Electron ν_e Muon ν_μ Tau ν_τ

GLOBAL COMPARISON OF ATMOSPHERIC MUON AND ELECTRON NEUTRINO FLUX MEASUREMENTS

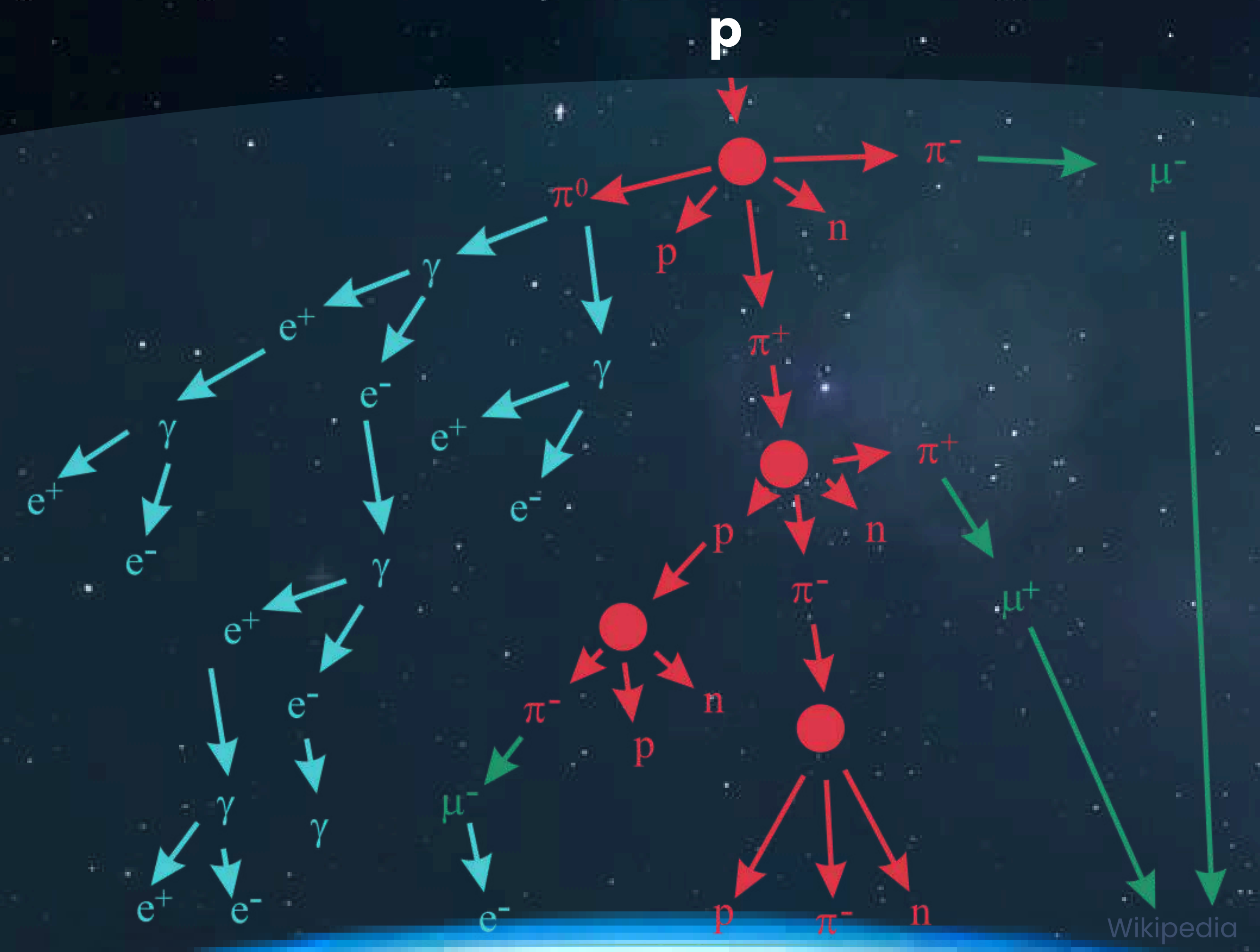
Evaluating Model-Dependence and Prompt Flux Fitting with MCEq

LAMARR INSTITUTE FOR MACHINE LEARNING AND ARTIFICIAL INTELLIGENCE

LENE VAN ROOTSELAAR | TEVPA TENDO | AUG 2026

Electron ν_e Muon ν_μ Tau ν_τ

Atmospheric Neutrinos



Primary cosmic rays collide with atmospheric nuclei.
These interactions produce

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

These particles can decay into neutrinos

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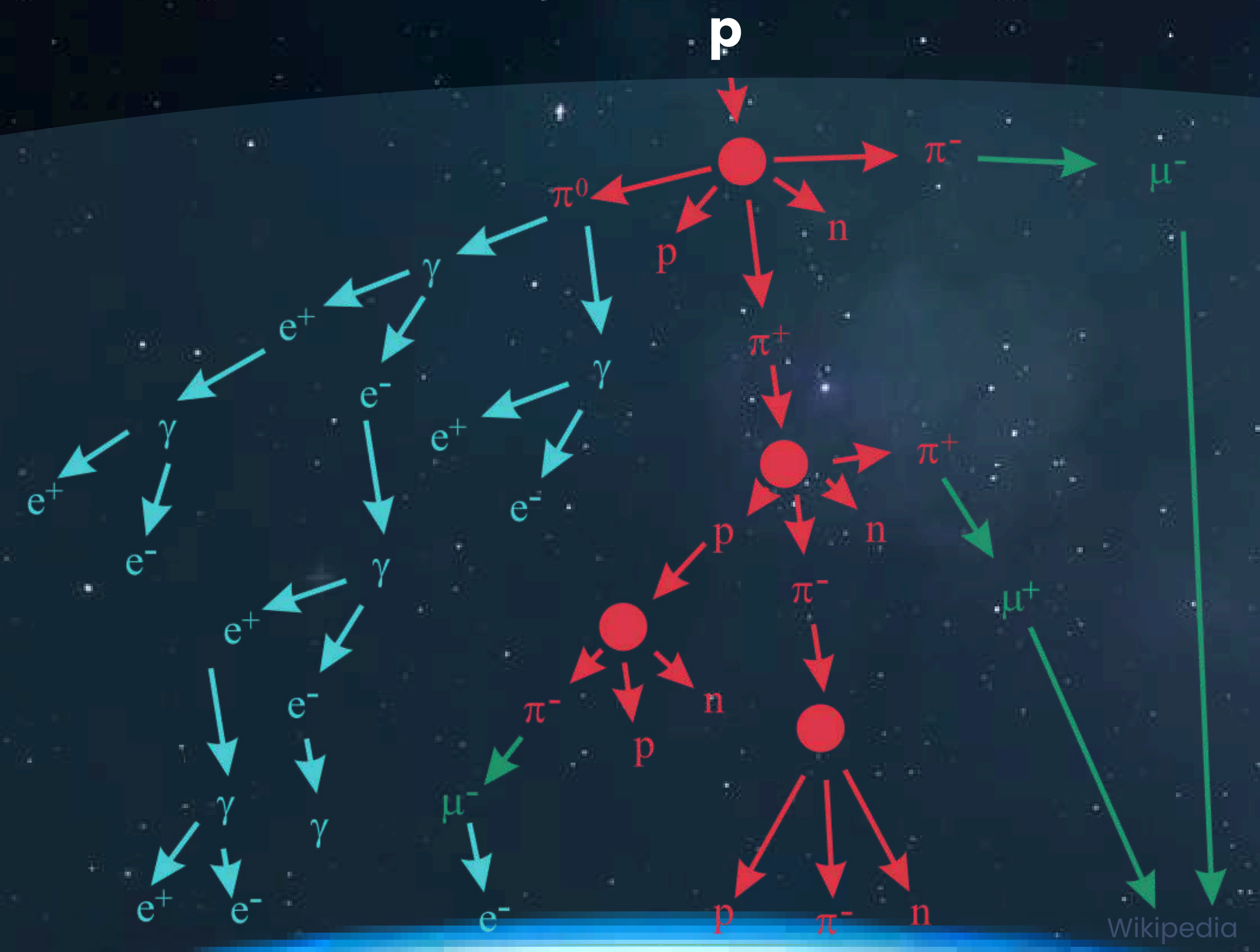
Atmospheric Neutrinos



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- ***pions***

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

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

- ***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***

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

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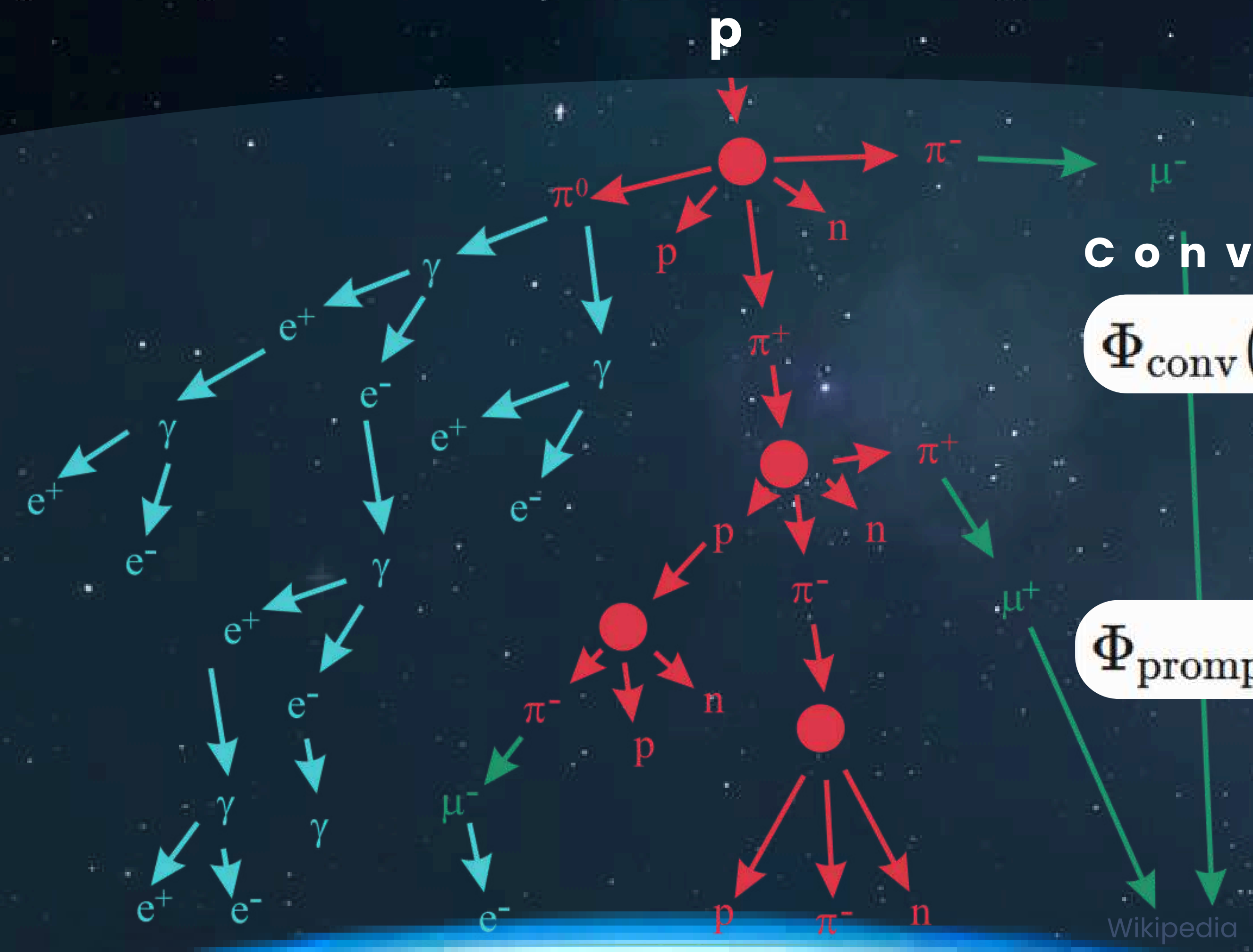

Conventional

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

Prompt

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

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- ***kaons***

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

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Matrix Cascade Equation solver (MCEq)

Calculation of conventional and prompt lepton fluxes at very high energy. A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn, T. Stanev, EPJ Web Conf. 99 (2015) 08001 arXiv:1503.00544

MCEq: Numerical toolkit that computes the evolution of atmospheric cascades in Earth's atmosphere and target media.

RESULT → DIFFERENTIAL ENERGY SPECTRA OR TOTAL PARTICLE NUMBERS.

https://mceq.readthedocs.io/en/latest/

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The following settings were varied to match the experimental set-ups:

Primary Models	Hadronic Interaction Models	Location	Angular Range
GSF	DPMJet-III-30.6	South Pole	0° - 180°
GST	EPOS-LHC	Mediterranean Sea	85° - 180°
H3a	SIBYLL-2.3c	Modane, France	90°
H4a	QGSJet-II-04	Hida, Japan	100° - 180°

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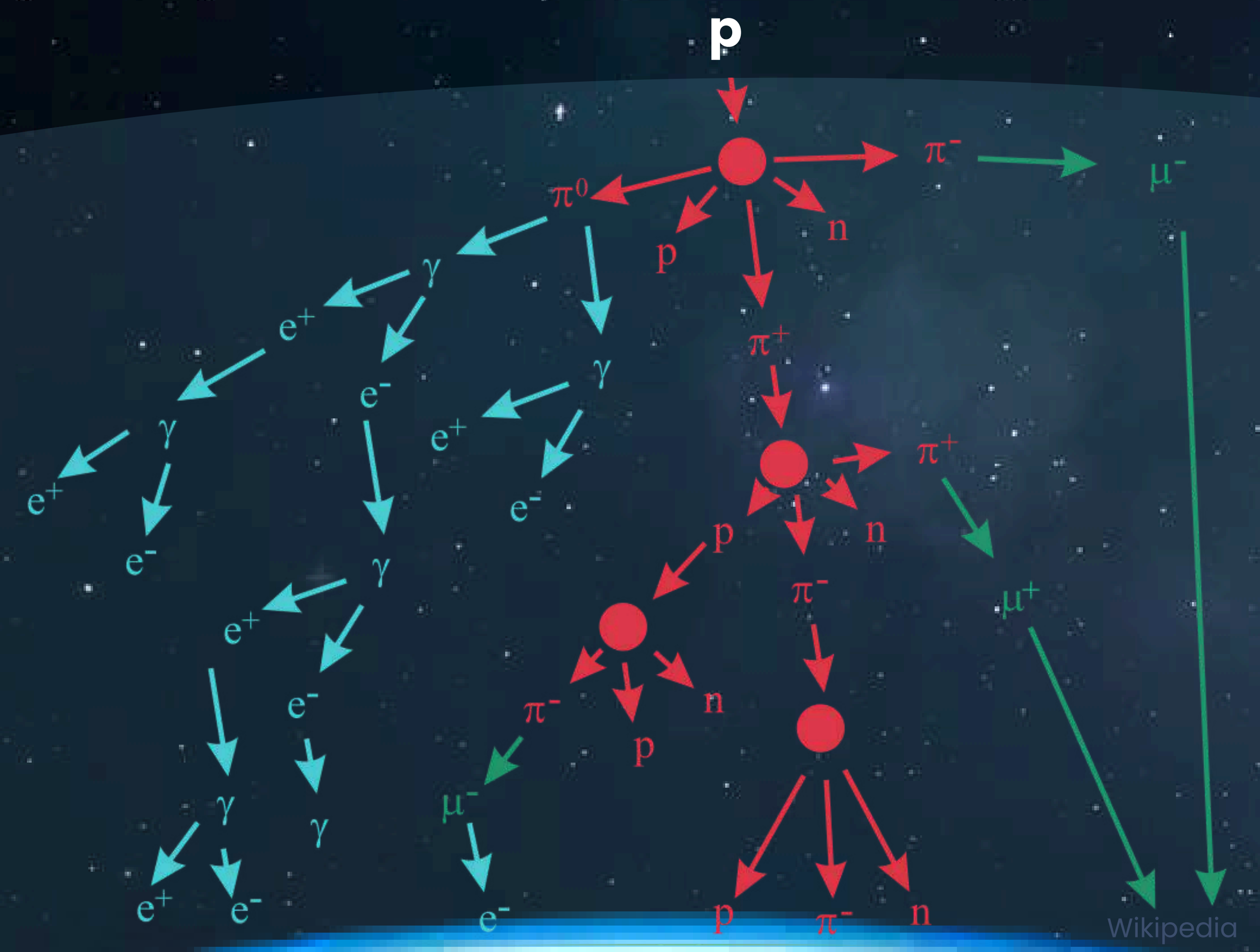
Atmospheric Neutrinos

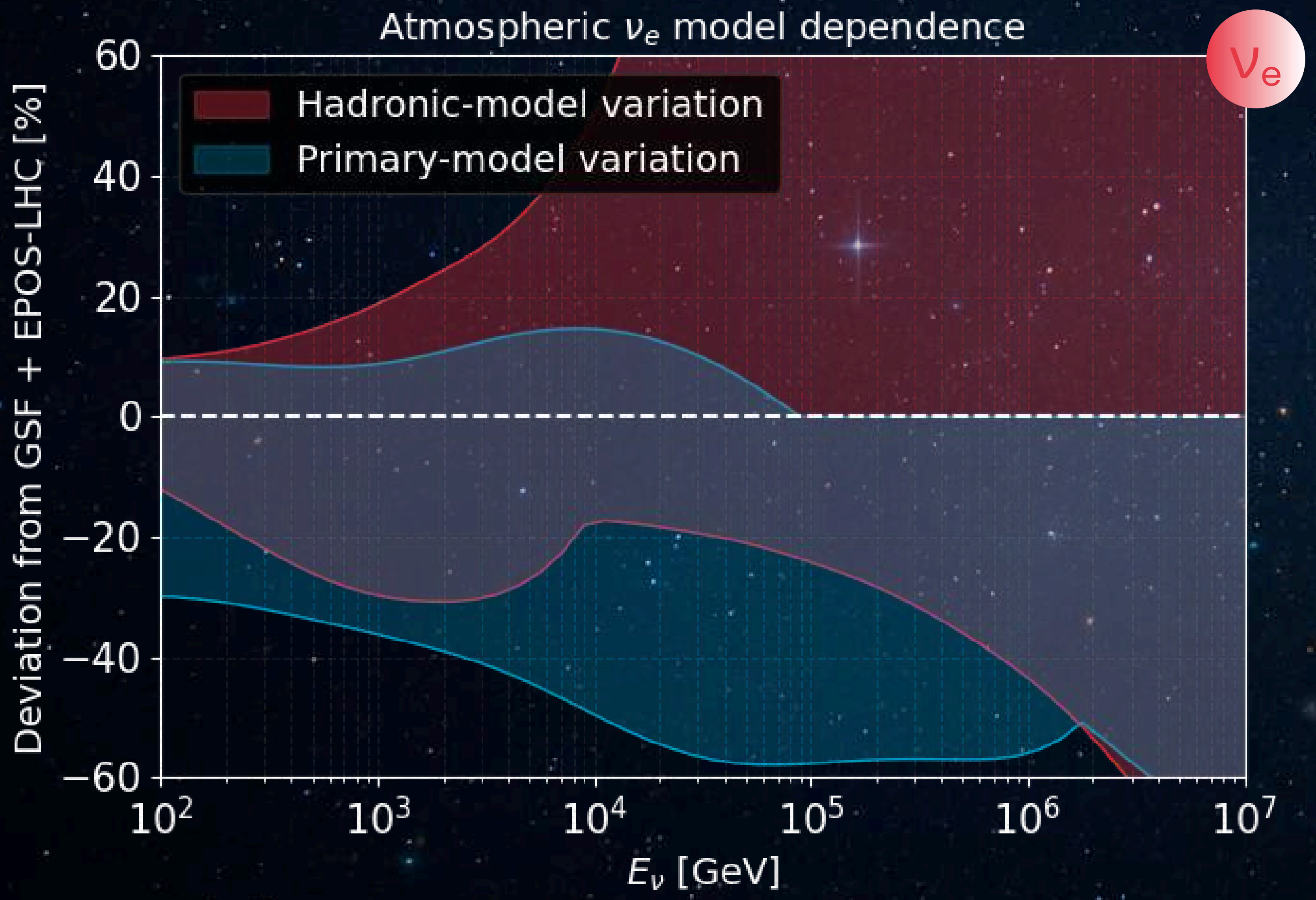


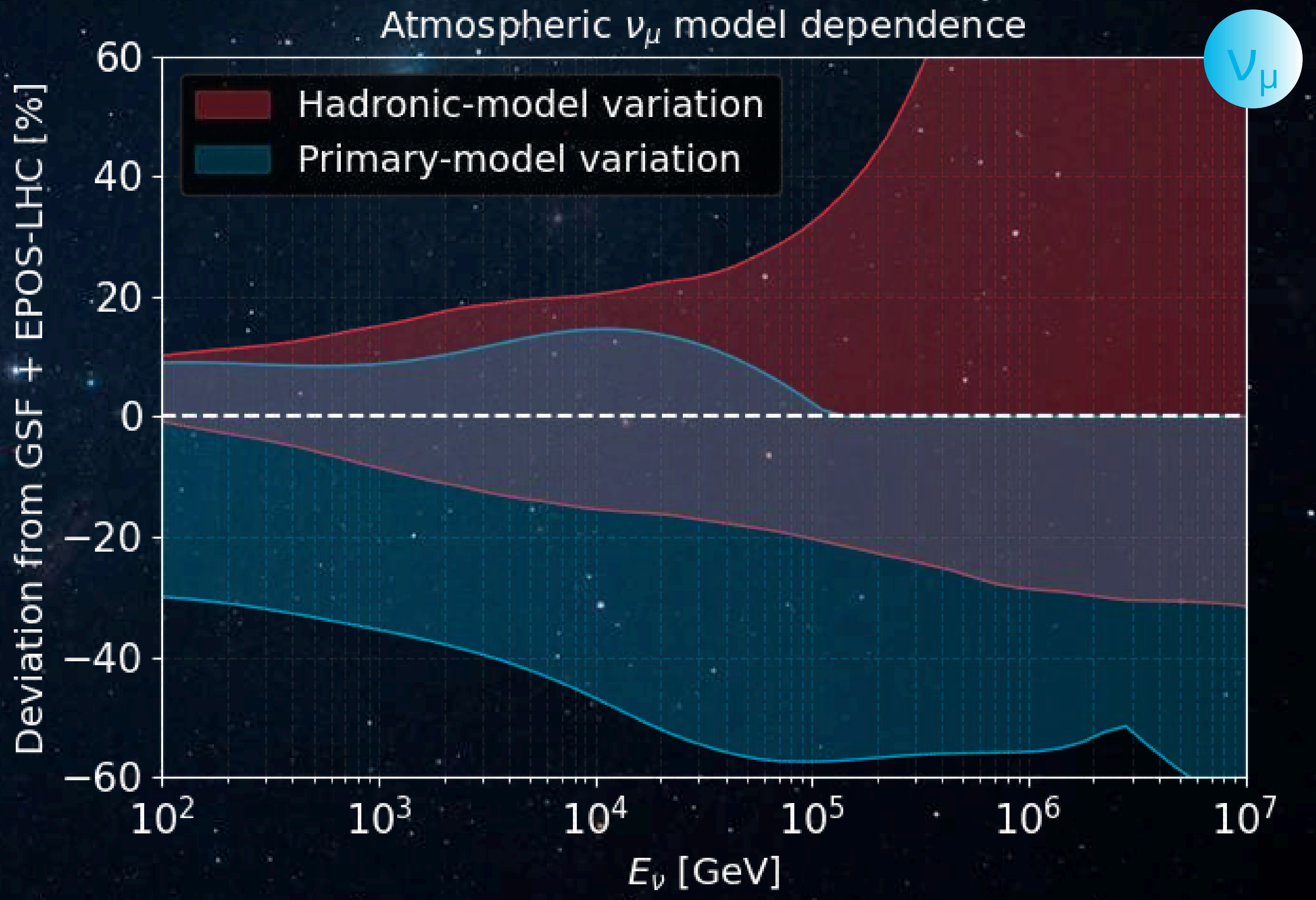
Described by Primary Models

Described by Hadronic Interaction Models

Model Dependence

Atmospheric neutrino fluxes remain poorly constrained, showing significant model-to-model variance.





Global Neutrino Experiments

Super-Kamiokande

- Large water-Cherenkov detector located in **Japan**.
- Provides high-statistics measurements of atmospheric neutrinos.
- Sensitive to both ν_e and ν_μ over the GeV energy range.

IceCube / AMANDA

- Located at the **South Pole**.
- Large-volume neutrino telescopes designed to detect high-energy neutrinos.
- Provides atmospheric neutrino measurements over a broad energy range.

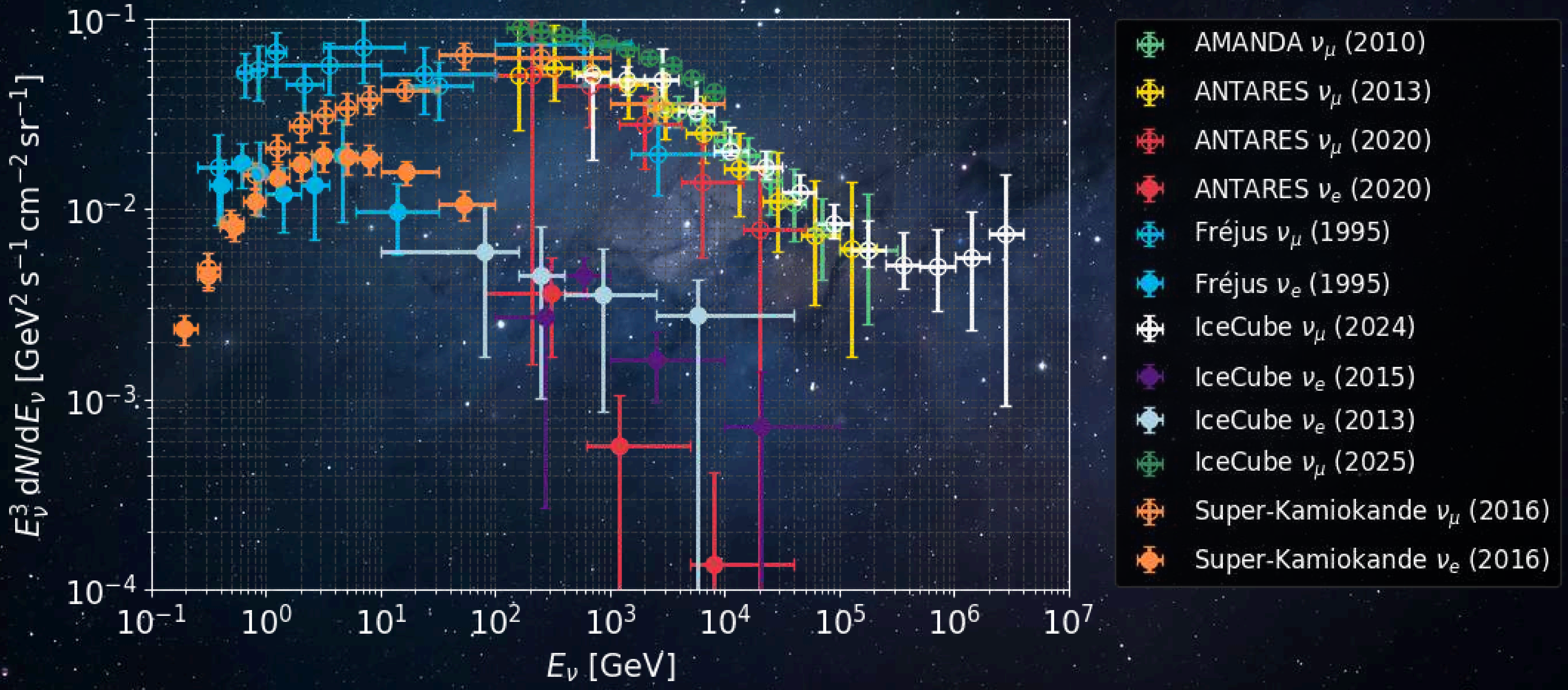
KM3NeT / ANTARES

- Underwater neutrino telescopes located in the **Mediterranean Sea**.
- Observe neutrinos from the Northern Hemisphere.
- Complement IceCube with a different geographical viewpoint.

Fréjus

- Underground neutrino detector located in the **French Alps**.
- One of the earlier experiments to measure atmospheric neutrino fluxes.
- Provides measurements at relatively low neutrino energies.

Global Neutrino Measurements



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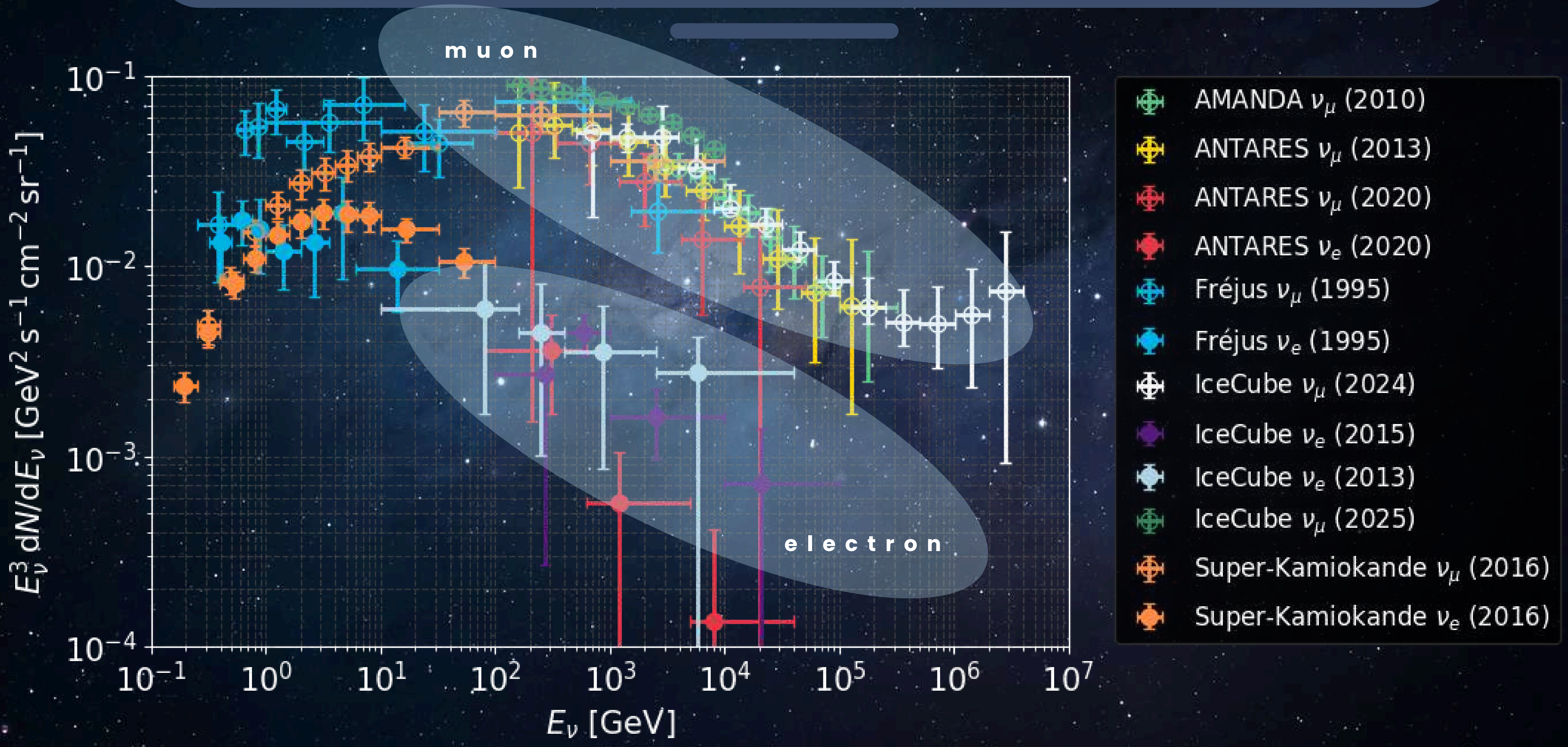

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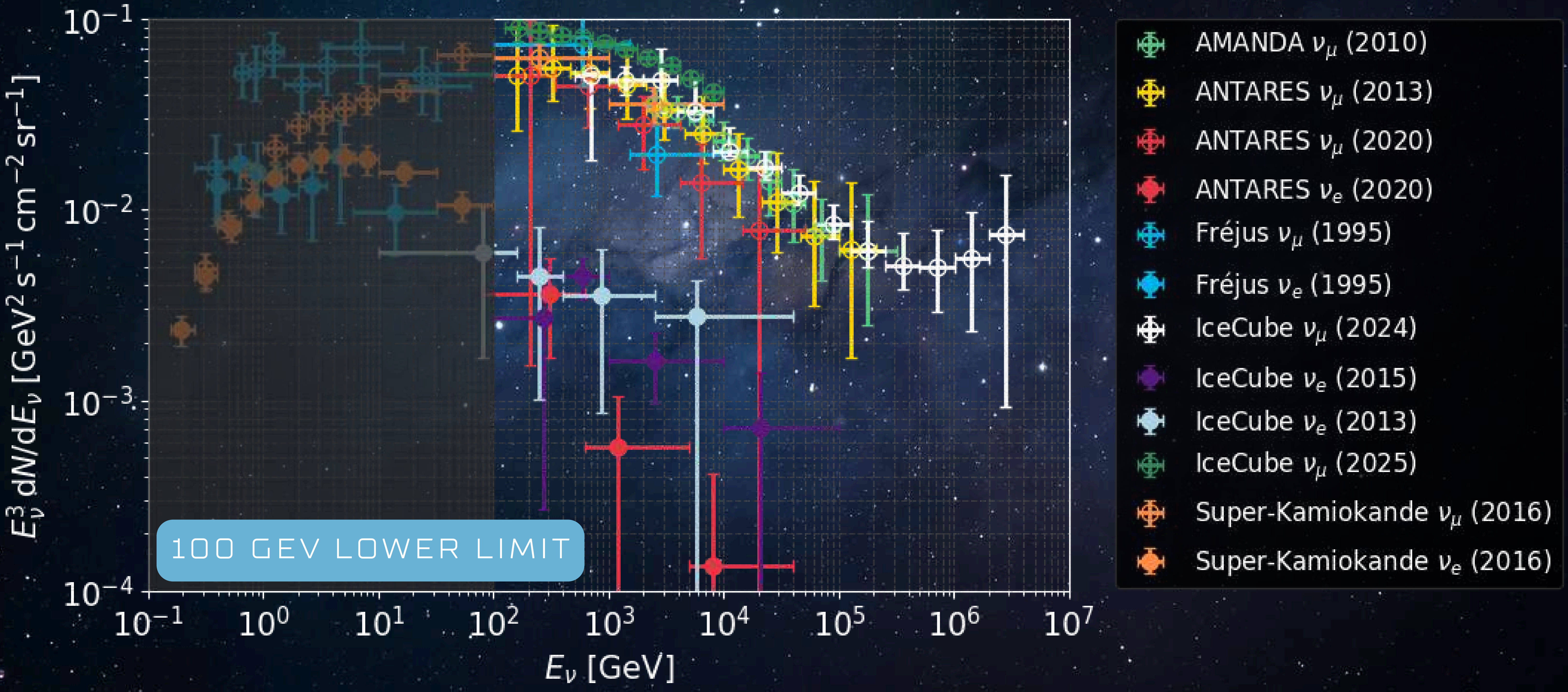

Global Neutrino Measurements

To quantify theoretical agreement, each MCEq prediction is **integrated over the experimental energy bins** and evaluated against measurement data using a **χ^2 minimization** function. This joint fit incorporates uncertainties and optional **astrophysical components**, to select the **best-fit primary composition and hadronic model** for each dataset.

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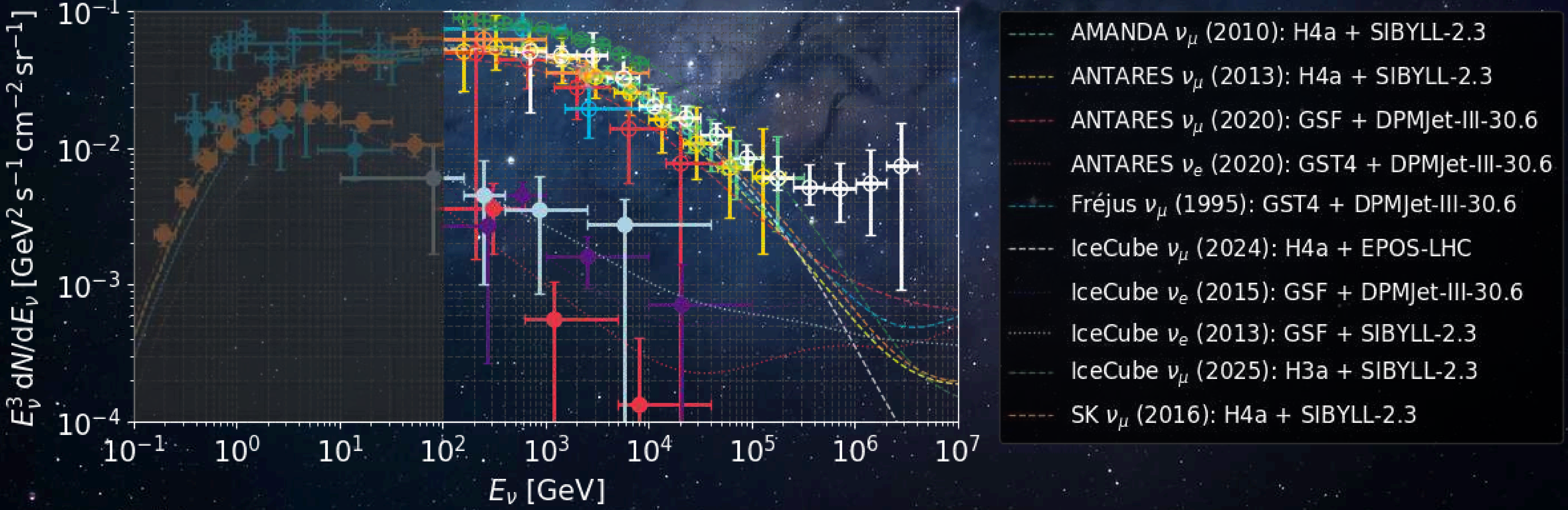

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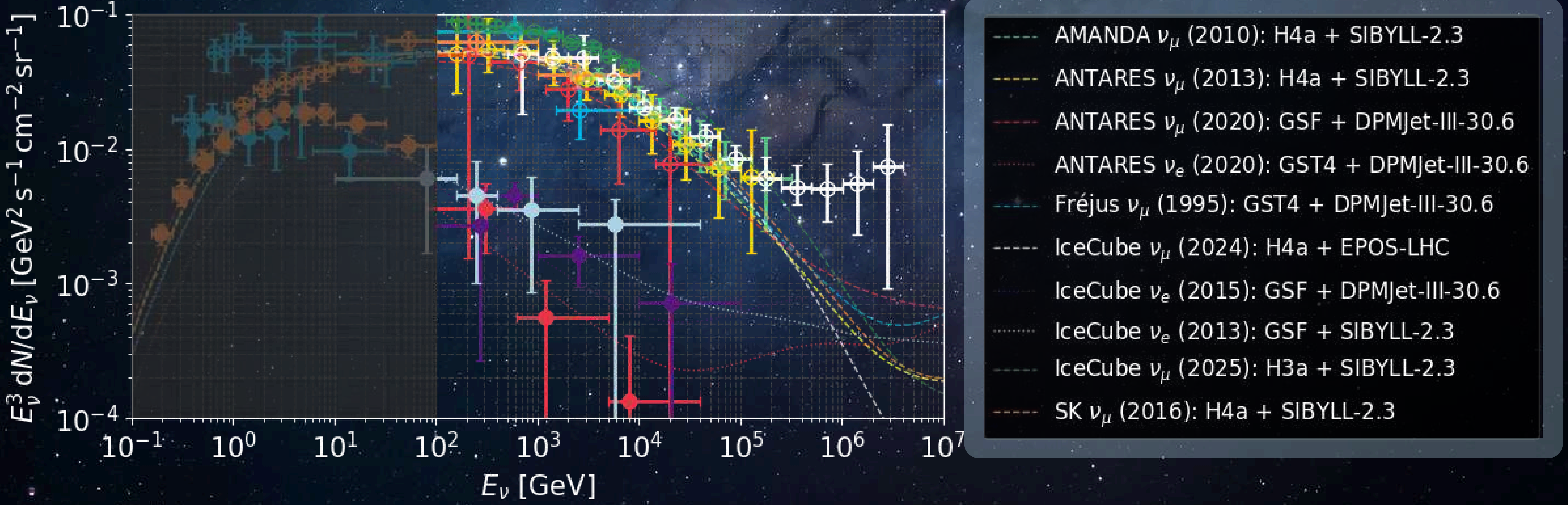
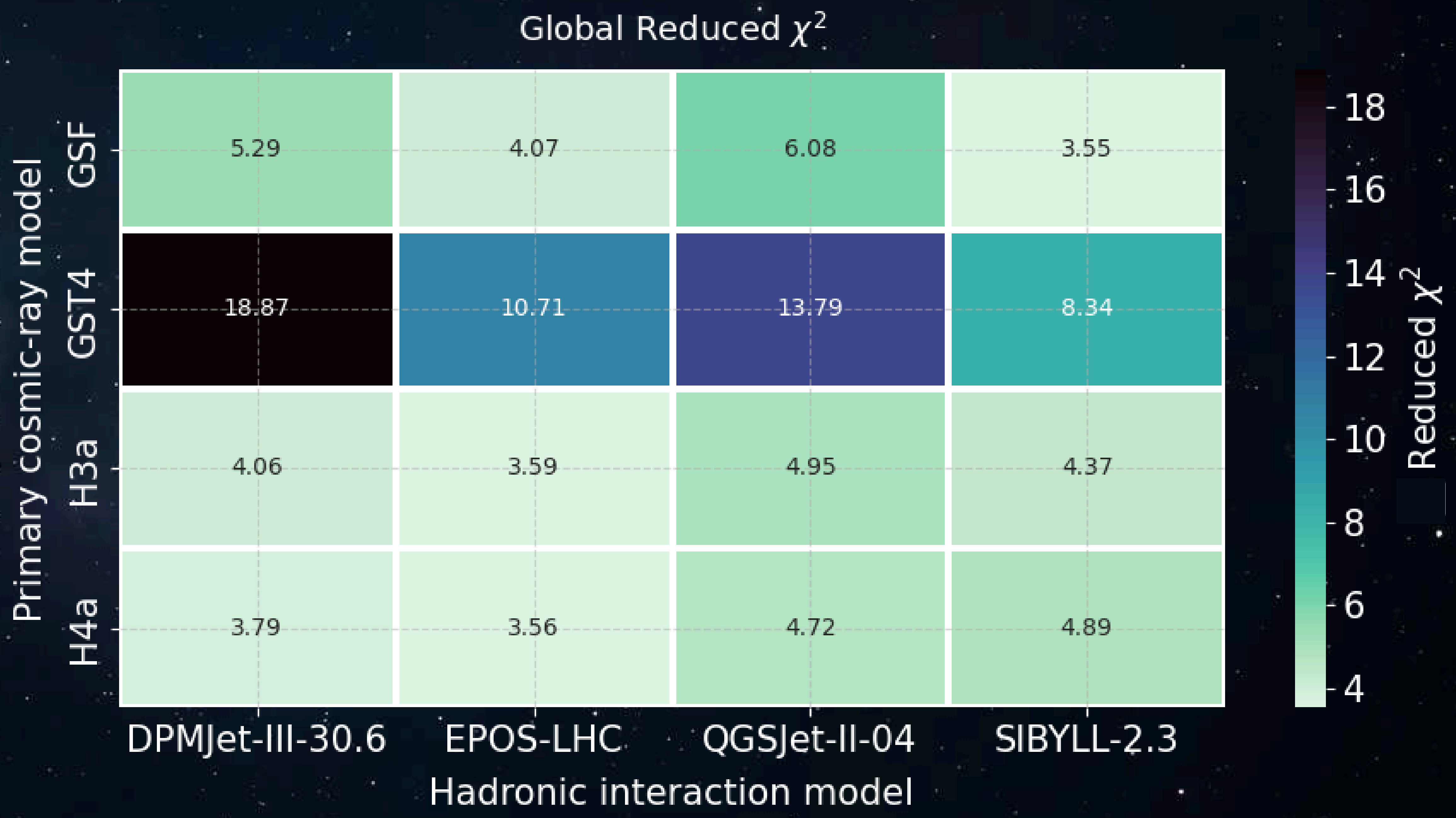


Overall Fit Performance

Global Model Performance

- **Global Model Ranking**: Evaluates overall agreement across all experimental datasets simultaneously.



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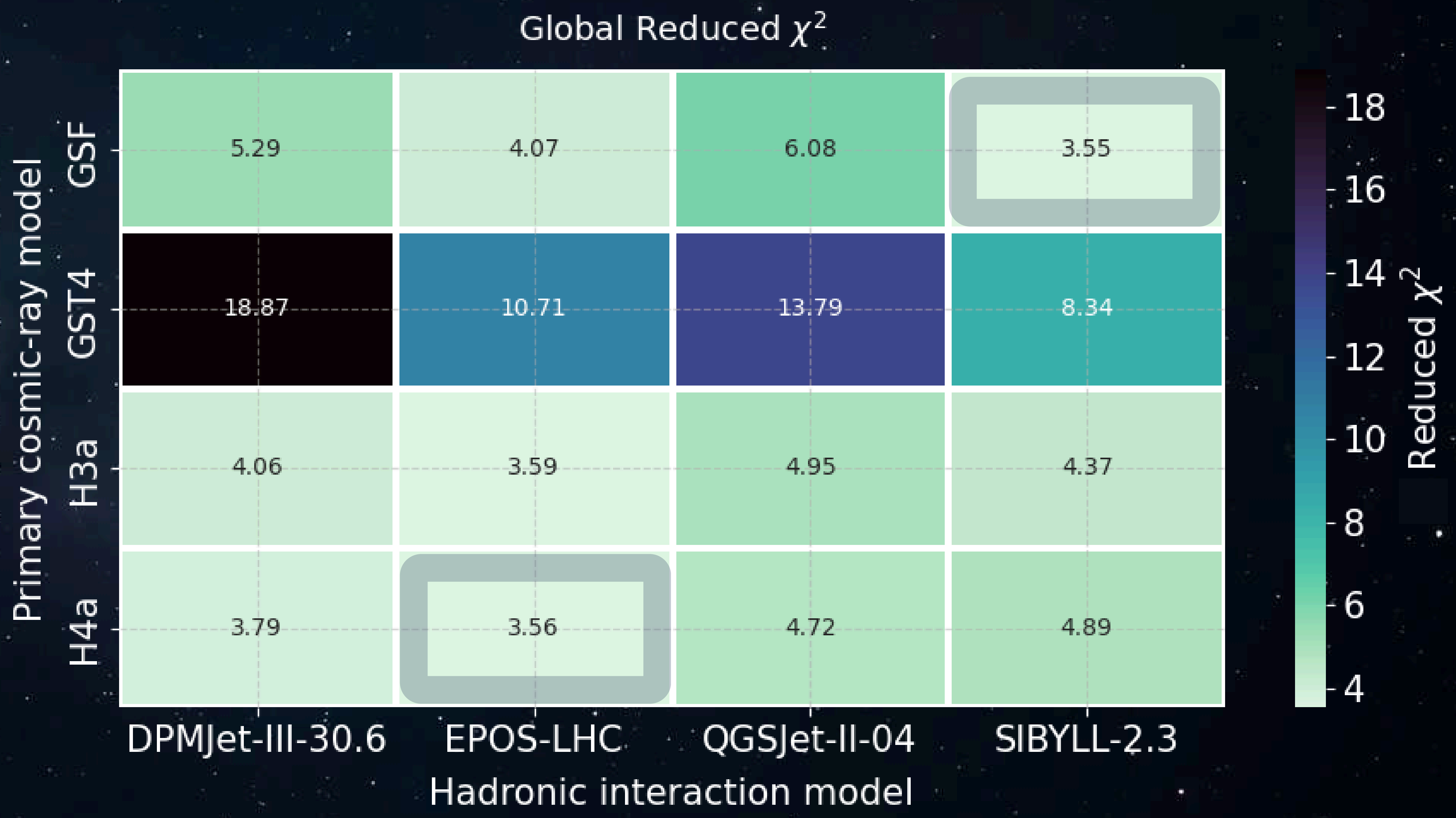
  GSF + SIBYLL-2.3 (χ^2 = 3.55) followed by **H4a + EPOS-LHC** (χ^2 = 3.56).



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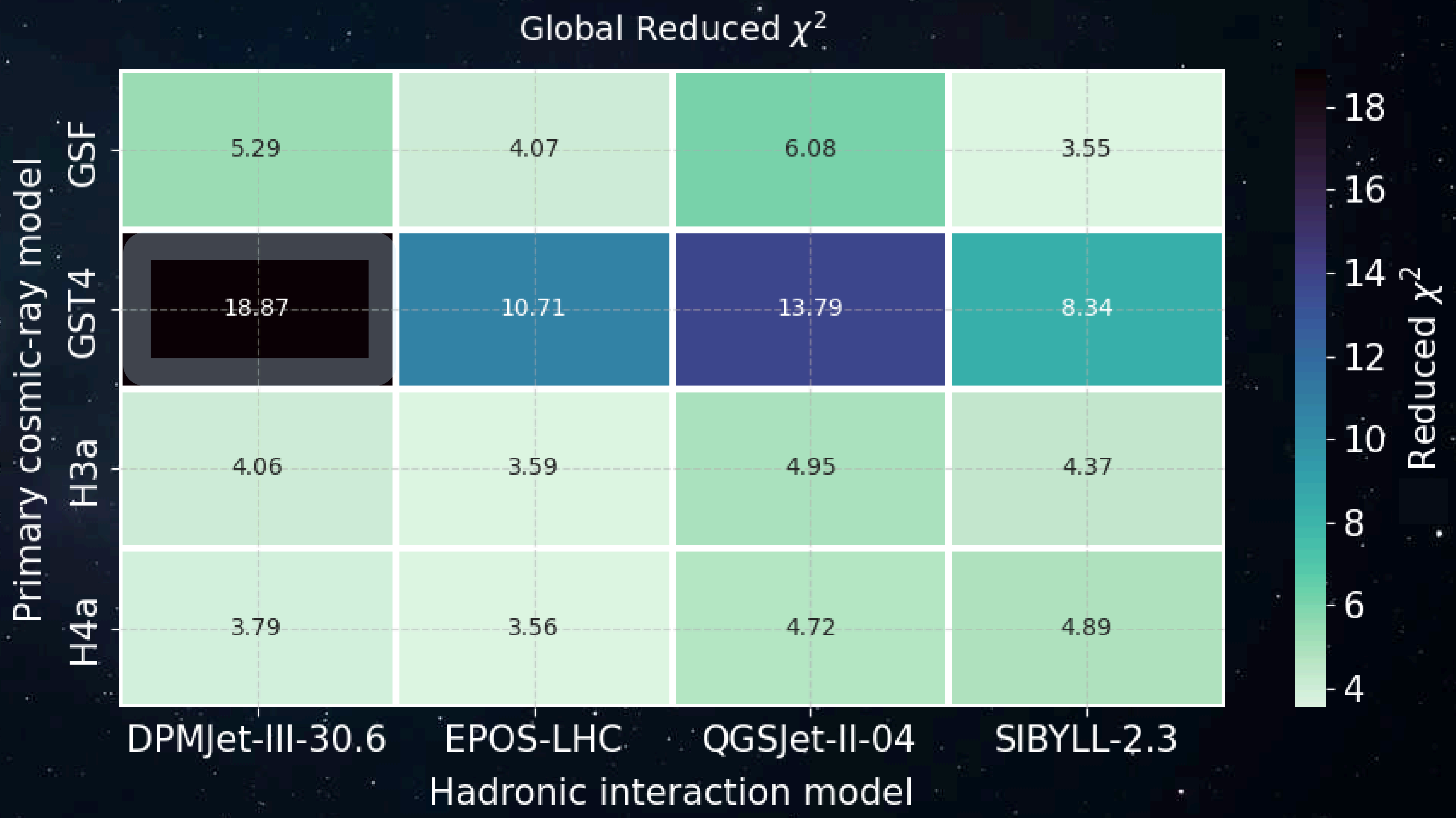
- Significant Discrepancies:
  GST4 + DPMJet-III-30.6 shows a severe mismatch (χ^2 = 18.87), driven by high energy flux overpredictions.



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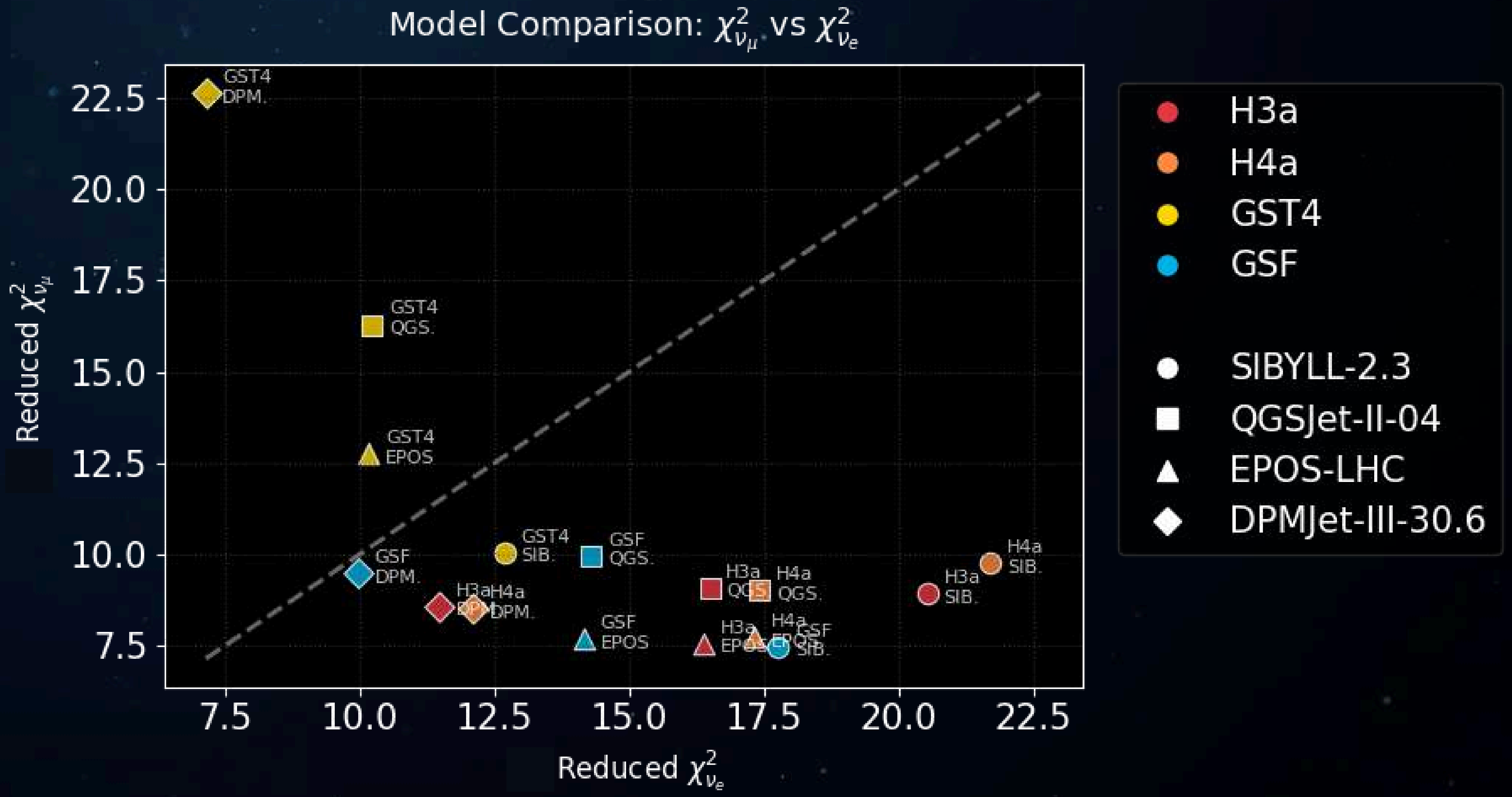
Flavor-Dependent Fit Quality

Model Performance per Flavor

- **Flavor Symmetry**: Points below the diagonal (y = x) line indicate models that fit ν_e **datapoints** worse than ν_μ **datapoints** , vice versa.



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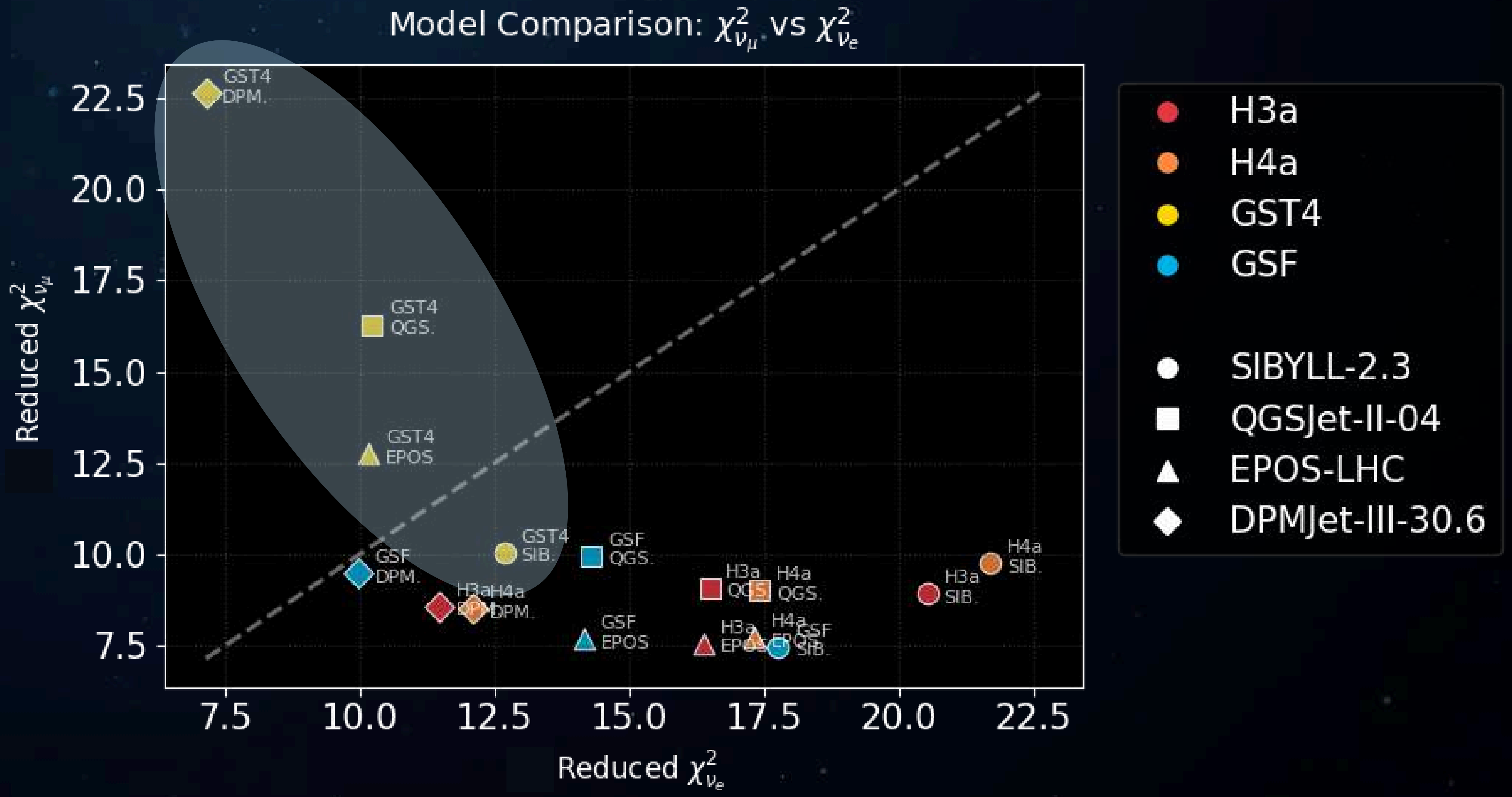

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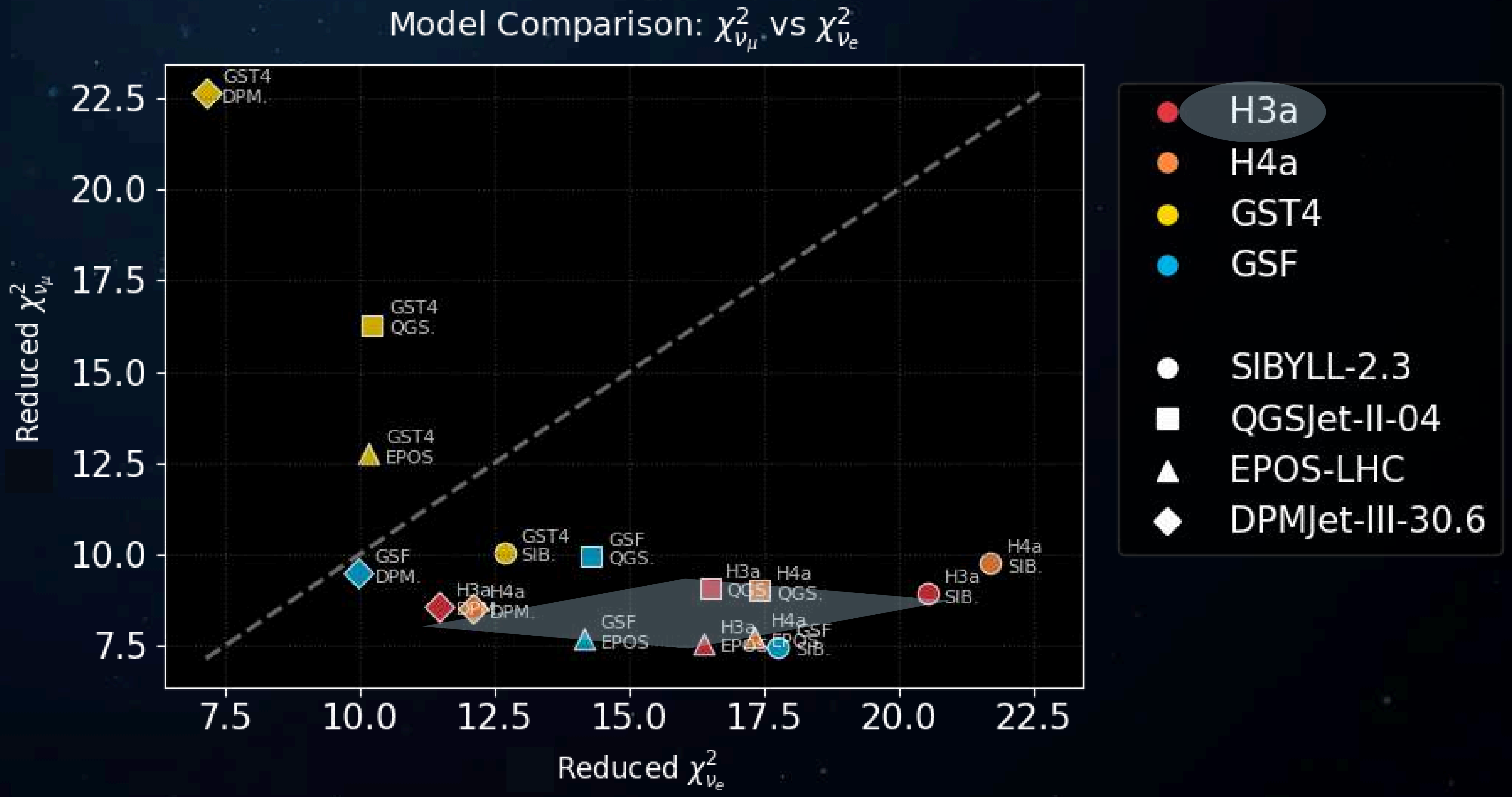

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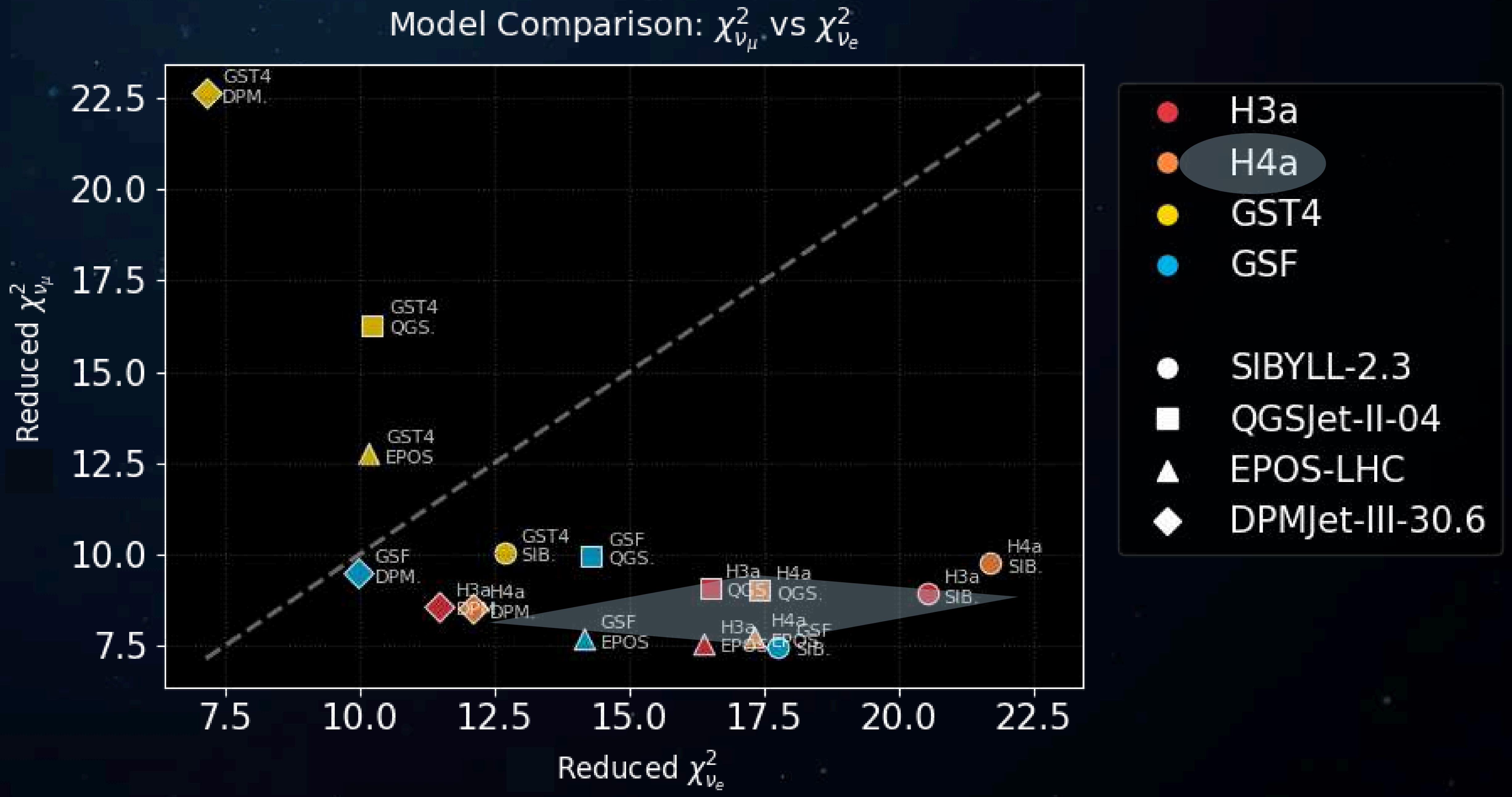

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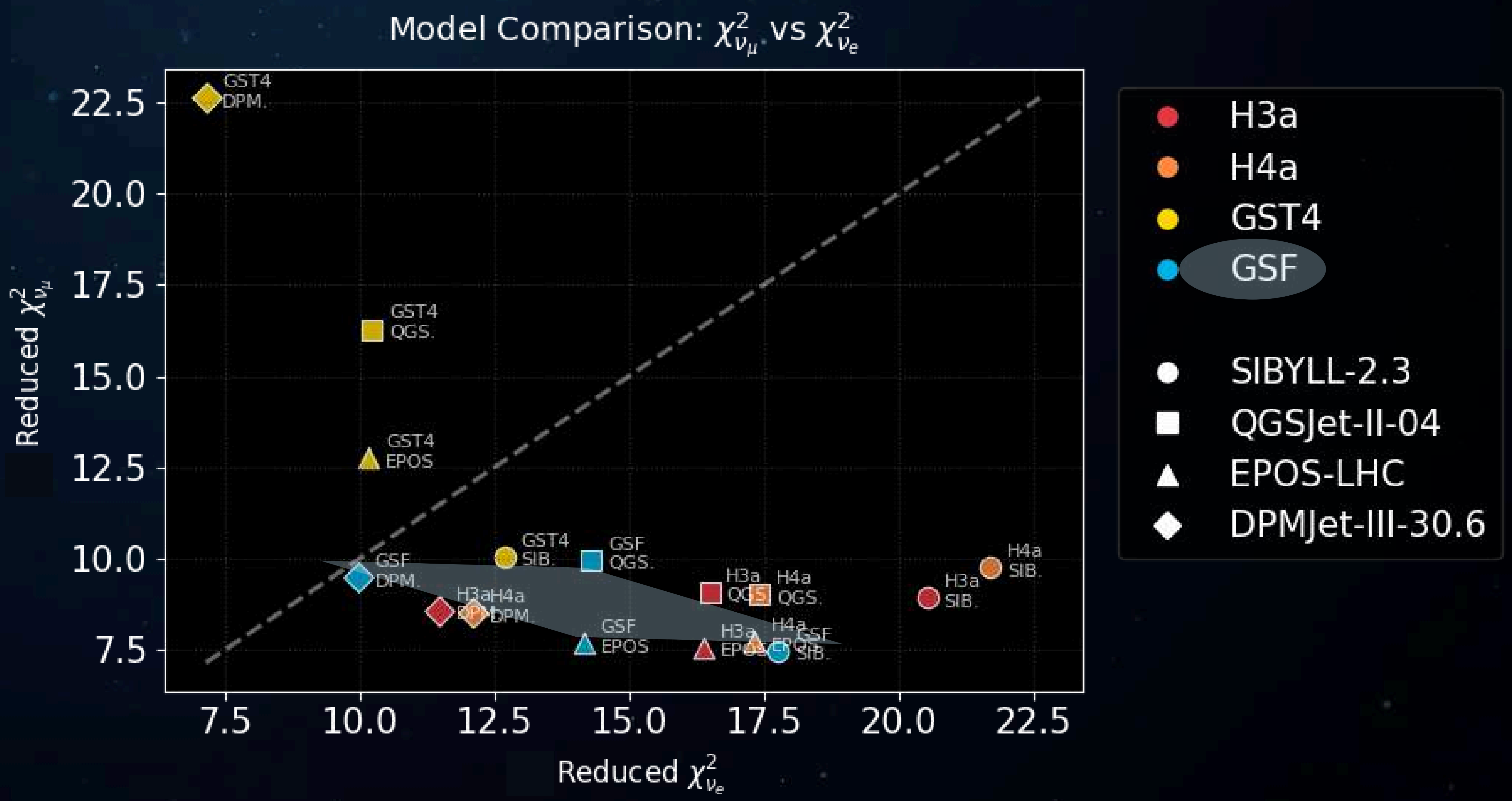

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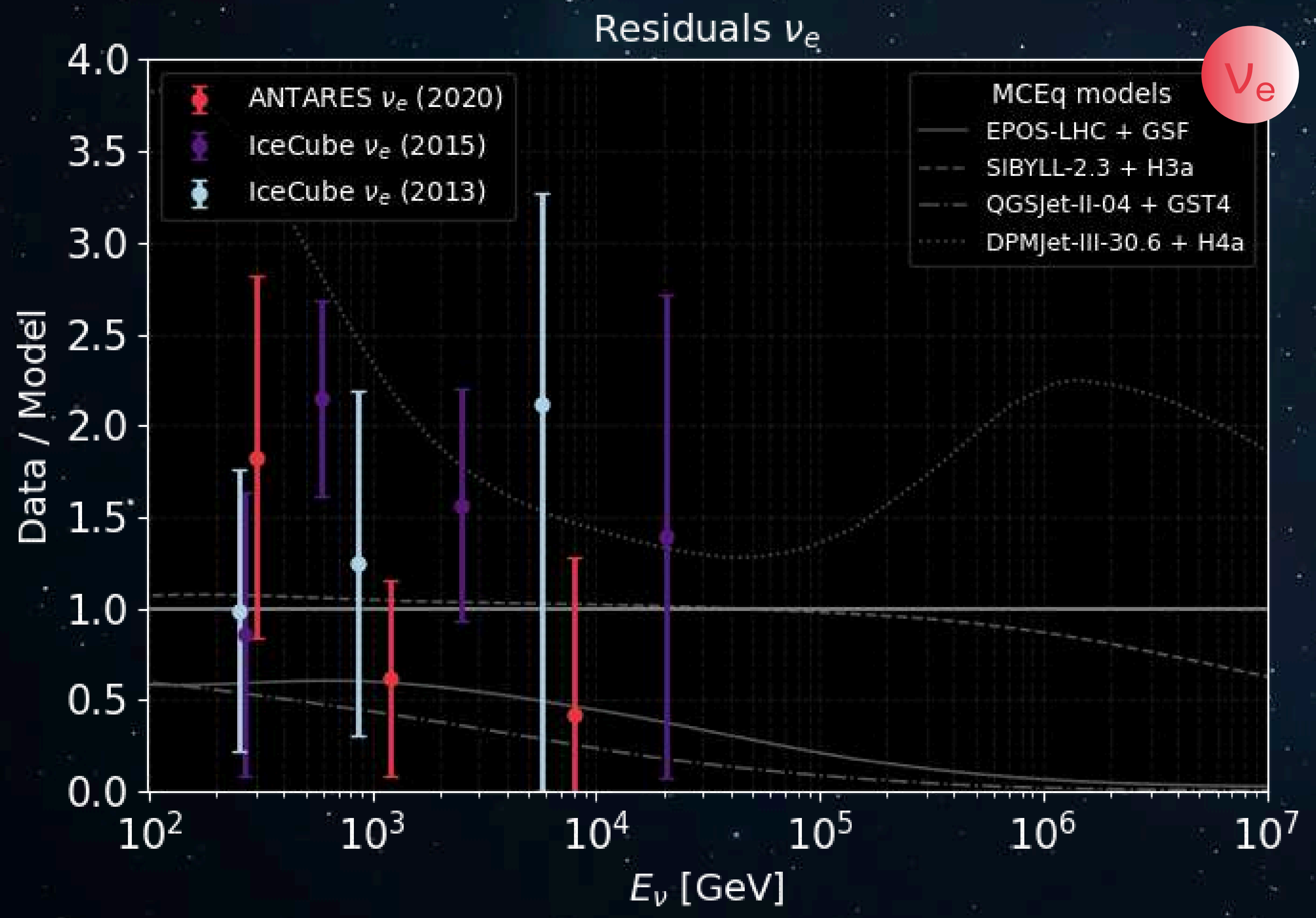
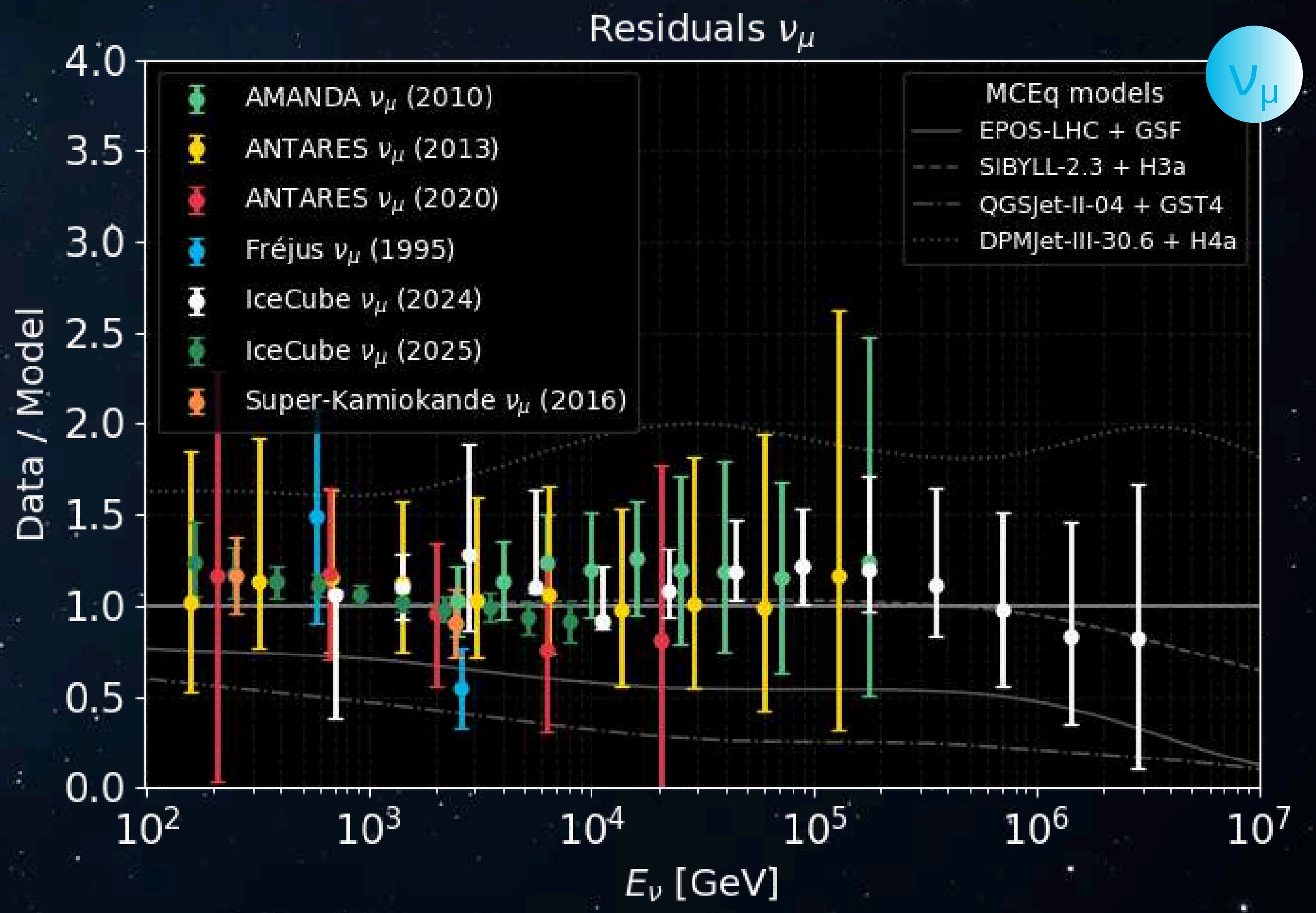
Residuals

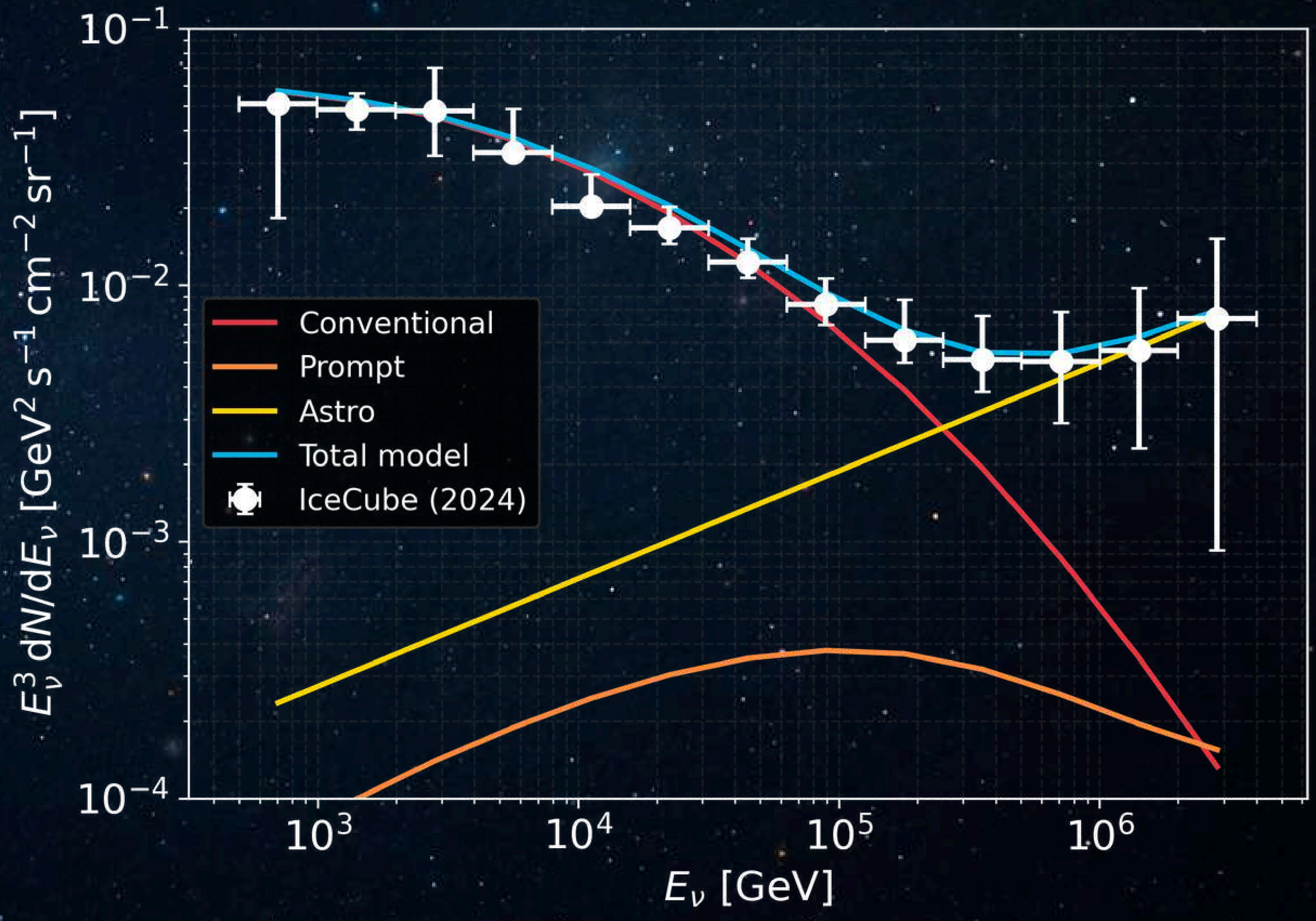
For ν_μ data-to-model flux ratios remain **well-centered** around unity across **10^2 to 10^7 GeV**, confirming **consistent flux agreement** across diverse experimental datasets with at least one theoretical model. For **ν_e** less constrainment visible.





Fit Atmospheric Normalisations

- *Component Decomposition*: Disentangles the total predicted flux into **Conventional** (π, K decay), **Prompt** (charmed hadron decay), and **Astrophysical power-law** contributions.



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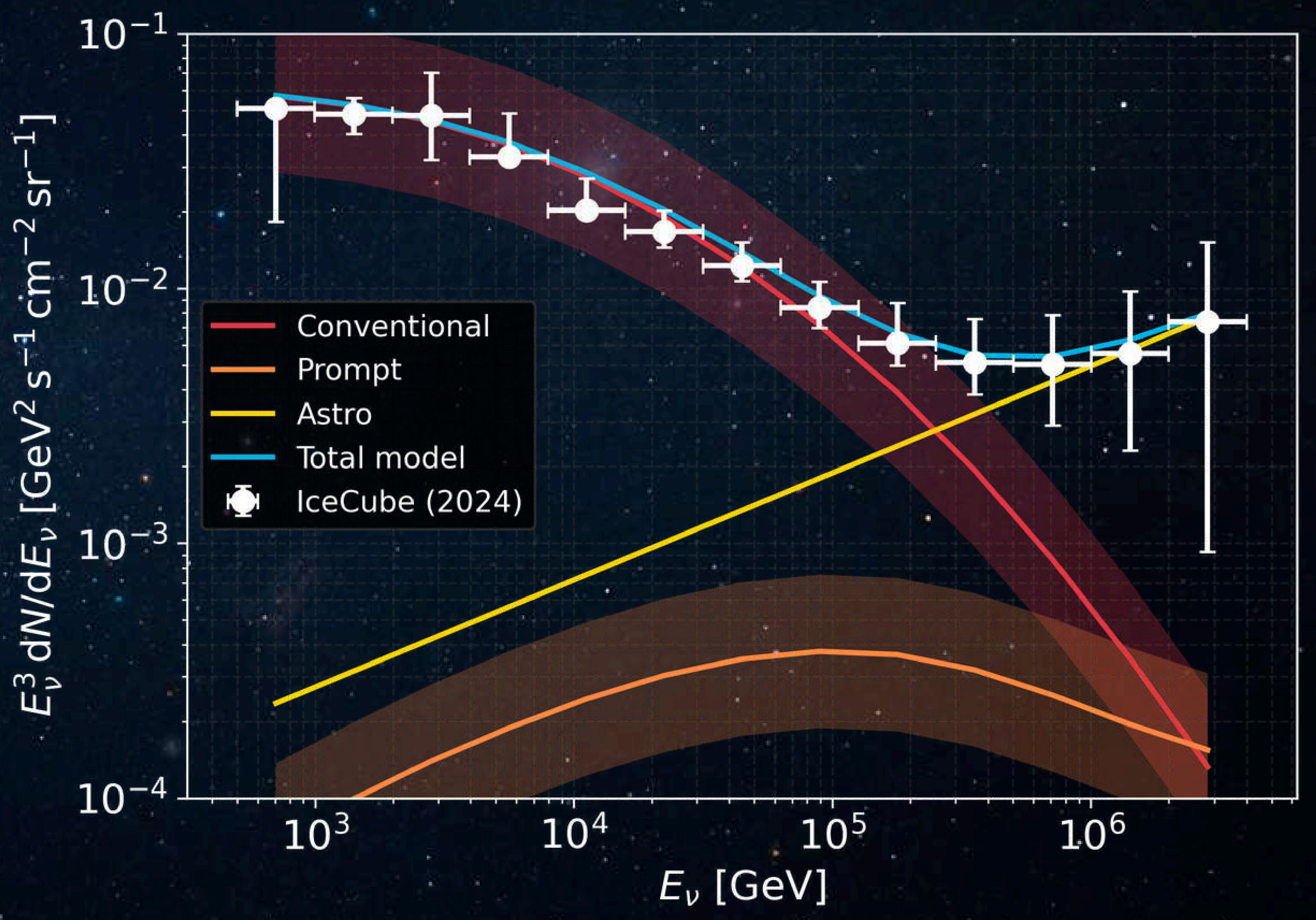

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- *Least-χ^2 Minimization*: **Fits model scale** factors directly to experimental data using asymmetric error weighting.

$$\Phi_{\text{total}}(E) = c_{\text{conv}}\,\Phi_{\text{conv}}(E) + c_{\text{prompt}}\,\Phi_{\text{prompt}}(E) + \Phi_{\text{astro}}(E)$$

$$\chi^2(c_{\text{conv}}, c_{\text{prompt}}) = \sum_i \left(\frac{\Phi_i^{\text{data}} - \langle \Phi_{\text{total}} \rangle_i}{\sigma_i} \right)^2$$

$$\text{where} \quad \sigma_i = \begin{cases} \sigma_i^{\text{high}}, & \text{if } \Phi_i^{\text{data}} < \langle \Phi_{\text{total}} \rangle_i \\ \sigma_i^{\text{low}}, & \text{if } \Phi_i^{\text{data}} \geq \langle \Phi_{\text{total}} \rangle_i \end{cases}$$

$$S_{\text{prompt}} = \sqrt{\Delta\chi^2} = \sqrt{\chi^2(c_{\text{prompt}} = 0) - \chi^2_{\text{min}}}$$

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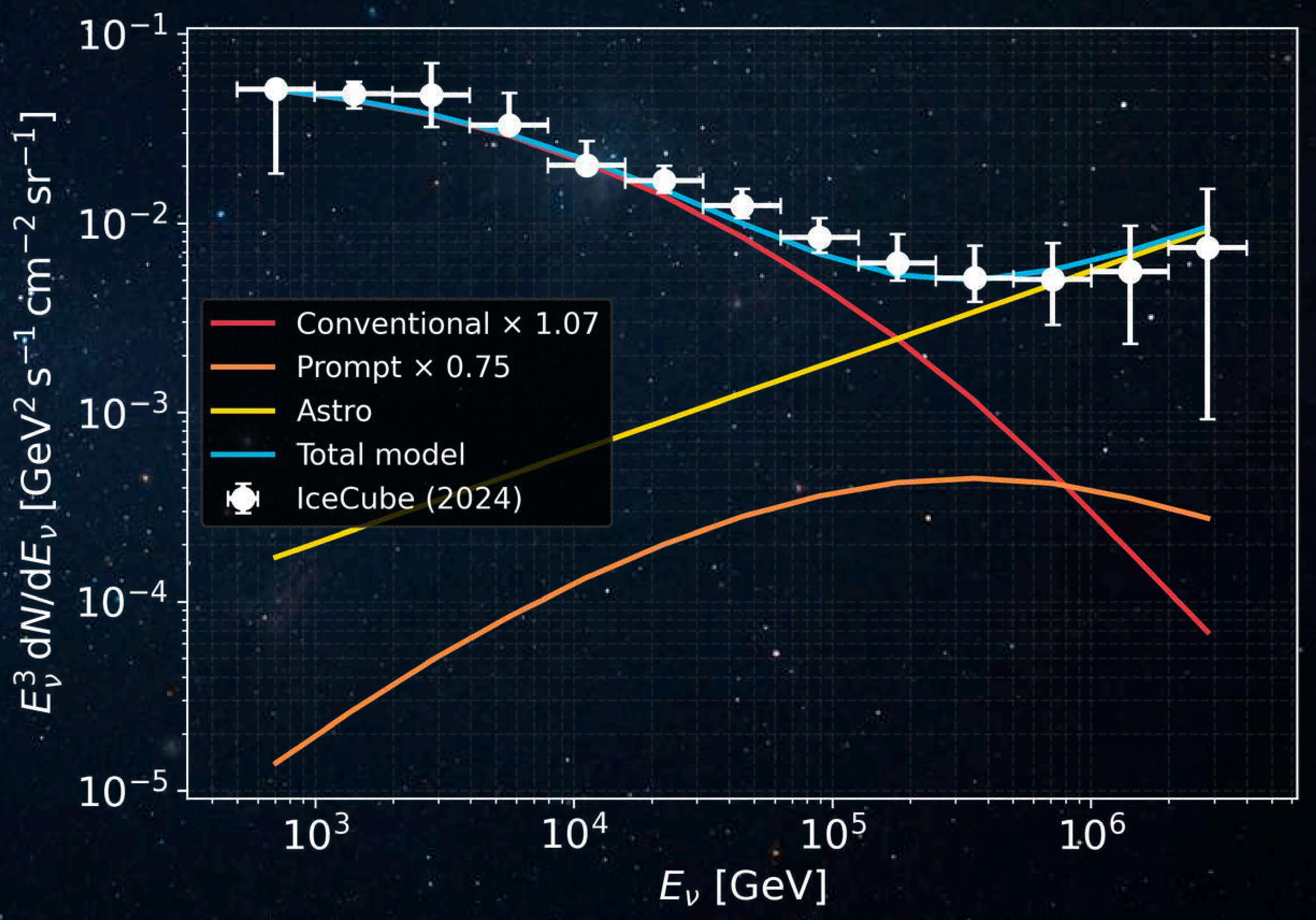
- Baseline Model for this example: **DPMJet-III-30.6** (Hadronic) + **H3a** (Primary Cosmic Ray)

- EXTRACTED SCALE FACTORS:
  - C_{CONV} = 1.07
  - C_{PROMPT} = 0.75

- Slight upward adjustment to π, K flux
- Suppressed charmed hadron contribution



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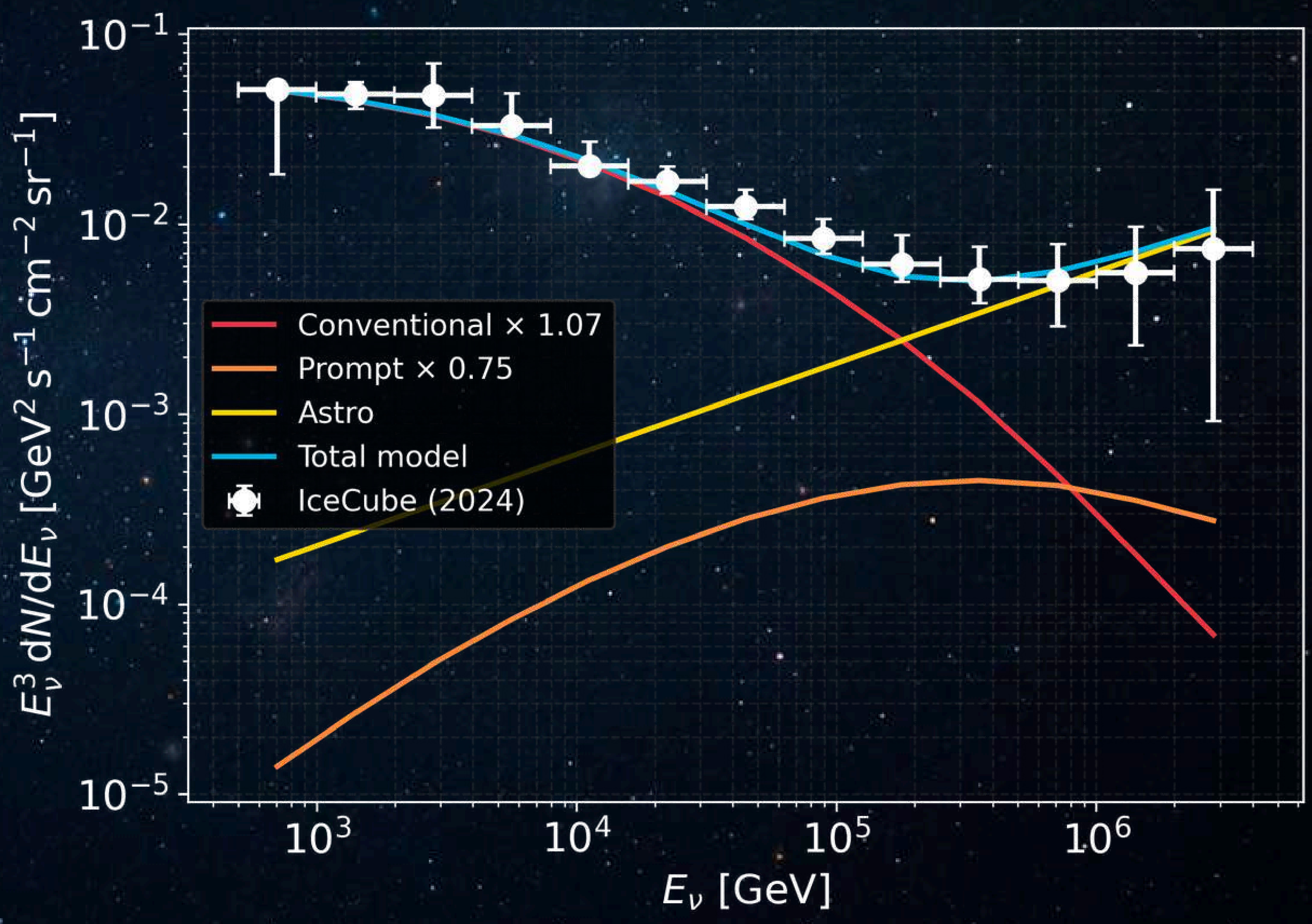

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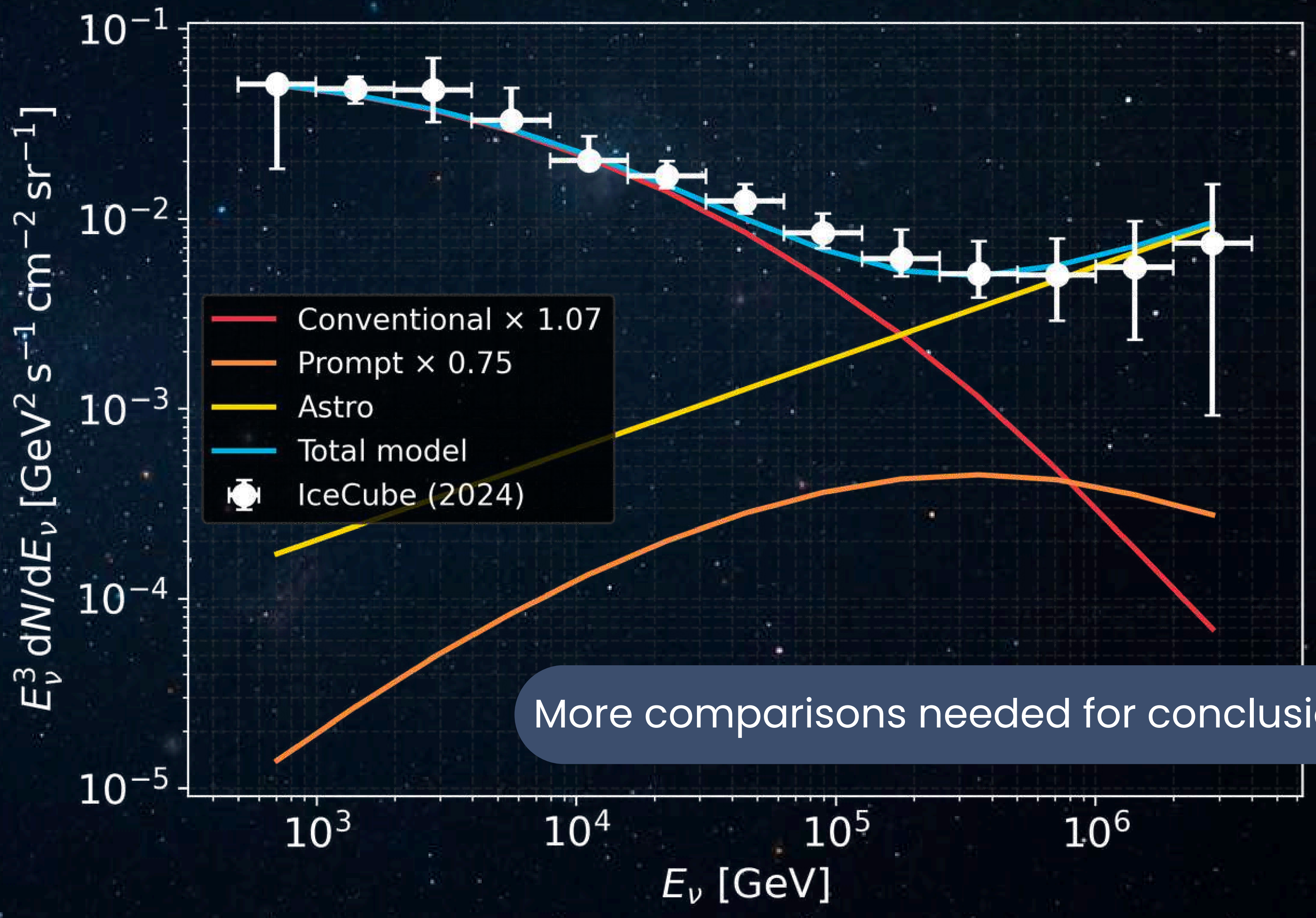
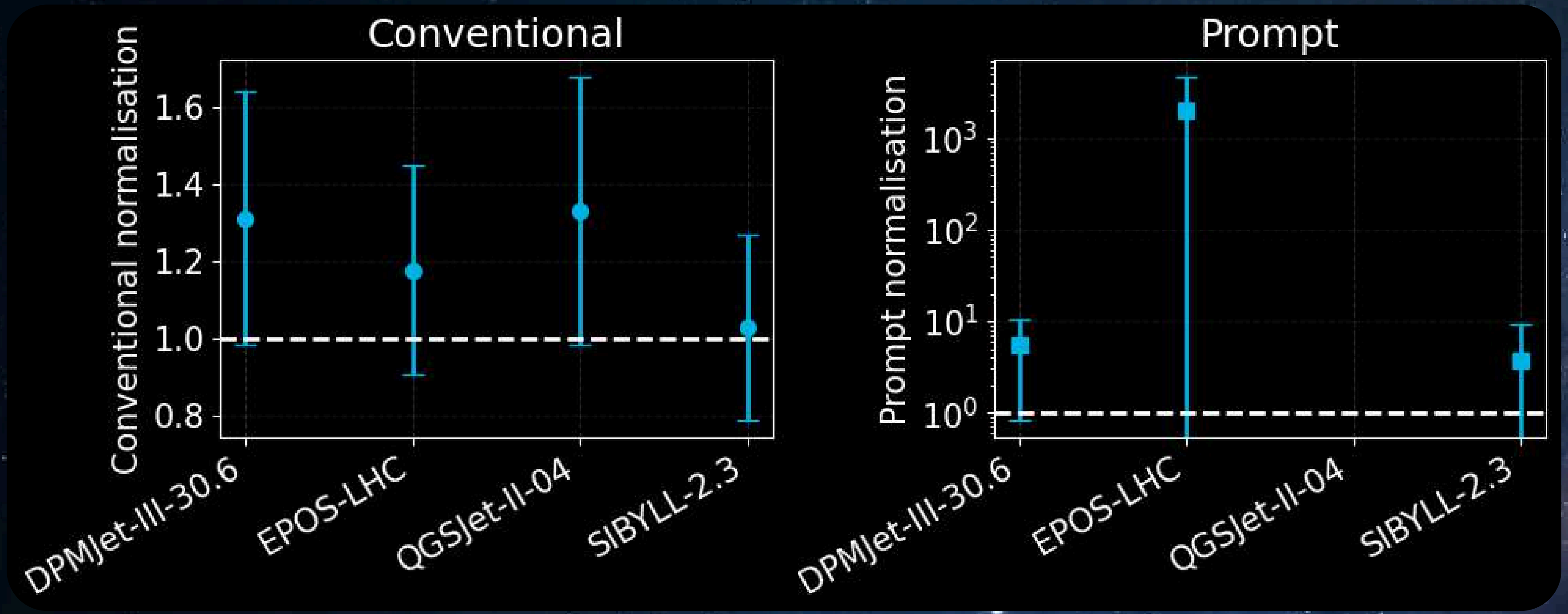
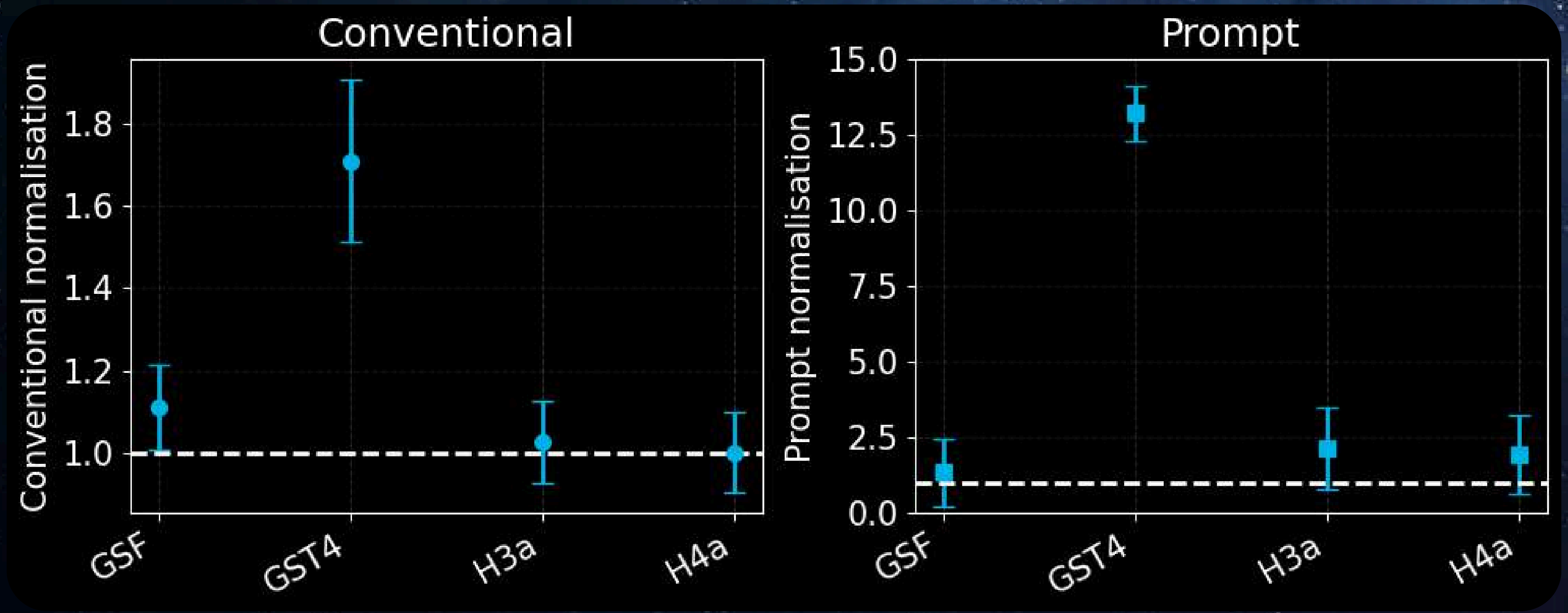


More comparisons needed for conclusions

IceCube ν_μ (2024) [500 GeV - 4 PeV]





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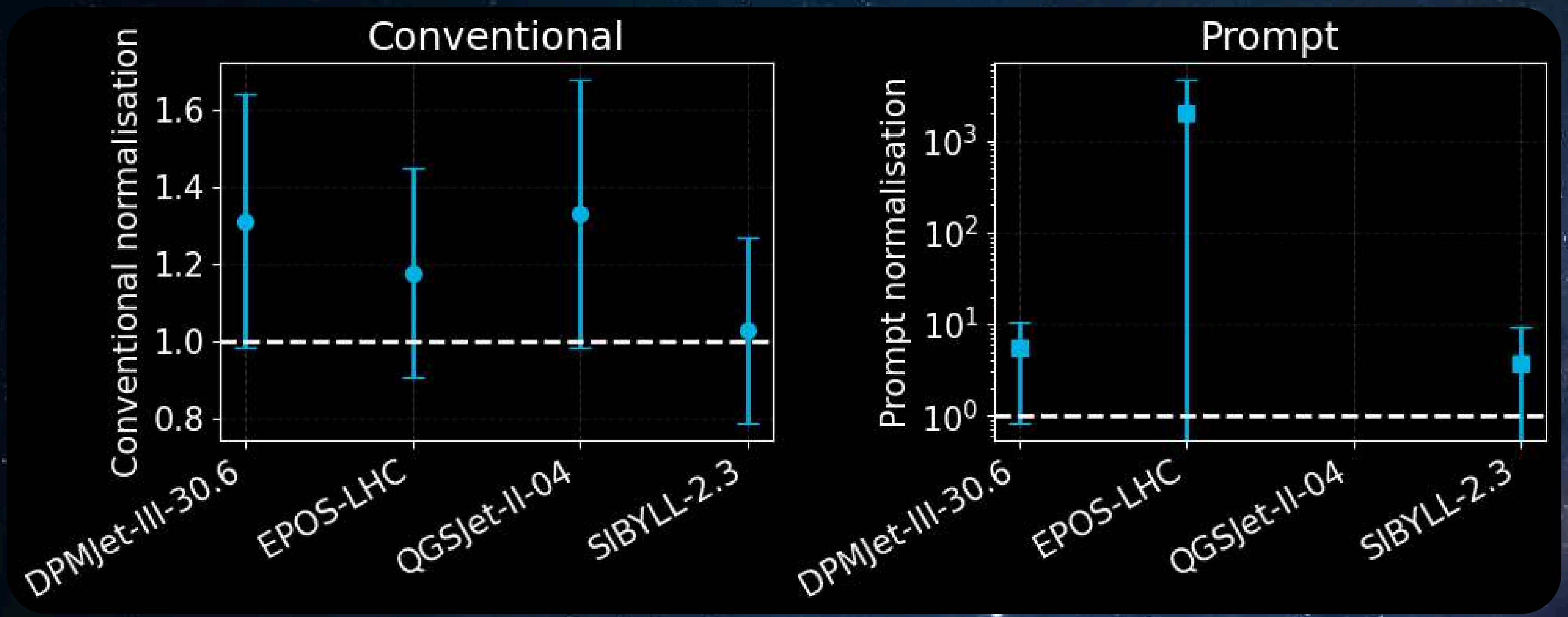
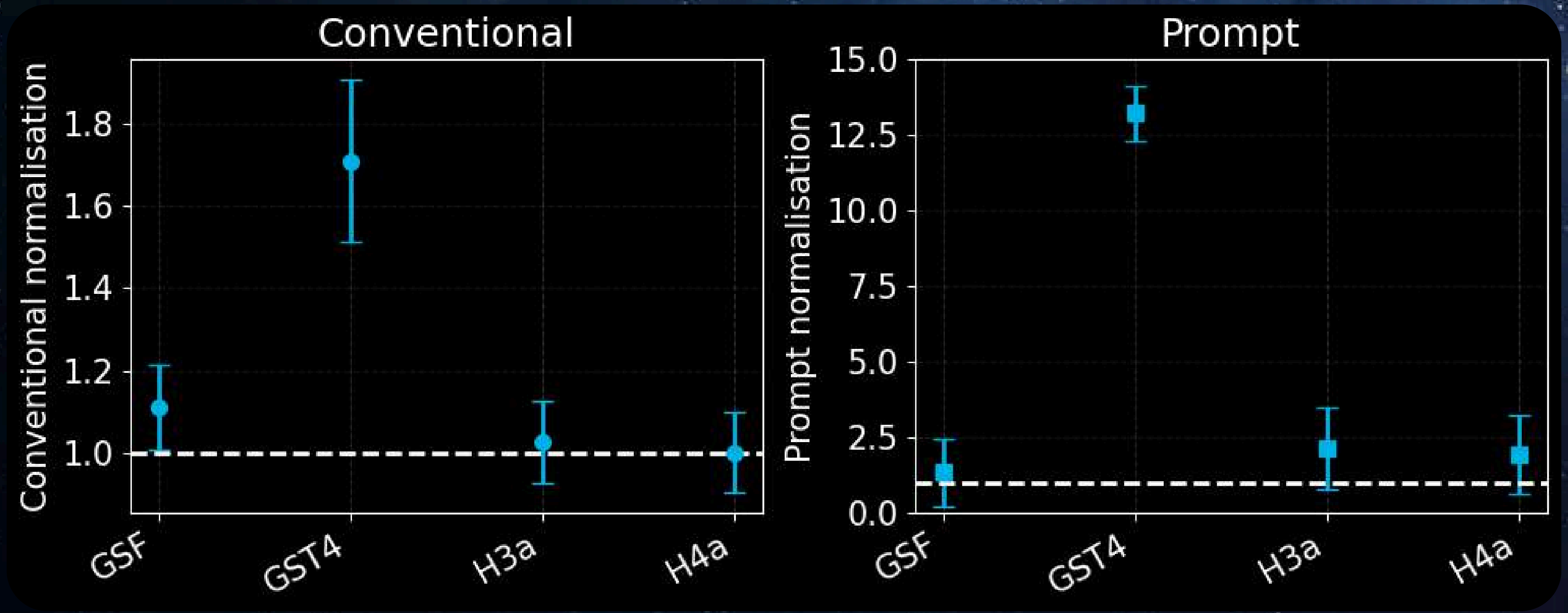
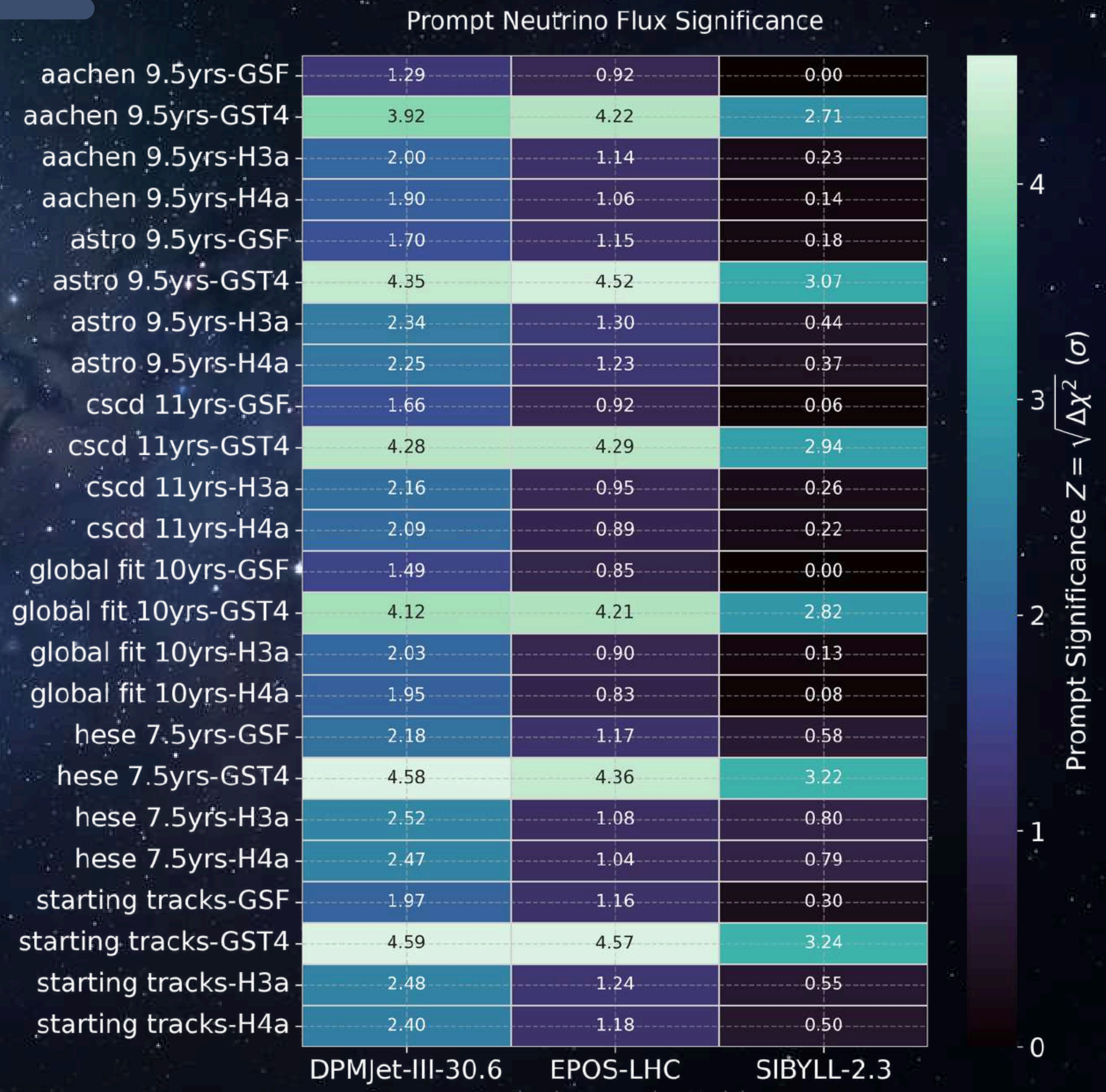
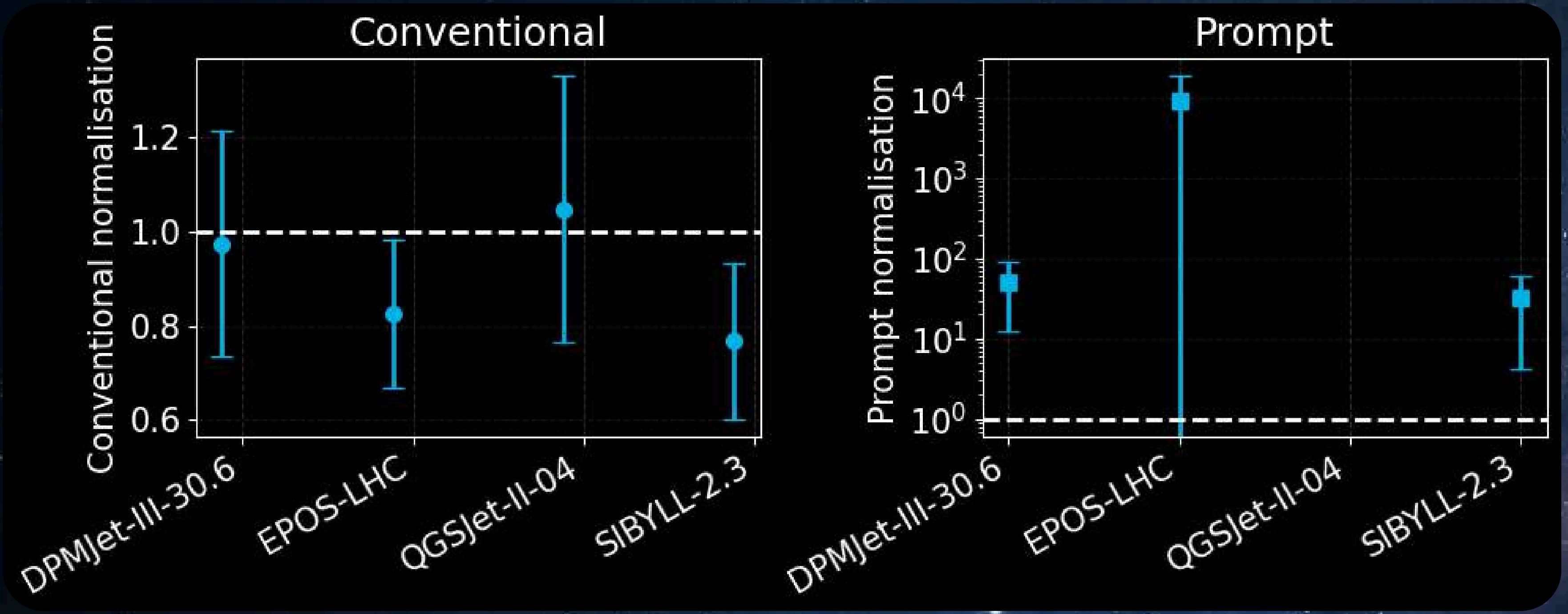
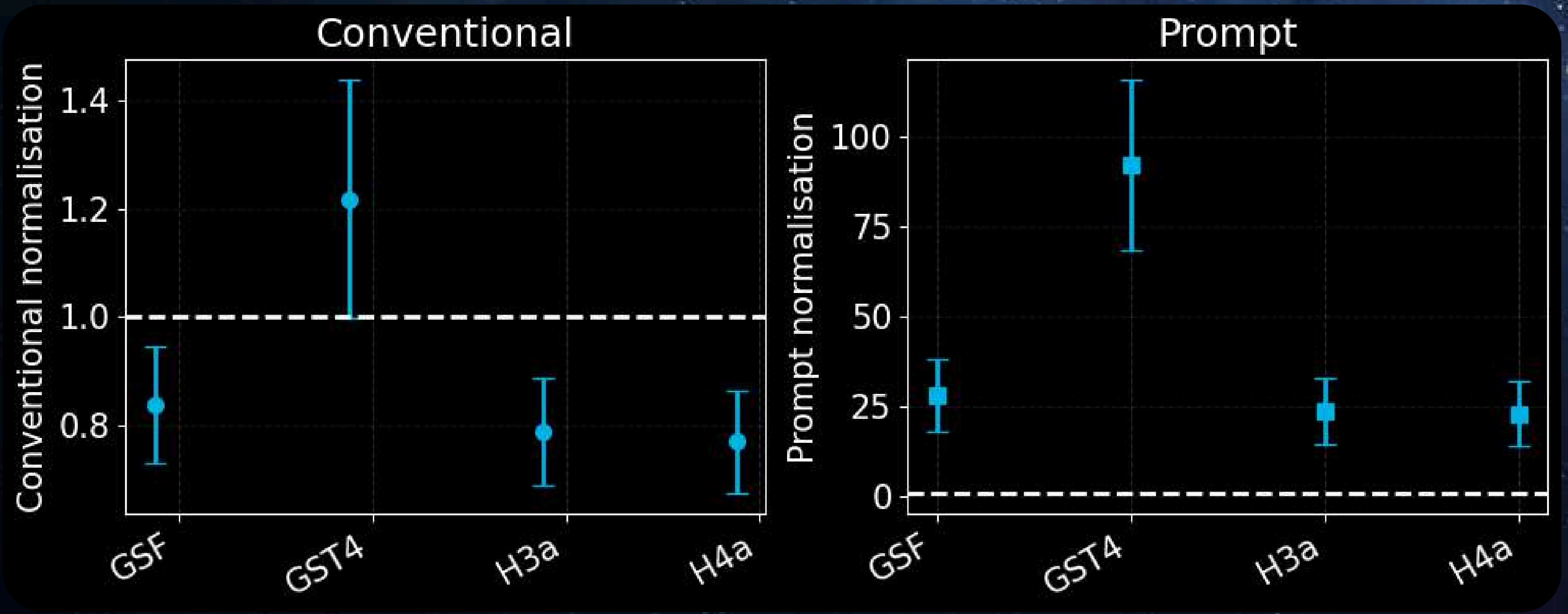


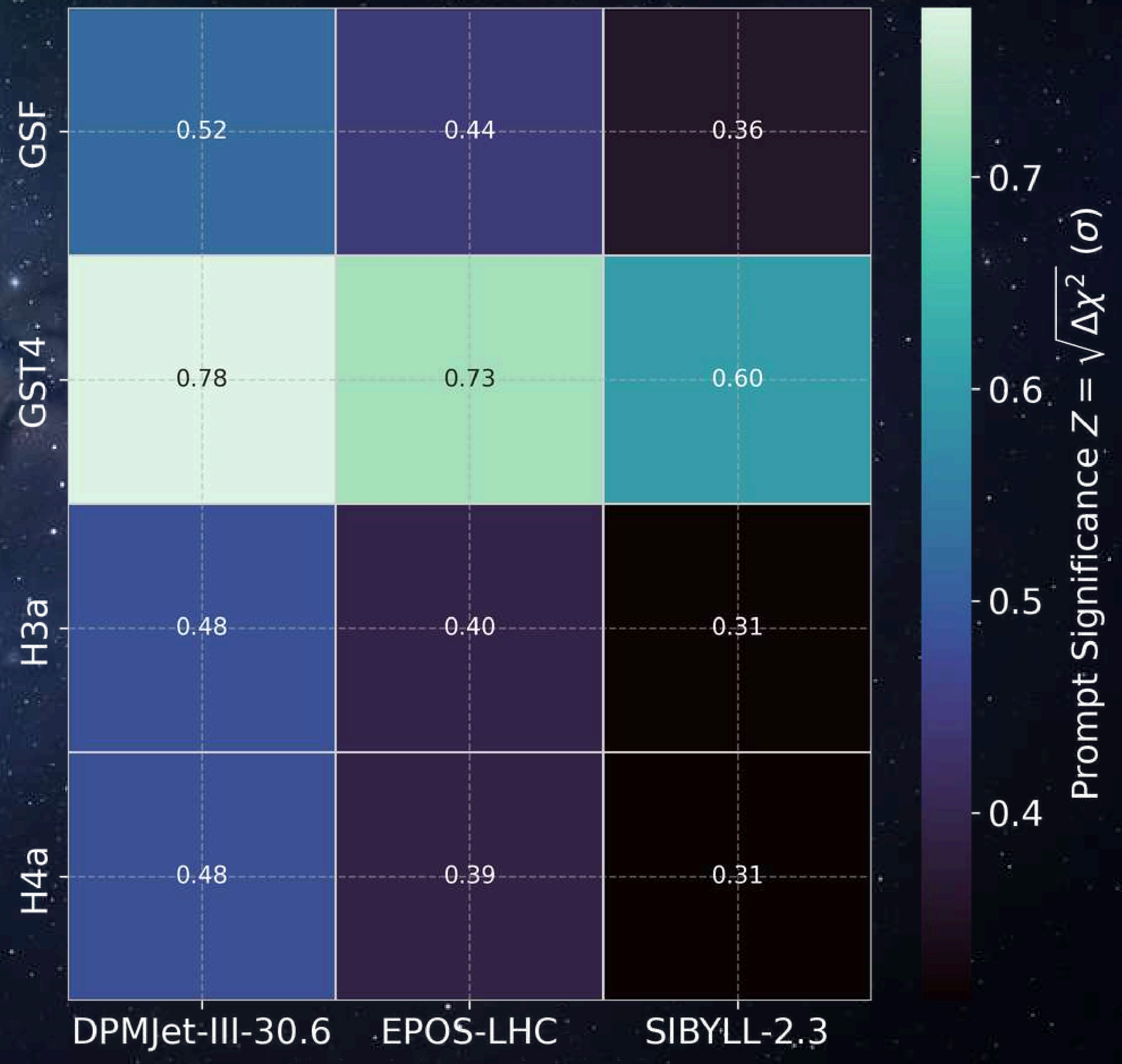




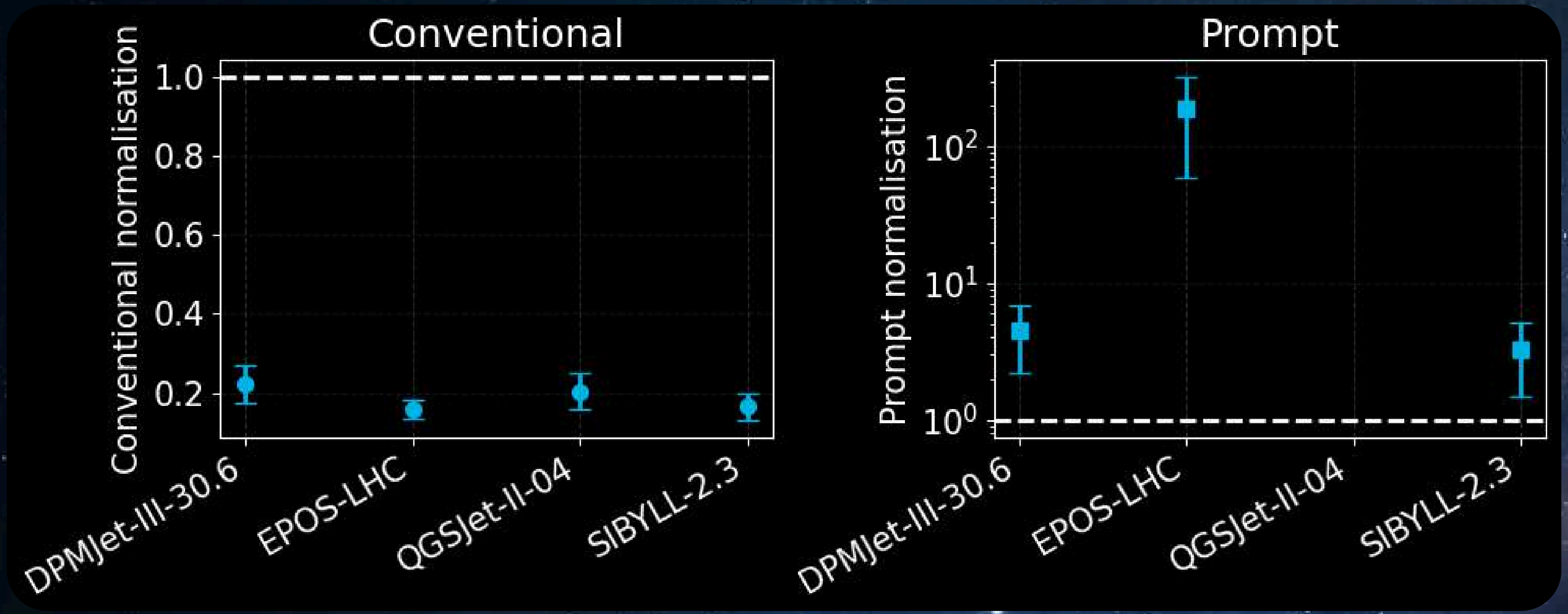
ANTARES ν_μ (2020) [200 GeV - ~50 TeV]

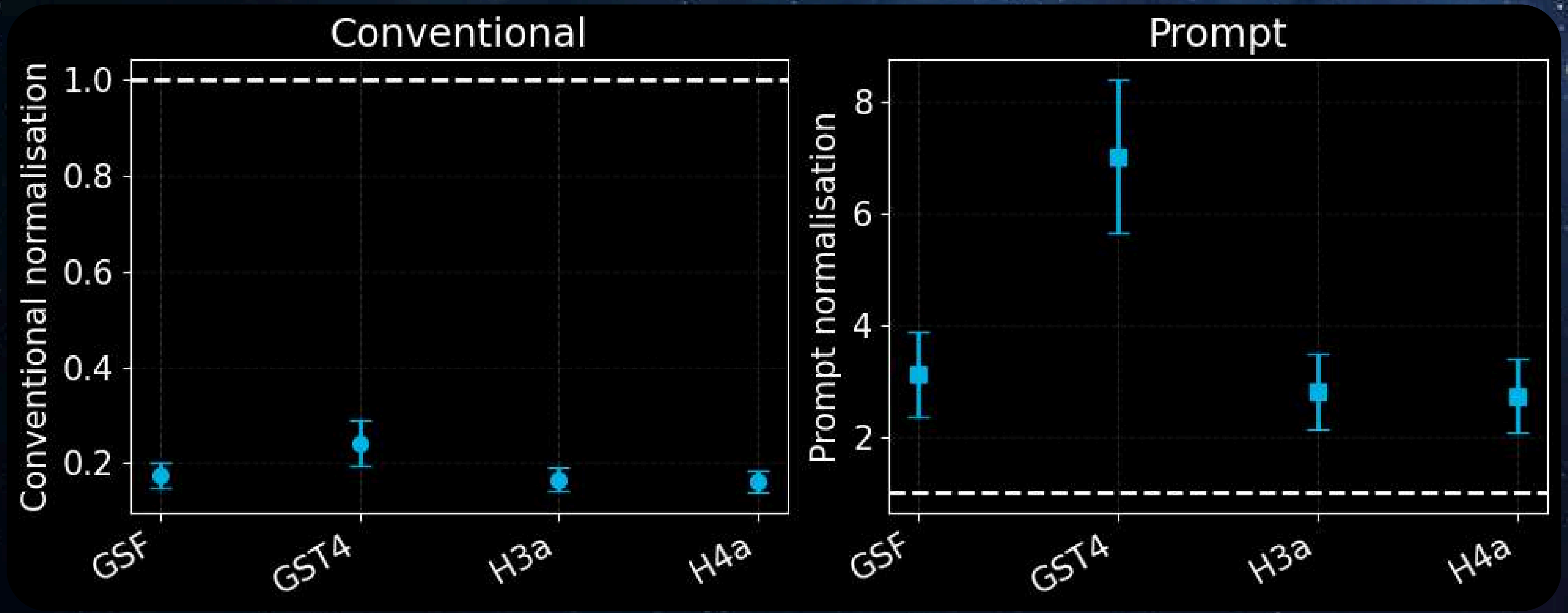


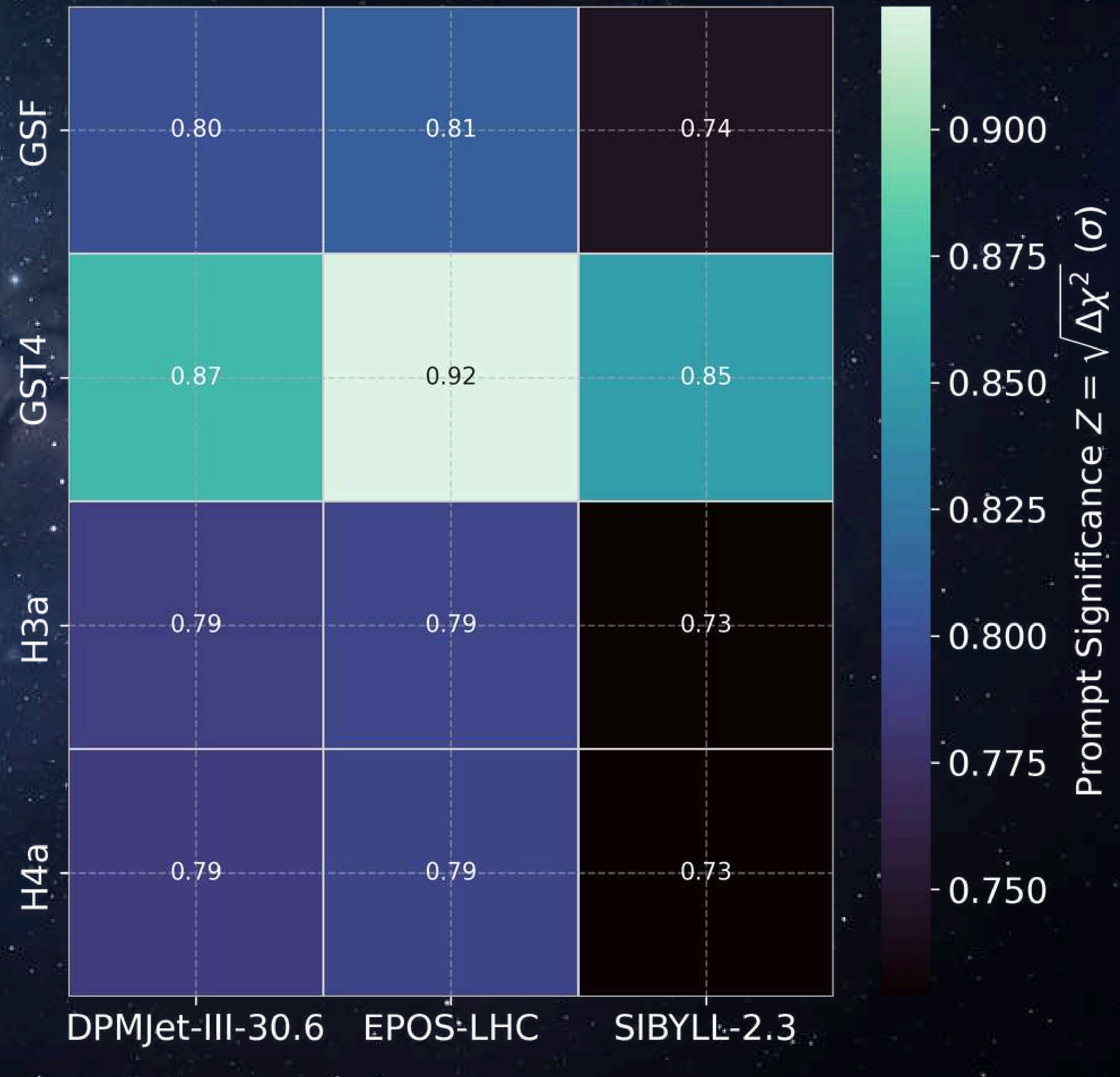




ANTARES ν_e (2020) [200 GeV - ~50 TeV]







Discussion

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Discussion

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- **Primary models:** H3a and H4a provide the **best overall agreement** with the measured spectra, closely followed by GSF. GST4 shows the **poorest agreement**.
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For the Future

- Update all the models to their **latest version**
  - Sibyll-2.3c → Sibyll-2.3d/e
  - EPOS-LHC → EPOS-LHC-R
  - etc.
- Extend the prompt-component fit to all used experimental measurements
- Assess the impact of astrophysical models. Currently, the fit uses only one fixed astrophysical model (**IceCube Combined FIt**).
  - Include alternative astrophysical models to evaluate their impact on the prompt contribution.

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OR USE A CHANNEL NOT POLLUTED BY ASTRO:
MUONS → SEE TALK BY **P. GUTJAHR** ON **THURSDAY 17:45H**

Electron ν_e Muon ν_μ Tau ν_τ

THANK YOU!

Any Questions?

Electron ν_e Muon ν_μ Tau ν_τ

Flux Spectra Sources

- **(AMANDA 2010)** → R. Abbasi et al. (AMANDA Collaboration), *"The Energy Spectrum of Atmospheric Neutrinos between 2 and 200 TeV with the AMANDA-II Detector,"* Astroparticle Physics 34, 48–58 (2010).
- **(ANTARES 2013)** → S. Adrian-Martínez et al. (ANTARES Collaboration), *"Measurement of the atmospheric ν_μ energy spectrum from 100 GeV to 200 TeV with the ANTARES telescope,"* European Physical Journal C 73, 2606 (2013).
- **(ANTARES 2020)** → A. Albert et al. (ANTARES Collaboration), *"Measurement of the atmospheric ν_e and ν_μ energy spectra with the ANTARES neutrino telescope,"* Physics Letters B 816, 136228 (2021).
- **(Fréjus 1995)** → K. Daum et al. (Fréjus Collaboration), *"Determination of the atmospheric neutrino spectra with the Fréjus detector,"* Zeitschrift für Physik C 66, 417–428 (1995).
- **(IceCube 2013)** → M. G. Aartsen et al. (IceCube Collaboration), *"Measurement of the Atmospheric ν_e Flux in IceCube,"* Physical Review Letters 110, 151105 (2013).
- **(IceCube 2015)** → M. G. Aartsen et al. (IceCube Collaboration), *"Measurement of the Atmospheric ν_e Spectrum with IceCube,"* Physical Review D 91, 122004 (2015).
- **(IceCube 2024)** → L. Kardum, *Unfolding the muon neutrino flux*, PhD thesis, TU Dortmund University (2023/accepted 2024).
- **(IceCube 2025)** → R. Abbasi et al. (IceCube Collaboration), *"Seasonal variations of the atmospheric muon neutrino spectrum measured with IceCube,"* European Physical Journal C 85, 1368 (2025).
- **(Super-Kamiokande 2016)** → E. Richard et al. (Super-Kamiokande Collaboration), *"Measurements of the atmospheric neutrino flux by Super-Kamiokande: Energy spectra, geomagnetic effects, and solar modulation,"* Physical Review D 94, 052001 (2016).

Primary Model Sources

- **H3a/H4a**→ T. K. Gaisser, *"Spectrum of cosmic-ray nucleons and the atmospheric muon charge ratio,"* Astroparticle Physics 35, 801–806 (2012). DOI: 10.1016/j.astropartphys.2012.02.010; arXiv:1111.6675 [astro-ph.HE].
- **GST4** → T. K. Gaisser, T. Stanev and S. Tilav, *"Cosmic Ray Energy Spectrum from Measurements of Air Showers,"* Frontiers of Physics 8, 748–758 (2013). DOI: 10.1007/s11467-013-0319-7; arXiv:1303.3565 [astro-ph.HE].
- **GSF** → H. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn and T. Stanev, "Data-driven model of the cosmic-ray flux and mass composition from 10 GeV to 101110^{11} GeV," Proceedings of Science (ICRC2017) 533 (2018). DOI: 10.22323/1.301.0533; arXiv:1711.11432 [astro-ph.HE].

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Electron ν_e Muon ν_μ Tau ν_τ

Hadronic Interaction Model Sources

- **SIBYLL-2.3** → A. Fedynitch, F. Riehn, R. Engel, T. K. Gaisser and T. Stanev, *"The hadronic interaction model SIBYLL-2.3c and inclusive lepton fluxes,"* Physical Review D 100, 103018 (2019) DOI: 10.1103/PhysRevD.100.103018; arXiv:1806.04140 [hep-ph].
- **QGSJet-II-04** → S. Ostapchenko, *"QGSJET-II: Towards reliable description of very high energy hadronic interactions,"* Nuclear Physics B – Proceedings Supplements 151, 147–150 (2006). arXiv:hep-ph/0412332.
- **EPOS-LHC**→ T. Pierog, Iu. Karpenko, J. M. Katzy, E. Yatsenko and K. Werner, *"EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider,"* Physical Review C 92, 034906 (2015). DOI: 10.1103/PhysRevC.92.034906; arXiv:1306.0121 [hep-ph].
- **DPMJet-III** → S. Roesler, R. Engel and J. Ranft, *"The Monte Carlo Event Generator DPMJET-III,"* in Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications, Proceedings of MC2000, Lisbon (2000). arXiv:hep-ph/0012252.

Astrophysical Parametrisations Sources

- **astro 9.5 yrs** → R. Abbasi et al. (IceCube Collaboration), *"Improved Characterization of the Astrophysical Muon–Neutrino Flux with 9.5 Years of IceCube Data,"* The Astrophysical Journal 928, 50 (2022). DOI: 10.3847/1538-4357/ac4d29; arXiv:2111.10299 [astro-ph.HE].
- **combined fit** → R. Abbasi et al. (IceCube Collaboration), *"Improved measurements of the TeV–PeV extragalactic neutrino spectrum from joint analyses of IceCube tracks and cascades,"* Physical Review D 113, 062002 (2026). DOI: 10.1103/4n6v-r7n4. arXiv: 2507.22234 [astro-ph.HE]
- **cscd 11 yrs** → Z. Chen, Z. Zhang, J. Kiryluk et al. (IceCube Collaboration), *"Astrophysical neutrino flux measurement and search for tau neutrino induced cascades with 11 years of IceCube data,"* Proceedings of Science (ICRC2025) 501, 1011 (2025). DOI: 10.22323/1.501.1011; arXiv:2507.08421 [astro-ph.HE].
- **hese 7.5yrs** → R. Abbasi et al. (IceCube Collaboration), *"IceCube high-energy starting event sample: Description and flux characterization with 7.5 years of data,"* Physical Review D 104, 022002 (2021). DOI: 10.1103/PhysRevD.104.022002; arXiv:2011.03545 [astro-ph.HE].
- **global fit 10yrs** → R. Naab, E. Ganster, Z. Zhang et al. (IceCube Collaboration), *"Measurement of the astrophysical diffuse neutrino flux in a combined fit of IceCube's high energy neutrino data,"* Proceedings of Science (ICRC2023) 1064 (2023). arXiv:2308.00191 [astro-ph.HE].

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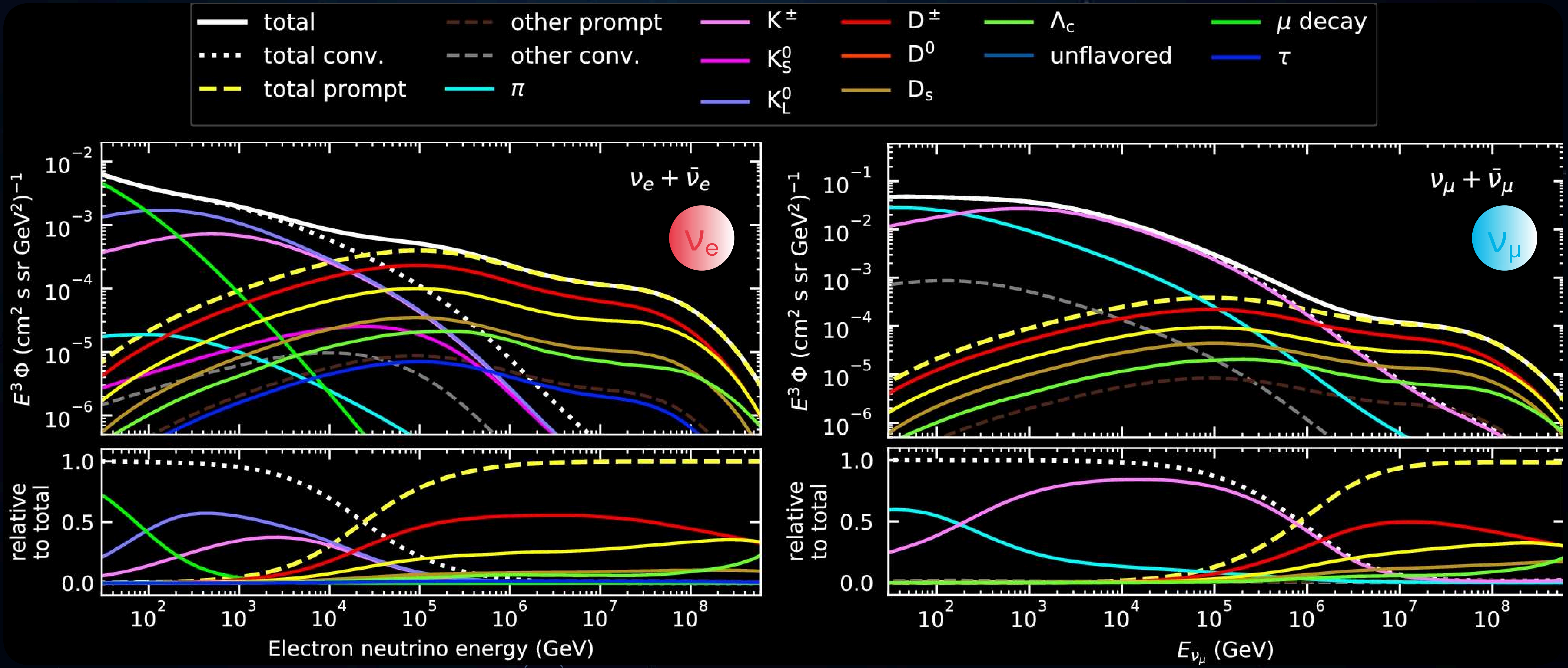
Electron ν_e Muon ν_μ Tau ν_τ

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

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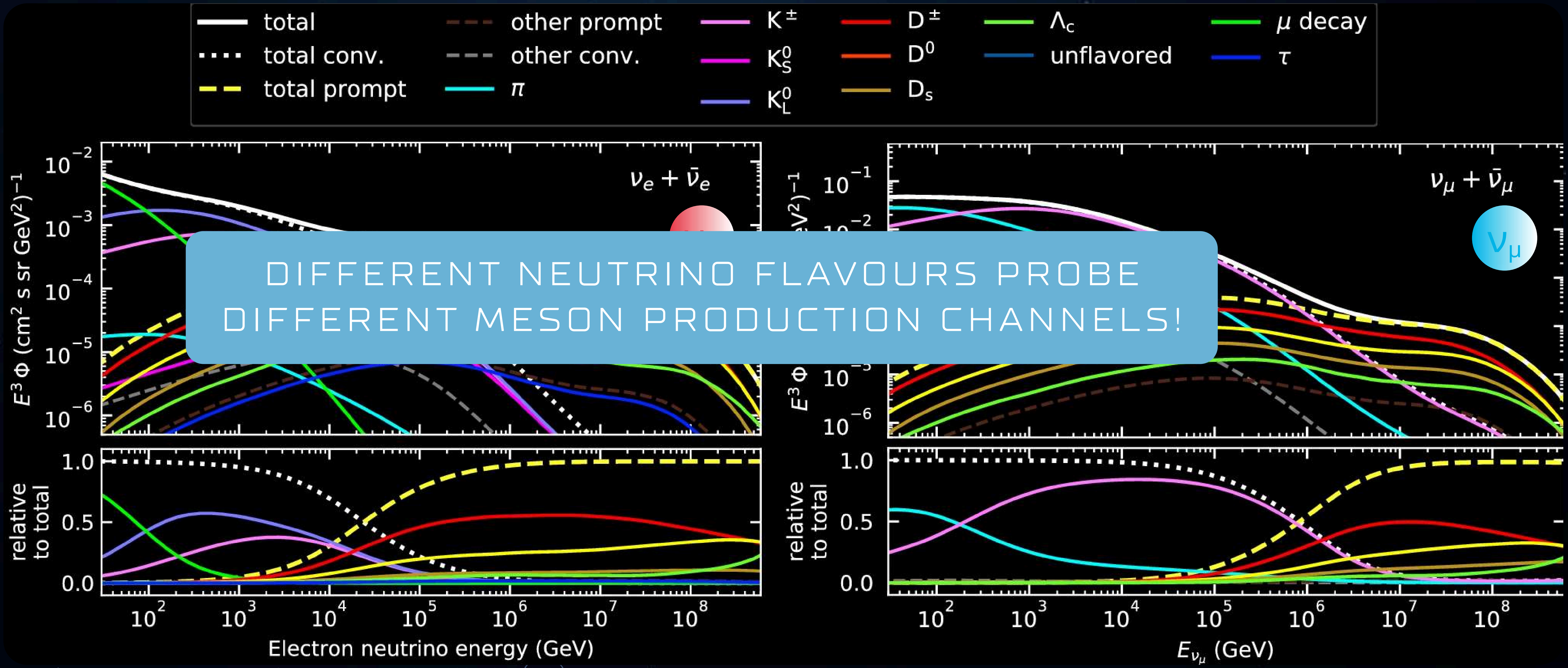


DIFFERENT NEUTRINO FLAVOURS PROBE DIFFERENT MESON PRODUCTION CHANNELS!

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

Electron ν_e Muon ν_μ Tau ν_τ

Atmospheric Neutrino Fluxes

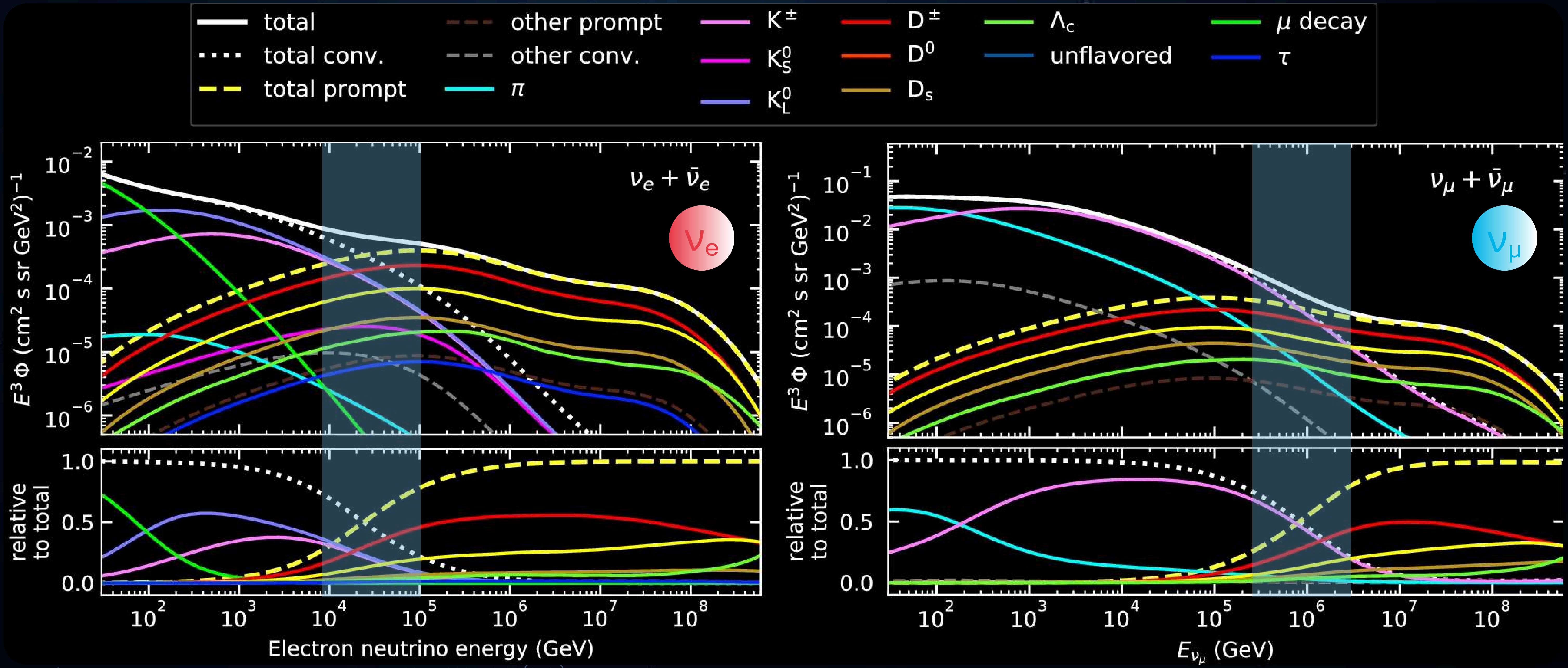
Neutrinos

1. *Electron* ν_e

~$10^{4.5}$ GeV

2. *Muon* ν_μ

~10^{6} GeV



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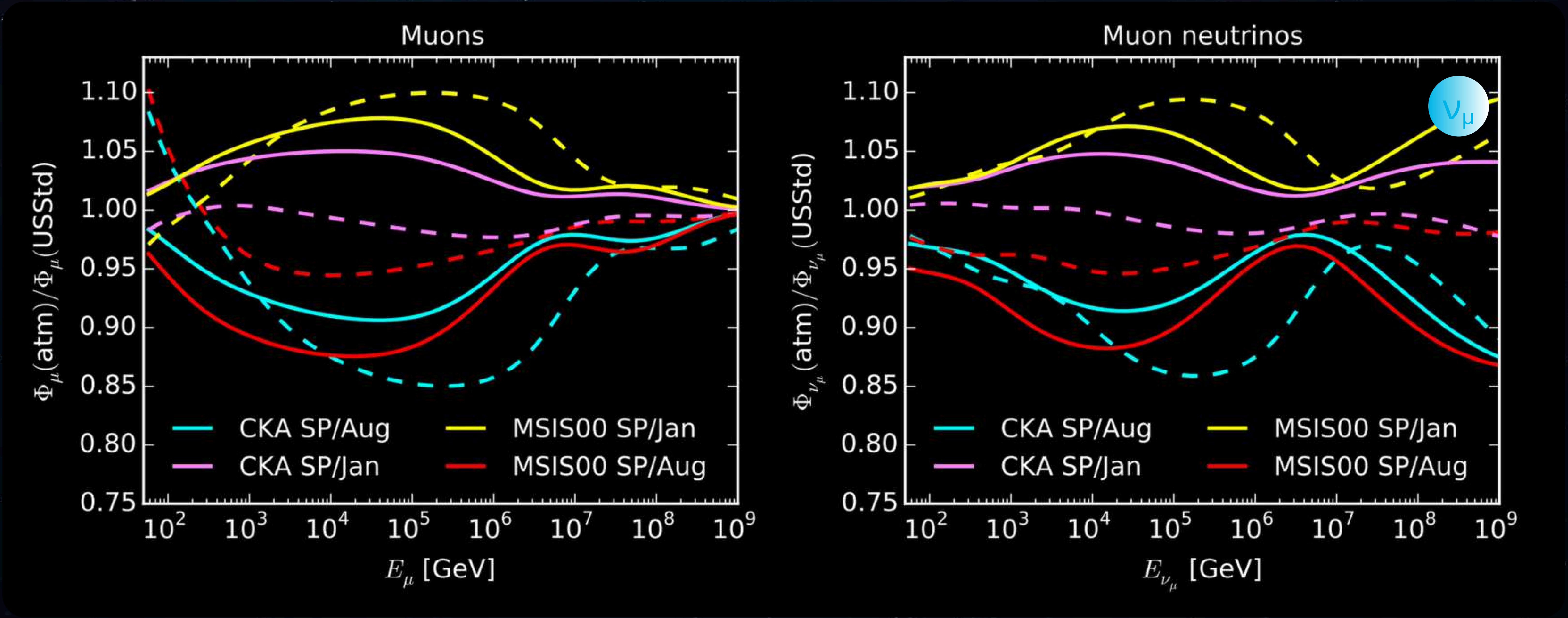
Atmosphere Models

Solid: θ = 0º
Dashed: θ = 90º



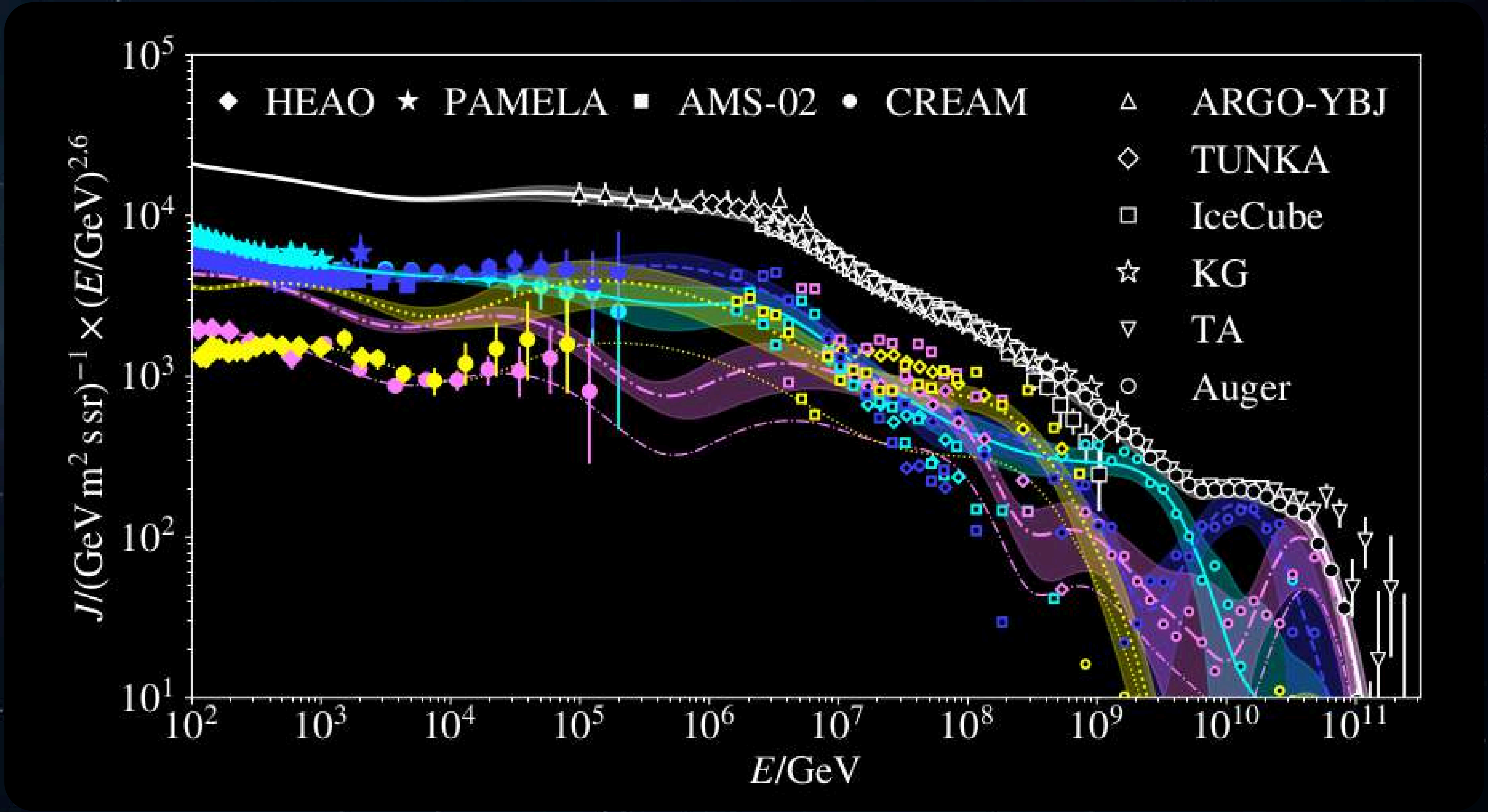
Fedynitch, A., Becker Tjus, J. & Desiati, P. EPJ Web of Conferences (2015)

Electron ν_e Muon ν_μ Tau ν_τ

Primary Fluxes + Hadronic Interactions

Cosmic-ray models 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**



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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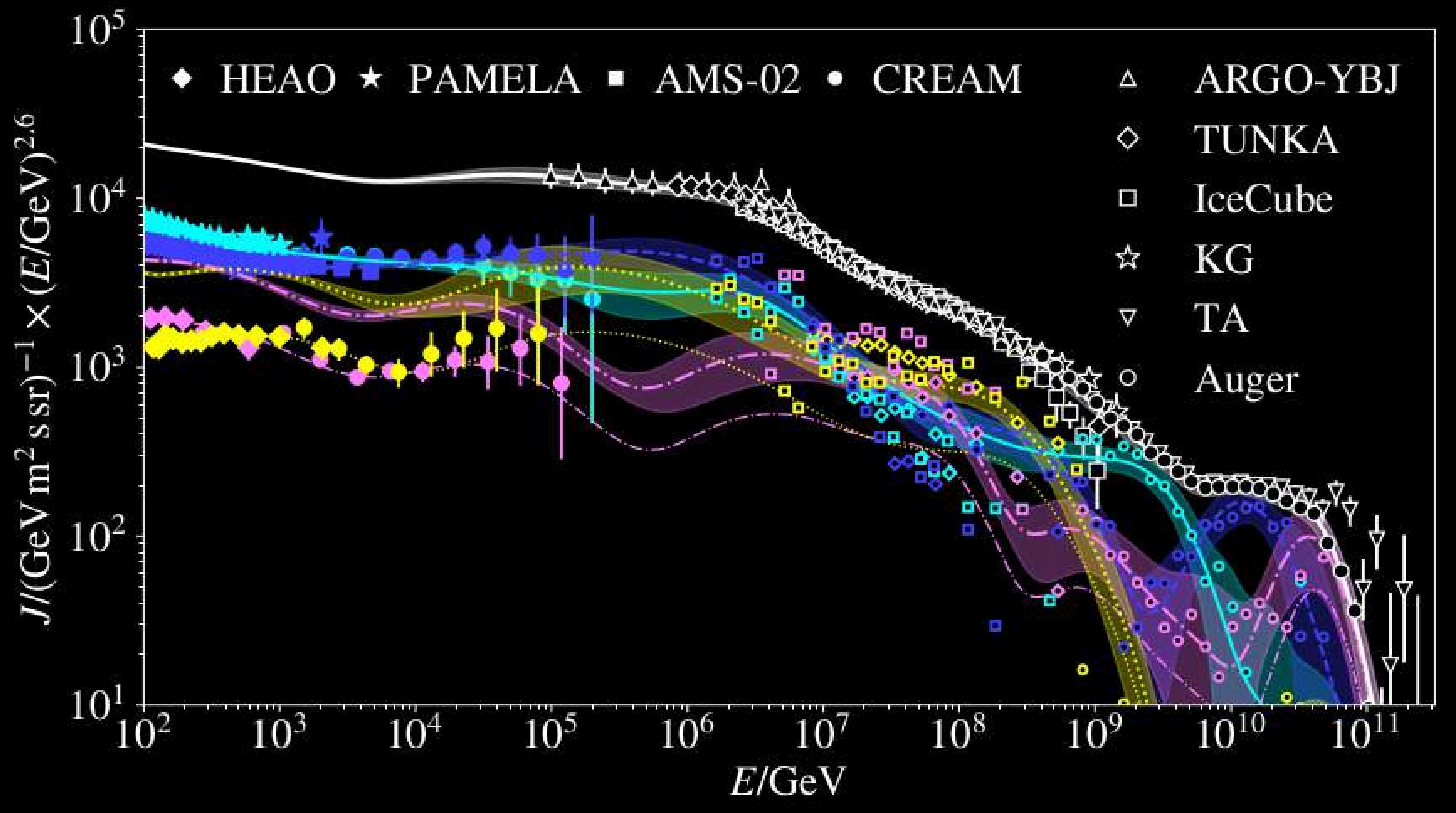
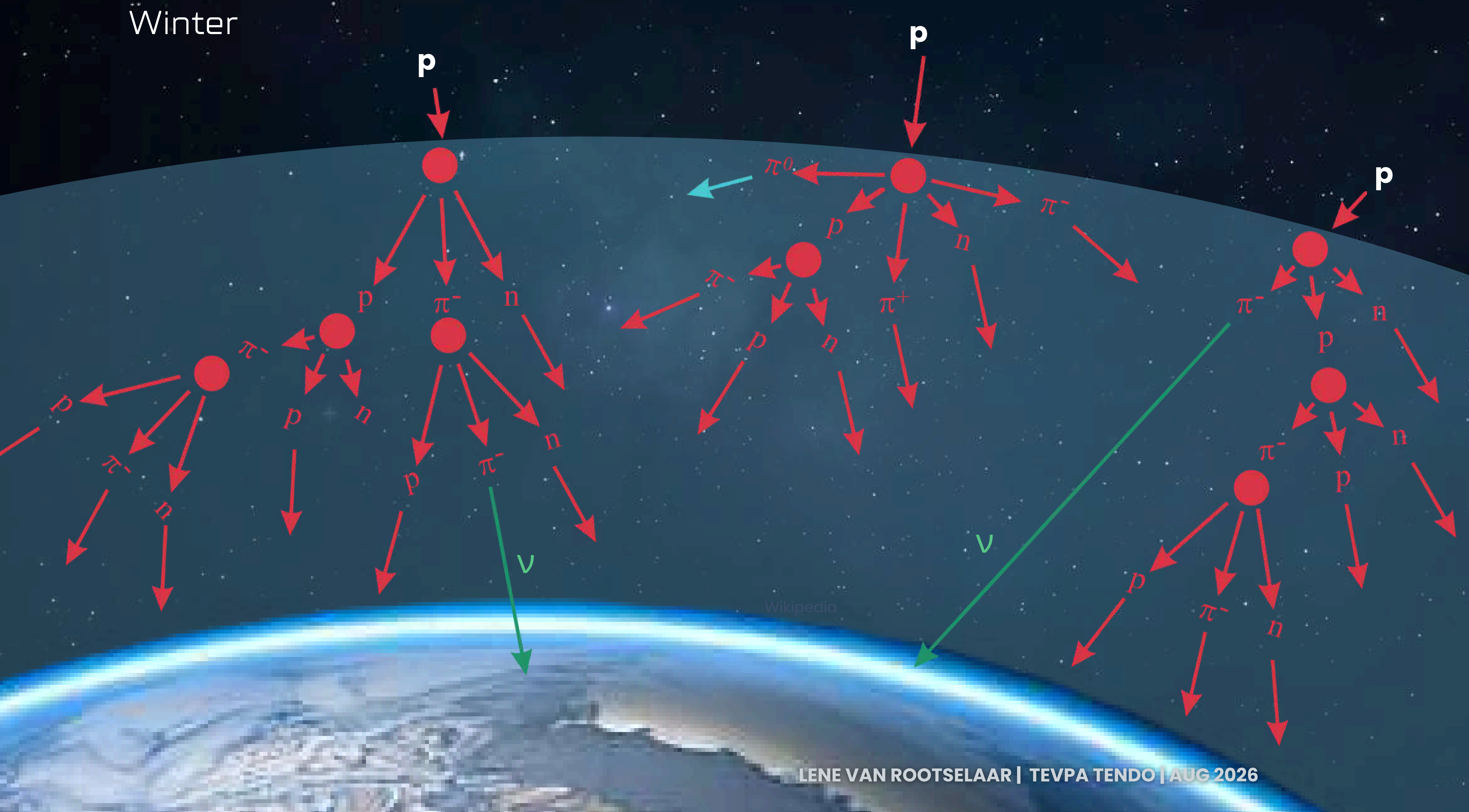
Hadronic interaction models describe particle production in cosmic-ray air showers.

- Production of **pions**, **kaons** and **charmed hadrons**
- Meson multiplicities and E distributions
- Interaction cross sections



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

Seasonal Variations

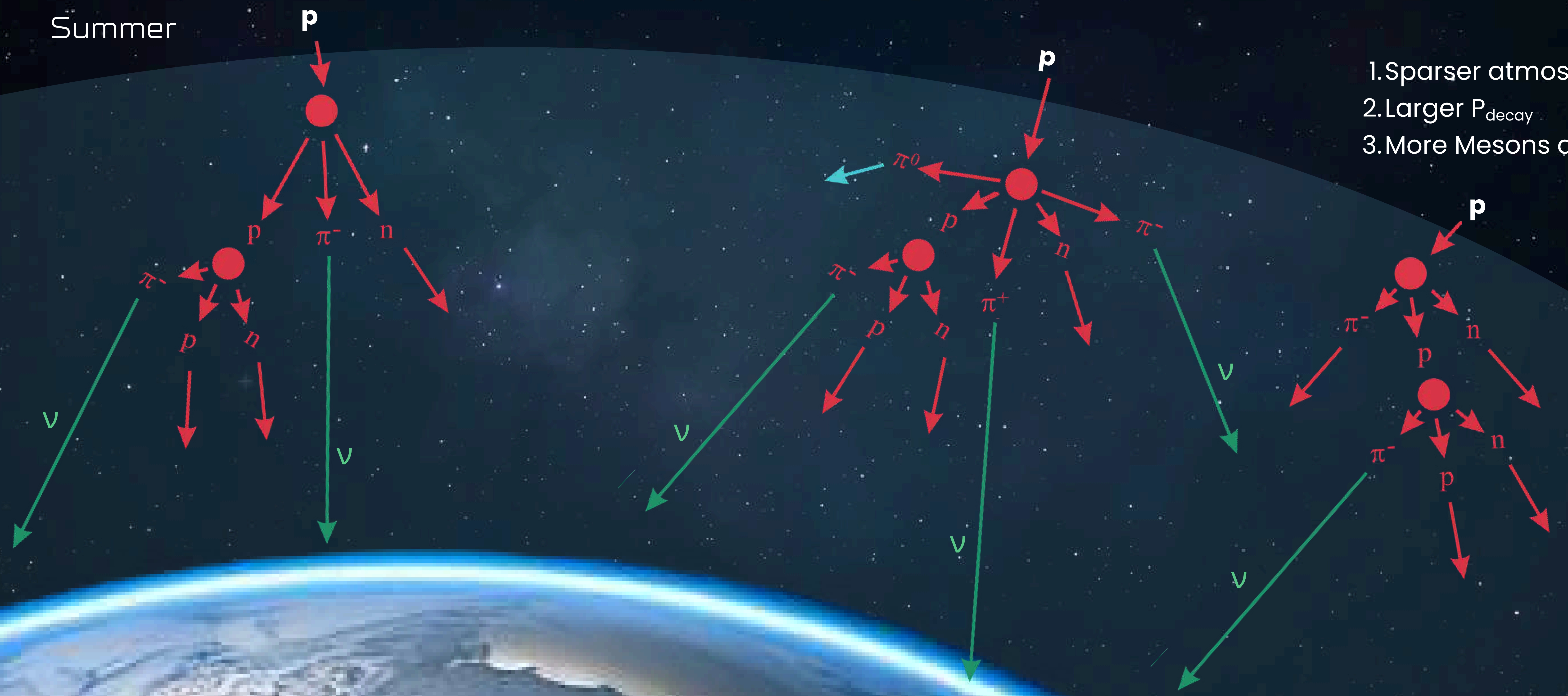


1. Denser atmosphere
2. Larger $P_{interact}$
3. Less Mesons decay into ν

Electron ν_e Muon ν_μ Tau ν_τ

Seasonal Variations

Summer



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

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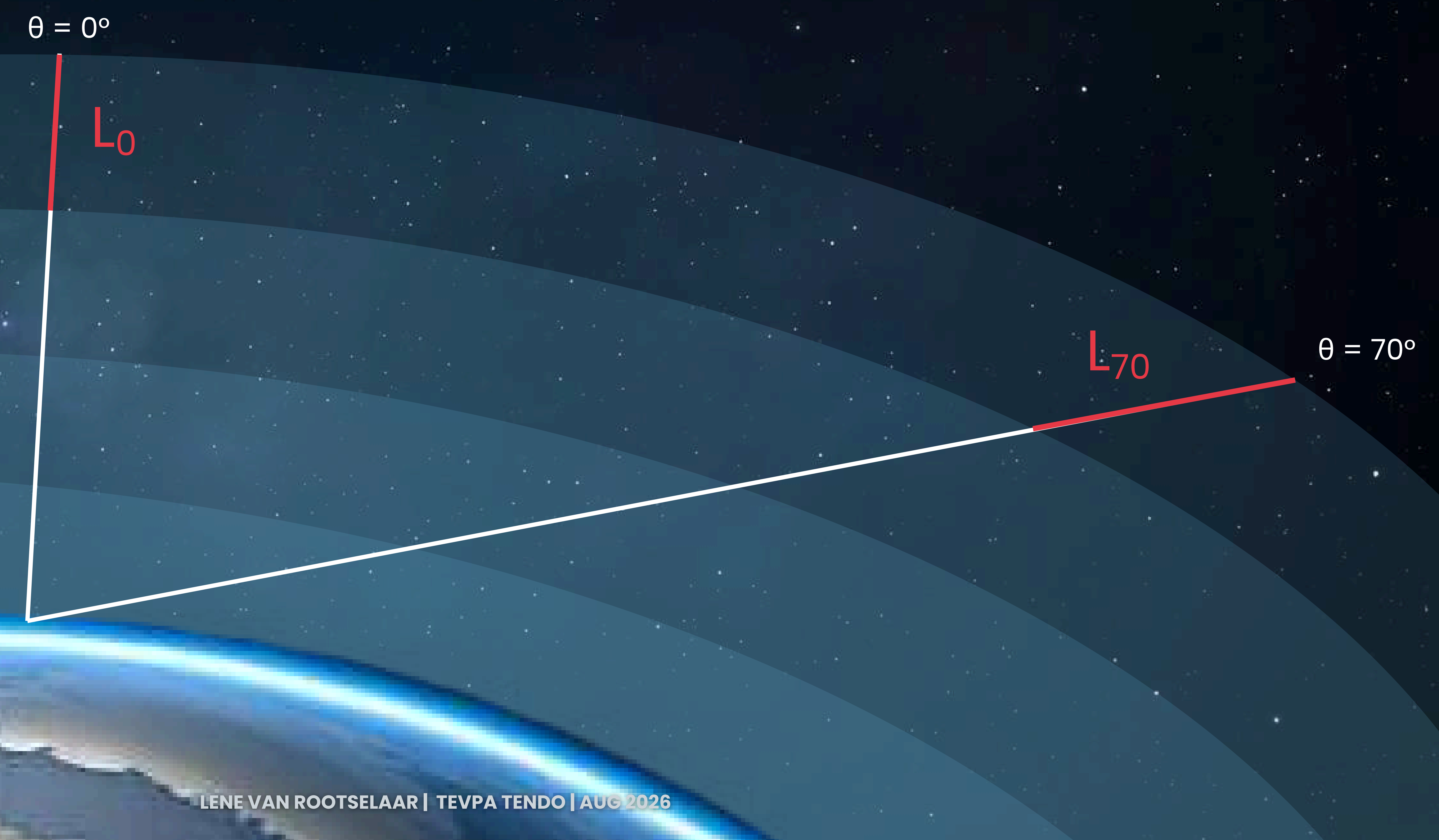
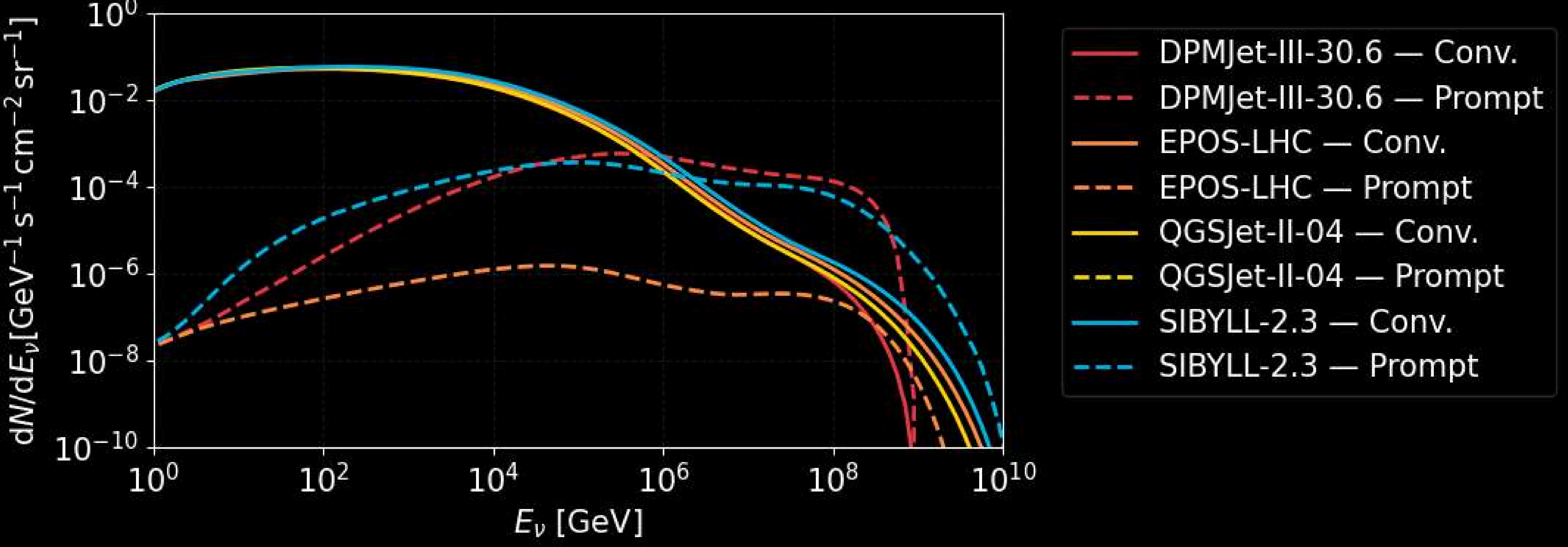
Angular Dependence

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



Hadronic Models Prompt Difference



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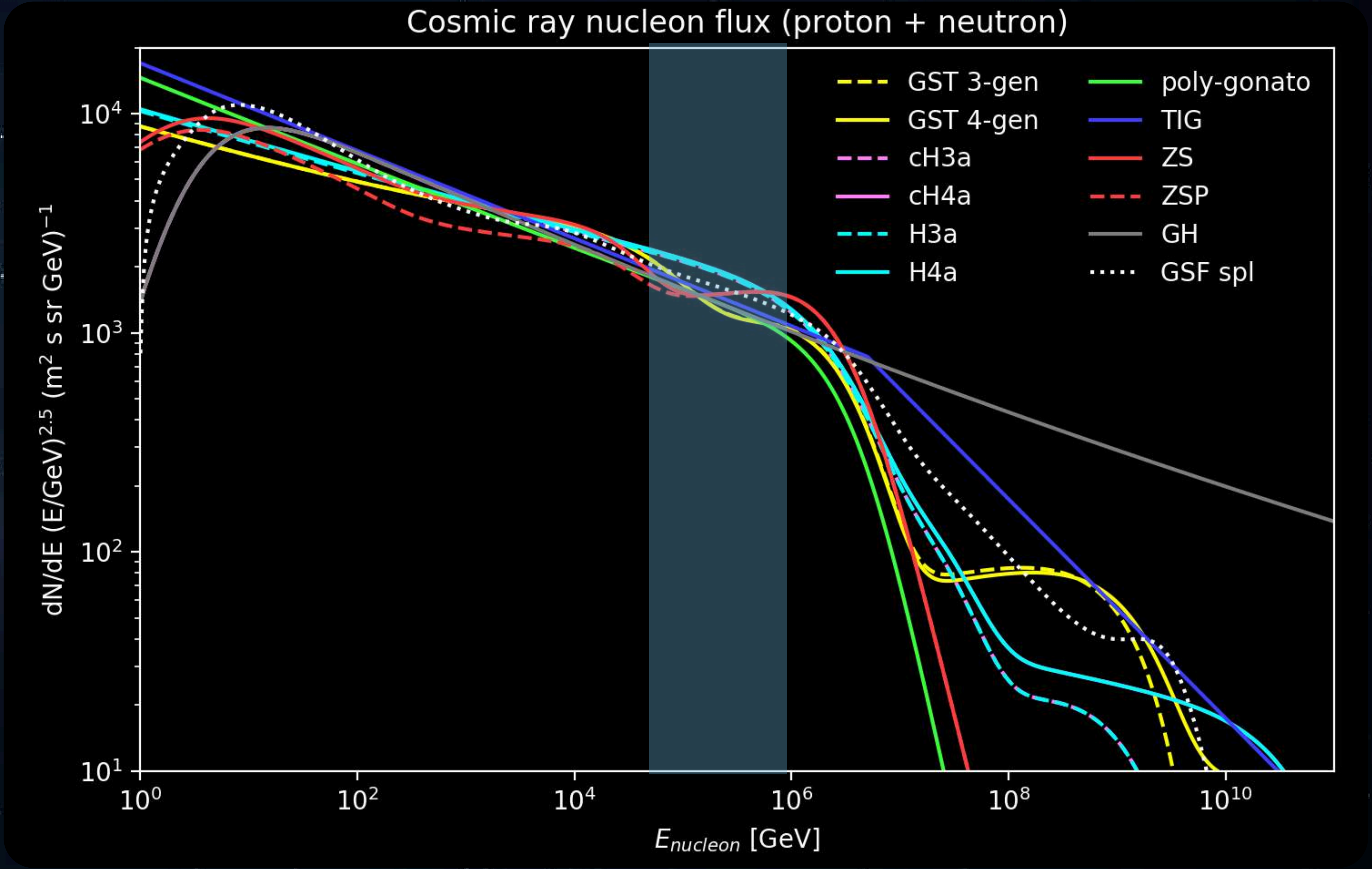
Primary Fluxes + Hadronic Interactions

Prompt important region

GST4 < GSF < H3a/H4a



A., Fedynitch,, CR Flux documentation (https://crfluxmodels.readthedocs.io/en/latest/)

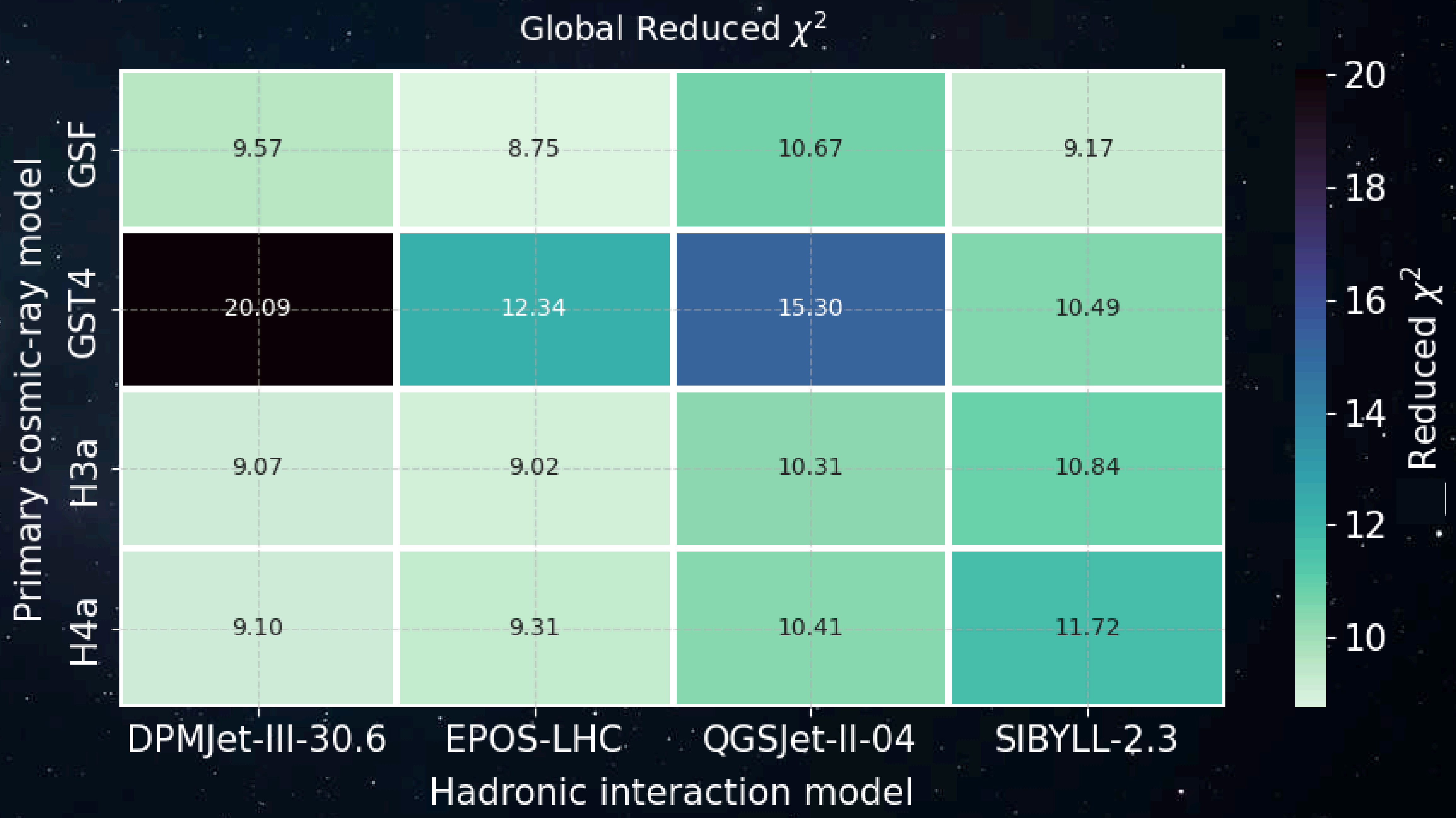
Electron ν_e Muon ν_μ Tau ν_τ

INCLUDING FRÉJUS DATA

Overall Fit Performance

Global Model Performance

- **Global Model Ranking**: Evaluates overall agreement across all experimental datasets simultaneously.



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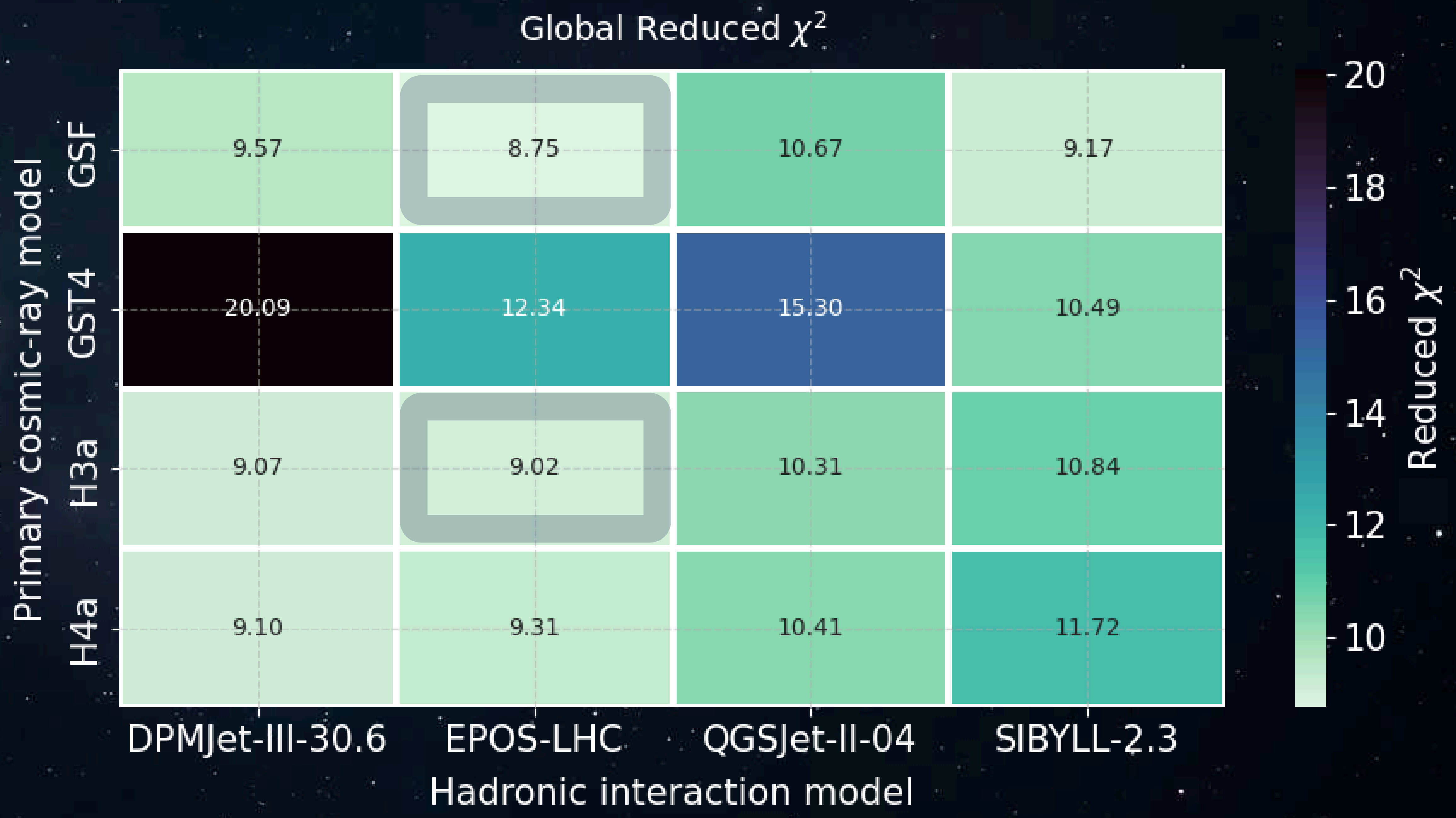

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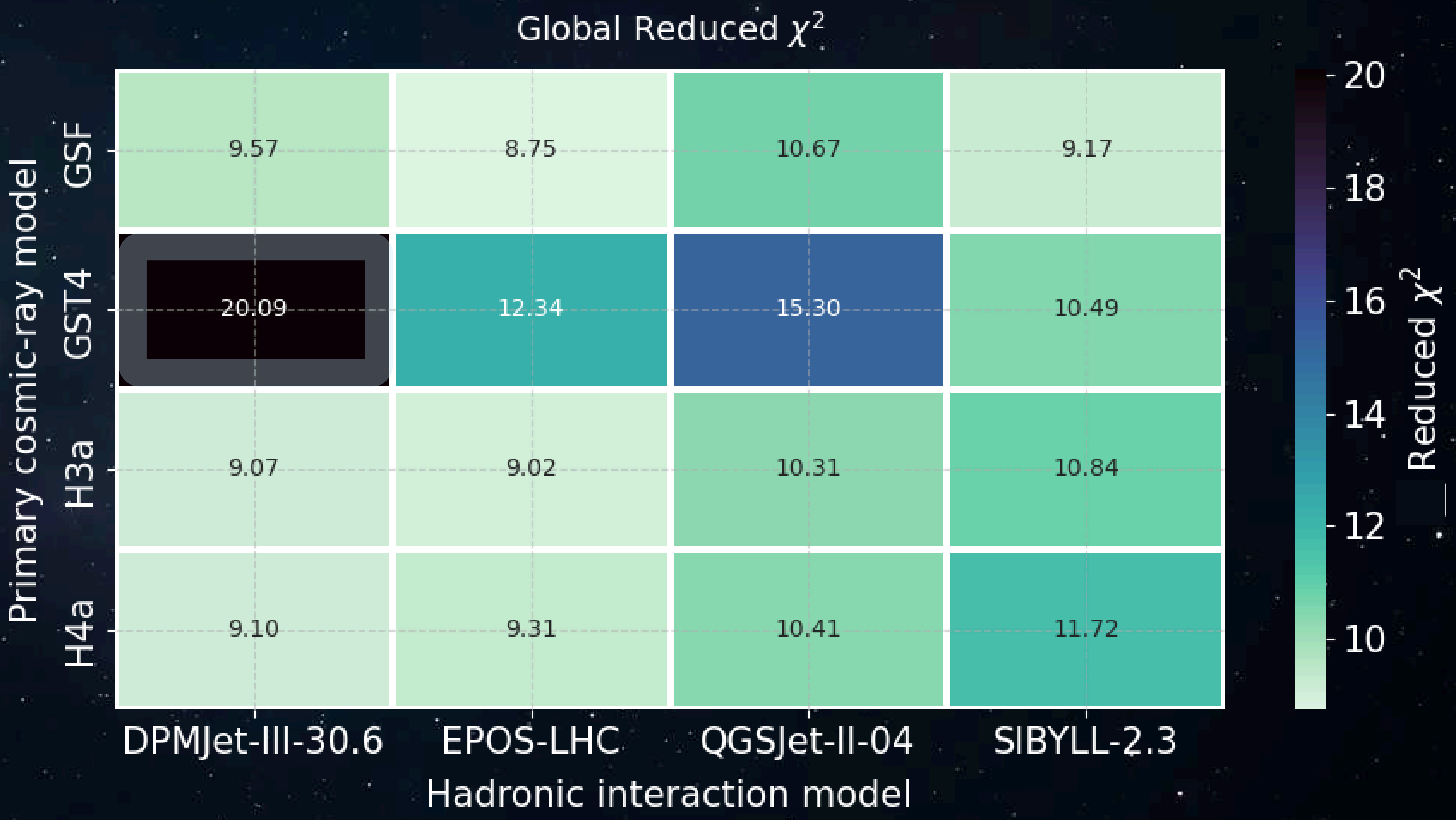
- Significant Discrepancies:
  GST4 + DPMJet-III-30.6 shows a severe mismatch (χ^2 = 20.09), driven by high energy flux overpredictions.



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*