
Fang et al. [27]	0.281	0.248	$3.83^{+0.81}_{-0.5}$	$2.56^{+1.28}_{-1.44}$
Kimura et al. (B1) [28]	4.84×10^{-6}	8.38×10^{-7}	$4.5^{+0.5}_{-0.67}$	$0.98^{+1.04}_{-0.98}$
Kimura et al. (B4) [28]	3.44×10^{-4}	0.666	$2.43^{+0.31}_{-0.26}$	$1.39^{+1.18}_{-0.77}$
Kimura et al. (two component) [28]	1.73×10^{-4}	6.12×10^{-6}	$4.15^{+0.84}_{-0.73}$	$0.0^{+0.69}_{-0}$
Padovani et al. [29]	6.20×10^{-11}	3.32×10^{-7}	$3.59^{+0.59}_{-0.34}$	$4.97^{+1.68}_{-1.46}$
Senno et al. [30]	0.256	3.52	$3.67^{+0.57}_{-0.62}$	$3.36^{+1.56}_{-1.34}$
Bartos et al. [31]	1.15×10^{-14}	2.81×10^{-16}	$4.25^{+0.75}_{-0.83}$	$0.0^{+0.49}_{-0}$
Tavecchio et al. [32]	0.0730	1.04	$3.88^{+0.65}_{-0.49}$	$3.7^{+1.39}_{-1.48}$
Biehl et al. [33]	8.66×10^{-7}	0.362	$3.35^{+0.4}_{-0.38}$	$5.09^{+2.07}_{-1.03}$

Summary

- Veto-based method produces a high-purity astrophysical neutrino sample at high energies
- Sample is sensitive to all neutrino flavors in the full sky
- Zenith distribution ⇒ background only hypothesis excluded
- Differing observations from different energy ranges and flavors may indicate additional features
- Tests of ad-hoc models show no strong preference beyond the single power law using this sample

https://pos.sissa.it/358/1004/pdf

Bonus Slides

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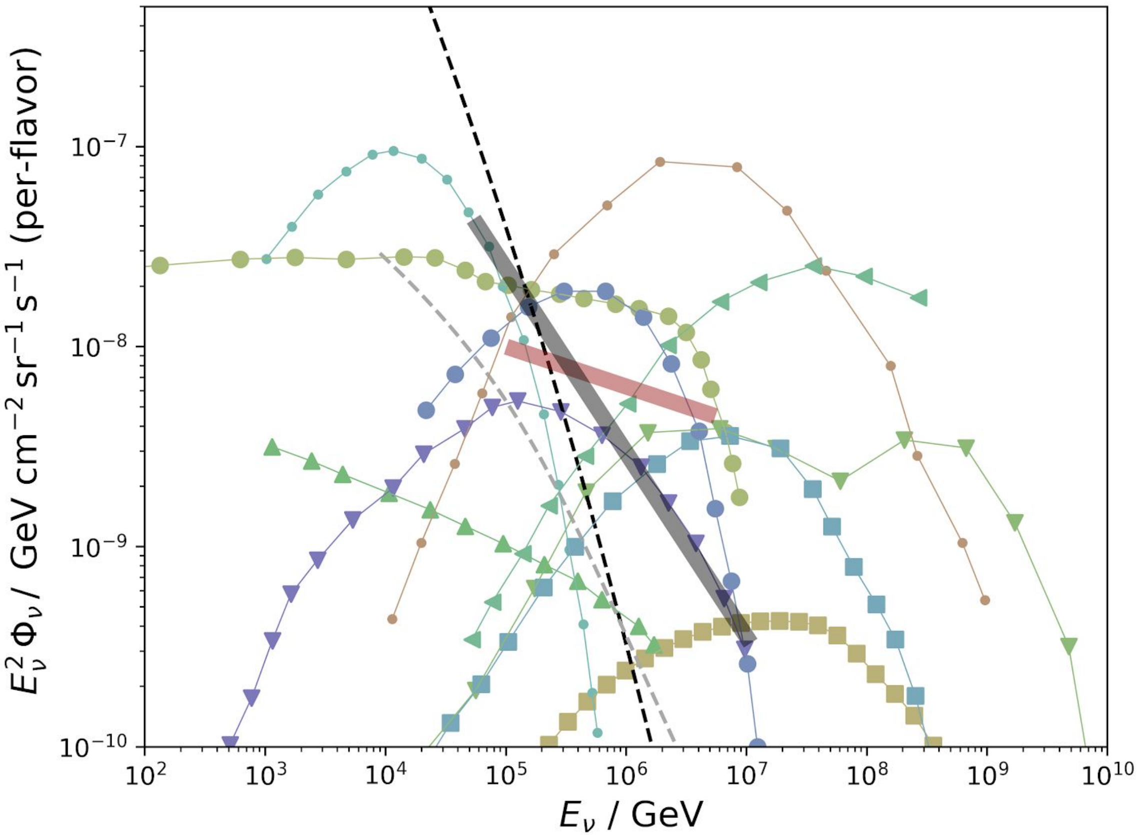
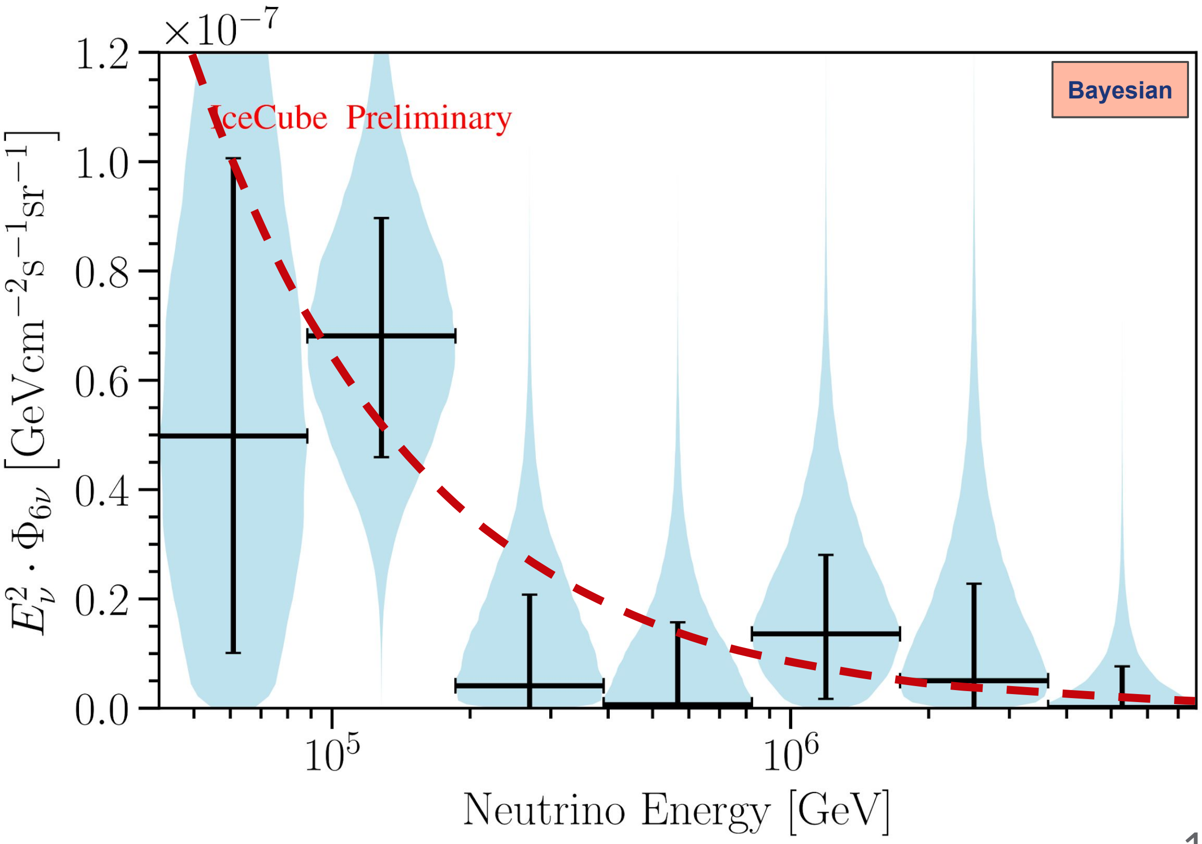
- Compare to single power law as a baseline



Getting More Generic - E^{-2} Segments

- We fit the normalization of many flux segments
- Errors show 68.3% credible regions
- Violins show the shape of the pdf
- Line shows approximately an E^-2.9 spectrum

- Unbroken power law works well for this data sample



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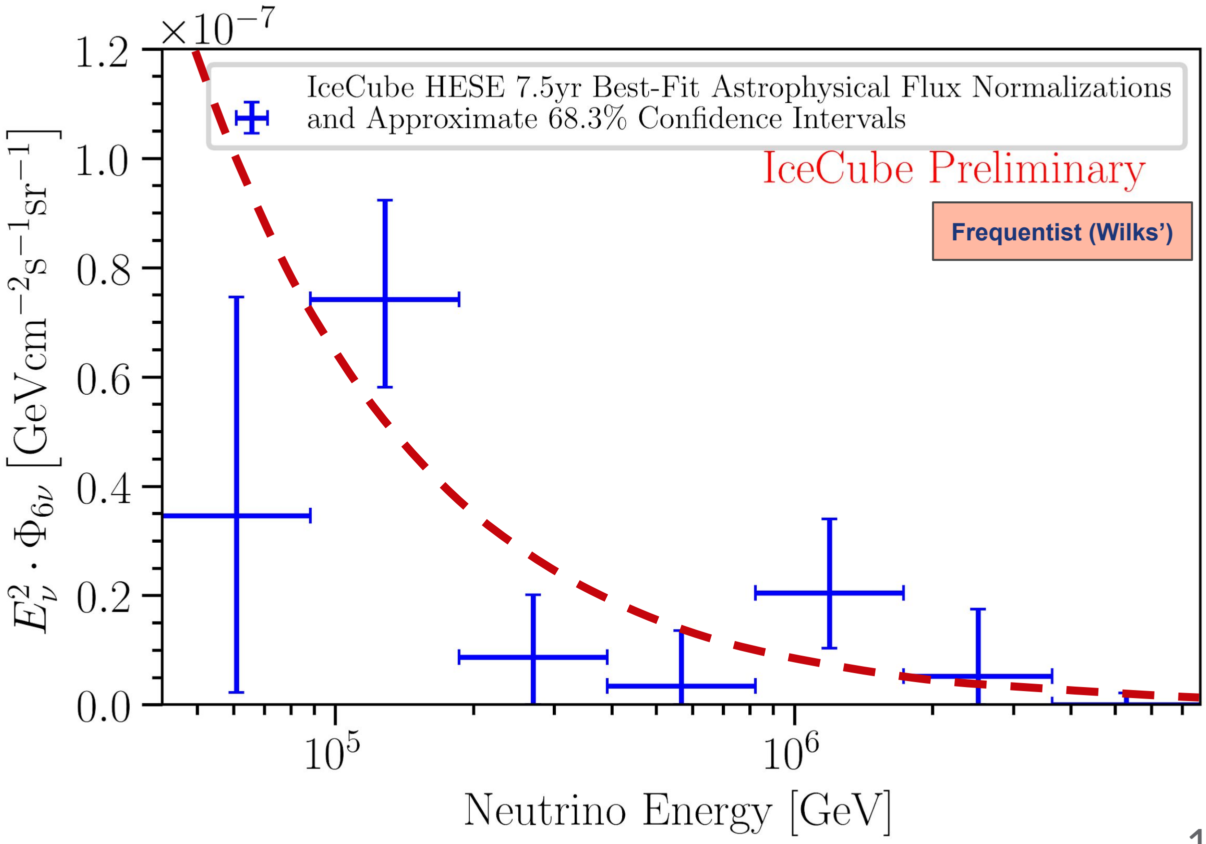

The Future

HESE ✚ Cascades ✚ NuMu ✚ Others

Want to disentangle the flux properties and apparent discrepancies

2 ways to improve measurements:

1. Combine existing samples
2. Move to lower energies

More statistics ⇒ systematically dominated

Systematically dominated ⇒ challenging analysis

Working to incorporate all known systematic uncertainties

- Atmospheric model
- Unconstrained hadronic interactions
- Cosmic ray flux/composition
- Neutrino cross section
- Earth model
- Charged lepton cross sections