RWTH AACHEN IceCube

IceCube SOUTH POLE NEUTRINO OBSERVATORY

Observations of High-Energy Astrophysical Neutrino Fluxes with IceCube

Christopher Wiebusch

XX International Workshop on Neutrino Telescopes
23.–27. Oct. 2023

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Outline

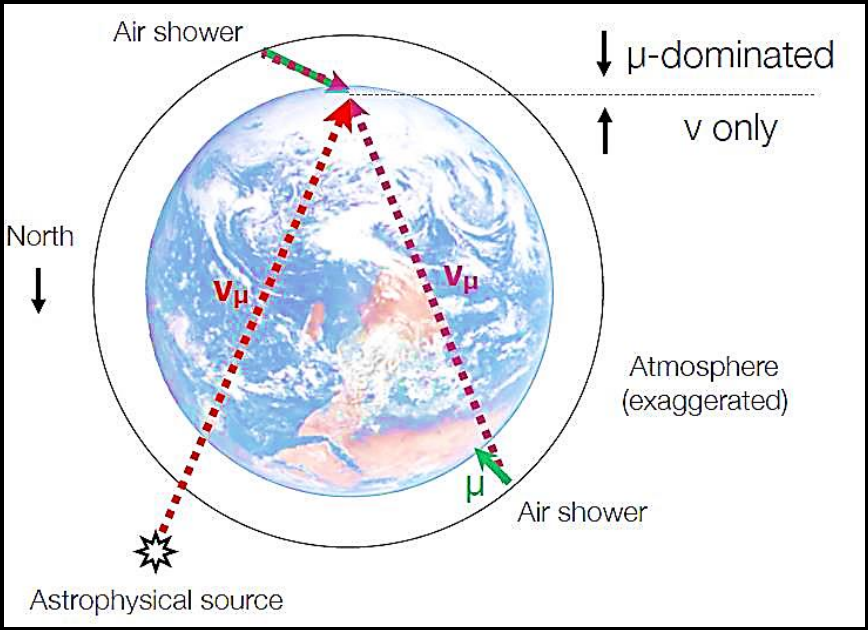
A. Observations of astrophysical neutrinos
   Updated recent results

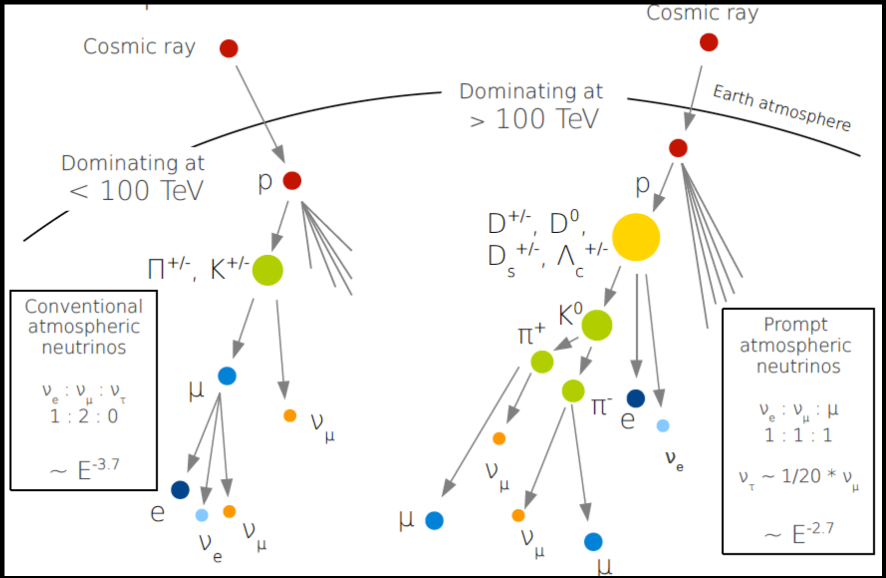
B. Galactic plane and implications

C. Combined fit – initial results

D. Discussion – Conclusions - Outlook

Atmospheric foregrounds to astrophysical neutrinos





Astrophysical neutrino signal

- Energy spectrum: $\boxed{\frac{d\phi}{dE} \propto E^{-2+x}}$
- ~100-200 /a

Cosmic ray induced muons

- High rate ~kHz
- Steep energy spectrum
- Enter dector from above

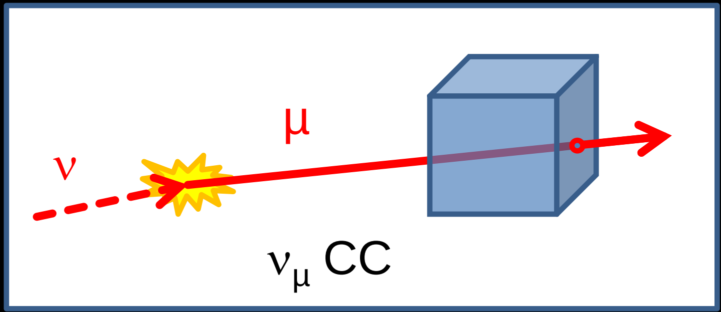
Conventional atmospheric neutrinos

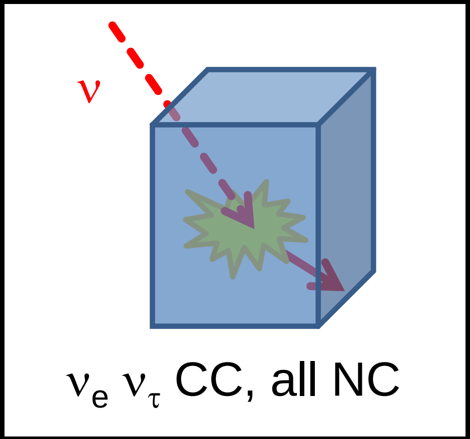
- Pion and kaon decays in the atmosphere
- Steep energy spectrum: $\boxed{\frac{d\phi}{dE} \propto E^{-3.7}}$
- 80,000/a

Prompt atmospheric neutrinos

- Heavy meson decays in the atmosphere (not measured yet)
- Energy spectrum: $\boxed{\frac{d\phi}{dE} \propto E^{-3.0}}$
- < 20/a

Neutrino detection channels: Tracks and Cascades





Tracks:

Uncontained events ⇒ **Large detection volume**

~ 10x > instrumented volume

~ 100-200 astrophysical events /year

Arrival time of photons ⇒ **direction & geometry**

$\Delta\psi$ ~ 0.3°

Number of registered photons ⇒ **energy-loss**

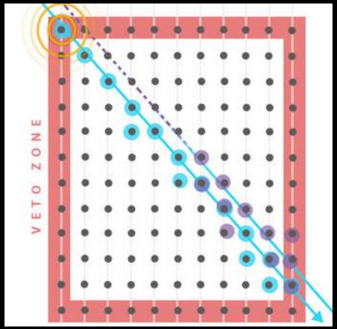
$\Delta E/E$ ~100% (events uncontained)

Cascades:

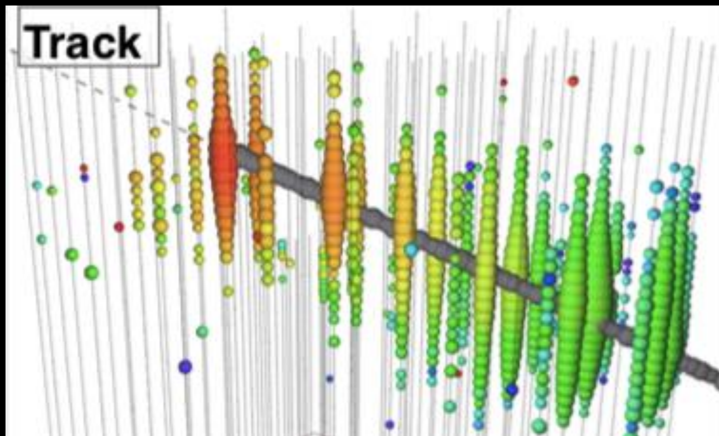
- Contained events
- Good energy resolution $\Delta E/E$ ~10%
- Smaller volume: 1 astro.ev /month
- angular resolution $\Delta\psi$ ~ 5° - 10°
- Smaller atmospheric background
- Self-veto: Largest signal above horizon

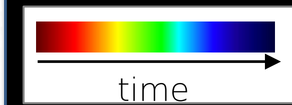
Hybrid channel: **High Energy Starting Events** (HESE)

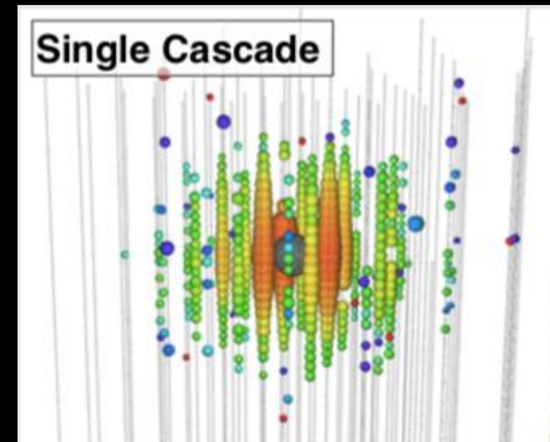
- Simple Veto from outer layers, background from experimental data
- All flavor: ν_e , ν_μ , ν_τ
- Variants: Starting tracks sample (**ESTES**), medium energy starting event (**MESE**)



Neutrino detection channels: Tracks and Cascades



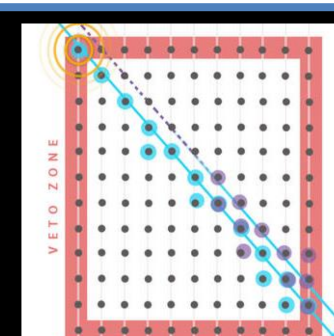




Tracks:
Uncontained events ⇒ **Large detection volume**
~ 10x > instrumented volume
~ 100-200 astrophysical events /year
Arrival time of photons ⇒ **direction & geometry**
$\Delta\psi$ ~ 0.3°
Number of registered photons ⇒ **energy-loss**
${}^{\Delta E}/_{E}$ ~100% (events uncontained)

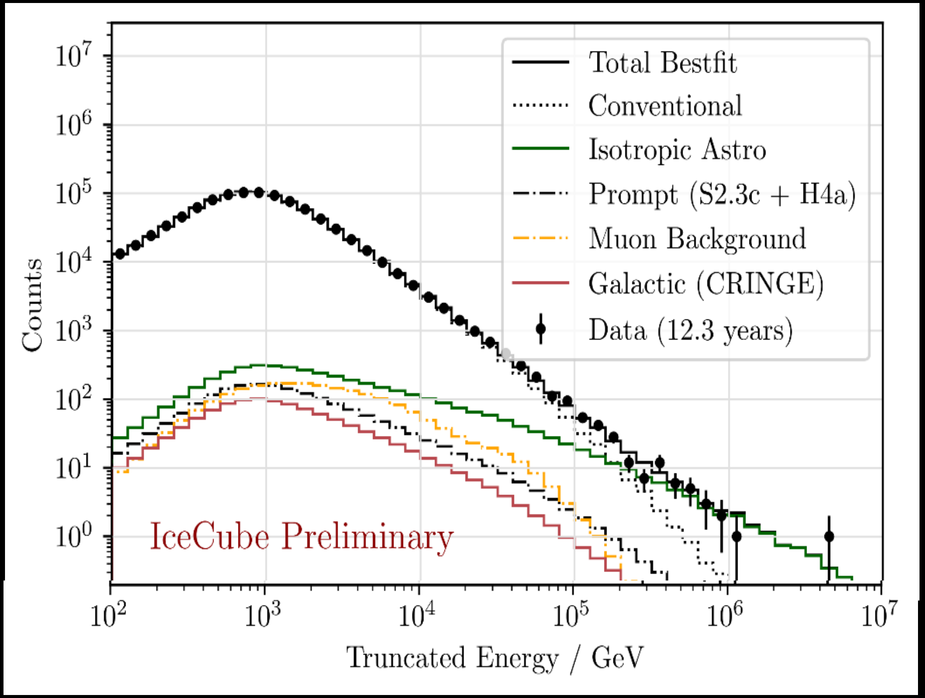
Cascades:
- Contained events
- Good energy resolution $\Delta E/E$ ~10%
- Smaller volume: 1 astro.ev /month
- angular resolution $\Delta\psi$ ~ 5° - 10°
- Smaller atmospheric background
- Self-veto: Largest signal above horizon

Hybrid channel: **High Energy Starting Events** (HESE)
- Simple Veto from outer layers, background from experimental data
- All flavor: ν_e, ν_μ, ν_τ
- Variants: Starting tracks sample (**ESTES**), medium energy starting event (**MESE**)



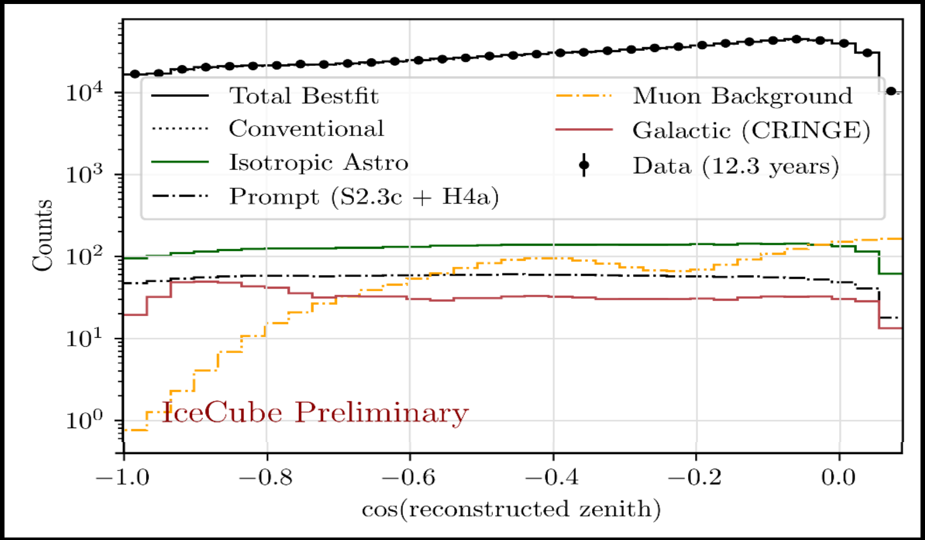
New Northern tracks result (ICRC 2023): 12.3 years

- 12.3 years
- 982,279 events
- Neutrino purity > 99.8%
- Northern Sky θ>85°
- 3d fit of energy, zenith, and azimuth Including
    - Isotropic Astro
    - Conventinal & Promt atmospheric
    - Galactic plane contribution
    - Muon background



Single Power-law fit

Bestfit	No galactic contribution
$\phi = 1.51 \pm^{0.22}_{0.23}$	$\phi = 1.61 \pm^{0.21}_{0.24}$ (+6.5%)
$\gamma = 2.38 \pm^{0.08}_{0.08}$	$\gamma = 2.40 \pm^{0.08}_{0.08}$



Isotropic distribution of excess events
$\Rightarrow$ Mostly extragalactic origin

Very similar to previous 9.5 year result
Astrophys. J. 928 (2022) 50, arXiv:2111.10299v1

New Starting Track result (ICRC 2023): ESTES

Starting track events with optimized muon veto for low energy

	Events
Astro Nu	**680**
Atmos Conv.	**10042**
Atmos Mu.	**75**
Total MC	**10797**
Data	**10798**

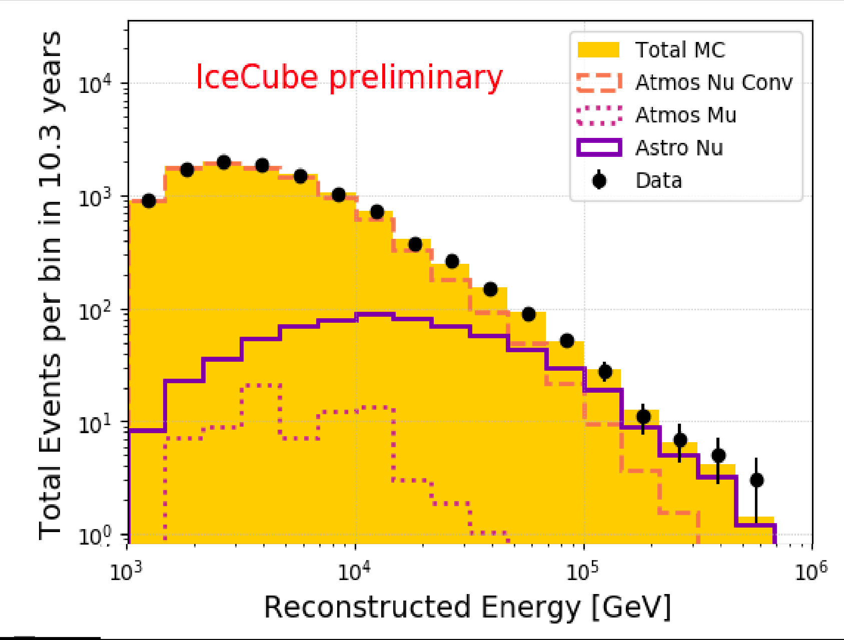
Single Power-law fit

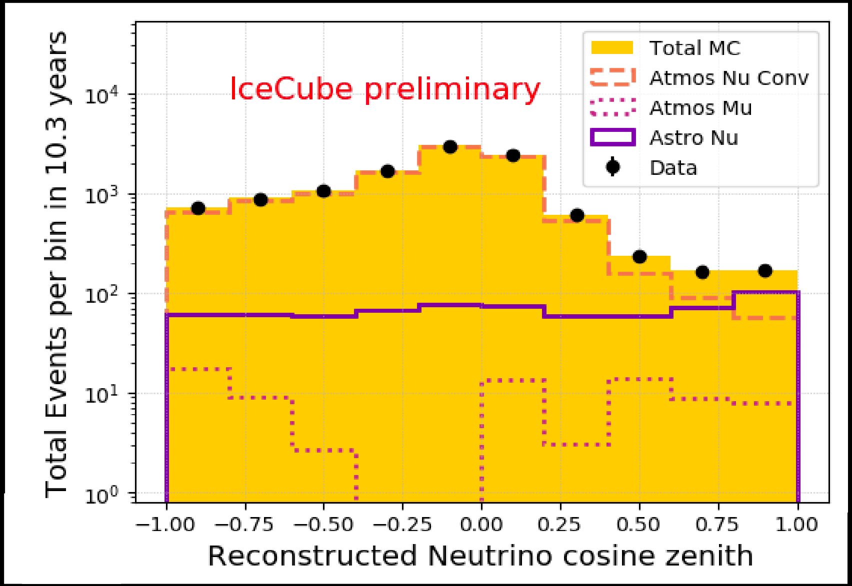
$$\Phi^{Total}_{Astro} = \phi^{\mathrm{per-flavor}}_{\mathrm{Astro}} \times (\frac{\mathrm{E}_\nu}{100\mathrm{TeV}})^{-\gamma} \times \mathrm{C}_0,$$

$$\mathrm{C}_0 = 3 \times 10^{-18} \times \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

where,

$$\phi^{\mathrm{per-flavor}}_{\mathrm{Astro}} = 1.68^{+0.19}_{-0.22}, \quad \gamma = 2.58^{+0.10}_{-0.09}$$

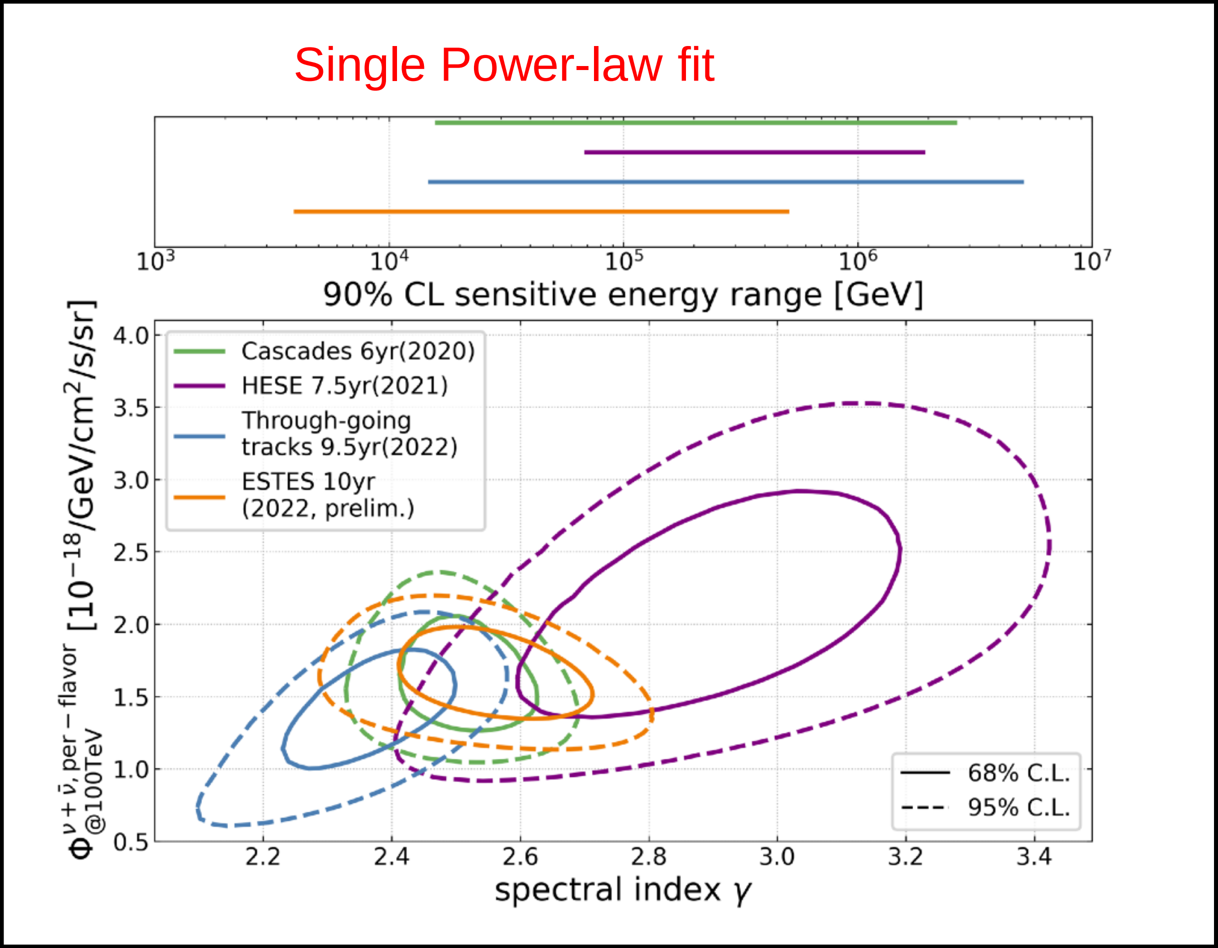




More results soon:
11 yr cascades
10 yr starting events (MESE)

Comparison of Observations and open questions

Differences in
- sensitive energy ranges
- angular acceptances
- backgrounds
- flavor composition
- systematic uncertainties



⇒ **Combined fit on an event-by-event basis**

⇒ **How about more complex spectra**

⇒ **Galactic versus extra-galactic**

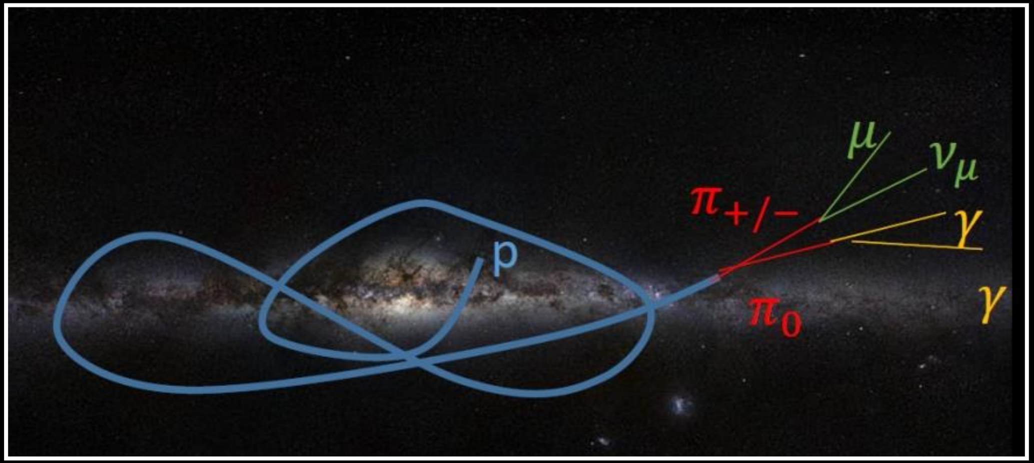
C. Characterisation of the cosmic neutrino flux

- Is there a Galactic contribution ?
- Are there ν_τ and what is the flavor composition ?
  $\Rightarrow$ Yes, well consistent with roughly 1:1:1,
  new result coming soon, see ICRC 2023 arXiv:2308.15213v1
- Are there Glashow-events at 6.3 PeV ?

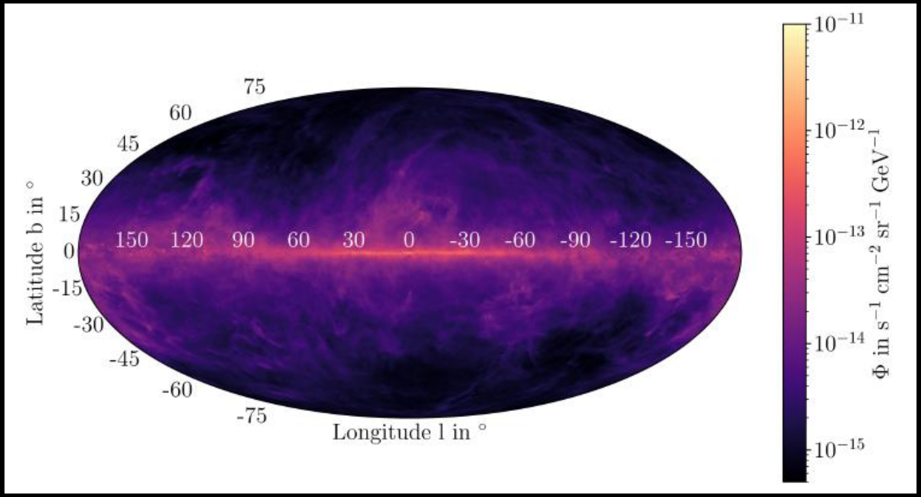
  $\Rightarrow$ Yes, see Nature 591, 220-224 (2021)
- Are there spectral features ?
- Is there a spectral cut-off ? – favored at the 2σ level
- Can we get a consistent picture?
- Observation of prompt atmospheric neutrinos from charmed meson decays ?

Neutrinos from our Galaxy

- unresolved sources
- CR interactions with the ISM



- Guaranteed flux of neutrinos in IceCube (~40/a expected)
- Template can be derived from gamma observations



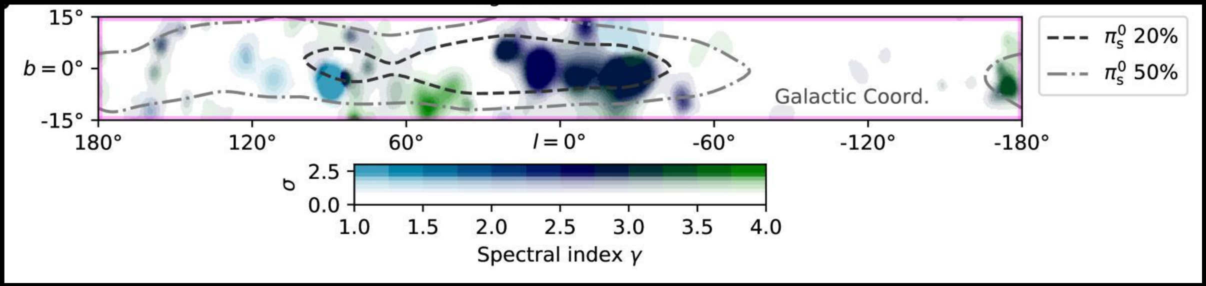
- Tomography of the CR injection & intensity throughout the Galaxy
- Bias on measured extra-galactic flux

Neutrino flux expectation based on Fermi π0 model from Fermi-LAT
$E\nu$ > 1TeV

Observation of Galactic Neutrinos with Cascades

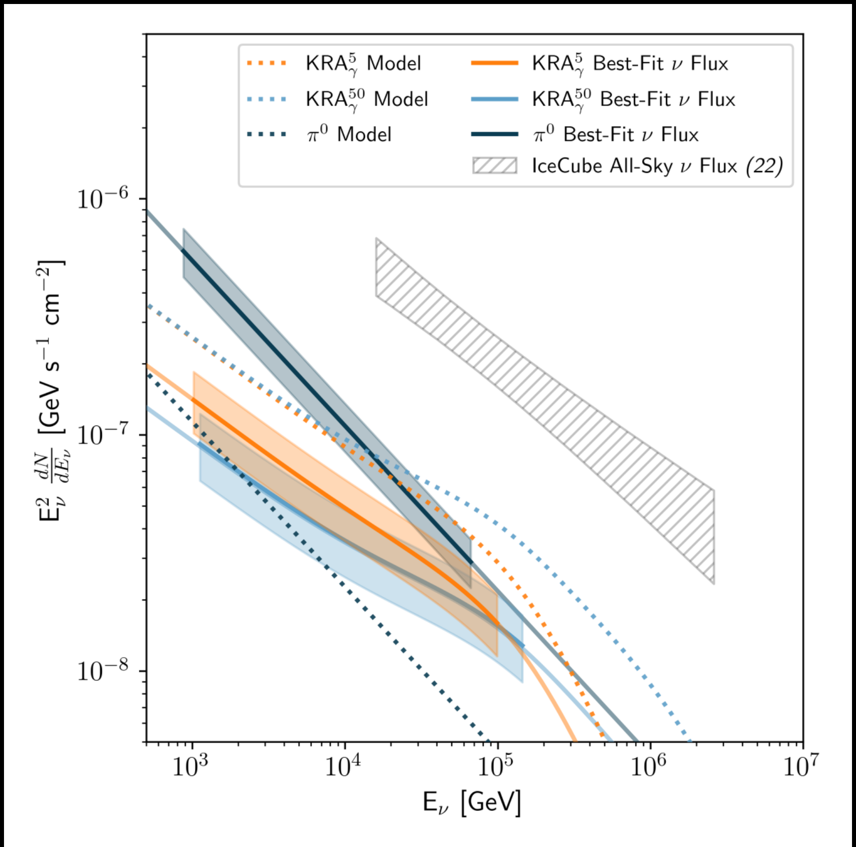
DNN selected cascade-like events

- 10yr data, 60,000 events
- All sky
- ML improved angular resolution
- Extended diffuse emission



Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA^5_γ	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA^{50}_γ	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	

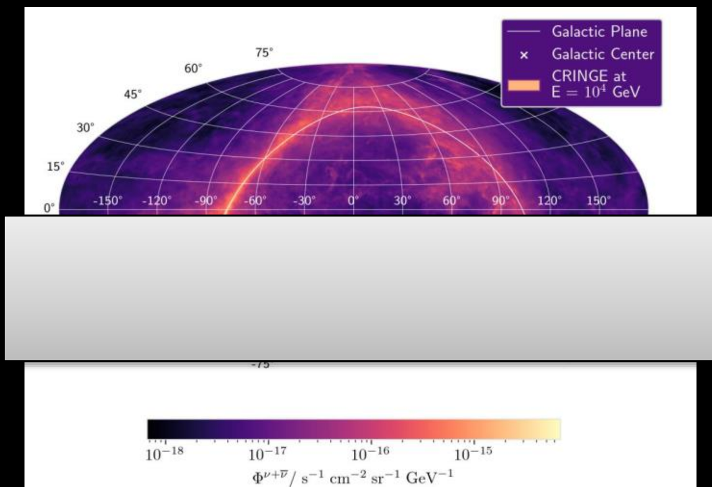
- Post-trial significance 4.5σ
- About 10% contribution to the total flux
- No ability to discriminate between different emission scenarios
  ⇒ Probably a combination of diffuse and unresolved source emission



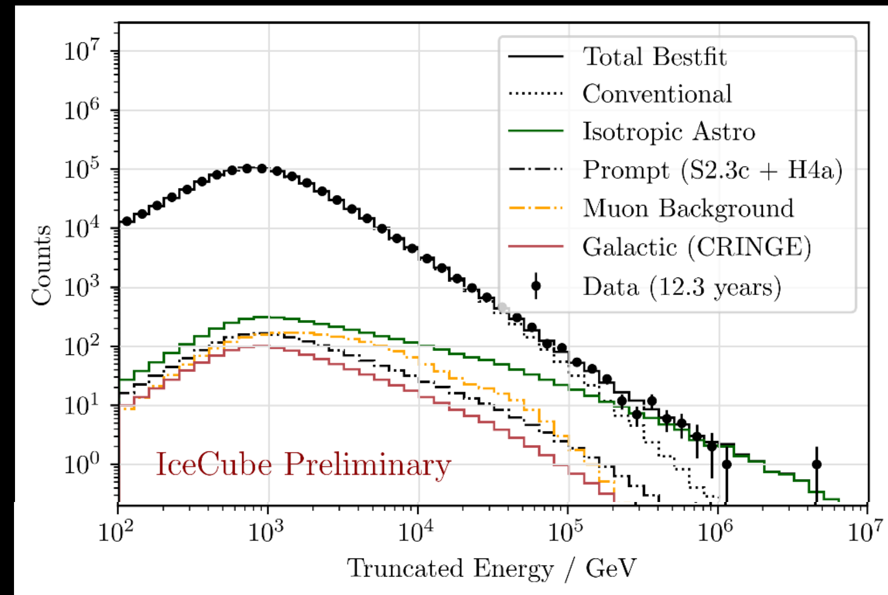
IceCubeCollaboration*†*Science* **380**,1338 1343(2023).DOI:10.1126/science.adc9818

Test the Galactic emission with Northern tracks (ICRC)

Expand 2d-fit (Zenith-Energy) to 3d fit (including Right Ascension)



CRINGE: *ApJ* 949, 16 (2023) arXiv:2211.15607



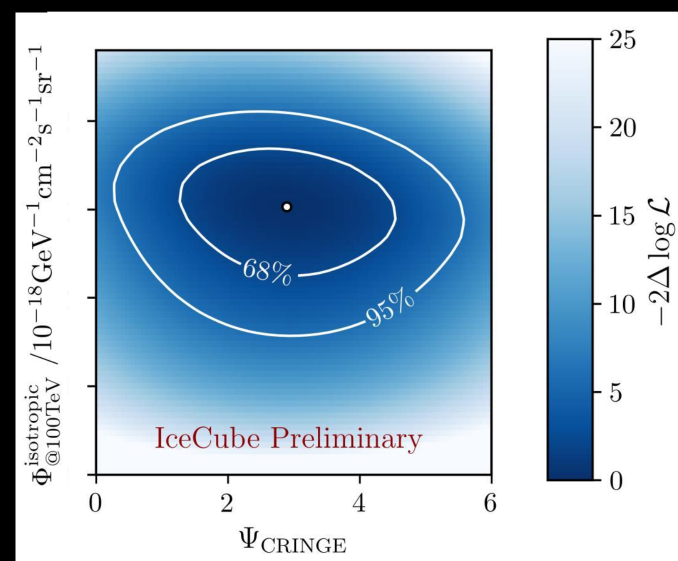
Data prefers non-zero galactic contribution (not yet significant)

Bestfit

- $\phi = 1.51 \pm^{0.22}_{0.23}$
- $\gamma = 2.38 \pm^{0.08}_{0.08}$
- $\Psi_{\mathrm{CRINGE}} = 2.9 \pm 1.1 \quad (2.7\sigma)$

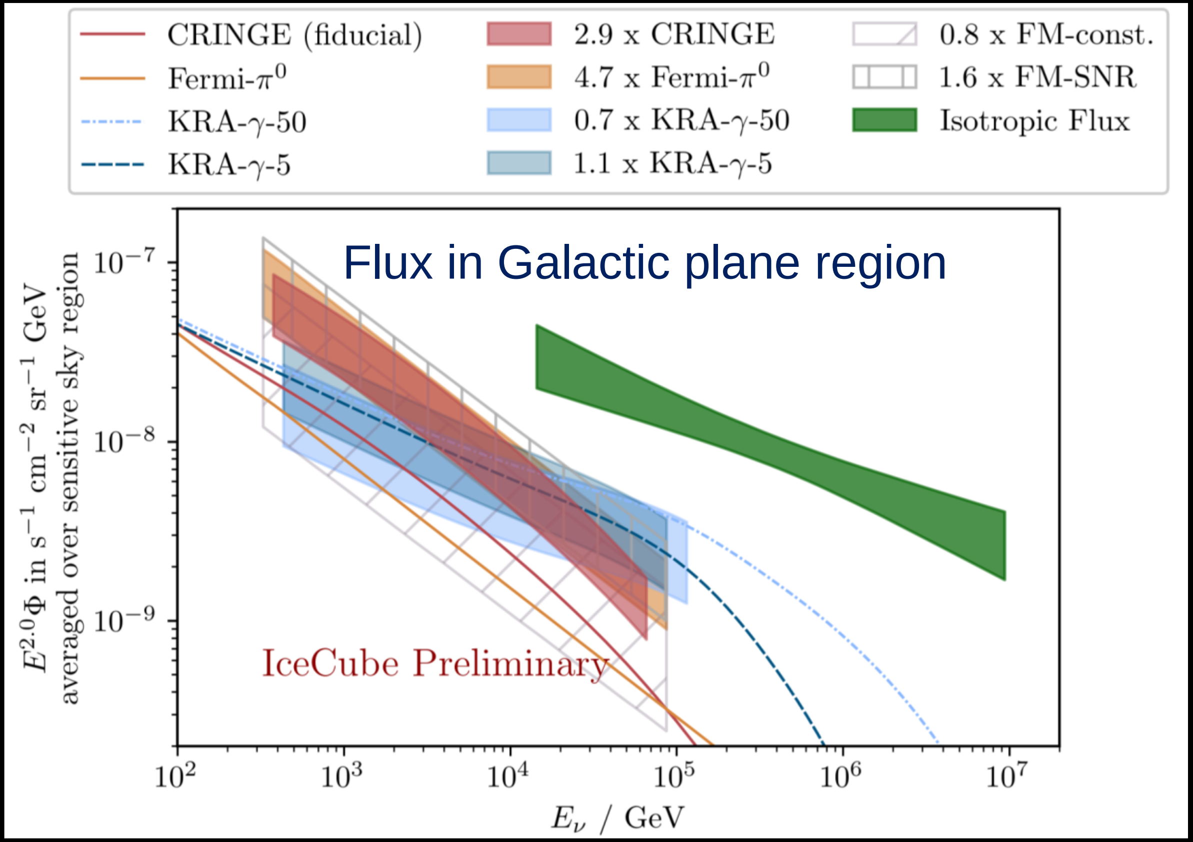
No galactic contribution

- $\phi = 1.61 \pm^{0.21}_{0.24}$ (+6.5%)
- $\gamma = 2.40 \pm^{0.08}_{0.08}$



Comparison Northern tracks with Cascades

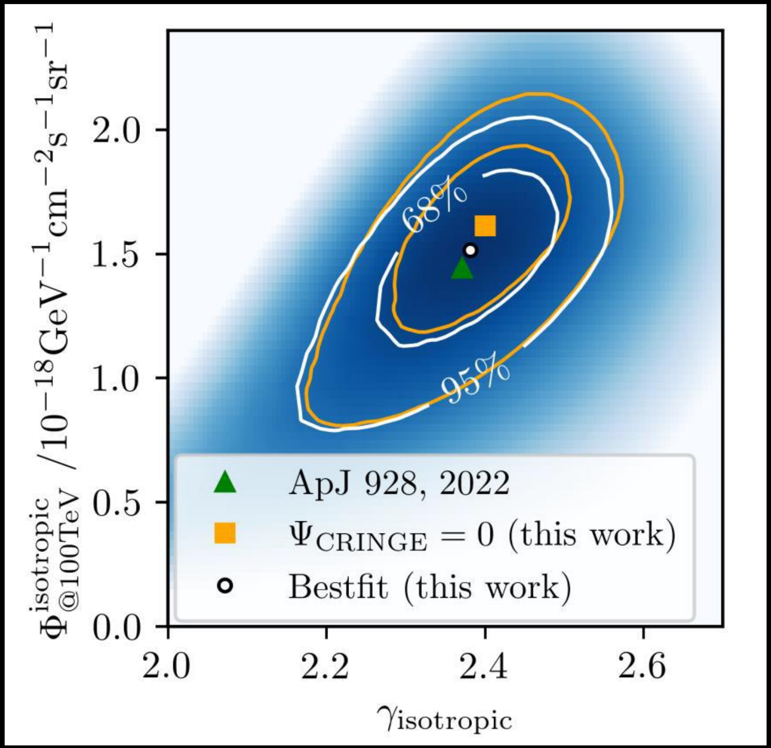
- CRINGE Model slightly preferred (2.7σ, 2.9x model)
- CRINGE/Fermi fits better than Kra-γ models (as cascades)
- Fitted flux norm. is consistent between tracks and cascades



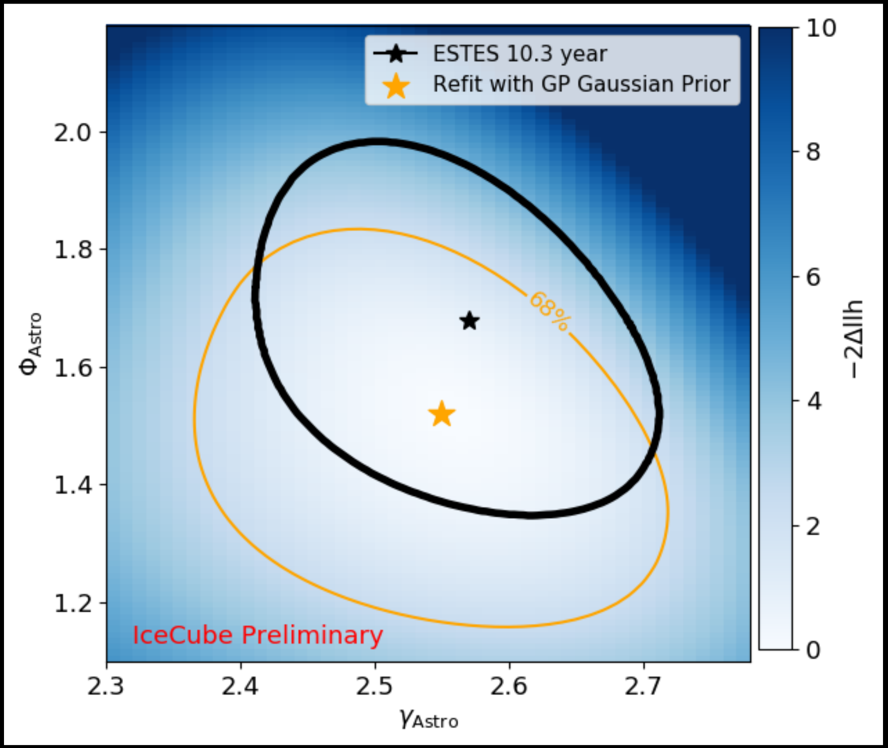
Model	Northern Tracks Model scale	DNNCascade (all-sky) Model scale
Fermi-π^0	4.7 +/-2.0 2.5 σ	5 +/-1.1
KRA-γ 50	0.7 +/-0.4 2.2 σ	0.37 +0.13/-0.11
KRA-γ 5	1.0 +/-0.5 2.4 σ	0.55 +0.18/-0.15

Effects of galactic neutrinos on the fit of the extragalactic flux

Northern Tracks



Enhanced Starting Tracks (ESTES)



Comparison

- 3d fit including galactic template (12.3 yr)
- Fit without galactic template (12.3yr)
- Previous 9.5 yr result (no galactic template)

Comparison

- Fit without Galactic component (default)
- Fit including a Galactic contribution fixed to the experimental cascade observation

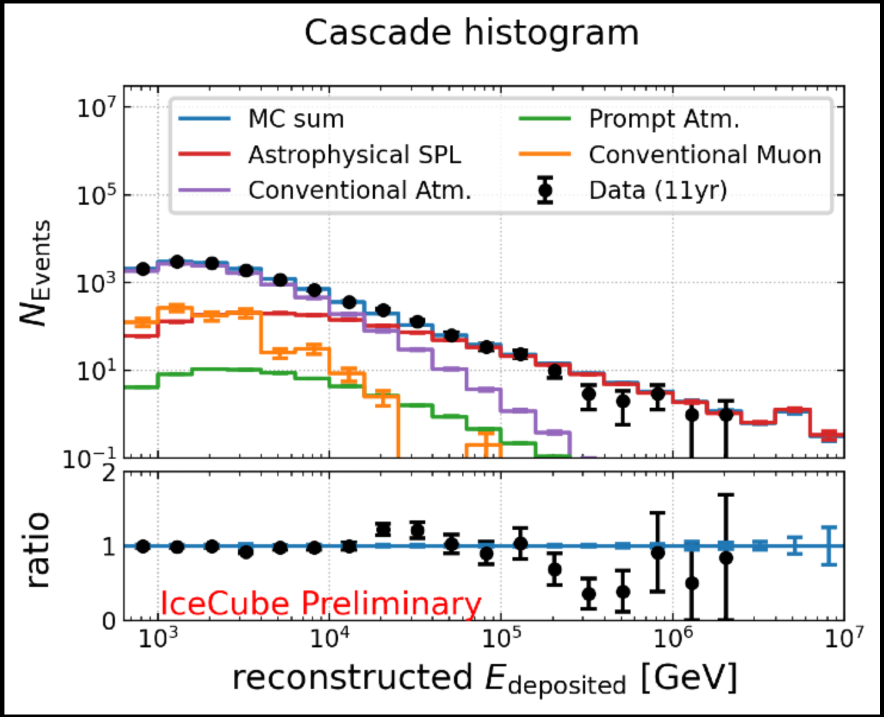
$\Rightarrow$ Fit of extra-galctic flux is very robust w.r.t. the Galactic contribution and mainly the flux changes by the expected 10%

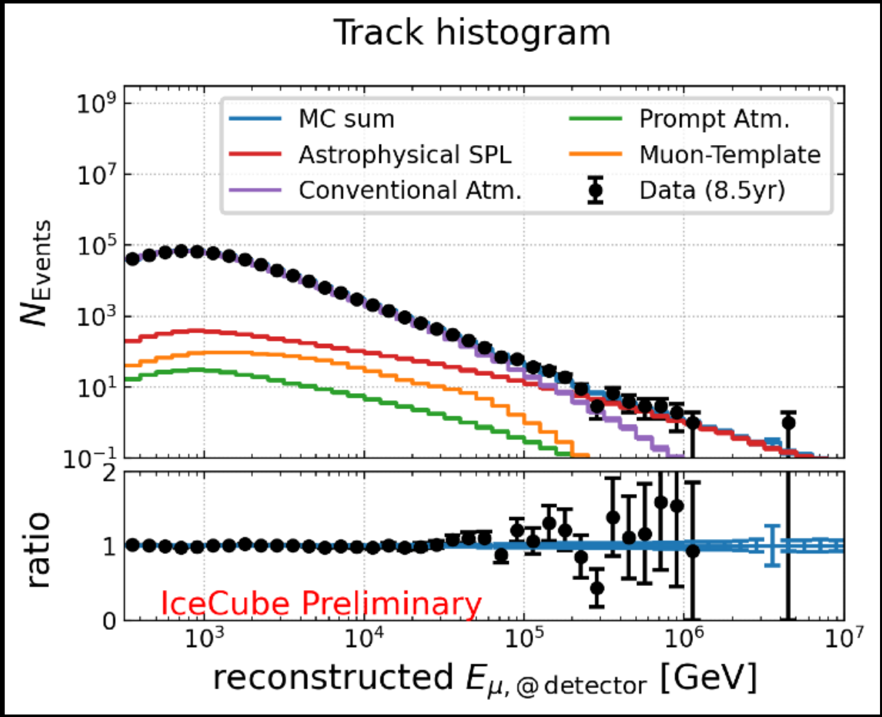
Combined fit of Tracks and Cascades (ICRC 2023)

$$\mathcal{L}_{\text{combined}} = \mathcal{L}_{\text{tracks}} \times \mathcal{L}_{\text{cascades}}$$

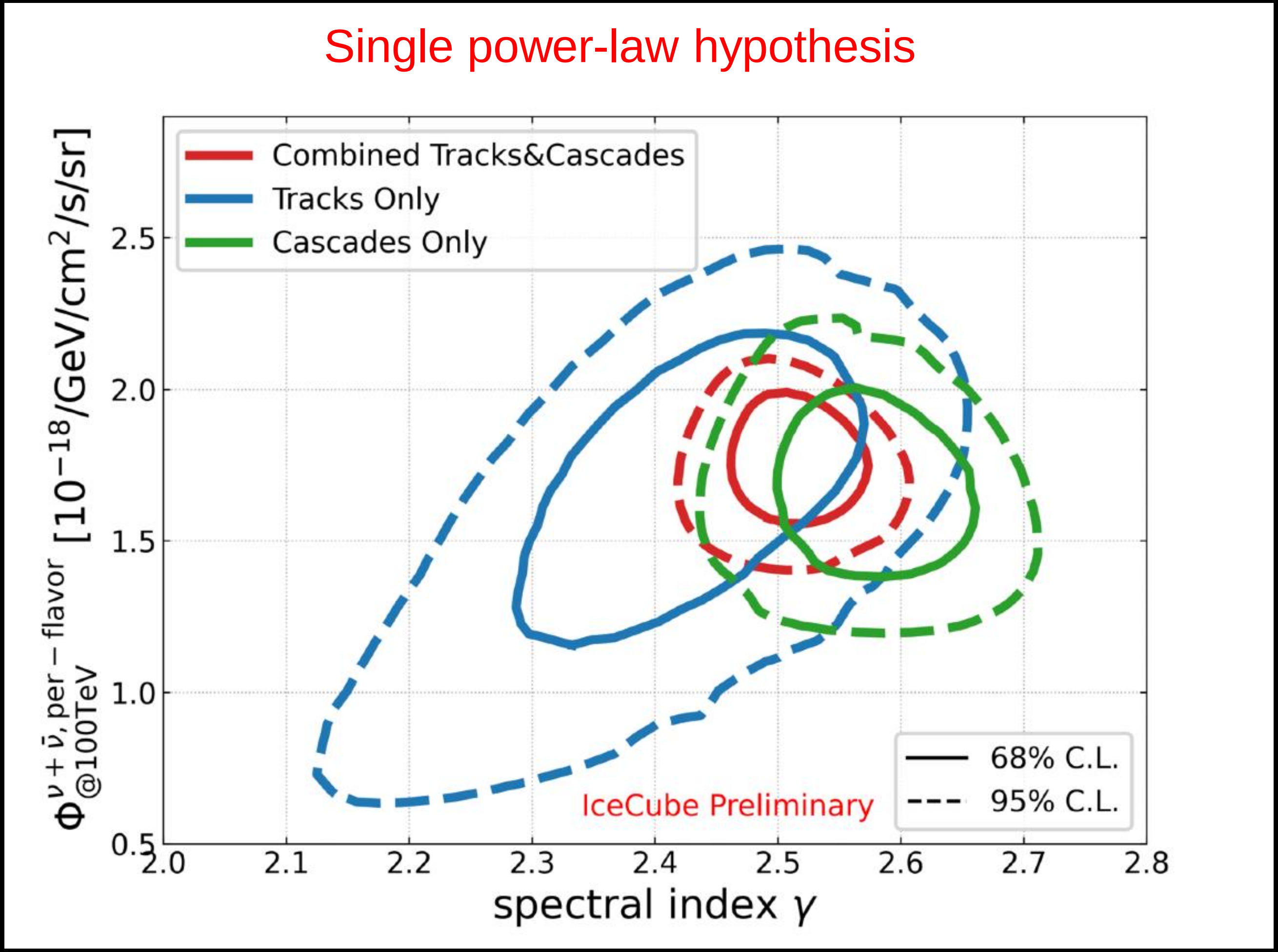
- Consistent treatment of systematic uncertainties
- Complete picture & probe structure in spectrum
- Northern tracks (8.5 years)
- Cascades (10.5 years)

Single power-law fit





Conturs of the combined Track-cascade fit



Strongly improved accuracy, but tension in energy spectrum between the two fits
…when a single power-law is assumed

Beyond the single Power-law (SPL)

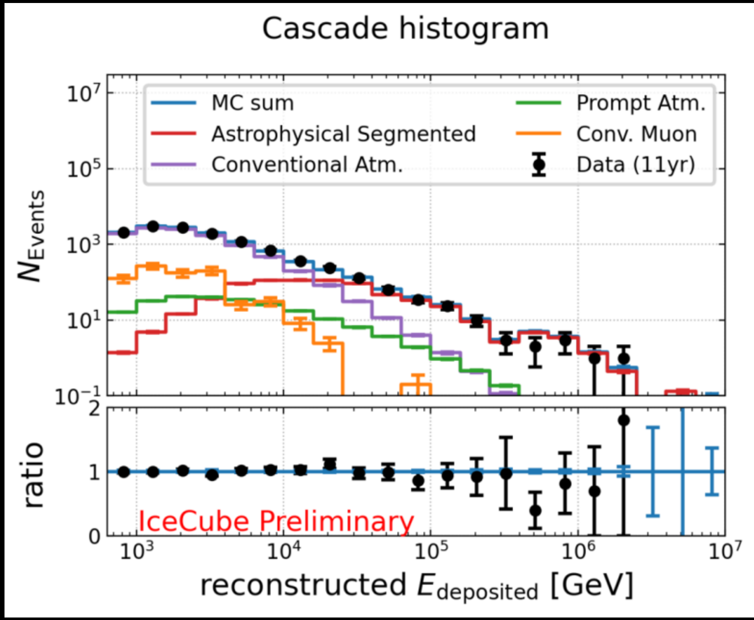
1. Log Parabola fit
2. Broken power-law (BPL)
3. Segmented Fit

Main results

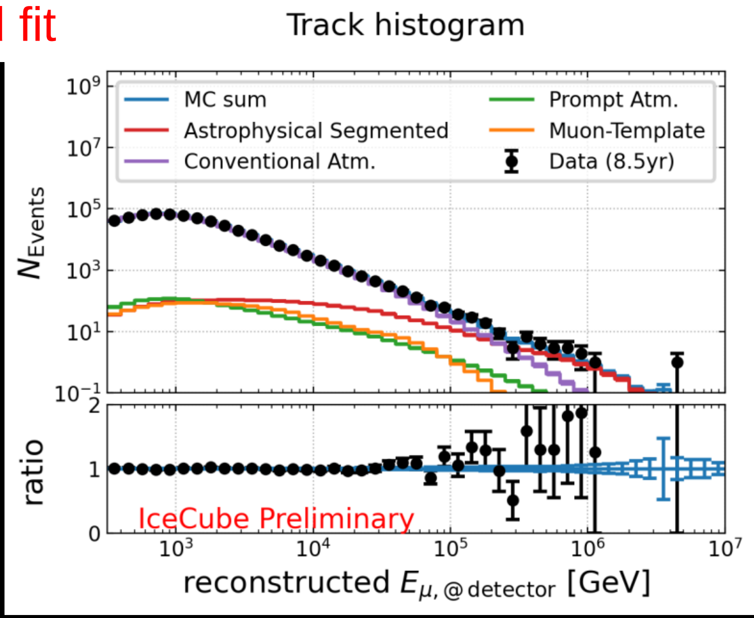
- All models are statistically preferred w.r.t the SPL at the >2-3 σ level
- The BPL model & segmented fit prefer a softening of the spectrum at around 30TeV
- tension between cascades and track

$\Rightarrow$ Work in progress

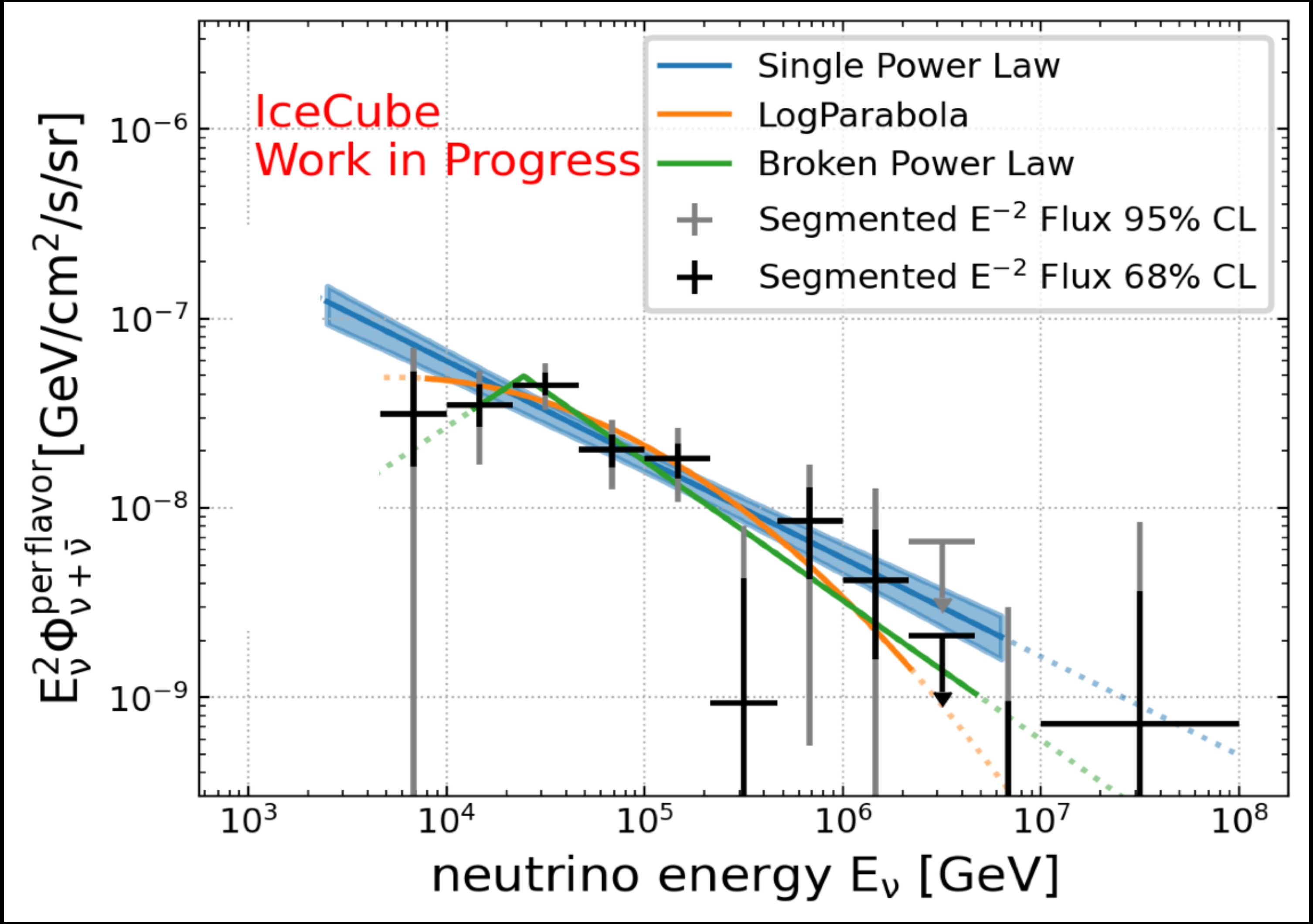
Astrophysical Model	Result	Energy Range (90% CL)	$-2\Delta\log\mathcal{L}$ over SPL
SPL	$\Phi^{\nu+\bar{\nu}}_{@100\mathrm{TeV}}/C = 1.80^{+0.13}_{-0.16}$ $\gamma = 2.52^{+0.04}_{-0.04}$	2.5 TeV to 6.3 PeV	-
LogP	$\Phi^{\nu+\bar{\nu}}_{@100\mathrm{TeV}}/C = 2.13^{+0.16}_{-0.19}$ $\alpha_{LP} = 2.57^{+0.06}_{-0.05}$ $\beta_{LP} = 0.23^{+0.10}_{-0.07}$	8.0 TeV to 2.2 PeV	16.4
BPL	$\Phi^{\nu+\bar{\nu}}_{@100\mathrm{TeV}}/C = 1.77^{+0.15}_{-0.11}$ $\log_{10}(E_{\mathrm{break}}/\mathrm{GeV}) = 4.39^{+0.09}_{-0.08}$ $\gamma_1 = 1.31^{+0.50}_{-1.21}$ $\gamma_2 = 2.74^{+0.06}_{-0.07}$	13.7 TeV to 4.7 PeV	24.7



Segmented fit



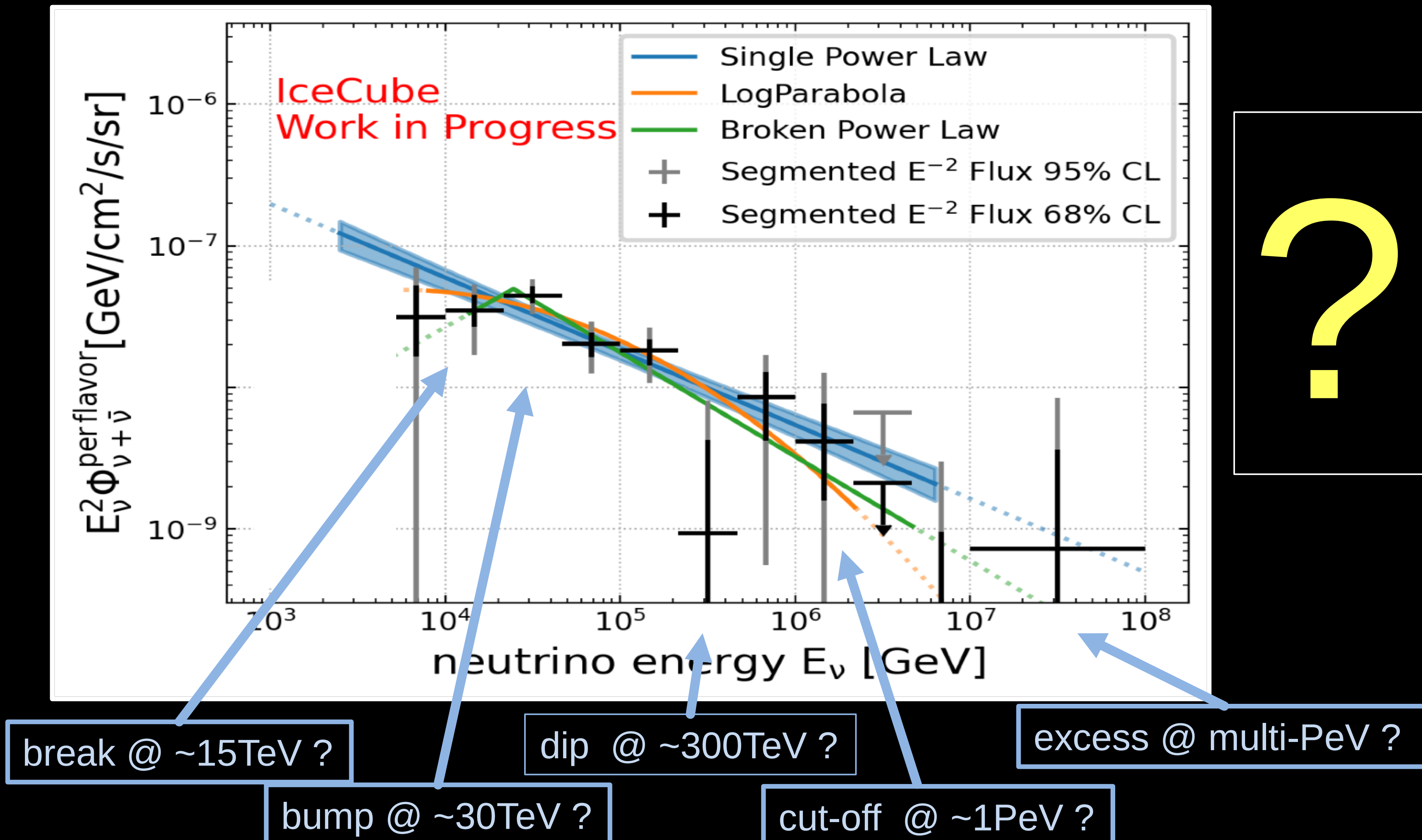
Summary of Combined fit of different hypotheses



Spectrum is still consistent with a single power-law
but more complex shapes provide a better fit on the 2σ level

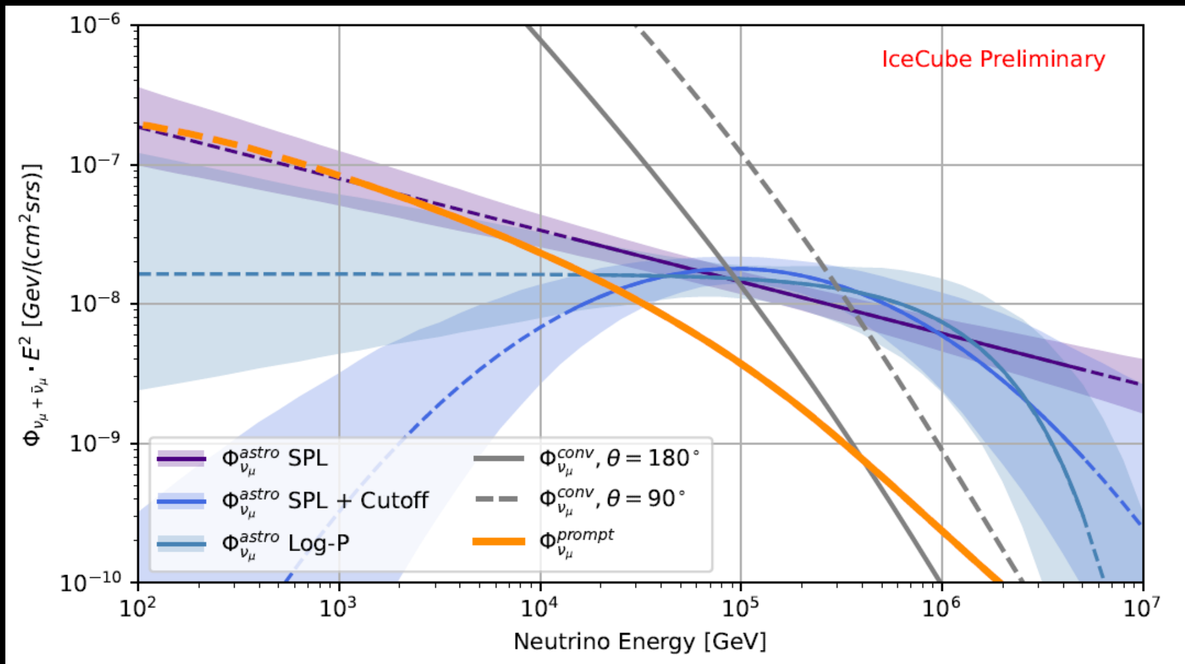
Summary of potential spectral anomalies

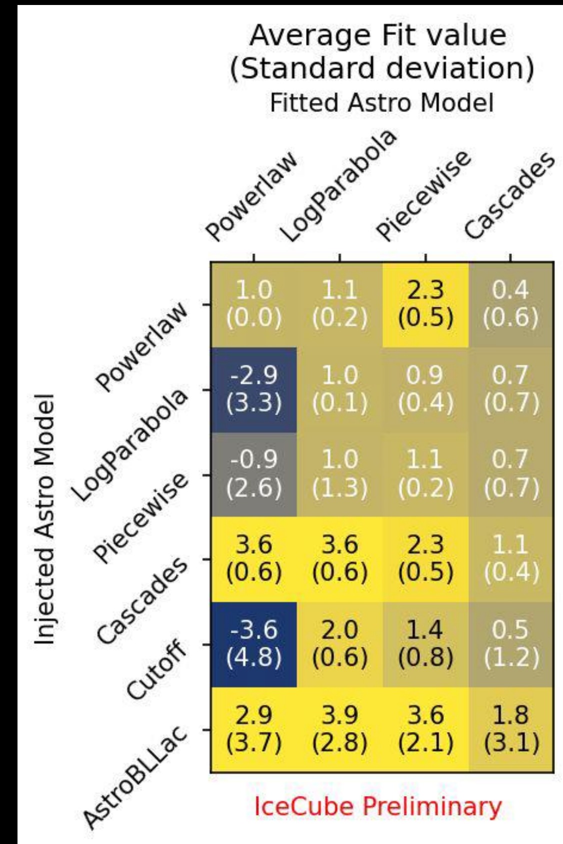
Spectrum is consistent with a single power-law
… but indications of potential features



The challenge of finding prompt neutrinos

ϕ_{prompt} Prediction: MCEq (Sybill 2.3c+H4a)





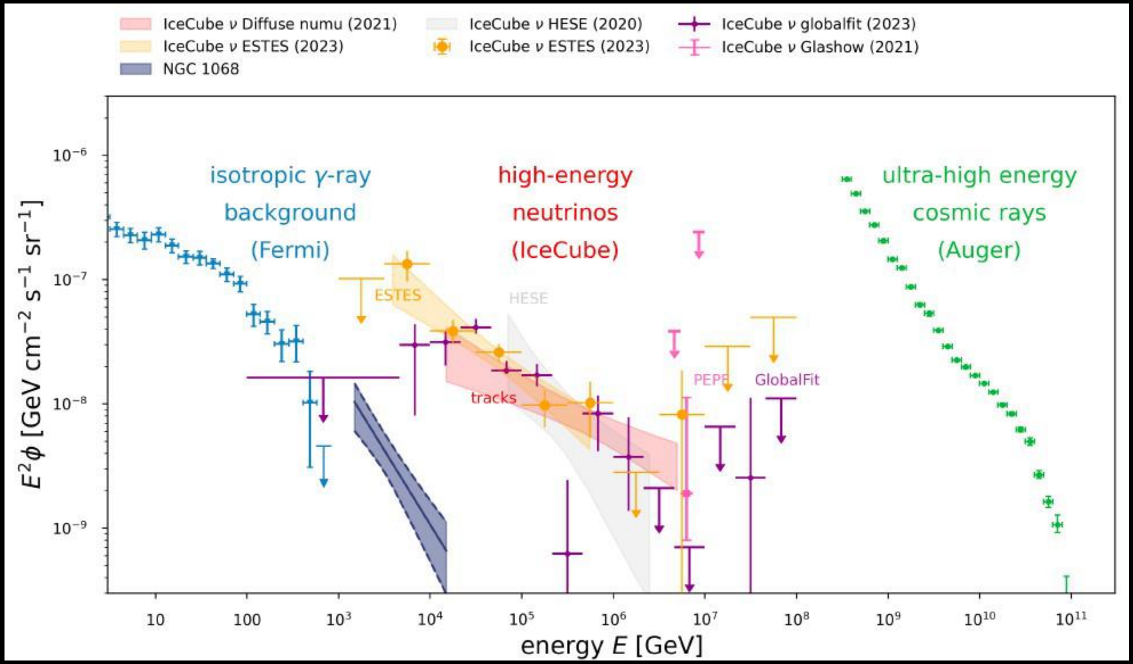
Careful determination of confidence
Conservative estimate results in
Sensitivity 1.5 (cascades) - 2.9 (power-law)
(model-prediction)

Likelihood scans (Asimov) experiments with injected astrophysical best fits and default ϕ_{prompt}
Expected fit result for ϕ_{prompt} (stand.dev.)

See POS (ICRC 2023) arXiv:2309.07560v1

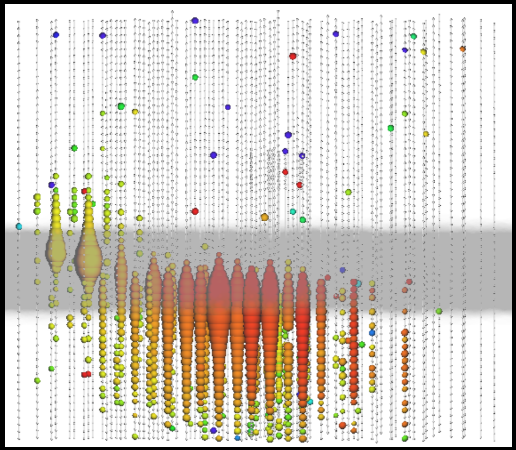
Summary and Outlook

- The observed astrophysical neutrino flux in IceCube originates from the Galaxy and from extra-galactic sources
- Both components can be well separated
- Analysing and combining different detection channels is a must and allows increasing understanding of the observed signal
- There are weak indications of features in the spectrum
- Several new results are work in progress (preliminary reports at ICRC 2023) and will be published soon



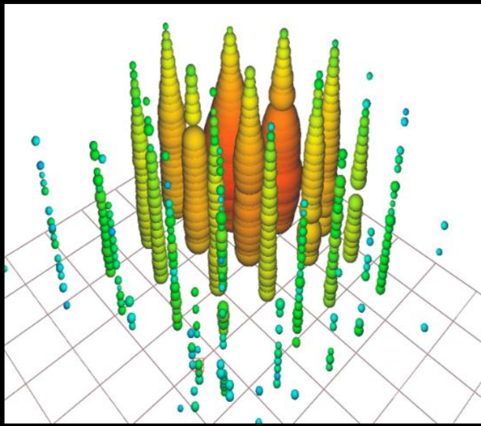
Multi-PeV events

1.) June 2014: High energy up-going muon



$E_{deposi}t = 2.6 \pm 0.3$ PeV
Muon energy 4.5 PeV (median)
Neutrino energy 8.7 PeV (median)
ATEL #7856, arXiv:1607.08006 [astro-ph.HE]

2.) Dec. 2016: Partially contained cascade



Glashow-event
⇒ 5.9 PeV eq. em. energy
⇒ 6.3 PeV hadr. energy

Nature 591, 220-224 (2021)

3.) Mar 2019: IceCube-20190331A
HESE-Track-Alert
199,000 p.e. ⇒ O(10PeV), not relased yet

ATel #12616, GCN 24028

4.) Dec. 2012: Big Bird,
HESE-Cascade 2 PeV

⇒ Despite of indications for a spectral cut-off at ~1PeV there are events far above the cut-off energy

Combined fit result in comparison to other results