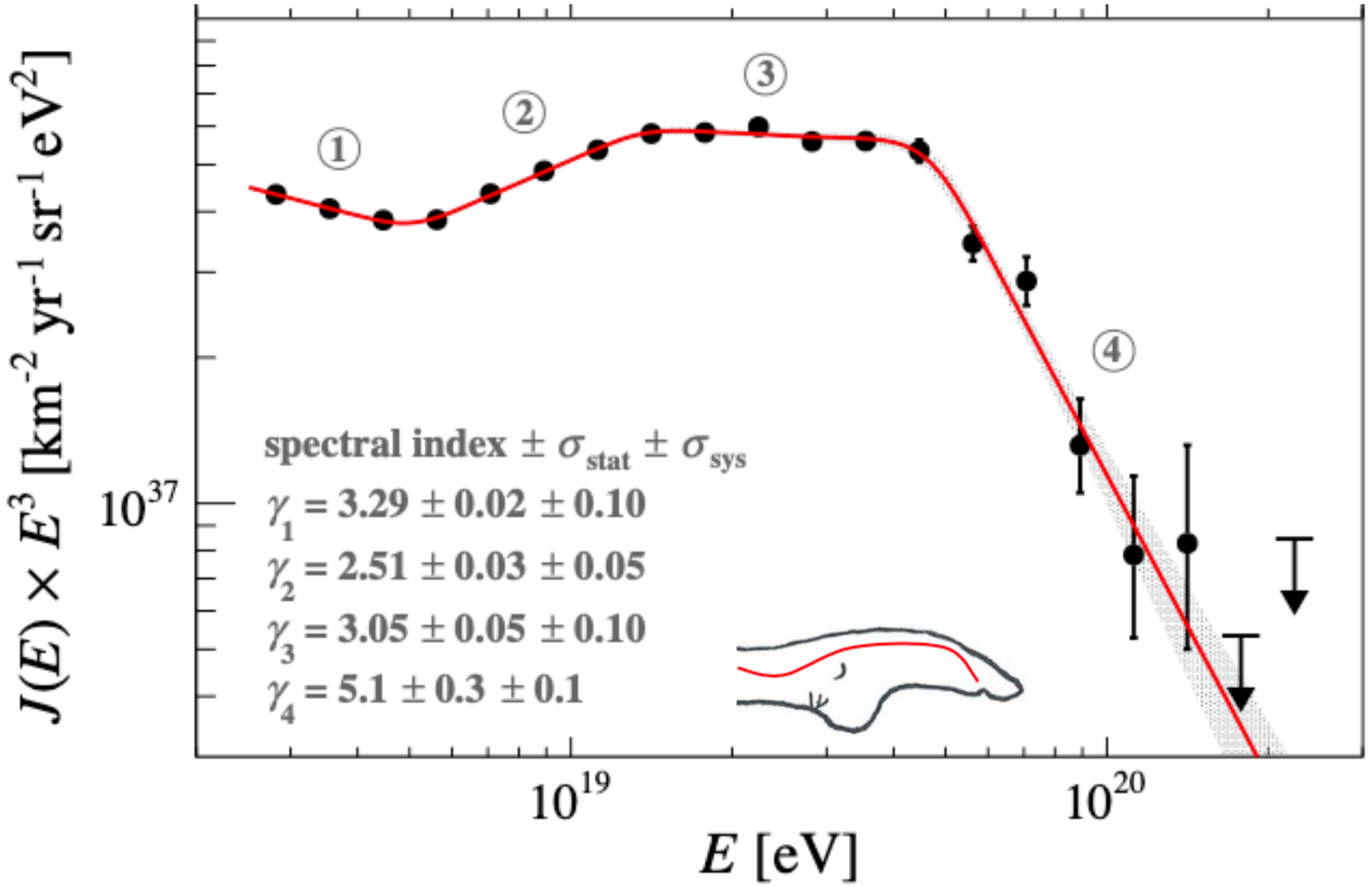
Astrophysical interpretation of Pierre Auger Observatory measurements of energy spectrum and mass composition

A. Condorelli

on behalf of the Pierre Auger Collaboration

RICAP, Roma, 07/09/2022

UHECRs measurements



A. Aab *et al*. (The Pierre Auger Collaboration)
Phys. Rev. Lett. **125**, 121106

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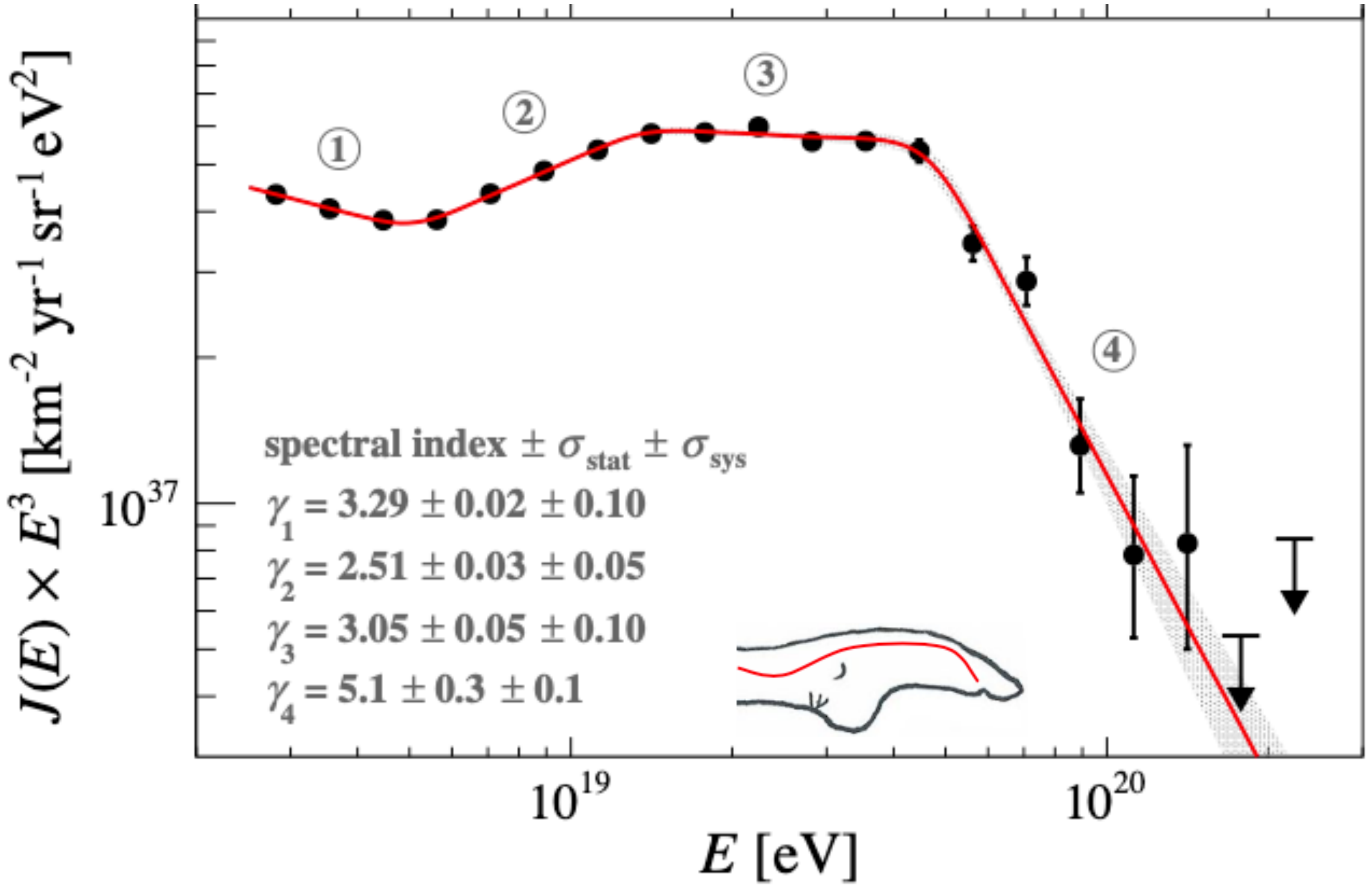

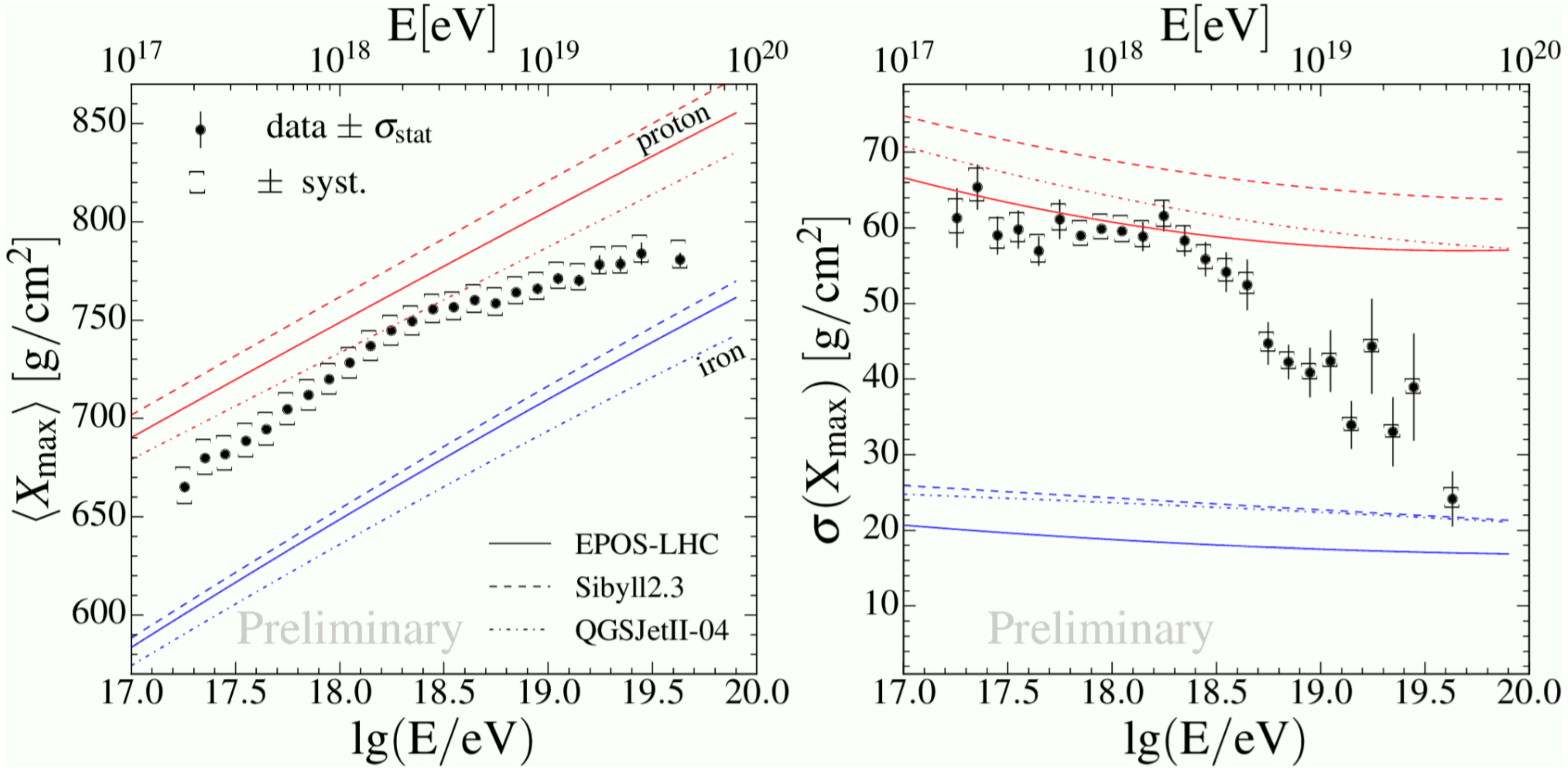

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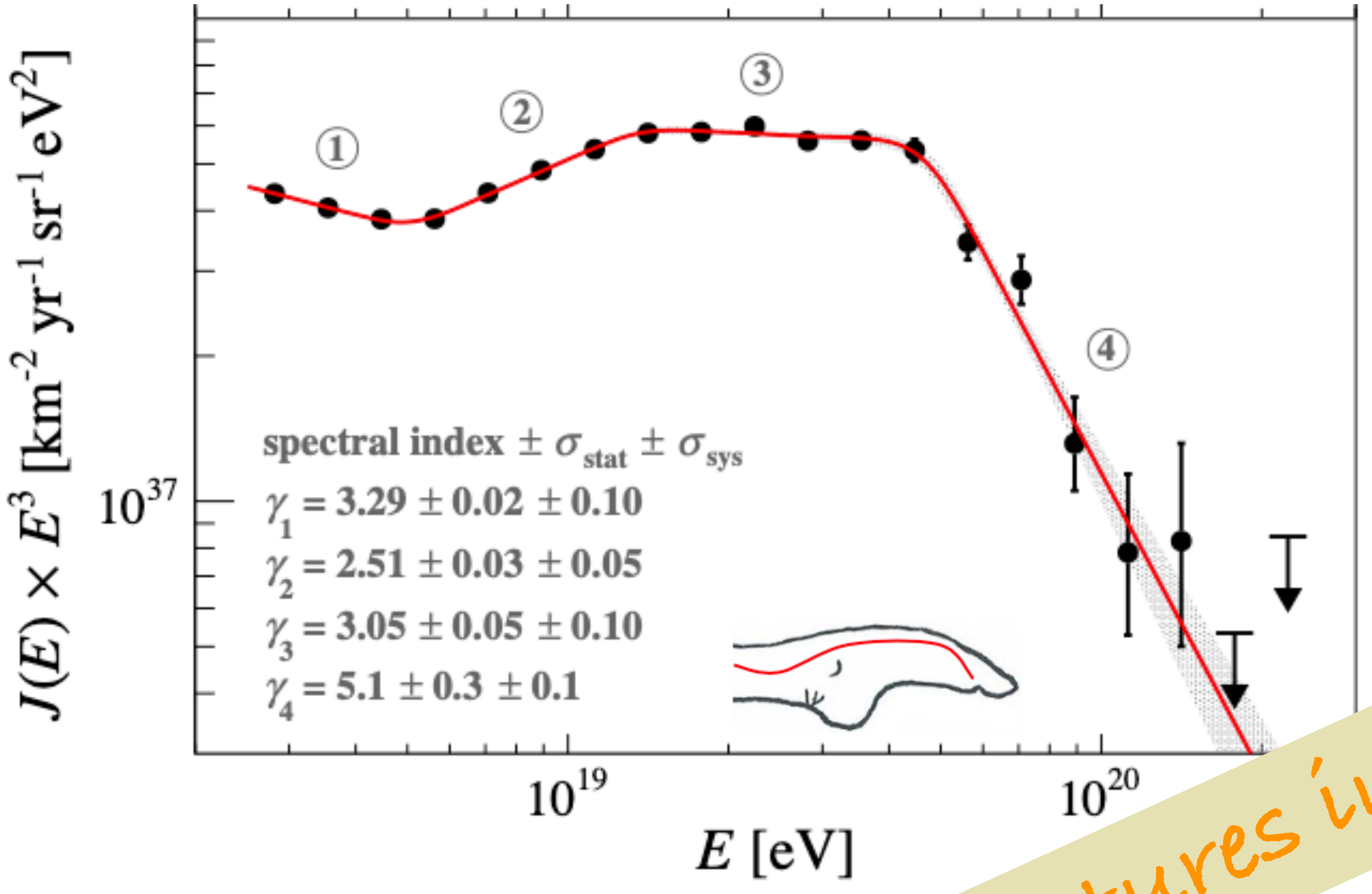
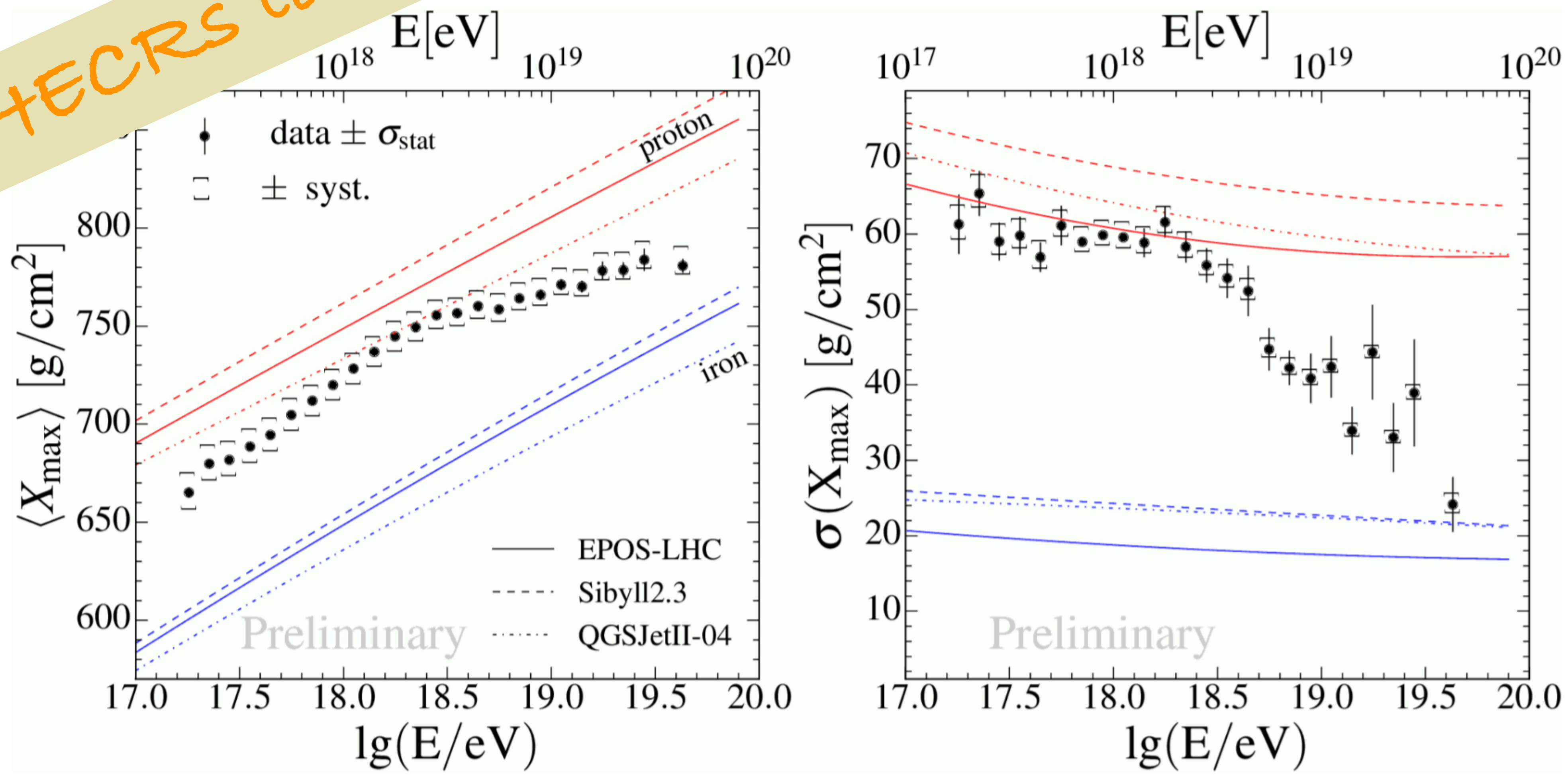
UHECRs measurements



It is possible to link features in the UHECRs to astrophysical processes?



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Source physics

Spectral index γ

Maximum energy $E_{\max}$

Mass composition f_A

Data

Energy spectrum $\Phi(E)$

Mass composition

$\langle X_{\max} \rangle$, $\sigma(X_{\max})$, etc..

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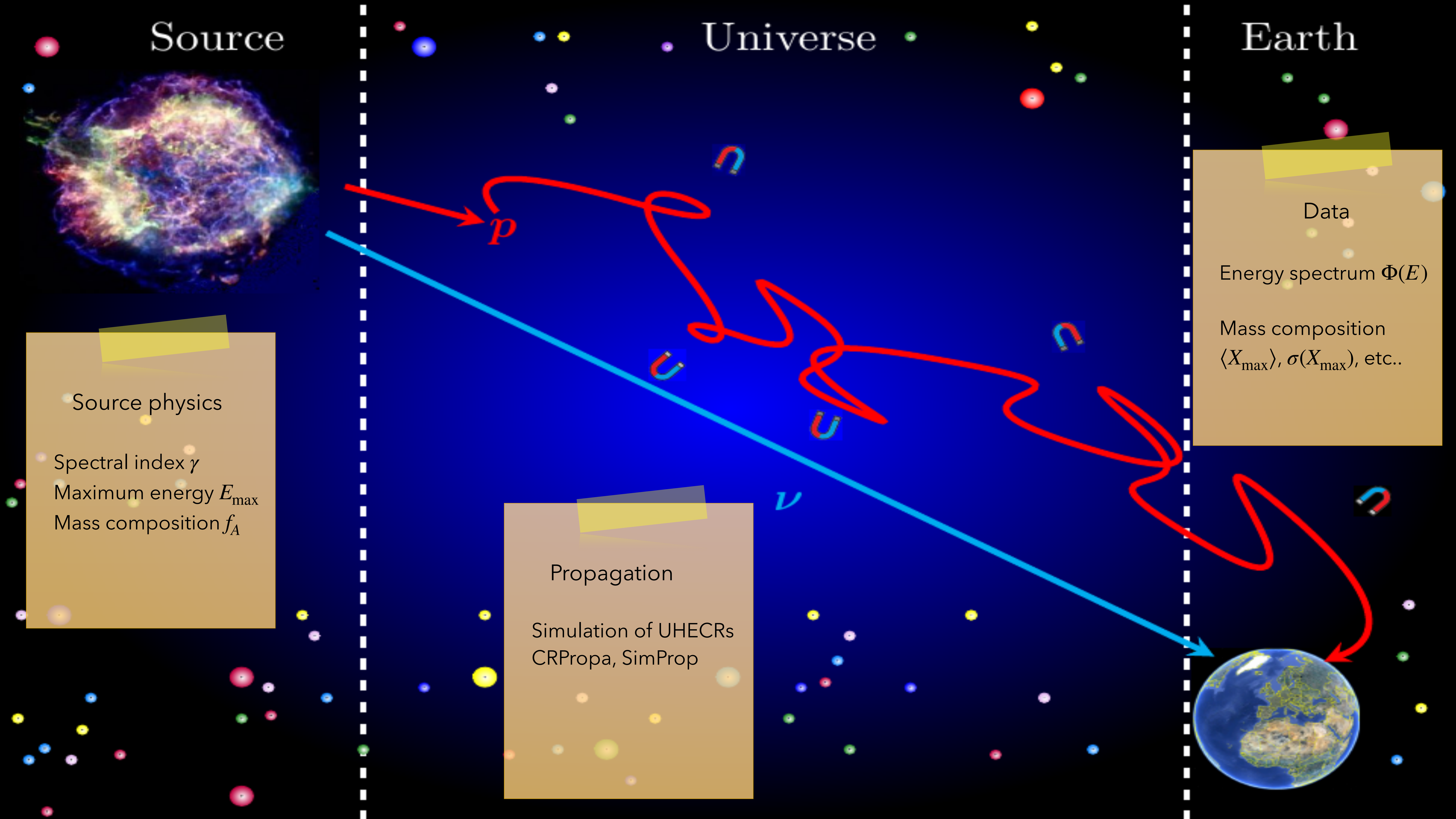

Source
Universe
Earth
p
ν
Source physics
Spectral index γ
Maximum energy $E_{\max}$
Mass composition f_A
Propagation
Simulation of UHECRs
CRPropa, SimProp
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$$J_k(E_i) = f_k J_0 \left(\frac{E_i}{E_0}\right)^{-\gamma} \cdot f_{\mathrm{cut}}(E_i, Z \cdot R_{\mathrm{cut}})$$

$$f_{\mathrm{cut}}(E_i, Z \cdot R_{\mathrm{cut}}) = \begin{cases} 1 & E_i < Z\ R_{\mathrm{cut}} \\ \exp\left(1 - \dfrac{E_i}{Z \cdot\ R_{\mathrm{cut}}}\right) & E_i > Z\ R_{\mathrm{cut}} \end{cases}$$

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A.Aab et al. (The Pierre Auger Collaboration), JCAP04(2017)038

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- The injected flux are propagated through the extra-galactic space and fitted to the Auger energy spectrum and composition.
- Free parameters of the fit are: $J_0, \gamma, R_{\mathrm{cut}}$ and $(N-1)\ f_k$.
- The total deviance is considered as the sum of the deviance of the spectrum and the deviance of the composition.

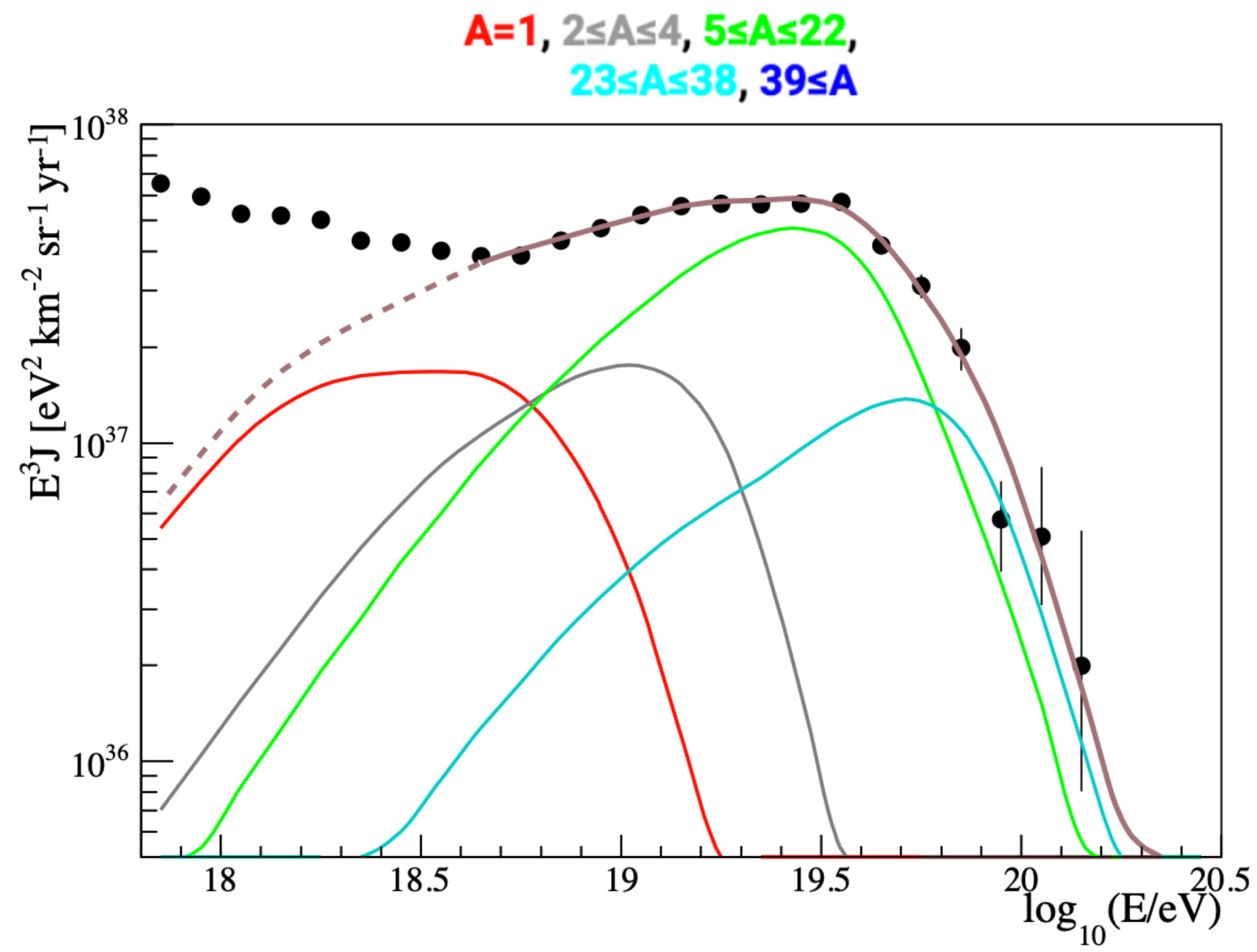
Astrophysical interpretation of Auger data

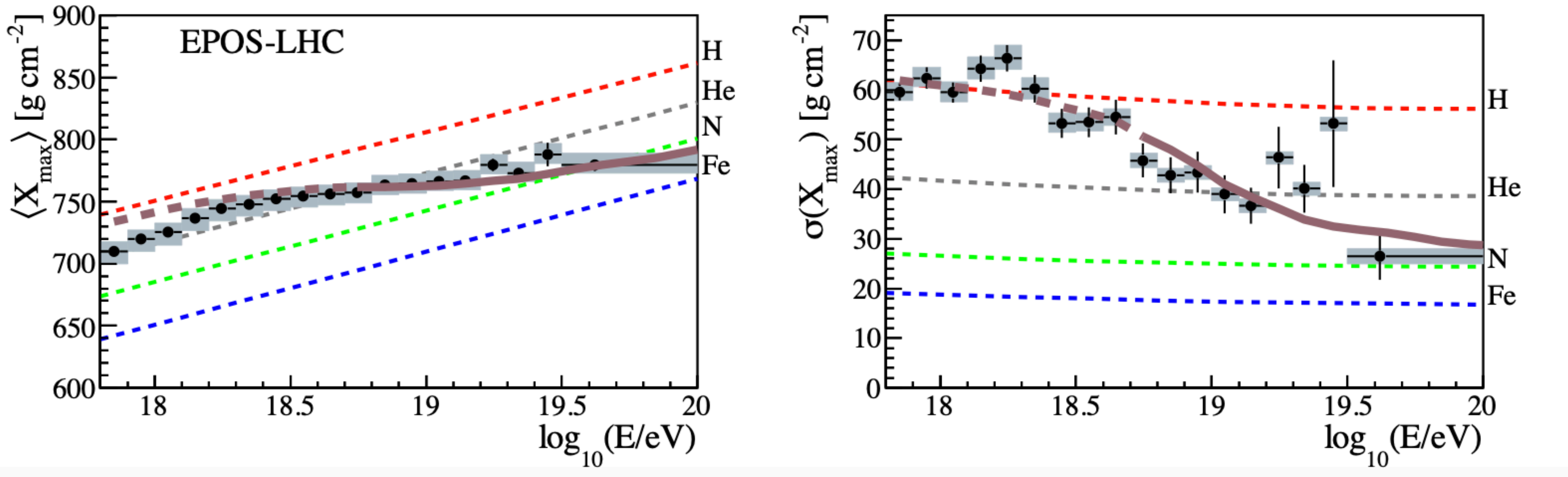
Fitting both the spectrum and composition, one can infer information about the source scenarios which are compatible data.

✳Nuclei are accelerated at the sources.

✳ A hard injection spectrum at the sources is required.

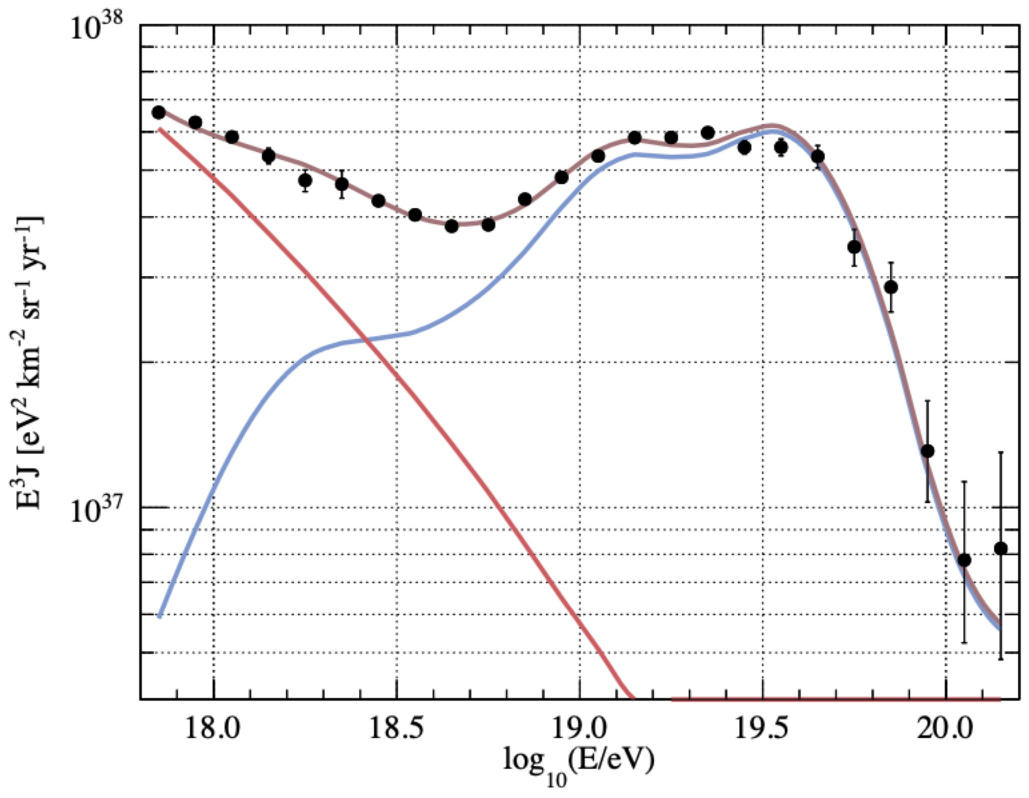
✳ Suppression due to photo-interactions and by limiting acceleration at the sources, while the ankle feature is not easy to accomodate.

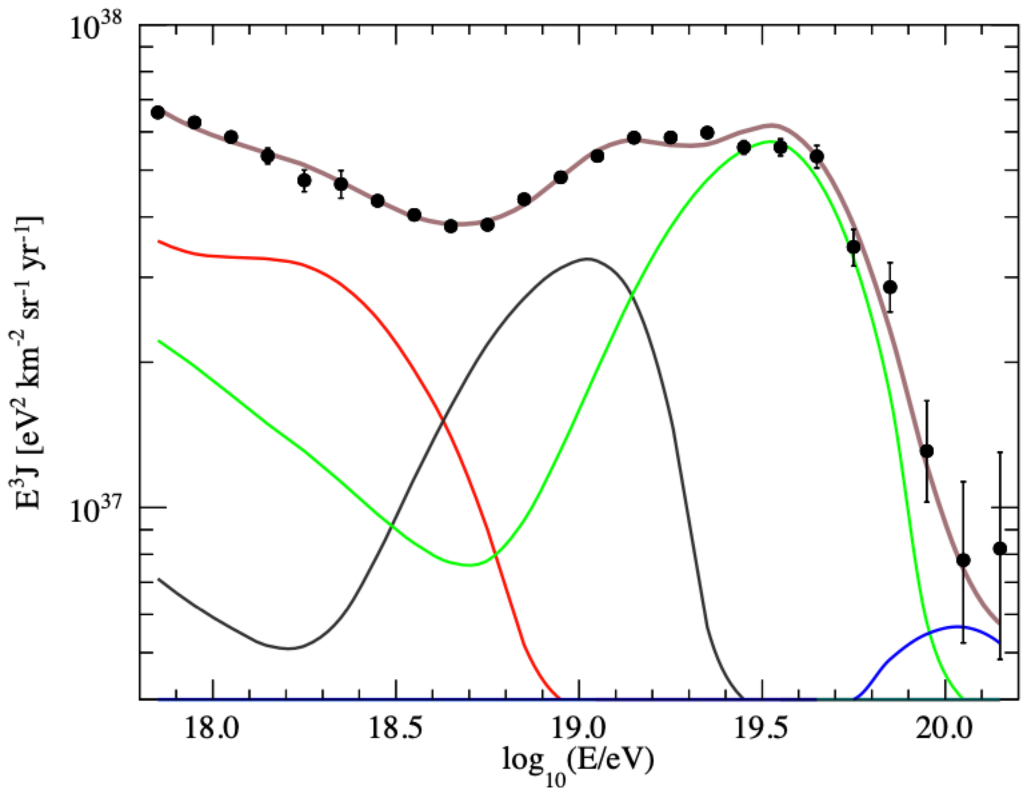




The extended combined fit

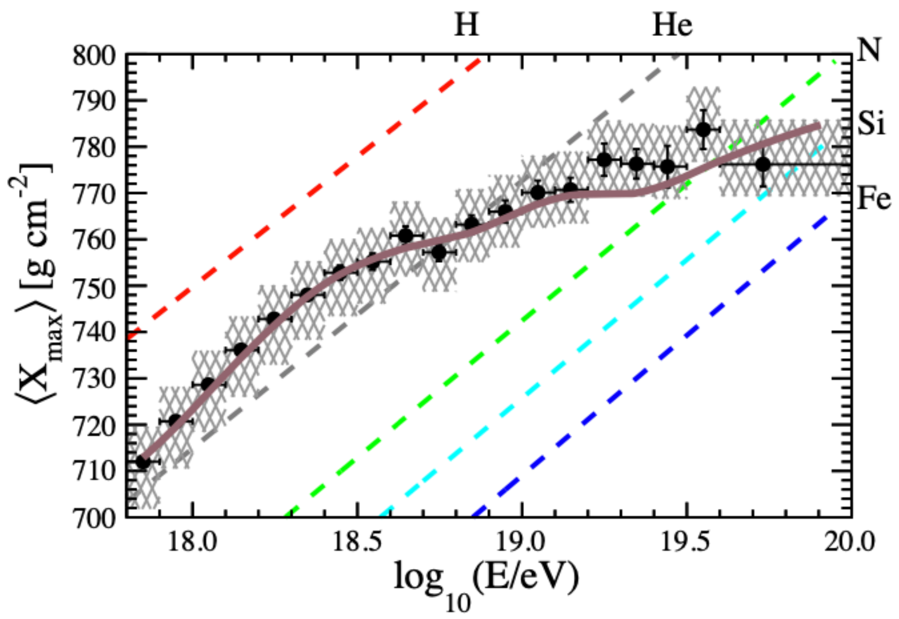
- ✳Duplicating the combined fit structure using two extra-galactic components;
- ✳The free parameters are duplicated with respect to the previous case.

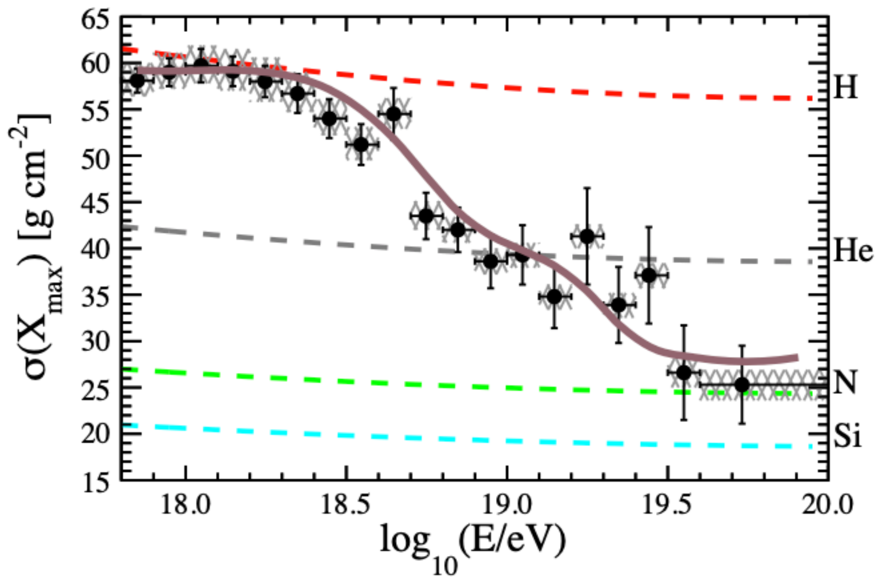




$$J_k^{\mathrm{LE}}(E) = J_0^{\mathrm{LE}}\ f_k^{\mathrm{LE}} \left(\frac{E}{E_0}\right)^{-\gamma^{\mathrm{LE}}} \cdot f_{\mathrm{cut}}(E, Z \cdot R_{\mathrm{cut}}^{\mathrm{LE}})$$

$$J_k^{\mathrm{HE}}(E) = J_0^{\mathrm{HE}}\ f_k^{\mathrm{HE}} \left(\frac{E}{E_0}\right)^{-\gamma^{\mathrm{HE}}} \cdot f_{\mathrm{cut}}(E, Z \cdot R_{\mathrm{cut}}^{\mathrm{HE}})$$





E.Guido for The Pierre Auger Collaboration, *PoS* ICRC2021 (2021) 311

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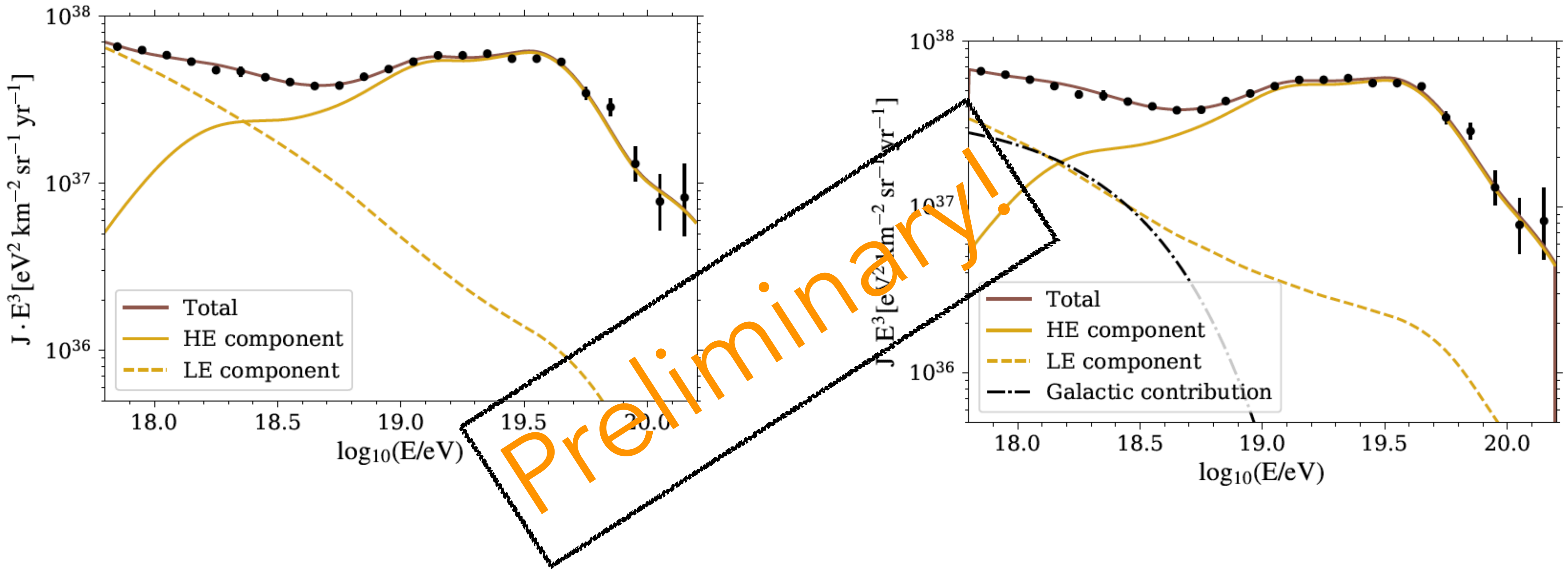
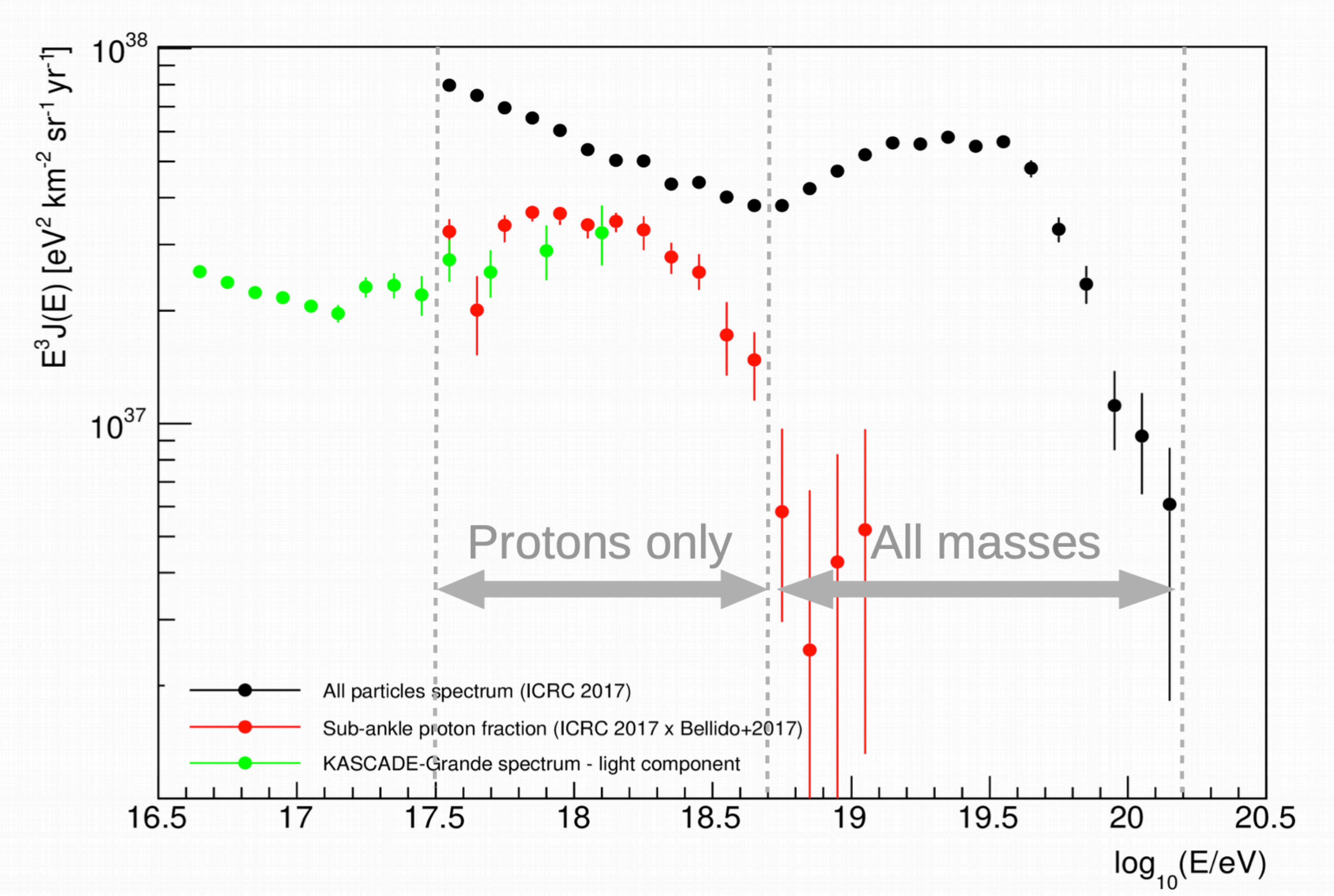
The extended combined fit



- ✳ Hard injection spectrum at high energies vs soft injection at low energies.
- ✳ Intermediate nuclei required at low energies.
- ✳ Impossibility to distinguish between a galactic and an extra-galactic contribution at low energies.
- ✳ Iron Galactic flux is strongly disfavoured.

Fitting the proton spectrum

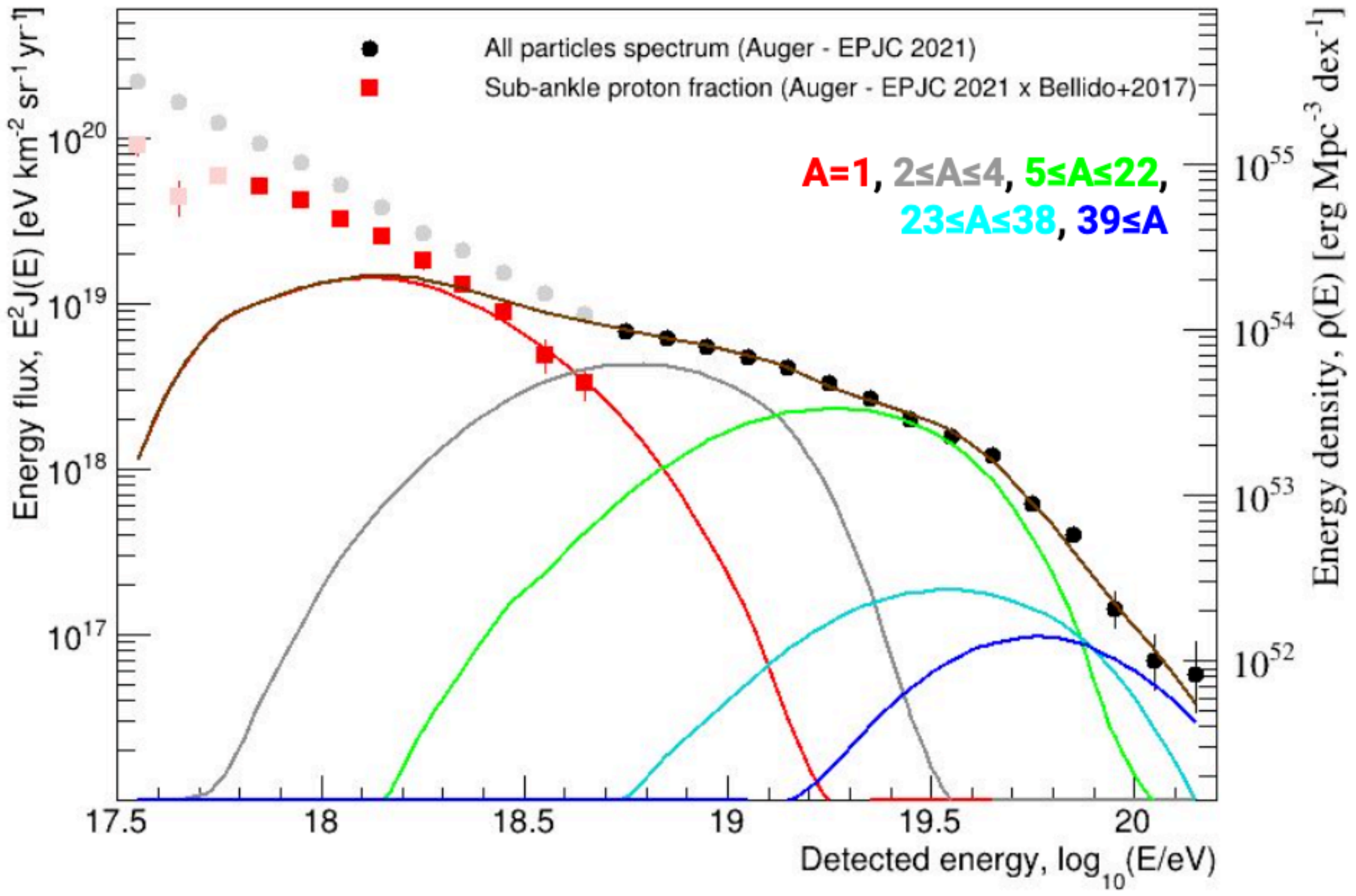
- ☐ How can we get information without extending the model?
- ☑ Fitting the proton spectrum in the energy below the ankle !

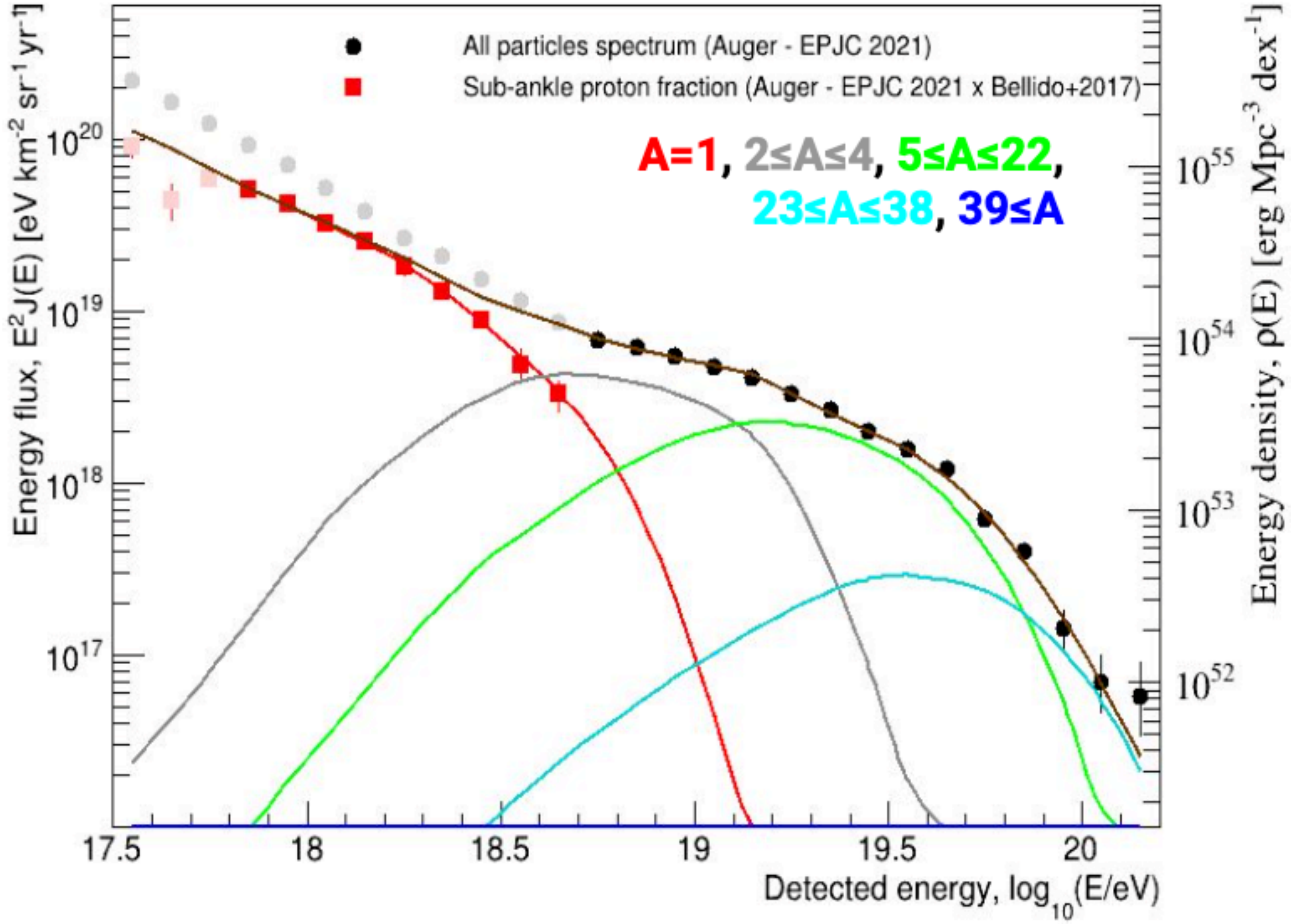


Comparison

Scenario	γ_p	γ_A	$\log_{10} E_{max}$ [eV]	$\bar{\mathcal{L}}_p/\mathcal{L}_0$	$\bar{\mathcal{L}}_{He}/\mathcal{L}_0$	$\bar{\mathcal{L}}_N/\mathcal{L}_0$	$\bar{\mathcal{L}}_{Si}/\mathcal{L}_0$	$\bar{\mathcal{L}}_{Fe}/\mathcal{L}_0$	D/ndf
$\gamma_p = \gamma_A$	γ_A	-1.54 ± 0.10	18.19 ± 0.01	0.63 ± 0.07	1.4 ± 0.1	3.1 ± 0.1	0.34 ± 0.21	0.12 ± 0.02	862.7/126
$\gamma_p \neq \gamma_A$	3.24 ± 0.10	-0.46 ± 0.03	18.35 ± 0.01	5.5 ± 0.2	1.7 ± 0.1	2.95 ± 0.06	0.62 ± 0.21	0.00 ± 0.19	236.8/125

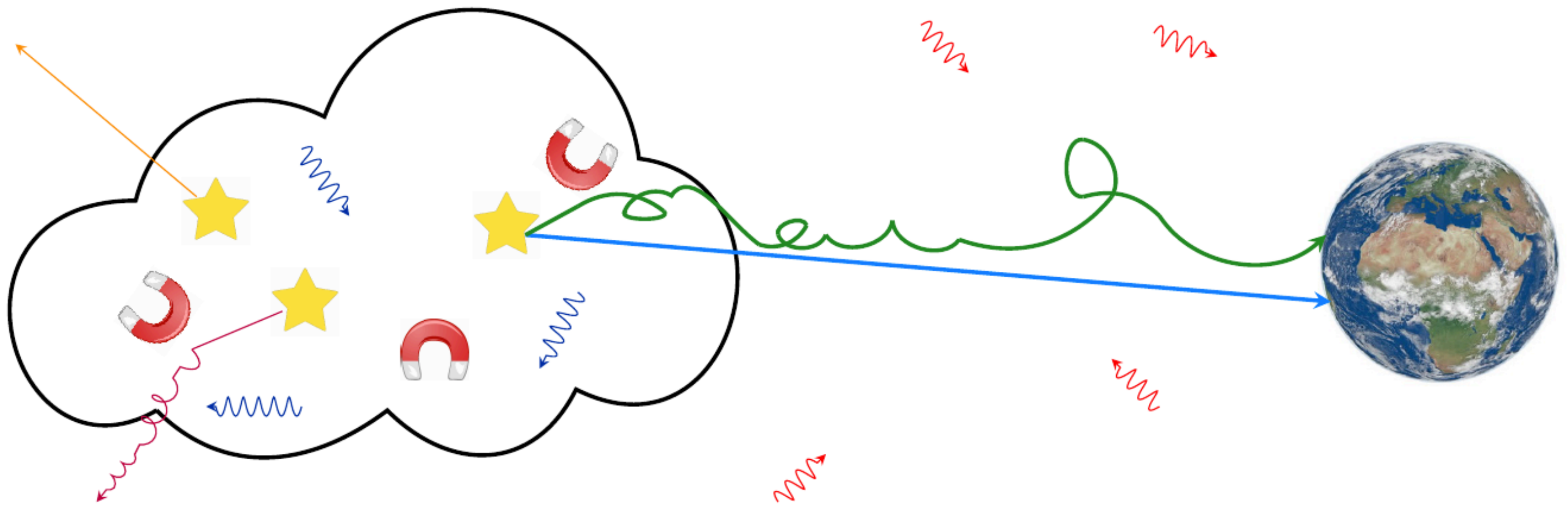
EPOS-LHC





Interactions at the source

- Accelerated particles confined in the environment surrounding the source;
- Presence of photon and gas density;
- High energy particles–> escape with no interaction;
- Low energy particles –> Pile-up of nucleons at lower energies.



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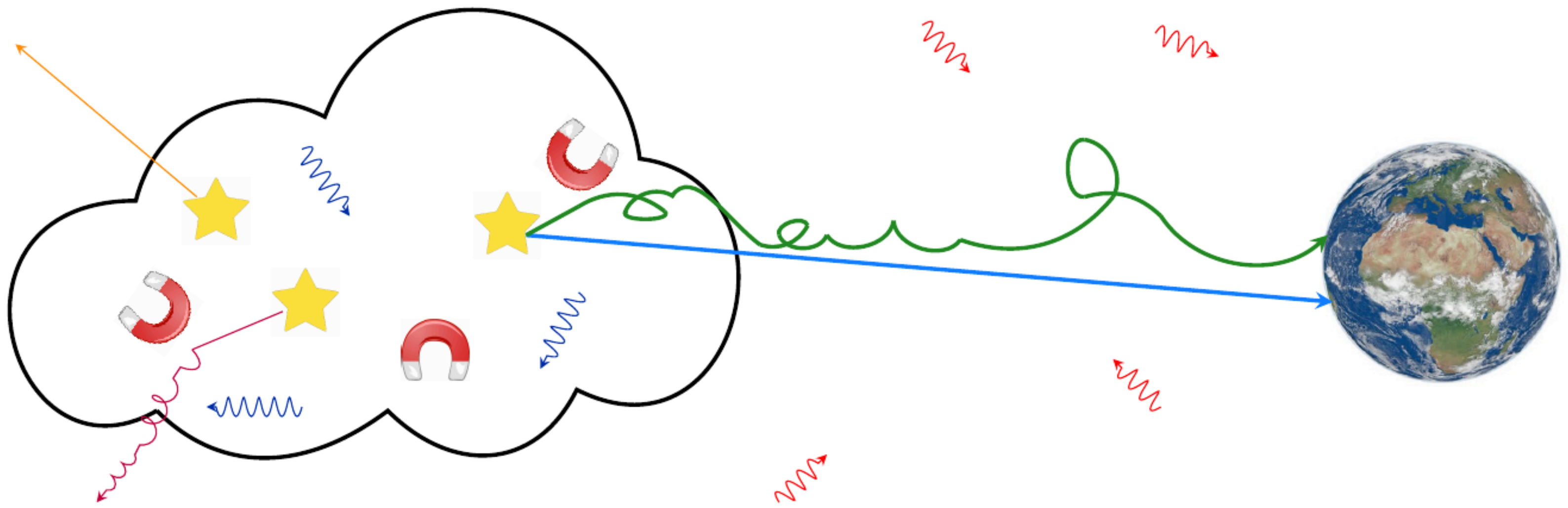

Interactions at the source already discussed in:

✓Unger, M., Farrar, G. R., & Anchordoqui, L. A. 2015, PhRvD, 92, 123001
✓Globus, N., Allard, D., & Parizot, E. 2015, PhRvD, 92, 021302
✓Biehl, D., Boncioli, D., Fedynitch, A., & Winter, W. 2018, A&A, 611, A101
✓Zhang, B. T., Murase, K., Kimura, S. S. Et al., P. 2018, PhRvD, 97, 083010
✓Fang, K., & Murase, K. 2018, Nature Phys., 14, 396
✓Supanitsky, A. D., Cobos, A., & Etchegoyen, A. 2018, PhRvD, 98, 103016
✓Boncioli, D., Biehl, D., & Winter, W. 2019, ApJ, 872, 110
✓Condorelli, A., Boncioli, D., Peretti., E., & Petrera, S., *PoS* ICRC2021 (2021) 959

Improvements and discussion

- ✳The CF of energy spectrum and composition could shed light of the features observed in the UHECR measurements;
- ✳Below the ankle a mix of protons and intermediate nuclei is required, while the presence of a heavy component is strongly disfavoured;
- ✳Secondary fluxes increase the constrain capability of the model;
- ✳Future analysis (ongoing) including arrival direction measurements will thus provide elements helping to understand the origin of UHECRs.

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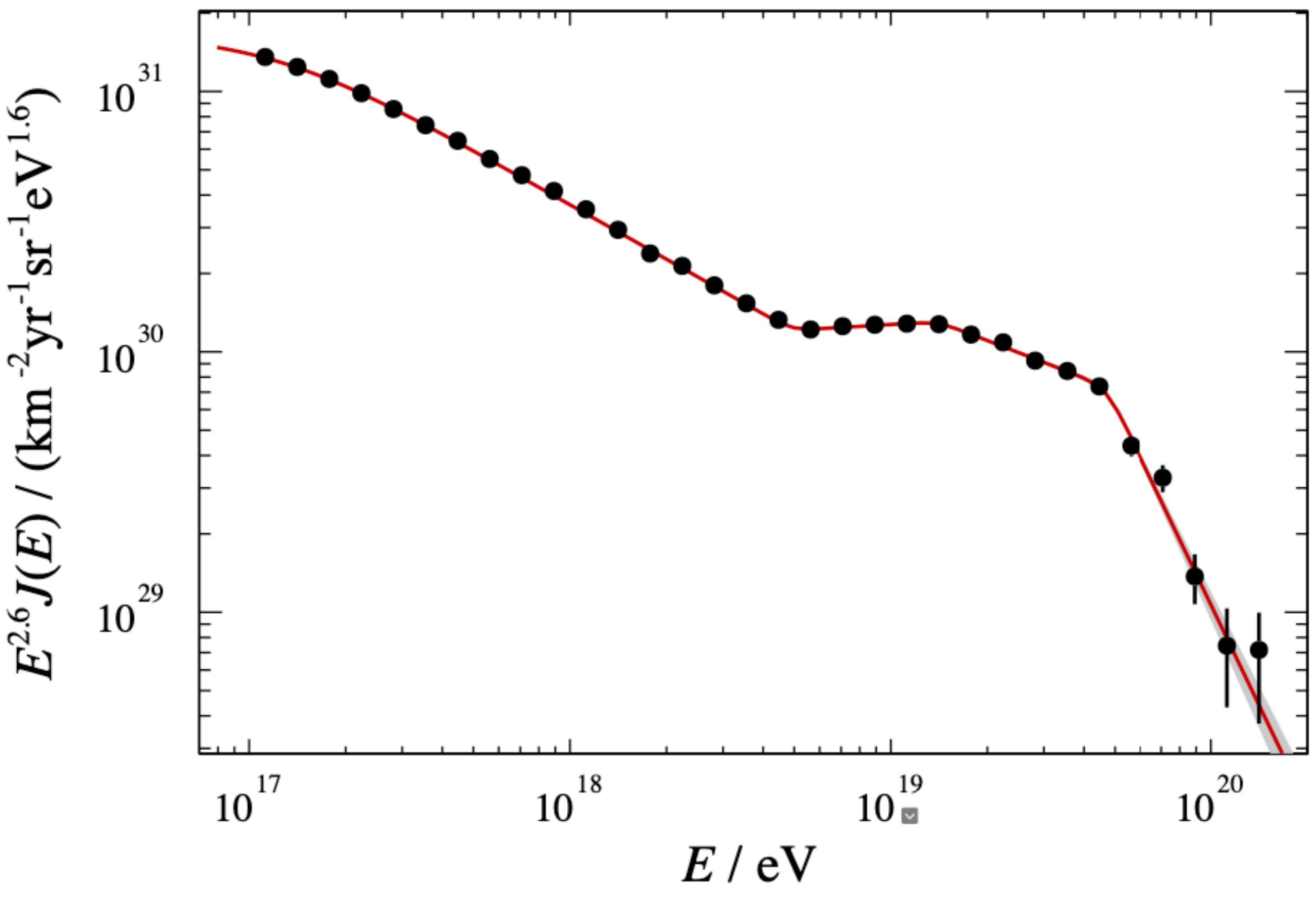
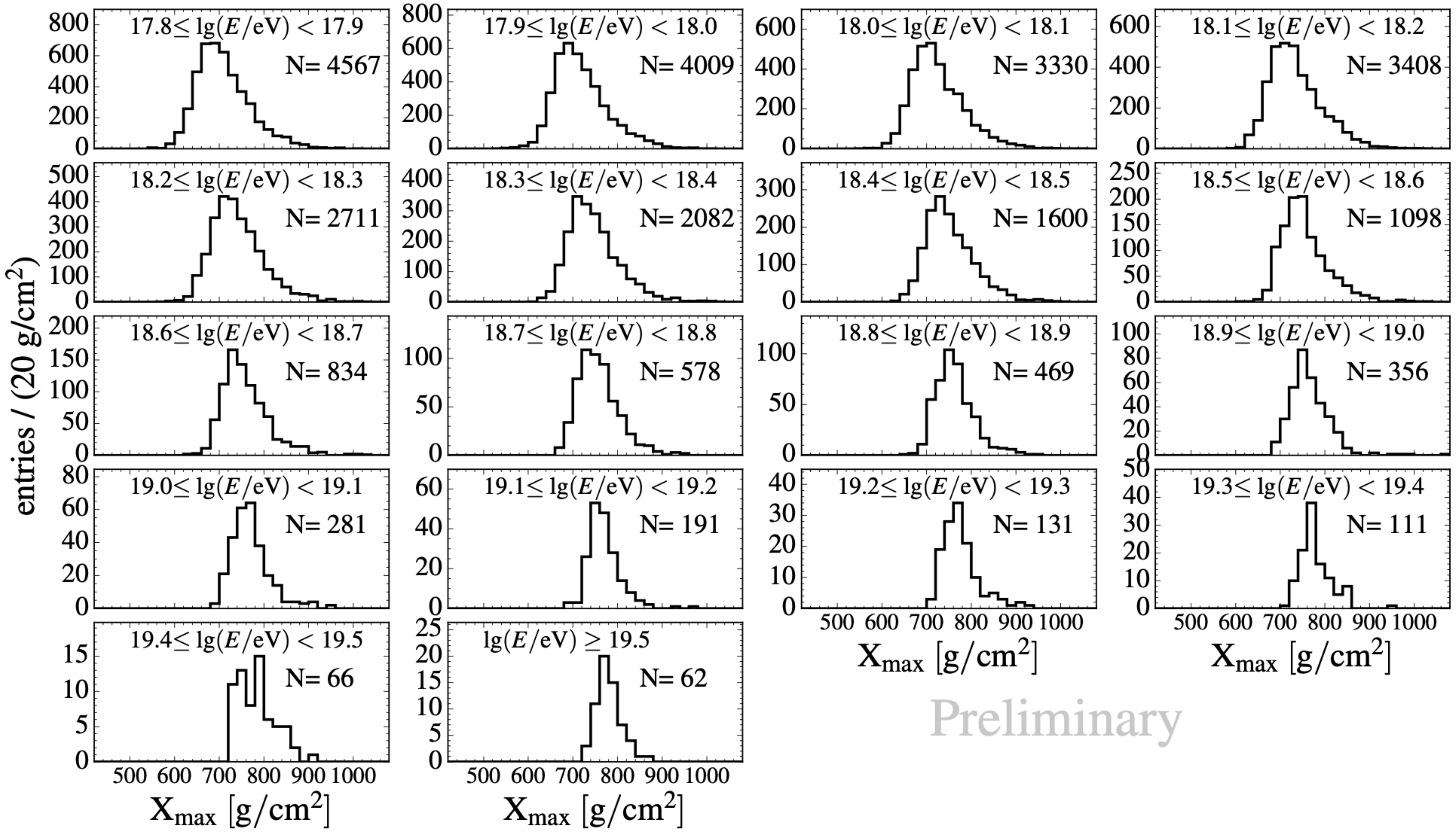
Thanks for your attention!

Back-up slides!

UHECRs measurements





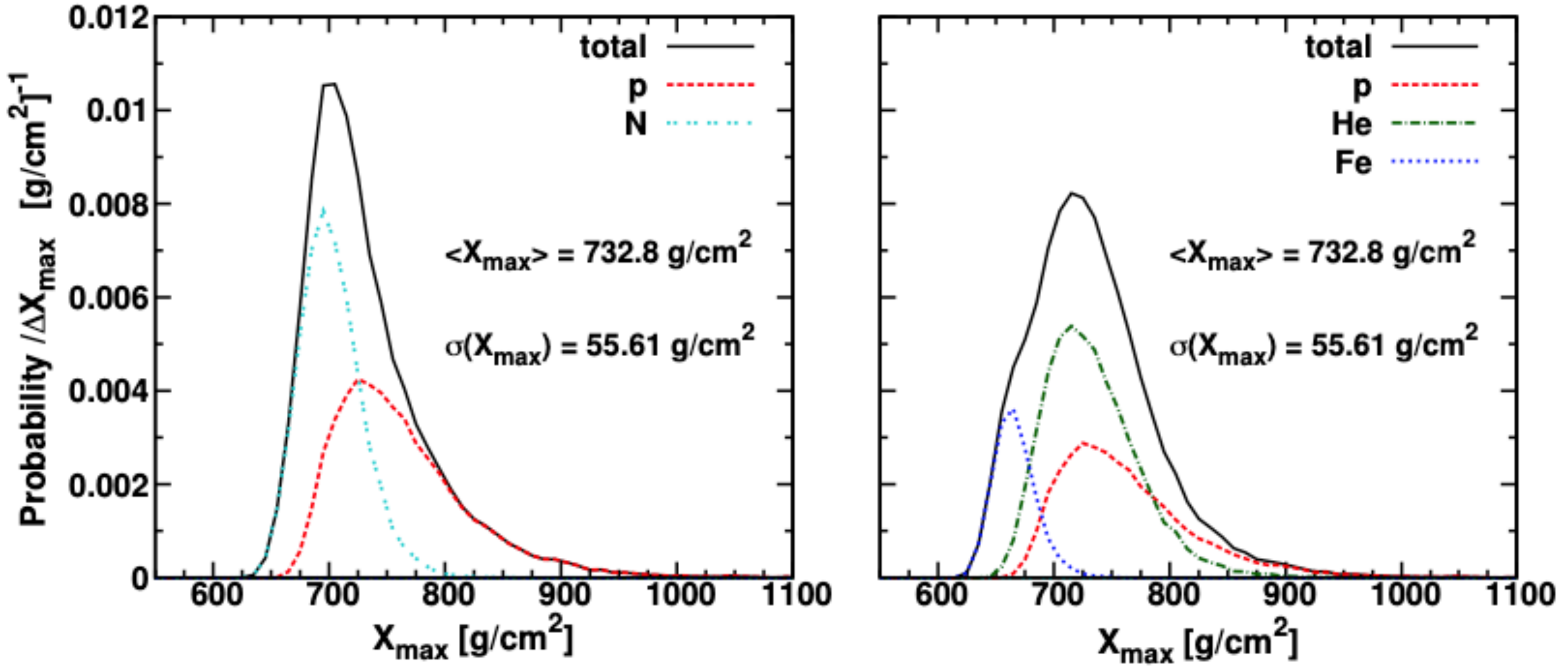
Combined fit above the ankle: ingredients

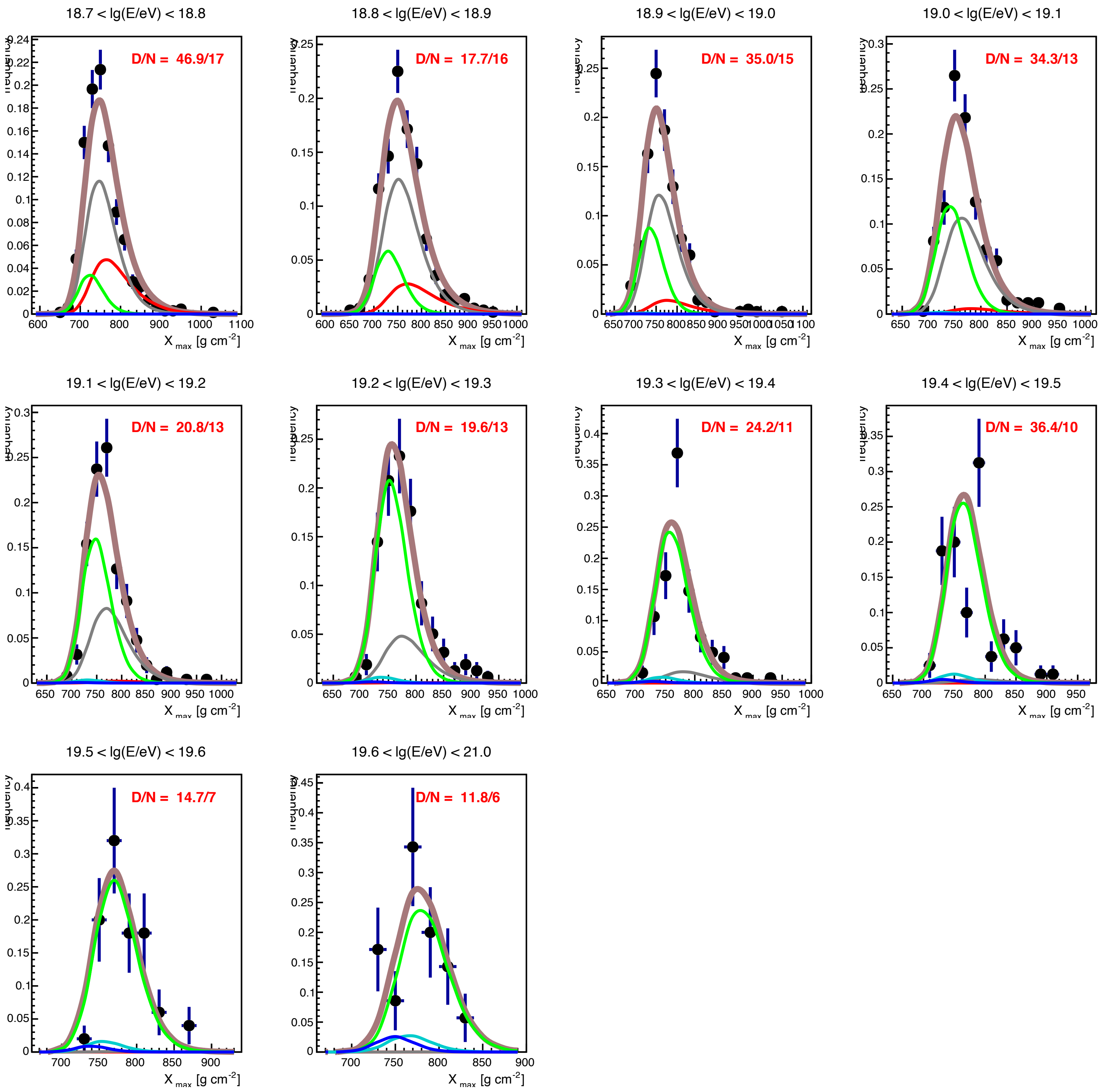
Parameters	*Values*
R_{cut}	18.25 ± 0.03
γ	$-1.06^{+0.22}_{-0.08}$
D_J (N_J)	20.1 (15)
D_{Xmax} (N_{Xmax})	203.4 (109)
D (N)	223.5 (124)
$\mathcal{L}_H$ [10^{43} erg Mpc^{-3} yr^{-1}]	6.6 ± 0.7
$\mathcal{L}_{He}$ [10^{43} erg Mpc^{-3} yr^{-1}]	14.4 ± 1.0
$\mathcal{L}_N$ [10^{43} erg Mpc^{-3} yr^{-1}]	36.4 ± 0.9
$\mathcal{L}_{Si}$ [10^{43} erg Mpc^{-3} yr^{-1}]	3.4 ± 1.4
$\mathcal{L}_{Fe}$ [10^{43} erg Mpc^{-3} yr^{-1}]	1.4 ± 1.3

Fit of the distribution

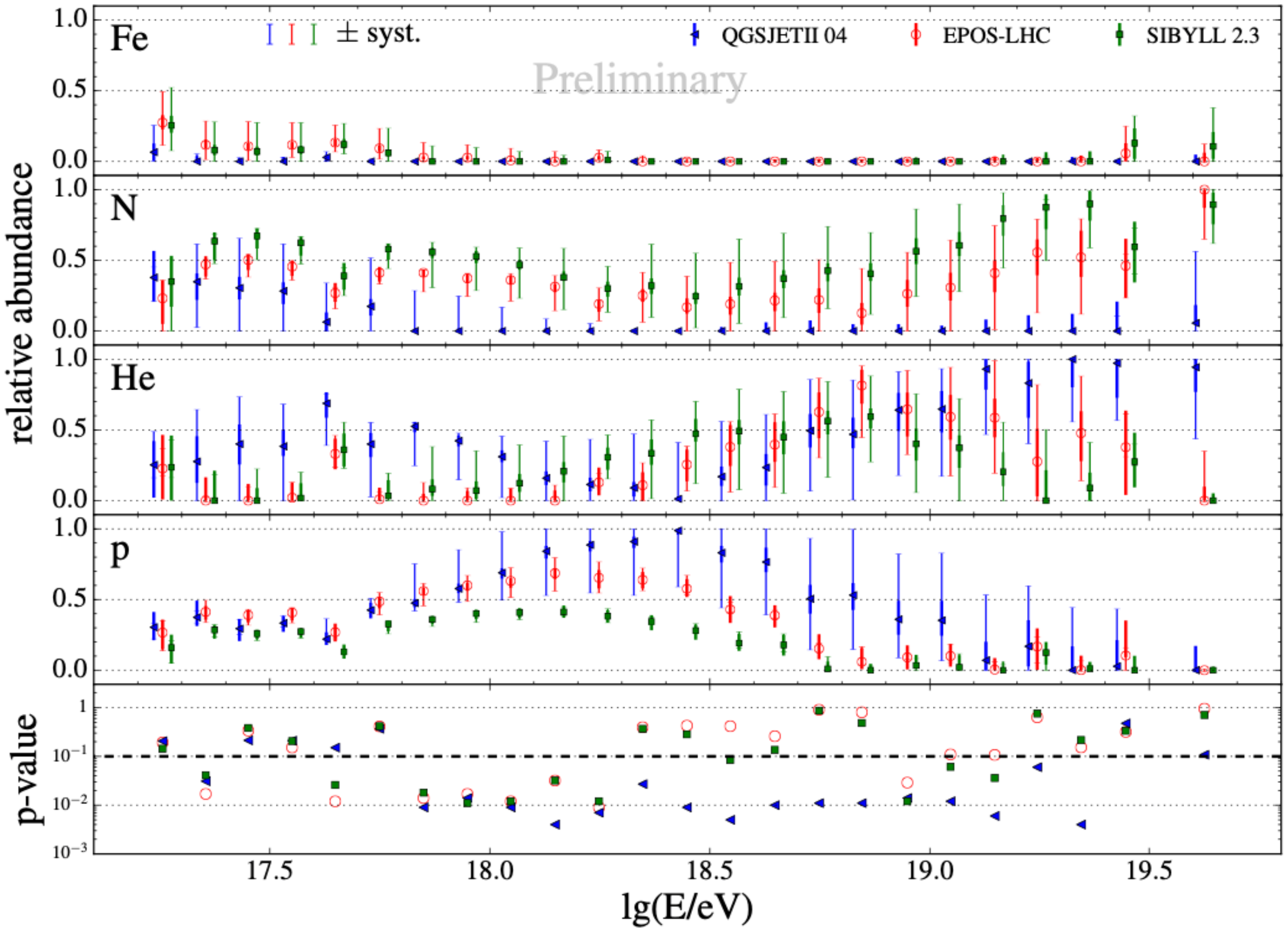
The expected $X_{\max}$ distributions are parametrized in terms of generalised Gumbel functions:

$$g(X_{\max}|\lg E, A) = \frac{\lambda^{\lambda}}{\sigma\Gamma(\lambda)}\exp\left(-\lambda\frac{X_{\max}-\mu}{\sigma} - \lambda\exp\left(-\frac{X_{\max}-\mu}{\sigma}\right)\right)$$





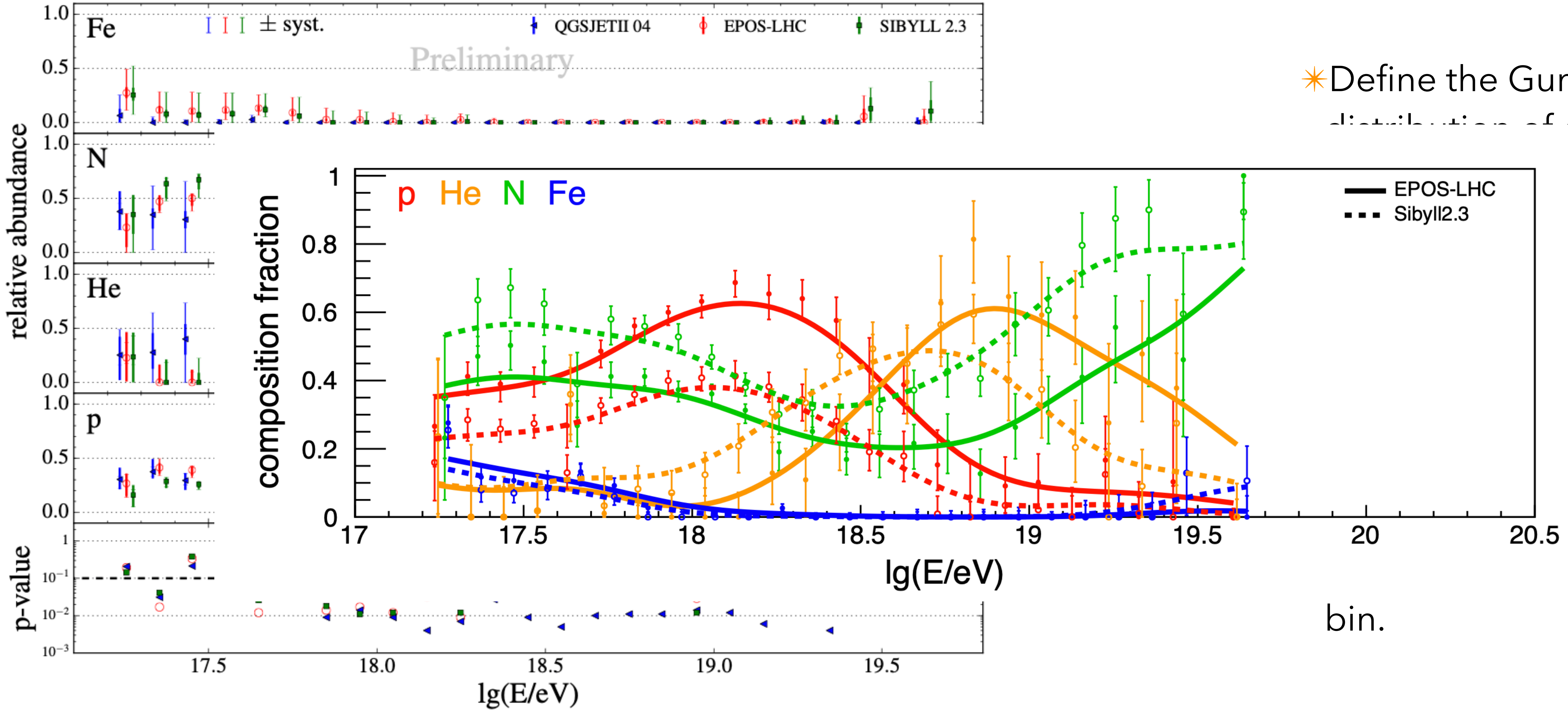
Fraction fit



- ✴Define the Gumbel distribution of a set of four masses (H, He, N, Fe);
- ✴Including detector effects;
- ✴Find the best fit fractions with respect to the chosen set of Gumbel distributions;
- ✴Analysis independent bin to bin.

J. Bellido for the Pierre Auger collaboration, ICRC2017

Fraction fit



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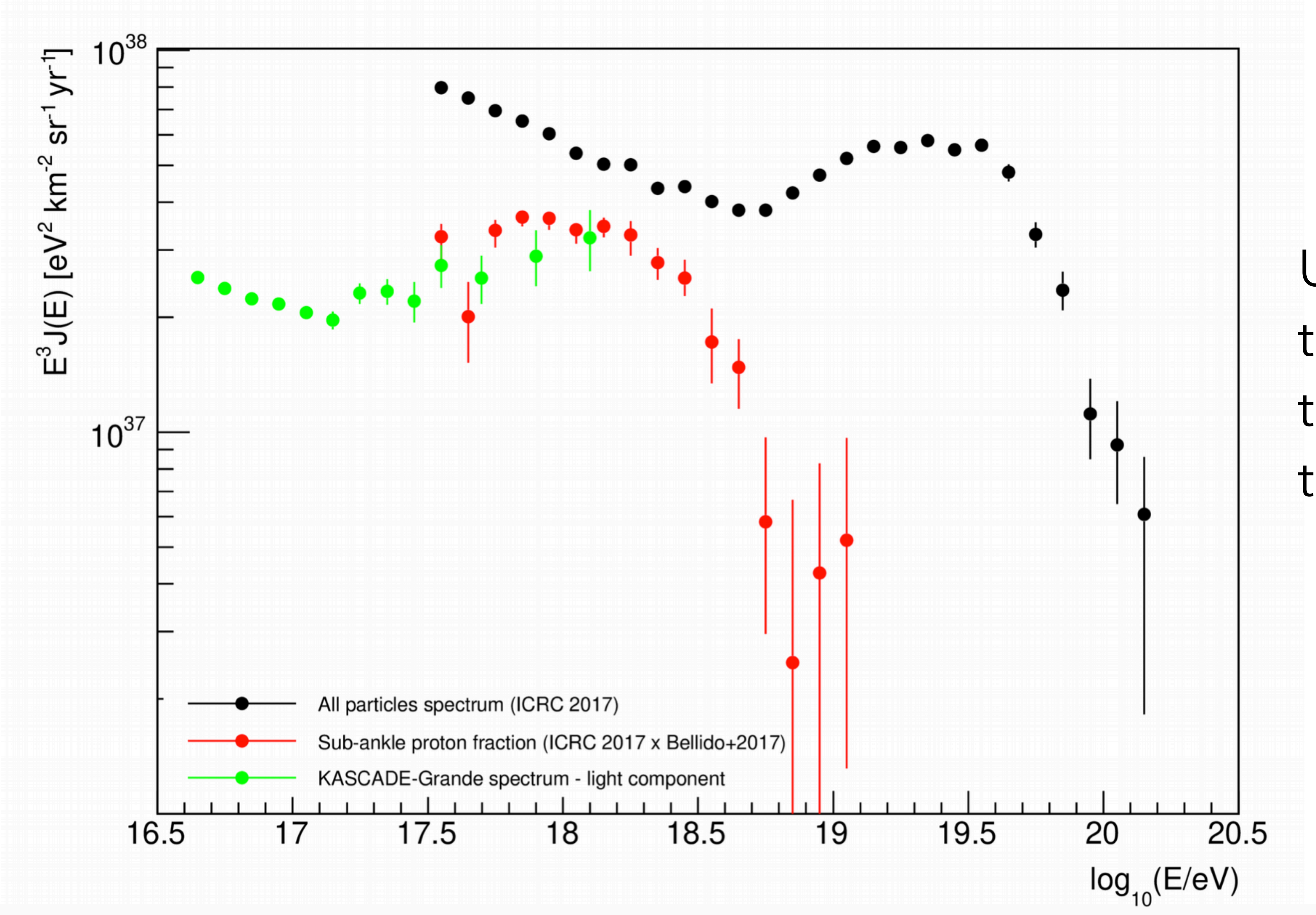
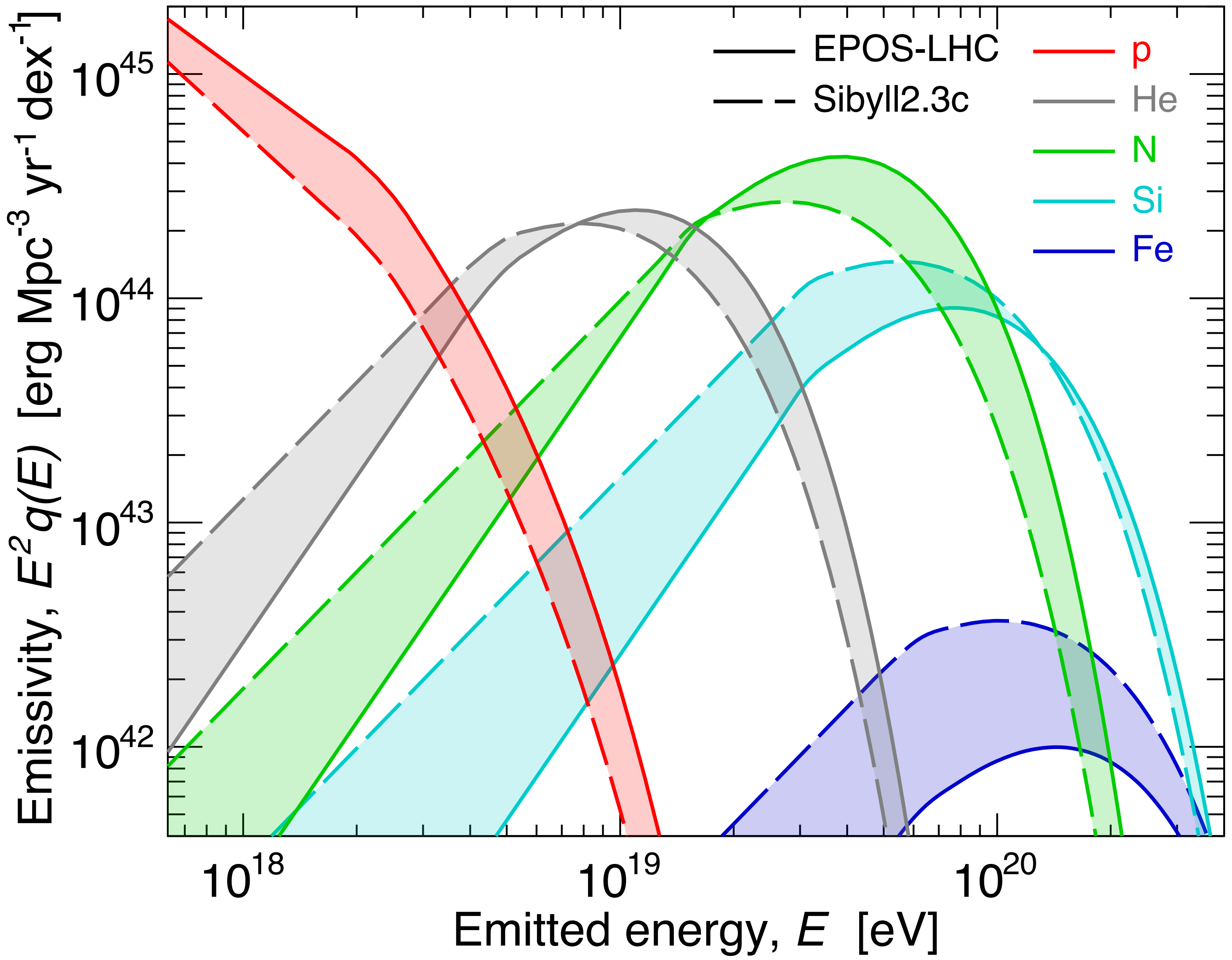
Defining the proton spectrum



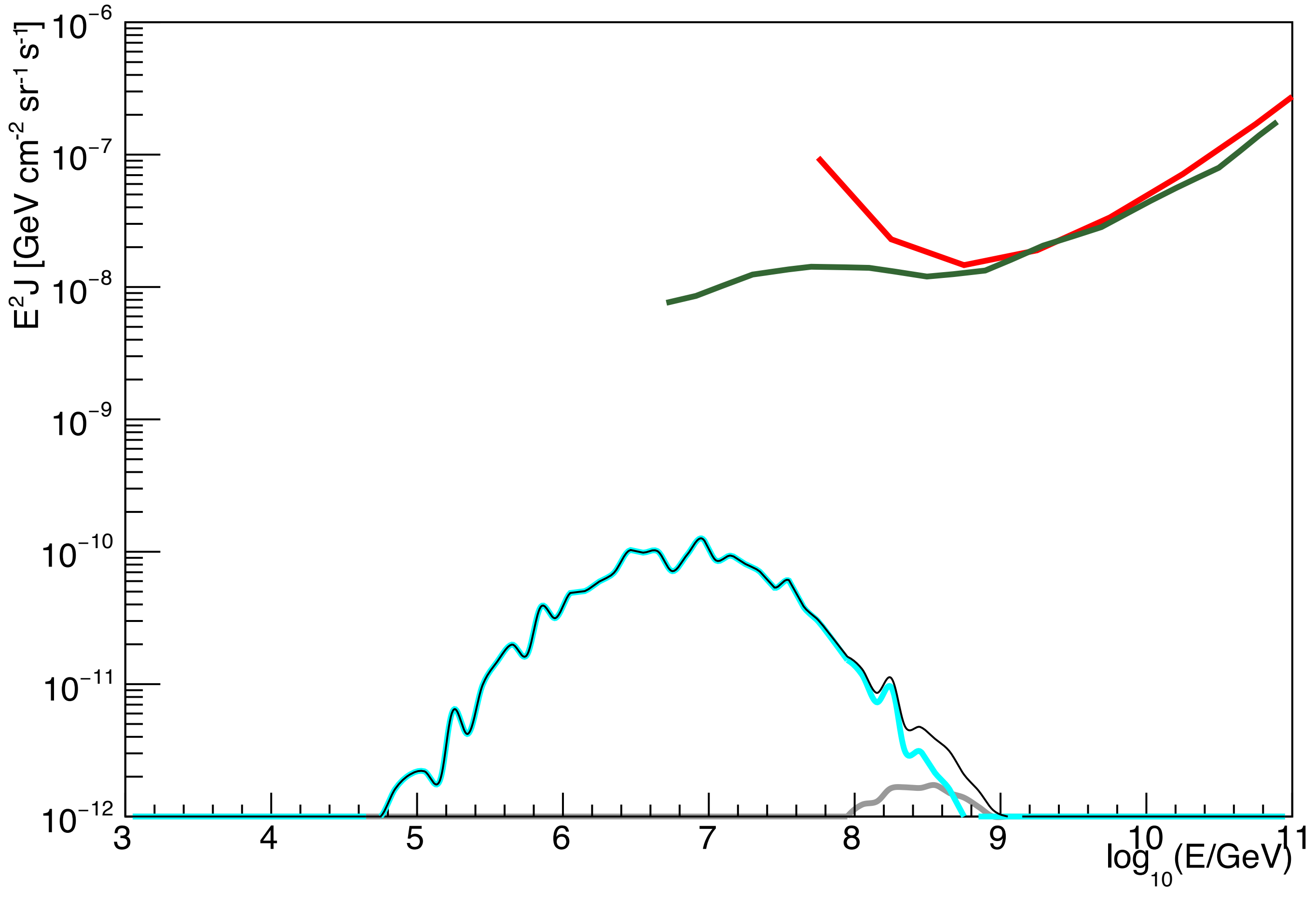
Use the fraction fit to define the proton spectrum–> total spectrum multiplied by the best fit proton fractions

Discussion

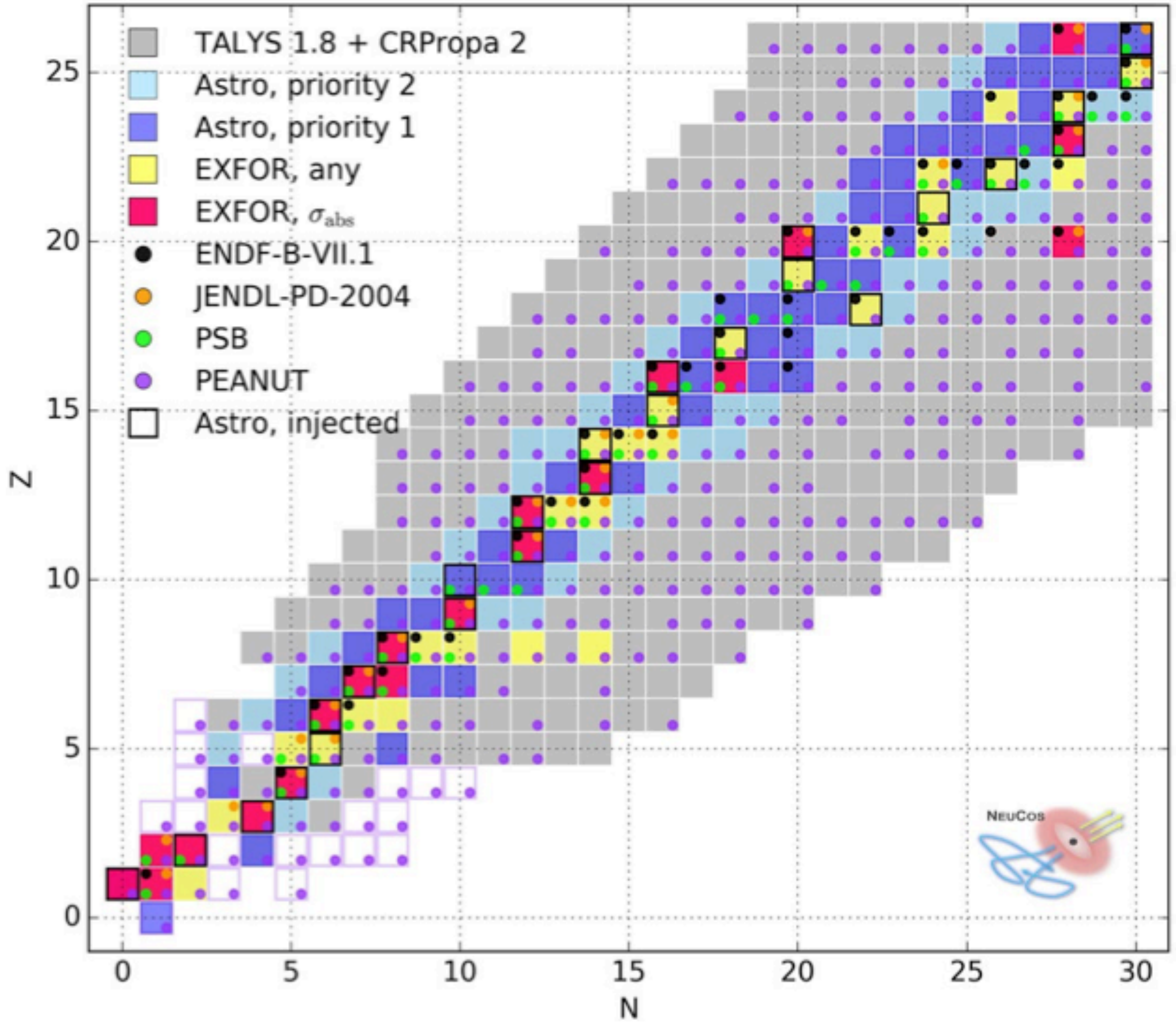
Emissivity



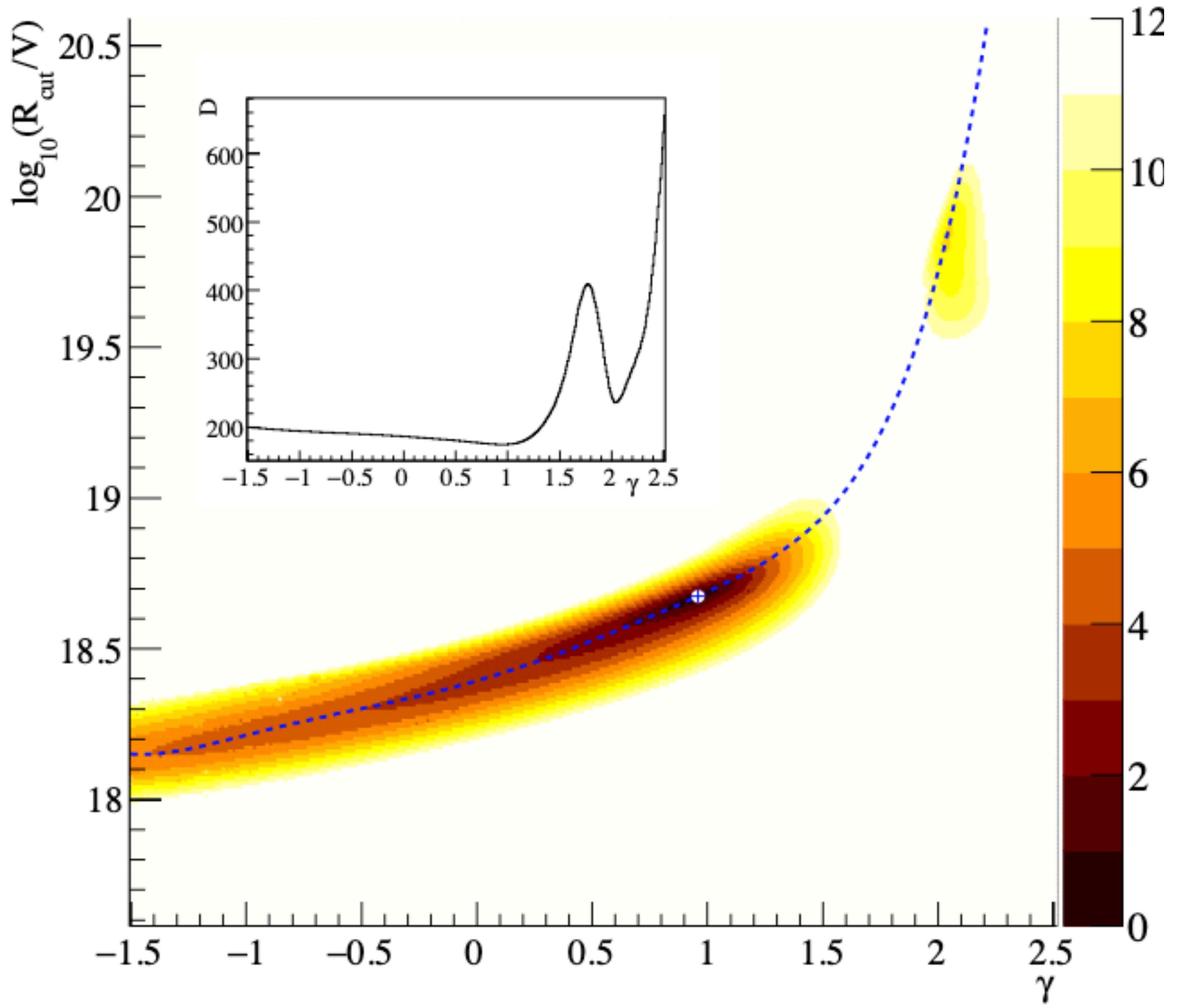
Expected neutrino flux

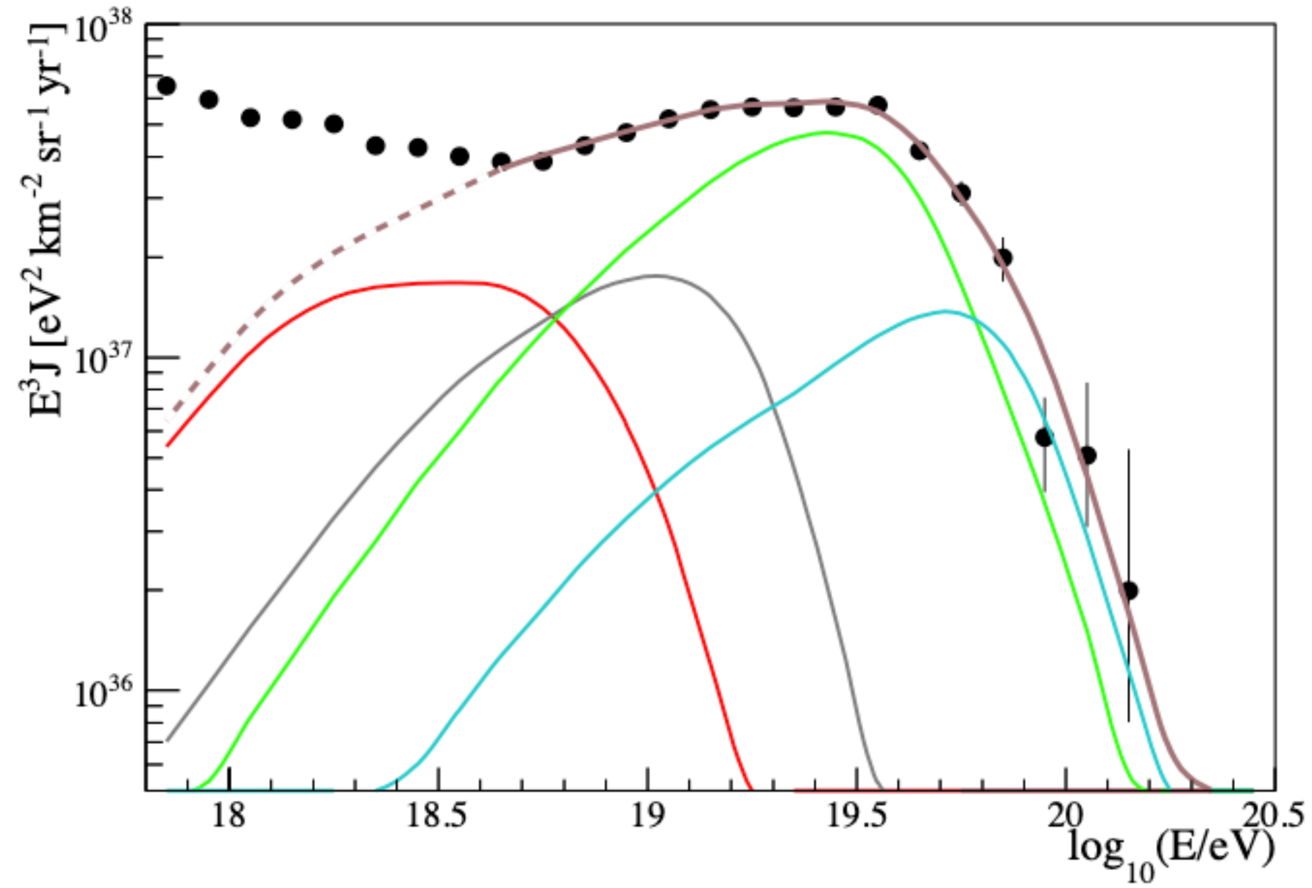


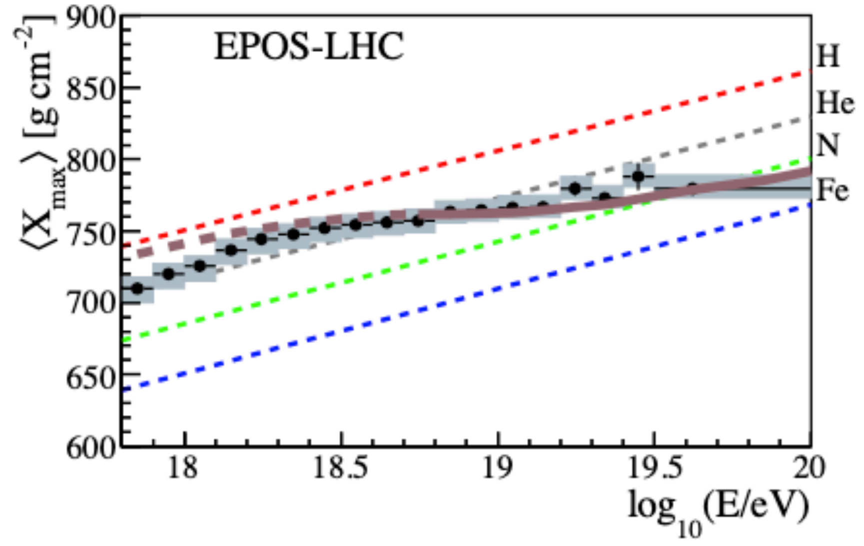
Methodology of source-propagation model

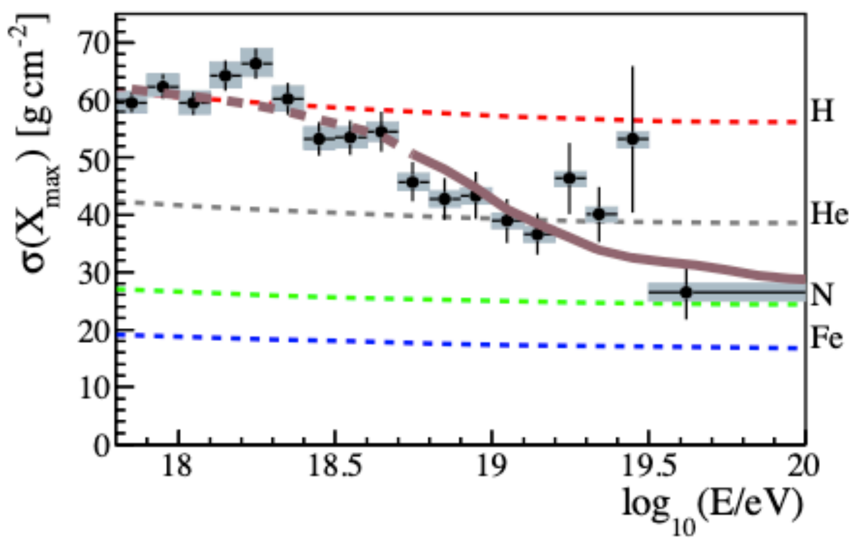


Combined fit above the ankle: results









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Second extra-galactic component