Electron ν_e Muon ν_μ Tau ν_τ

UNFOLDING NEUTRINO FLUXES

From cosmic-ray air showers to the measured neutrino flux

IceCube Neutrino Observatory

LENE VAN ROOTSELAAR | ISCRA ERICE | AUG 2026

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Neutrino Astronomy

A NGC 1068

NASA, ESA & A. van der Hoeven

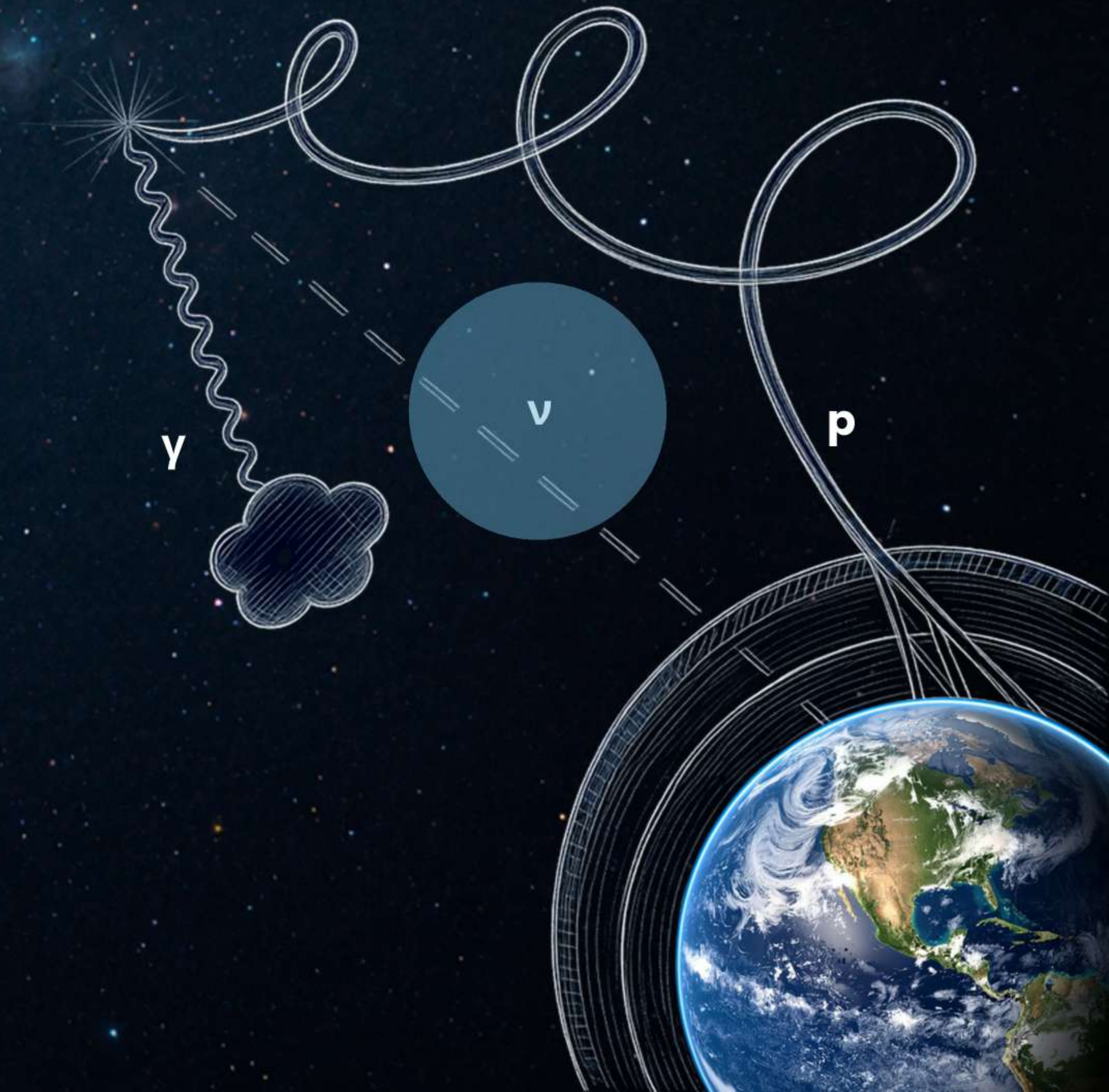
B TXS 0506+056

DESY, Science Communication Lab

C Milkyway

Neutrinos travel almost undeflected from their sources, making them unique messengers of the Universe.

Astrophysical neutrinos *probe the most energetic environments, such as* ***active galaxies*** *(A),* ***blazars*** *(B), and other cosmic accelerators (C). Detecting these neutrinos is a major goal of neutrino telescopes.*



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Neutrino Astronomy

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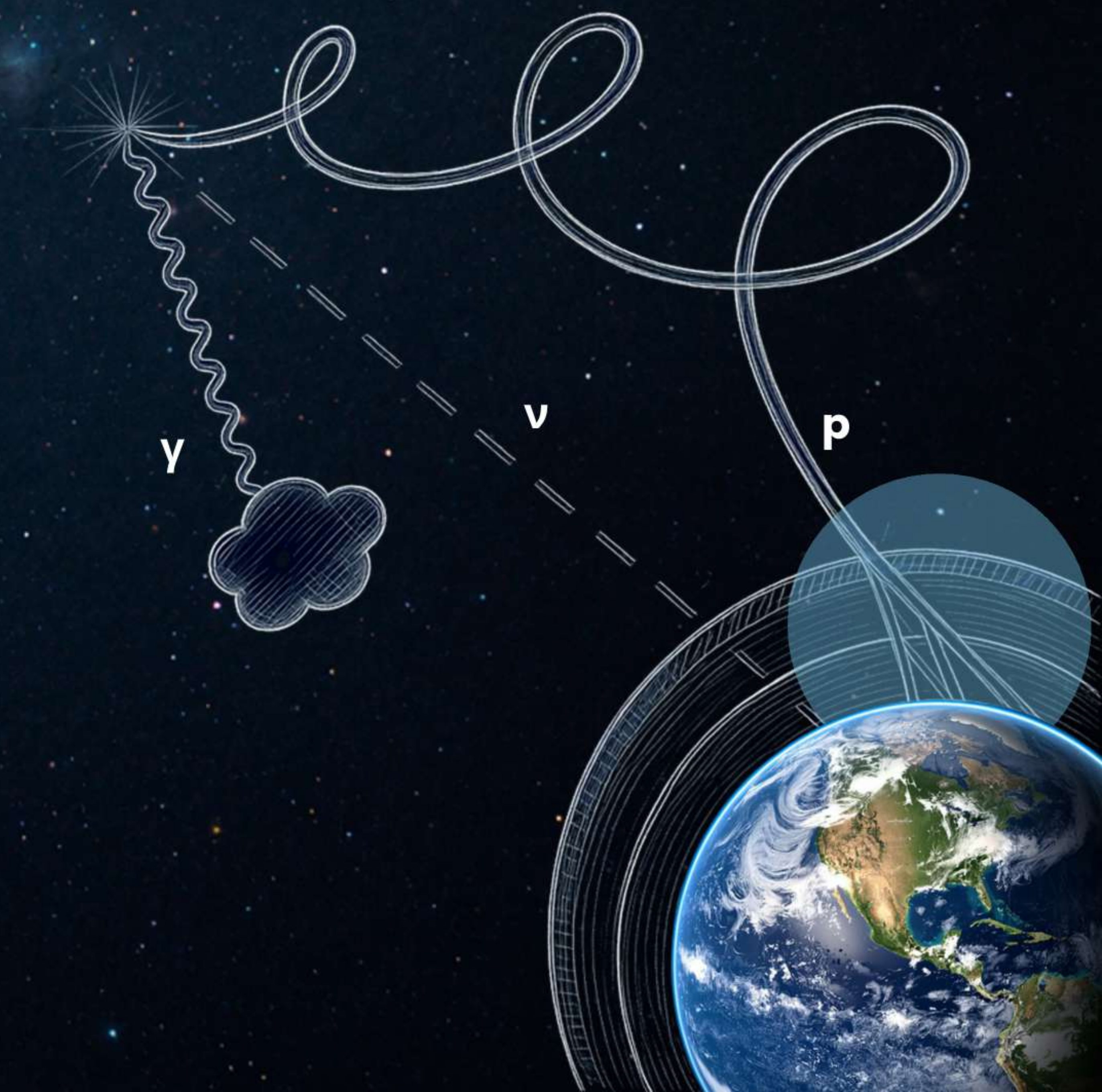
__Astrophysical neutrinos__ probe the most energetic environments, such as __active galaxies__ (A), __blazars__ (B), and other cosmic accelerators (C). Detecting these neutrinos is a major goal of neutrino telescopes.

Cosmic rays interacting with Earth's atmosphere produce extensive air showers, creating atmospheric neutrinos.
These __atmospheric neutrinos__ form the dominant background in searches for astrophysical neutrinos.



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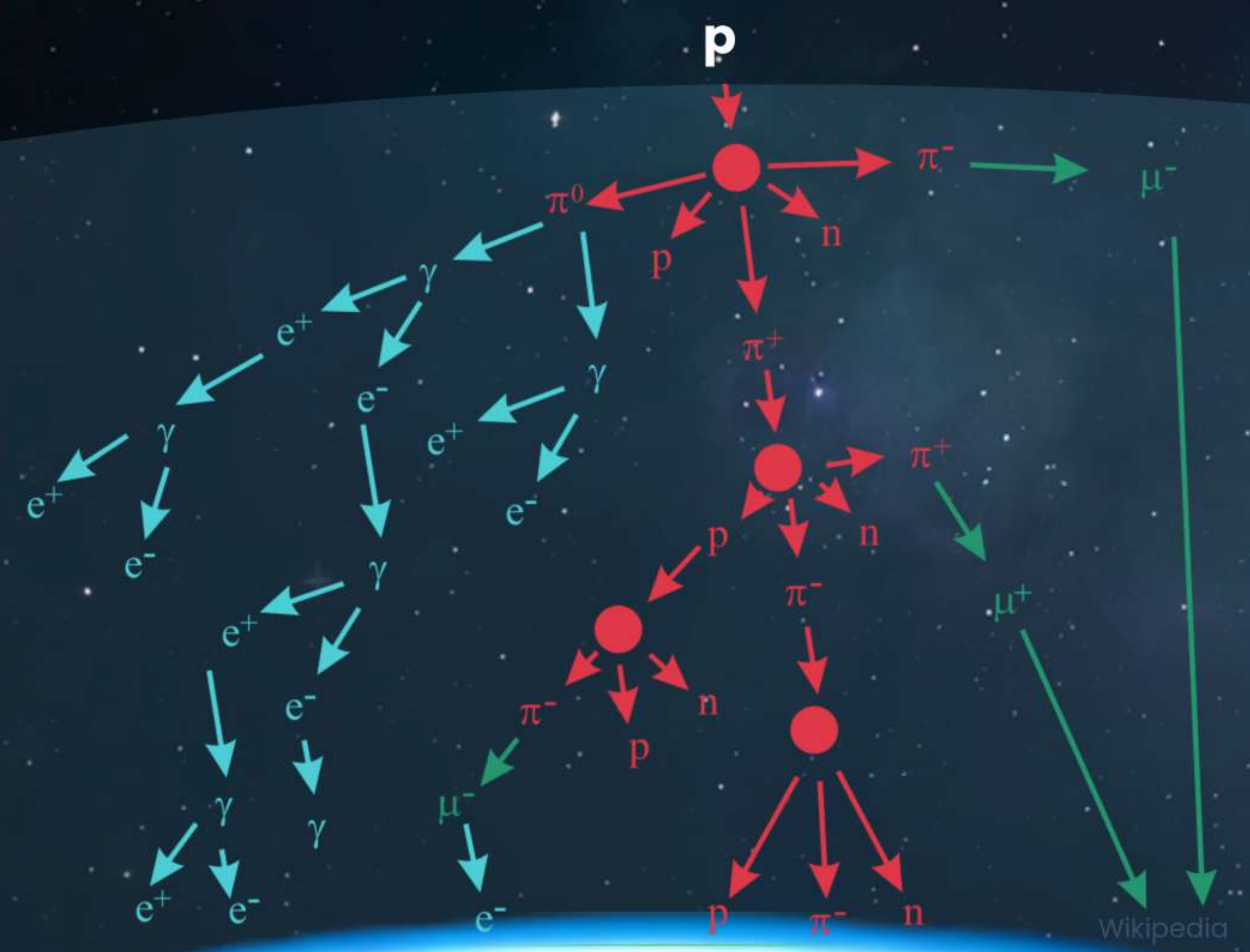
Air Showers



Primary cosmic rays collide with atmospheric nuclei.

These interactions produce

- ***pions***
- ***kaons***
- ***charmed hadrons***

These particles can decay into neutrinos

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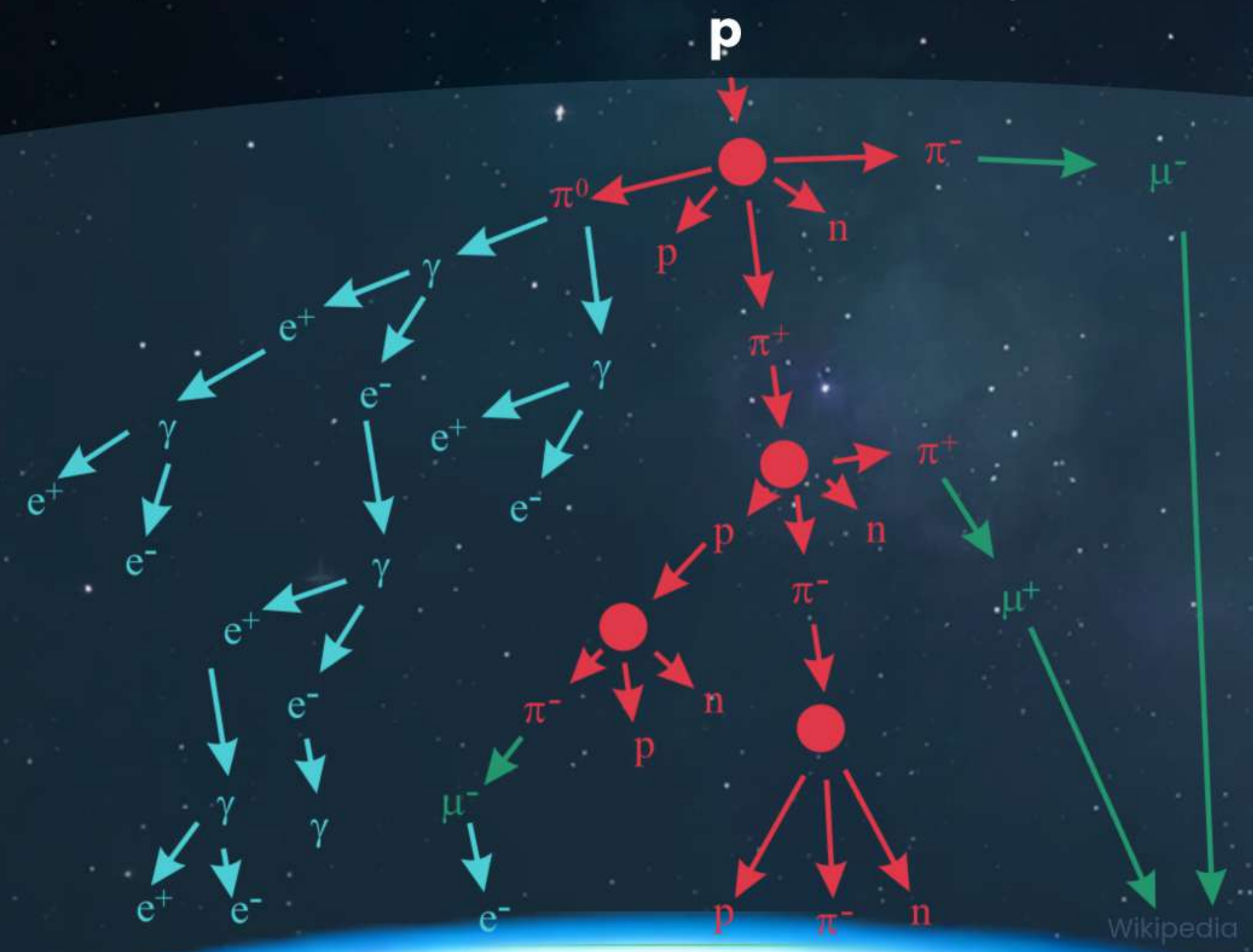
Air Showers



Primary cosmic rays collide with atmospheric nuclei.

These interactions produce

- ***pions***

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \qquad + \ldots$$

$$\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

- ***kaons***

$$K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \quad + \quad \begin{matrix} K^\pm \to \pi^0 + e^\pm + \nu_e(\bar{\nu}_e) \\ K^\pm \to \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \end{matrix} \quad + \ldots$$

- ***charmed hadrons***

$$D^\pm \to X\,\ell^\pm + \nu_\ell(\bar{\nu}_\ell) \quad + \quad D^0(\bar{D}^0) \to K^\mp \ell^\pm + \nu_\ell(\bar{\nu}_\ell) \quad + \ldots$$

These particles can decay into neutrinos

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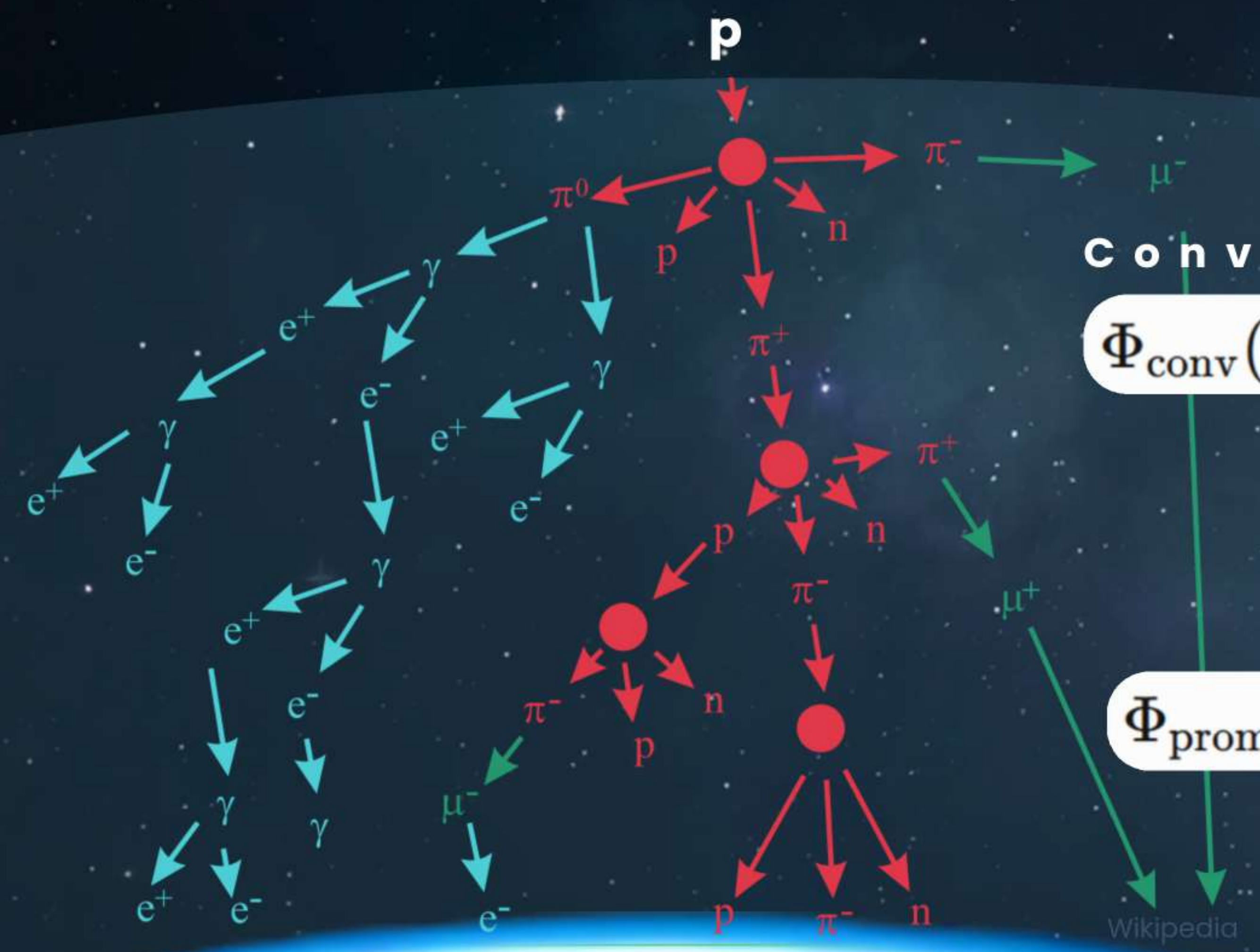
Air Showers



Primary cosmic rays collide with atmospheric nuclei.

These interactions produce

Conventional

$$\Phi_{\text{conv}}(E) \propto E^{-3.7}$$

- ***pions***

$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \quad + \ldots$$

$$\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$

- ***kaons***

$$K^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \quad + \quad \begin{matrix} K^\pm \to \pi^0 + e^\pm + \nu_e(\bar{\nu}_e) \\ K^\pm \to \pi^0 + \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \end{matrix} \quad + \ldots$$

Prompt

$$\Phi_{\text{prompt}}(E) \propto E^{-2.7}$$

- ***charmed hadrons***

$$D^\pm \to X\,\ell^\pm + \nu_\ell(\bar{\nu}_\ell) \quad + \quad D^0(\bar{D}^0) \to K^\mp \ell^\pm + \nu_\ell(\bar{\nu}_\ell) \quad + \ldots$$

These particles can decay into neutrinos

Electron ν_e Muon ν_μ Tau ν_τ

Atmospheric Neutrino Fluxes

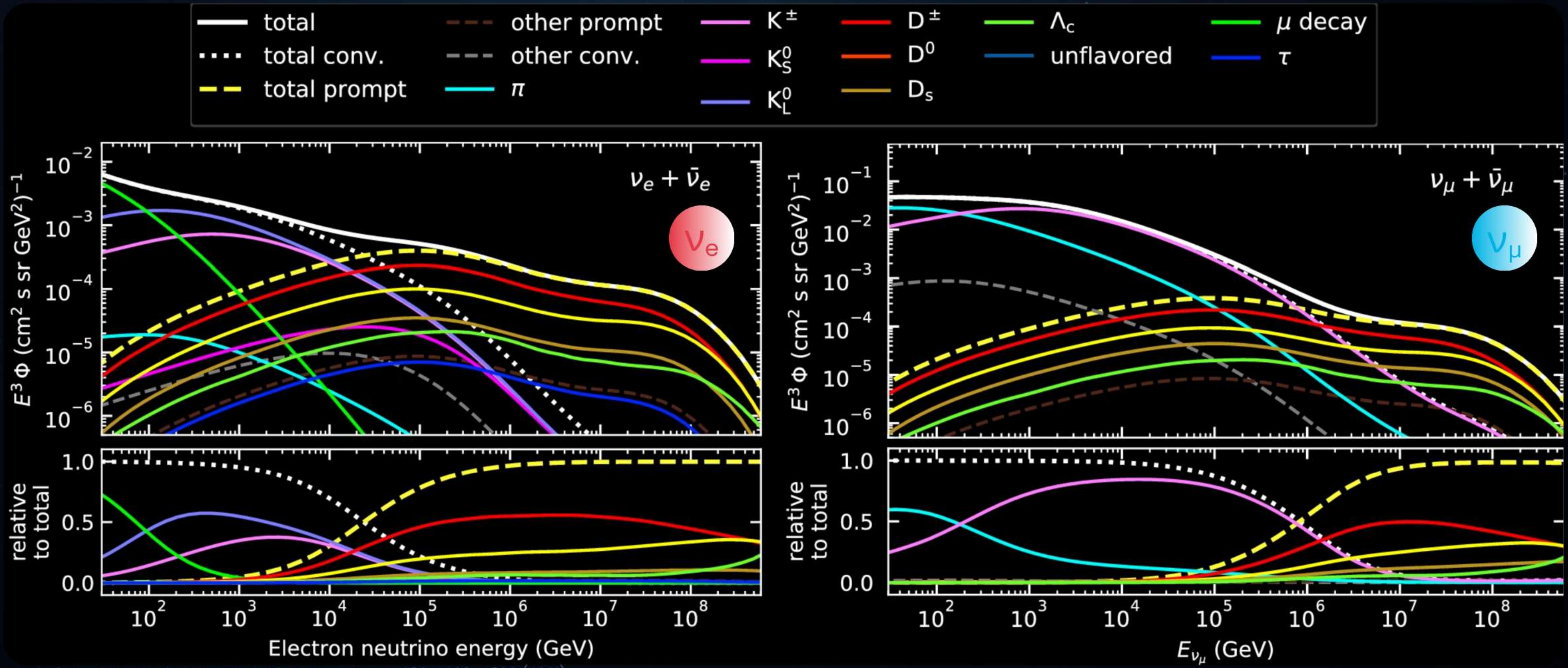
Neutrinos

1. *Electron* ν_e

μ → K^0_L → $D^\pm$

2. *Muon* ν_μ

π → $K^\pm$ → $D^\pm$



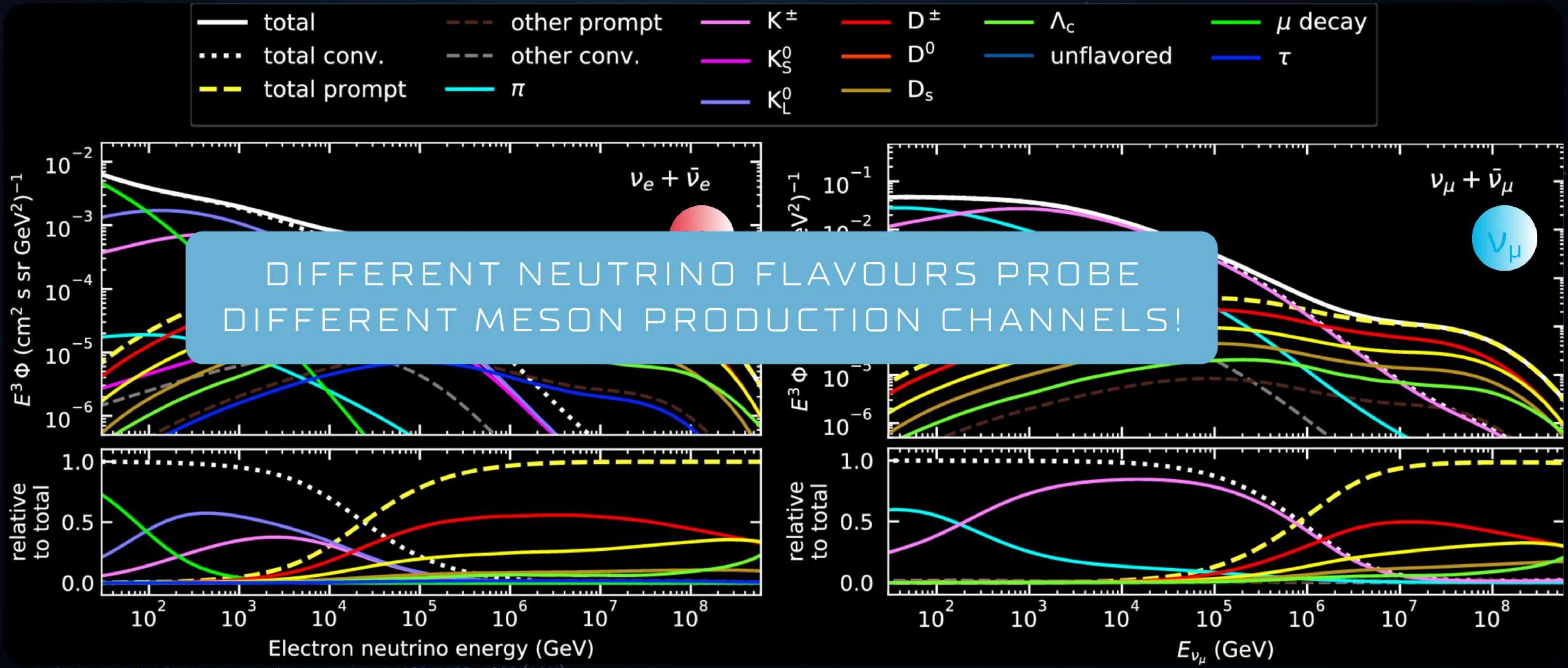
Katori, T., Yanez, J.P. & Yuan, T. *Eur. Phys. J. Spec. Top.* 230, 4293–4308 (2021)

Electron ν_e Muon ν_μ Tau ν_τ

Atmospheric Neutrino Fluxes

Neutrinos

1. *Electron* ν_e: μ → K^0_L → $D^\pm$
2. *Muon* ν_μ: π → $K^\pm$ → $D^\pm$



DIFFERENT NEUTRINO FLAVOURS PROBE DIFFERENT MESON PRODUCTION CHANNELS!

Katori, T., Yanez, J.P. & Yuan, T. *Eur. Phys. J. Spec. Top.* 230, 4293–4308 (2021)

Electron
Muon
Tau

Atmospheric Neutrino Fluxes

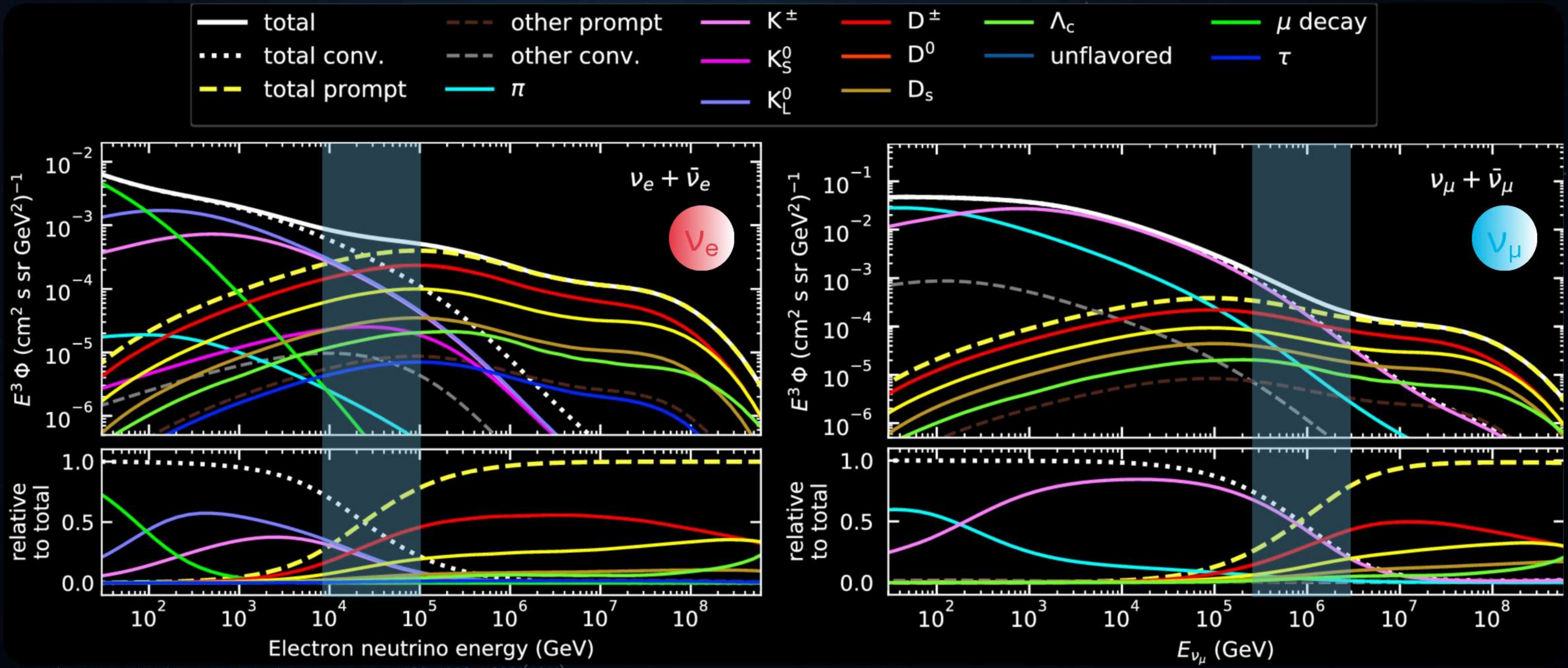
Neutrinos

1. *Electron*

~$10^{4.5}$ GeV

2. *Muon*

~10^{6} GeV



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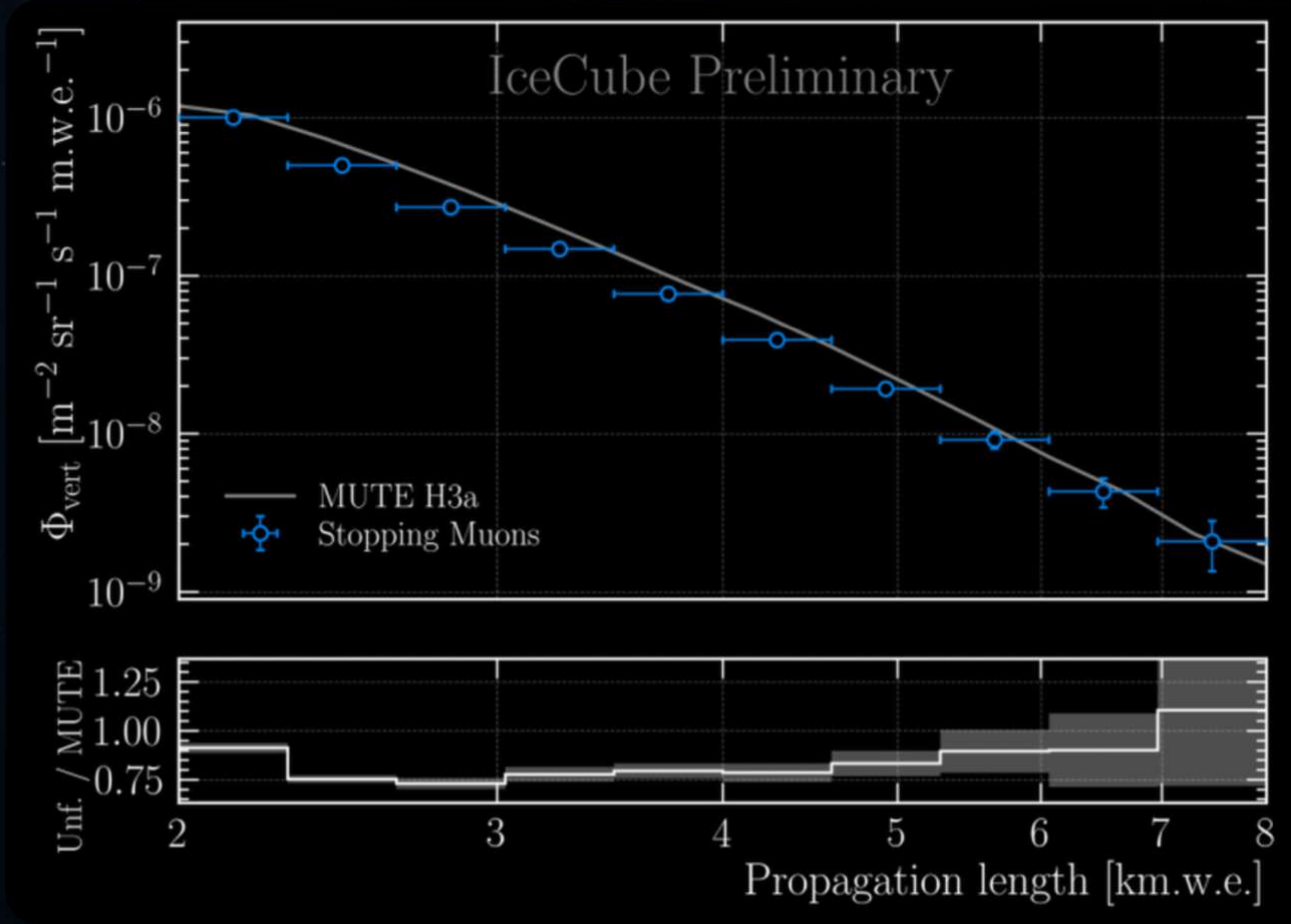
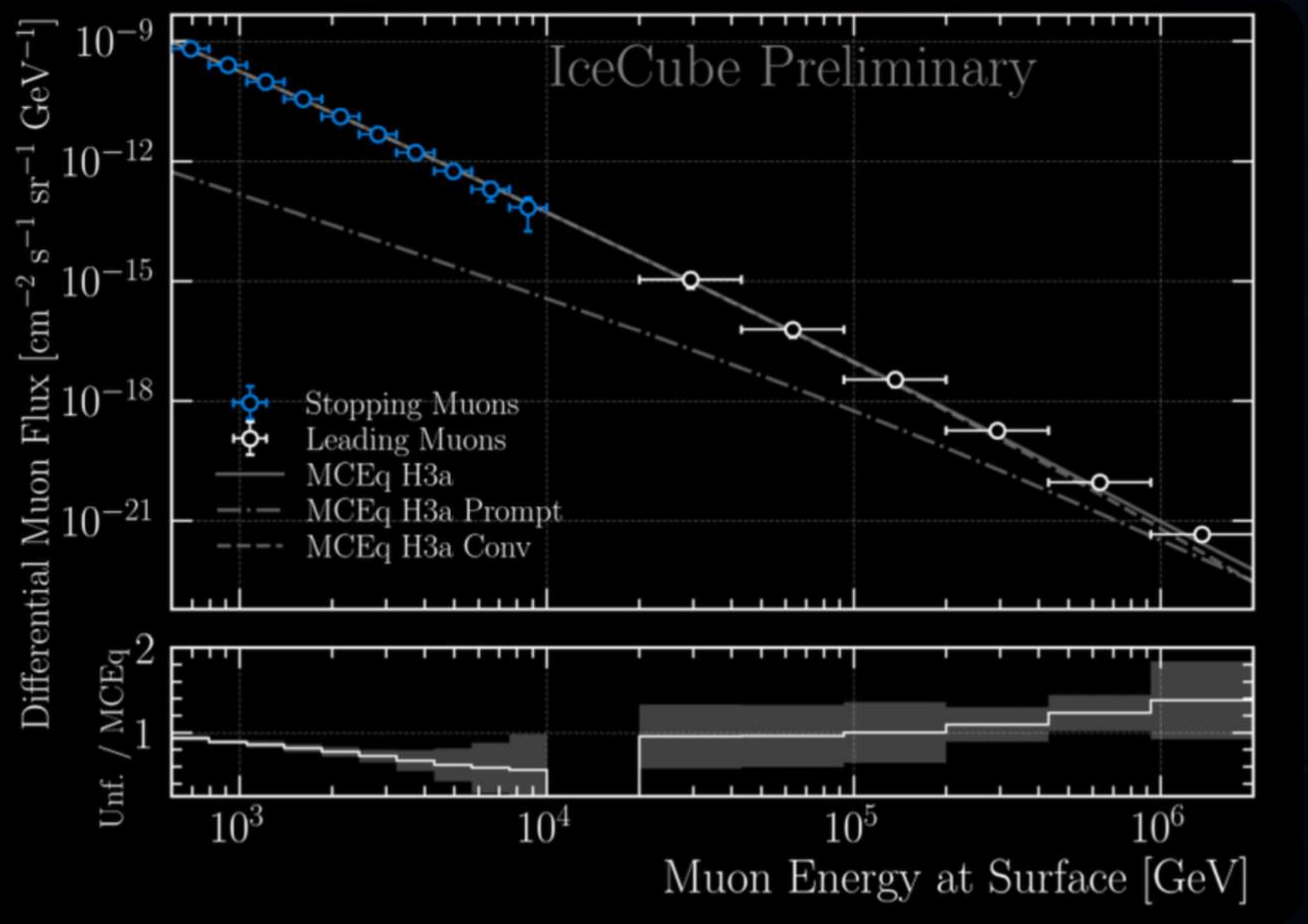
Electron ν_e Muon ν_μ Tau ν_τ

Muon Spectrum Unfolding (MC)

Stopping Muon Flux:



Leading + Stopping Muon Flux:



IceCube Collaboration / P. Gutjahr, L. Witthaus (IceCube Collaboration), PoS ICRC2025 (2025) 281

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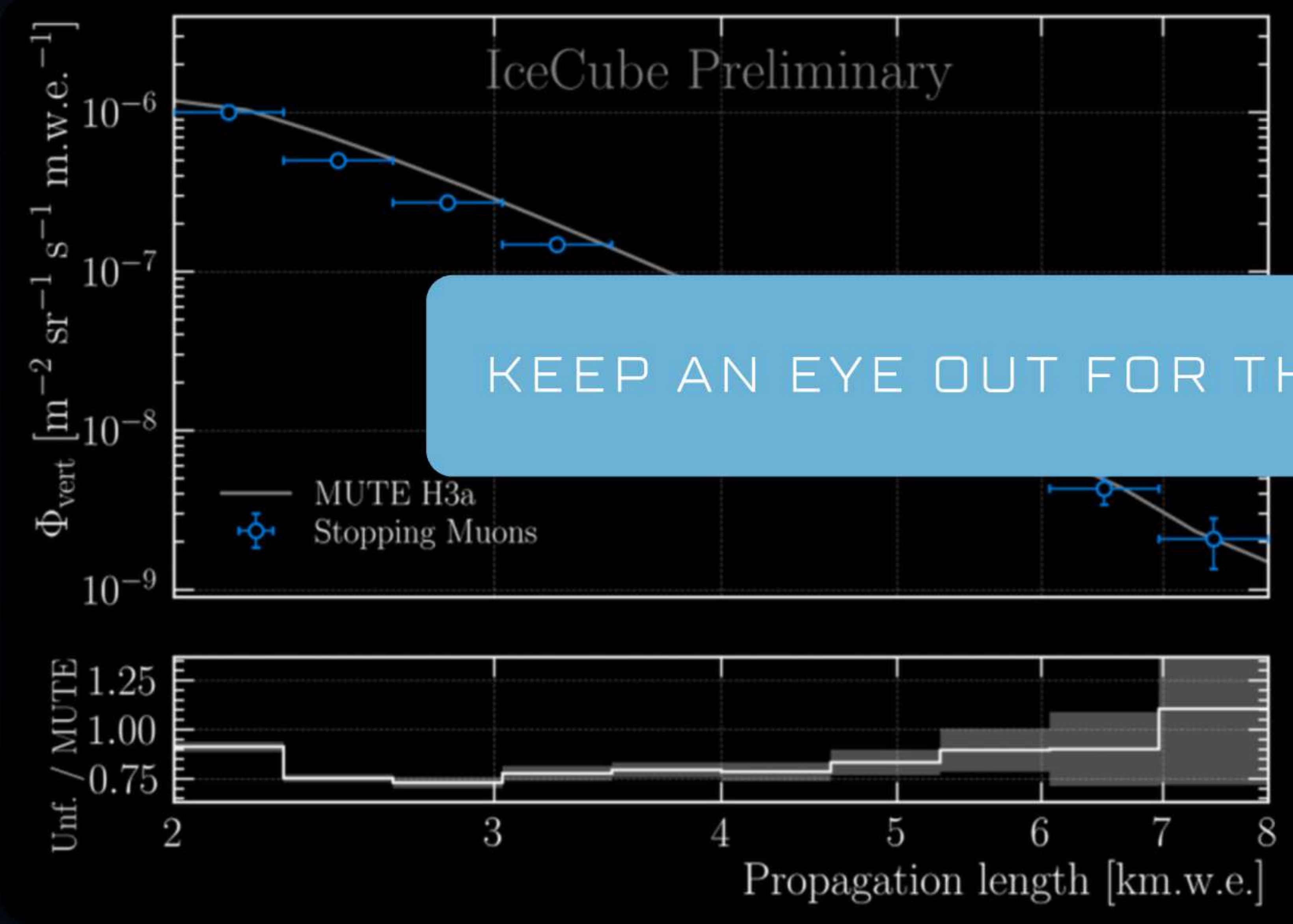
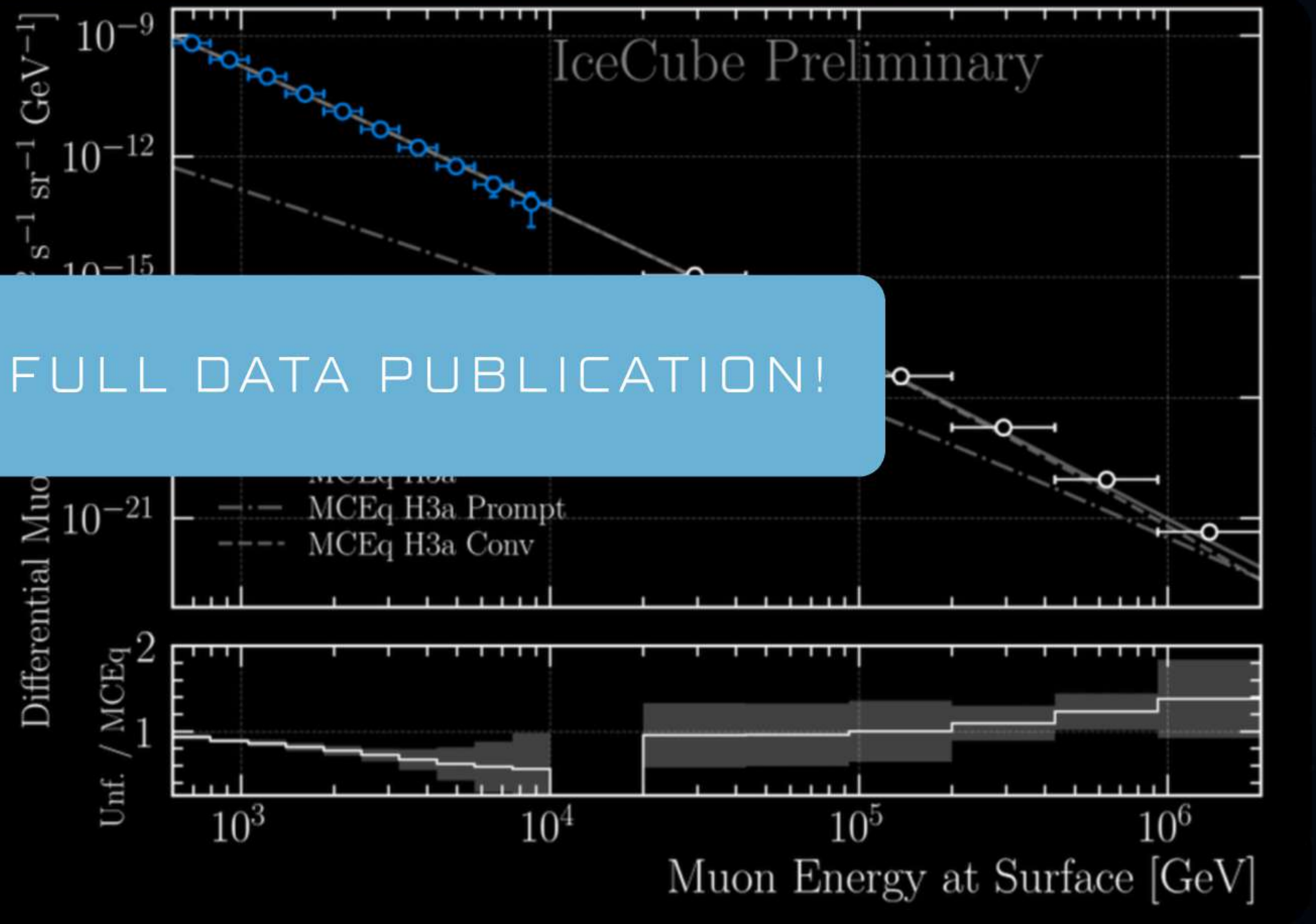


Leading + Stopping Muon Flux:



KEEP AN EYE OUT FOR THE FULL DATA PUBLICATION!

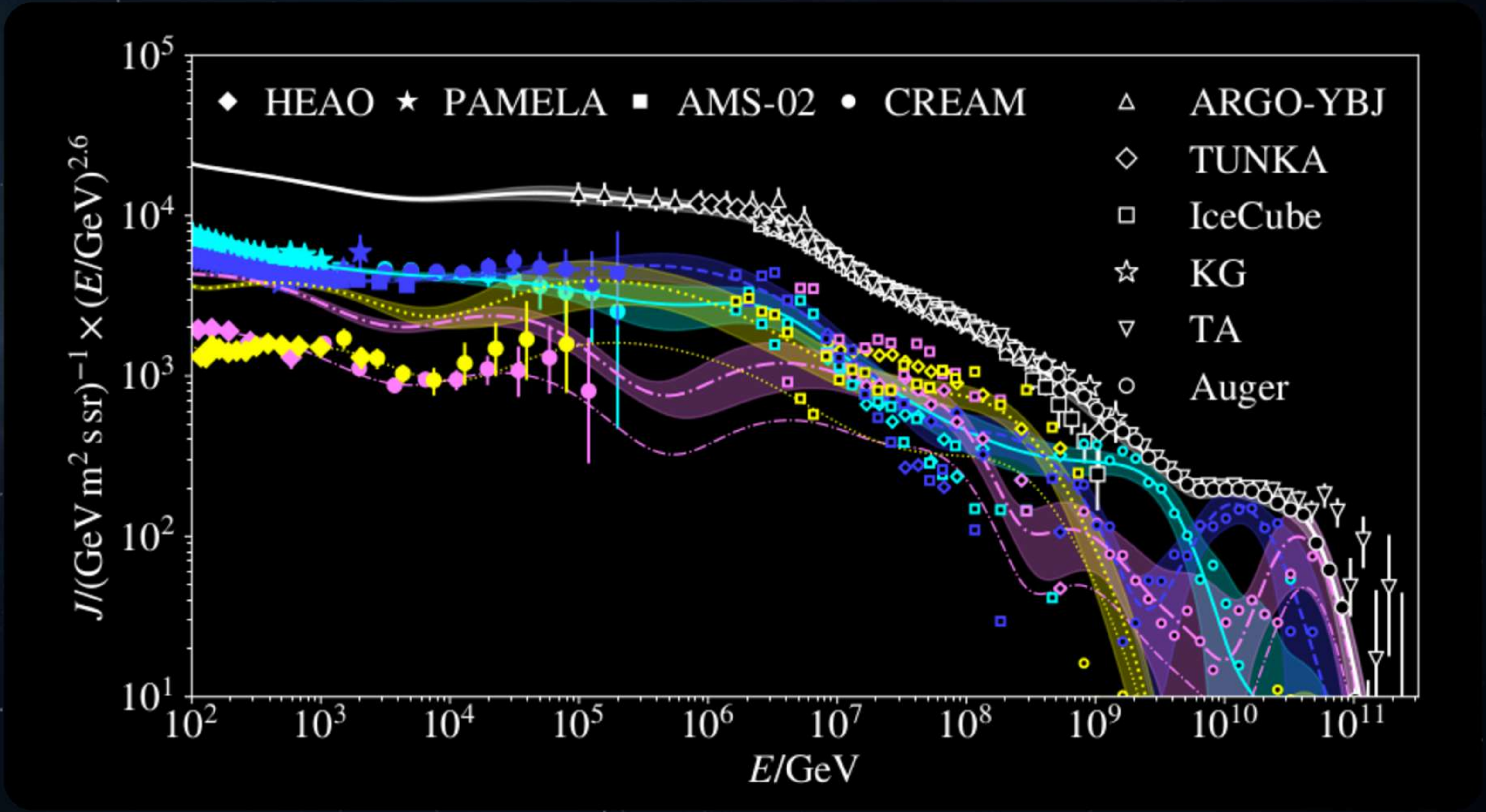
IceCube Collaboration / P. Gutjahr & L. Witthaus, arXiv:2507.14525.

Electron ν_e Muon ν_μ Tau ν_τ

Cosmic Ray Fluxes

<u>Cosmic-ray models</u> describe the spectrum and composition of the primary CRs entering the atmosphere.

- *Energy spectrum of primary particles*
- *Elemental composition (**p**, **He**, **CNO**, **Fe**, ...)*
- *Features such as the **knee** and **ankle***
- *Examples:*
  - *H3a/H4a*
  - *GST3/GST4*
  - *Global Spline Fit (GSF)*



Dembinski, H., Engel, R., Fedynitch, A., Gaisser, T., Riehn, F. & Stanev, T. PoS(ICRC2017)533

Electron ν_e Muon ν_μ Tau ν_τ

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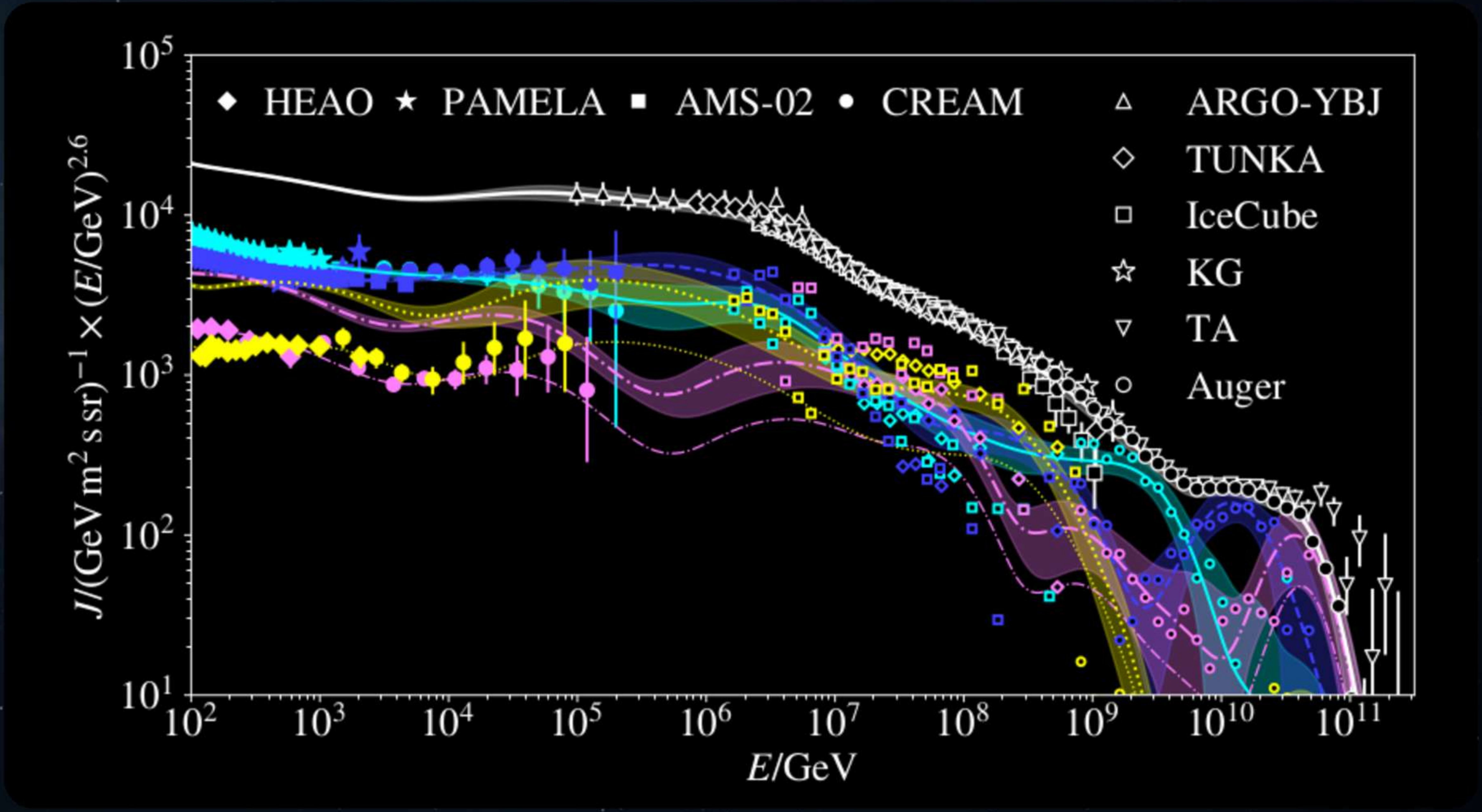
  - *H3a/H4a*
  - *GST3/GST4*
  - *Global Spline Fit (GSF)*

<u>Hadronic interaction models</u> describe particle production in cosmic-ray air showers.

- *Production of **pions**, **kaons** and **charmed hadrons***
- *Meson multiplicities and E distributions*
- *Interaction cross sections*
- *Examples:*
  - *SIBYLL 2.3c*
  - *EPOS-LHC*
  - *QGSJet-II*

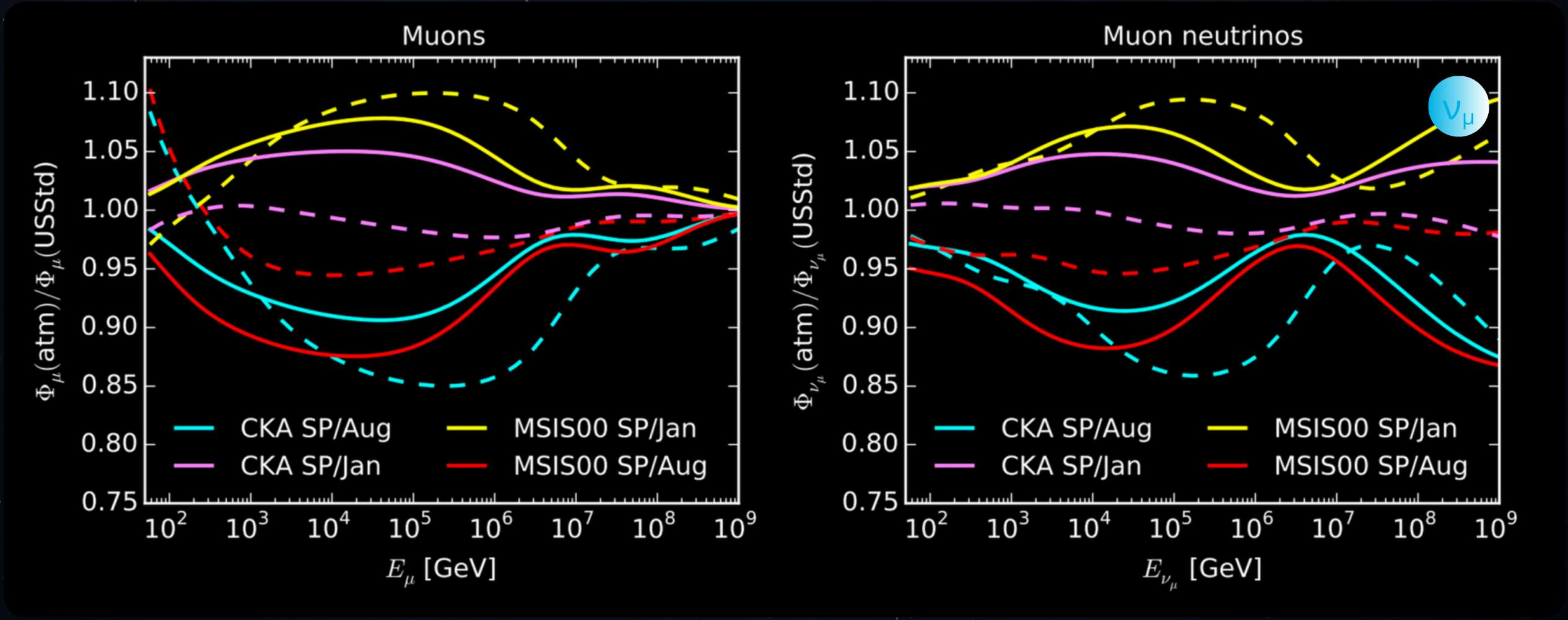


Dembinski, H., Engel, R., Fedynitch, A., Gaisser, T., Riehn, F. & Stanev, T. PoS(ICRC2017)533

Electron Muon Tau

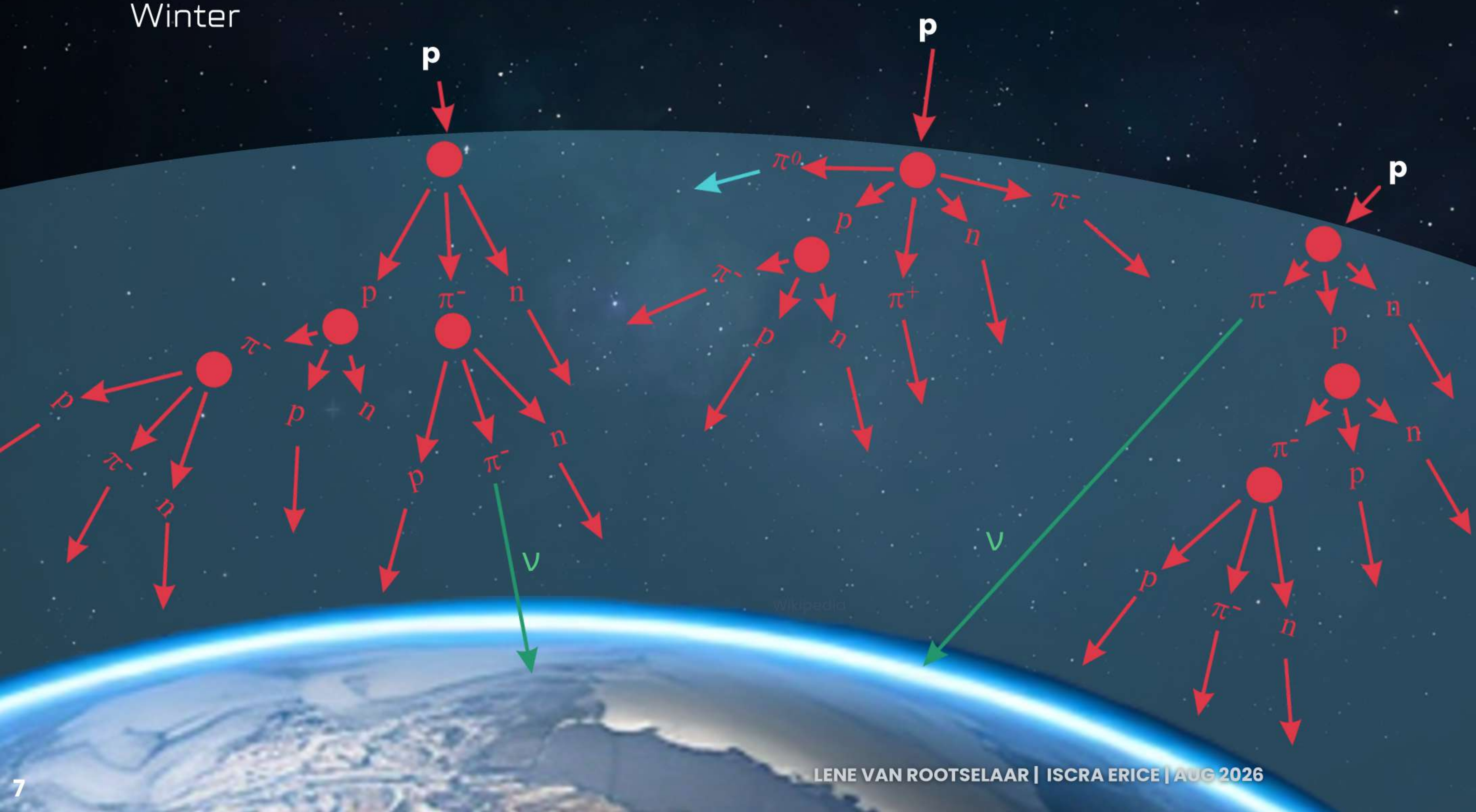
Atmosphere Models

Solid: θ = 0°
Dashed: θ = 90°



Fedynitch, A., Becker Tjus, J. & Desiati, P. EPJ Web of Conferences (2015)

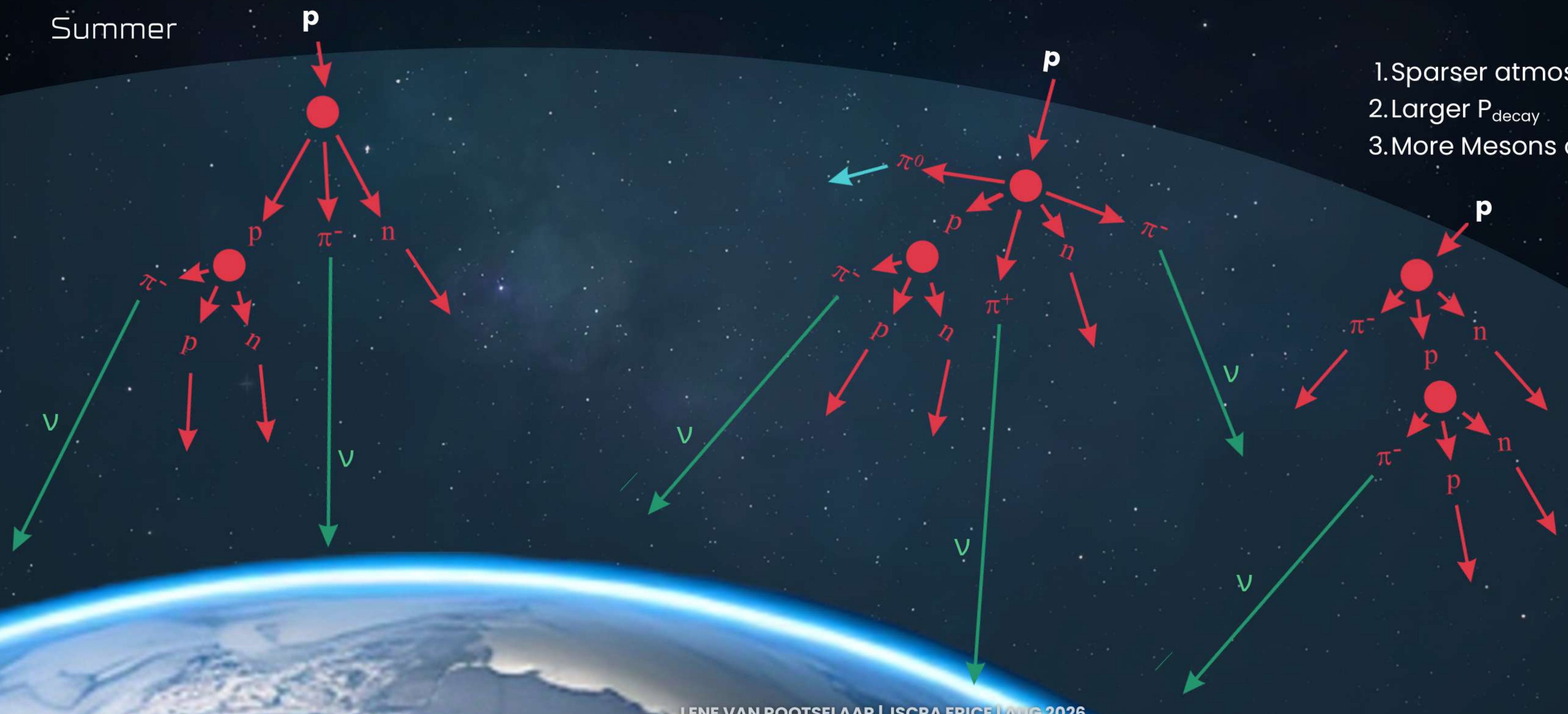
Seasonal Variations



1. Denser atmosphere
2. Larger $P_{interact}$
3. Less Mesons decay into ν

Electron ν_e Muon ν_μ Tau ν_τ

Seasonal Variations



1. Sparser atmosphere
2. Larger P_{decay}
3. More Mesons decay into ν

Electron ν_e Muon ν_μ Tau ν_τ

Muon Neutrino Spectrum Unfolding

Seasonal Variation:

Theoretical Models.

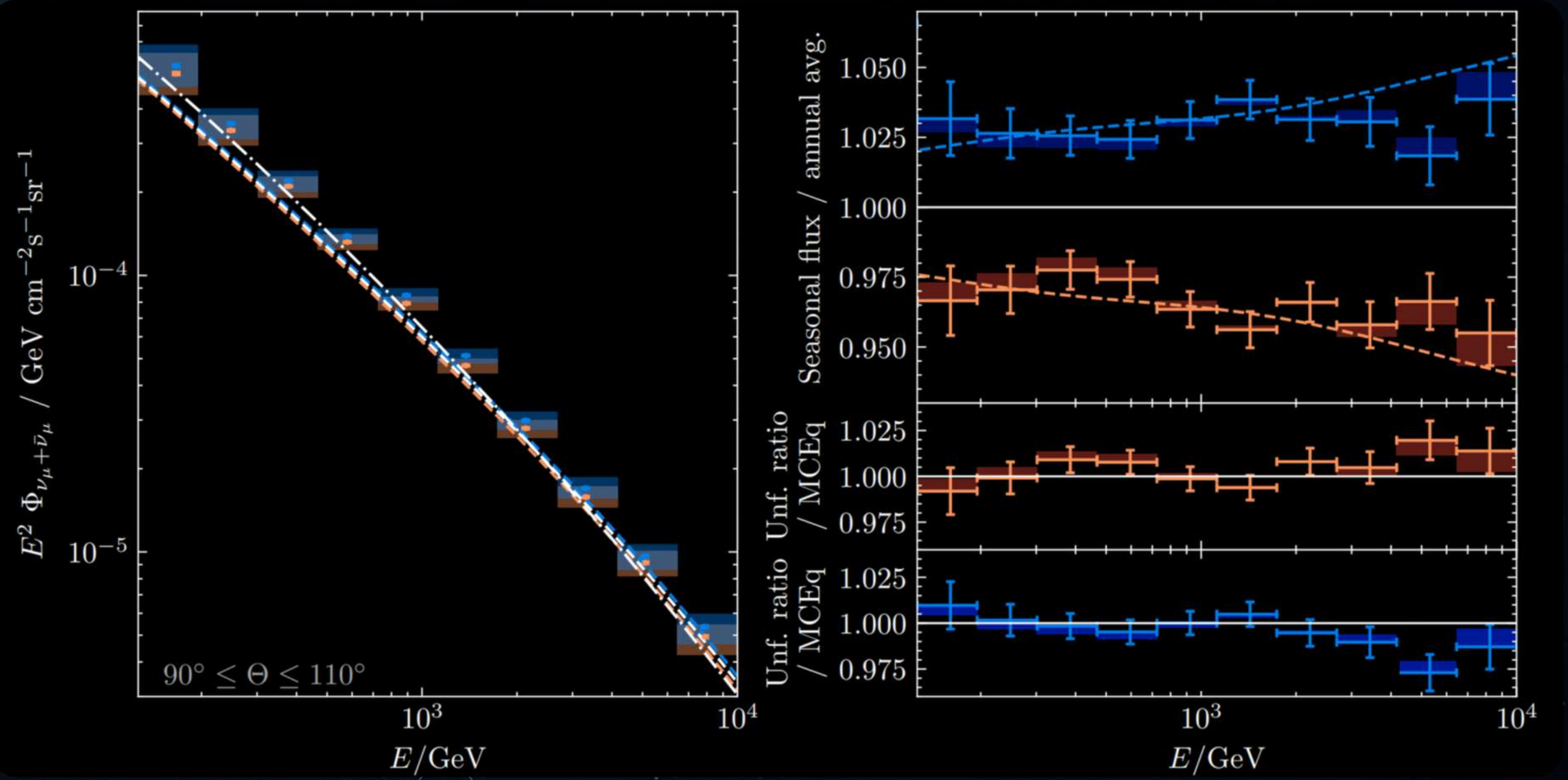
- *Different seasons versus the average*

MCEq + NRLMSISE-00 (May-Aug)
MCEq + NRLMSISE-00 (Oct-Jan)
MCEq + NRLMSISE-00 (annual avg.)
daemonflux (annual avg.)

Unfolded data points with 11.3 yrs of IceCube data

- *Winter and summer months*

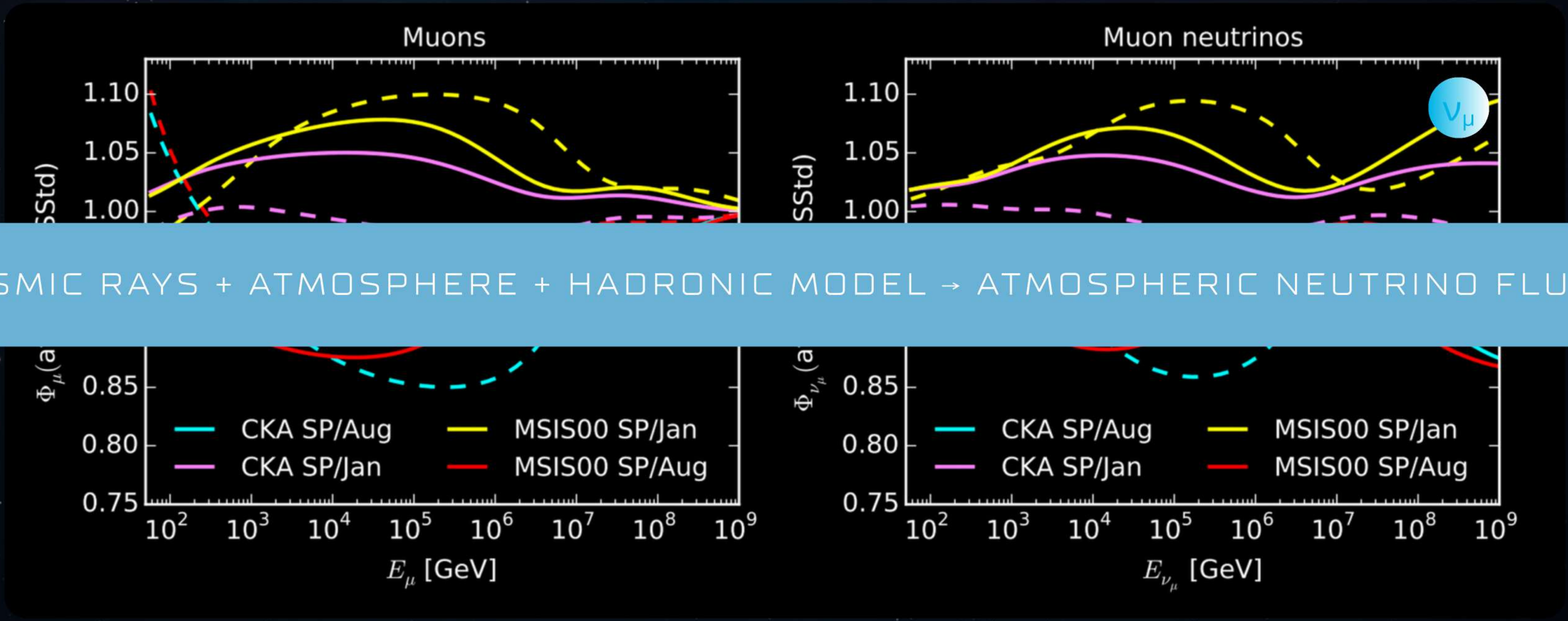
May-Aug (syst.+stat.)
Oct-Jan (syst.+stat.)
May-Aug (stat.)
Oct-Jan (stat.)
May-Aug (bias)
Oct-Jan (bias)



IceCube Collaboration, Eur. Phys. J. C 85, 1368 (2025)

Electron ν_e Muon ν_μ Tau ν_τ

Atmosphere Models



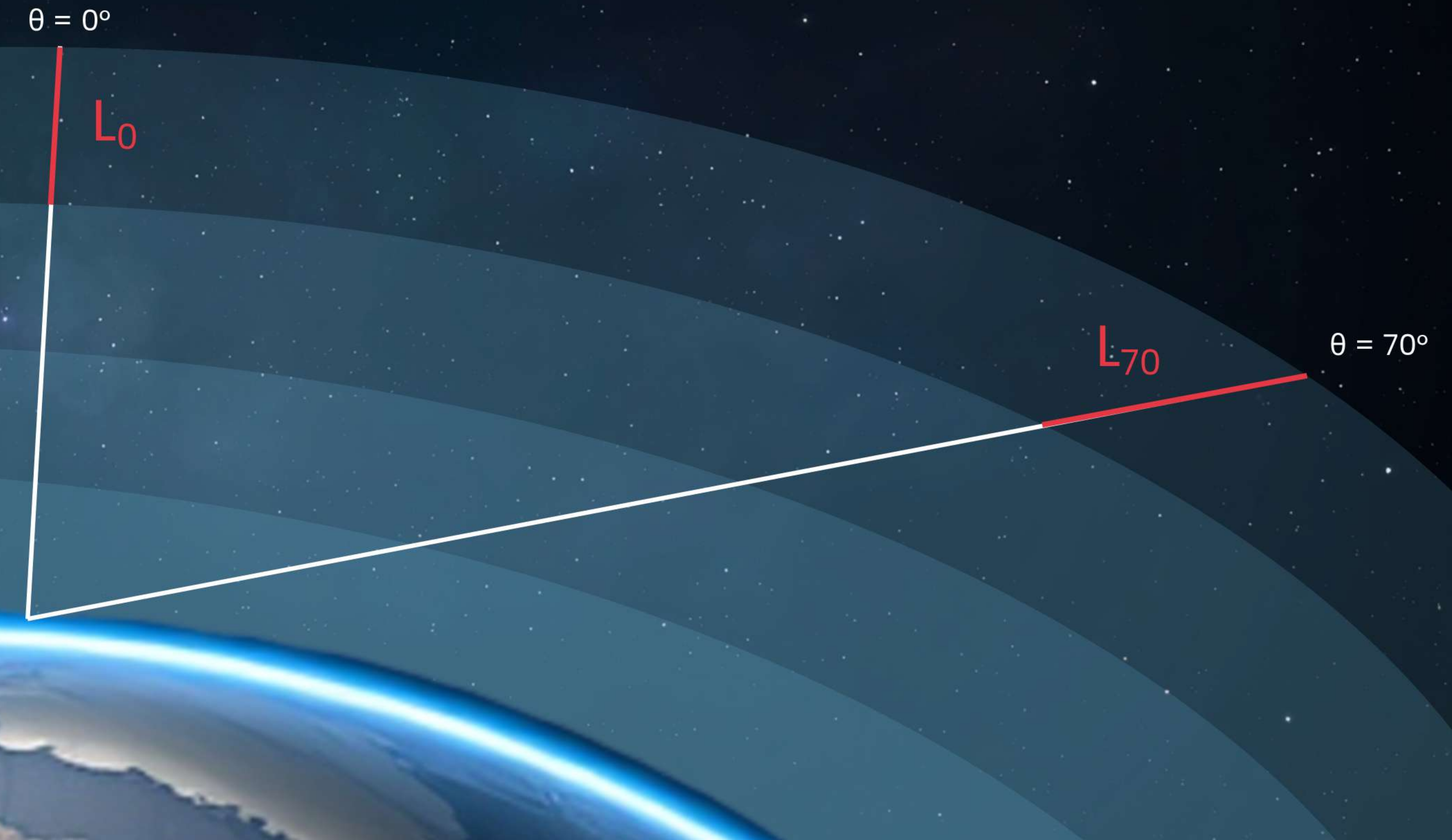
COSMIC RAYS + ATMOSPHERE + HADRONIC MODEL → ATMOSPHERIC NEUTRINO FLUX

Fedynitch, A., Becker Tjus, J. & Desiati, P. EPJ Web of Conferences (2015)

Electron ν_e Muon ν_μ Tau ν_τ

Angular Dependence

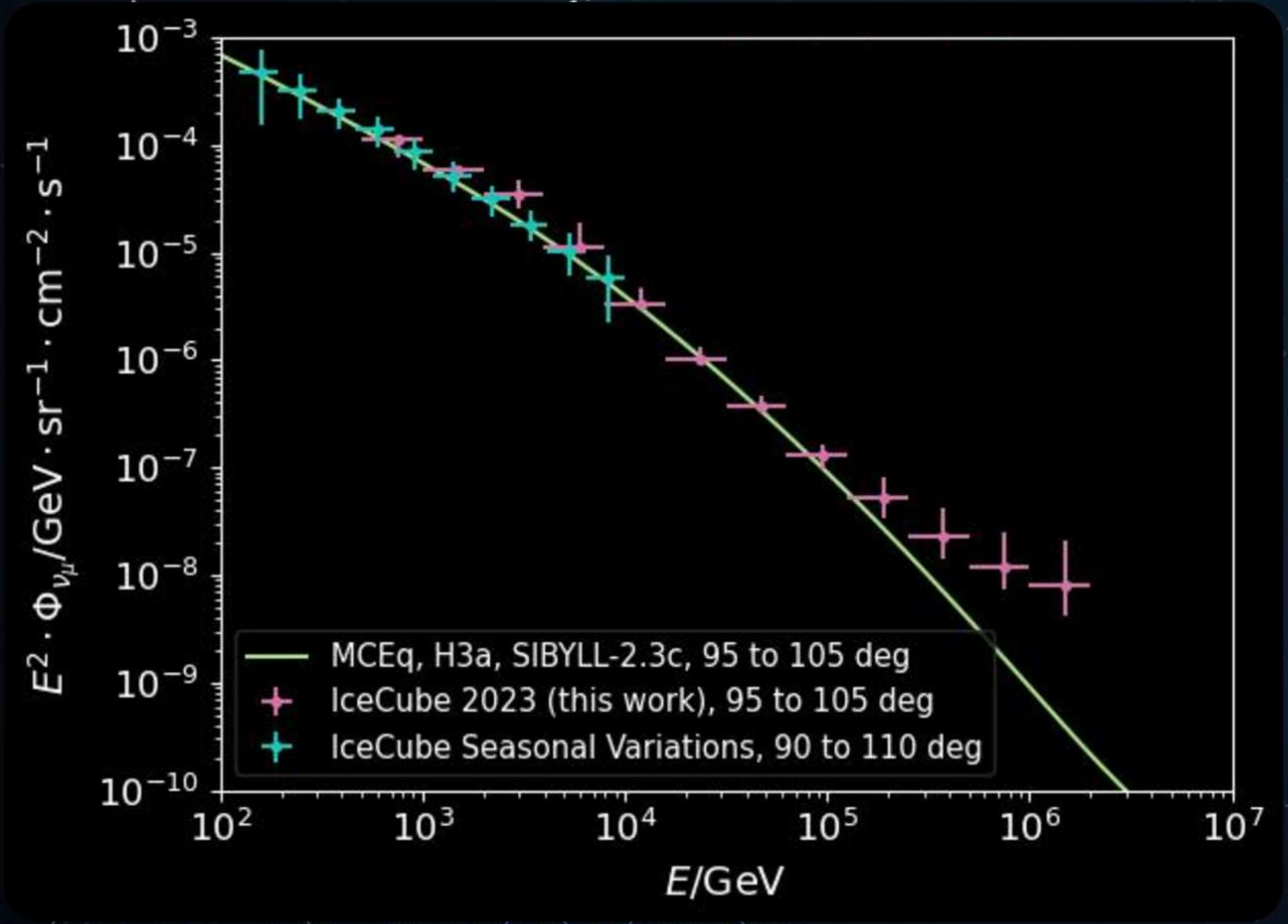
0°		70°
L_0	<	L_0
$P_{interact}$	>	$P_{interact}$
P_{decay}	<	P_{decay}
Φ_ν	<	Φ_ν



Electron ν_e Muon ν_μ Tau ν_τ

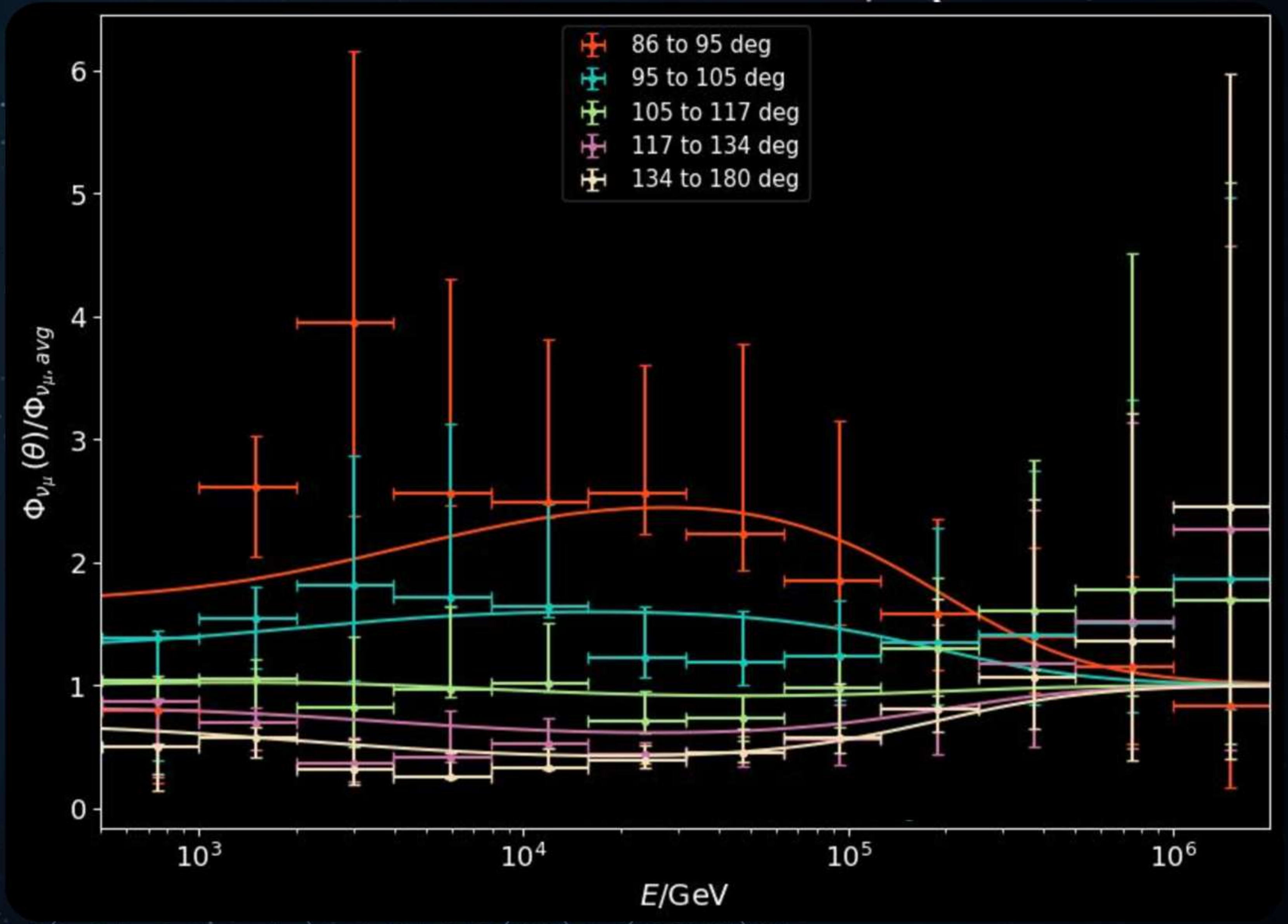
Muon Neutrino Spectrum Unfolding

Muon Neutrino Flux:



LvR (IceCube Collaboration), Proc. 39th ICRC (2025), PoS(ICRC2025)1199

Angular Dependence:

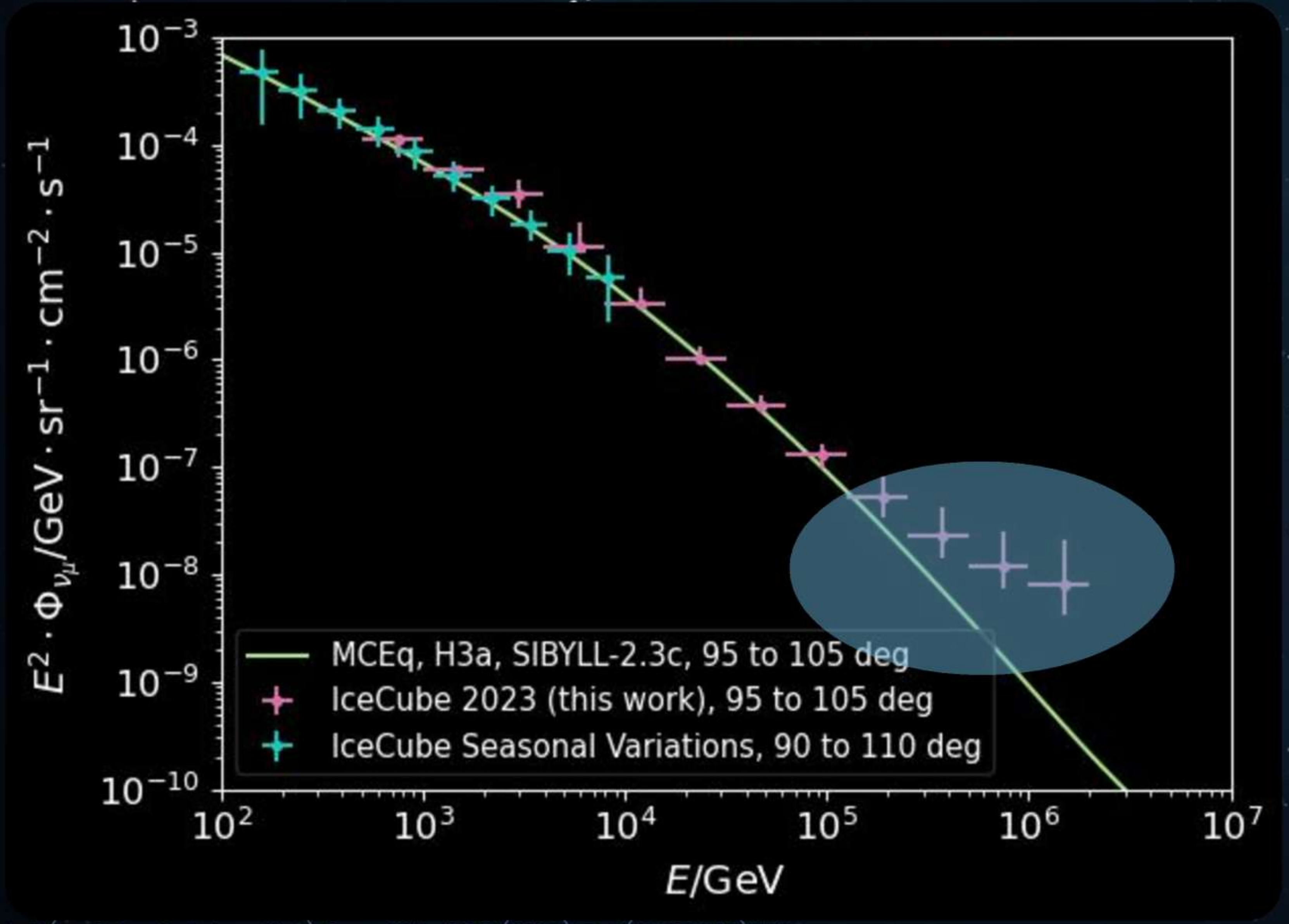


LvR (IceCube Collaboration), Proc. 39th ICRC (2025), PoS(ICRC2025)1199

Electron ν_e Muon ν_μ Tau ν_τ

Muon Neutrino Spectrum Unfolding

Muon Neutrino Flux:



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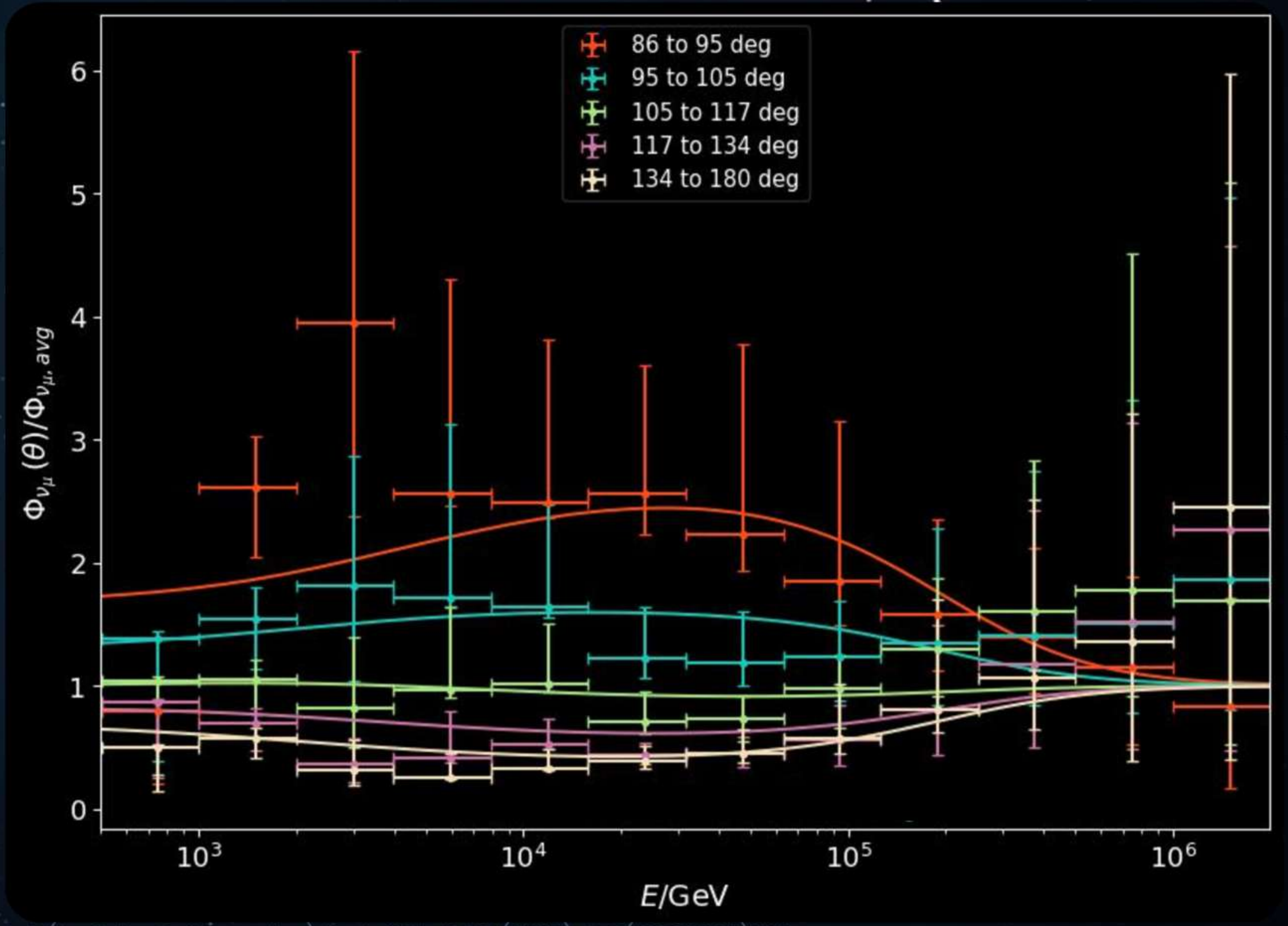
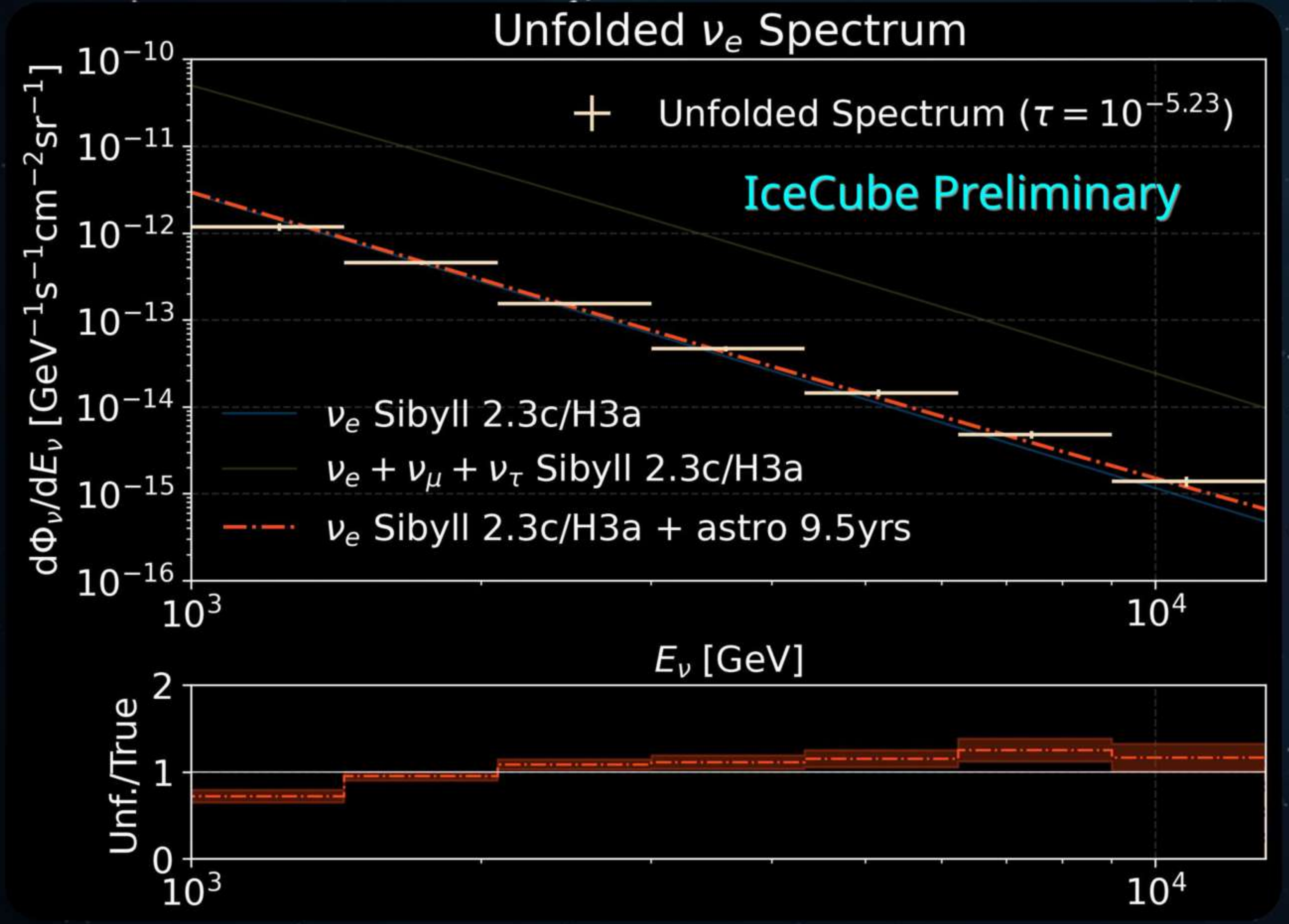


LvR (IceCube Collaboration), Proc. 39th ICRC (2025), PoS(ICRC2025)1199

Electron ν_e Muon ν_μ Tau ν_τ

Electron Neutrino Spectrum Unfolding (MC)

Electron Neutrino Flux:



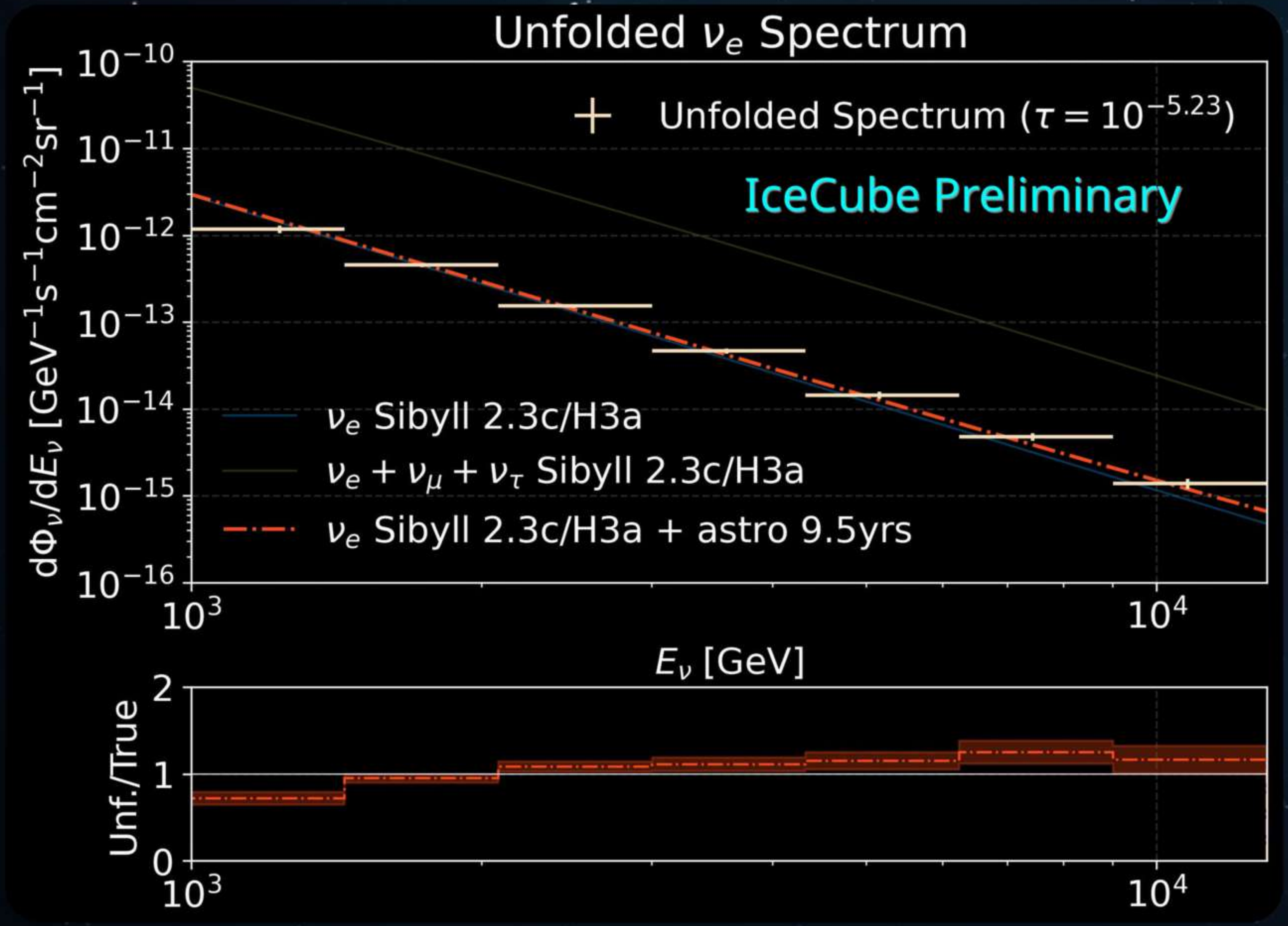
Shows the unfolded atmospheric electron neutrino flux across an energy window (1 to >10 TeV).

- ***Regularization Applied***: *Data points are unfolded using Tikhonov regularization with an optimized strength parameter to balance statistical variance and physical smoothness.*
- ***Model Baseline***: *The data steps track the* ***Sibyll 2.3c / H3a*** *hadronic/primary interaction model baseline (orange line).*
- ***Livetime***: *MC data represents 10 years of livetime.*
- ***Proxy Variable***: Reconstructed energy

Electron ν_e Muon ν_μ Tau ν_τ

Electron Neutrino Spectrum Unfolding (MC)

Electron Neutrino Flux:



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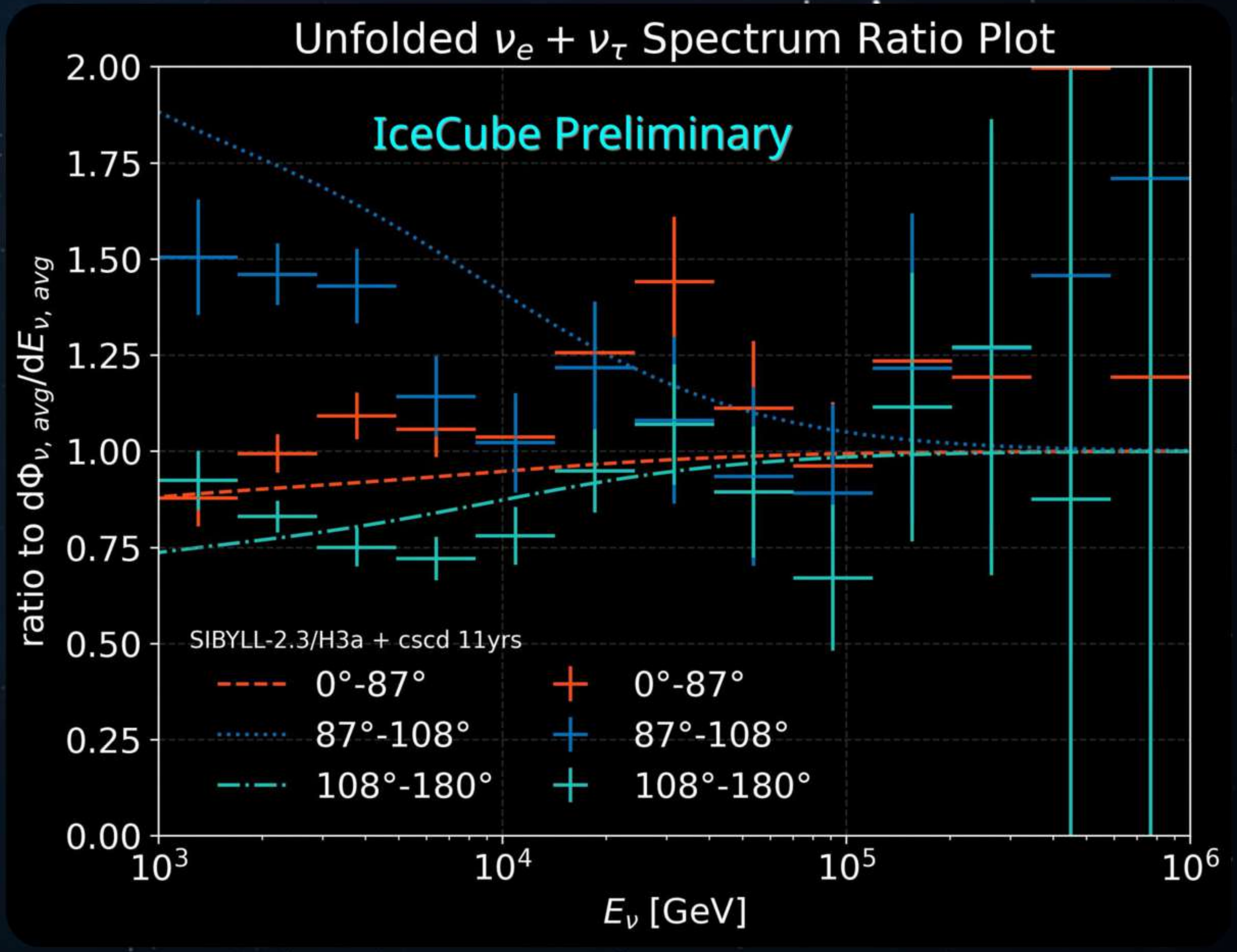
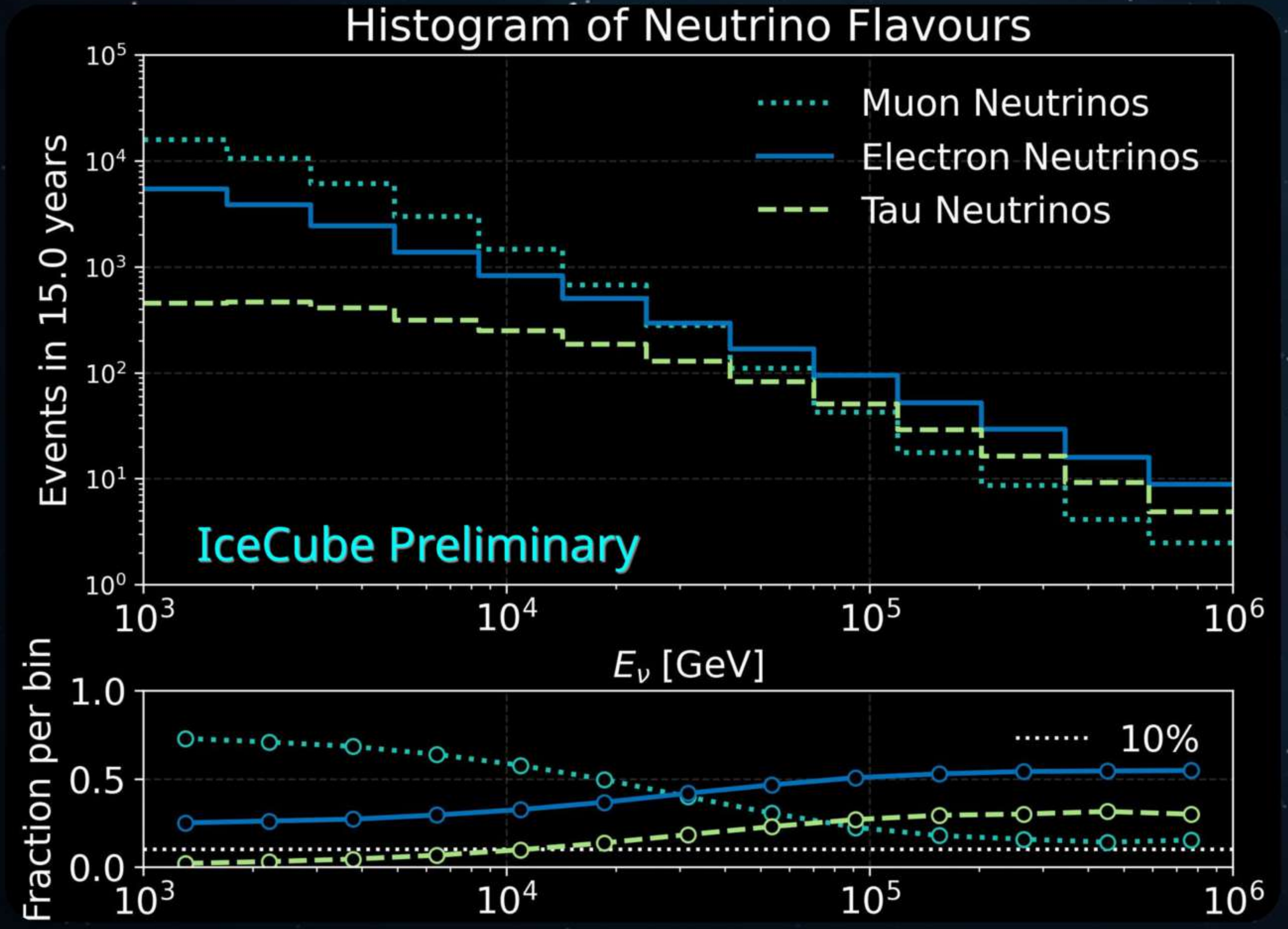


Electron ν_e Muon ν_μ Tau ν_τ

Electron Neutrino Spectrum Unfolding (MC)

Flavour Ratios:



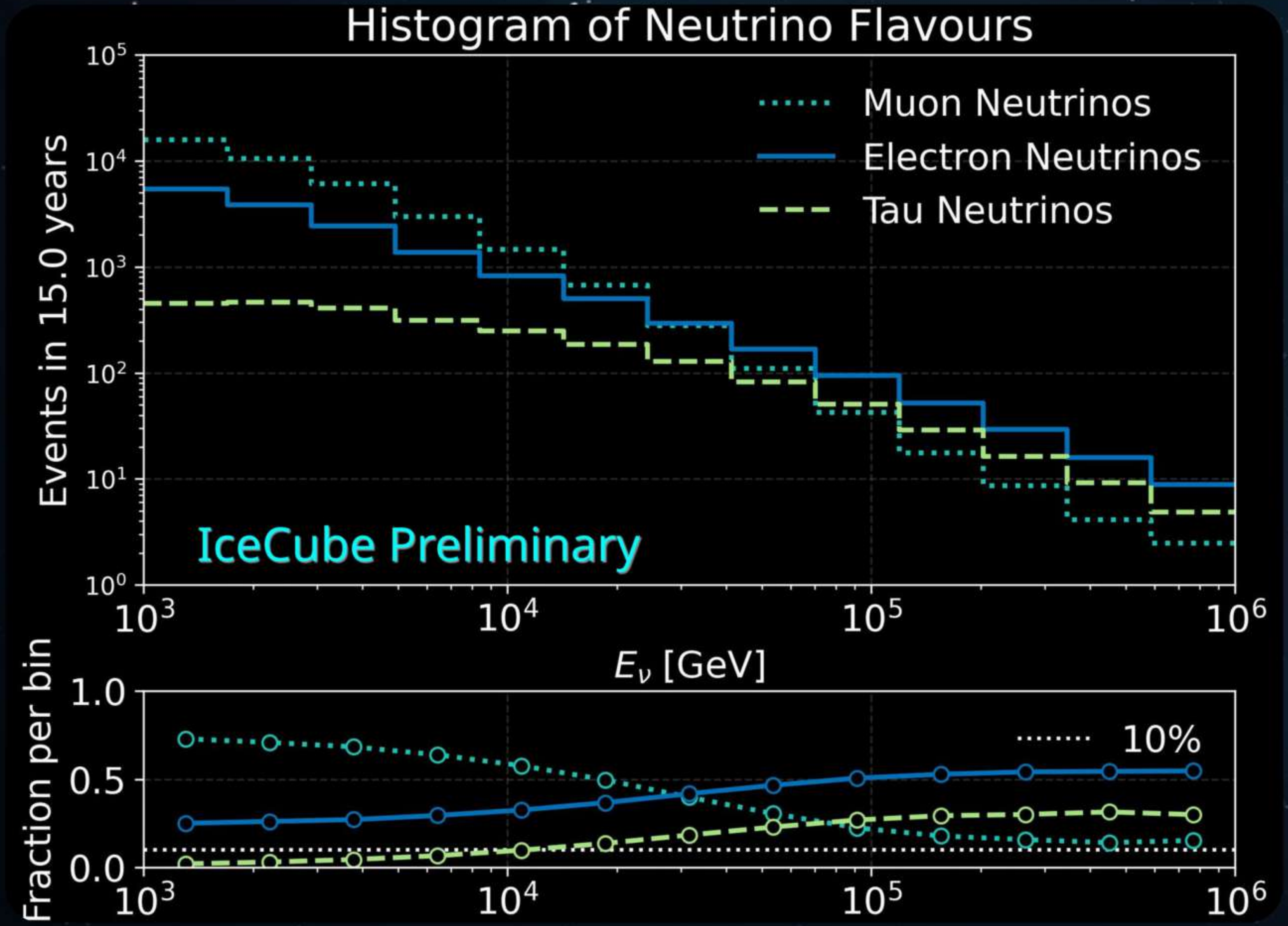
Neutrino flavour ratio is dependent on energy

- *In the lower energies the production of **tau leptons** is kinematically **heavily suppressed**.*
- *Above 10^5 the **astrophysical neutrino signal** begins to take over. A flavour ratio of 1:1:1 is assumed.*

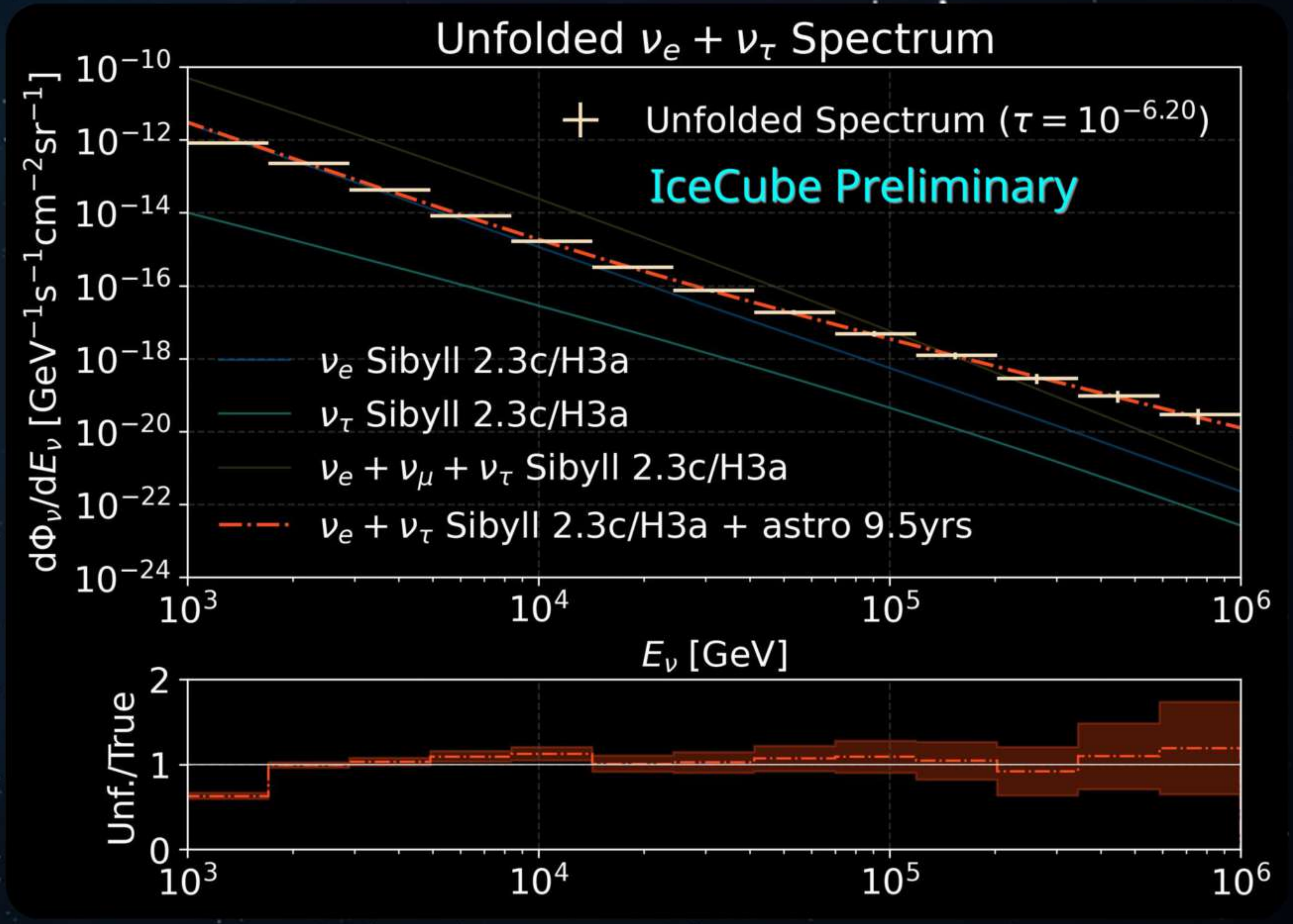
Electron ν_e Muon ν_μ Tau ν_τ

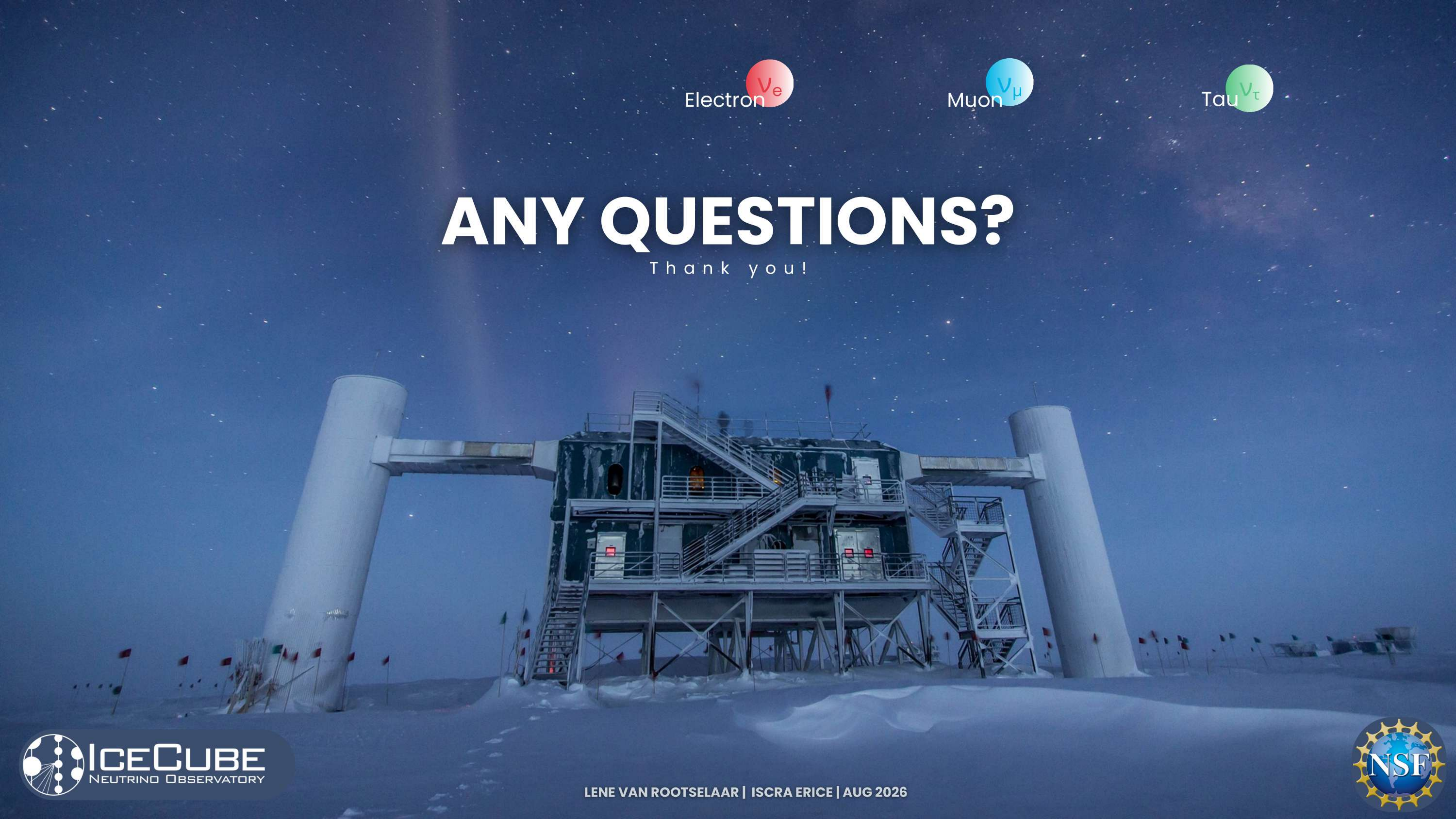
Electron Neutrino Spectrum Unfolding (MC)

Flavour Ratios:



Electron + Tau Neutrino Flux:

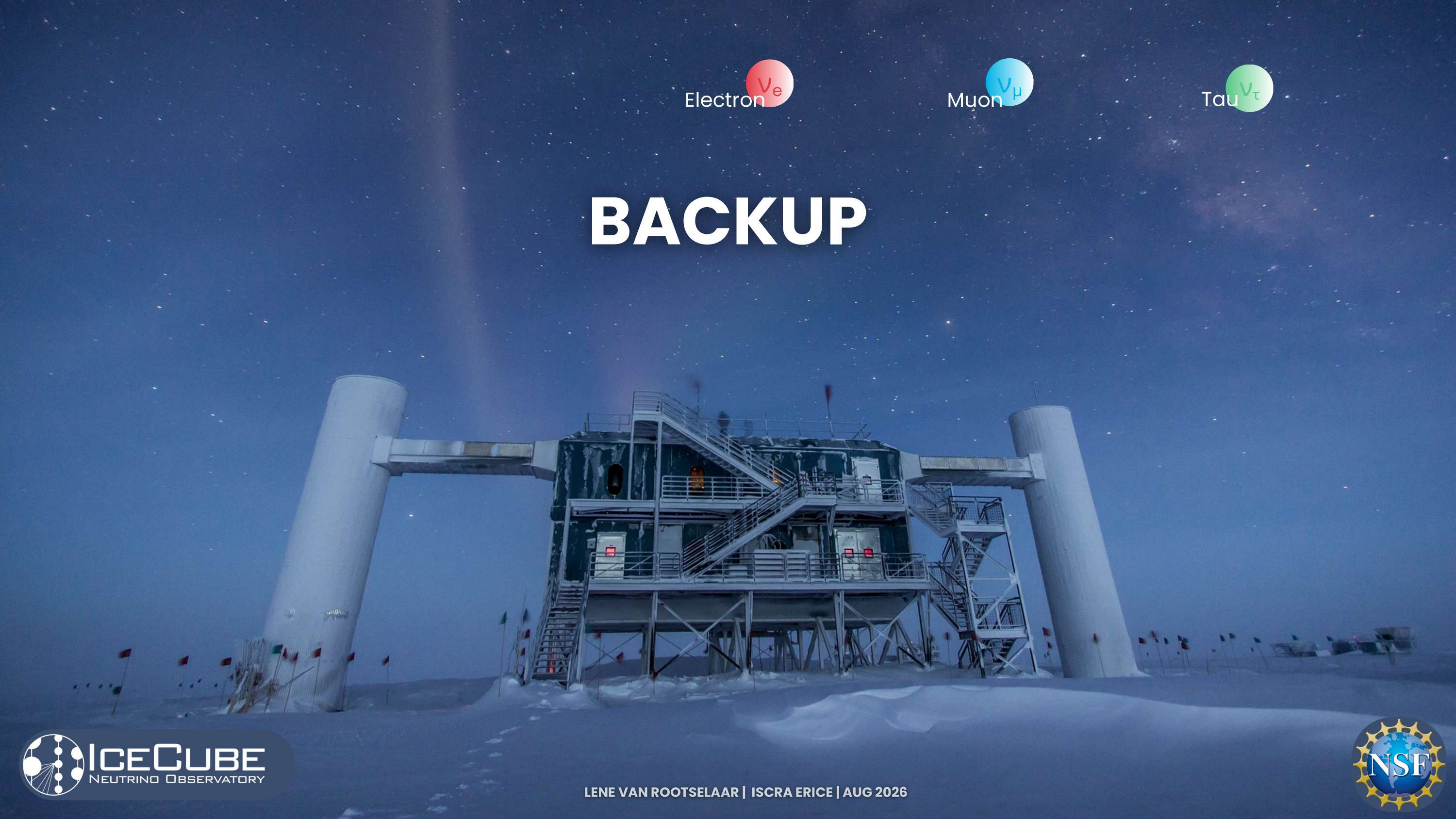




Electron ν_e Muon ν_μ Tau ν_τ

ANY QUESTIONS?

Thank you!



Electron ν_e Muon ν_μ Tau ν_τ

BACKUP

IceCube Neutrino Observatory

Electron ν_e Muon ν_μ Tau ν_τ

Unfolding

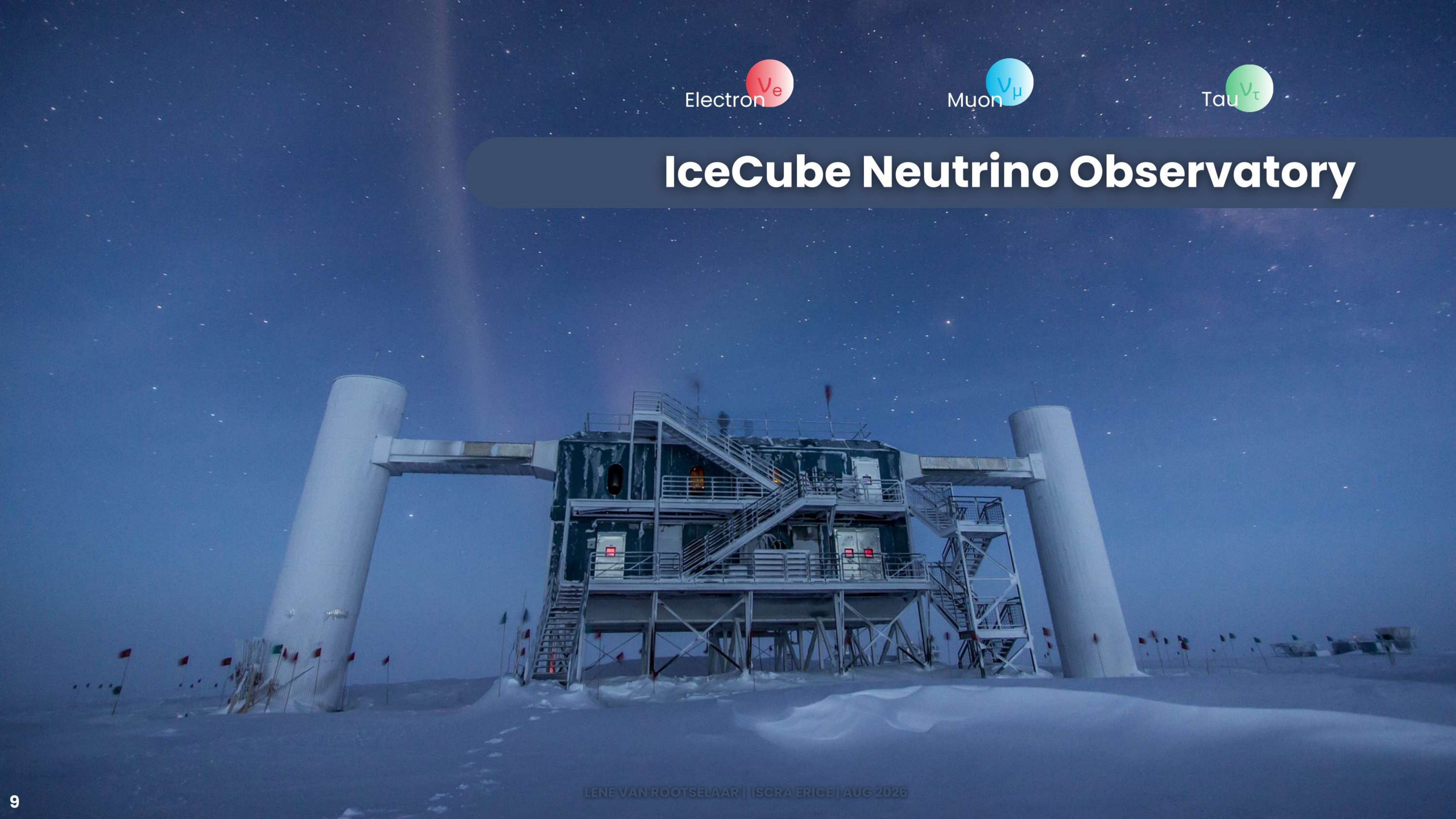
- ***Target***: *true energy distribution.*
- **Background**: muon neutrino flux as measured in 2023.
- **Measured proxy**: reconstructed energy and zenith variables
- **Detectror Response Function**: description of detector effects, created with MC.

Funfolding package:
Likelihood-based Unfolding

measured proxy *true energy distribution*

$$g(y) = \int A(y, E_\nu)\, f(E_\nu)\, dE_\nu + b(y)$$

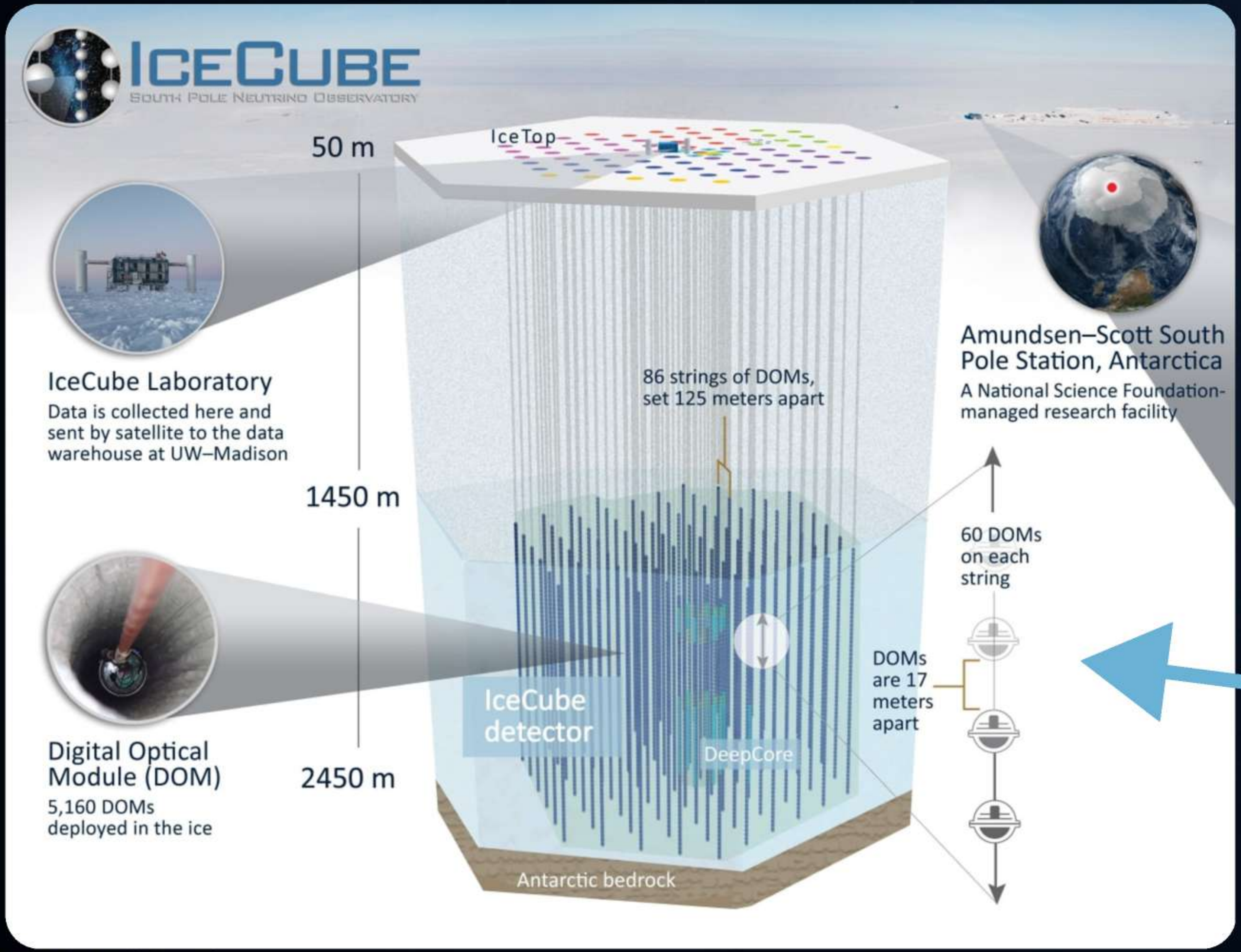
detector response function *background*



IceCube Neutrino Observatory

Electron ν_e Muon ν_μ Tau ν_τ

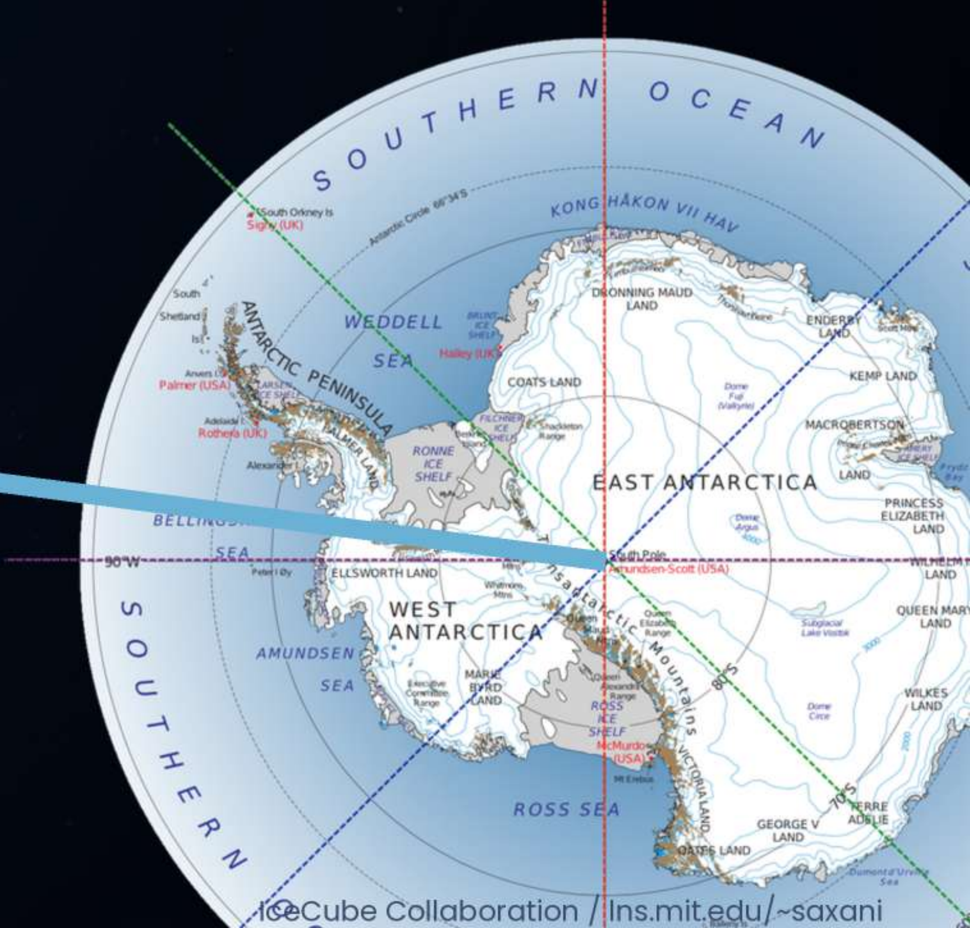
IceCube Neutrino Observatory



IceCube Collaboration

IceCube is a km^3 detector located at the Amundsen-Scott South Pole Station.

- **Depth**: Deployed 1,450 to 2,450 meters below the surface.
- **Instrumentation**: 5,160 Digital Optical Modules (DOMs) on 86 strings.
- **Medium**: Utilizes ultra-pure Antarctic ice as the detection medium.



IceCube Collaboration / lns.mit.edu/~saxani