

Some thoughts on the global picture

Ralph Engel

Anatoli Fedynitch

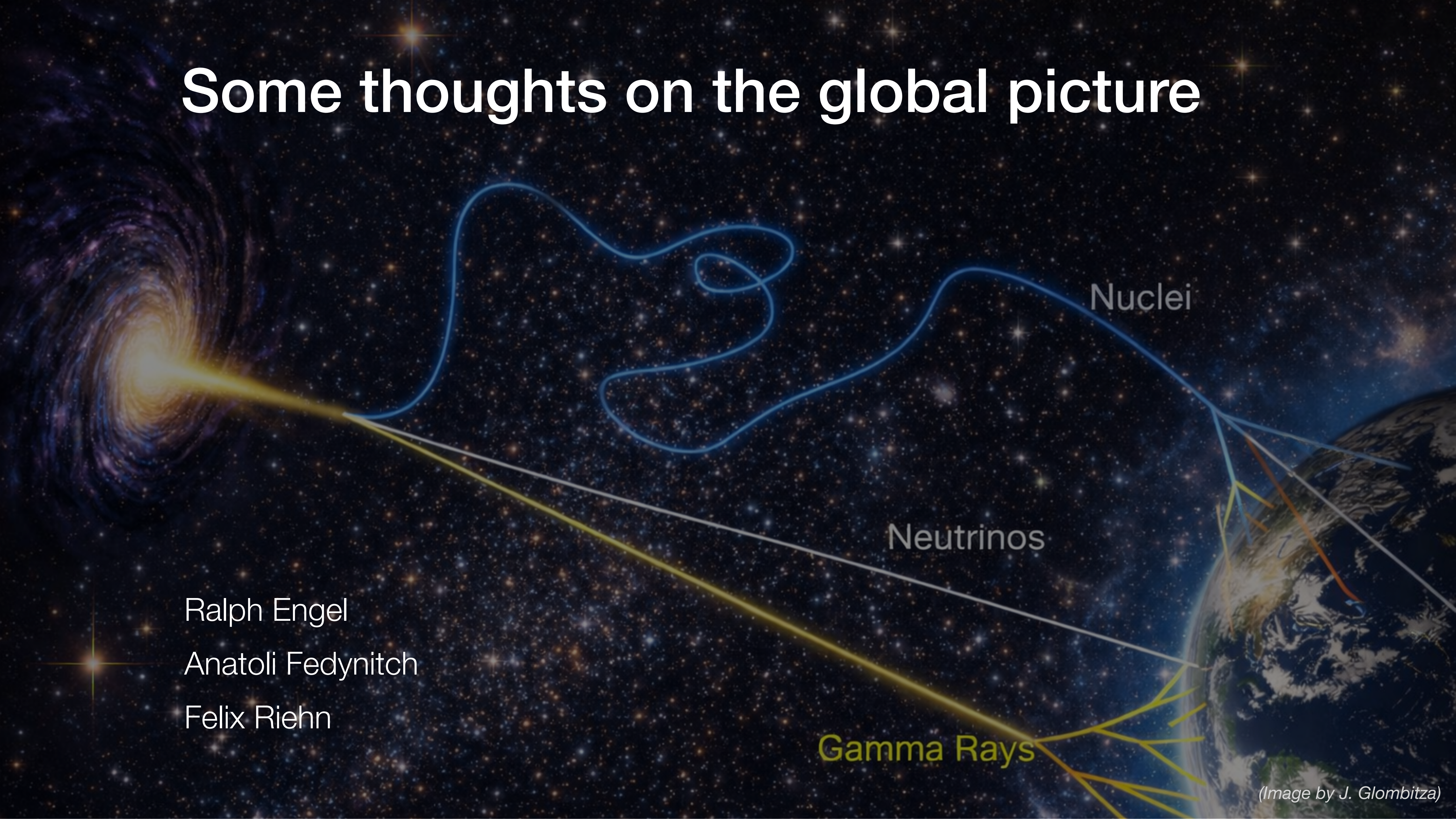
Felix Riehn

Gamma Rays

Neutrinos

Nuclei

(Image by J. Glombitza)



Global Spline Fit: A unified data-driven view of the cosmic-ray spectrum and mass composition from GeV to the highest energies

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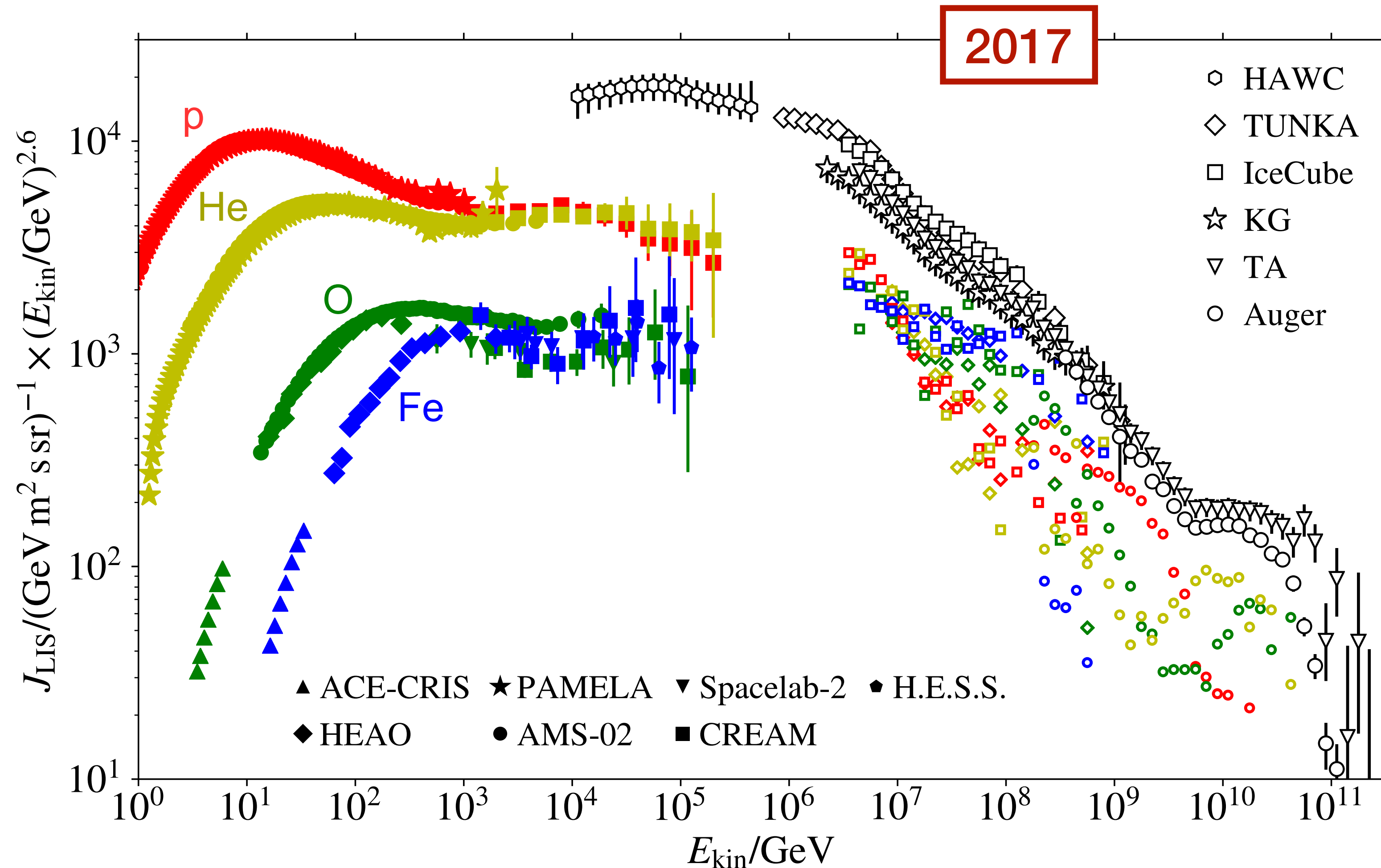
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(Dated: September 9, 2026)

The energy spectrum and mass composition of cosmic rays are measured by two complementary classes of instruments: space- and balloon-borne detectors that resolve individual elements up to sub-PeV energies, and ground-based air-shower observatories that extend the reach to beyond 10^{11} GeV but resolve only broad mass groups. The Global Spline Fit (GSF) is a data-driven model that combines both into a single, self-consistent description of the flux of all elements from hydrogen to nickel. The flux of four leading mass groups is parametrized by cubic basis splines, imposing smoothness but no astrophysical expectation on the spectral shape, while the energy-scale offsets of the participating experiments are cross-calibrated within their quoted systematic uncertainties as part of the fit. The model is defined at the local interstellar spectrum, with the effect of solar modulation at the lowest energies accounted for in the fit. The fit uses the most precise recent data, among them the elemental spectra from AMS-02, CALET, and DAMPE, the knee-region measurements of LHAASO, and the fluorescence-based composition of the Pierre Auger Observatory, and describes about one thousand data points with $\chi^2/\text{ndf} \approx 1.3$, or 0.83 after de-weighting localized disagreements between data sets, demonstrating that the global body of cosmic-ray data is consistent once energy scales are aligned. The model delivers the flux, the mass composition, and their full covariance, along with a compact reduced representation for uncertainty propagation. We further provide the cosmic-ray nucleon flux, which differs from widely used parametrizations by 20–50% over four decades in energy. This amounts to many times the remaining model uncertainty and has direct consequences for atmospheric neutrino and muon flux predictions.

In preparation, to be submitted within days

Global Spline Fit – Initial Version of ICRC 2017



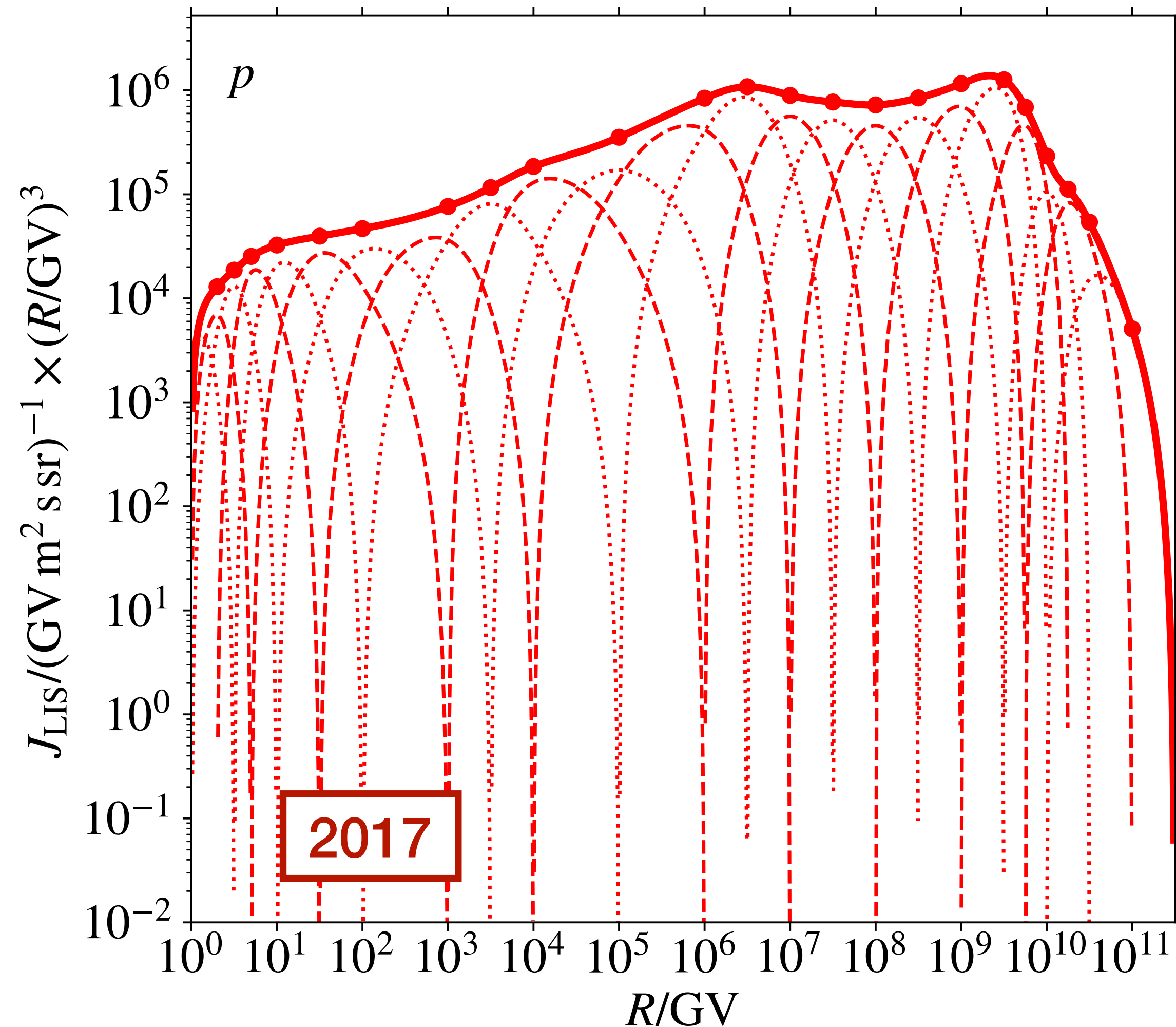
Observation:

Increasingly complete
and consistent data sets

Aim:

- Agnostic flux parametrization (minimum of assumptions)
- Sys. and stat. uncertainties of data sets
- Parametrization with uncertainties and correlations (covariance matrix)

Parametrization by B-splines (defined by knots)



Flux of individual element (rigidity)

$$J_L(R) = (R/\text{GV})^{-3} \sum_k \underbrace{a_{Lk}}_{\text{amplitude}} \underbrace{b_k(\ln(R/\text{GV}))}_{\text{spline curve}}$$

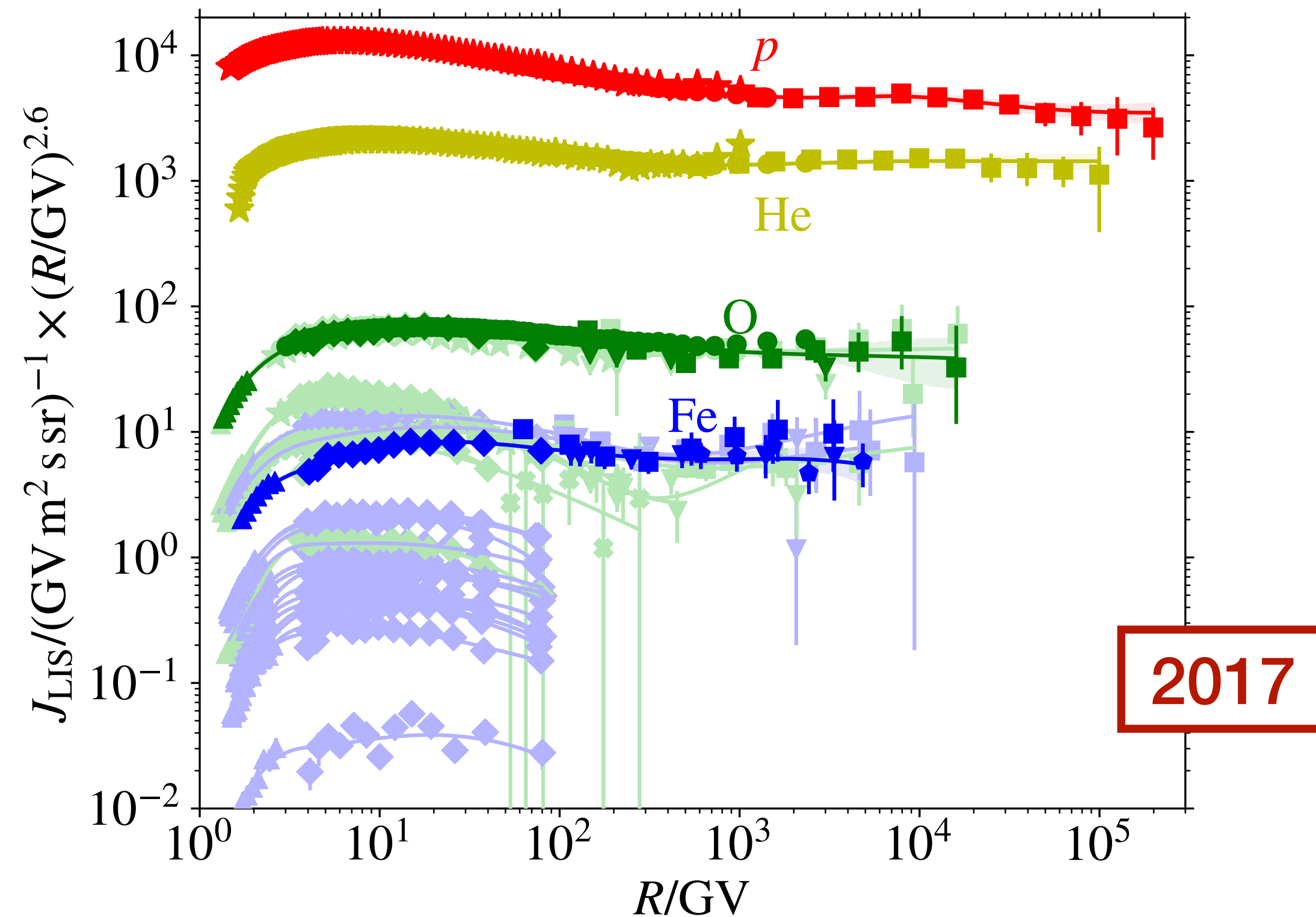
All-particle flux (particle energy)

$$J(E) = \sum_L \sum_j \underbrace{w_{Lj}}_{\text{flux ratio}} J_L(R_j(E)) \left(\frac{dR}{dE} \right)_j$$

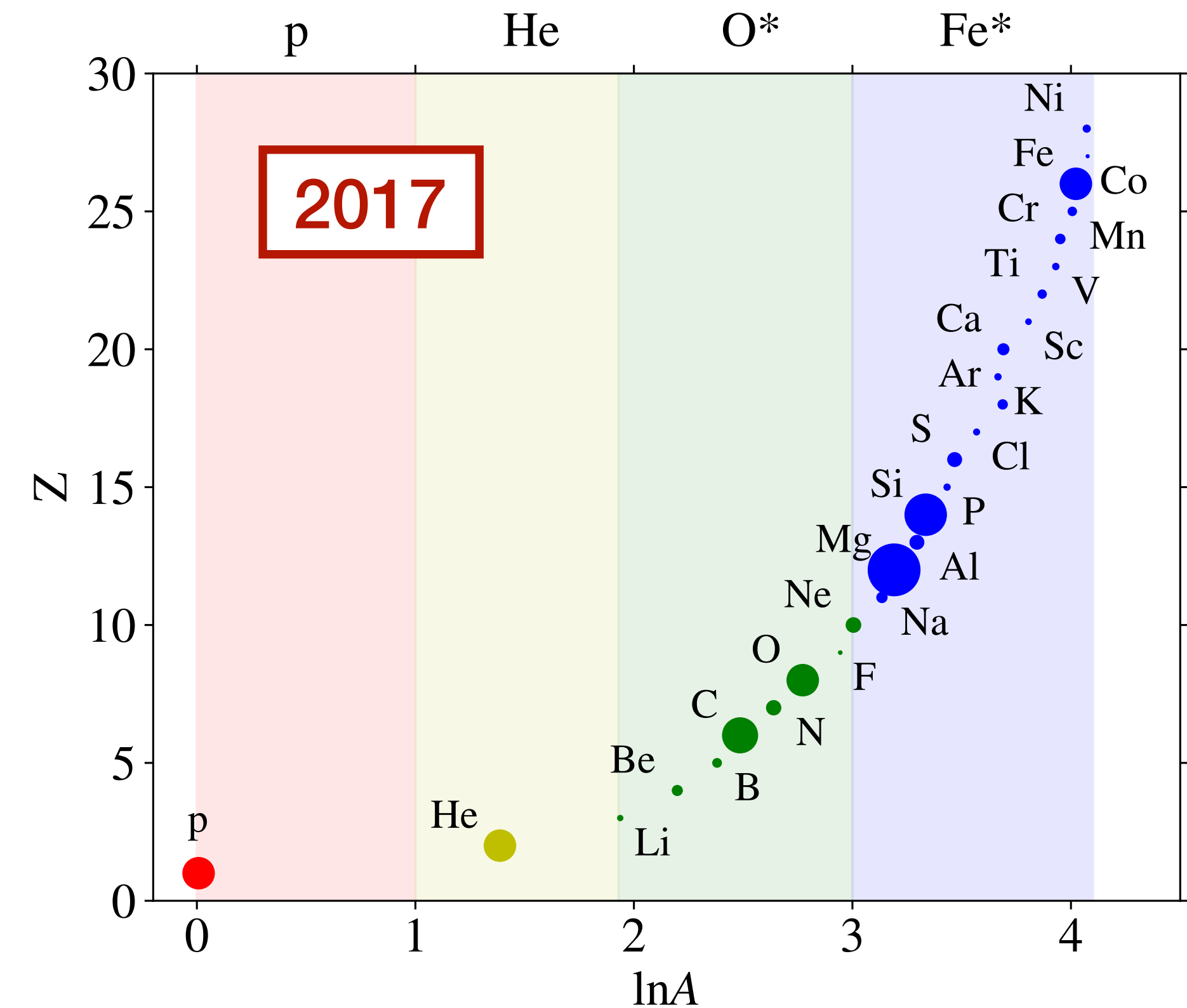
weights for mass groups

Connection between direct and indirect measurements

▲ ACE-CRIS ★ PAMELA ▼ Spacelab-2 ✱ Balloon 1971 ◆ H.E.S.S.
 ◆ HEAO ● AMS-02 ■ CREAM ✱ Balloon 1977



Where available individual elements are used,
above this energy range weight is kept constant



$$J_{L^*}(E) = \sum_j \underbrace{w_{Lj}}_{\text{flux ratio}} J_L(R_j(E)) \left(\frac{dR}{dE} \right)_j$$

Treatment of energy scale differences and uncertainties

Allow shift in energy scale (nuisance parameter)

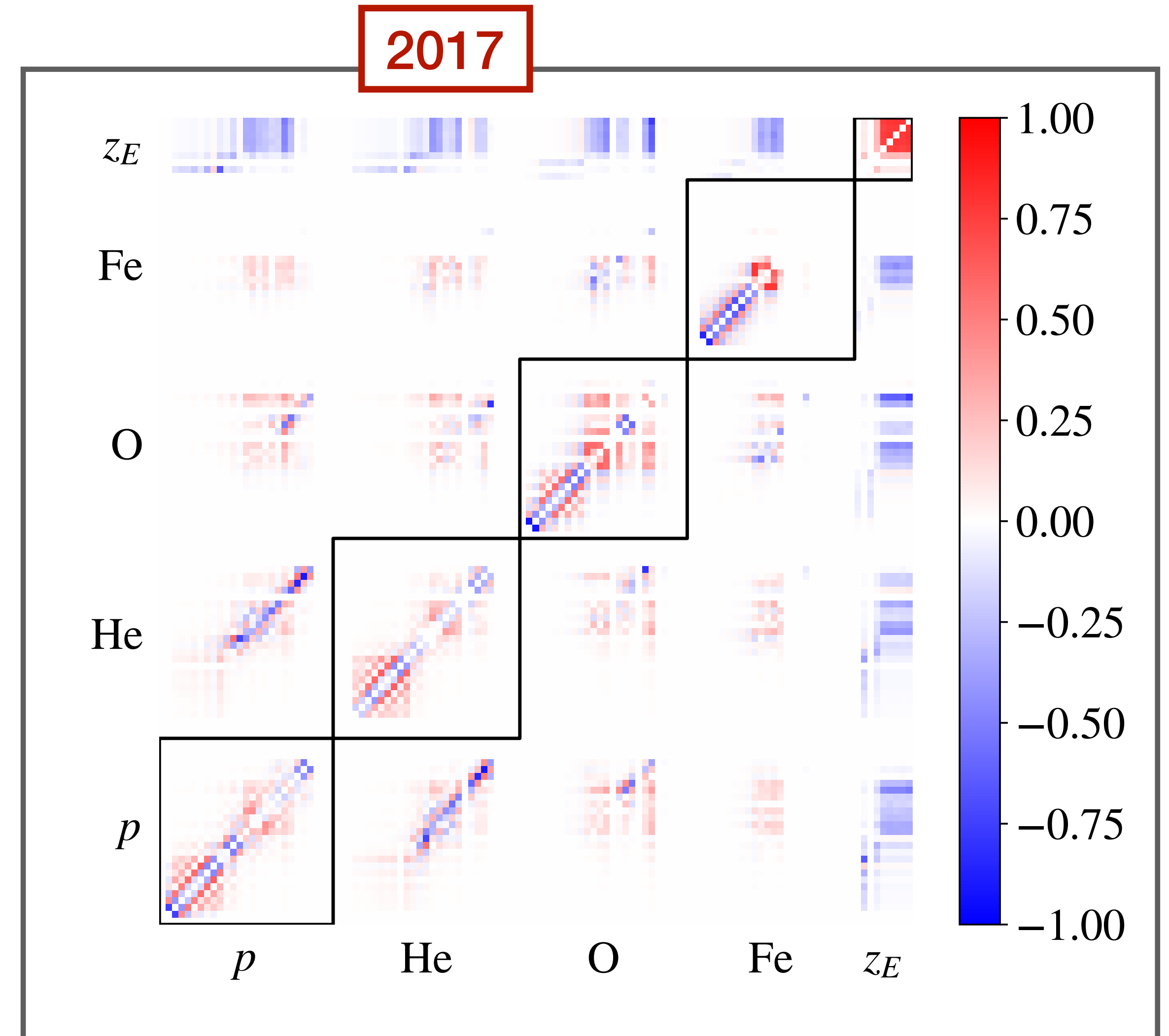
$$\tilde{J}(\tilde{E}) = J(E) \frac{dE}{d\tilde{E}} = J\left(\frac{\tilde{E}}{1+z_E}\right) \frac{1}{1+z_E}$$

Global minimization of all parameters

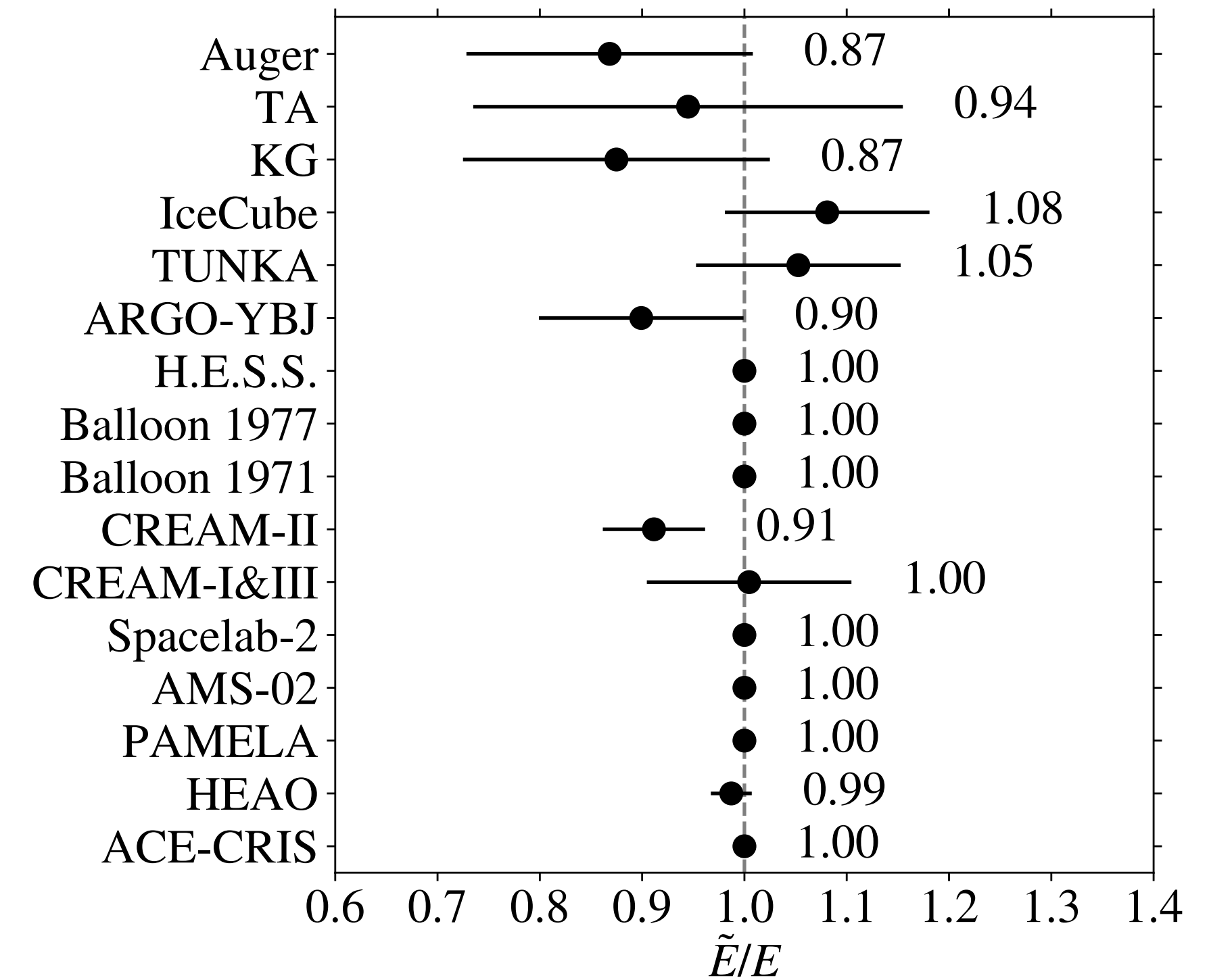
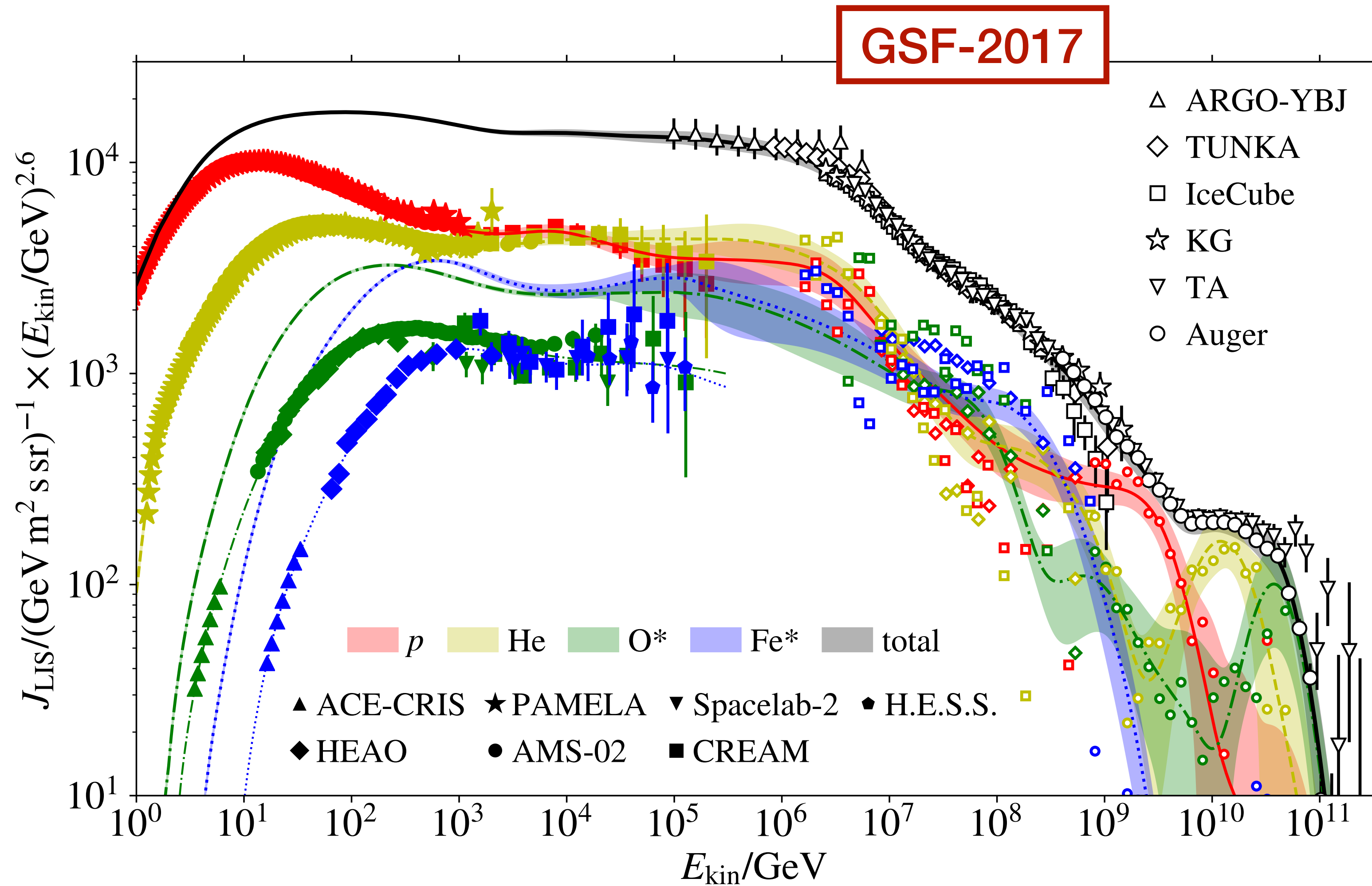
$$S = \sum_i z_i^2 + \sum_j \left(\frac{z_{Ej}}{(\sigma[E]/E)_j} \right)^2$$

Flux and $\langle \ln A \rangle$ residuals Energy-scale offset residuals

Calculation of covariance matrix (uncertainties)



Global Spline Fit – Initial version of ICRC 2017



Many new and updated data sets available

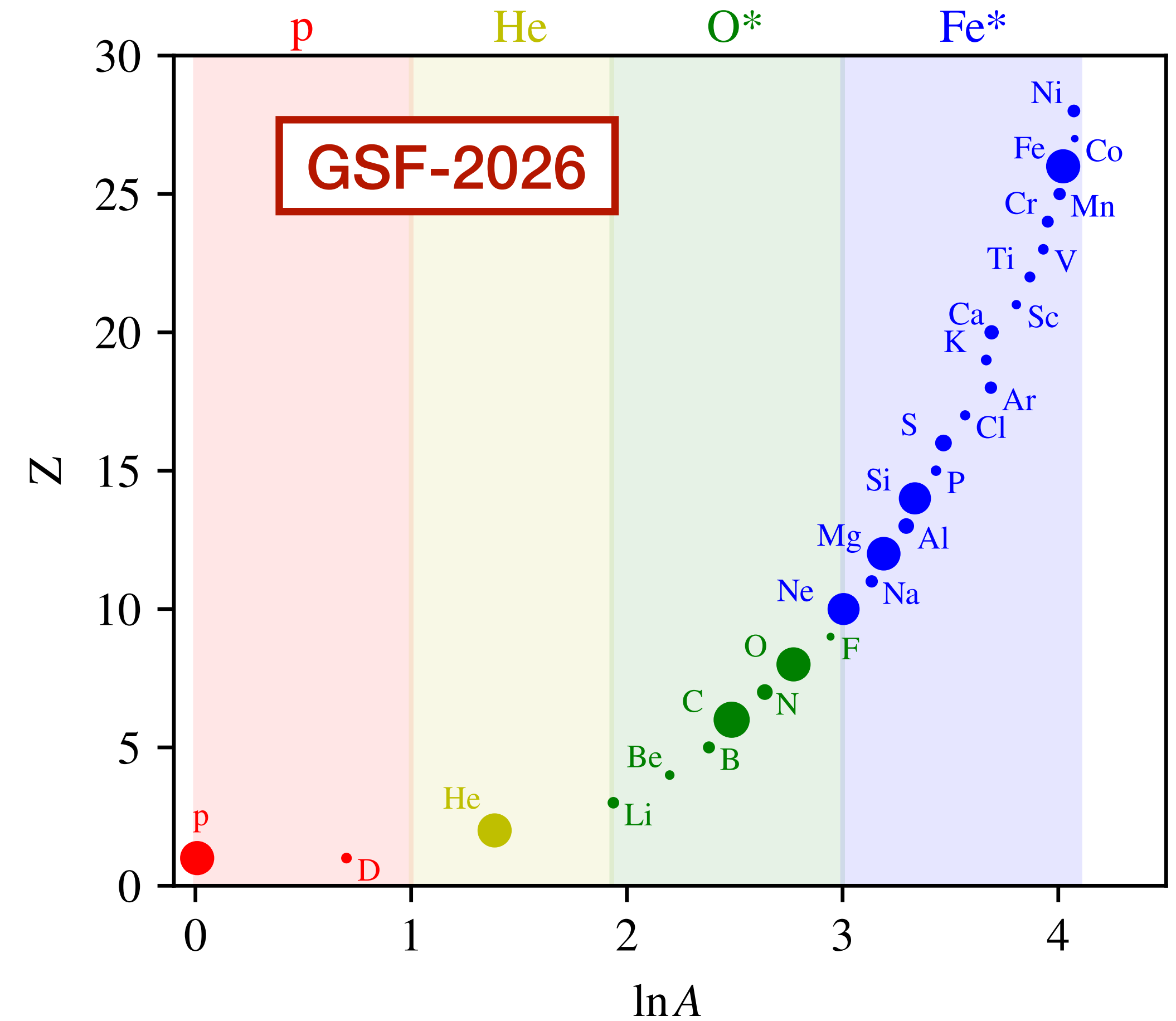
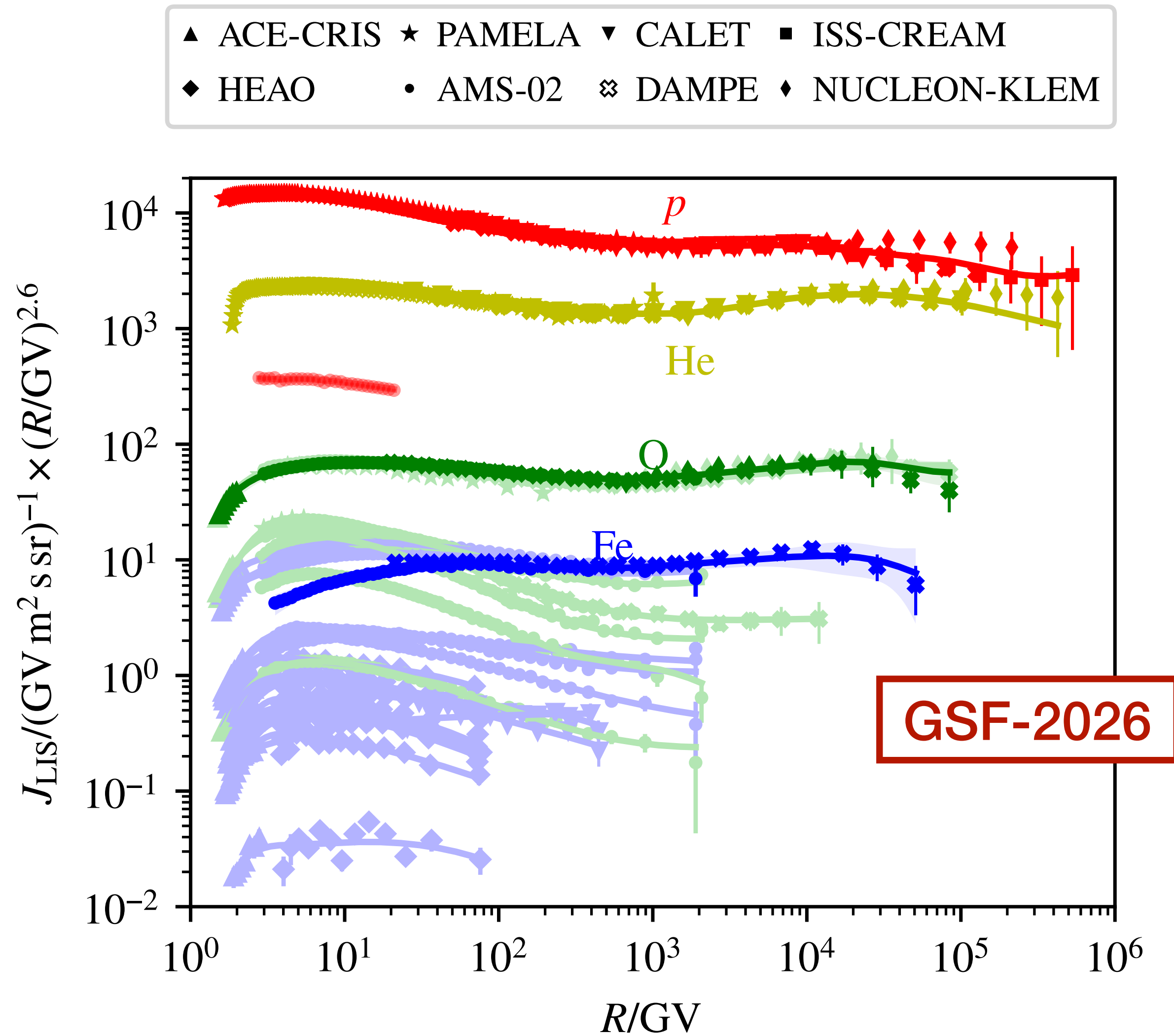
TABLE I. Data sets in the GSF. For each experiment we list the detection technique, the observables used, and the quoted energy-scale systematic σ_E/E that defines the offset parameter of Eq. (4). Spectrometer scales (—) are treated as exact. Daggers ($\dagger$) mark σ_E/E values that are not published by the experiment but adopted here as representative conventions. Detailed treatment (observation windows, hadronic models, covariance structure) is tabulated in the SM.

Experiment	Technique	Observables in fit	σ_E/E	Ref.
<i>Direct (elemental fluxes vs. rigidity; solar modulation per observation window)</i>				
ACE-CRIS	satellite spectrometer	sub-leading elements; O	—	[31, 32]
HEAO-3	satellite	heavy elements P–Ni (w/o S, Fe)	2%	[33]
PAMELA	satellite spectrometer	p, He	—	[34]
AMS-02	station spectrometer	p–Fe, D	—	[23, 35–38]
CALET	station calorimeter	p, He, Ni, Ti, Cr	2%	[21, 39–41]
DAMPE	satellite calorimeter	p, He, C, O, Fe, B	2%	[42, 43]
ISS-CREAM	station calorimeter	p	2%	[44]
NUCLEON-KLEM	satellite	p, He, C, O; all-particle	5%	[45]
<i>Indirect (air showers: group fluxes, fractions, $\langle \ln A \rangle$)</i>				
HAWC	surface array	all-particle; p+He	16%	[46, 47]
GRAPES-3	surface array	p	25% †	[48]
LHAASO	surface + imaging Cherenkov	all-particle; $\langle \ln A \rangle$; p; He	8%	[13, 49, 50]
IceCube/IceTop	surface + in-ice array	all-particle; 4 fractions	10% †	[51]
IceTop (low energy)	surface array	all-particle	10% †	[52]
Tunka-133	non-imaging Cherenkov	all-particle; 4 fractions	10% †	[53, 54]
TALE (hybrid)	hybrid	$\langle \ln A \rangle$	10% †	[55]
Telescope Array	surface array	all-particle ($E \geq 10^{18.25}$ eV)	21%	[56]
Pierre Auger	hybrid	all-particle; 4 FD fractions	14%	[57, 58]
<i>Excluded: KASCADE-Grande [59]; CALET B [60], C, O, Fe [21] (SM S3); H.E.S.S./VERITAS iron [61, 62]; NUCLEON-KLEM iron; ACE-CRIS iron; TALE monocular [63]</i>				

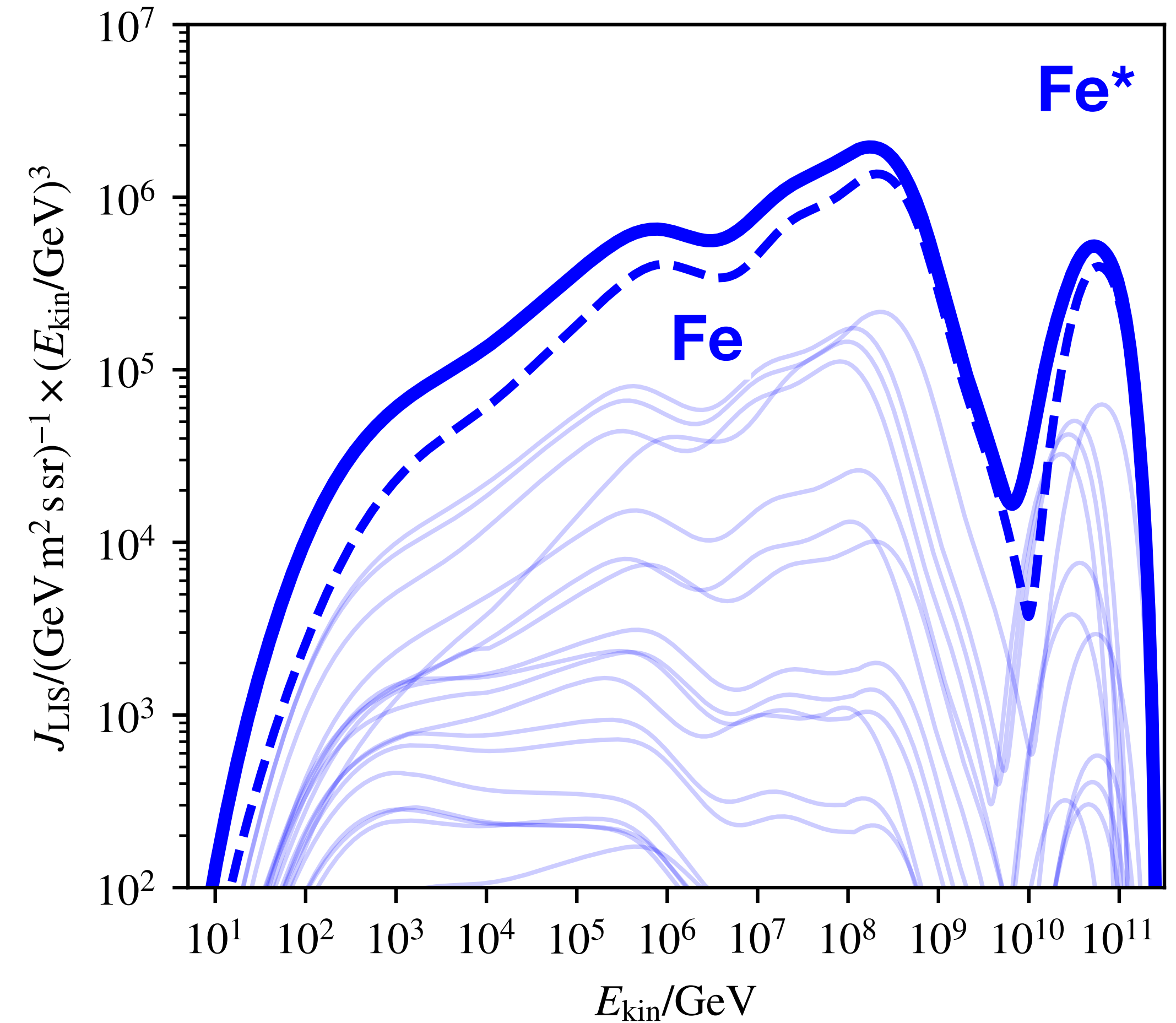
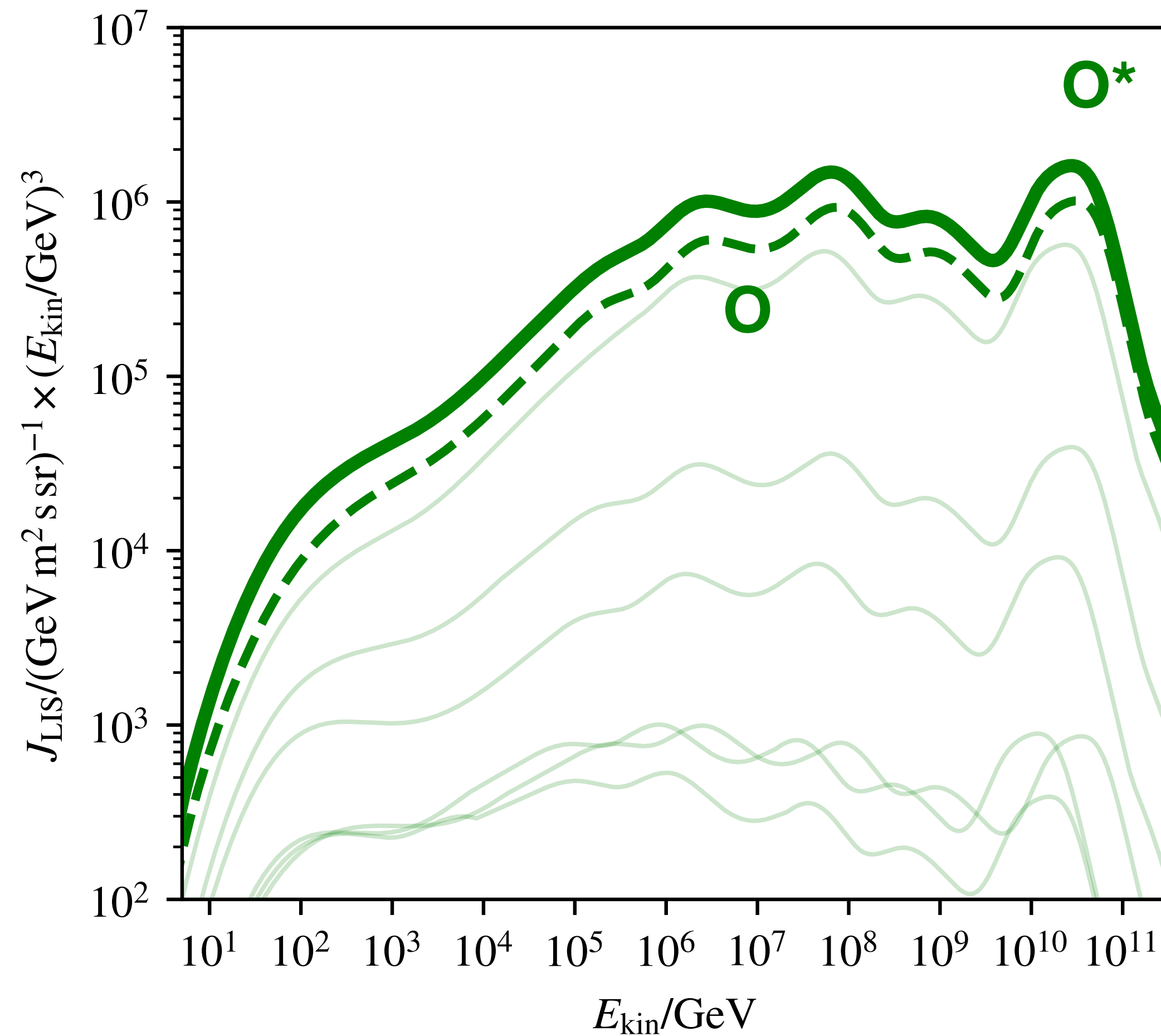
GSF-2026

**Hadronic interaction models:
separate fits, average used,
sys. uncertainty from envelope**

Direct measurements and mass groups

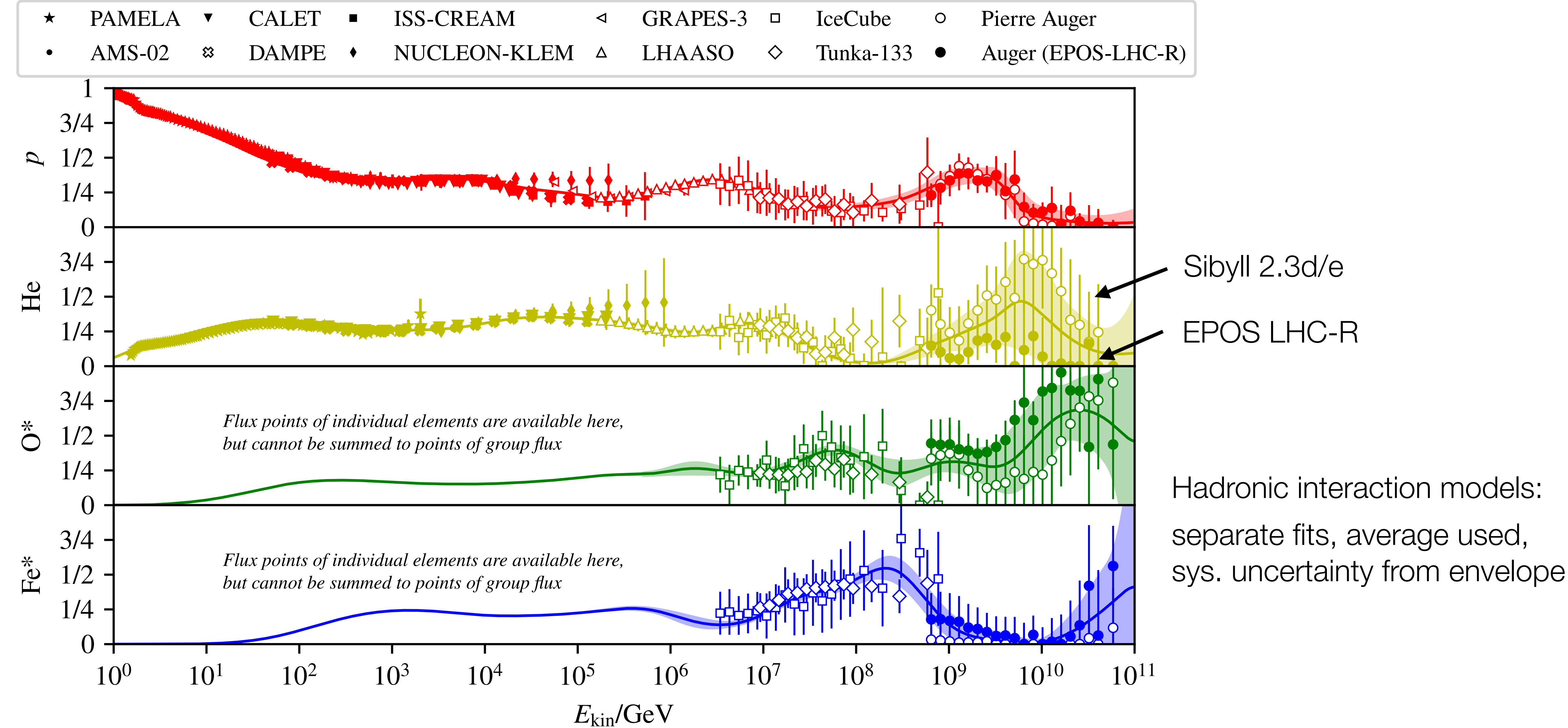


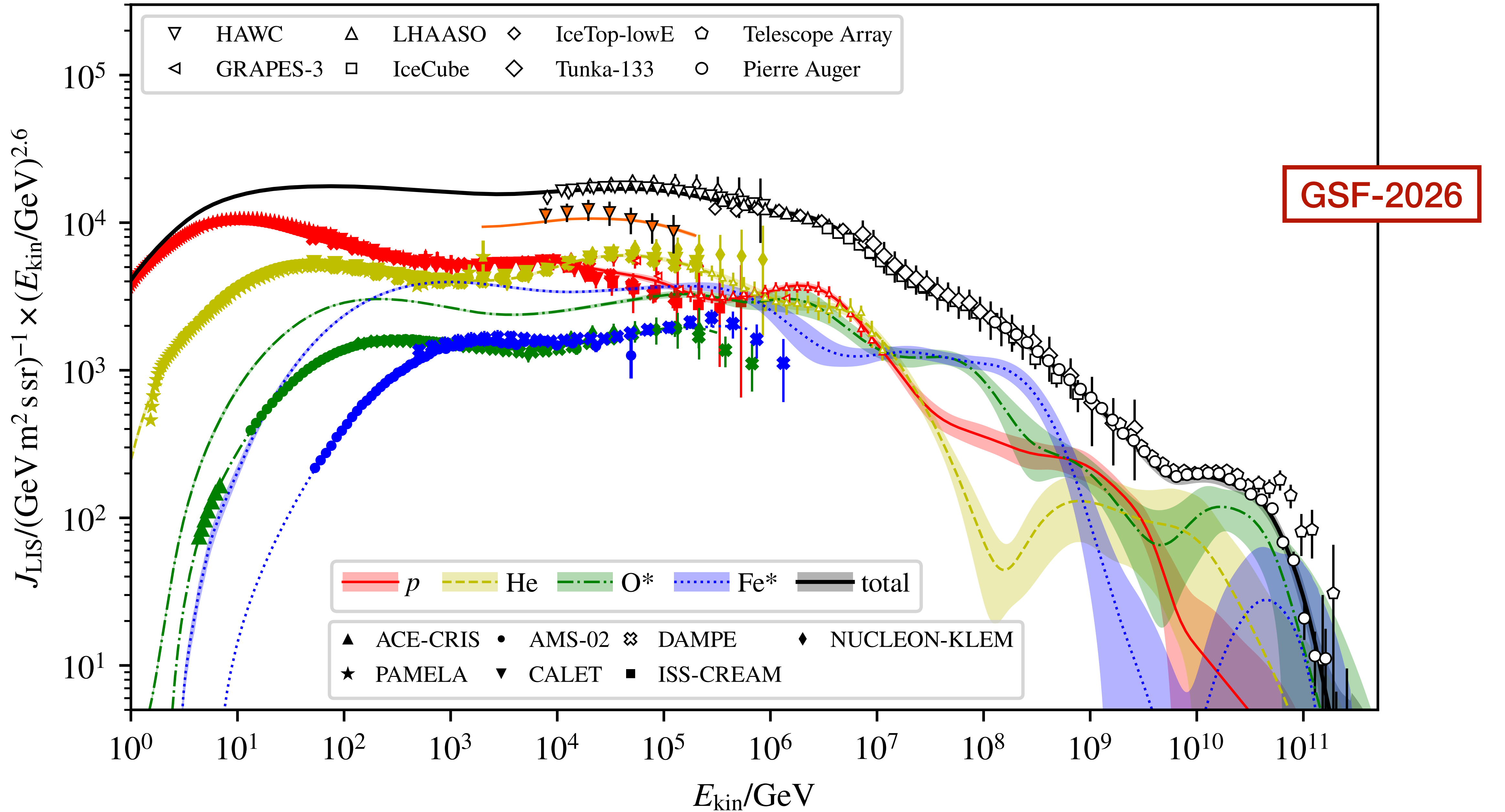
Importance of distinguishing elements and mass groups



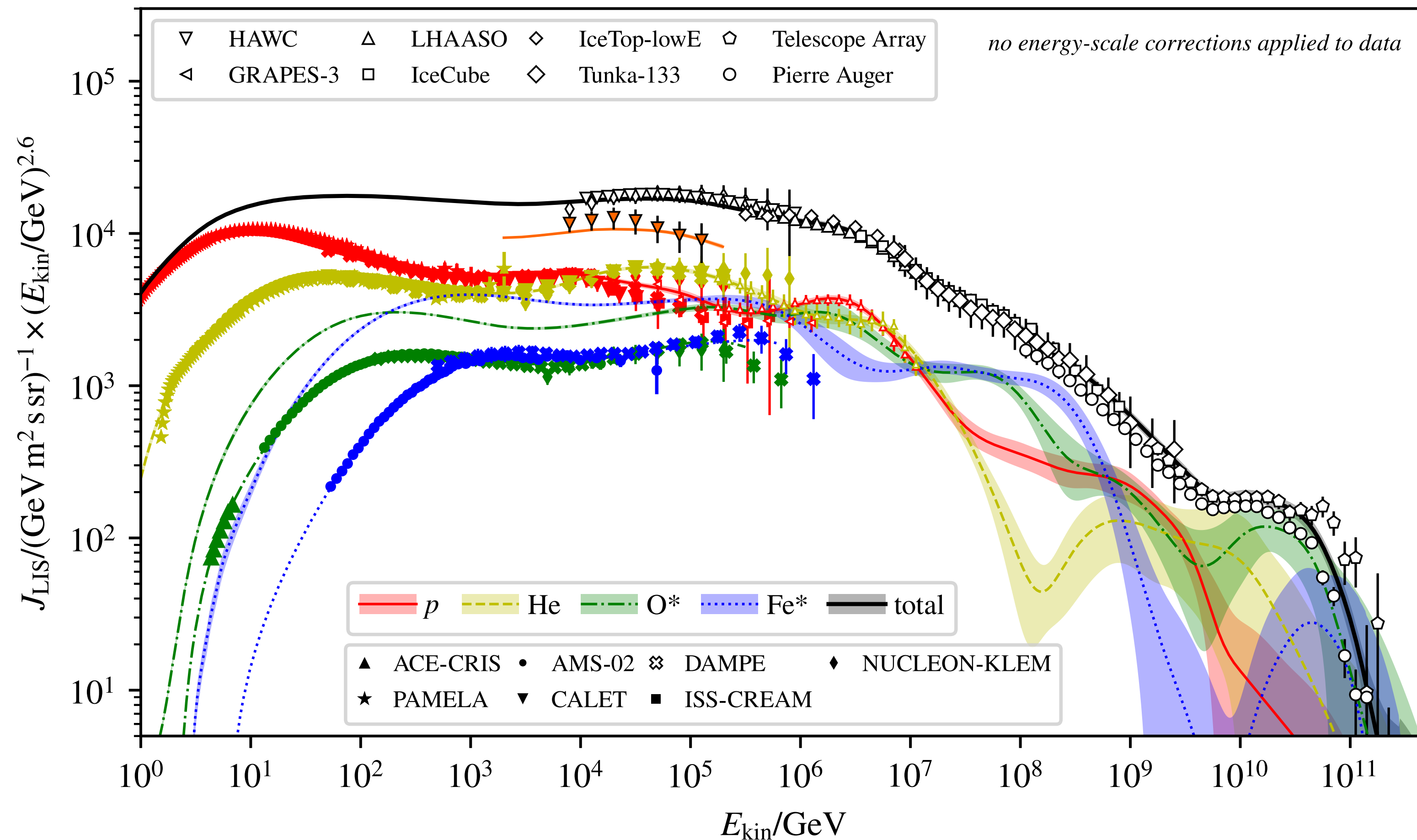
Extrapolation: abundance ratios kept fixed for energies without direct data

Connection between direct and indirect measurements

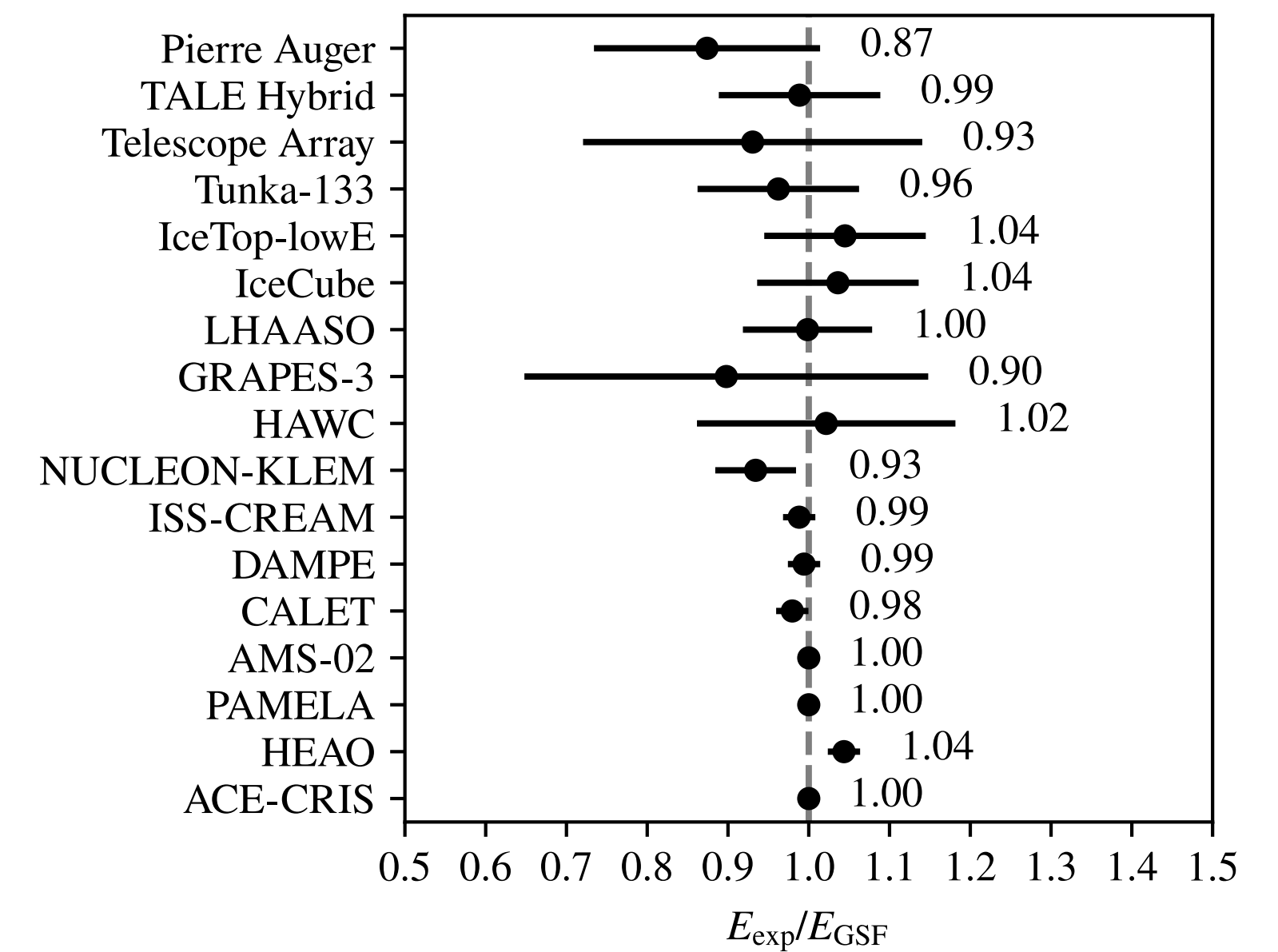




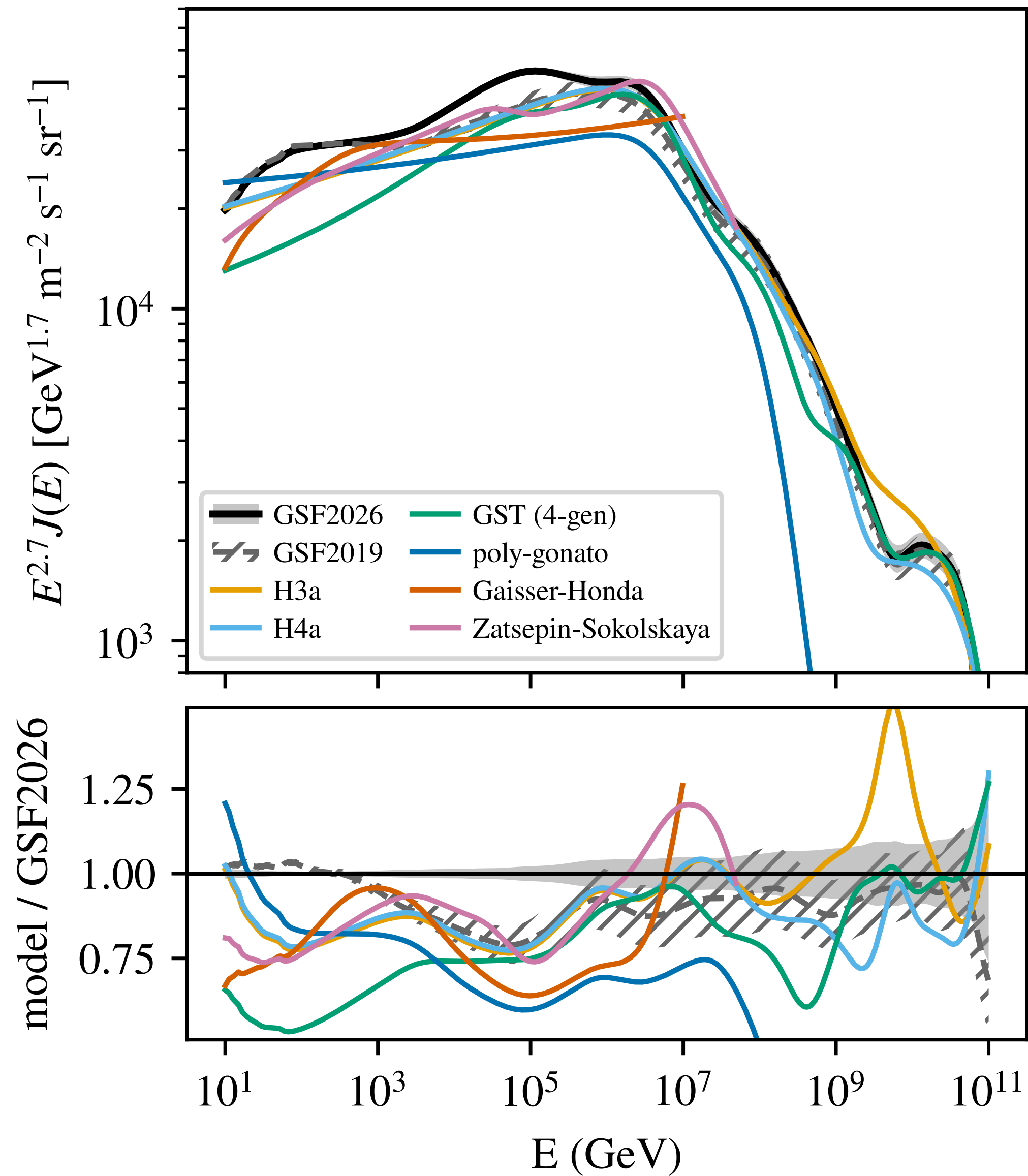
GSF-2026 – shown with original energy scales



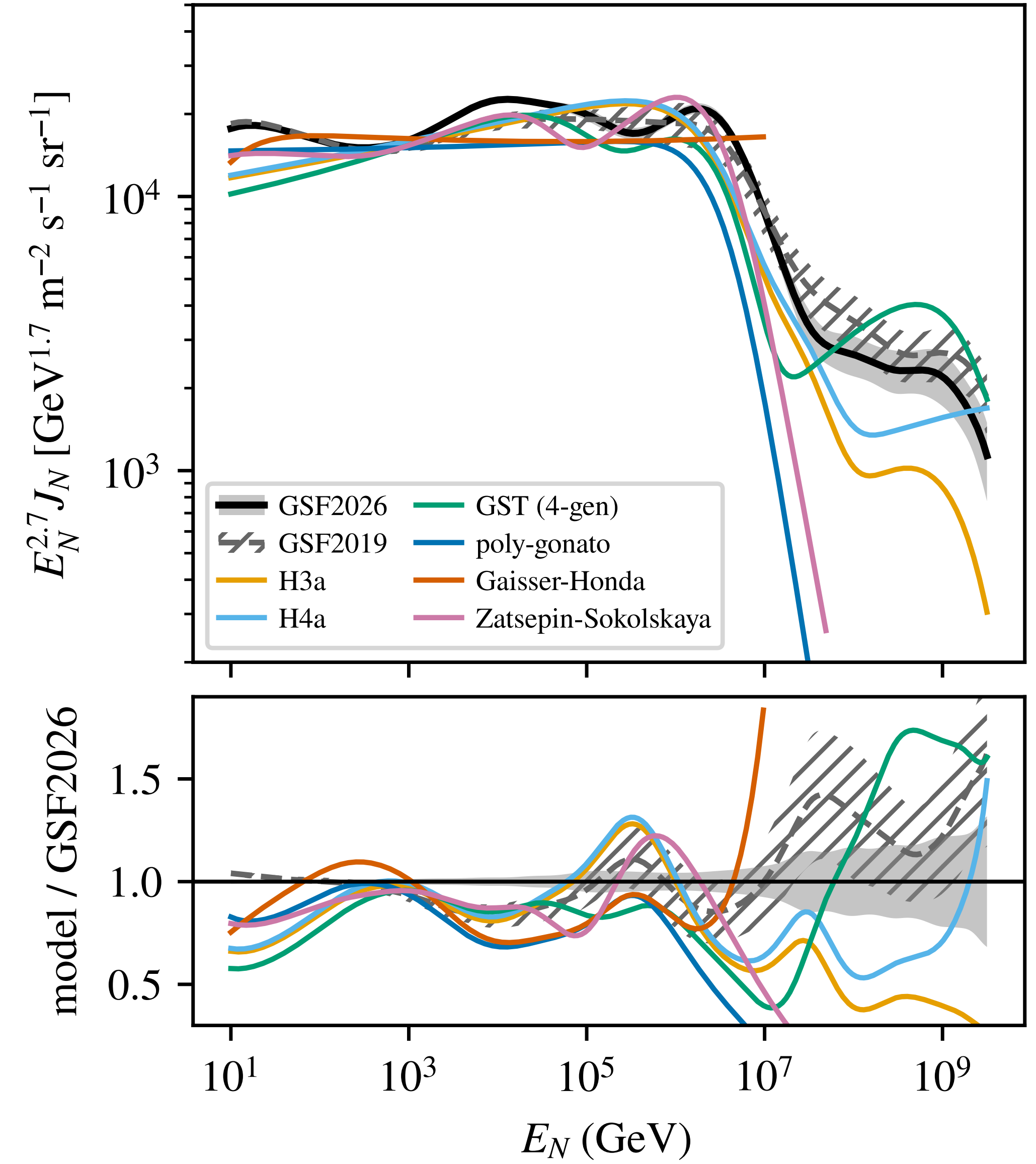
GSF-2026



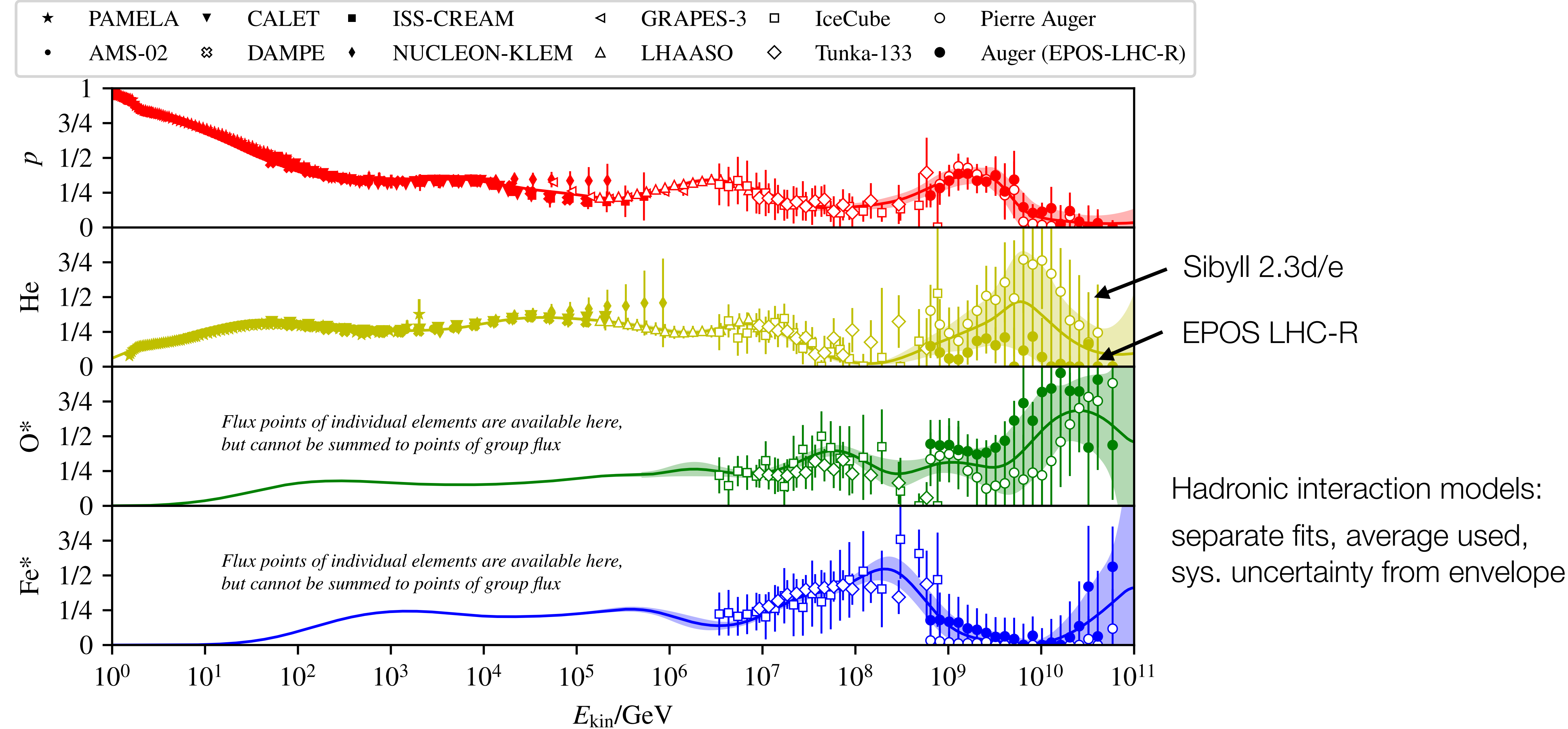
All-particle flux vs. particle energy



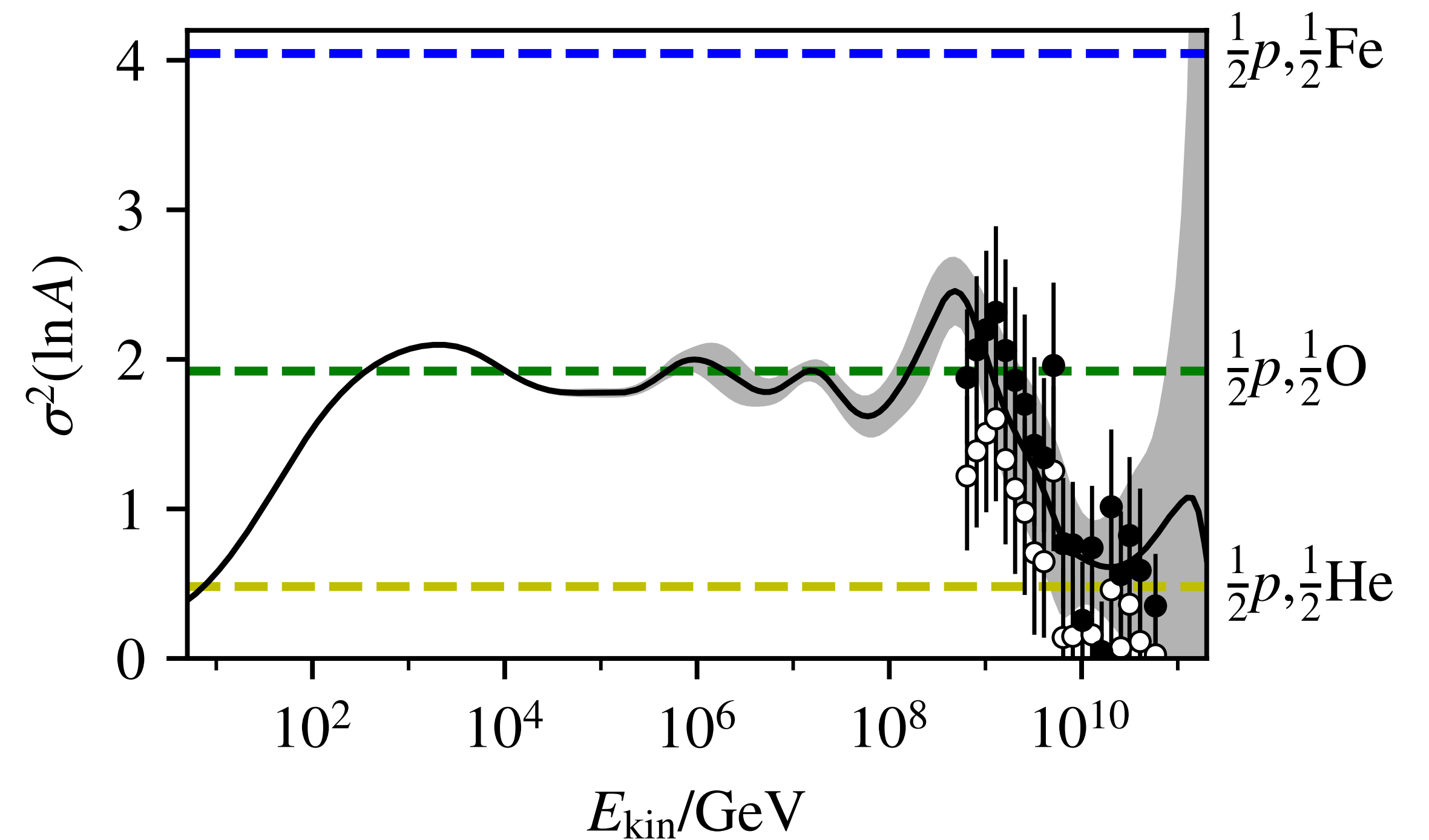
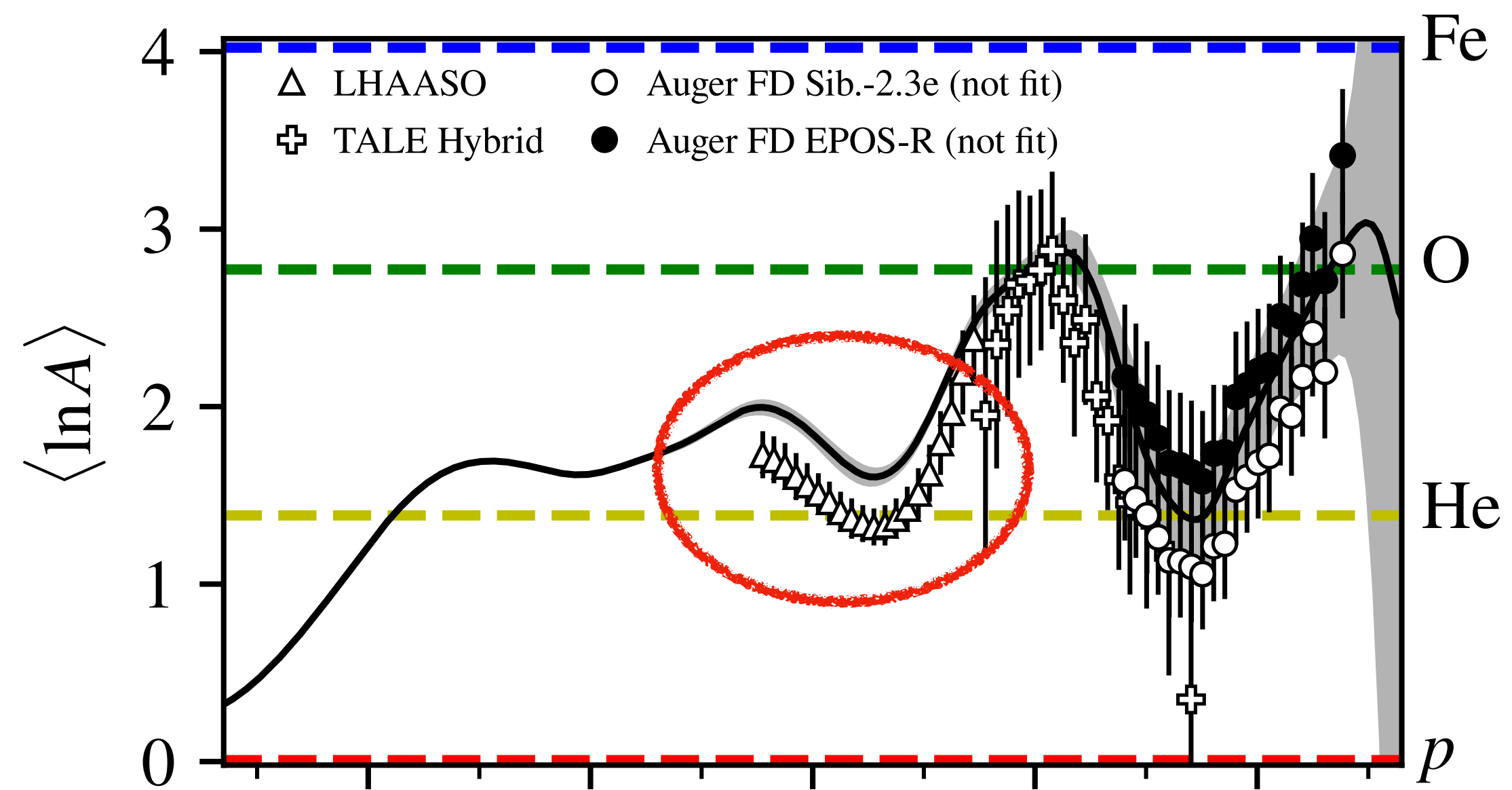
Inclusive nucleon flux vs. nucleon energy



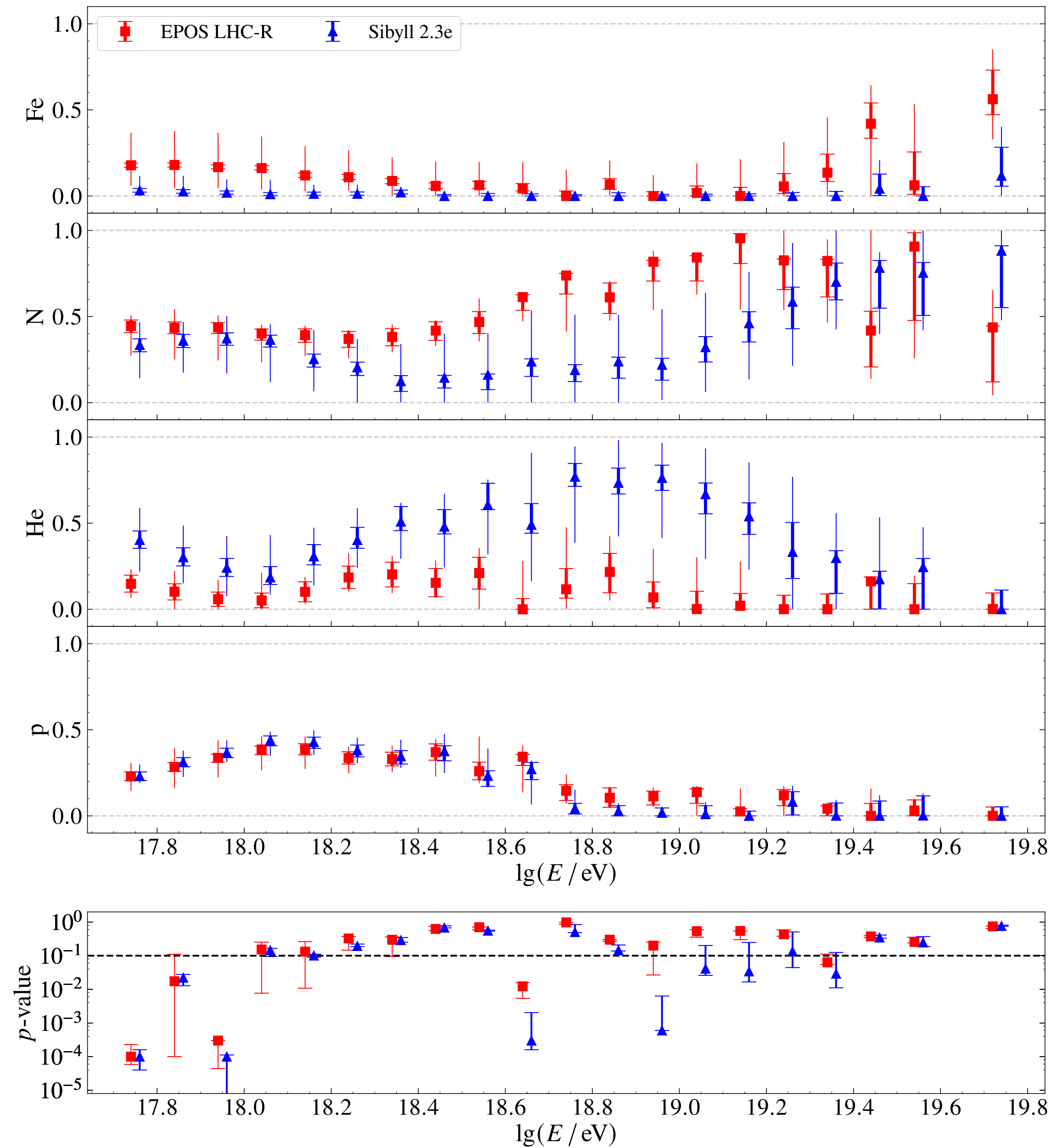
Mass composition uncertainty at highest energies



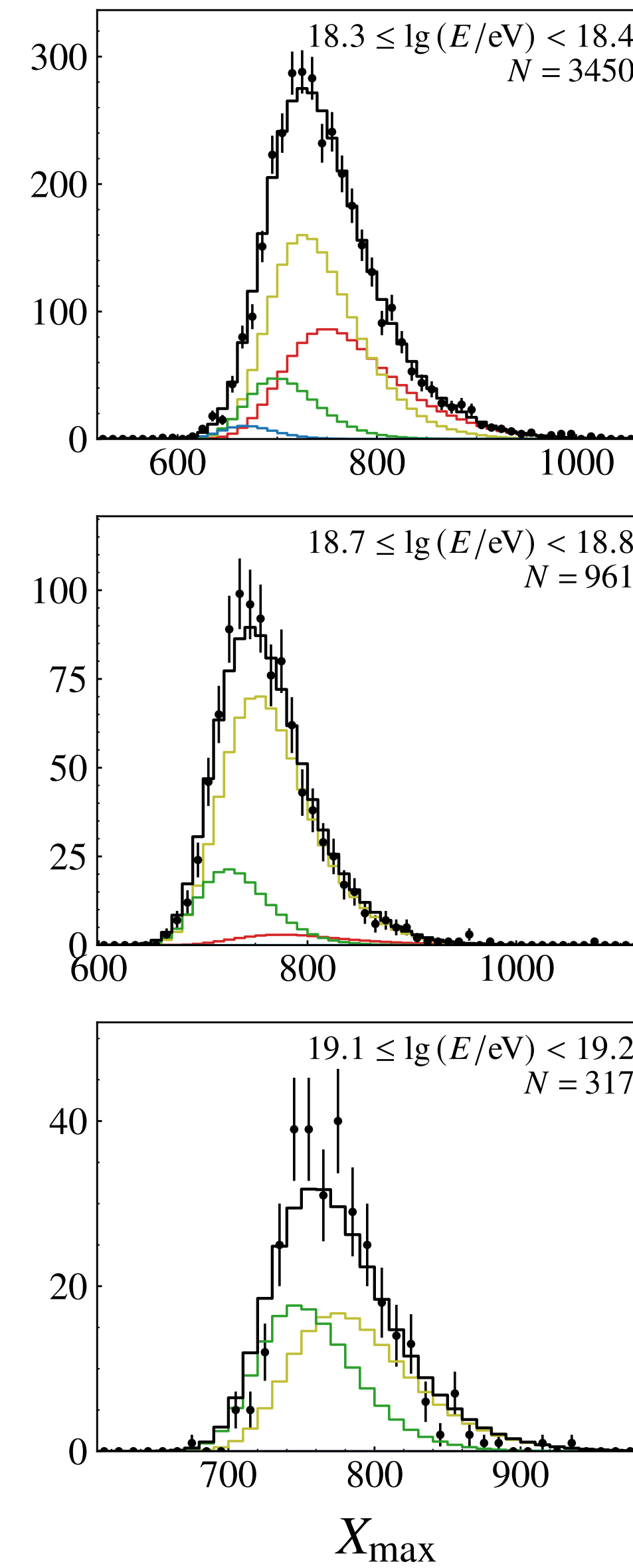
Comparison of GSF-2026 prediction for $\ln(A)$ with data



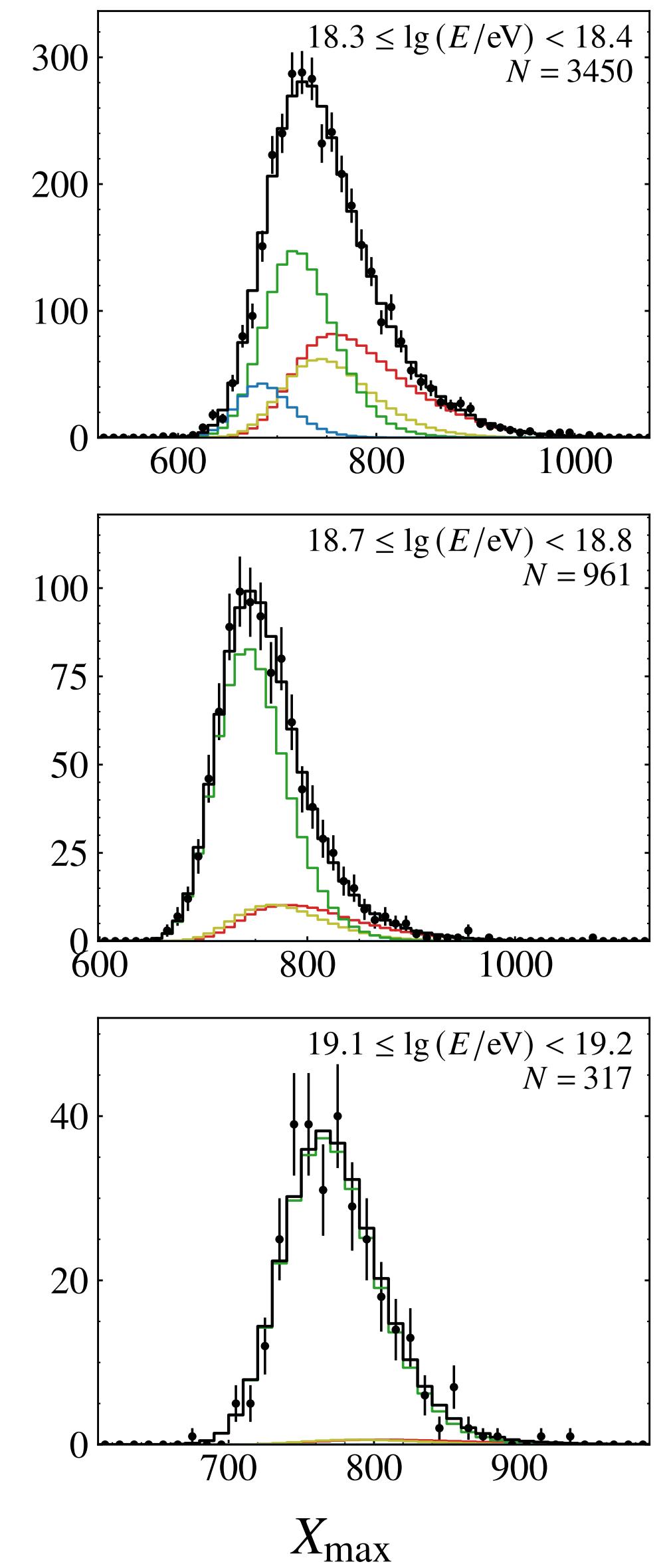
Some tension found for LHAASO data (probably related to four mass groups)

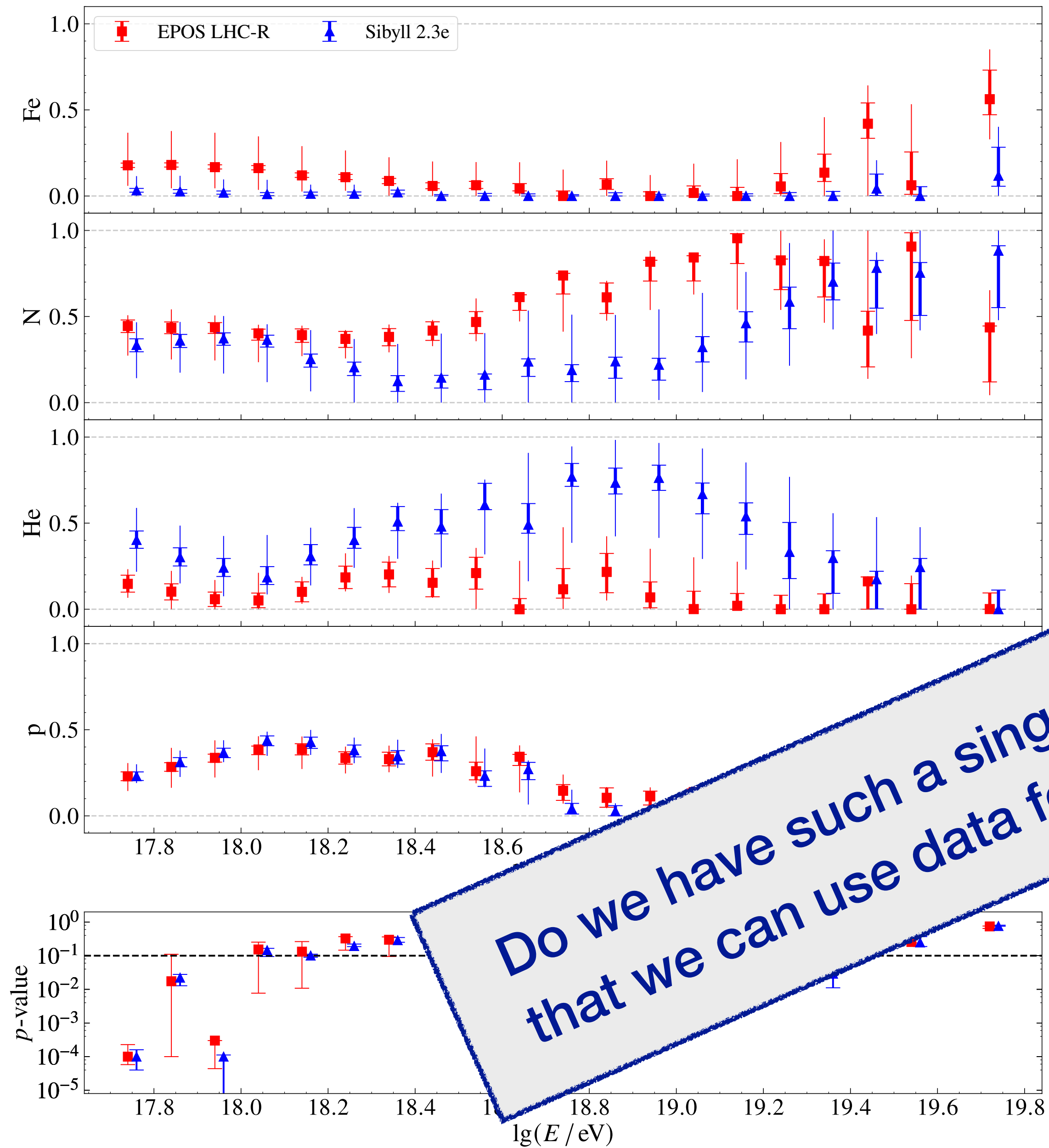


Sibyll 2.3e

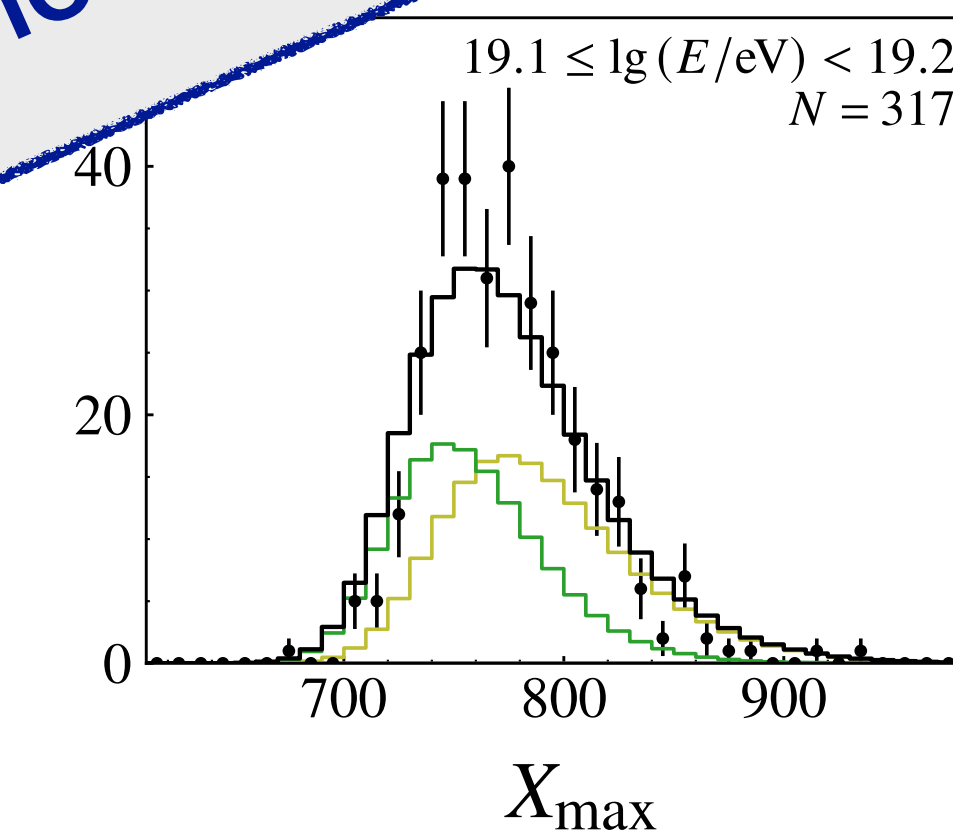
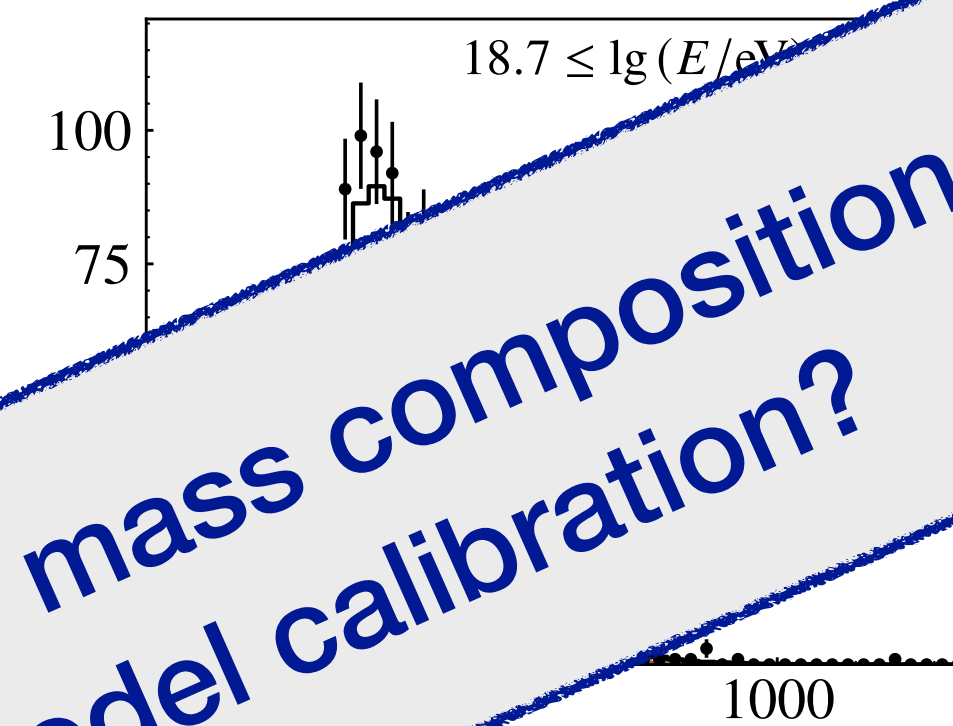
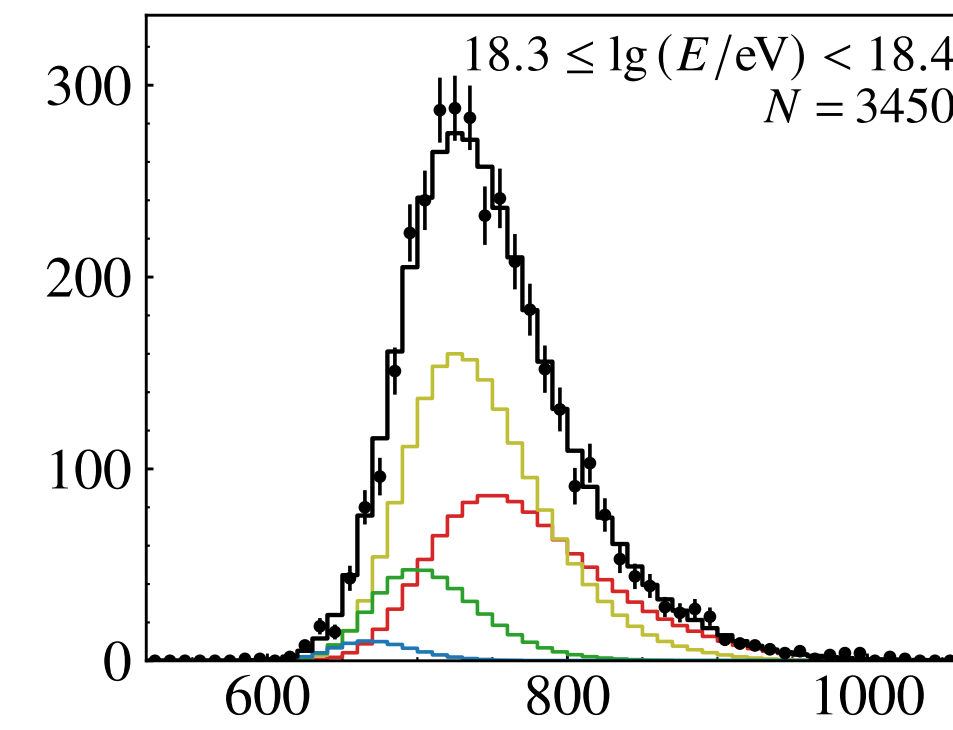


EPOS-LHC-R

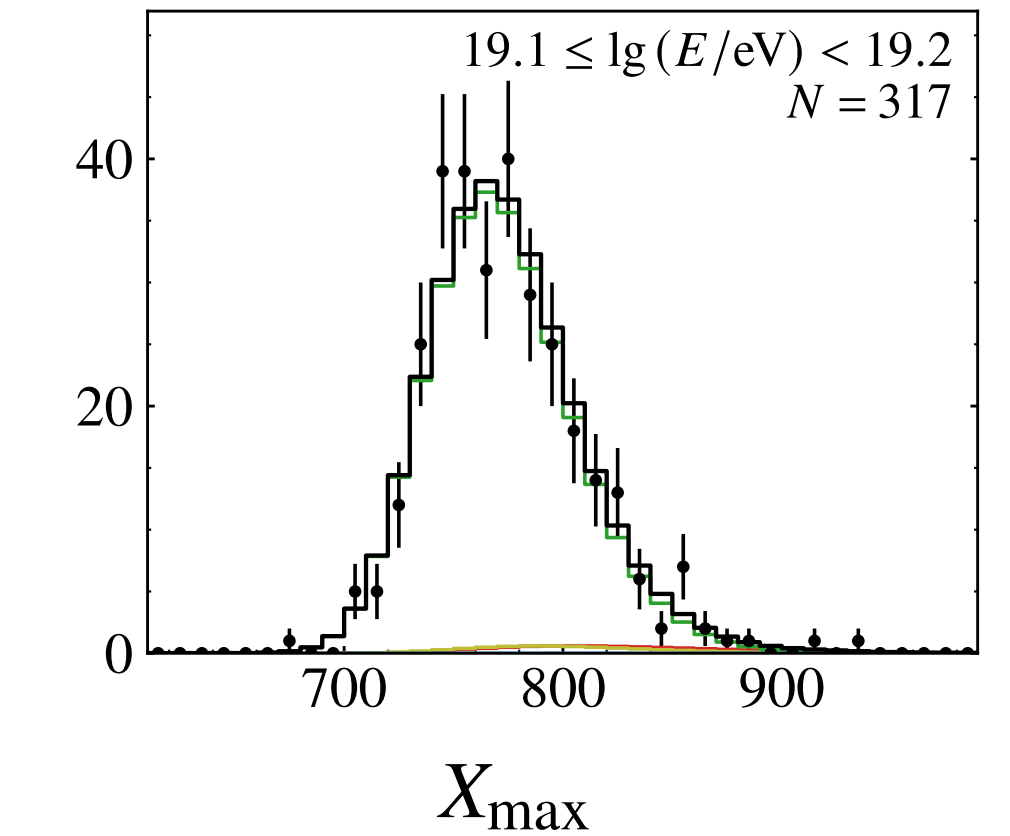
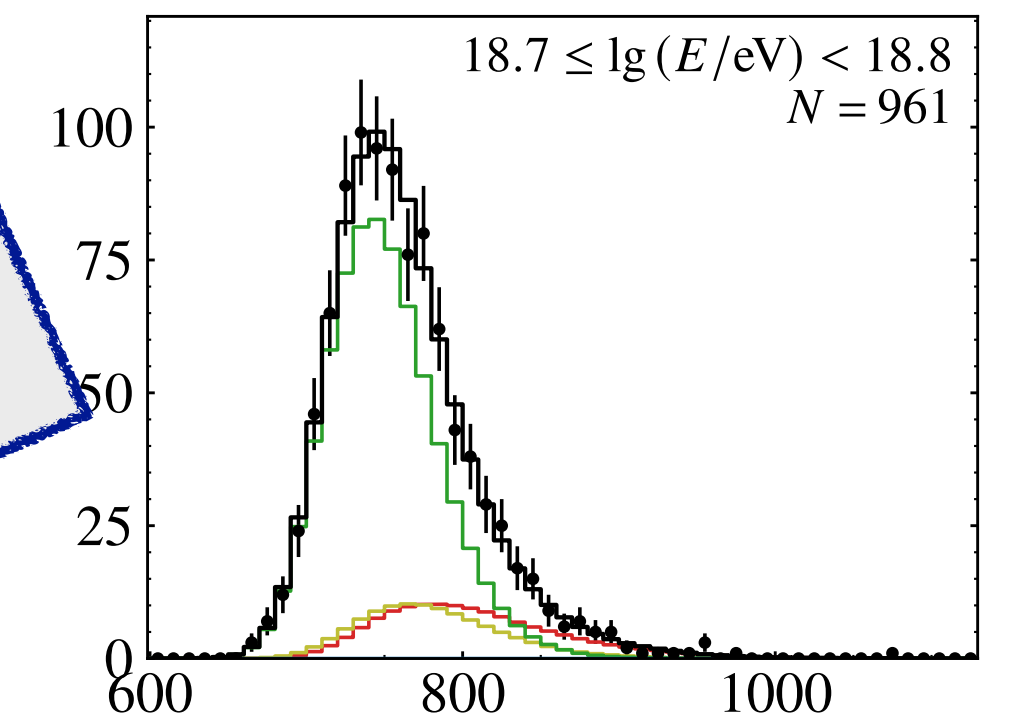
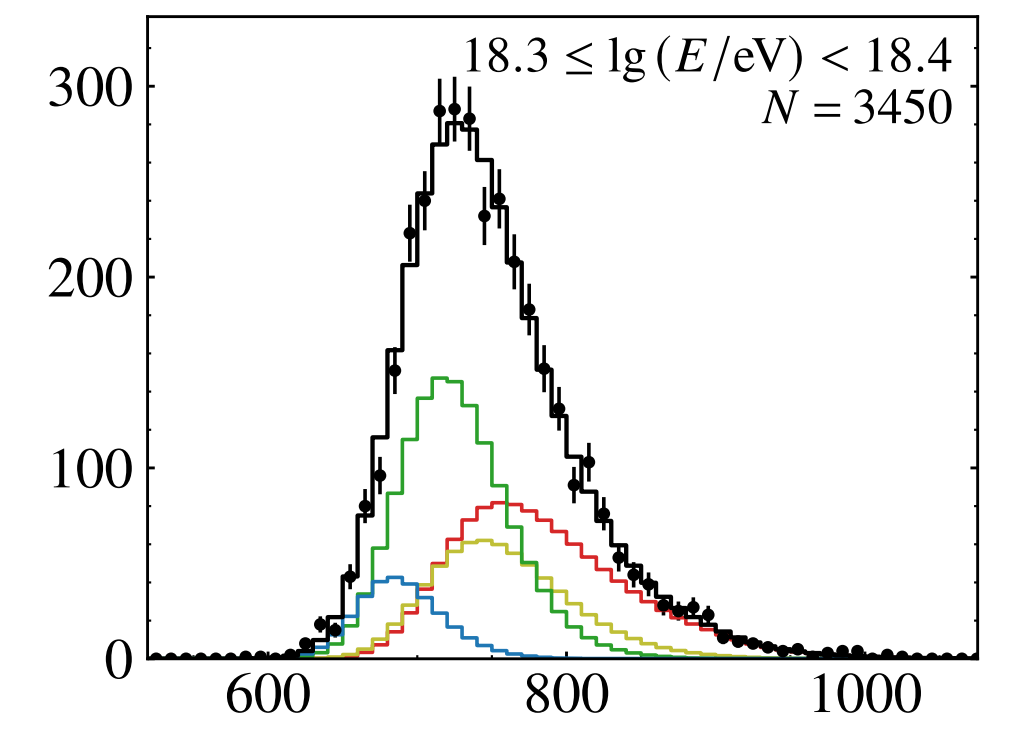




Sibyll 2.3e



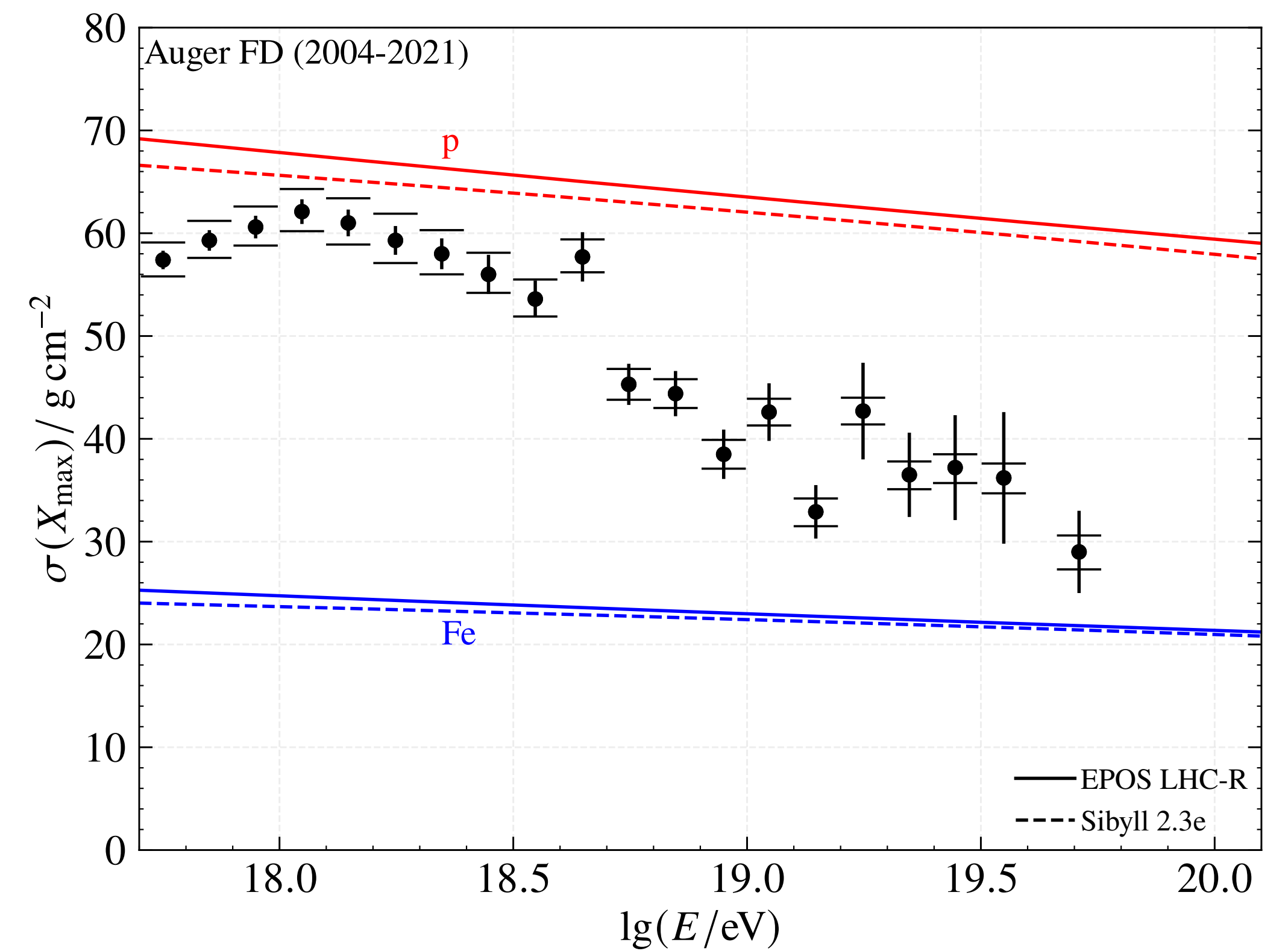
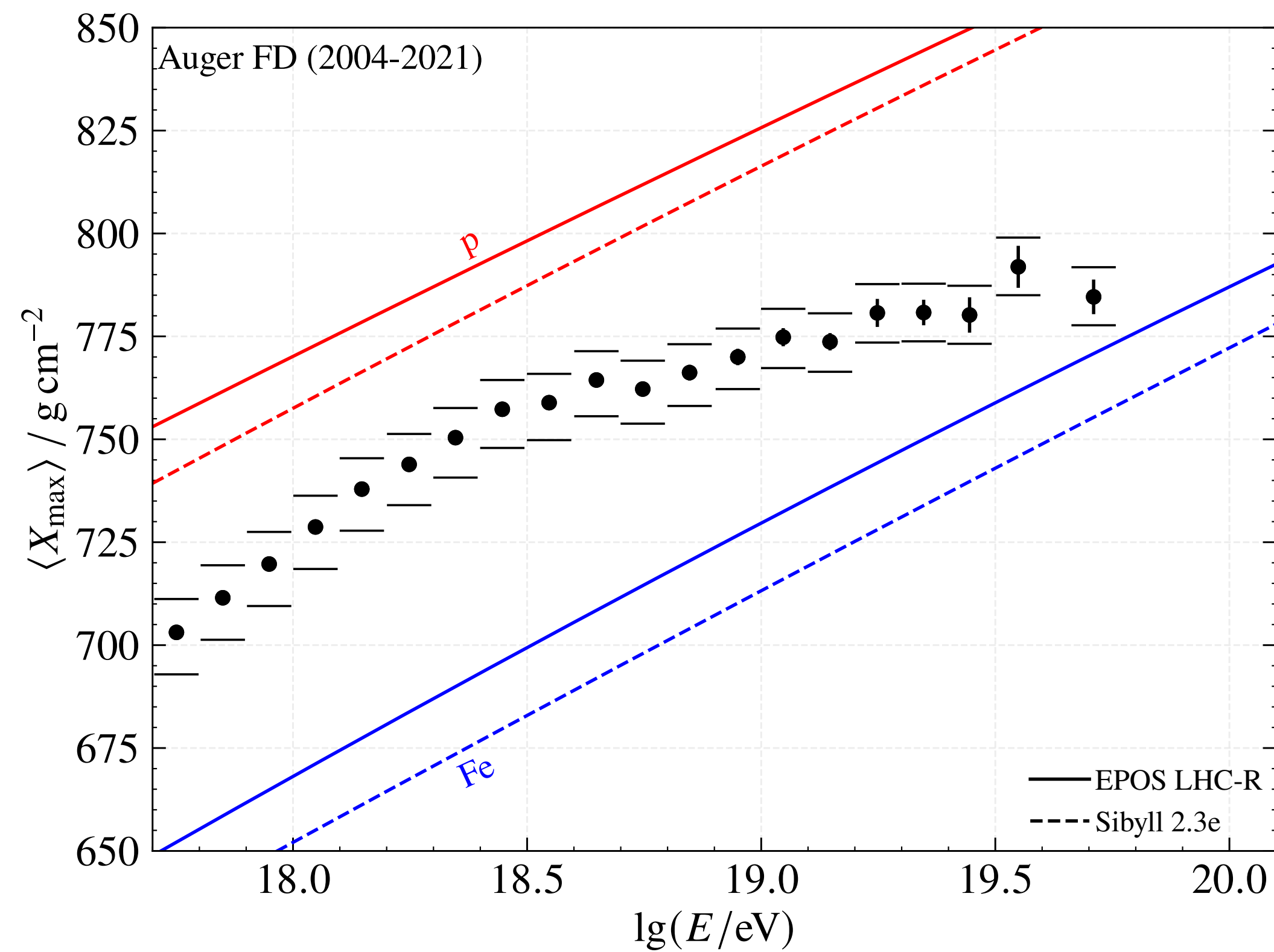
EPOS-LHC-R



Do we have such a singular mass composition
that we can use data for model calibration?

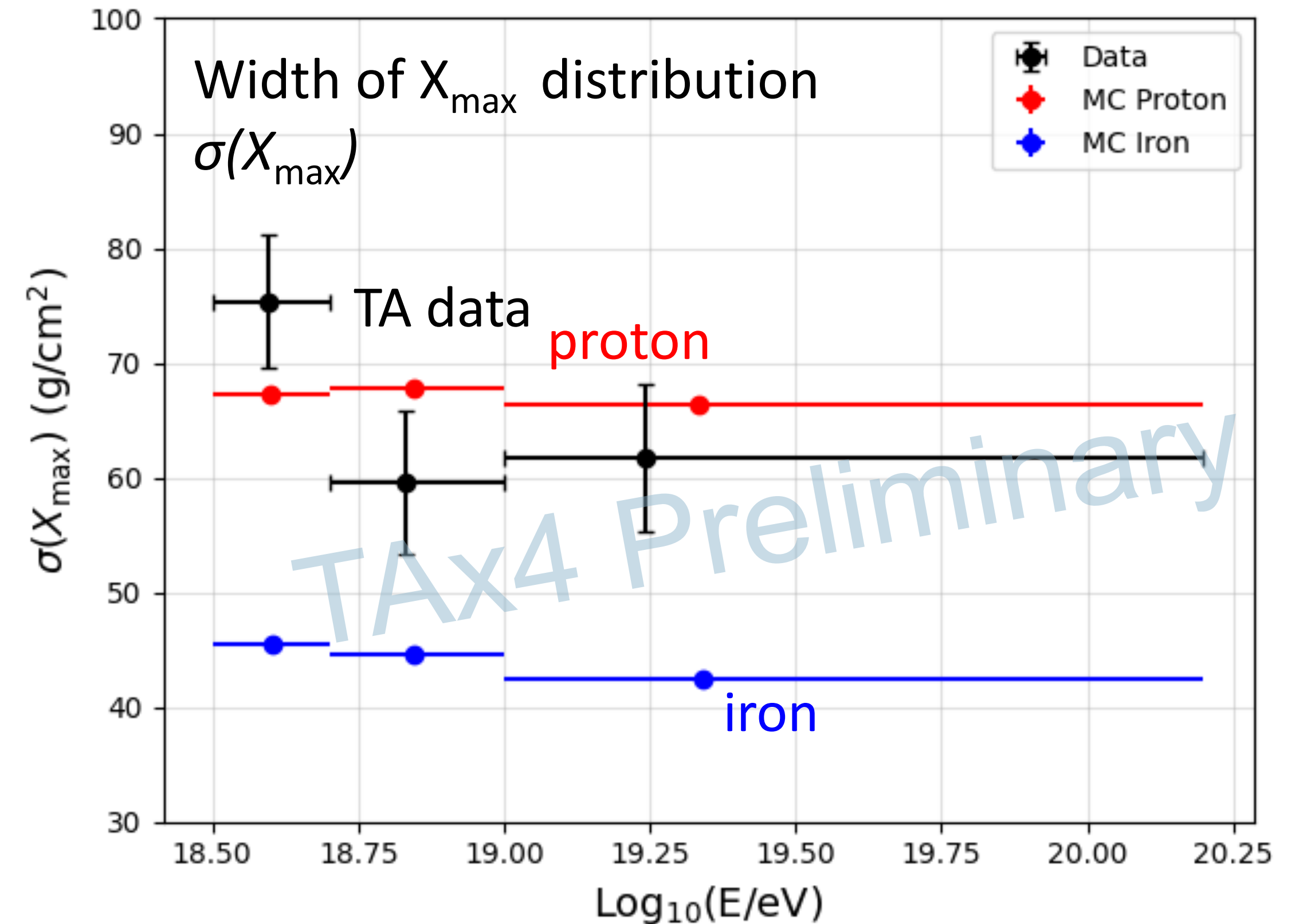
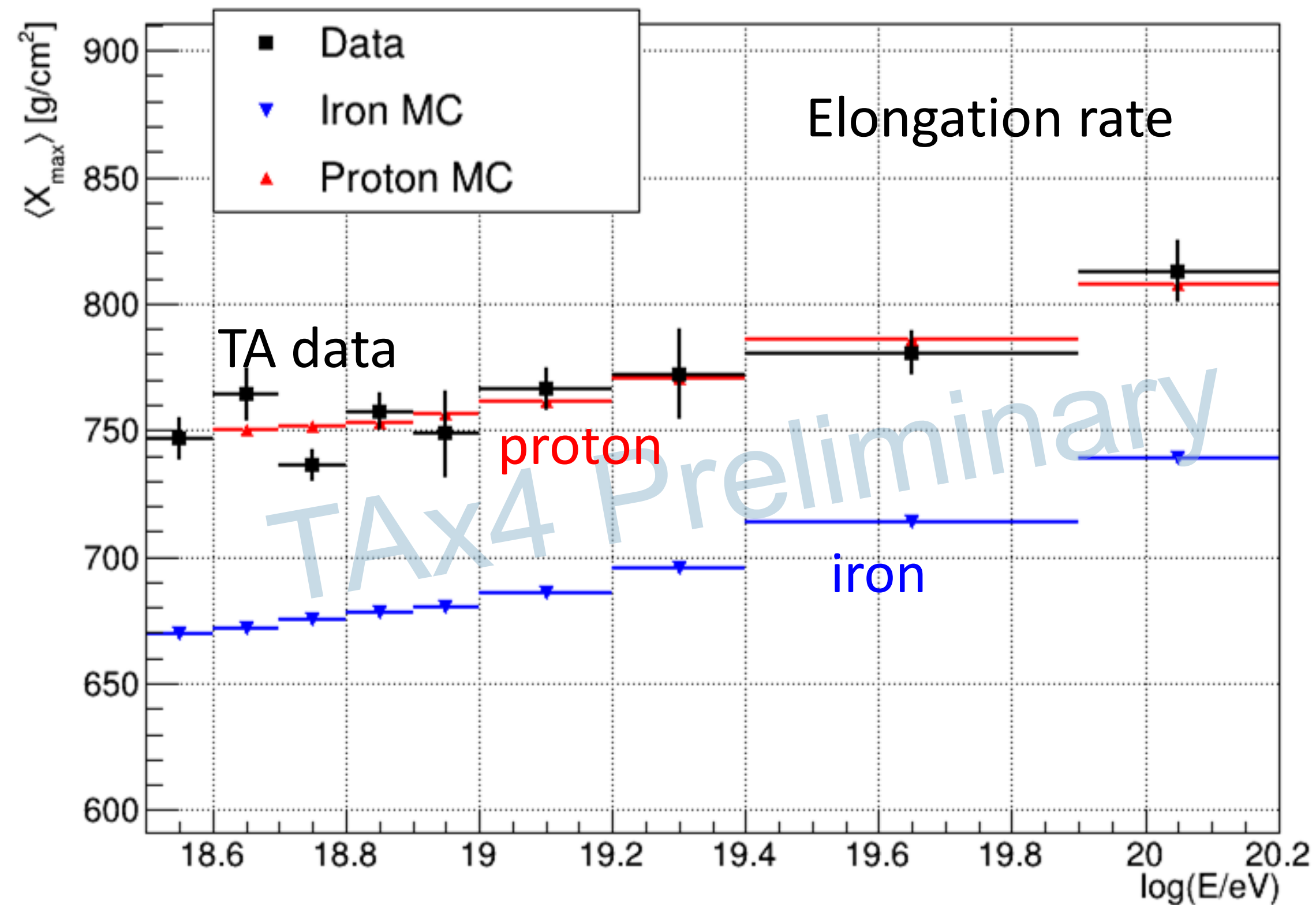
Xmax moments – Auger Observatory Phase I

Auger Phase I final data on Xmax measurement with fluorescence telescopes



Xmax moments – Preliminary TAx4 results

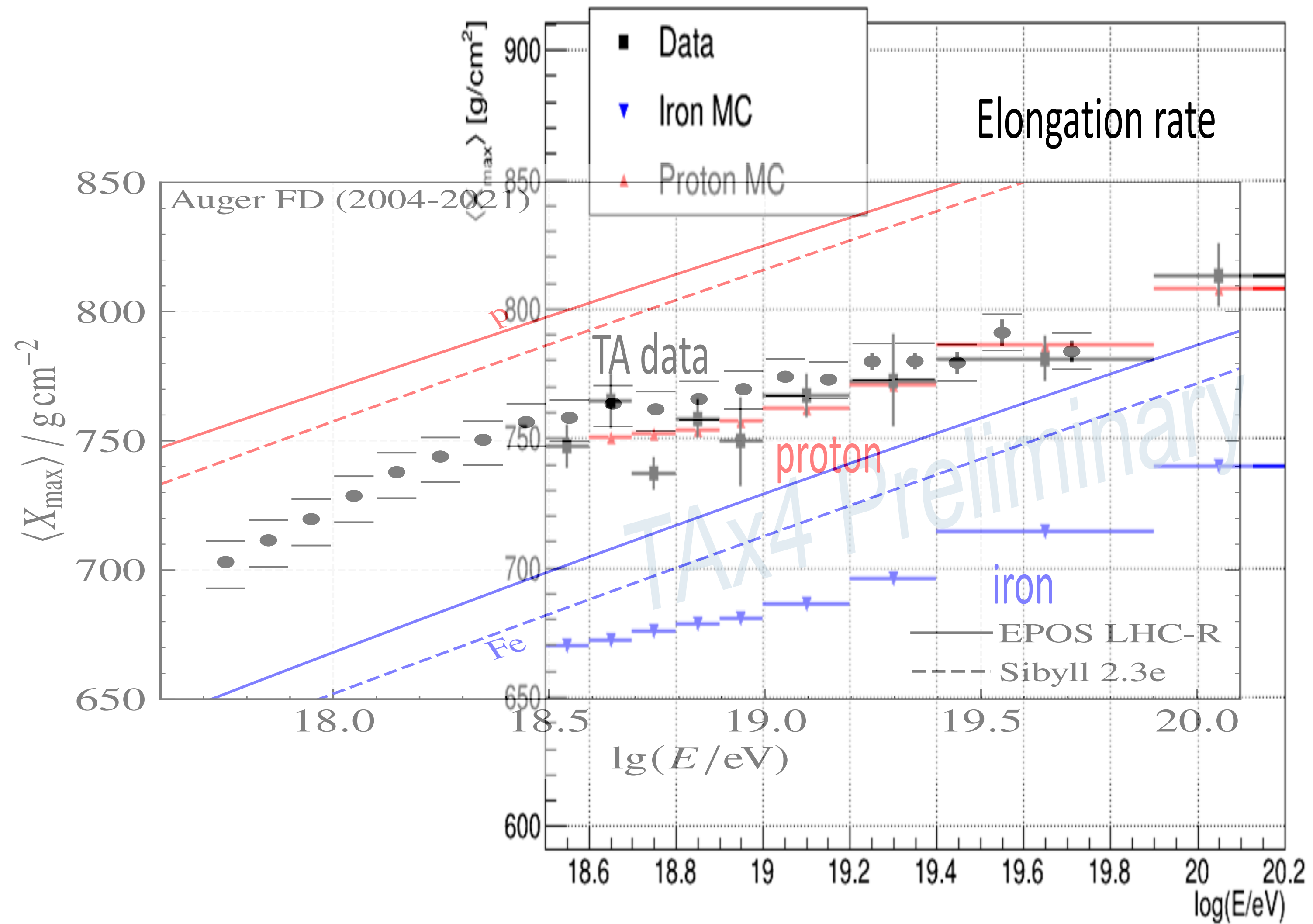
TA, Gerber, PoS(ICRC2025)269



TAx4 data points are not much different from Auger results,
interpreted at face value would be primaries heavier than Auger mass fits

Model: QGSjet II.03

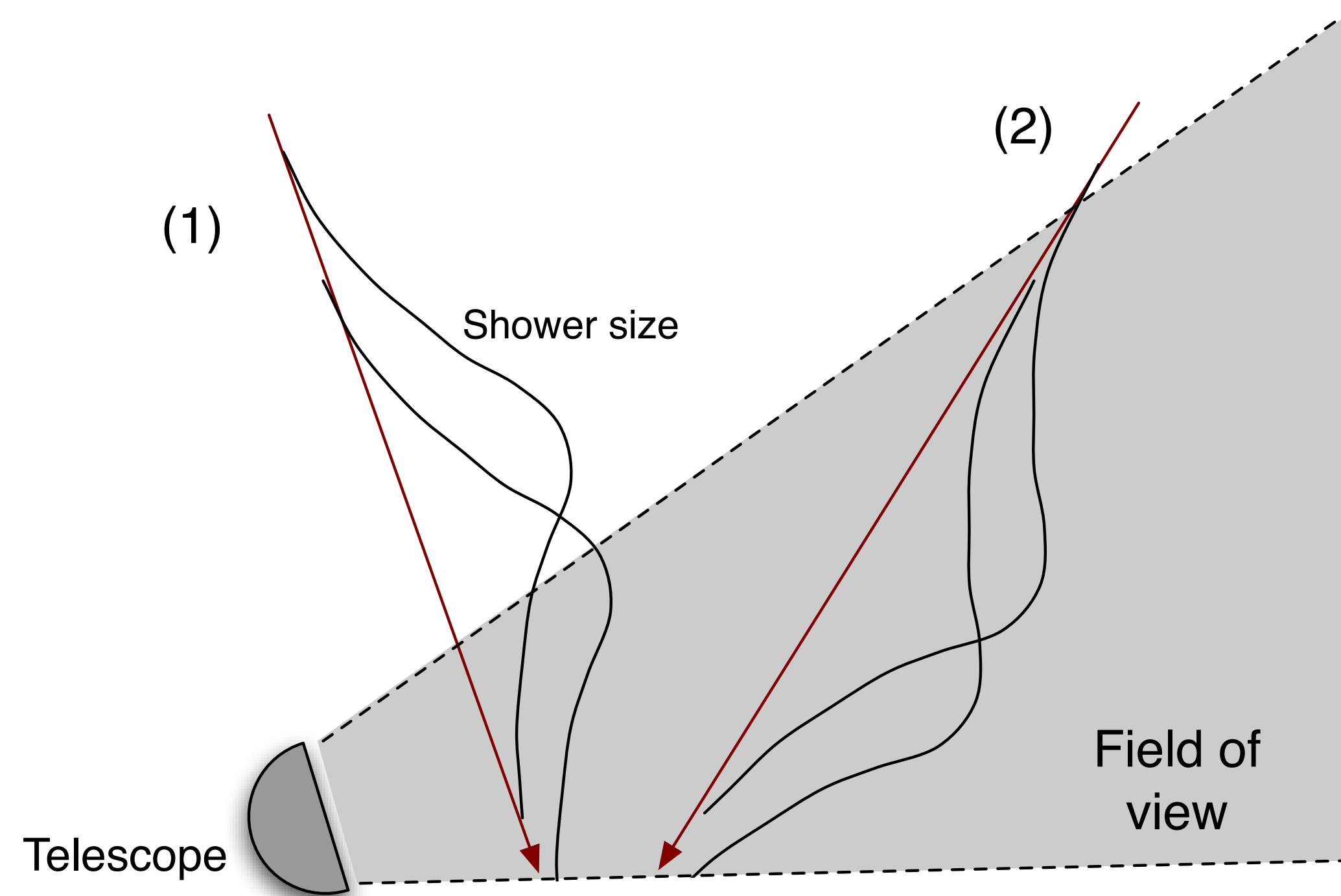
Comparison ignoring field-of-view biases



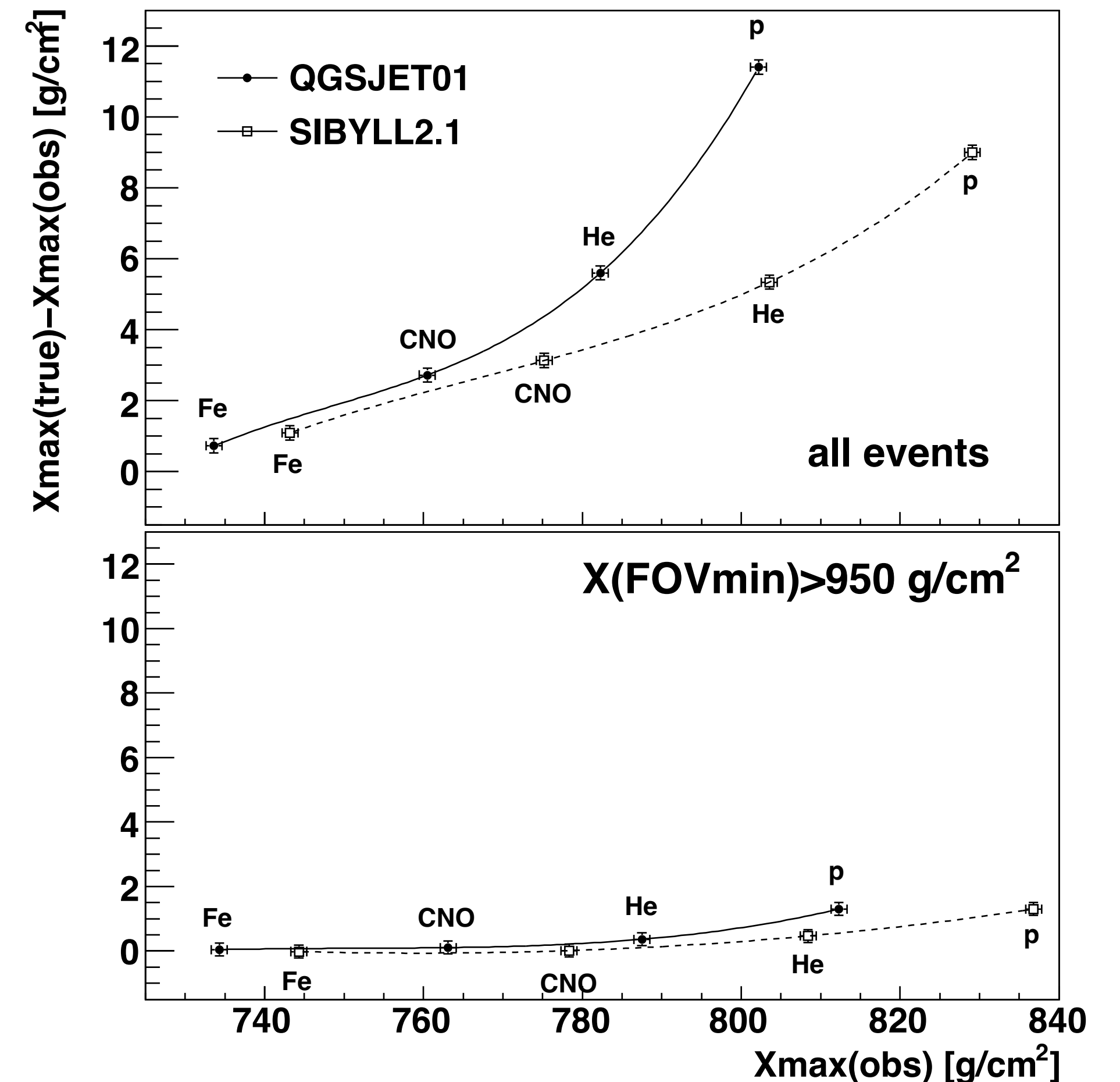
Comparison of composition data – field of view effects

Auger: only analysis of showers for which all relevant $X_{\max}$ are observable, comparison with theoretical $X_{\max}$ distributions

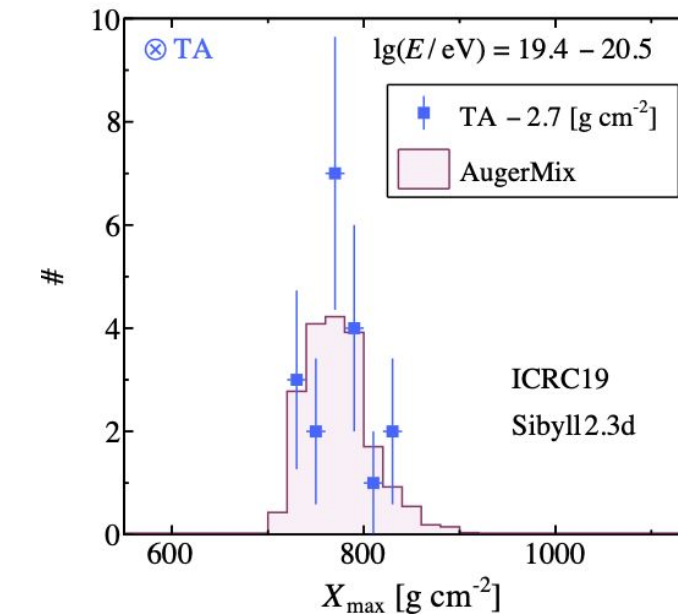
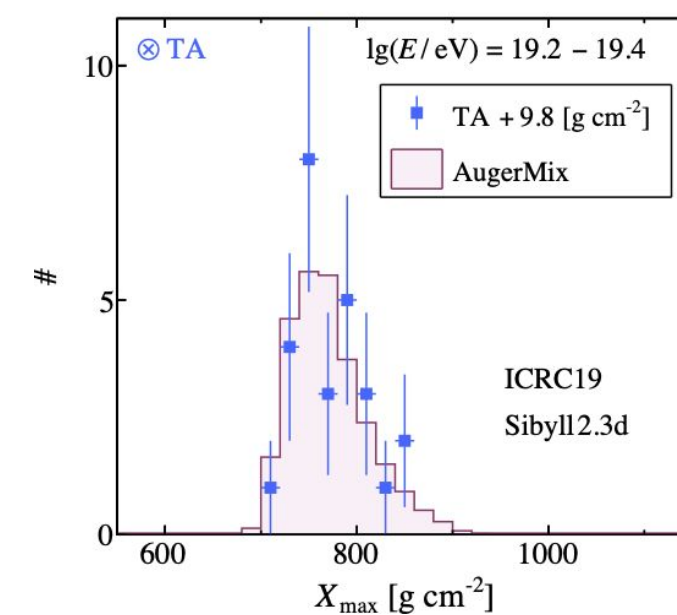
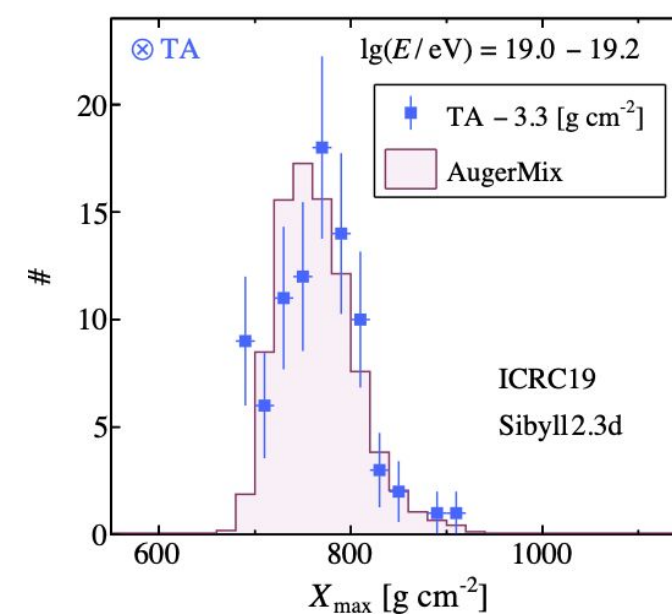
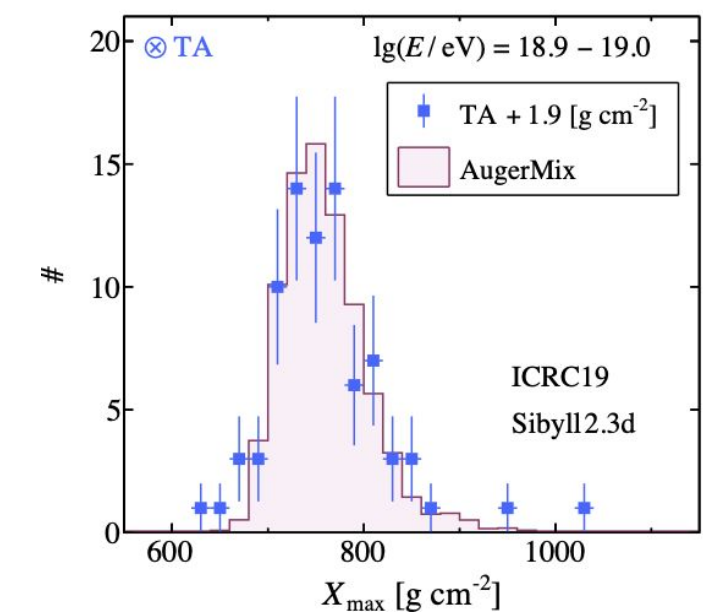
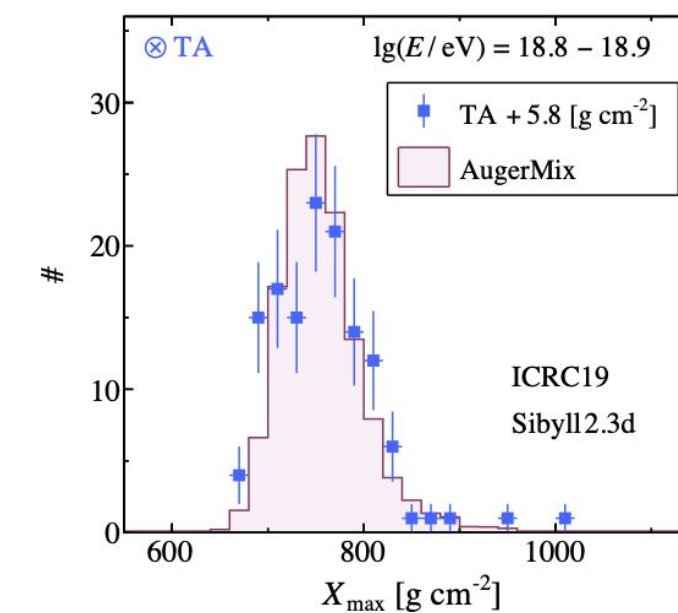
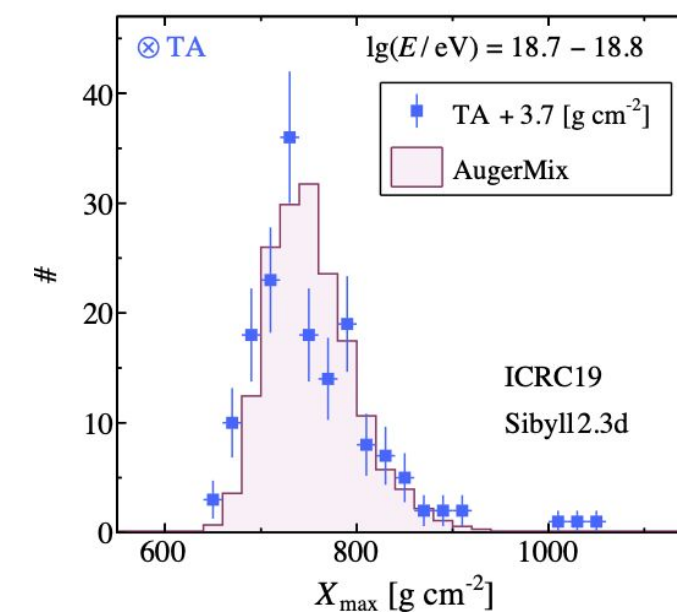
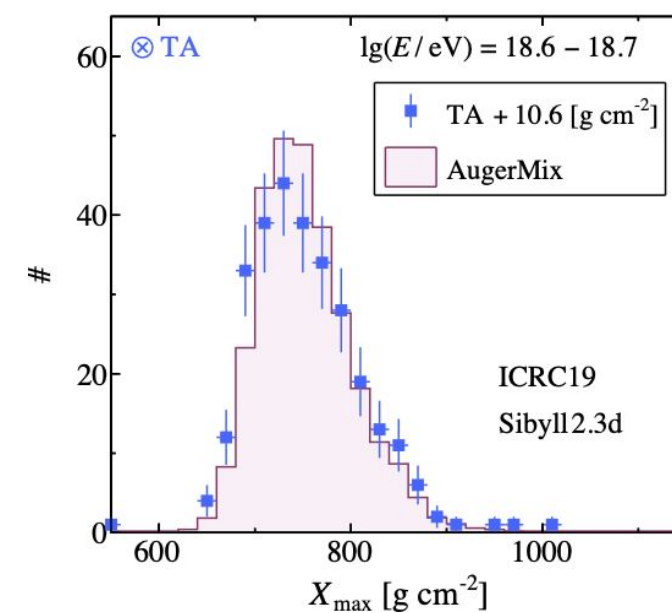
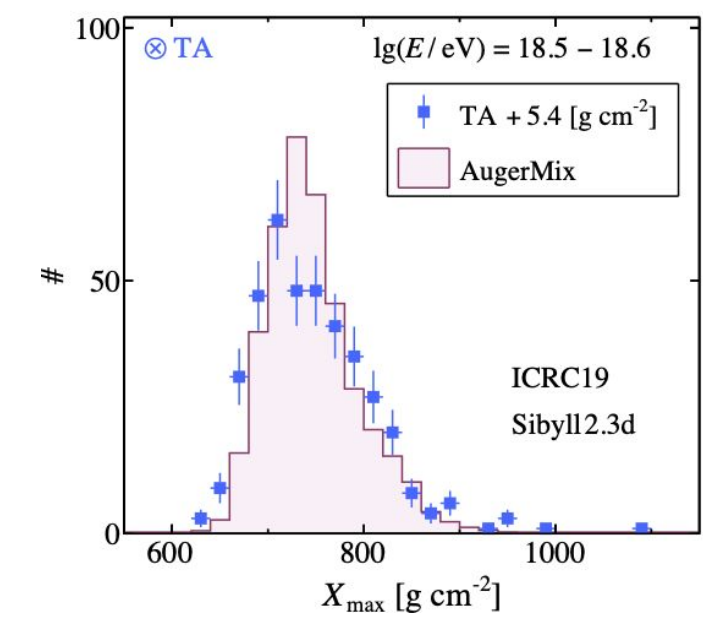
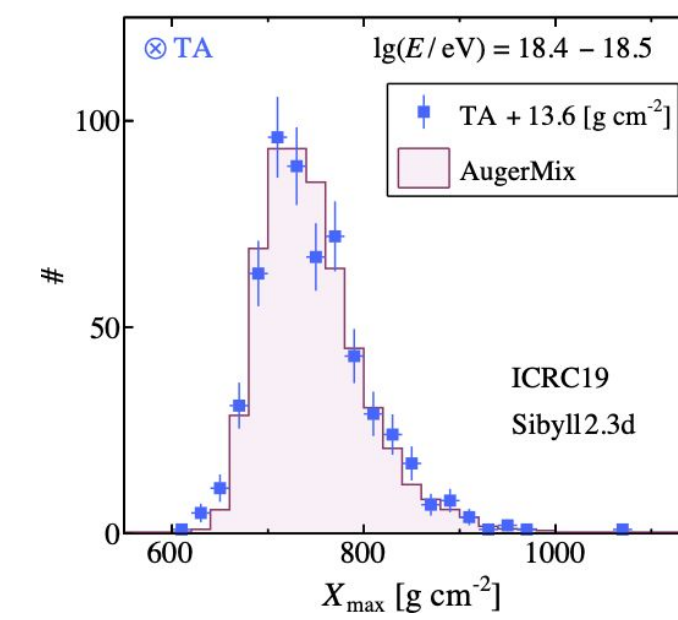
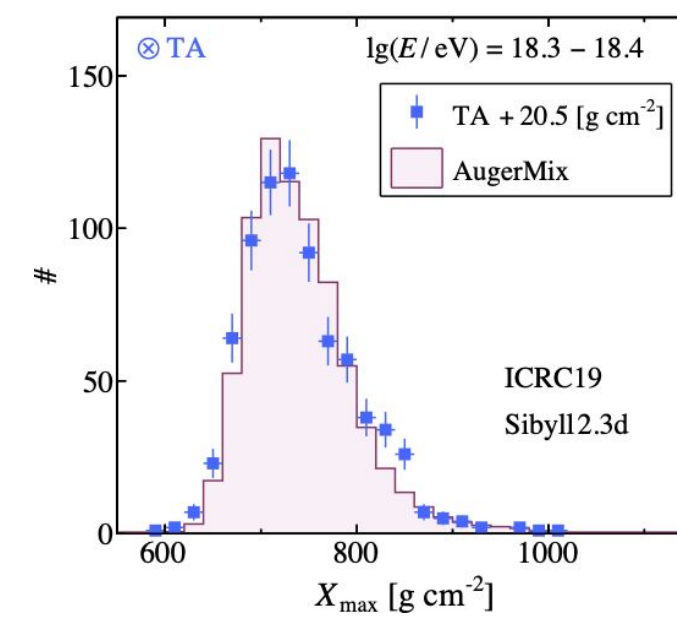
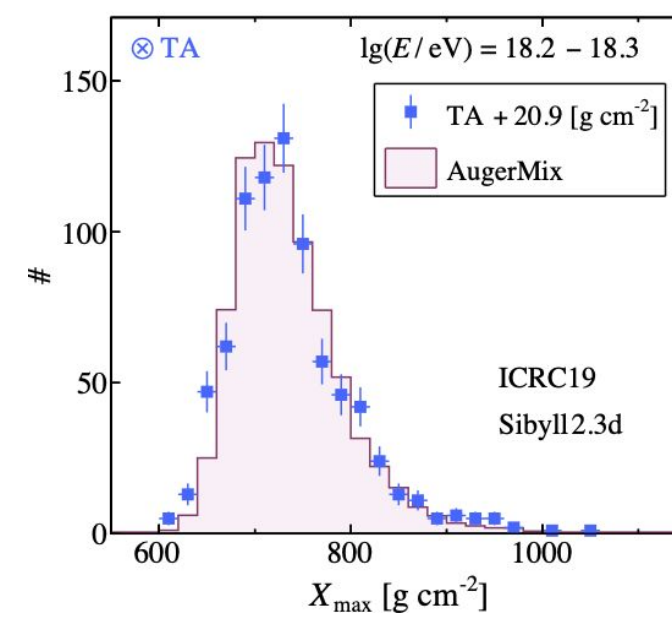
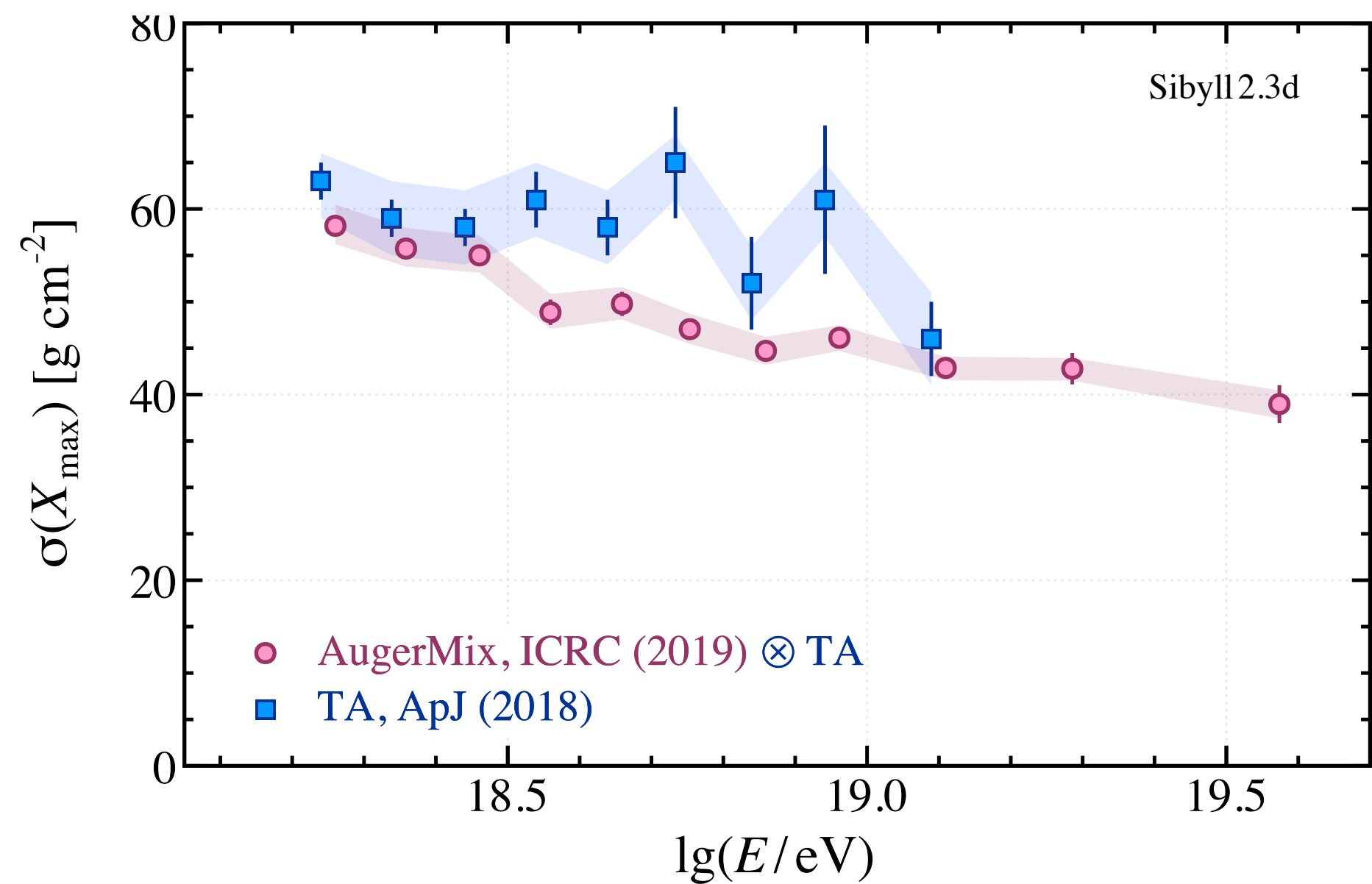
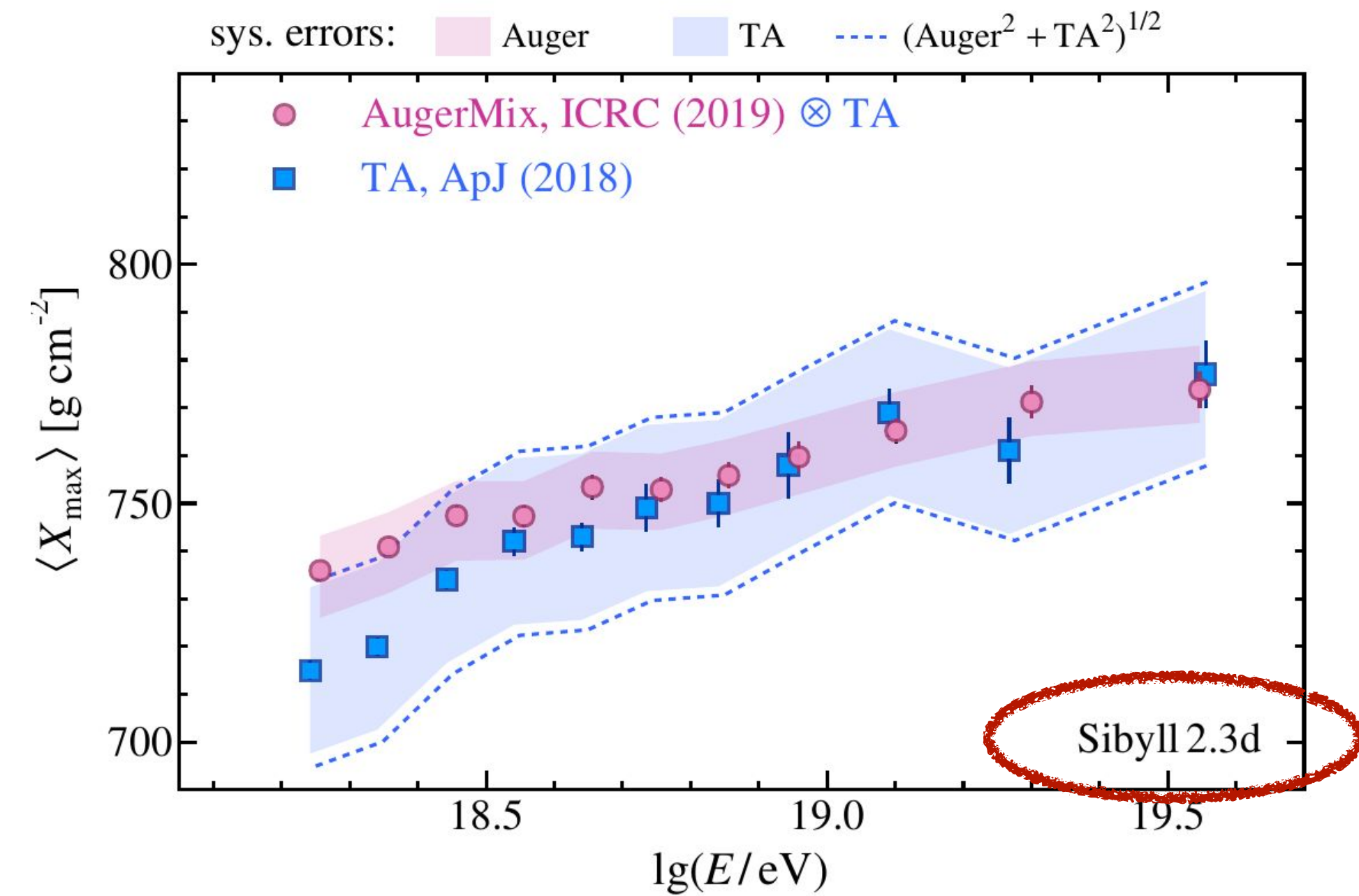
TA: all showers analyzed, comparison with detector-folded $X_{\max}$ distributions (biased by limited field-of-view)



(Unger, NP Proc. Suppl. 190 (2009) 240)



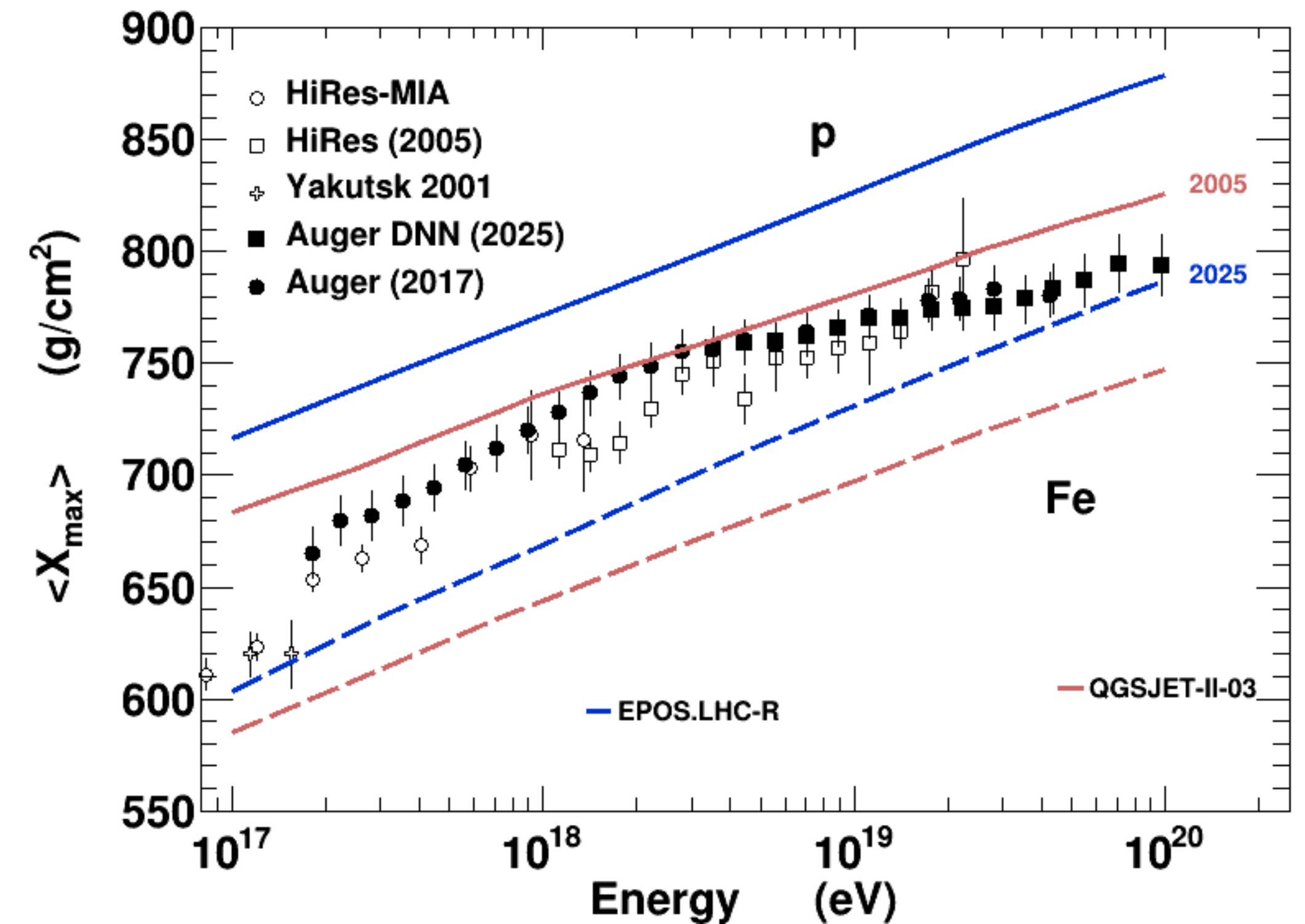
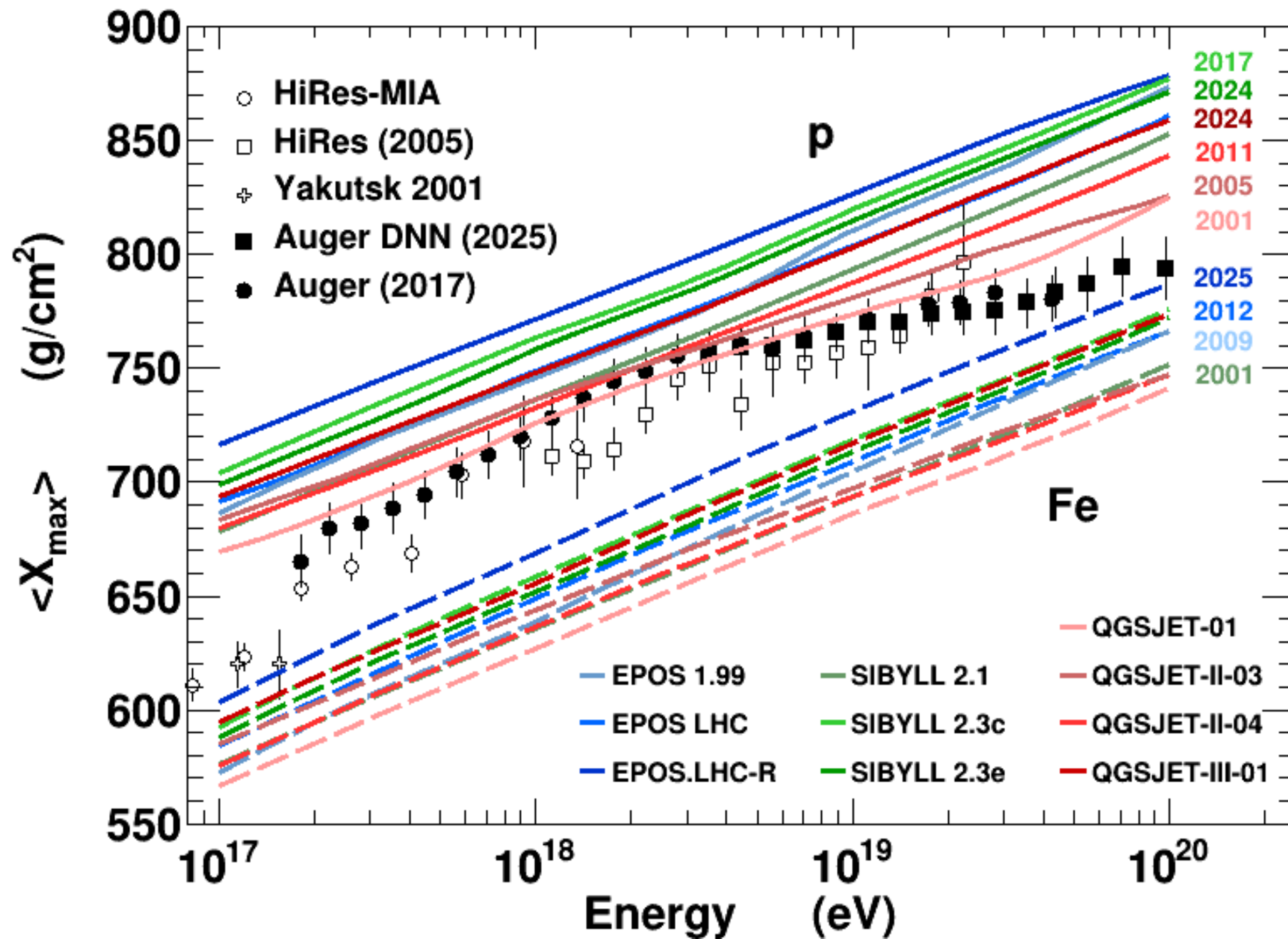
Auger-TA comparison of $X_{\max}$ distributions (2024)



(Yushkov, Auger & TA,
UHECR 2024)

Joint working group: no significant difference found

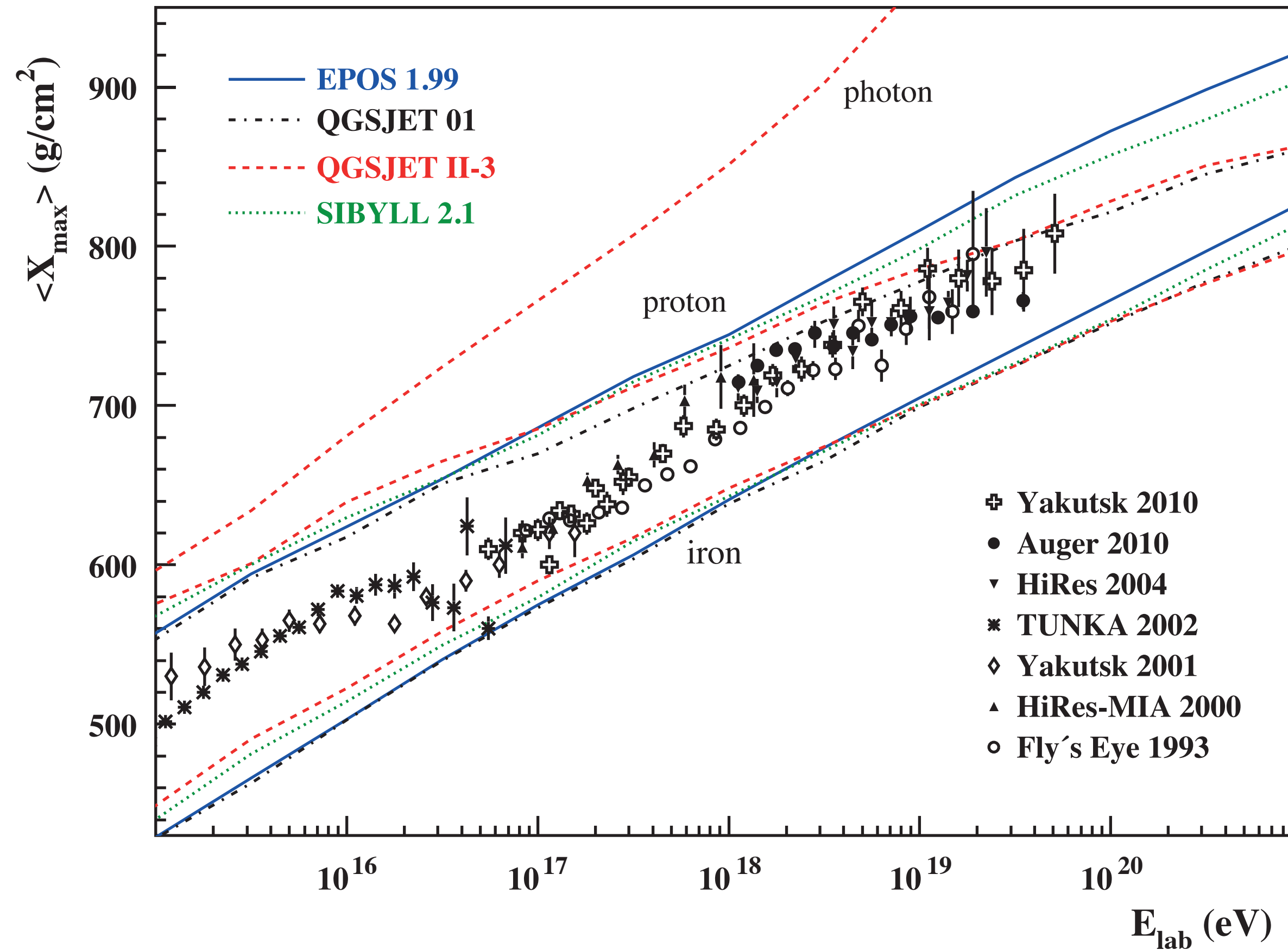
History of predictions: average depth of shower maximum



TA: many analyses done with QGSjet II.03 (protons)
 Auger: newest EPOS, Sibyll with mass composition

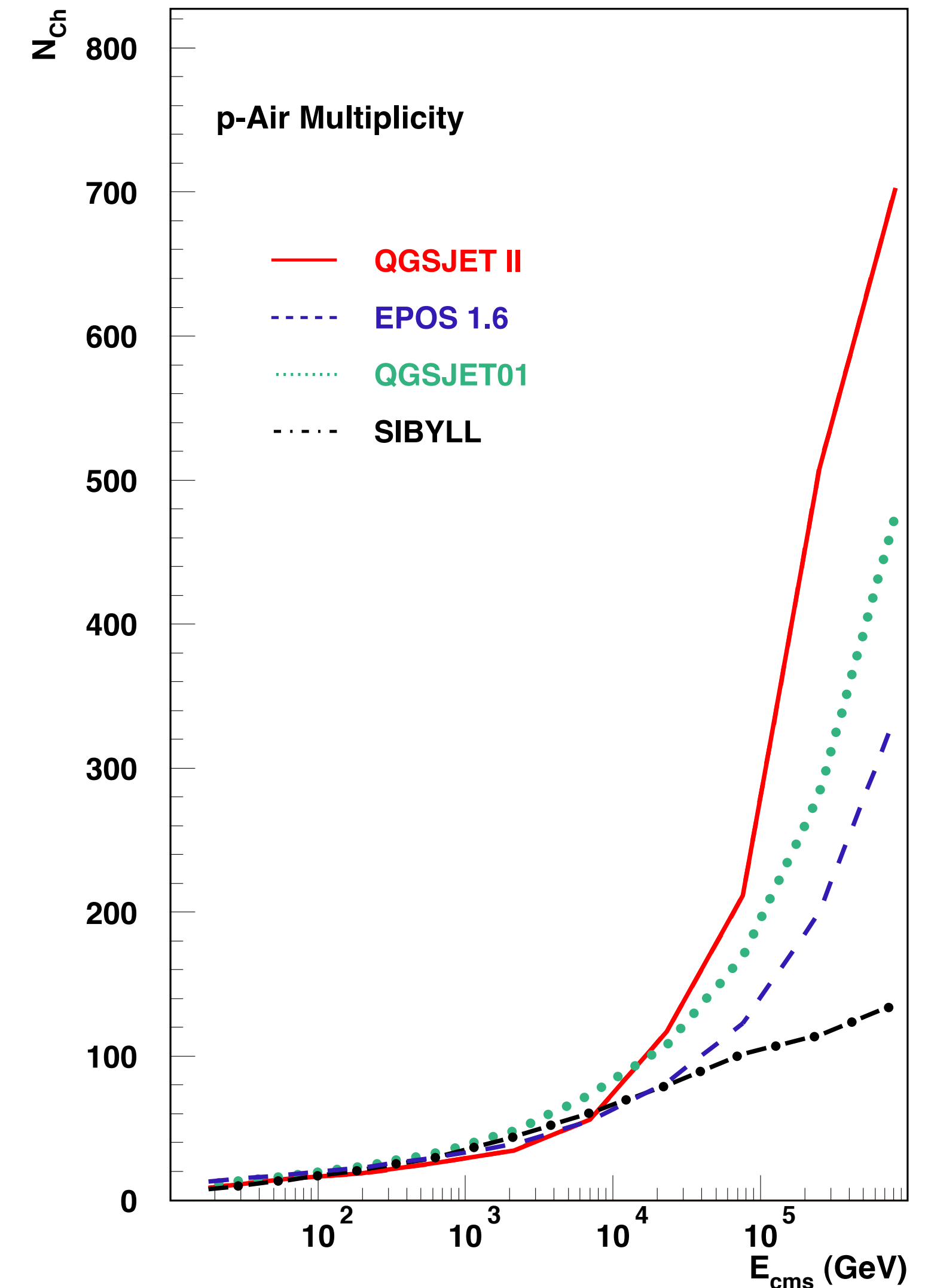
(Pierog, ISVHECRI 2026)

History of predictions: elongation rate theorem

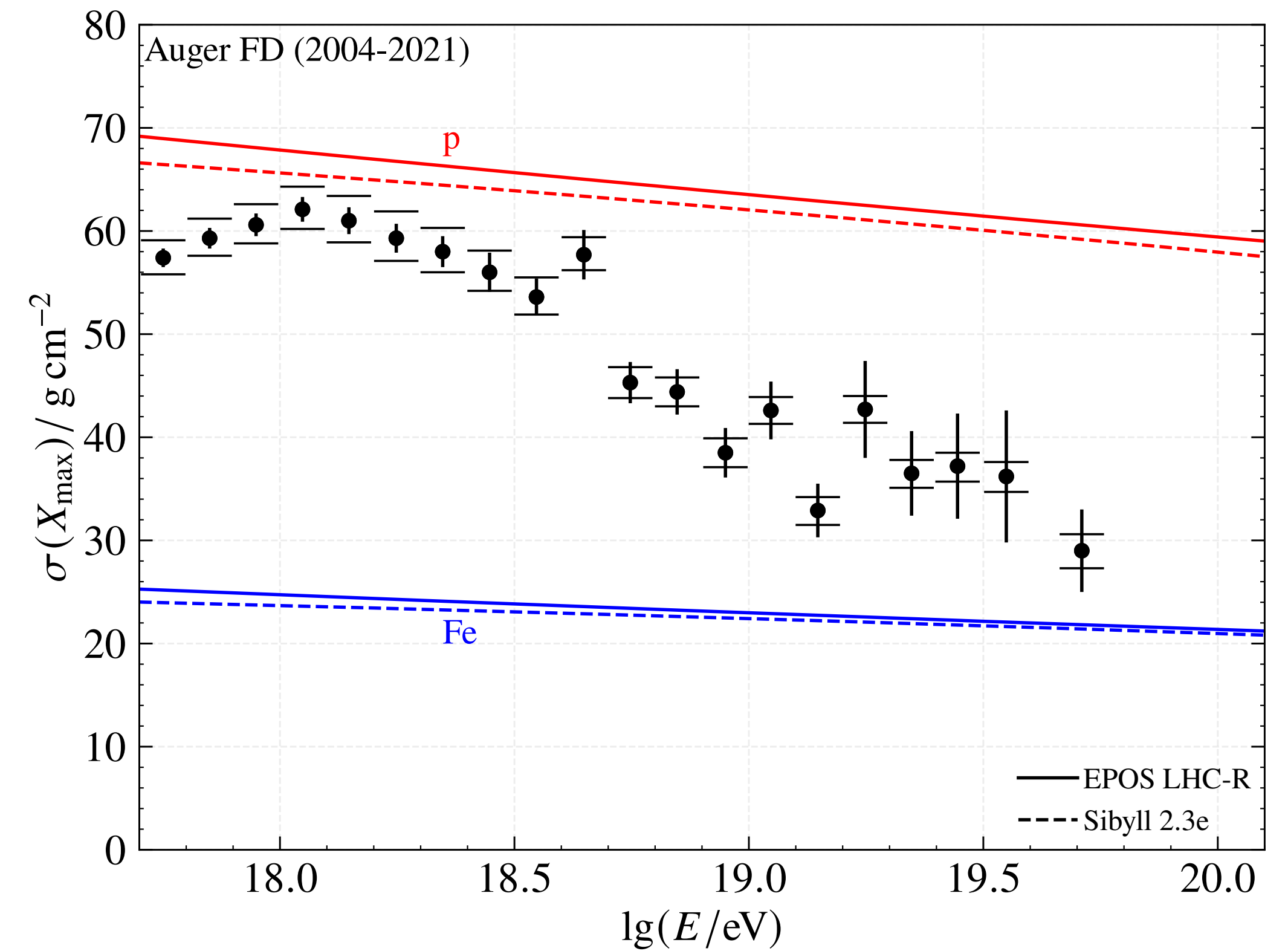
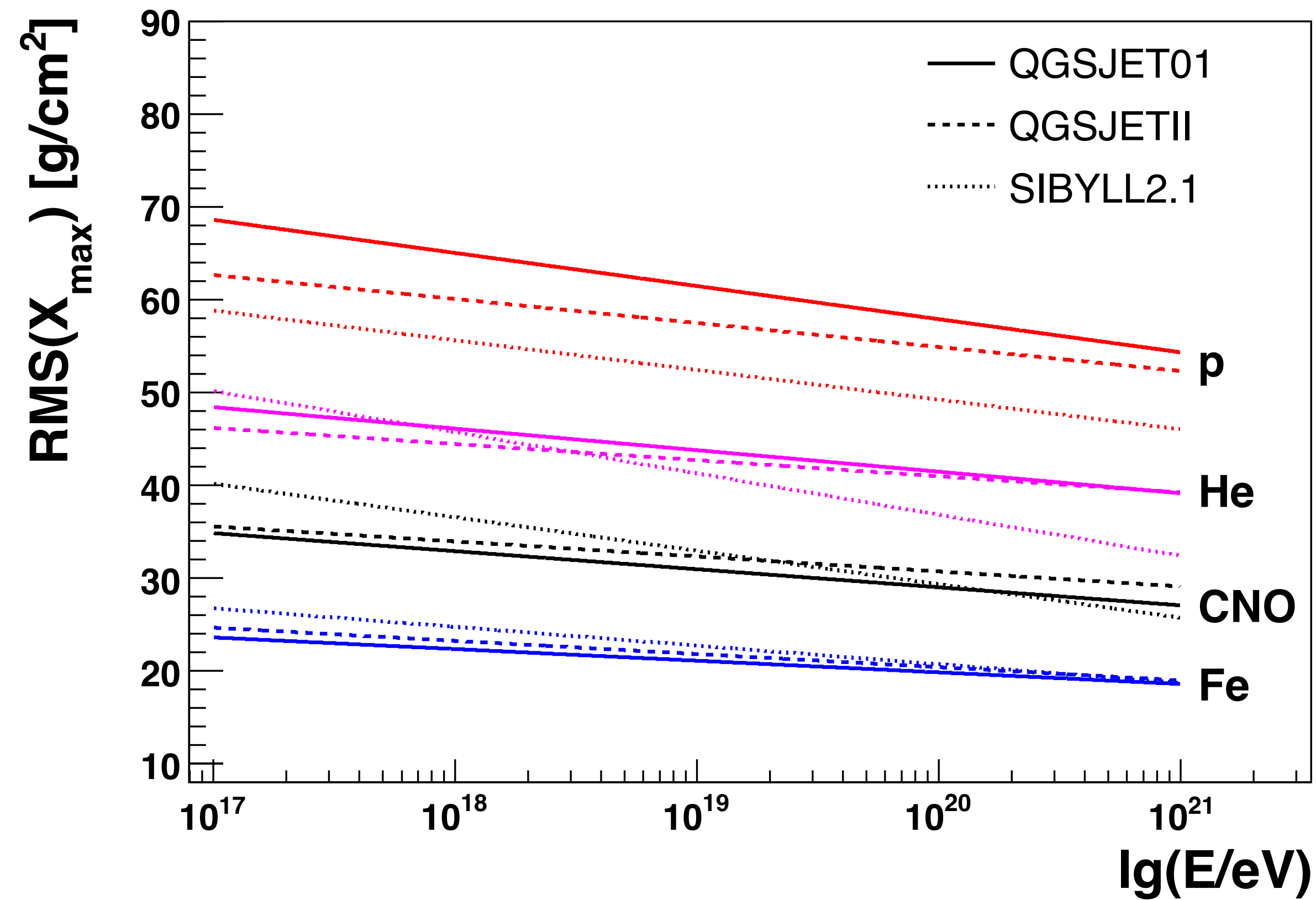


(Linsley, Watson PRL46, 1981)

$$D_e = \frac{d\langle X_{\max}(E) \rangle}{d \ln E} \leq X_0 - X_0 \frac{d \ln n_{\text{tot}}}{d \ln E} + \frac{d \lambda_{\text{int}}}{d \ln E}$$

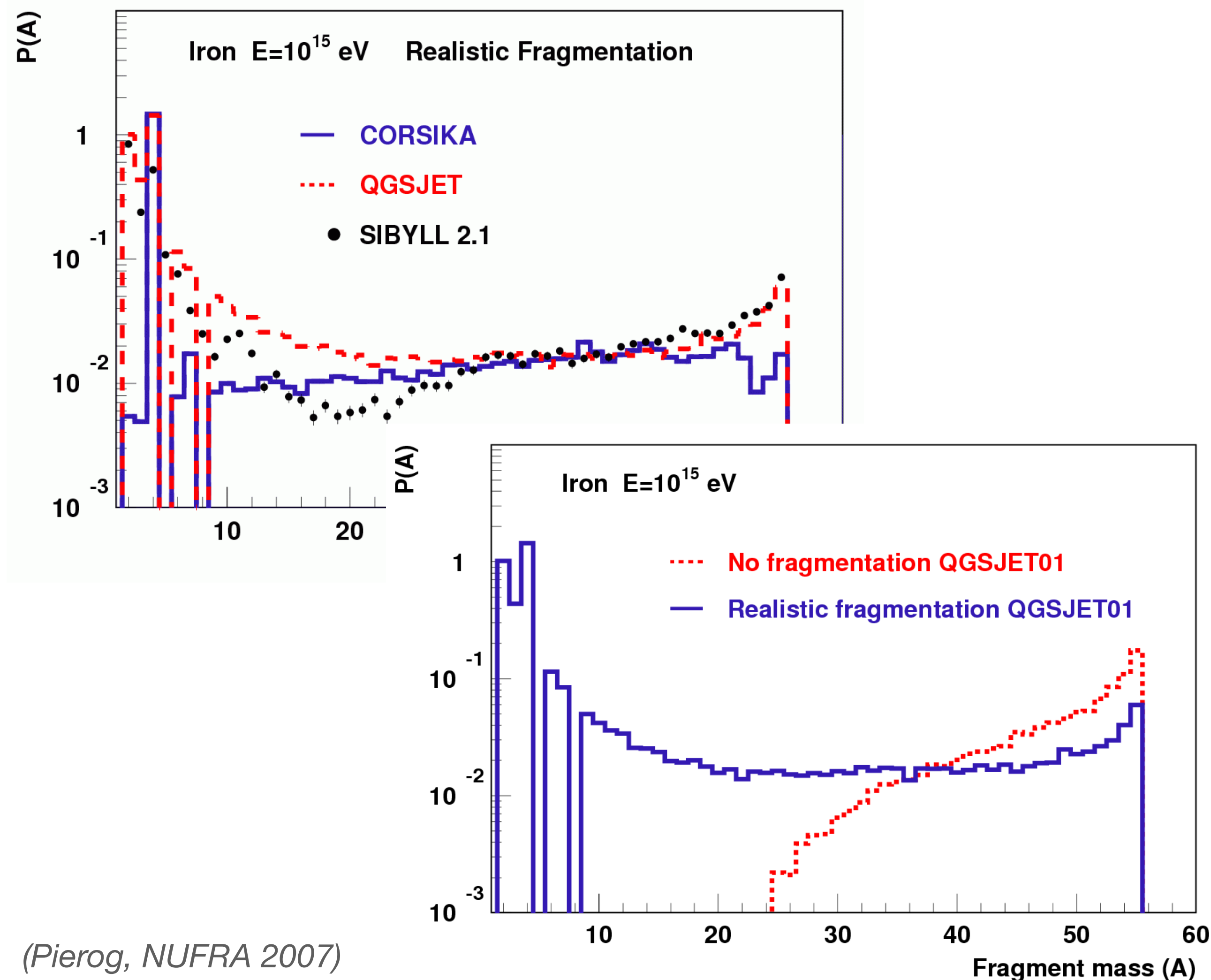


History of predictions: shower-to-shower fluctuations

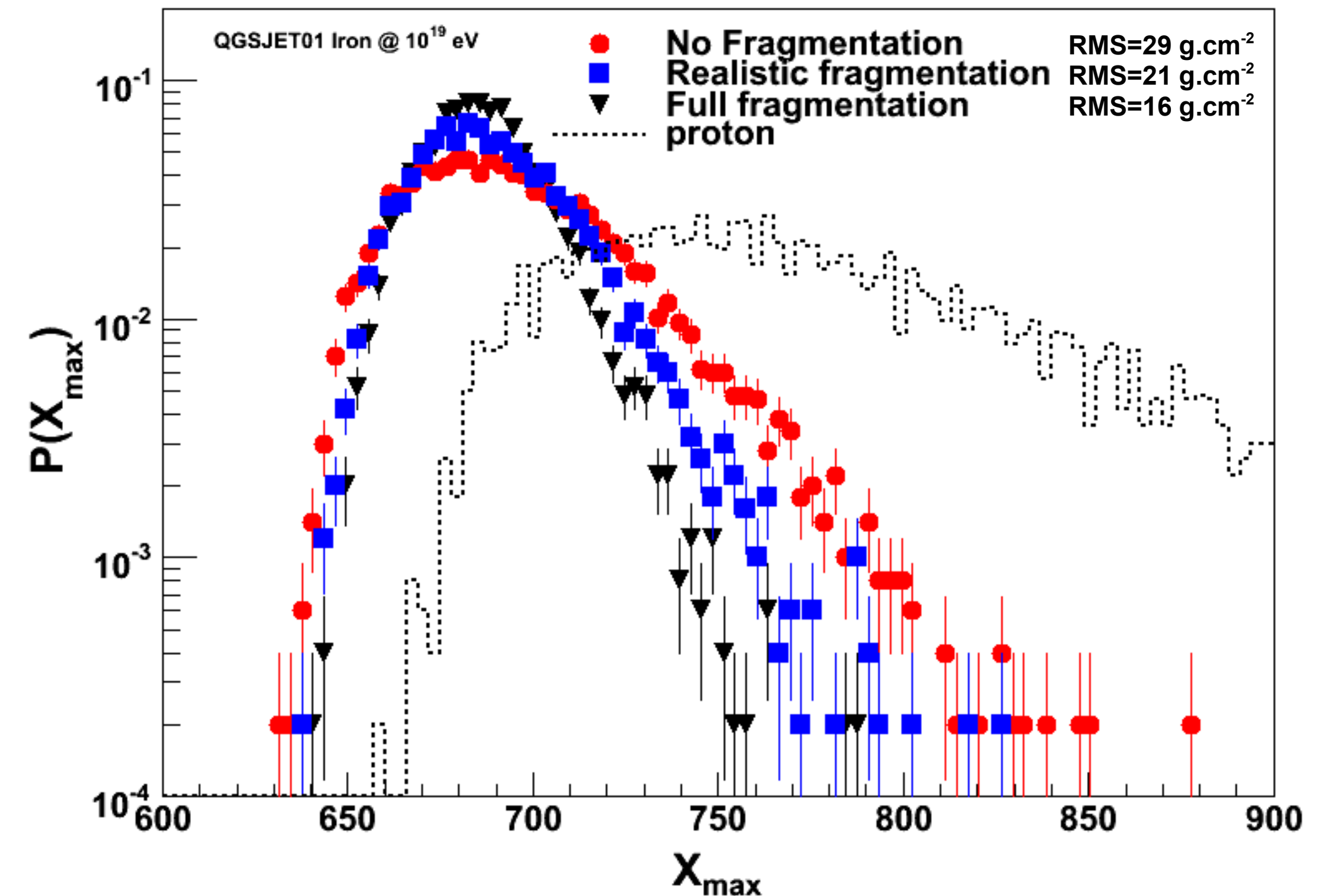


Predictions much more stable in time (more robust?)

Importance of nuclear fragmentation for fluctuations

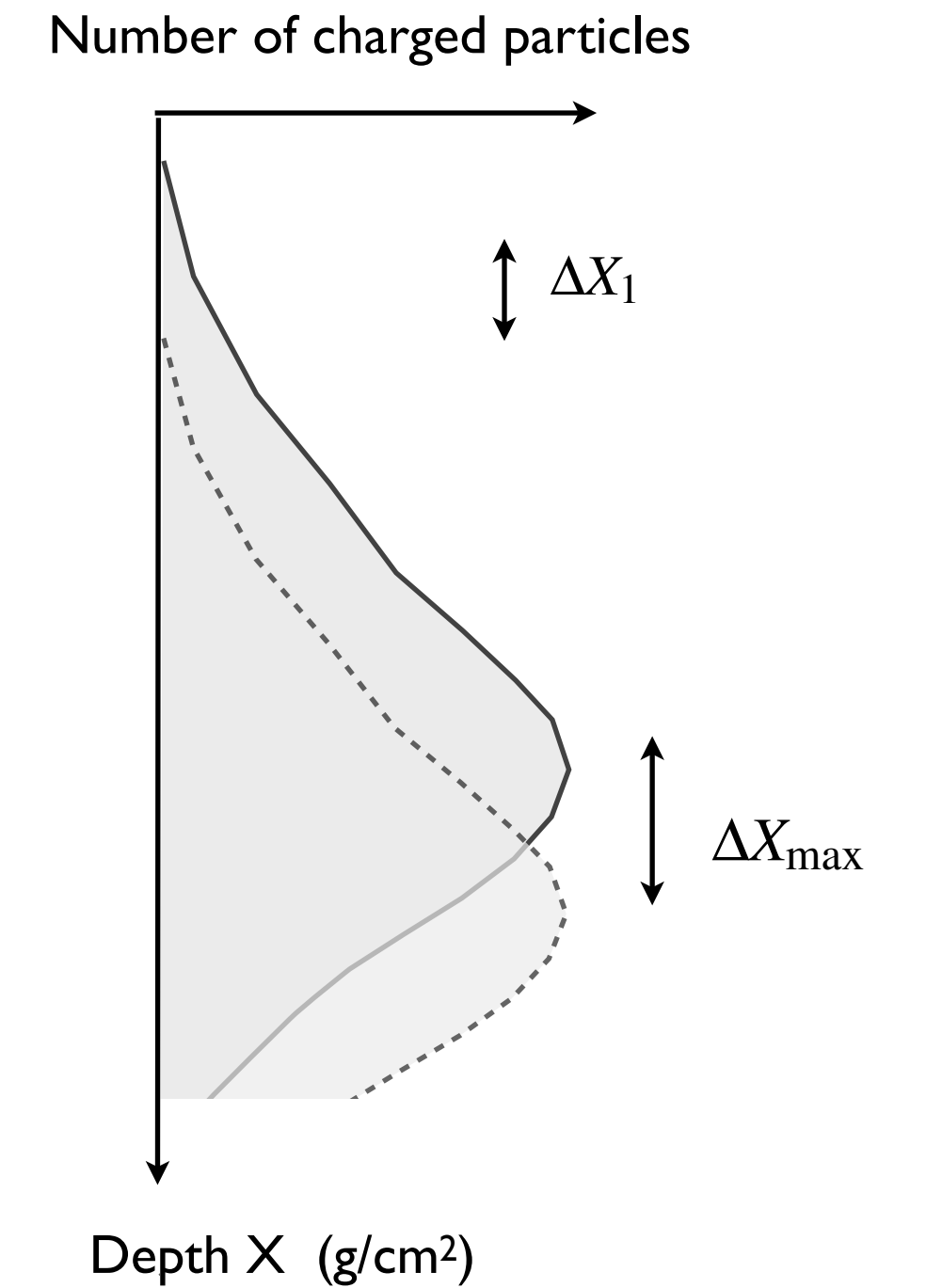
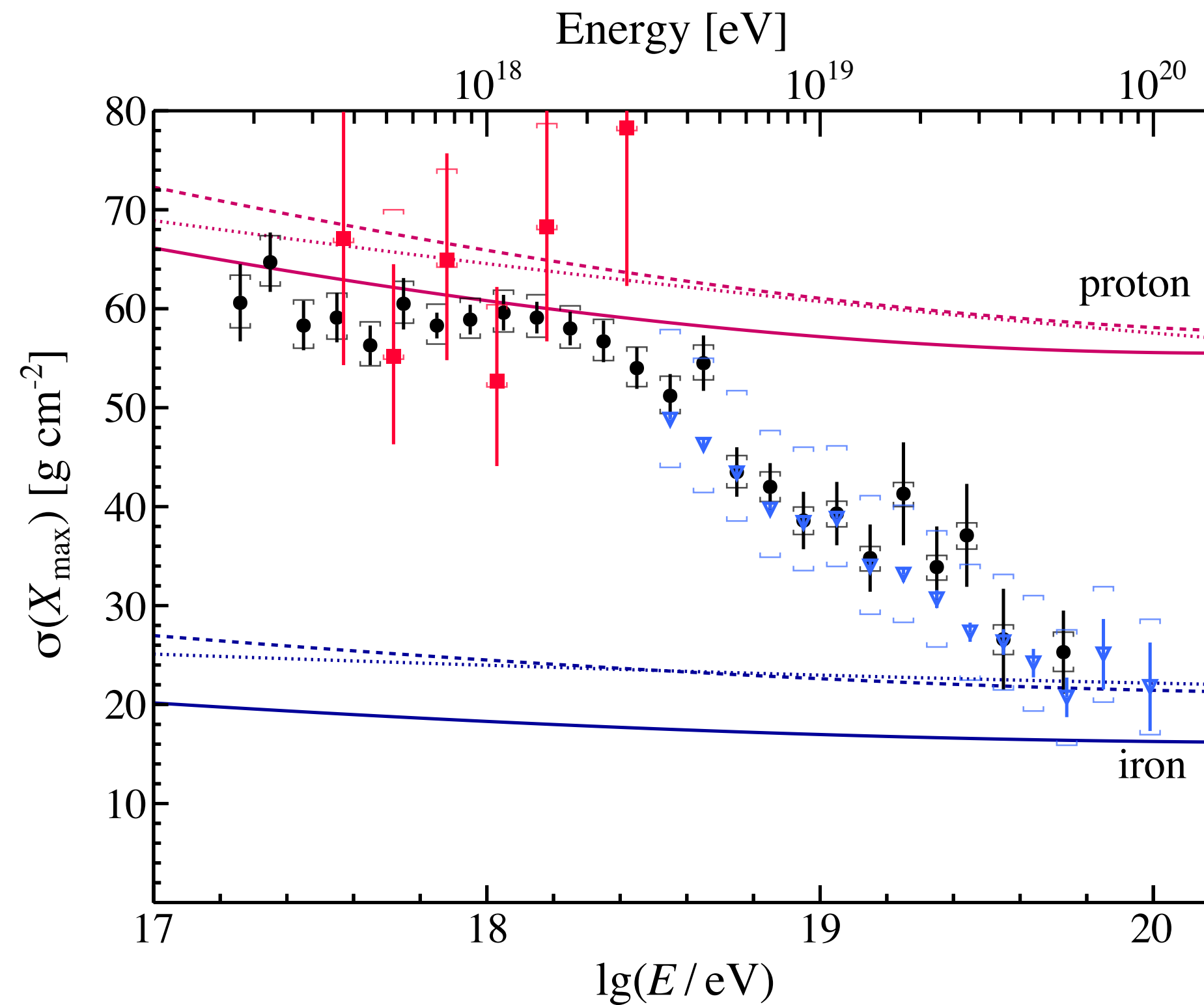
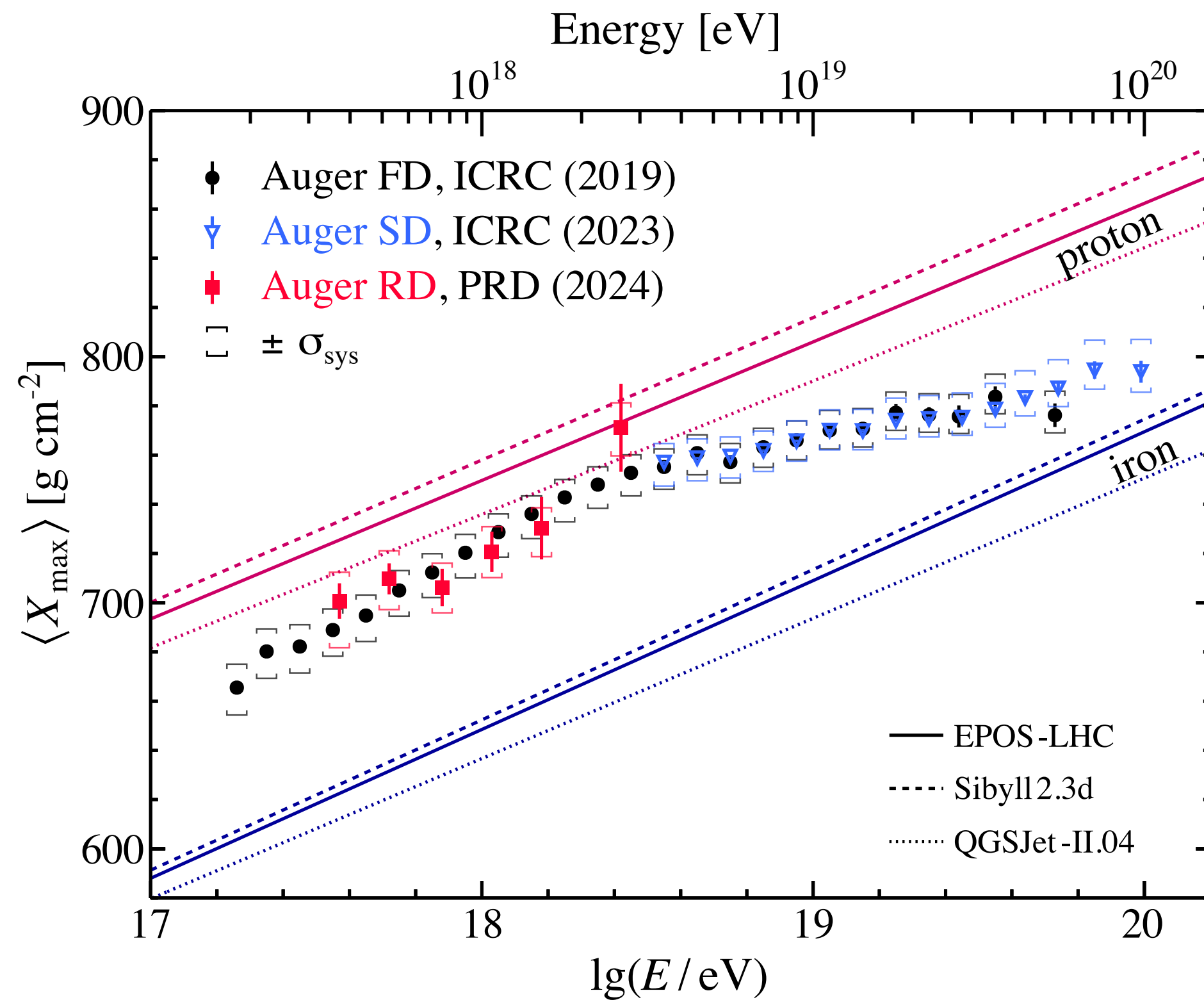


(Pierog, NUFRA 2007)



Nobody has really worked on
nuclear fragmentation, no new data

There is no (reasonable) way out, there are nuclei at UHE



$$\frac{dP}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}}$$

Important: LHC-tuned interaction models used for detailed interpretation

(FD telescopes: PRD 90 (2014), 122005 & 122005, PRD 114 (2026), 043016)

(AERA/radio: PRL & PRD 2023)

(SD risetime: Phys. Rev. D96 (2017), 122003)

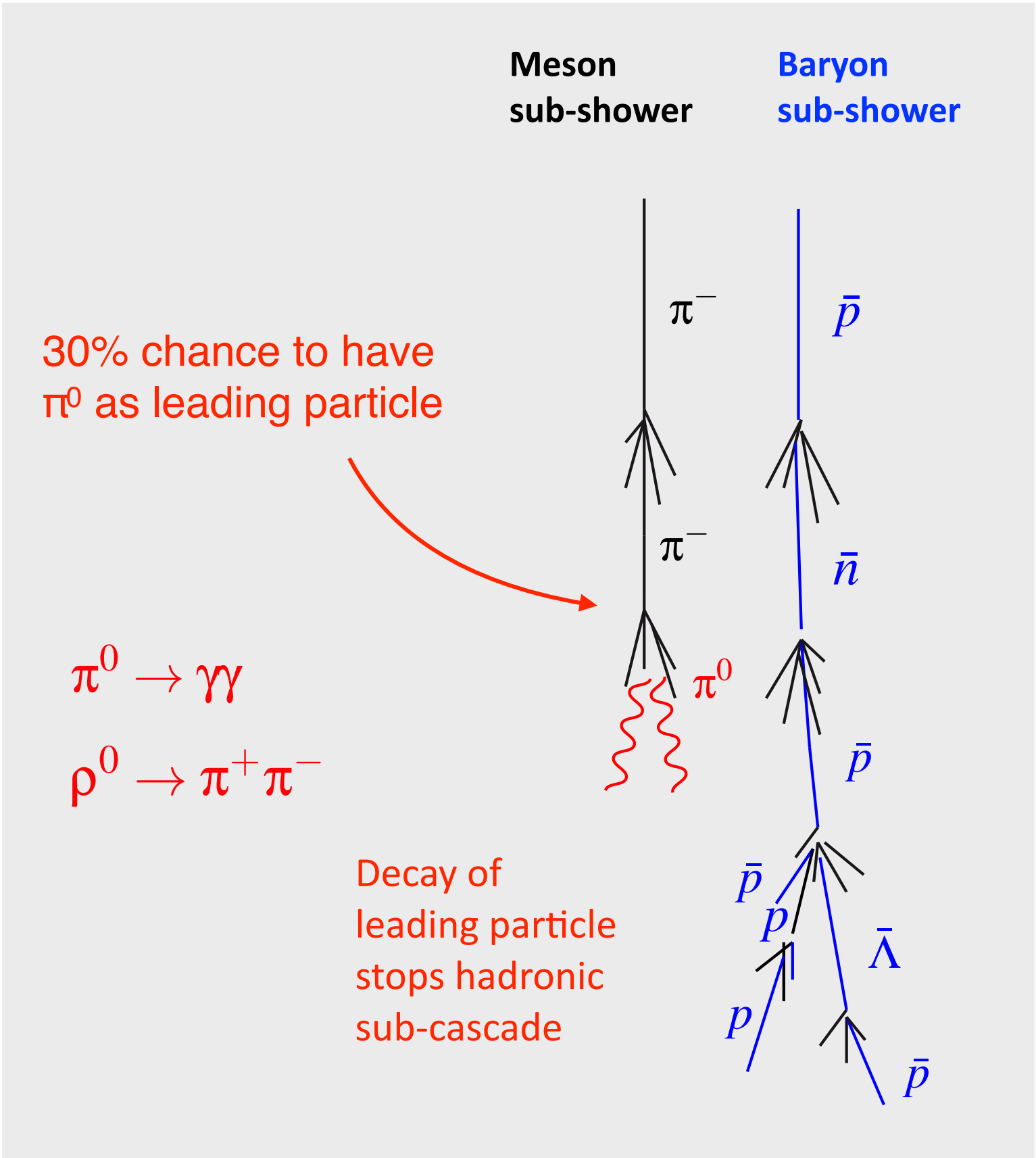
(SD DNN: PRL 134 (2025) 021001 & PRD 111 (2025) 022003)

$$\begin{aligned} \sigma_{X_1,p} &\sim 45 - 55 \text{ g/cm}^2 \\ \sigma_{X_1,\text{Fe}} &\sim 10 \text{ g/cm}^2 \end{aligned}$$

($E \sim 10^{18} \text{ eV}$)

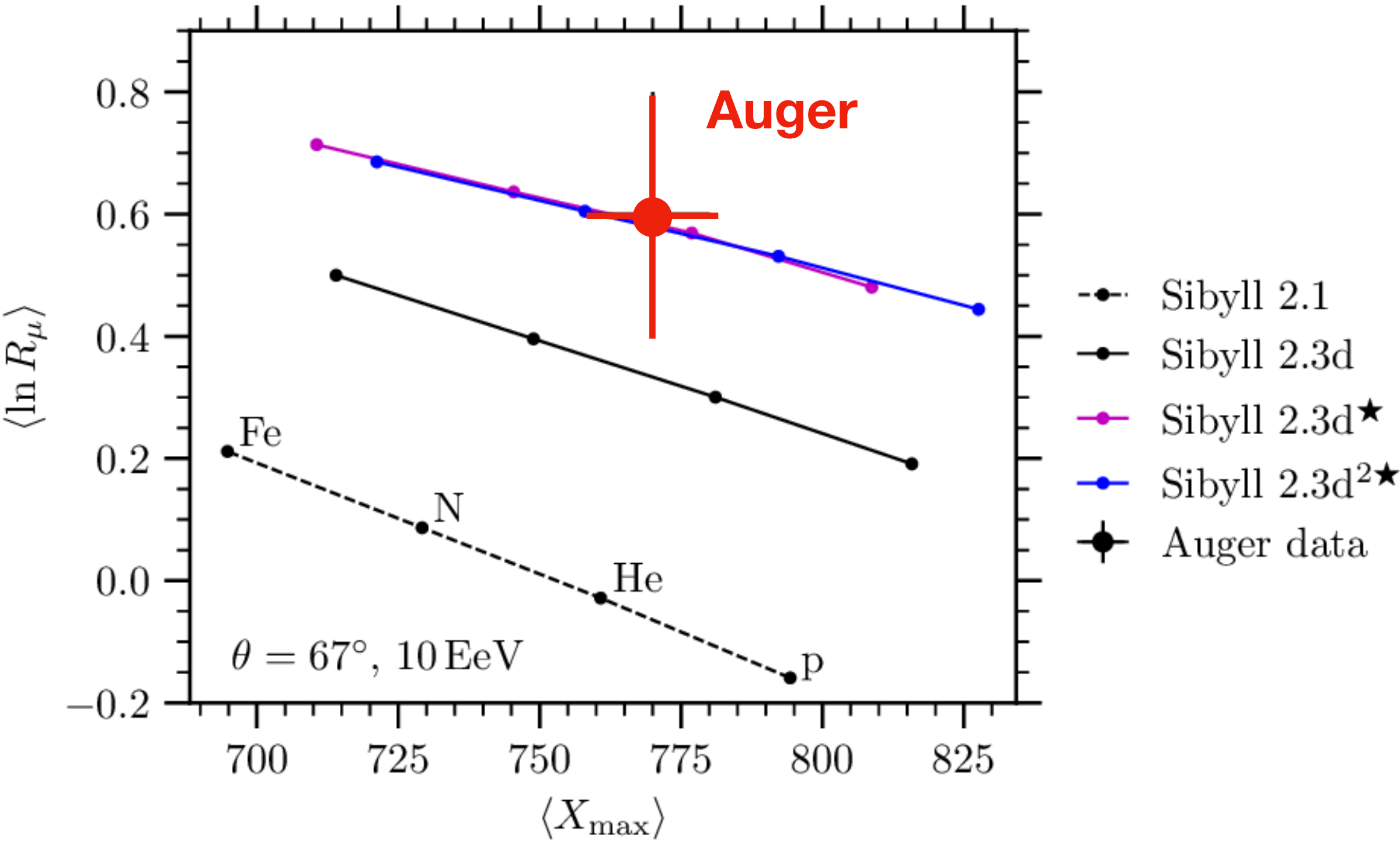
Testing consistency of data with Sibyll* and Sibyll**

Conventional options for enhancing muon production

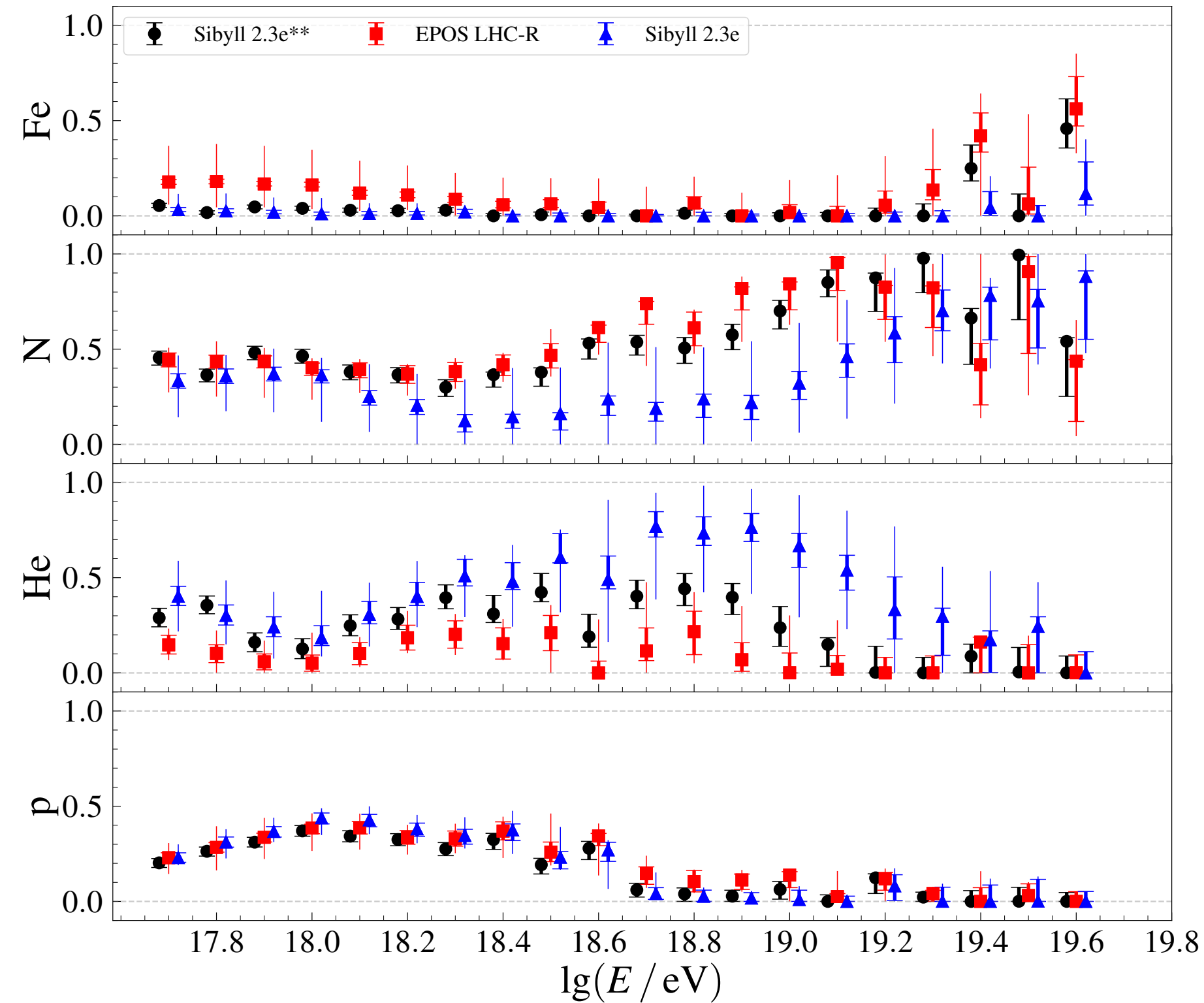


Phenomenological modification

- Sibyll* enhanced muon production
- Sibyll** enhanced muon production & lowered pion-air cross section

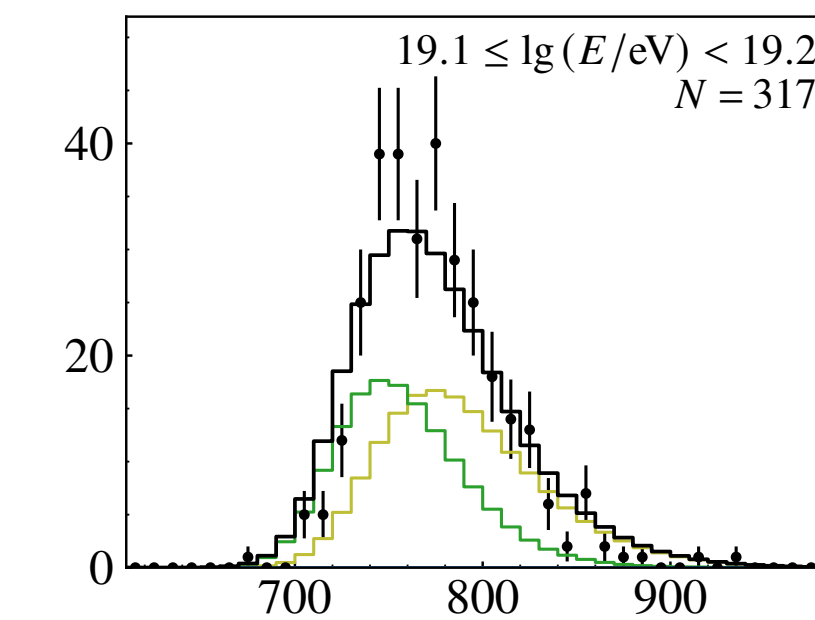
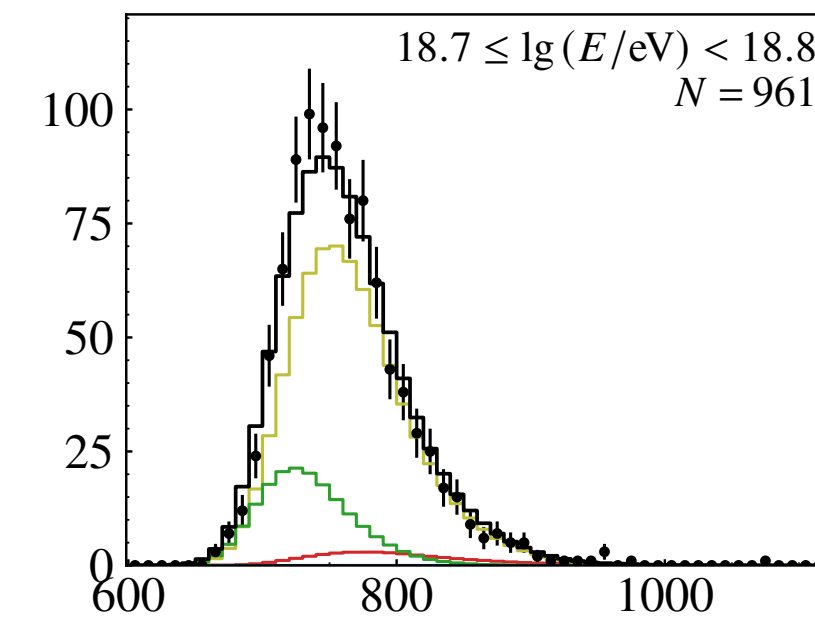
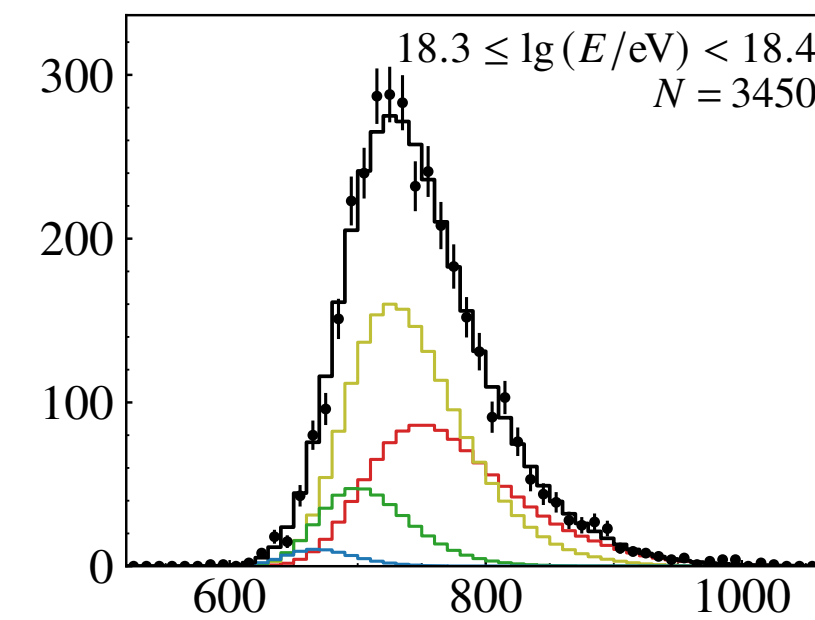


Use data for absolute calibration of mass scale?

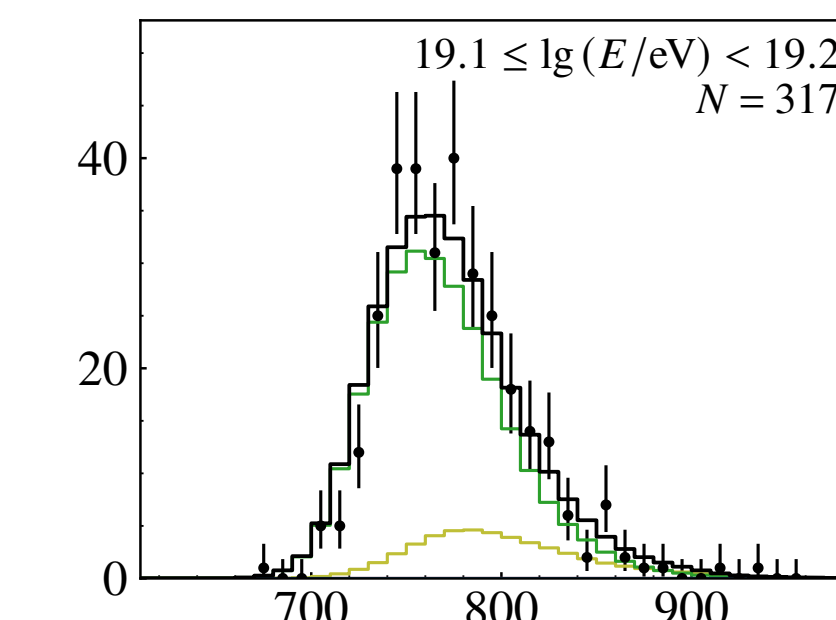
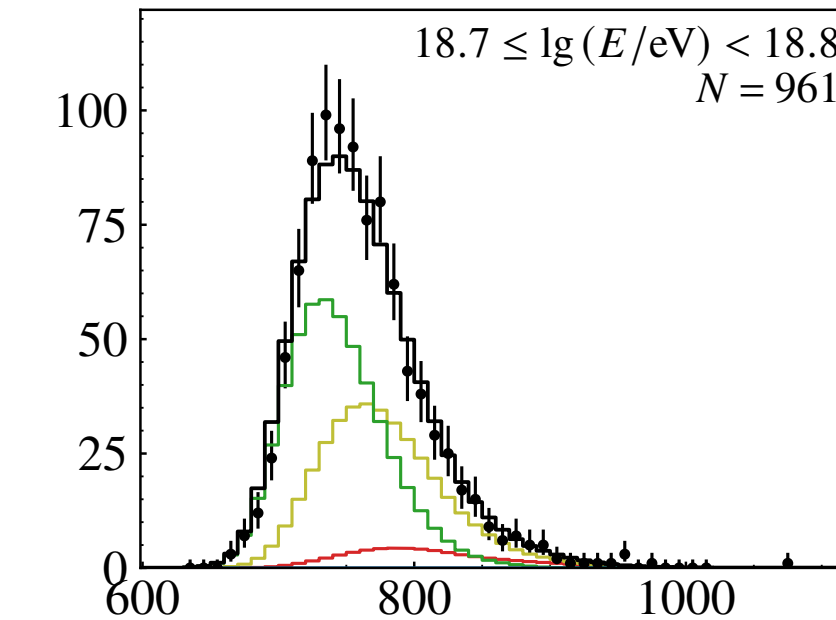
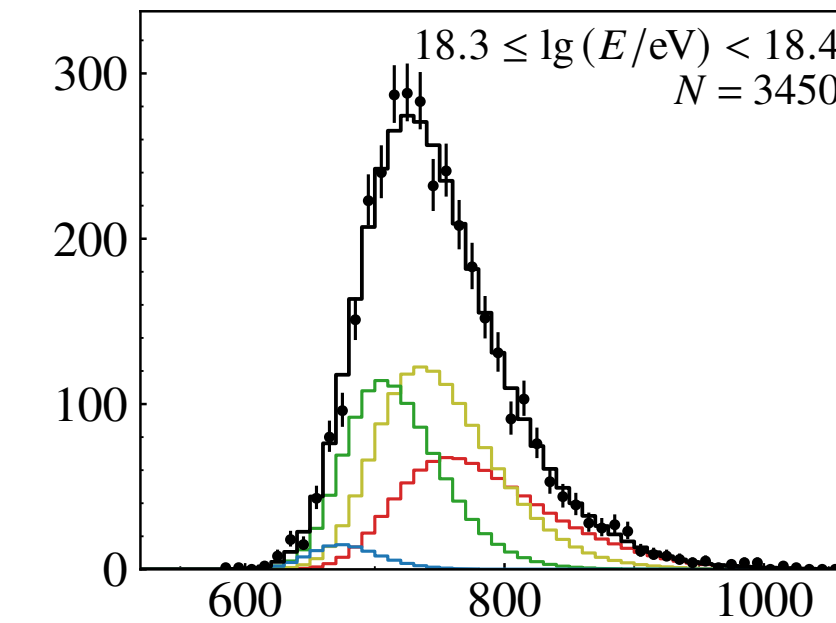


Details set mass scale, simple
shift of X_{max} might not be solution

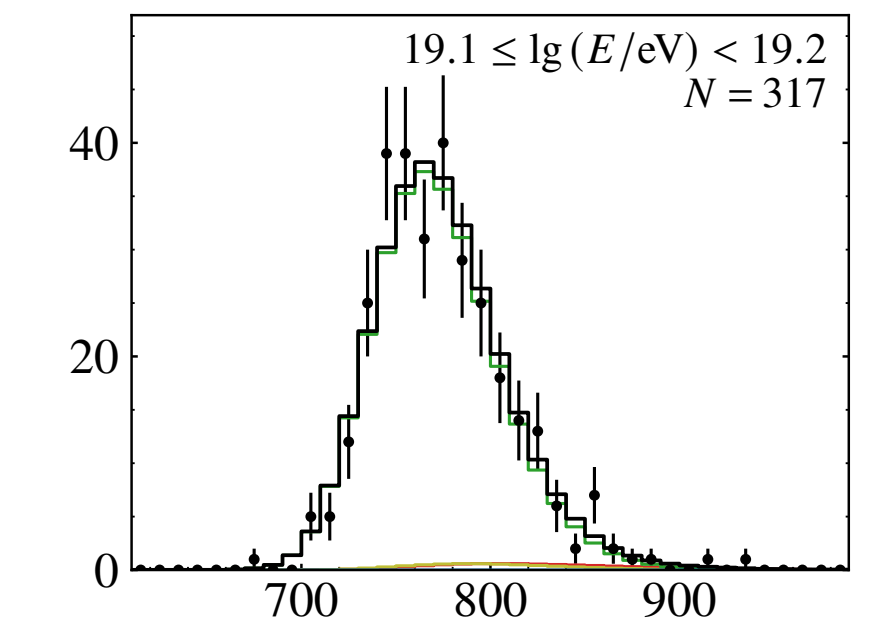
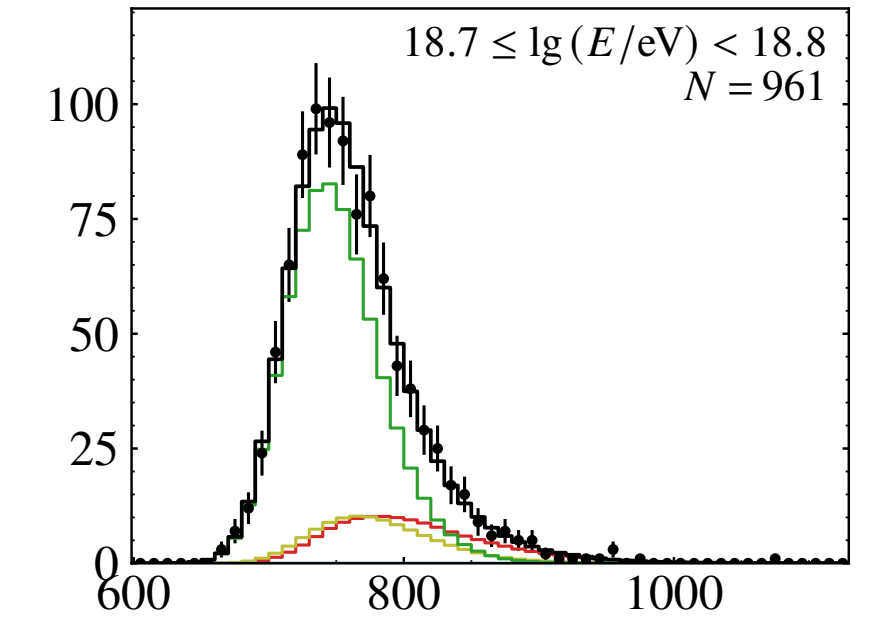
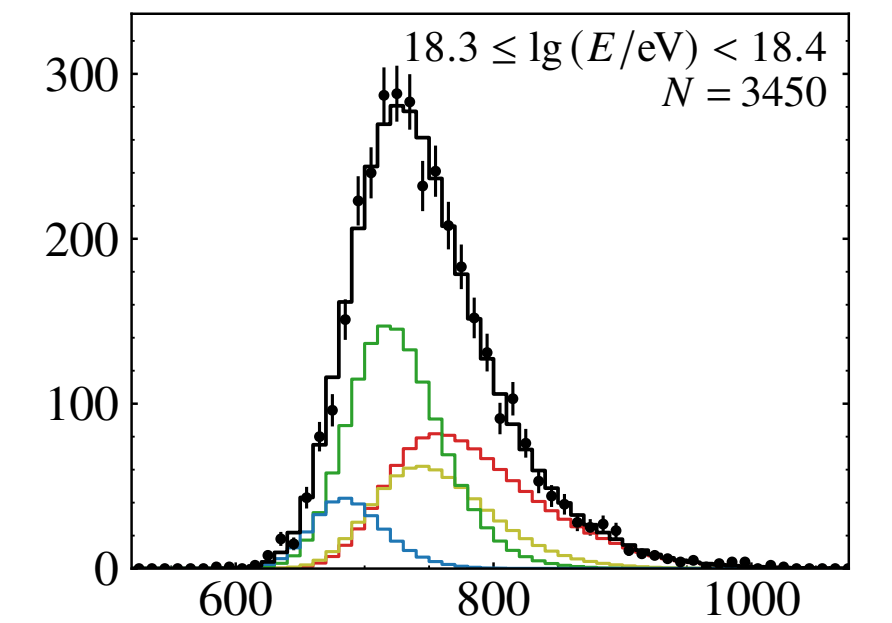
Sibyll 2.3e

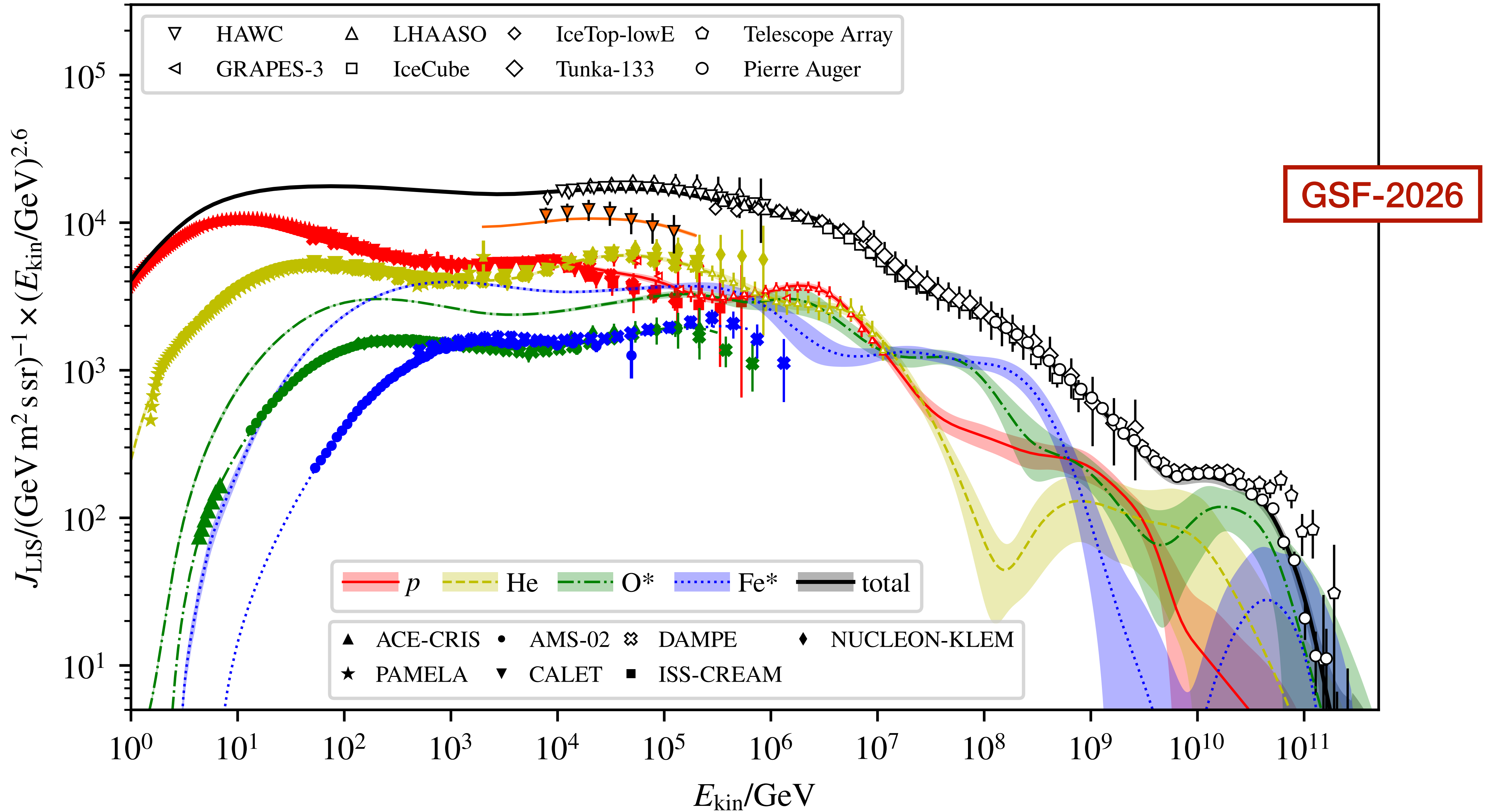


Sibyll** 2.3e

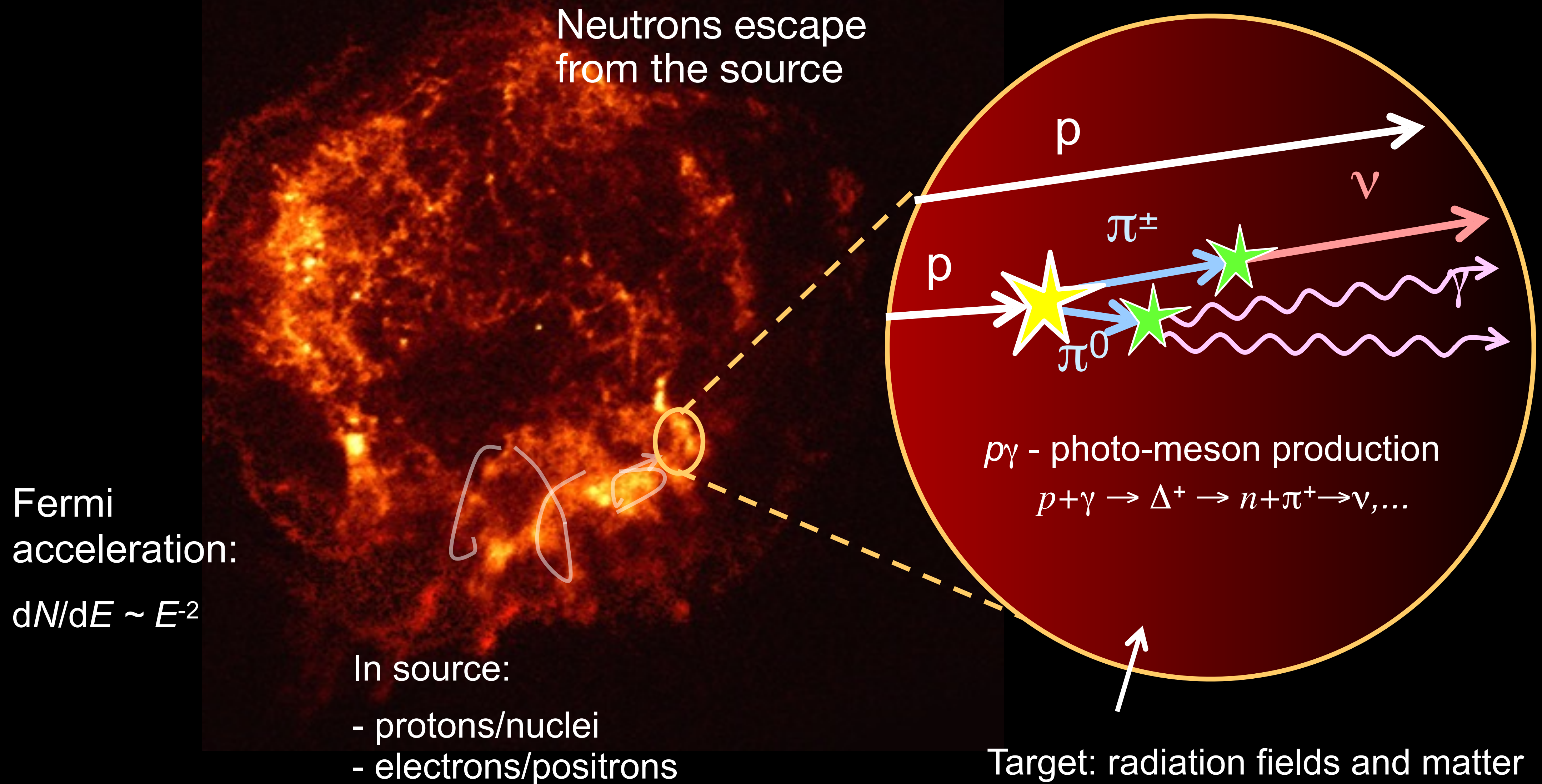


EPOS-LHC-R





Physics scenario of Waxman-Bahcall bound: one interaction



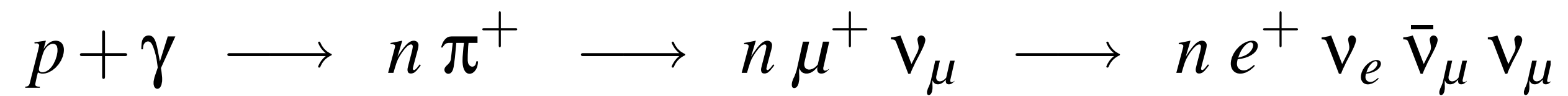
Assumptions and resulting bound

Sources inject only protons, luminosity normalized to CR data in range $10^{19} - 10^{20}$ eV

$$Q_p(E_p) = A E_p^{-2}$$

(Fermi acceleration of protons)

For each proton escaping the source exactly one interaction is assumed



(single interaction)

branching
ratio 0.33

20% of p
energy



each particle has 25% of the
energy of the π^+

Neutrino flux

$$\Phi_{\nu_\mu}(E_{\nu_\mu}) = 0.33 \times 0.2 \times 0.25 \times A E_{\nu_\mu}^{-2}$$

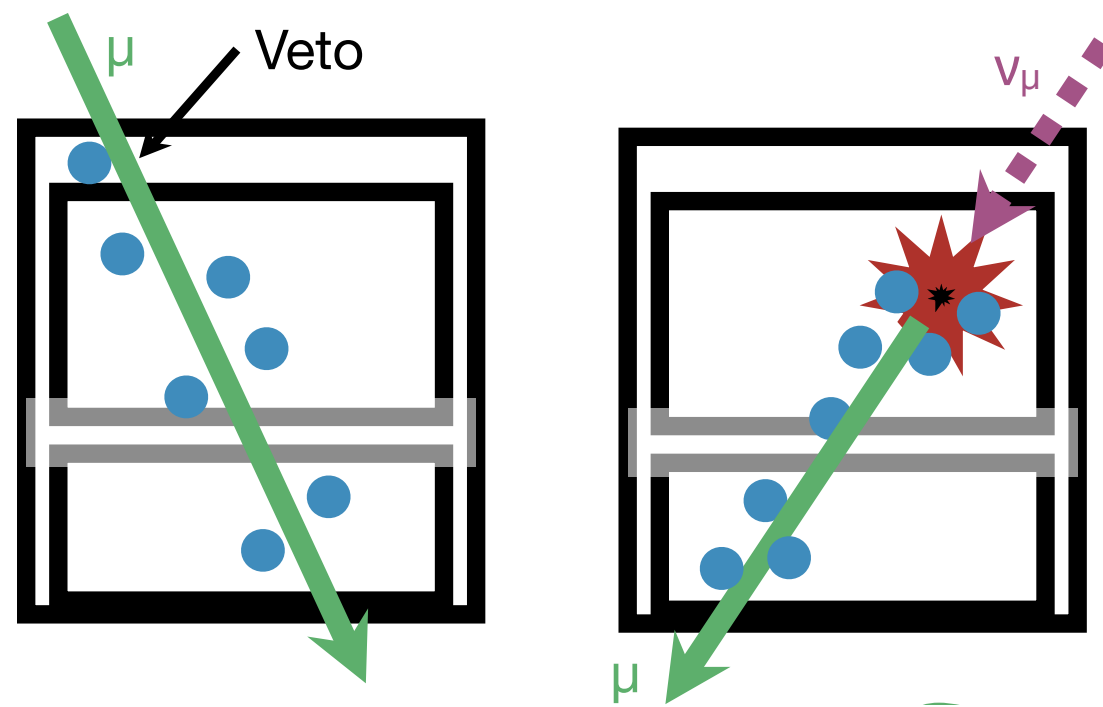
Correction factors related to

- cosmological evolution of sources
- neutrino oscillations

$$\Phi_{\nu_\mu}(E_{\nu_\mu}) < 2 \times 10^{-8} \text{ GeV/cm}^2 \text{ s sr}$$

(Waxman & Bahcall, PRD59, 1998)

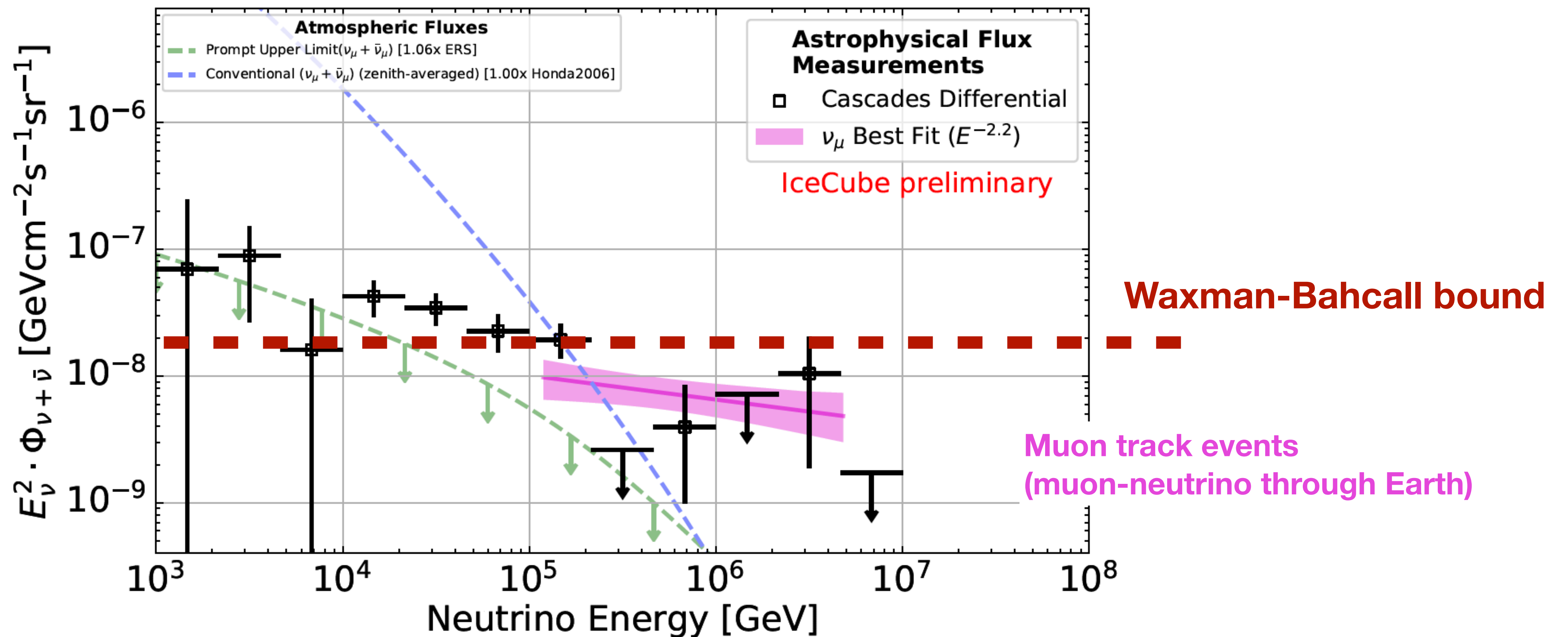
Neutrino flux found at level of Waxman-Bahcall bound



Veto technique

High energy starting events (HESE)

(IceCube, Science 342 (2013) 1242856)



Assumptions of WB upper bound for UHECRs

(Waxman & Bahcall, Phys. Rev. D59 (1999) 023002)

- Extragalactic cosmic-ray protons extending to the highest energies
- One interaction with photon field per proton in source or source region
- Source production spectrum similar to Fermi acceleration



$$\frac{dN}{dE} \sim E^{-\gamma} \quad \gamma = 1.8 \dots 2.3$$



- Energy production rate (normalization) of 4×10^{44} erg Mpc⁻¹ yr⁻¹

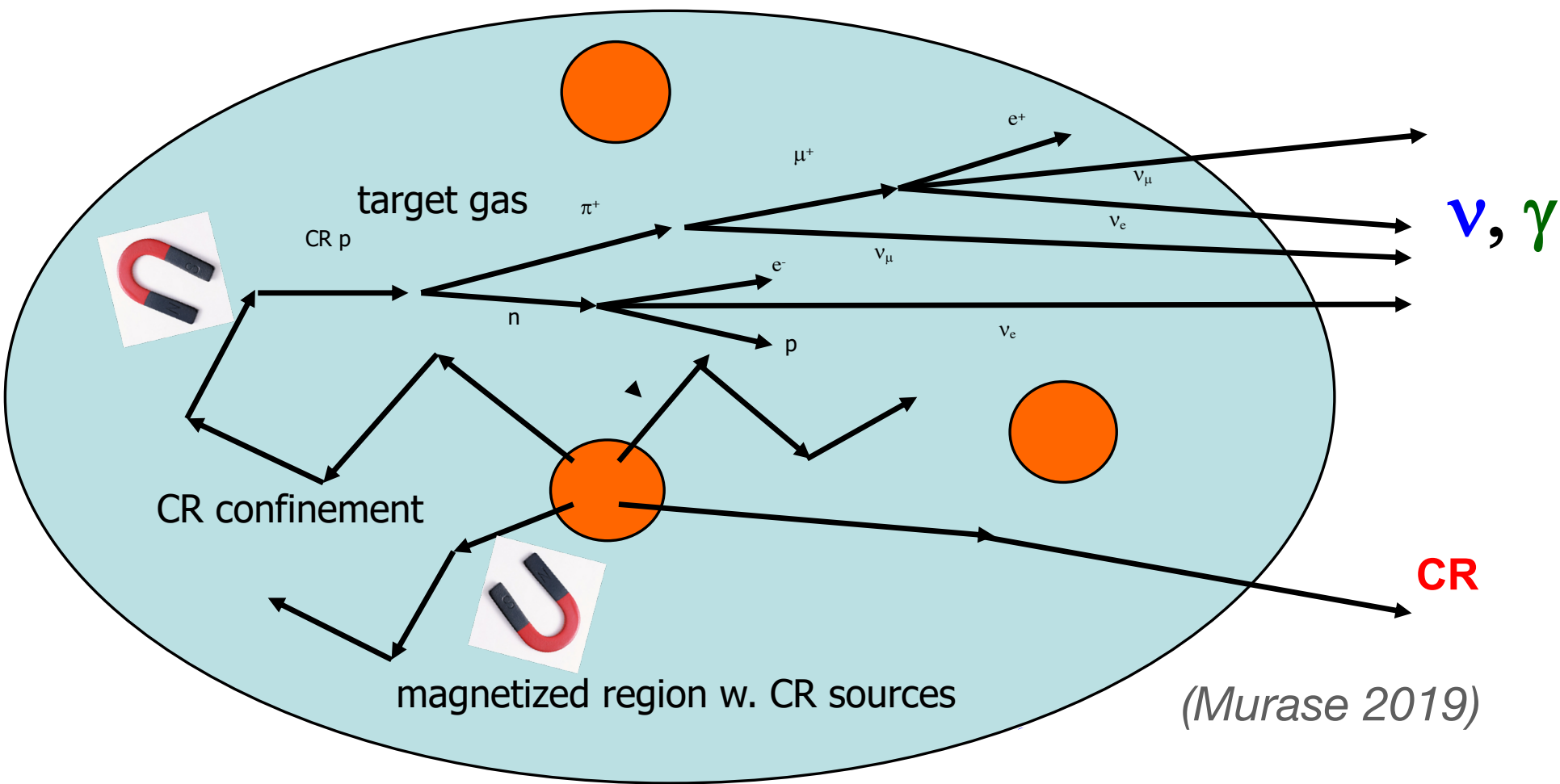


(Waxman, ApJ 452 (1995) L1)

Size of neutrino detector (water, ice) for observing this flux has to be $V \sim 1$ km³



Challenges for building UHECR models & predicting neutrinos



- Problem 1: injection of mainly heavy elements**
- Problem 2: ions have to leave source**
- Problem 3: hard source spectrum**
- Problem 4: no diversity of source population**
- Problem 5: large degree of isotropy**

UHE protons at Earth:

- $E_p \approx 0.5 \dots 5 \text{ EeV}$

→ maximum rigidity of accelerators:

protons primary?

- $\mathcal{R}_{\text{max}} \simeq E_{\text{max}}^p = 5 \text{ EV}$

protons secondary?

- $\mathcal{R}_{\text{max}} \simeq A/Z E_{\text{max}}^p = 10 \text{ EV}$

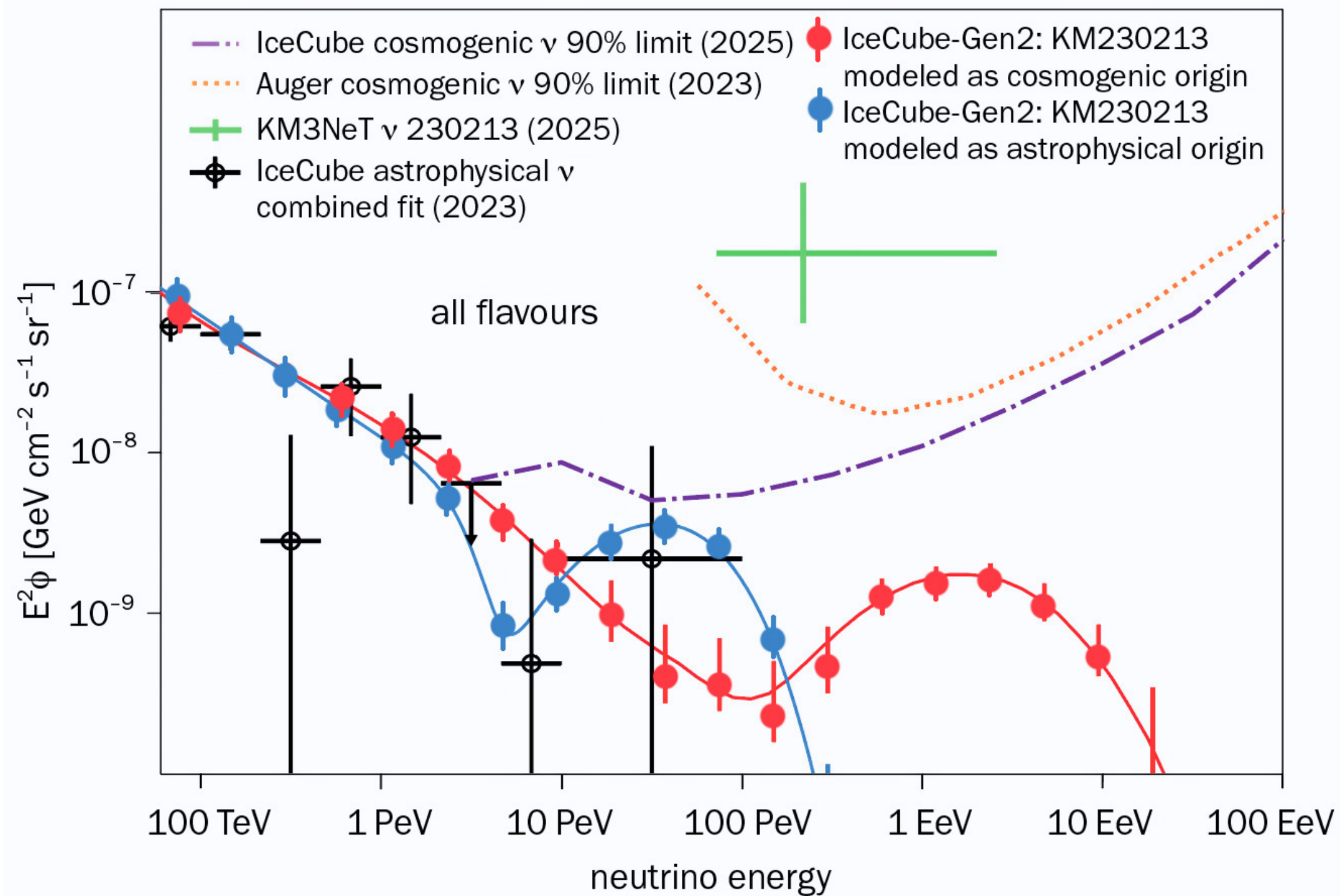
→ typical neutrino energies

- $E_\nu \simeq \frac{1}{20} E_{\text{CR}}/A$

neutrinos associated with UHECRs:

$$12.5 \text{ PeV} \lesssim E_\nu \lesssim 250 \text{ PeV}$$

(Lu, CERN Courier, 2025)



(Unger, Farrar, Anchordoqui, PRD 92, 2015)

