A consistent picture of UHECRs with the Pierre Auger Observatory

and the new questions that arise from data

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7th International Symposium on Ultra-High-Energy Cosmic Rays

17-21 November 2024, Malargüe

The Pierre Auger Observatory… is here!

Southern hemisphere: Malargüe, Province Mendoza, Argentina

Surface detector (SD)

- 1600 stations, 1.5 km grid, 3000 km^2, E > $10^{18.5}$ eV
- 61 stations, 750 m grid, 23.5 km^2, E > $10^{17.5}$ eV
- 19 stations, 433 m grid, E > 6×10^{16} eV

Fluorescence detector (FD)

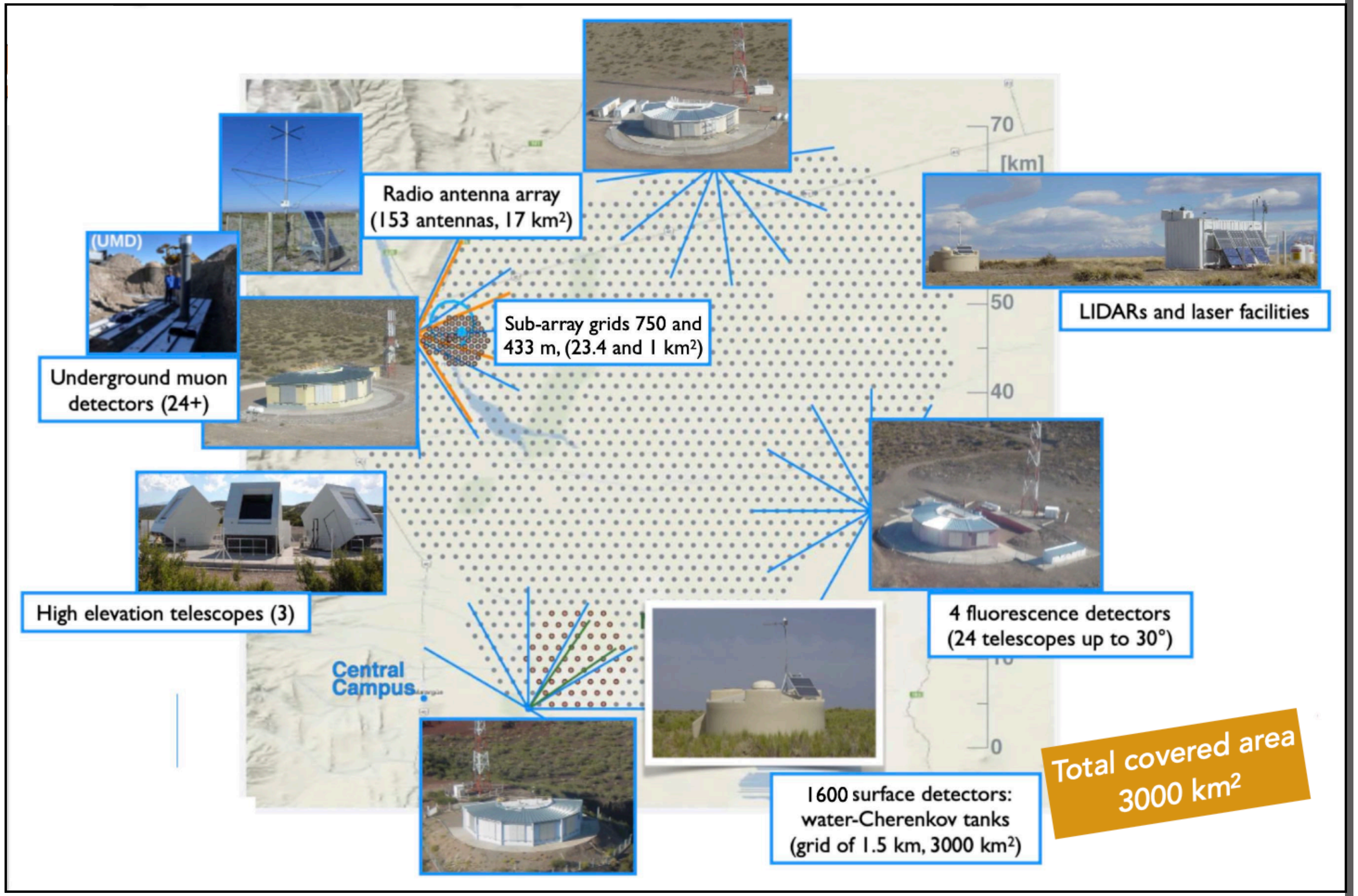
- 24 telescopes in 4 sites, FoV: 0-30^o, E > 10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60^o, E > 10^{17} eV

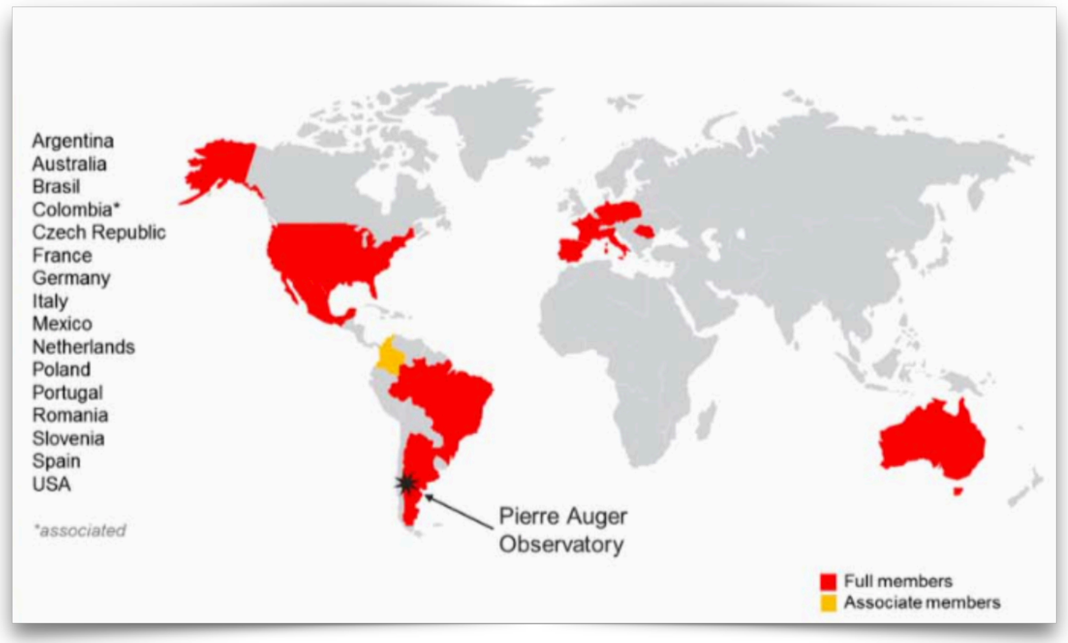
Auger Engineering Radio Array (AERA)

- 153 antennas, 17 km^2 array, E> 4×10^{18} eV

Underground muon detector

- 19(61) stations, 433(750)m array $10^{16.5}$ < E < 10^{19} eV



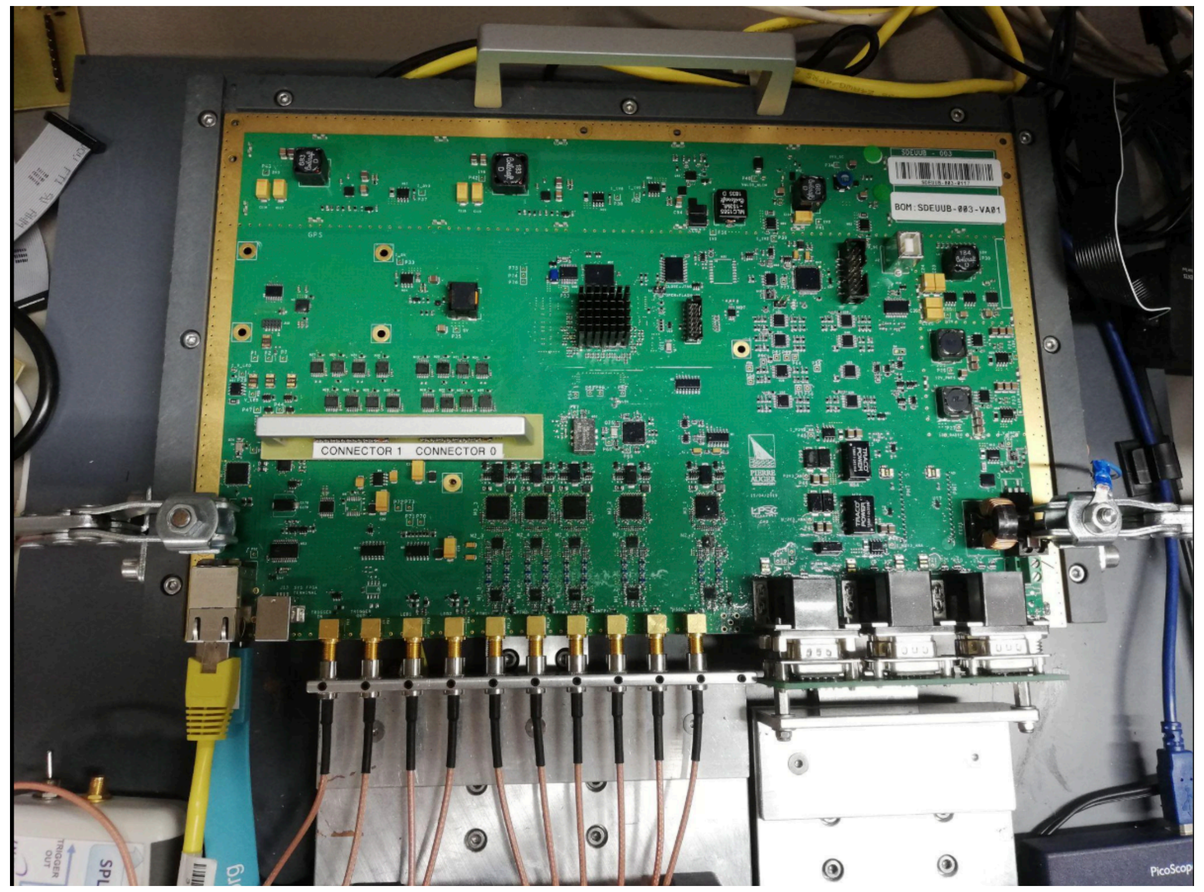


17 countries, more than 400 members

AugerPrime…

D. Schmidt, talk, Thu 21

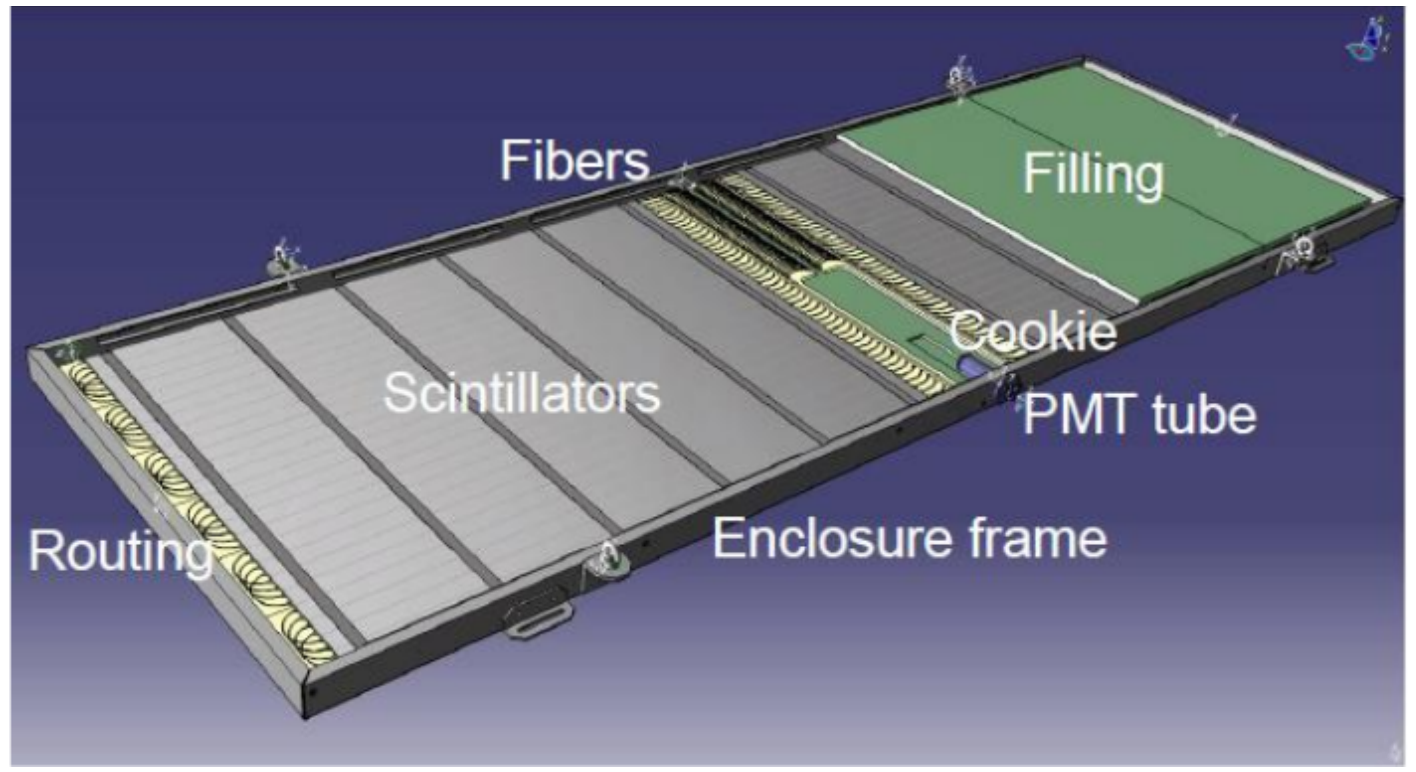
New electronics

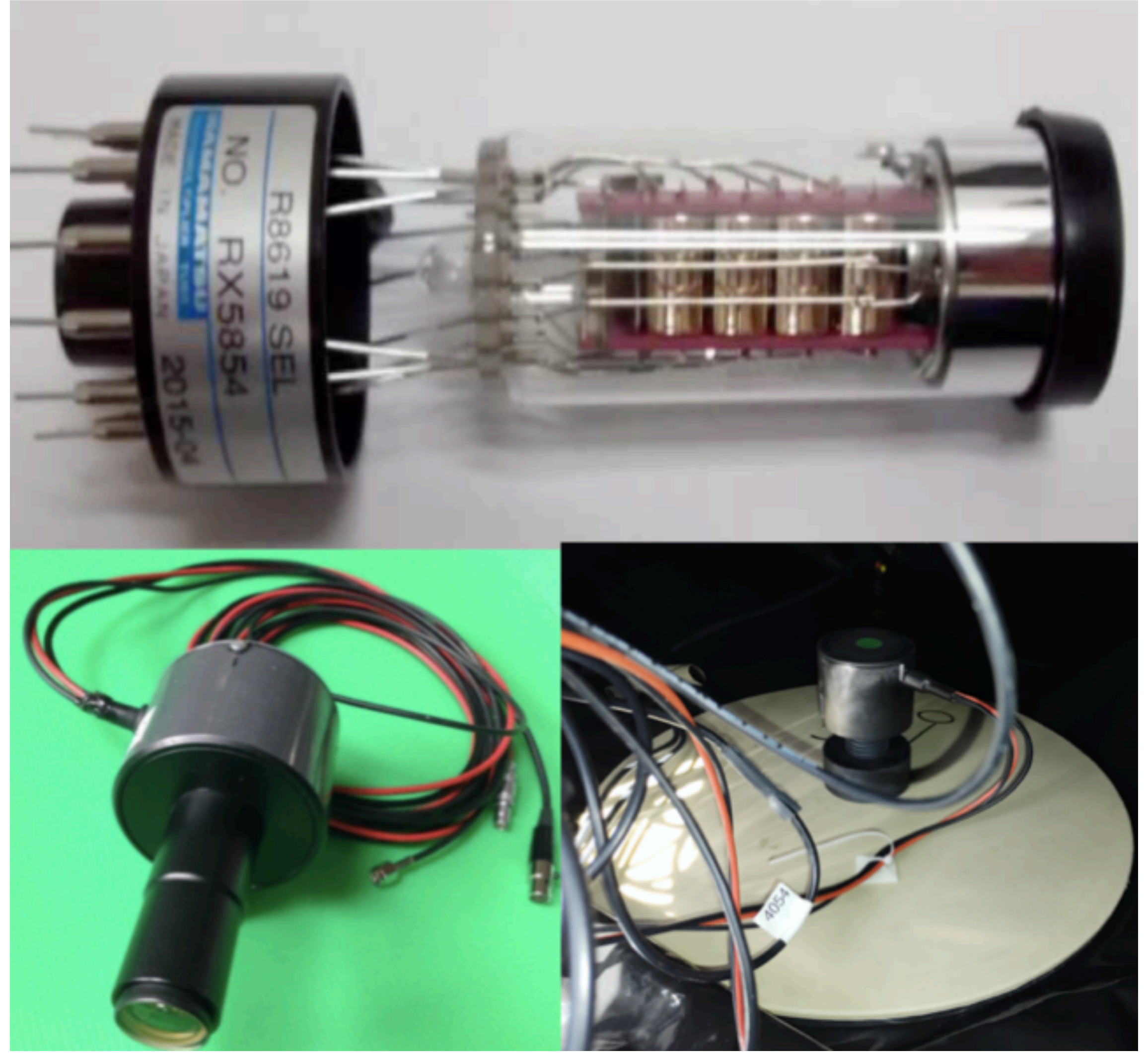


Underground muon detectors

Radio upgrade

Scintillators





High-dynamic range PMTs

Towards multi-hybrid observations of extensive air showers!

AugerPrime... is now!

Nov. 16th 2024: signature for the extension of the International Agreement to continue the operation of the Pierre Auger Observatory in the upcoming Phase II

Outline

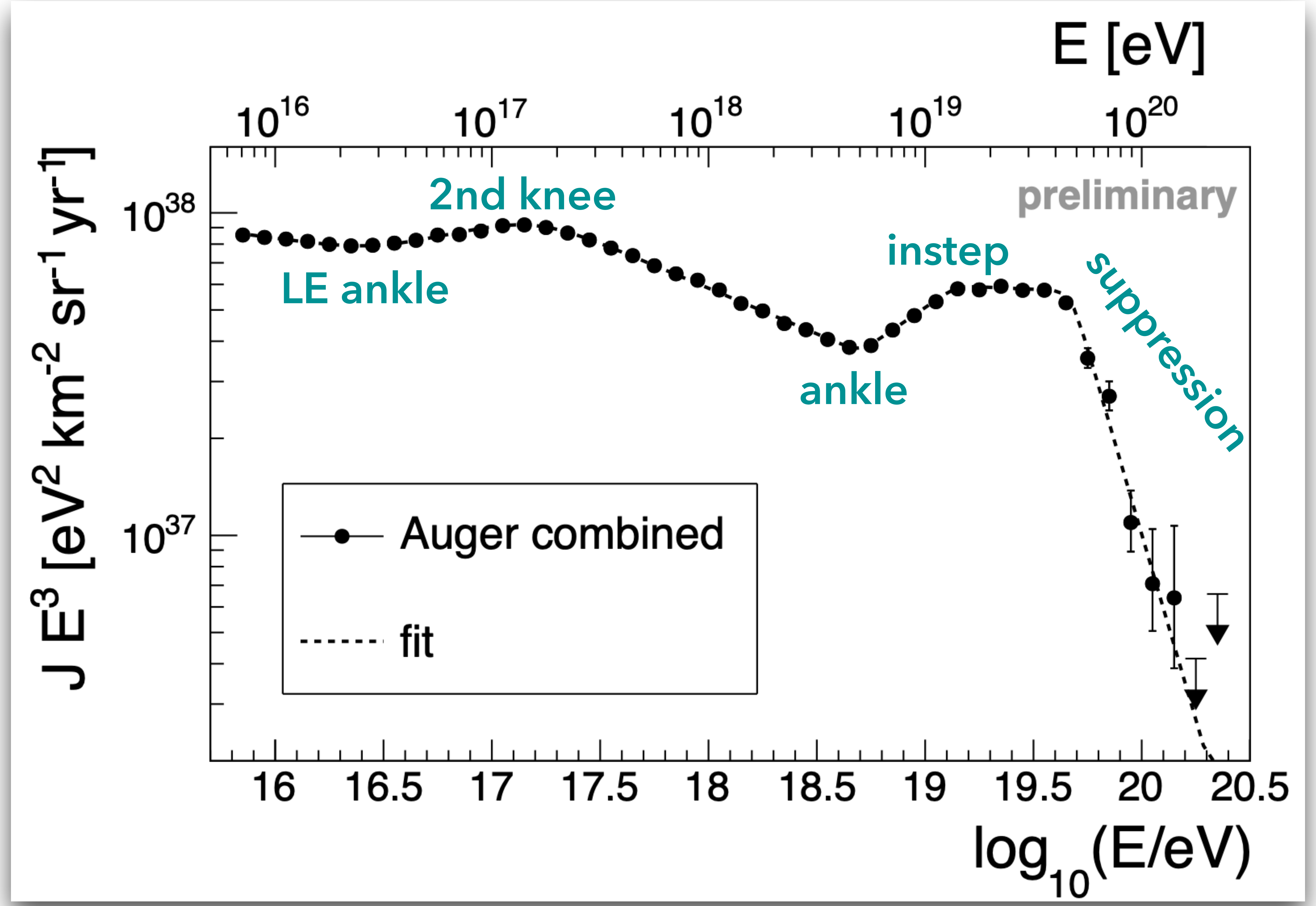
- Evidences in the data of the Pierre Auger Observatory will be discussed:
    - The shape of: energy spectrum, X_{max}, and dipole amplitude as a function of the energy
    - The non-observation of cosmogenic neutrinos and photons
- A consistent UHECR picture from these evidences can be derived

- Thanks to the increasing precision of data, new questions arise, related to:
    - Details of particle interactions at the highest energies
    - Influence of the magnetic fields in the understanding of UHECR characteristics
    - Characteristics of UHECR sources
    - Transition from Galactic to extragalactic CRs
    - Non-standard physics

A consistent picture of UHECRs with the Pierre Auger Observatory

The energy spectrum of UHECRs

D. Ravignani, talk, Wed 20



Combined spectrum (hybrid, SD-1500 vertical, SD-1500 inclined, SD-750, Cherenkov); SD-433 shown at ICRC23

- Evidences:
  - the energy spectrum shows several changes of slope
  - no dependence on the declination is found

$$J(E) = J_0 \left(\frac{E}{10^{16}\,\mathrm{eV}}\right)^{-\gamma_0} \prod_{i=0}^{4} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}}$$

$\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

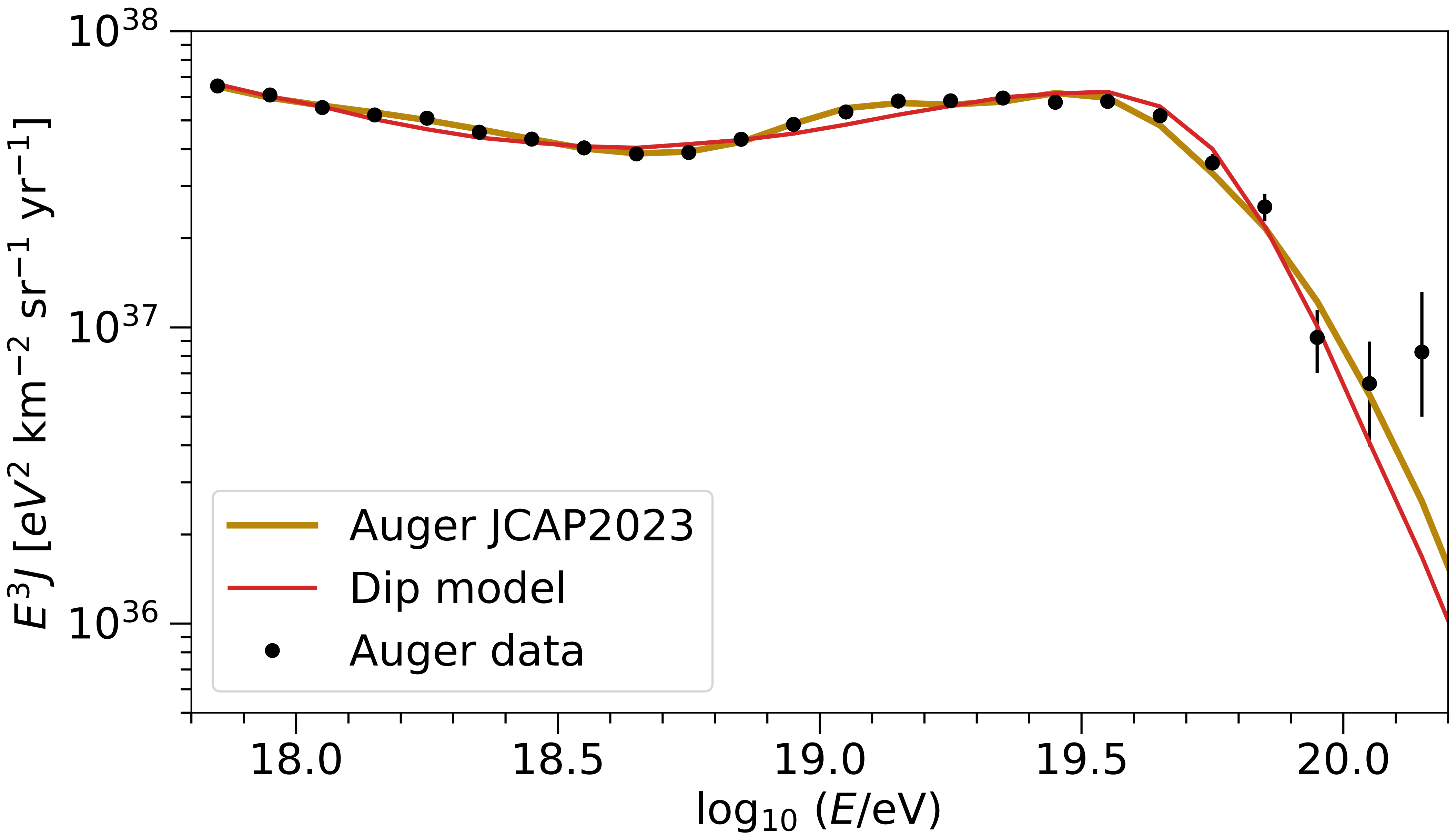
$J_0 = (8.34 \pm 0.04 \pm 3.40) \times 10^{-11}\ \mathrm{km^{-2} sr^{-1} yr^{-1} eV^{-1}}$

low energy ankle	$E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16}$ eV
2nd knee	$E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17}$ eV
ankle	$E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18}$ eV
instep	$E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19}$ eV
suppression	$E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19}$ eV

Auger Collab. ICRC21; PRD 102 & PRL 125 (2020); Eur Phys J C81 (2021)

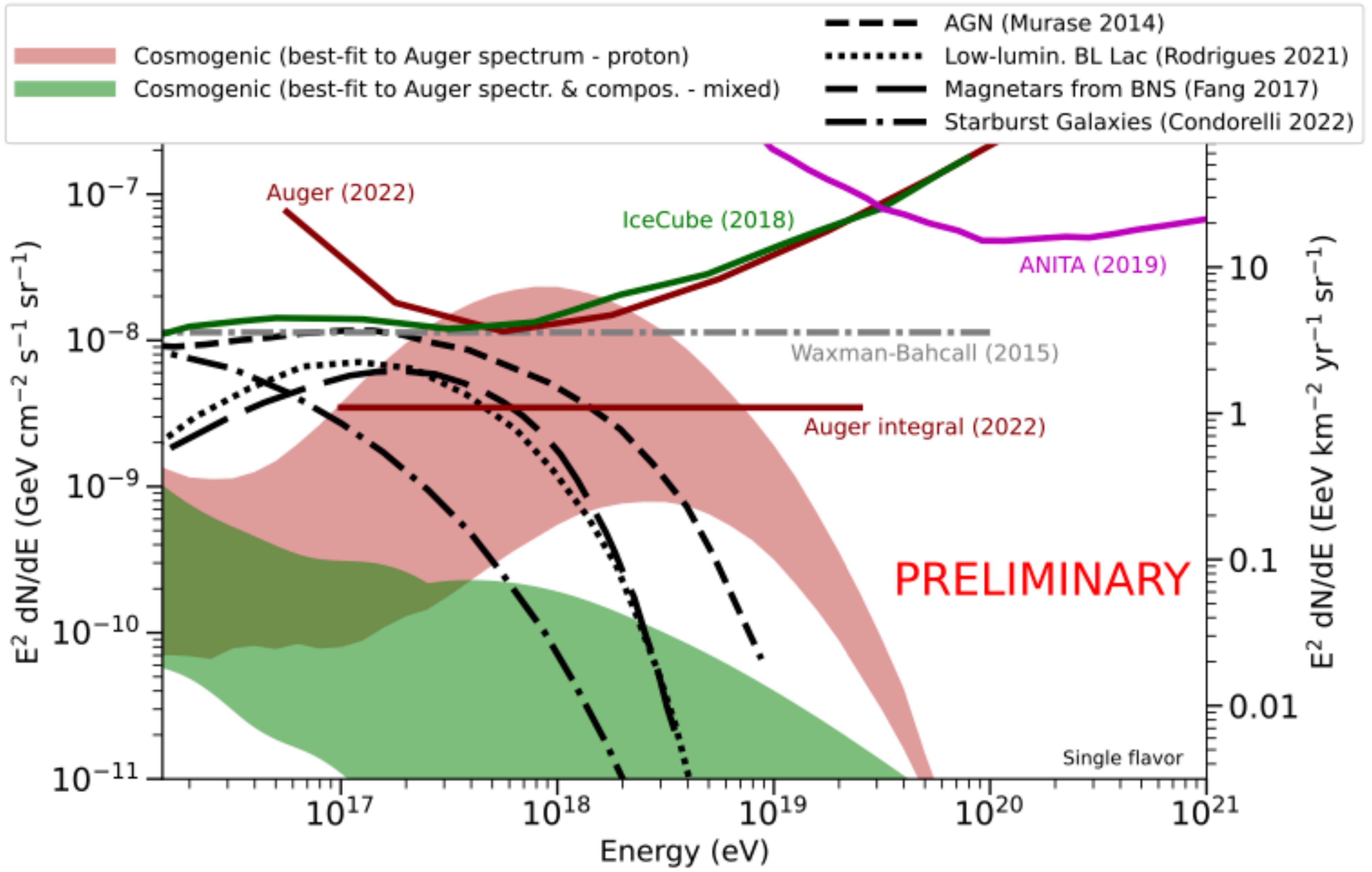
The energy spectrum of UHECRs

Expected cosmic-ray energy spectrum with propagated protons
-> **dip model**, see Berezinsky et al. Phys.Rev.D 74 (2006)

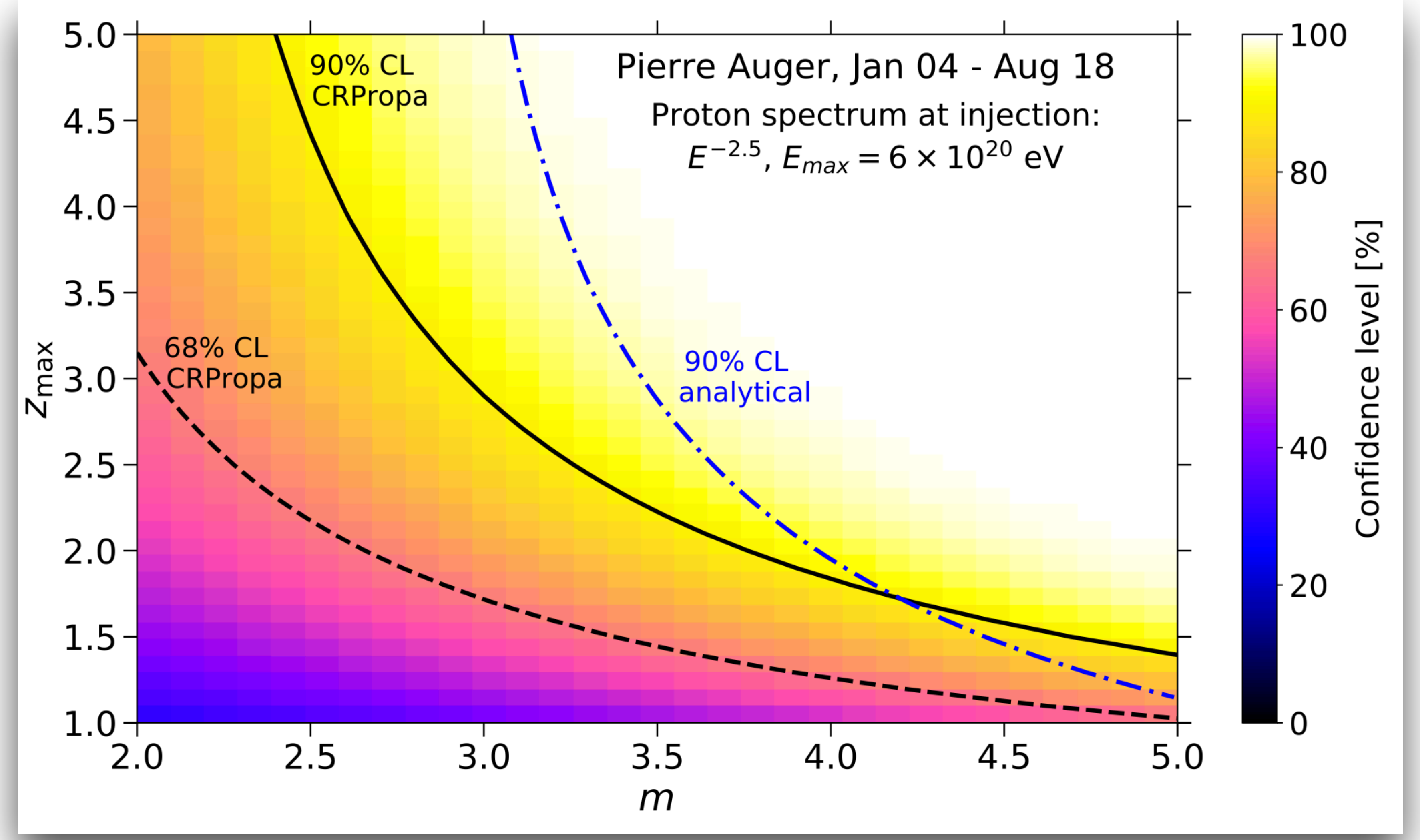


- The expected cosmic-ray energy spectrum with propagated protons does not properly reproduce the data
  - See Auger Collab. JCAP 04 (2017) 038; JCAP 05 (2023) 024; JCAP 01 (2024) 022; JCAP 07 (2024) 094 for alternative scenarios
- The associated cosmogenic neutrinos would violate the limit

Auger Collab. JCAP 10 (2019); ICRC2023



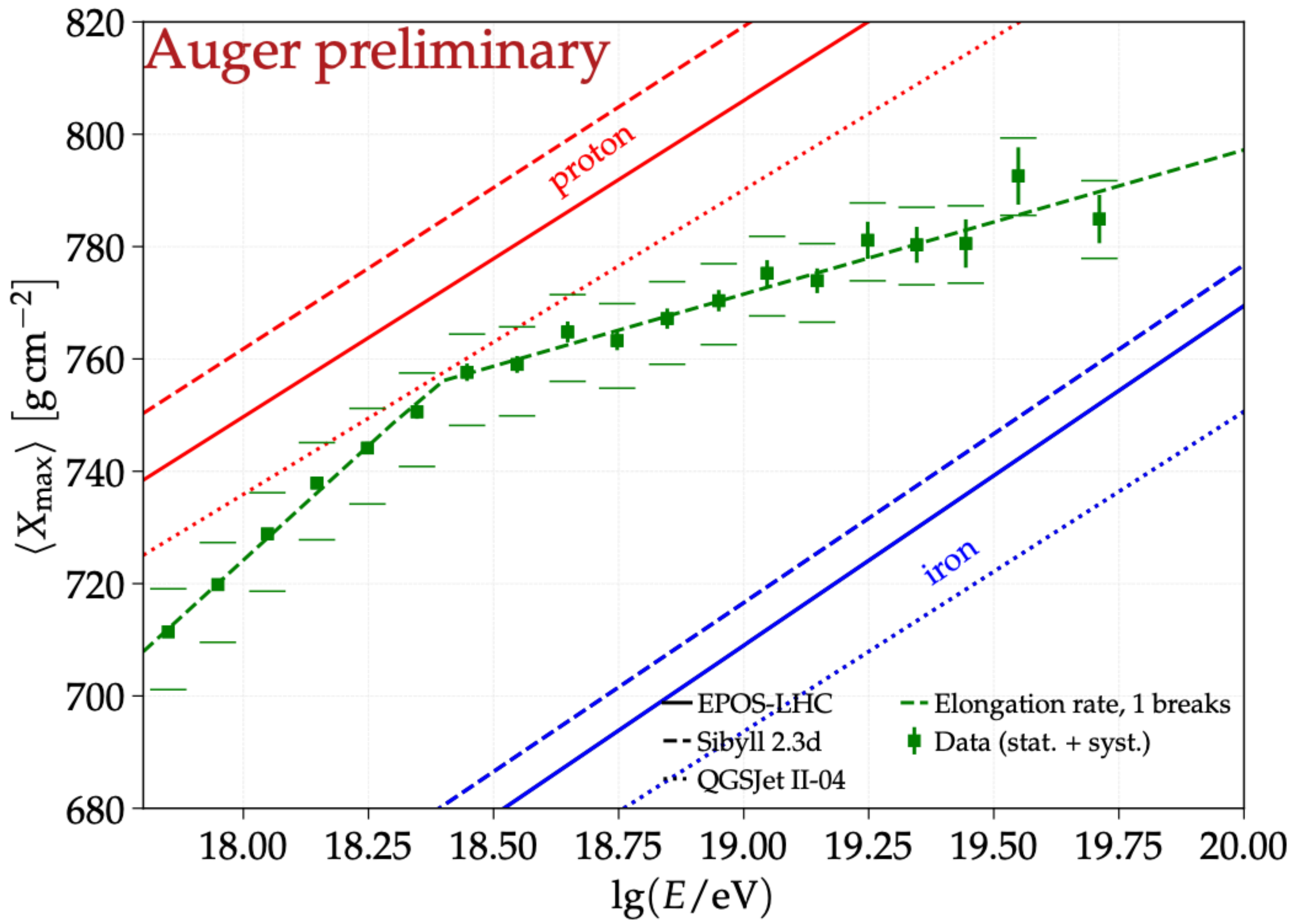
J. Alvarez-Muniz, talk, Tue 19

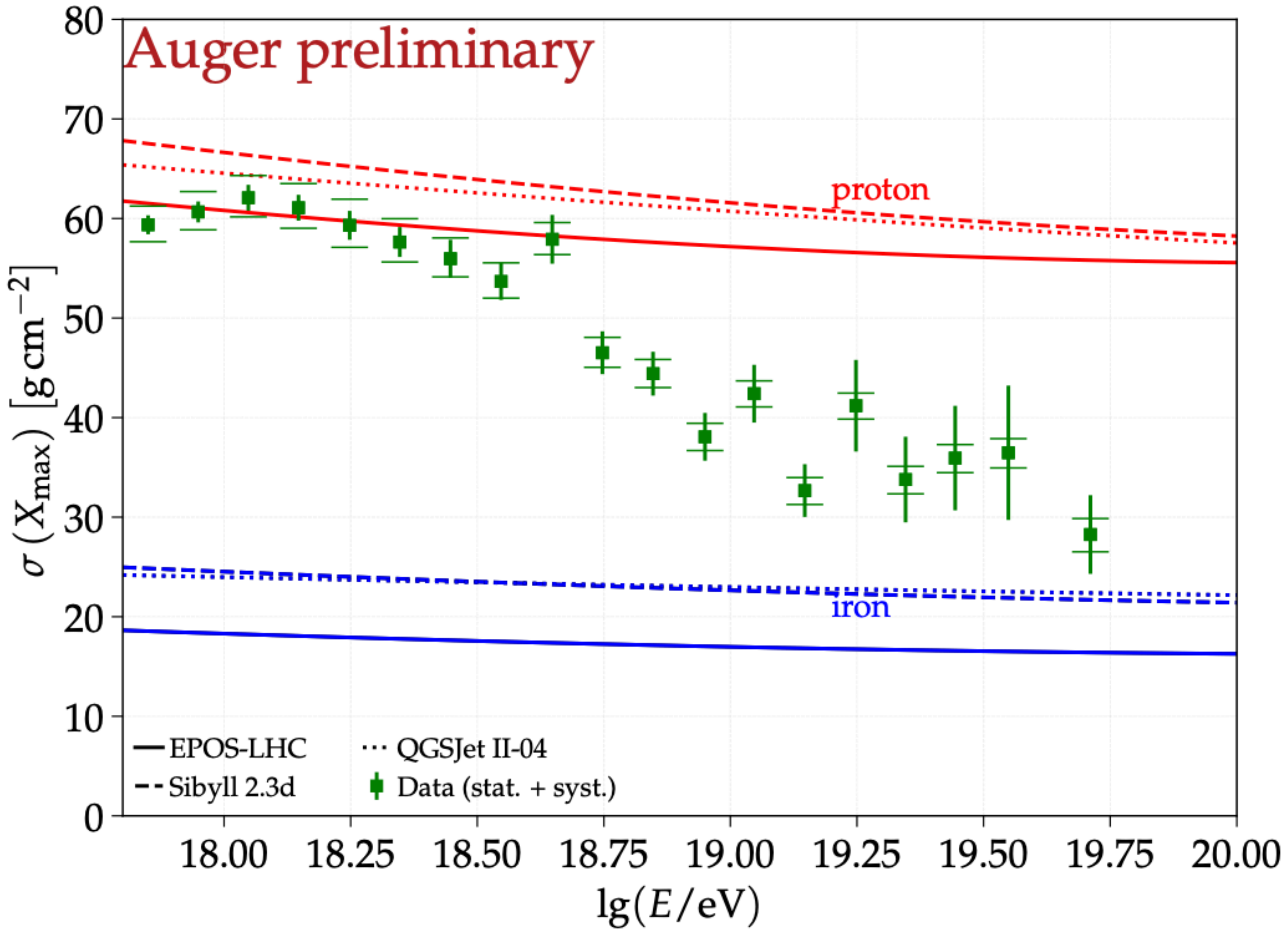


The mass composition of UHECRs

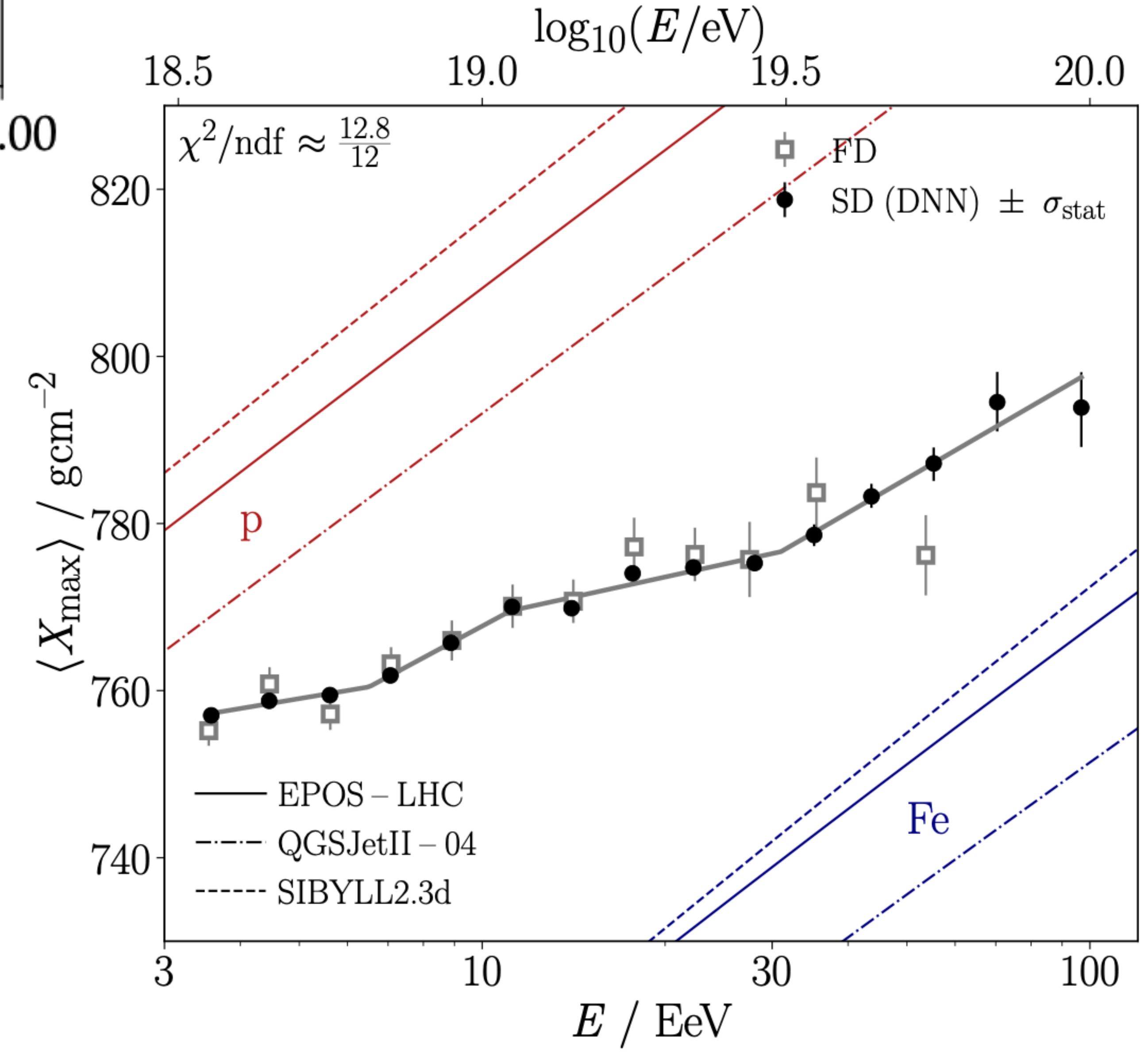
T. Fitoussi, talk, Wed. 20 A. Yuskhov talk, Wed. 20

Auger Collab. PDG 90 (2014), ICRC23





Auger Collab. arxiv:2406.06319 & 2406.06315, accepted in PRD & PRL, ICRC23



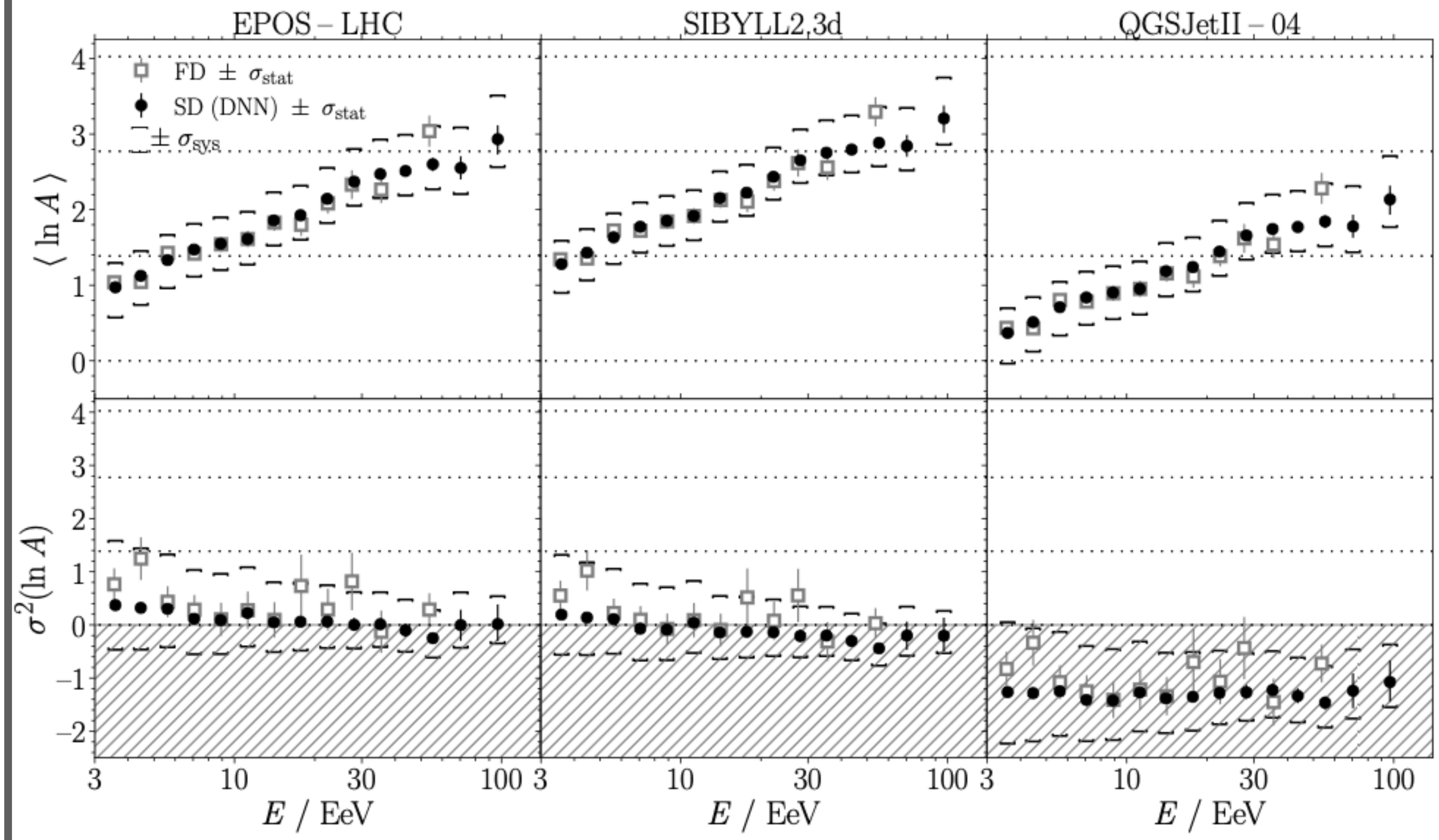
- Evidences:
  - <X_{max}> increases until $10^{18.4}$ eV and decreases afterwards; $\sigma(X_{max})$ shows a trend towards heavier (and less mixed) composition above $10^{18.6}$ eV
  - SD <X_{max}> (DNN), absence of breaks can be rejected at a level of 4.6 σ

The mass composition of UHECRs

T. Fitoussi, talk, Wed. 20 | A. Yuskhov talk, Wed. 20

X_{max} converted to average and variance of lnA

Auger Collab. *JCAP* 02 (2013)



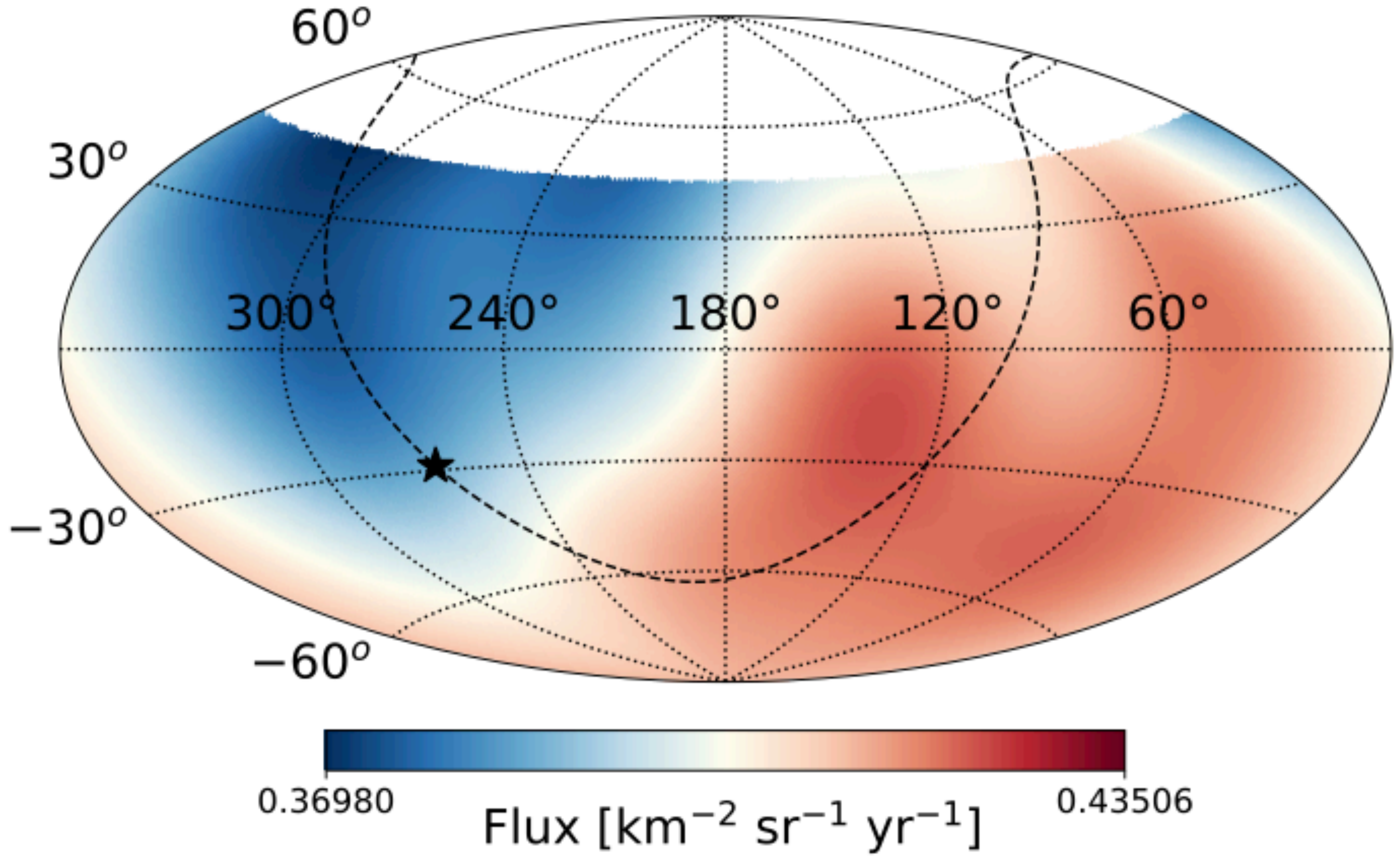
- Inferring the mass composition depends on the hadronic interaction model
- $\sigma^2<0$ for QGSJet-II.04
  - it is not recommended to be used for inferring the mass composition
  - X_{max} shift is allowed by data (see Auger Collab. Phys.Rev.D 109 (2024)), which could alleviate the tension with with QGSJet-II.04 (with the additional cost of predicting heavier mass composition overall)

Auger Collab. arxiv:2406.06319 & 2406.06315, accepted in PRD & PRL

The arrival directions of UHECRs

E. Roulet, talk, Mon 18

A. Di Matteo, talk, Mon 18

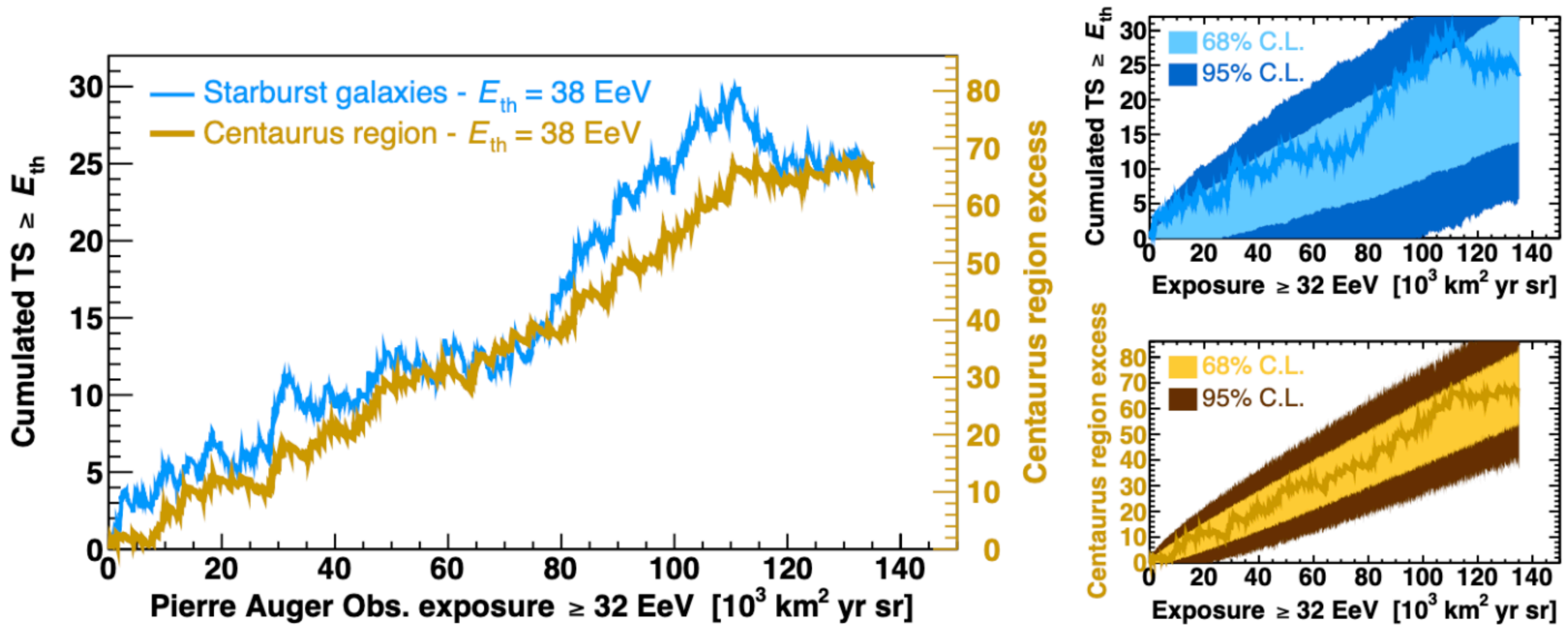


Flux above 8 EeV (equatorial coordinates)

- Evidence:
    - Dipolar anisotropy: for E ≥ 8 EeV, the significance is at 6.8 σ; in the 8-16 EeV bin, the significance is at 5.7 σ; direction 113° away from the Galactic center -> <u>extragalactic origin of UHECRs above 8 EeV</u>

Auger Collab. Science 357 (2017);
arxiv:2408.05292, submitted to ApJ

- Evidences:
    - All-sky search for overdensities -> **Centaurus region**: 4.0 σ significance at E_{thr}=38 EeV at ψ=27°
    - Catalog-based search -> highest significance for **starburst galaxies**

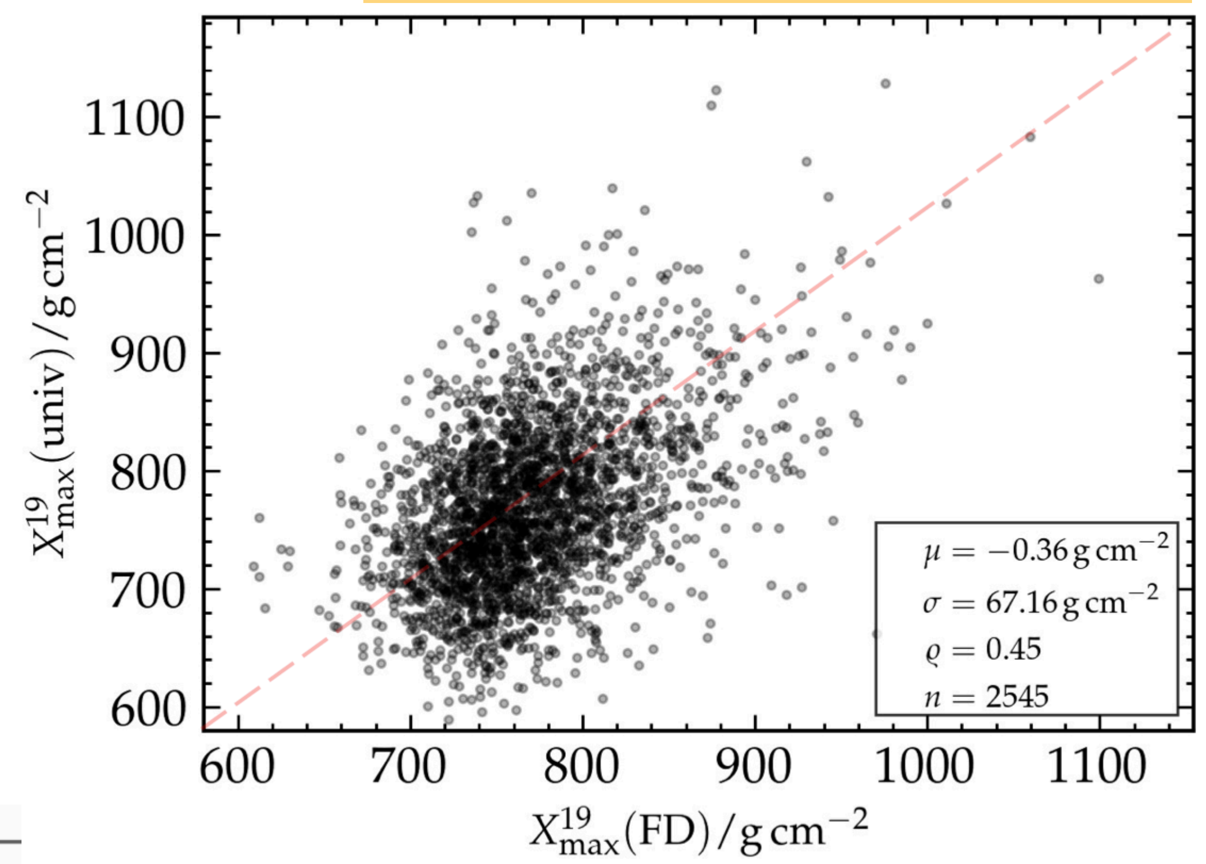


Auger Collab. ApJ 935 (2022)

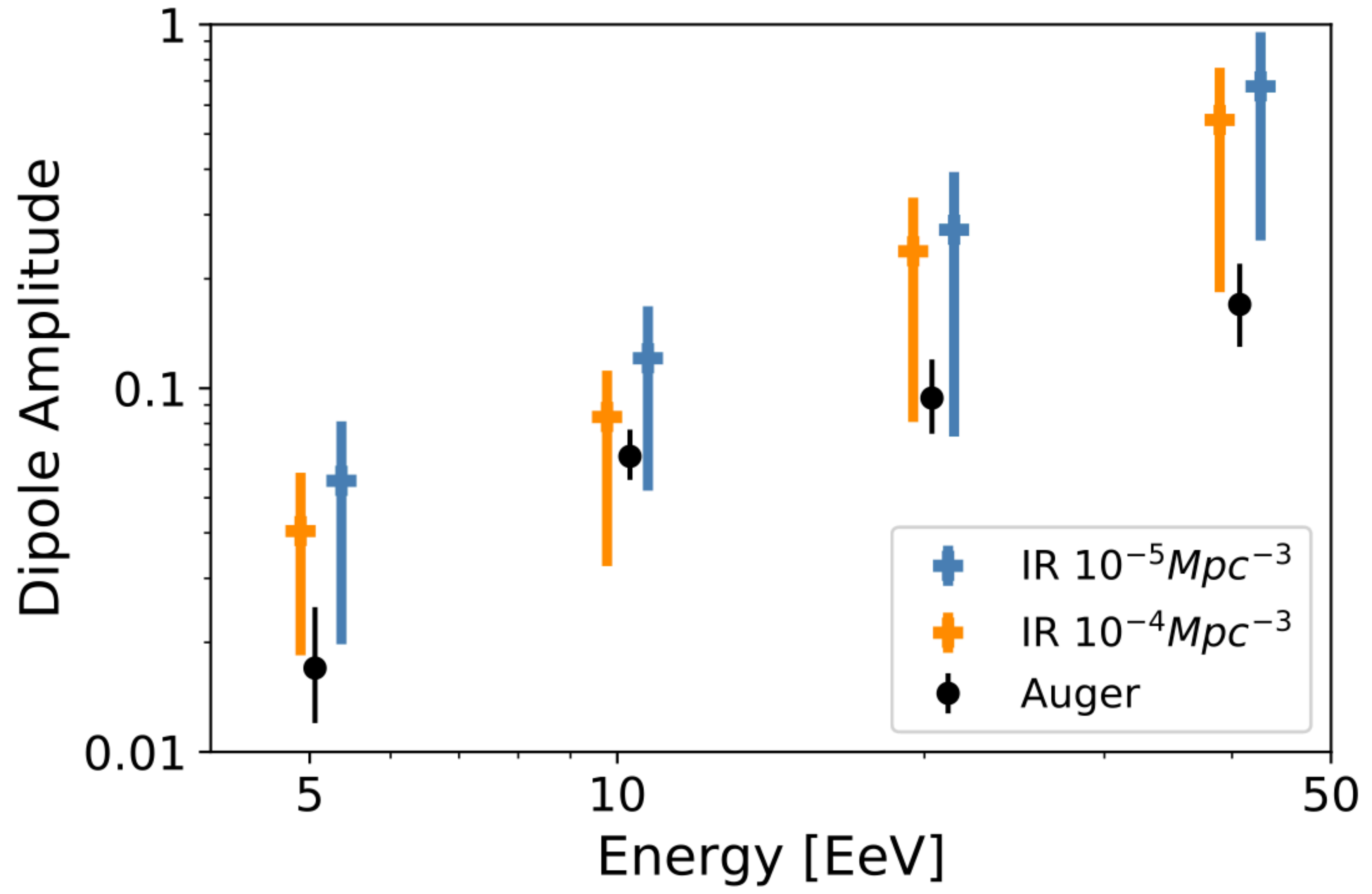
The arrival directions of UHECRs

- Focusing on the dipole: the dipole amplitude increases with energy, possibly due
  - to the larger relative contribution from the nearby sources for increasing energies, whose distribution is more inhomogeneous, and
  - to the growth of mean primary mass of the particles

M. Stadelmaier, poster

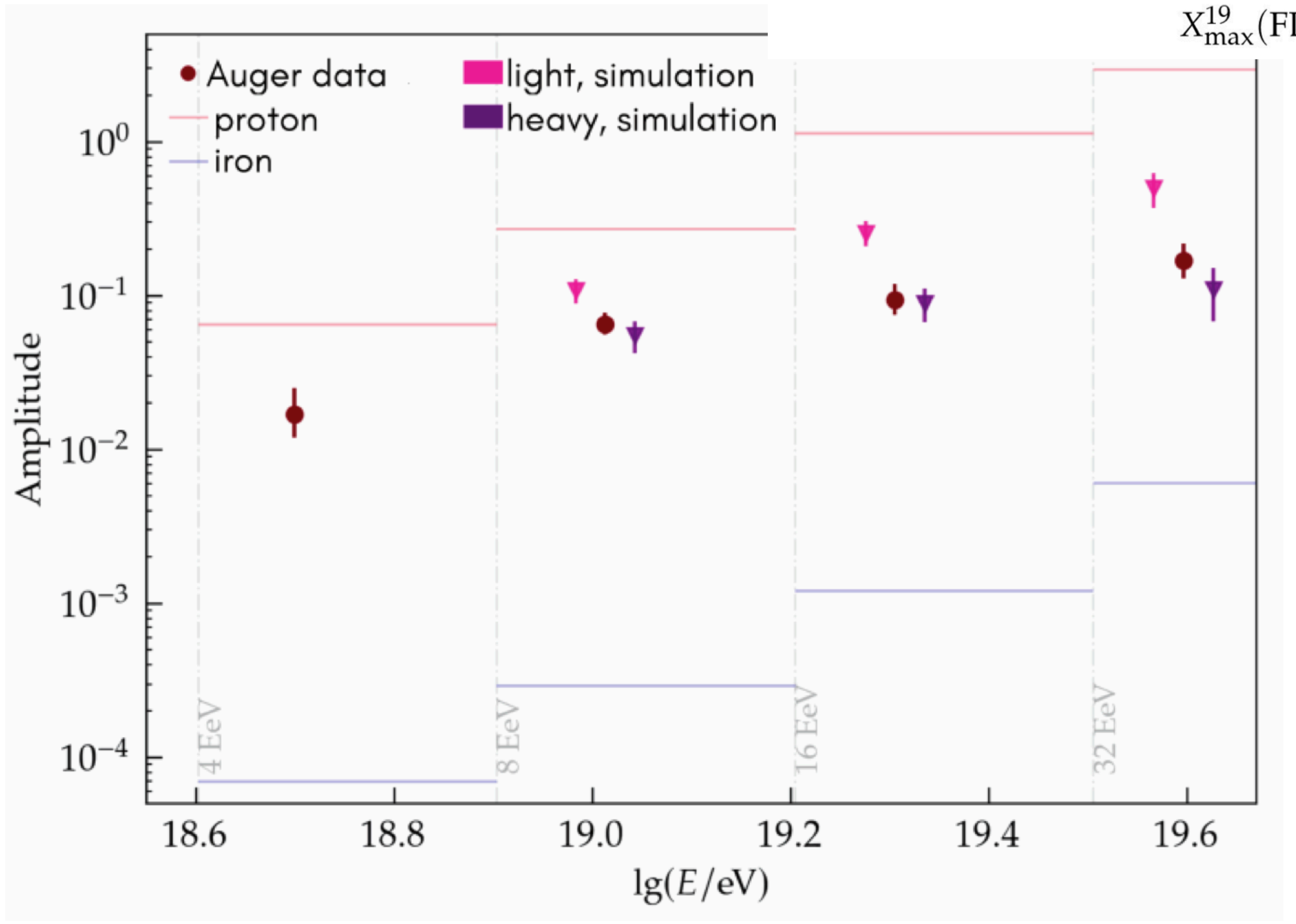


E. Roulet, talk, Mon 18



Comparison to expectations for astrophysical scenarios obtained from spectrum + composition interpretation -> if UHECR have a non-protonic mass composition, the dipole is compatible with the matter distribution of the large scale structure

E. E. Martins, poster



Defining light and heavy populations, through a mass estimator with universality -> potential to observe a separation in total amplitude in mass-selected subsets of data (probed on simulations)

Consistent UHECR picture and new scenarios suggested by data

- UHECR data show features increasingly significant and independent of models
  - Several changes of the spectral index of the measured energy spectrum are firmly established, including the recently observed “instep”
  - The absence of breaks $<X_{max}>$ can be rejected
  - The dipole signal is directed outside the Galactic center, and its amplitude increases with energy
- The current precision of data challenges basic astrophysical scenarios, as the UHECR-proton paradigm

- Which new scenarios are suggested by the UHECR data? Unexpected aspects of UHECR data regard:
  - Details of particle interactions at the highest energies
  - Influence of the magnetic fields in the understanding of UHECR characteristics
  - Characteristics of UHECR sources
  - Transition from Galactic to extragalactic CRs
  - Non-standard physics

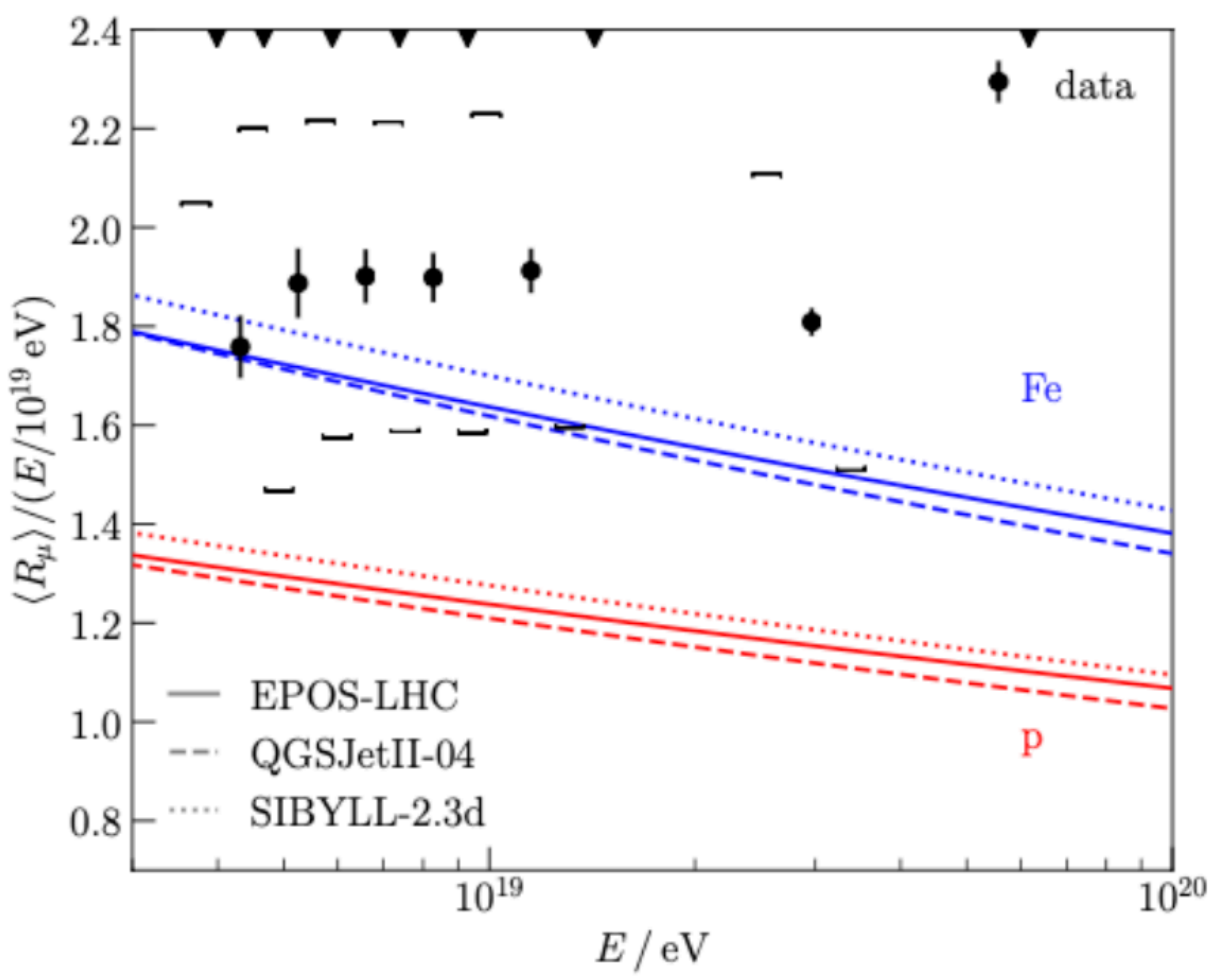
(Some of the) new questions arising from data

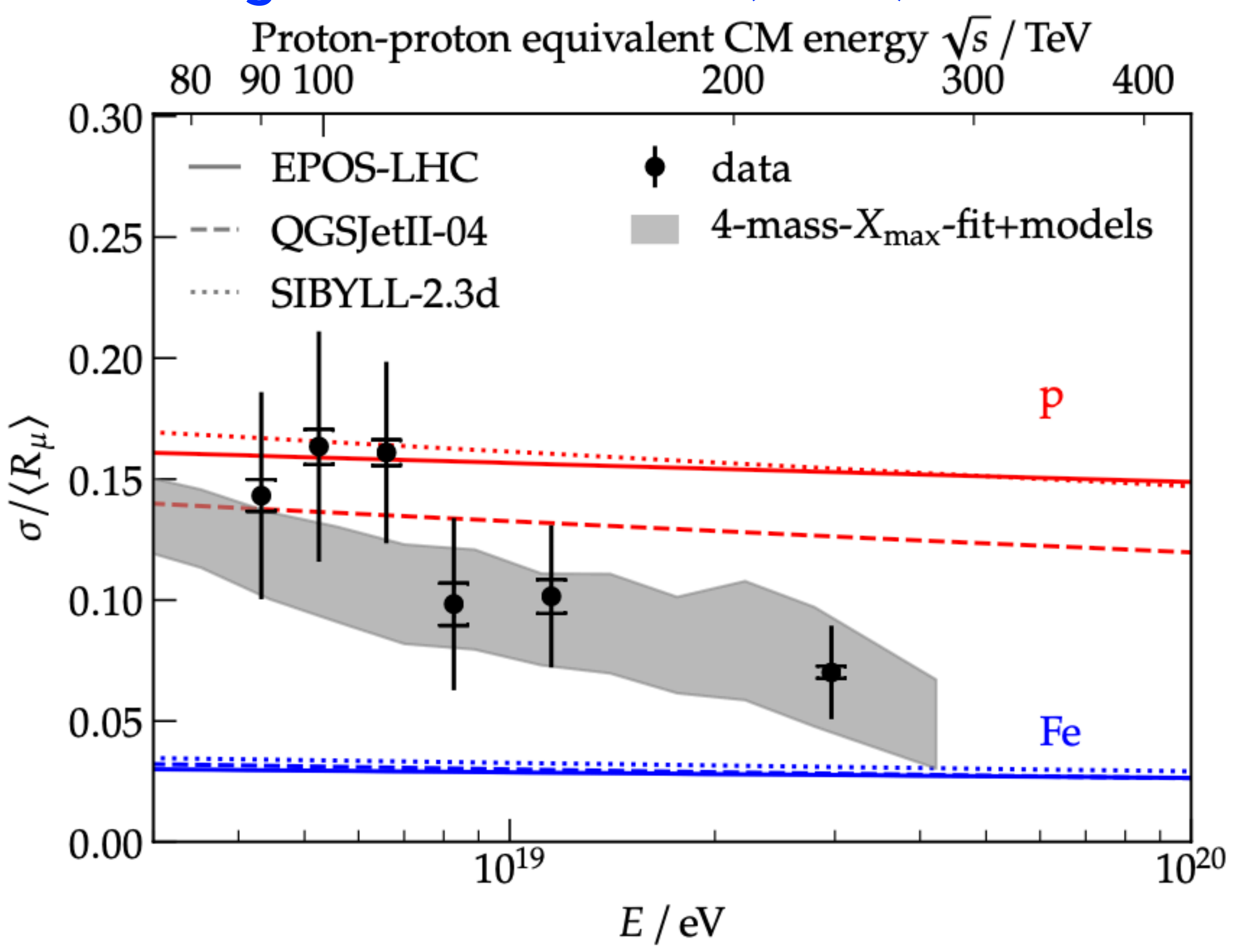
Particle interactions

J. Vicha, talk, Wed 20

O. Tkachenko, talk, Wed 20

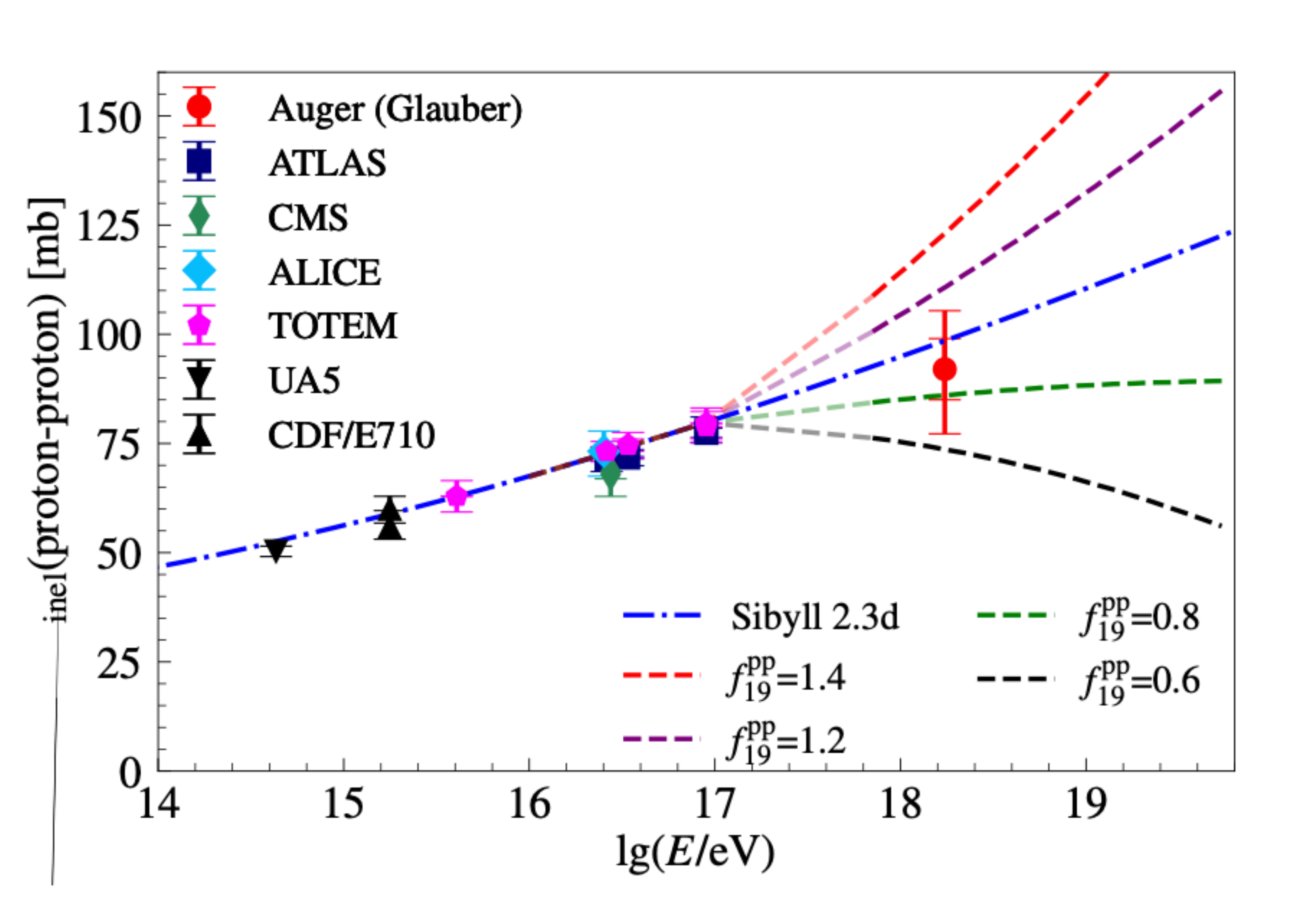
Auger Collab. PRL 126 (2021)





- A **deficit in the number of muons in simulations** with respect to measurements is observed
- The fluctuations of the number of muons are in good agreement with model predictions
- Is this due
  - to a small effect accumulating over many generations?
  - to a modification of the first interaction that changes the number of muons without changing the fluctuations?

- How to improve the **measurement of the pp cross section**?
  - simultaneous estimate of the cosmic-ray mass composition and the proton-proton interaction cross section

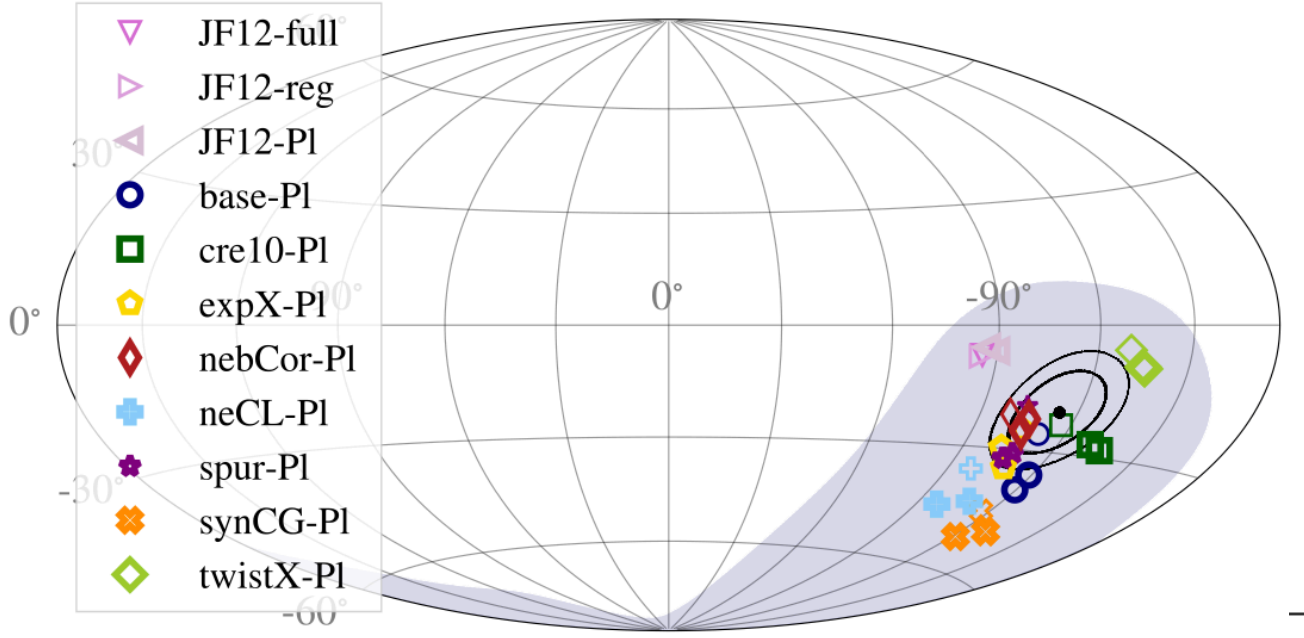


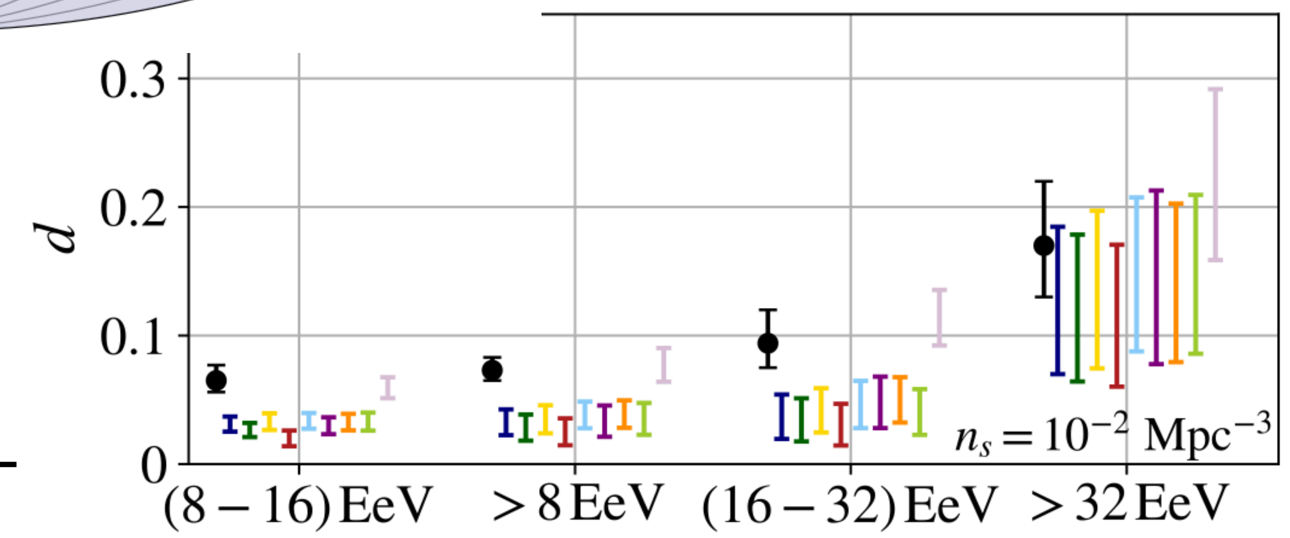
Auger Collab. ICRC23

Magnetic fields and source classes

UHECR anisotropy and magnetic field properties

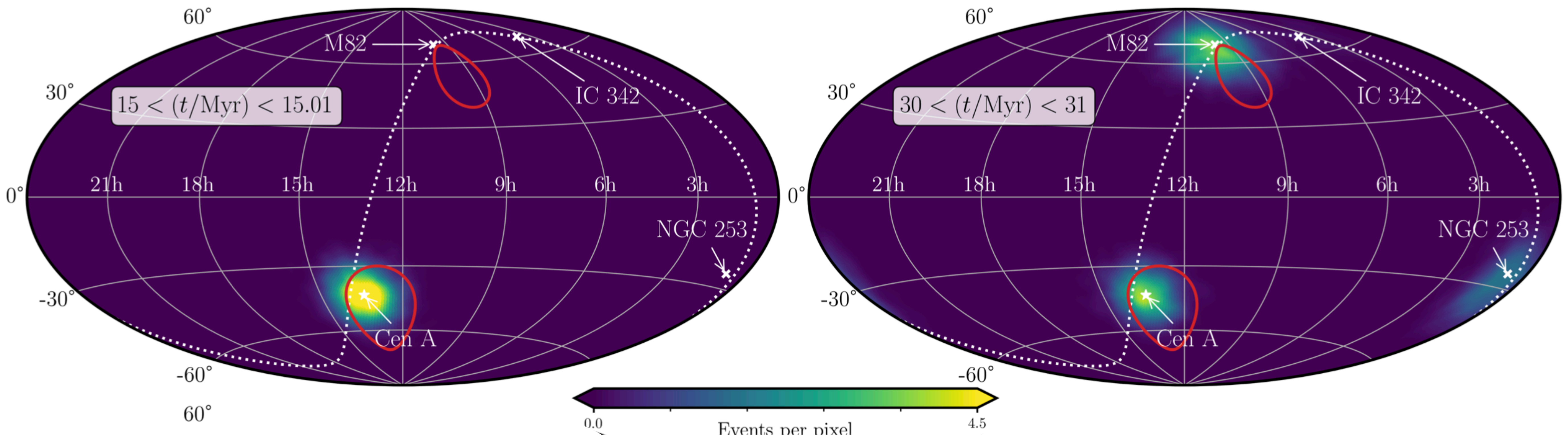
- Dipole measurements:
  - The dipole direction and amplitude are sensitive to the Galactic magnetic field model (Bister, Farrar & Unger, ApJL 975 (2024); Ding, Globus & Farrar ApJ 913 (2021)) -> <u>**tool to probe the Galactic magnetic field models and the source distribution** (and hadronic interaction models, due to their impact in the charge assignment)</u>?



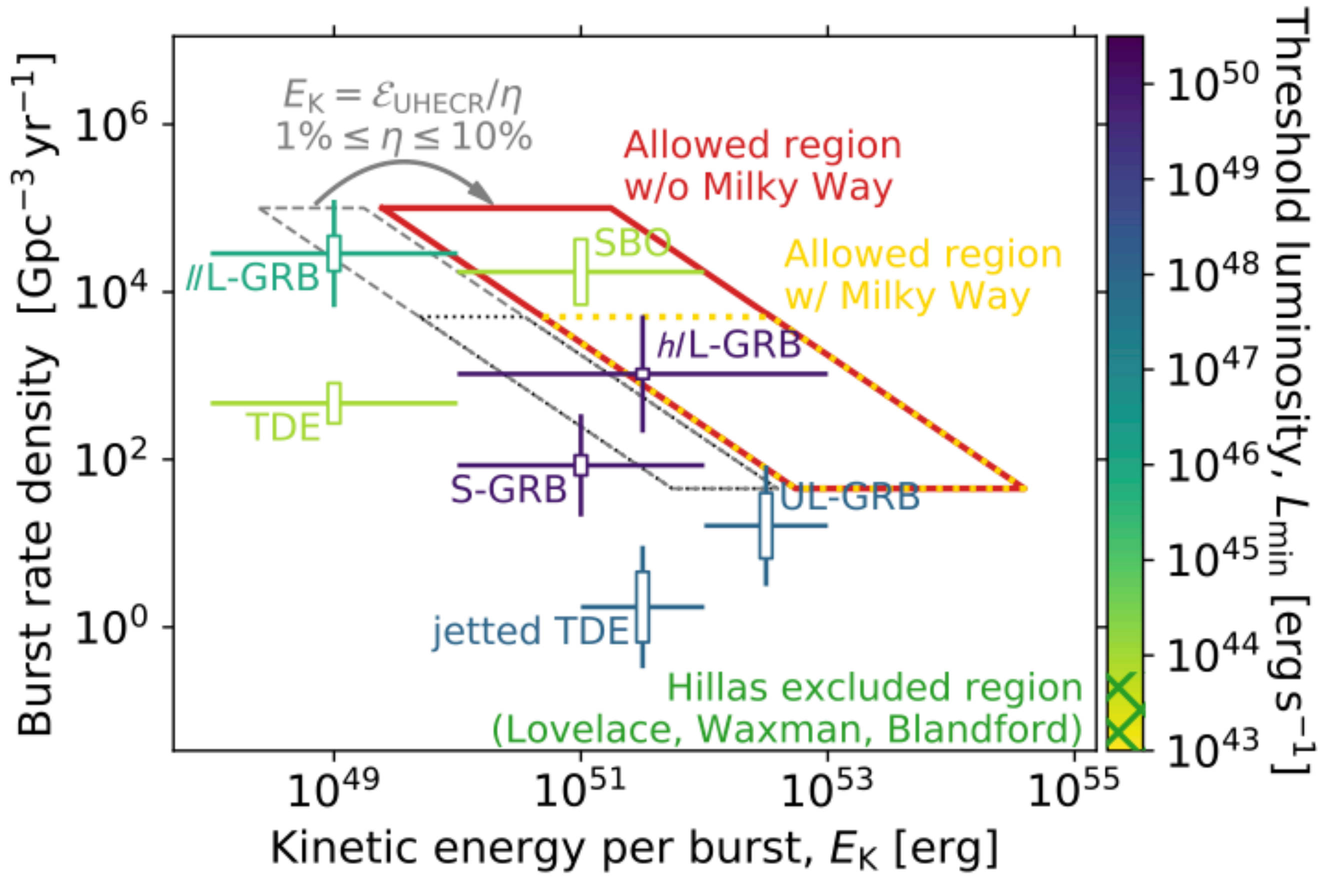


UHECR sources: persistent vs transient

- Auger Collab. ApJ 935 (2022): the starburst catalog enables the identification of the most significant deviation from isotropy. <u>Can this be reconciled with magnetic deflections?</u>
  - Are starburst galaxies scattering UHECRs from a past burst from the jetted active galactic nucleus of Centaurus A? Bell & Matthews, MNRAS 511 (2022)



- Can we constrain the bursting activity of a source, taking into account the spread in time due to magnetic deflections? How does considering a transient nature of UHECR sources complement the determination of the constraint on the production rate of UHECRs? Marafico, Biteau, Condorelli, Deligny & Bregeon, ApJ 972 (2024)

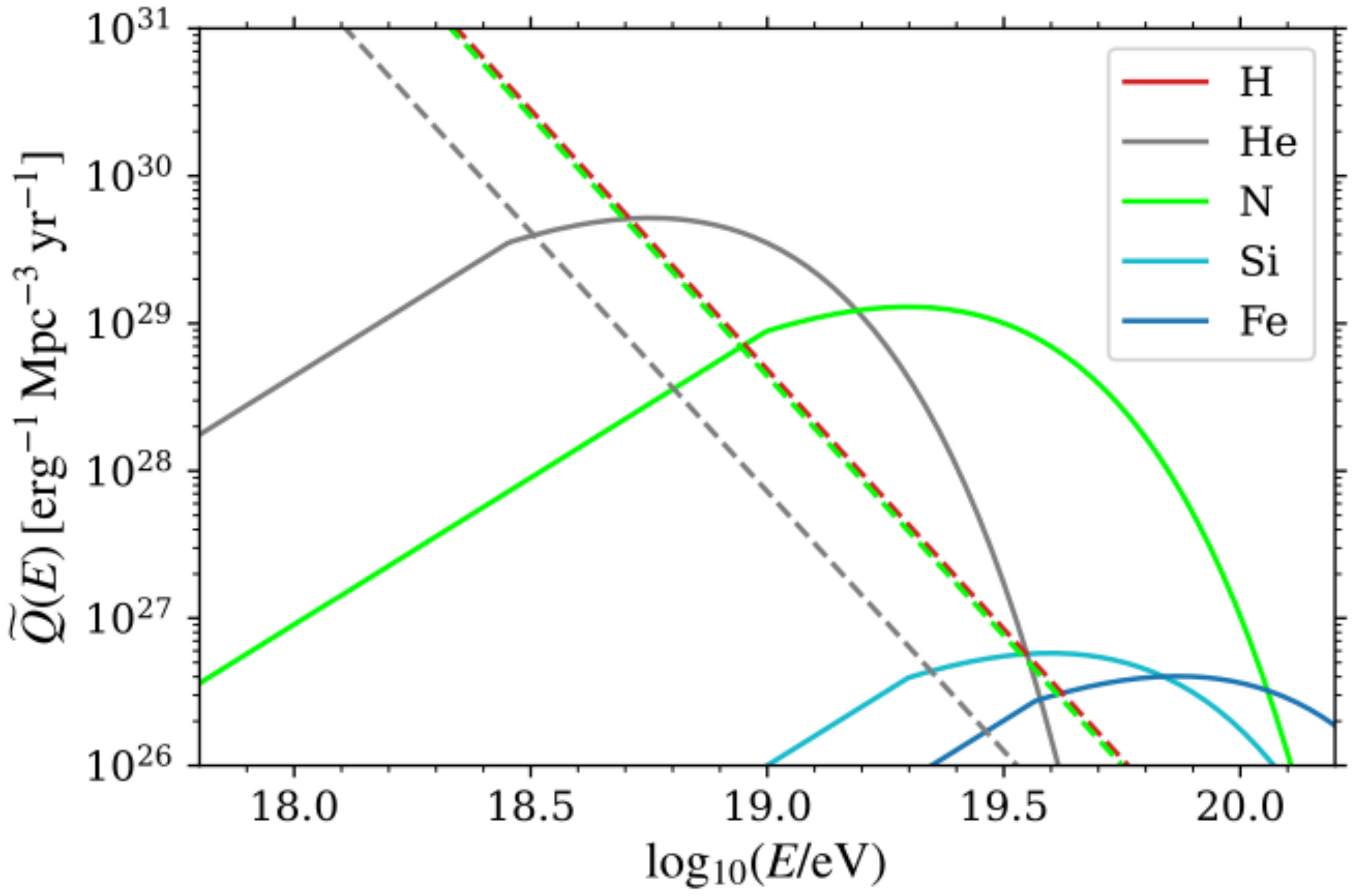


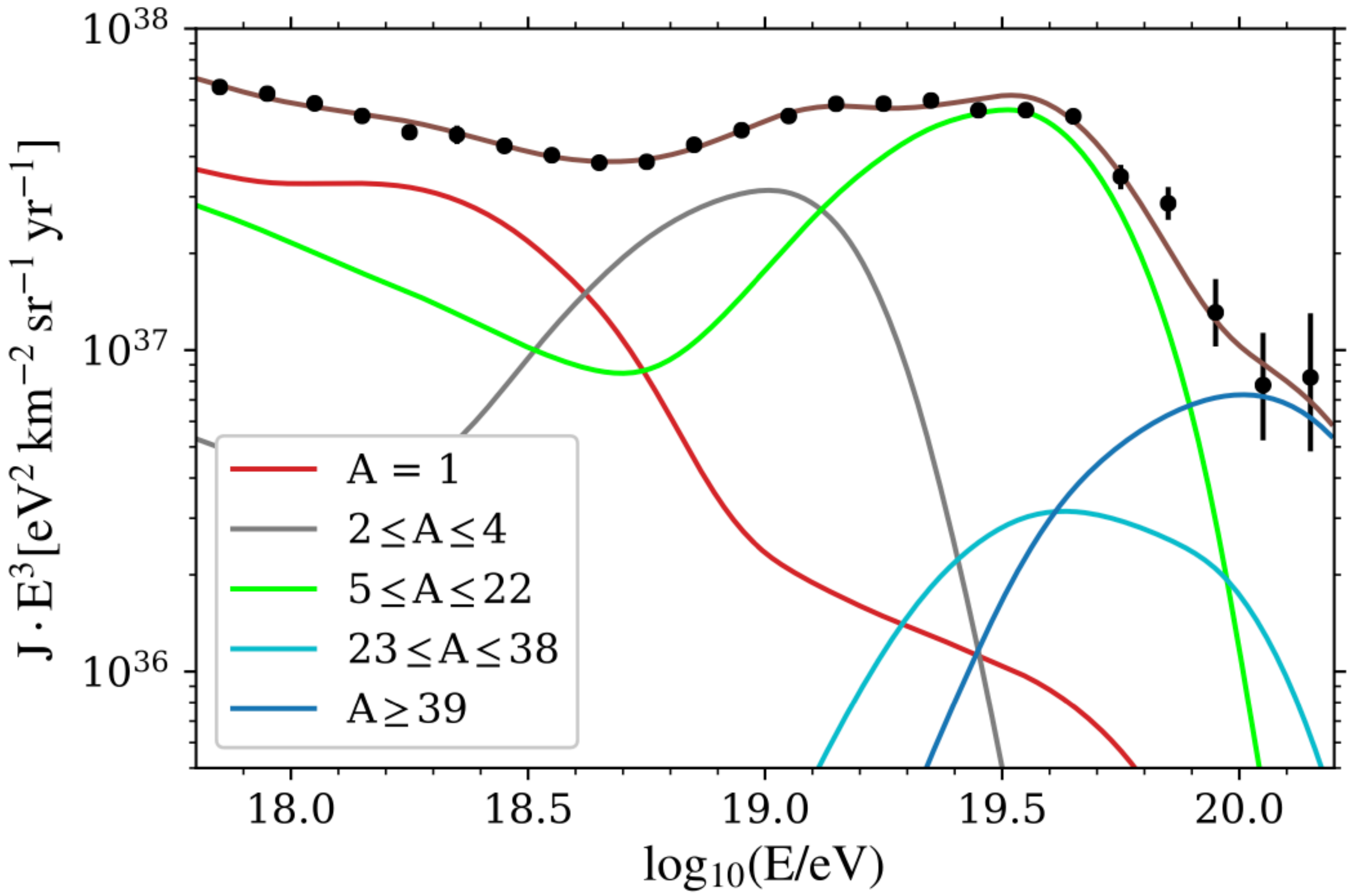
Characteristics of UHECR sources

J. M. Gonzalez, talk, Mon 18

- evidence of several nuclear species at the top of atmosphere -> which sources can be responsible of accelerating different nuclei?
  - **Understanding the heaviest nuclear component** at the highest energies -> can probe the nature of the accelerator
  - **Determining the amount of protons** -> can contribute to constrain the characteristics of the UHECR source distribution in redshift
- **if interpreted in terms of astrophysical scenarios**, a limited mixing of spectra of different nuclear species at HE is required by data, imposing hard spectra + low rigidity cutoff at the escape of UHECR sources. Consequences in terms of astrophysical sources are:
  - limited source-to-source variations (see Ehlert, Oikonomou & Unger Phys.Rev.D 107 (2023))
  - limited power for acceleration at the sources
    - To which extent the **suppression** of the UHECR spectrum is due to acceleration power and to propagation effects?
  - very hard spectral index
    - effect of UHECR confinement in the source environment? (see Unger, Farrar & Anchordoqui Phys.Rev.D 92 (2015))
    - effect of extragalactic magnetic fields? (see Auger Collab. JCAP 07 (2024) 094)

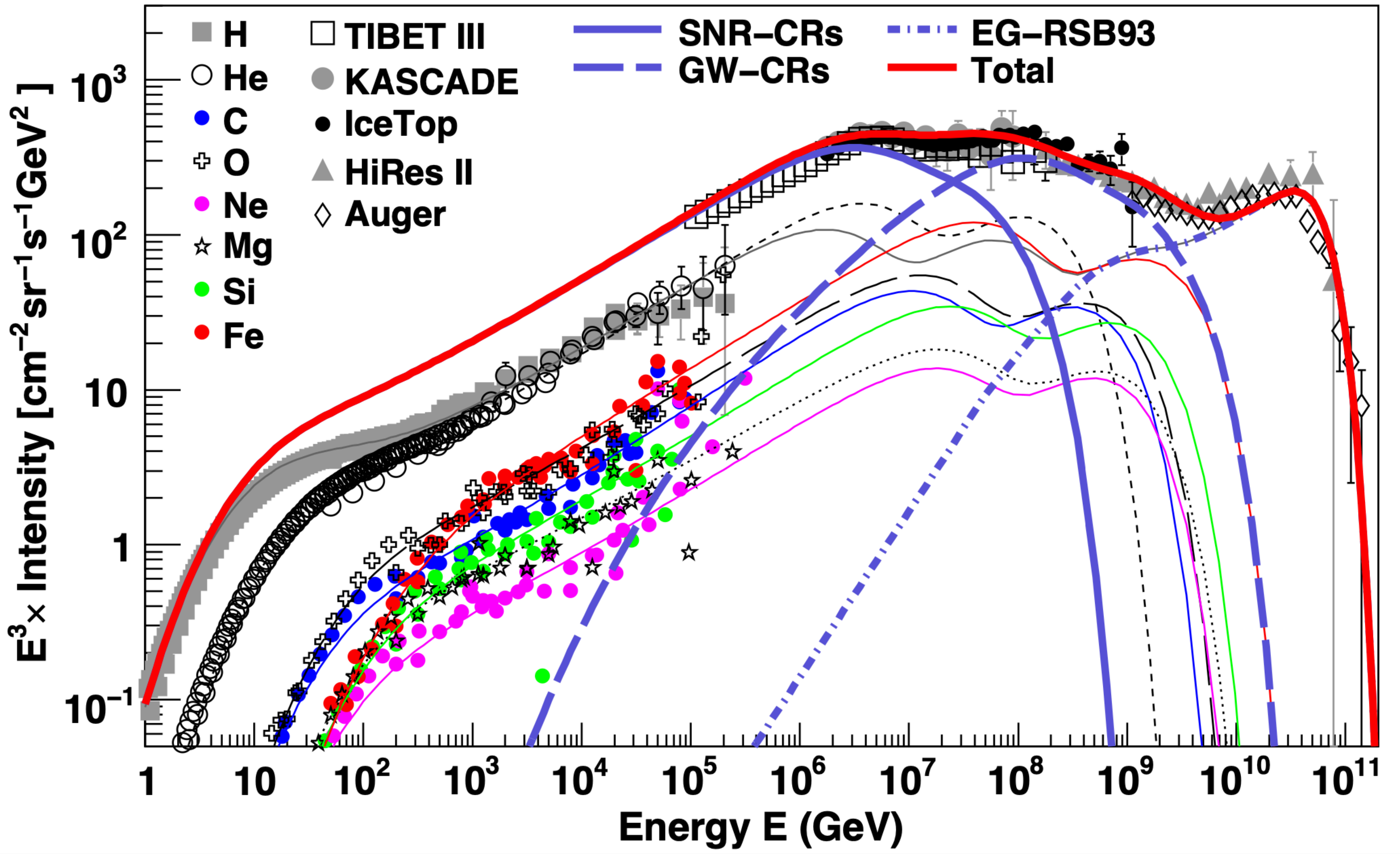
Auger Collab. JCAP 05 (2023)





Transition from Galactic to extragalactic CRs

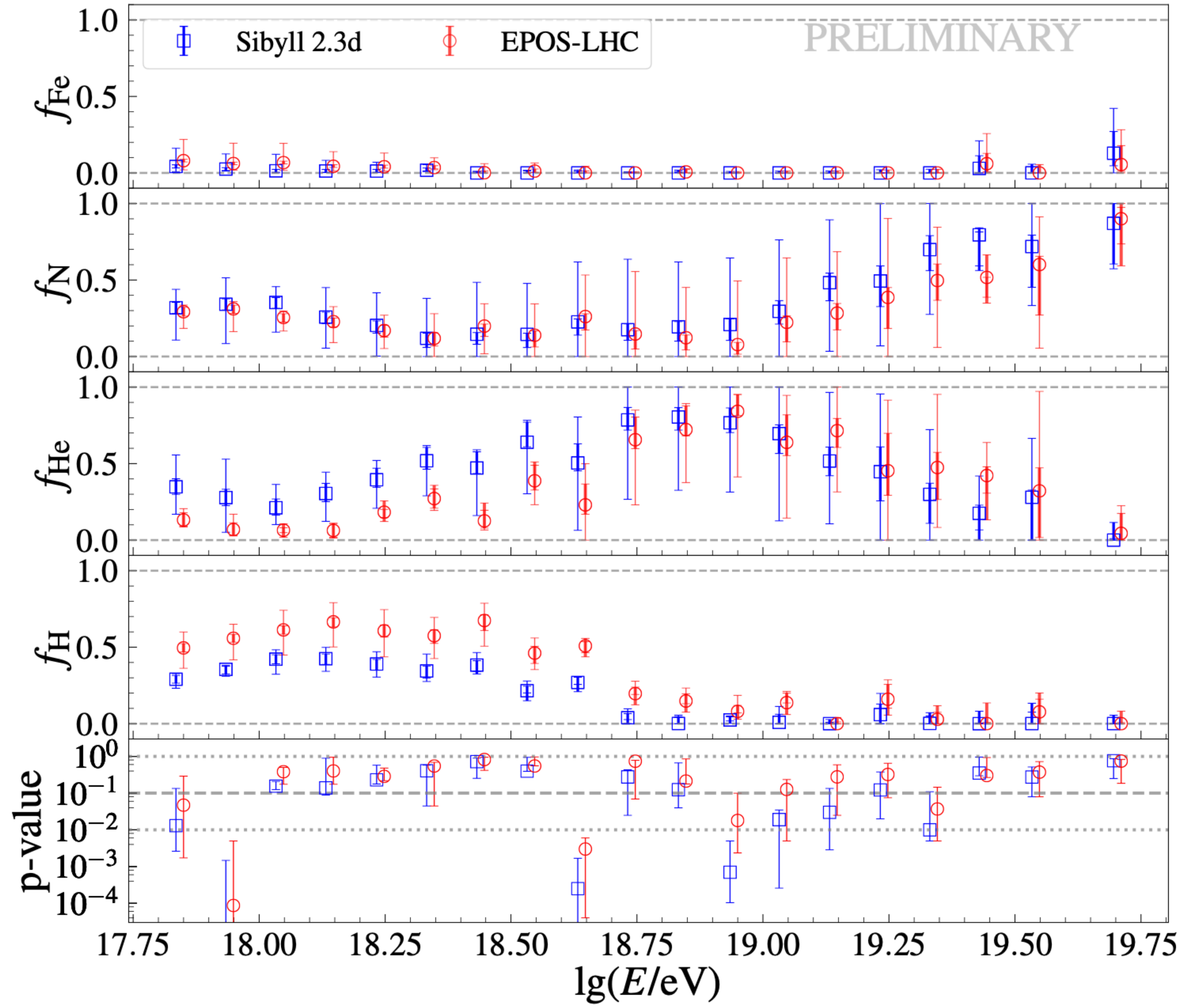
Thoudam, Rachen, van Vliet, Achterberg, Buitink A&A 595 (2016)



- Are different spectral contributions needed at energies below and above the ankle (see Auger Collab. JCAP 05 (2023) 024))?

- is the **ankle** shaped by the contribution of different source populations or by interactions in the source environment? (see Luce, Marafico, Biteau, Condorelli & Deligny, ApJ 936 (2022) for the proton component below the ankle, and Auger Collab. JCAP 05 (2023))

Auger Collab. ICRC23



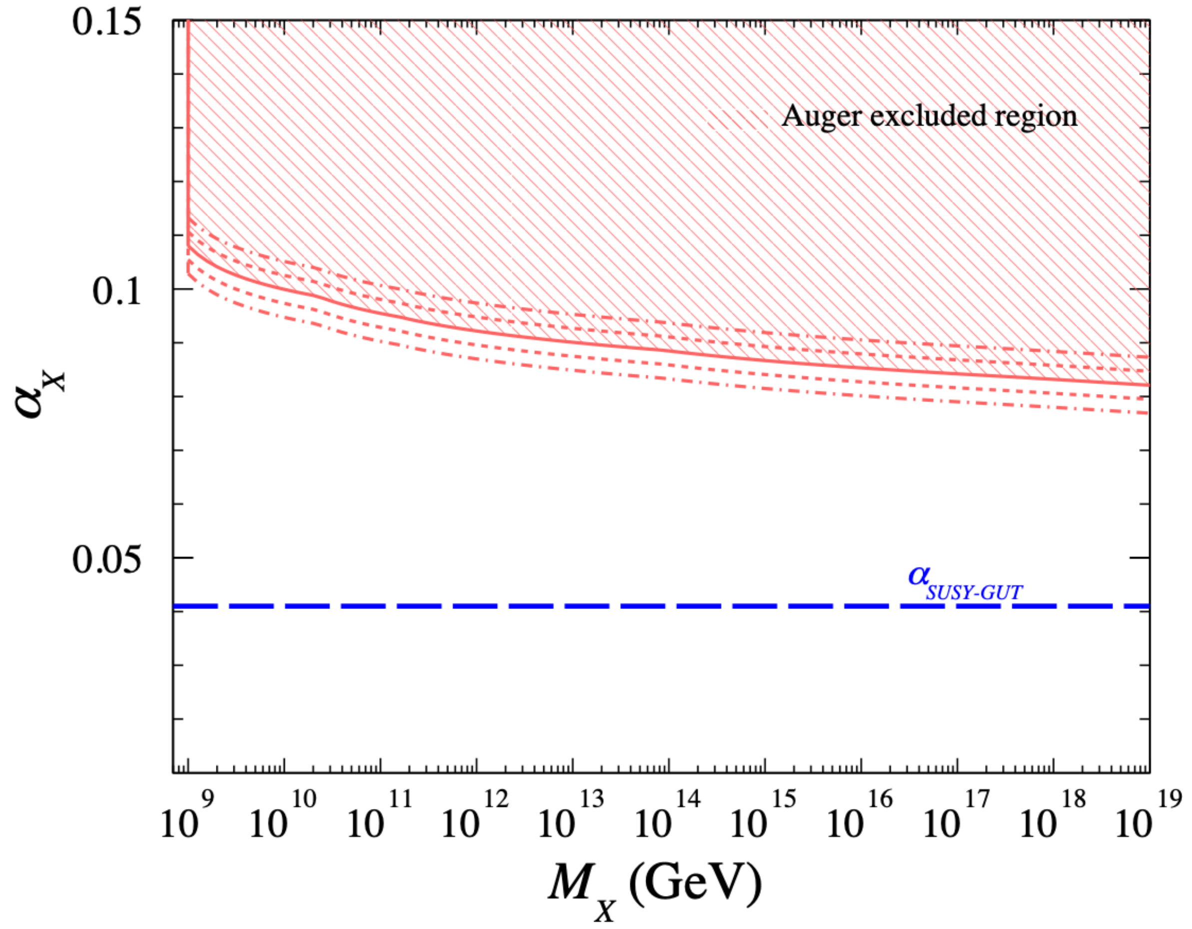
- What is the origin of the <u>sub-ankle intermediate-to-light nuclear species</u>?

- are the nuclear species at the escape from the source ordered in terms of **rigidity or Lorentz factor?** (see Muzio, Anchordoqui & Unger, PRD 109 (2024)) -> relevant to evaluate the efficiency of in-source interactions (see Biehl, Boncioli, Fedynitch & Winter A&A 611 (2018))

Non-standard physics

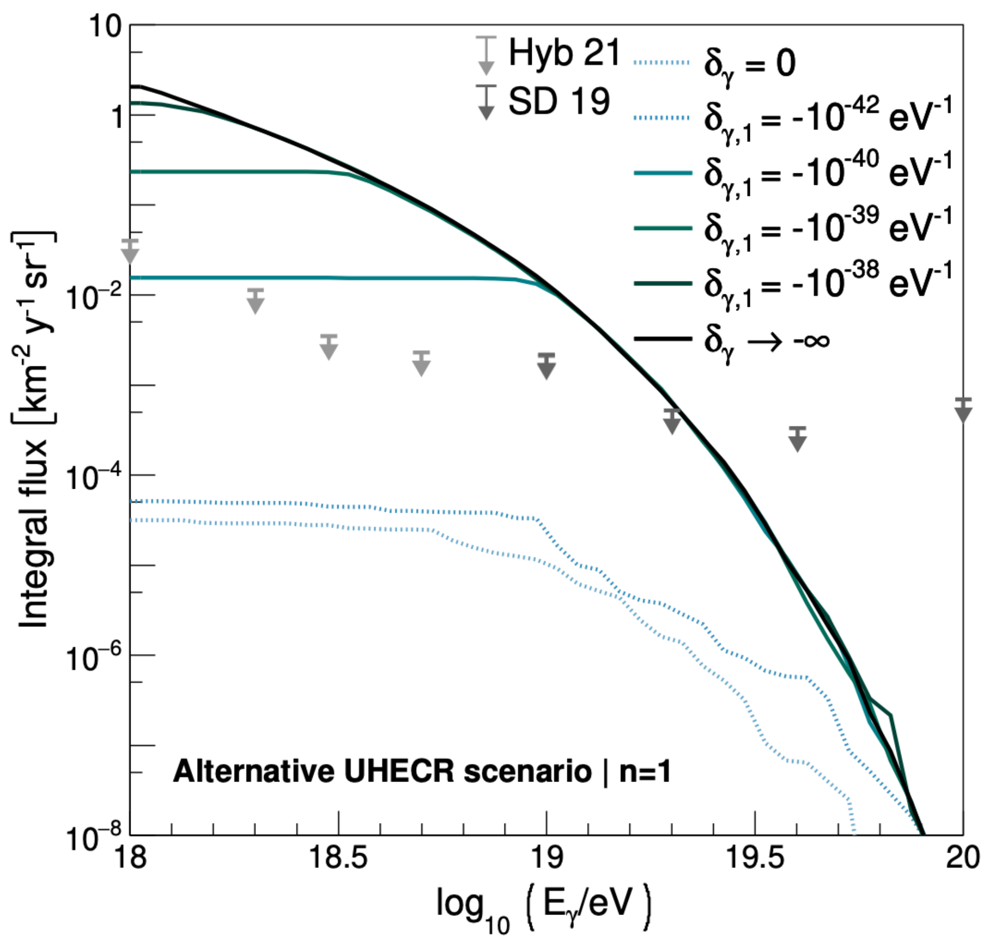
R. Aloisio, talk, Tue 19

- **Violations of Lorentz invariance** could modify the cross section and the threshold of interactions of UHECRs and secondary particles
  - in the extragalactic propagation, and
  - in the atmospheric showers

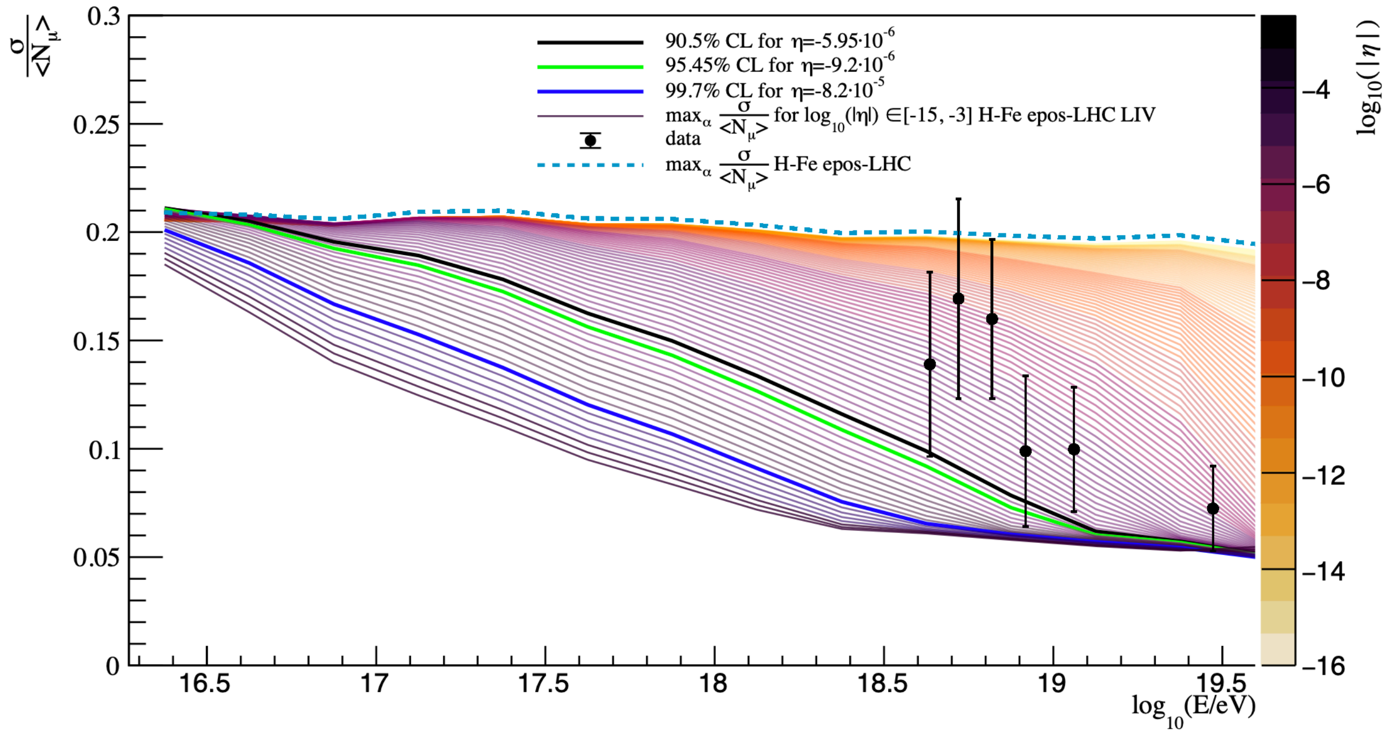


- Decay products of **super-heavy dark matter** particles can be constrained with UHECR measurements (non-observation of cosmogenic particles)

Phys.Rev.D **107 (2023)**



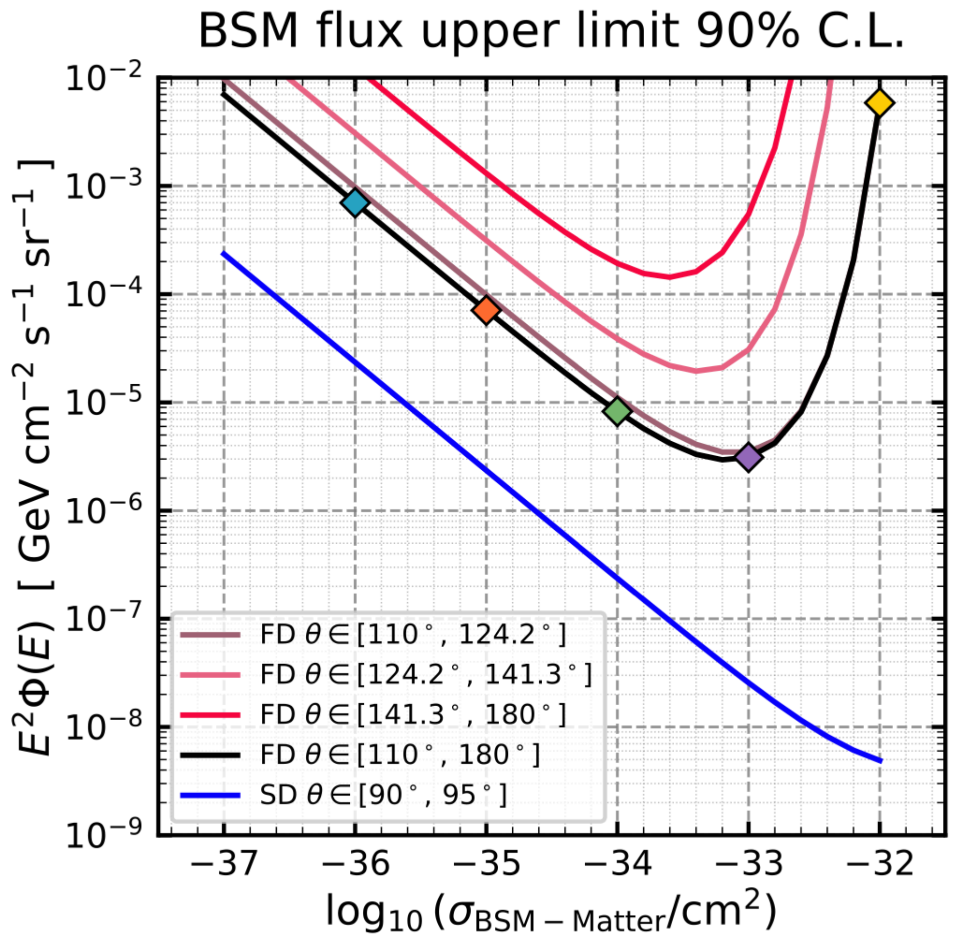
JCAP 01 (2022)

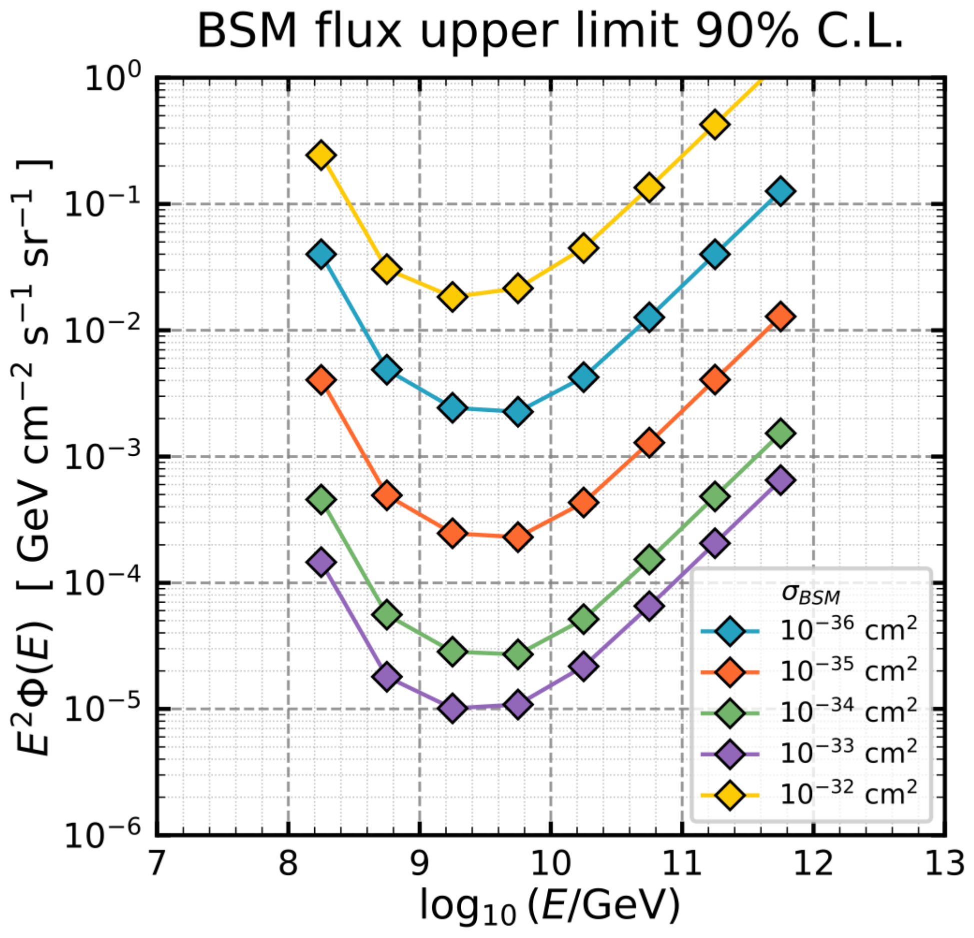


ICRC21

- Investigating **BSM particles with interaction cross section lower than that of neutrinos:** upward-going showers initiated by tau leptons could be resulted from an unknown type of ultra high energy BSM particle

ICRC23





- Effects of changing **cosmological parameters** in UHECR propagation, example in Meinert, Morejon, Sandrock, Eichman, Kreidelmeyer & Kampert, ApJ 967 (2024)

- **The current sensitivity to several aspects of non-standard physics is strongly affected by the determination of the proton fraction -> AugerPrime will contribute significantly to improve these constraints**

Summary

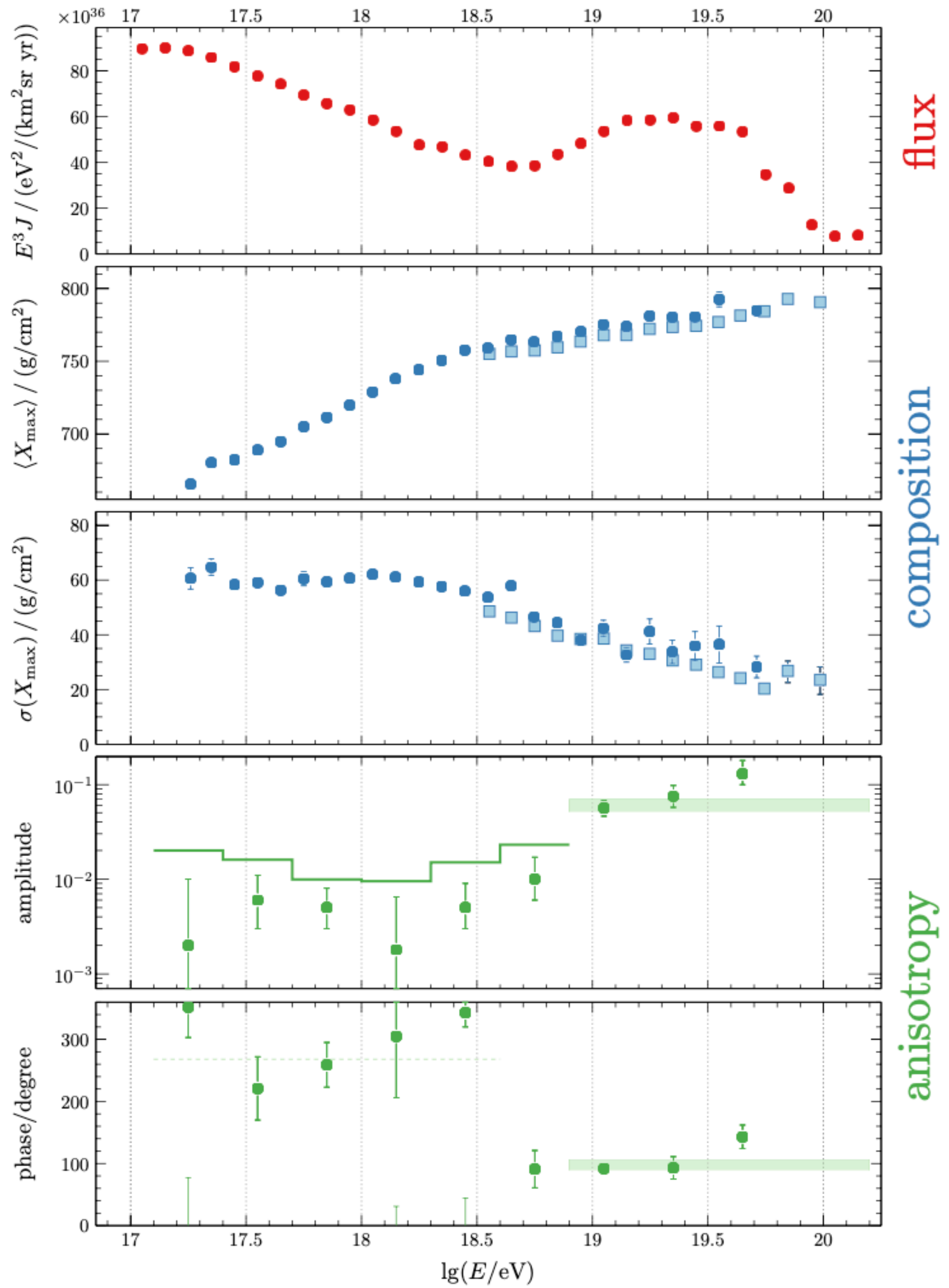
Summary

- The data of the Pierre Auger Observatory contribute to shape **a consistent picture of the characteristics of UHECRs**, which challenges basic scenarios, such as the UHECR-proton paradigm, **but… this is not the end of the story!**

- Thanks to the increasing precision and complexity of data, a variety of new scenarios to be investigated with UHECRs is arising

D. Schmidt, talk, Thu 21

- Towards a 100% duty cycle collection of multi-hybrid events -> **AugerPrime** will push the understanding of UHECR source characteristics, particle physics aspects and fundamental physics



- Not only cosmic-ray physics at the Auger Observatory: with UHECR data, cosmo-geophysics is possible

R. Mussa, poster

- Auger open data, see https://opendata.auger.org/

V. Scherini, poster