Recent UHECR results and their interpretation

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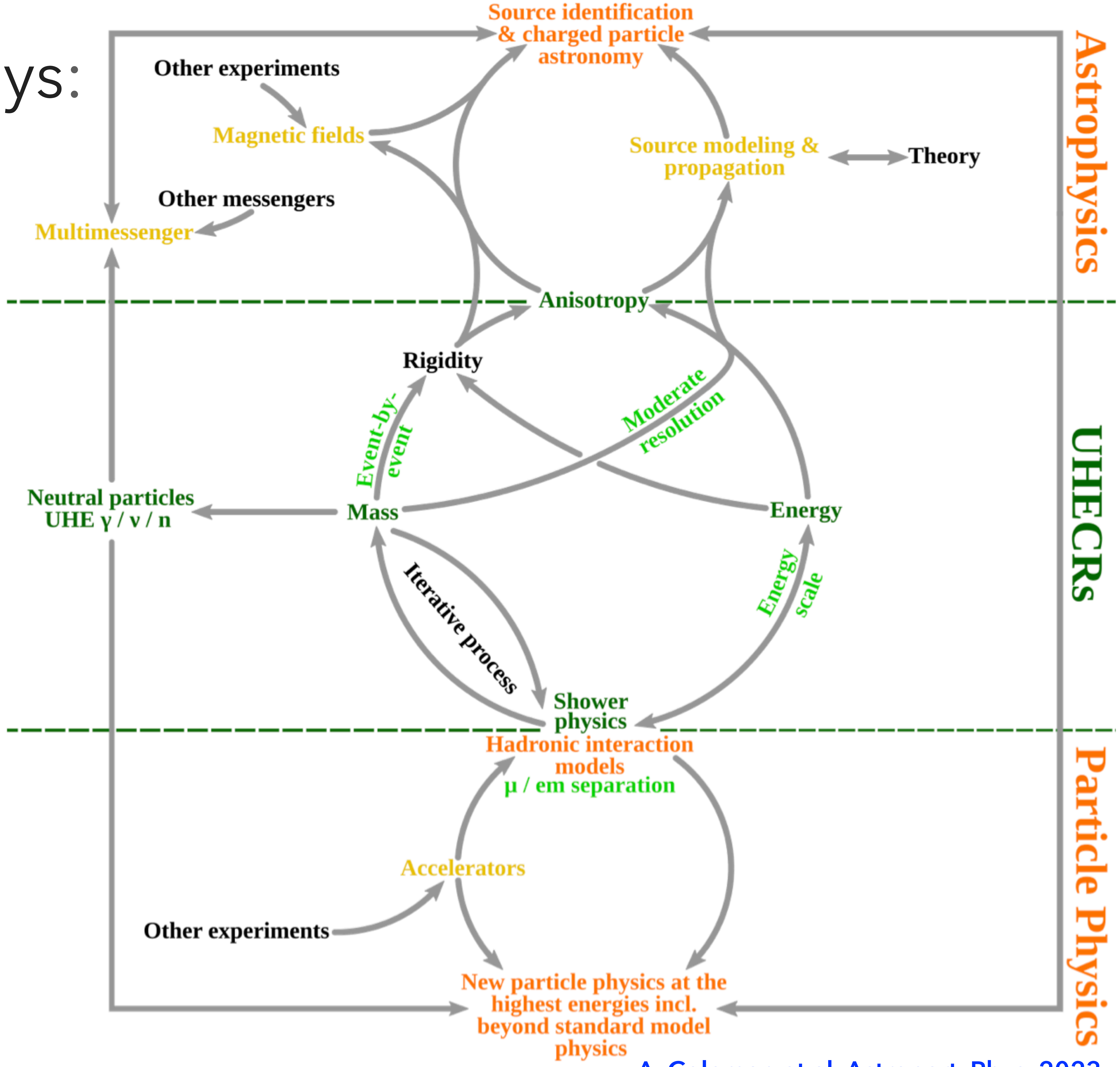
Ultra-High-Energy Cosmic Rays:

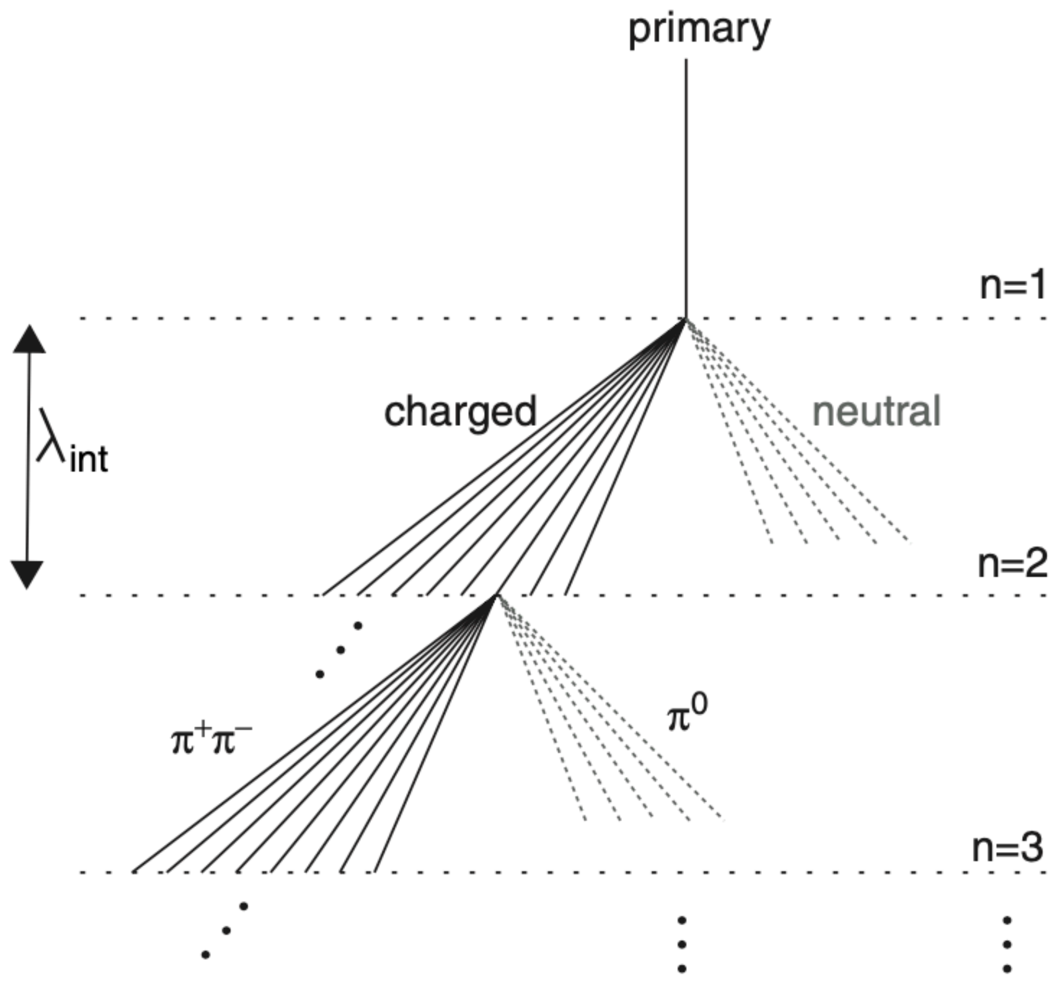
a field of... connections!

- The observables:
  - Energy, mass, arrival direction
- The messengers:
  - Cosmic Rays, Neutrinos, Photons, ...
- Physics:
  - Astrophysics, Particle Physics, Physics beyond the Standard Model...

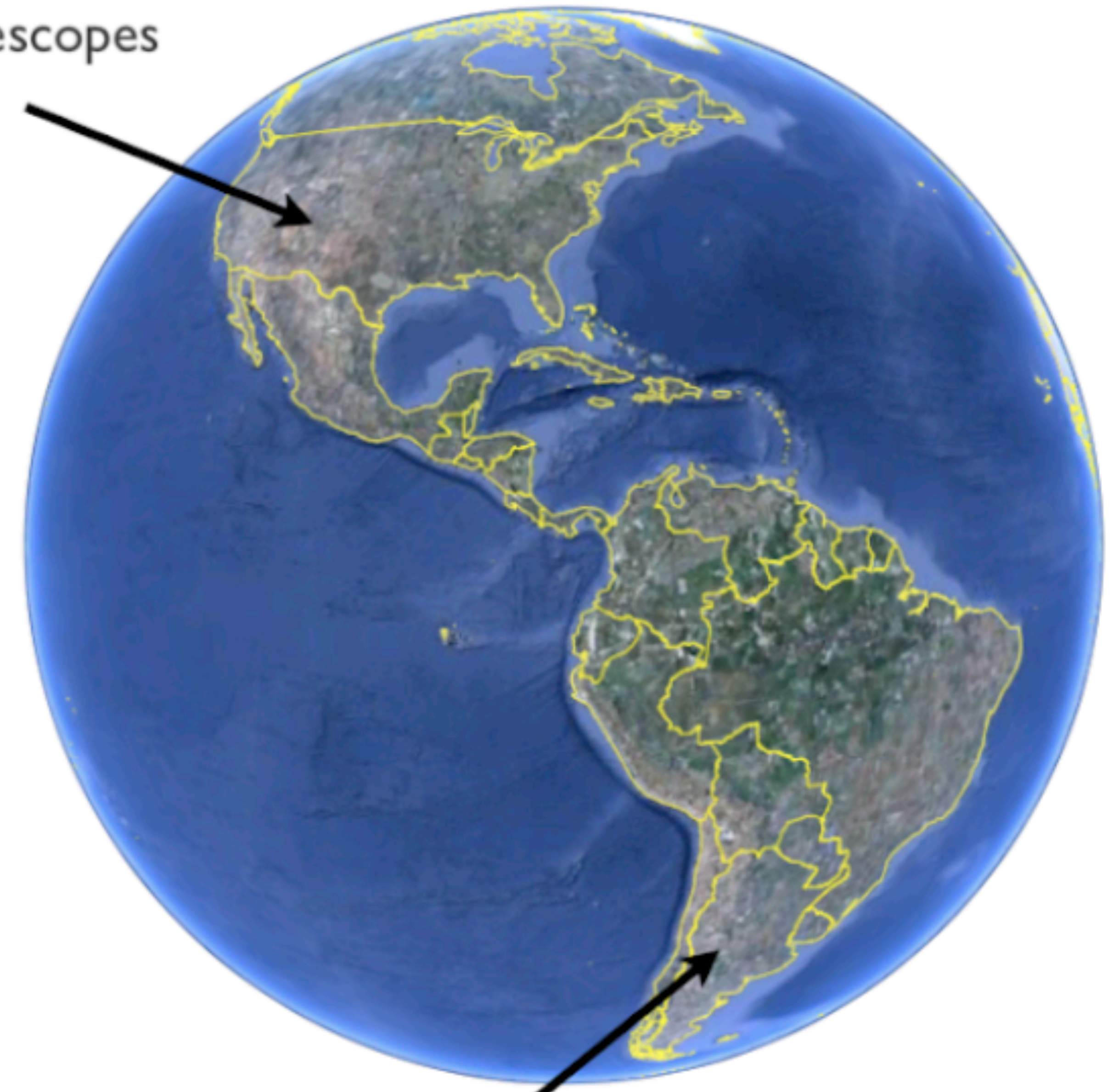


A. Coleman et al. Astropart. Phys. 2023

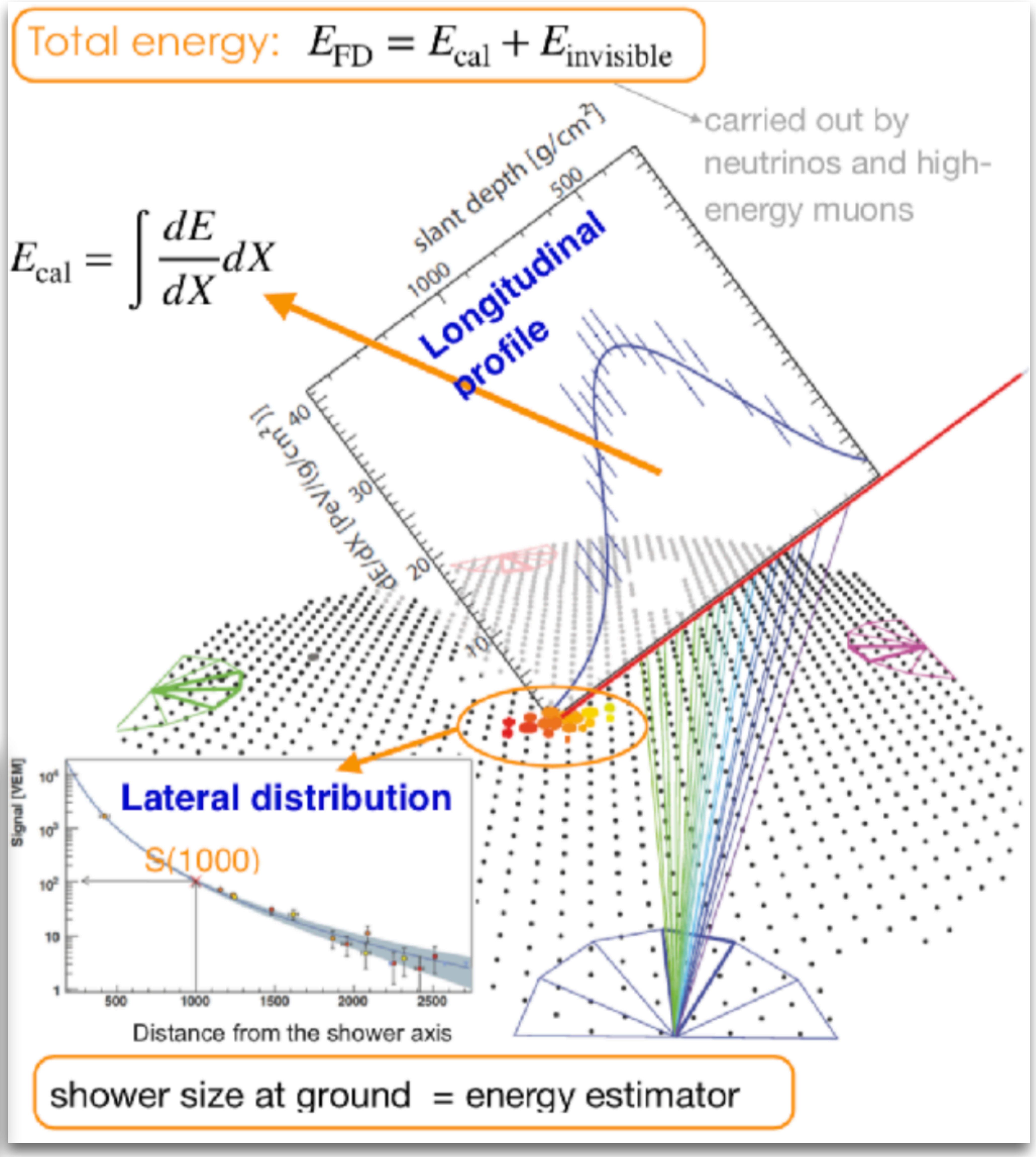
THE ERA OF **GIANT OBSERVATORIES**



Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes



Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes



BELIEVES FROM THE PAST AND CURRENT EVIDENCES

ONE EXAMPLE: THE **UHECR MASS COMPOSITION**

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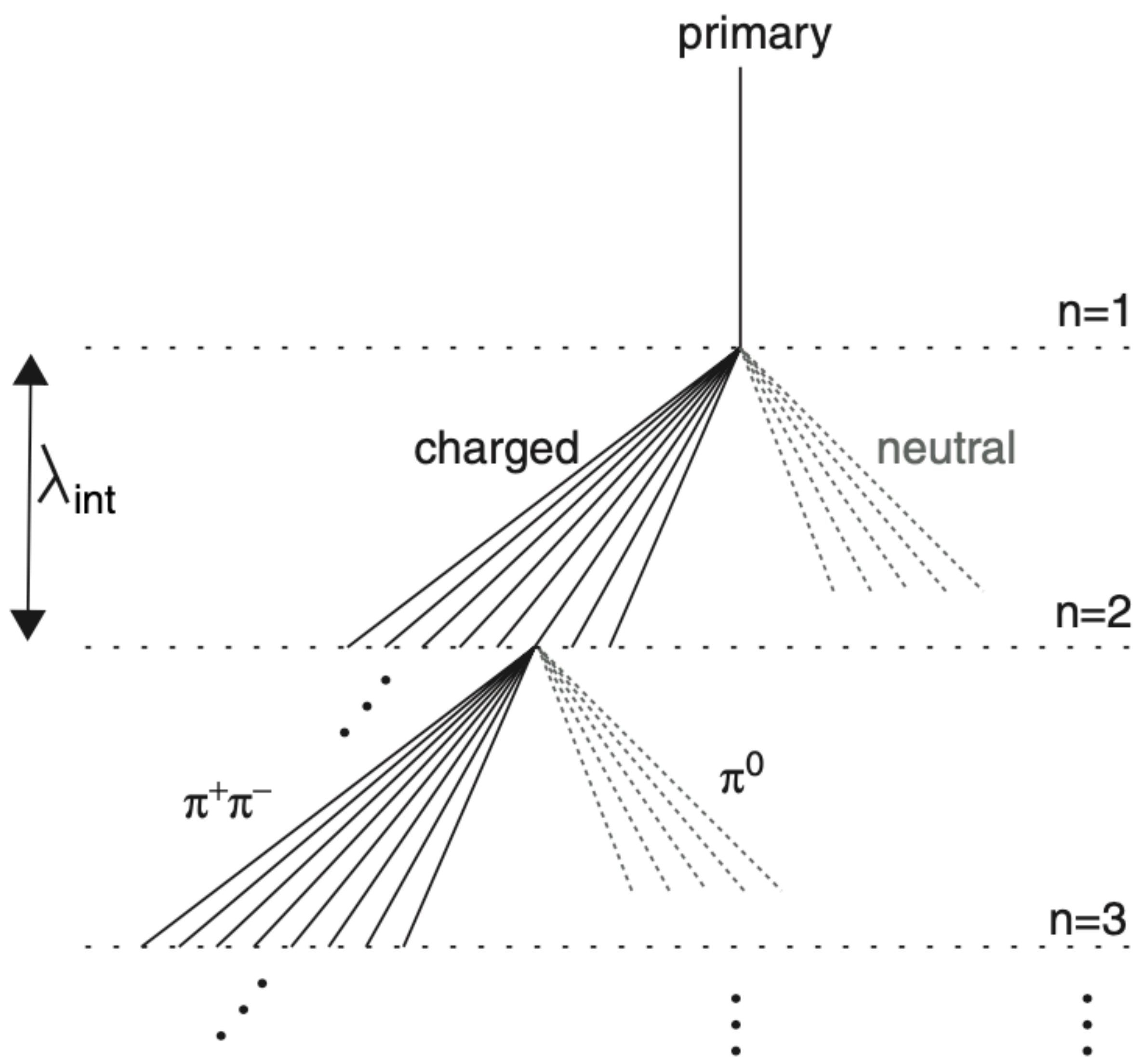

$$X_{\max} \propto \ln(E_0/E_c)$$

$$^{A}X, E_0 \leftrightarrow A \times n, E_0/A$$

$$X^{A}_{\max} \propto X_{\max}(E_0/A)$$

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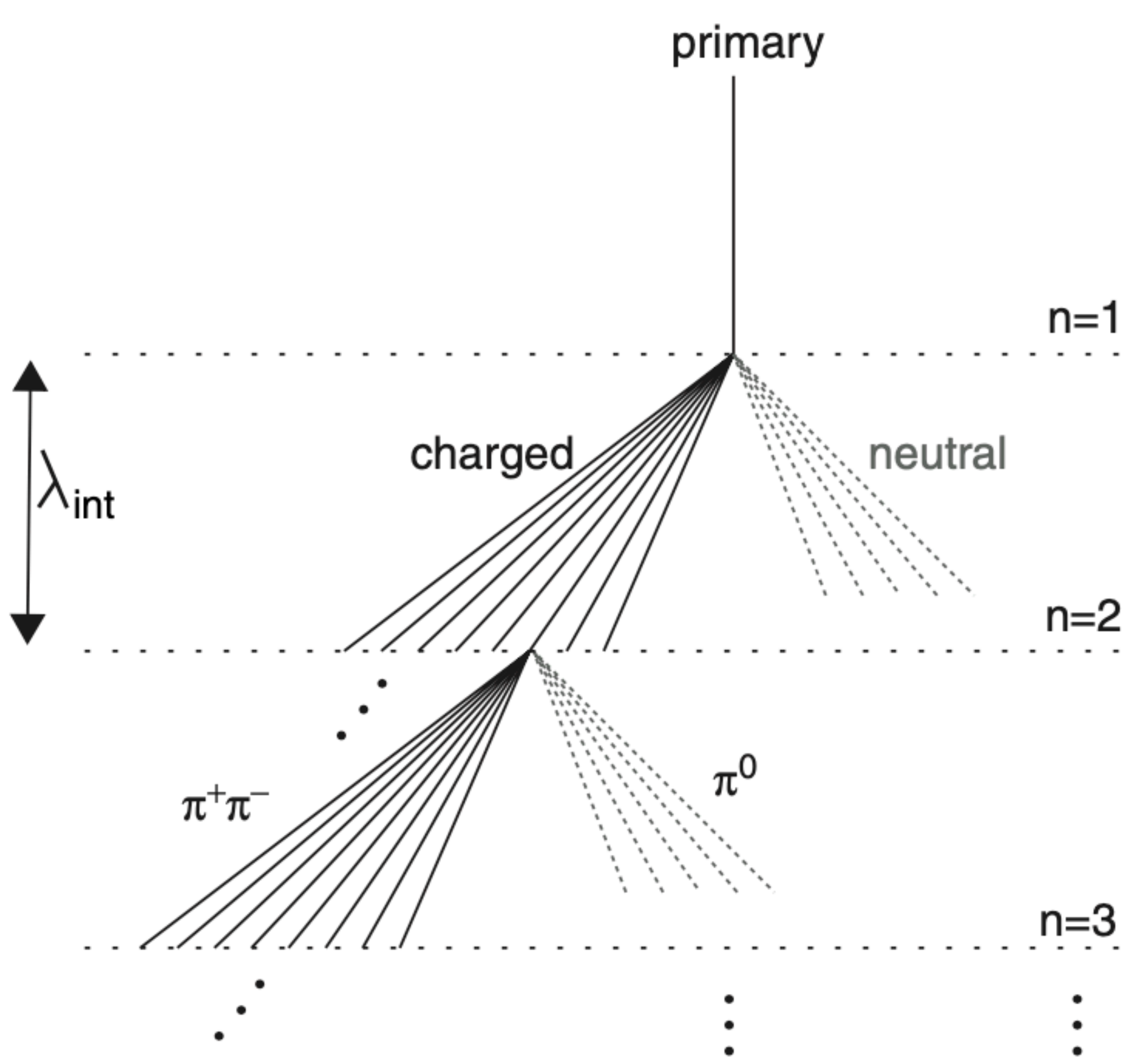

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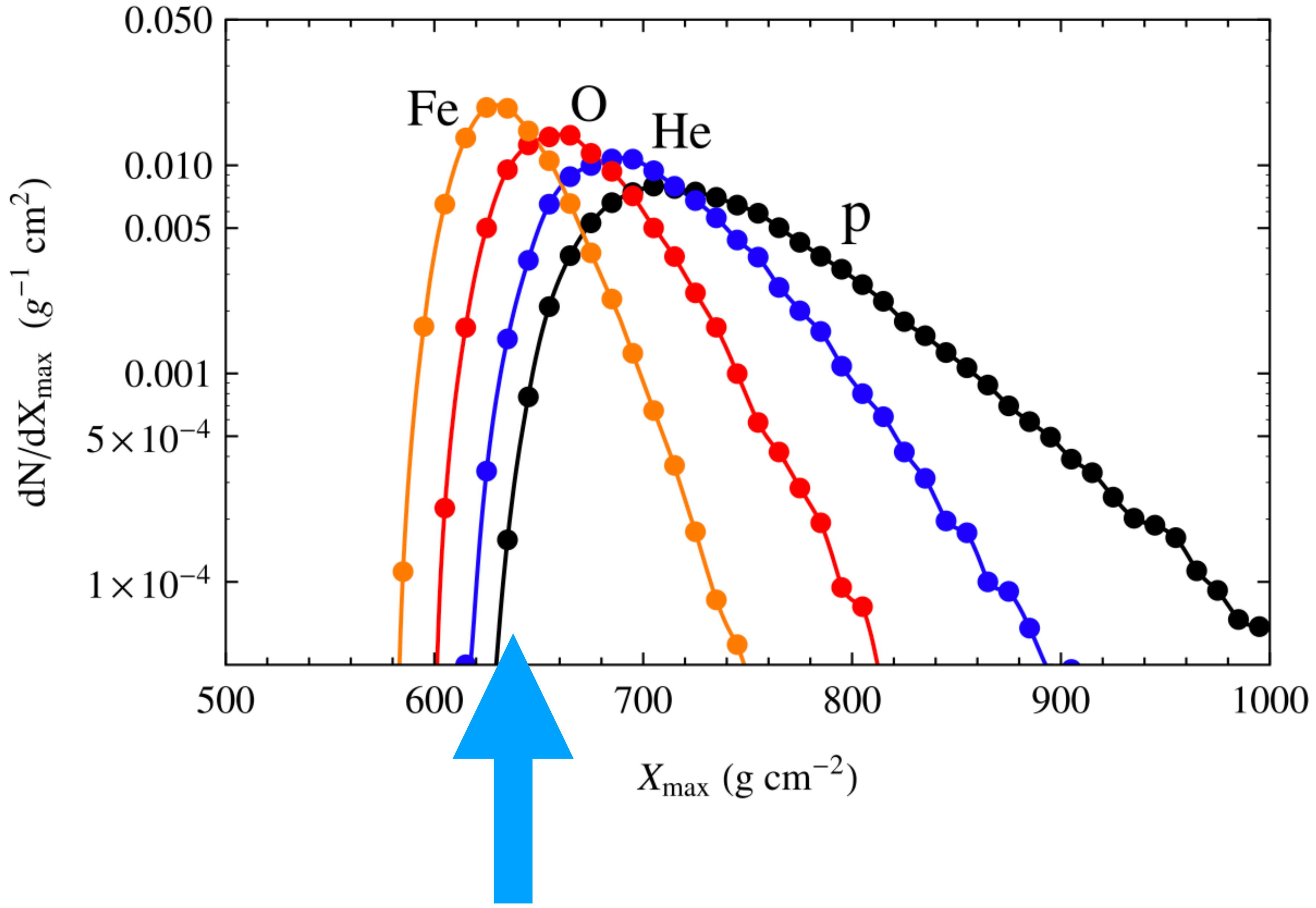
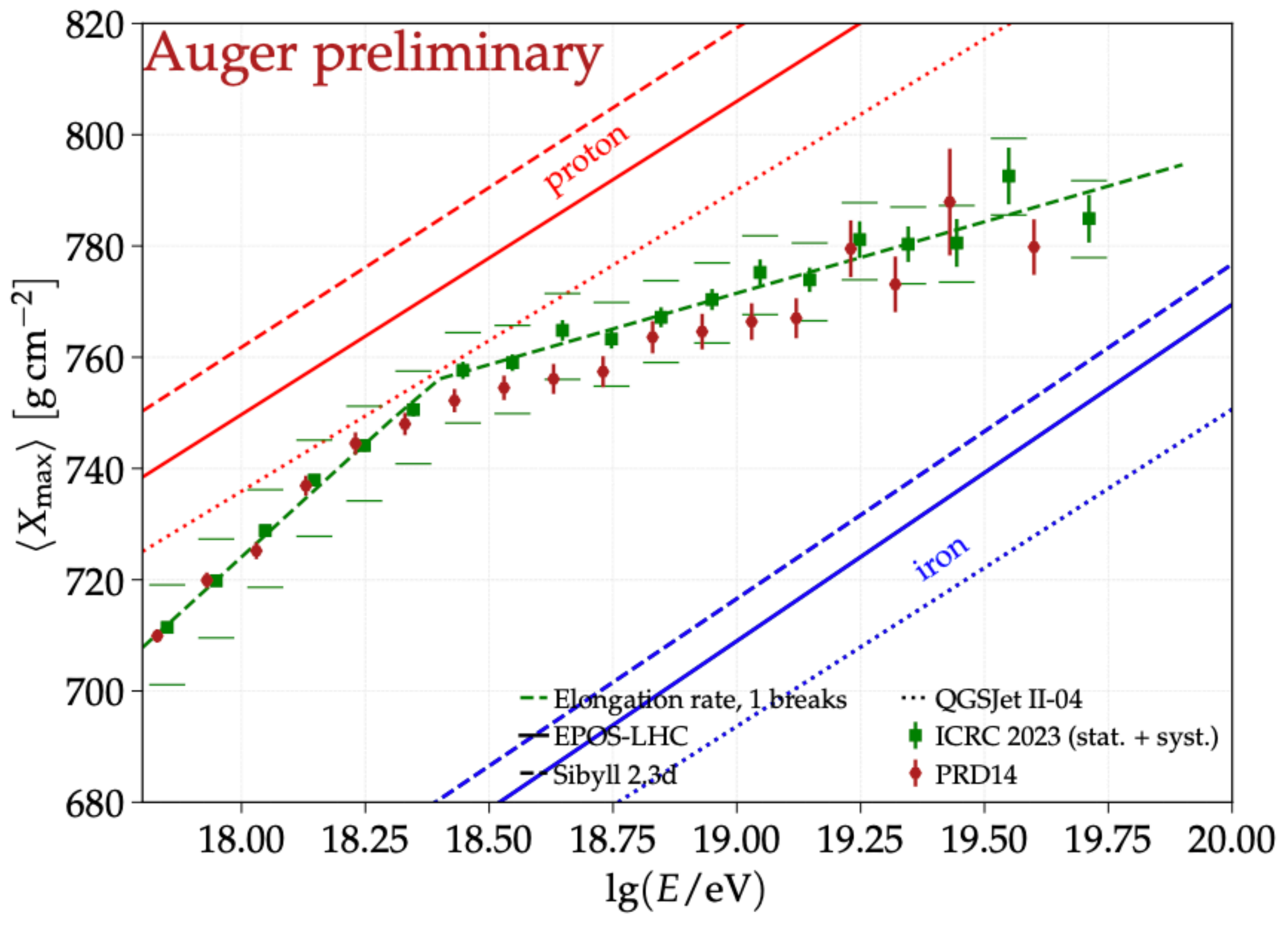


Evidences:

- First momentum: elongation rate is not constant

The Pierre Auger Collab. ICRC23



$$D = \frac{d\langle X_{\max}\rangle}{d \ln E}$$

BELIEVES FROM THE PAST AND CURRENT EVIDENCES

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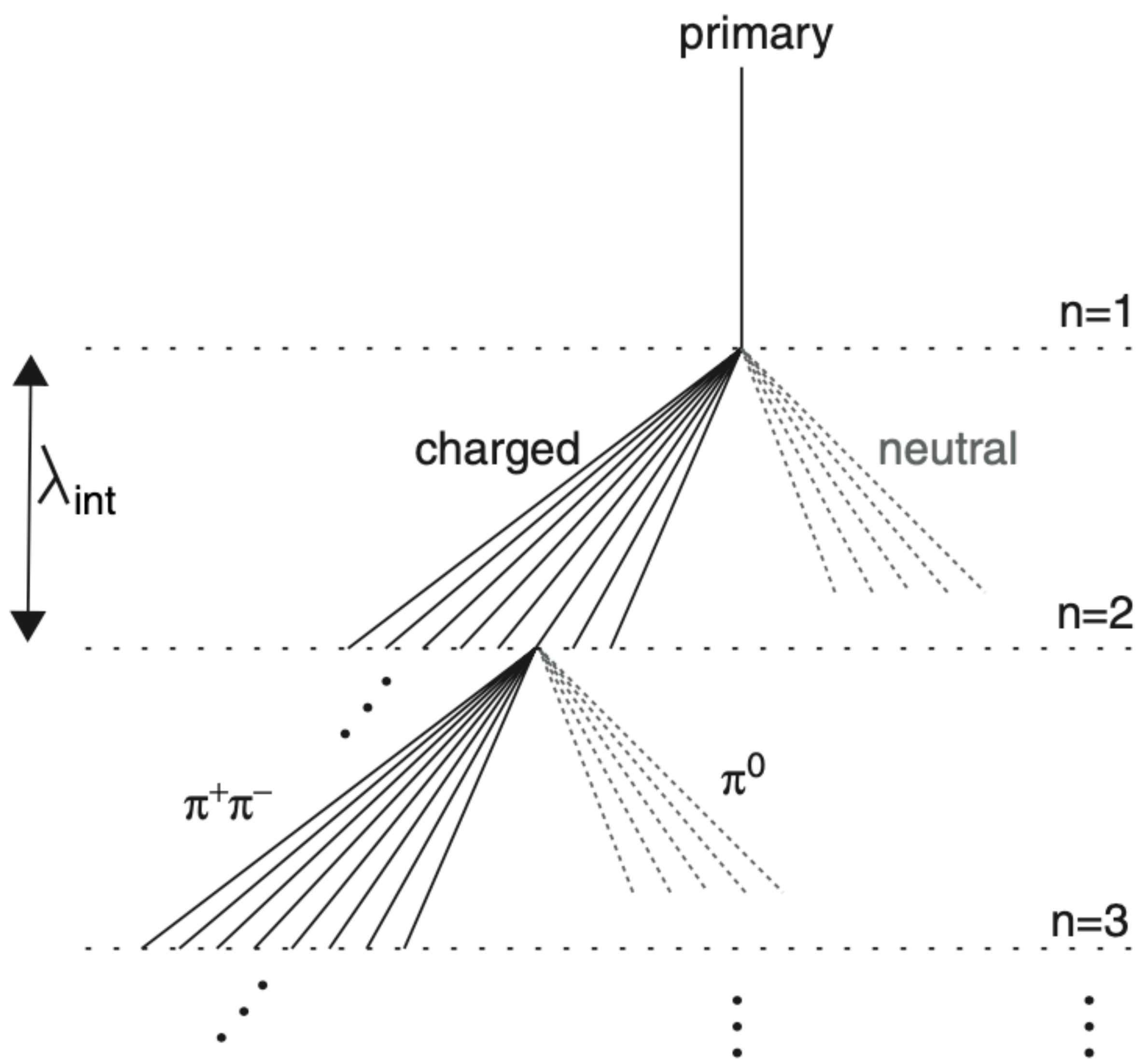

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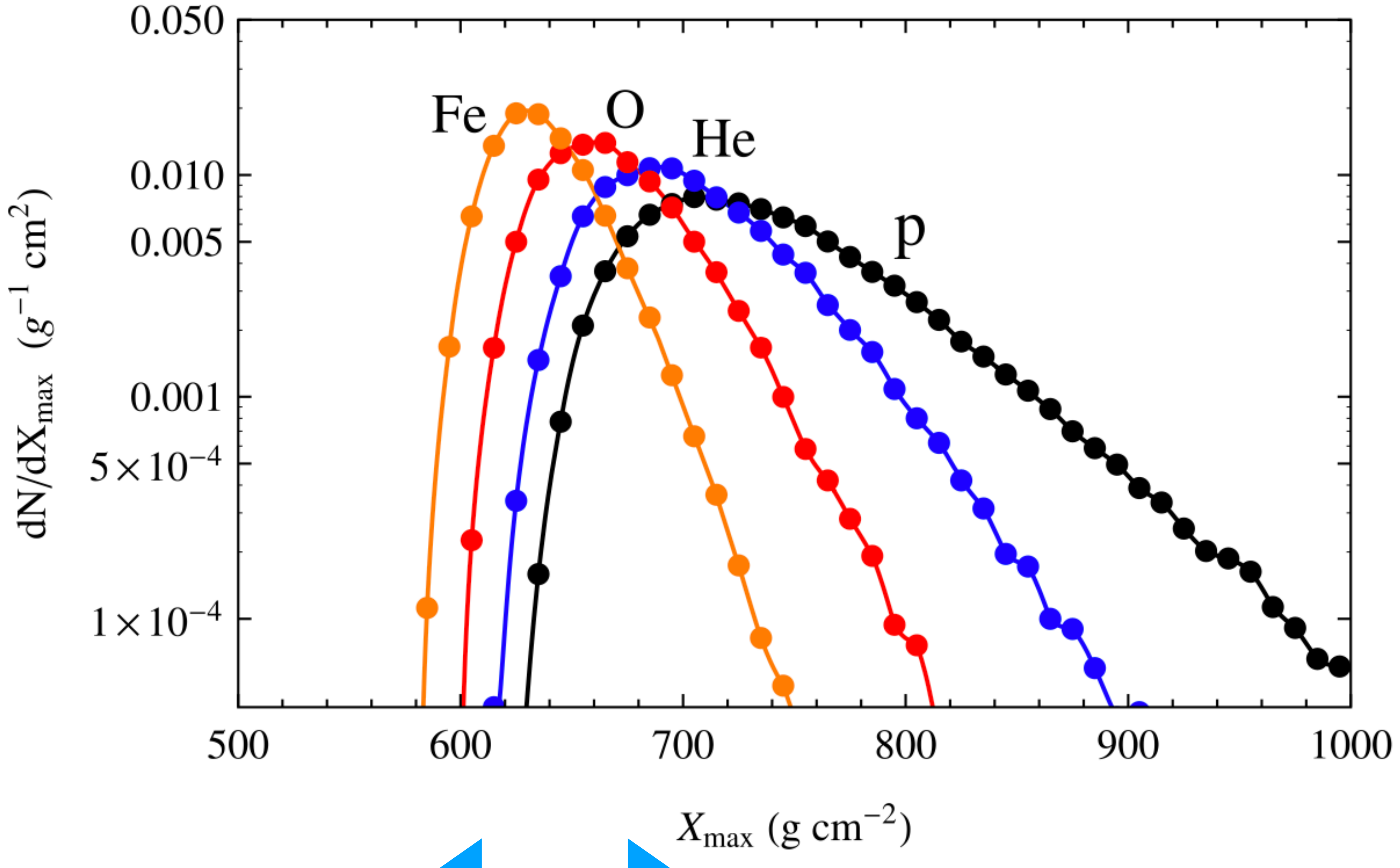
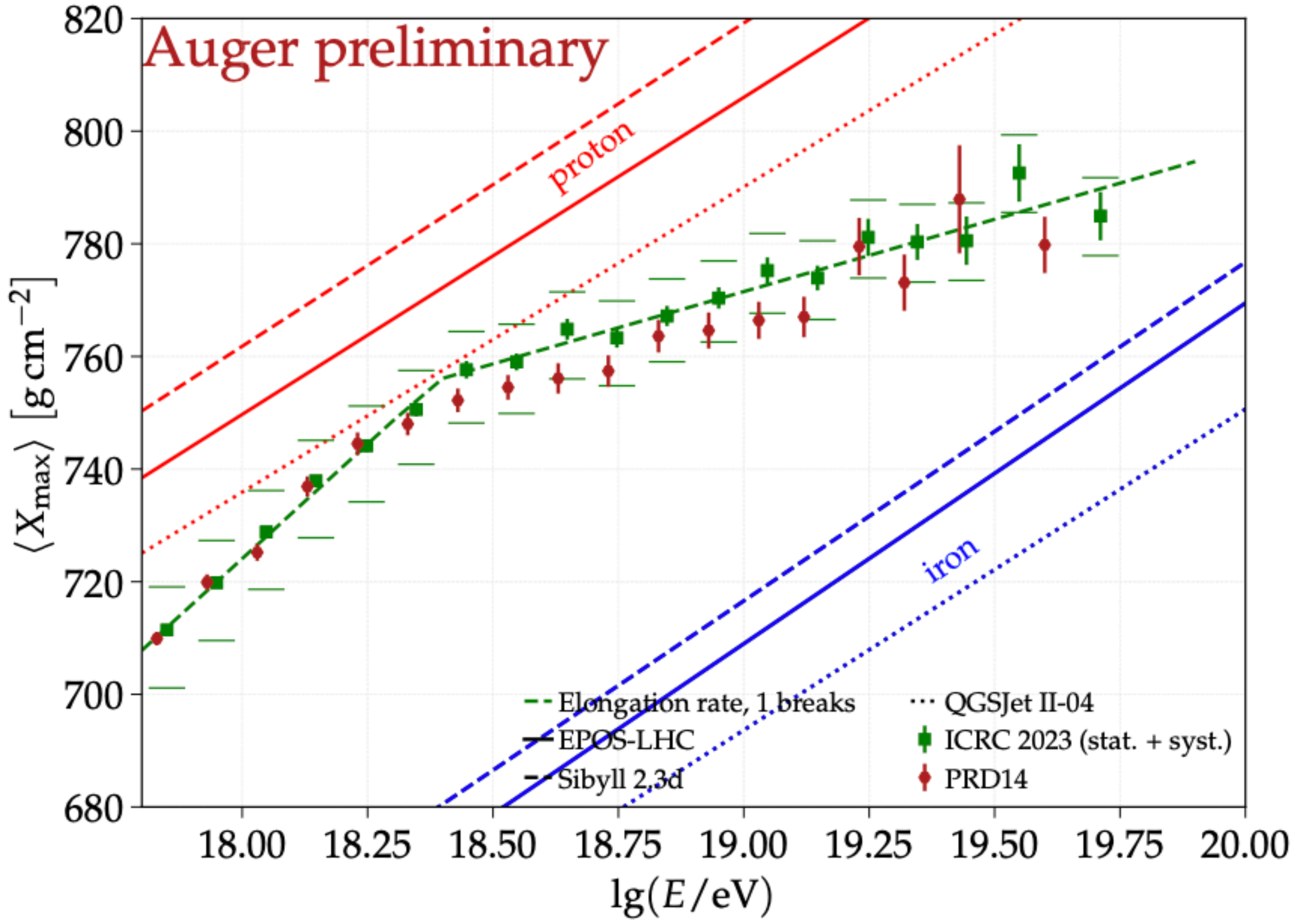
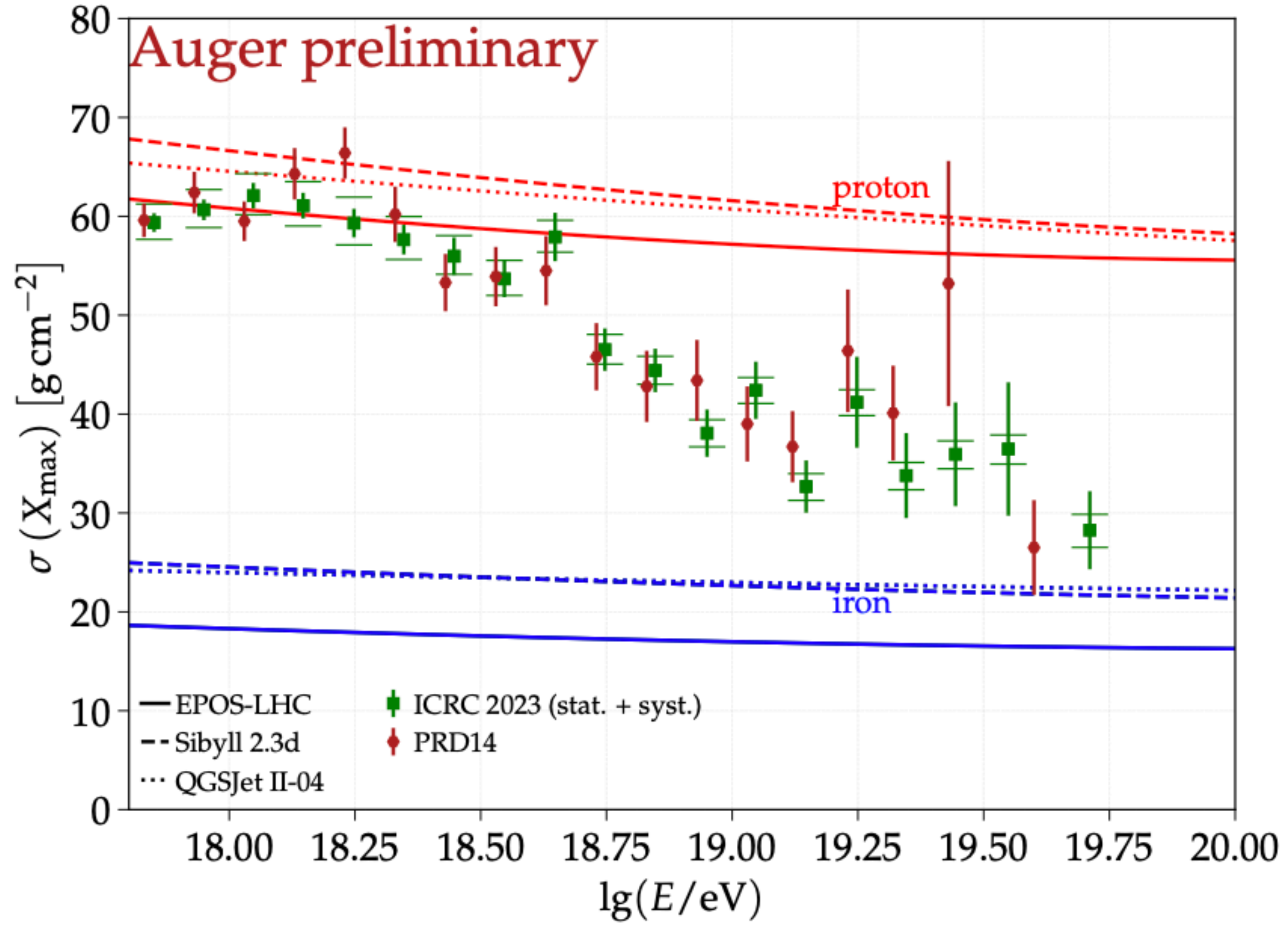


Evidences:

- First momentum: elongation rate is not constant
- Second momentum: fluctuations decrease

The Pierre Auger Collab. ICRC23



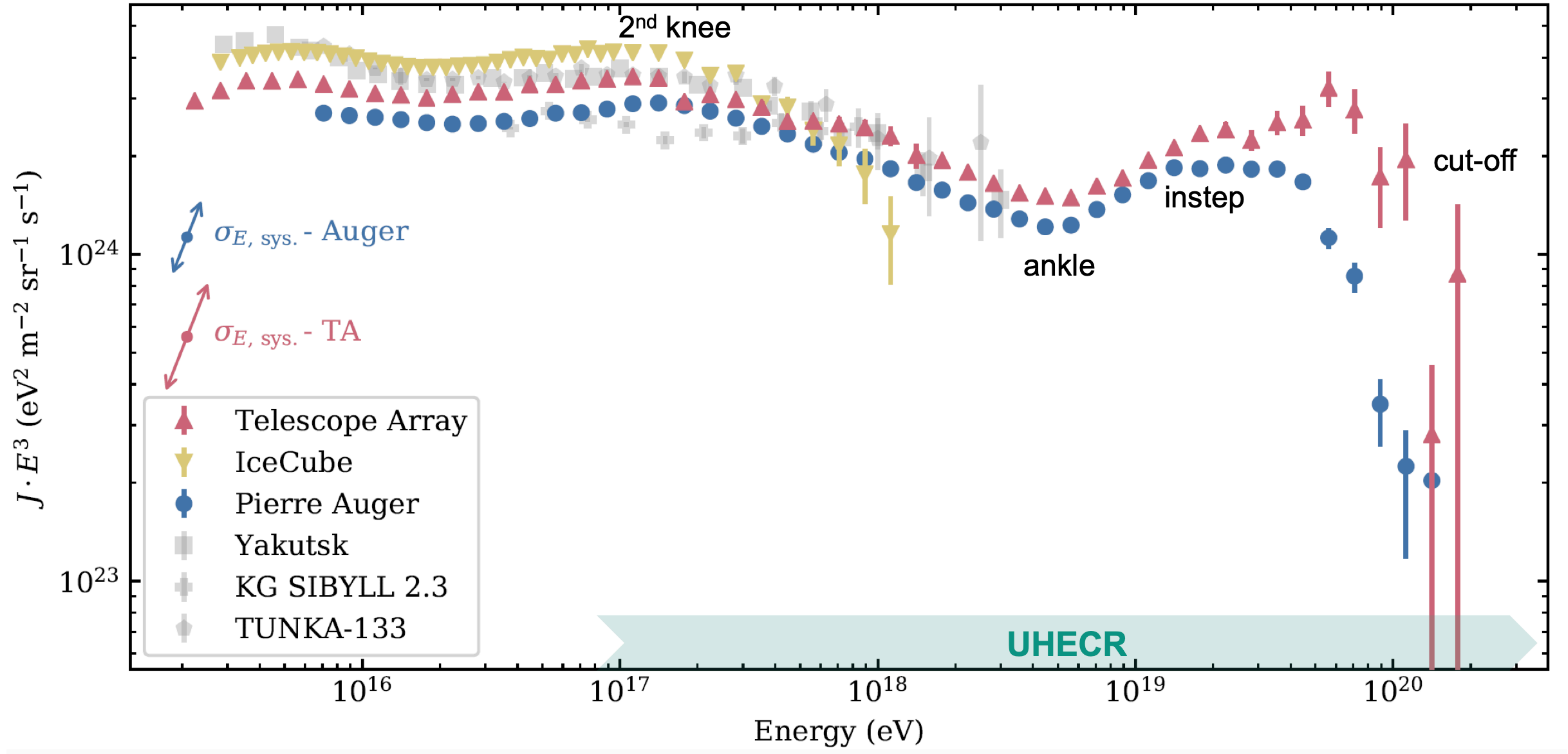


- See A. Watson EPJ Web Conf. 2023 for a historical overview about composition measurements

MEASURING UHECRS

THE UHECR ENERGY SPECTRUM

Talks by **K. Fujisue** and **F. Convenga**:
Wed, CCR session



Origin of inflection points: imprints of:

- Extragalactic propagation?
- Power of sources?
- Distribution of sources?
- Transition from Galactic to extragalactic contribution?

A. Coleman et al. Astropart. Phys. 2023

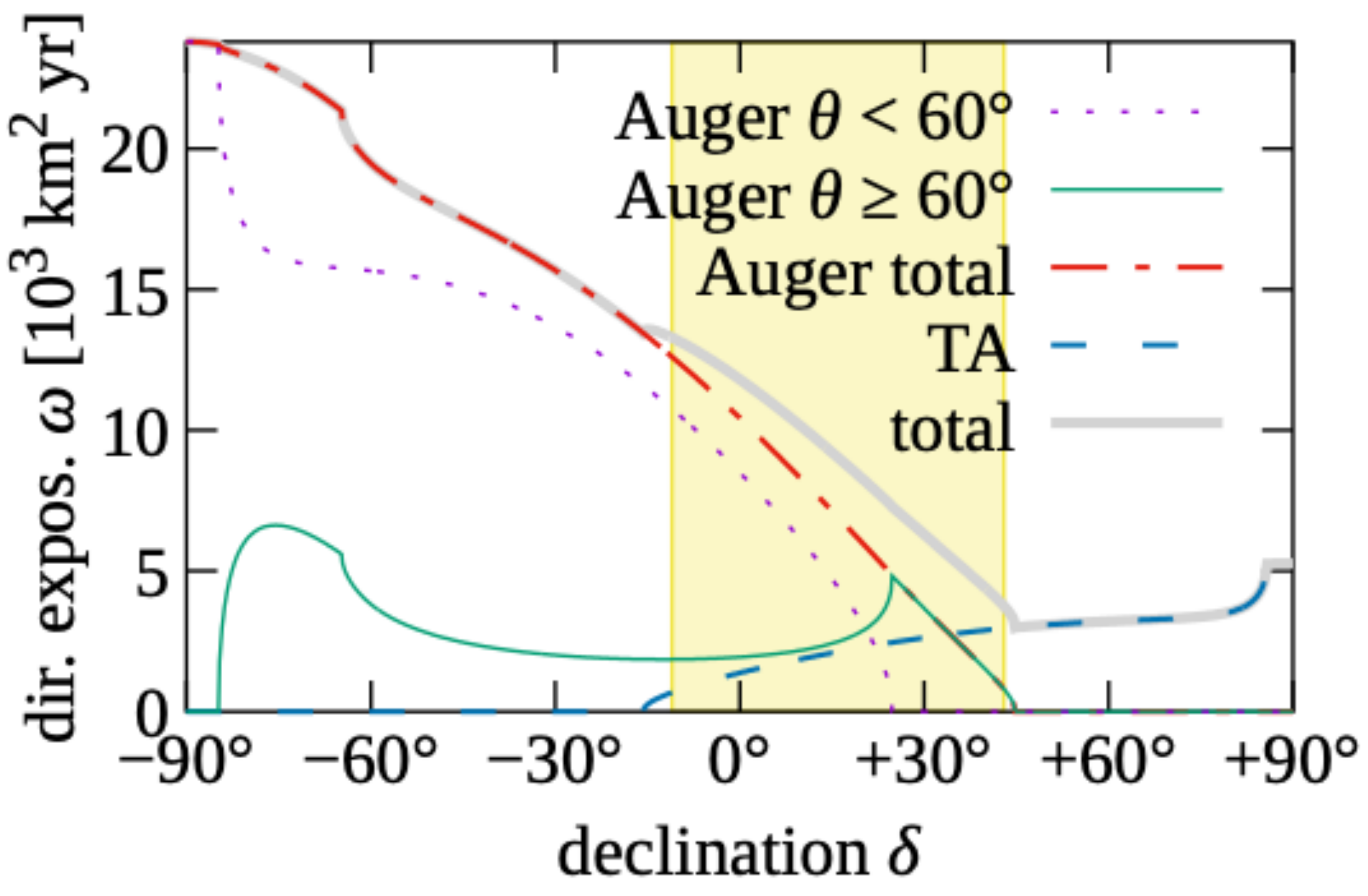
THE UHECR ARRIVAL DIRECTIONS

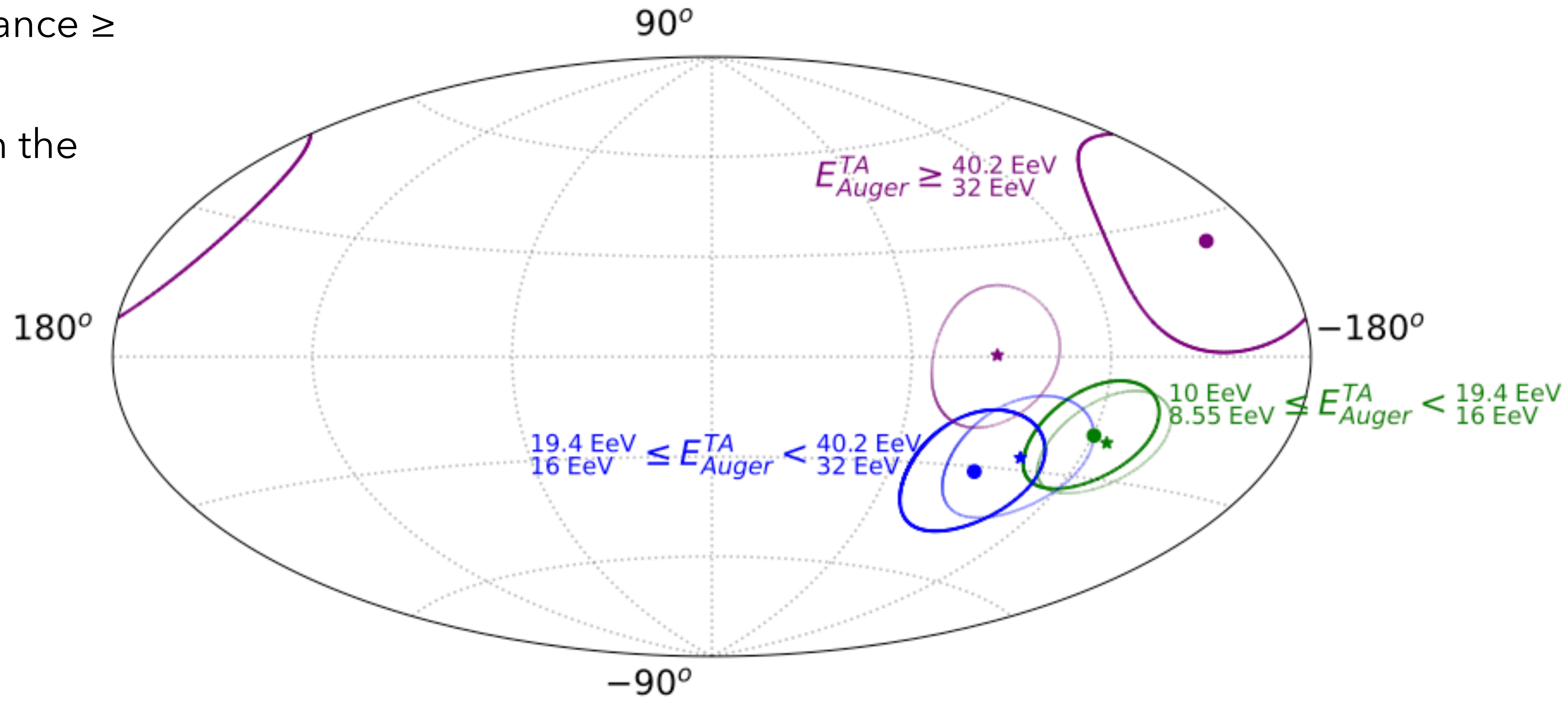
Telescope Array and Pierre Auger Collab. Joint WG on Arrival Directions, ICRC23

Talks by **K. Fujisue** and **E. Martins**, Wed, CCR session

- Full sky coverage thanks to Auger + TA
- Anisotropy detected with statistical significance ≥ 5 sigma: **modulation in right ascension**
  - Dipole pointing 114 degrees away from the Galactic center

-> extragalactic origin of UHECRs





THE UHECR ARRIVAL DIRECTIONS

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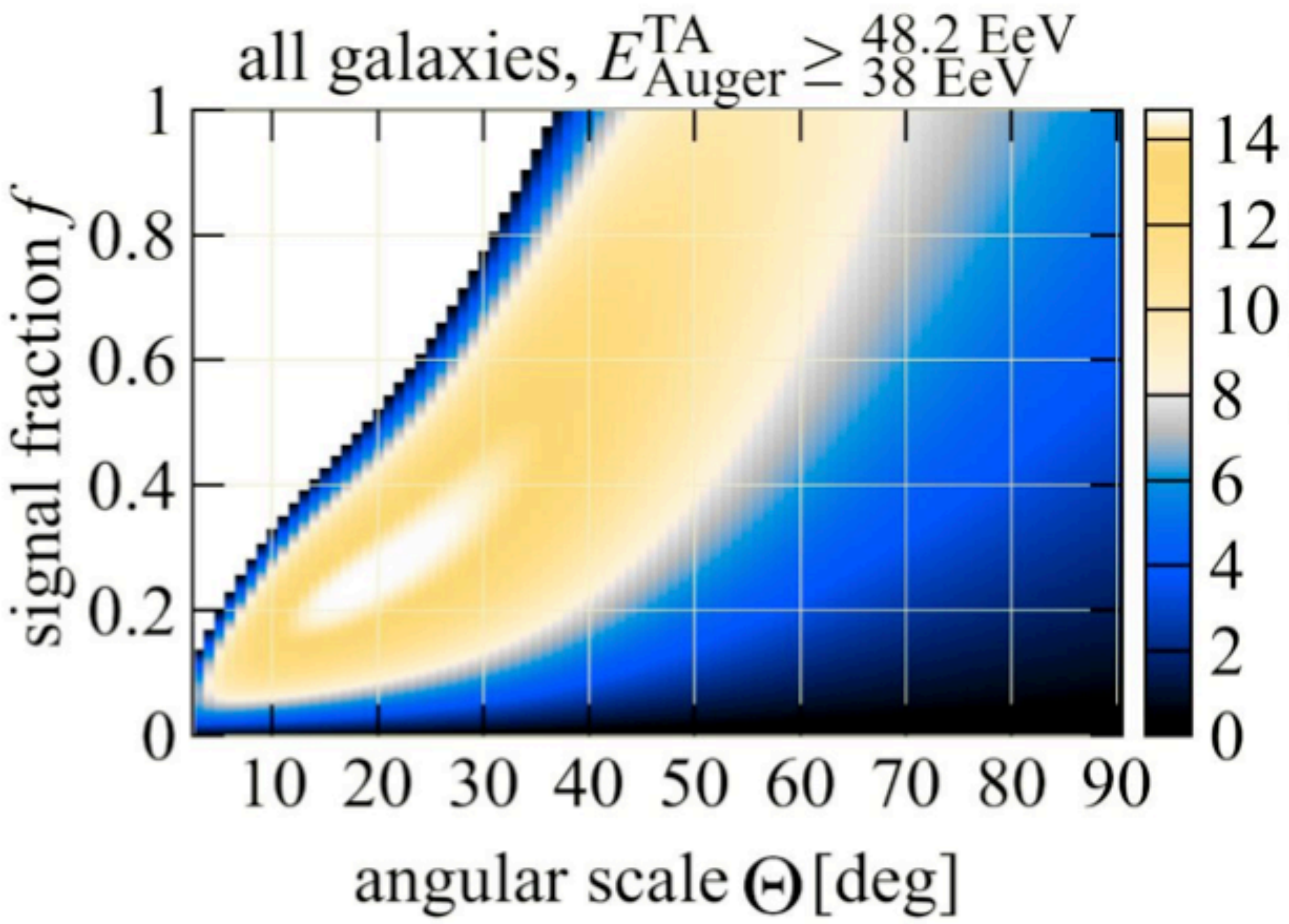
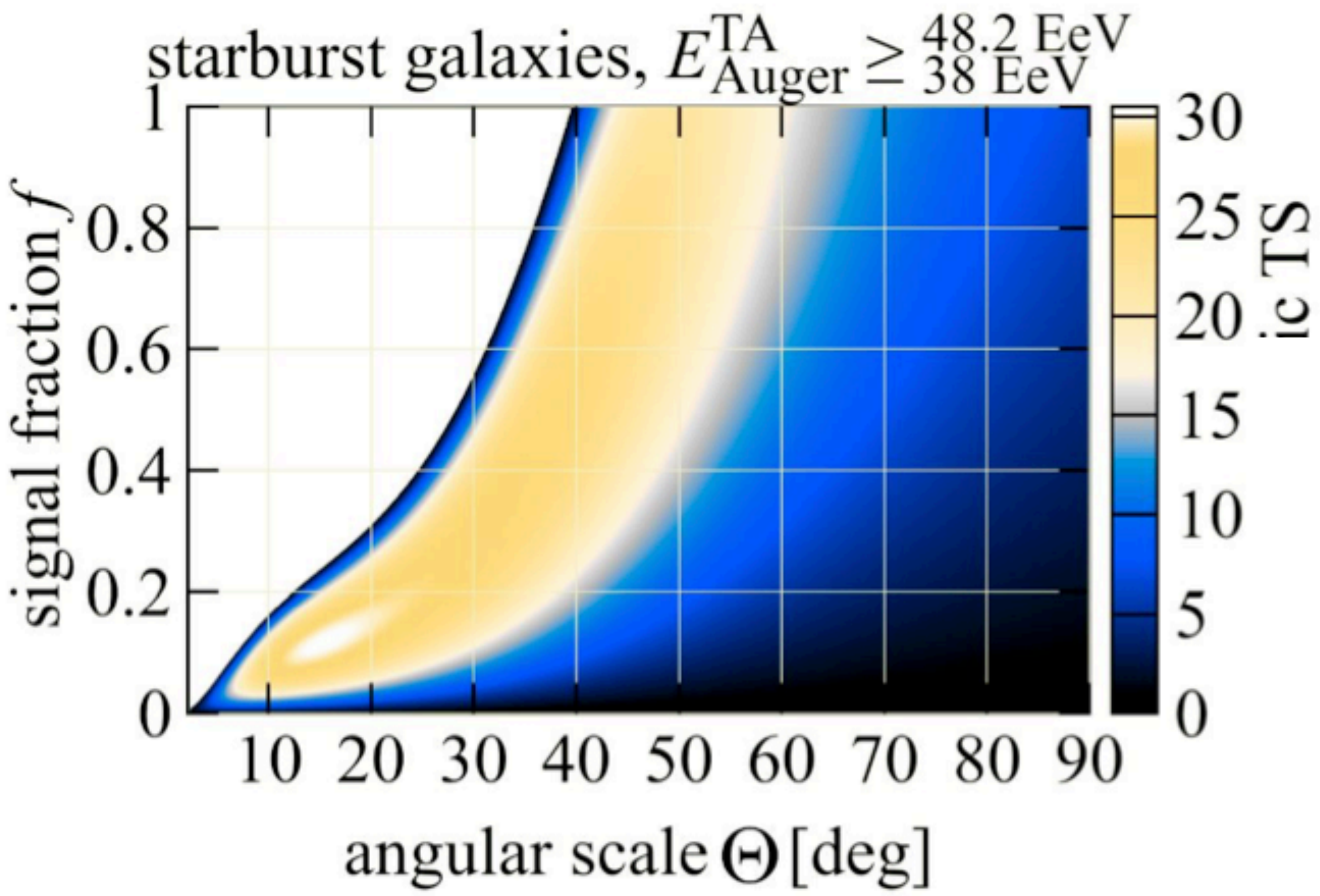
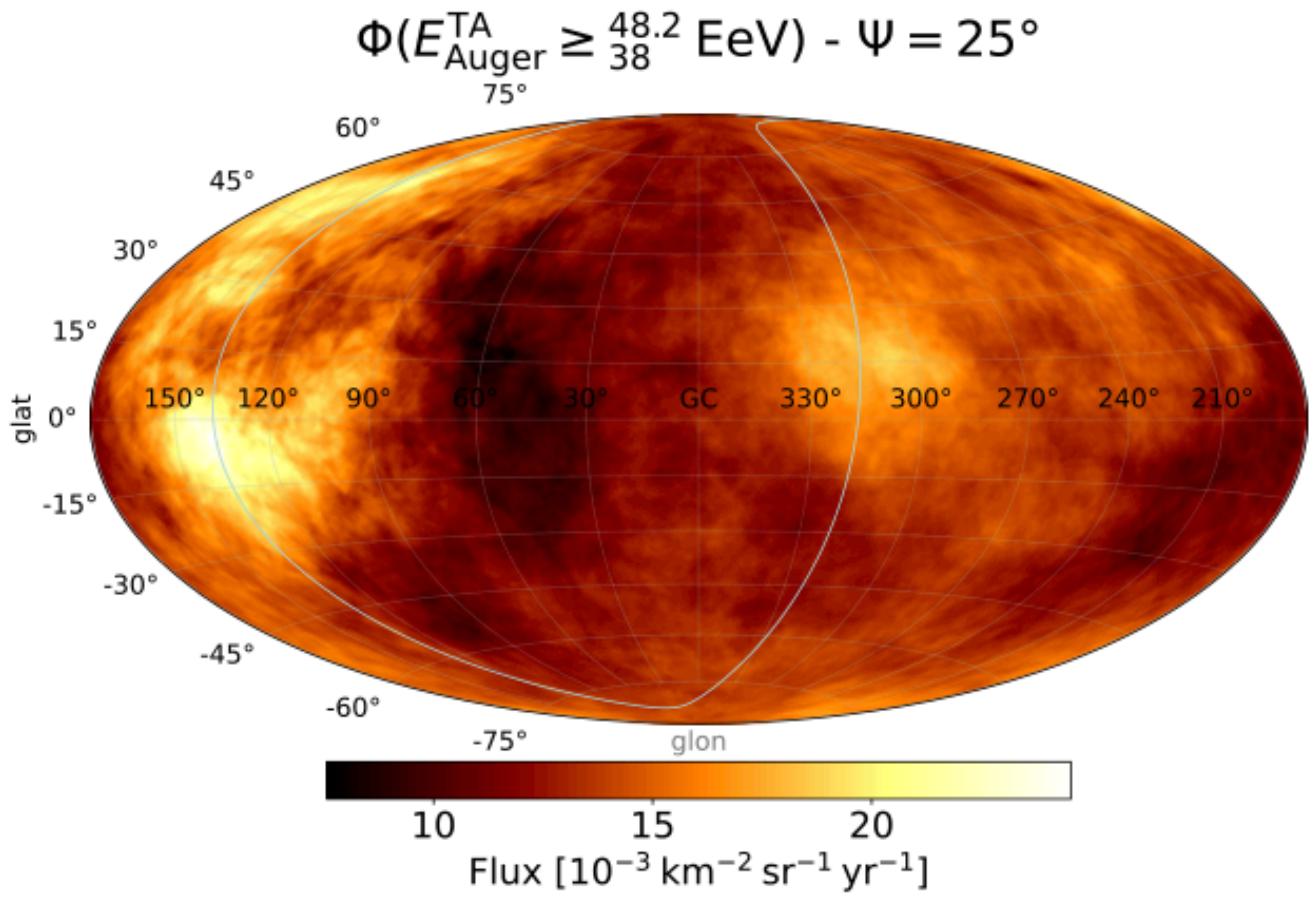
- Catalogs are used to compare the arrival directions with positions of source classes
  - The contribution of each object is weighted based on its relative flux in the band chosen for each catalog
  - Parameters: angular width and relative weight



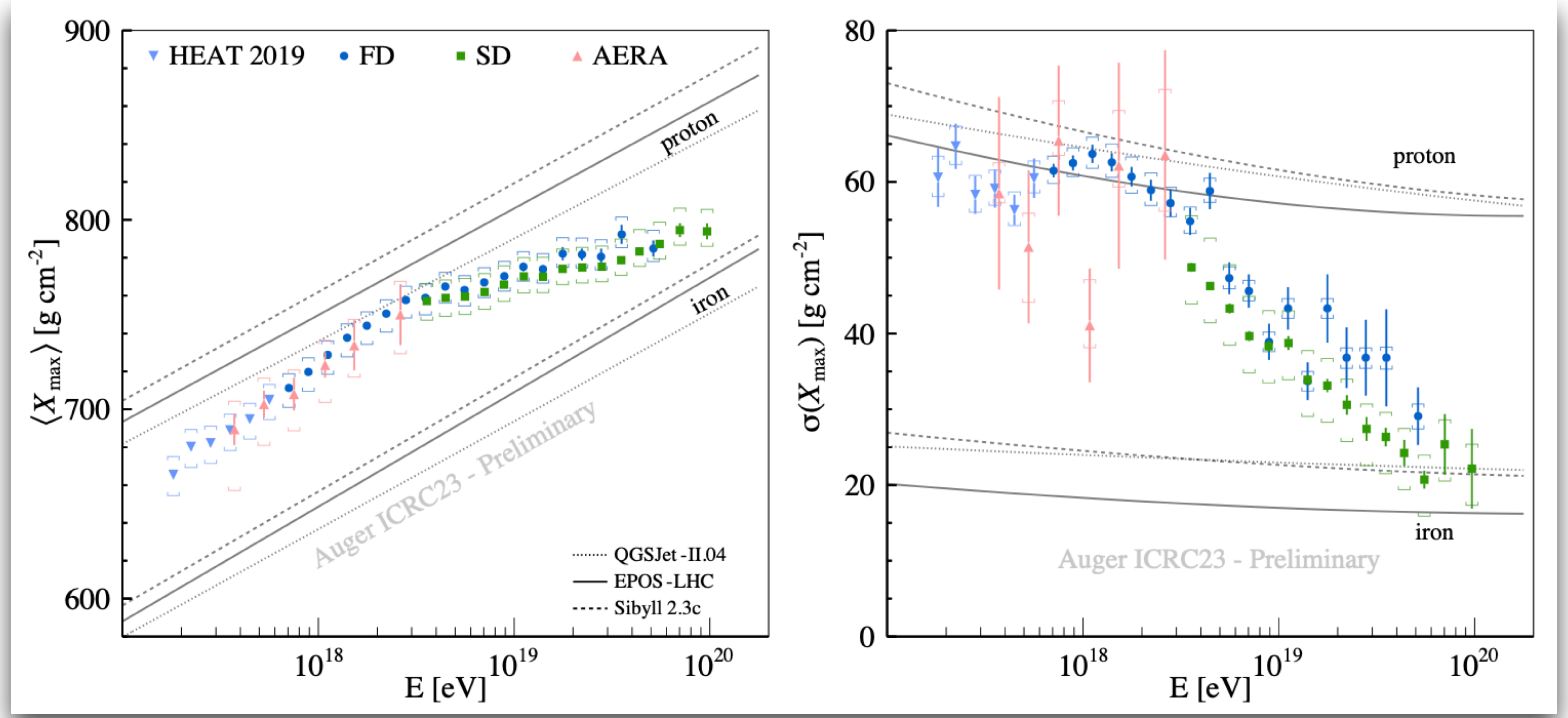




- **Significance of Starburst catalog: 4.6 sigma**
- Spots in the southern hemisphere (Centaurus region) and in the northern hemisphere (two spots: Perseus-Pisces region and Ursa Major region)

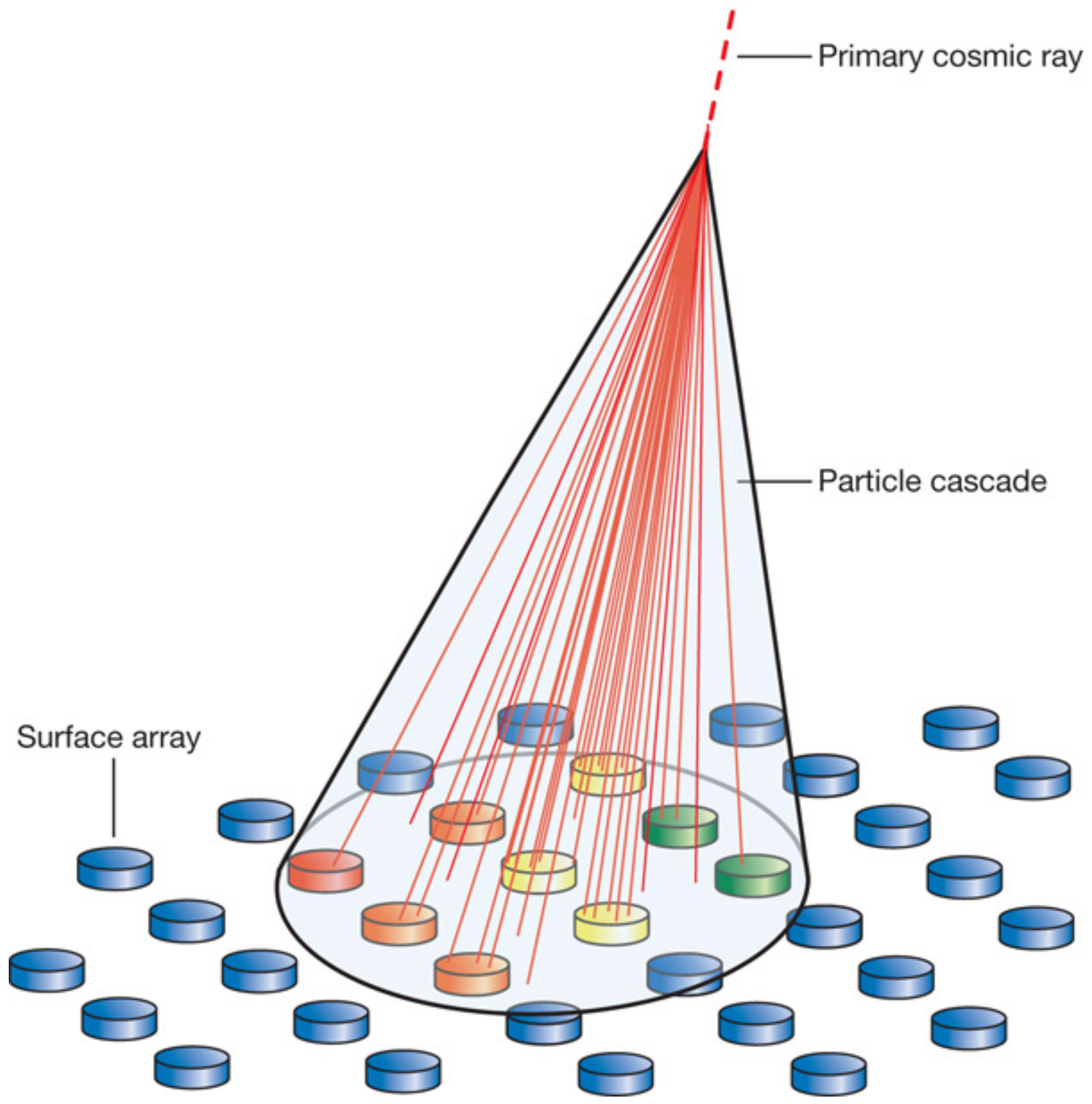
THE UHECR MASS COMPOSITION

The Pierre Auger Collab. ICRC23



Mass composition observables from the

- **longitudinal profile**
- **lateral distribution**
- **radio** measurements



Independently from the hadronic interaction model:

- From the first moment: the mean mass of the nuclei decreases and then increases with energy
- From the second moment: the flux increases in purity as the energy increases

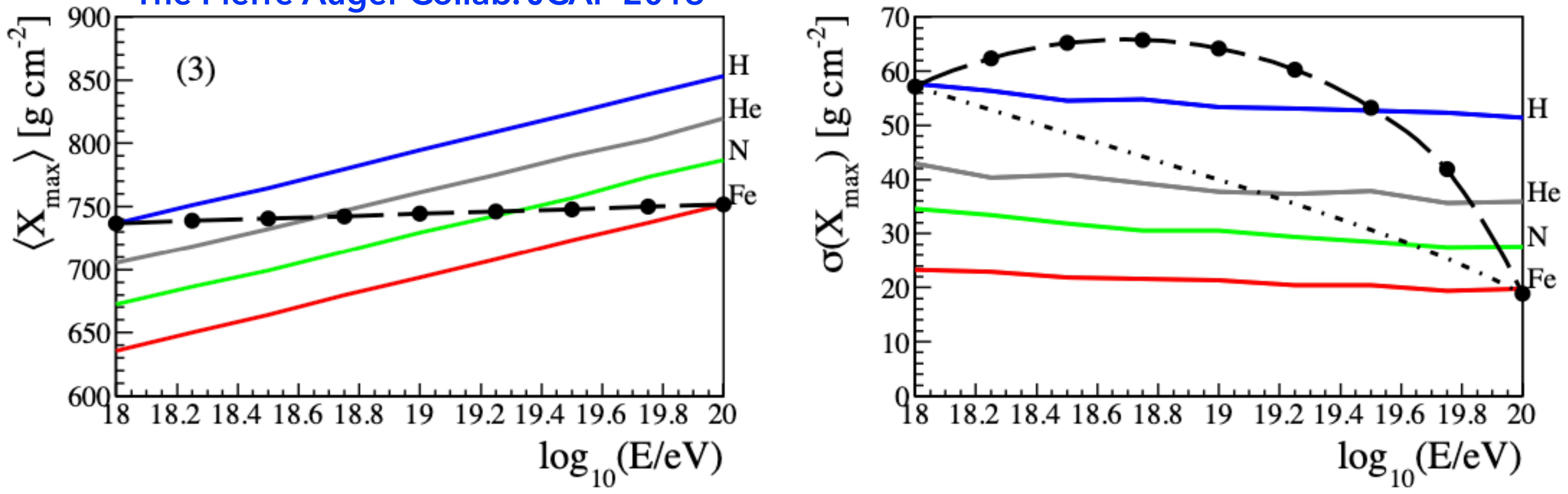
LEARNING FROM THE MASS COMPOSITION

$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f \, \langle \ln A \rangle$ $\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f^2 \, \sigma^2(\ln A)$

Focusing on the second moment: it contains

- the shower-to-shower fluctuations (first term) AND
- the dispersion of the masses as they hit the Earth atmosphere:
  - spread of nuclear masses at the sources
  - modifications that occur during their propagation to the Earth

The Pierre Auger Collab. JCAP 2013

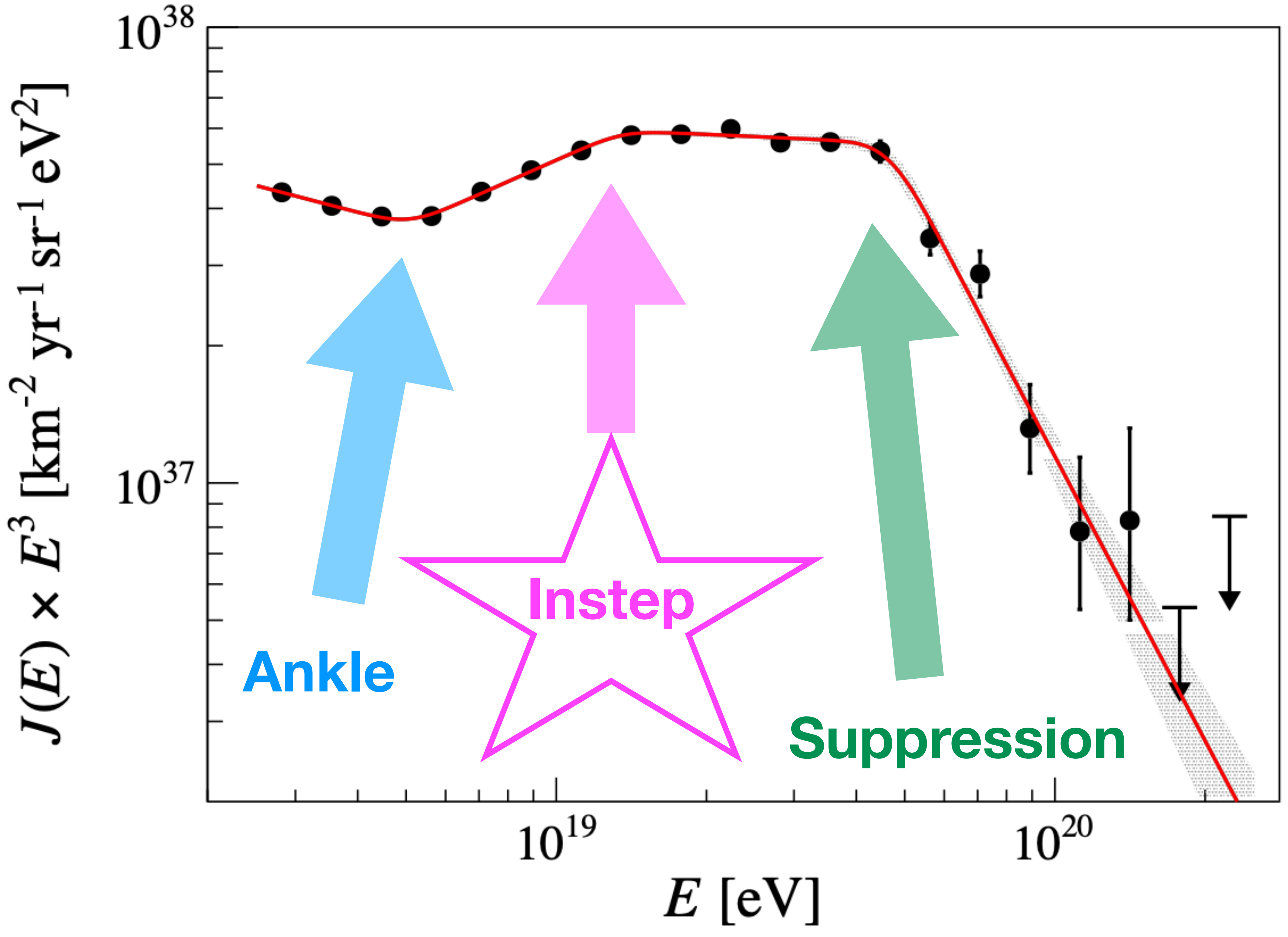


- Example for H and Fe masses, fraction of H decreasing linearly with energy

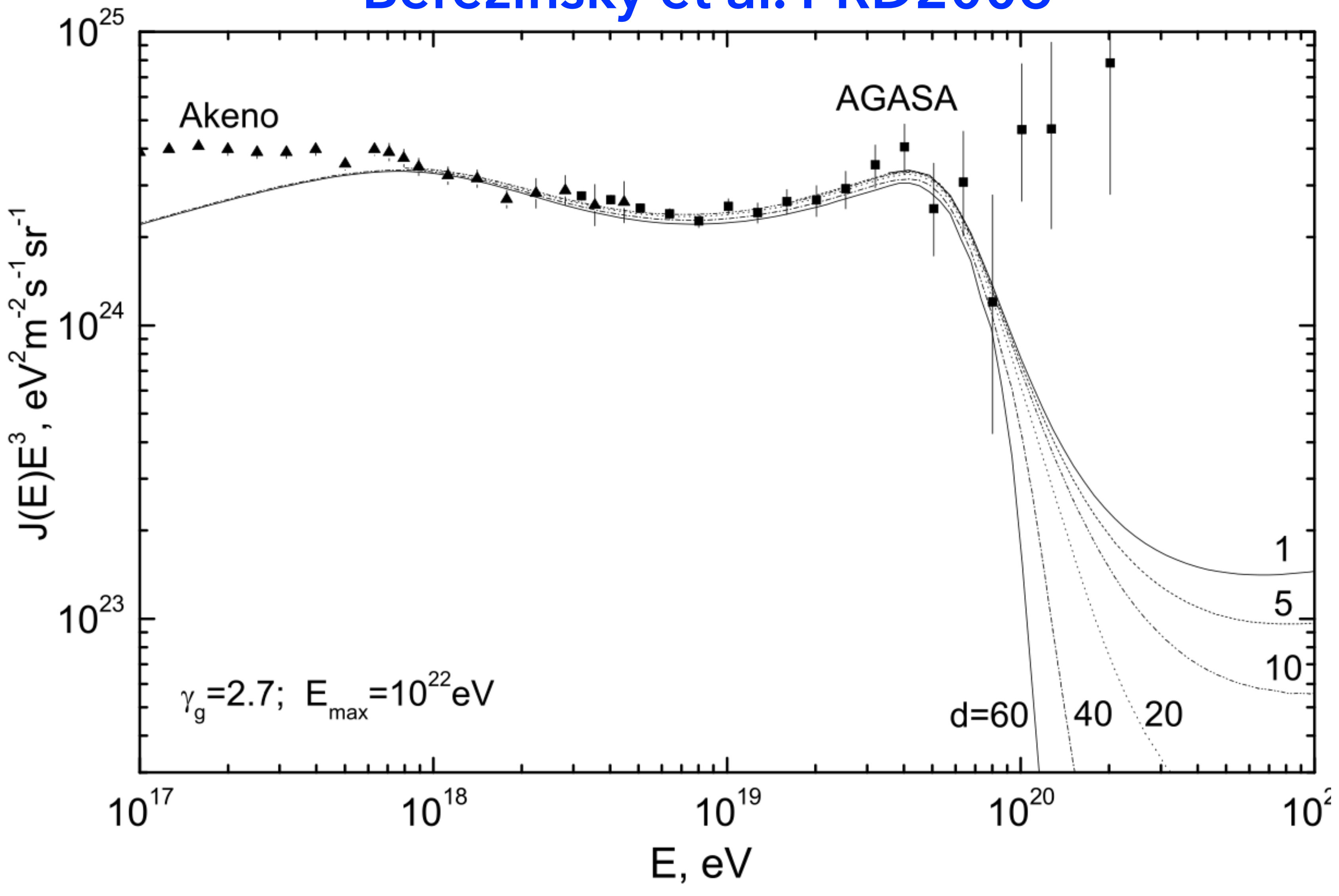
THE ASTROPHYSICAL PICTURE

ASTROPHYSICAL INTERPRETATION(S)

The Pierre Auger Collab. PRD2020

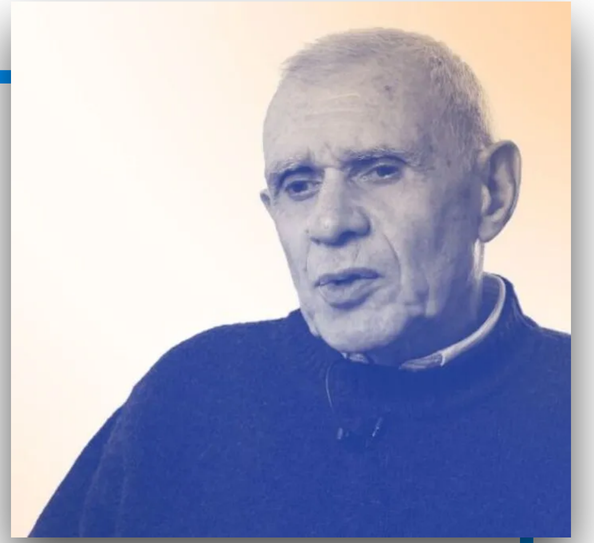


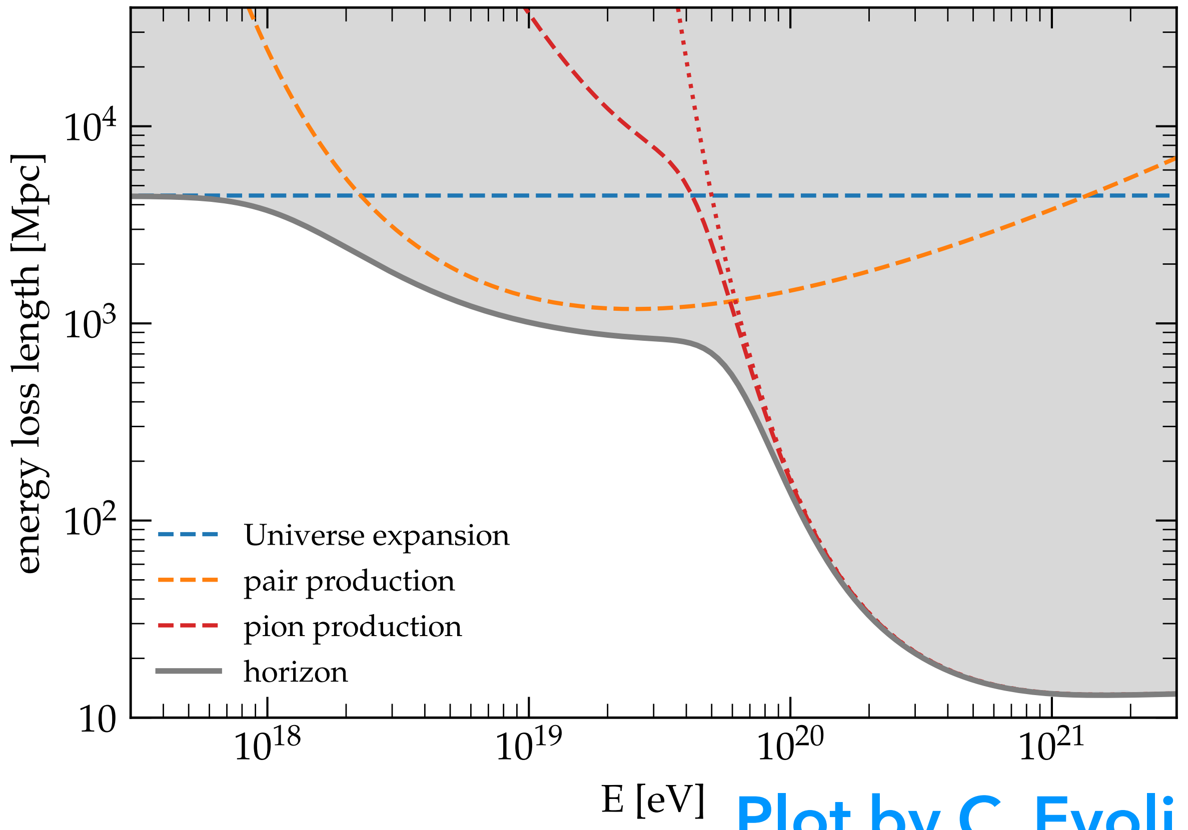
Berezinsky et al. PRD2006



- Identical sources, uniformly distributed
- Pure protons at emission, power law-spectrum

V. Berezinsky, 1934-2023

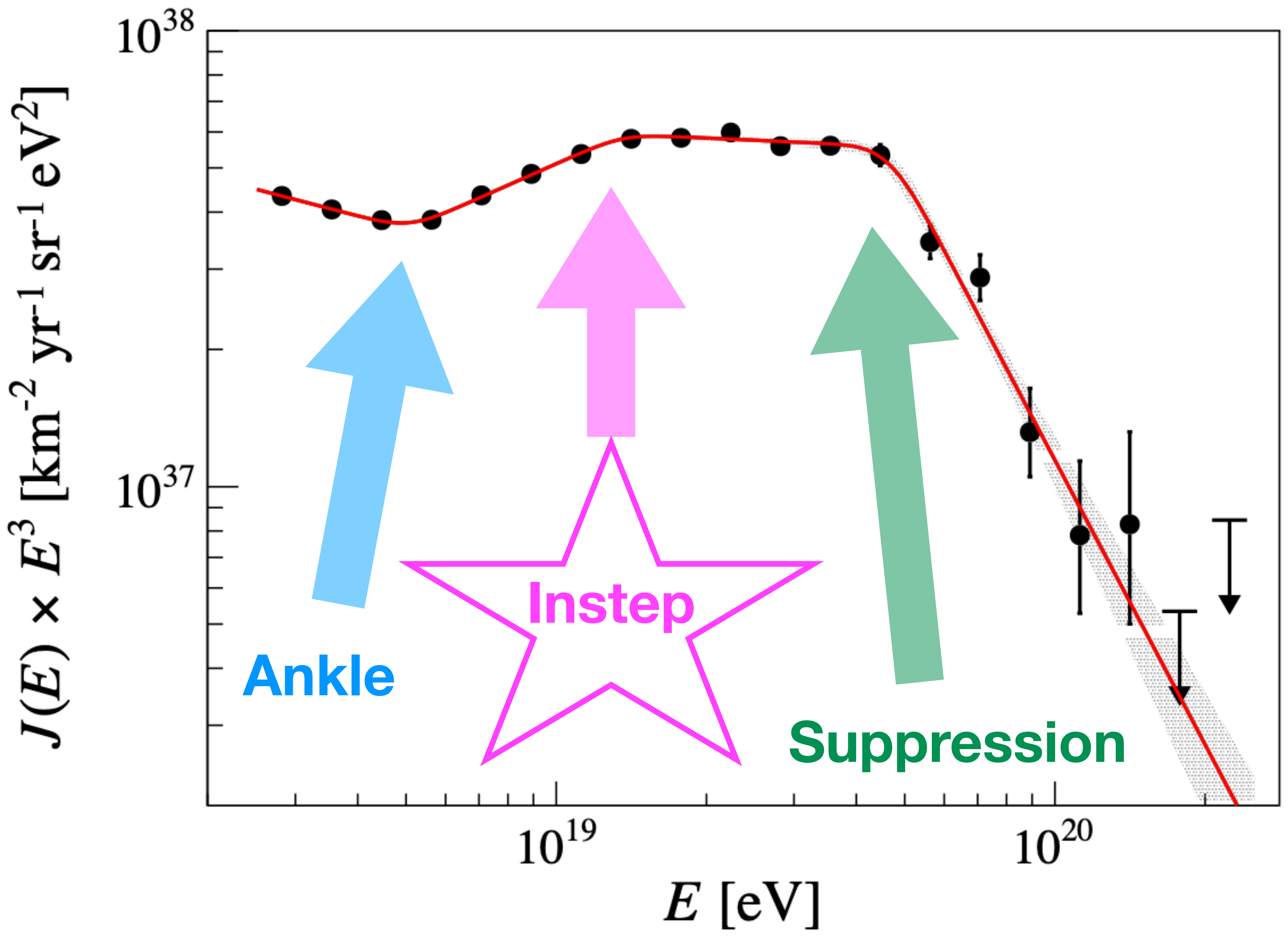




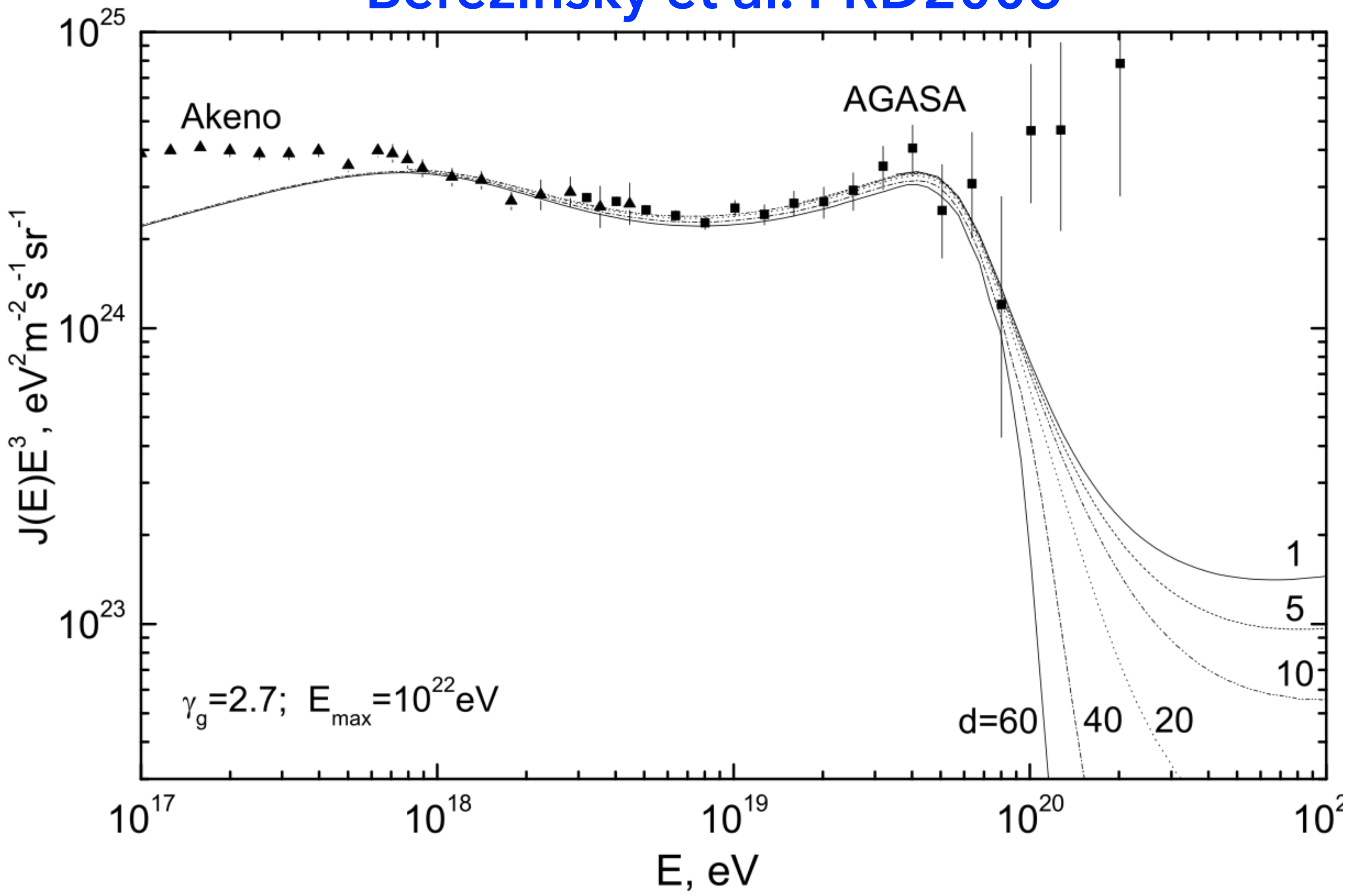
Plot by C. Evoli

ASTROPHYSICAL INTERPRETATION(S)

The Pierre Auger Collab. PRD2020



Berezinsky et al. PRD2006



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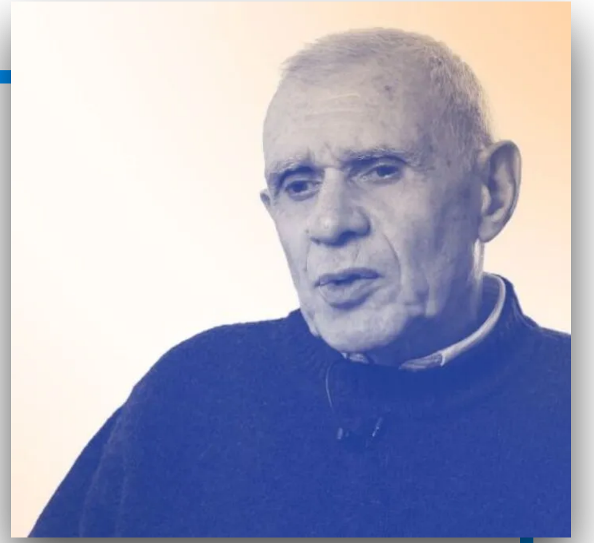

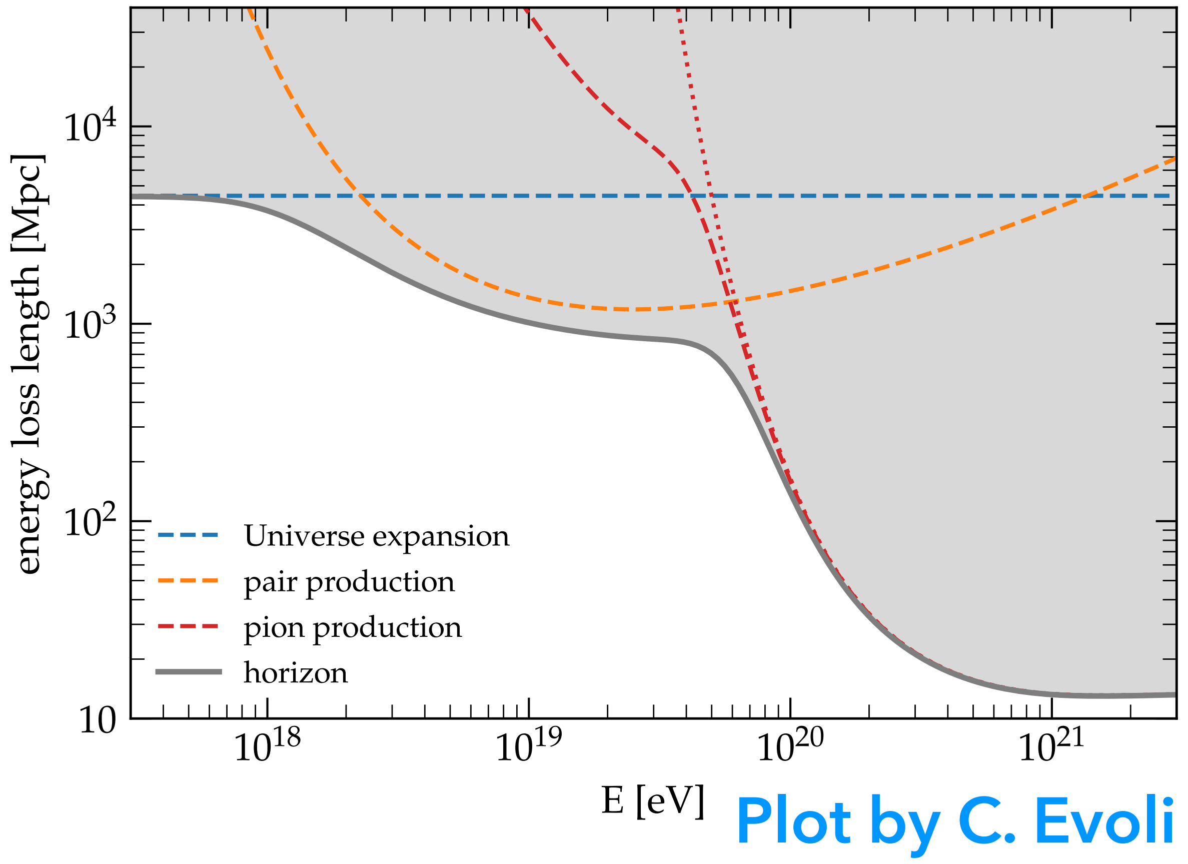

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- Identical sources, uniformly distributed
- Pure protons at emission, power law-spectrum

"**Dip model**" interpretation is challenged due to

- Evidence for heavier mass composition
- Sharpness of the ankle feature
- Instep not explained

- Extended range of nuclear species to be considered at the source
- Consider more than one source population?

ASTROPHYSICAL INTERPRETATION(S)

Basic scenario:

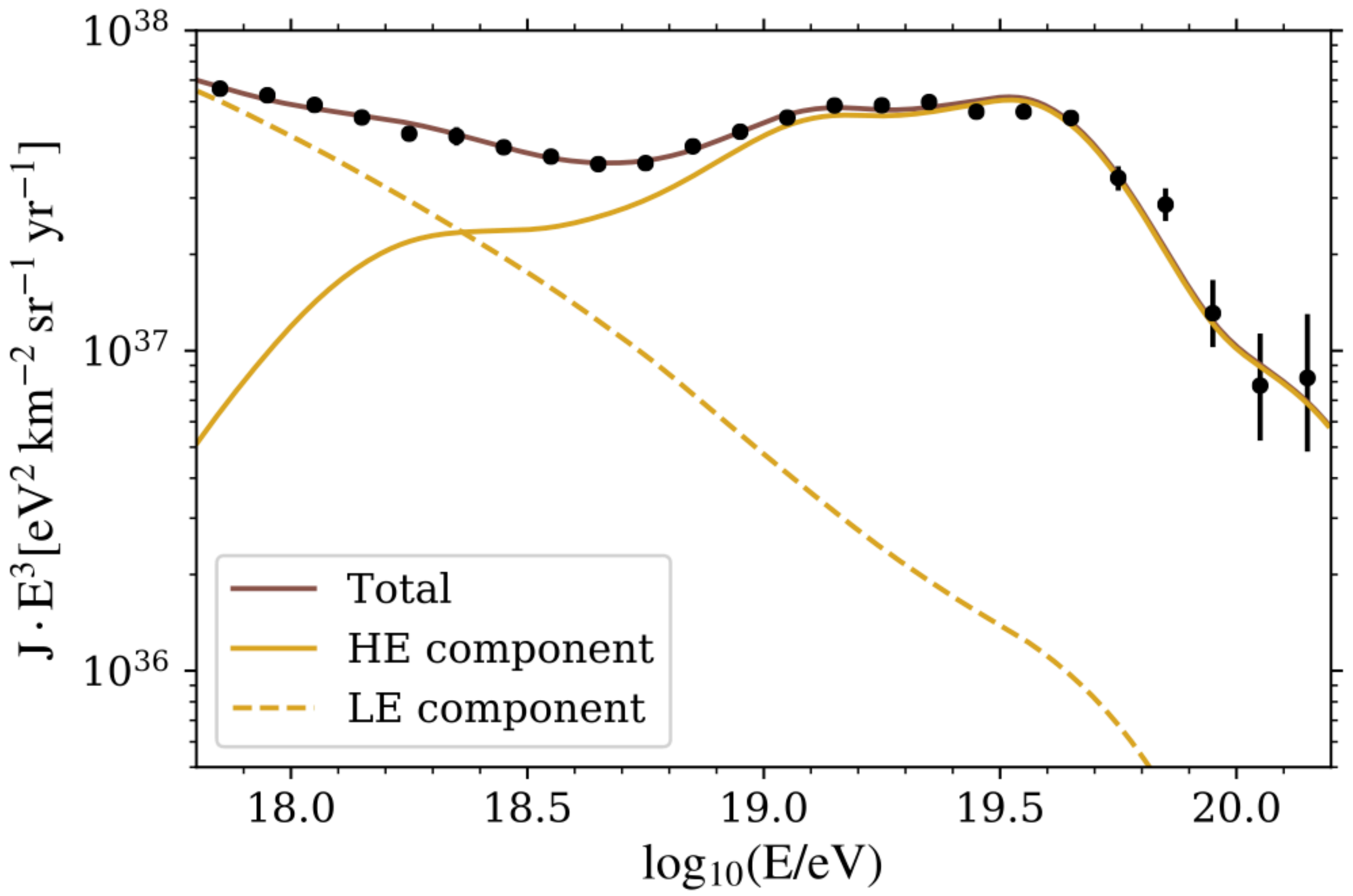
- identical sources
- power-law spectra at escape, with rigidity dependence

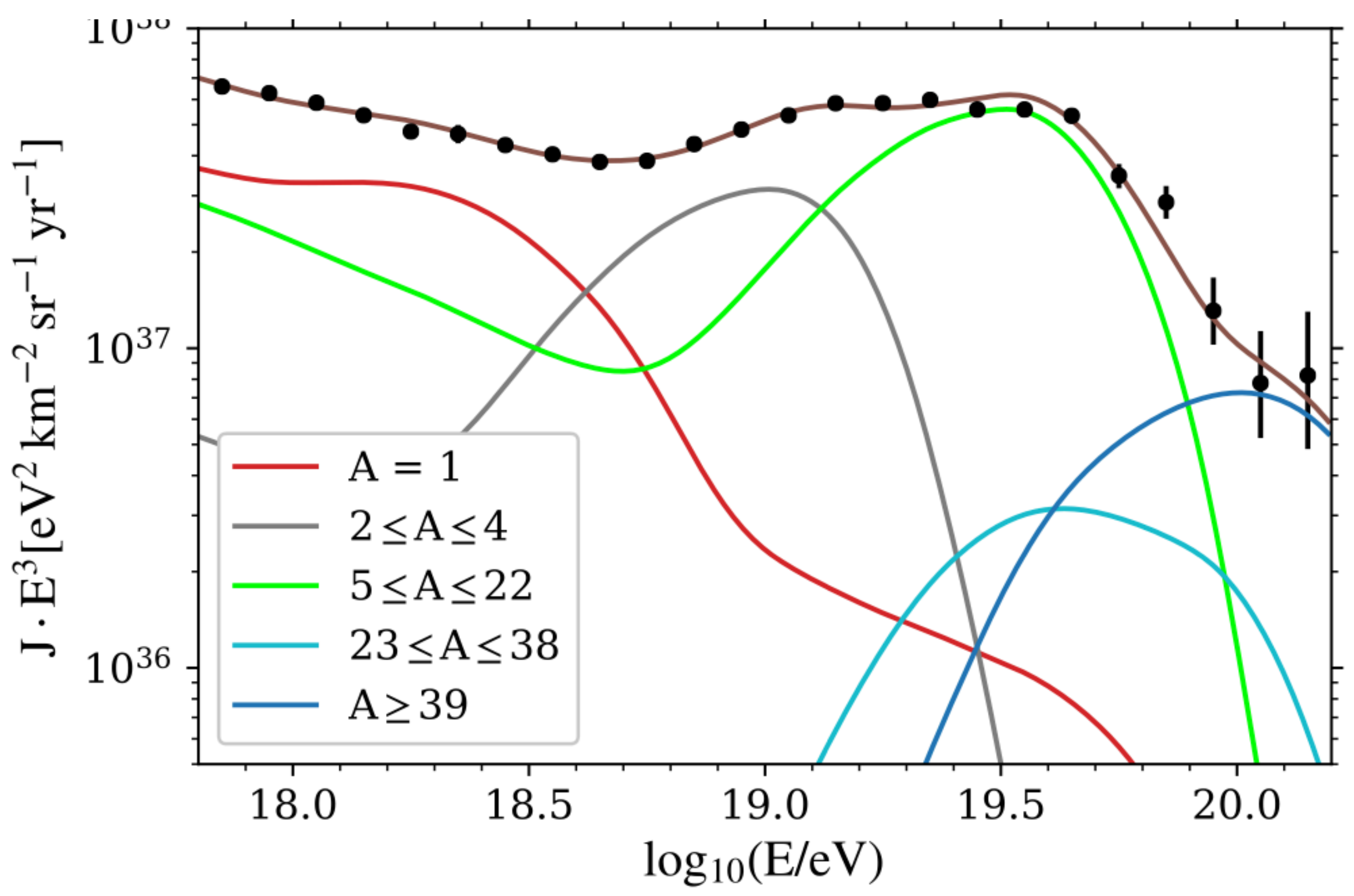
Extragalactic propagation taken into account; results presented in this talk are obtained with:

- **SimProp**, Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017
- **CRPropa**, R. Alves Batista et al JCAP2022

ASTROPHYSICAL INTERPRETATION(S)

Different populations of sources contributing at LE and HE





Aloisio et al, JCAP 2014; Mollerach & Roulet PRD 2020; **The Pierre Auger Collab. JCAP 2023**

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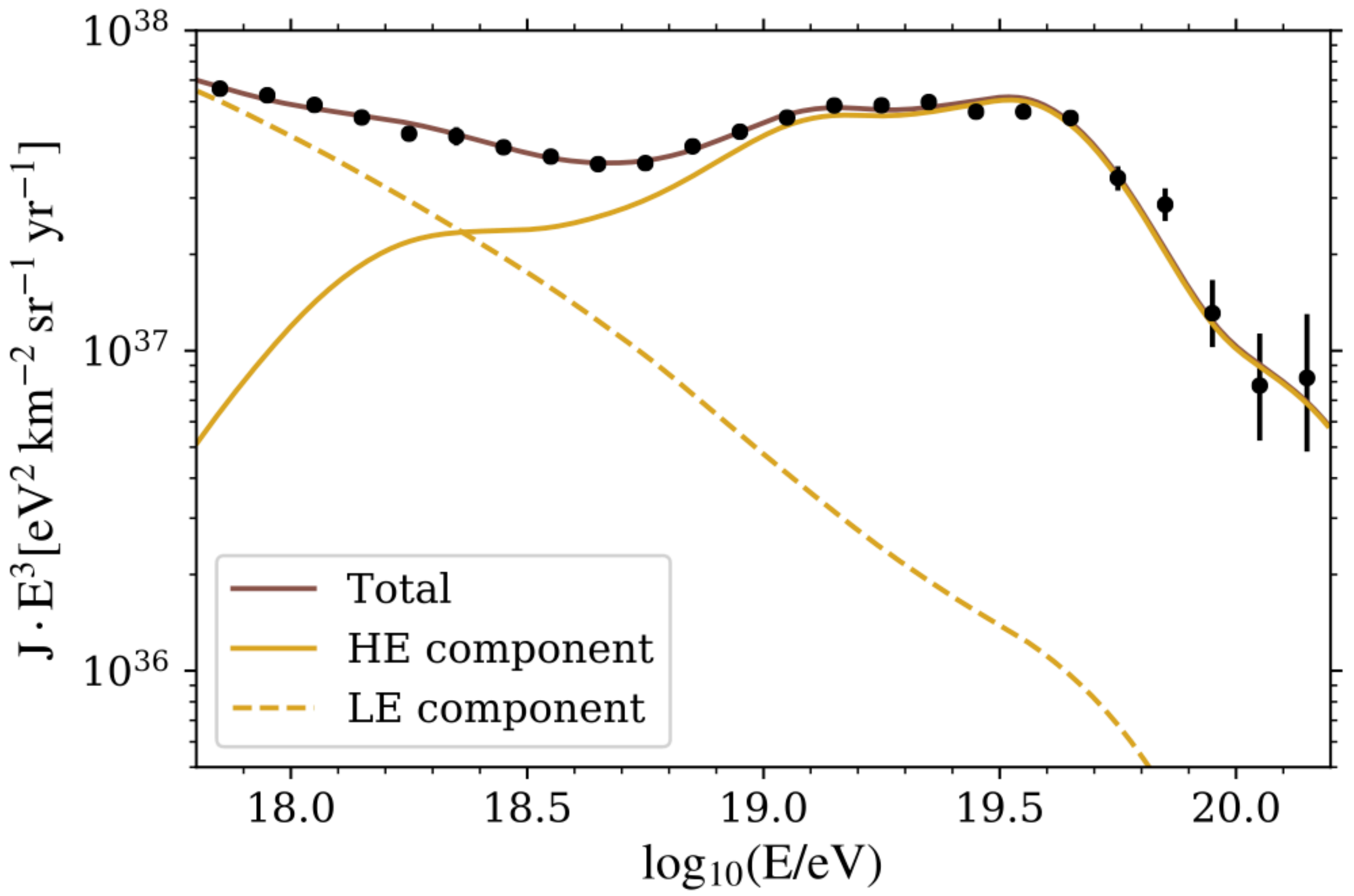

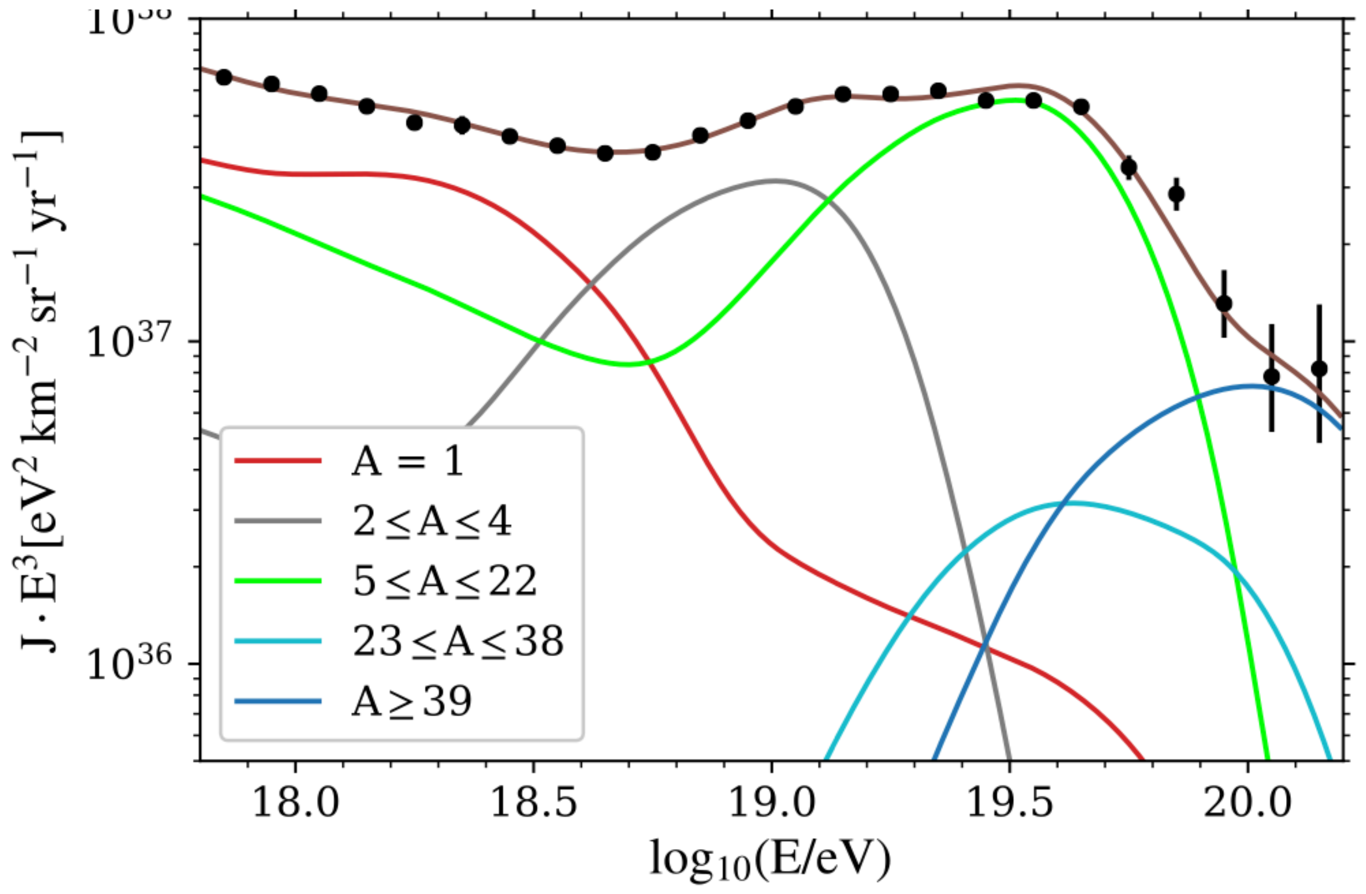

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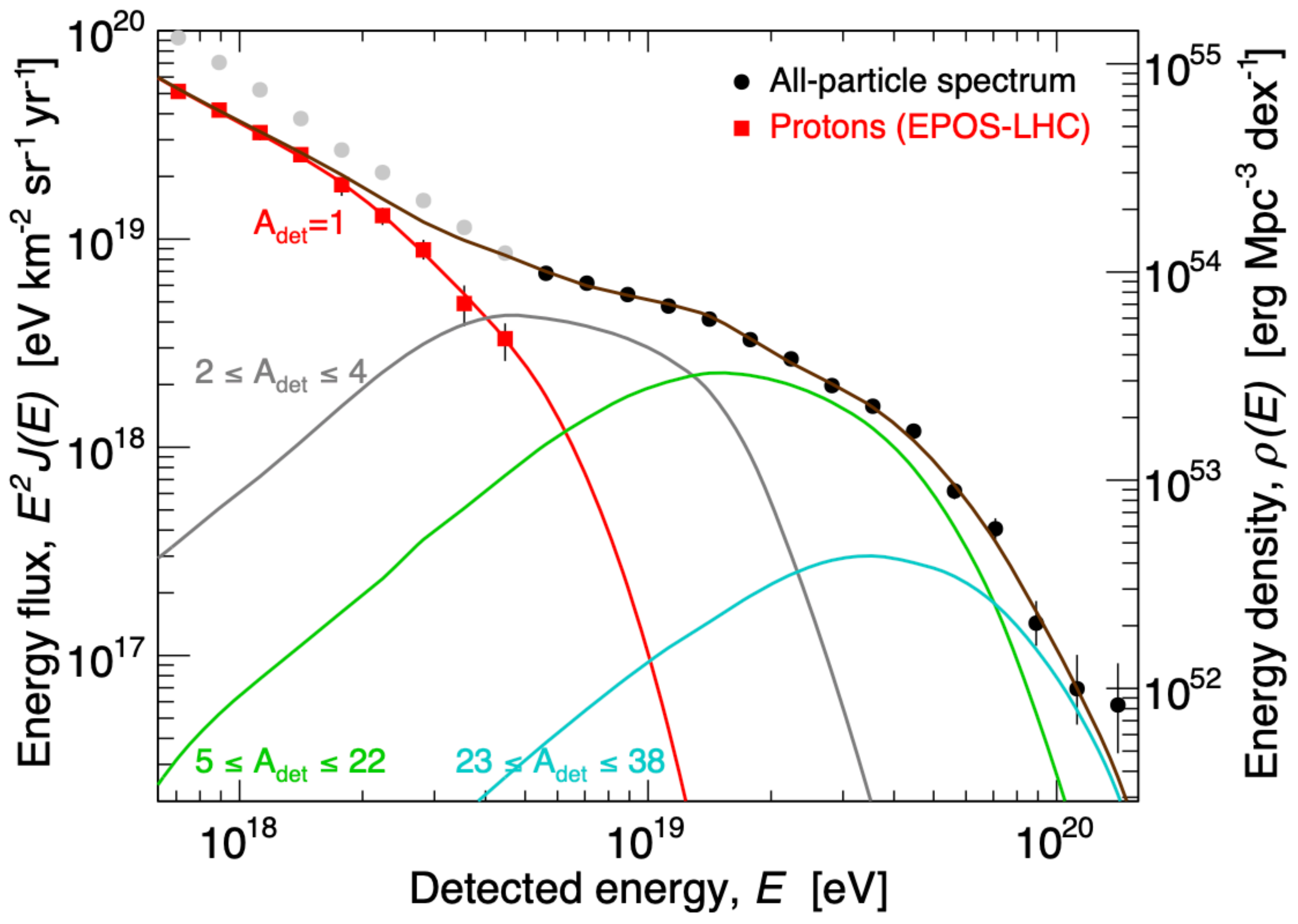
One population of sources, softer spectrum of protons due to in-source interactions



Contribution from <u>heavier particles below the ankle</u> needed to account for

- mixed composition
- missing flux

Luce et al, ApJ 2022

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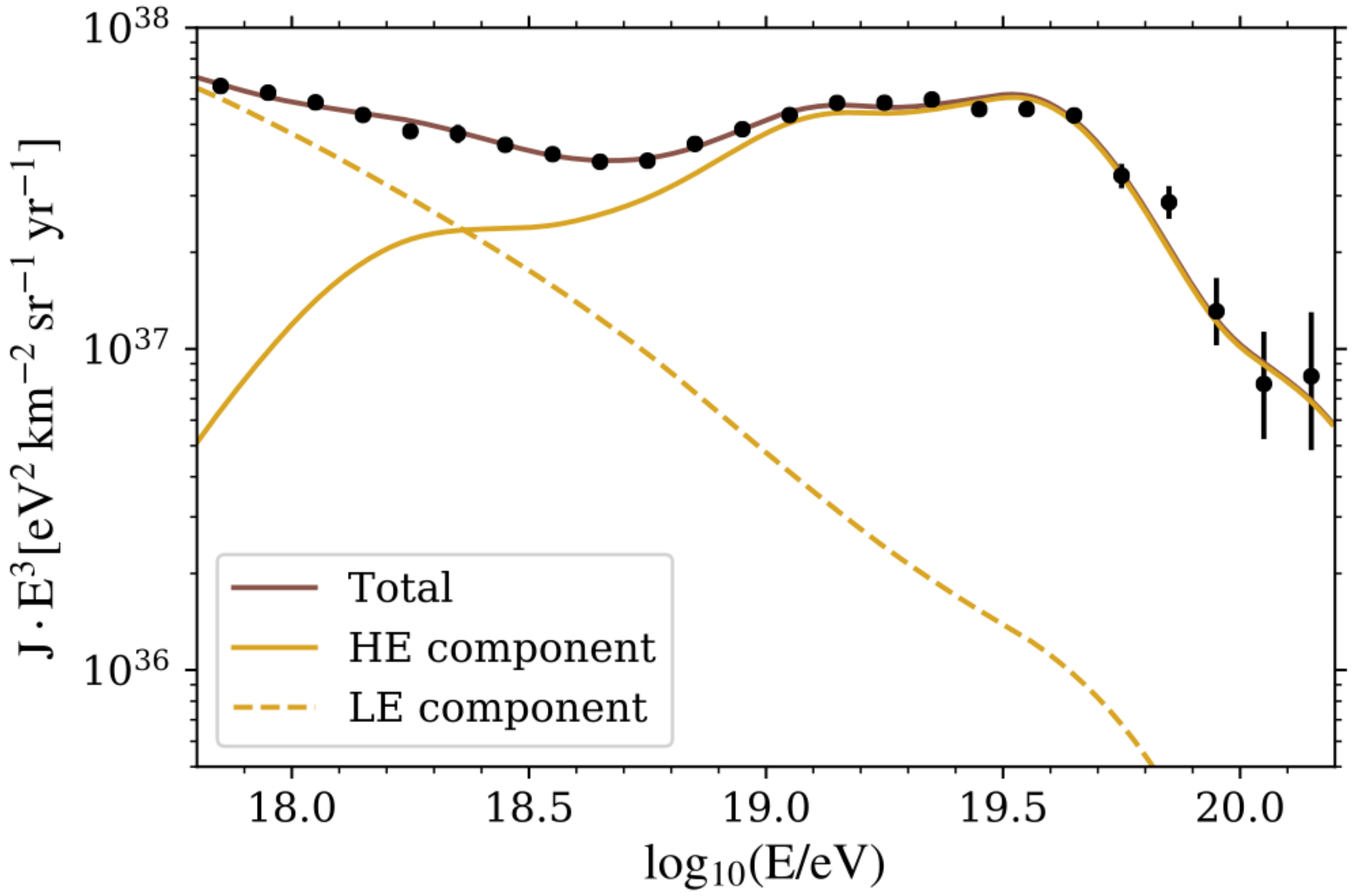

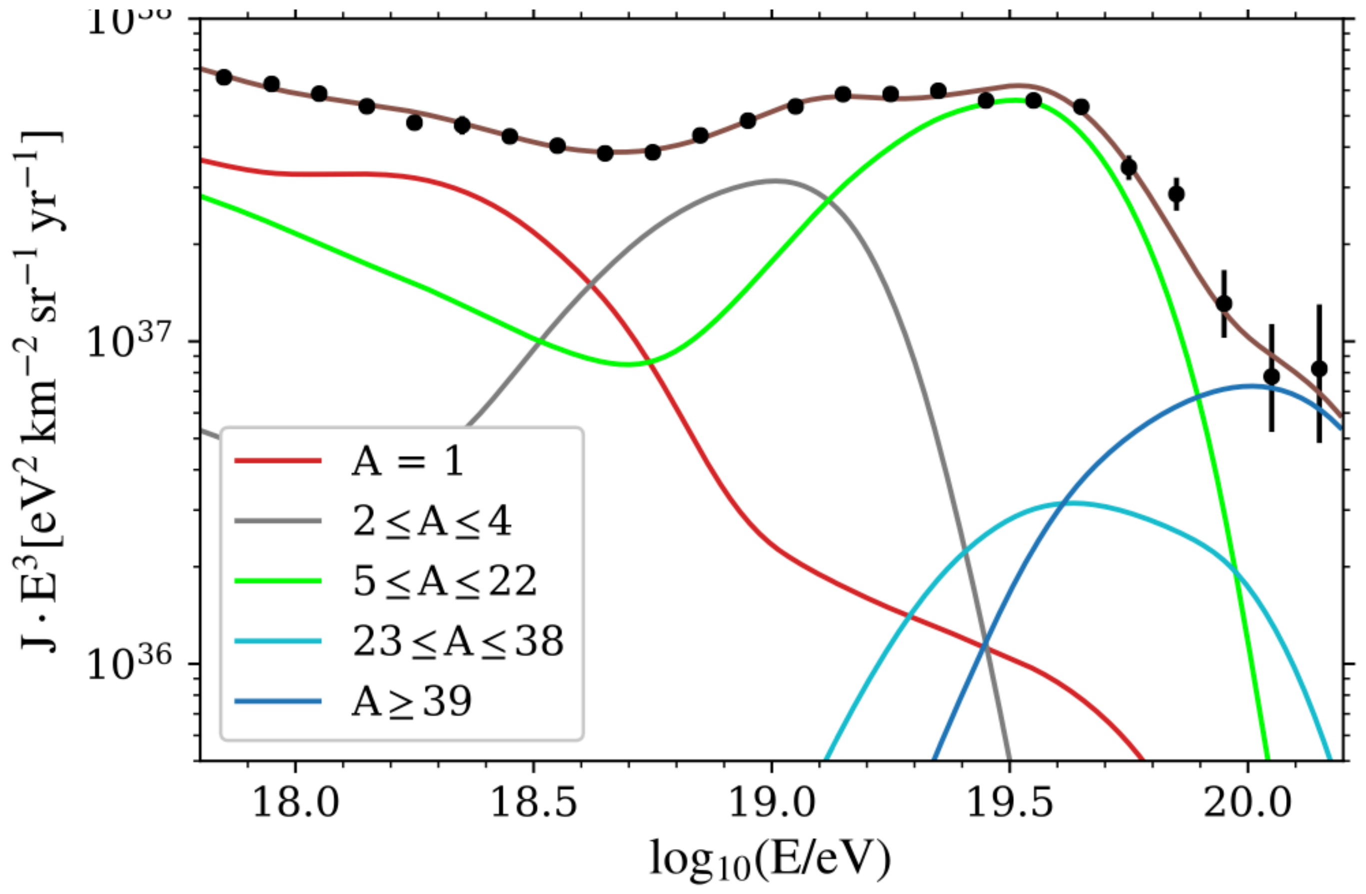

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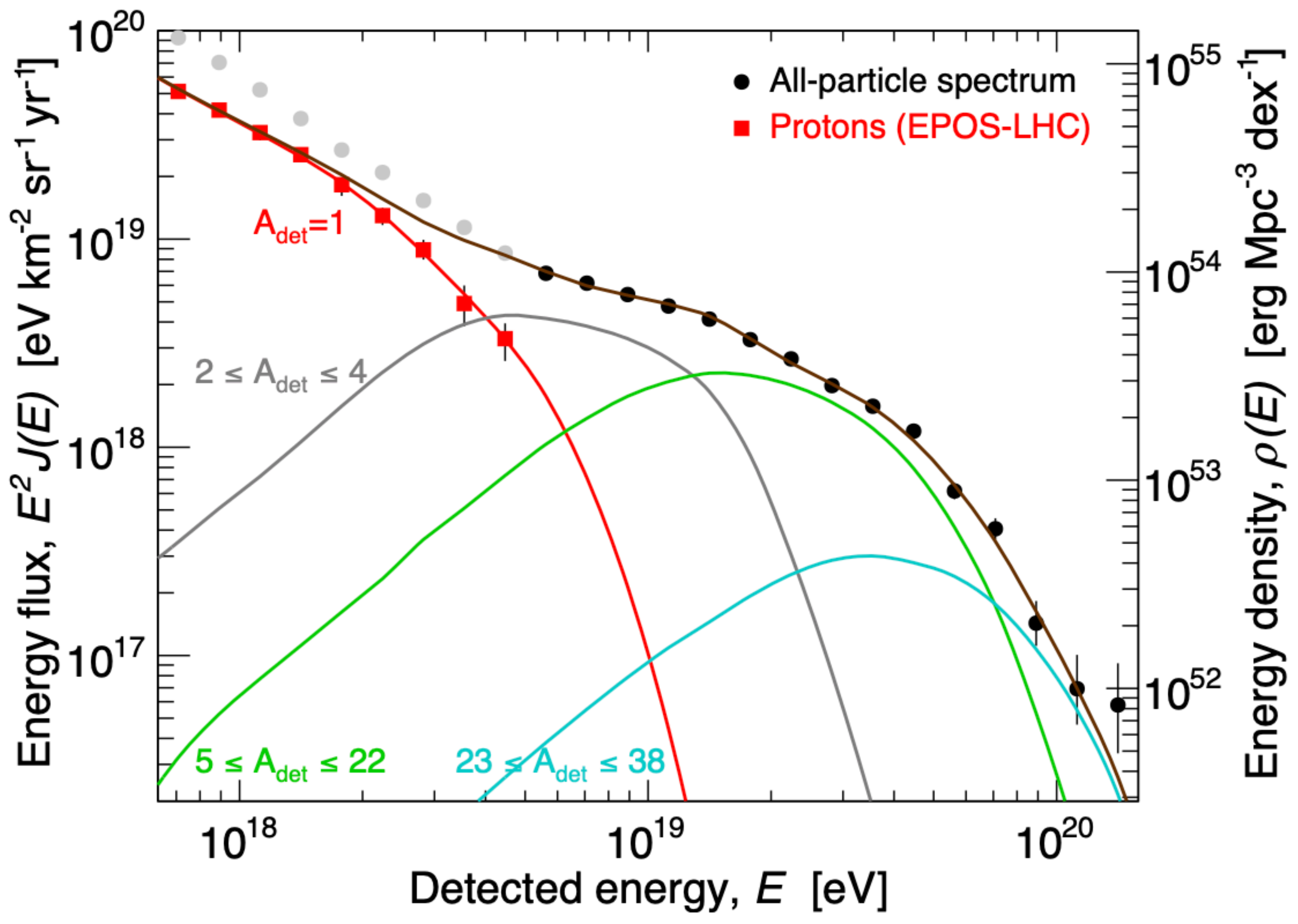

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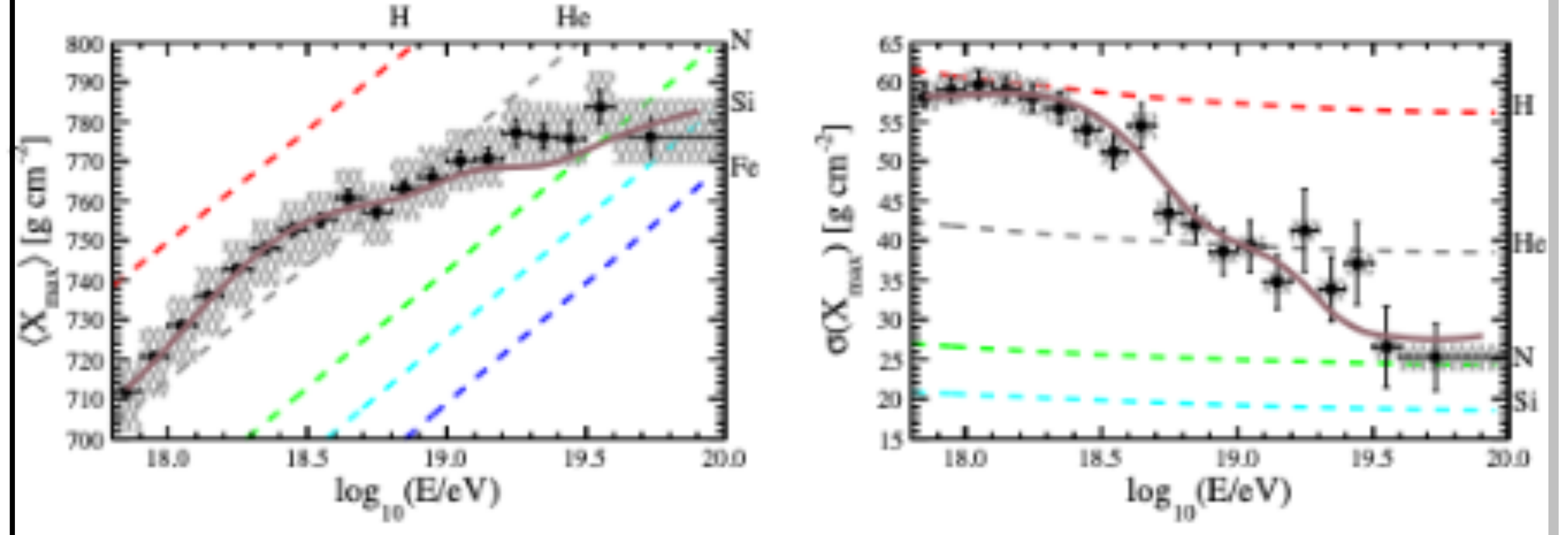
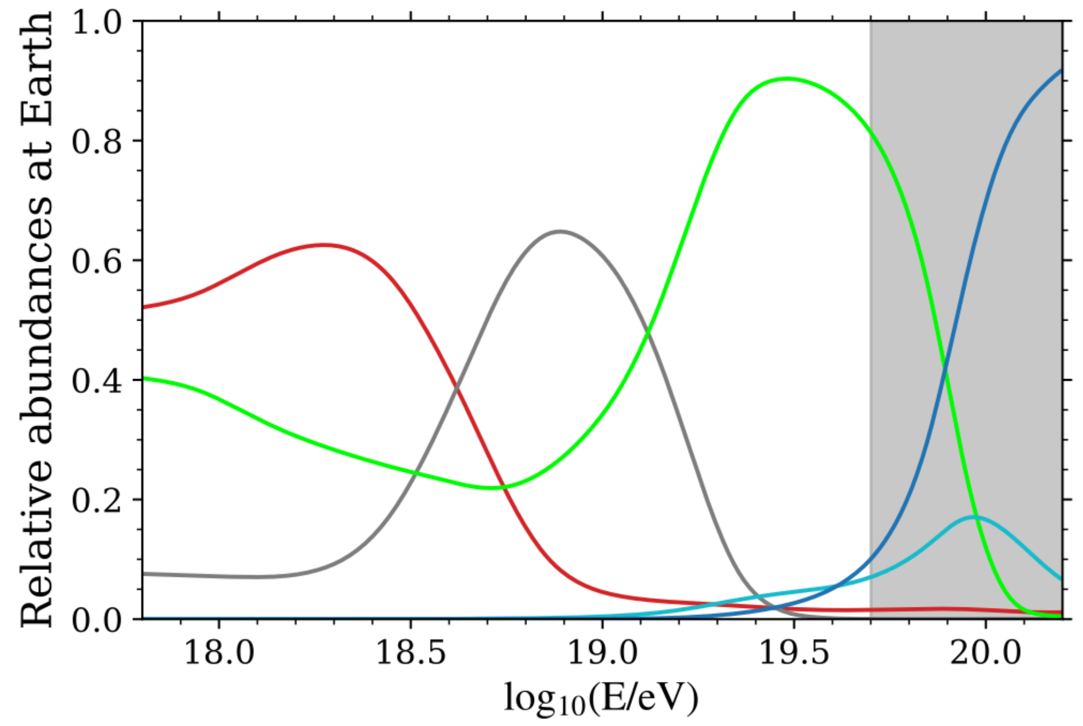
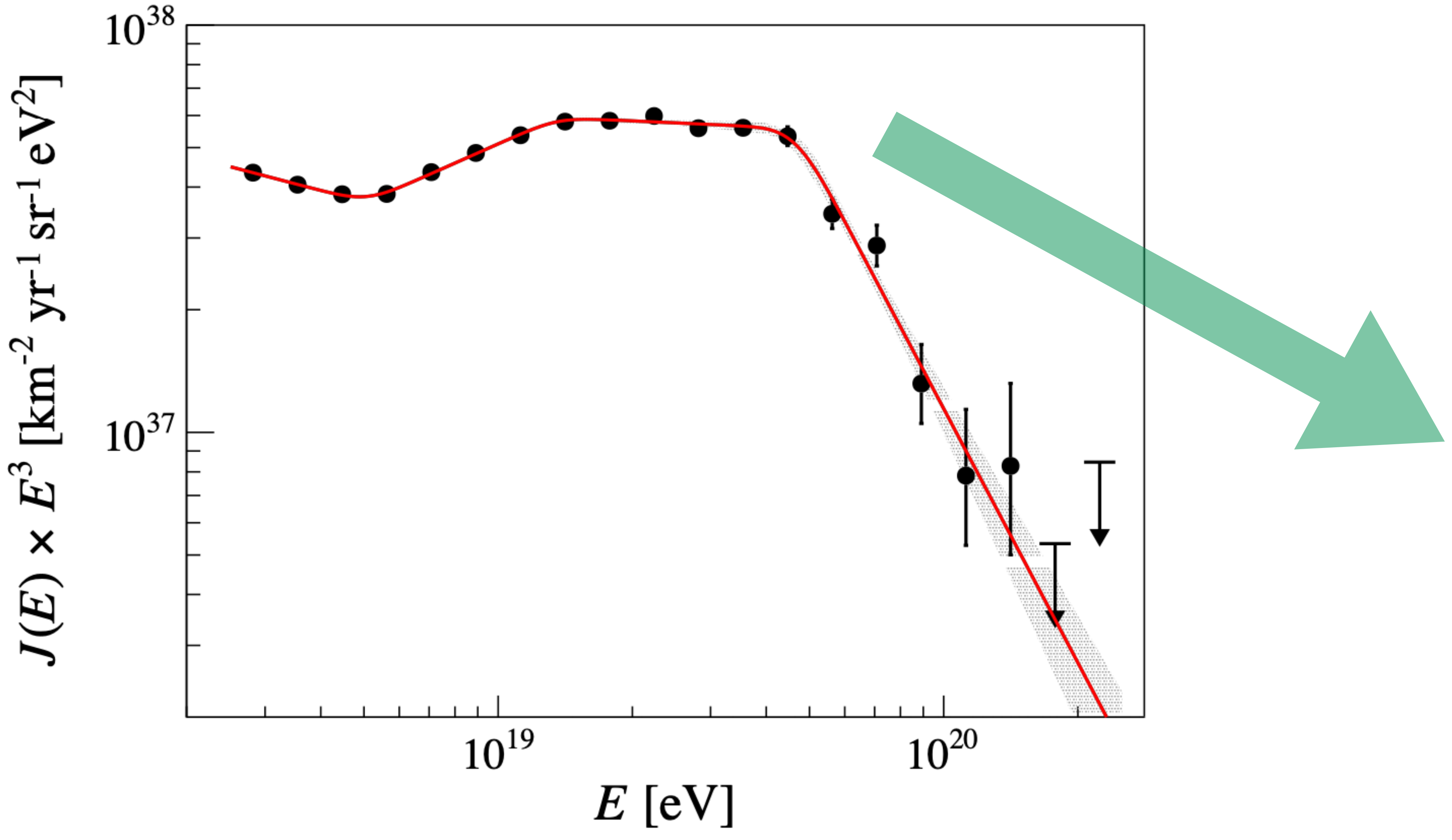


- Independently of the scenario, decreasing fluctuations of Xmax can be found corresponding to **limited mixing of spectra of different nuclear species at HE**, meaning
  - HE: hard spectra + low rigidity cutoff
  - LE: soft spectra + rigidity less constrainable



WHAT IS THE ORIGIN OF THE SPECTRUM (AND COMPOSITION) FEATURES ?

The Pierre Auger Collab. JCAP 2023



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In terms of interpretation the **suppression**,

- Propagation effect
- Indication of source power

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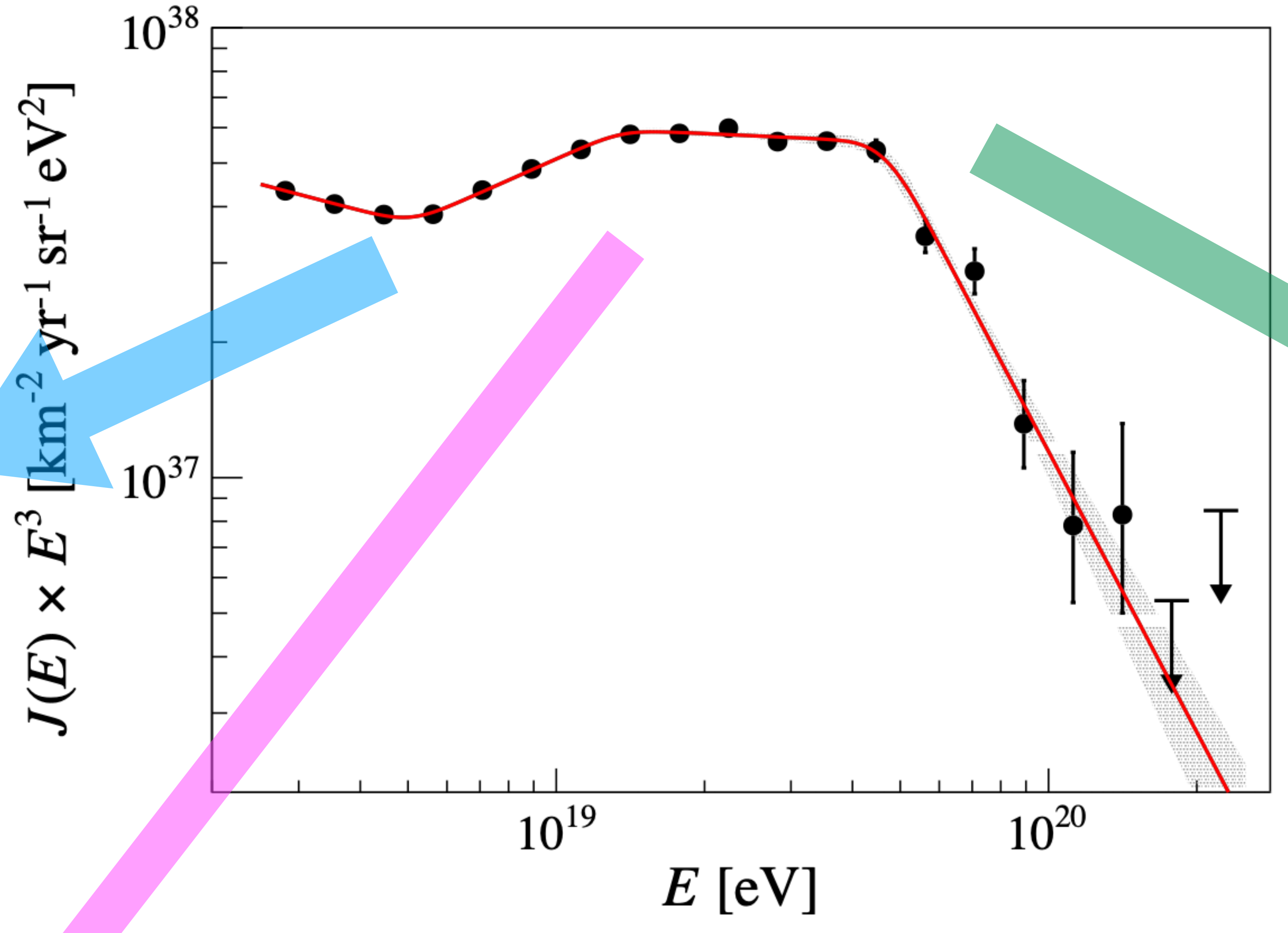
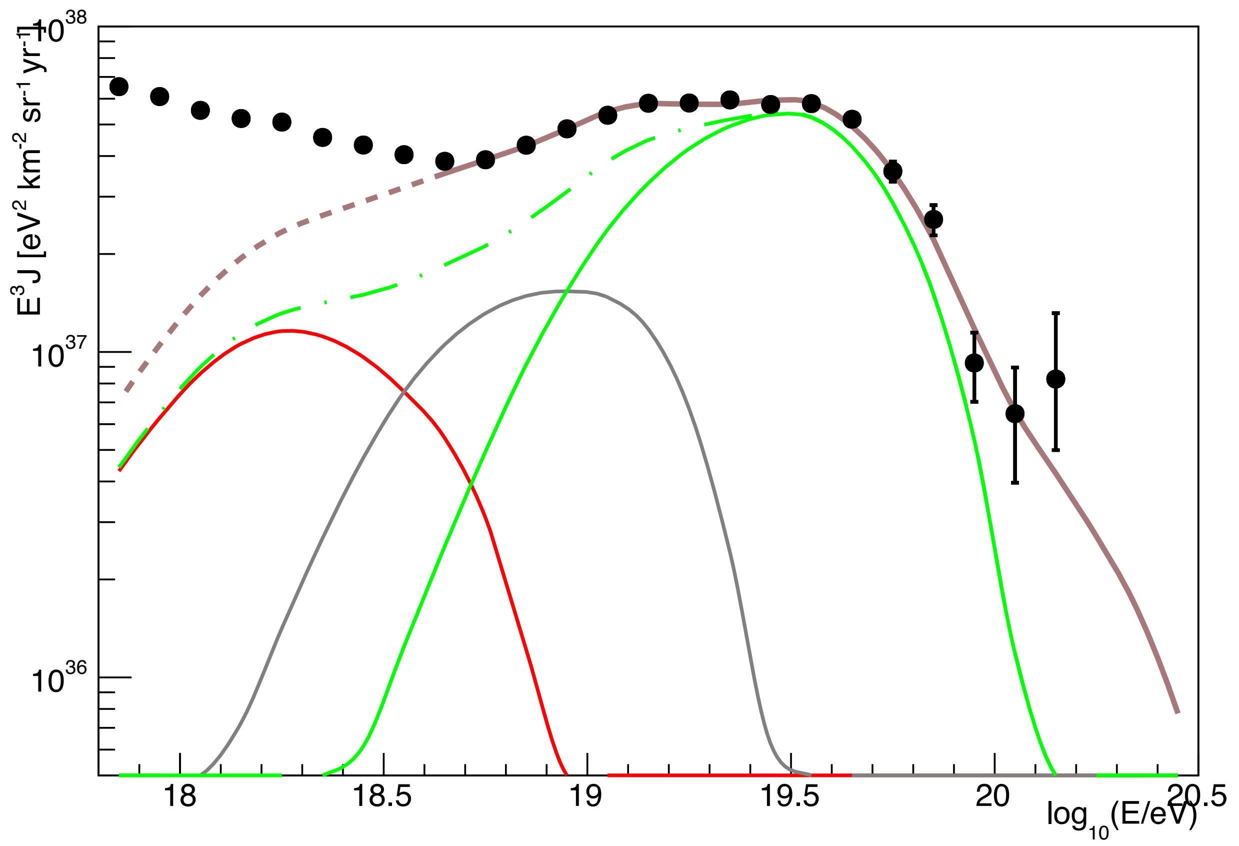


Ankle: interplay between (soft) LE and (hard) HE components

- Different populations of UHECR sources
- In-source interactions

Instep: interplay between the flux contributions of the He and CNO components injected at the source with their distinct cut-off energies, shaped by photodisintegration during the propagation



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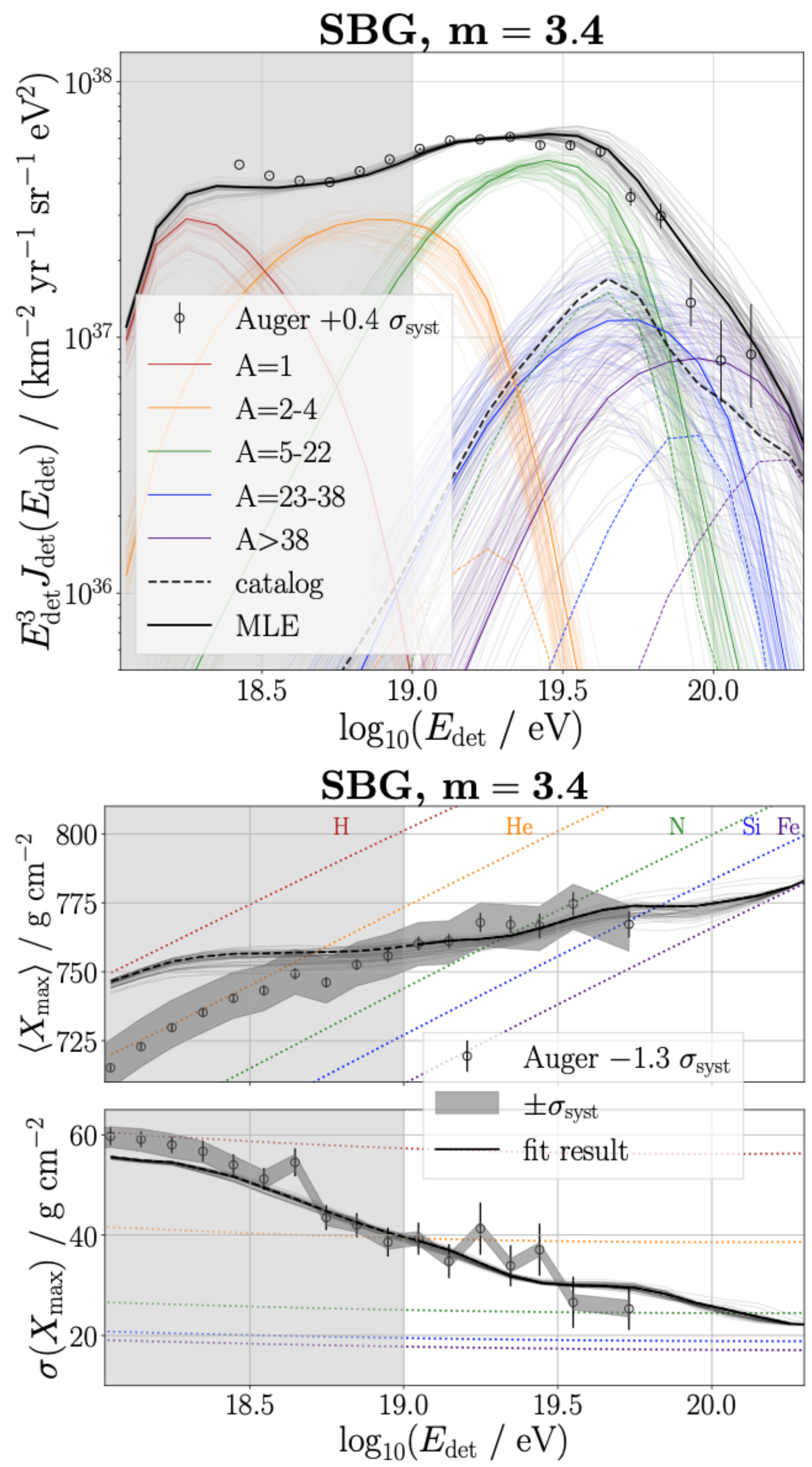
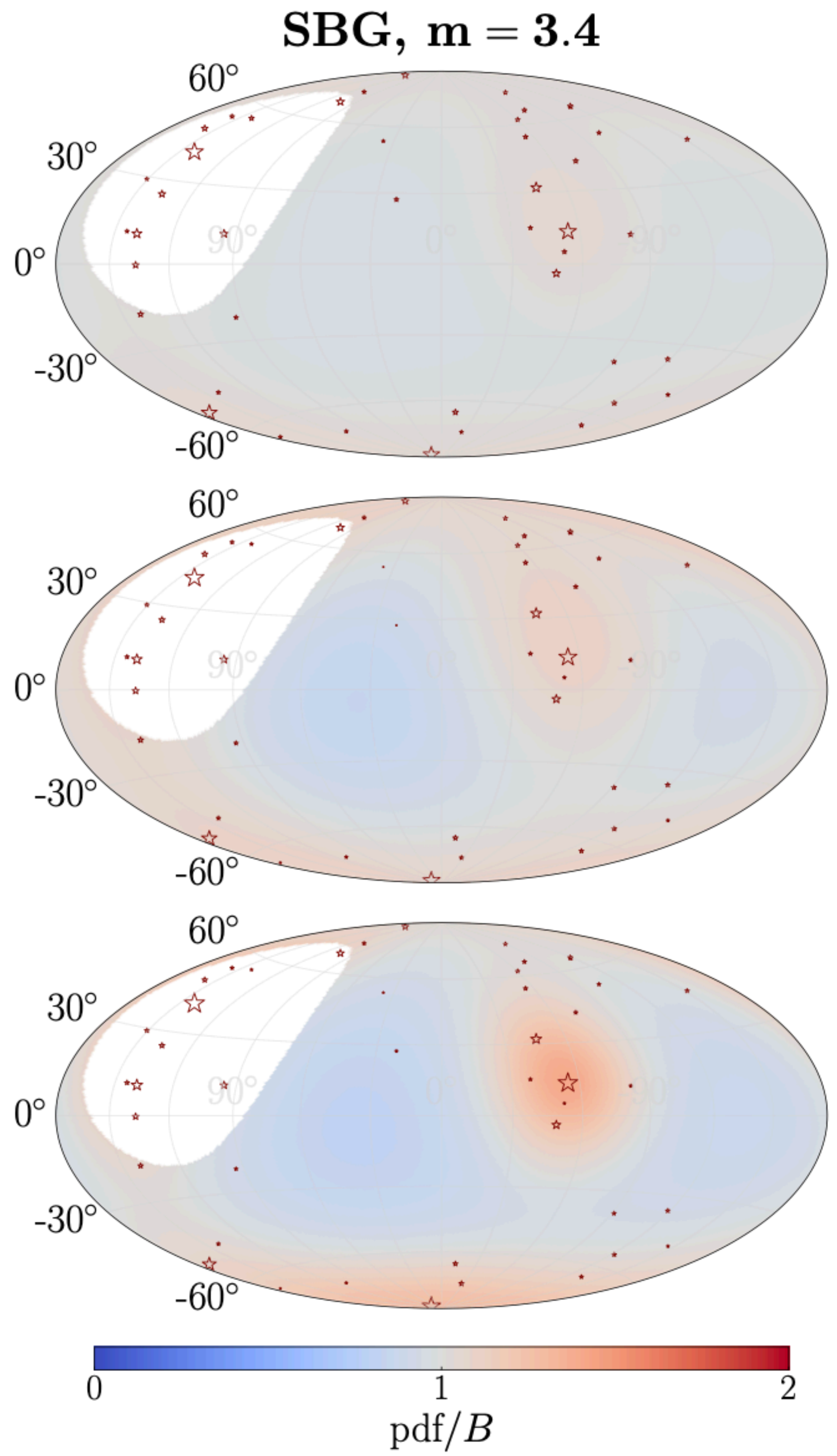
REFINING THE BASIC PICTURE





- Signal fraction and uncertainty in arrival direction included in the analysis
- Best improvement with respect to spectrum + composition fit found for **starburst sources**
- gamma-AGN sources disfavoured

Talk by **E. Martins**, Wed, CCR session

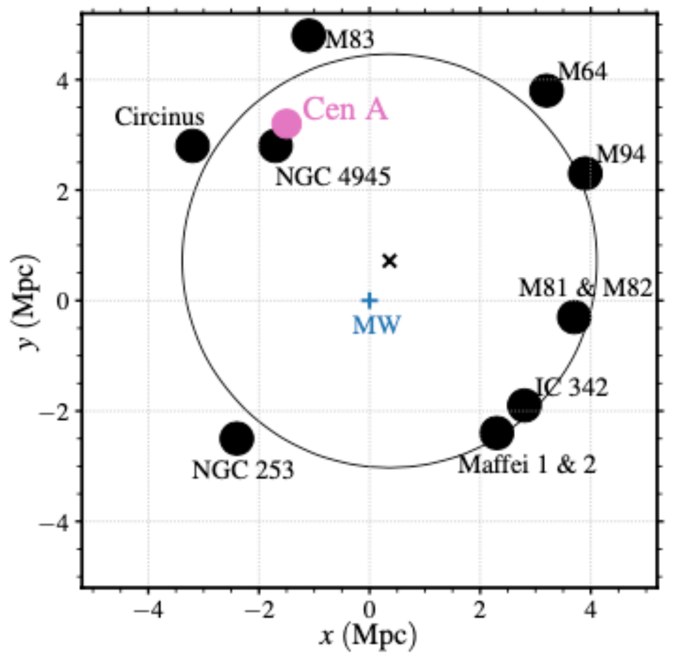
The Pierre Auger Collab. arXiv:2305:16693v1

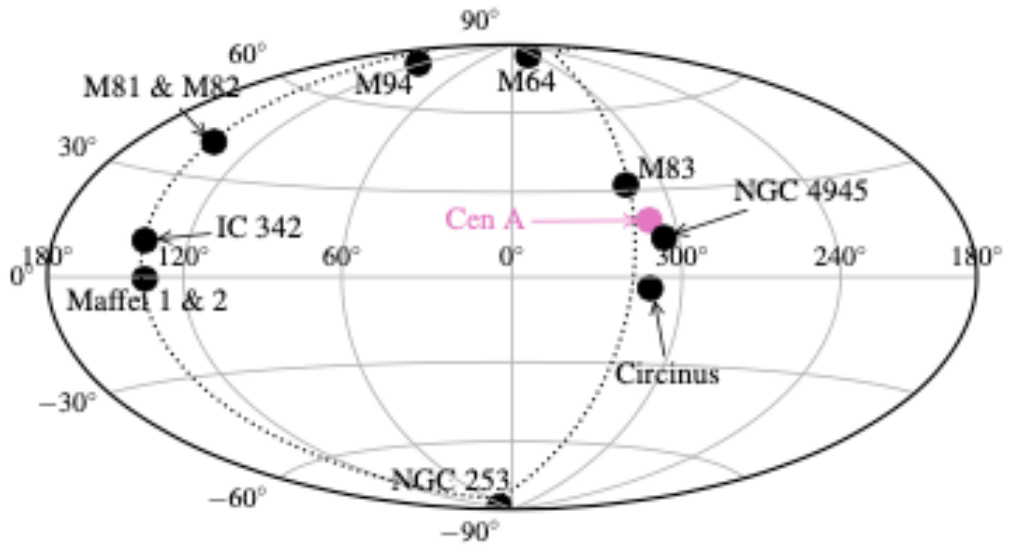
REFINING THE BASIC PICTURE

Investigating the source distribution

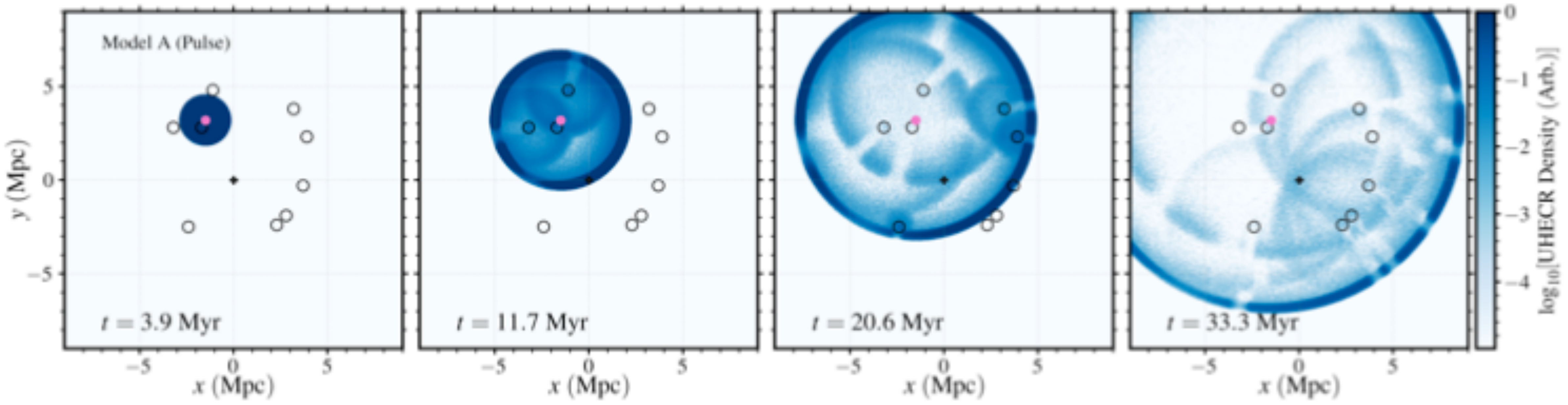
- Correlation with SBGs established
  - Can the correlation of UHECR with local structure be ascribed to the deflection of UHECRs, initially released by Cen A, on nearby galaxy systems?

Bell & Matthews MNRAS 2022;
Taylor et al MNRAS 2023

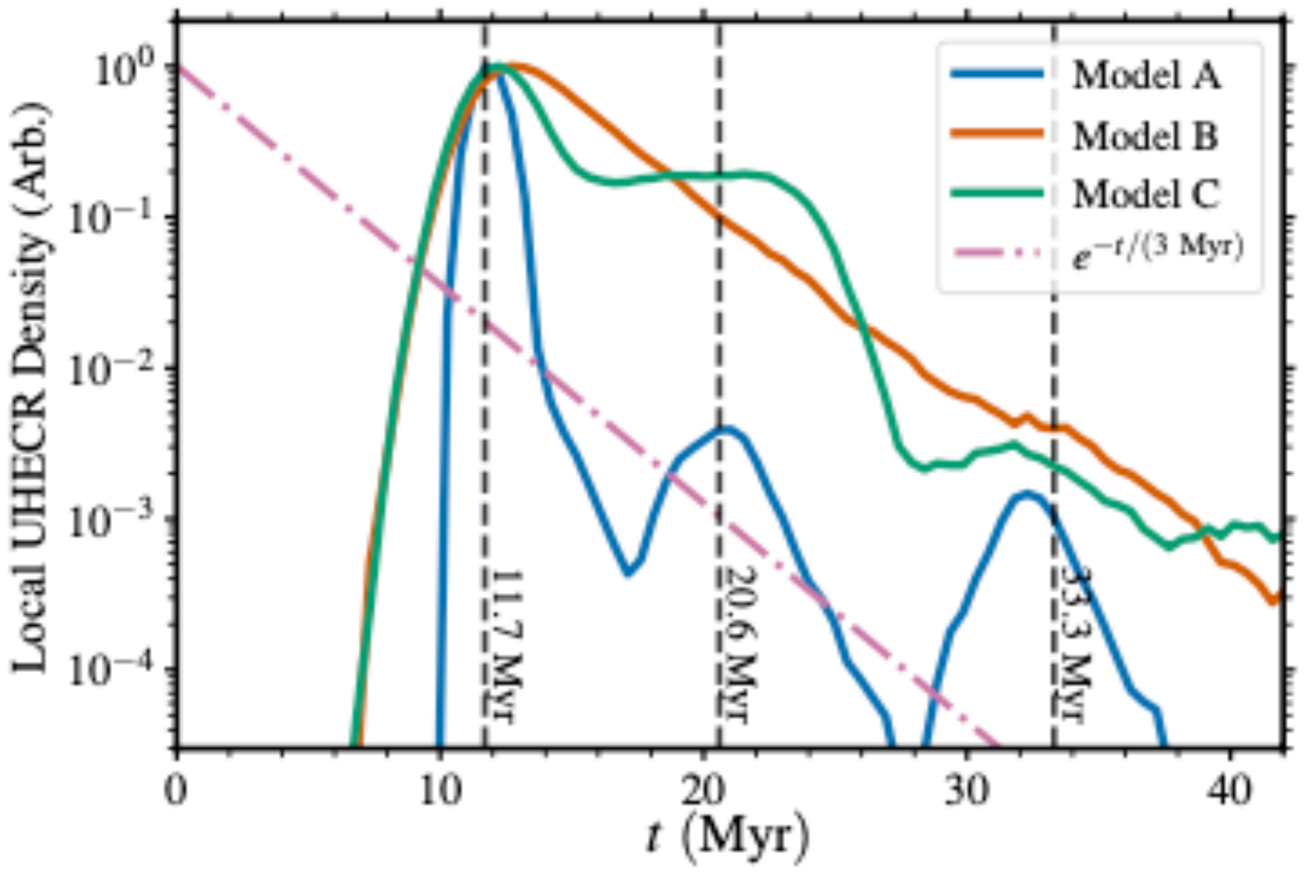




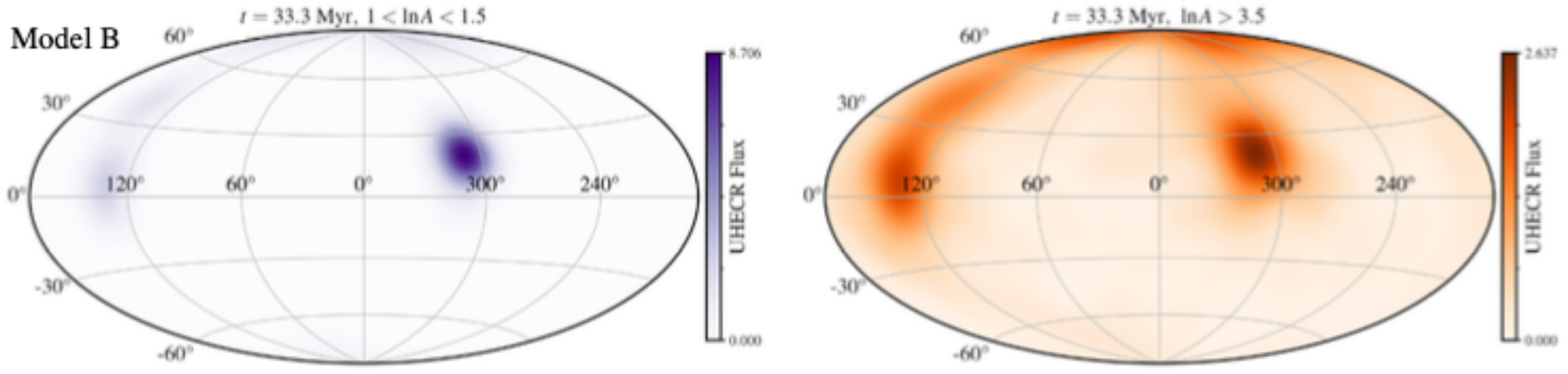
Council of Giants



After the release from CenA, particles are scattered by magnetic fields around galactic structures



Local particle density depends on release models

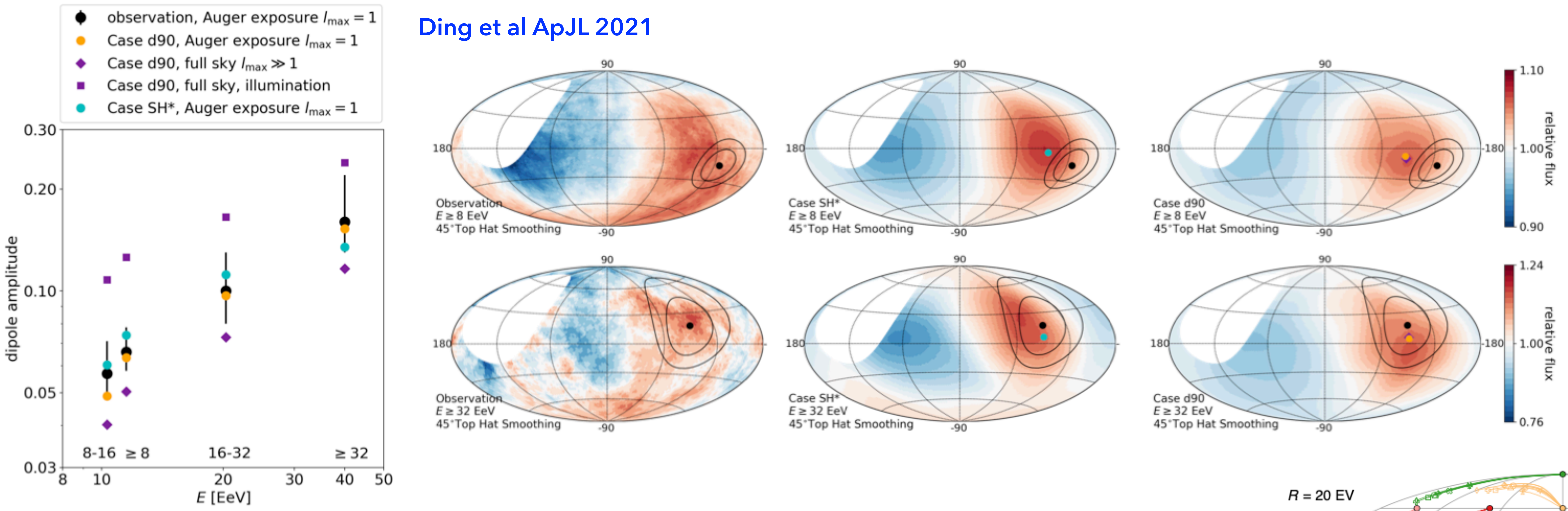


- UHECR nuclei provide a signature of the propagation scenario

REFINING THE BASIC PICTURE

Including magnetic fields

- Hypothesis: the UHECR source distribution follows the large-scale structure
- Dipole anisotropy and its evolution can be explained as a signature of the local LSS, if the diffusion in the extragalactic magnetic fields and the deflections by Galactic magnetic field (ordered + turbulent component) are taken into account

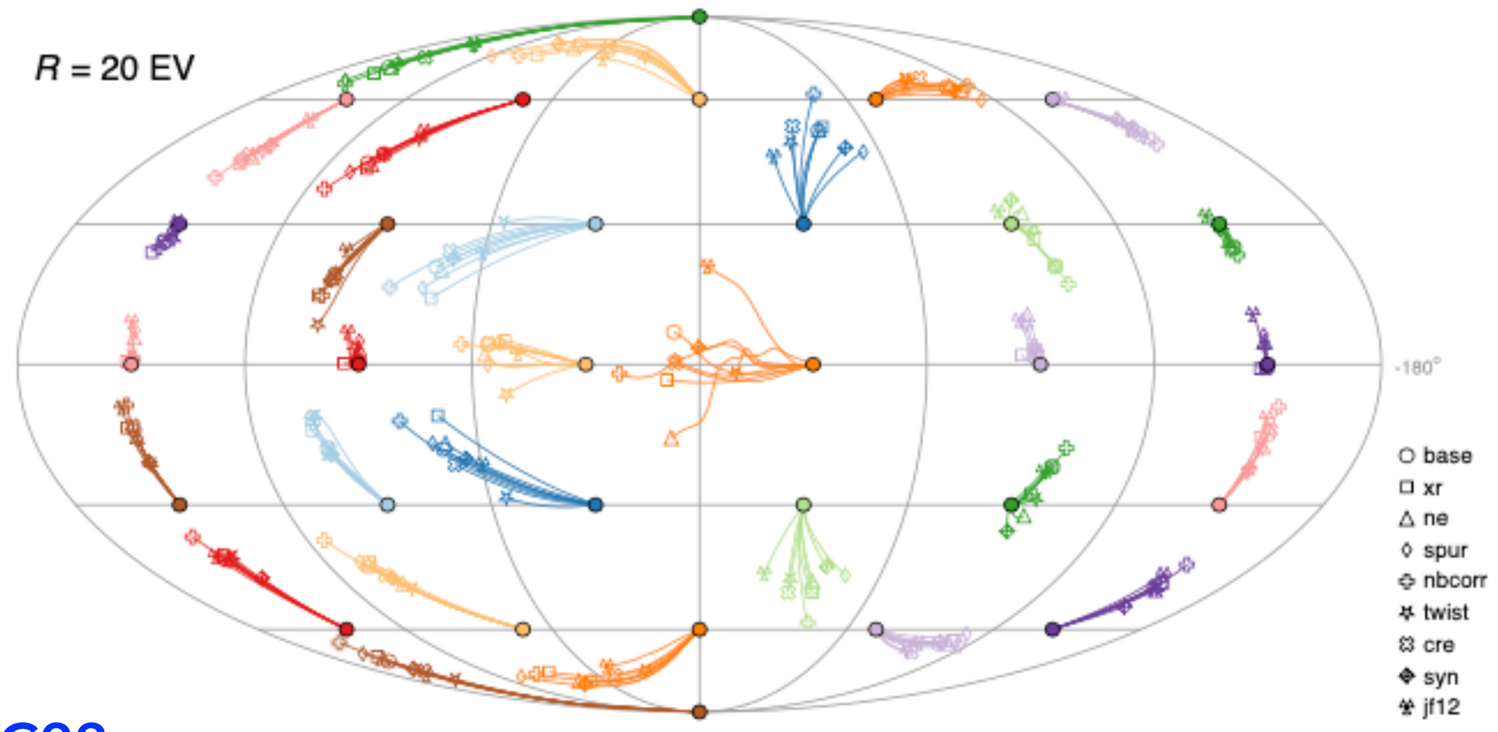


Ding et al ApJL 2021

- **Transient versus steady nature of sources** can influence the pattern; see Globus et al ApJ 2023

See talk by **O. Deligny** on **transient UHECR sources**, Wed, CCR session

- Example of backtracking of particles (from Jansson&Farrar2012 model for the Galactic magnetic field)



Unger&Farrar ICRC23

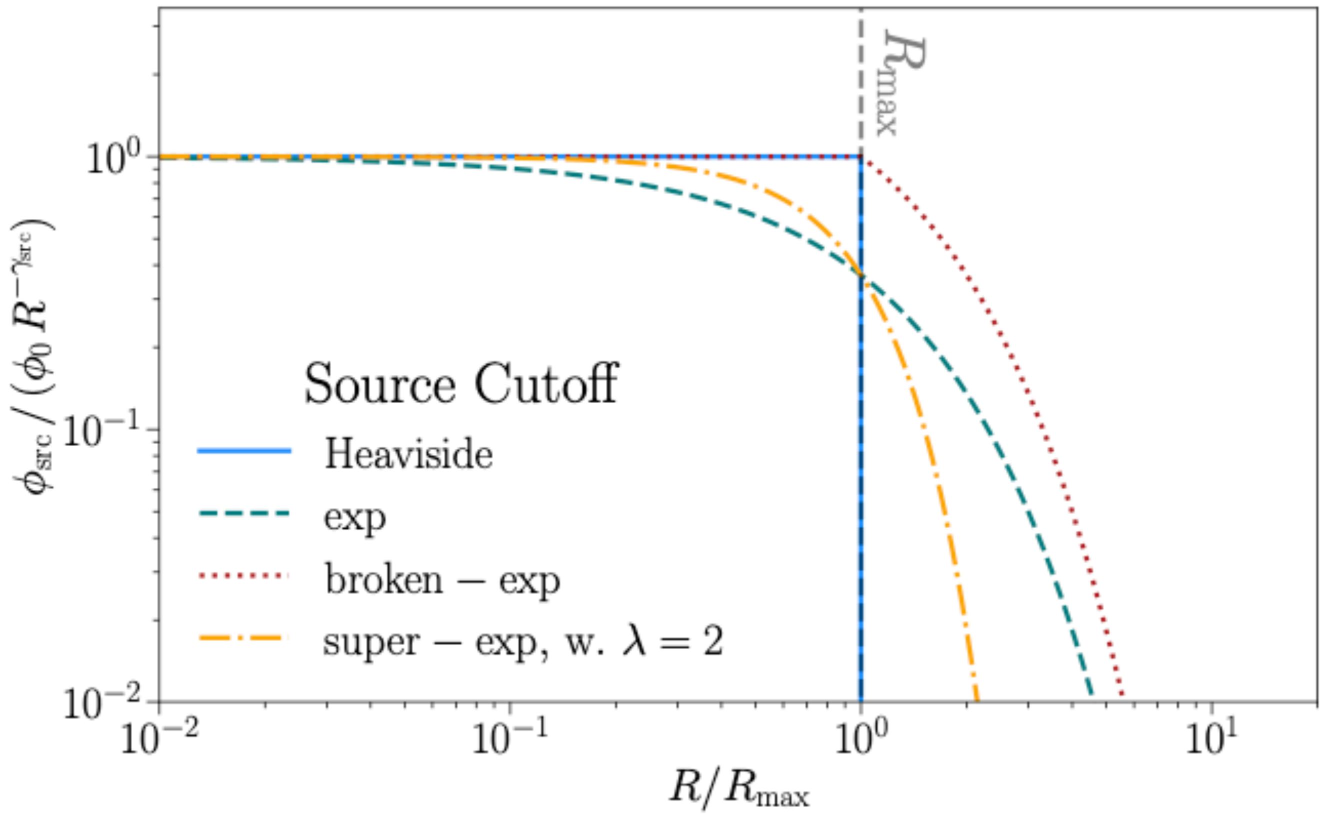
REFINING THE BASIC PICTURE

Testing the assumption of identical sources

- Relax the assumption of identical maximum energy at the sources
  - Because of different candidate sources of UHECRs: maximum rigidity can be connected to **Lorentz factor of relativistic jets**, to the observed **source luminosity**, etc…

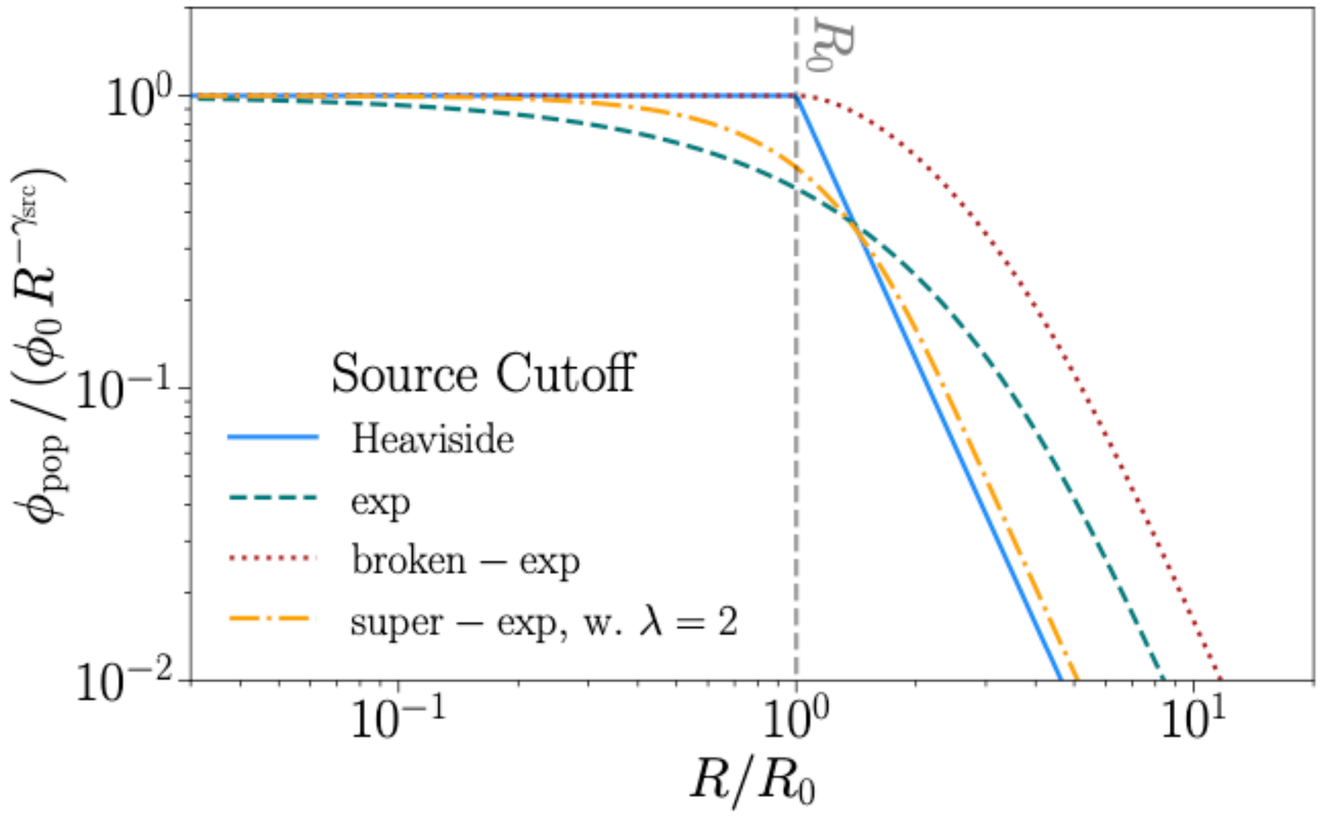
Ehlert et al PRD 2023; Mollerach & Roulet PRD 2020; Kachelriess & Semikoz PLB 2006

Source



$$\frac{dN}{dR} \propto R^{-\gamma_{\rm src}}$$

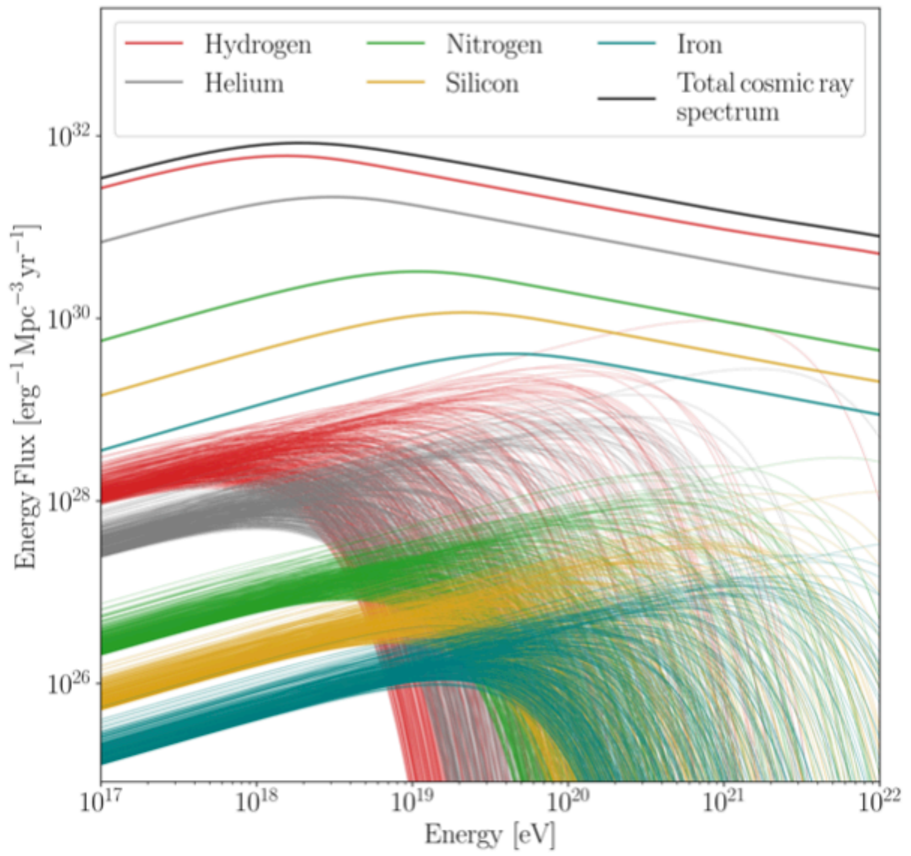
Population



$$\frac{dN}{dR_{\max}} \propto R_{\max}^{-\beta_{\rm pop}}$$

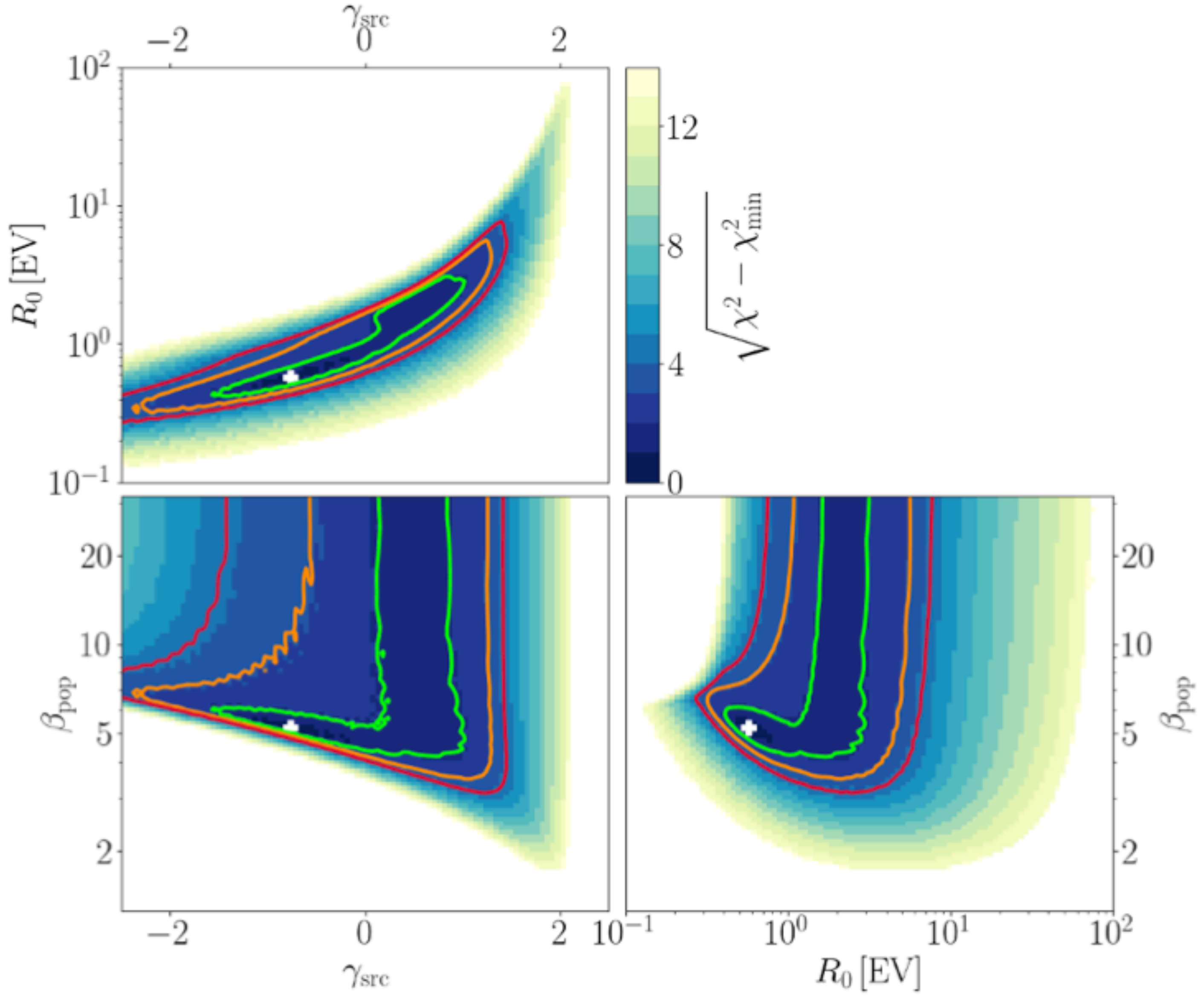
$$\phi_{\rm pop} \propto R^{-\gamma_{\rm src}} \text{ if } R < R_0$$

$$\phi_{\rm pop} \propto R^{-\gamma_{\rm src}-\beta_{\rm pop}+1} \text{ if } R > R_0$$



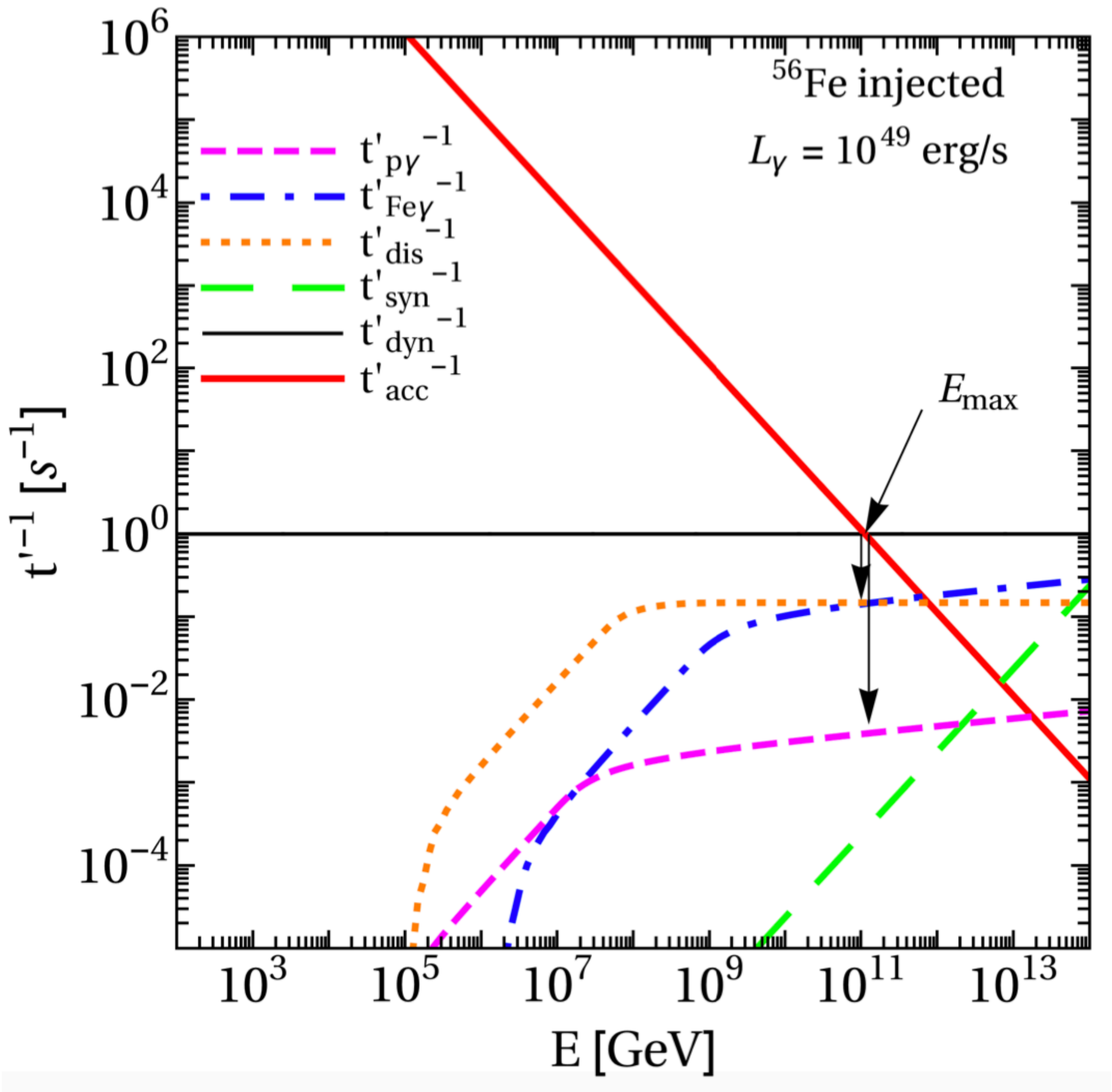
Plot from talk by F. Oikonomou @ICRC23

- To minimize the superposition of nuclear species, the population spectrum must be steep after the cutoff
- Combined with the finding on the source spectrum, **data favour the hypothesis of identical sources**
- Examples rated already (for GRB variability) in Globus et al MNRAS 2015; Heinze, Biehl, Fedynitch, **DB**, Rudolph & Winter MNRAS 2020

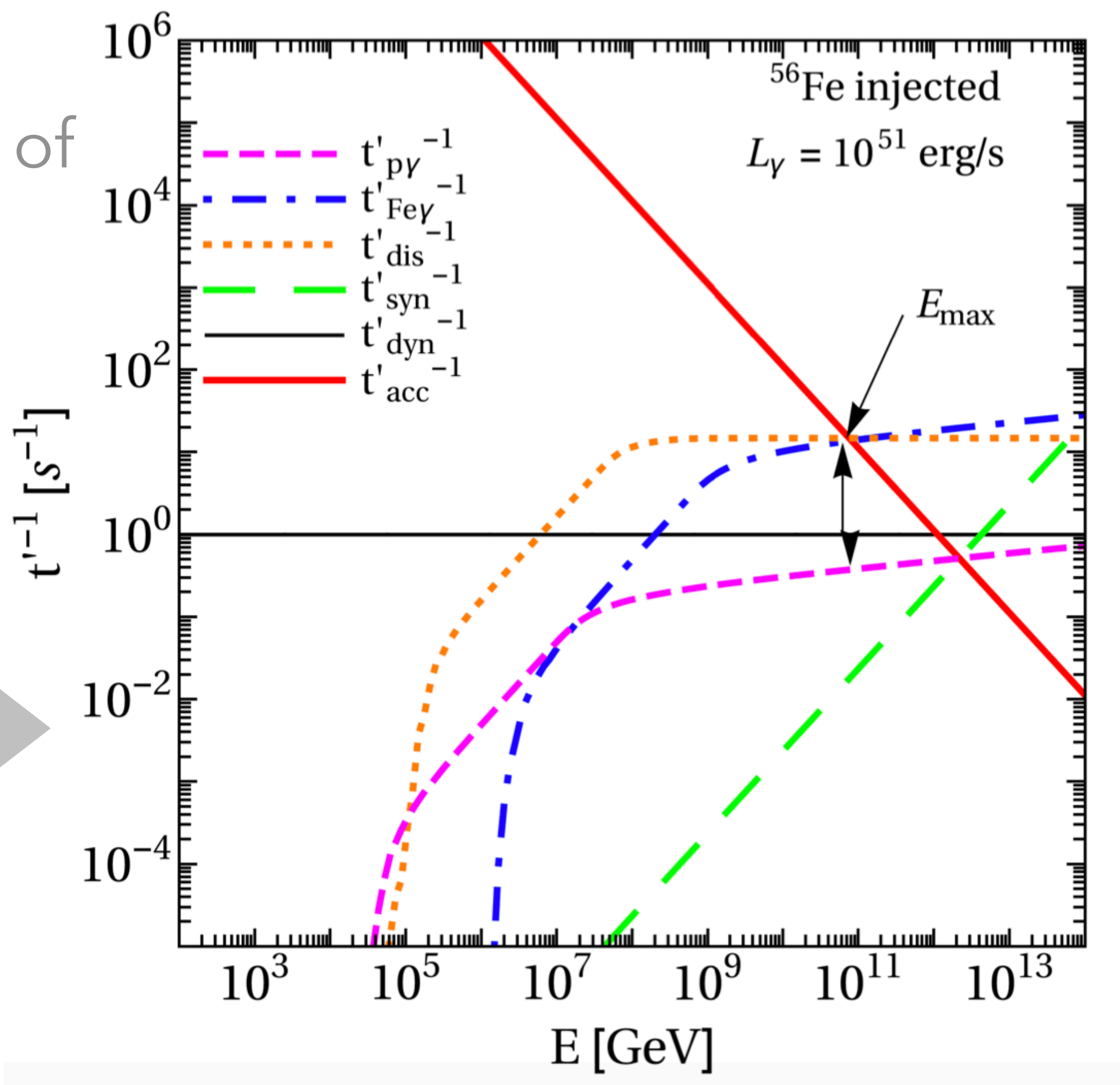


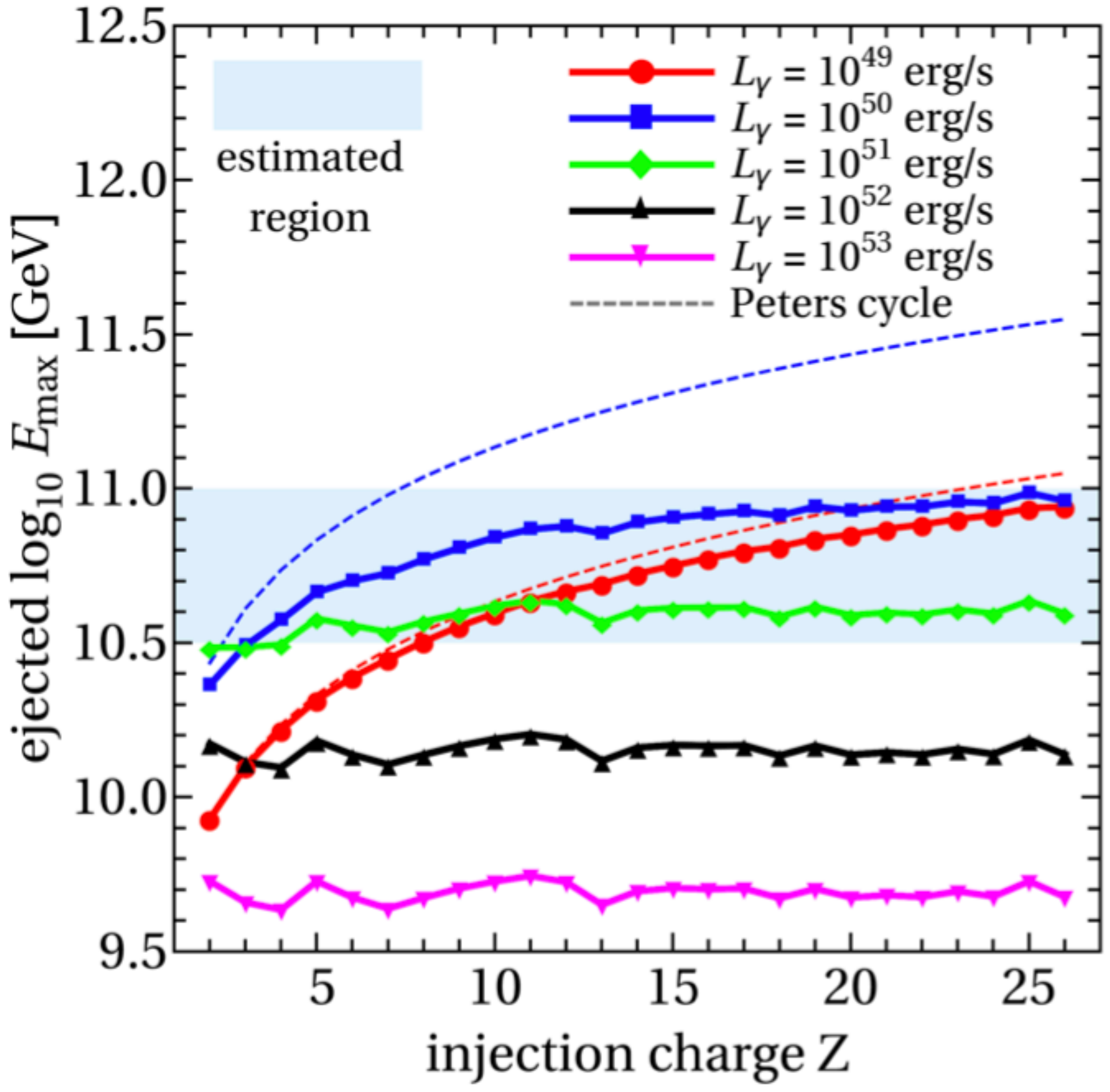
REFINING THE BASIC PICTURE

Testing the rigidity-dependence assumption at the escape



Increase of photon density

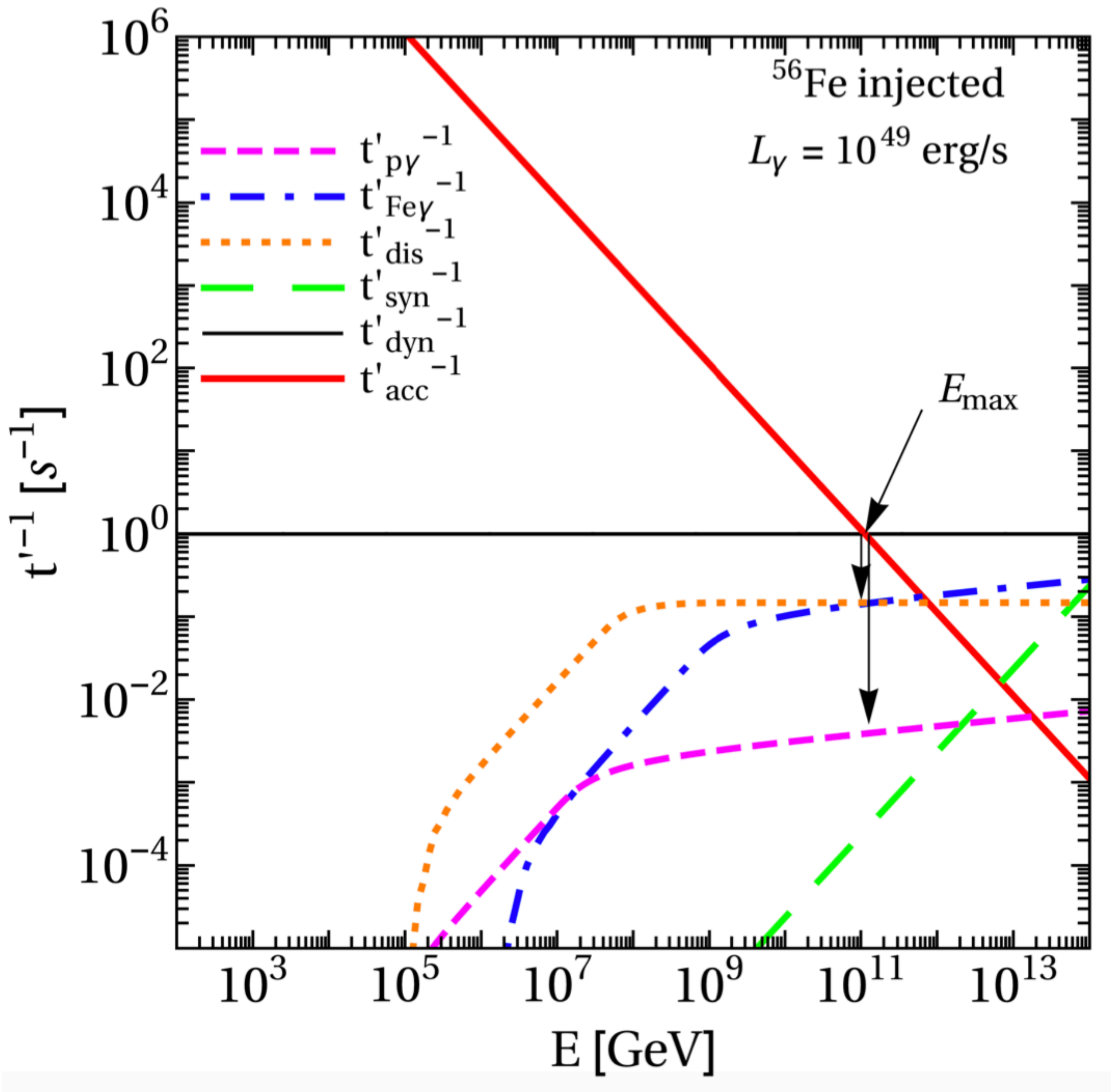




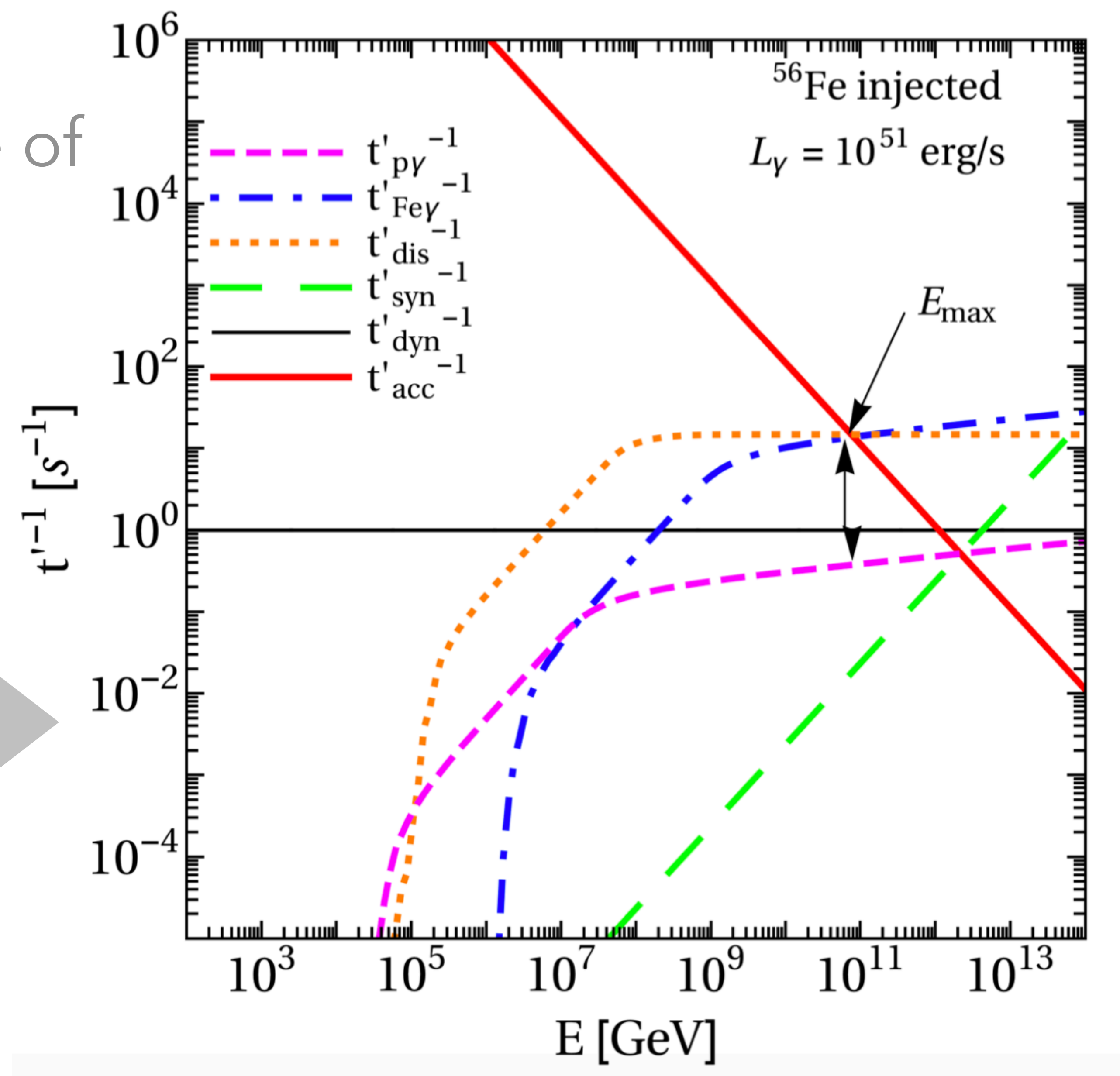
- Maximum energy defined by acceleration -> rigidity dependence
- If UHECR interactions in sources are considered
  - Large photon density -> acceleration timescale to be compared with typical interaction rates

Biehl, **DB** et al Astron. Astrophys. 2018

REFINING THE BASIC PICTURE



Increase of photon density

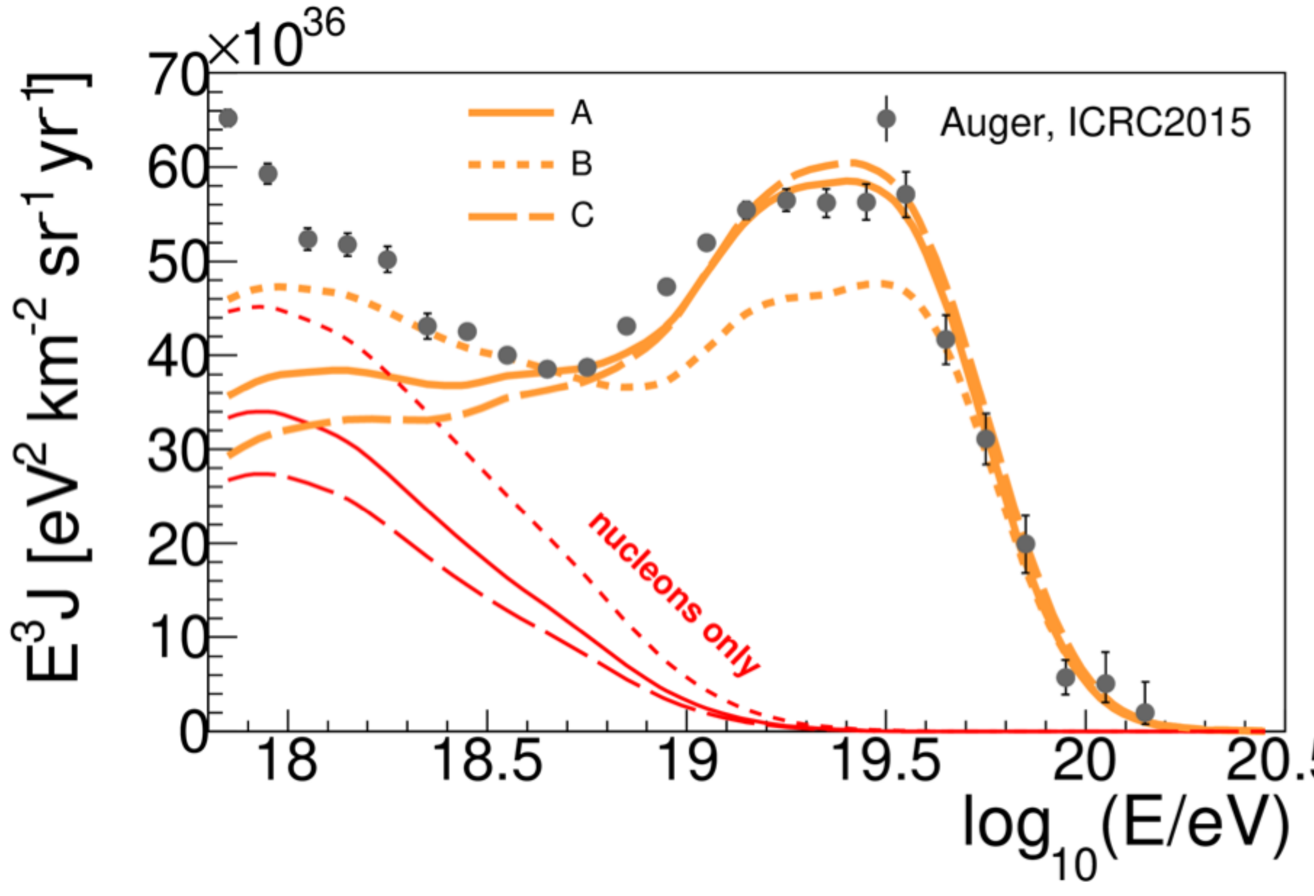


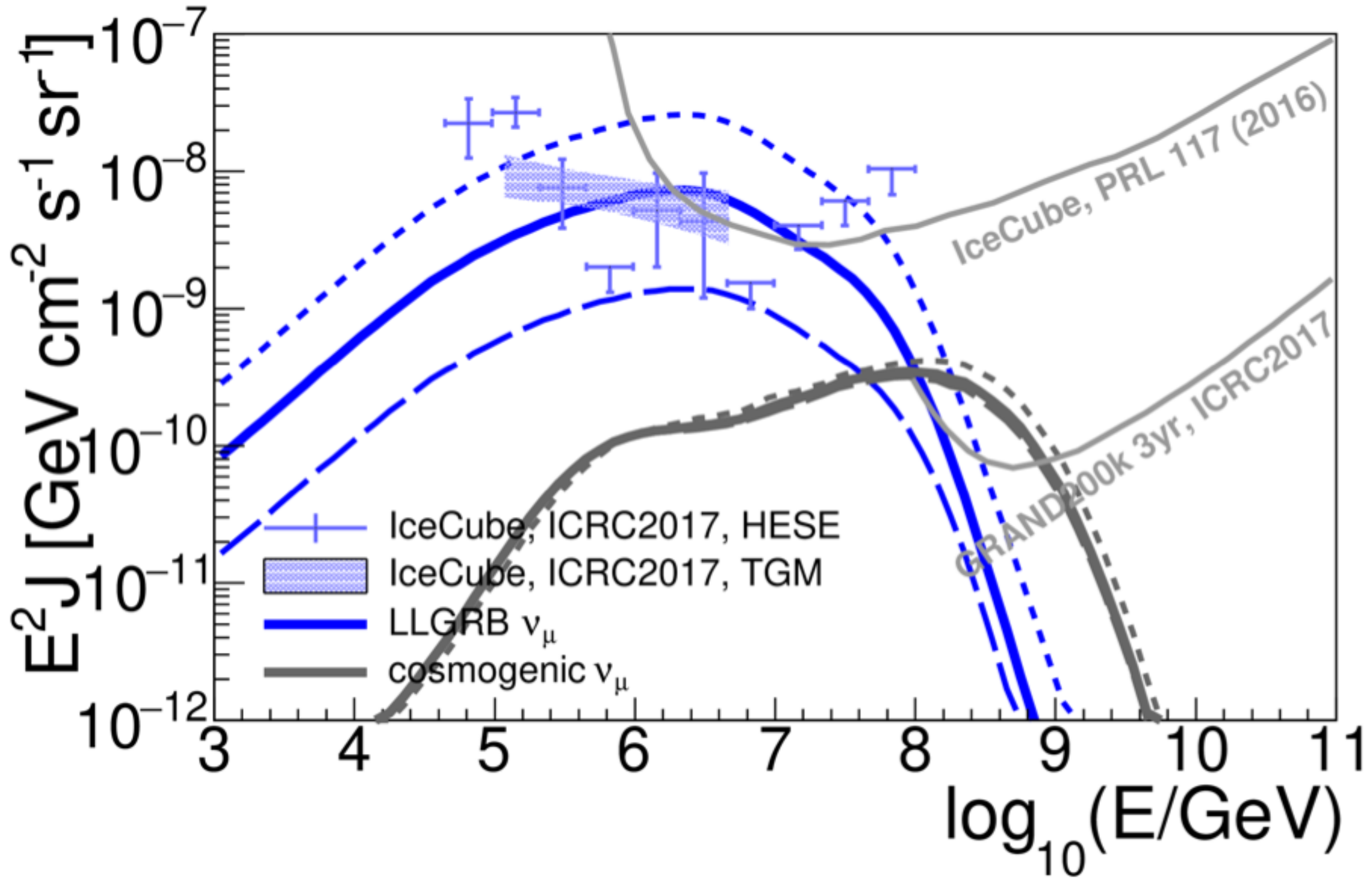
- Flux at escape (spectral index, mass composition, maximum energy) from source environment depends on source details (interaction efficiency, diffusion…)
  - Example from GRBs and LL-GRBs; other cases explored for TDEs, blazars, SBG nuclei…
  - **Basic conclusion: large photon density -> efficient interactions -> large amount of protons at escape & neutrinos**

- UHECR-astrophysical neutrino connection: energies below the ankle

Unger et al PRD 2015; Biehl, **DB** et al Astron. Astrophys. 2018; **DB** et al ApJ 2019; Muzio et al PRD 2019; Condorelli, **DB**, Peretti & Petrera PRD 2023

See other talks about in-source interactions and multimessenger connections: **E. Peretti** (this session); **X. Rodrigues** and **A. Reimer** (CCR session, today); **S. Hussain** (GRA session, Thu); **R. Matsui** (GWMM session, Thu)

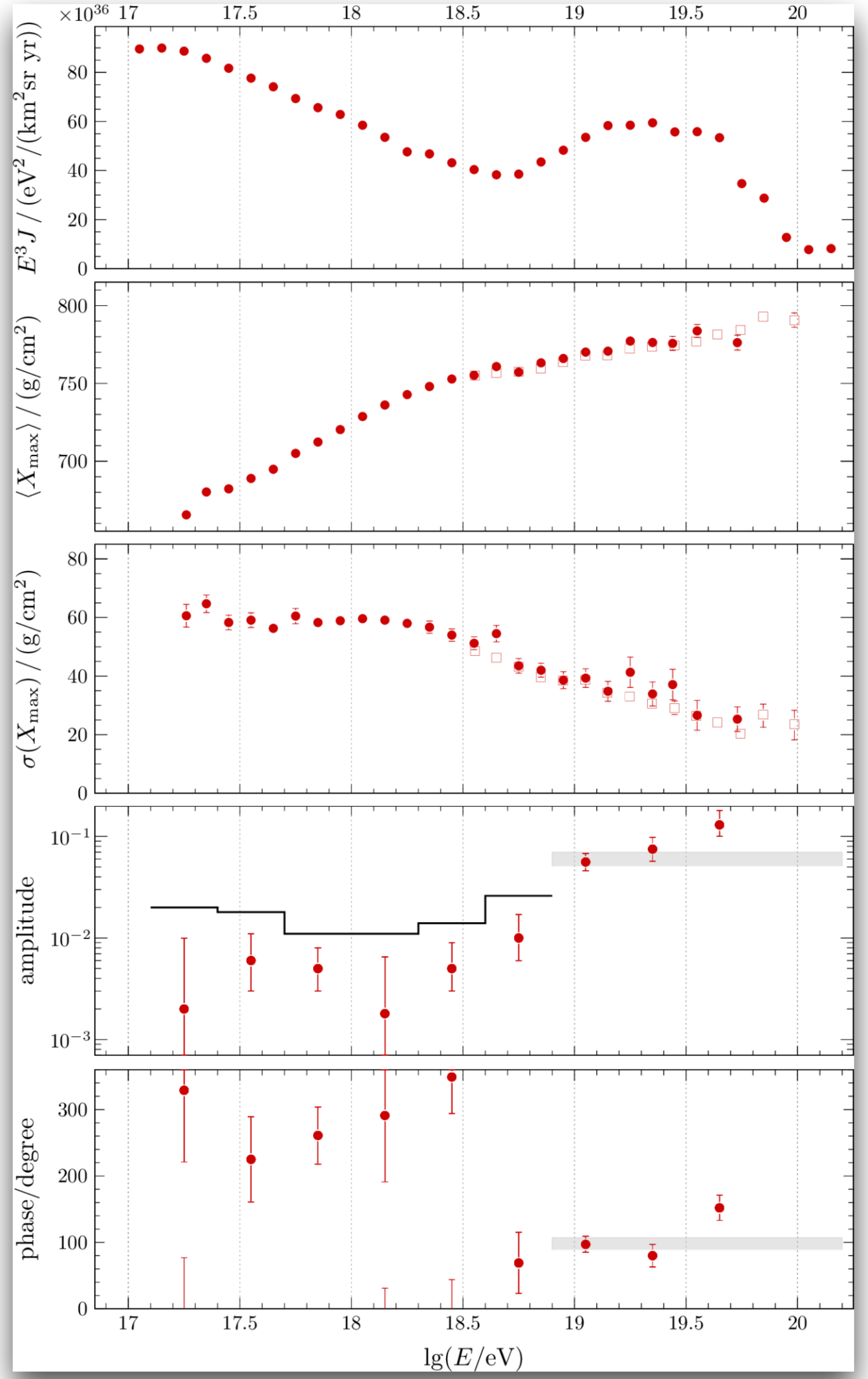




- Other info from UHECR-cosmogenic neutrino connection: UHECR source evolution

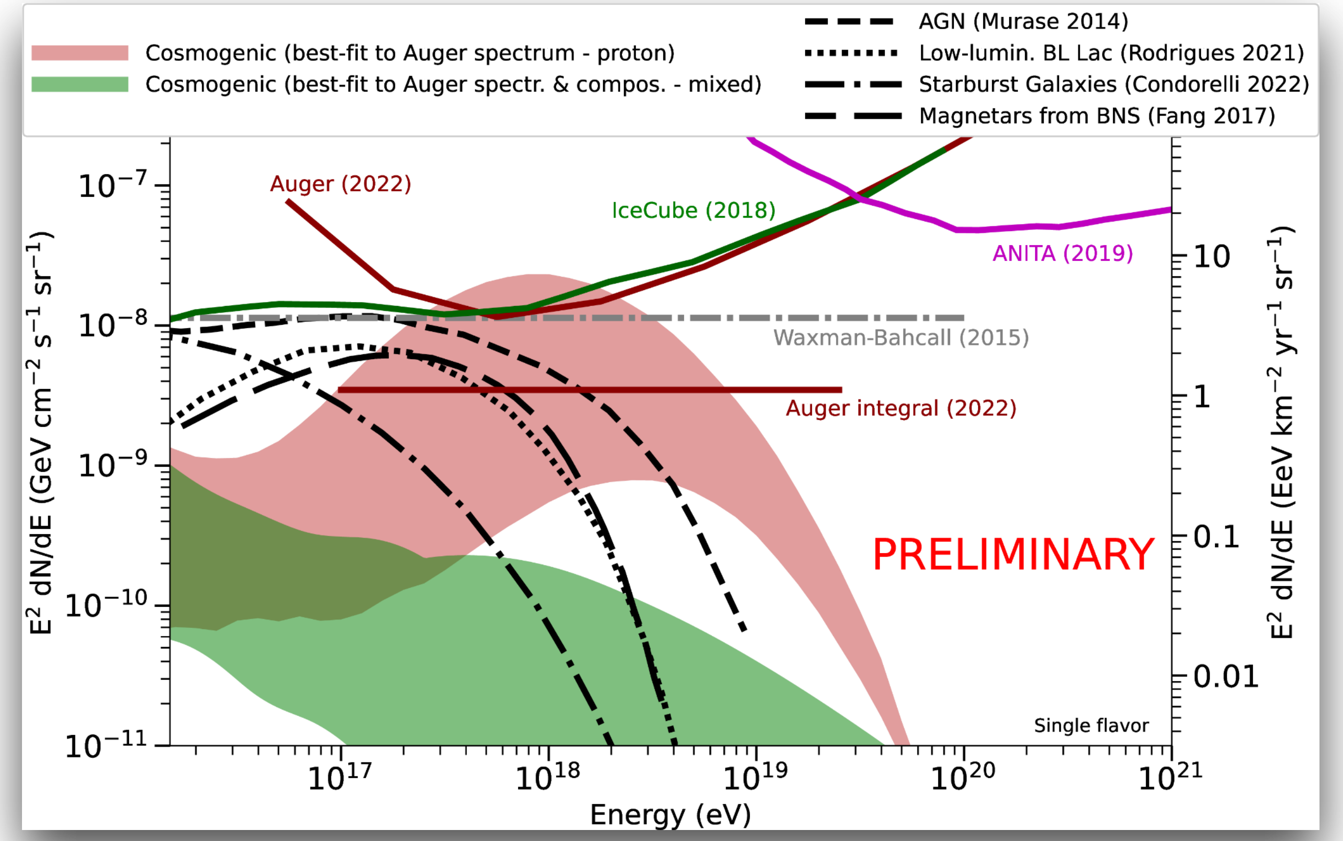
THE FUTURE

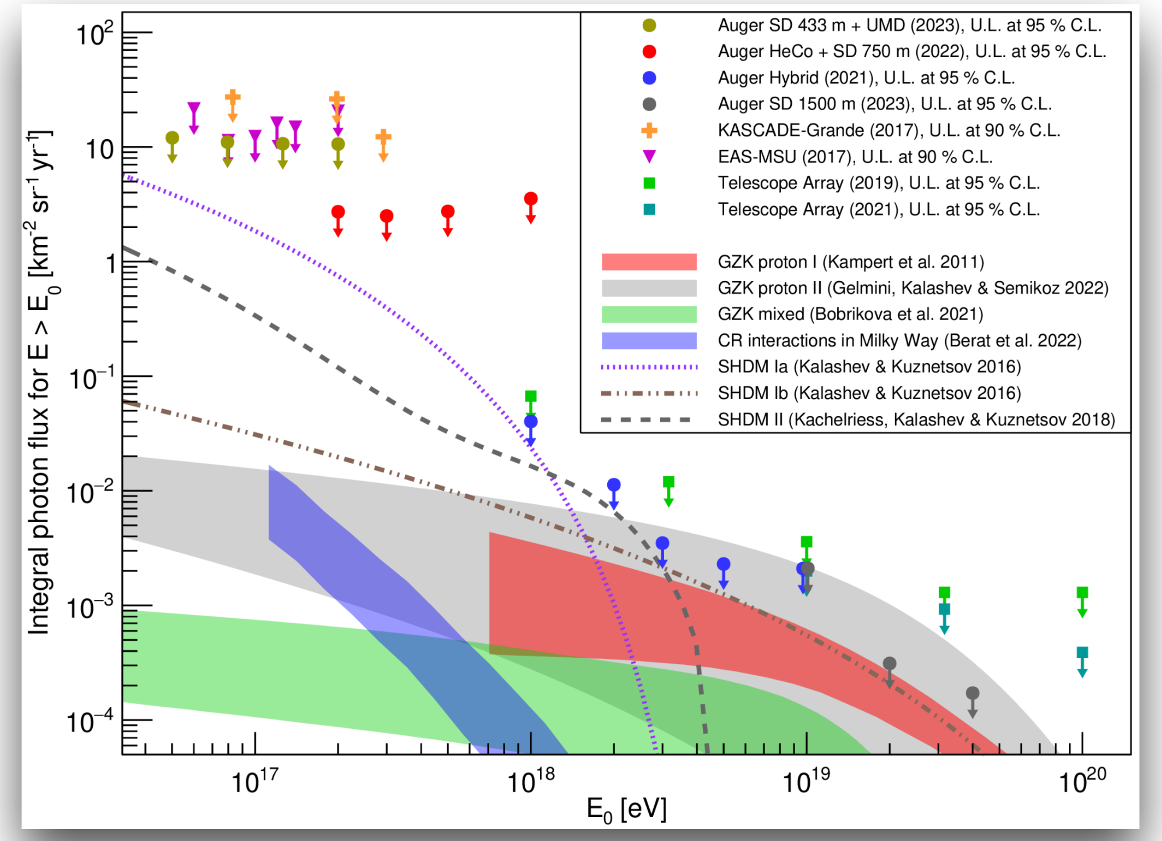
UHECRS: PRESENT AND FUTURE



Plot from talk by F. Salamida @ICRC23

- **The picture emerging from data is exciting!**
  - Features in the energy spectrum
  - Changes in mass composition
  - Extragalactic origin from anisotropy signal
  - Coherent results with non-observation of cosmogenic particles





The Pierre Auger Collab. ICRC23

Talk by **V. Scherini**: Wed, GWMM session

Multimessenger perspectives **including gravitational waves** -> see talk by **M. Branchesi**: Wed, plenary session

UHECRS: PRESENT AND FUTURE

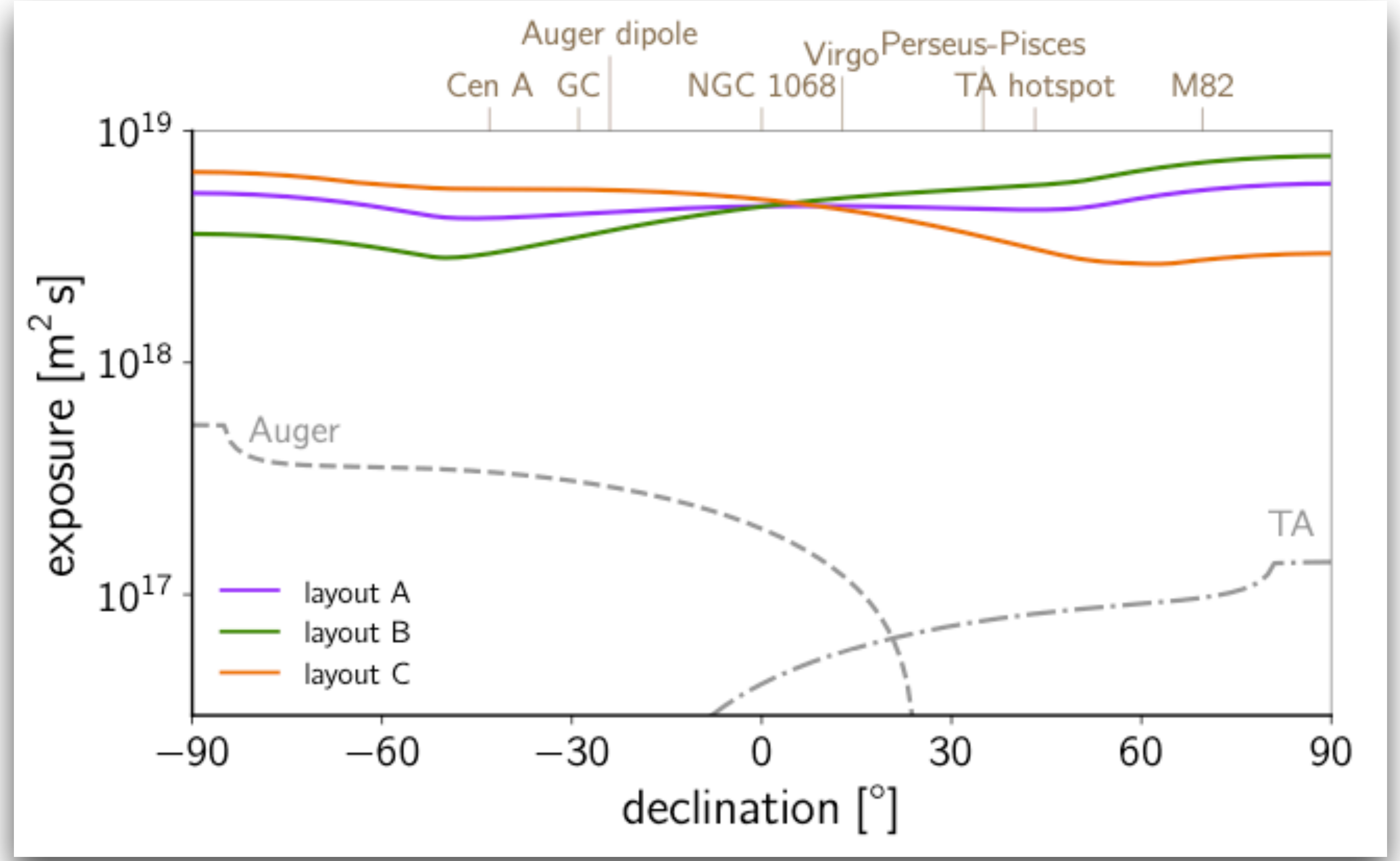
- **Upgrades** of the Pierre Auger Observatory and Telescope Array are expected to push forward the understanding of several issues:
  - Mass composition at the highest energies
  - Air-shower physics
  - Physics beyond the standard model
  - Fundamental symmetries

Talk by **O. Deligny**, Thu, IDM session

Talk by **I. Allekotte**, Wed, CCR session

- Next-generation experiments are foreseen to deepen the multimessenger approaches
  - GCOS, POEMMA, GRAND

R. Alves Batista et al ICRC23



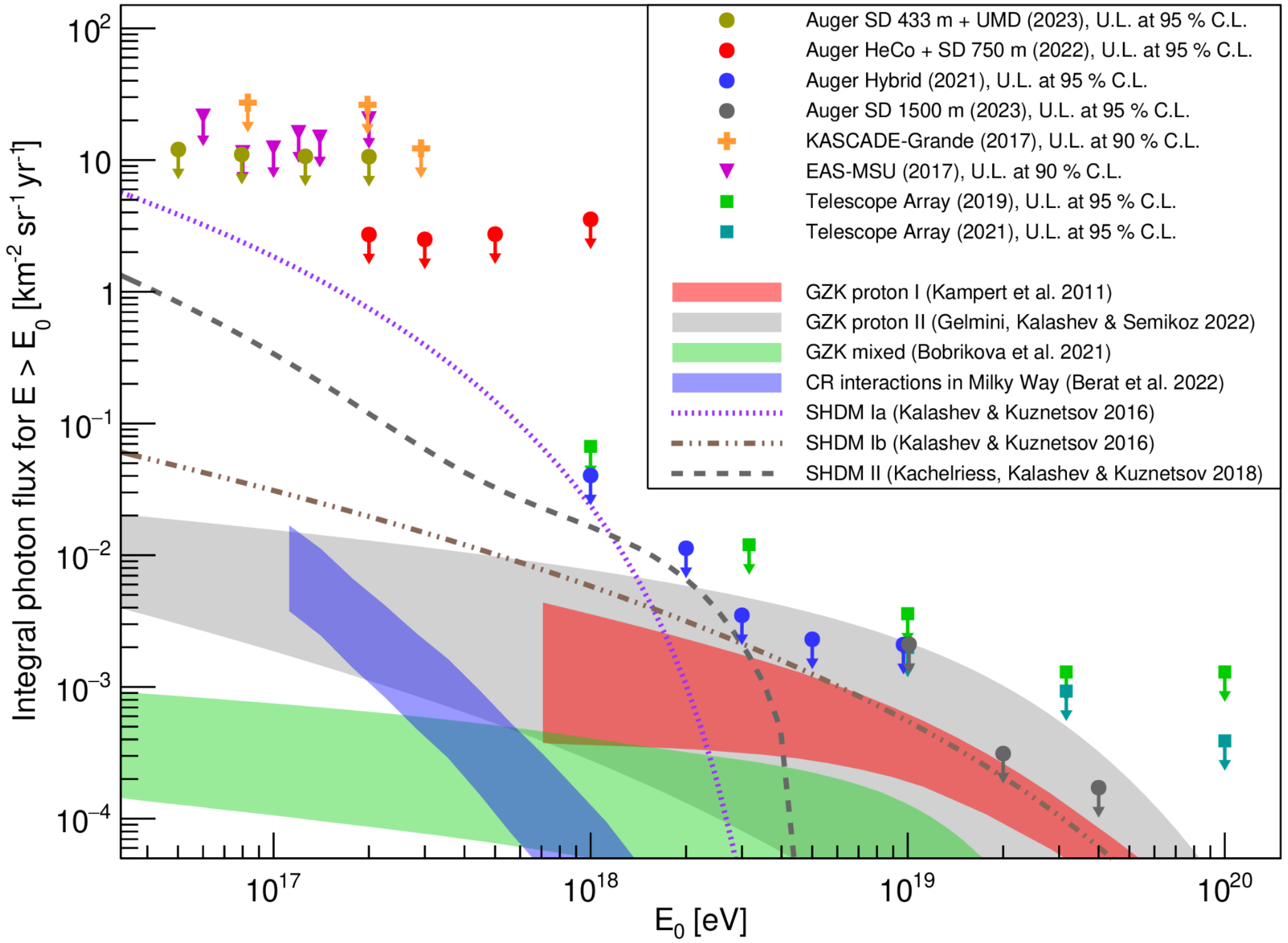
- **Combining (future and current) measurements with improved modelling of UHECR interactions and magnetic fields, and exploiting the multimessenger connections, will strongly refine the astrophysical picture about the origin of UHECRs**

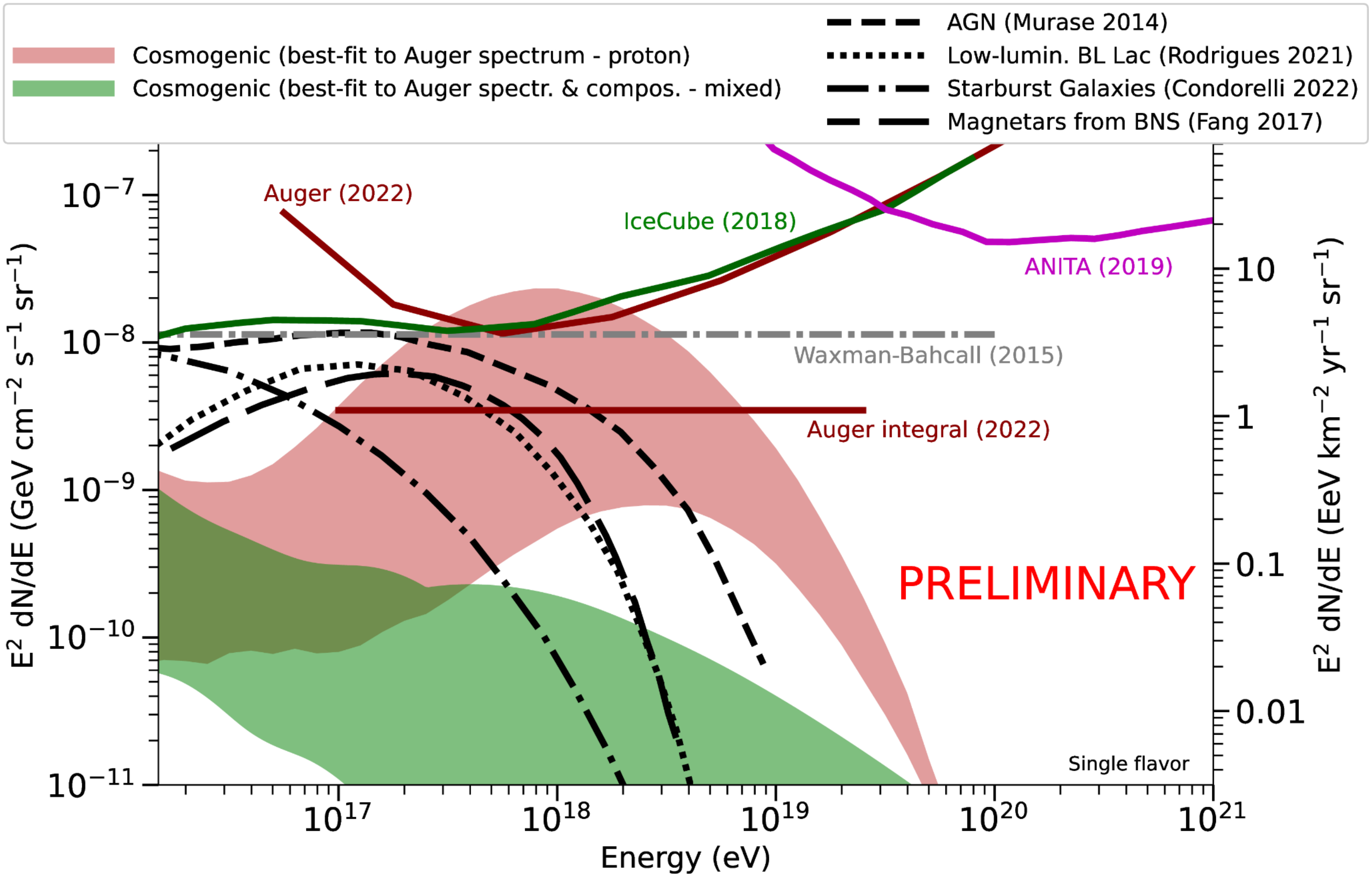
BACKUP SLIDES

UHECR SOURCES
AND
MESSENGERS FROM THE UNIVERSE

SENSITIVITY TO COSMOGENIC PARTICLES

The Pierre Auger Collab. ICRC23

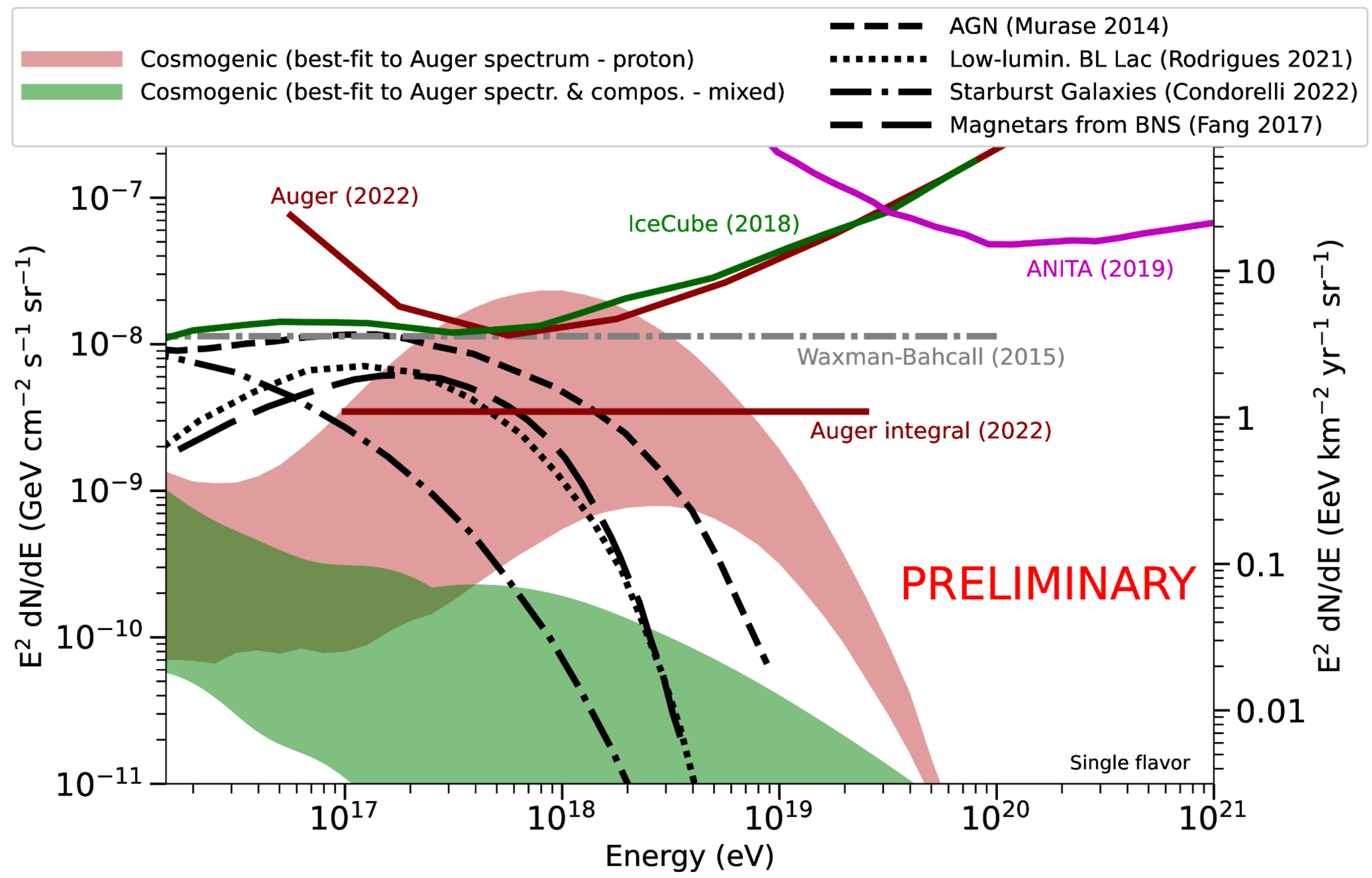




- Sensitivity approaching models for photons from GZK protons
- Sensitivity already able to exclude some proton scenarios (high maximum redshift and strong source evolution)

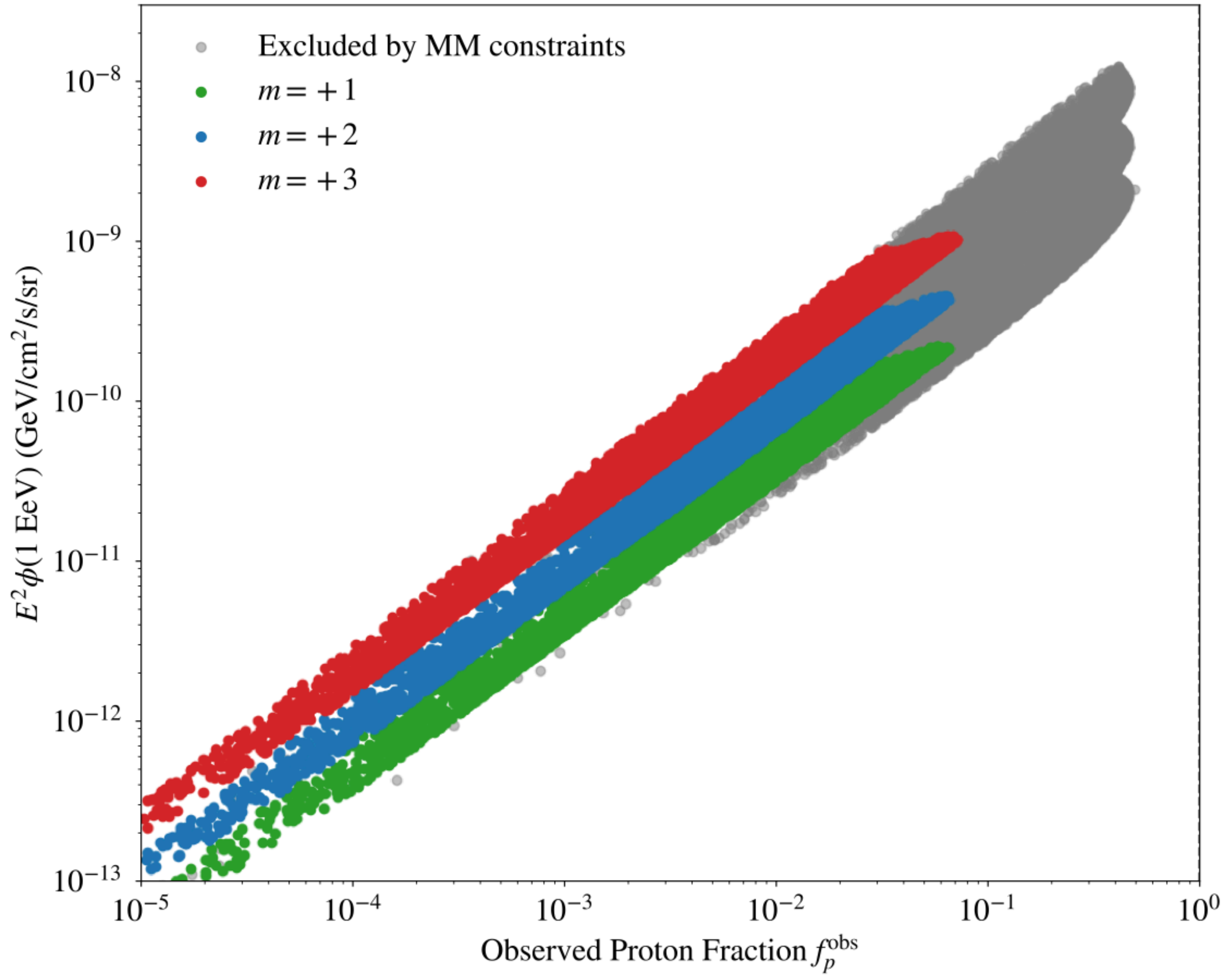
UHECR PROTONS AND COSMOGENIC PARTICLES

The Pierre Auger Collab. ICRC23



Mixed composition above 10^{18} eV

Pure protons above 10^{18} eV



UHECR flux vs neutrino flux, depending on

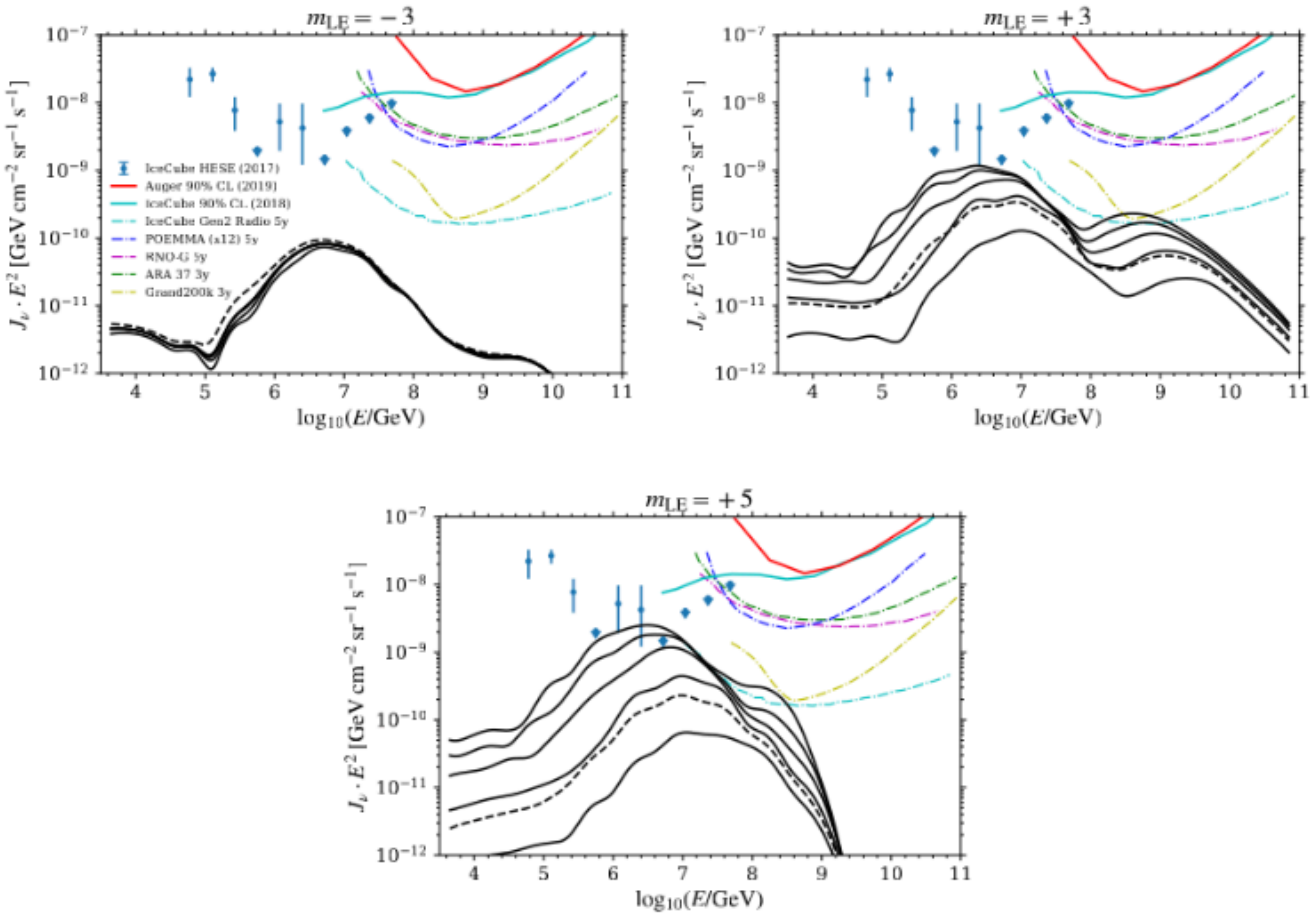
- UHECR spectral parameters
- UHECR mass composition
- Maximum redshift of UHECR sources
- Cosmological evolution of UHECR sources

- Expected increase in sensitivity to proton fraction can constrain UHECR source evolution
- **UHECR-cosmogenic neutrino connection: energies above the ankle**
  - Strongly dependent on H fraction and maximum energy

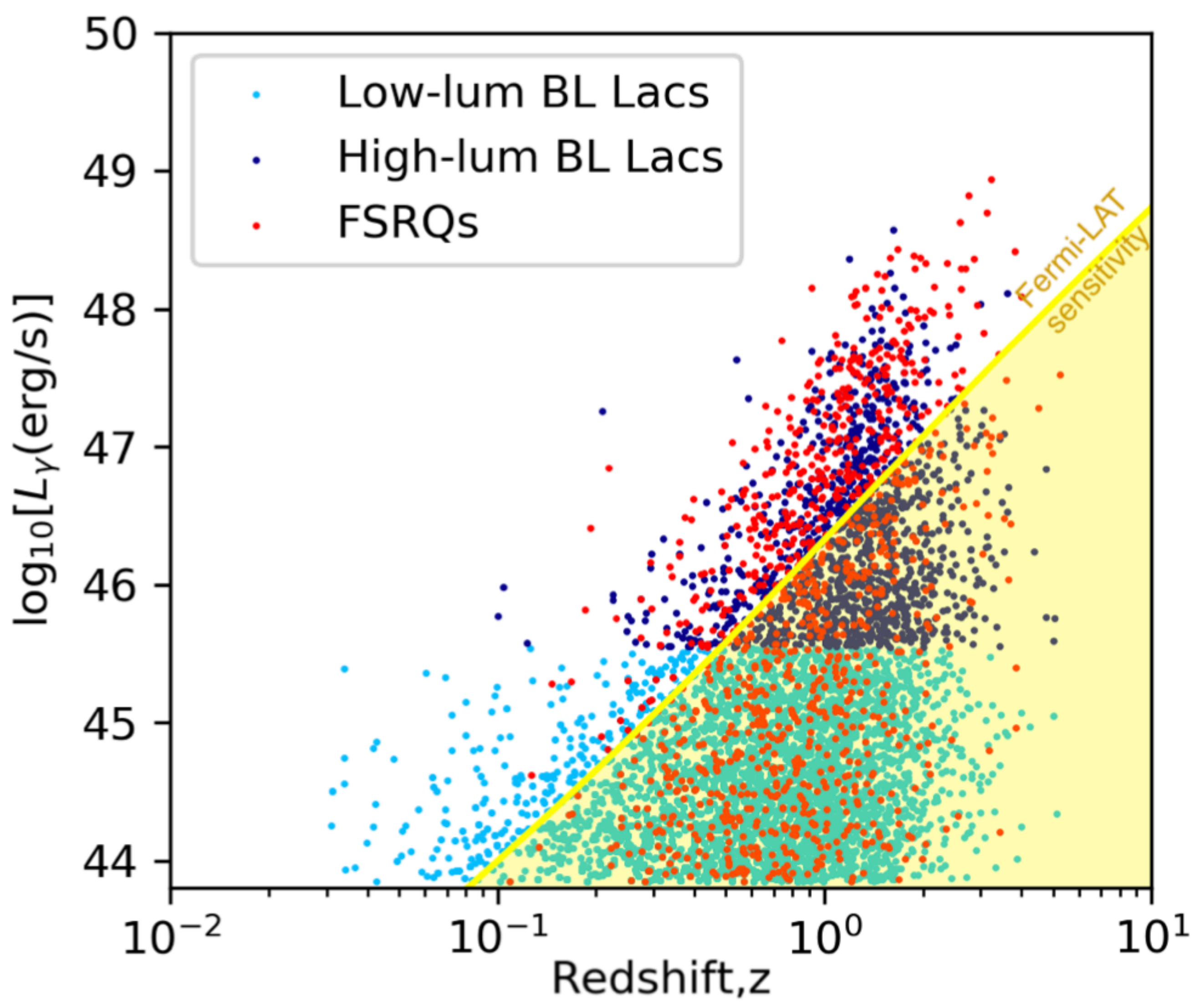
Muzio et al. PRD2023; Ehlert et al. arXiv:2304.07321;
The Pierre Auger Collab. ICRC23; van Vliet et al. PRD 2019

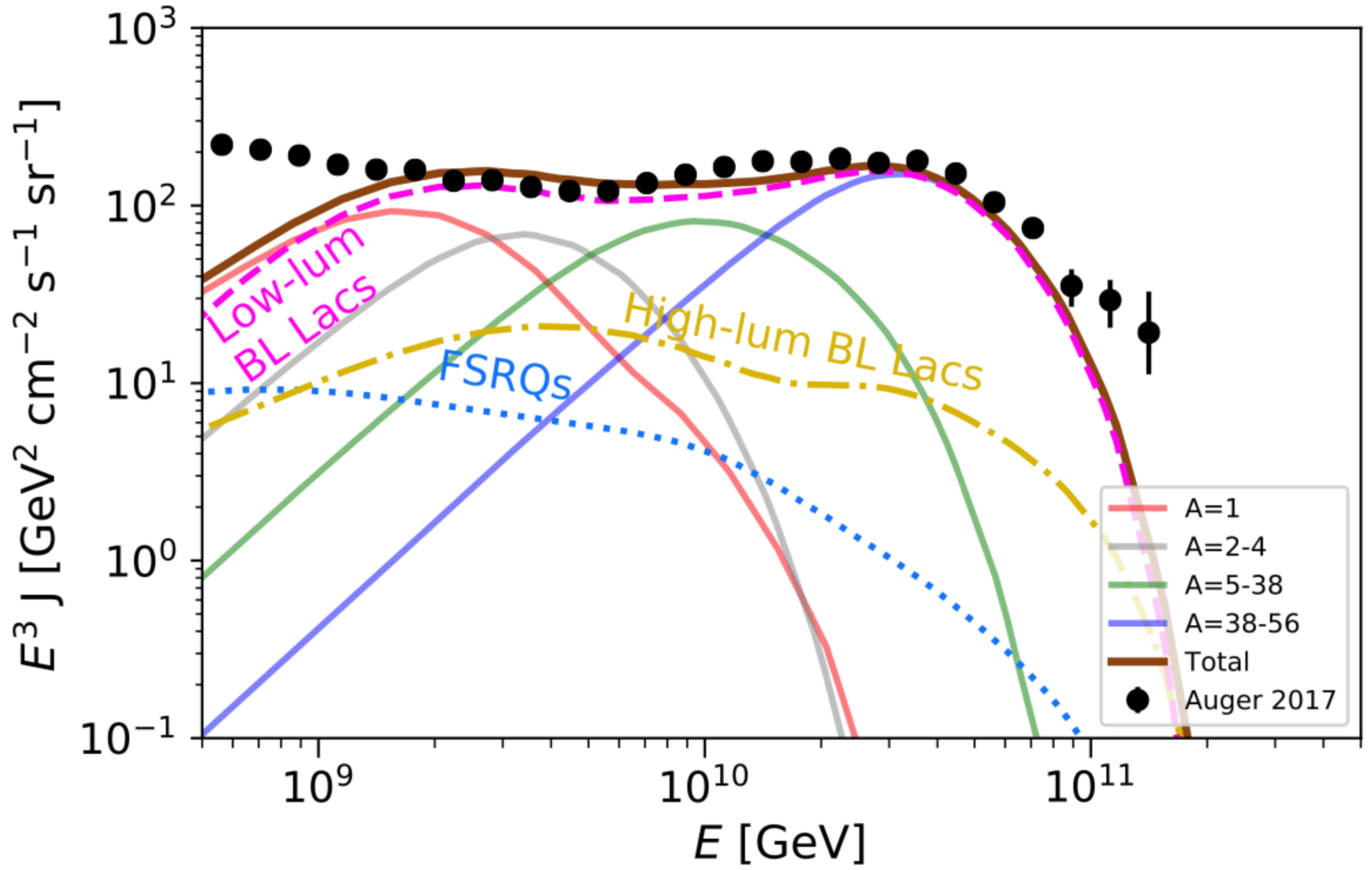
UHECR PROTONS AND COSMOGENIC PARTICLES

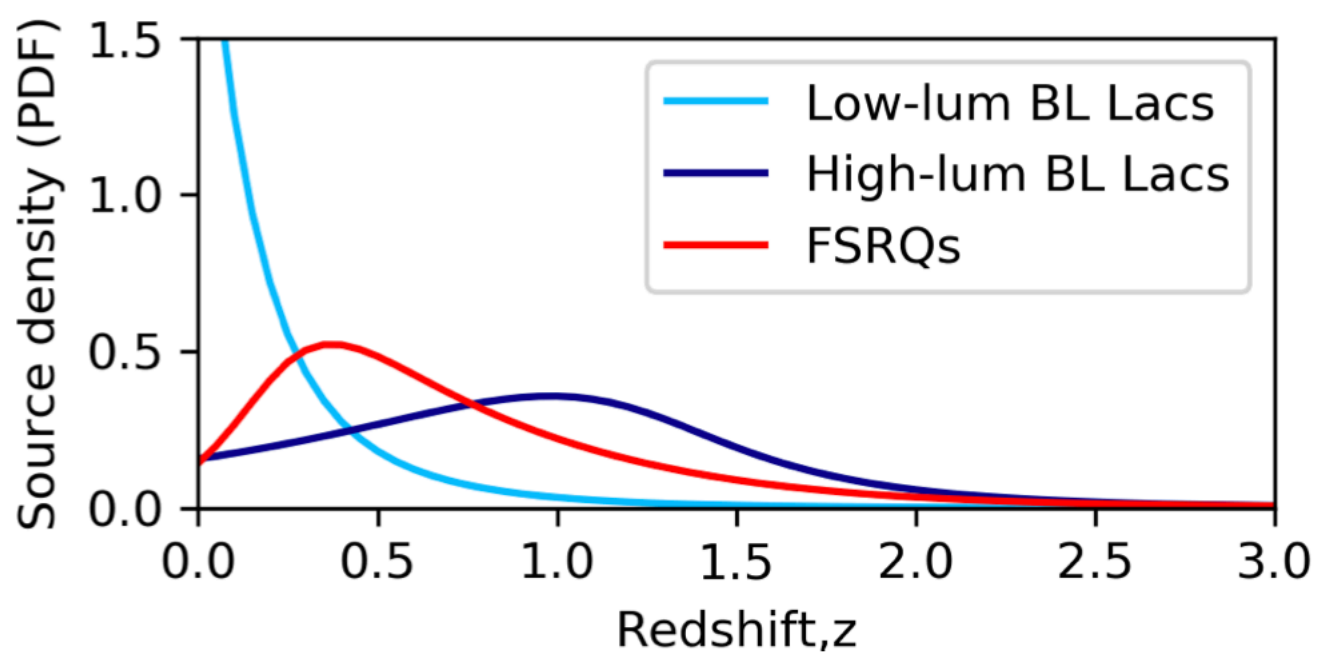
The Pierre Auger Collab. JCAP 2023

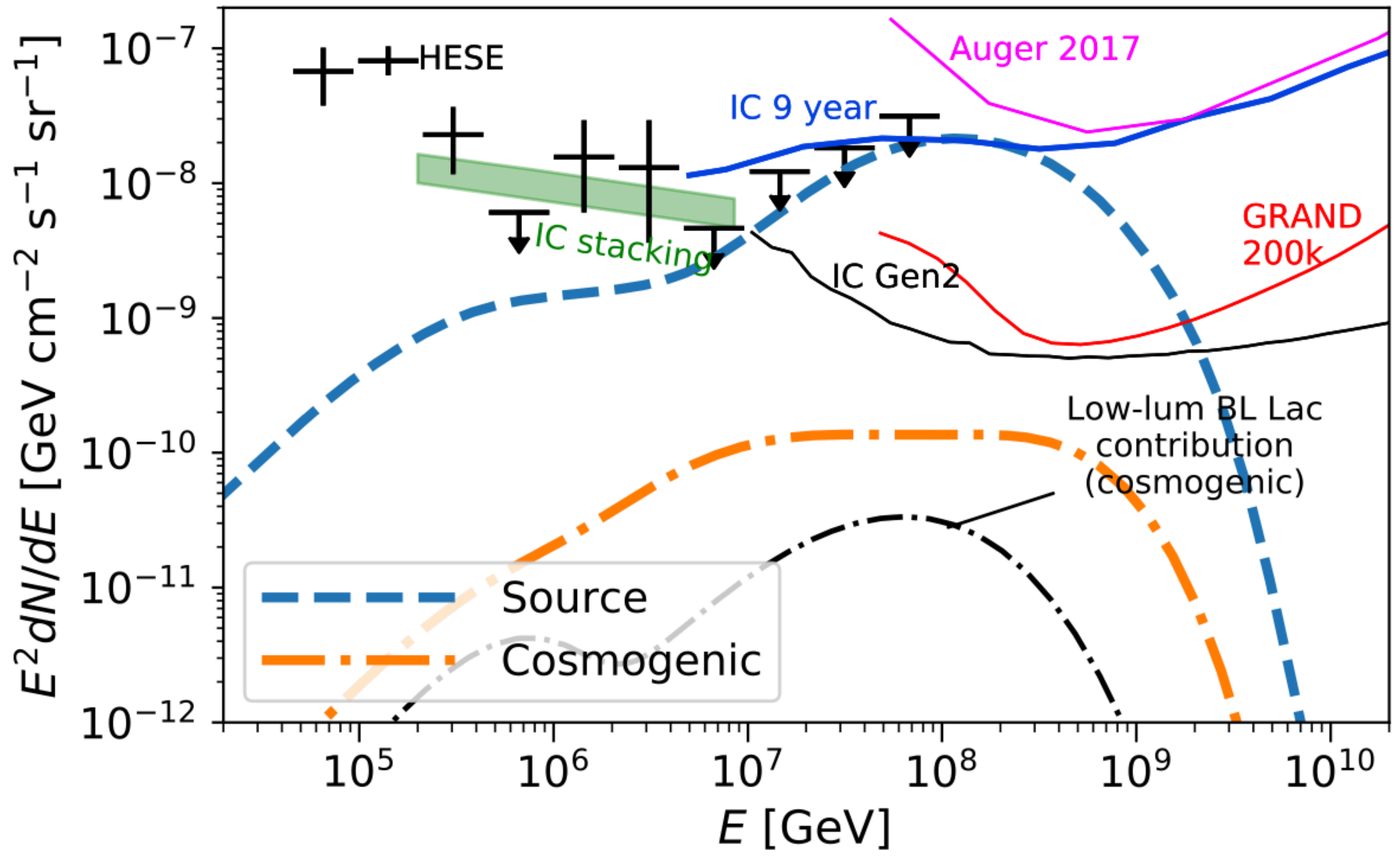


UHECRS AND NEUTRINOS







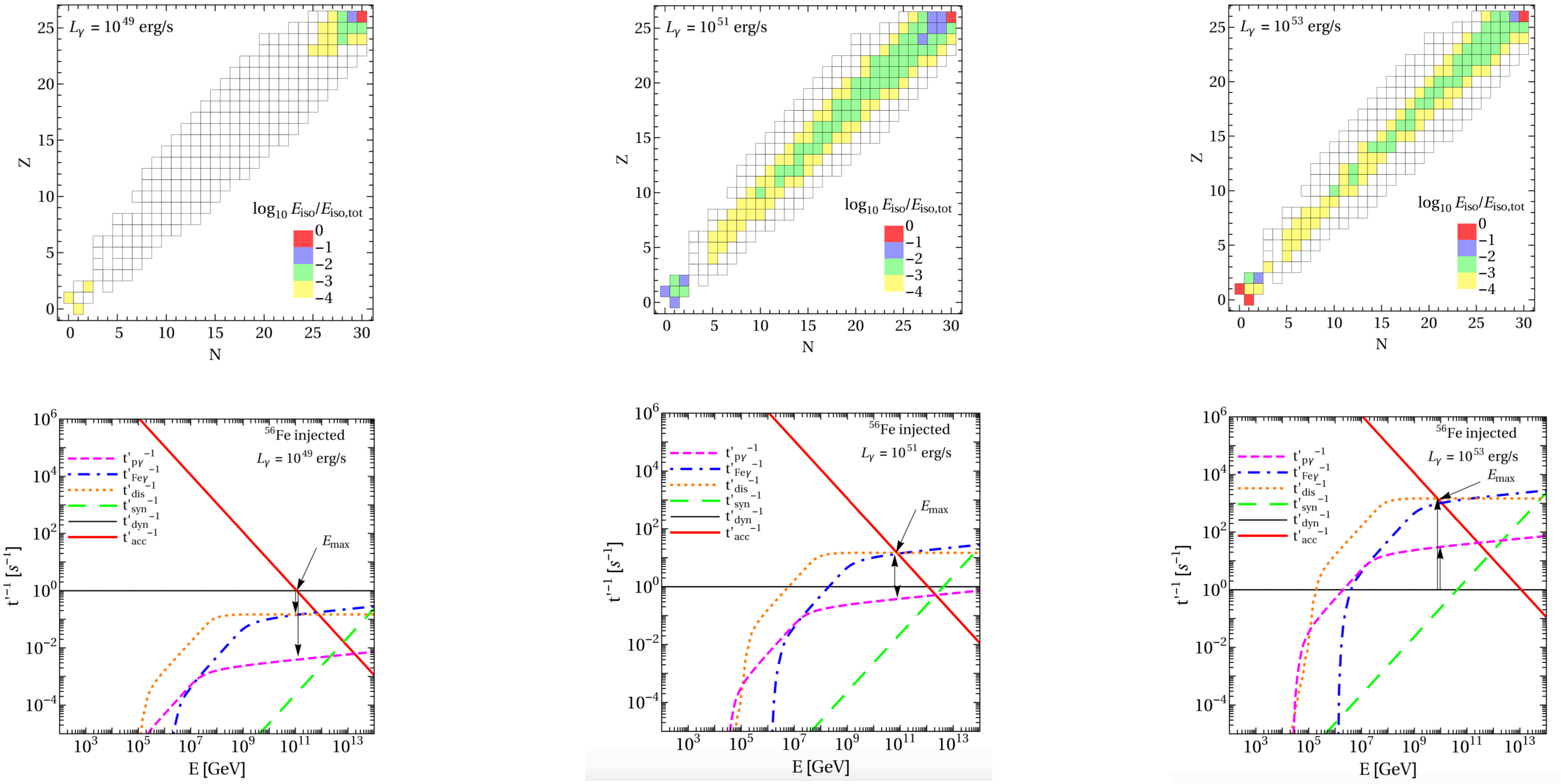


Rodrigues et al PRL 2021; Rodrigues, Gao, Fedynithc, **DB** & Winter ApJ 2018; Murase et al PRD 2014

Talk by X. Rodrigues, CCR session, today

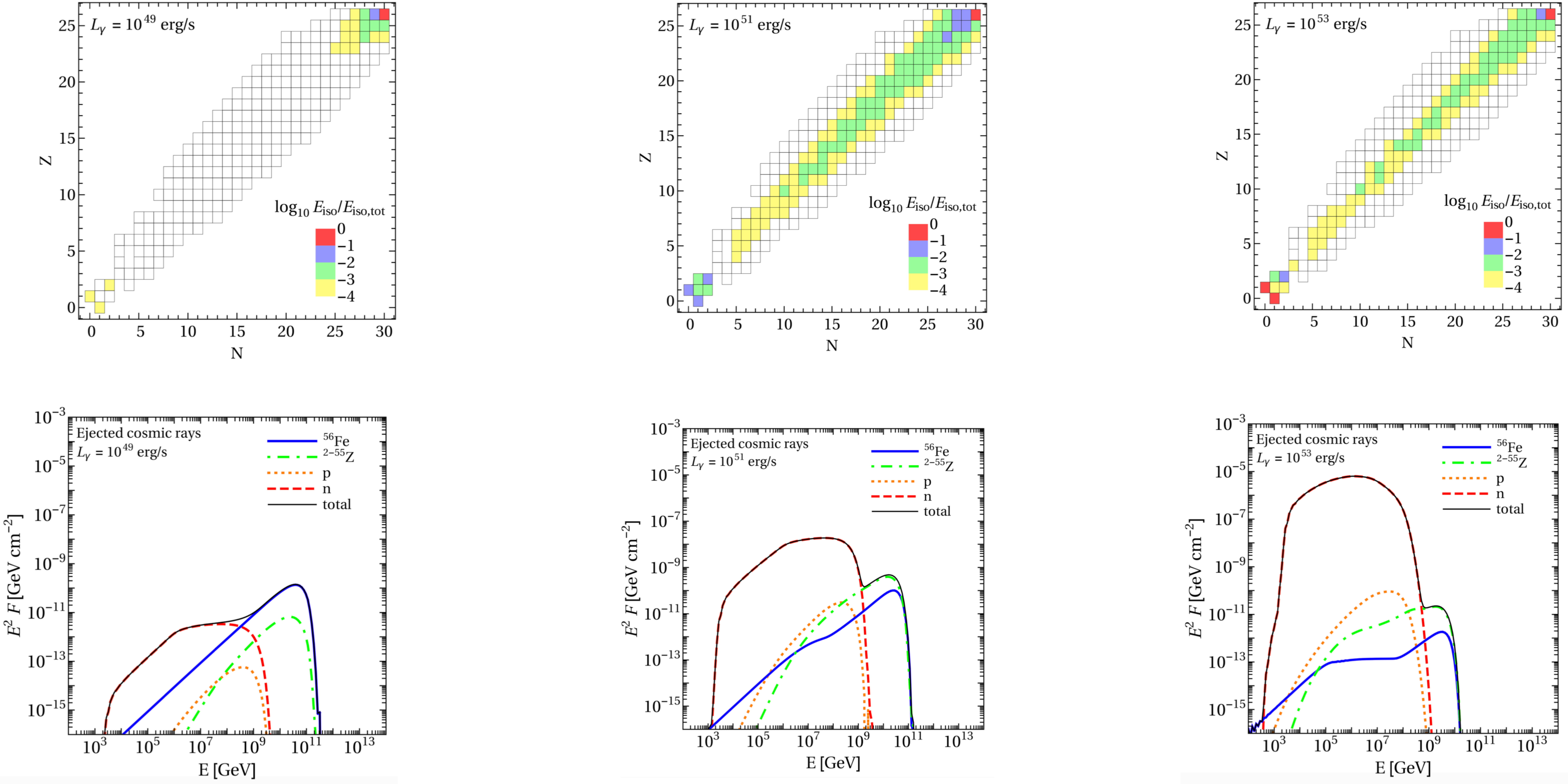
IN-SOURCE INTERACTIONS

*Biehl, **DB**, Fedynitch & Winter, A&A 2018*



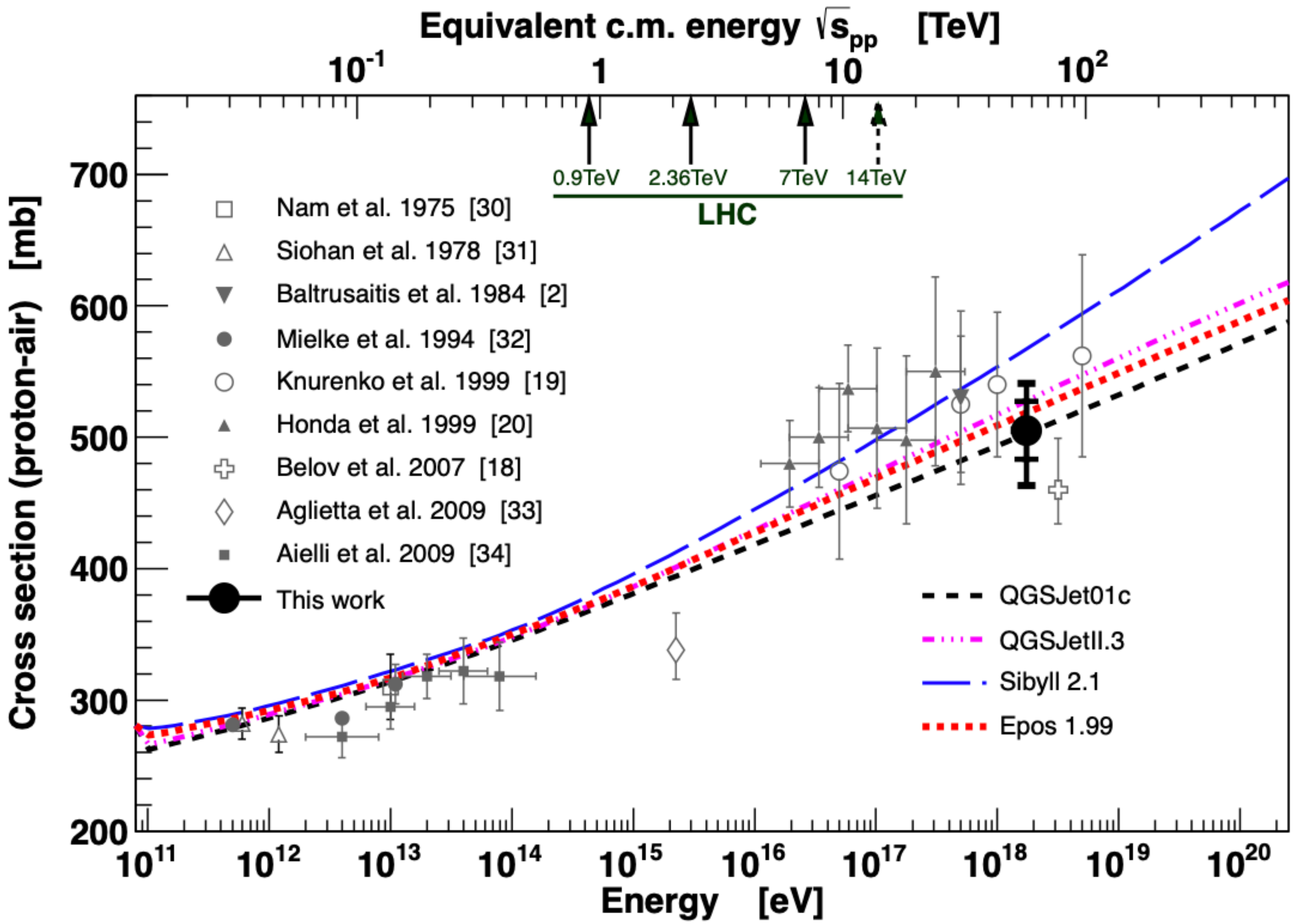
IN-SOURCE INTERACTIONS

*Biehl, **DB**, Fedynitch & Winter, A&A 2018*



THE HIGH-ENERGY FRONTIER

UHECRS AND PARTICLE PHYSICS

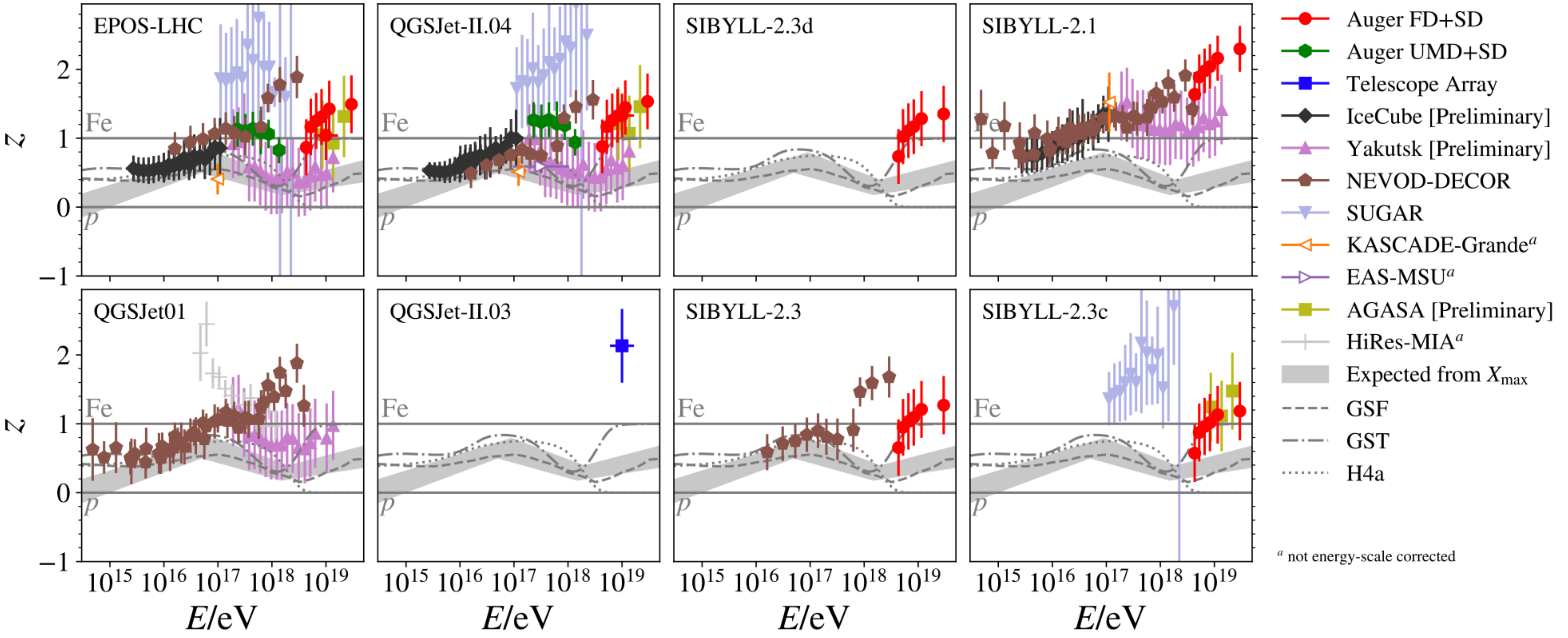


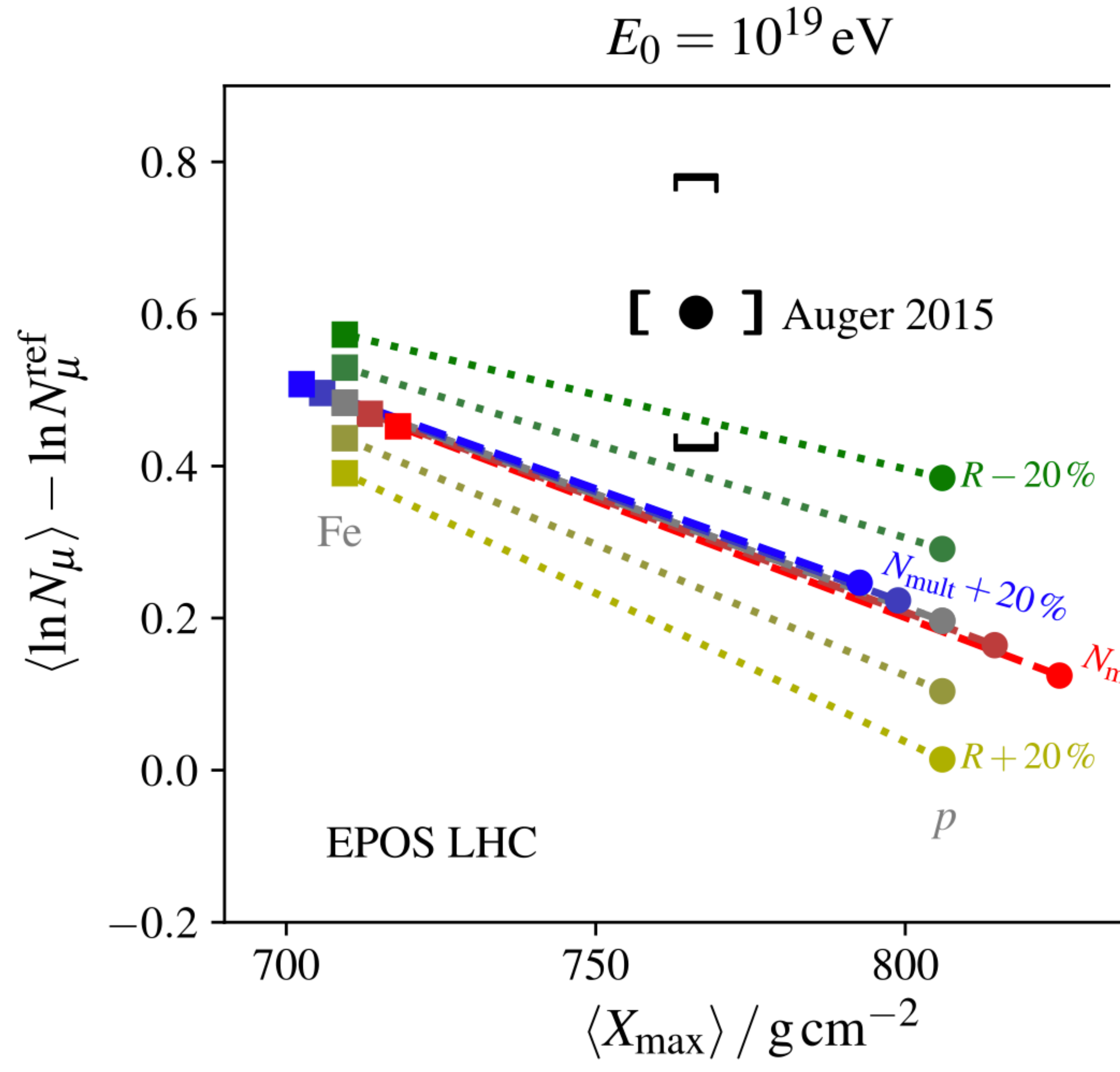
The Pierre Auger Collab. PRL 2012

- p-air cross section from very penetrating showers
- Conversion in pp cross section through Glauber calculations

UHECRS AND PARTICLE PHYSICS

Albrecht et al. ICRC21





$$R = \frac{E_{em}}{E_{had}},$$

$$z = \frac{\ln N_\mu - \ln N_{\mu,p}}{\ln N_{\mu,\mathrm{Fe}} - \ln N_{\mu,p}},$$

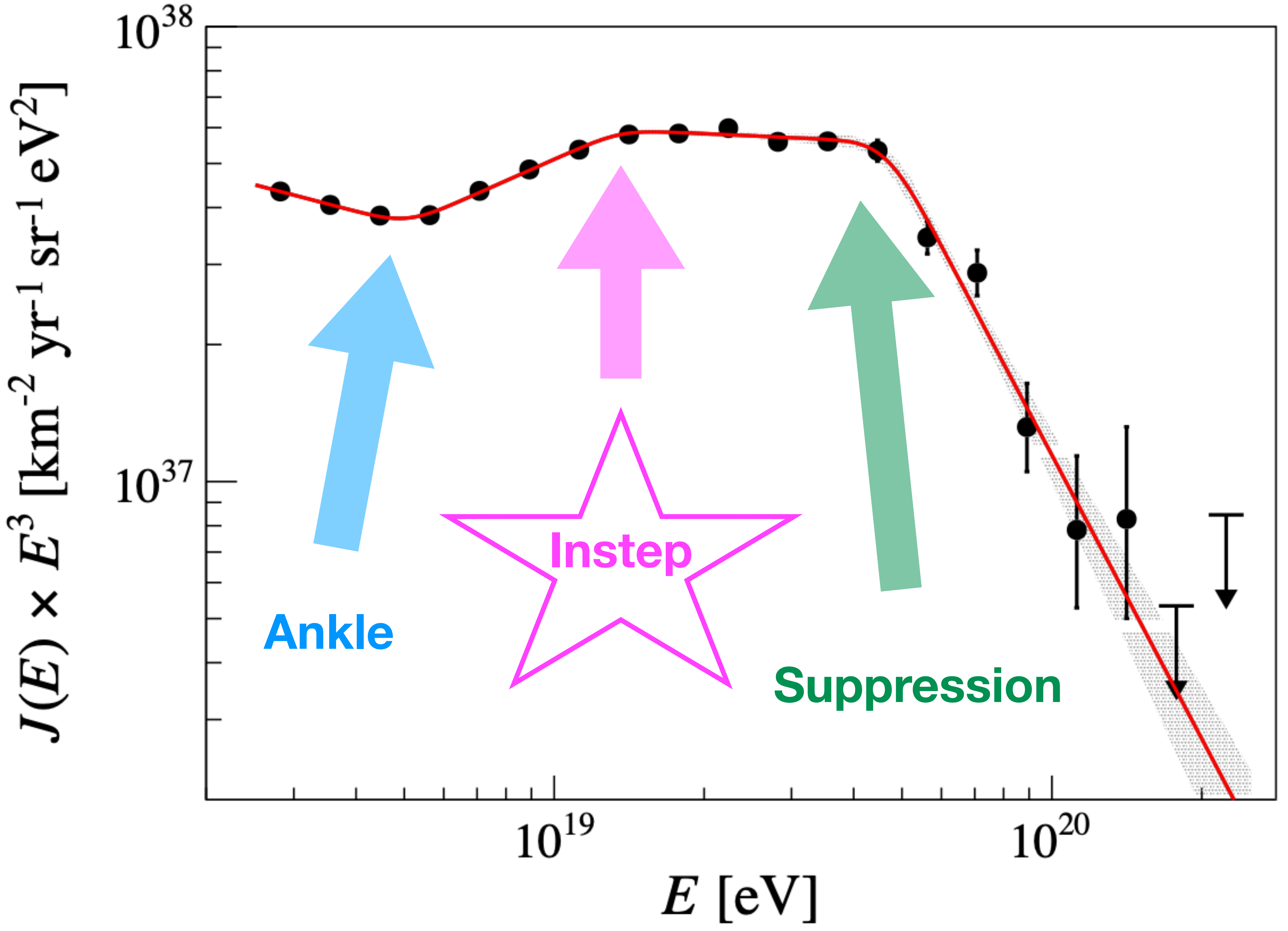
- Air-shower simulations with state-of-the-art QCD models show a significant **muon deficit** with respect to measurements starting at TeV scale in center-of-mass frame

- Ratio of energy in electromagnetic vs muonic component influenced by:
  - cross section
  - elasticity
  - multiplicity
  - fraction of neutral mesons
- Fluctuations of number of muons are less affected (see Cazon et al PRL 2018; The Pierre Auger Colla. PRL 2019)

UHECR MEASUREMENTS

THE UHECR ENERGY SPECTRUM

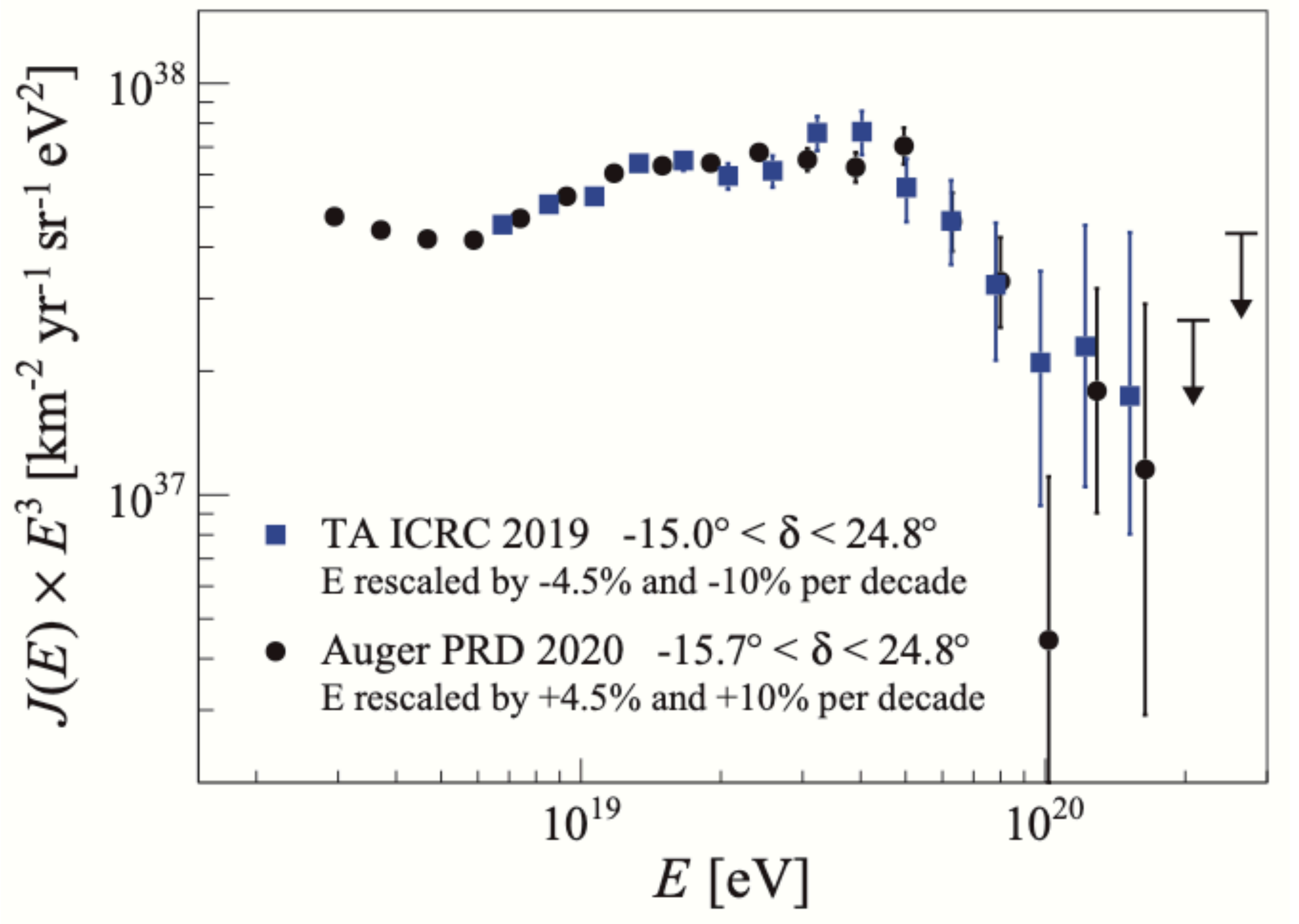
The Pierre Auger Collab. PRD2020



Spectrum at Earth characterised by 4 broken power laws, defining 3 inflection points:

- Ankle
- Instep
- Suppression

Telescope Array and Pierre Auger Collab.
Joint WG on Spectrum, UHECR22

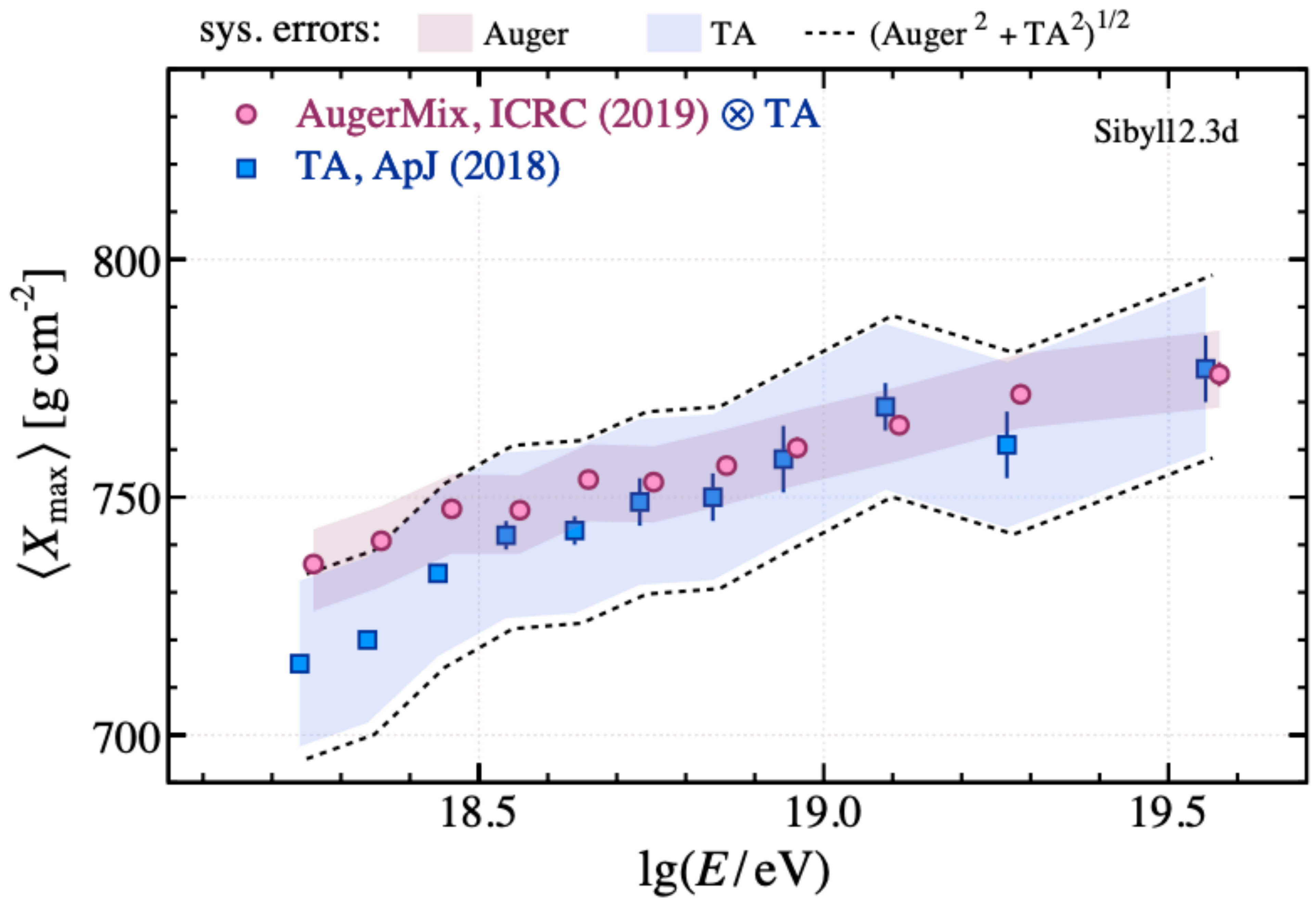


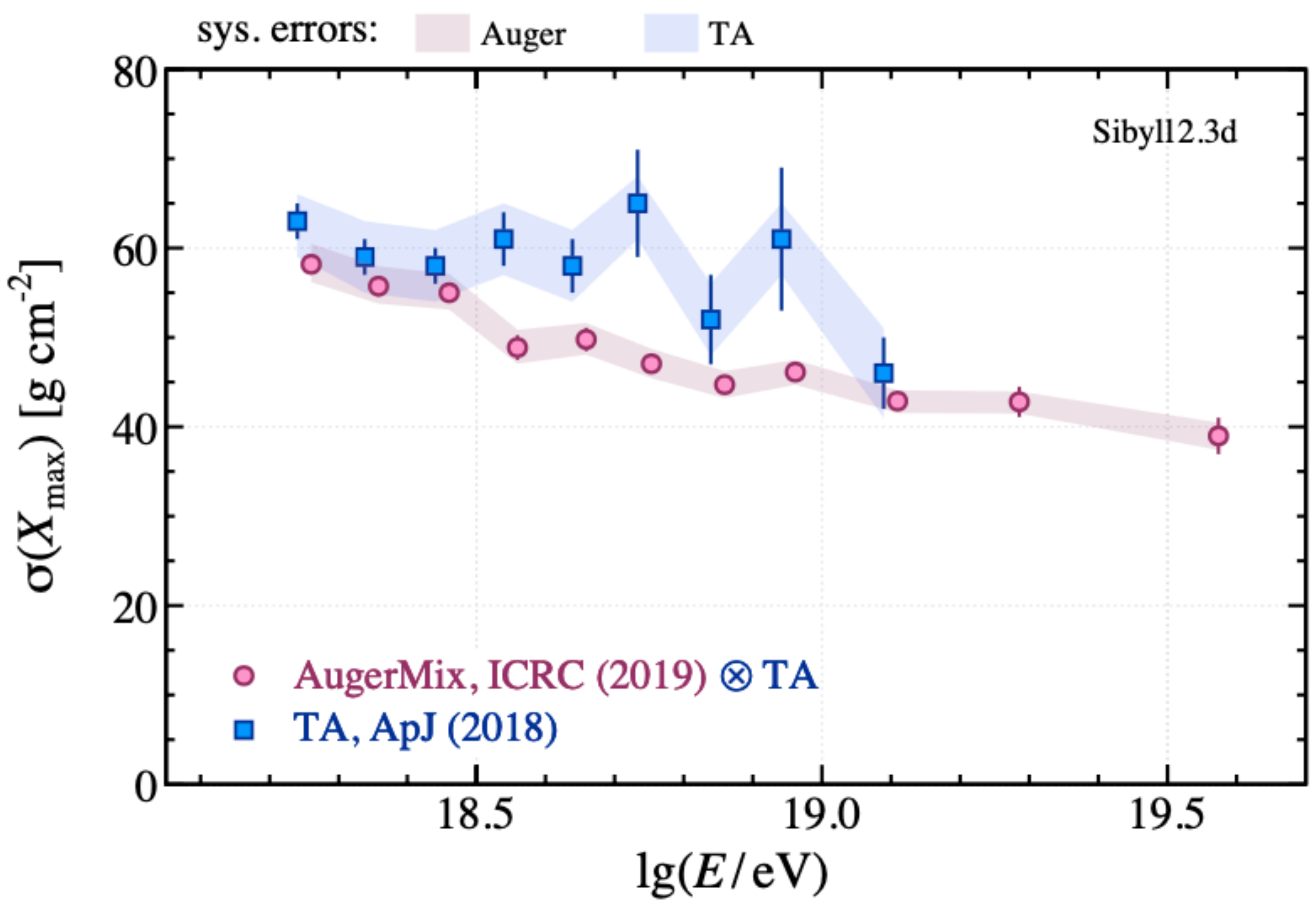
TA data points higher than Auger, larger discrepancy at highest energies

- Energy dependent shift due to statistical fluctuations excluded with significance 3 sigma
- Details of event reconstruction and calibration procedure

THE UHECR MASS COMPOSITION

Telescope Array and Pierre Auger Collab.
Joint WG on Mass Composition, ICRC23



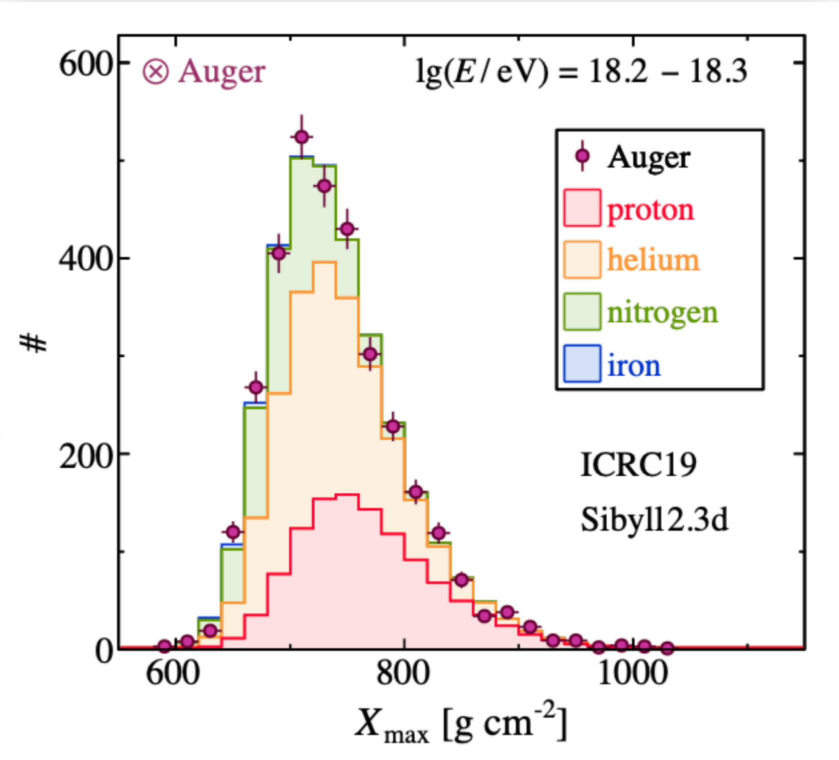


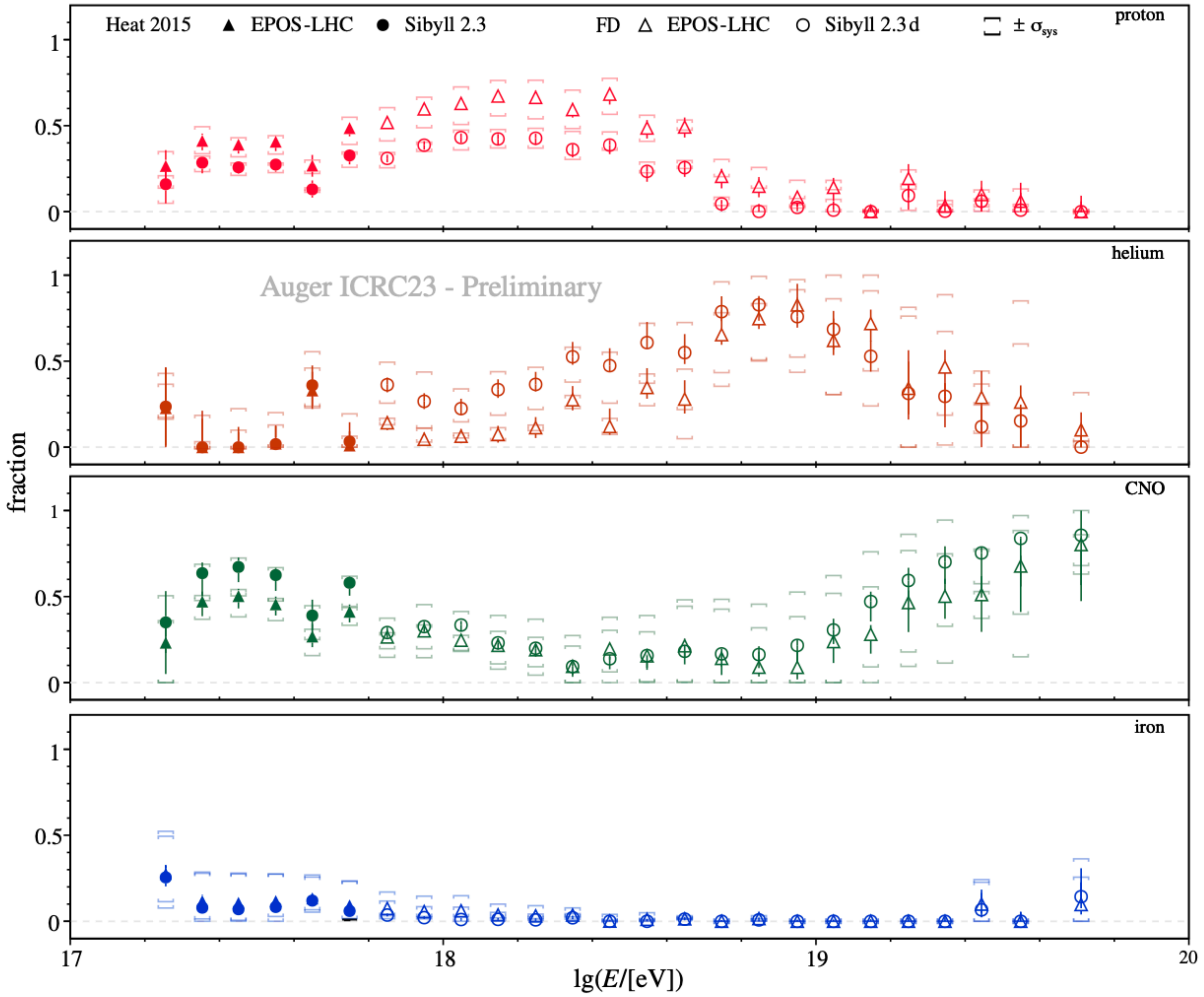
- the TA X_{max} measurements can be compared only to other measurements or simulations folded with the TA experimental effects
- to transfer the Auger data to the TA detector, we use as a proxy simulated X_{max} distributions for the mass compositions with which the best description of the Auger X_{max} distributions in each energy bin is achieved

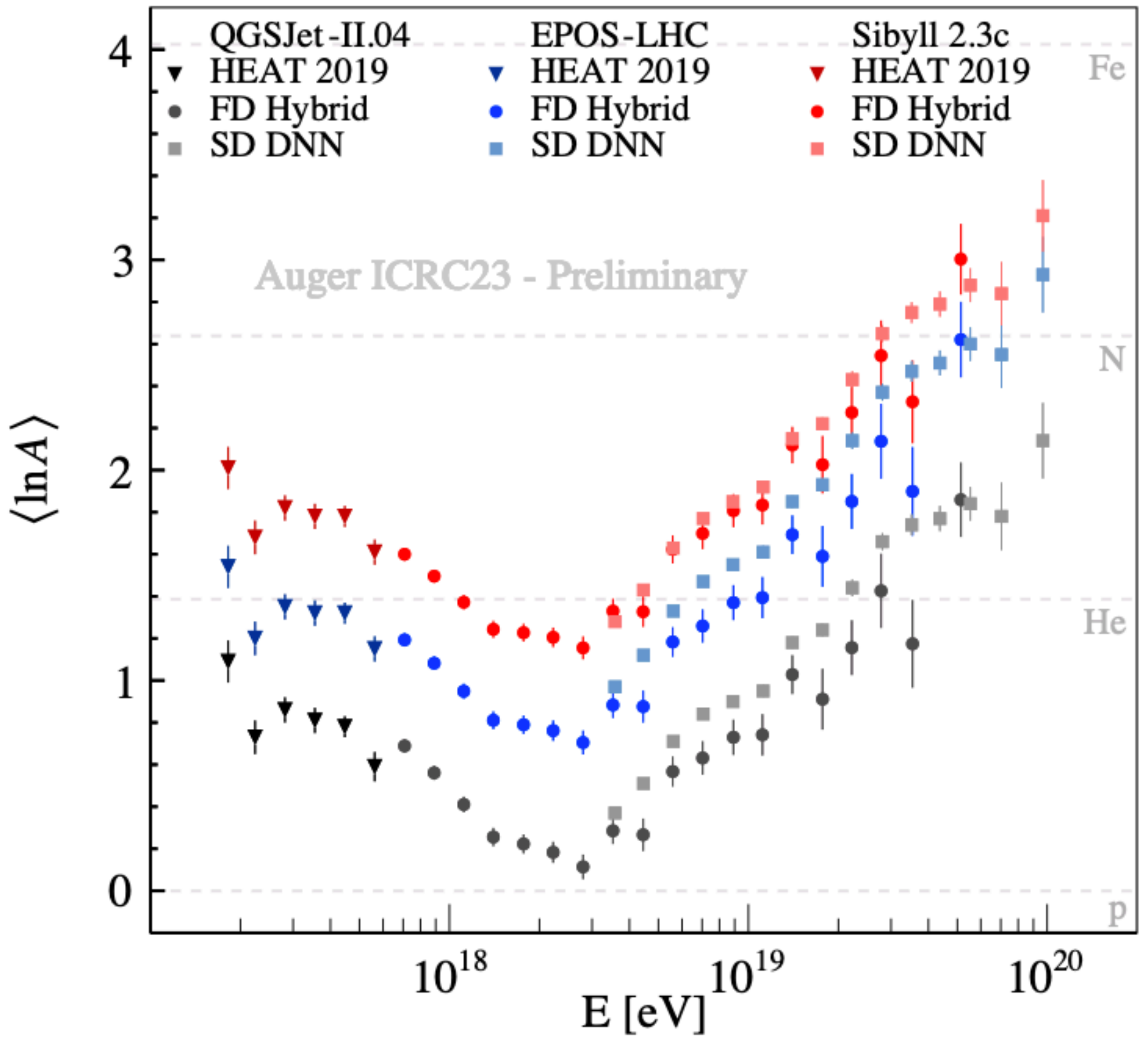
THE UHECR MASS COMPOSITION

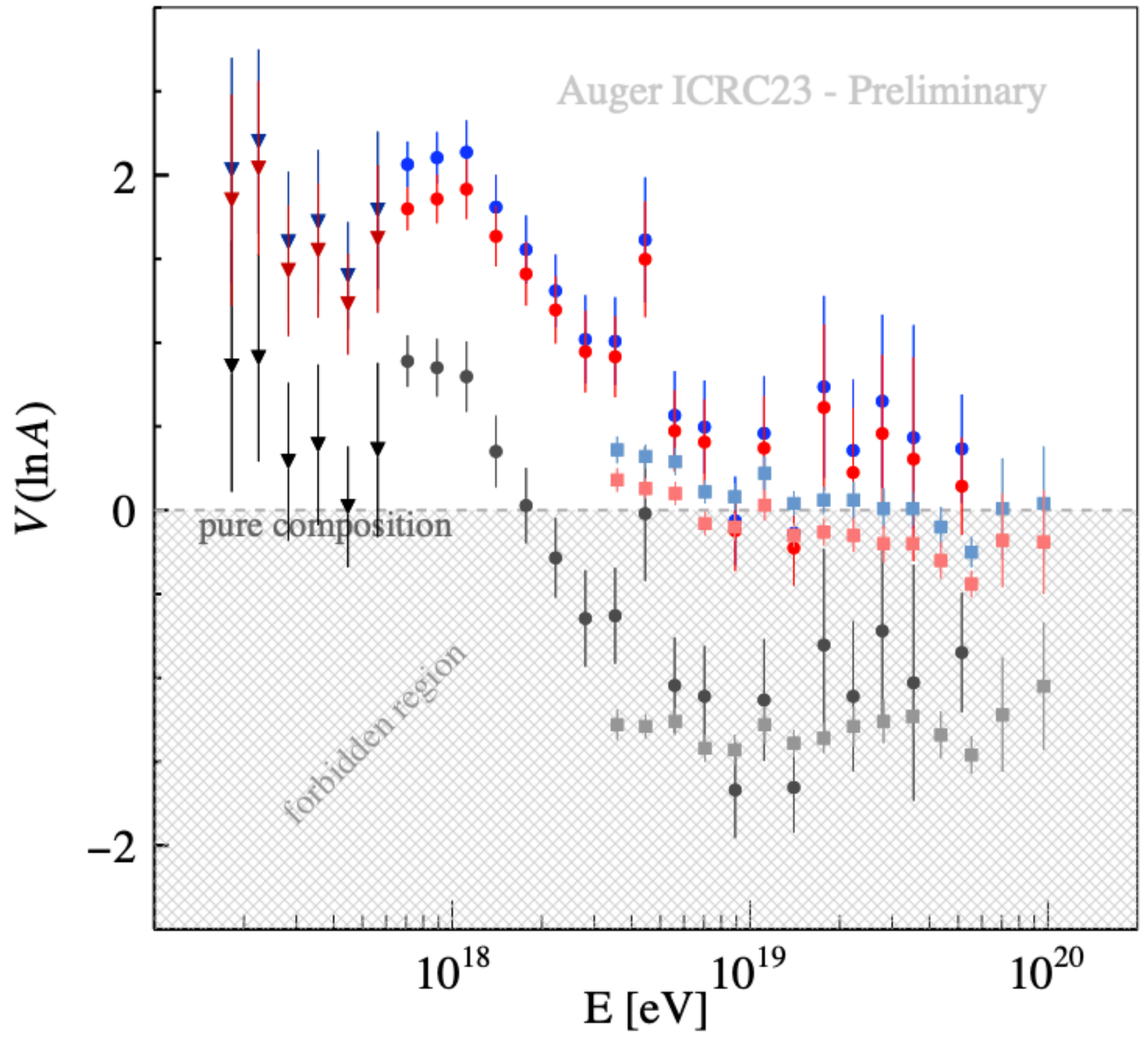
The Pierre Auger Collab. ICRC23

Fit of observed distributions of Xmax with model-generated templates of different primary mass groups to estimate how much each group contributes to the overall flux









$\boxed{\langle X_{max}\rangle = \langle X_{max}\rangle_p + f\,\langle \ln A\rangle}$

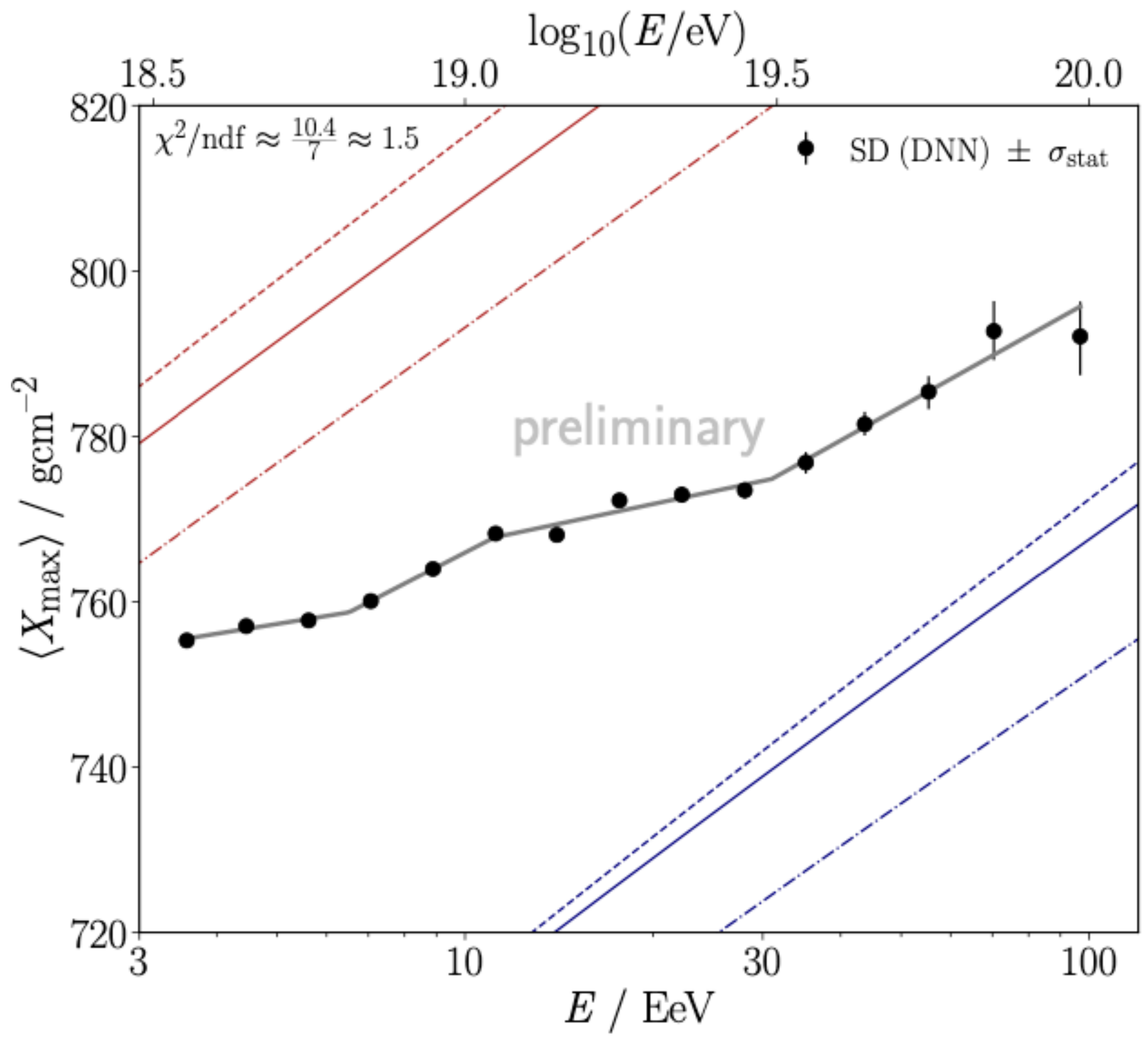
$\boxed{\sigma^2(X_{max}) = \langle \sigma^2_{sh}\rangle + f^2\,\sigma^2(\ln A)}$

Combining the Xmax measurement with the predictions from hadronic interaction models

- shows the variance of lnA crosses below the values associated with a pure composition into a forbidden regime

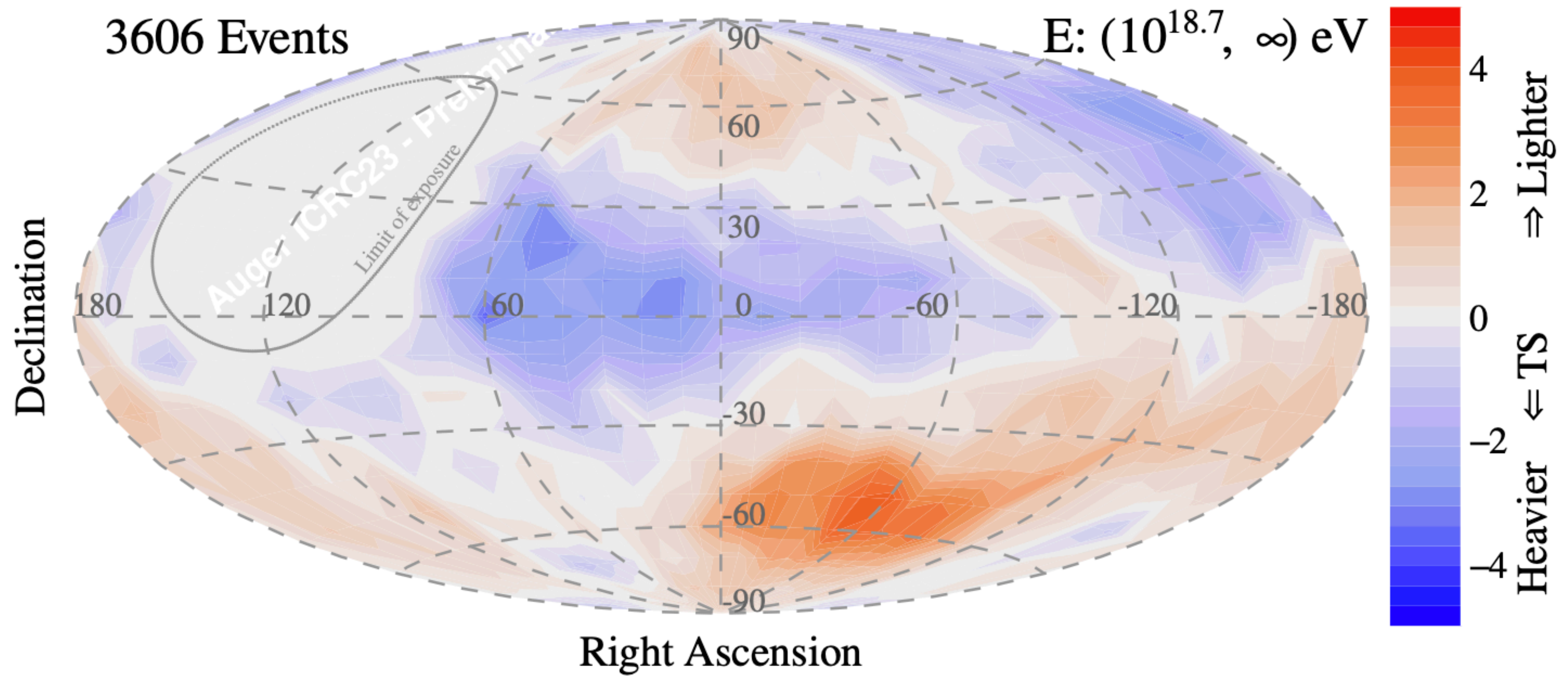
COMBINING UHECR MEASUREMENTS

The Pierre Auger Collab. ICRC23



First moment of the Xmax distributions obtained using the deep-learning-based reconstruction of the SD data

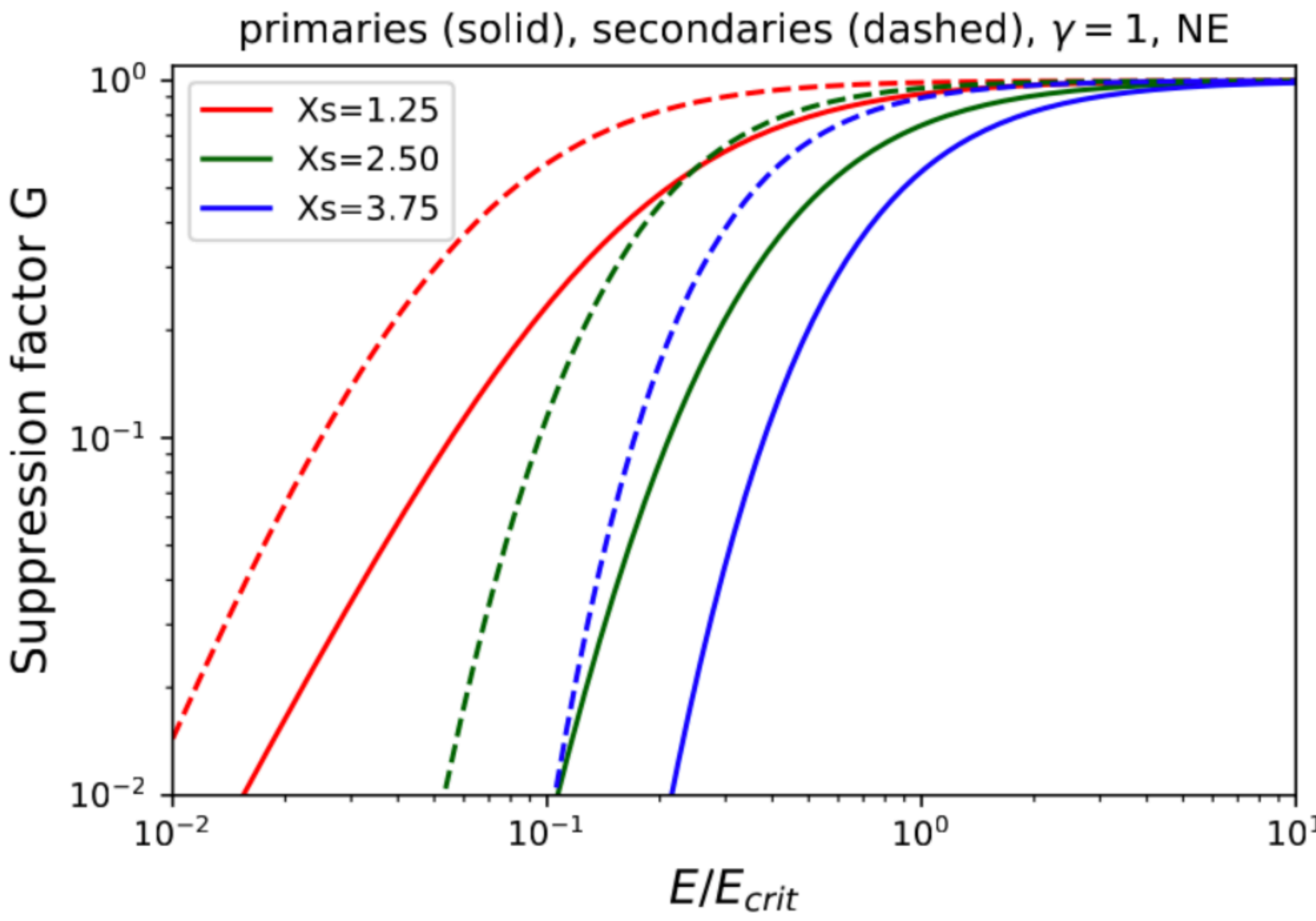
- Enlargement in statistics by a factor of 10 with respect to previous FD analyses
- Investigate elongation rate: **3 breaks found, coinciding with feature of the energy spectrum**



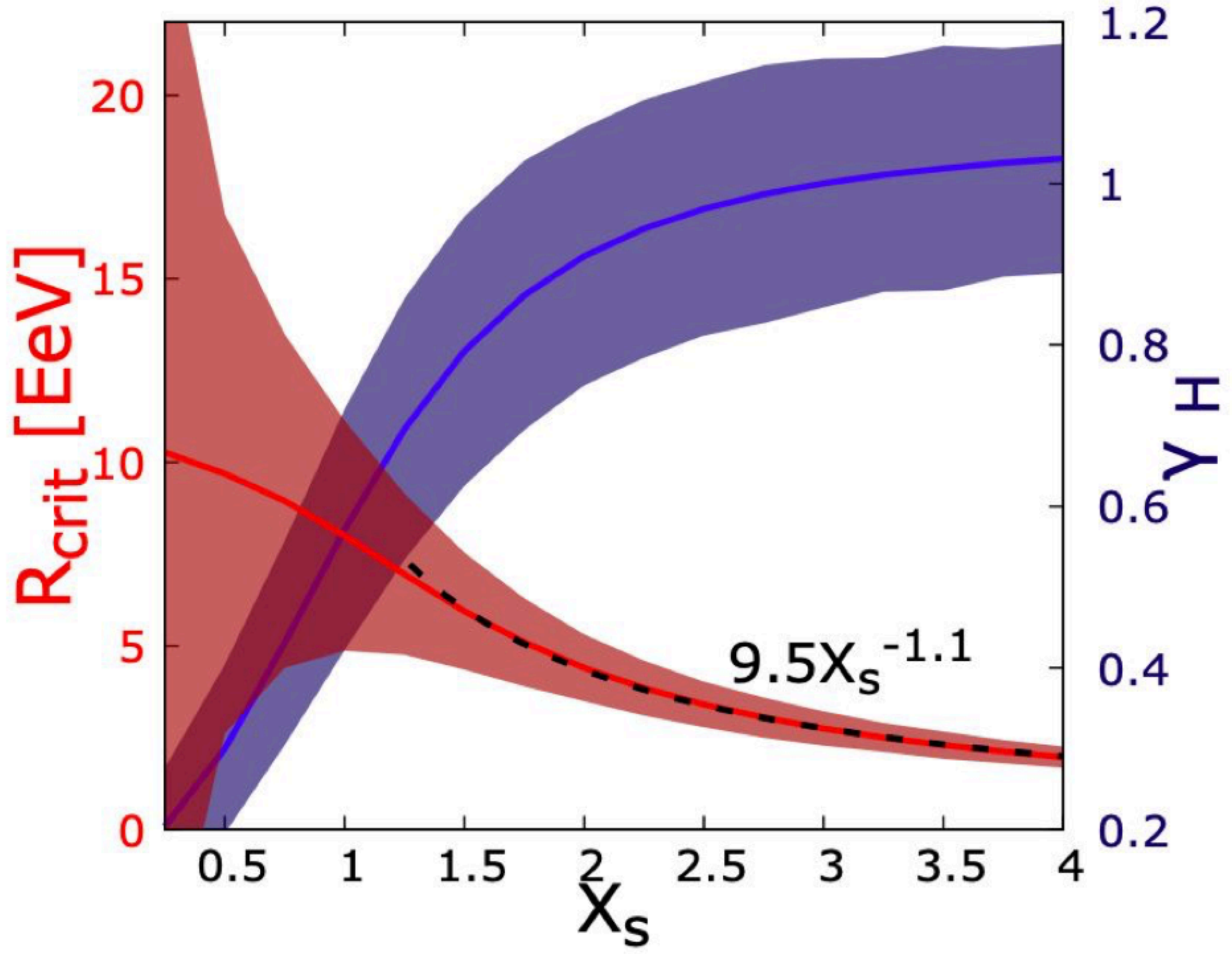
Hint of excess of heavier cosmic rays coming form Galactic Plane with significance of 2.5σ

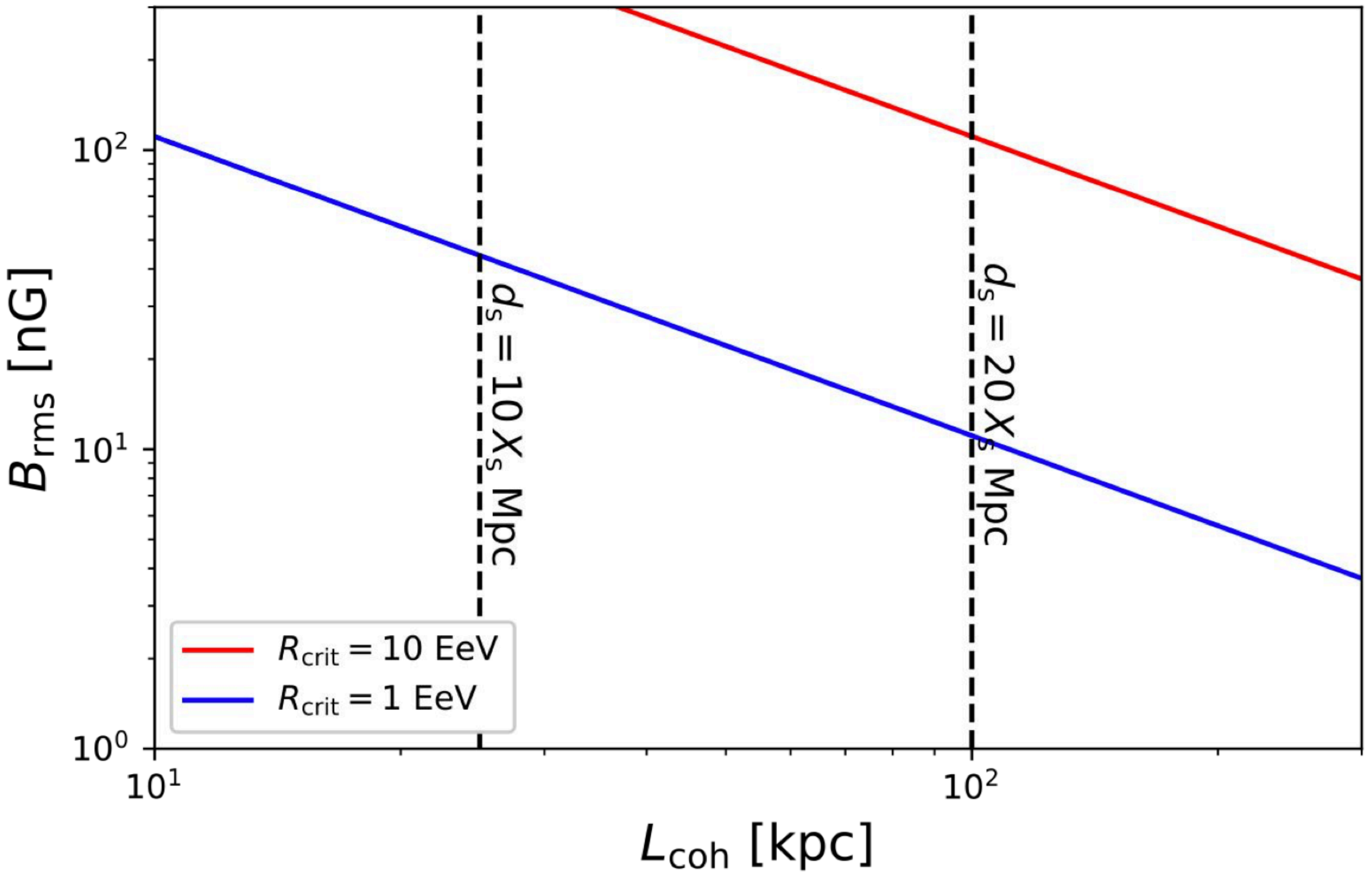
EFFECT OF EGMF ON SPECTRUM AND COMPOSITION

$$R_{\rm crit} \equiv |e| B_{\rm rms} L_{\rm coh} \simeq 0.9 (B_{\rm rms}/{\rm nG})(L_{\rm coh}/{\rm Mpc})$$



$$X_{\rm s} = d_{\rm s}/\sqrt{r_H L_{\rm coh}},$$





$$\frac{X_{\rm s} R_{\rm crit}}{10\,{\rm EeV}} \simeq \frac{d_{\rm s}}{40\,{\rm Mpc}} \frac{B_{\rm rms}}{100\,{\rm nG}} \sqrt{\frac{L_{\rm coh}}{25\,{\rm kpc}}}.$$

- From the fit of spectrum + composition, including the suppression factor at LE due to magnetic fields

- Large inter-source distances and large amplitudes for the B rms are requested to have a relevant effect in explaining the observations

Mollerach & Roulet PRD 2020; Gonzalez et al, PRD 2021; The Pierre Auger Collab. ICRC23