MEASUREMENT OF THE ASTROPHYSICAL DIFFUSE FLUX USING MUON NEUTRINOS WITH A CONTAINED VERTEX

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for the IceCube Collaboration

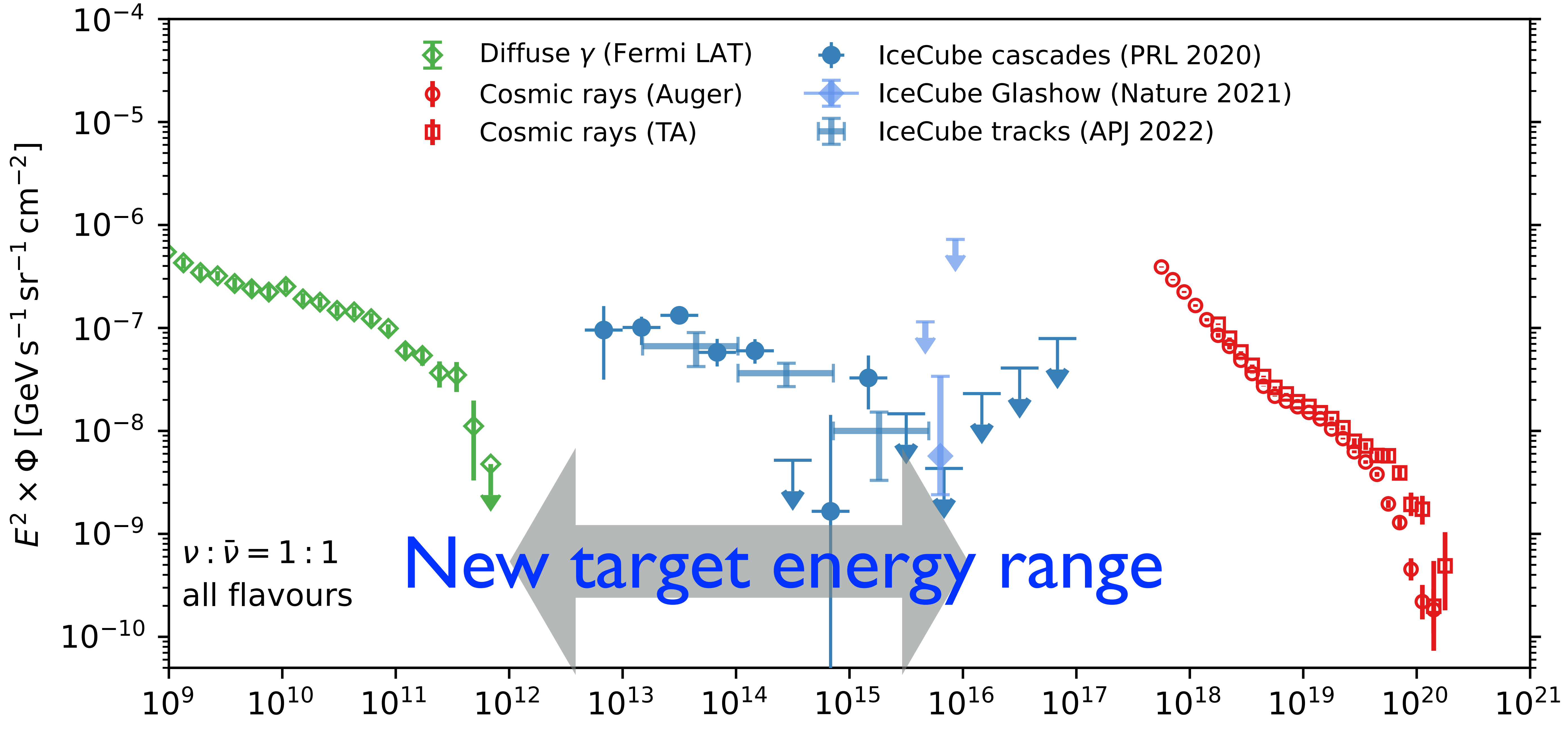
TeVPa - Kingston, On - August 10, 2022

WISCONSIN

REMINDER: DIFFUSE FLUX

- Energy density of gamma rays, neutrinos, and ultra-high energy cosmic rays are comparable

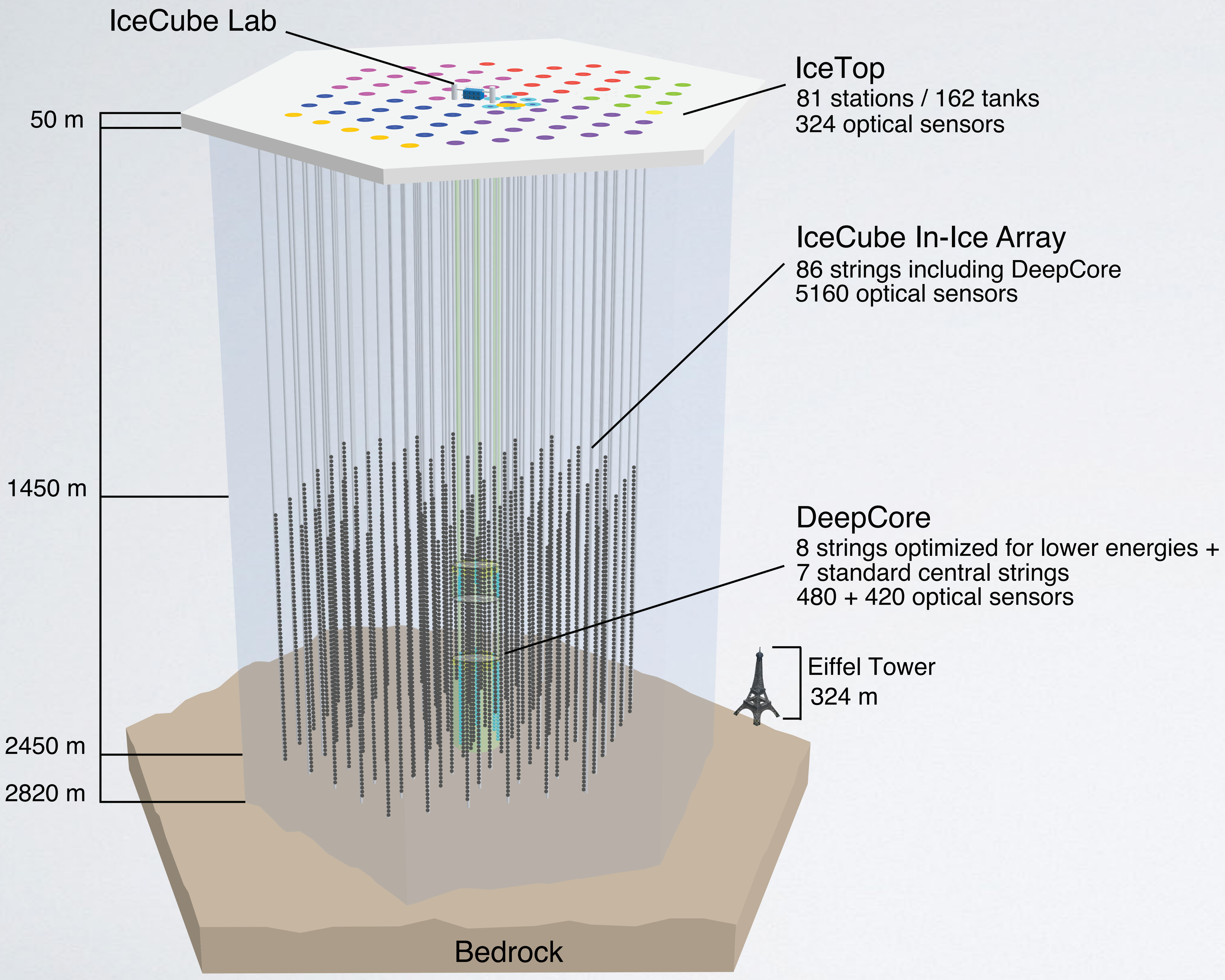
- Astrophysical diffuse neutrino flux measured using:
  - "Tracks" (ν_μ)
  - Starting "cascades" ($\nu_e + \nu_\tau$)



arXiv:2203.08096

- Lingering question:
  - Is diffuse neutrino flux more complex than an isotropic single power law?

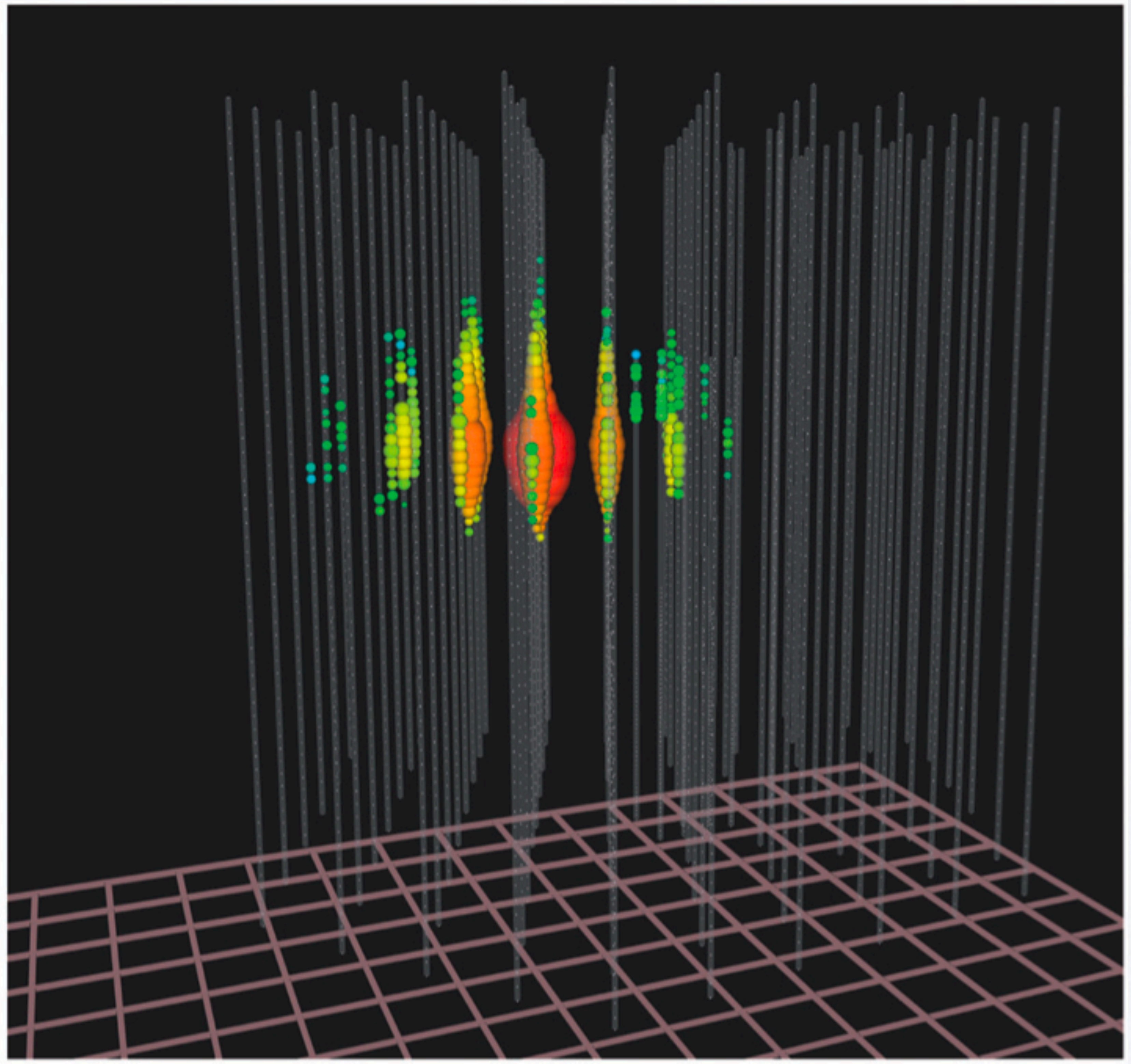
ICECUBE NEUTRINO OBSERVATORY



- IceCube neutrino observatory located at geographic South Pole
- Neutrinos interact within the ice, secondary particles from interaction produce Cherenkov radiation
- First detection of high energy astrophysical neutrinos in 2013.
  Science 342, 1242856 (2013)

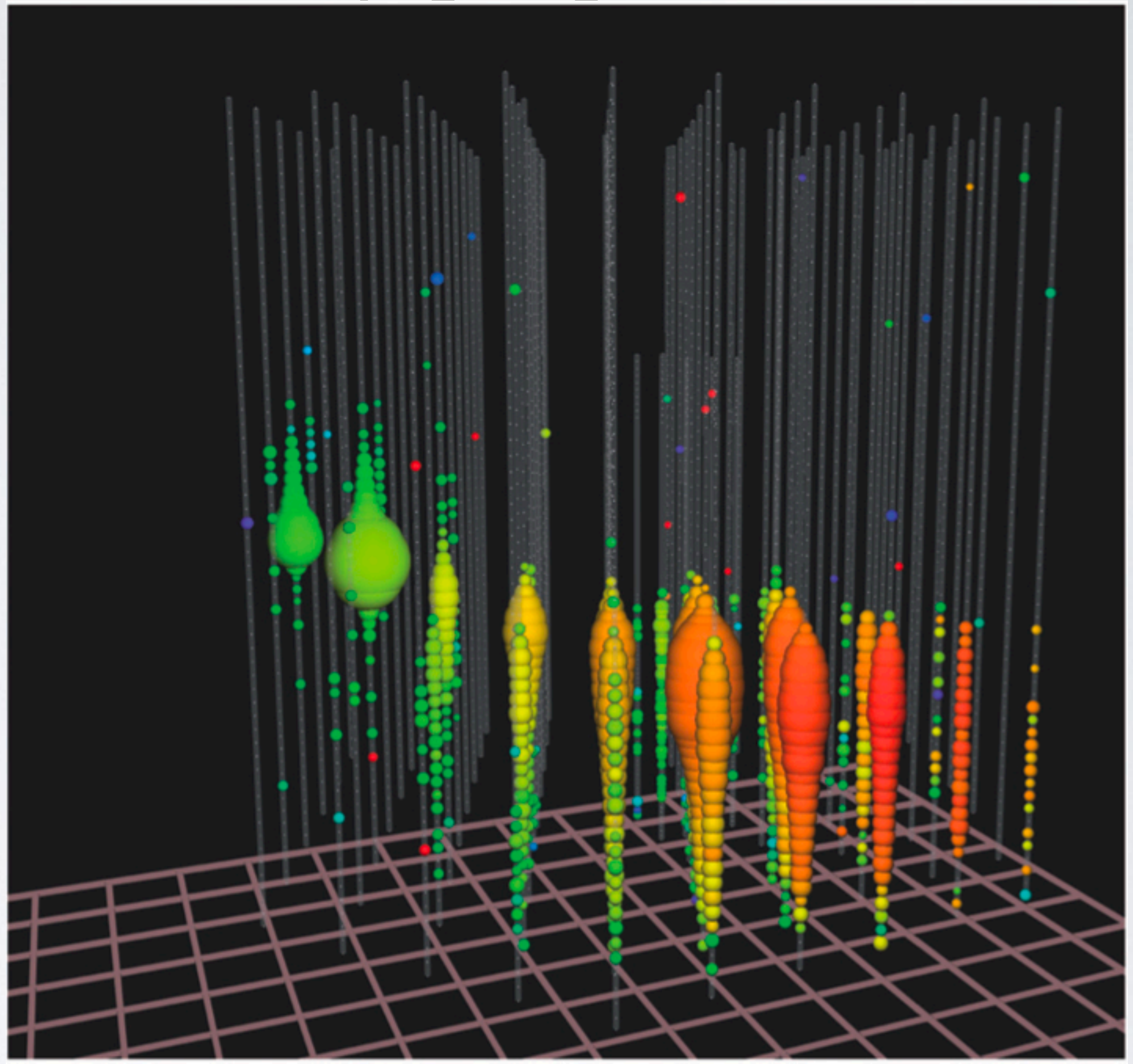
TRADITIONAL EVENT TOPOLOGIES

Starting Cascades



Advantage: Energy resolution ~10%, high astrophysical purity, sensitive to astrophysical flux in southern sky
Disadvantages: Poor angular resolution, complex atmospheric neutrino flux

Up-going Tracks

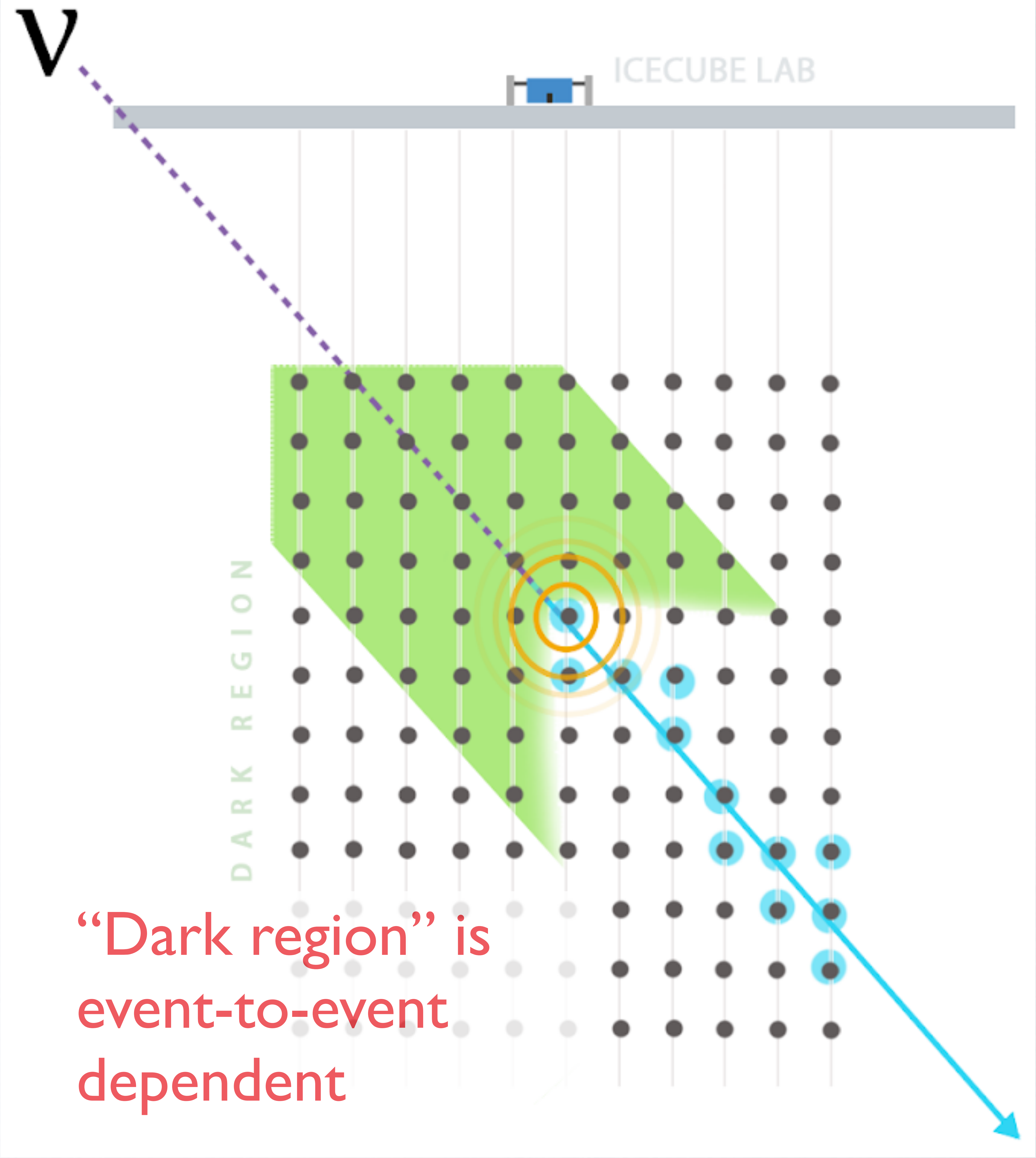


Advantage: Large number of events, angular resolution 0.25° at 1 PeV, high muon neutrino purity
Disadvantages: Poor energy resolution, only sensitive to astrophysical flux above ~40 TeV

NEW: STARTING TRACKS

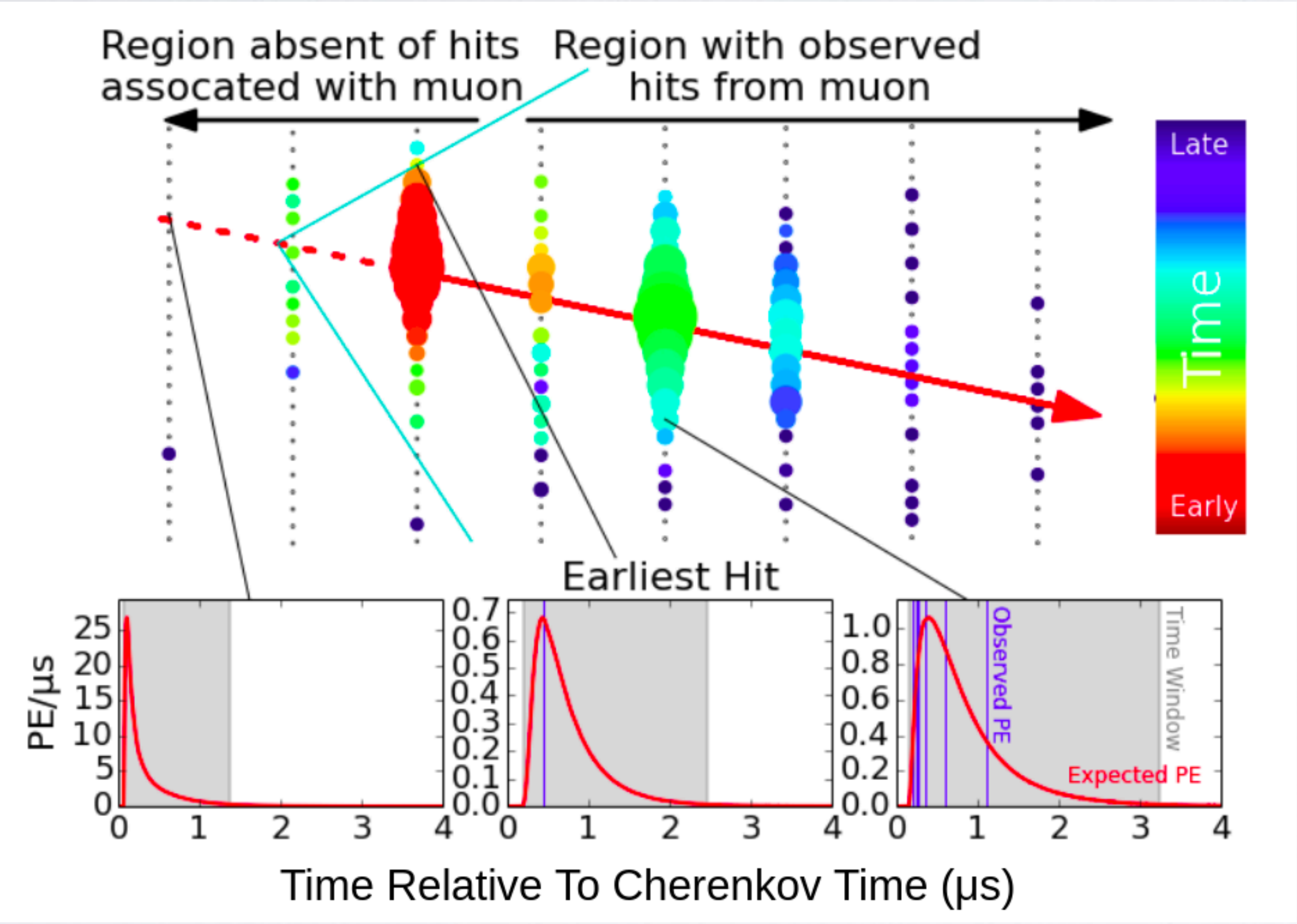
Advantages:
- Excellent angular resolution
- Excellent energy resolution
- Most sensitive to southern sky neutrino flux
- High purity (>99%)

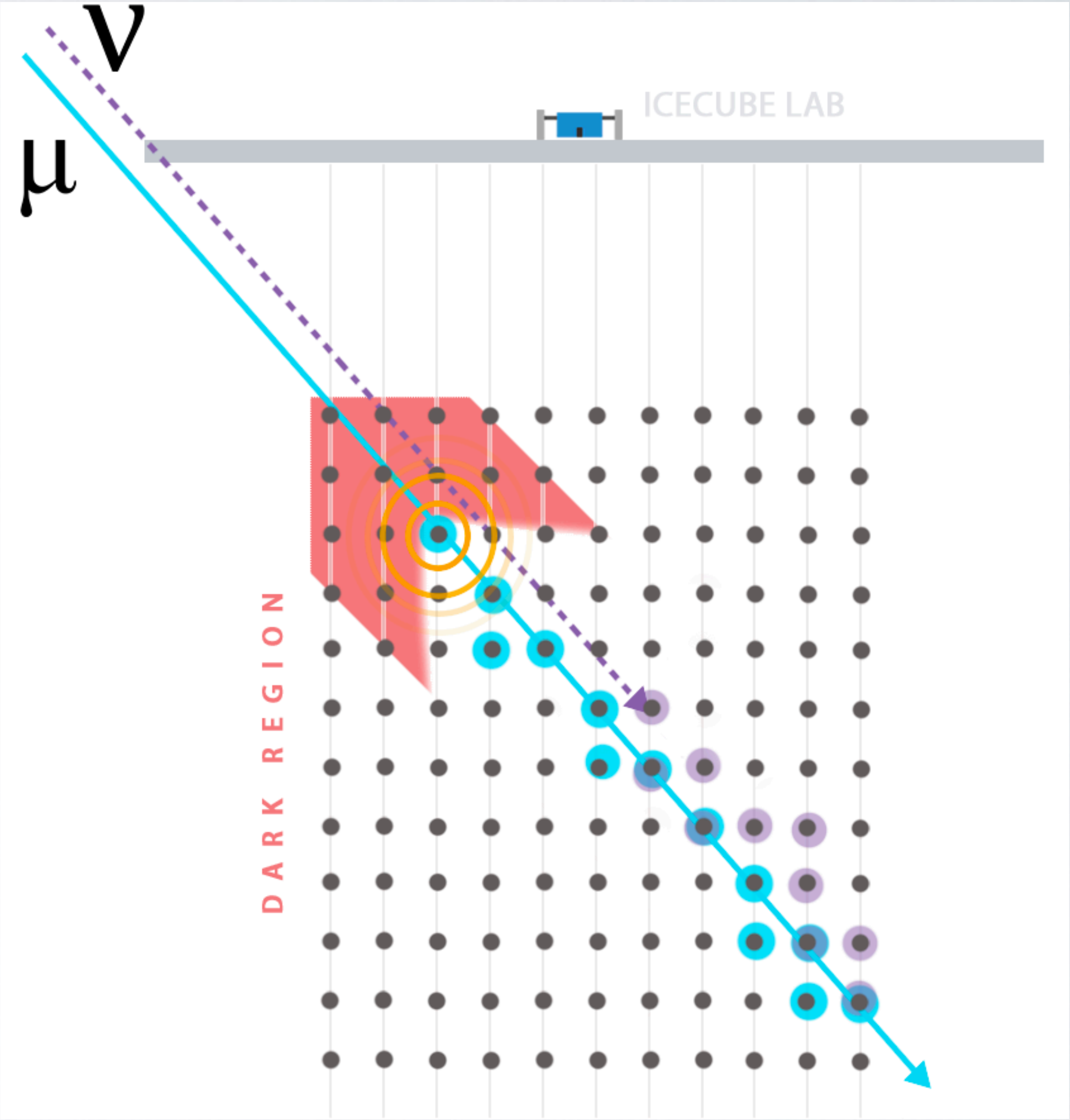
Disadvantages:
- Systematic uncertainties require precise modeling over the entire sky
- 3kHz muon background



ATMOSPHERIC MUON VETO - CUT #1

- Muon reconstructed track direction and vertex used to define our "veto region"

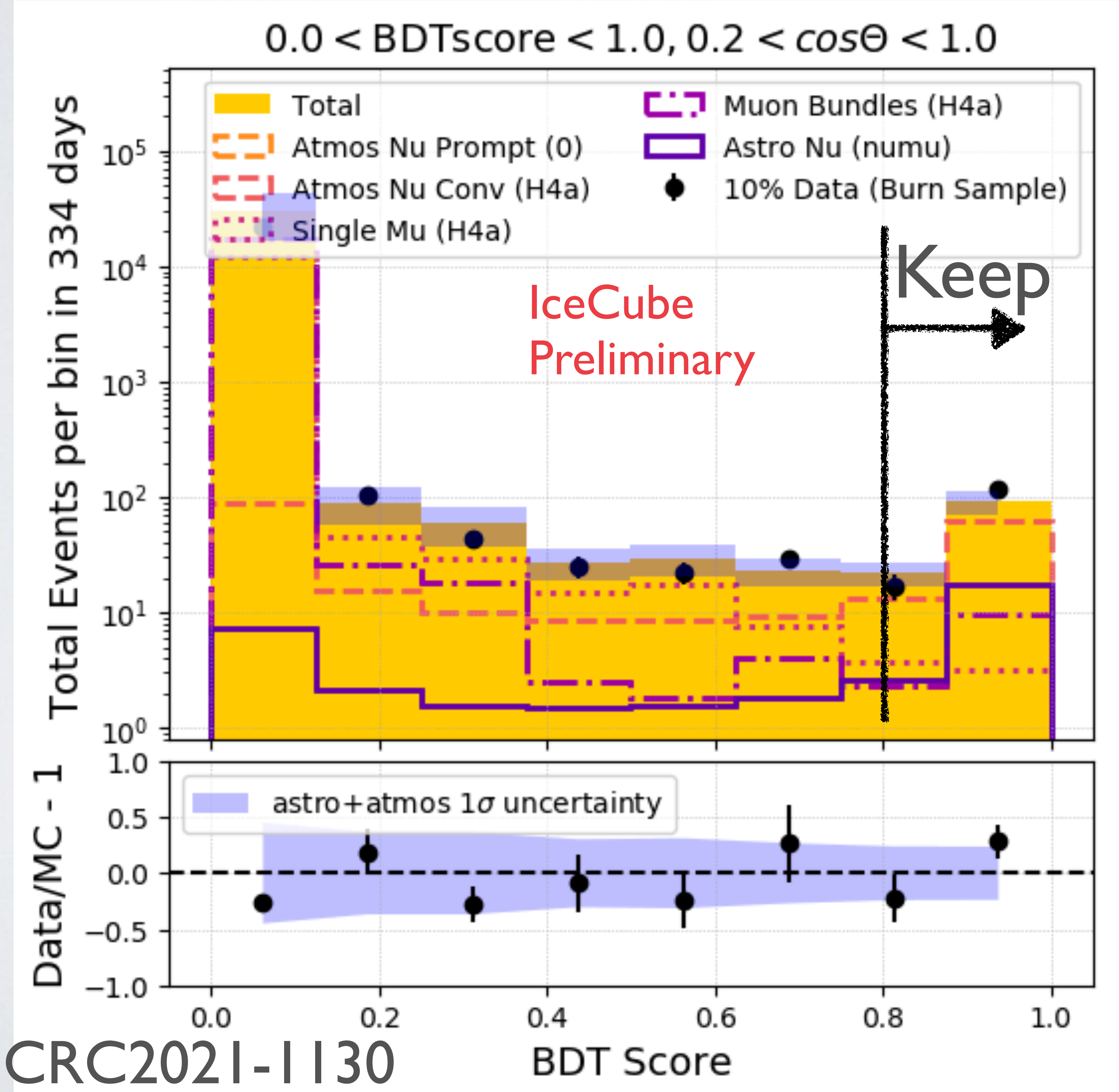


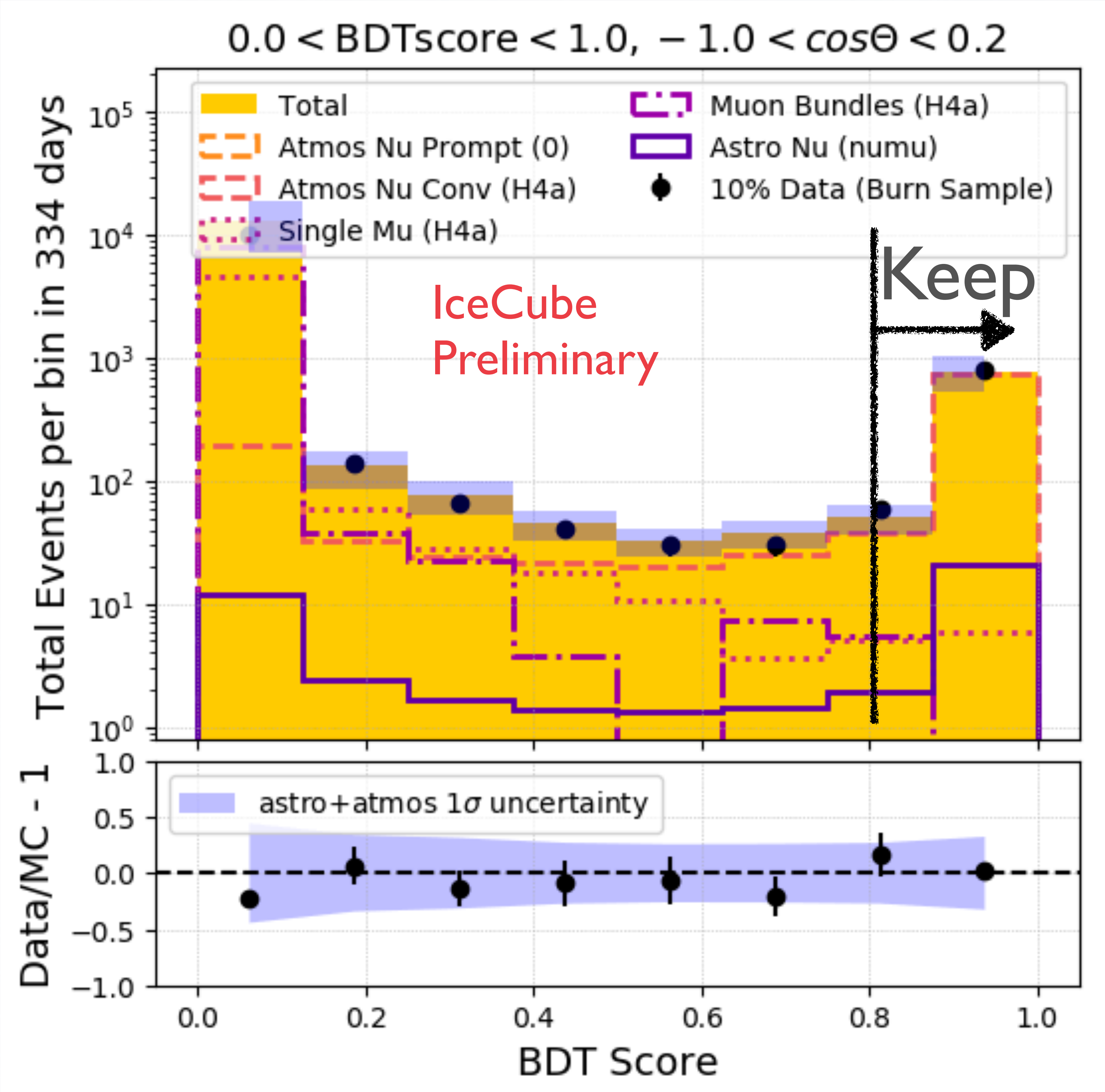


- Veto region is event-to-event dependent

STARTING TRACKS BDT - CUT #2

- Cut on BDT score defined such that atmospheric muon background reduced to ~handful of muons per year
- Use 334 days of data to validate performance of BDT scores





PoS-ICRC2021-1130

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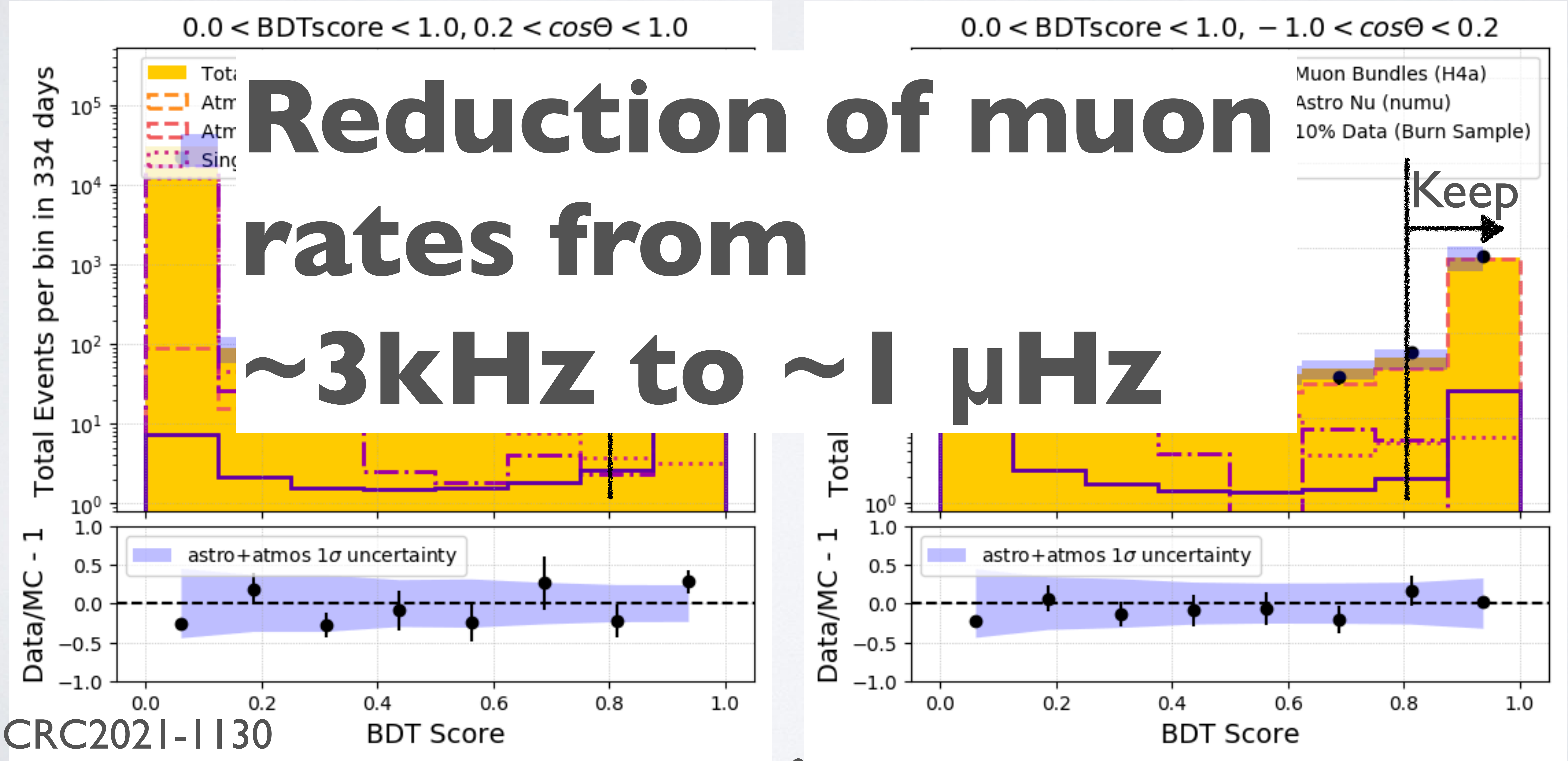
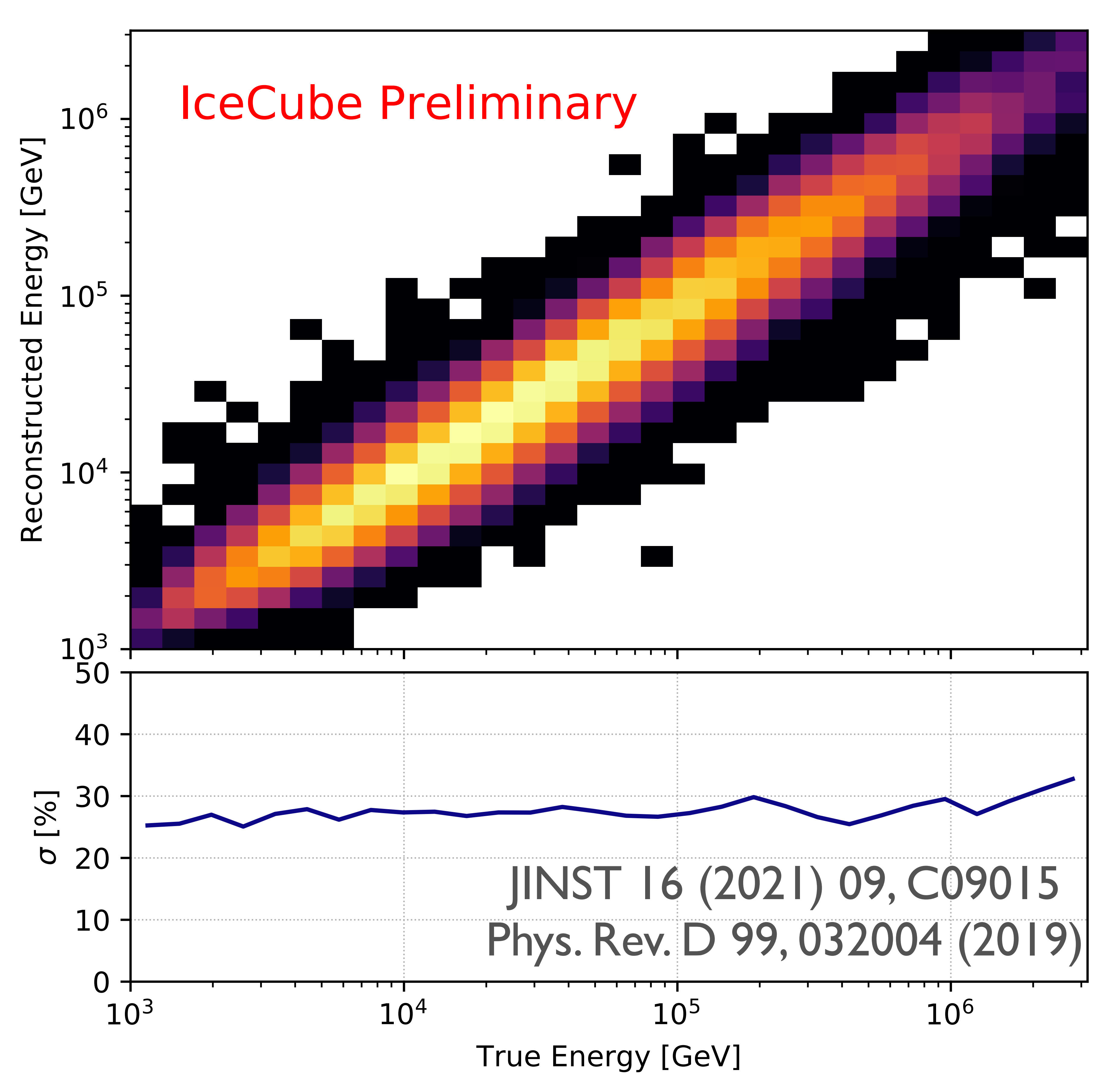
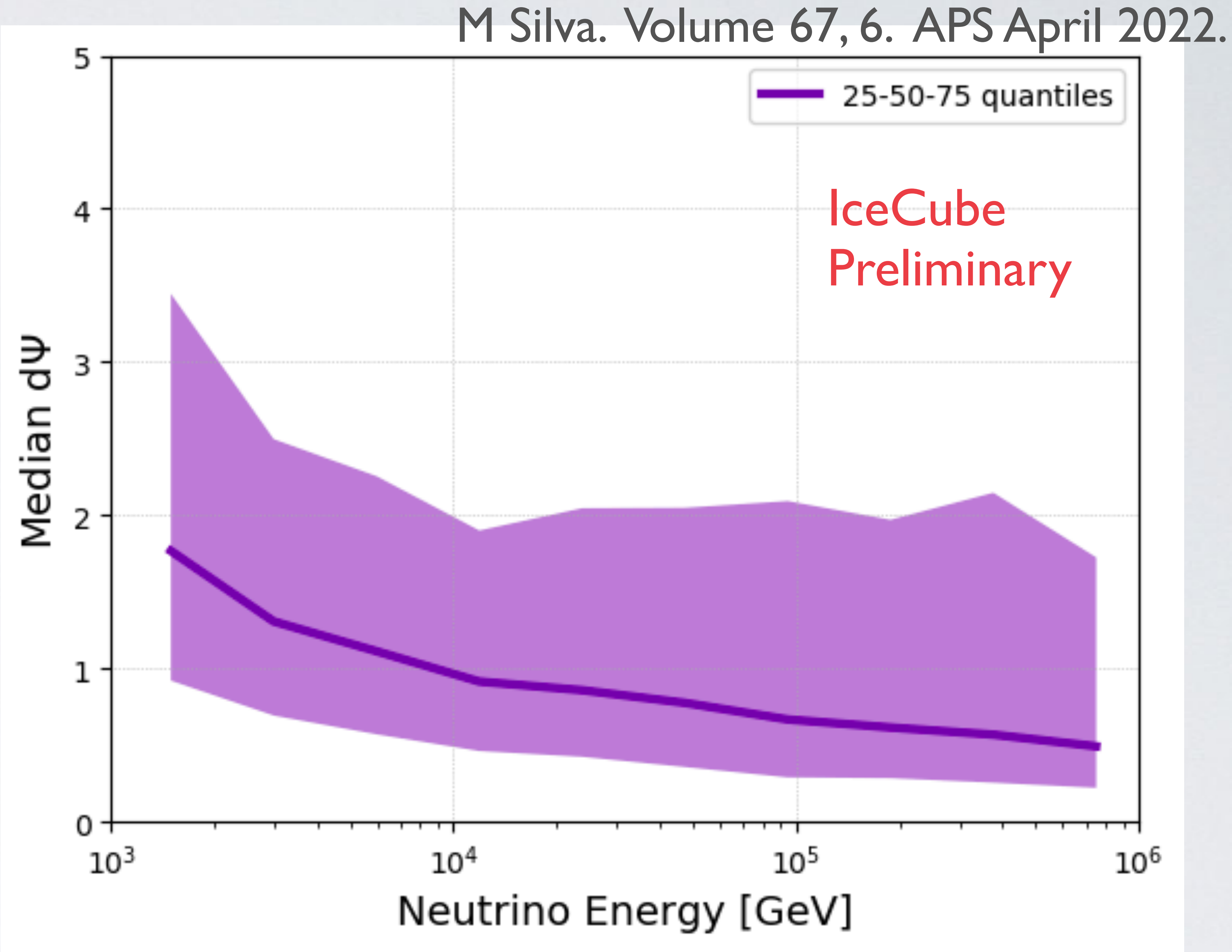


Reduction of muon rates from ~3kHz to ~1 μHz

PoS-ICRC2021-1130

RECONSTRUCTED EVENT OBSERVABLES





- Energy resolution ~25%
- Energy resolution limited by: muon track length, overlap of cascade and muon energy losses in the detector

- Directional resolution is ~1.6° at 1 TeV down to ~0.5° at 1 PeV

MEASUREMENT OF THE DIFFUSE FLUX

Parameter	Flux
ϕ_{astro}	-
γ_{astro}	-
ϕ_{conv}	**Gaisser H4a**
ϕ_{pr}	**Gaisser H4a**
Self-Veto Threshold	**100 GeV**
ϕ_{muon}	**Gaisser H4a**

$$\mathscr{L}(\lambda(\vec{\Theta}), x) = \prod_{i=1}^{190} \frac{e^{-\lambda_i(\vec{\Theta})} \lambda_i(\vec{\Theta})^{x_i}}{x_i!} \times \prod_{j=1}^{6} \mathscr{G}_j(\hat{\Theta}_j, \Theta_j, \sigma_j)$$

18 bins from 1 TeV to 1PeV, 1 from 1 - 10 PeV
10 bins from -1 to 1 cosine zenith

- Atmospheric muon and neutrino fluxes pre-defined
  - Fit to overall normalization
- 11 theory and detector systematics included in fit to data (details in backup)

- Astrophysical flux assumes single power law, assuming 1:1:1 flavor ratio
  - Astrophysical normalization quoted today is per flavor

$$\Phi^{\nu+\bar{\nu},\text{all flavors}}_{\text{astro}} = \phi_{\text{astro}} \times \left(\frac{\text{E}}{100\text{TeV}}\right)^{-\gamma} \times 3 \times 10^{-18}\text{GeV}^{-1}\text{s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$$

NEW RESULTS: SINGLE POWER LAW

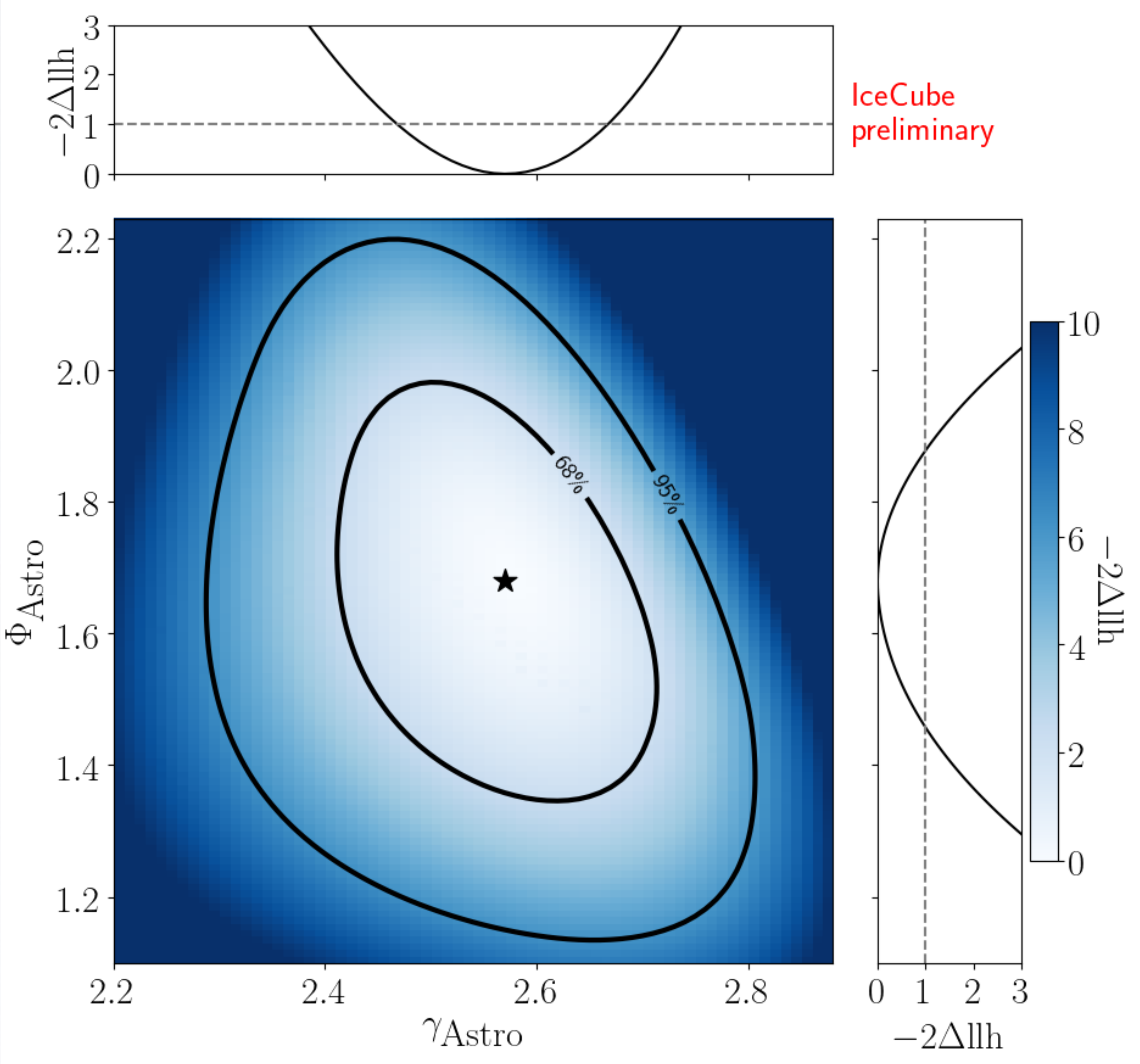
- Single power law flux

$$\Phi_{\text{astro}}(E)/C_0 = \phi_{\text{astro}} \cdot (E/100\text{TeV})^{-\gamma}$$

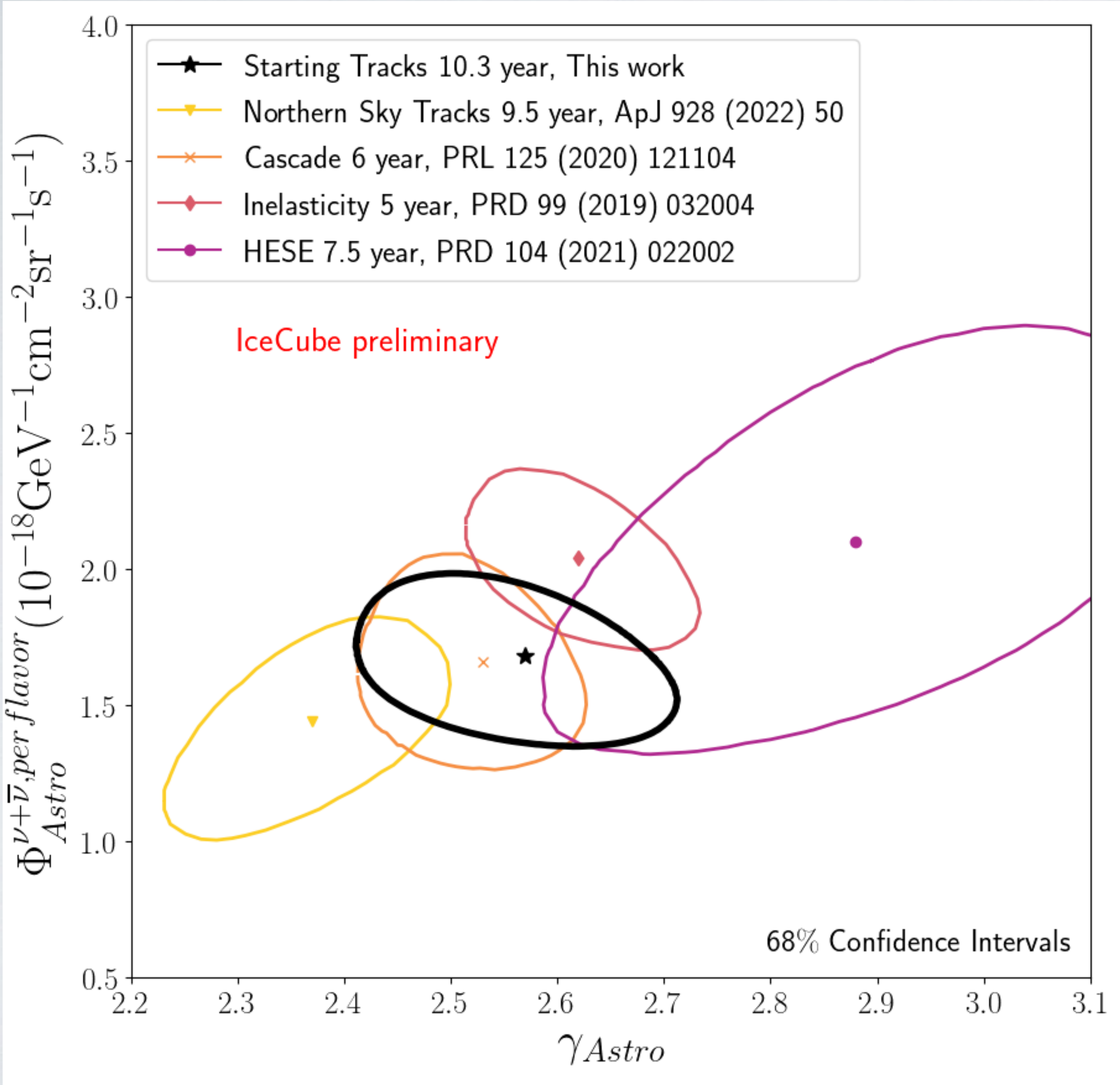
$$\Phi_{\text{astro}} = 1.68^{+0.19}_{-0.22}$$

$$\gamma_{\text{astro}} = 2.57^{+0.09}_{-0.09}$$

- **New IceCube result using 10.3 years of data!**

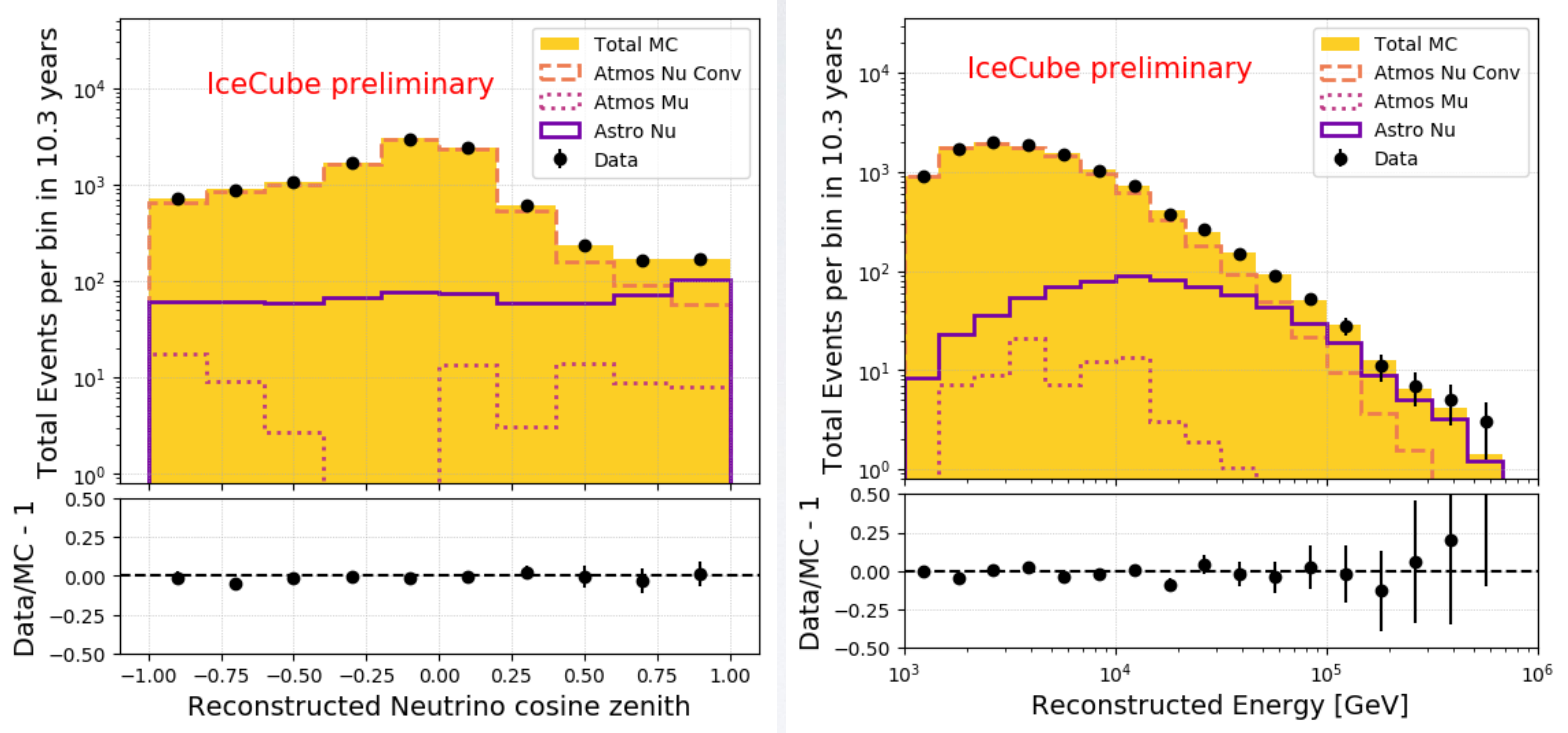


NEW RESULTS: ICECUBE FLUX SUMMARY

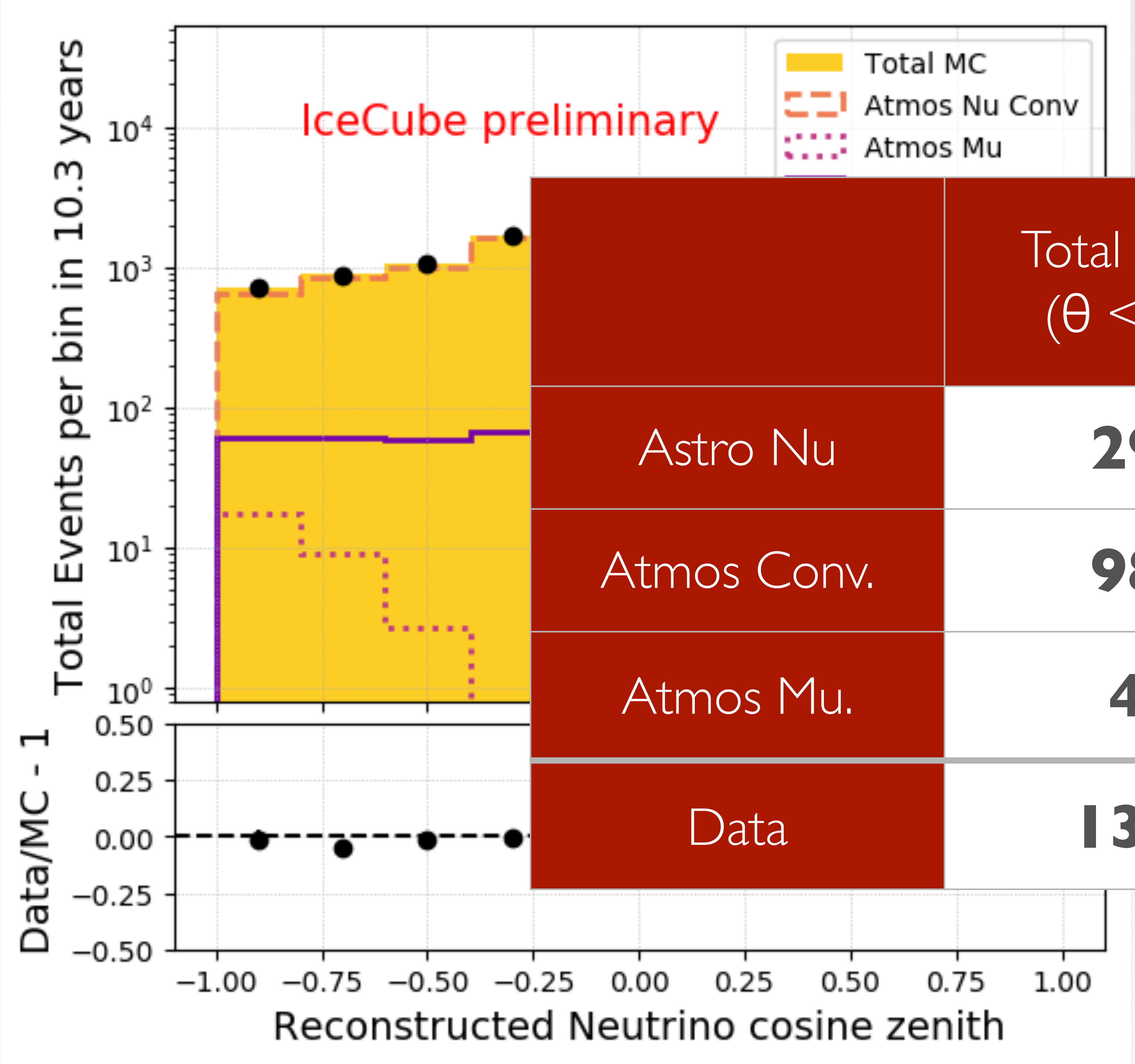


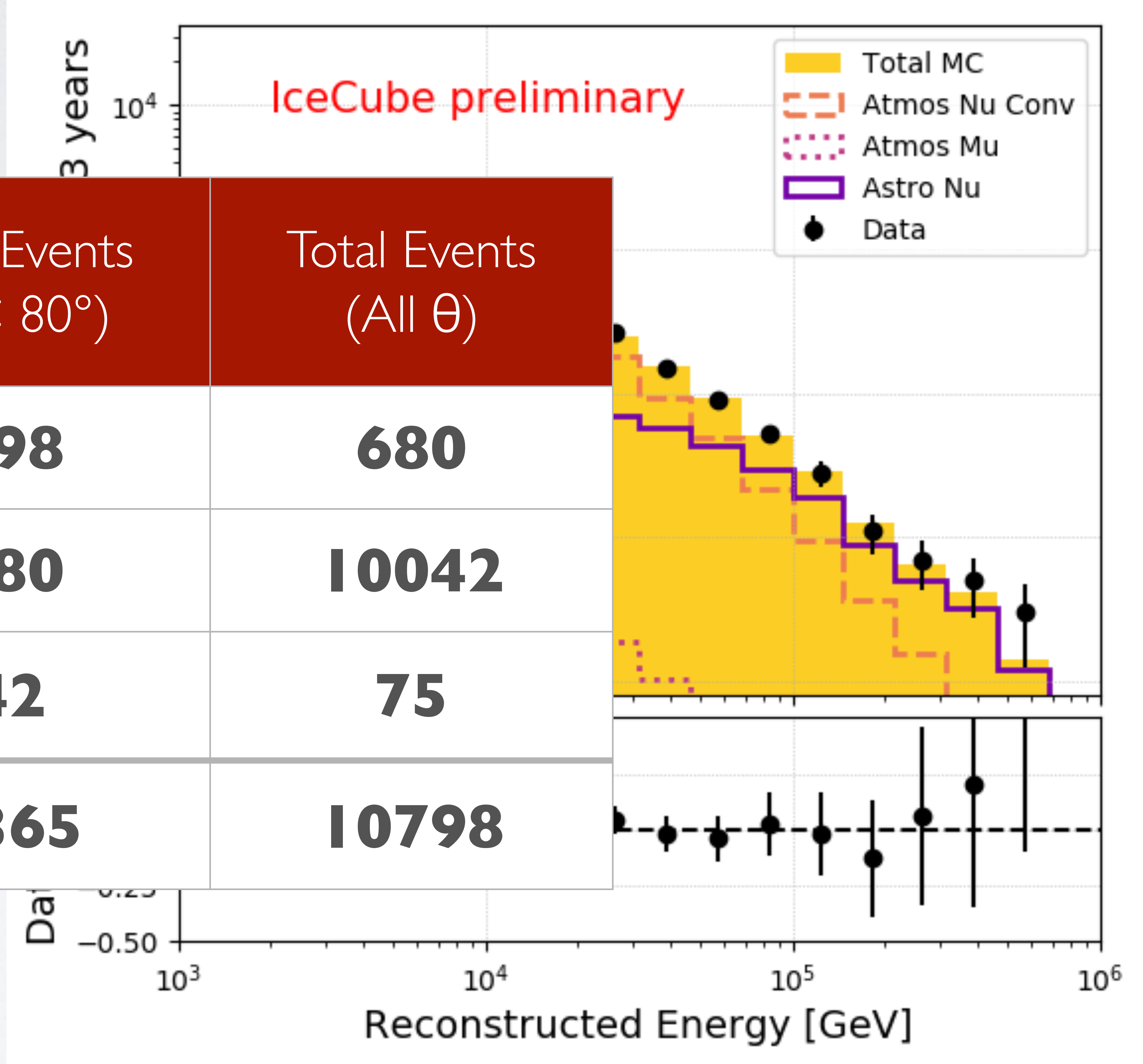
- This is the first event selection dominated by muon neutrinos in the southern equatorial sky
- Within 68% confidence intervals, all single power law flux measurements are in agreement

NEW RESULTS: RECONSTRUCTED OBSERVABLES



NEW RESULTS: RECONSTRUCTED OBSERVABLES





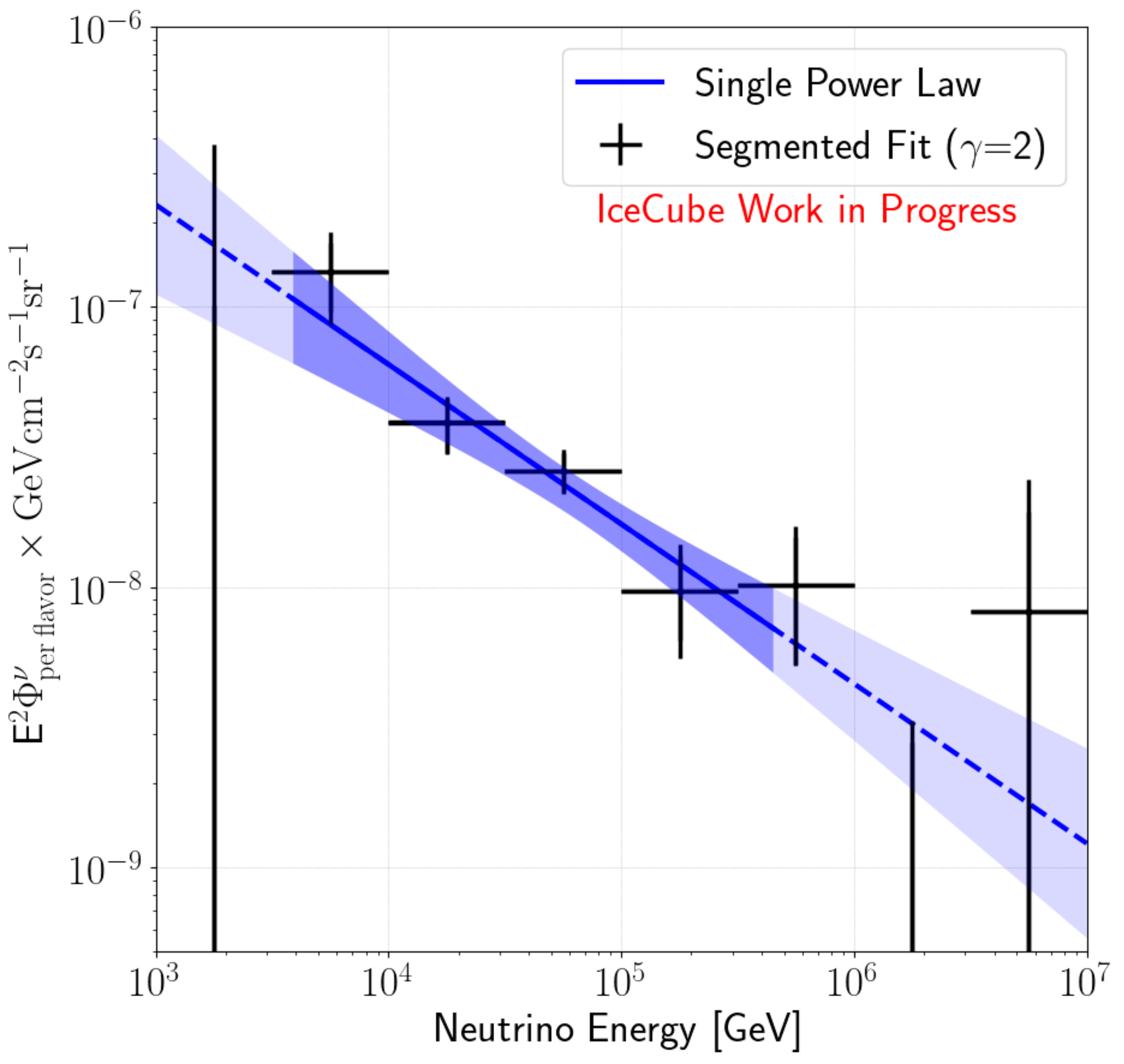
	Total Events (θ < 80°)	Total Events (All θ)
Astro Nu	**298**	**680**
Atmos Conv.	**980**	**10042**
Atmos Mu.	**42**	**75**
Data	**1365**	**10798**

NEW RESULTS: PIECE-WISE POWER LAW

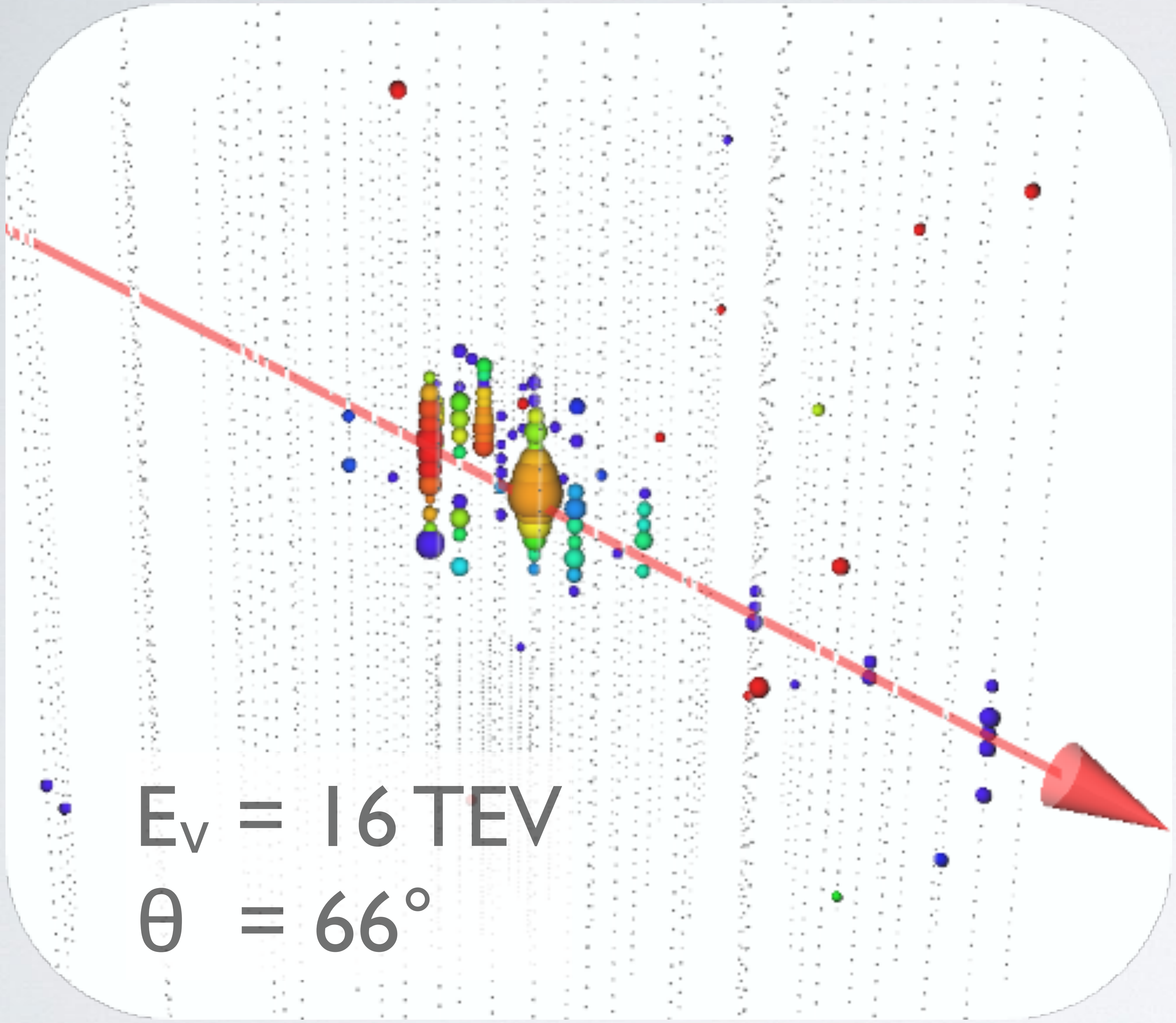
- Piece-wise power law flux ($\gamma = 2$)

$$\Phi_{\text{astro}}(\text{E})/C_0 = \Sigma_{n=0}^{8} \phi_{\text{astro,n}} \cdot (\text{E}_\text{n}/100\text{TeV})^{-\gamma}$$

- Darker shaded region shows our **90% sensitivity** to the astrophysical flux (**3TeV-530TeV**)
- All pieces consistent with a SPL flux hypothesis



SUMMARY



- A new dataset searching for starting track events in IceCube
  - **~11k starting tracks observed**
- Measurement of the astro diffuse flux
  - **ϕ_{astro} = 1.68, γ_{astro} = 2.57**
  - **90% sensitivity** to astro flux **3-550TeV**
- Unfolded flux from 1 TeV-10 PeV
  - All pieces were compatible with single power law flux hypothesis

NEXT STEPS FOR *NEW* STARTING TRACKS DATASET

Diffuse flux measurement

1. Broken power law
2. Log-parabolic power law
3. Power law with a cut-off
4. Simultaneous northern and southern hemisphere single power law fit
5. Simultaneous isotropic single power law and diffuse galactic plane component

Search for neutrino sources

(Sarah Mancina at 4:10pm today!)

1. All-sky neutrino clustering
2. Catalog and stacking sources
3. Neutrinos from diffuse galactic plane

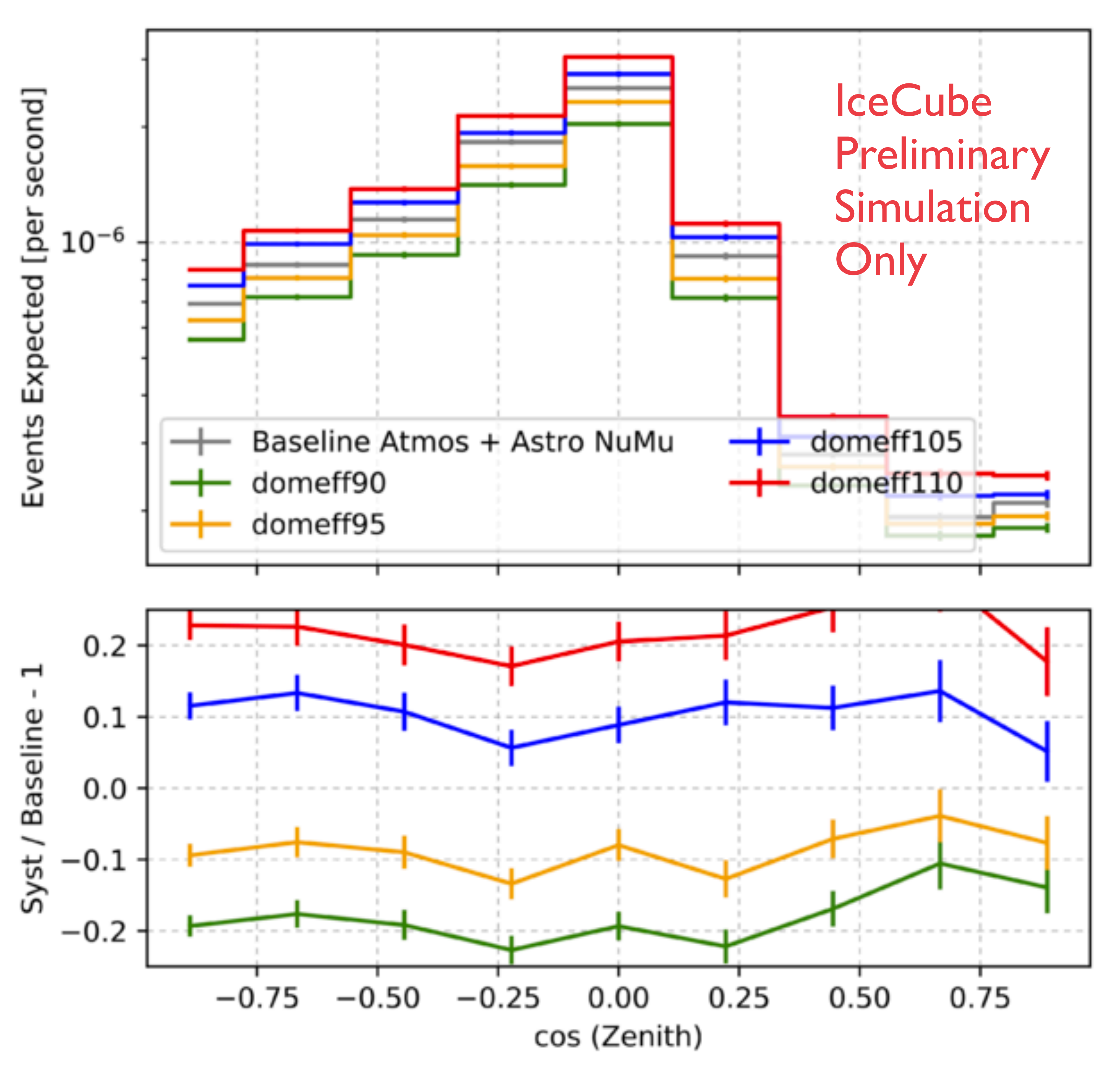
BACKUP

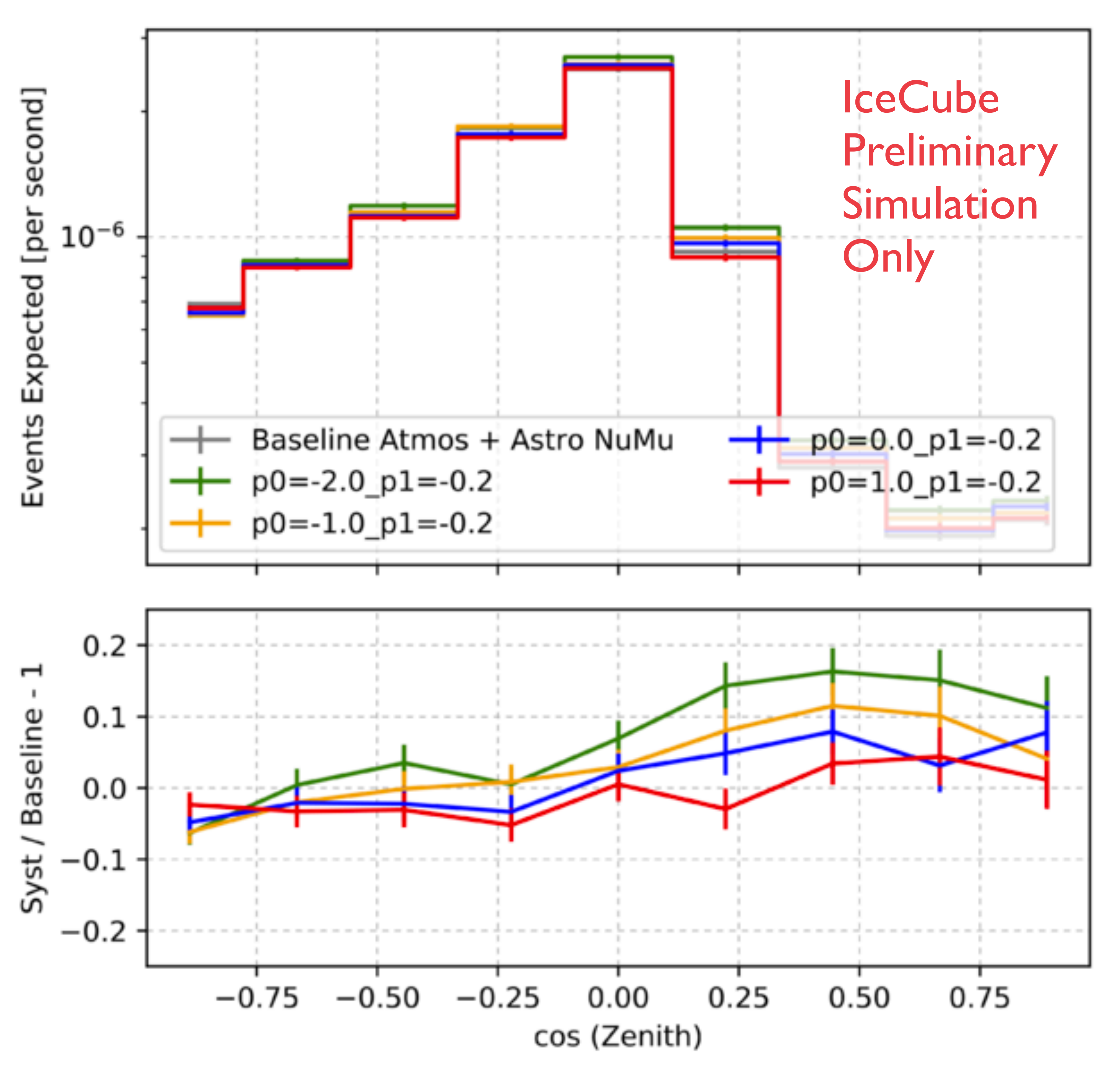
DETECTOR SYSTEMATICS

Parameter
Optical Module Overall Efficiency
Photon Absorption in Ice
Photon Scattering in Ice
Optical Module Angular Efficiency p_0
Optical Module Angular Efficiency p_1

- Treat each nuisance parameter listed here as Gaussian uncertainty
  - Assume no correlation between systematics
- Detector and ice systematics use full simulation to compute the detector response

OPTICAL MODULE EFFICIENCY





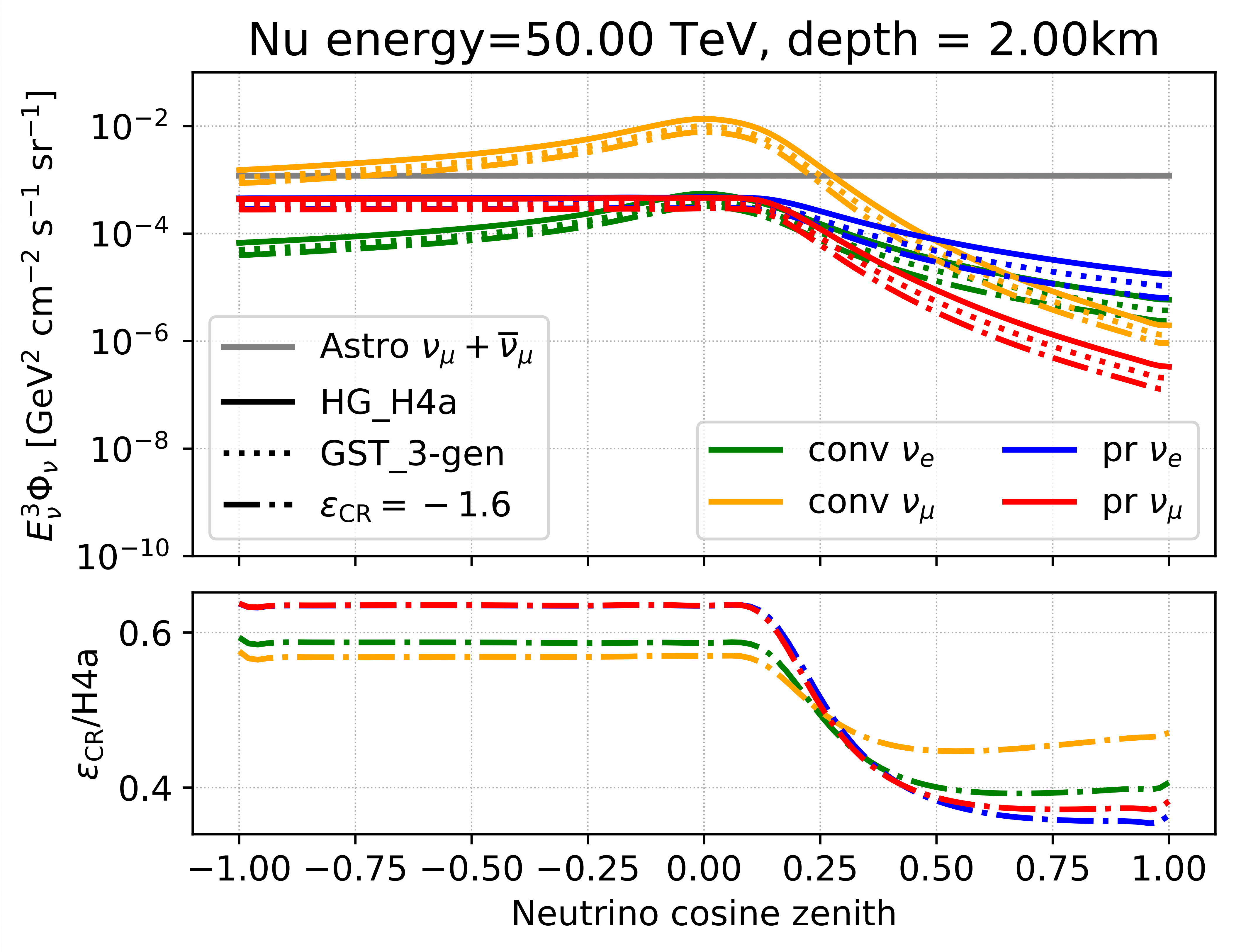
- Overall efficiency as a function of zenith for neutrino energies above 10 TeV
- Angular efficiency as a function of zenith for neutrino energies above 10 TeV

THEORY SYSTEMATICS

Parameter
Atmospheric Muon Flux
Atmospheric Neutrino Flux
Cosmic Ray Flux
Hadronic Interaction Model
Self-Veto Threshold
Nu-Nubar Ratio

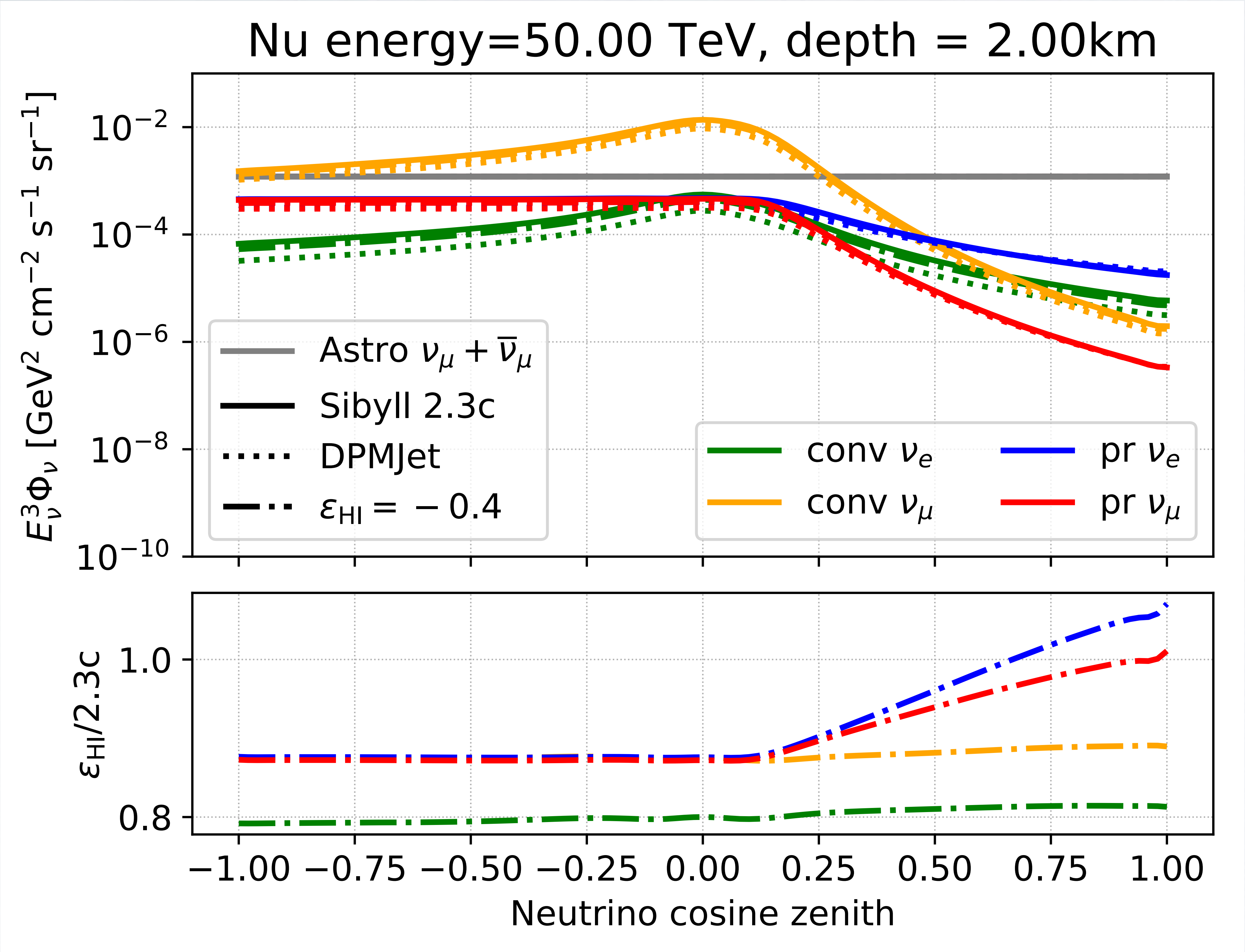
- Atmospheric muon and neutrino fluxes overall normalization are fit parameters
- CR, HI, SV uncertainties are defined in following slides (**new diffuse flux measurement systematics!**)
- Nu-Nubar ratio is defined as $\mathrm{R} = (\frac{2\nu}{\nu + \bar{\nu}})$
  - Modeled as Gaussian with mean at 1.0 standard deviation of 0.10

COSMIC RAY FLUX UNCERTAINTY



- Brute force MCEq calculation used to compute neutrino fluxes over various CR flux models
- CR flux uncertainty is defined as difference between H4a (ε_{CR} = 0) and GST-3gen (ε_{CR} = -1). Fit to data prefers ε_{CR} = -1.6.
- Fit to data was rerun with various combinations of CR flux models, change to SPL best-fit was negligible.

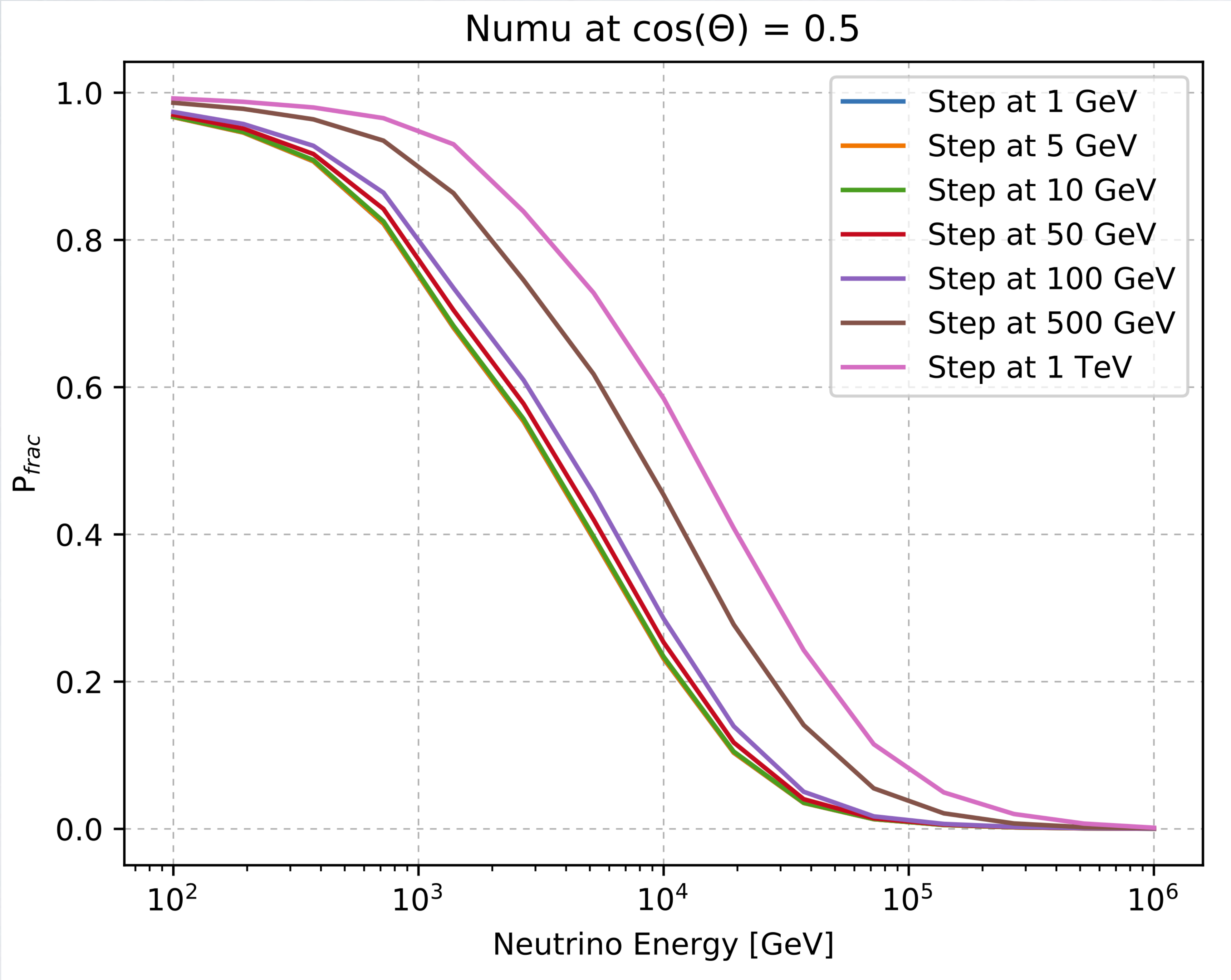
HADRONIC MODEL UNCERTAINTY



- Brute force MCEq calculation used to compute neutrino fluxes over various hadronic interaction models

- HI model uncertainty is defined as difference between 2.3c (ε_{HI} = 0) and DPMJey (ε_{HI} = -1). Fit to data prefers ε_{HI} = -0.4.

SELF-VETO UNCERTAINTY

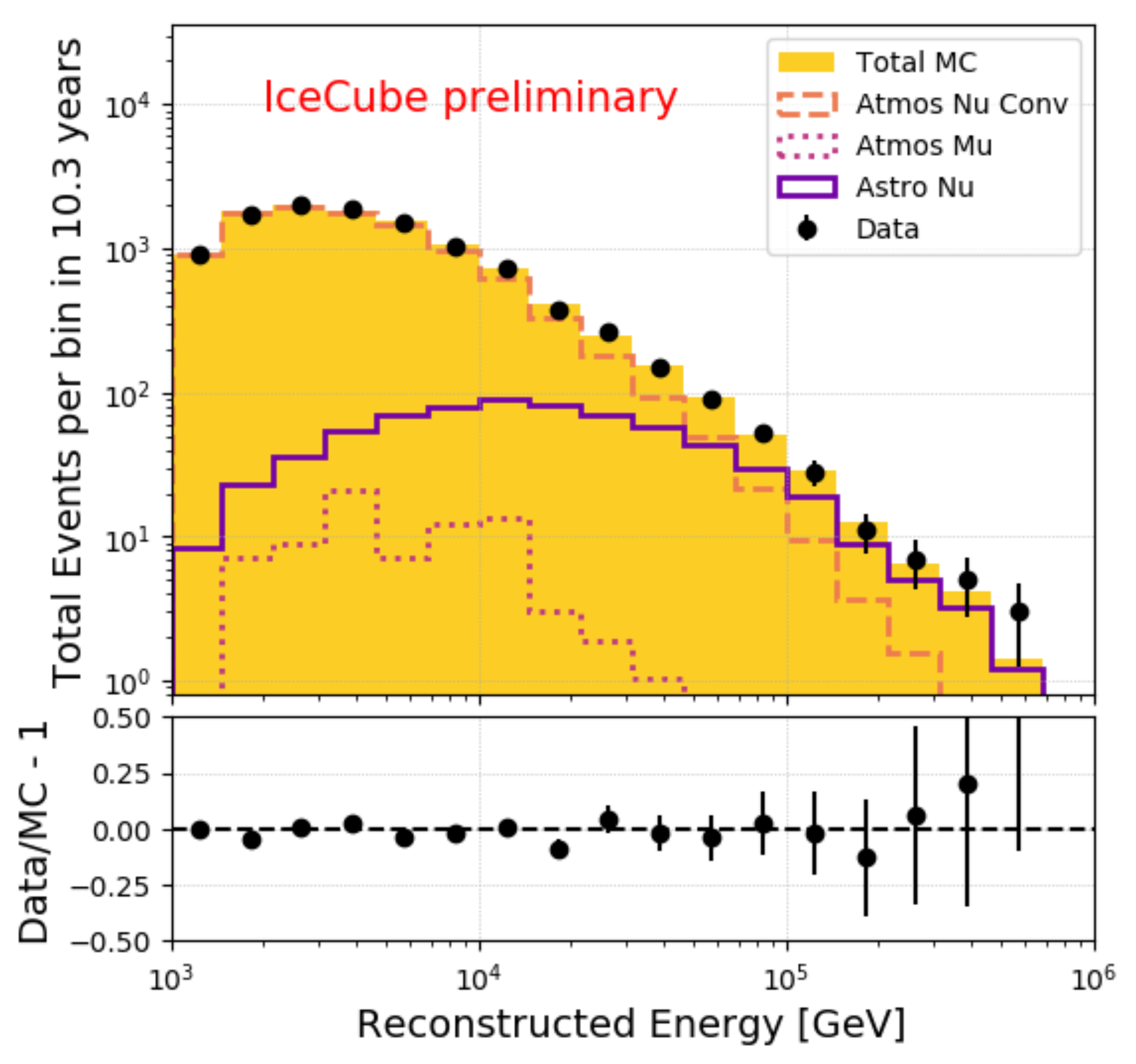


- In southern sky, event selection is capable of identifying and removing atmospheric neutrinos with an accompanying muon
- "Correction" to atmospheric neutrino flux is analytic calculation depending on the rejection probabilities of muons (eg step function at muon energy = 1 GeV)
- Threshold is free parameter in fit to data. Fit to data prefers ε_{SV} = 120 GeV.

MEASUREMENTS USING TEV ENERGY STARTING EVENTS

Starting Tracks 10 year

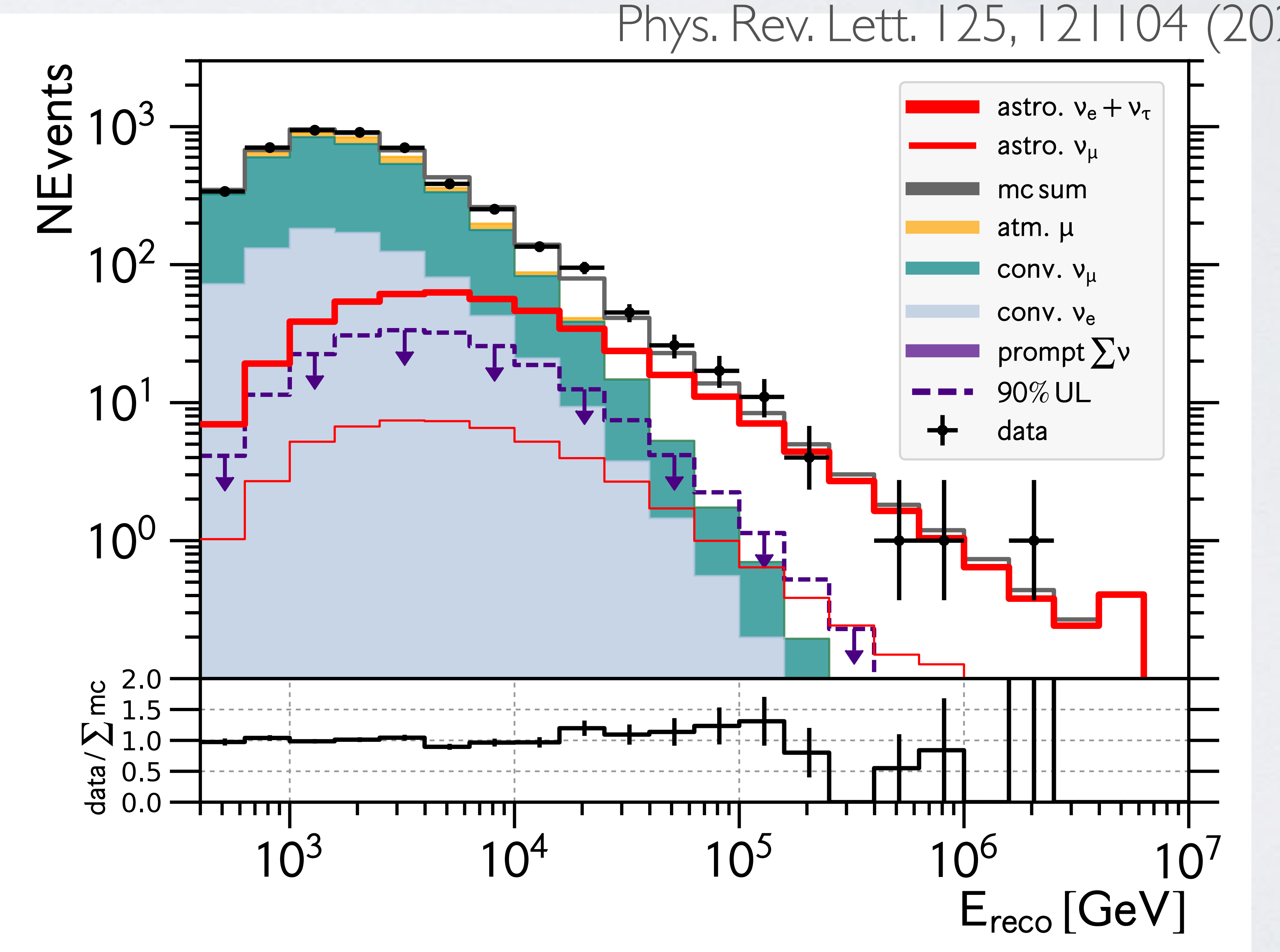
	θ < 80°	All Sky
Astro	**298**	**680**
Atmo conv	**980**	**10042**
Total ν	**1278**	**10722**



Starting Cascades 6 year

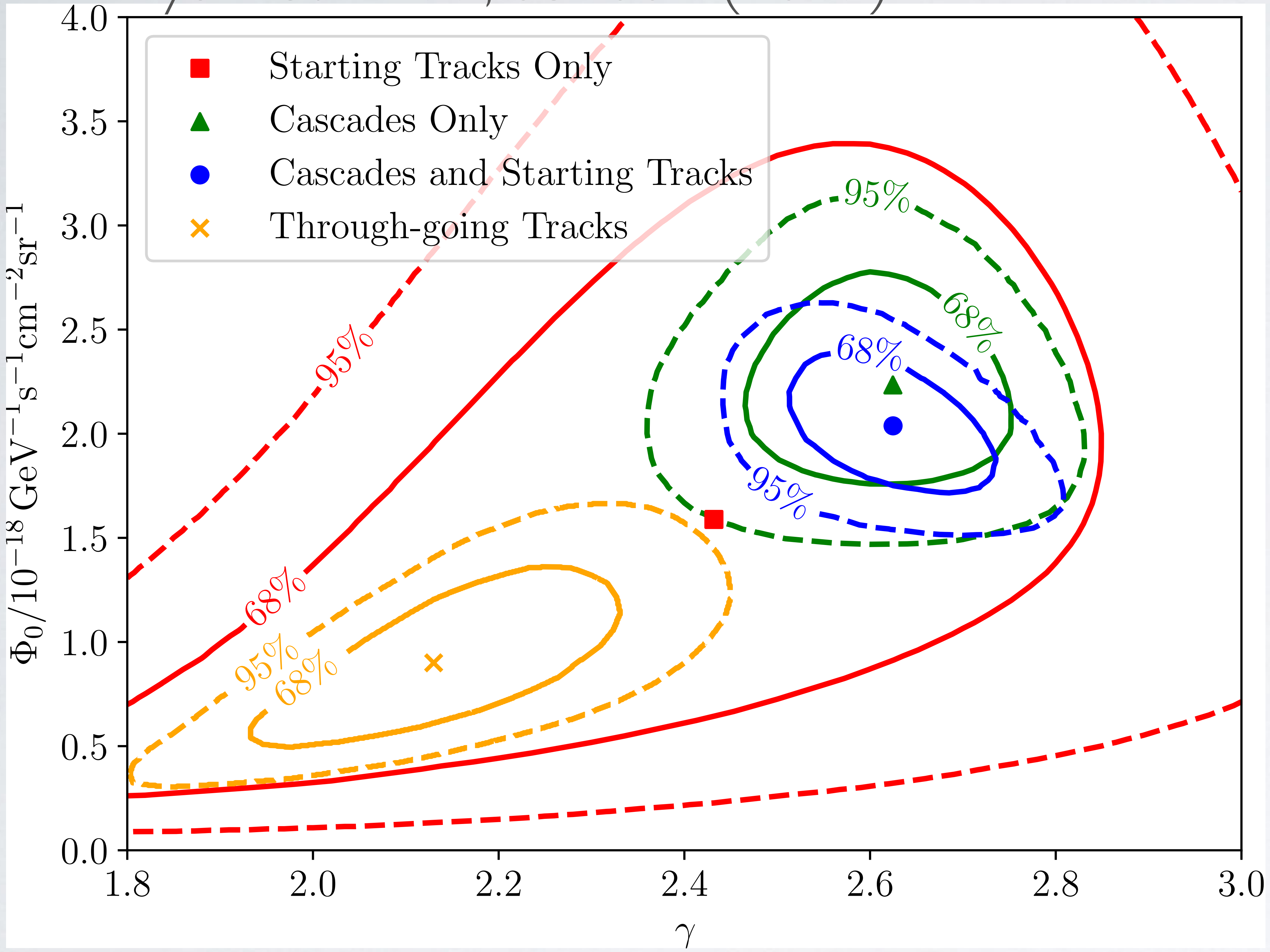
	All sky
Astro	**566**
Atmos conv	**3752**
Total ν	**4318**

Phys. Rev. Lett. 125, 121104 (2020)



STARTING TRACKS - 2019

Phys. Rev. D 99, 032004 (2019)



- Dedicated IceCube search for starting tracks observed 2650 tracks in 5 years of data.
- Very aggressive cuts at zenith > 0.2 reduce most IceCube sensitivity to astrophysical flux measurement (red line)