Making science with the Pierre Auger Observatory

Phase I achievements and brainstorming towards Phase II aims

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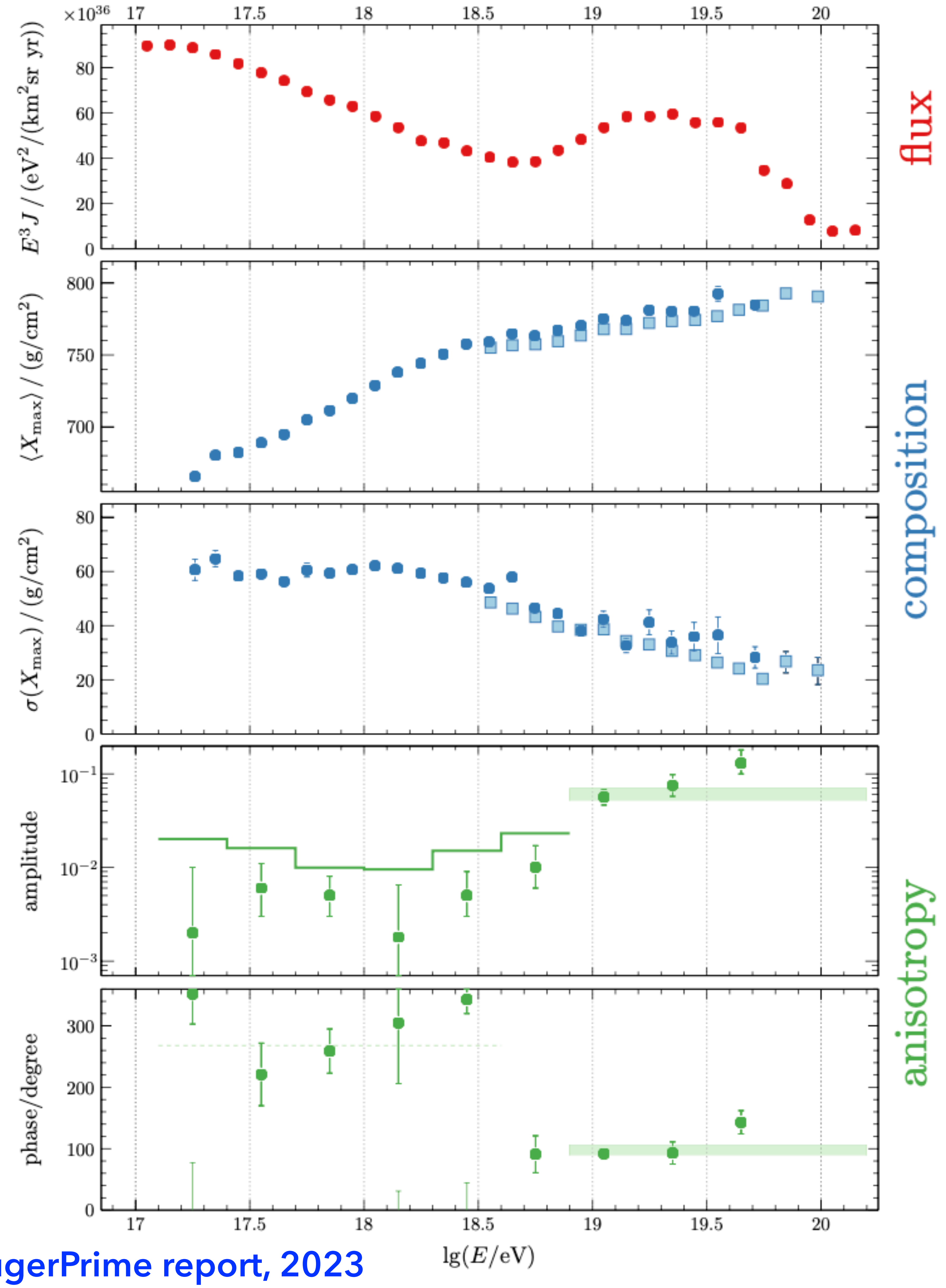
Meeting Auger Italia
Torino, February 3-5, 2025

Outline

- Summary of major results of Phase I
- Open questions (from the AugerPrime report, 2023)
- **Status of (some) ongoing analyses (and some references to contributions of Italian groups and/or young collaborators) and (refined) open questions**
- Final summary

Major results of Phase I

Summary of Phase I results above 10^{17} eV related to the main UHECR observables



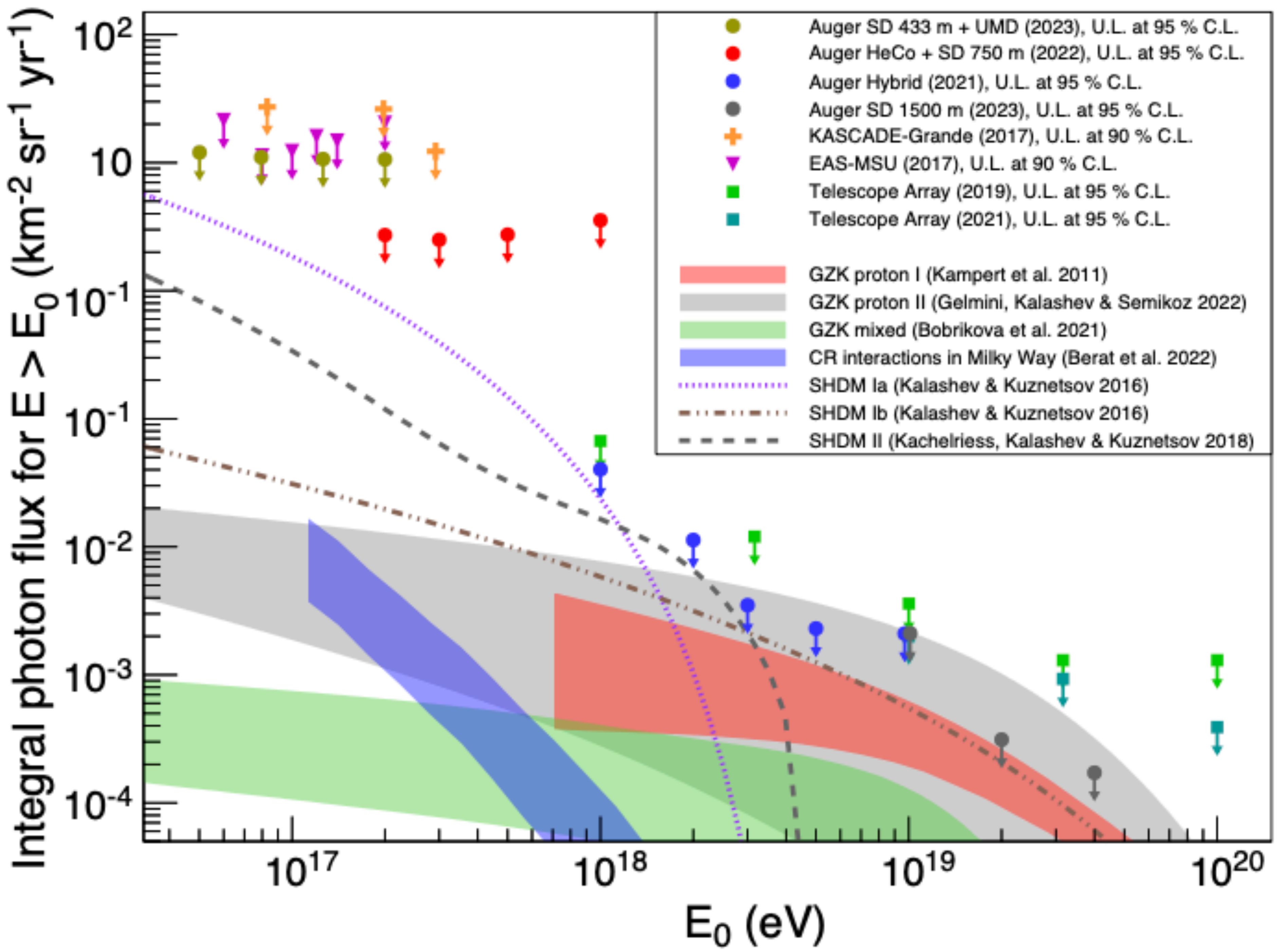
AugerPrime report, 2023

- The energy spectrum shows several changes of slope ("instep" firstly shown by Auger); no dependence on the declination found

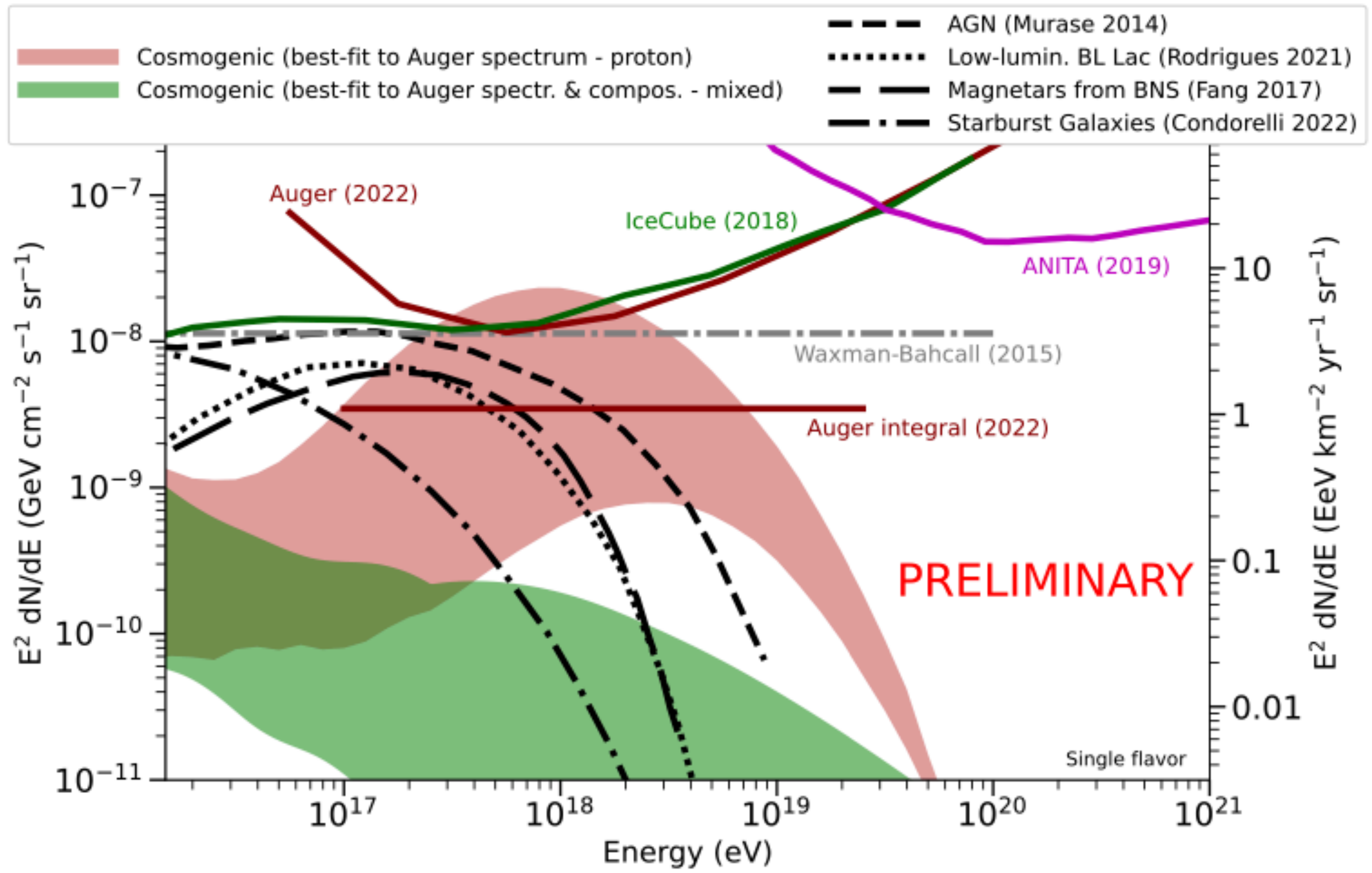
- <X_{max}> increases until $10^{18.4}$ eV and decreases afterwards; $\sigma(X_{max})$ shows a trend towards heavier (and less mixed) composition above $10^{18.6}$ eV (behaviour confirmed by the fit of the composition fractions); the absence of breaks can be rejected with high significance thanks to SD <X_{max}> (DNN)

- Non-zero amplitude of the first harmonic in right ascension above 8 EeV discovered with a direction of maximum intensity pointing towards 113^0 away from the Galactic center
- Other searches for anisotropies: all-sky search for overdensities (Centaurus region); catalog-based searches (starburst galaxies)

Additional results (non-observations) contributing to the UHECR picture



Auger Collab. JCAP 10 (2019); ICRC2023



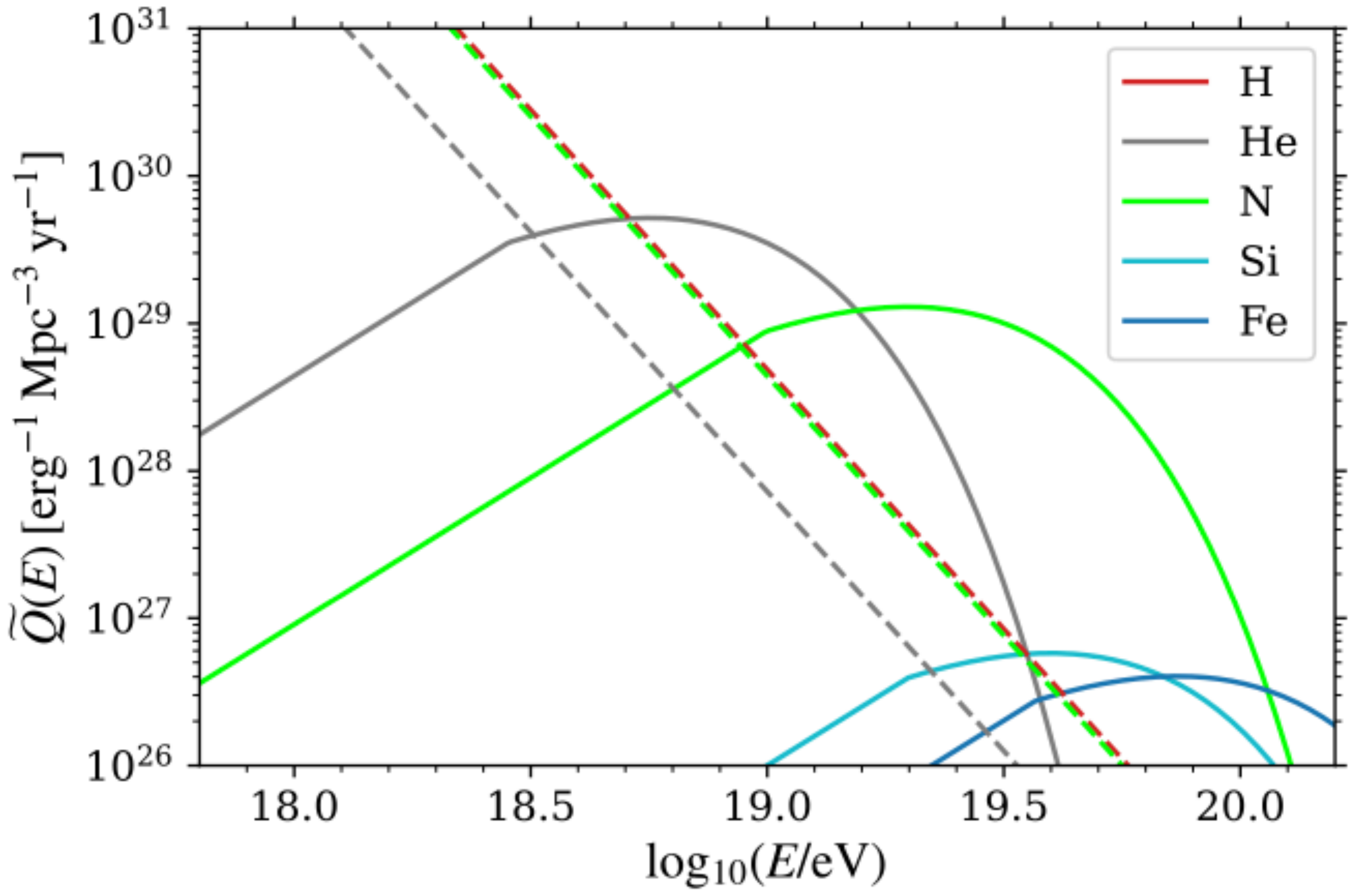
Upper bounds derived on diffuse fluxes of both UHE photons (left) and neutrinos (right)

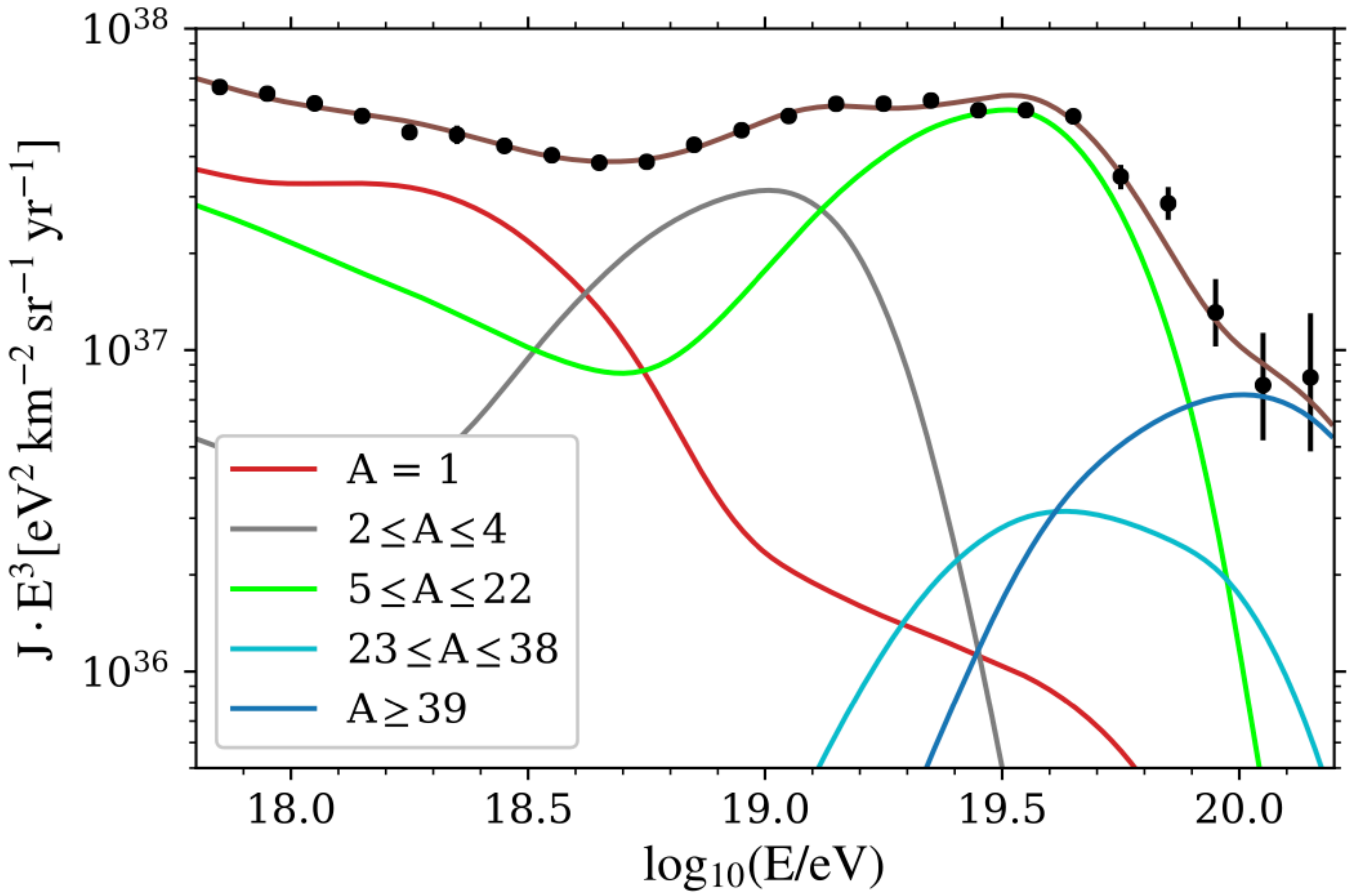
- The current precision of data challenges basic astrophysical scenarios, as the UHECR-proton paradigm, which was the leading (pre-Auger) scenario
- More refined UHECR scenarios can be tested with Auger data

Characteristics of UHECR sources

- 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)

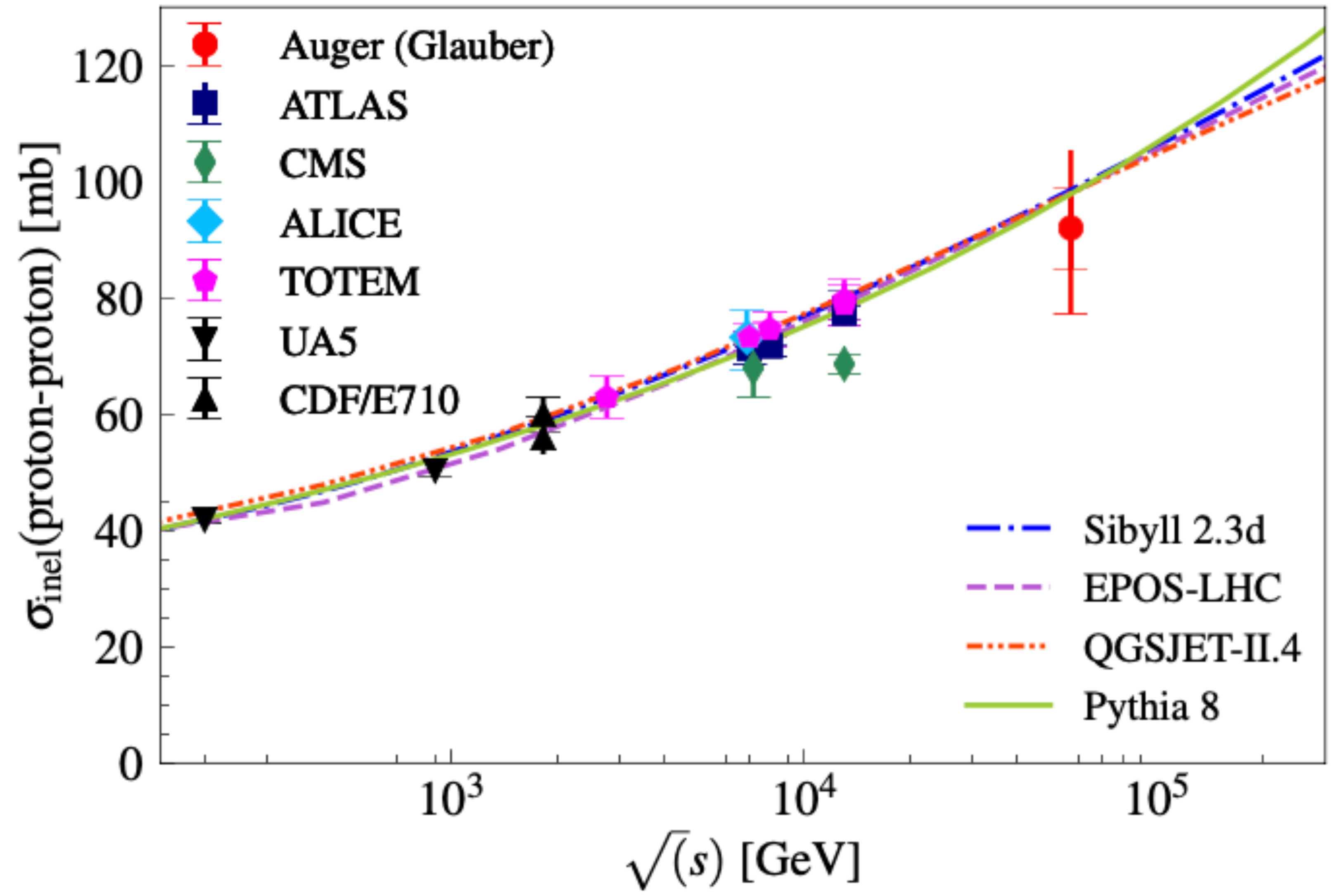
Auger Collab. JCAP 05 (2023)





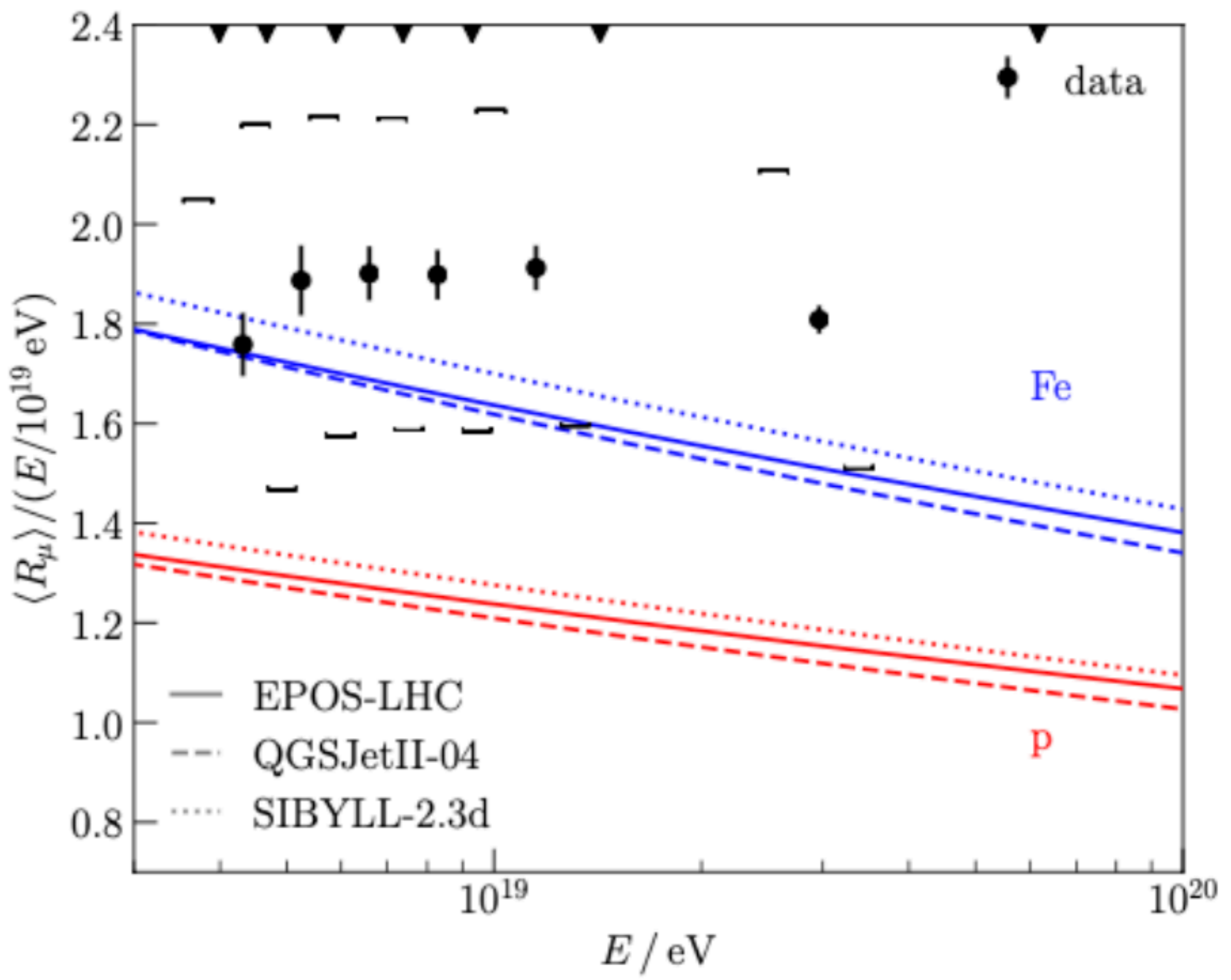
Role of UHECR measurements in investigating particle physics

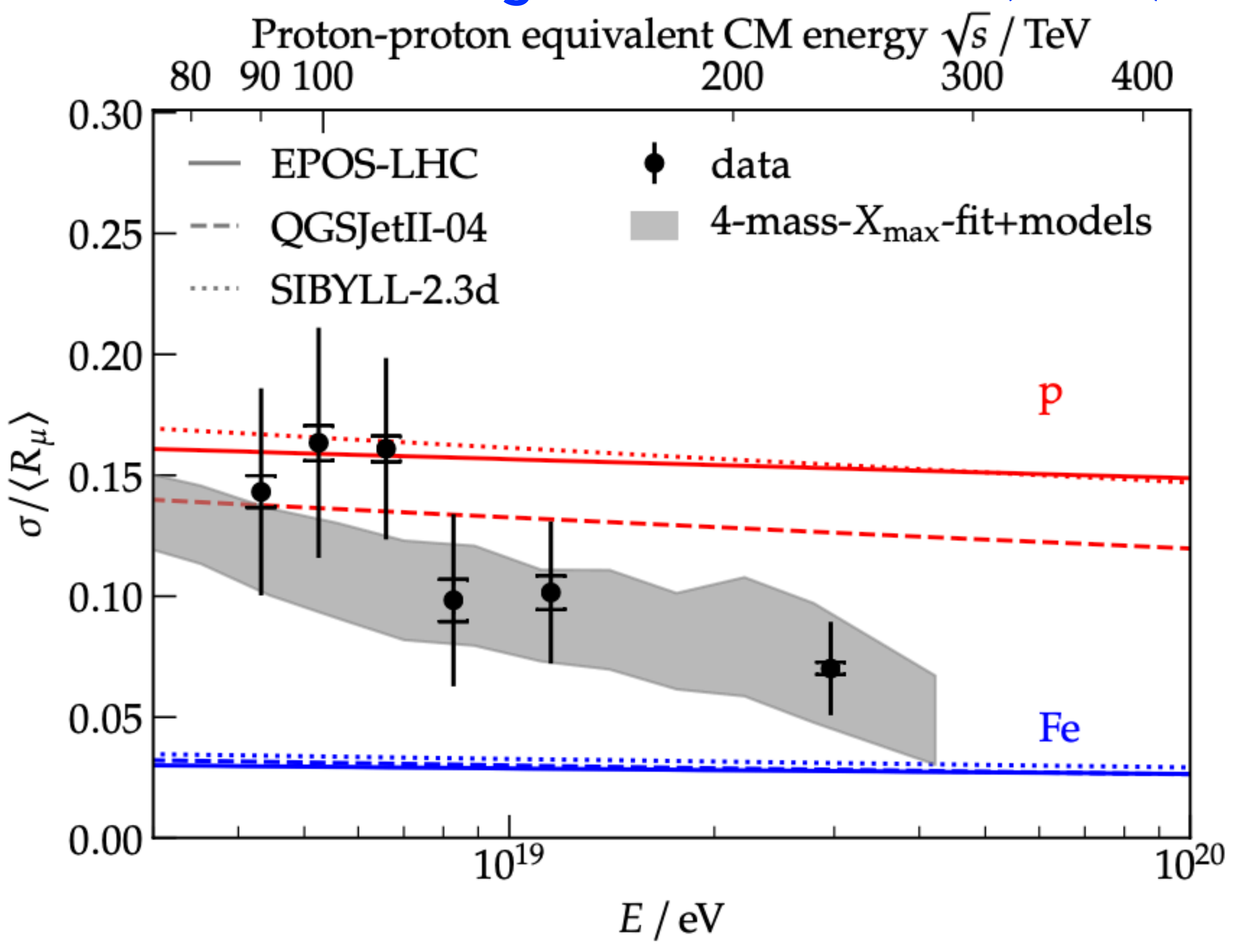
- pp cross section measurement agrees well with the standard model extrapolations to ultra-high energies



Auger Collab. PRL 2012

Auger Collab. PRL 126 (2021)

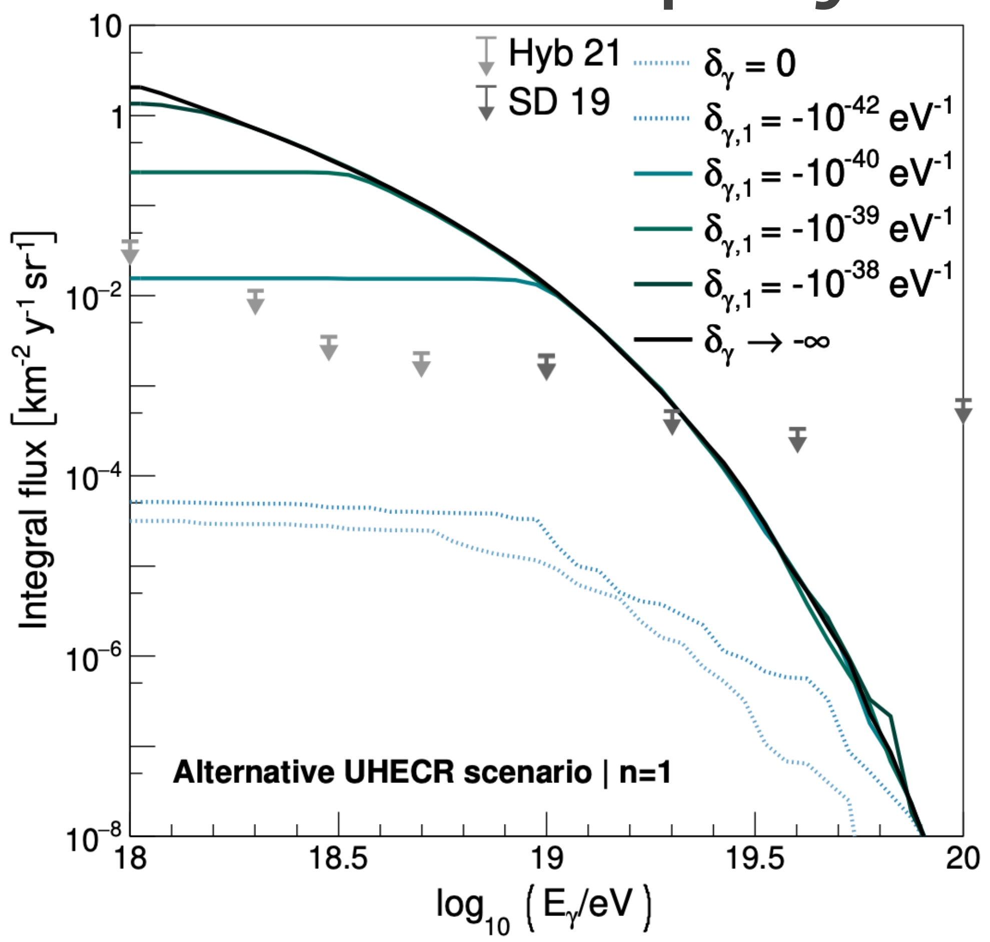


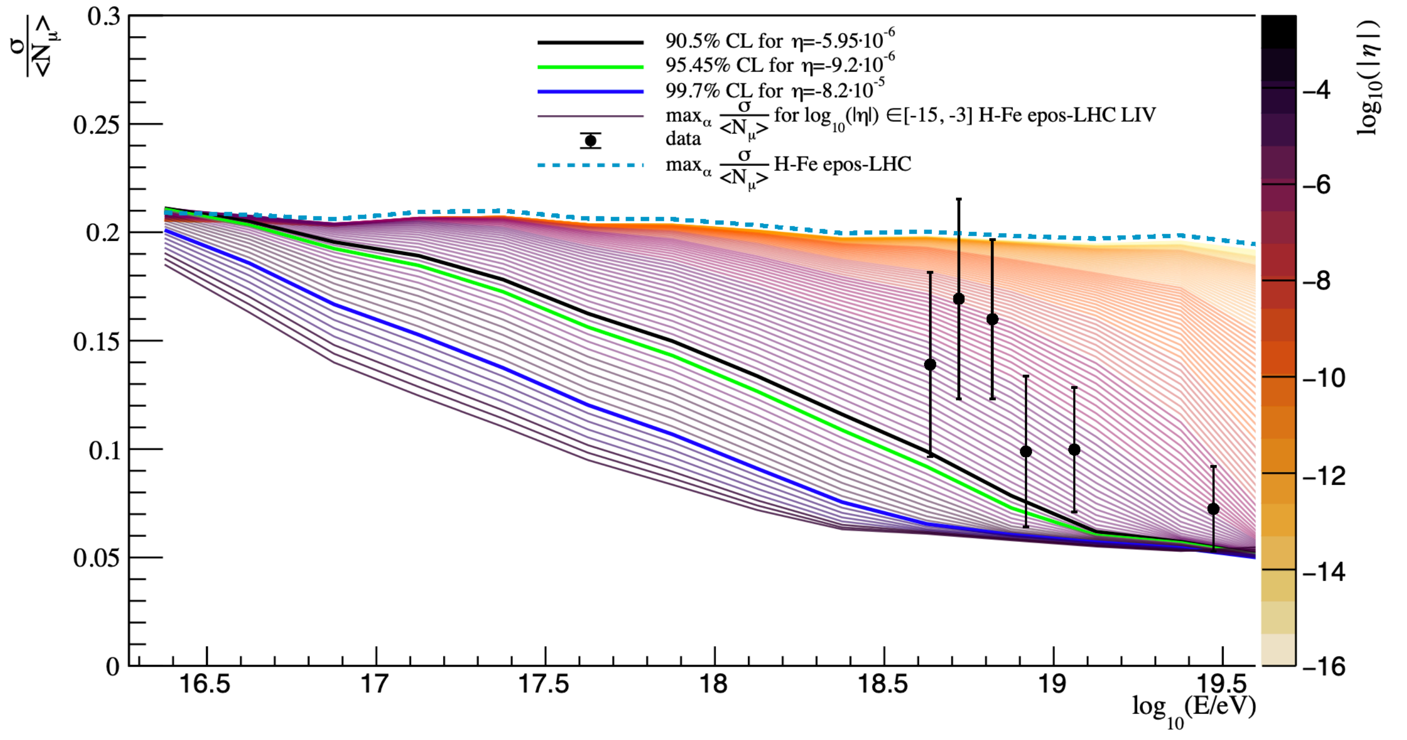


- The predicted absolute number of muons falls shows a deficit with respect to measurements
- The event-by-event fluctuation of the muon number is well described by air shower simulations

Role of UHECR measurements in testing fundamental physics

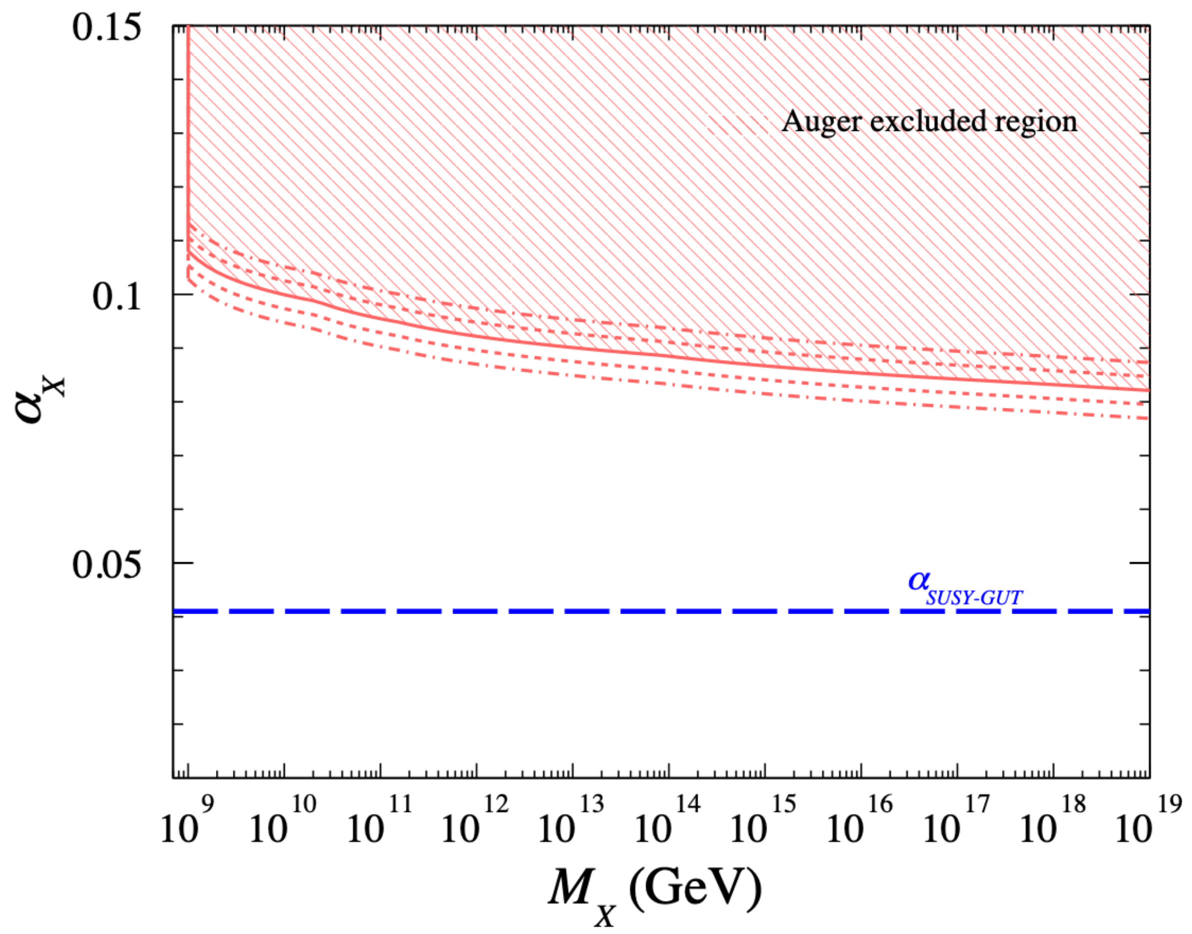
- **Violations of Lorentz invariance** could modify the cross section and the threshold of interactions of UHECRs and secondary particles
  - in the extragalactic propagation, and
  - in the atmospheric showers





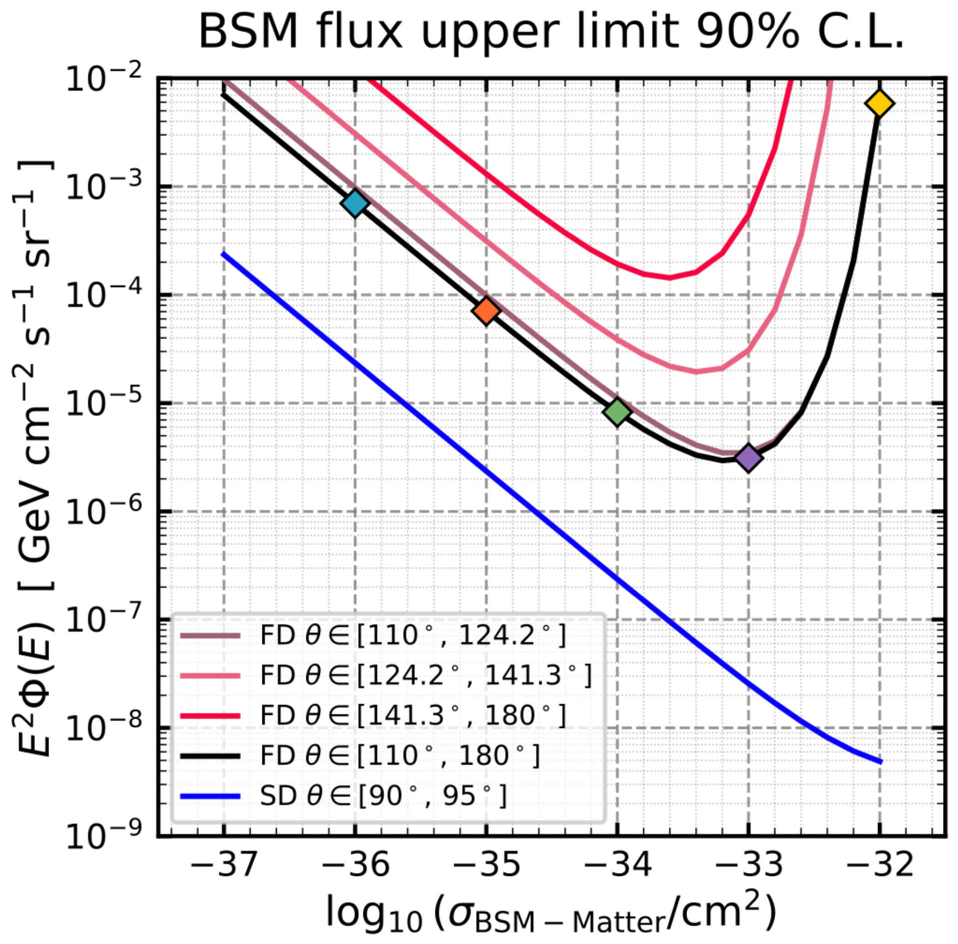
JCAP 01 (2022)

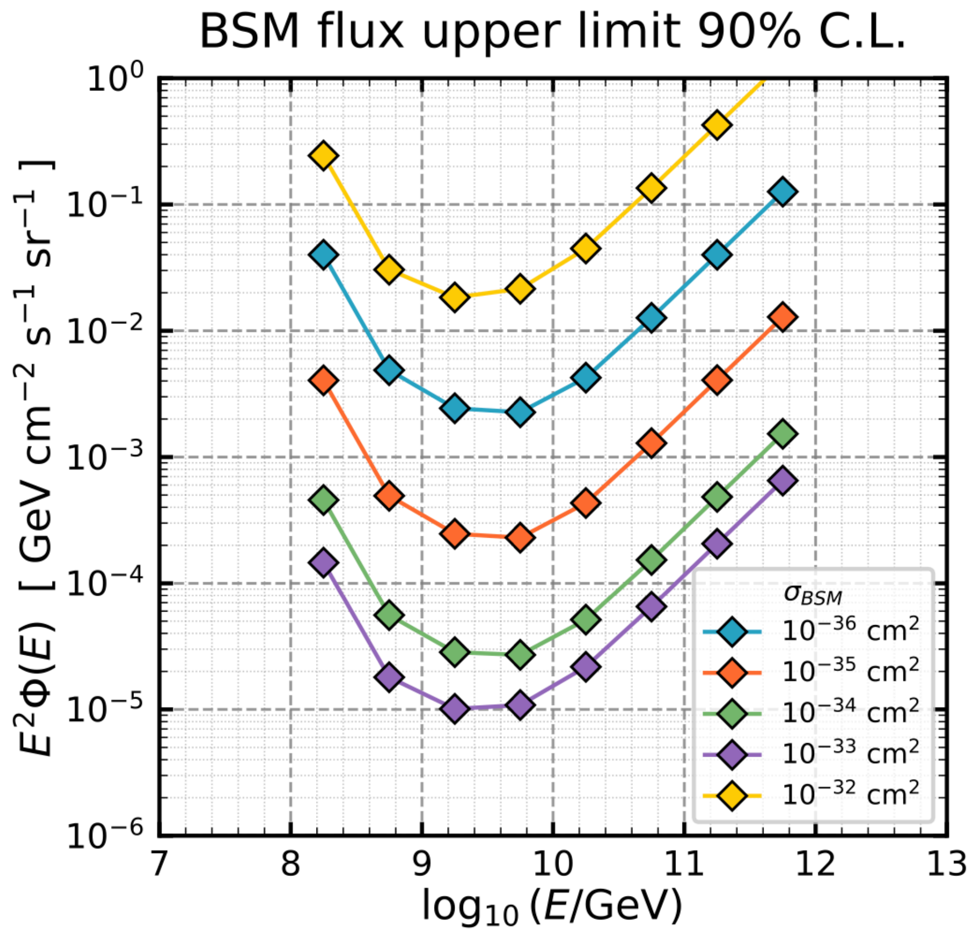
ICRC21



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

Phys.Rev.D 107 (2023)

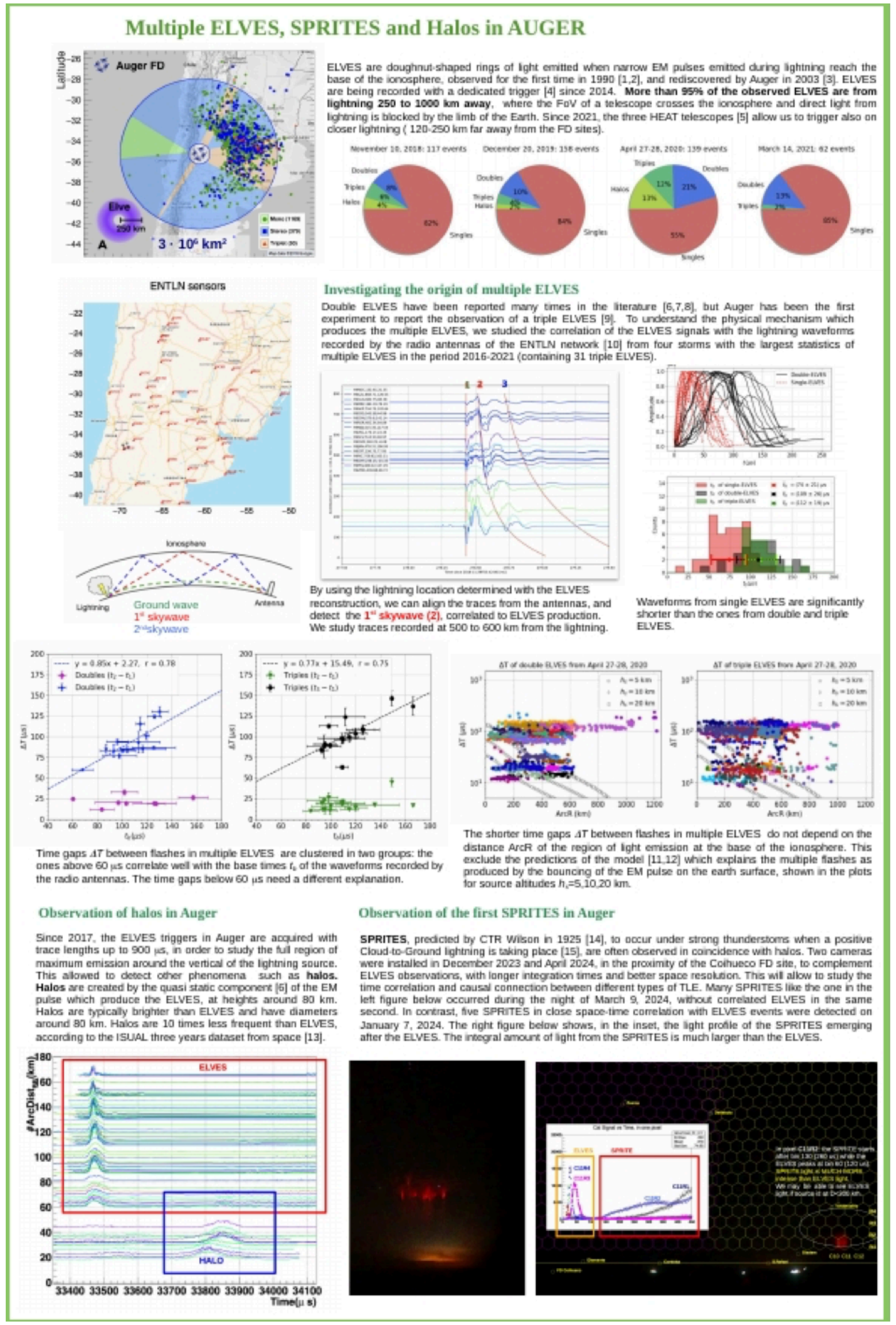


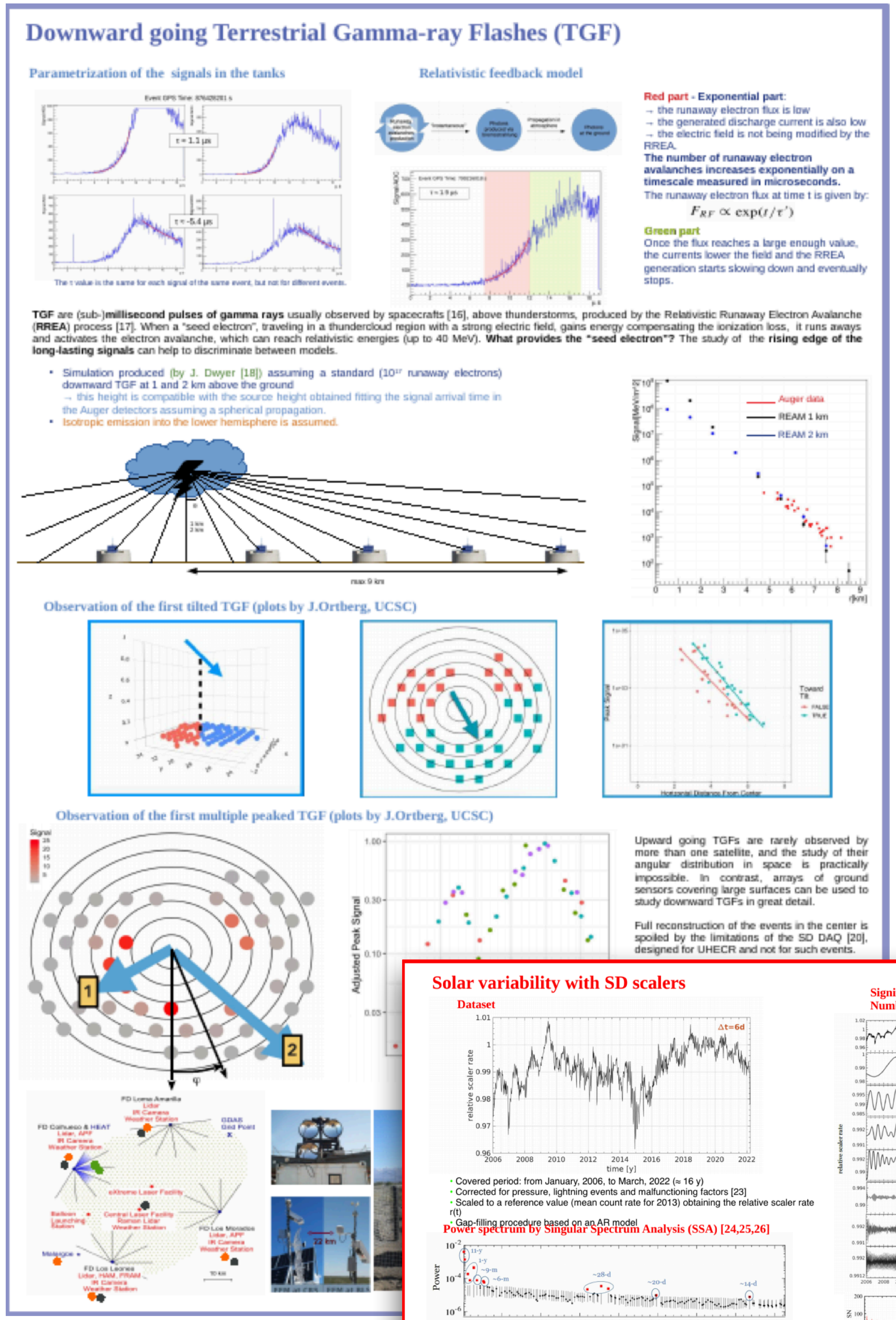


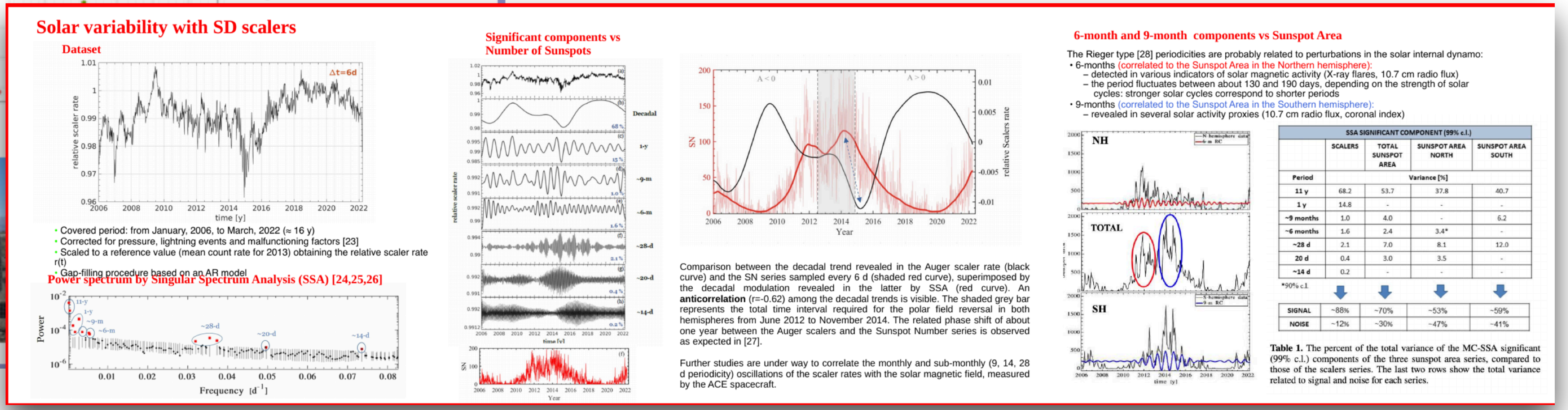
- Investigating **BSM particles with interaction cross section lower than that of neutrinos**: upward-going showers initiated by tau leptons could be resulted from an unknown type of ultra high energy BSM particle

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

Cosmogeophysics and the Pierre Auger Observatory as a test environment







- The Pierre Auger Observatory as a **test environment**:
  - IceCube, TA, FAST, IceTop hosted
  - See AugerPrime report and session in Malargue Nov. 2024

Roberto M. & Roberta @ UHECR24

Open questions

AugerPrime report, 2023

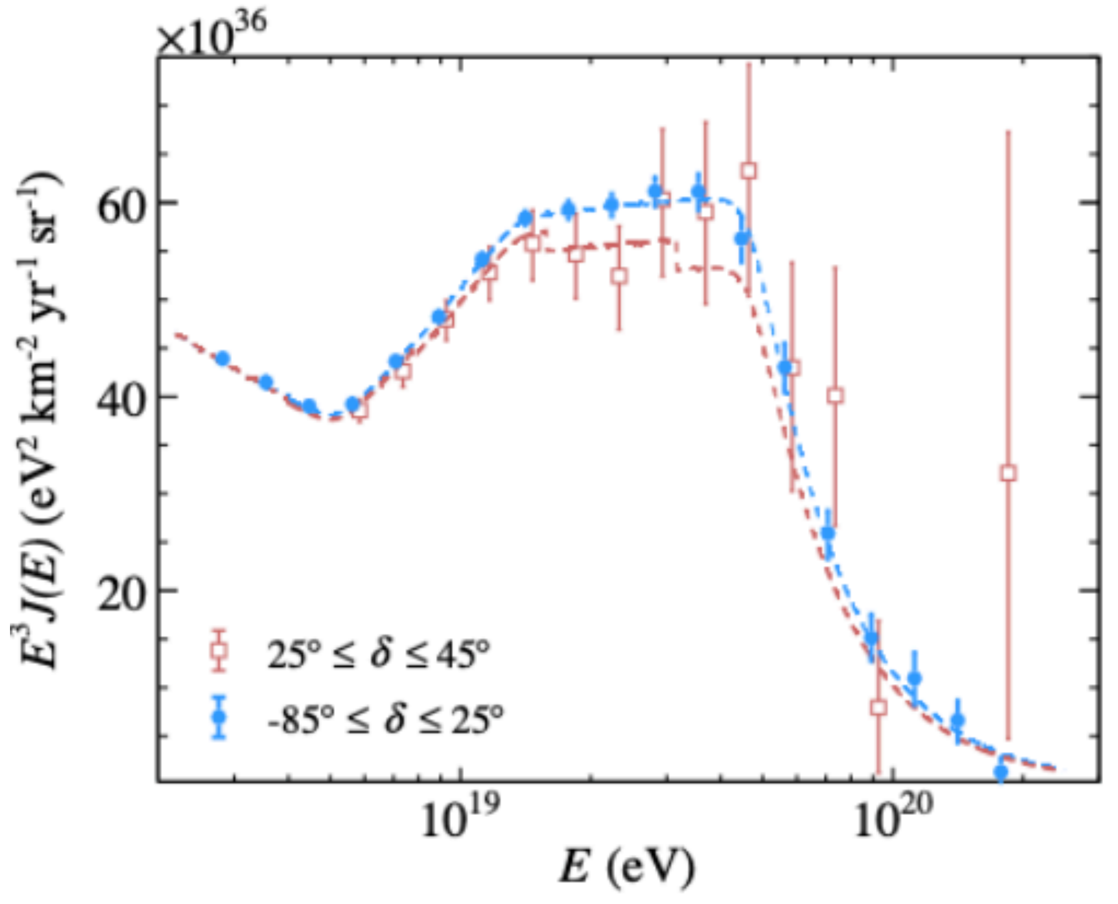
- What is the nature and origin of UHECRs?
- What is the origin of the observed flux suppression?
- Do UHE neutrinos and photons exist?
- What is the origin of the muon puzzle?
- Is physics beyond standard model hiding at the energy frontier?

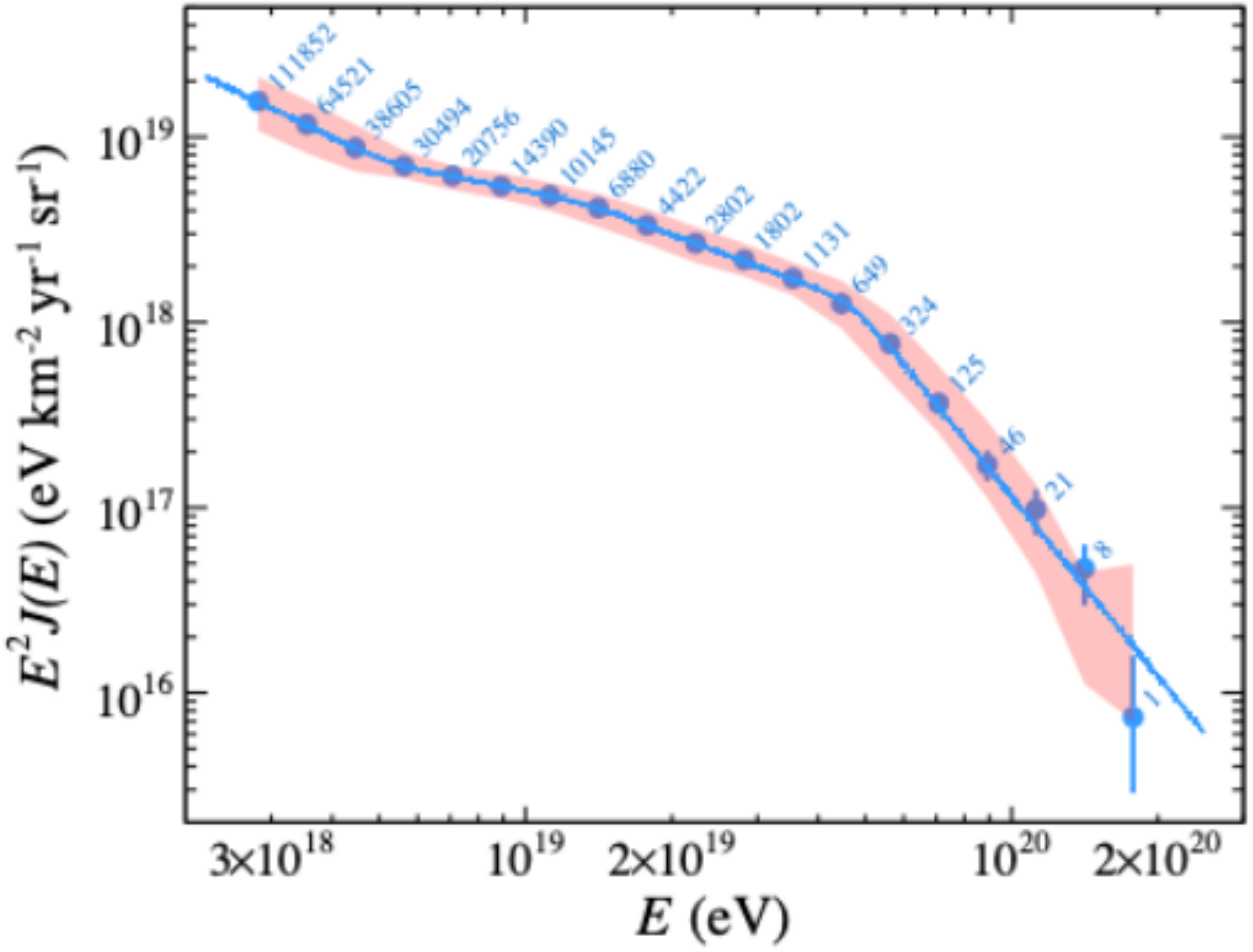
Investigating the mass composition of UHECRs in more detail is the key to making progress, both in the field of astrophysics - the search for the sources of UHECRs and understanding our astrophysical environment - and in the fields of particle and fundamental physics

(Some) current studies and brainstorming towards aims of Phase II

Energy spectrum

Auger Collab. in preparation





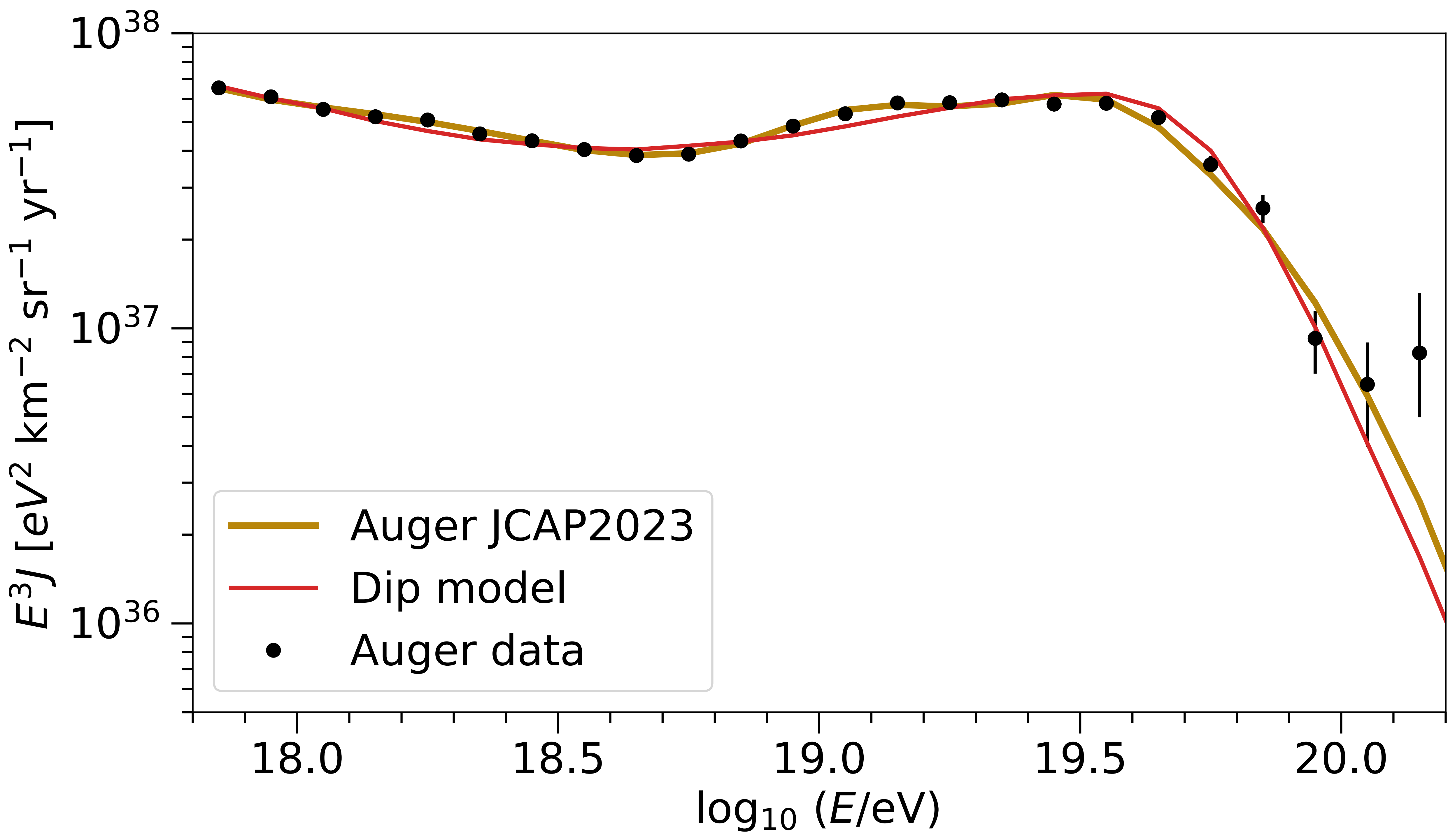
- Spectra in different declination bands (combined until 25, only inclined above 25)

- Energy spectrum over 3/4 of the sky
- Absence of declination dependence of the spectrum confirmed
- **What are the implications on the UHECR origin (also seen the results of the work on the supergalactic flux)?**

- TA results in contradiction:
  - TA claim: different spectra in the northern and southern hemispheres, due to events from the Hotspot and Perseus-Pisces supercluster excess regions

Energy spectrum

DB and Camilla @ UHECR24

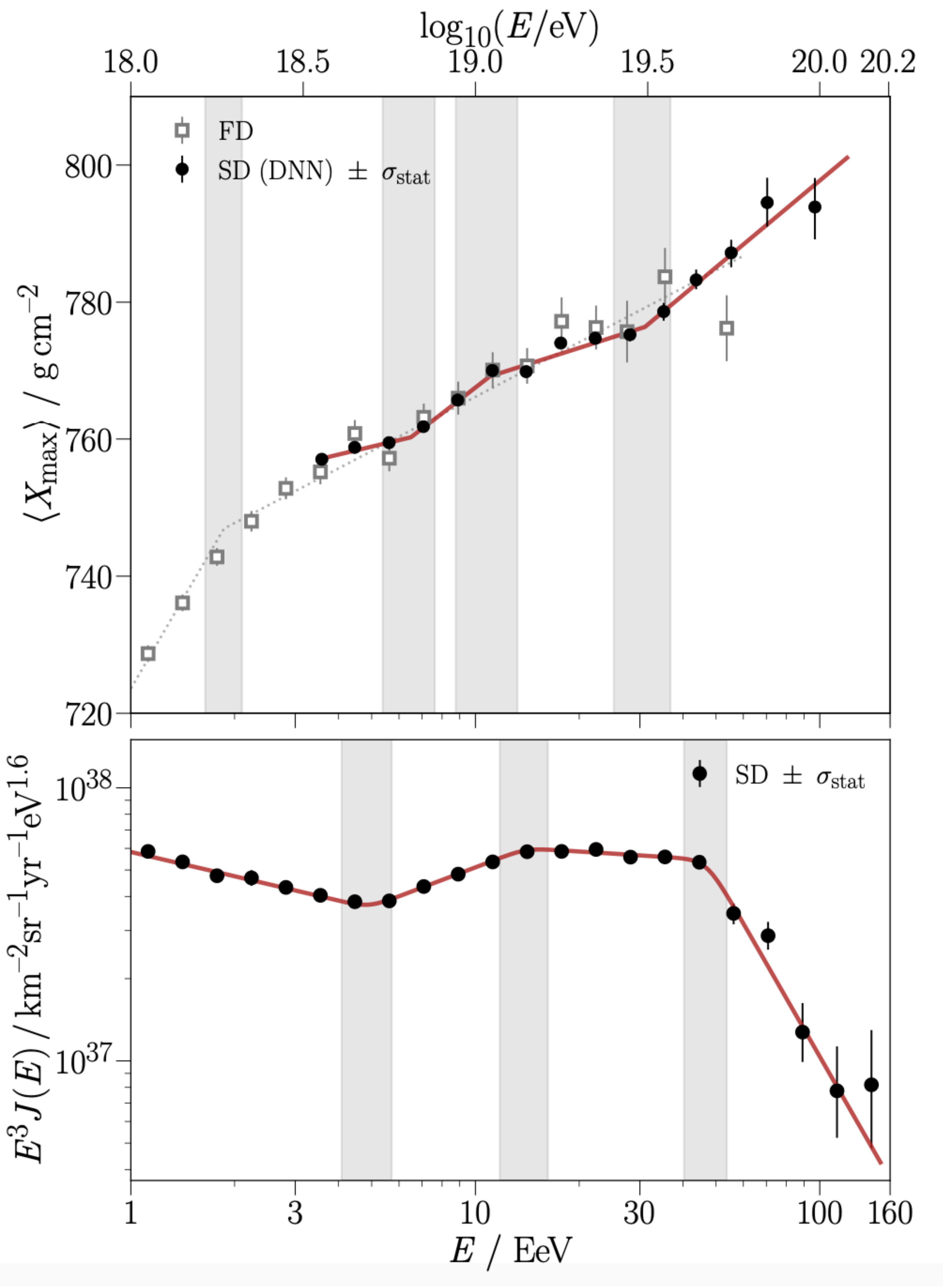


Dip model (readapted) vs the combined fit of spectrum and composition

- Note that **the instep feature has a larger significance, now > 5 sigma**

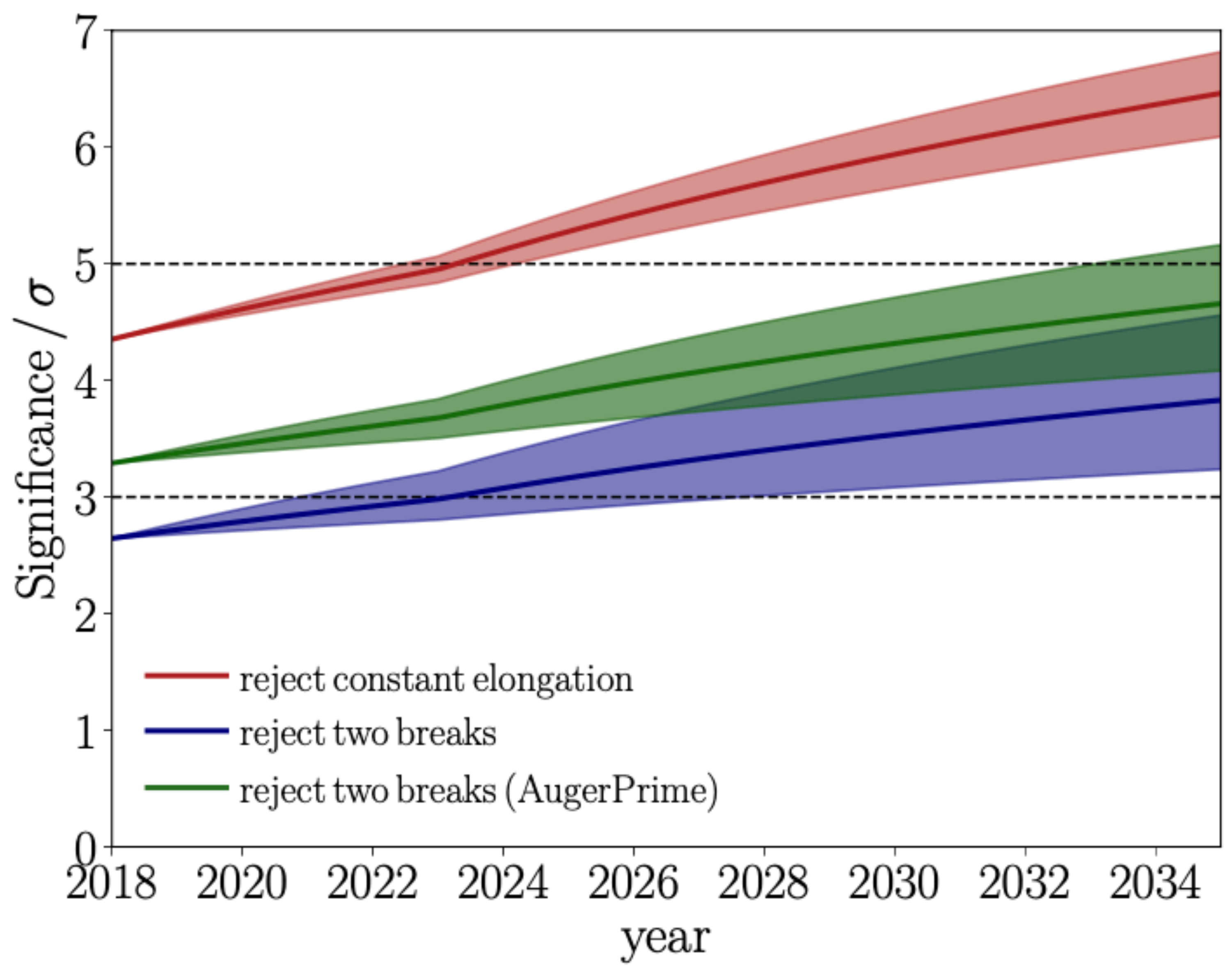
- Can we quantify the exclusion of the dip model with the shape of the spectrum (mainly the ankle and the instep)?
- Can the shape of the instep mimicked by local effects?
- Can we quantify the contribution to the suppression of the source power vs propagation effects?

Energy and mass composition



Auger Collab. PRL 134 (2025)

AugerPrime report, 2023



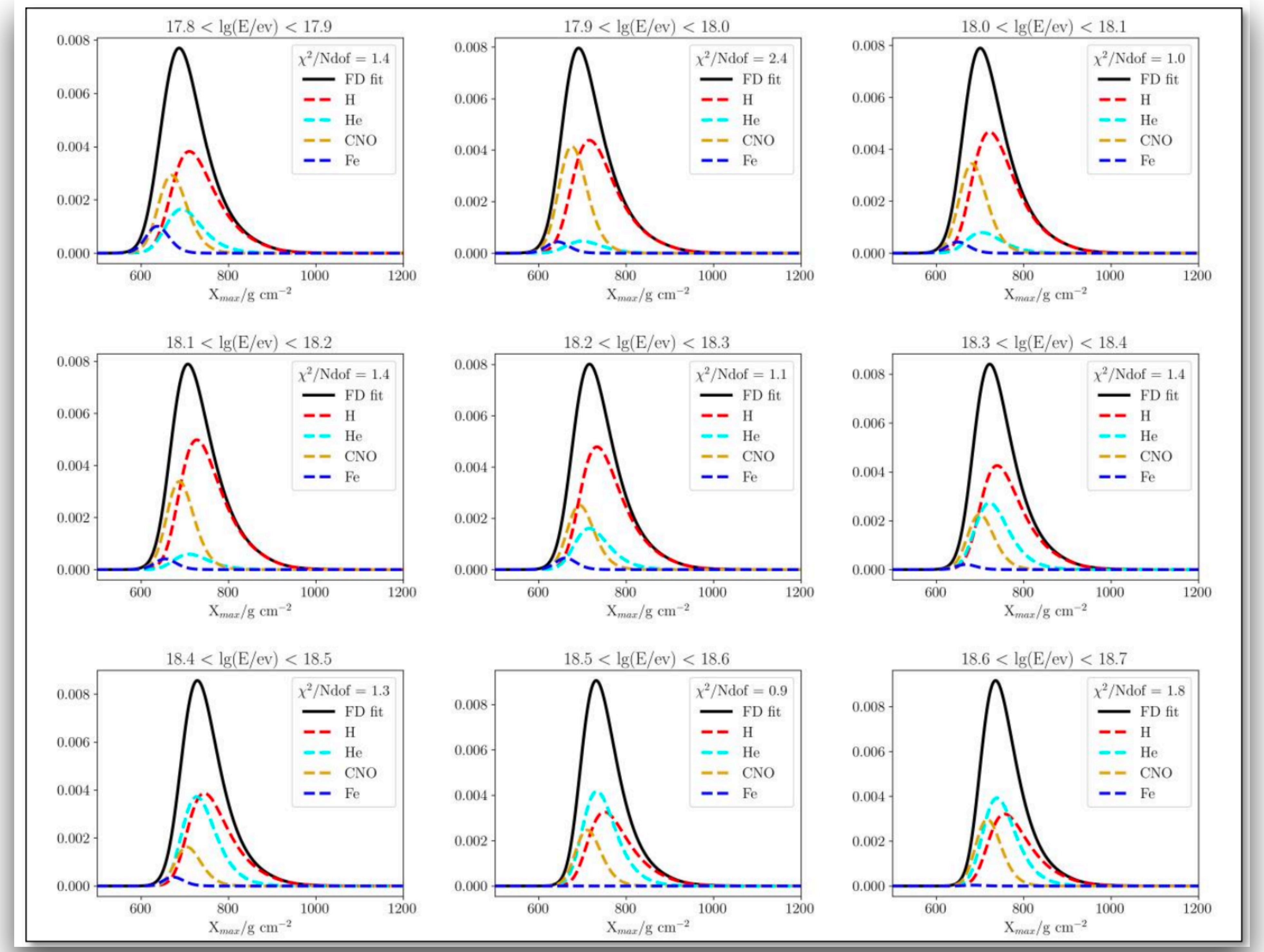
Extrapolated significance for identifying two breaks (red) and three breaks (blue) in the elongation rate curve, as a function of time extrapolated using the current measurements. The green line shows the extrapolated significance for re-analyzing Phase I data with the expected sensitivity improvements of AugerPrime

- Correlation of spectrum and mass features
  - Hints of astrophysical origin?

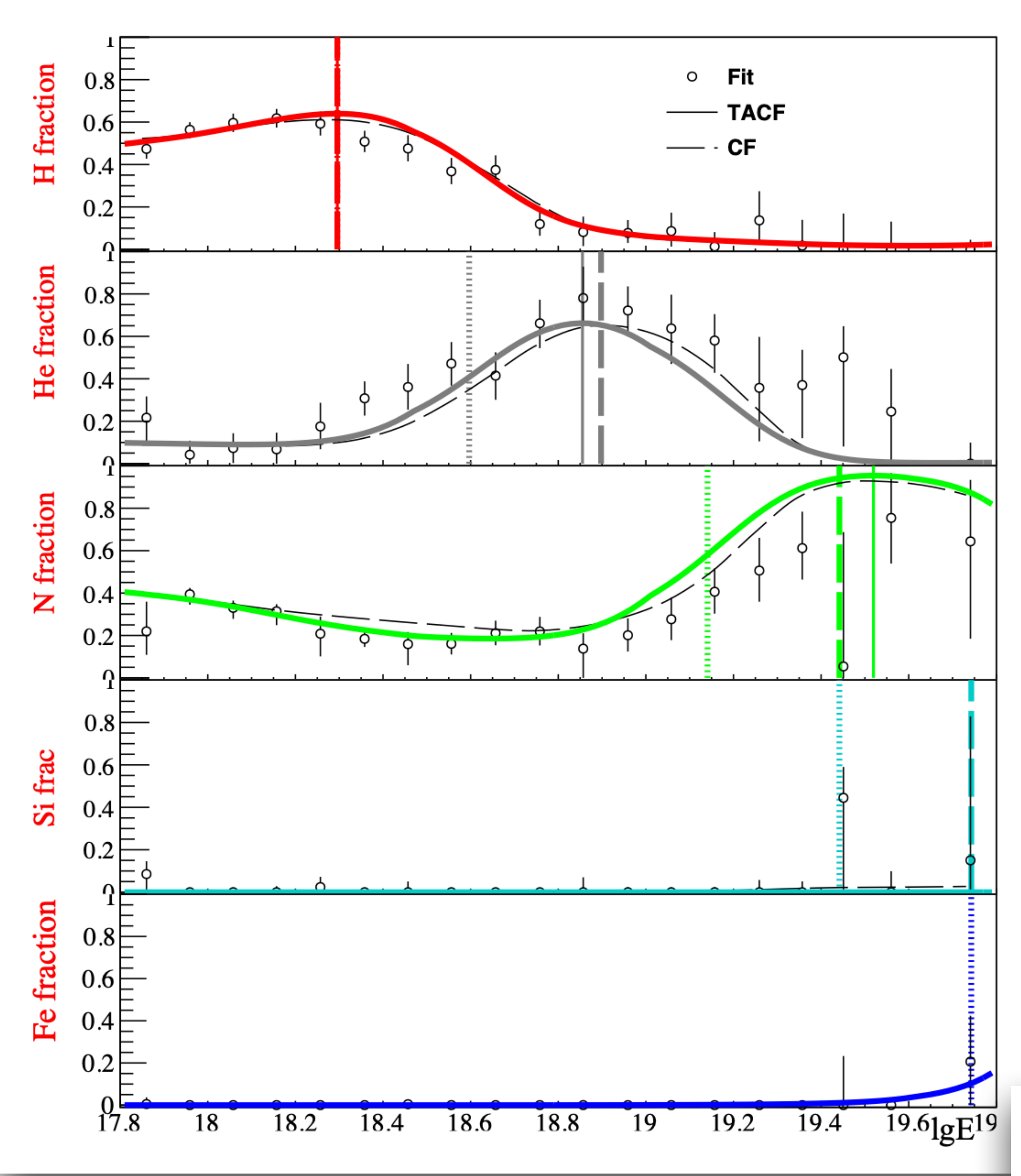
- Is a non-parametric approach (for instance in the combined fit efforts) going to help in the understanding of the physical meaning of the breaks in the different observables? **Inputs from** Carmelo & Igor

Energy and mass composition -> testing the purity of mass composition

Fabio @ Malargue, Nov 2024



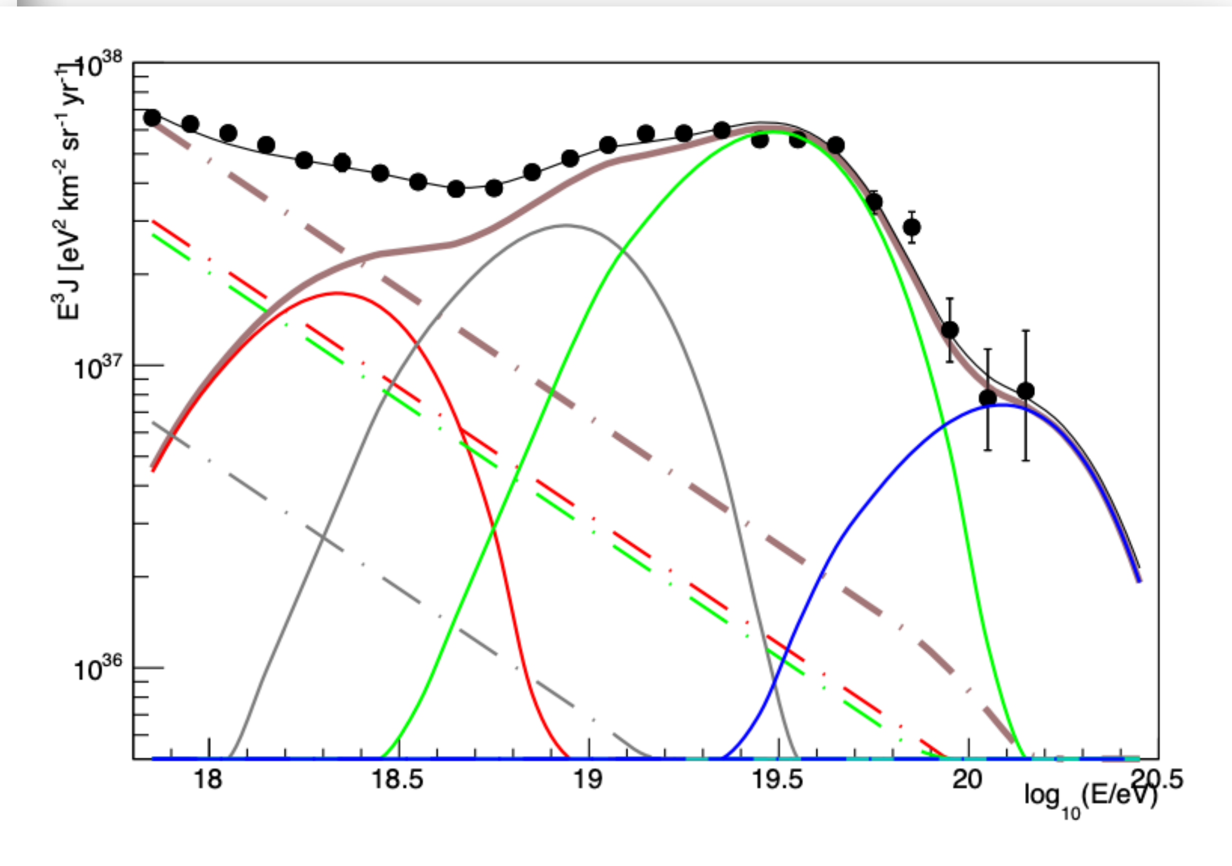
- Updated code for mass fraction fit;
  - Results compatible with previous code version (Caterina); ongoing work by Fabio and Igor
- **SD DNN issues**
- Open topics:
  - spectra of mass fractions (in Xmax contrib. at ICRC25?)
  - H upper limit; H+He (?)



- To model the mass fractions below the ankle, no propagation model is needed -> adjustment of mass fractions and spectral index at Earth
  - Modelling the additional component towards the Gal-extragal transition…

Trimarelli, DB, Petrera & Salamida, ICRC23

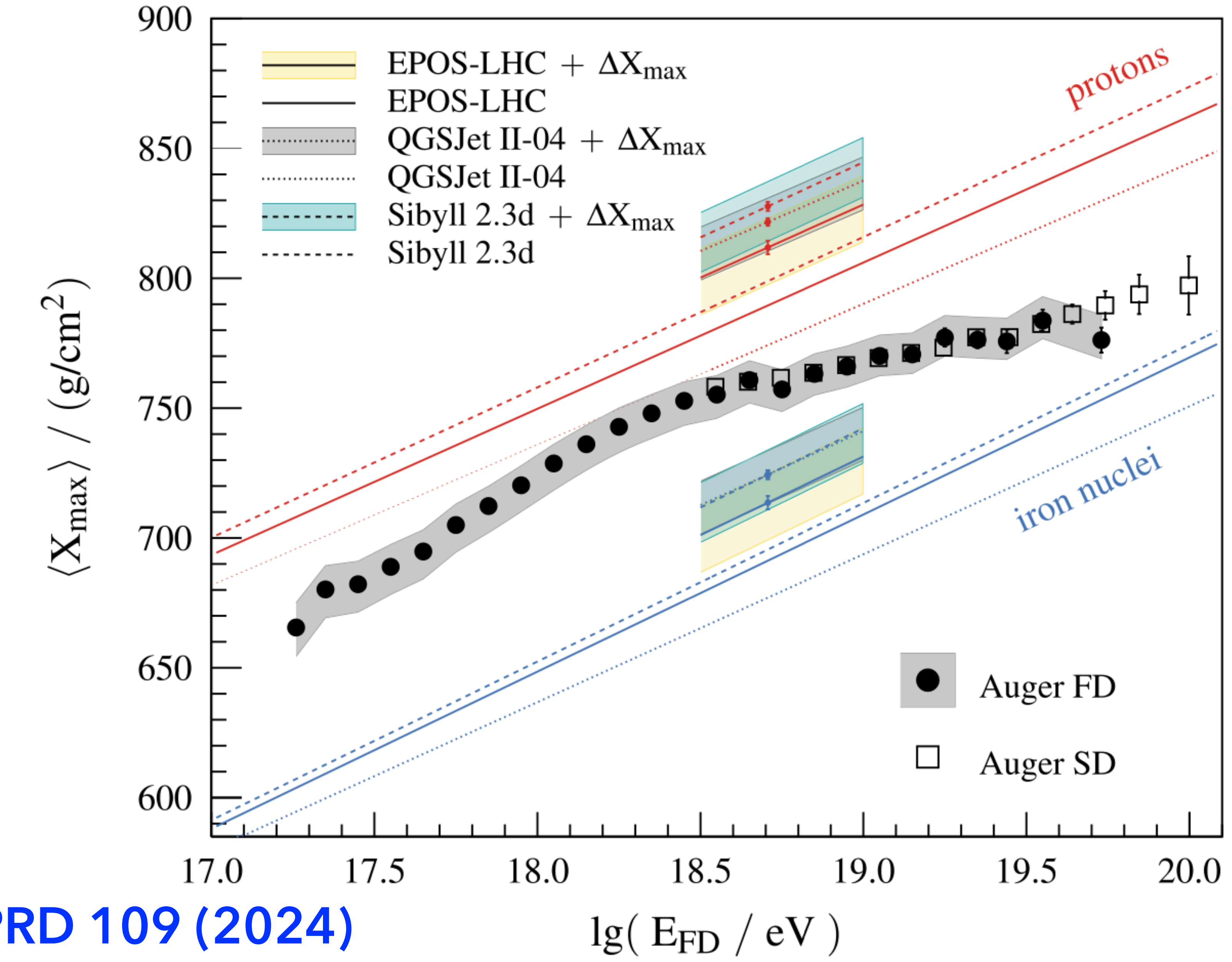
- The mass fractions peaks at Earth:
  - are ordered as a function of increasing mass, and not charge -> imprint of propagation
  - depend on the spectra of the HE component (driven by the mass composition above the ankle)



Mass composition and hadronic models

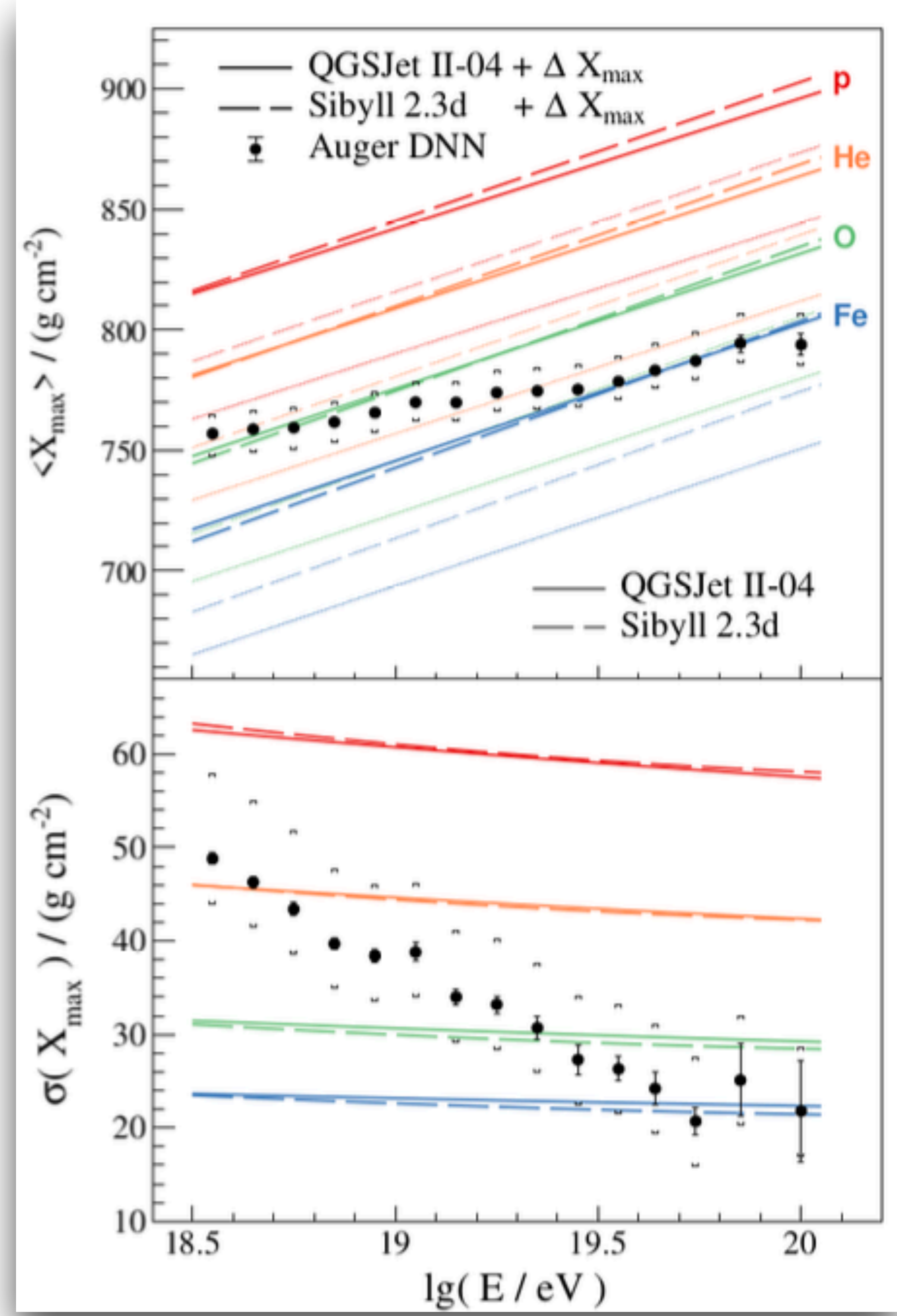
Jakub et al. @ UHECR24

- Evidence: lnA and muon number cannot be consistently interpreted with current hadronic interaction models
- Test the predictions of hadronic interaction models regarding Xmax and S(1000); free parameters: scale of Xmax and signals from hadronic component at ground data
  - Best description achieved if the predictions of the hadronic interaction models are shifted to **deeper Xmax values** and larger hadronic signals at all zenith angles; it also alleviates the tension with QGSJet



Auger Collab. PRD 109 (2024)

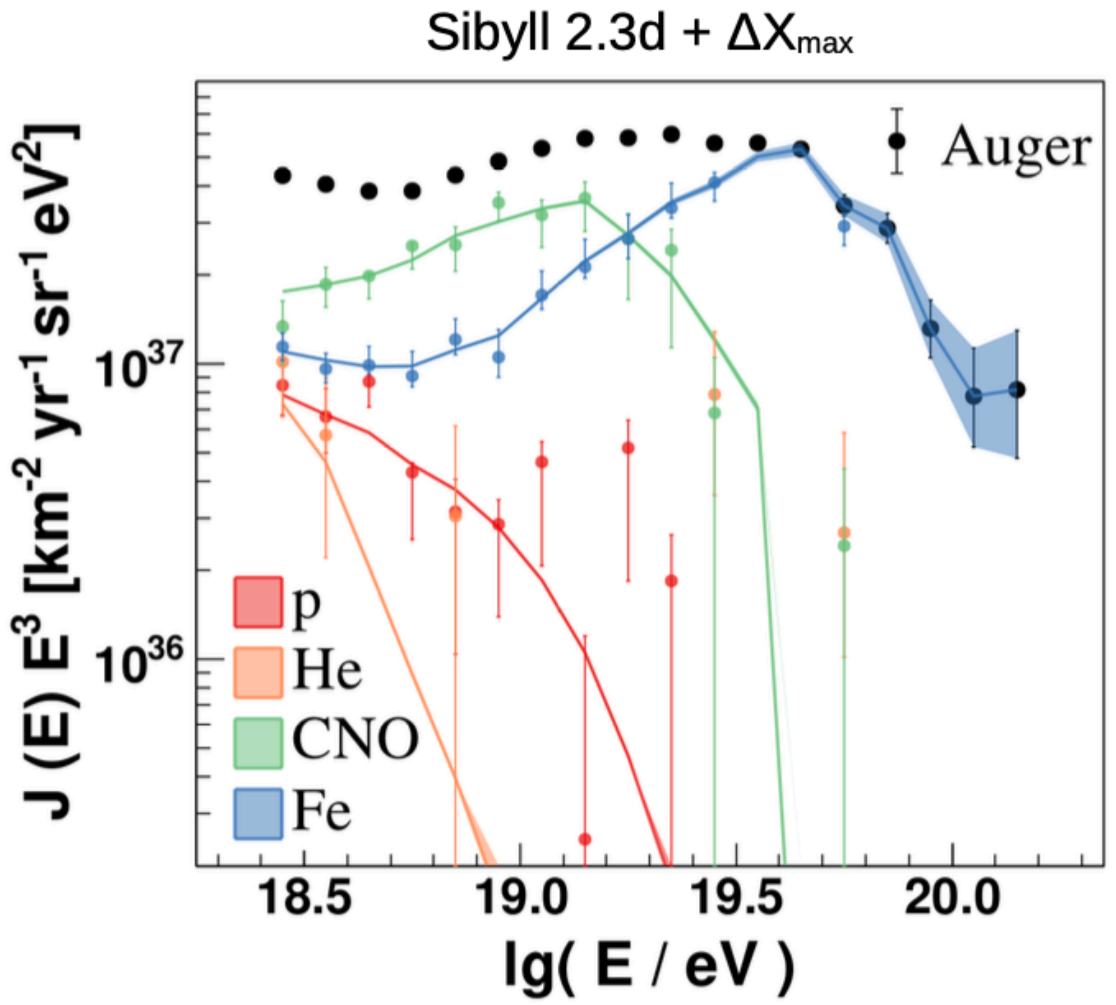
- Does this favor iron at the highest energies? What are the consequences in terms of UHECR physics?



QGSJet II-04: $\Delta X_{max} = 52 \pm 1^{+11}_{-8}$ g/cm^2

Sibyll 2.3d: $\Delta X_{max} = 29 \pm 1^{+12}_{-7}$ g/cm^2

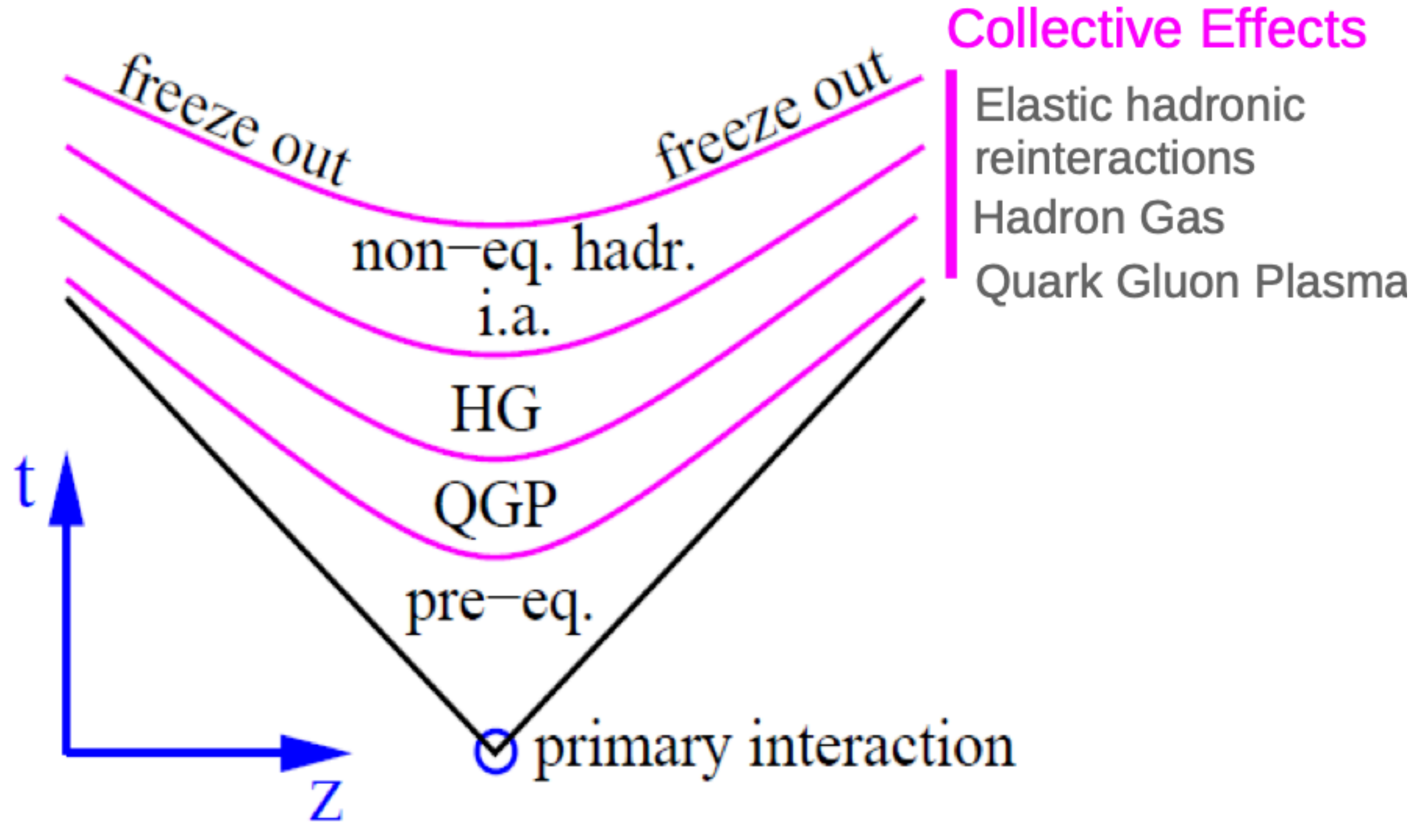
- Backtracking of arrival directions (and understanding of magnetic fields); interpretation of instep and suppression; muon puzzle; cross section

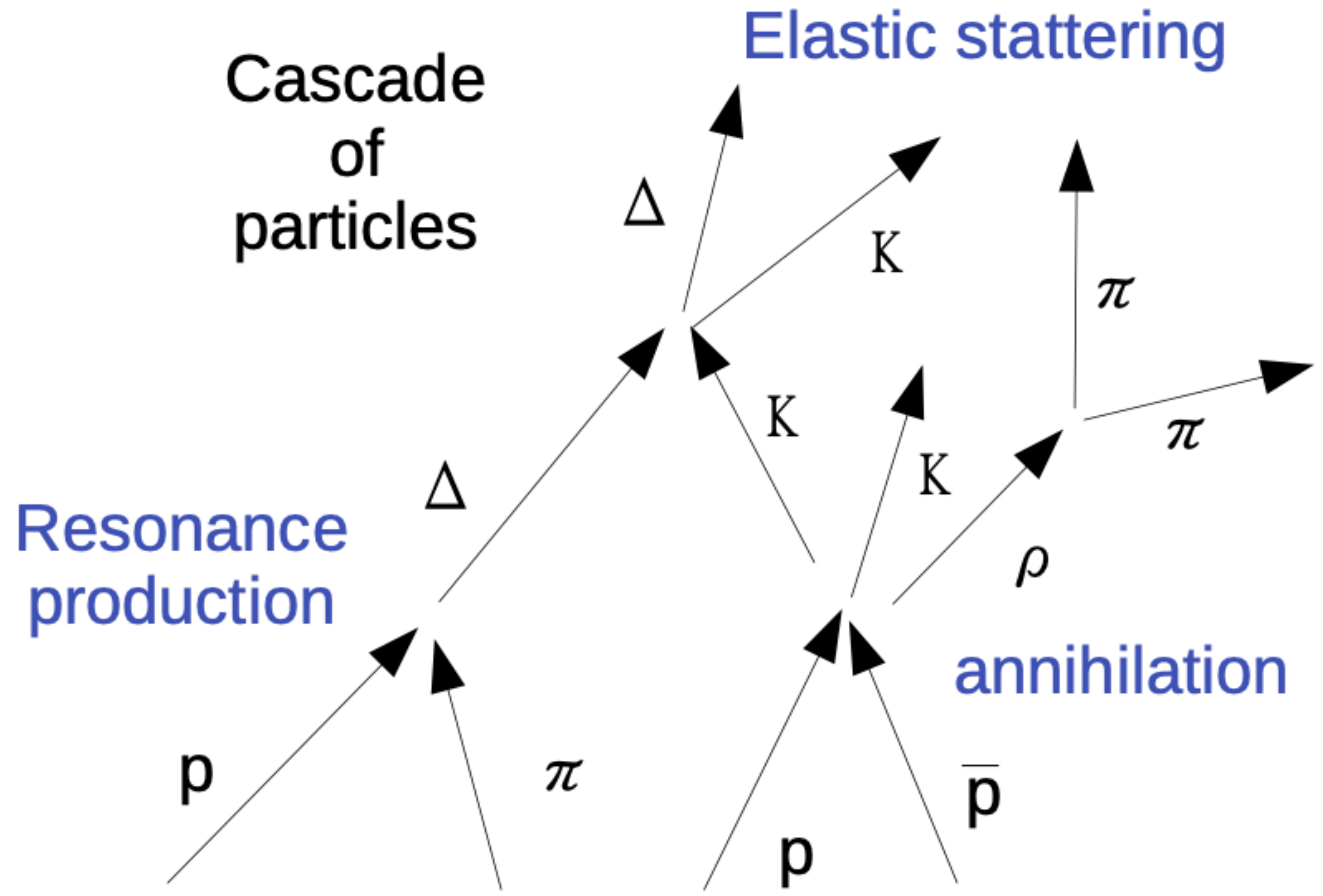


Hadronic models

Tanguy @ UHECR24

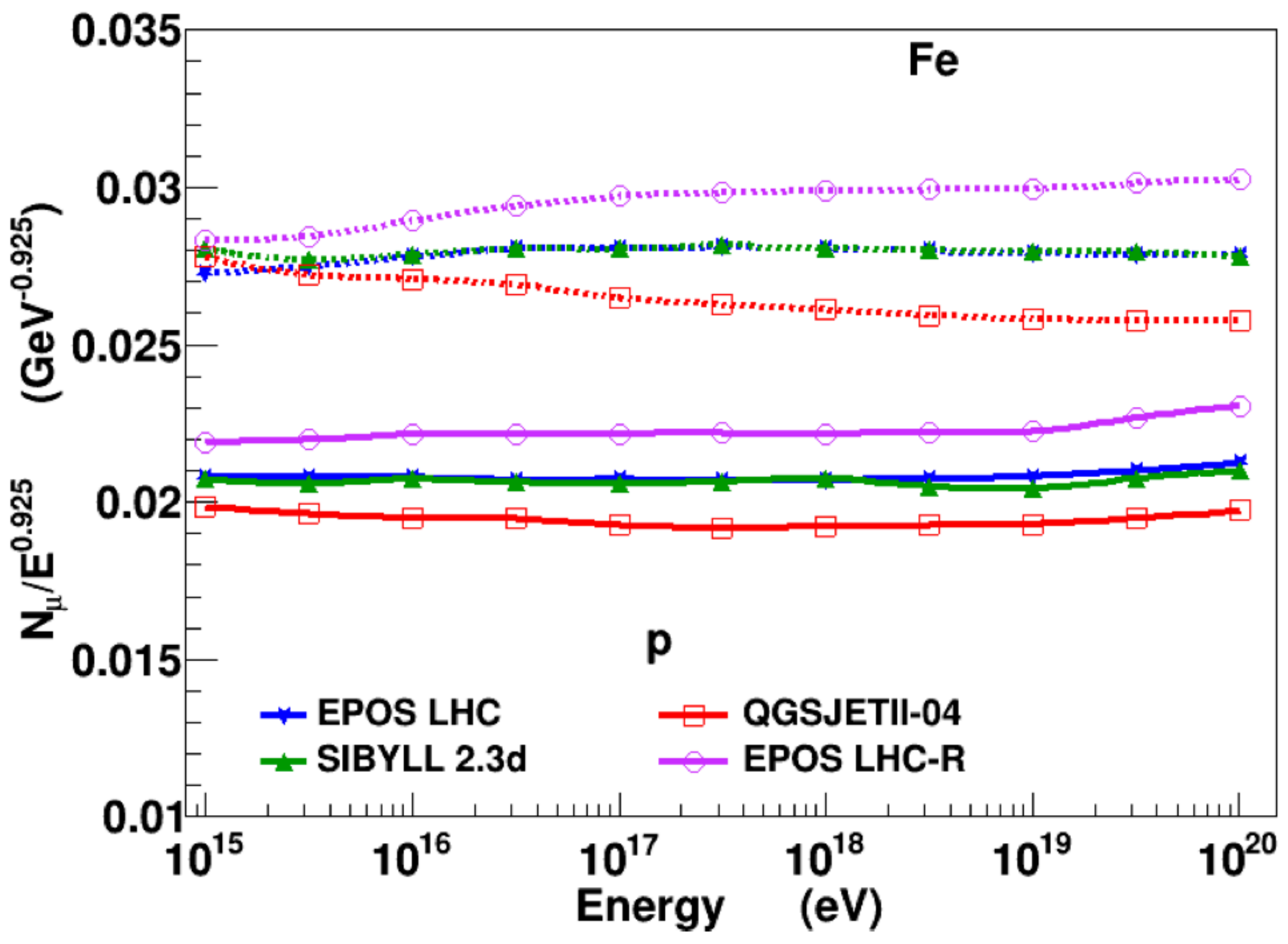
- **Air shower development dominated by few parameters**
  - ➡ mass and energy of primary CR
  - ➡ cross-sections (p-Air and (π-K)-Air)
  - ➡ (in)elasticity
  - ➡ multiplicity
  - ➡ charge ratio and baryon production

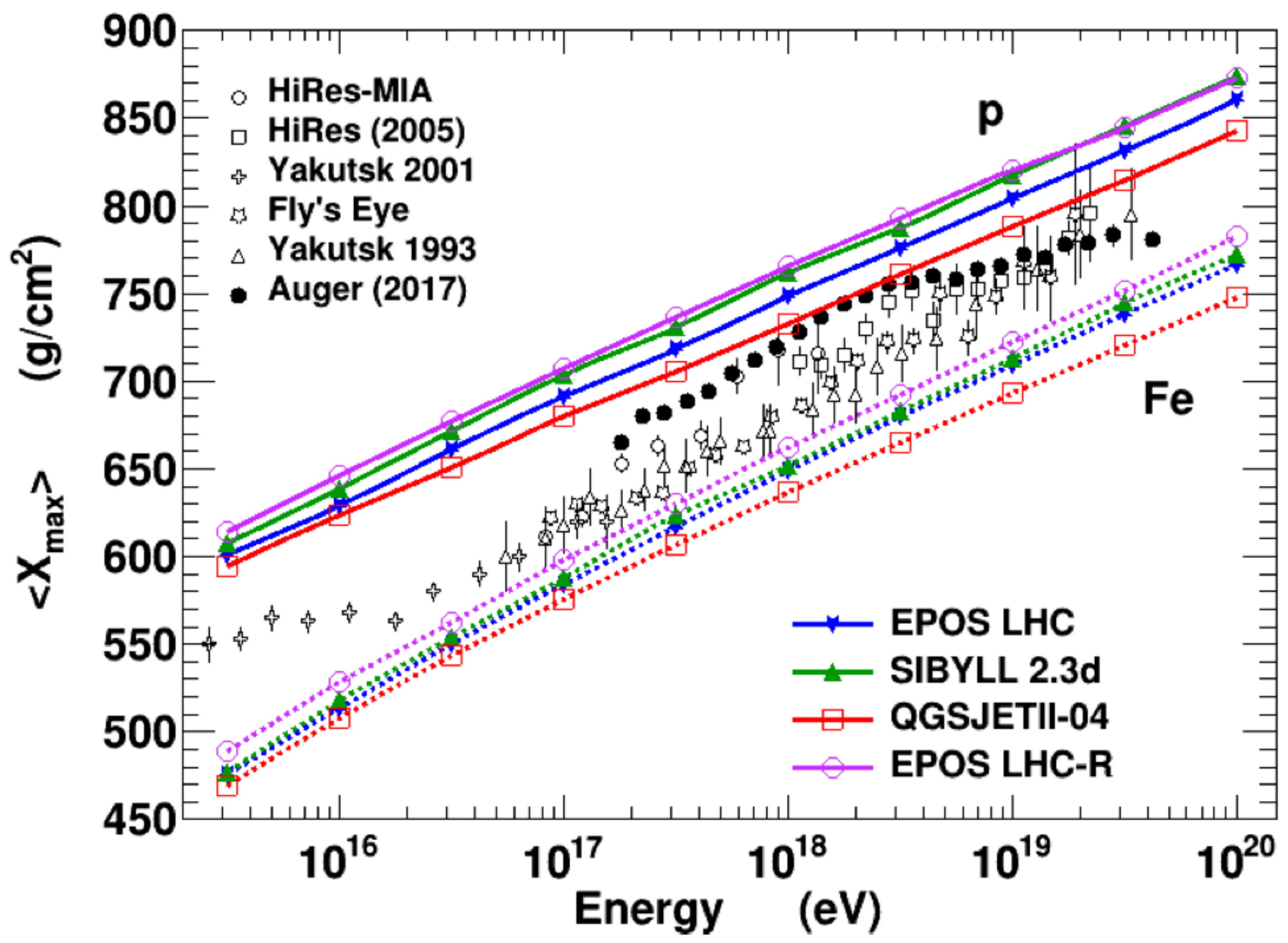




- **Details of hadronization matters**
  - ➡ Important role of resonance with sparse data
    - ➡ ρ^0 impacted by hadronic rescattering, important to take it into account
  - ➡ Evolution of strangeness with multiplicity
    - ➡ Different type of hadronization in core = more muons
  - ➡ **Combination of the 3 effects may solve the muon puzzle (to be confirmed) !**
- **Source of muon puzzle probably due to the fact that hadron rescattering was always neglected**
  - ➡ Rescattering change the correlation between mid-rapidity (data and tuning) and forward particle production (EAS)

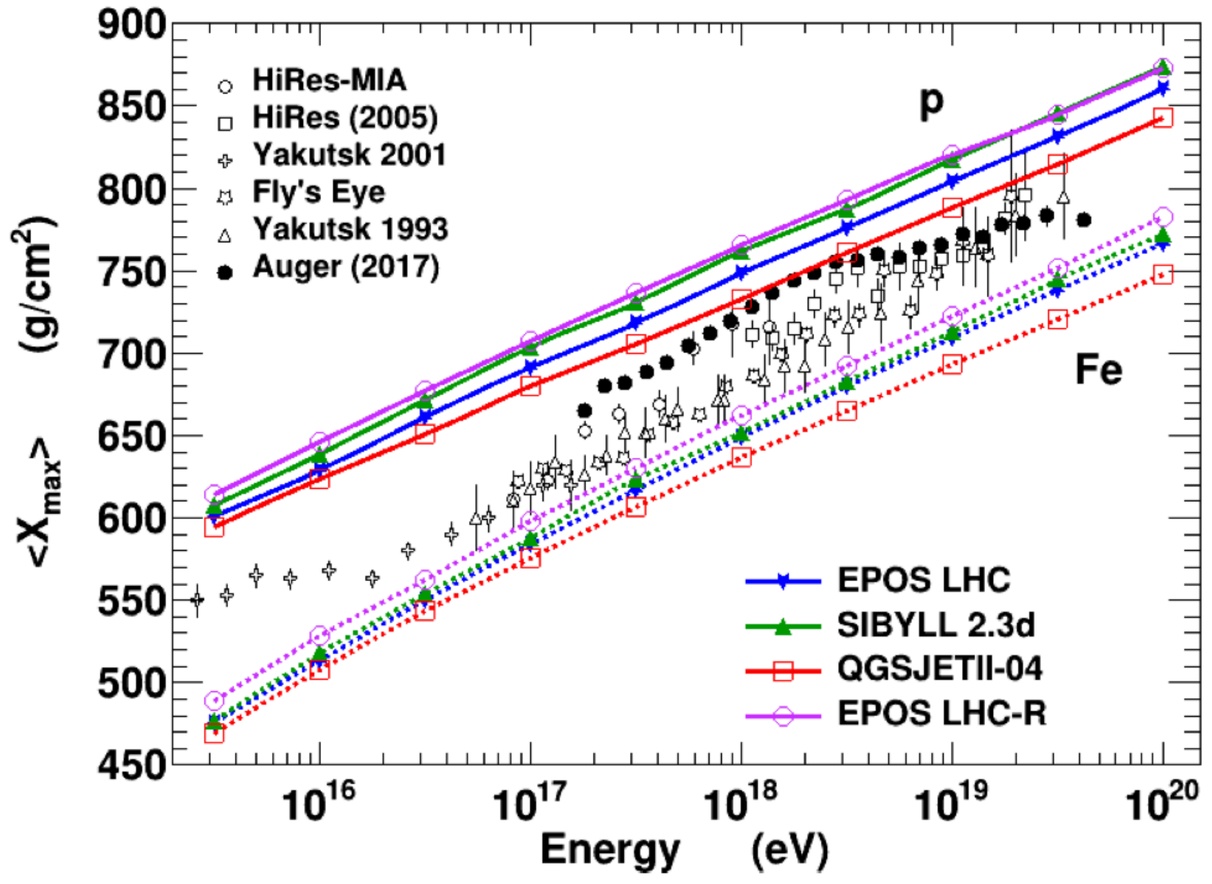
Updated EPOS LHC-R released in 2024 and then adapting EPOS 4 for CR

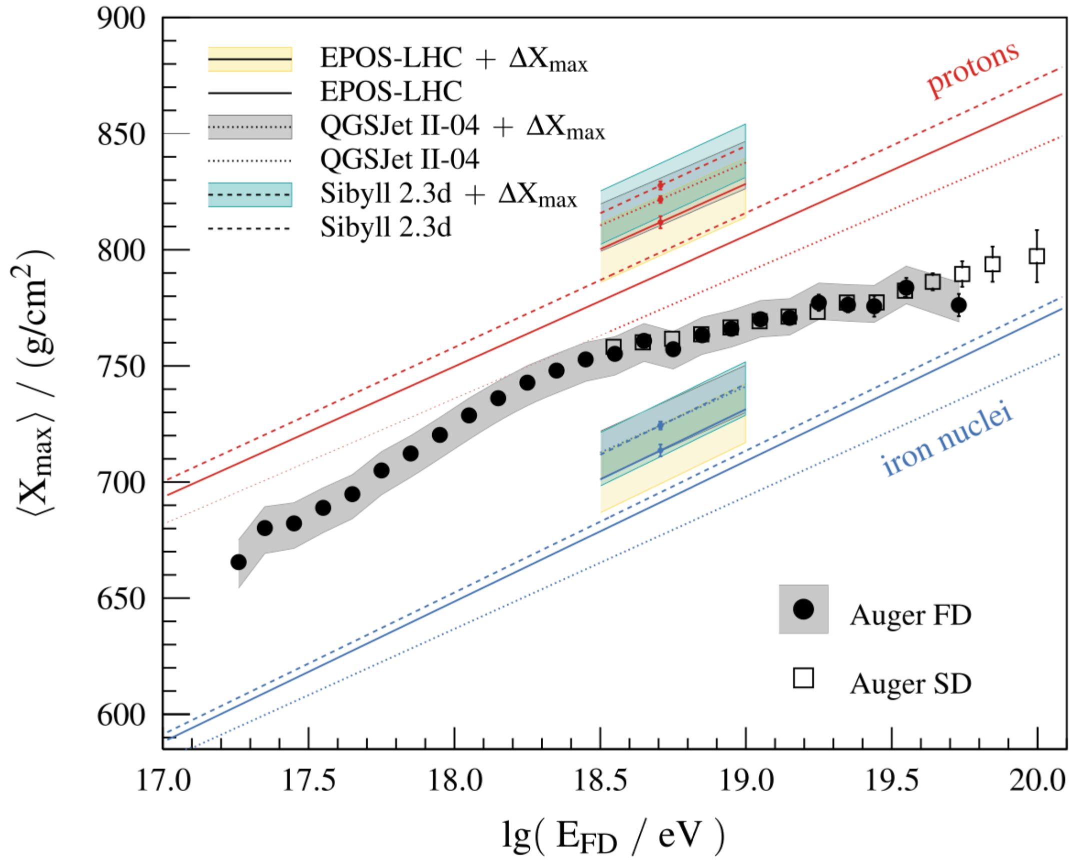




Mass composition at the highest energies

- What is the heaviest CR nuclear species? At what energy is it dominating?

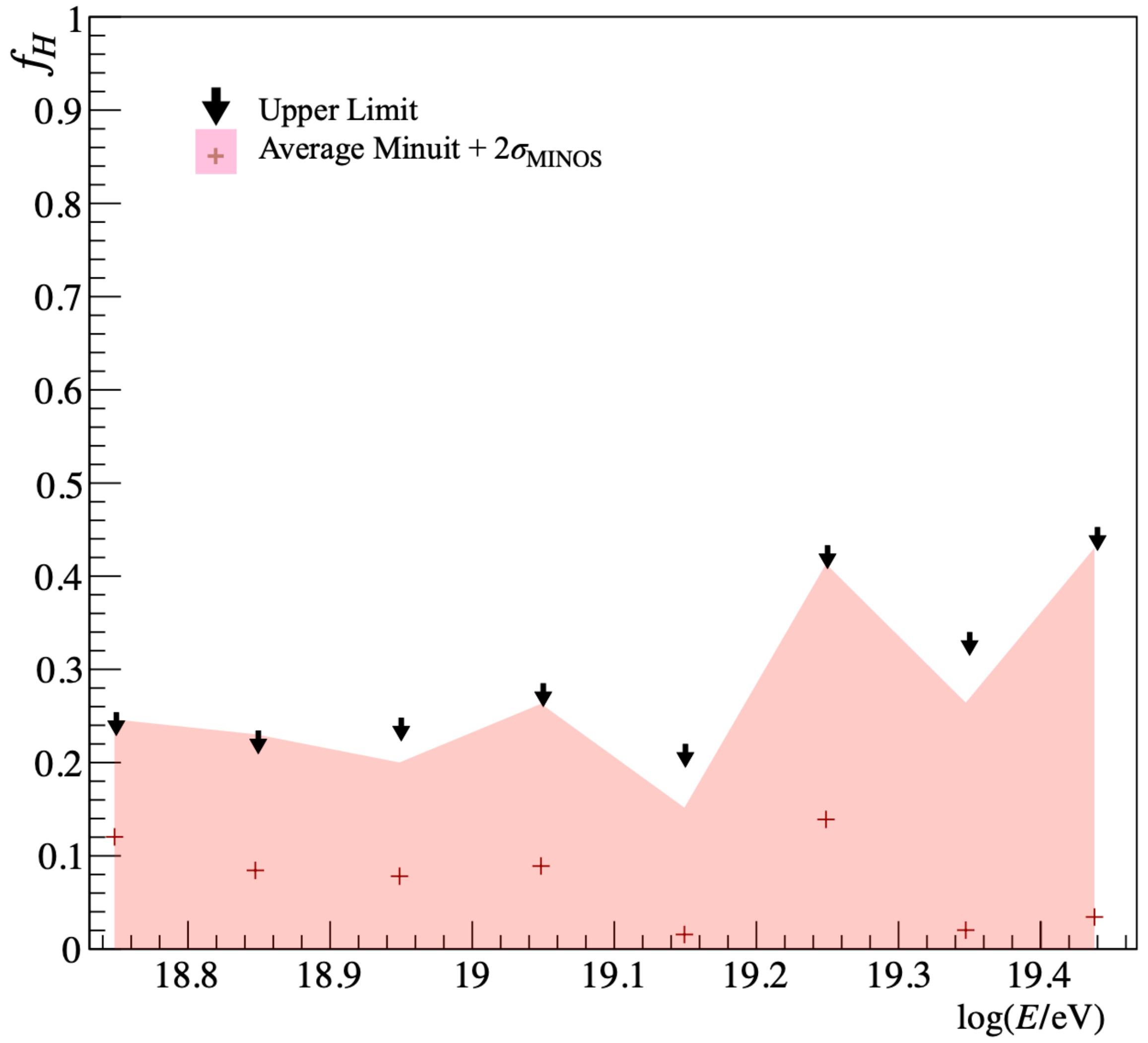




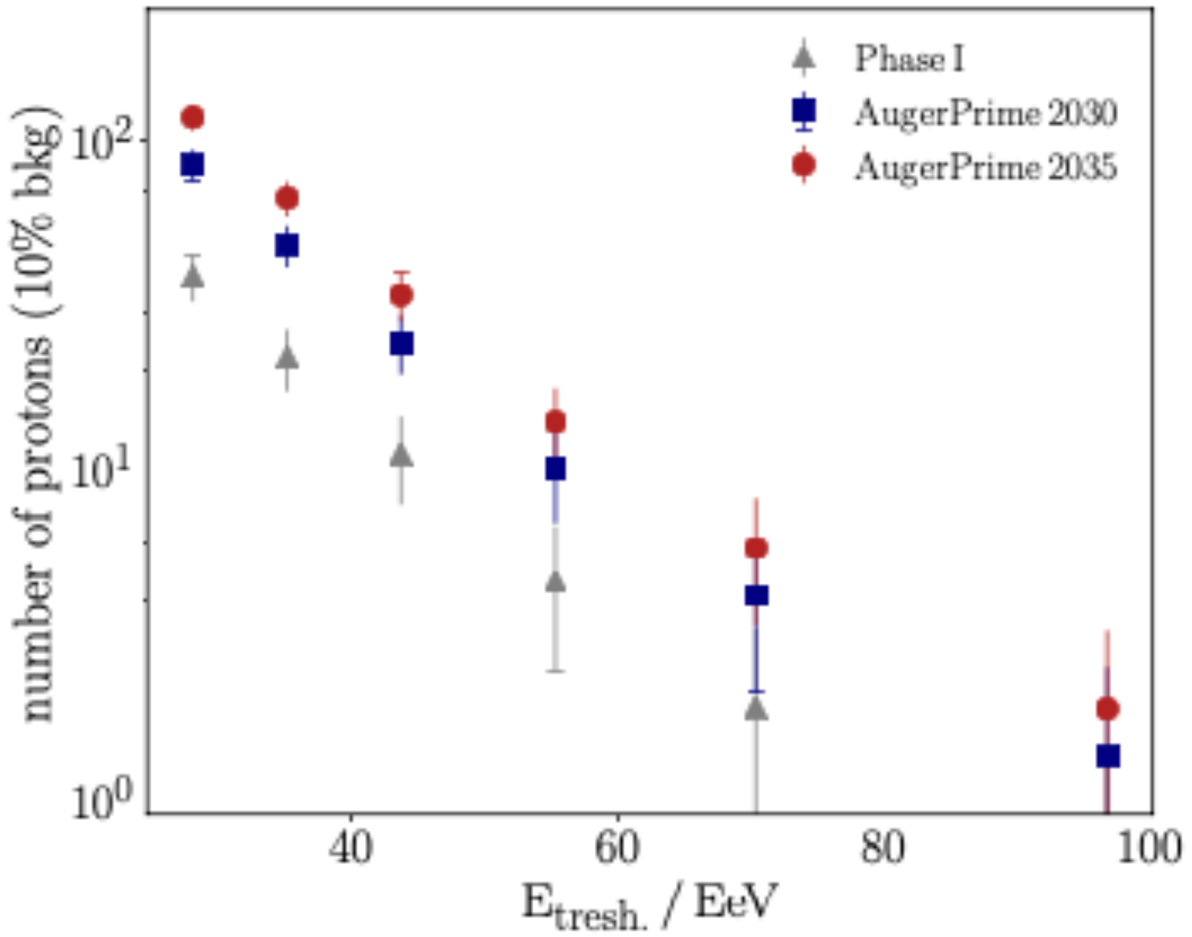
- New hadronic interaction models and analyses of FD&SD observables favor heavy nuclear species at the highest energies
  - What are **the heaviest nuclear species** compatible with our data?
    - Investigation of the type of accelerator; **ultra-heavy nuclei** to be considered?
  - <Xmax> **and RMS** to be considered (see also SD, universality); where is the last change of slope of the RMS? Can AugerPrime constrain a pure beam at the highest energies, by looking at the breaks in the RMS(Xmax))?

- What is the fraction of protons at the highest energies?

Caterina, PhD Thesis, 2023



AugerPrime report, 2023

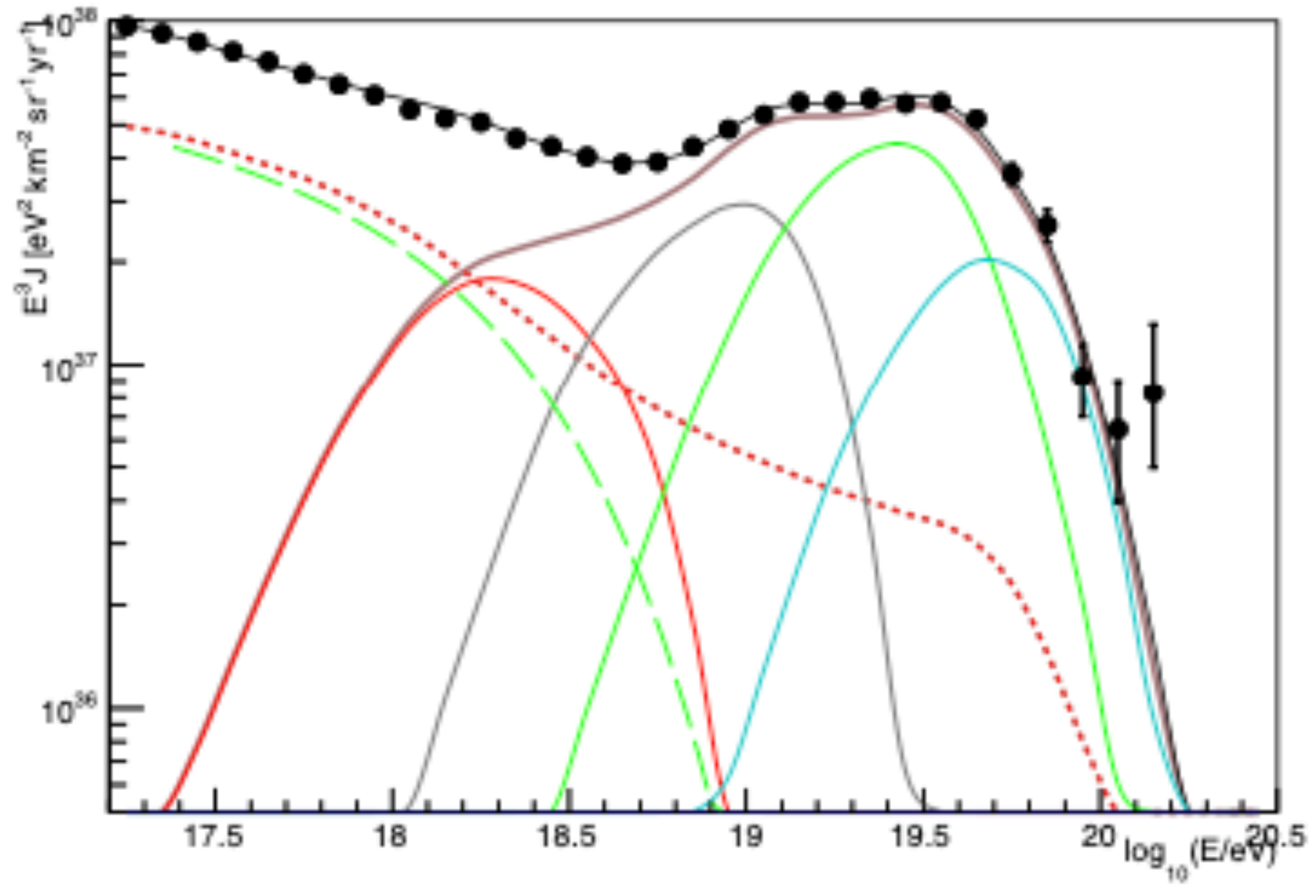


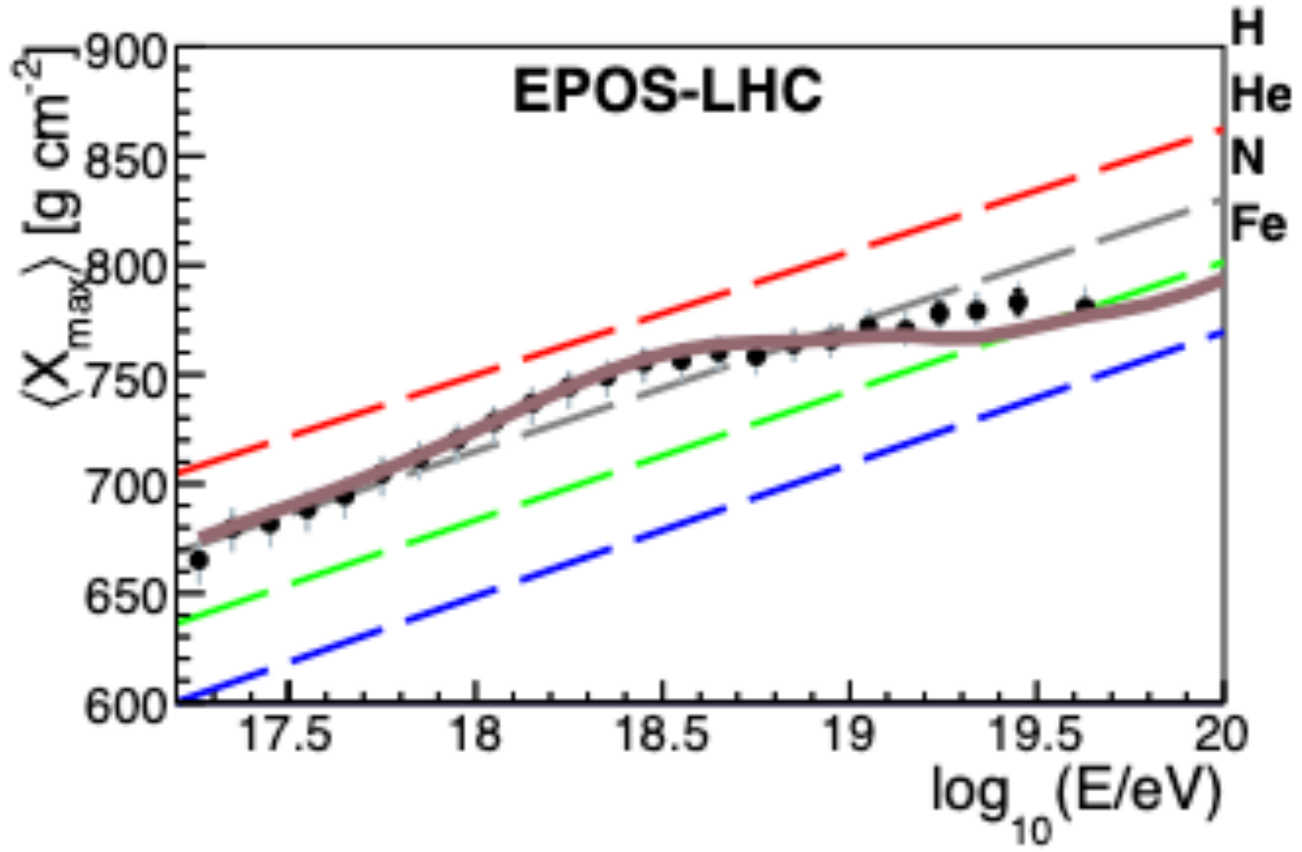
Expected integrated number of events identified as protons (containing 10% background) for a given threshold energy assuming a 5% proton / 95% iron fraction beyond 30 EeV for Phase I data (grey triangular), and running AugerPrime to 2030 (blue squares) and 2035 (red circles)

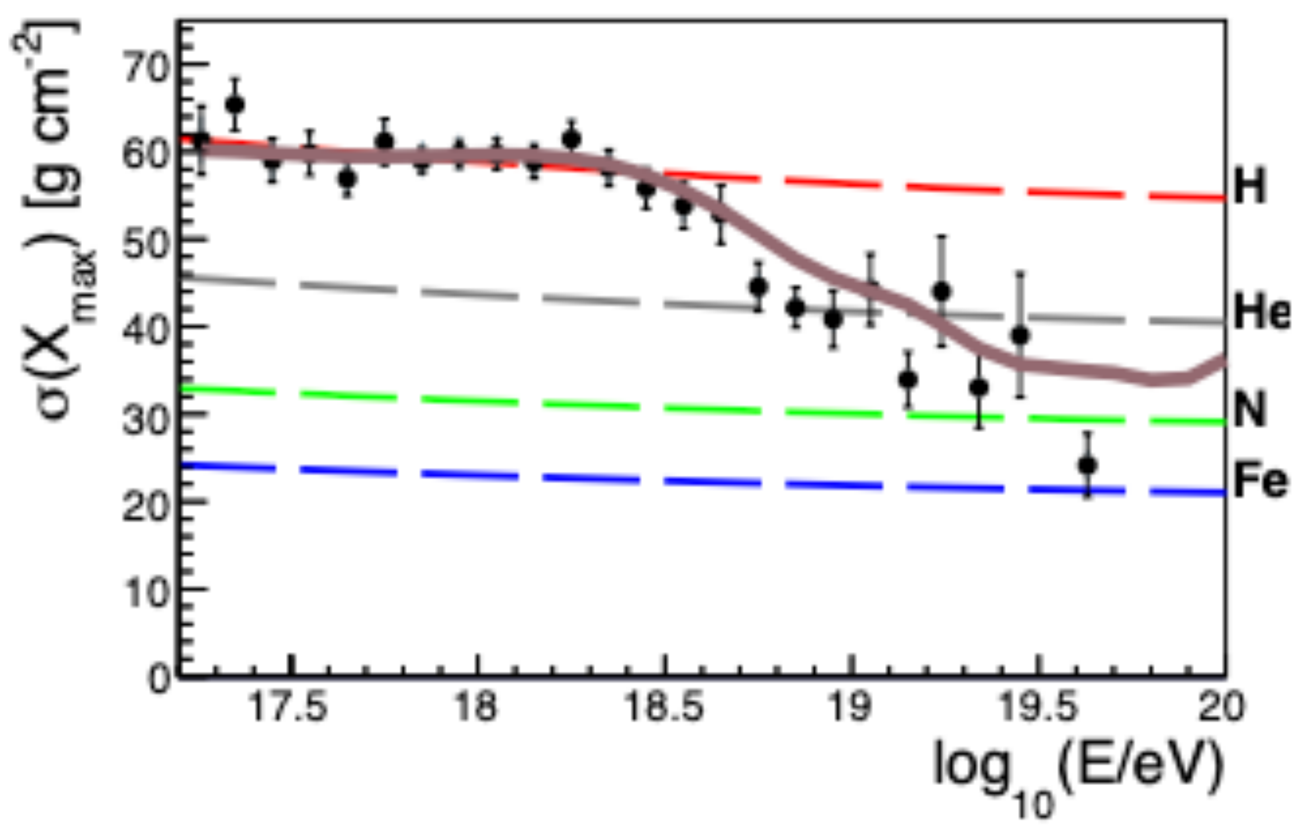
- Relevant to
  - constraining UHECR source evolution with redshift
  - BSM studies

Transition to Galactic (?) cosmic rays

Camilla, PhD Thesis, 2025

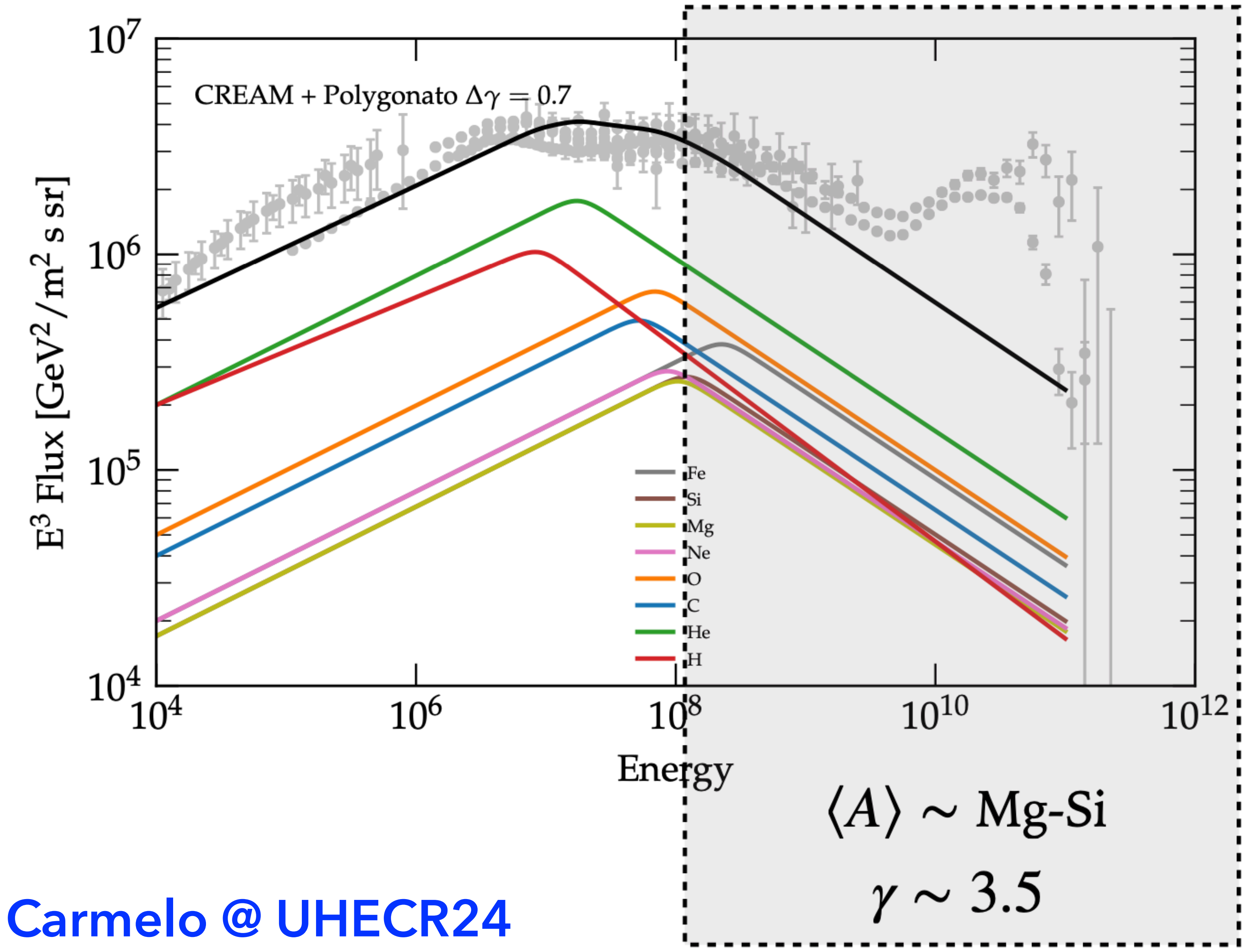


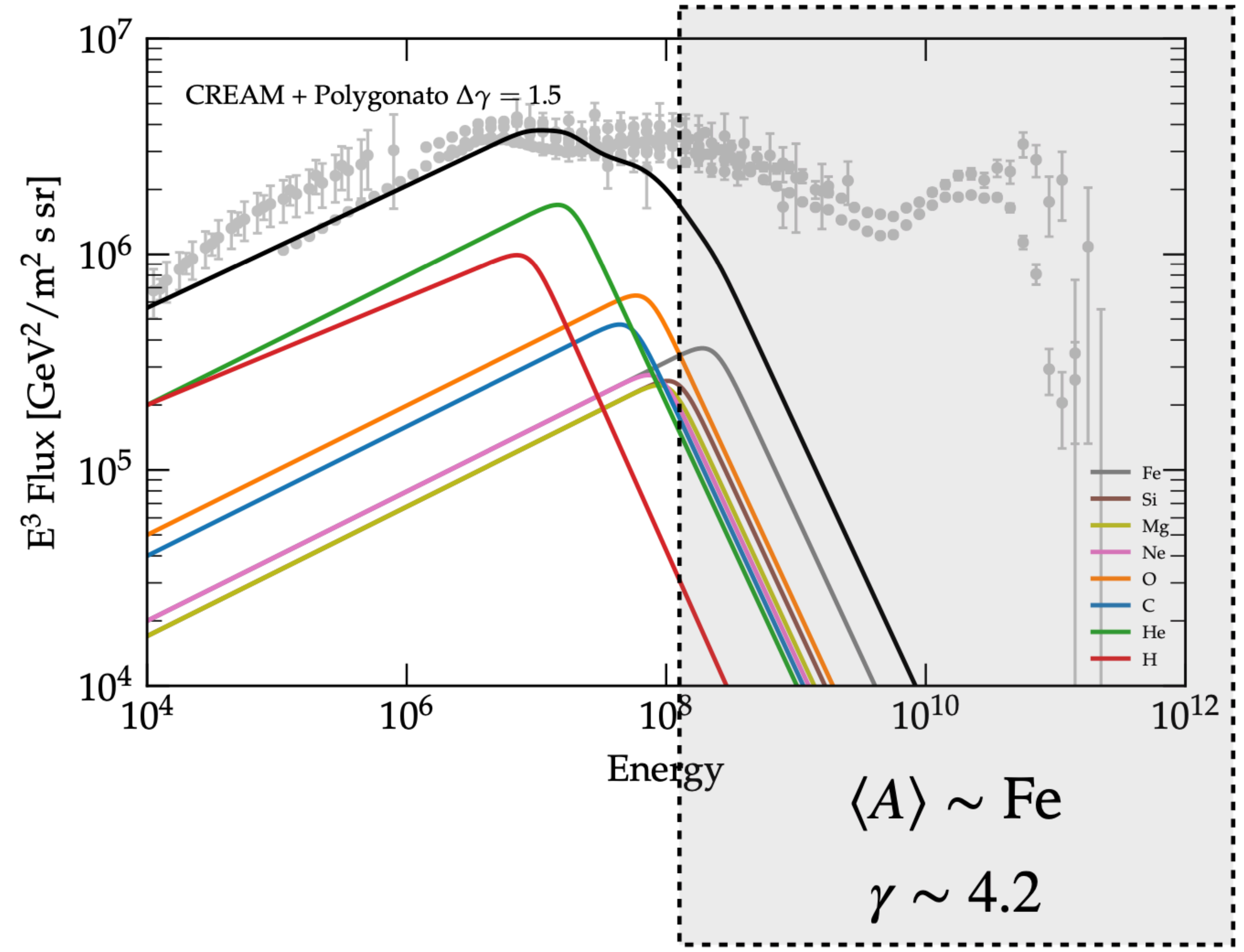




- 2 scenarios investigated in CF works:
  - 2 extragal populations, with mixed composition
  - 2 extragal populations (HE with mixed composition, LE with protons -> LE component could be from in-source interactions) + additional heavier composition (end of Galactic spectrum?) below the ankle
- No need of propagation effects below the ankle!
- Can Auger data add information on Galactic scenarios?

Once the Galactic composition is determined, our model depends solely on the behavior of the Galactic component above the first knee

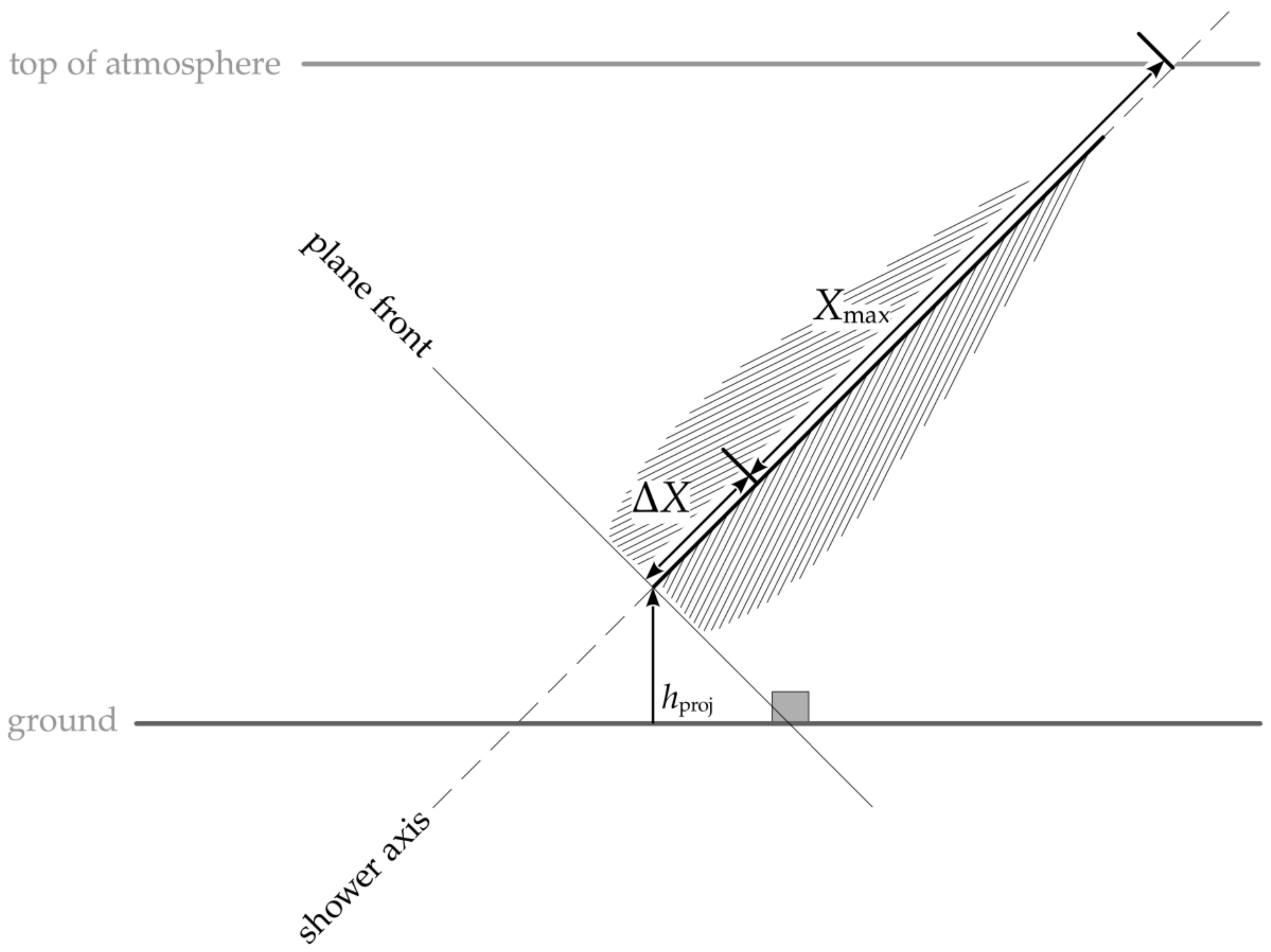




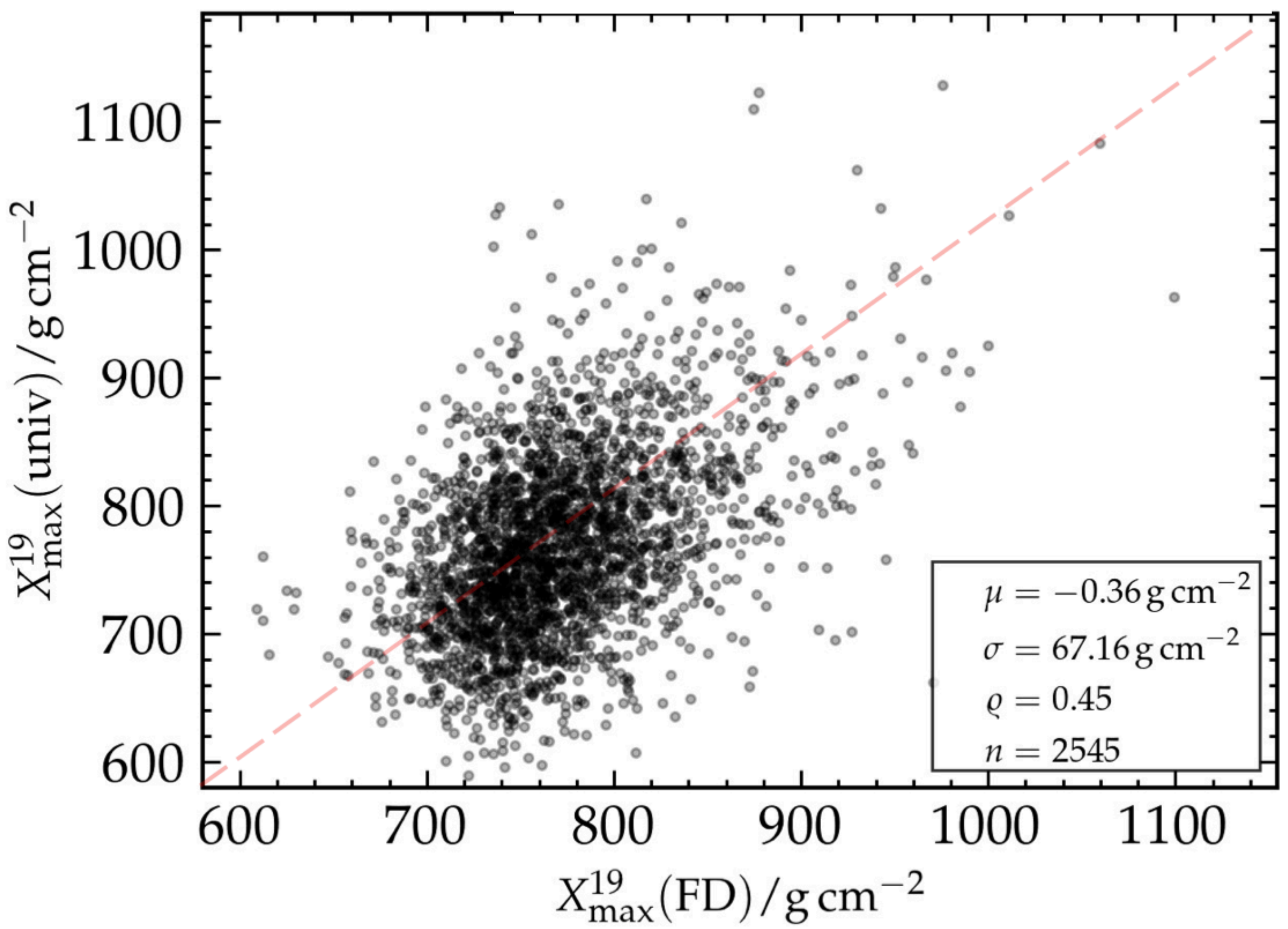
Carmelo @ UHECR24

Universality

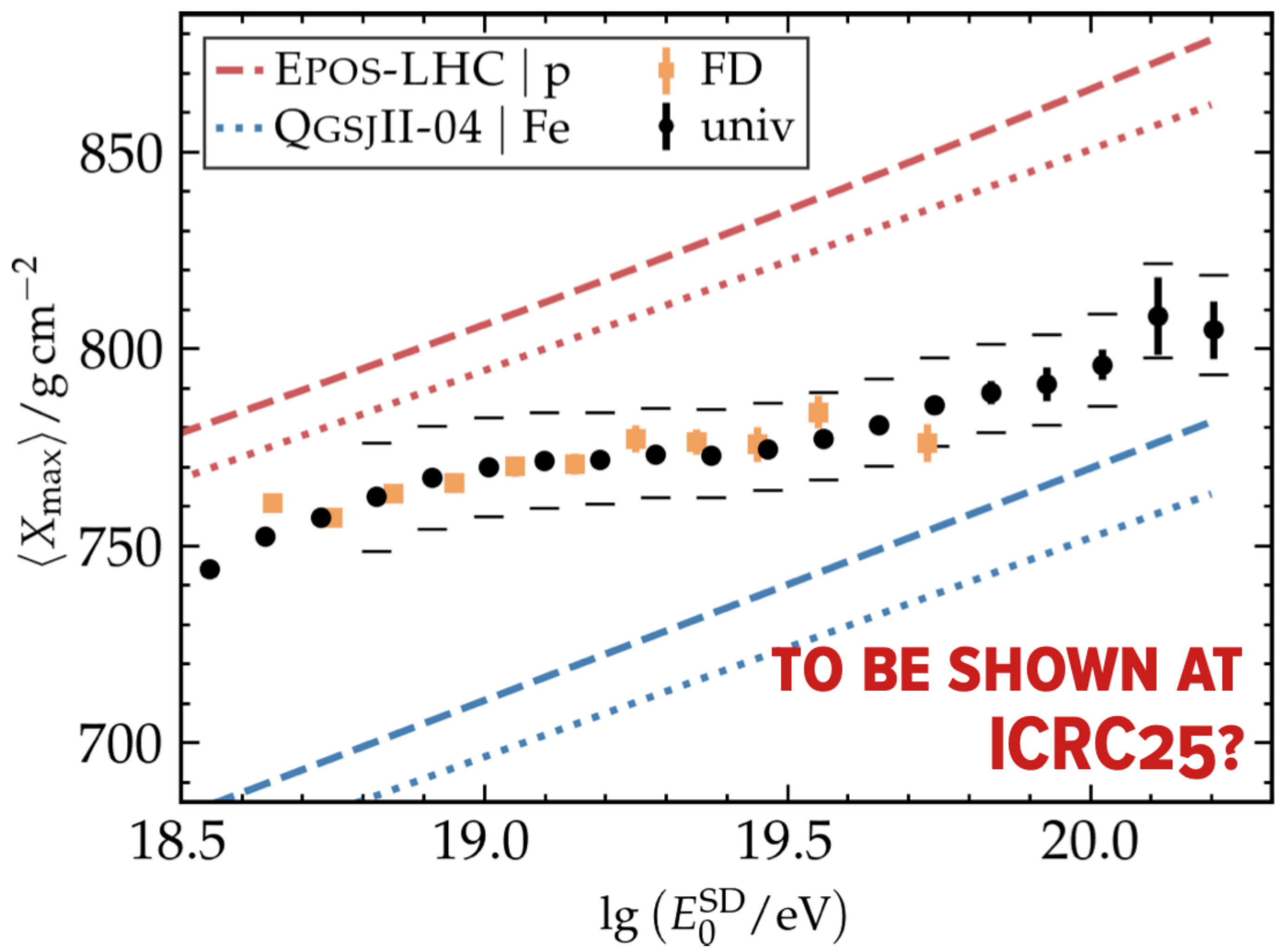
Max S. @ Malargue, Nov 2024

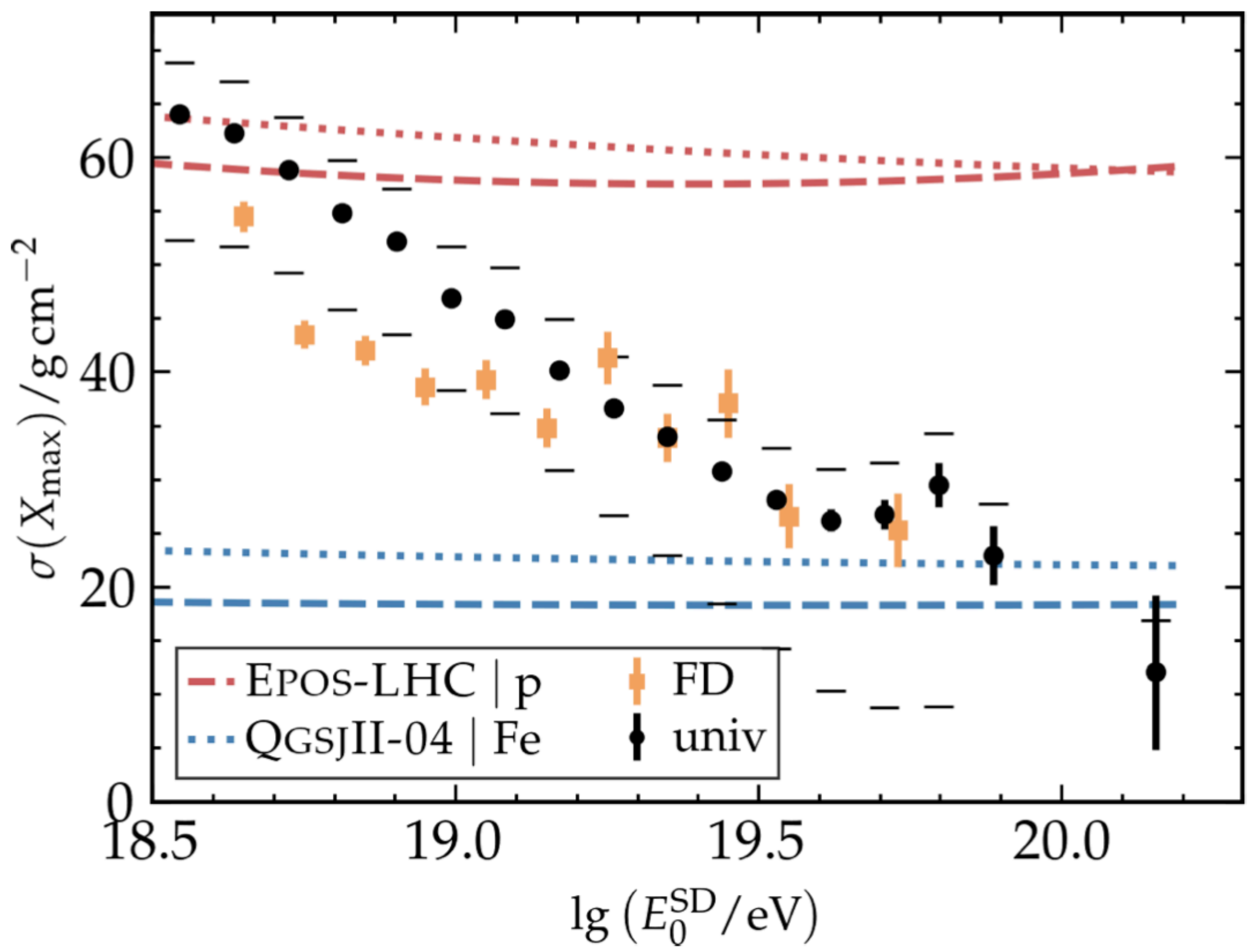


$$X_{max}^{19} = X_{max} - D_{10}\,\lg(E_0/10^{19}\,\mathrm{eV})$$



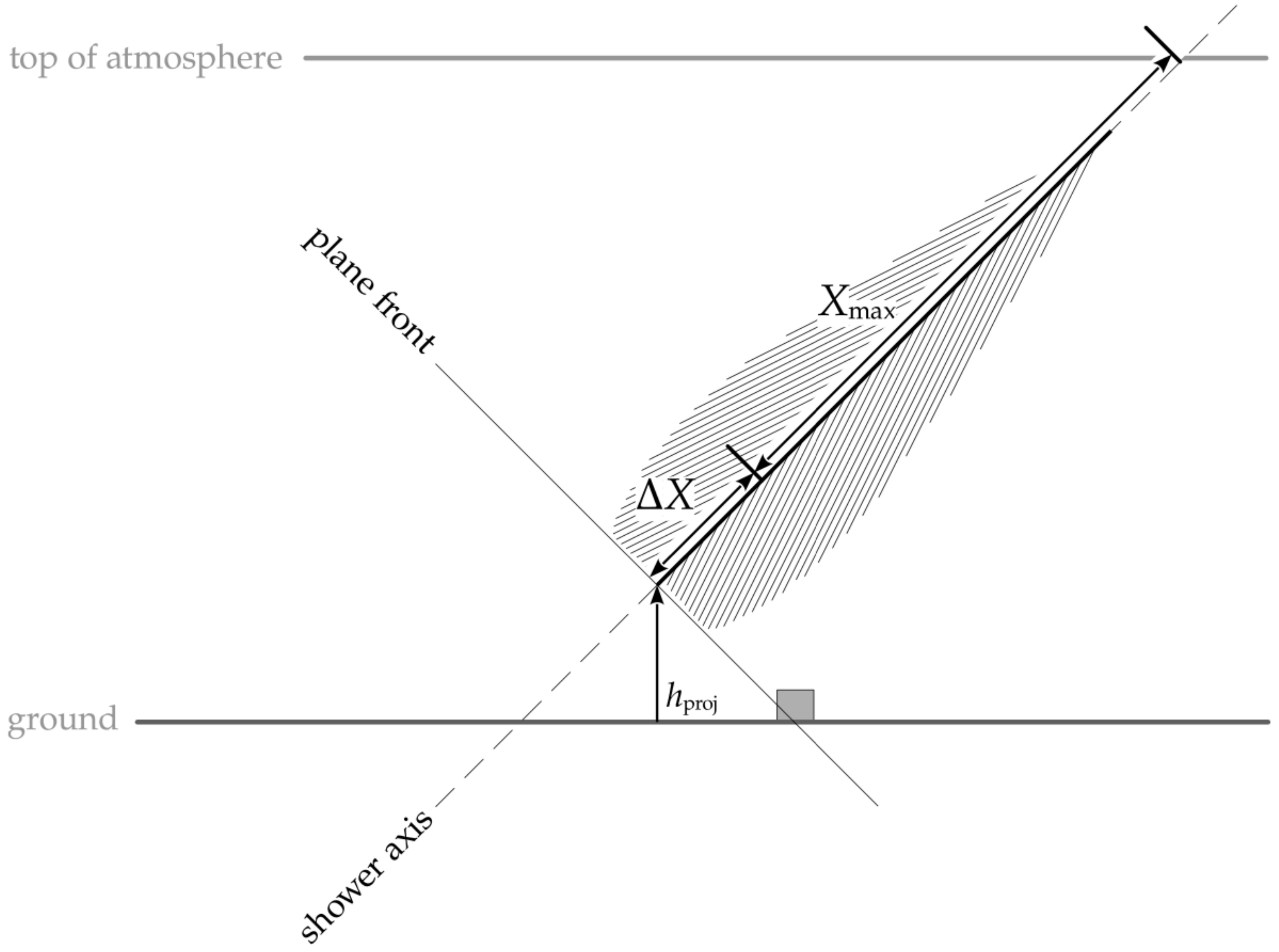
- Contribution of the different types of particles modelled depending on distance to the shower maximum, and distance to the shower axis
- LDF fit and trace shape
- See also use of universality in Pierpaolo's work, and in the following slides for applications to mass-AD analyses





Universality

Max S. @ Malargue, Nov 2024



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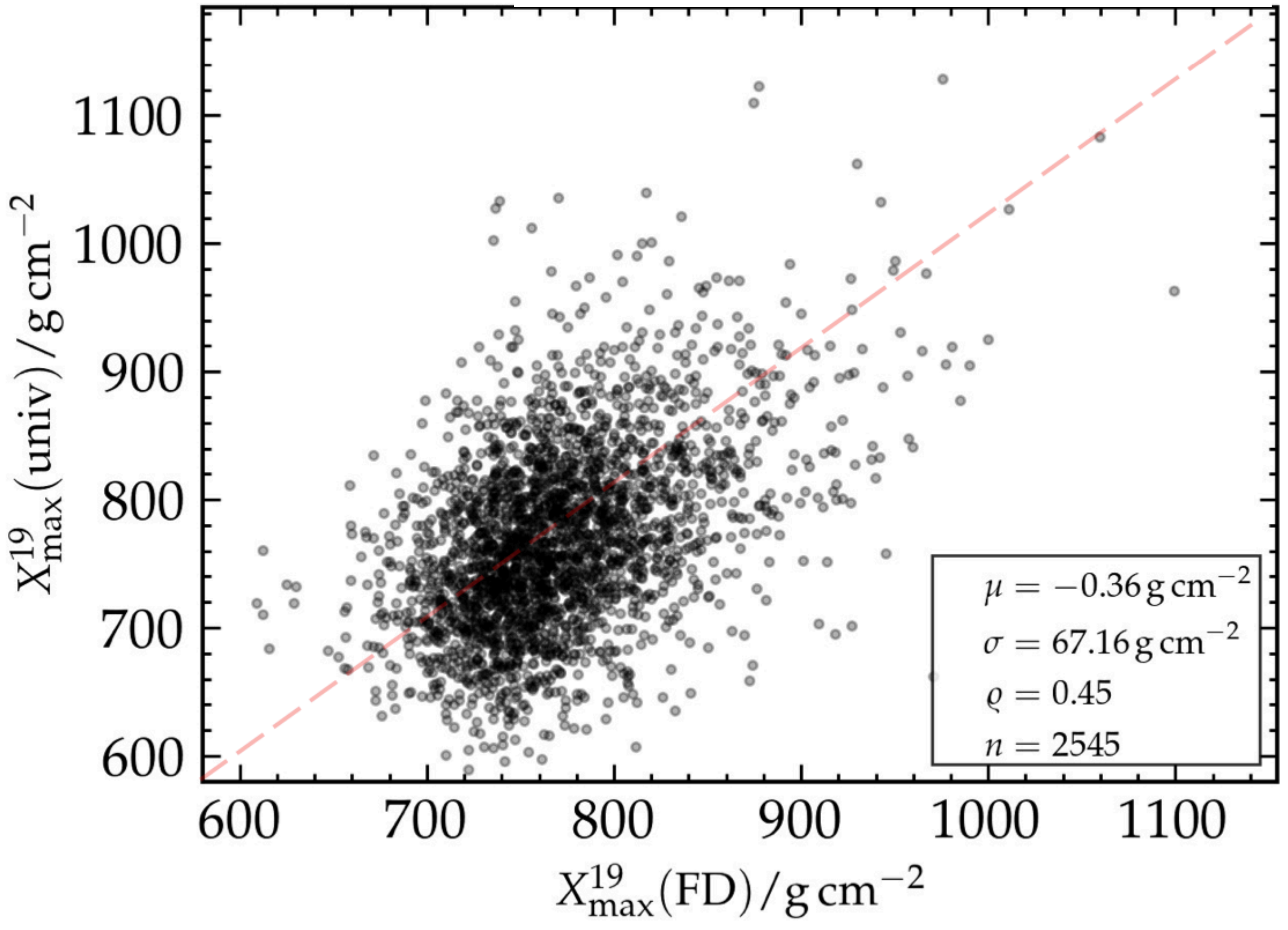
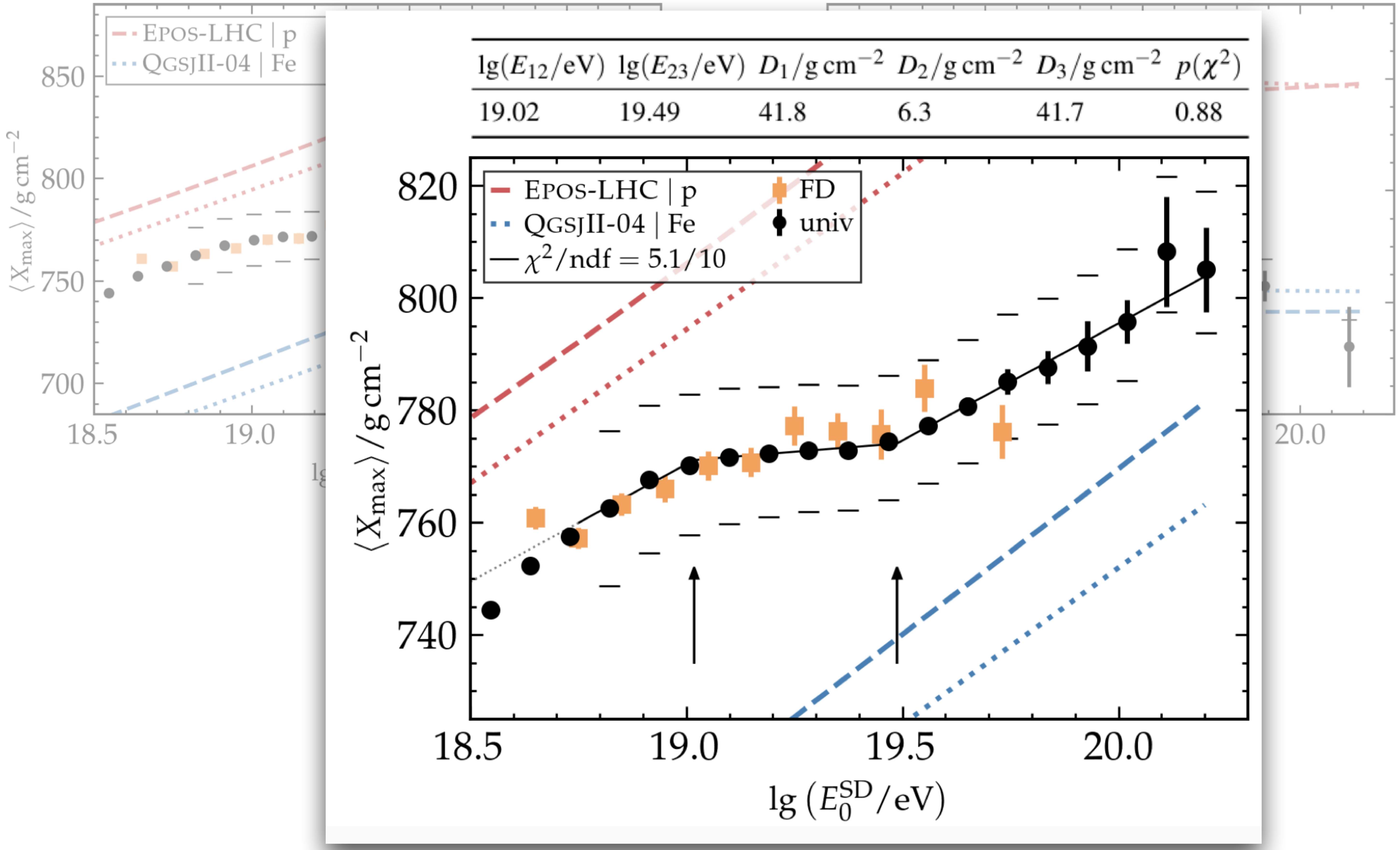
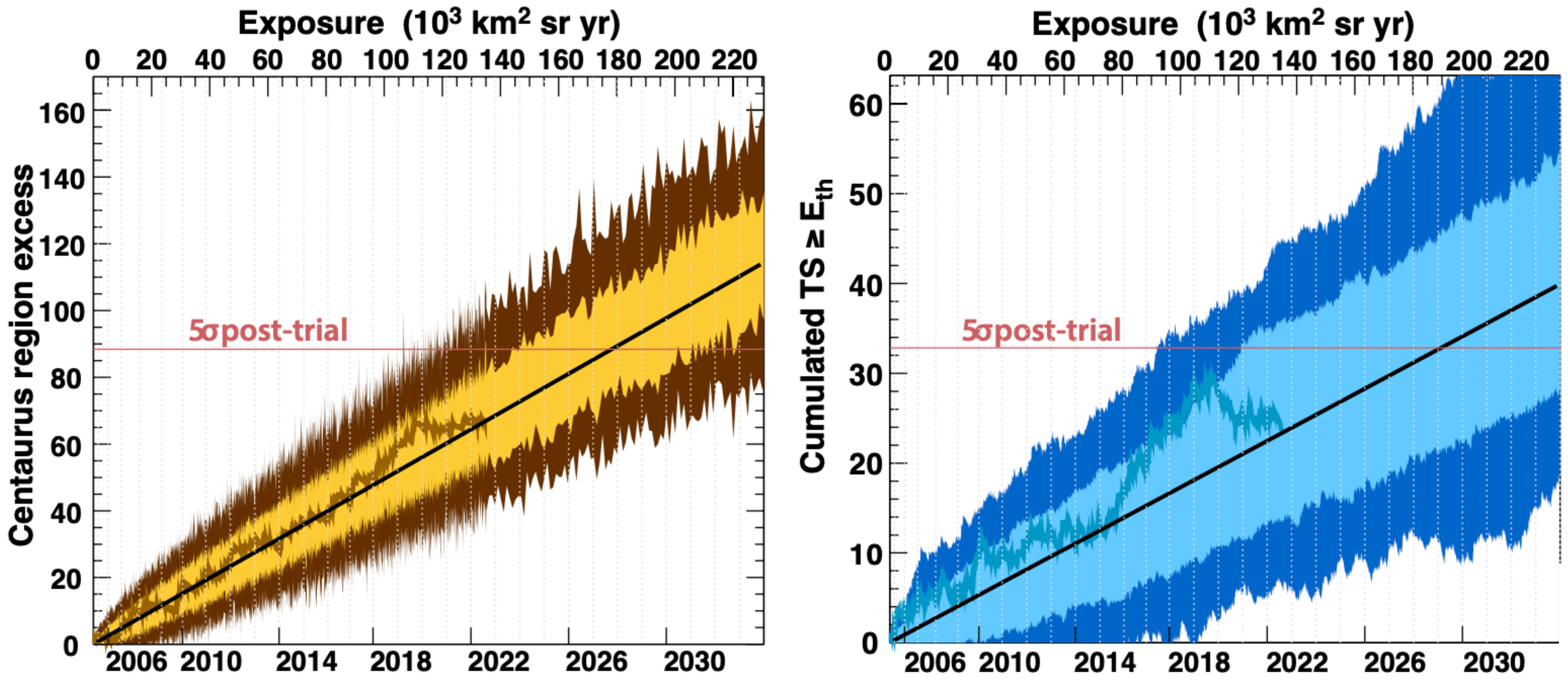
$$X^{19}_{max} = X_{max} - D_{10}\,\lg(E_0/10^{19}\,\mathrm{eV})$$



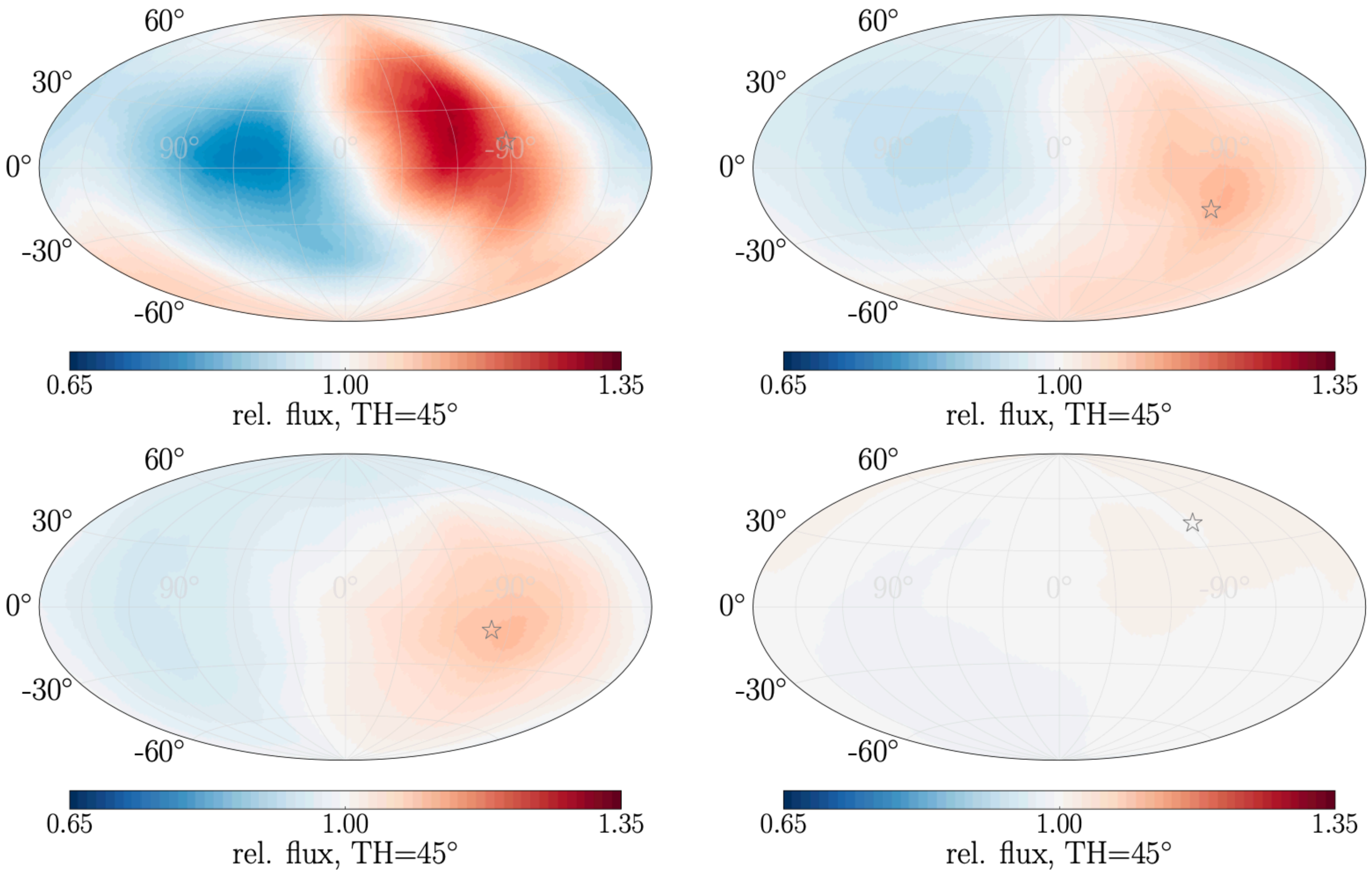


Arrival directions

AugerPrime report, 2023



Excess in the Centaurus region (left) and test statistic of the starburst model (right) as a function of time and accumulated exposure. The black line shows the projection from the last data (1σ and 2σ contours)



Predicted dipole anisotropy (Gal coord) for CRs above 8 EeV (in the LSS) divided into 4 rigidity bins each containing 25% of the events, top left the highest and bottom right the lowest rigidity -> **rigidity-binned observations can provide valuable constraints on the GMF** which do not require adopting any particular assumption about the sources of UHECRs or what produces the anisotropy

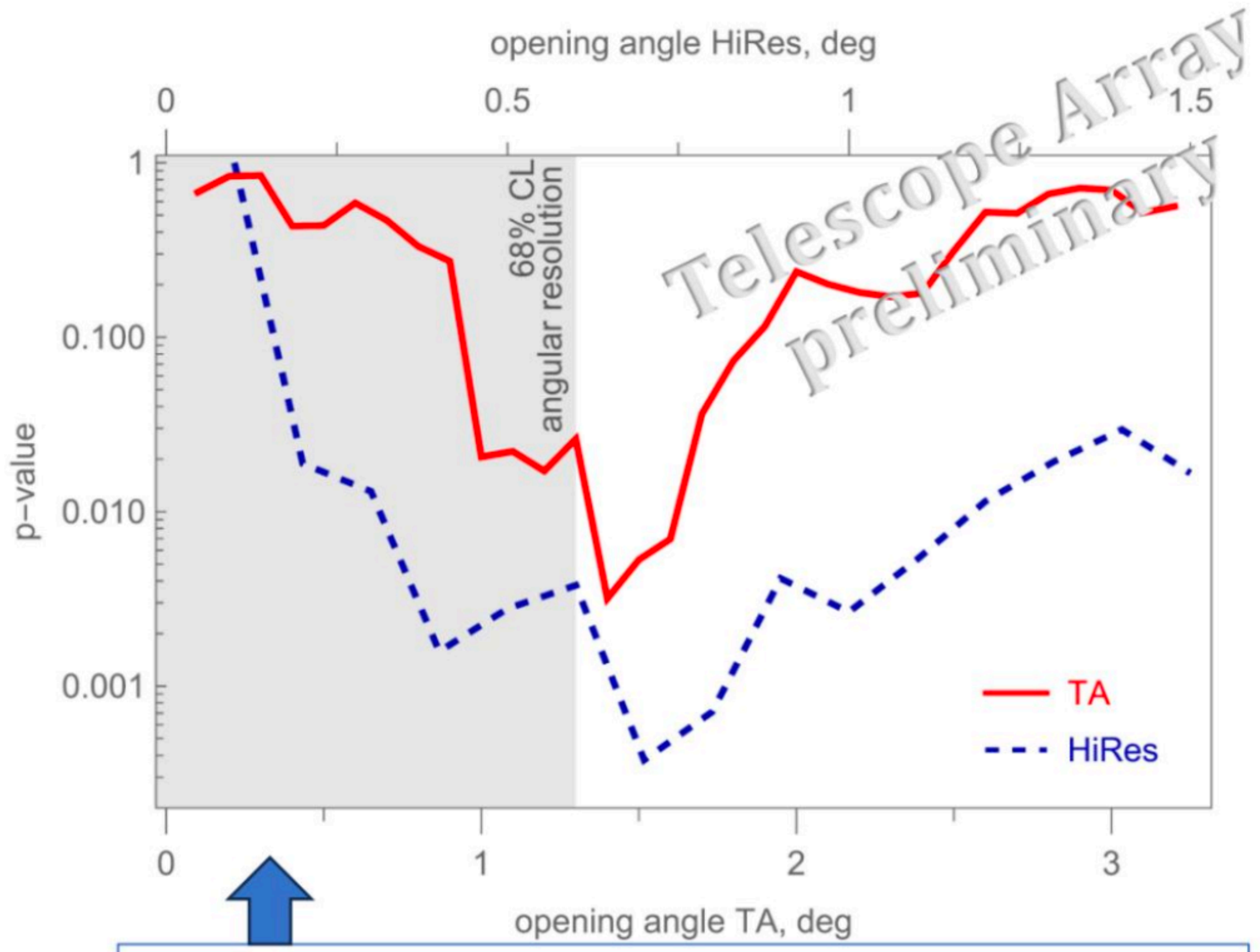
Arrival directions

Neutron paper: Hires claim on correlation with BL-LACs

We are finalizing the Neutron paper, will be circulated in the EB in these days.

One thing to be decided: what do we do with the **HiRes** correlation with **BL-LACs**?

- In the early 2000s, HiRes claimed a possible correlation at very small angular scale (at the AR level) with BLLACs from the VCV catalog.
- No clear physical interpretation of the correlation was suggested, if true it would call for new BSM physics
- Ralph and Michael suggested to include this in the neutron paper a while ago
- At UHECR, TA presented a follow-up of the claim (See talk by Sergey Troitsky), saying that they find a **"consistent but weaker"** signal



opening angles scaled to 68% CL resolutions

Lorenzo C. @ Dec. AD meeting

Expertise of the neutron analyses could be extended to BSM studies

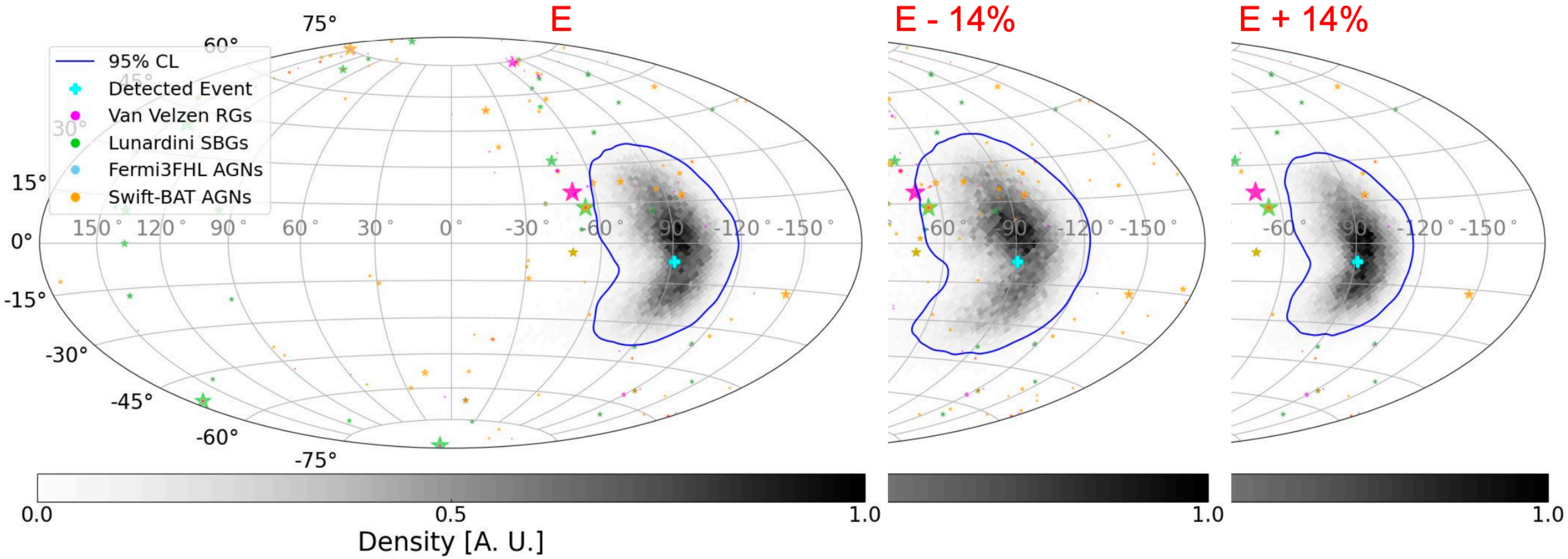
- Dark matter (see presentation by Antonio @ Malargue Nov. 2024):
  - SHDM templates could be produced for a dedicated AD analysis
  - Extragalactic dark matter?
- TA tested the correlation with BLLacs found by HiRes
  - Possible test of LIV? If neutrons (or photons) this is a test of anomaly in propagation <u>if the horizon is also included</u>

Arrival directions

- Inspired by TA study
- Constraints on the volume of the universe responsible of the highest energy events, when the horizon is accounted for -> see also Luciana's presentation
- Extension of the study to comparison to catalogs: 3D correlation study

Single-event study - results

Results - highest-energy Auger event, E = 166 EeV:



Few AGNs within CL + horizon, brightest sources (CenA, NGC4945) only when energy is negatively shifted

8

- Include source characteristics?
  - Power in luminosity band
- Can the 3D correlation study be applied to
  - photon searches? See proposal of IceCube-Auger combined analysis
  - LIV constraints? See TA presentation at UHECR
- Ultra-heavy nuclei to be considered?
  - CRPropa? SimProp? See my talk in Malargue, Nov. 2024

Marta @ last CRPheno

Arrival directions and mass composition

- Mass dependent variables reconstructed, using Xmax or Rmu, with Universality or DNN
  - For instance, to find the optimal fraction of heavy/low-rigidity events to be discarded in order to optimize the significance of the Centaurus A targeted analysis

how to sort?

$$X^{19}_{\max} := X_{\max}(E) - D \log\left(\frac{E}{10^{19}\,\mathrm{eV}}\right)$$

decadal elongation rate

the only inserted model parameters are those that are approximately constant for all hadronic interaction models!

$$1/\widetilde{Z} := 2\exp\left((X^{19}_{\max} - X_{\mathrm{ref}})/\lambda\right)$$

charge-like parameter, but real number (not integer)! NOT ABSOLUTE VALUE OF THE CHARGE!

hadron multiplicity parameter from Heitler-Matthews model

$$\widetilde{R} := E_0/\widetilde{Z}$$

$D = 58\,\mathrm{g/cm^2}$

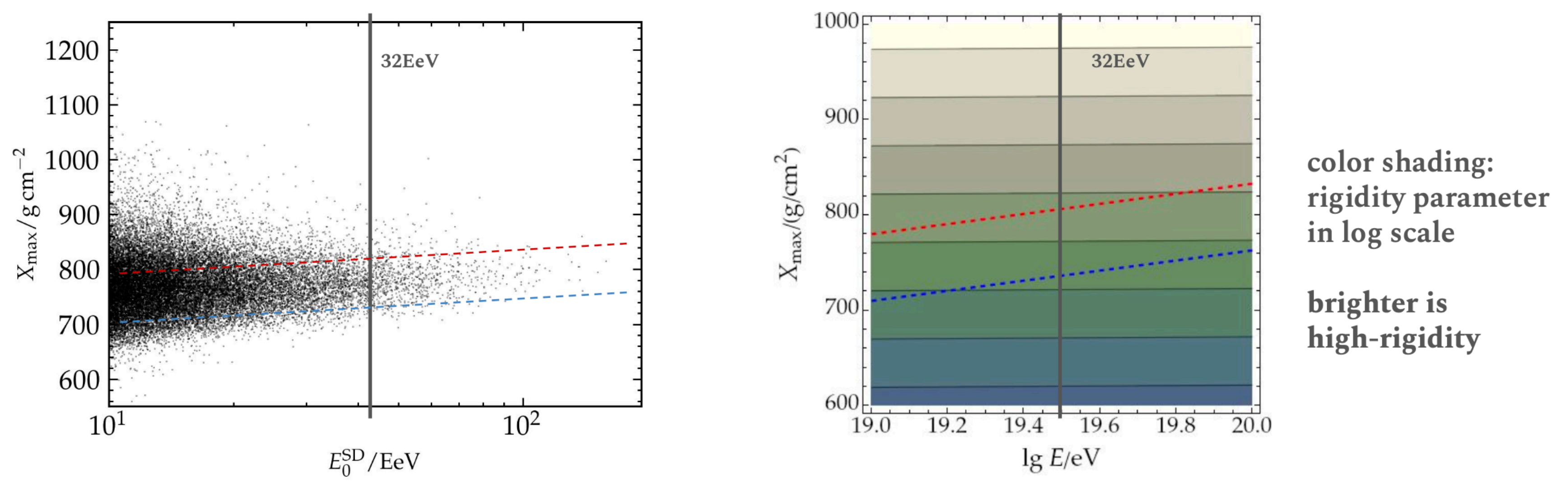
$\lambda = 22.3\,\mathrm{g/cm^2}$

$X_{\mathrm{ref}} = 742\,\mathrm{g/cm^2}$

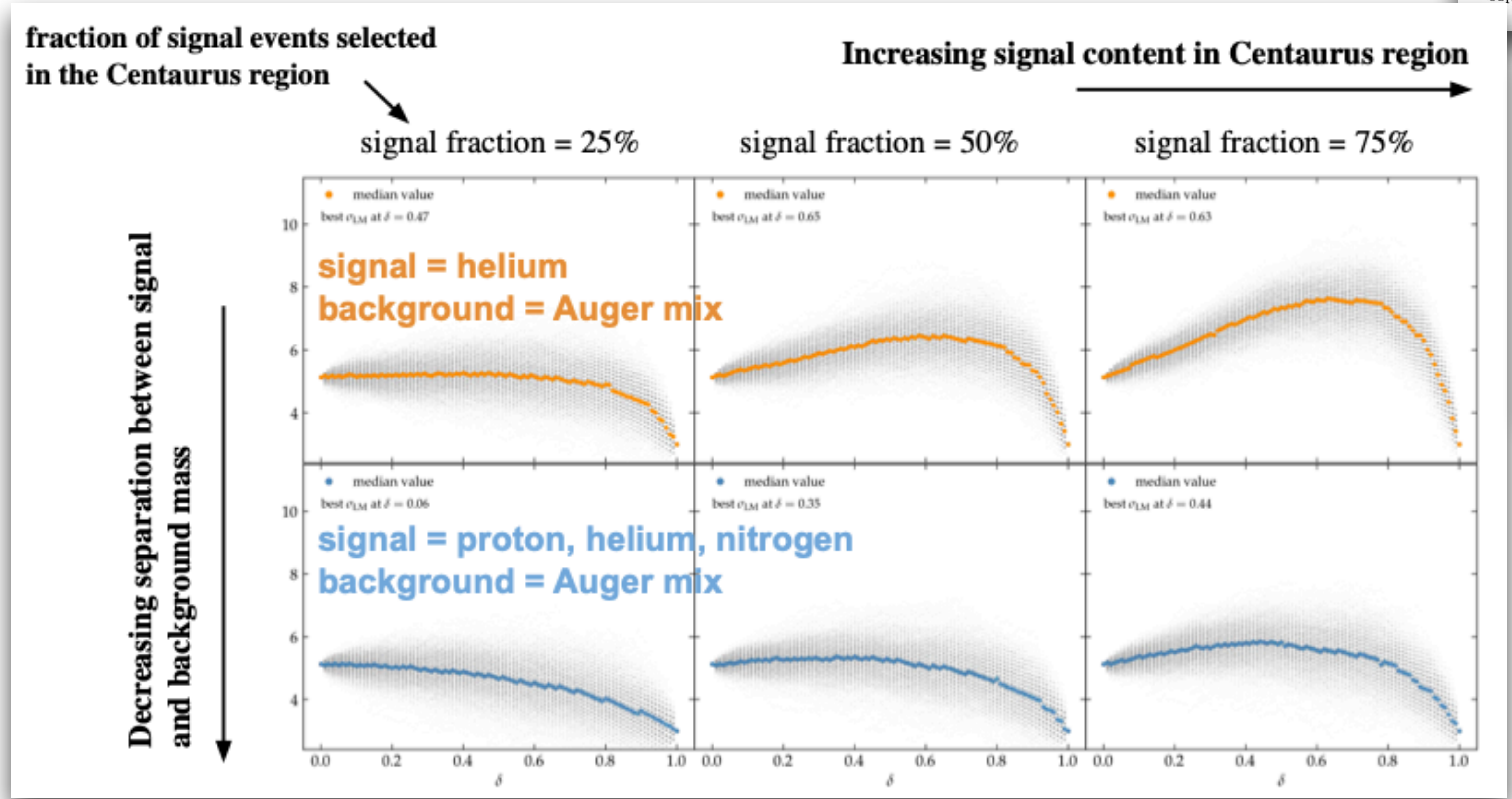
Average $X^{19}_{\max}$ reconstructed with Universality of the events with E ≥ 32 EeV

rigidity-like parameter maintaining the rigidity-order NOT ABSOLUTE VALUE OF THE RIGIDITY!

using the rigidity parameter, the events are selected "downwards" in the $X_{\max}$-energy-plane, the model parameters define the "slope"



- Test of mass ordering in the simulated data set?
- Attenuation of CRs?
- Applications to investigation of source density?



Lorenzo A. @ UHECR24

Arrival directions and mass composition

Emily @ UHECR24

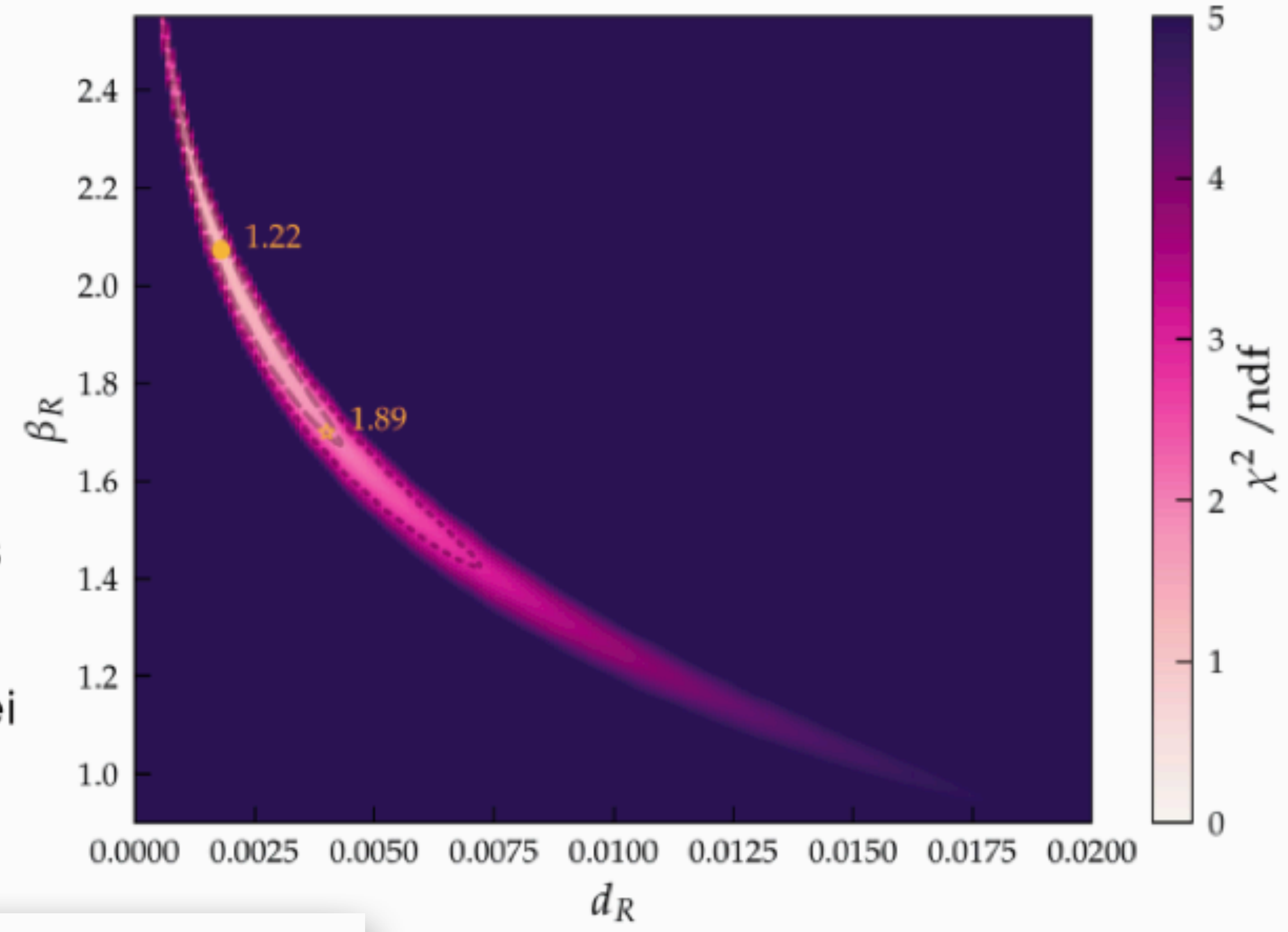
Model & analysis method

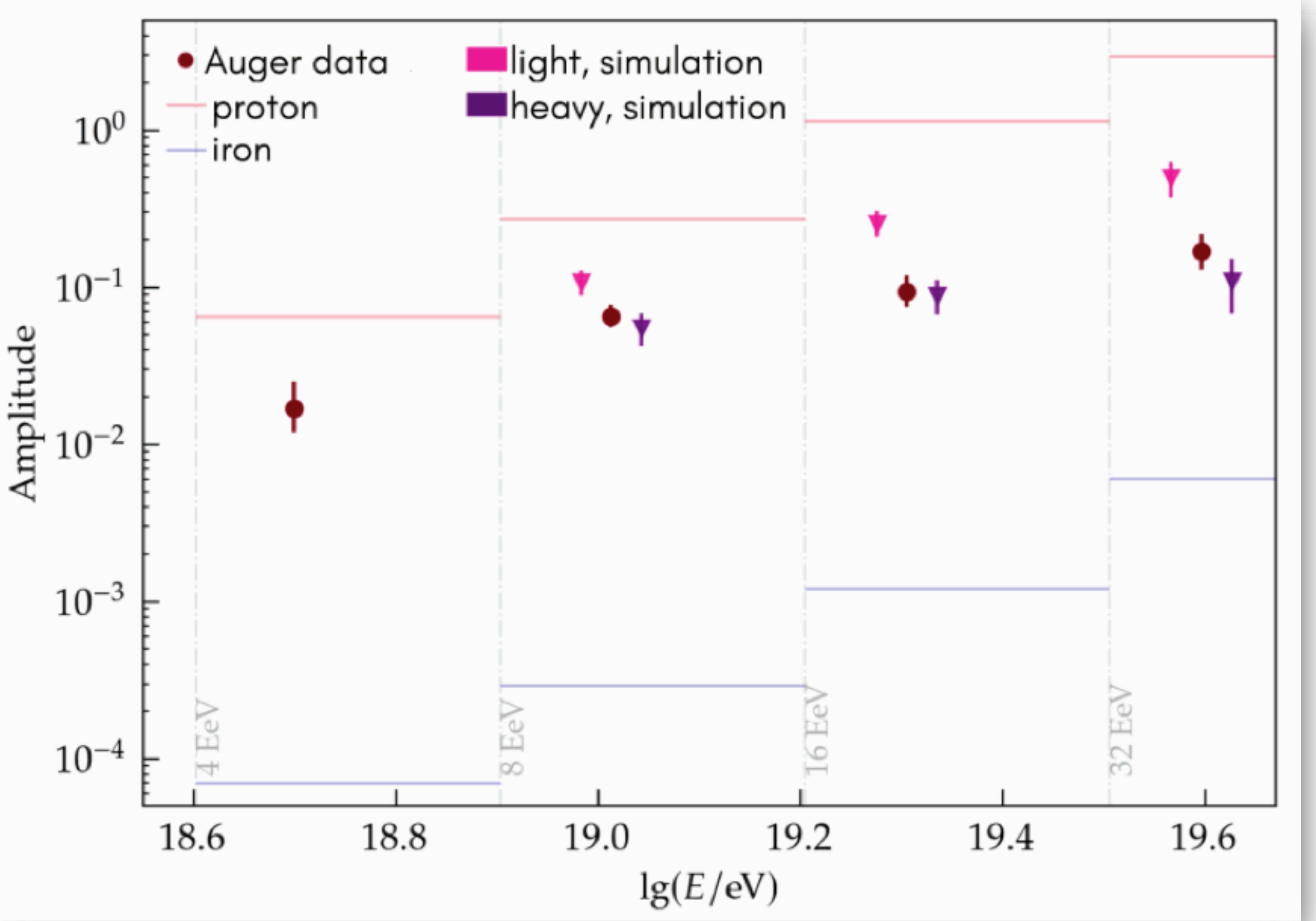
- Empirical model of rigidity dependence

$$d(E,Z) = d_R\left(\frac{E/\mathrm{EeV}}{Ze}\right)^{\beta_R}$$

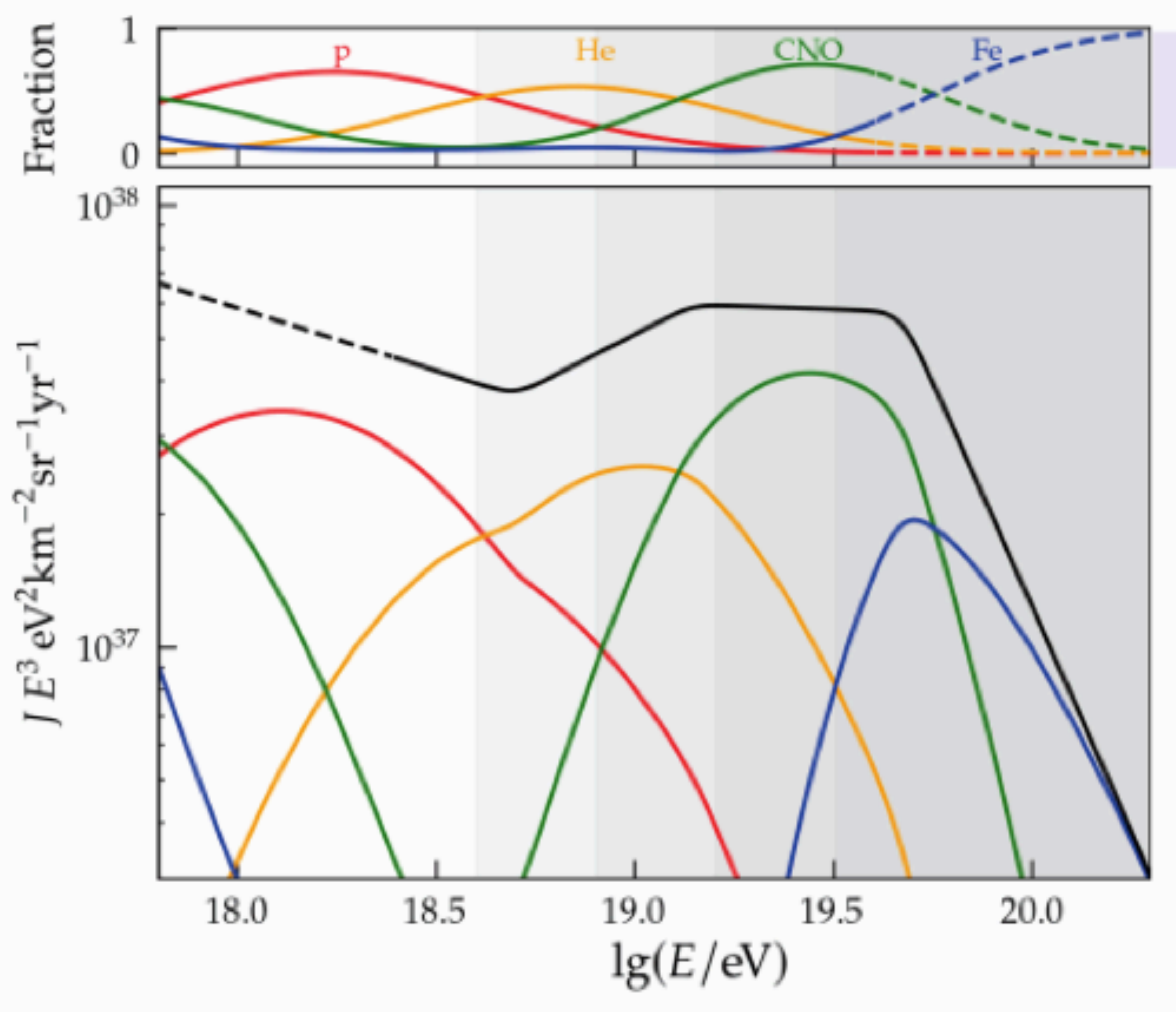
with parameters set to reproduce measurements

- Assuming composition model
- Assuming the same dipole direction for all nuclei
- Scan ln A values in the simulation library to define the **light** and **heavy** populations





Extrapolation of the mass fractions at the highest energies



- In a mixed composition scenario, a separation in total amplitude is expected to be observed in mass-selected subsets of the data
- Different directions of the dipole in each population can contribute to the separation
- Analysis applied to data: **upcoming publication**

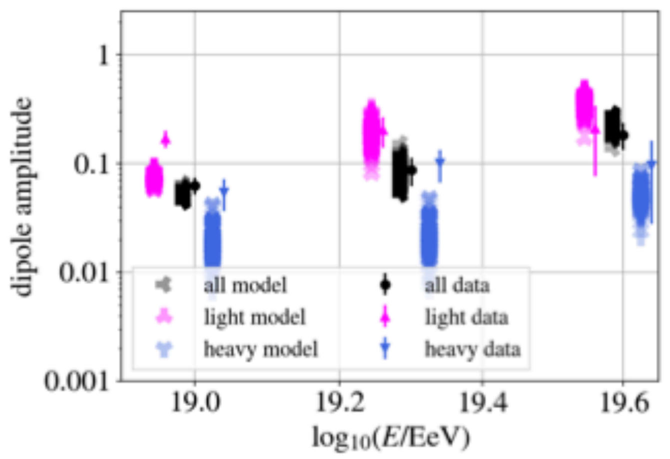
-> Dipole amplitude = amplitude of the heavy component

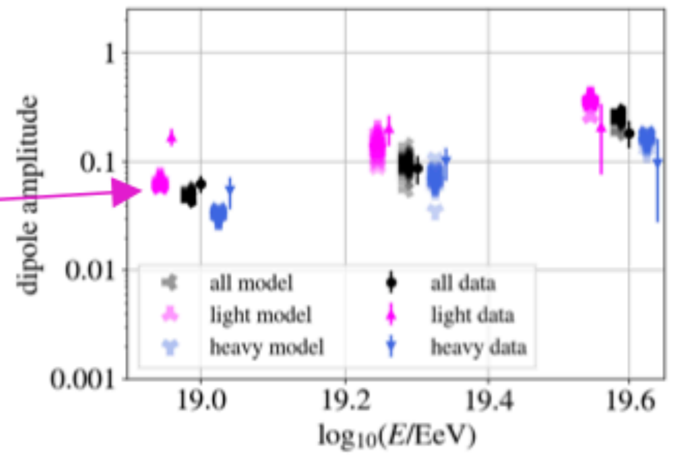
Arrival directions and mass composition

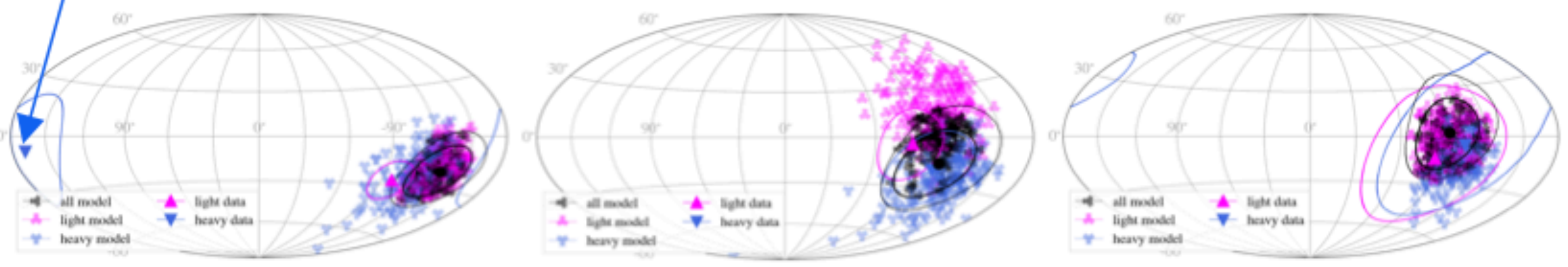
- What is the effect of the separation of light and heavy in the dipole direction, if the LSS is taken into account?

Conclusion

- **LSS model reproduces large-scale anisotropies well**
  - ➔ see talk at UHECR next week
- **composition-dependent dipole:**
  - **amplitudes and directions can be reproduced well - independently of the GMF model!**
  - ➔ apart from light component amplitude & heavy component direction at 8-16 EeV
    - ➔ could be from larger proton fraction (local source, second population?), model inaccuracies ...



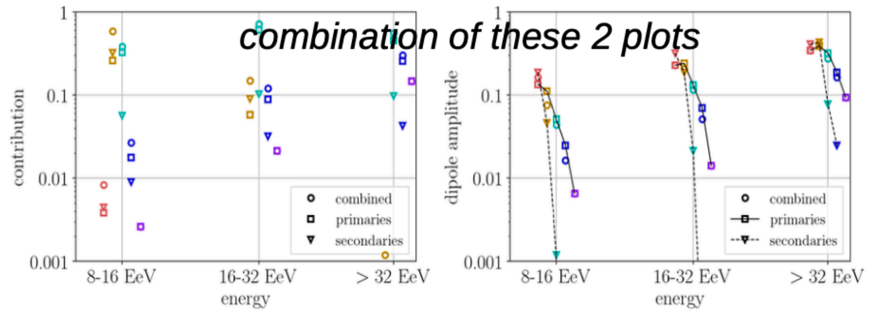


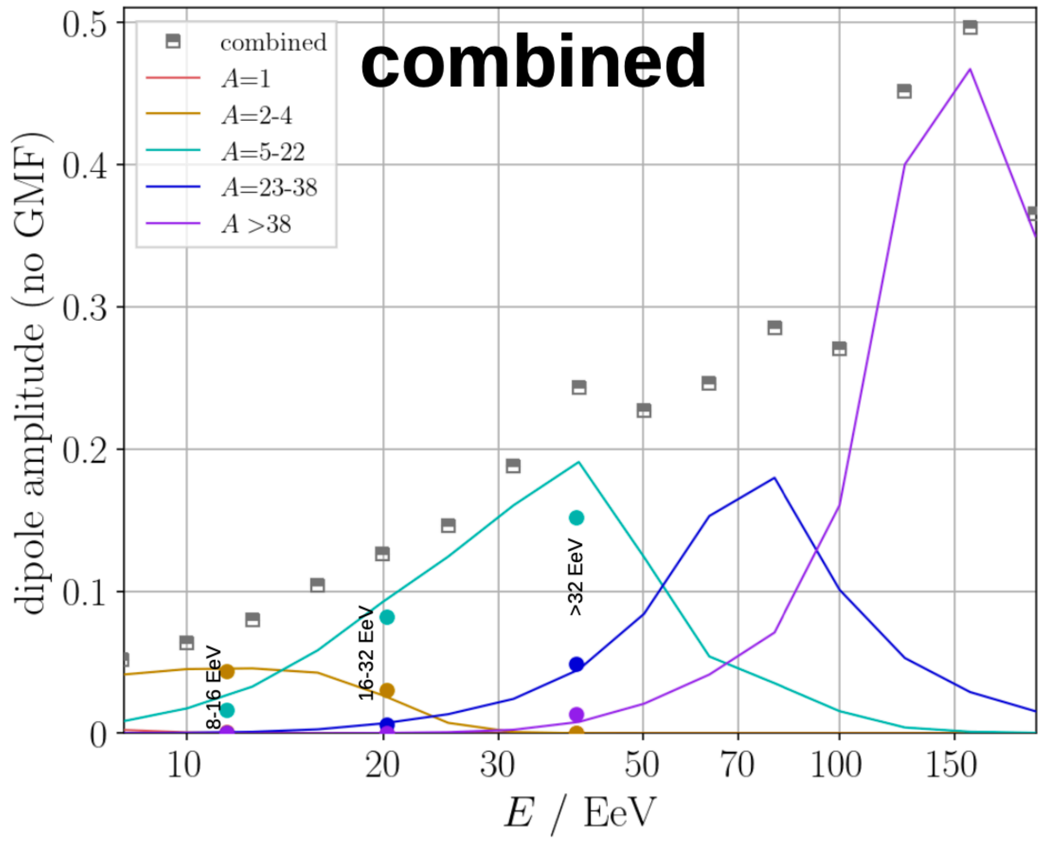


Teresa @ UHECR24

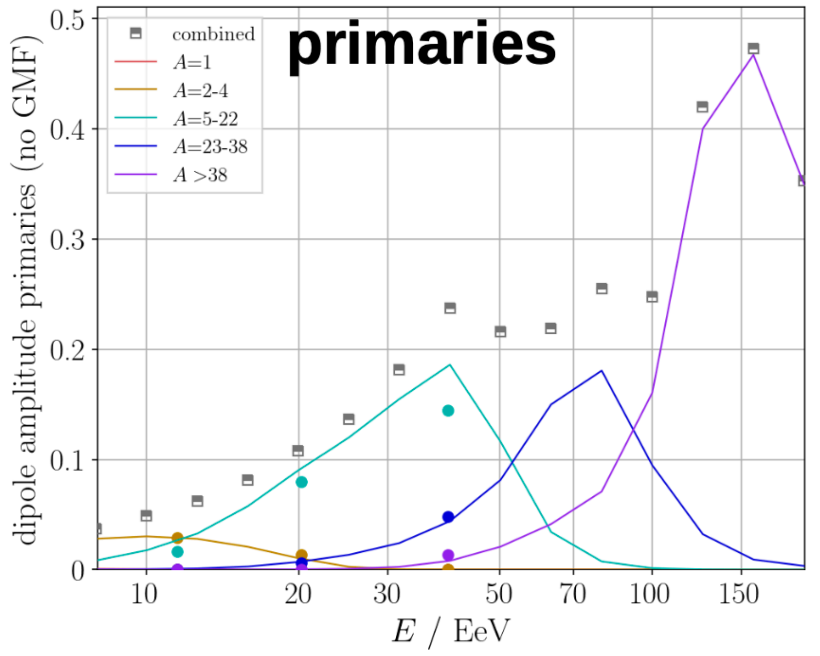
Which elements form the dipole? (outside MW)

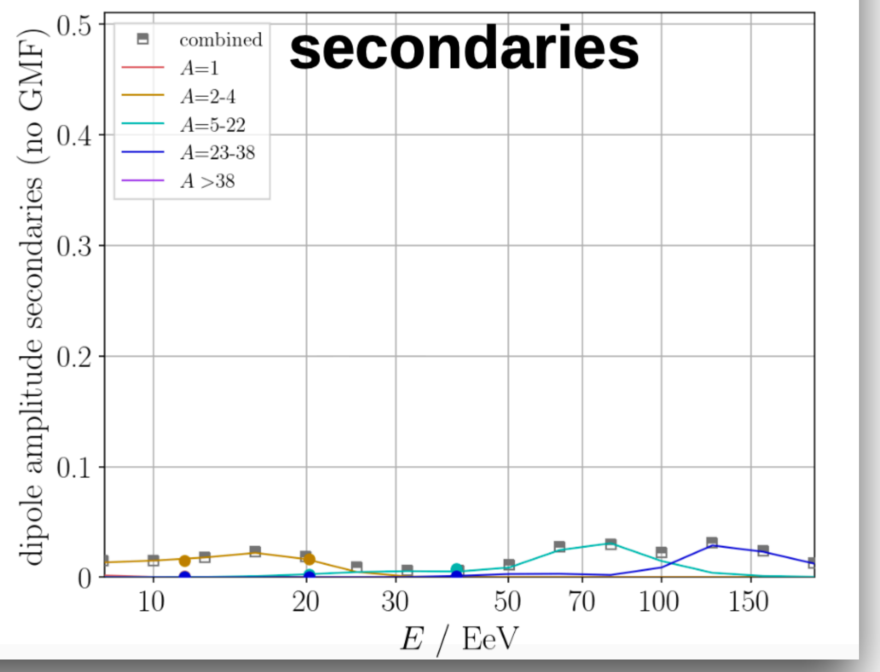
Weighted average dipole amplitude:





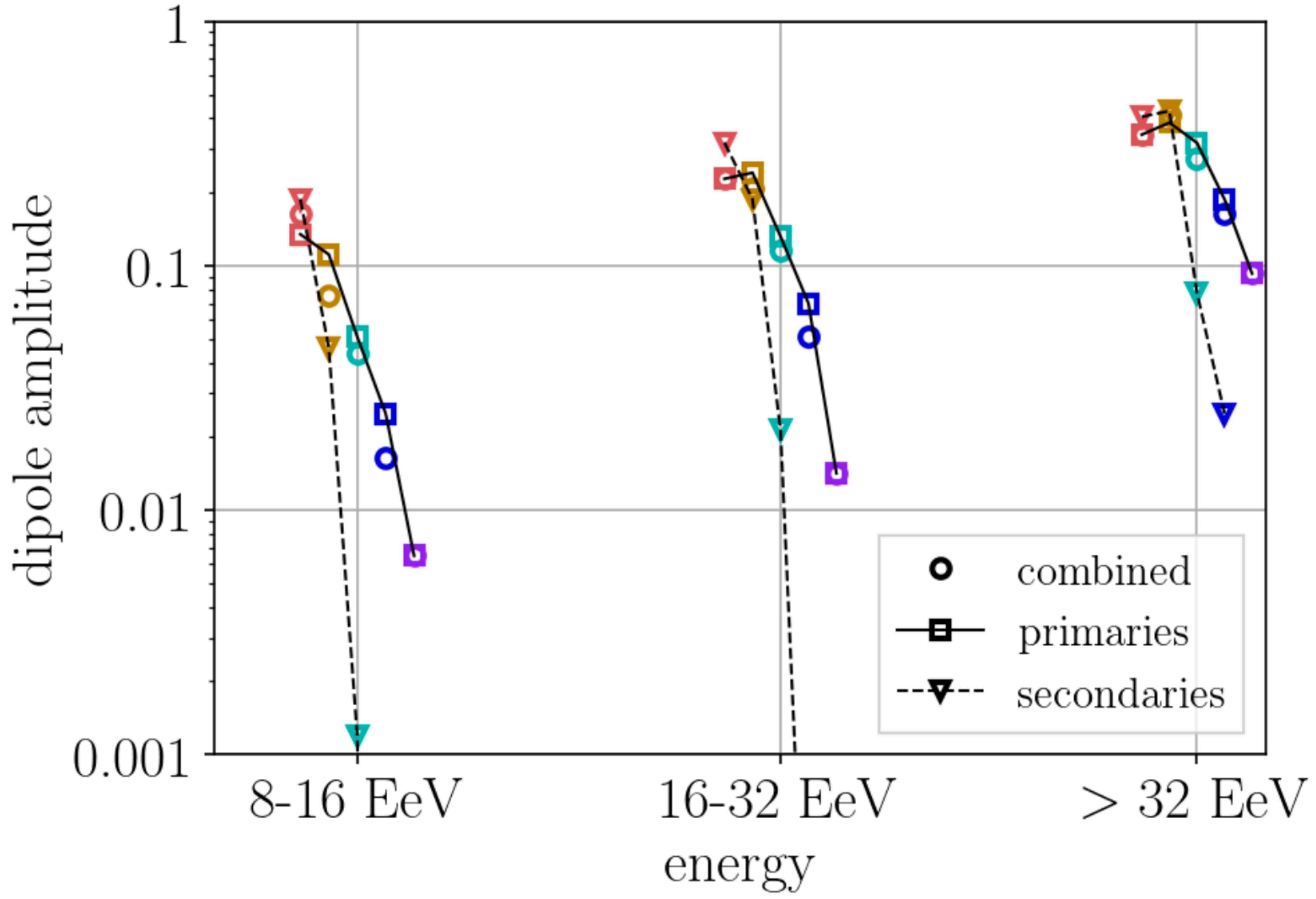
→ dipole formed mostly by primaries, moving from He to CNO



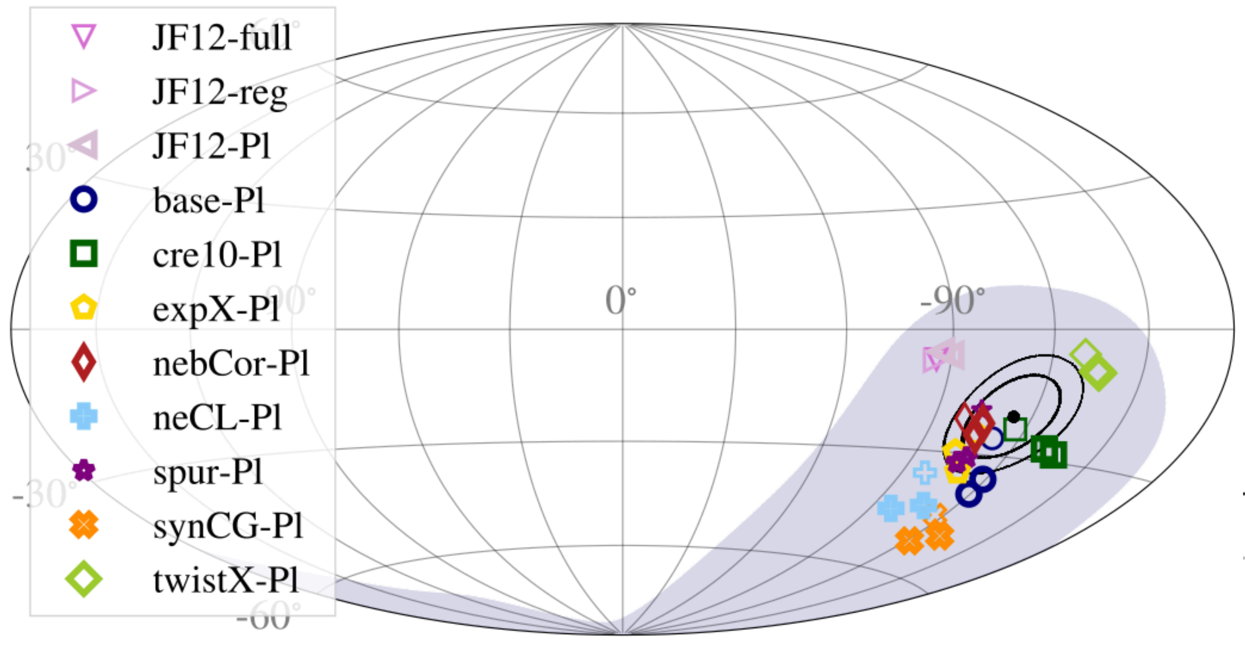


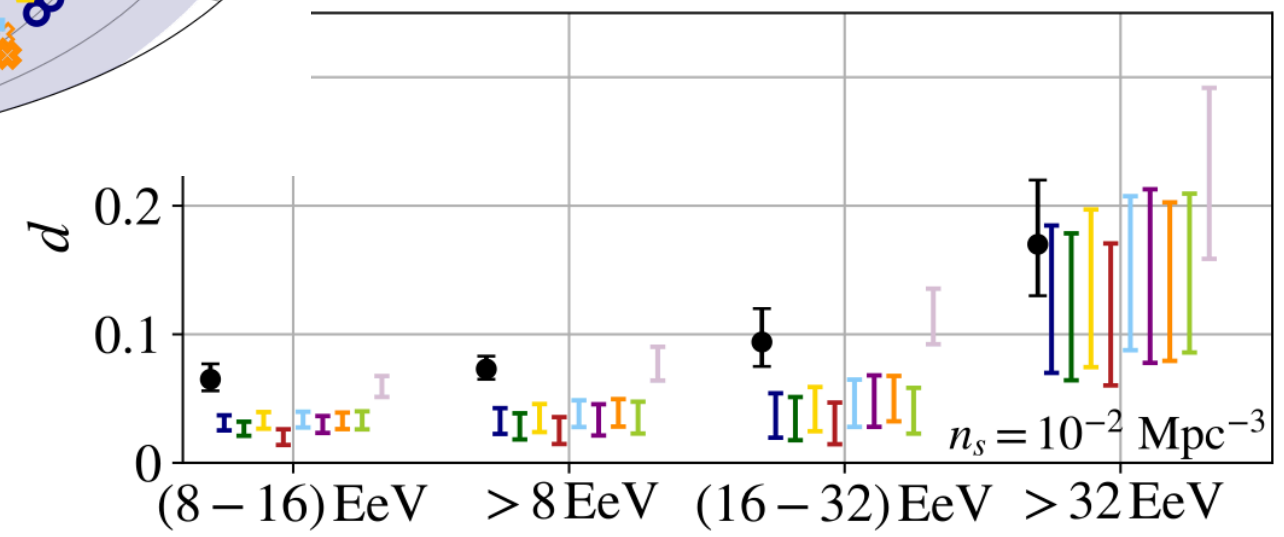
Teresa @ last CRPheno

- **primaries:**
  smallest propagation length leads to largest dipole
  - because anisotropy is mainly close-by
  - propagation length is smallest for He at higher energies, largest for Fe
- **secondaries:**
  effect even bigger as lighter elements are decay products from heavier ones at higher energies where the propagation length is smaller



Magnetic fields





- 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>?

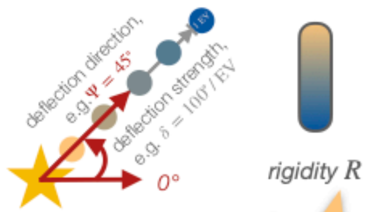
- **Reconstructing coherent magnetic field deflections:**
  - Can we detect coherent deflections induced by the GMF in AD data?

Josina @ last AD meeting

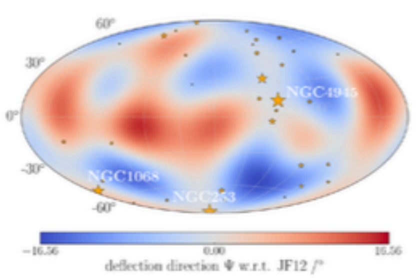
Coherent Deflection Model

- local magnetic field deflections described by spherical harmonics expansion (deflection direction Ψ & strength δ)

$$\Psi(\theta, \phi) = \sum_{l=0}^{l_{\max}} \sum_{m=-l}^{l} a_{l,m} Y_{l,m}(\theta, \phi)$$

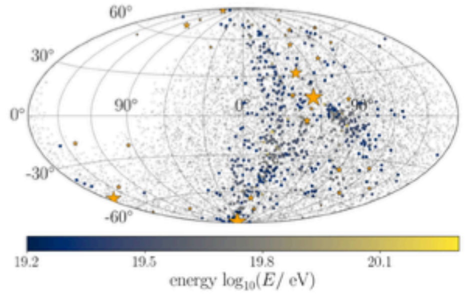


  - deflection direction: $\mathcal{N}(0°, 60°)$ w.r.t. JF12 model (new)
  - deflection strength: $\mathcal{N}(100\,\%, 30\%)$ w.r.t. JF12 model
- free parameters: coefficients of spherical harmonic expansion $a_{l,m}$
  - deflection direction: up to $l_{\max} = 5$
  - deflection strength: up to $l_{\max} = 5$



Source Model

- energy threshold $10^{19.2}$ eV
  - 12,606 events in standard AD dataset (x, y, z, E)
- **SBG catalog** + background sources
  - source energy spectrum & composition as found by CFAD (*JCAP01(2024)022*)
  - variable **signal fraction** $f_s \in [0\,\%, 10\%]$ (new)
    - also fit parameter!
- apply **turbulent** deflections, too
  - $\beta = 20°/(R/\mathrm{EV})$



- Reverse the question: **is it possible to build UHECR-informed model of GMF?**

- **Including coherent and turbulent magnetic field deflections:**

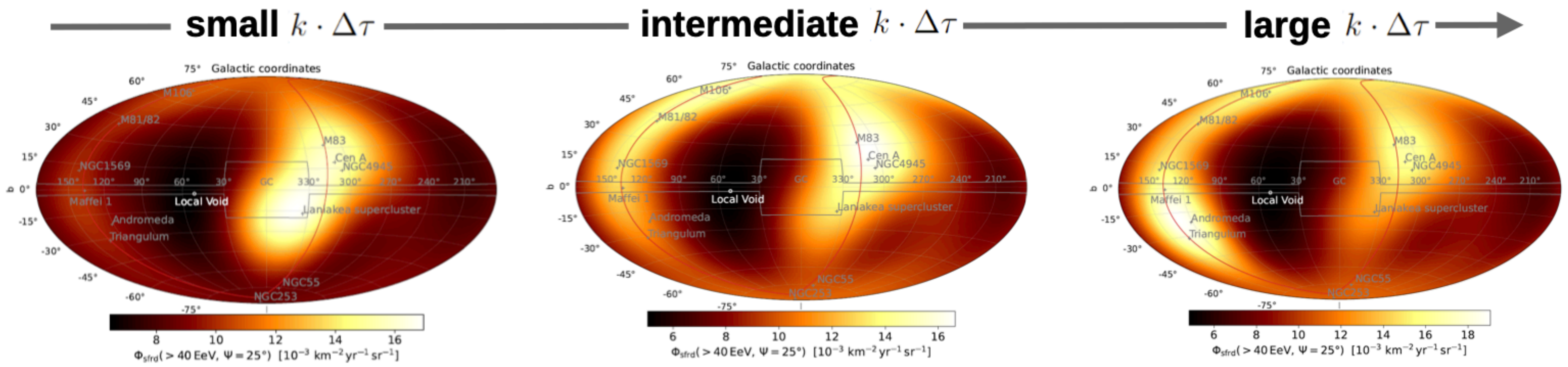
- Including GMF in correlation studies -> SBG+GMF scenarios are statistically compatible with Auger results
- What is the effect of introducing a smearing due to EGMF?

Luca @ UHECR24

Transient sources

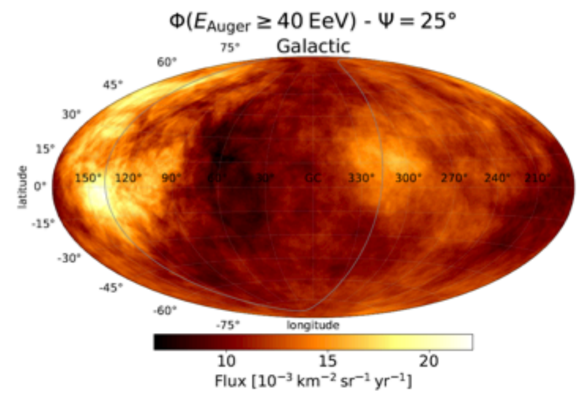
- **assumption: UHECR sources are transients that occur proportionally to SFR in every galaxy**

- **<u>model:</u> *Marafico, Biteau, Condorelli, Deligny, Bregeon 2024***
  - injection: broken power law, fit to spectrum and Xmax
  - injection rate S_i proportional to SFR_i and burst rate k
  - time spreading due to magnetic field delays: $\Delta\tau$
    - parameter $k \cdot \Delta\tau$ determines visible galaxy contributions



local galaxies do not contribute → observer between bursts

almost continuous emission → local galaxies dominate

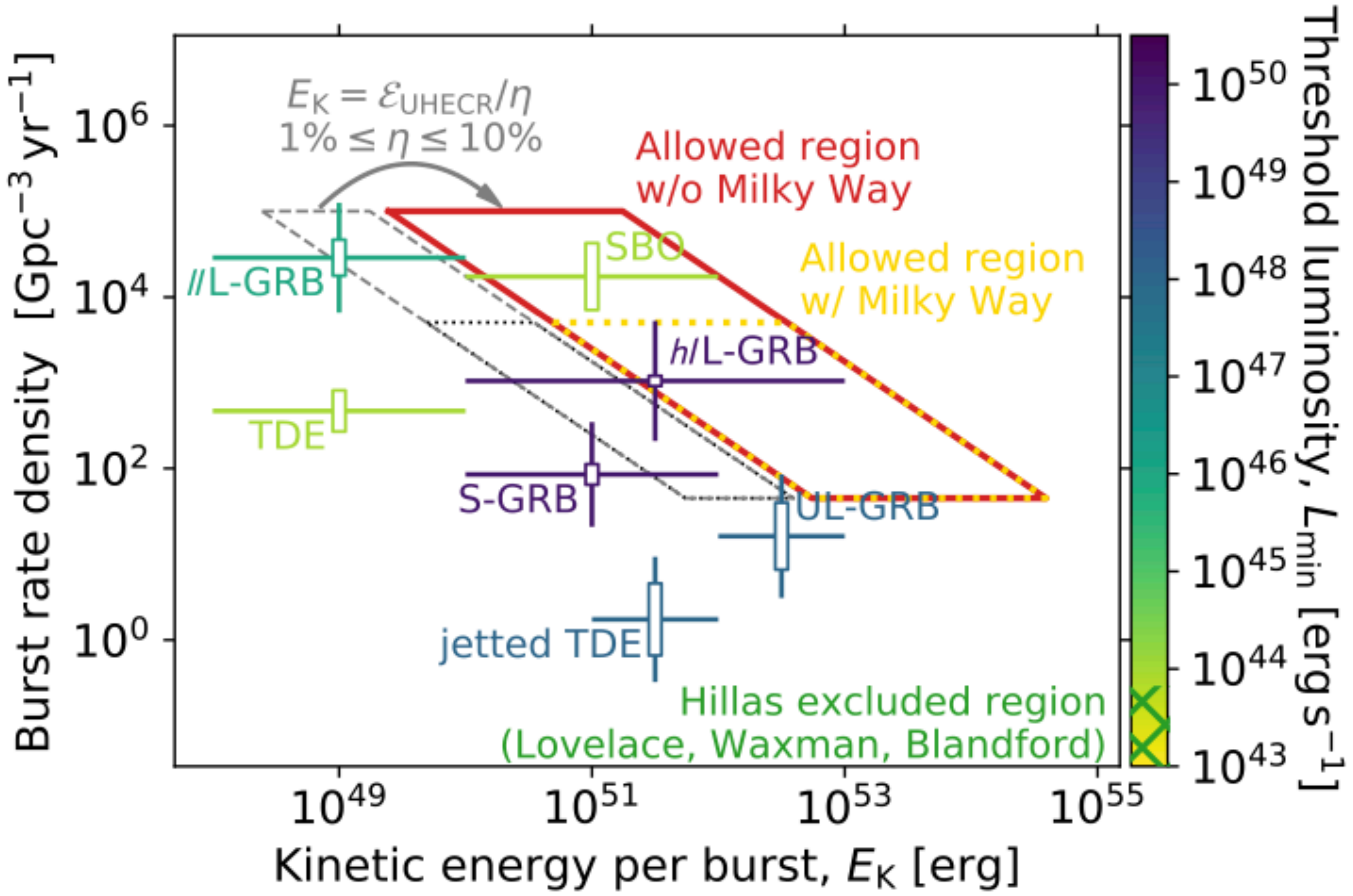


→ **can use Auger data to constrain $k \cdot \Delta\tau$**

Radboud University Teresa Bister | 13.11.2024 | slide 3

Teresa @ Malargue, Nov. 2024

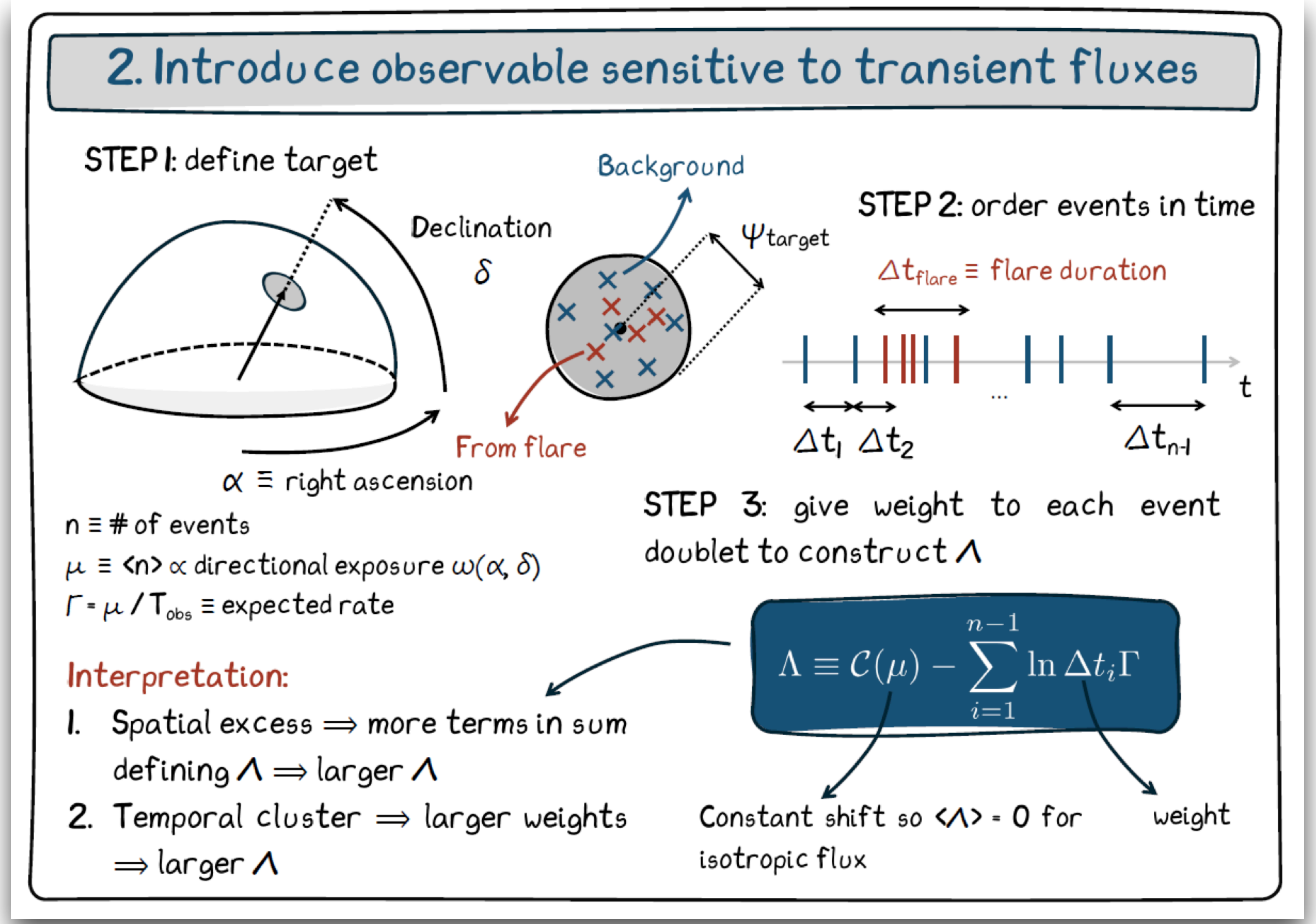
- Can we constrain the bursting activity of a source, taking into account the spread in time due to magnetic deflections?
- How does considering a transient nature of UHECR sources complement the determination of the constraint on the production rate of UHECRs?



Marafico, Biteau, Condorelli, Deligny & Bregeon, ApJ 972 (2024)

Transient sources

Miguel @ Malargue, Nov 2024



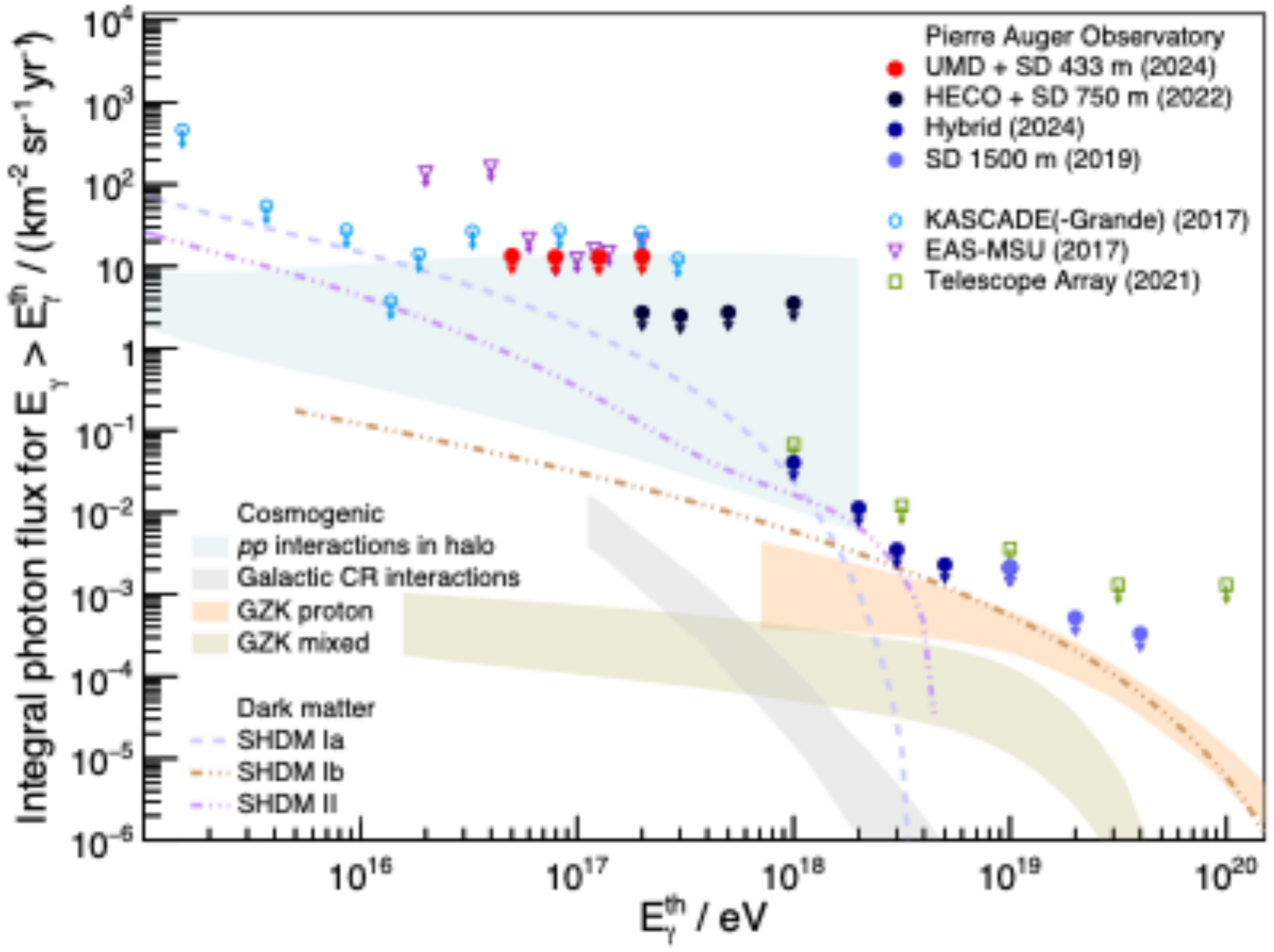
- Attempts to search for spatial and temporal correlations
- Similar ideas also exploited in BSM searches (with target defined by catalogs)

Conclusions:

- New estimator Λ highly sensitive to variety of transient fluxes with different intensities and durations
- Noticeable increase in sensitivity to transient fluxes with respect to spatial only analysis in all 3 Auger-like datasets

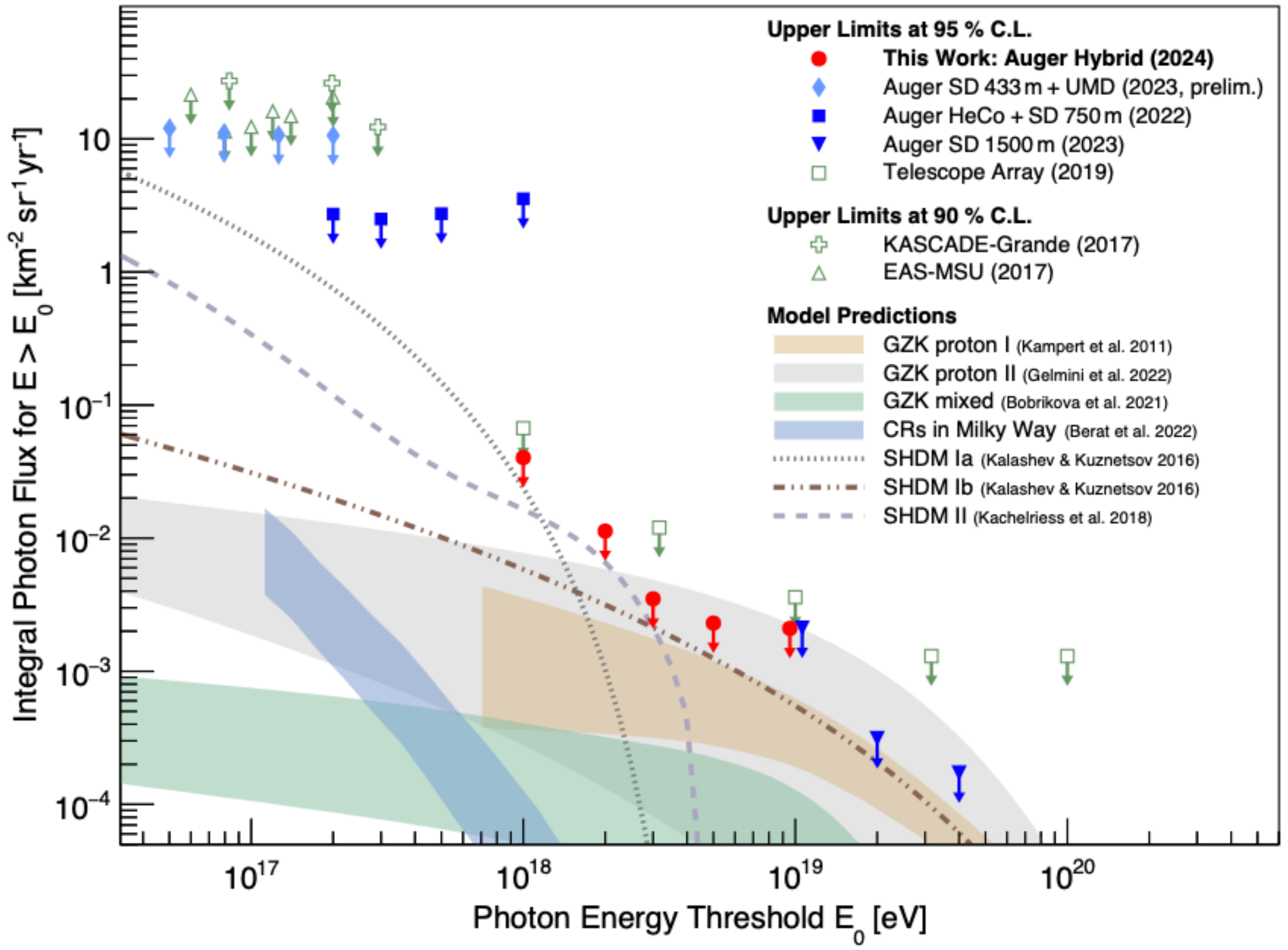
Neutral particles

Nicolas, in preparation



- 433 WCDs + UMD measurements

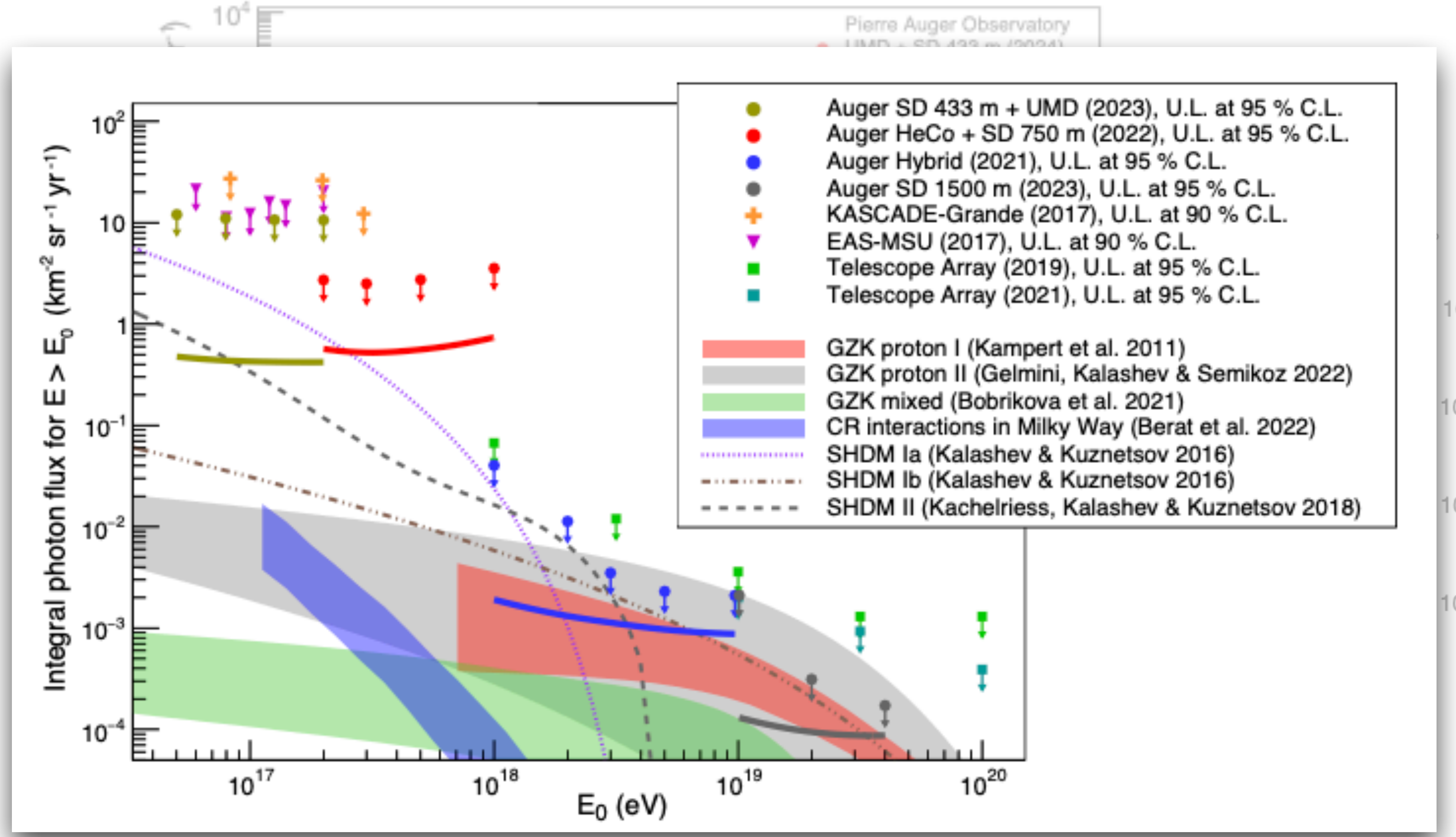
Pierpaolo, published

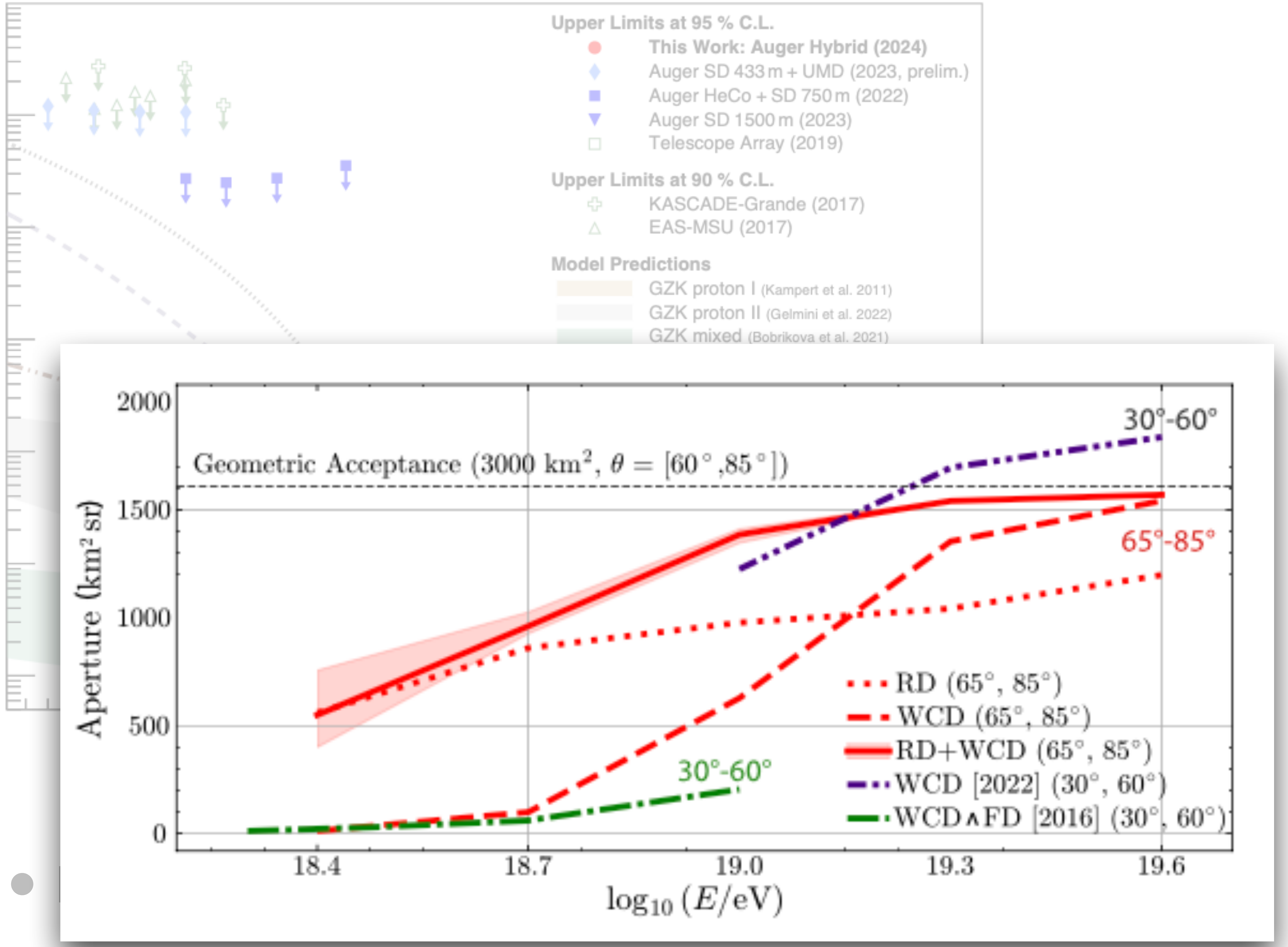


- Hybrid (with universality)

Neutral particles

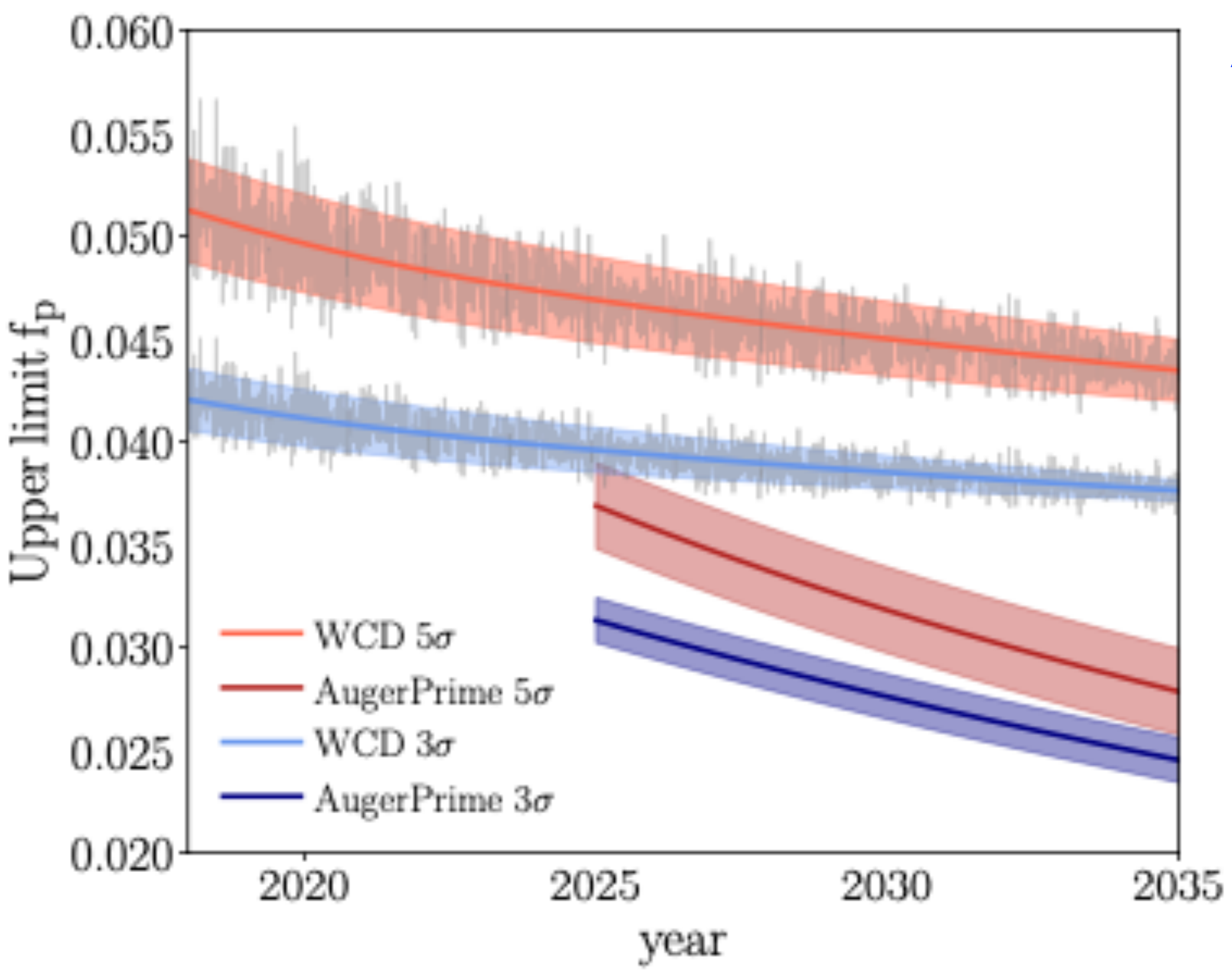
AugerPrime report, 2023





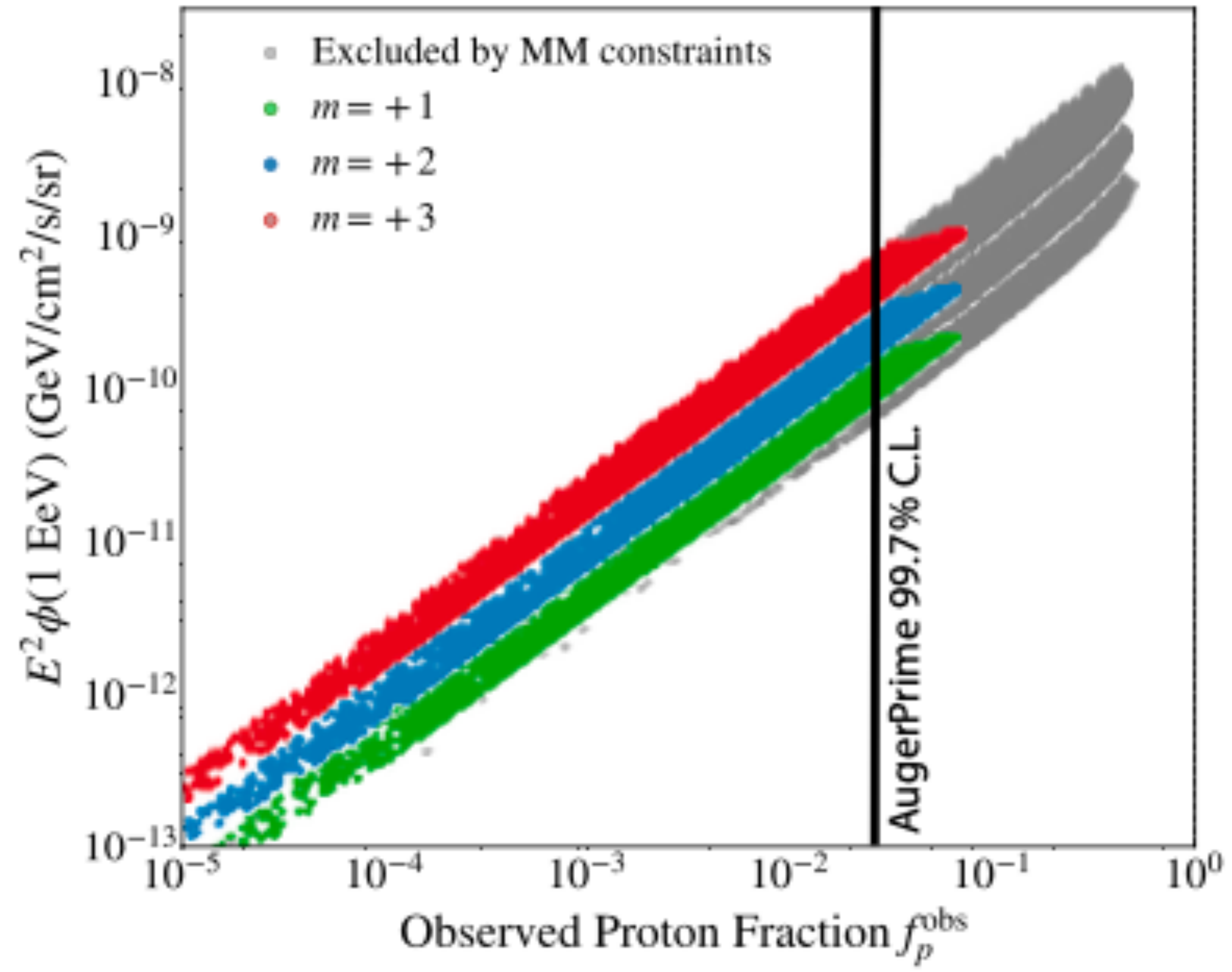
- Extrapolations to the end of 2035 of the current upper limits (points) for the respective analysis in the legend, under the assumption that with AugerPrime the hadronic background can be fully suppressed
- Improvements expected from RD self-trigger
- New proposal for photon identification: photons as an excess over the background, see Pierpaolo's proposal in Malargue, Nov 2024

Neutral particles



AugerPrime report, 2023

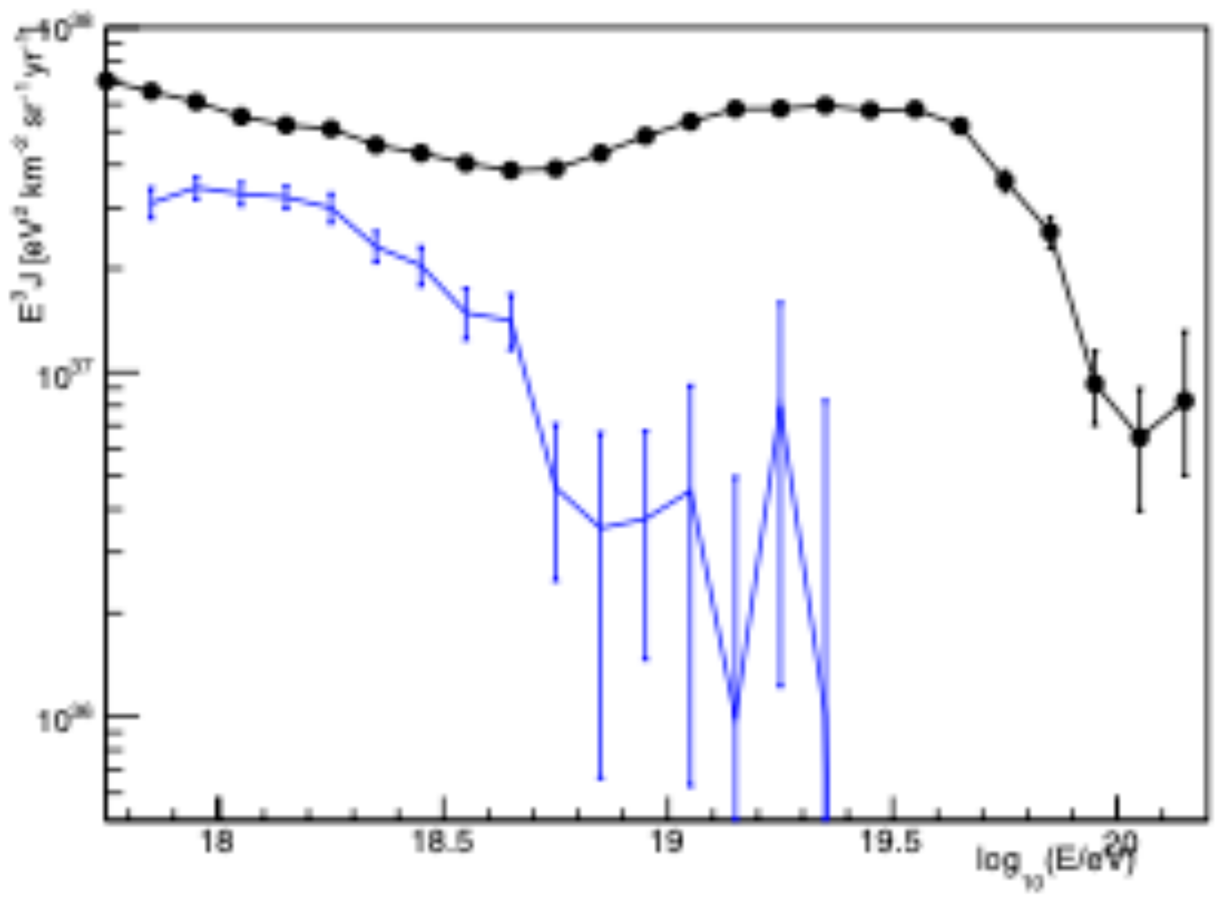
Expected upper limits of the proton fraction above 30 EeV obtained using the measurement of sigma(Xmax) using the WCD only compared to the expected limits achieved using the increased sensitivity of AugerPrime.

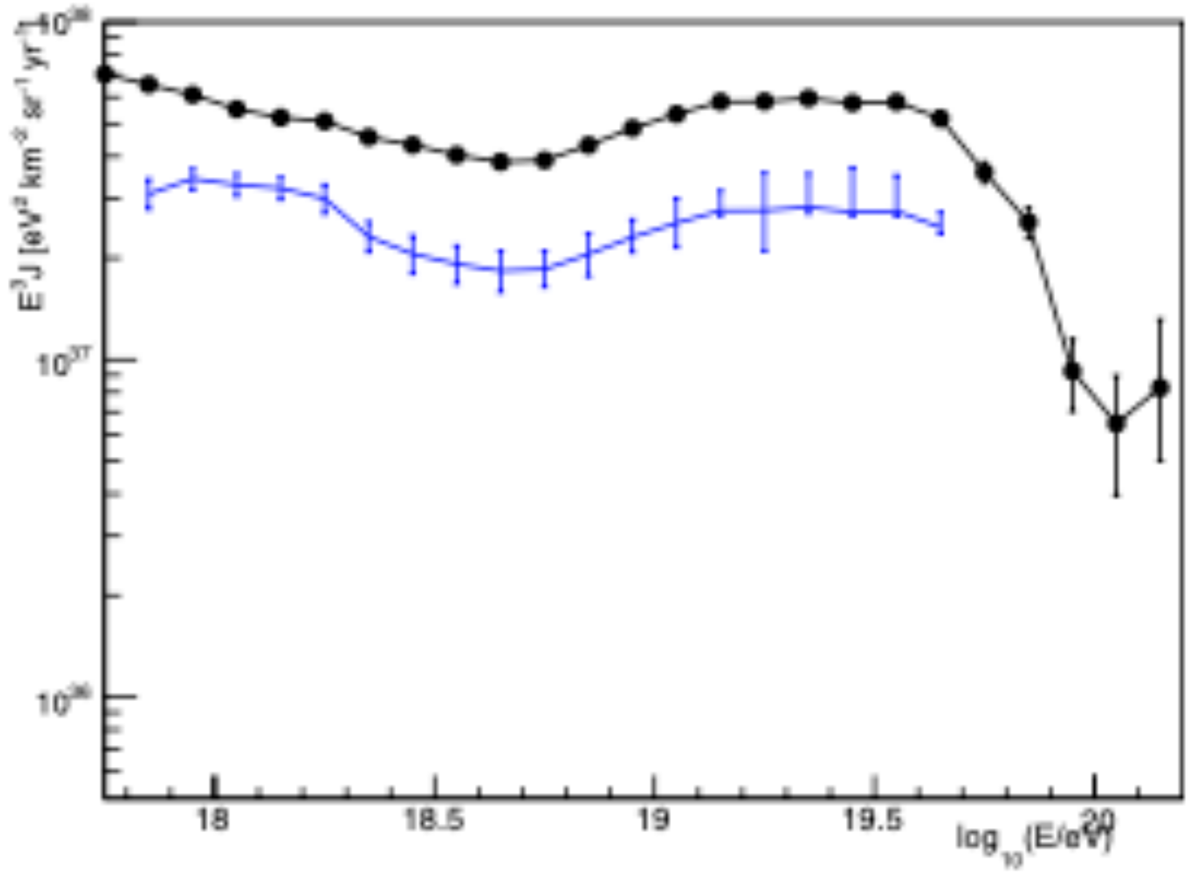


Muzio et al. PRD 107 (2023)

Neutrino flux at 1 EeV as a function of the proton fraction above 30 EeV. The proton-fraction sensitivity of AugerPrime from the left panel is indicated with a vertical line at the 3 σ level

Camilla, PhD Thesis, 2025





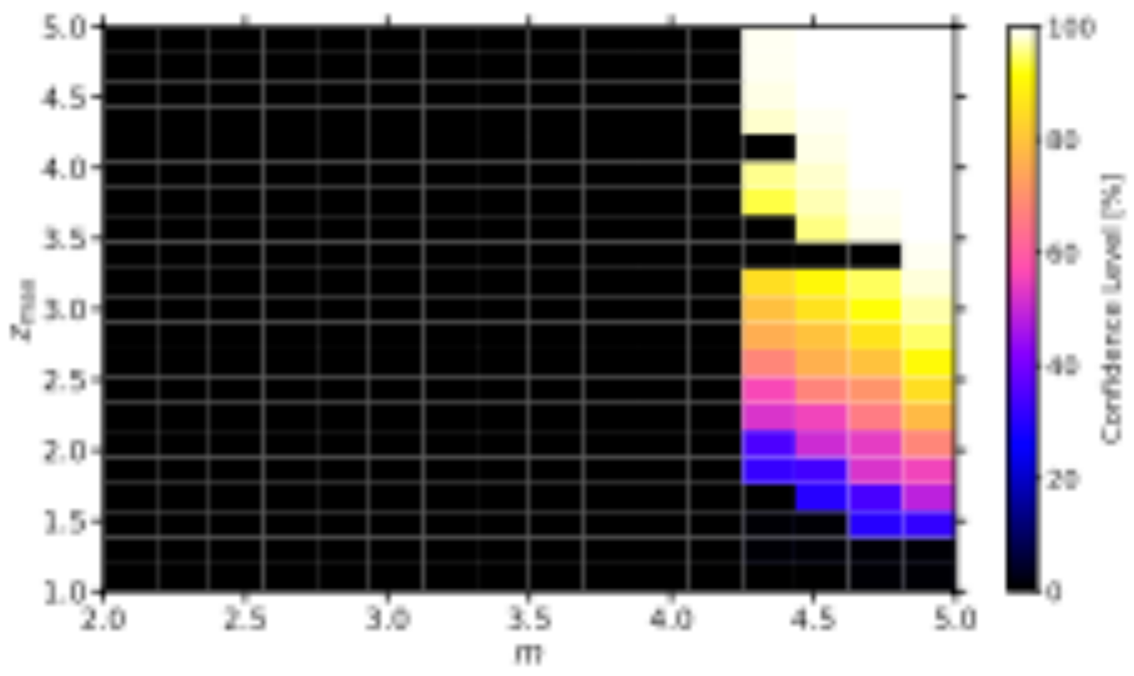
Blue,

- Upper plot: proton spectrum (EPOS-LHC)
- Lower plot: proton spectrum (EPOS-LHC + 0.475 for energies greater than 2.5 × 10^{18} eV

Bottom-right plot: exclusion power in the zmax-m parameter space for the increased proton-fraction

To complete the picture: cosmogenic photons are missing

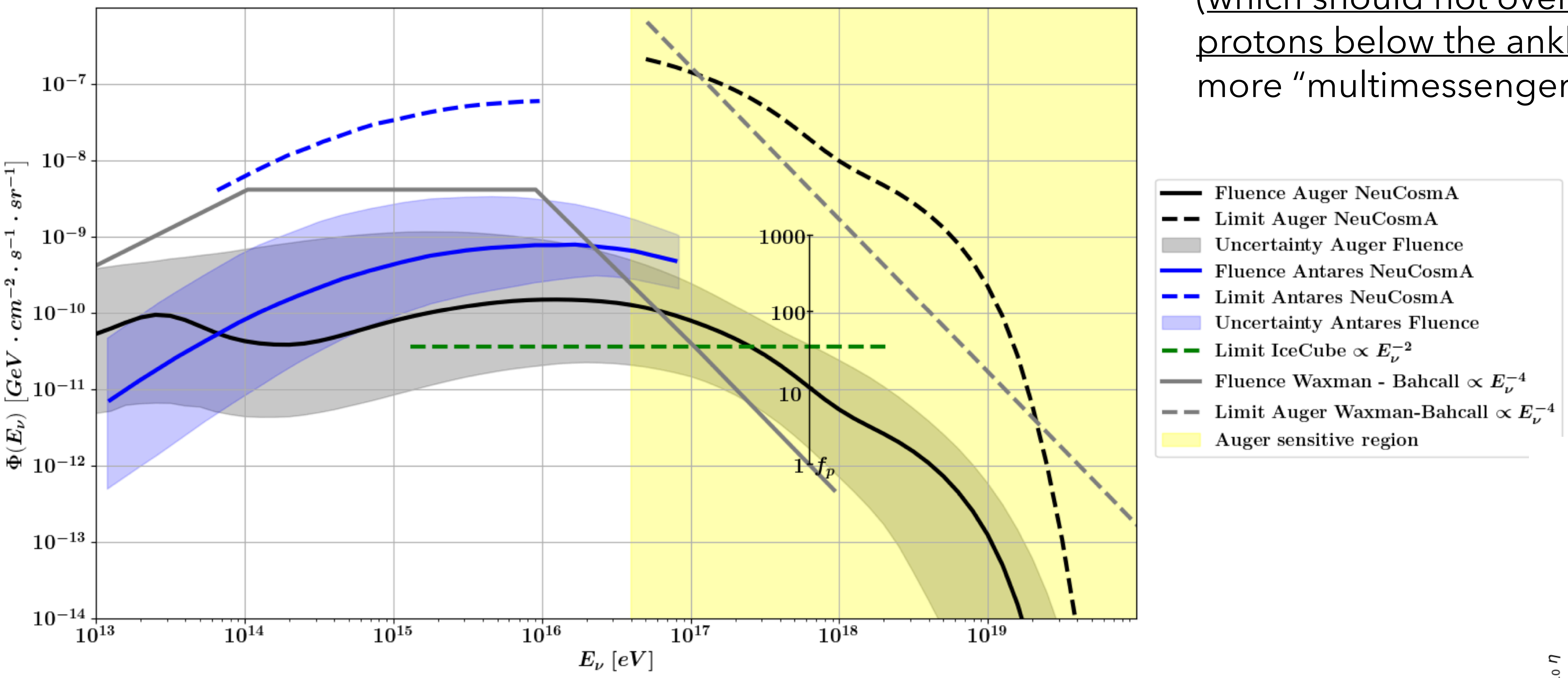
Ongoing work by Alessandro, Antonio, Carmelo, DB



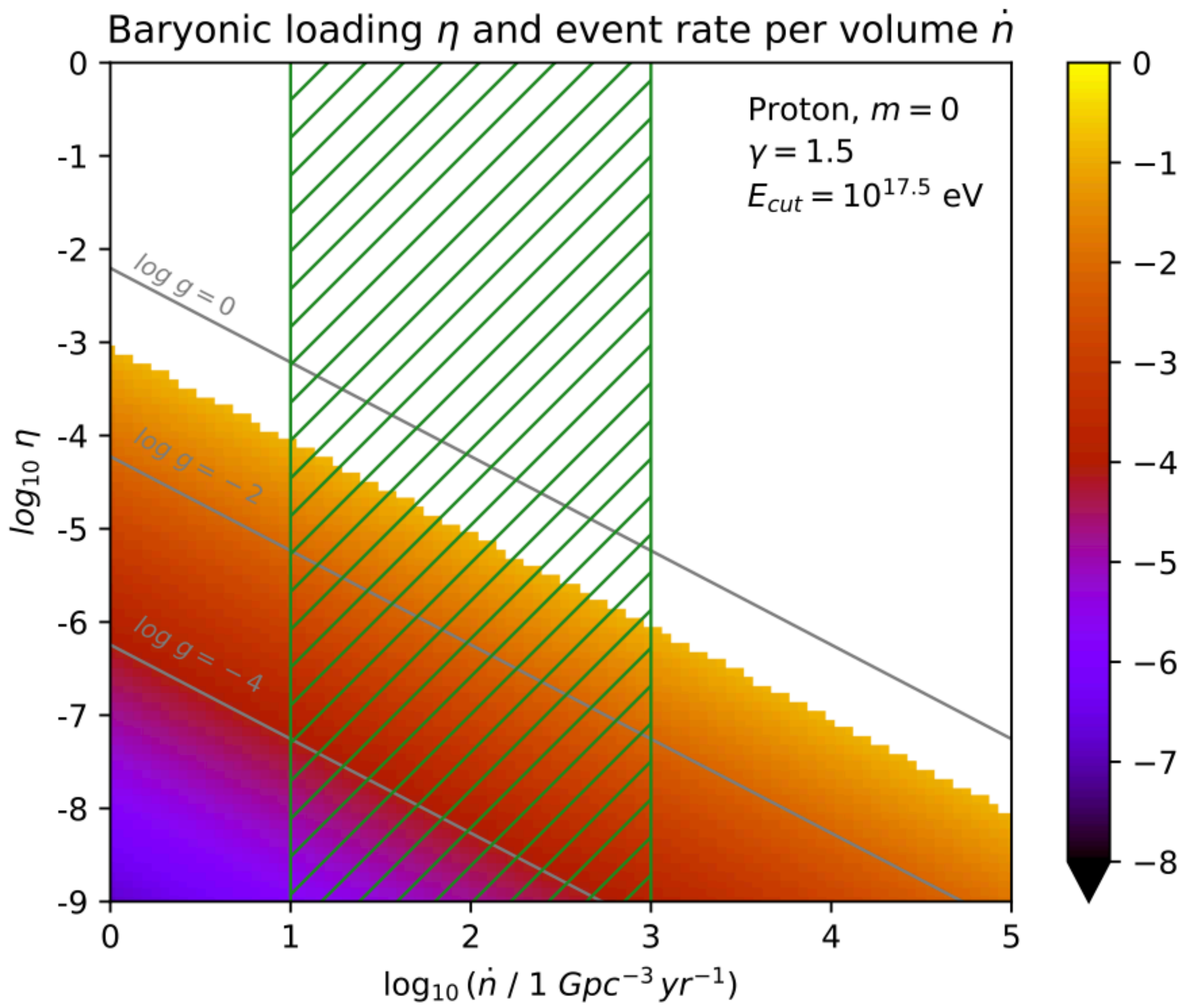
Multimessenger

Yago @ Malargue, Nov 2024

- Computation of neutrino flux (from protons only) from prompt phase of a sample of GRBs in our field of view -> model dependent analysis
- A check in luminosity of the parent protons to be done (<u>which should not overshoot the power to produce the protons below the ankle!</u>), in order to make the analysis more "multimessenger"



- Example of a parametric and complete study in binary neutron star mergers, Rossoni, DB & Sigl JCAP 2025



- Can we estimate upper limits in luminosity for arbitrary neutrino emissions, taking into account the constraints from protons below the ankle), avoiding as much as possible the dependence from models?

Some attempts towards a summary

Energy, arrival directions and mass composition

Arrival directions and mass composition measurements and analyses benefit from each other in making progress to understand where UHECRs come from

- Energy spectrum -> basic astrophysical scenarios to be constrained with Phase I data, and ability of constraining more refined scenarios to be better explored (including mass composition and arrival directions)
- **Mass composition is the key to making progress**
  - per se
    - what are the nuclear species in the measured flux of UHECRs?
      - What is the heaviest mass composition at the highest energies -> information on the astrophysical accelerator
      - What is the mass composition at the lowest accessible energies? Can we contribute to understanding the transition to Galactic CRs?
  - when arrival directions are also included in the analyses
    - exploring the interesting regions (Centaurus A) -> work by Lorenzo A., and existing correlations (SBGs)
    - exploiting the mass information in the dipole amplitude with mass estimators from universality -> work by Emily and Teresa, and in the direction -> work by Teresa
    - looking at the highest energy events -> work by Marta and Luciana

Neutrinos, photons, astrophysics

Cosmogenic particles can reveal the cosmological distribution of UHECRs

- Search for neutrinos and photons ongoing and foreseen with the upgrade -> Nicolas, Pierpaolo, Lecce group…
  - Limits on cosmogenic particles can constrain UHECR source characteristics; strong connection to **proton fraction** -> work by Camilla, Alessandro, Antonio
  - Can source neutrinos and photons be constrained? Multimessenger GRB studies ongoing -> Yago, Therese…

A UHECR data-driven approach could improve the understanding of magnetic fields

- Galactic magnetic fields induce changes in the arrival directions of cosmic rays
  - Effects in dipole amplitude, direction, correlation with source catalogs -> works by Teresa, Emily, Rosina, Luca, Marta…
  - is it possible to build **UHECR-informed model of GMF**?
- Effects of extragalactic magnetic fields

Fundamental physics

Increasing the sensitivity to photon and neutrino searches is the main way to unveiling new physics

- **What more could be explored**
  - from upward going showers? Up to now: variable cross section of BSM particles -> efforts from the Lecce group in the ANITA test and exposure
  - from LIV tests in the development of showers? The most sensitive test is the **fluctuation in the number of muons**, but… **what about photons**?
    - Photons in extragalactic space: the pair production is inhibited, so less photons are absorbed
    - Photons in the atmosphere: the pair production is inhibited as well, so less photons are absorbed -> the shower does not have enough space to start!
      - the development of the shower is shifted next to the Earth crust… what if the shower starts in the Earth? **Can a photon be tested as a neutrino-like event?** Francesco & DB brainstorming
  - from cosmogenic neutrino limits -> superluminal neutrinos can decay through the emission of an electron-positron pair or a neutrino-antineutrino pair, see Reyes, DB, Carmona & Cortes ICRC23
  - from **searches for correlations** (see TA presentation at UHECR24) -> horizon to be included in the studies
    - space-time correlation to be considered for LIV searches
  - dark matter studies -> see presentation by Roberto A. and work by Antonio presented in Malargue

Methods - neural networks

Xmax reconstruction using deep learning

This page is dedicated to the Xmax reconstruction using Deep Learning and offers reconstructions of simulations. Besides, you can find information on systematic uncertainties of the method and a brief discussion of the performance.

The production of the reconstruction of SD-1500 (ICRC2019) is already finished. The way the reconstructed Xmax values for the complete SD-1500 data is distributed in the collaboration is currently discussed.

More information can be found at the Xmax_DNN page

The latest version of AixNet provides a reconstruction of Xmax for:

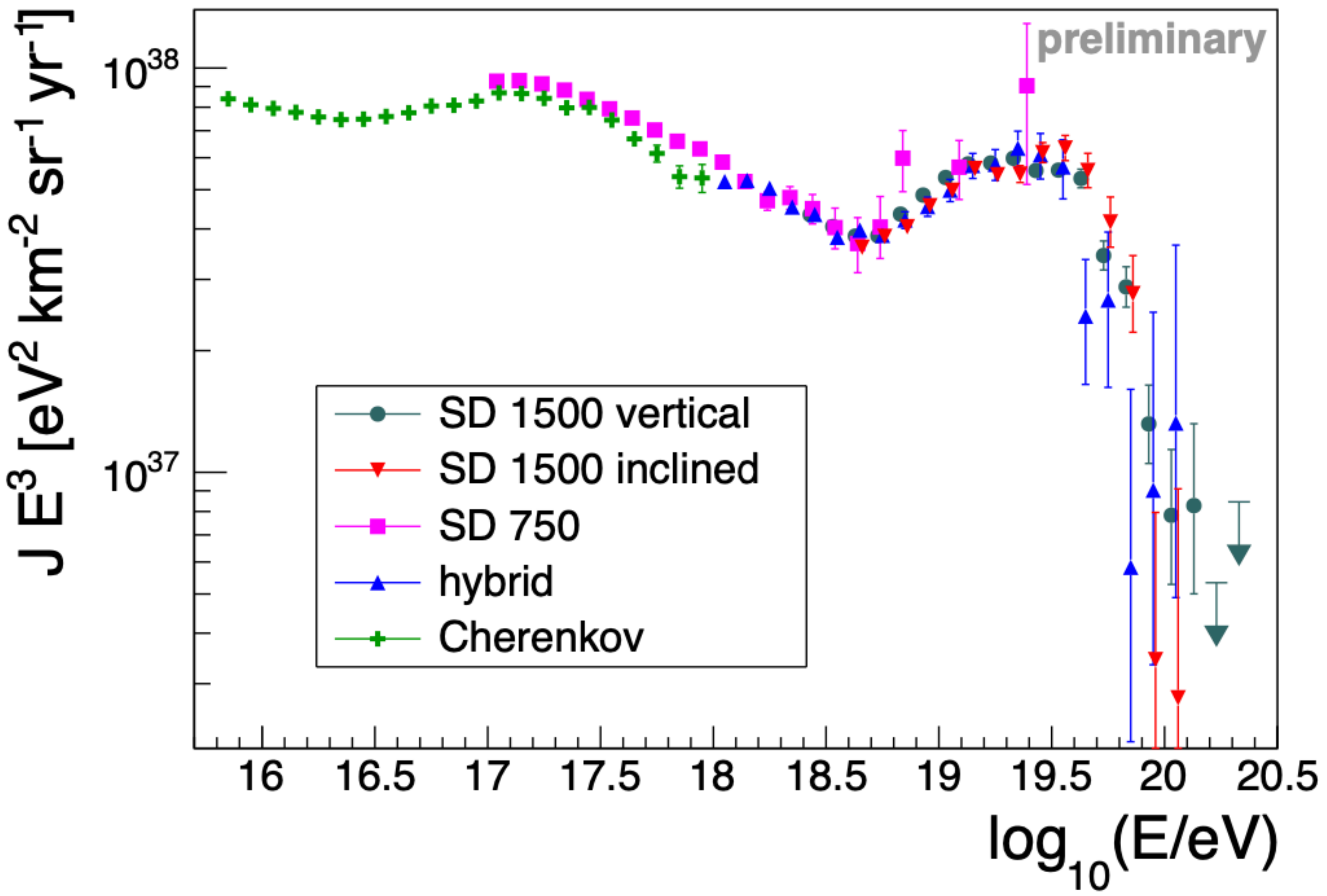
- events until 60 deg zenith of the SD-1500 array
- old electronics (WCD with 25ns time steps)
- saturated and unsaturated events
- events with a 6T5 trigger (in principle 4T5 and 5T5 should work as well. However, no such studies were performed yet.)

- Summary of existing analyses exploiting neural networks:
  - SD Xmax (training with three SD traces and arrival time of the shower) -> Jonas
  - UMD muon reconstruction (training with UMD binary traces) -> Ezequiel
  - Proton-photon separation -> Fiona
  - Reconstruction of magnetic field coherent deflection in AD data -> Josina
- **Do we have any existing expertise to join these efforts?**

BACKUP slides

The energy spectra

Auger Collab. ICRC21



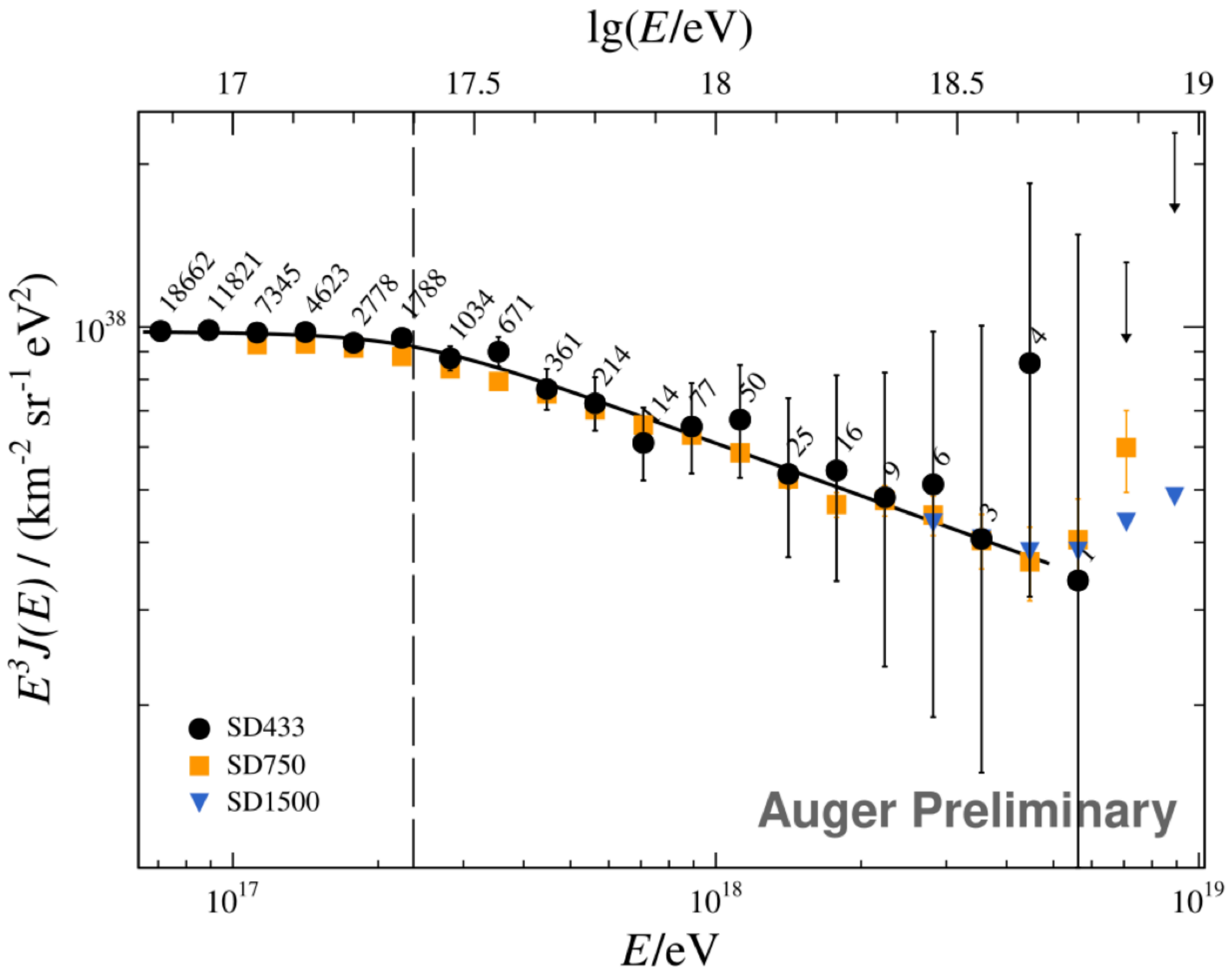
- SD-1500
  - 01/2004 - 08/2018
  - ~215 000 events
  - Energy threshold: $10^{18.4}$ eV

- SD-1500 inclined
  - 01/2004 - 08/2018
  - ~24 000 events
  - Energy threshold: $10^{18.6}$ eV

- SD-750
  - 01/2014 - 08/2018
  - ~545 000 events
  - Energy threshold: 10^{17} eV

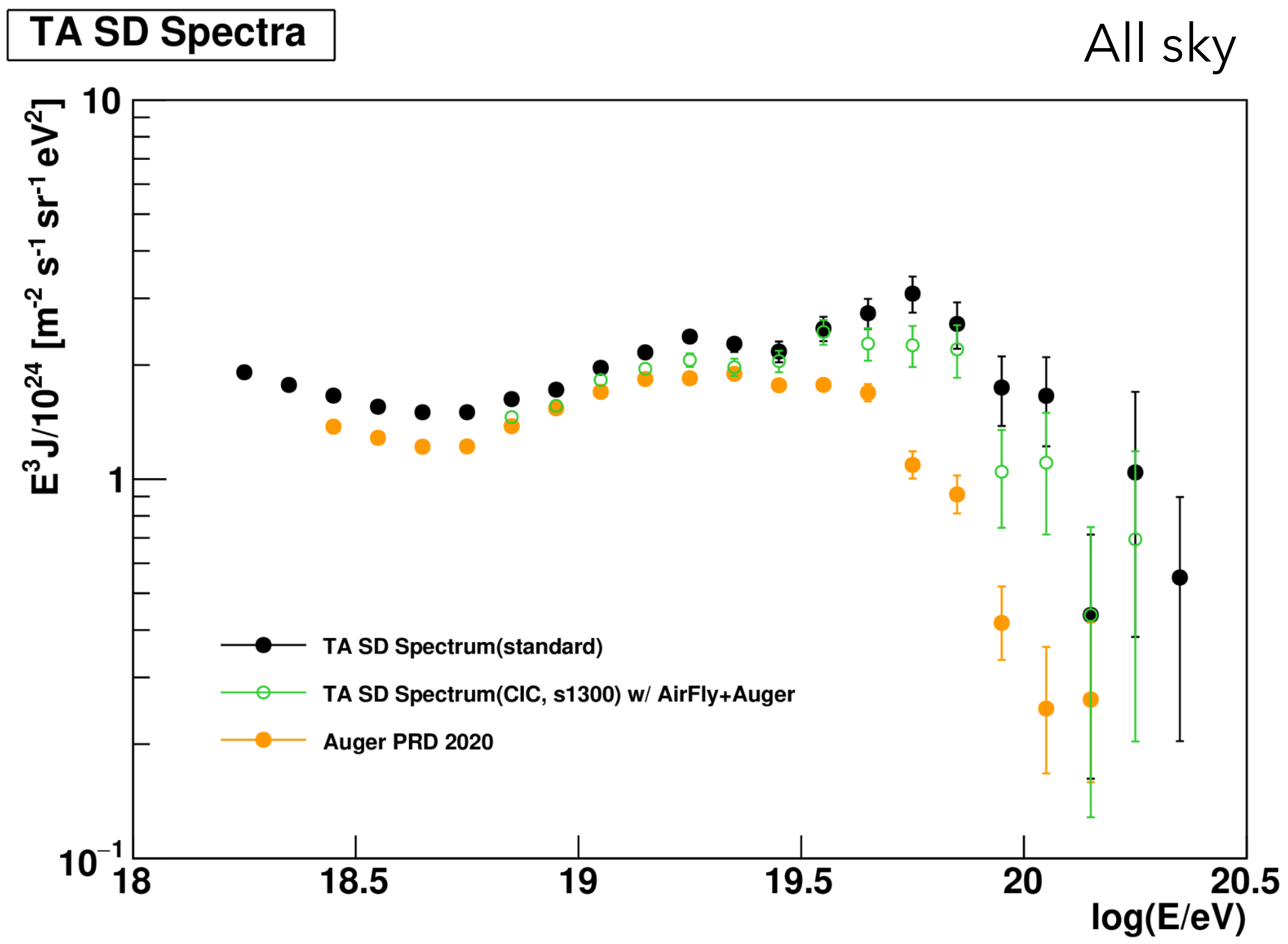
- SD-433
  - 01/2018 - 12/2021
  - ~50 000 events
  - Energy threshold: $10^{16.8}$ eV

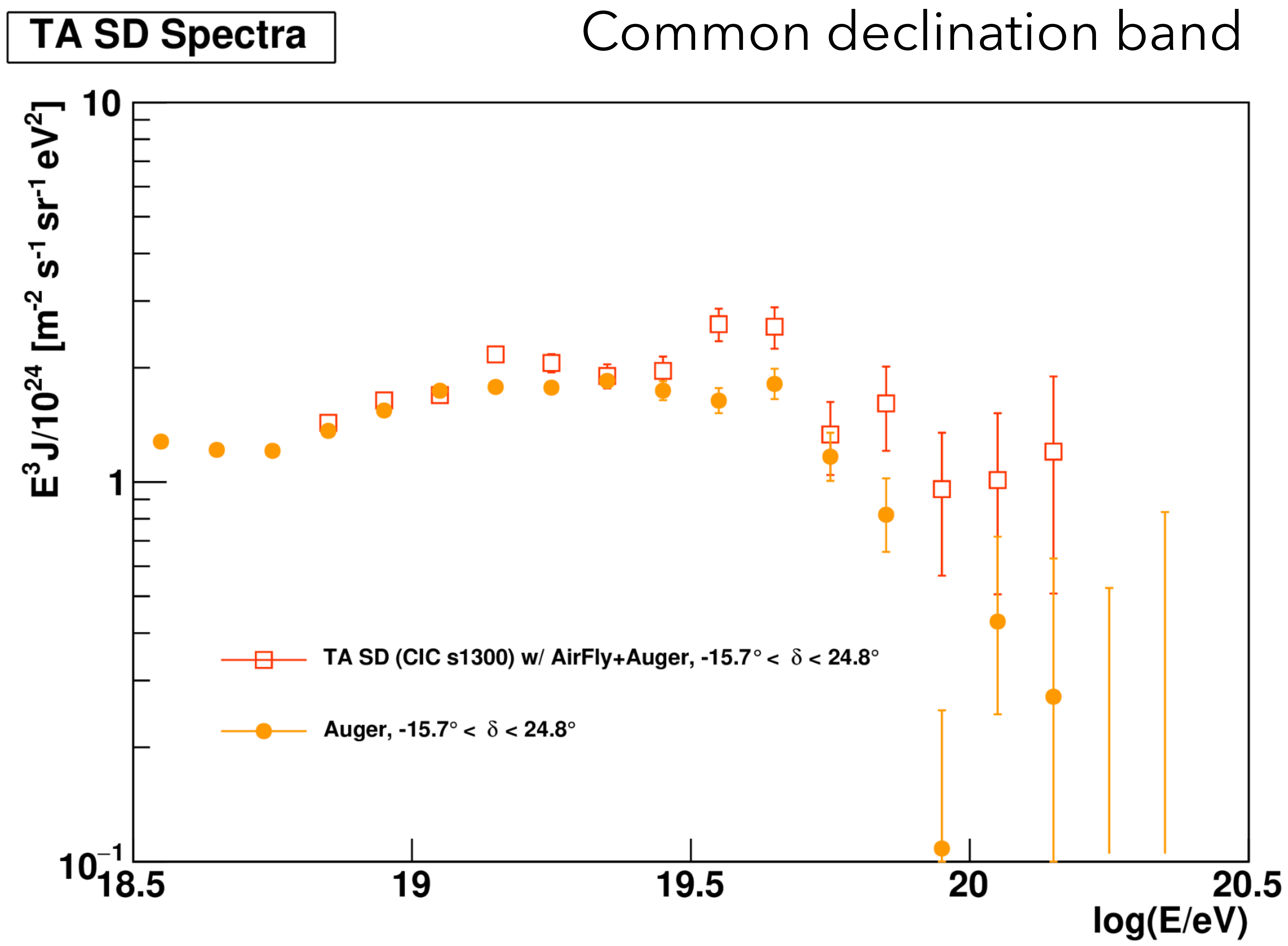
Auger Collab. ICRC23



Auger vs TA energy spectrum

ICRC23

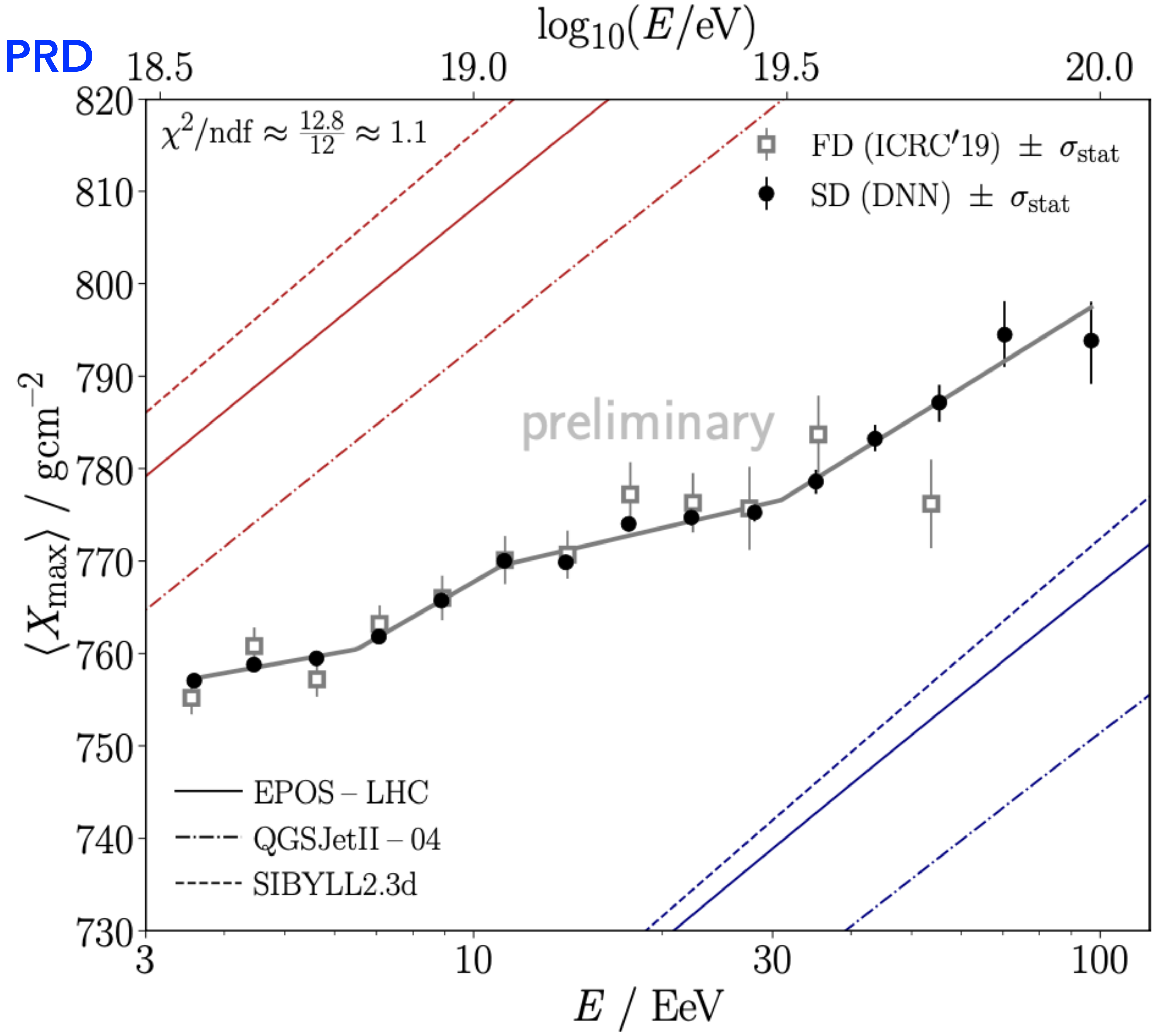


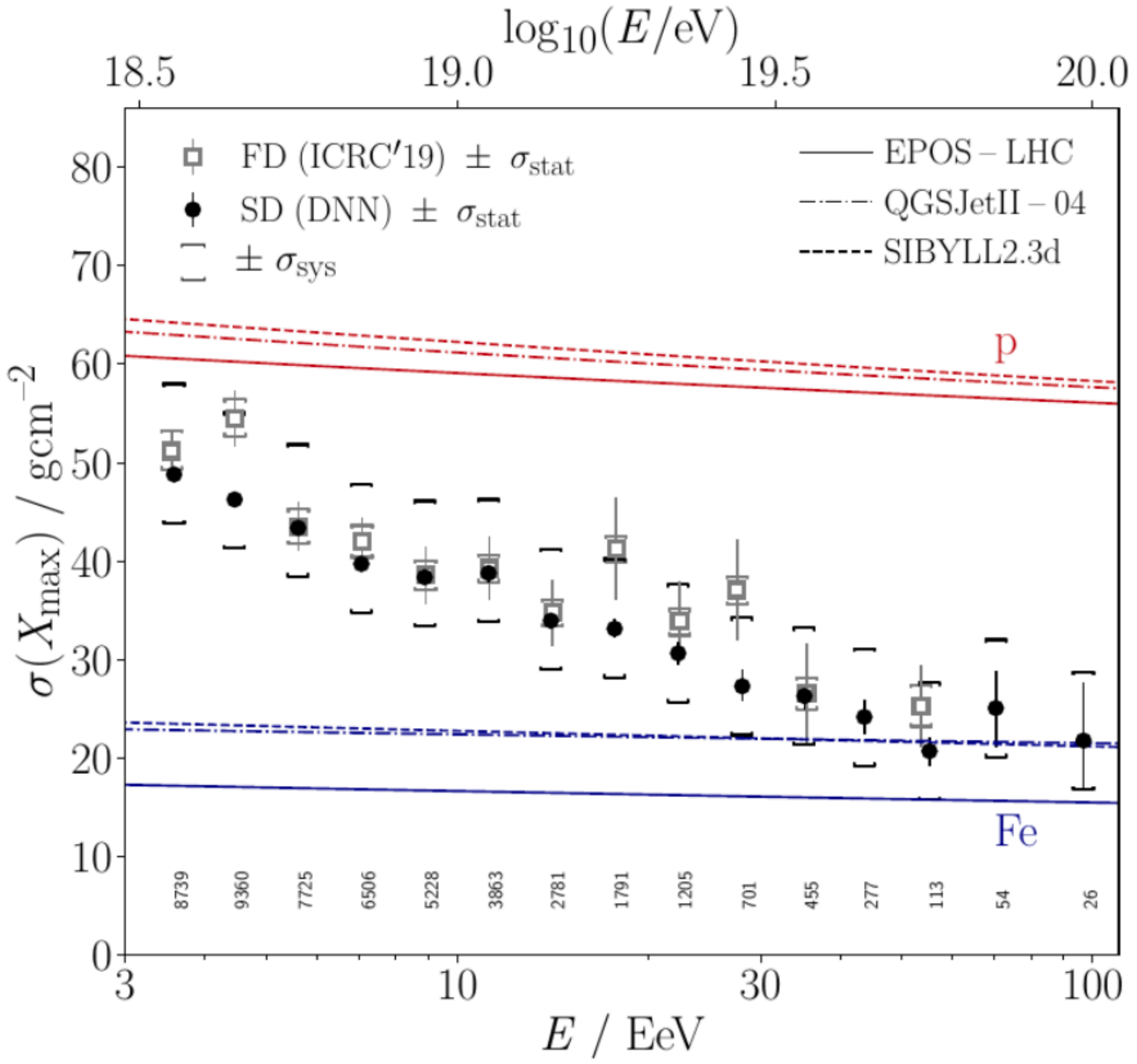


- Auger analysis + Fluorescence Yield reconcile low energies (~1% difference)
- Remaining difference at the highest energies, also in the common sky region, but compatibility under study

Mass composition with neural networks

Accepted in PRL & PRD



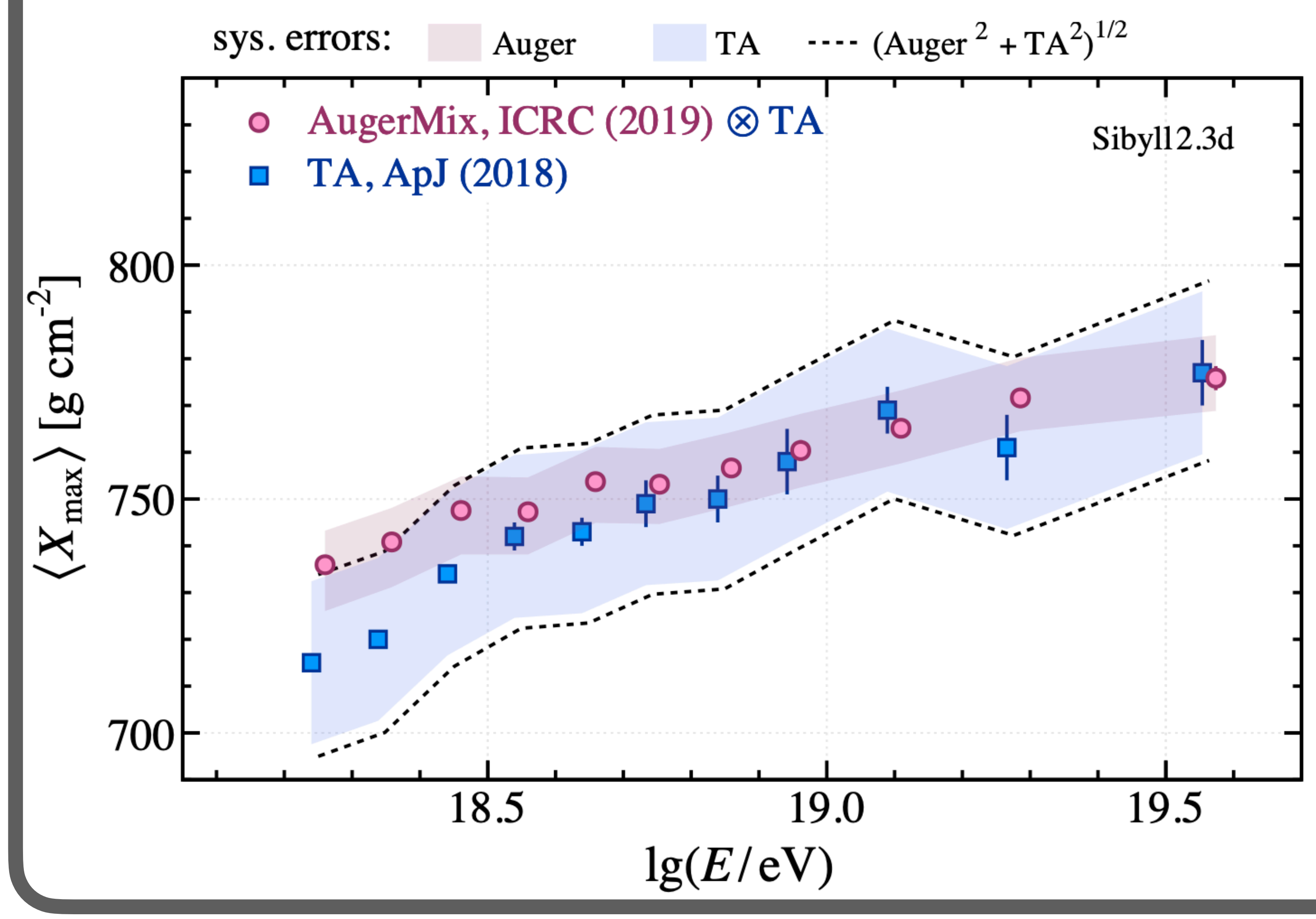


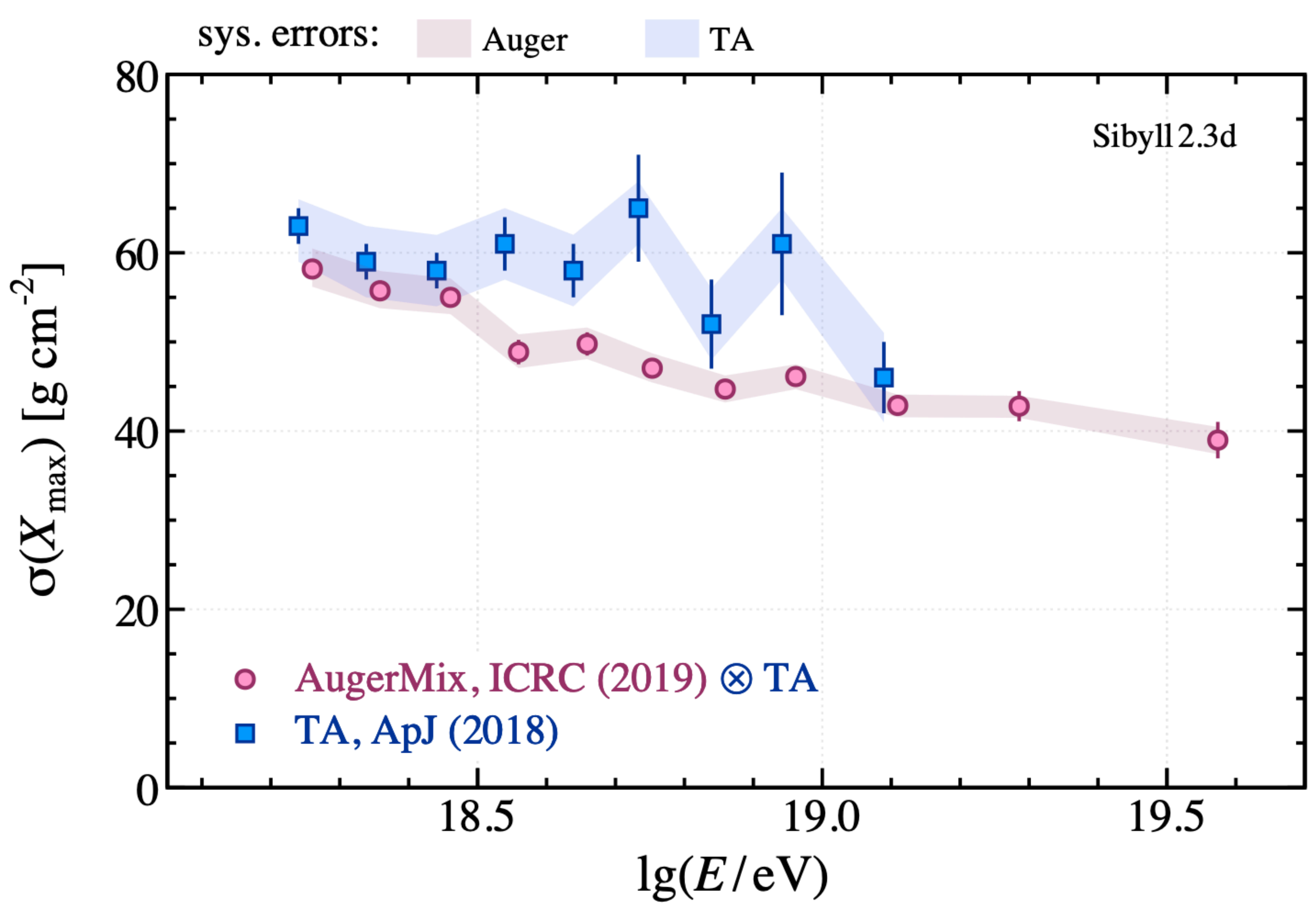
- SD(DNN) data: 10 times larger statistics than FD in the same energy range (50000 events)
- Xmax reconstruction and training of the network:
  - Signal traces analysed on station-by-station level
  - Exploring of the spatial distribution of the signal footprint induced on the SD grid by combining the outputs of the first part
- measured hybrid data are used to crosscheck and cross-calibrate the algorithm
- Excellent agreement with FD

Auger and TA mass composition

- To compare the data, we need to take into account that:
  - Auger: Xmax and sigma(Xmax) are unbiased, directly comparable to predictions of air-shower simulation codes
  - TA: Xmax and sigma(Xmax) are not corrected for experimental biases and are not directly comparable to predictions of air-shower simulation codes
- How to compare the data: simulate Xmax mixes (AugerMixes) and process them with the TA machinery
  - AugerMixes ⊗ TA – representation of Auger Xmax distributions folded with the TA detector and analysis effects

- Xmax: agreement within statistical and systematic uncertainties, in particular for lg(E/eV) > 18.5
- Sigma: larger values in TA for lg(E/eV) = 18.5 – 19.0; possible reasons:
  - constant aerosol profiles used in TA increase sigma
  - a few deep events in data can increase sigma



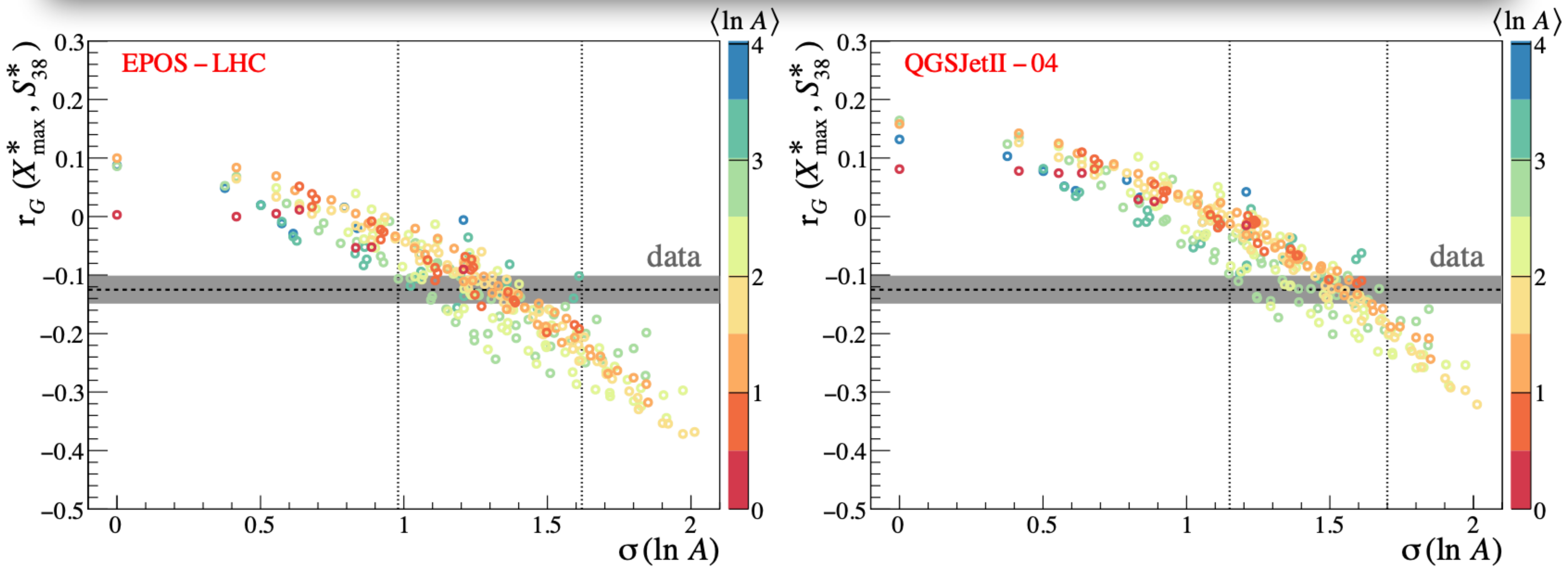


- Agreement within statistical and systematic uncertainties
- Origin of the energy trend in Xmax is not clear
- sigma (TA) > sigma(Auger) can be partly attributed to the use of a static atmosphere model at TA

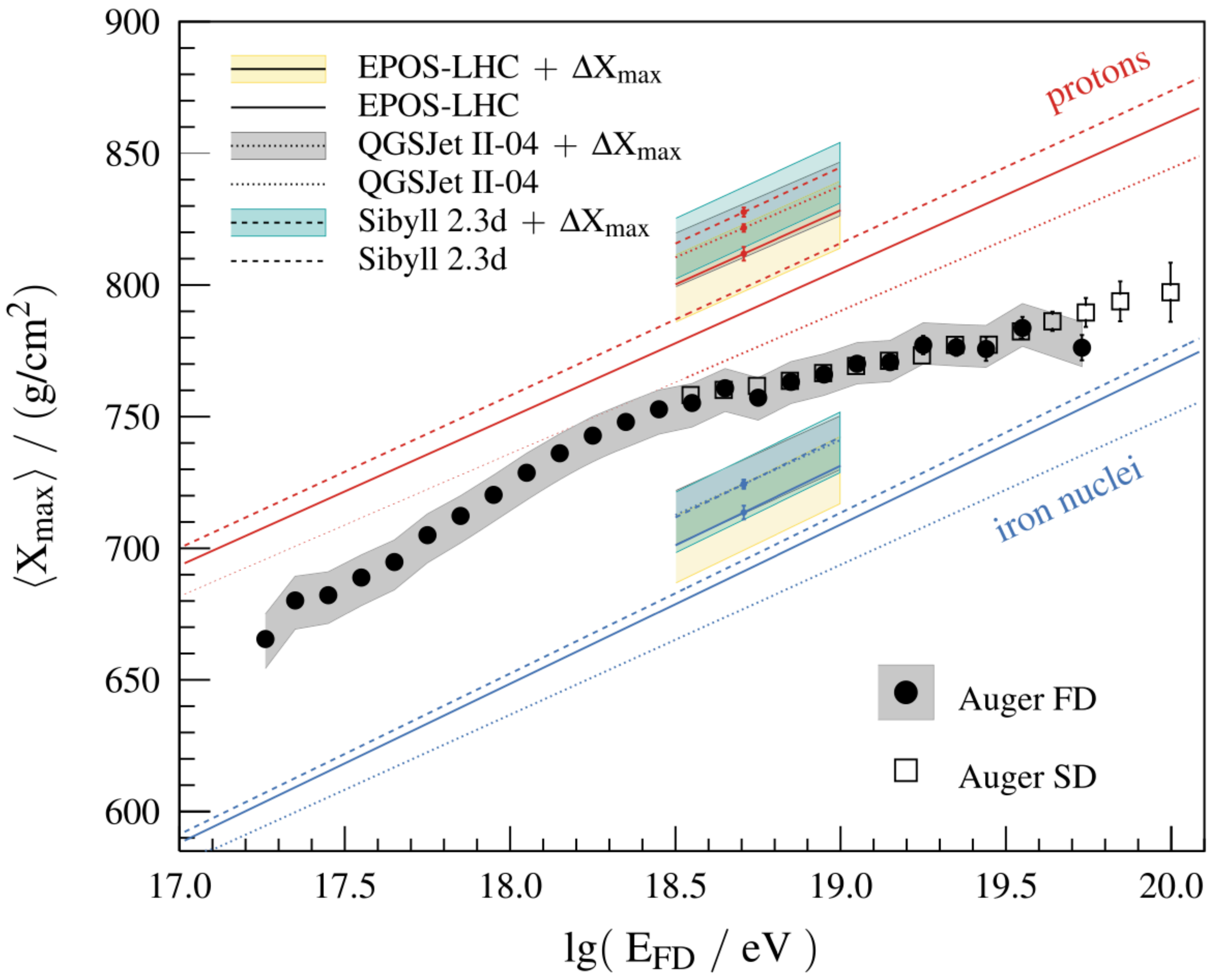
Signal at ground and longitudinal profile of the shower

Table 1: Observed $r_G(X^*_{max}, S^*_{38})$ with statistical uncertainty, and simulated $r_G(X^*_{max}, S^*_{38})$ for various compositions using different interaction models (statistical uncertainties are ≈0.01).

data	-0.125 ± 0.024 (stat)		
	EPOS-LHC	QGSJetII-04	Sibyll 2.1
p	0.00	0.08	0.06
He	0.10	0.16	0.14
O	0.09	0.16	0.17
Fe	0.09	0.13	0.12
$0.5\,p - 0.5\,\mathrm{Fe}$	-0.37	-0.32	-0.31
$0.8\,p - 0.2\,\mathrm{He}$	0.00	0.07	0.05



- Dependence of the correlation coefficient on hadronic models; each simulated point corresponds to a mixture of different mass fractions



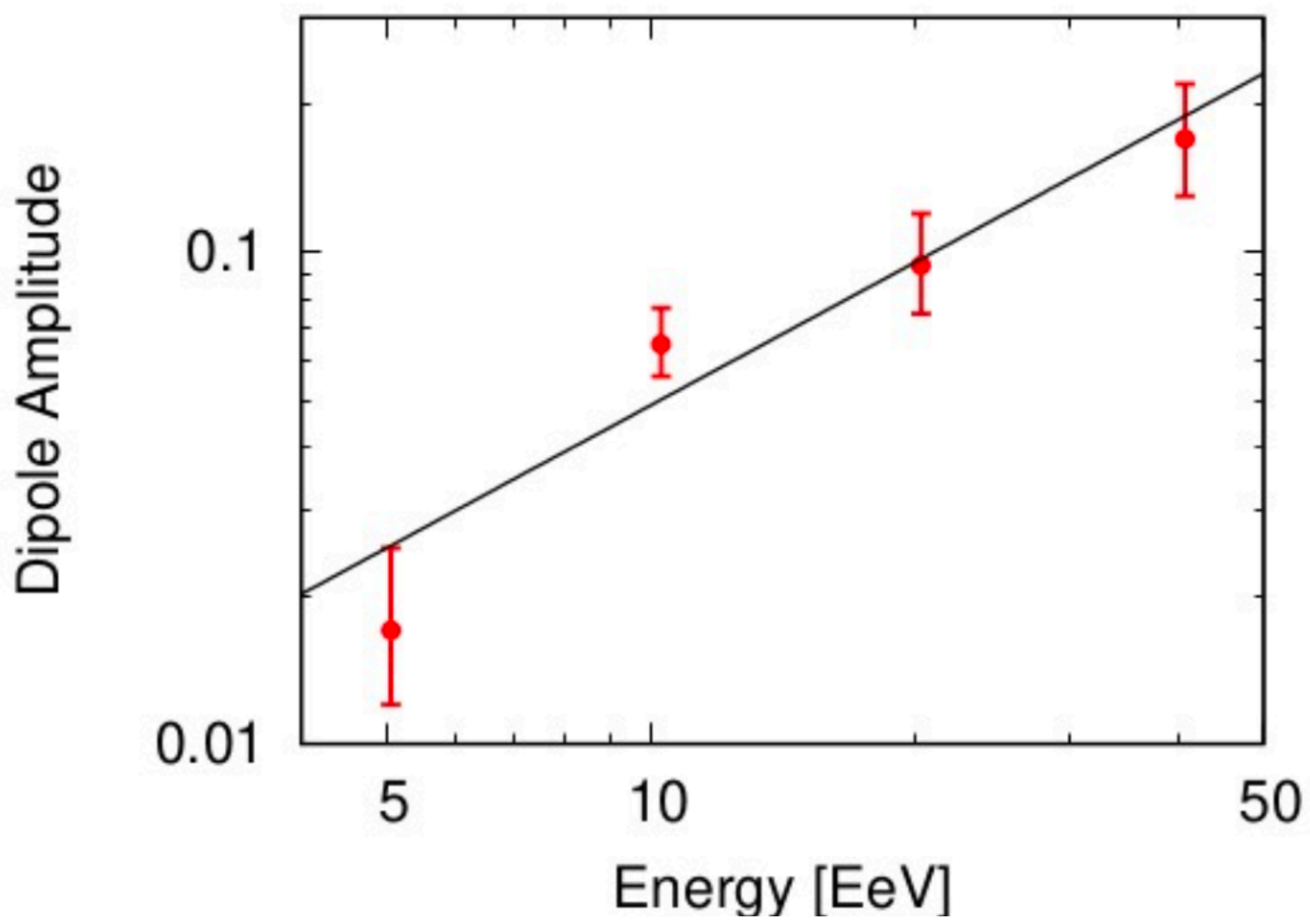
- All hadronic models fit data best with X_{max} scales shifted 20 g cm^{-2} to 50 g cm^{-2} deeper
- Consequence: heavier (iron?) composition beyond 50 EeV

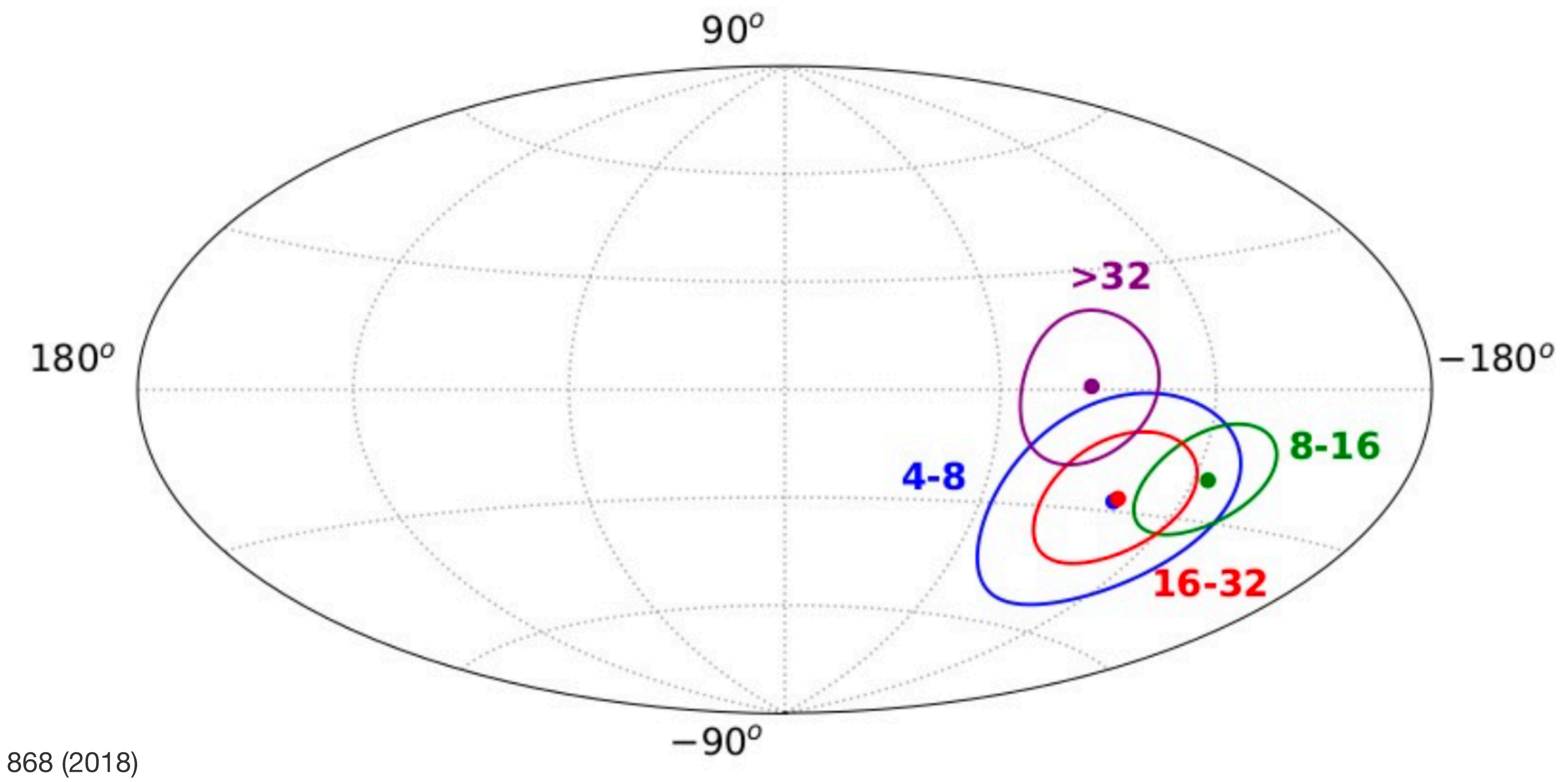
PLB 762 (2016)

PRD 109 (2024)

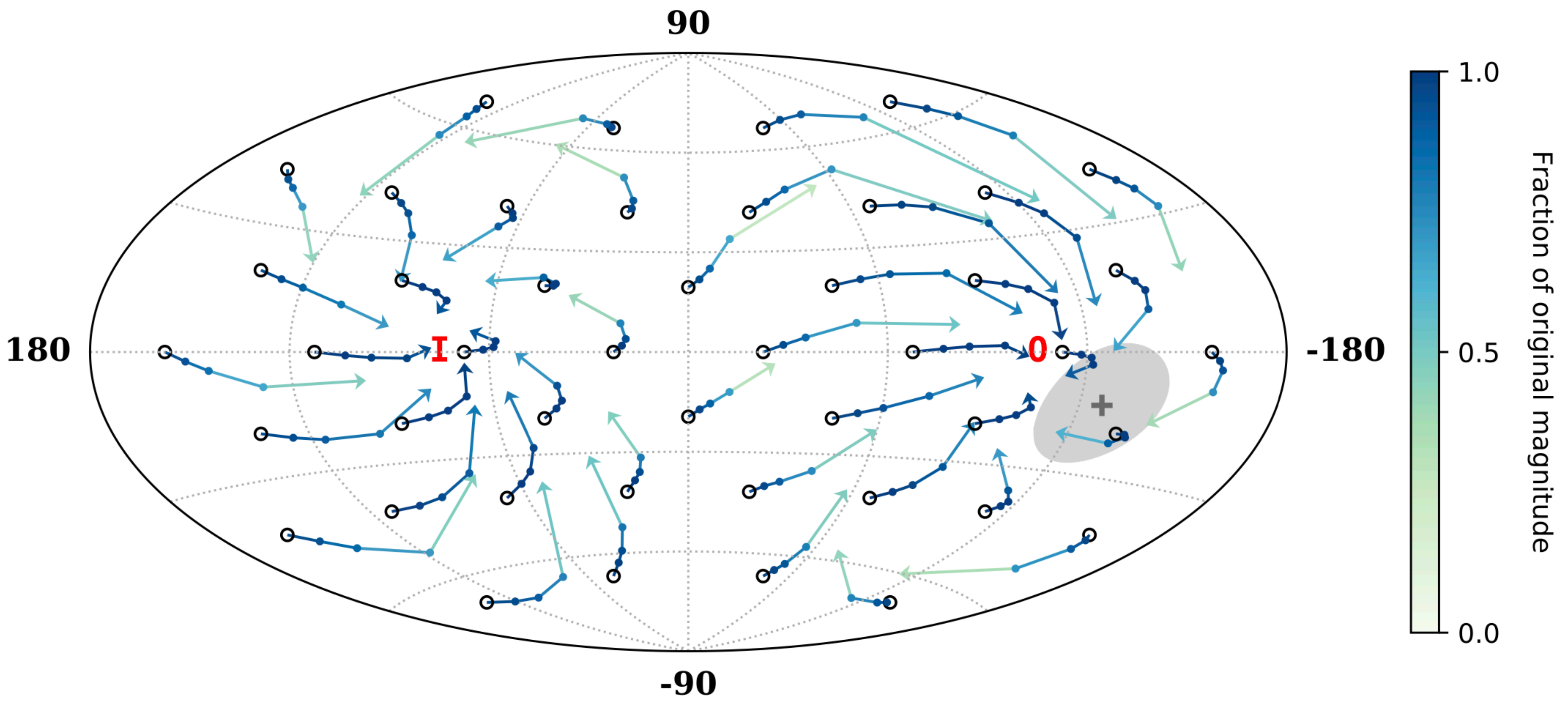
The dipole

arxiv:2408.05292, submitted to ApJ





Astrophys.J. 868 (2018)

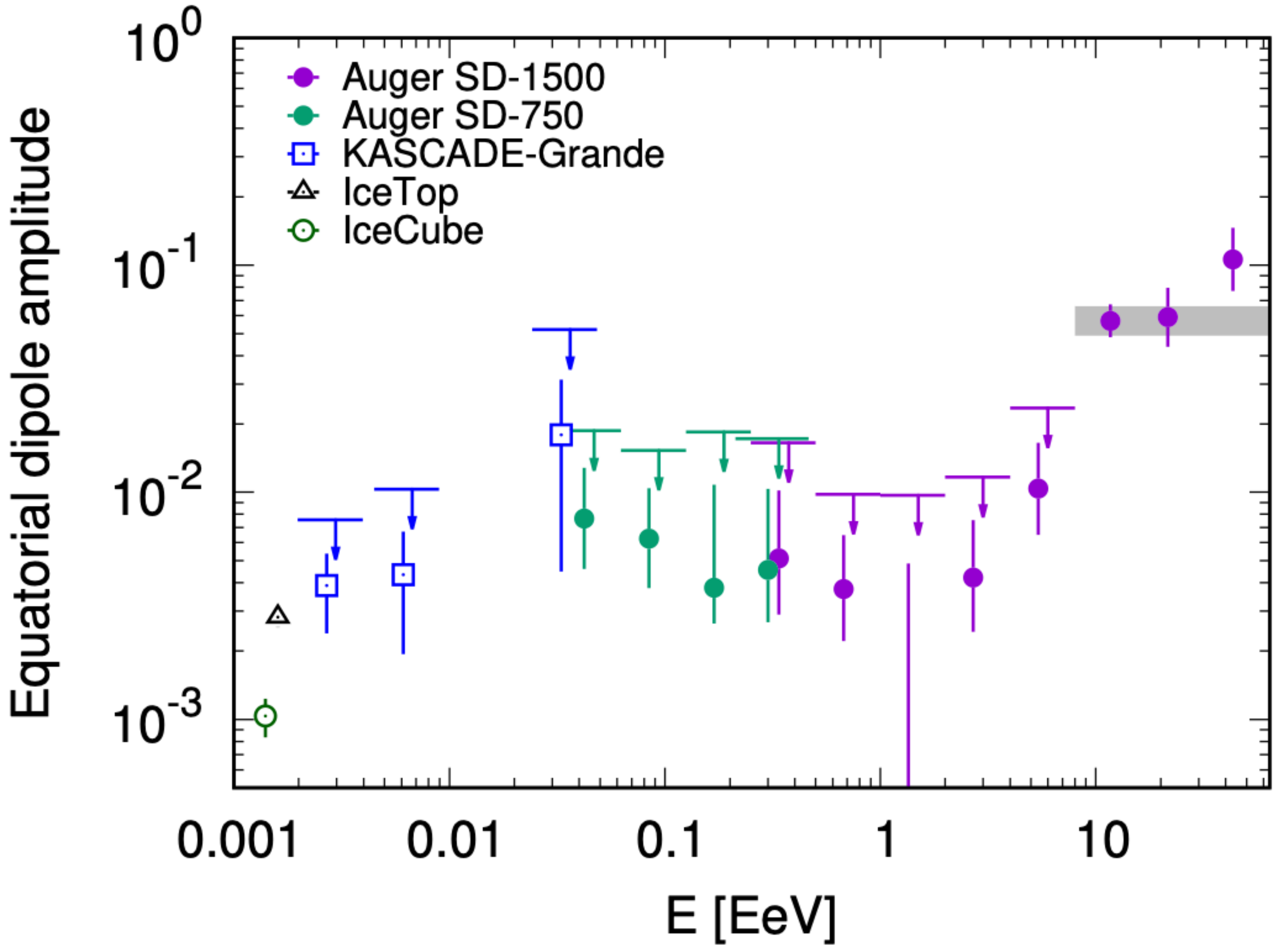


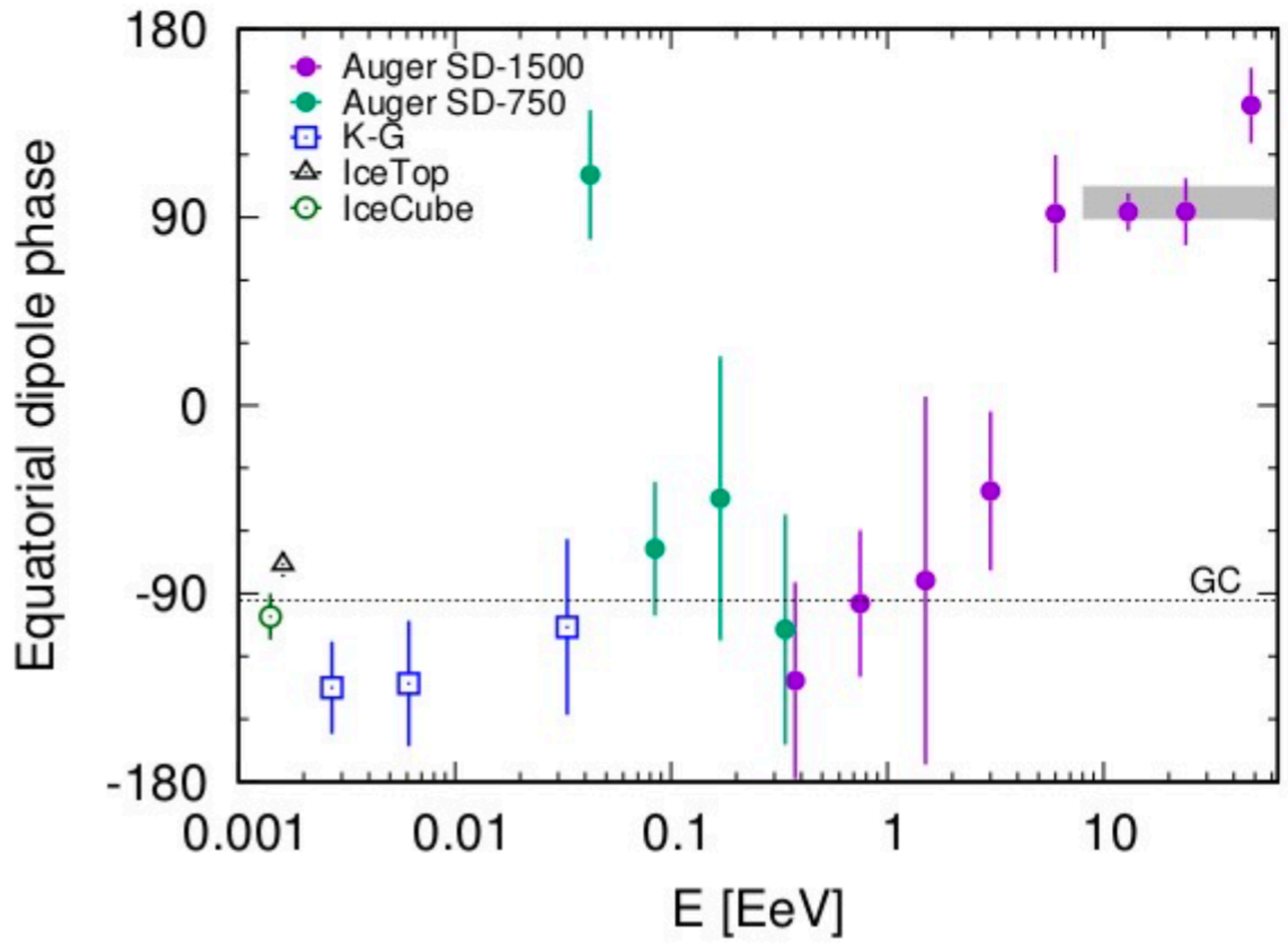
-> the change in the direction of an originally dipolar distribution after traversing a particular Galactic magnetic field. The arrows start in a grid of initial directions for the dipole outside the Galaxy and indicate the dipole directions that would be reconstructed at the Earth for different CR rigidities.

The dipole amplitudes for E ≥ 8 EeV turn out to be of the order of the one observed for a range of magnetic-field parameters and their model is consistent with an increase of the dipole amplitude with energy

Astrophys.J. 868 (2018)

The dipole at lower energies



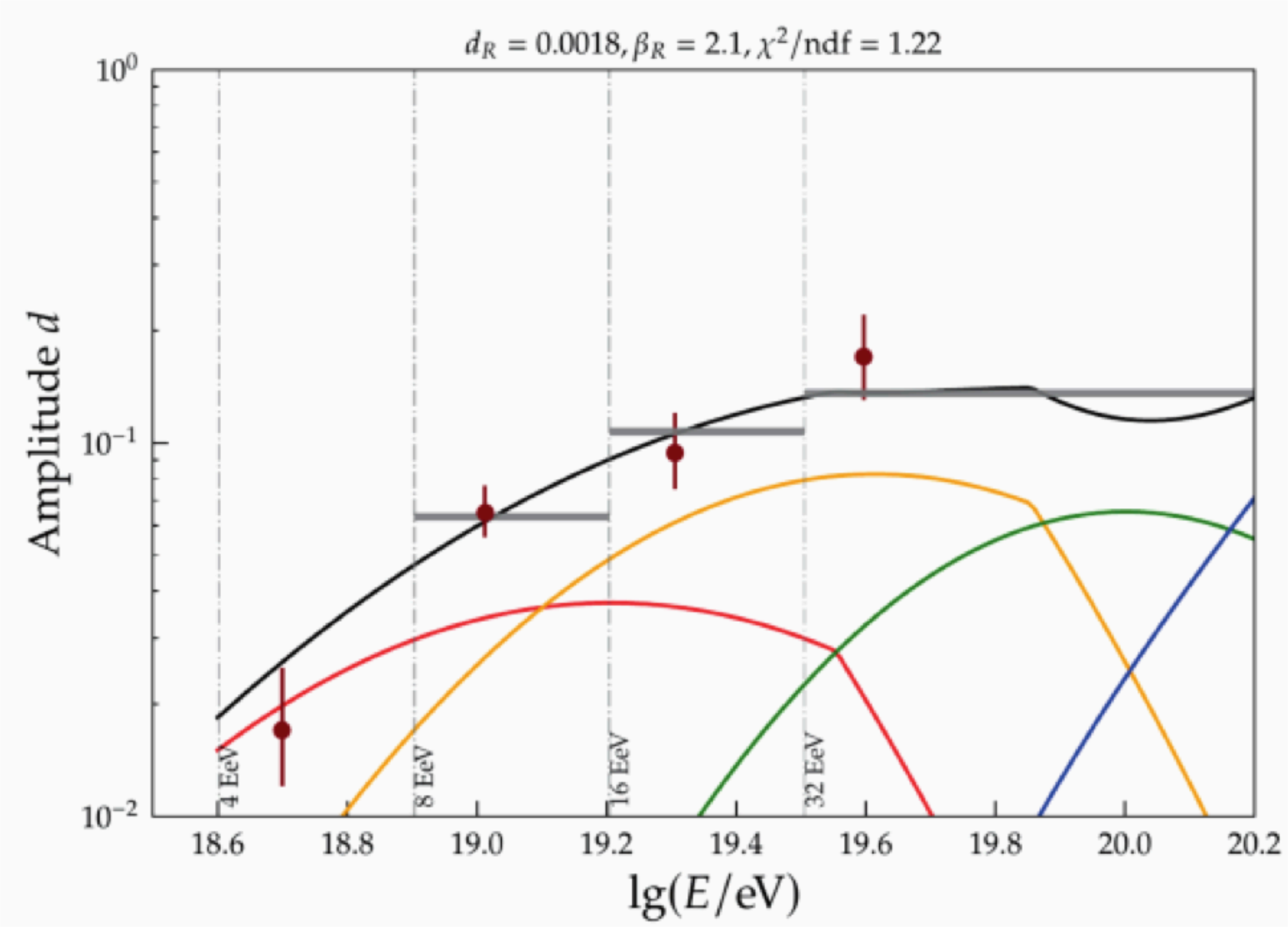


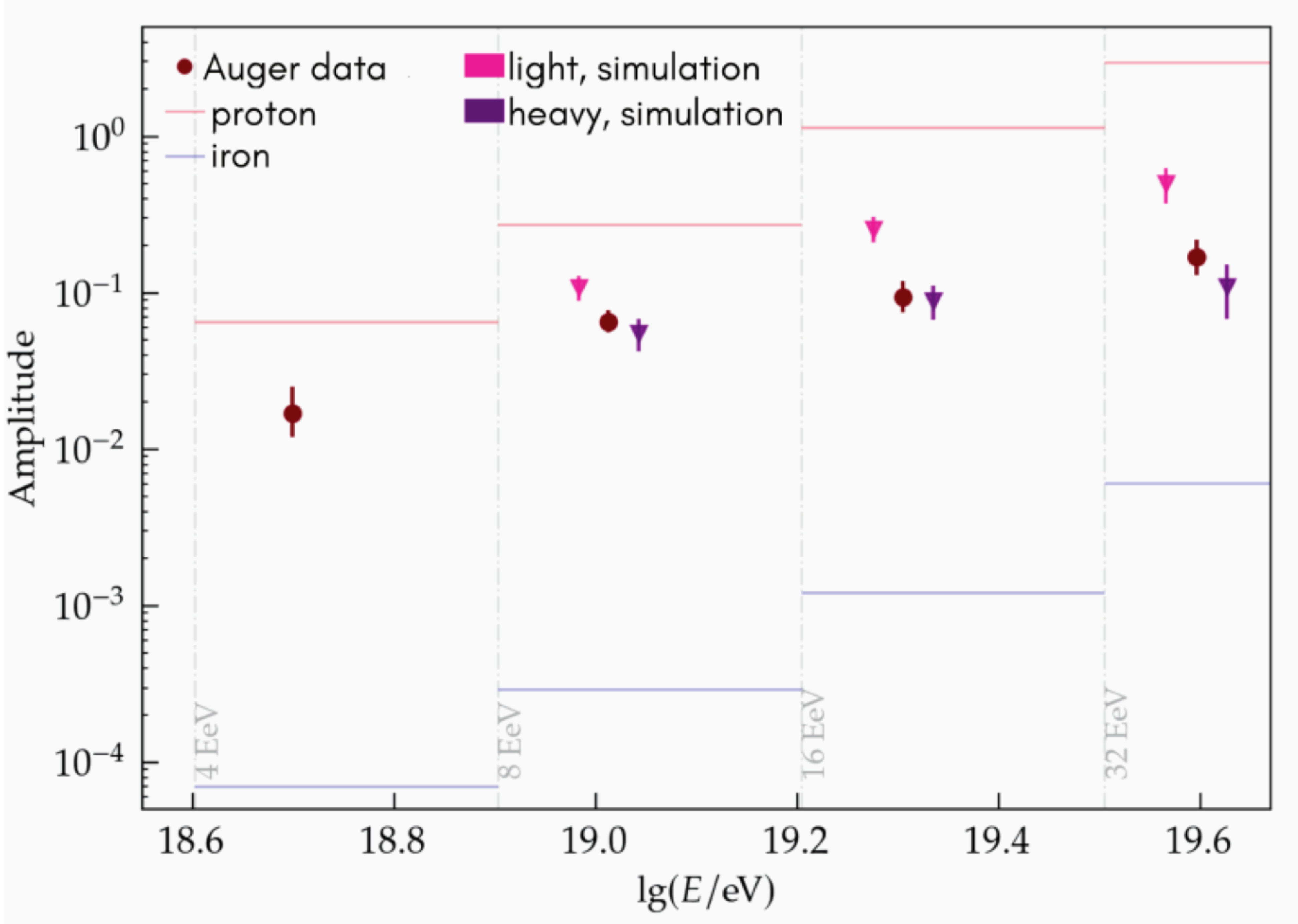
Anisotropy dominated by Galactic contribution below a few EeV?

arxiv:2408.05292, submitted to ApJ

The composition-informed dipole

- Mass estimator with universality, using Xmax and relative-to-proton-shower muon number





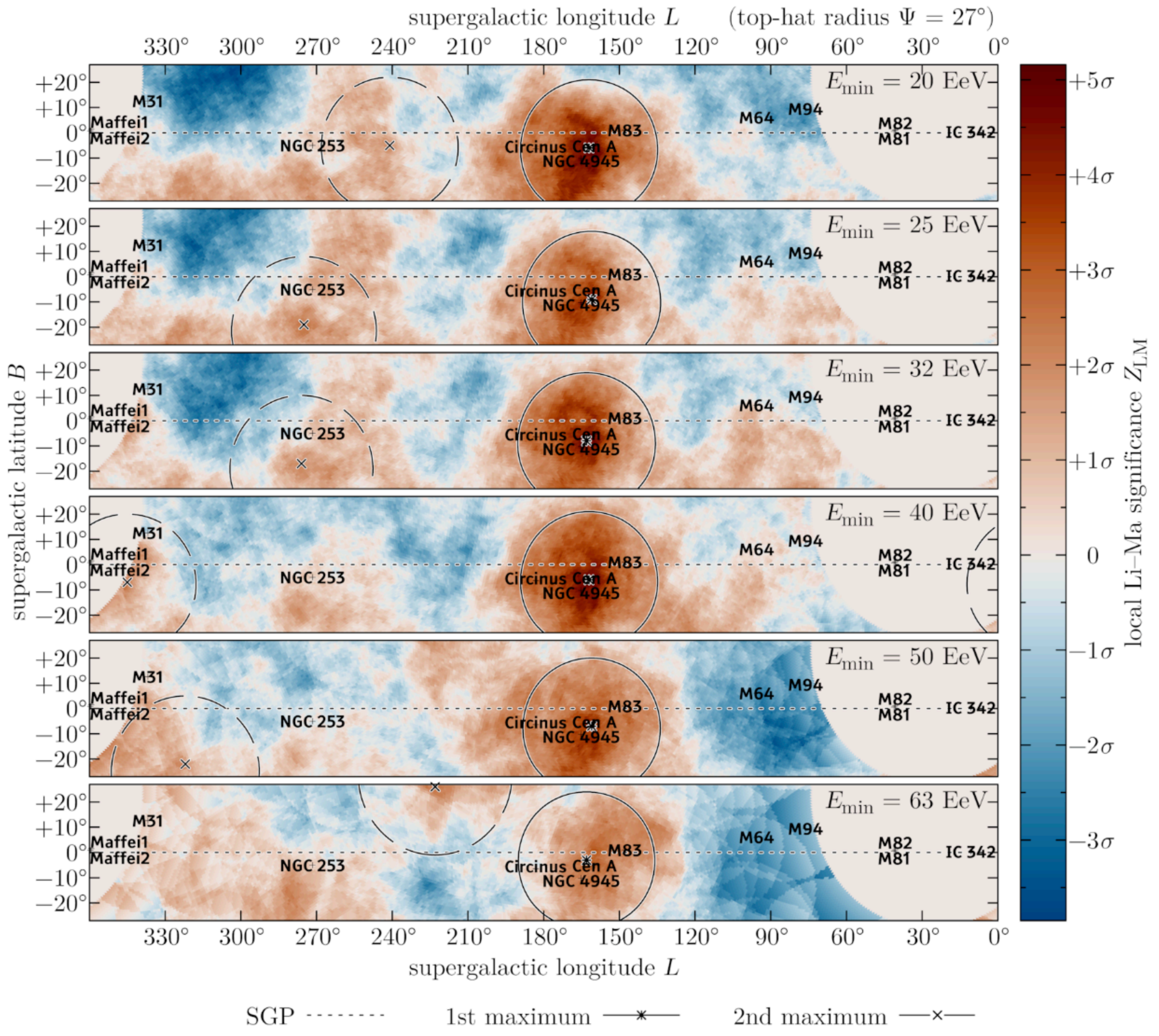
- Empirical model of rigidity dependence

$$d(E, Z) = d_R \left(\frac{E/\mathrm{EeV}}{Ze}\right)^{\beta_R}$$

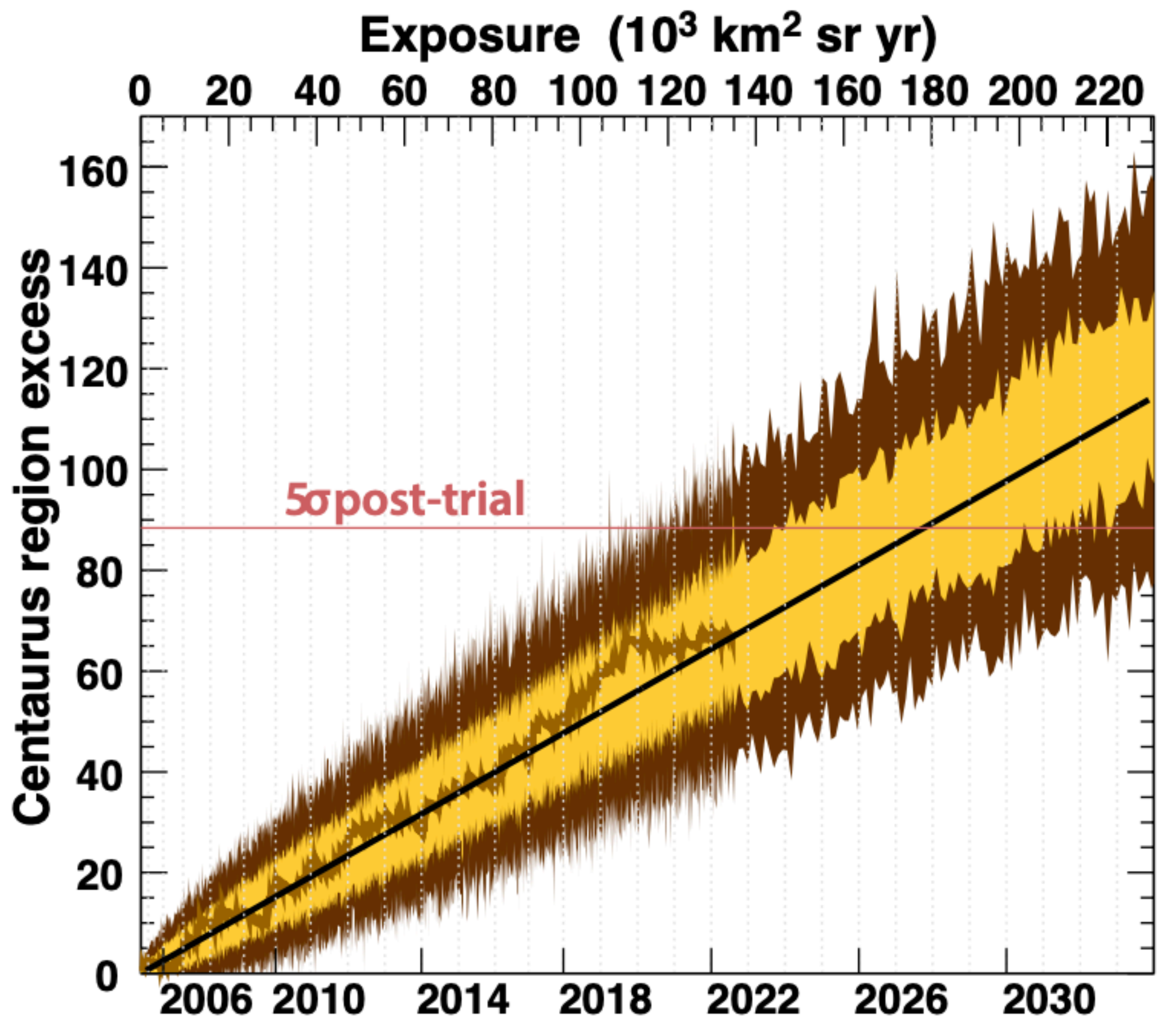
with parameters set to reproduce measurements
- Assuming composition model
- Assuming the same dipole direction for all nuclei
- Scan ln A values in the simulation library to define the **light** and **heavy** populations

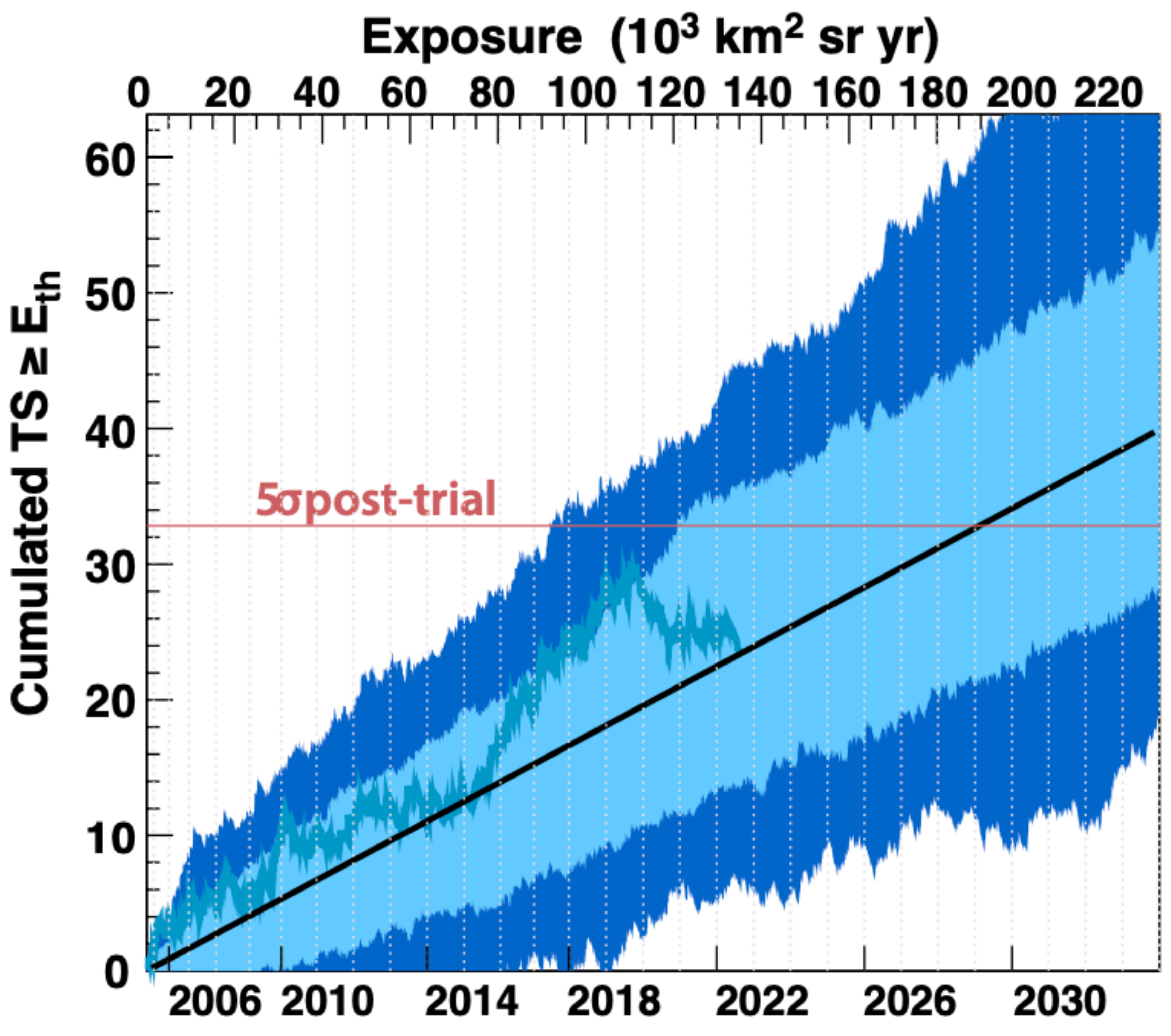
The supergalactic plane

- Indications for excesses above a few tens of EeV have been reported
- Regions along the supergalactic plane, galaxies within 100 Mpc
- ApJ 2022: no statistically significant excess of events in bands of 1°–30° around the whole supergalactic plane
- Investigation of smaller regions along it
  - Most significant excess very close to Centaurus A for all energy thresholds
  - No strong indication for excesses anywhere else along the supergalactic plane
  - no confirmation of the indications reported by TA



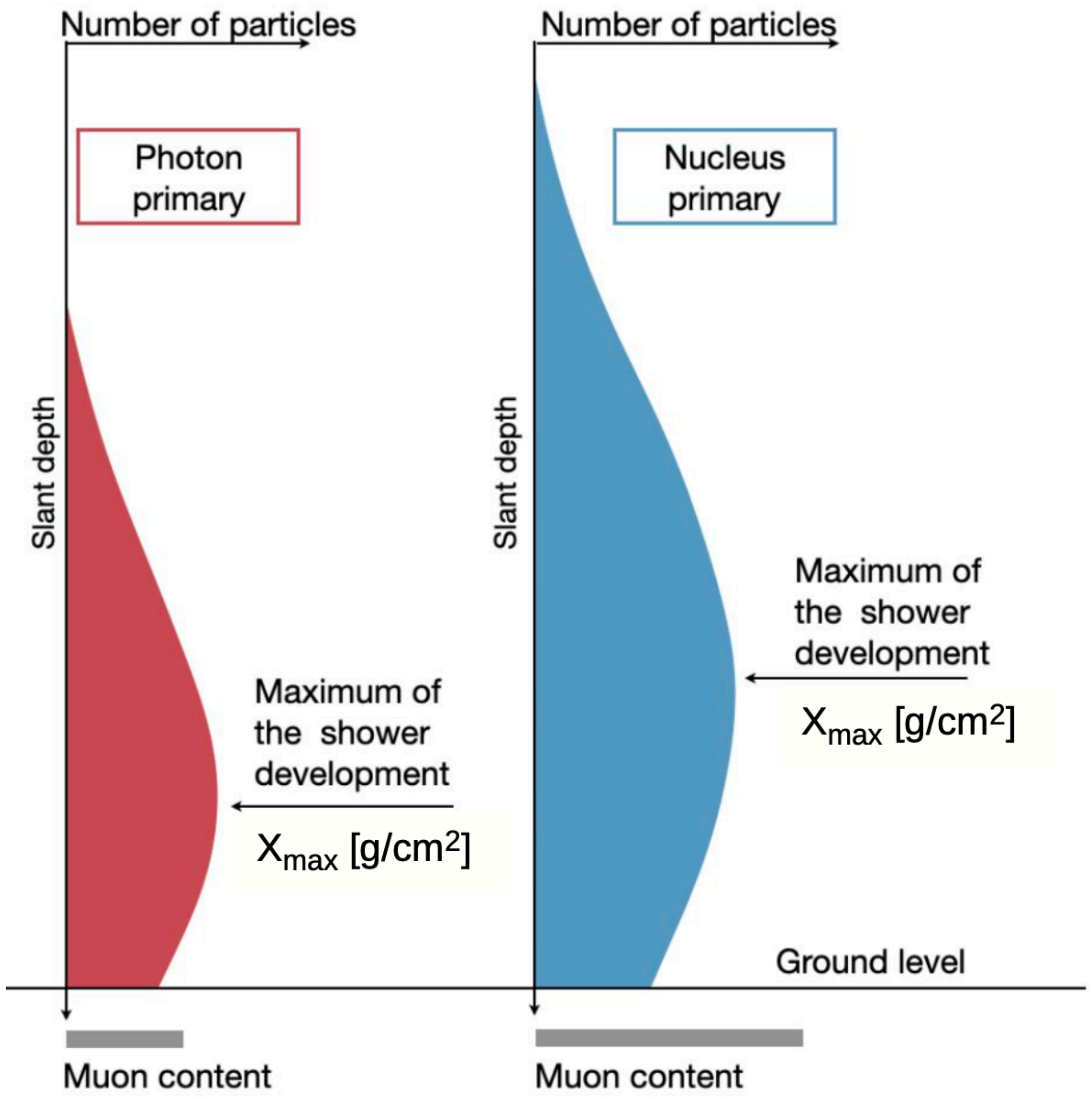
Excess regions and catalog searches



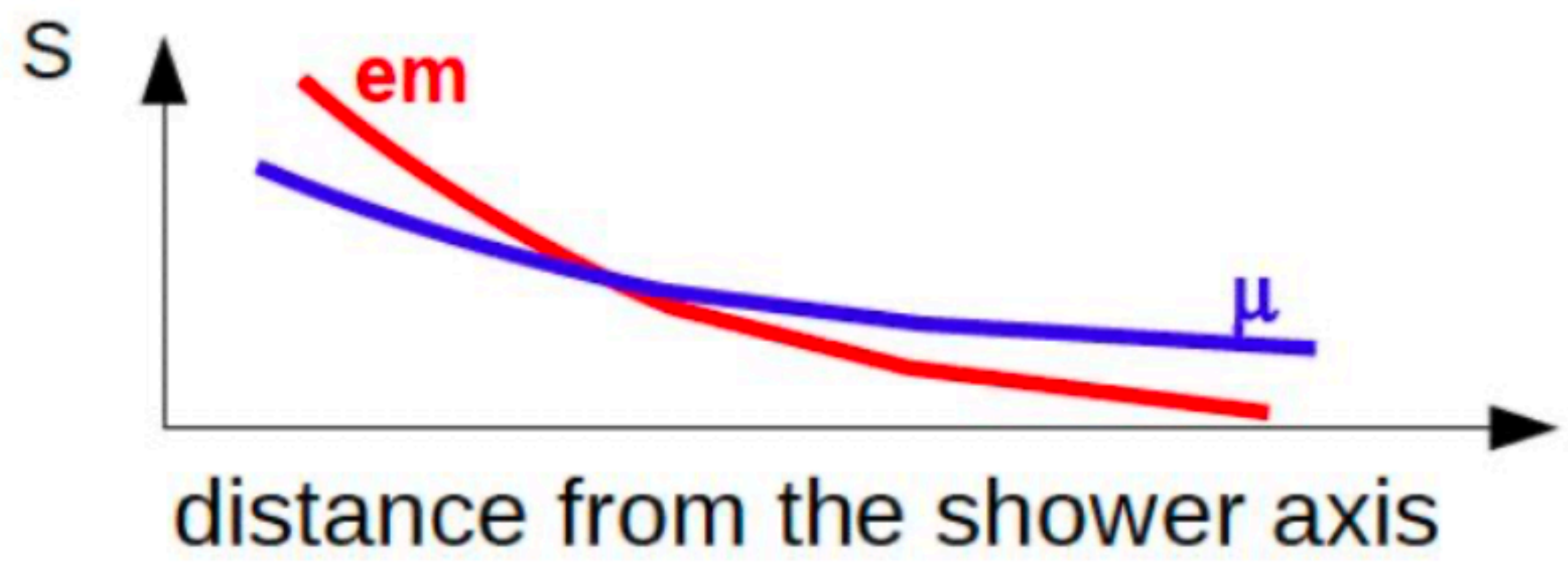


Excess in the Centaurus region and test statistic of the starburst model as a function of time and accumulated exposure. The black line shows the projection from the last data

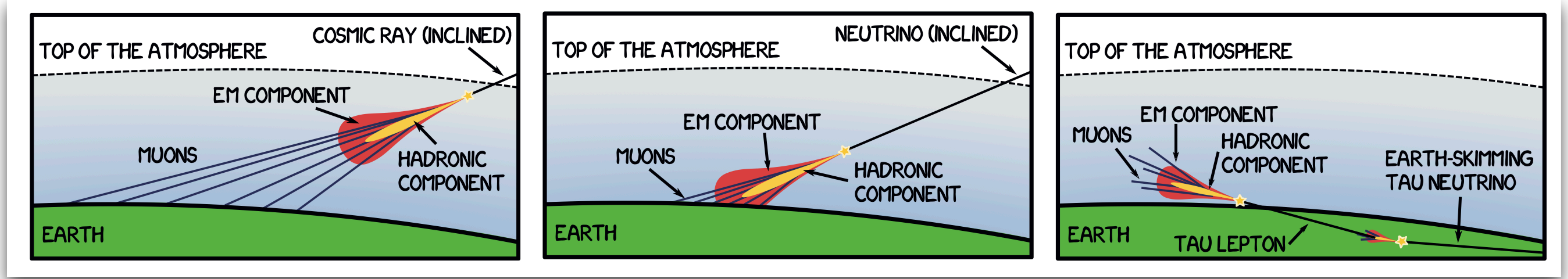
Photon searches



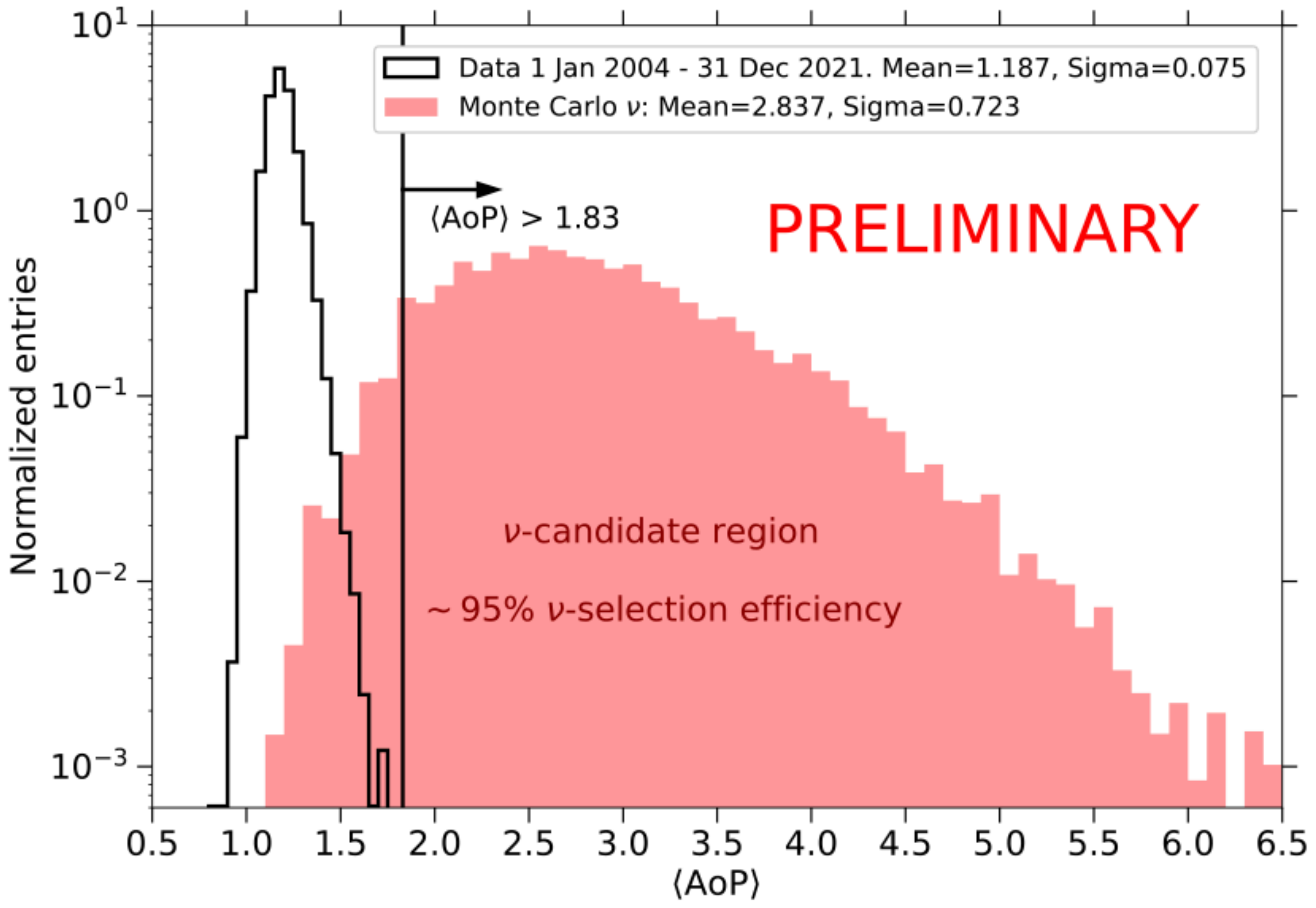
- Air showers initiated by photons have:
  - Deeper Xmax
  - Small content of muons

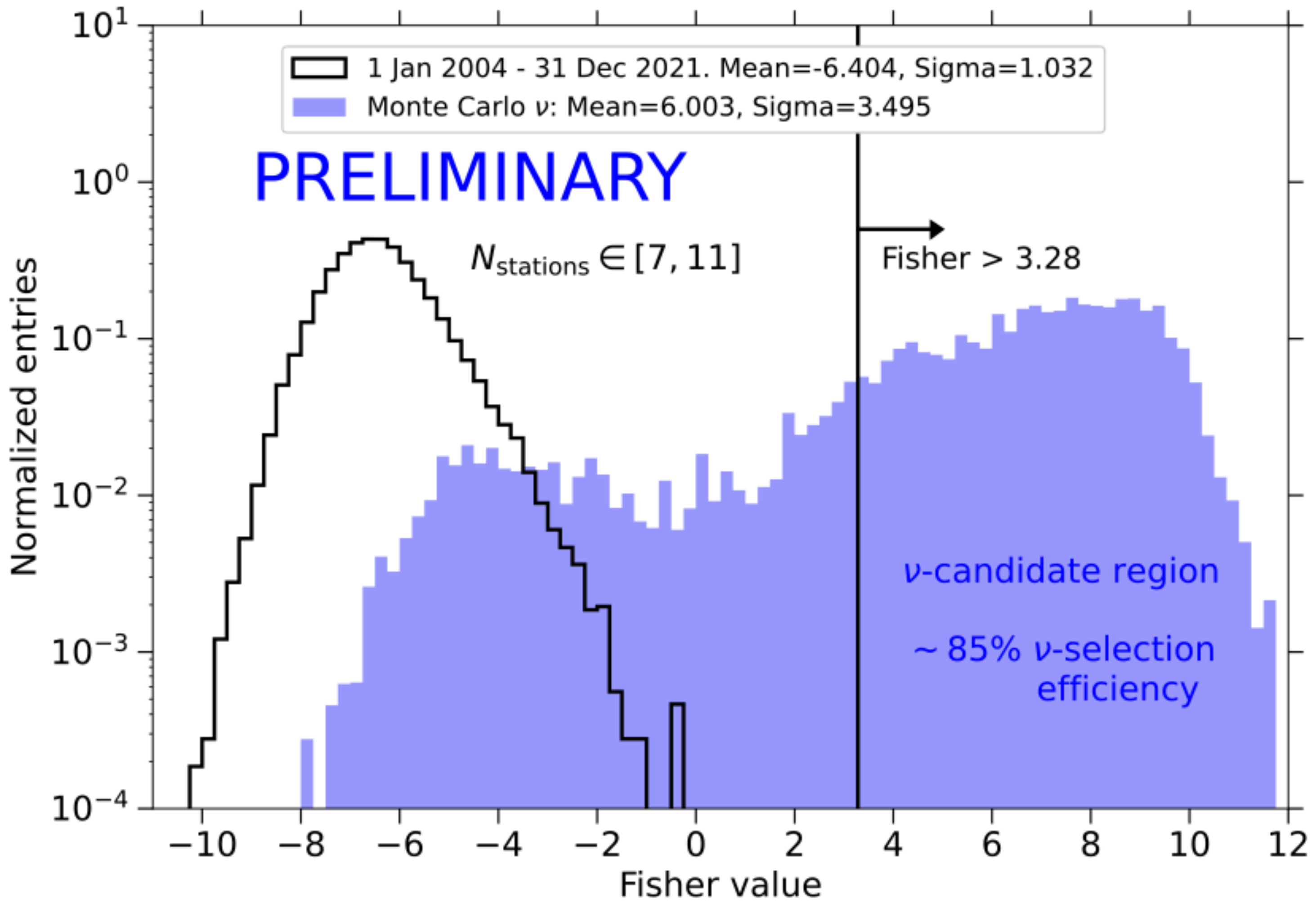


Neutrino searches

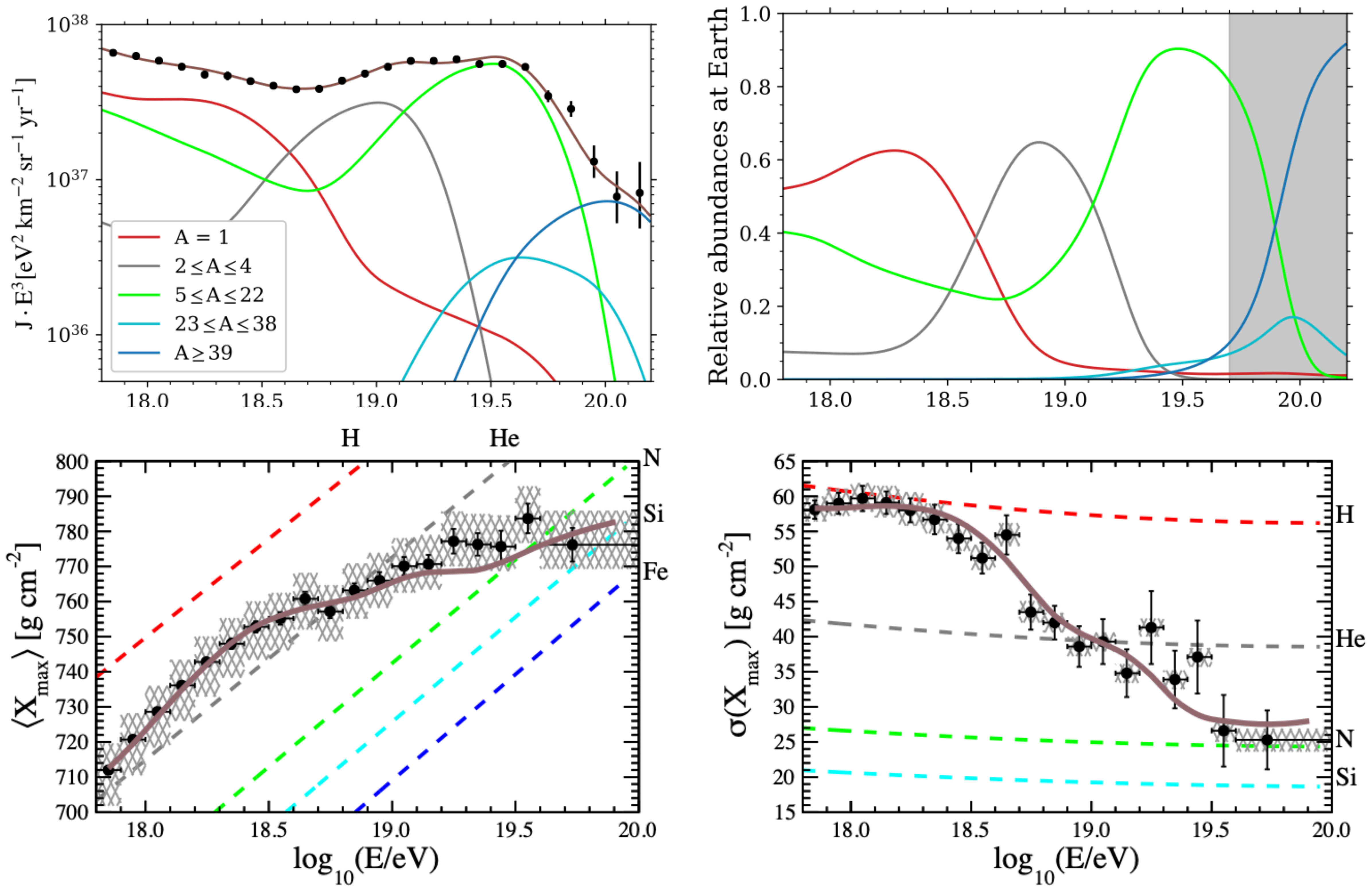


- For the ES channel, AoP averaged over the triggered stations in SD events is used
- For the DG channel, individual AoP are considered and subsequently combined in a Fisher analysis
- No candidate events identified





Predictions on UHECR source classes



	Scenario 1		Scenario 2	
Galactic contribution (at Earth)	pure N		—	
$J_0^{\mathrm{Gal}}/(\mathrm{eV}^{-1}\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1})$	$(1.06 \pm 0.04)\times 10^{-13}$		—	
$\log_{10}(R_{\mathrm{cut}}^{\mathrm{Gal}}/\mathrm{V})$	17.48 ± 0.02		—	
EG components (at the escape)	LE	HE	LE	HE
$\mathcal{L}_0/(10^{44}\,\mathrm{erg\,Mpc}^{-3}\,\mathrm{yr}^{-1})$ *	6.54 ± 0.36	5.00 ± 0.35	11.35 ± 0.15	5.07 ± 0.06
γ	3.34 ± 0.07	-1.47 ± 0.13	3.52 ± 0.03	-1.99 ± 0.11
$\log_{10}(R_{\mathrm{cut}}/\mathrm{V})$	>19.3	18.19 ± 0.02	>19.4	18.15 ± 0.01
I_{H} (%)	100 (fixed)	0.0 ± 0.0	48.7 ± 0.3	0.0 ± 0.0
I_{He} (%)	—	24.5 ± 3.0	7.3 ± 0.4	23.6 ± 1.6
I_{N} (%)	—	68.1 ± 5.0	44.0 ± 0.4	72.1 ± 3.3
I_{Si} (%)	—	4.9 ± 3.9	0.0 ± 0.0	1.3 ± 1.3
I_{Fe} (%)	—	2.5 ± 0.2	0.0 ± 0.0	3.1 ± 1.3
$D_J\ (N_J)$	48.6 (24)		56.6 (24)	
$D_{X_{\max}}\ (N_{X_{\max}})$	537.4 (329)		516.5 (329)	
$D\ (N)$	586.0 (353)		573.1 (353)	

* from $E_{\min} = 10^{17.8}$ eV.

$$\frac{dN}{dE} \propto f_A \left(\frac{E}{10^{18}\mathrm{eV}}\right)^{-\gamma} \times f_{cut}(E, Z_A R_{cut}) \times (1+z)^m$$

$$\longrightarrow \phi(E_\nu) \longrightarrow N_{evt} = \int_{E_\nu} \epsilon(E_\nu)\phi(E_\nu)dE_\nu$$

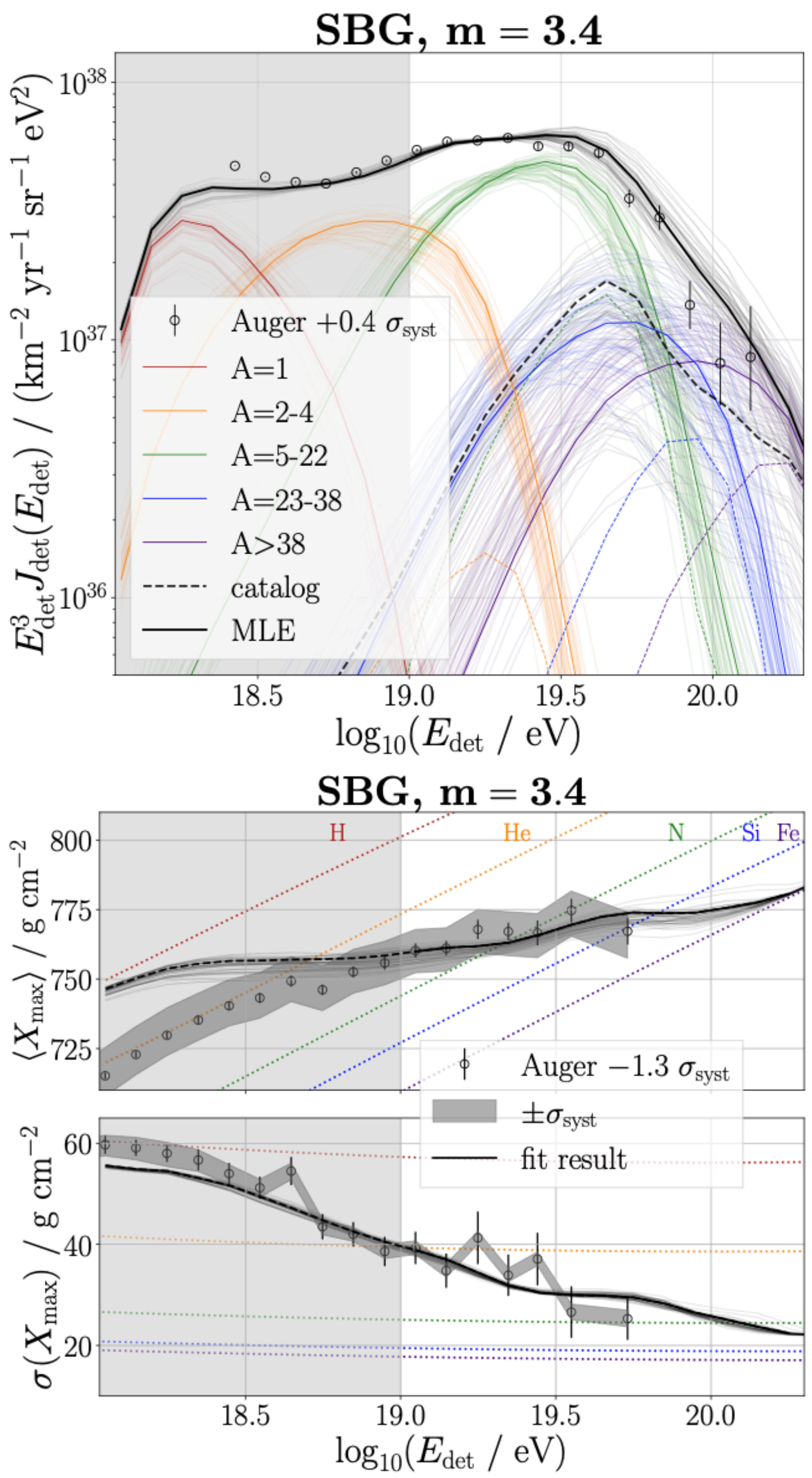
- To be compared to the fit of the energy spectrum with pure protons:

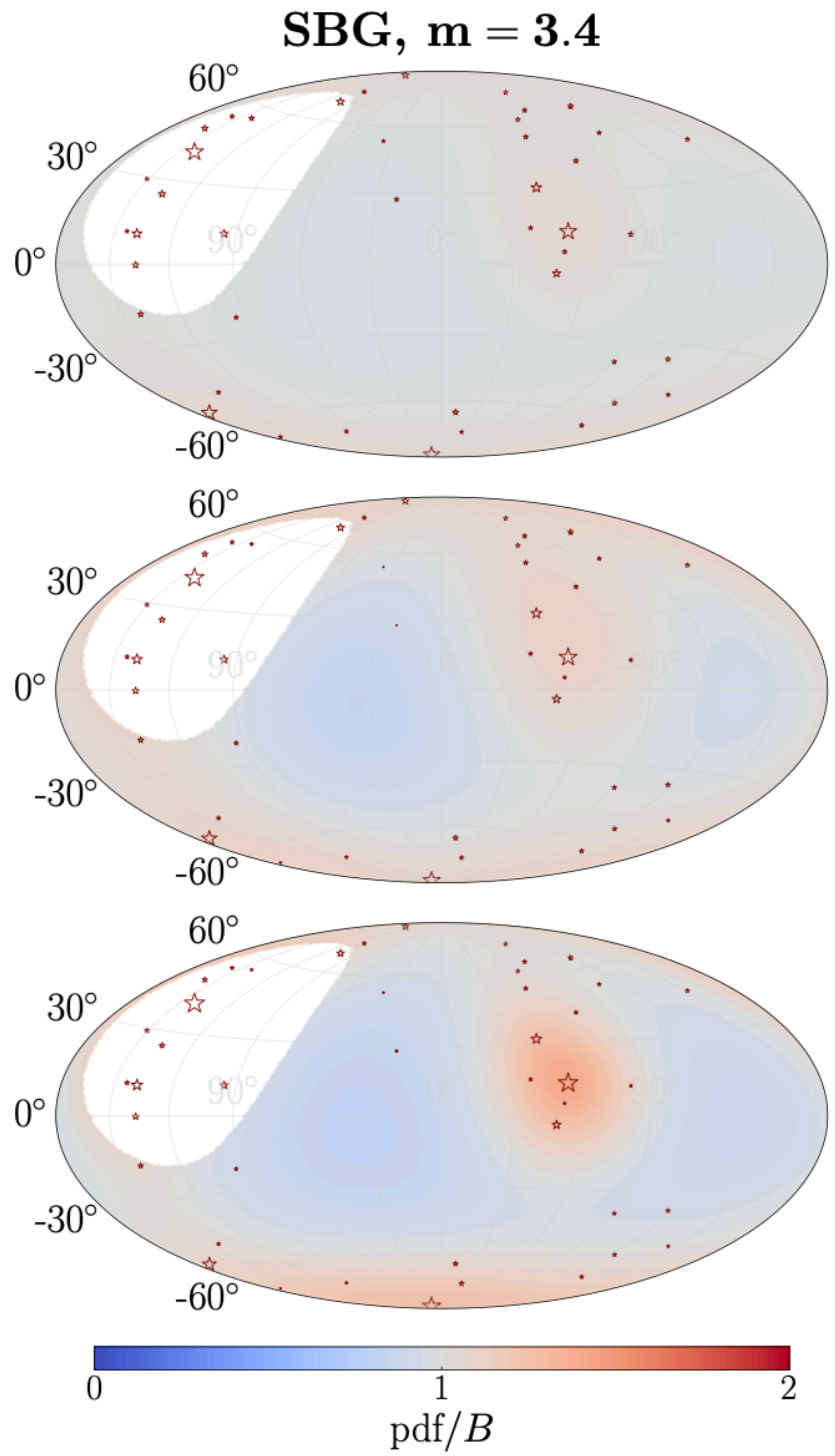
$$\gamma = 2.25;\quad E_{\mathrm{cut}} = 10^{19.75}\ \mathrm{eV};\quad m = 5$$

$$\chi^2/dof = 483.5/24$$

JCAP 05 (2023) 024

Predictions on UHECR source classes

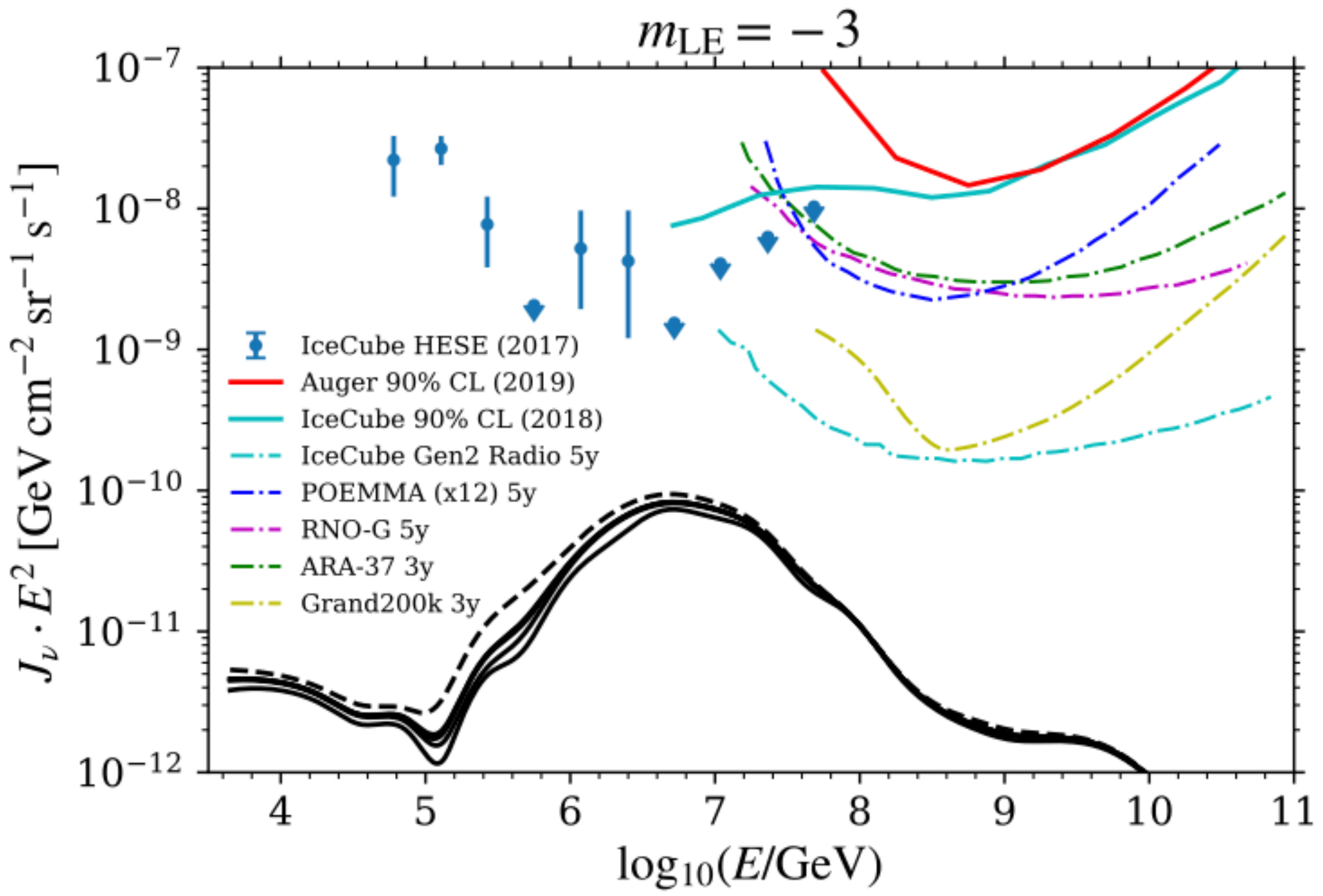


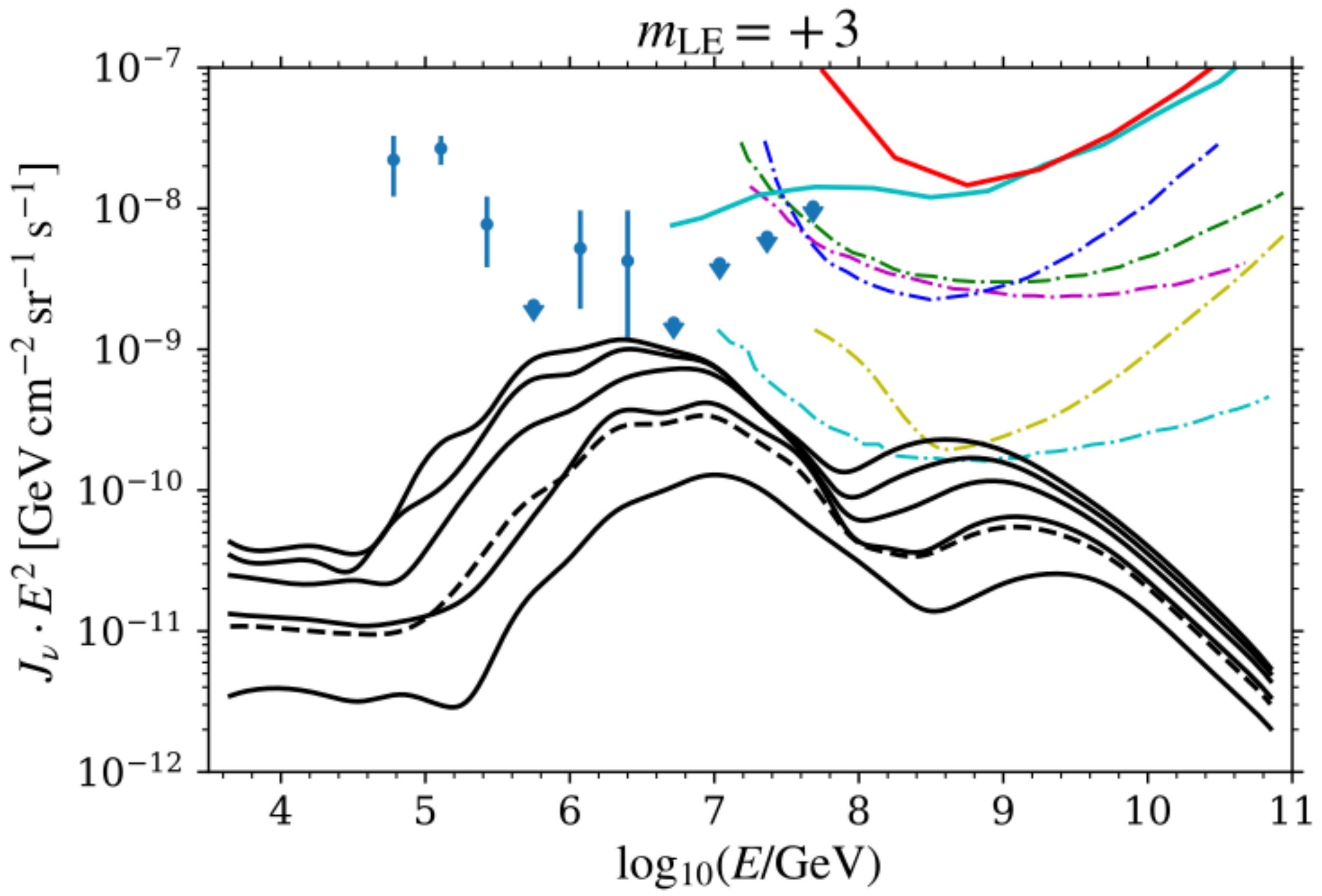


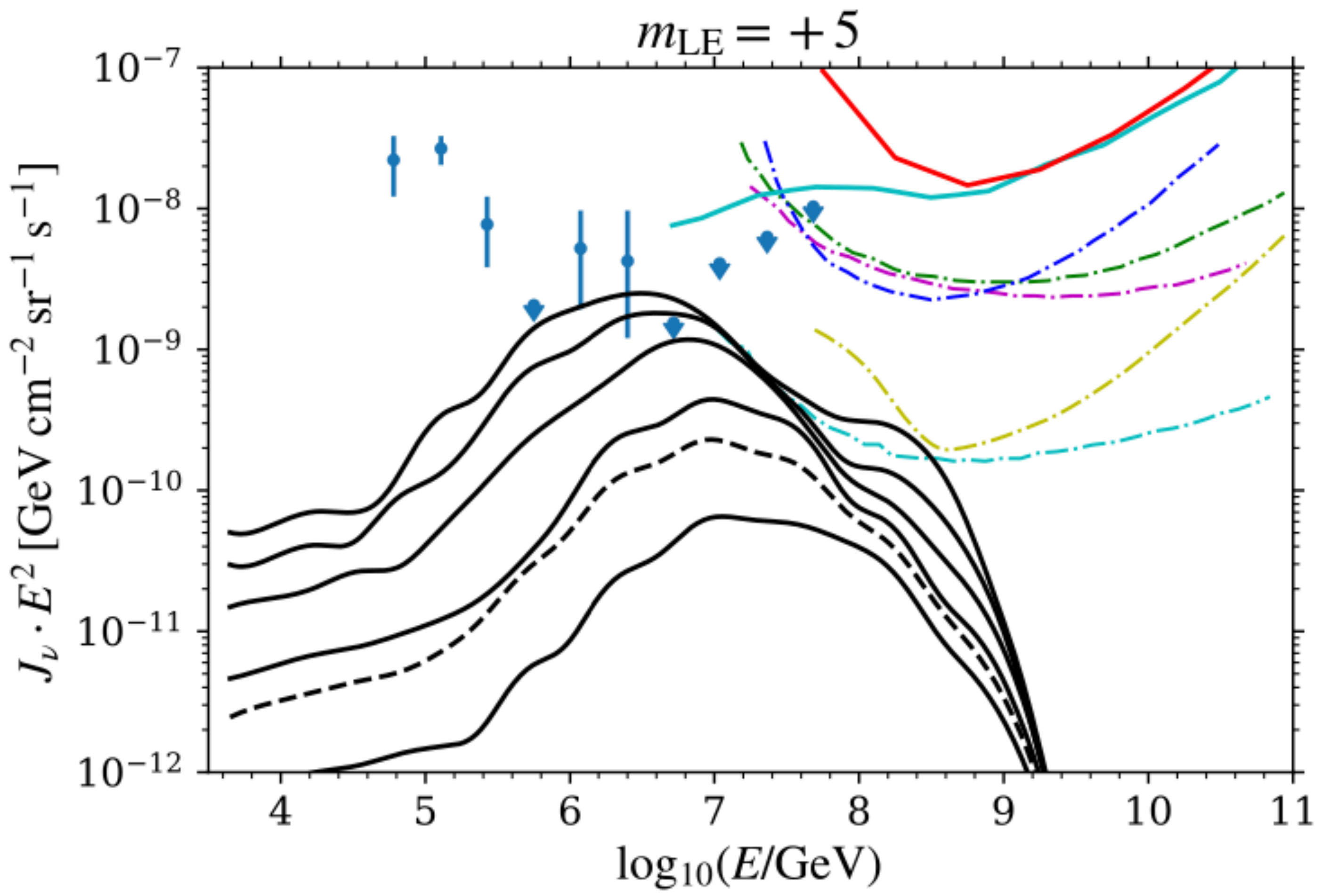
- Signal fraction and uncertainty in arrival direction included in the analysis
- Best improvement with respect to spectrum + composition fit found for **starburst sources**
- gamma-AGN sources disfavoured

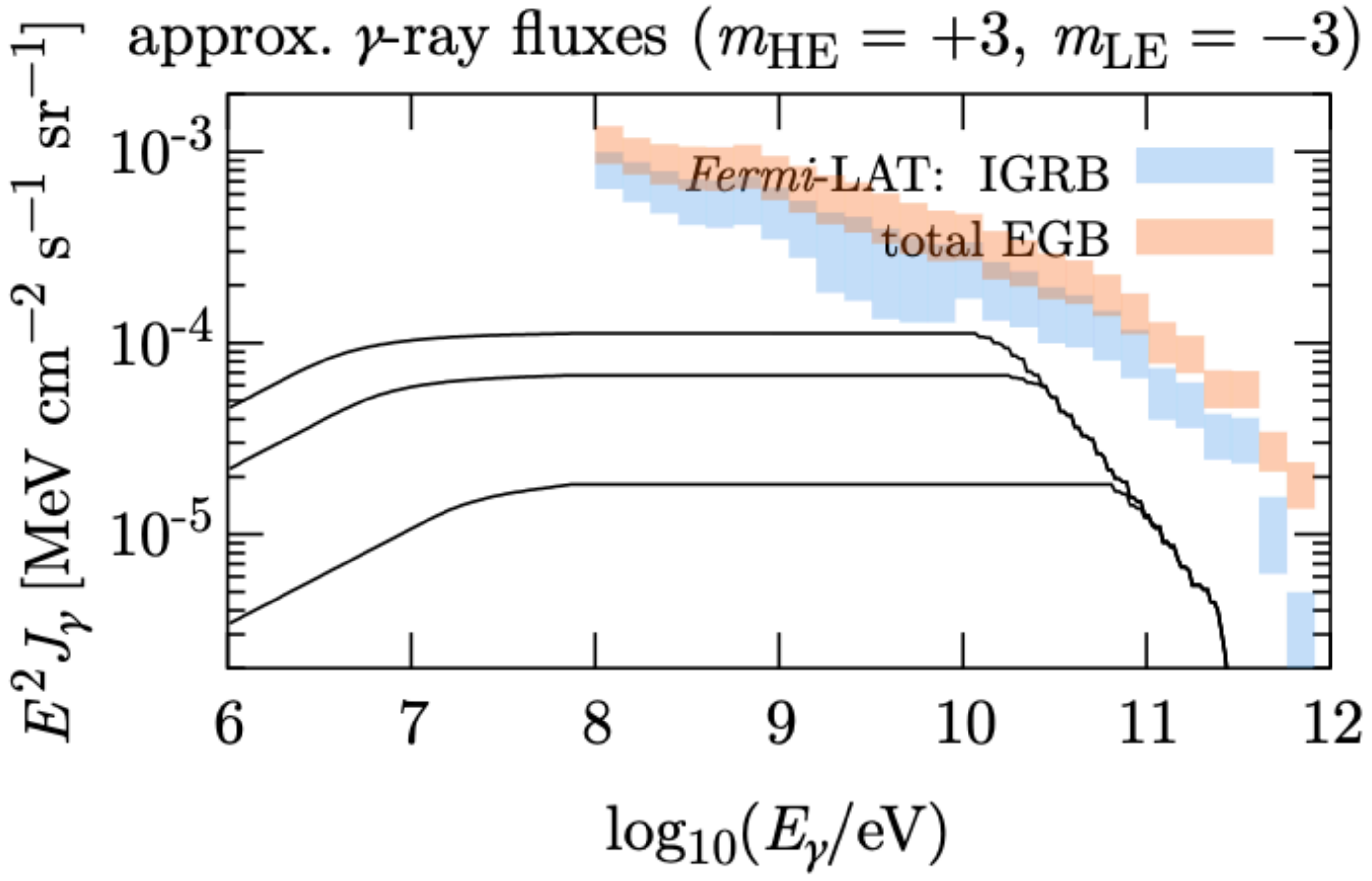
JCAP 01 (2024) 022

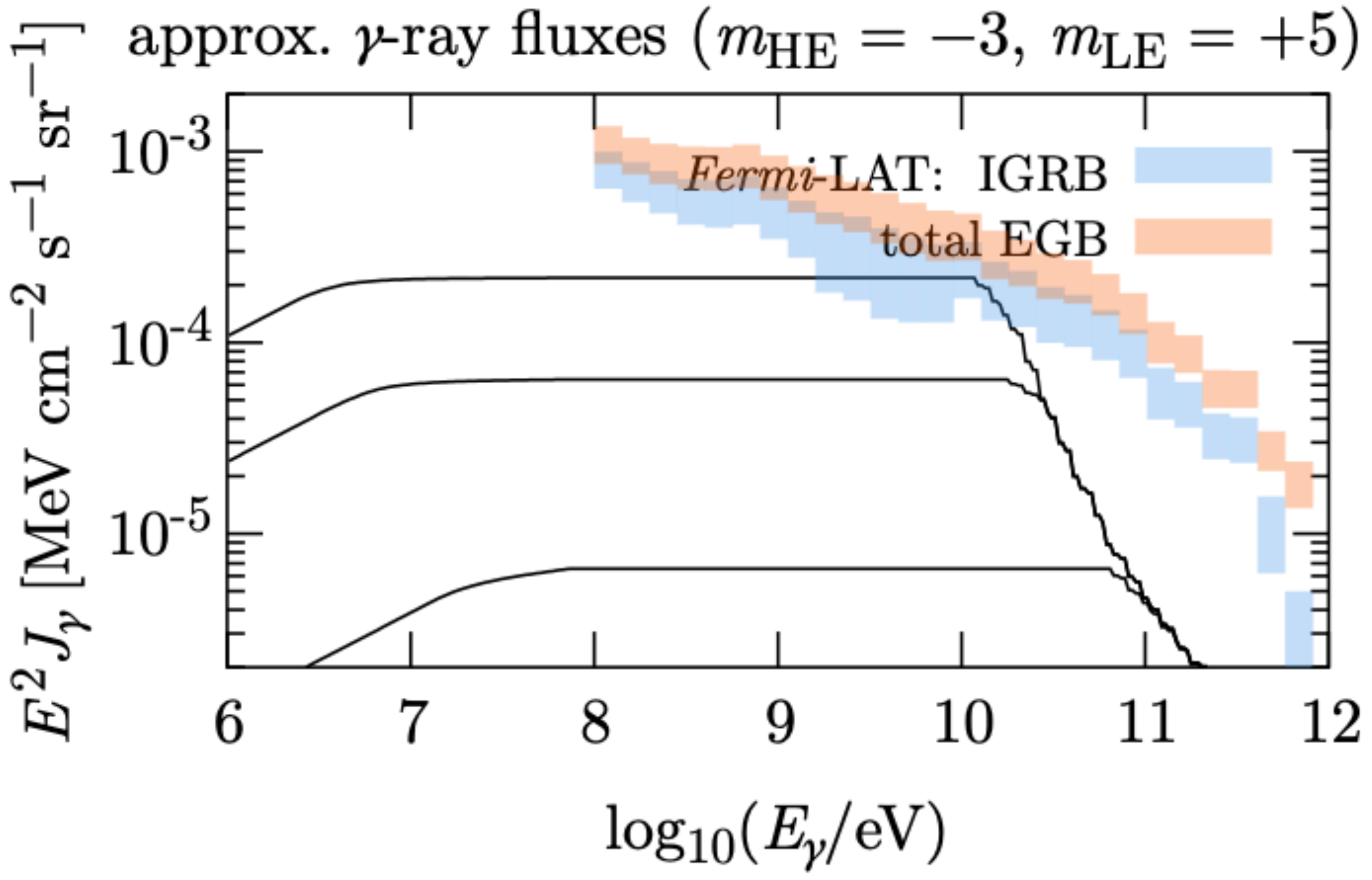
Predictions on UHECR source classes from multimessenger constraints







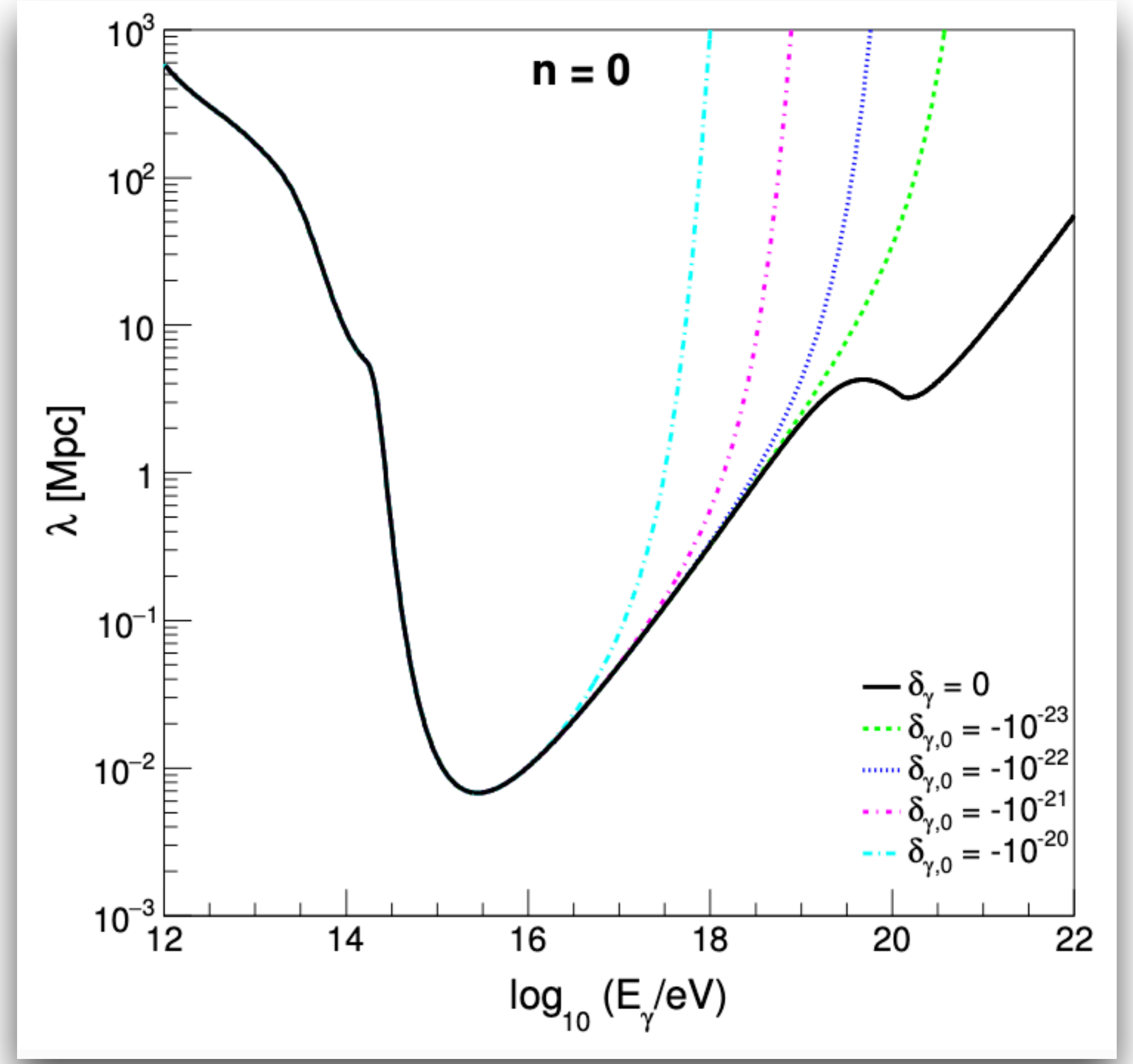


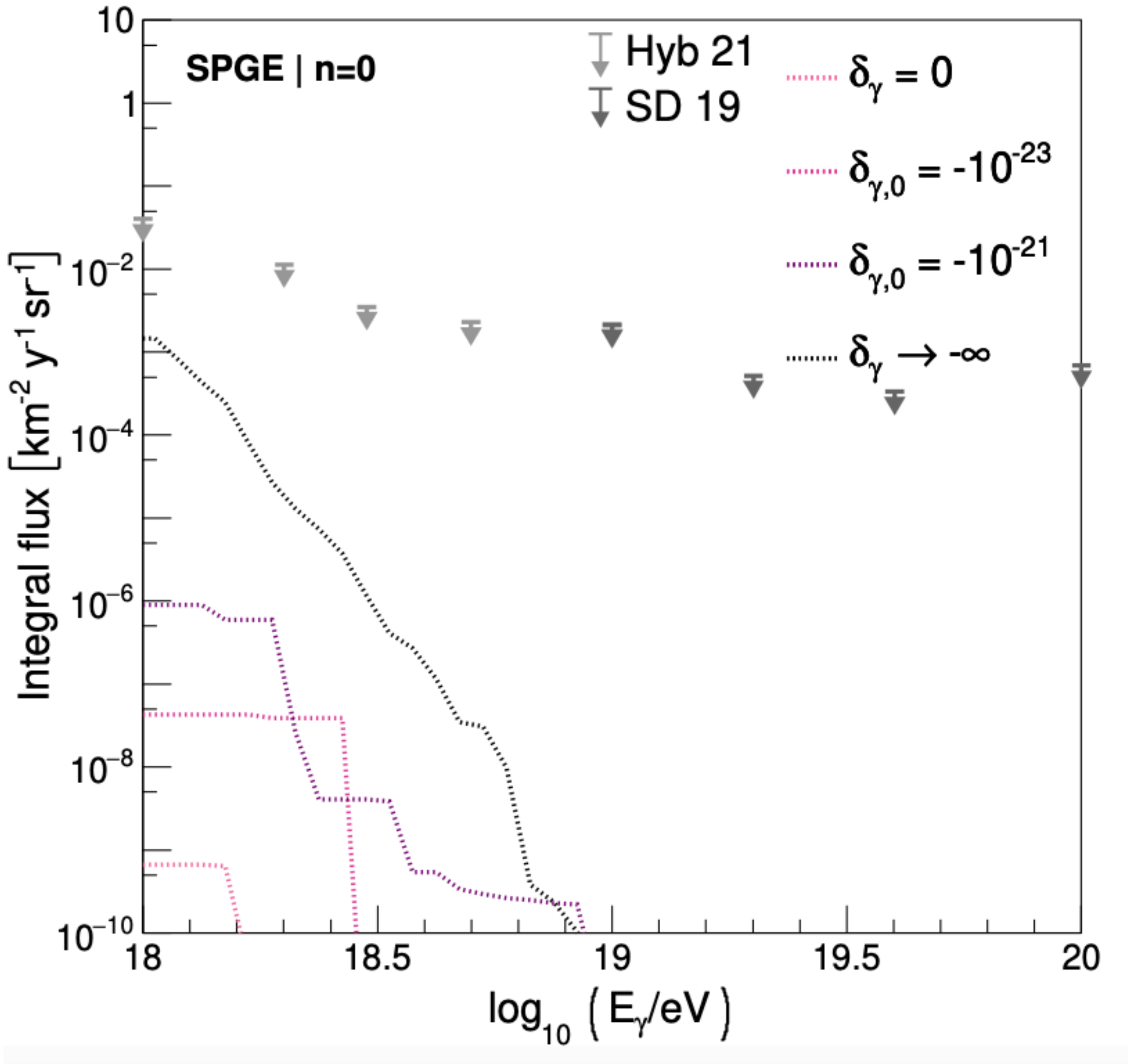


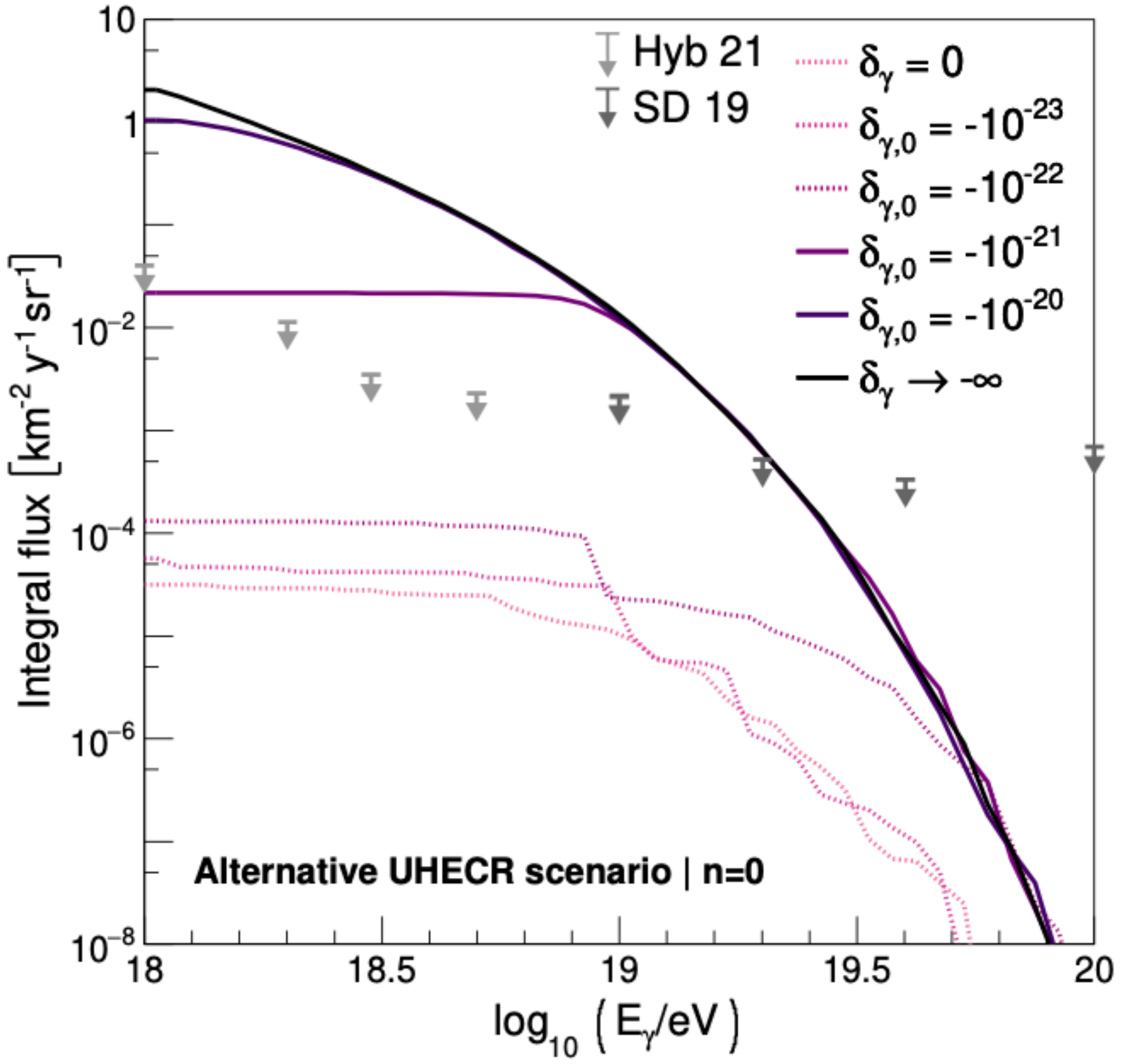
LIV IN EXTRAGALACTIC PROPAGATION

The Pierre Auger Collaboration, JCAP 2022

- LIV can inhibit pair production at the highest energies
- More photons could reach the Earth



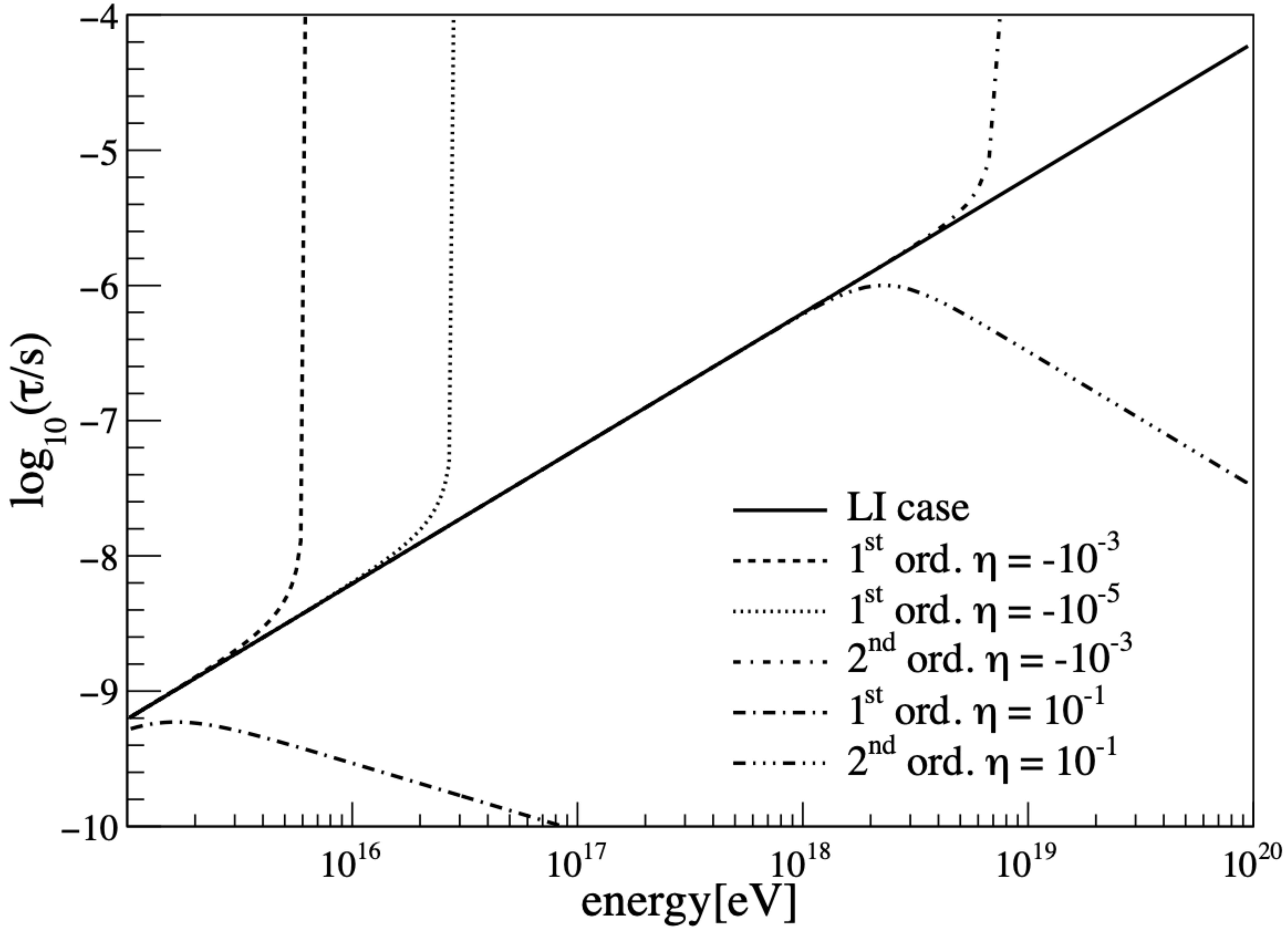




MODIFICATIONS TO EAS DEVELOPMENT

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

$$E_i^2 - p_i^2 = m_i^2 + \sum \eta_{i,n} \frac{E_i^{2+n}}{M_{Pl}^n}$$



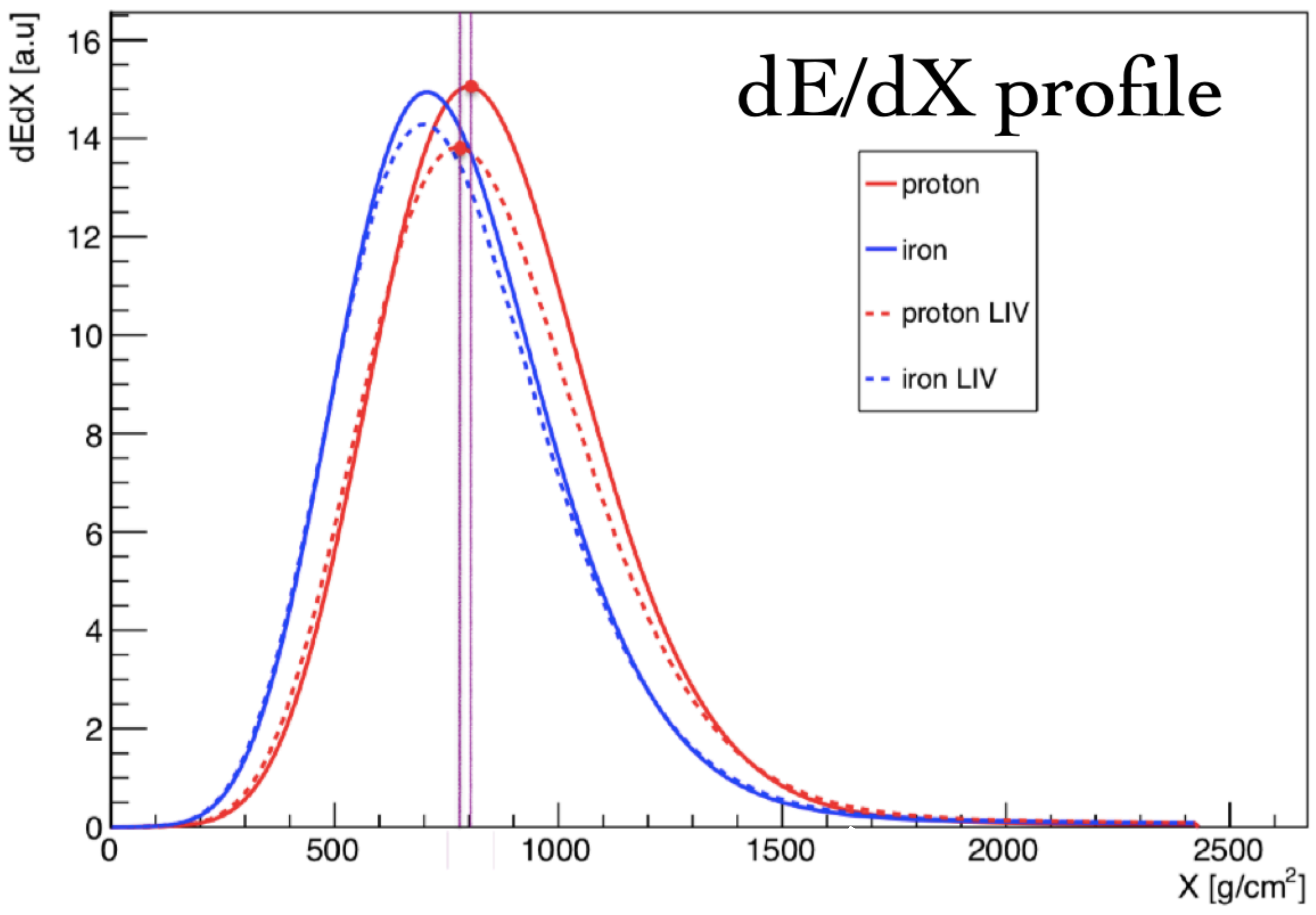
$$\Gamma = \frac{E}{m_{\mathrm{LIV}}} \qquad \tau = \Gamma \tau_0$$

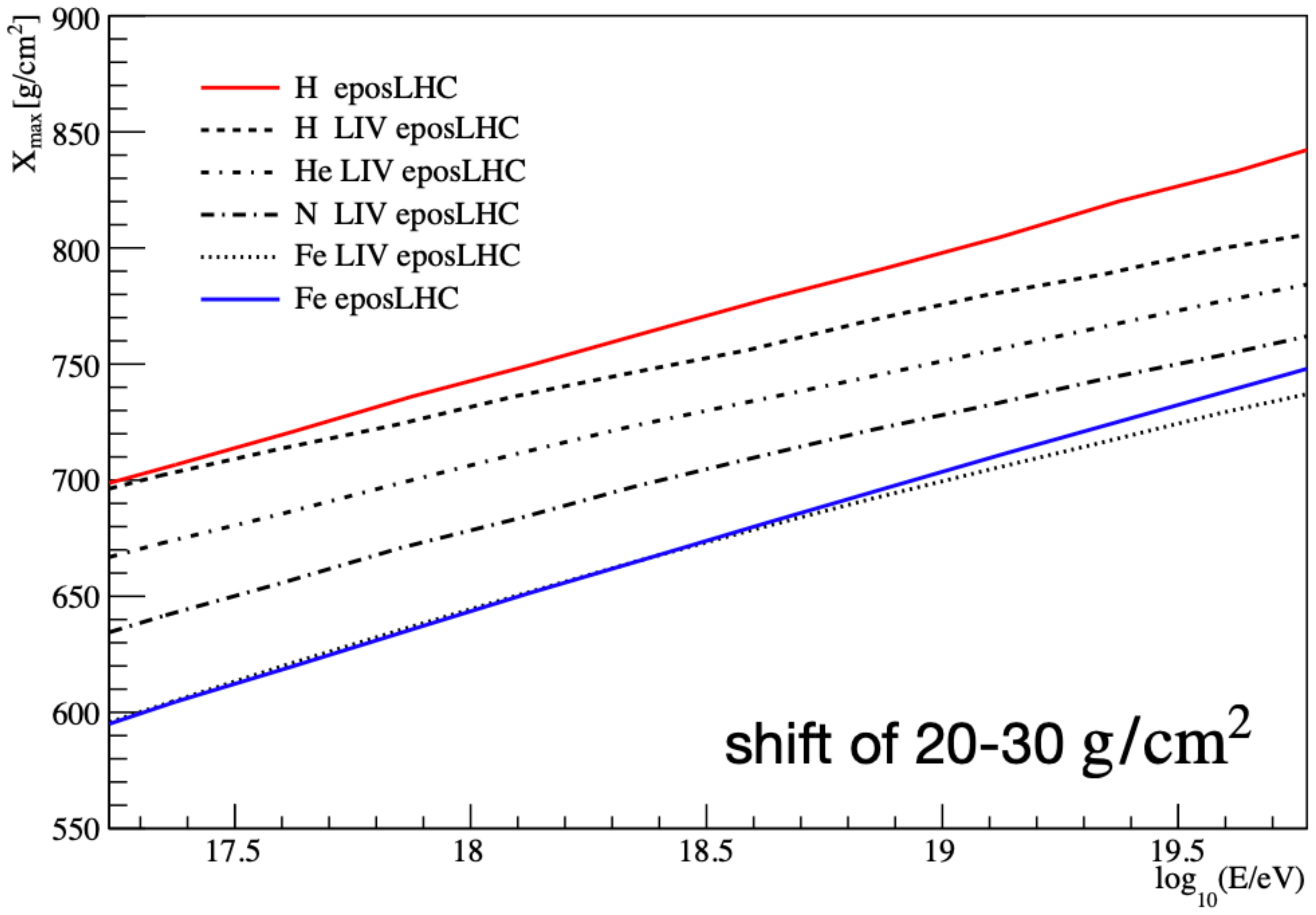
1. Positive eta: negligible effects
2. Negative eta: forbidden neutral pion decay if…

$$m_\pi^2 + \eta_\pi^{(n)} \frac{E_\pi^{2+n}}{M_{Pl}^n} < 0$$

MODIFICATIONS TO MASS OBSERVABLES

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

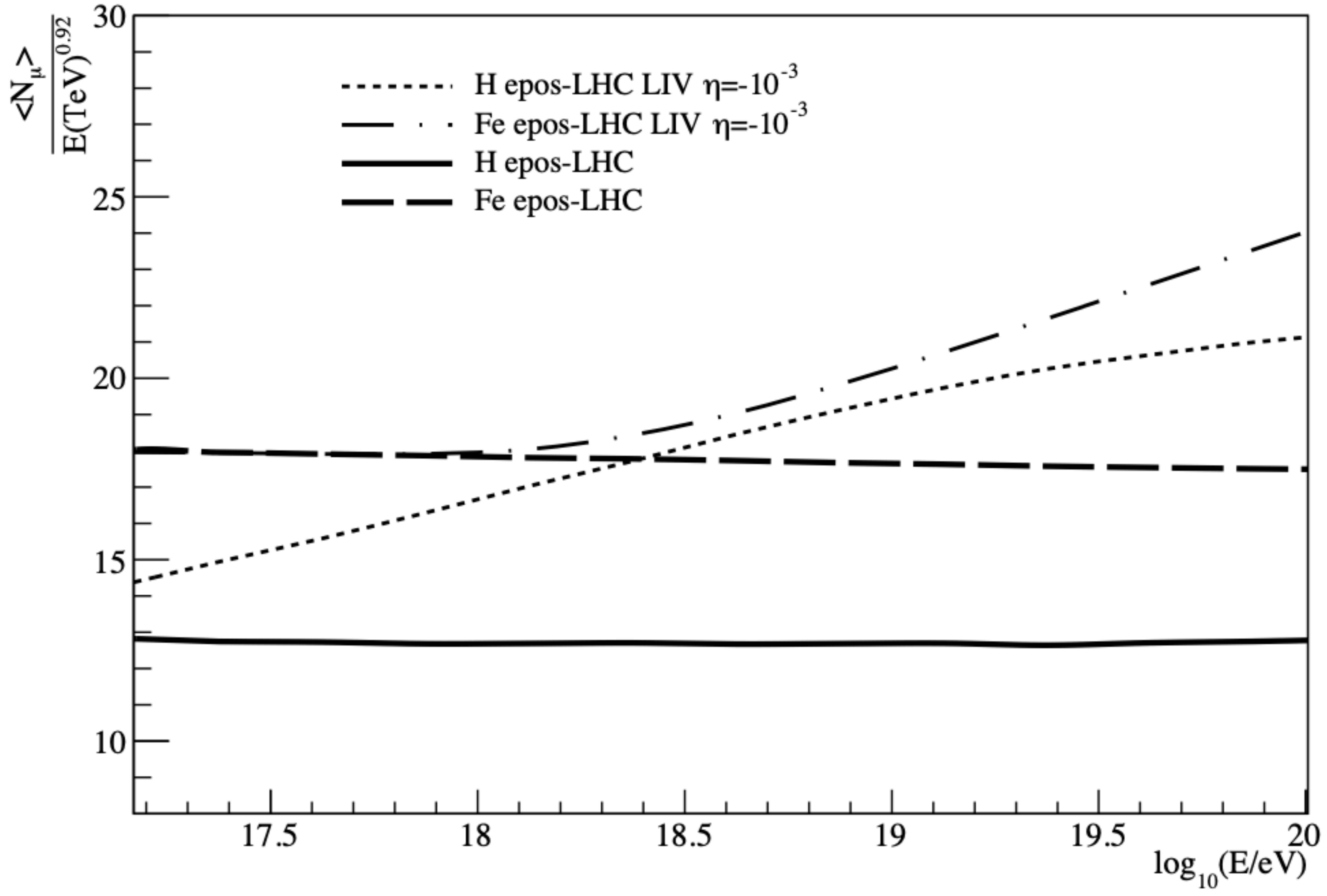


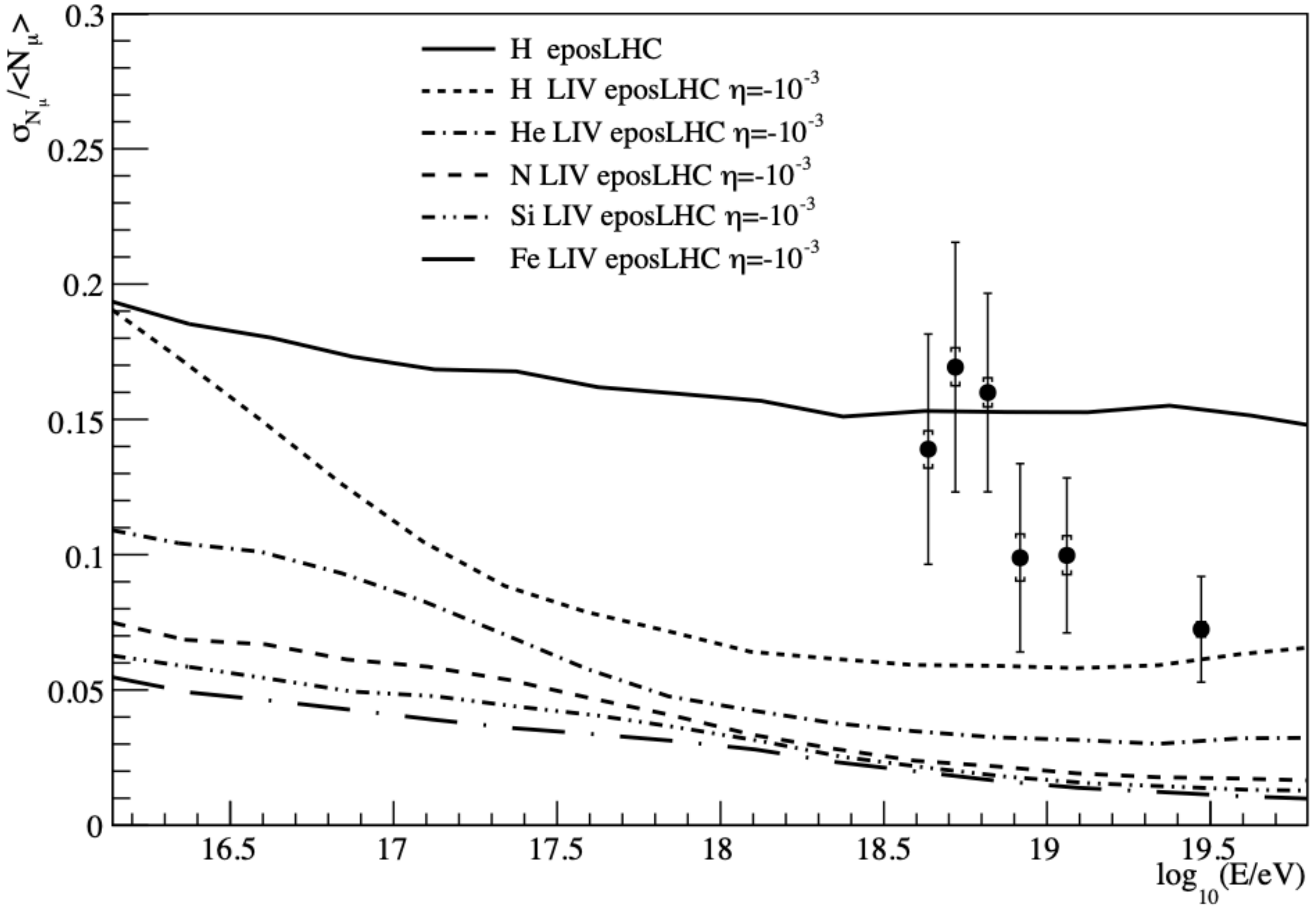


- If neutral pion does not decay, it can interact
  - Calorimetric energy is smaller than in the LI case
  - Predictions for Xmax decrease with energy with respect to the LI case

MODIFICATIONS TO MASS OBSERVABLES

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021





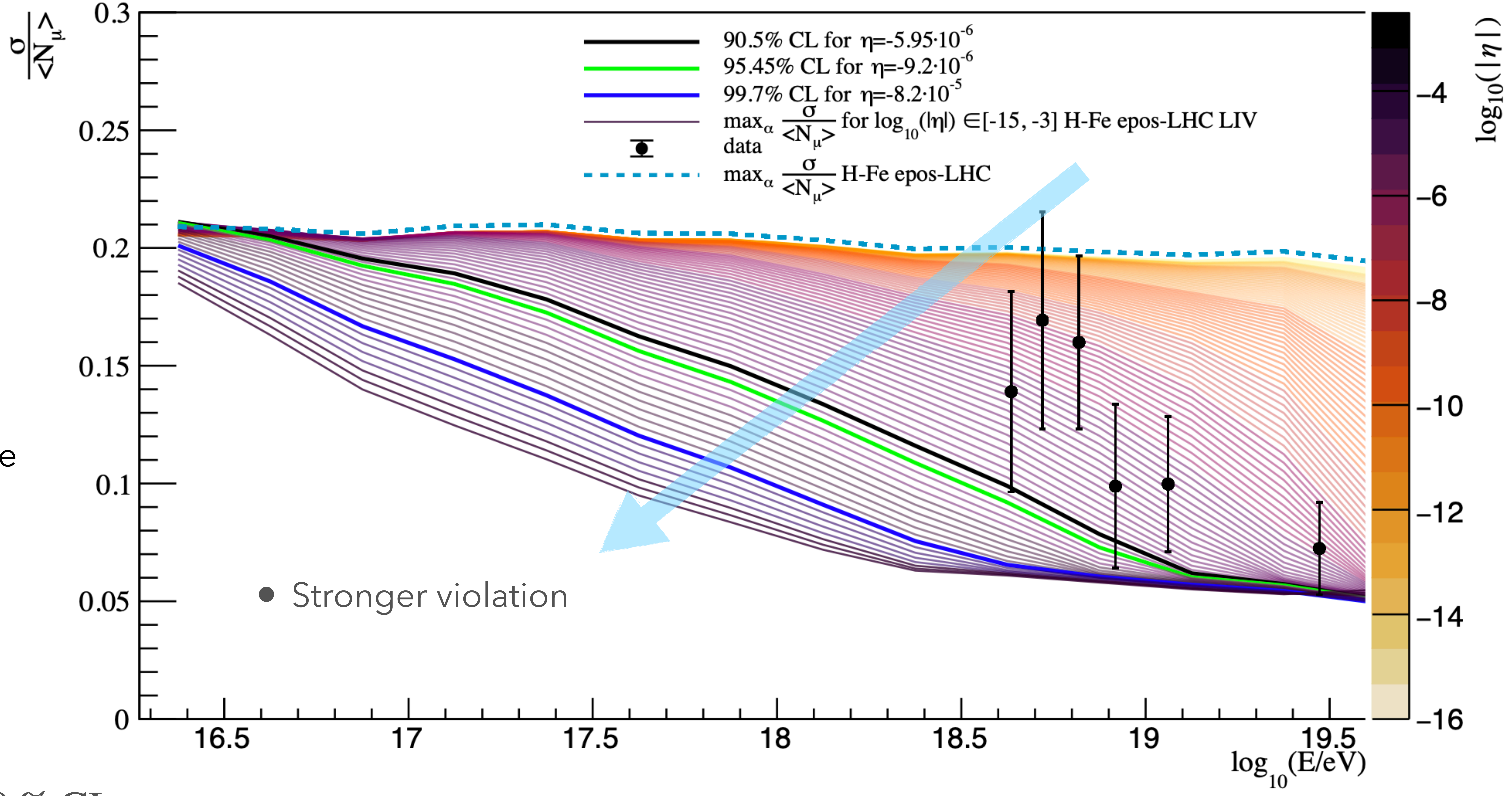
- LI case:
  - number of muons larger (and less fluctuations) in showers initiated by heavy nuclear species with respect to protons
- LIV case:
  - Fluctuations decrease with respect to the LI case

- Focus on <u>fluctuations in the number of muons</u>
  - **Decrease** if (pure) mass becomes heavier
  - **Increase/decrease** depending on the mass mixing
  - **Decrease** if LIV strength increases

CONSTRAINTS FROM MUON FLUCTUATIONS

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

- Procedure:
  - Combine masses as a function of energy and LIV strength in order to have the largest fluctuation for each LIV parameter
  - Compare the data to the predictions corresponding to LIV parameters



$$\eta^{(1)} > -5.95 \cdot 10^{-6},\ 90\,\%\,\mathrm{CL}$$

MOTIVATIONS TO LOOK AT **ULTRA-HEAVY NUCLEI**

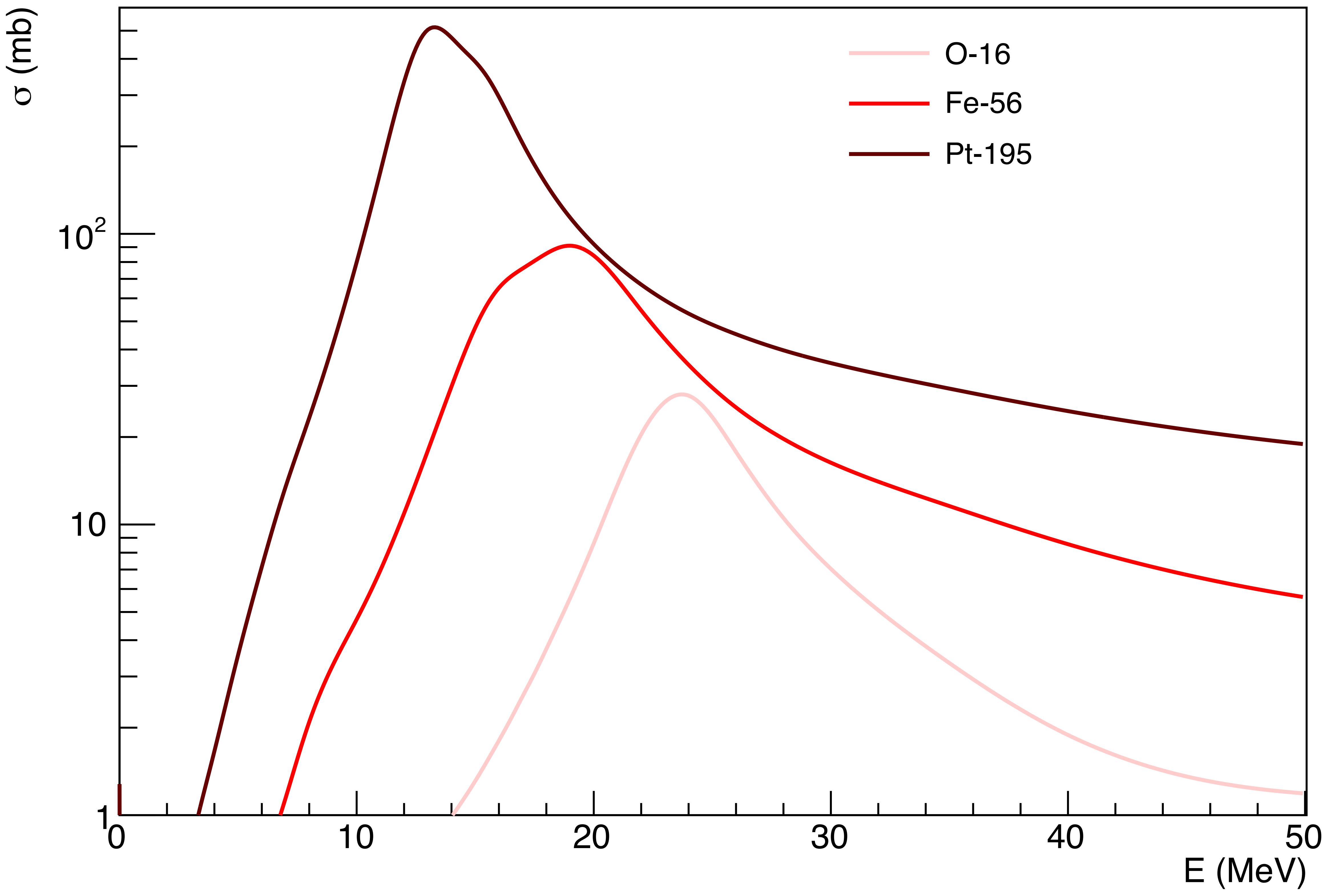
- Def: a ultra-heavy nucleus has A>56
- Heavy nuclei are synthesised due to the r-processes inside neutron-rich environments (compact binary mergers, including binary neutron star and neutron-star–black-hole mergers; collapsars)

  -> see Farrar arxiv:2405.12004 for motivations (and also the presentation by Glennys at the April Malargue meeting), and Decoene et al JCAP 2020; Rossoni, DB & Sigl arxiv:2407.19957 for computations of CR interactions in the photon fields of a BNS merger (a thermal photon field is produced due to the nuclear decay of the unstable species synthesised in the ejecta by the merger) -> energetics inspired from the electromagnetic counterpart of GW170817

- To be considered as UHECRs they have to:
  - Be accelerated (advantage: large Z)
    - But could escape from the source "dressed up" again (see Esmaeili et al. arxiv:2410.11958) -> process of pair production with electron capture: the interaction of a single photon with a nucleus produces an electron/positron pair with the subsequent capture of electron by the nucleus (not relevant in propagation)
  - Escape from the acceleration environment
  - Propagate through the extragalactic space

- Only nuclei up to A=56 are considered for the interpretation of UHECR data
  - Could heavier nuclei account for the observed trend of the mass composition at the highest energies? See Zhang et al arxiv:2405.17409

CROSS SECTIONS



Note that if one-nucleon emission is taken into account, the threshold does not depend on the nuclear mass:

$$E_{\text{th}} \approx \frac{m_p A \Delta B}{2\varepsilon} \qquad \Gamma_{\text{th}} = \frac{\Delta B}{2\varepsilon}$$

Total inelastic photo-absorption cross section

-> from **TENDL-2021** (nuclear data library which provides the output of the **TALYS** nuclear model)

-> **TALYS** (nuclear reaction program for simulations of nuclear reactions up to energies of 200 MeV)

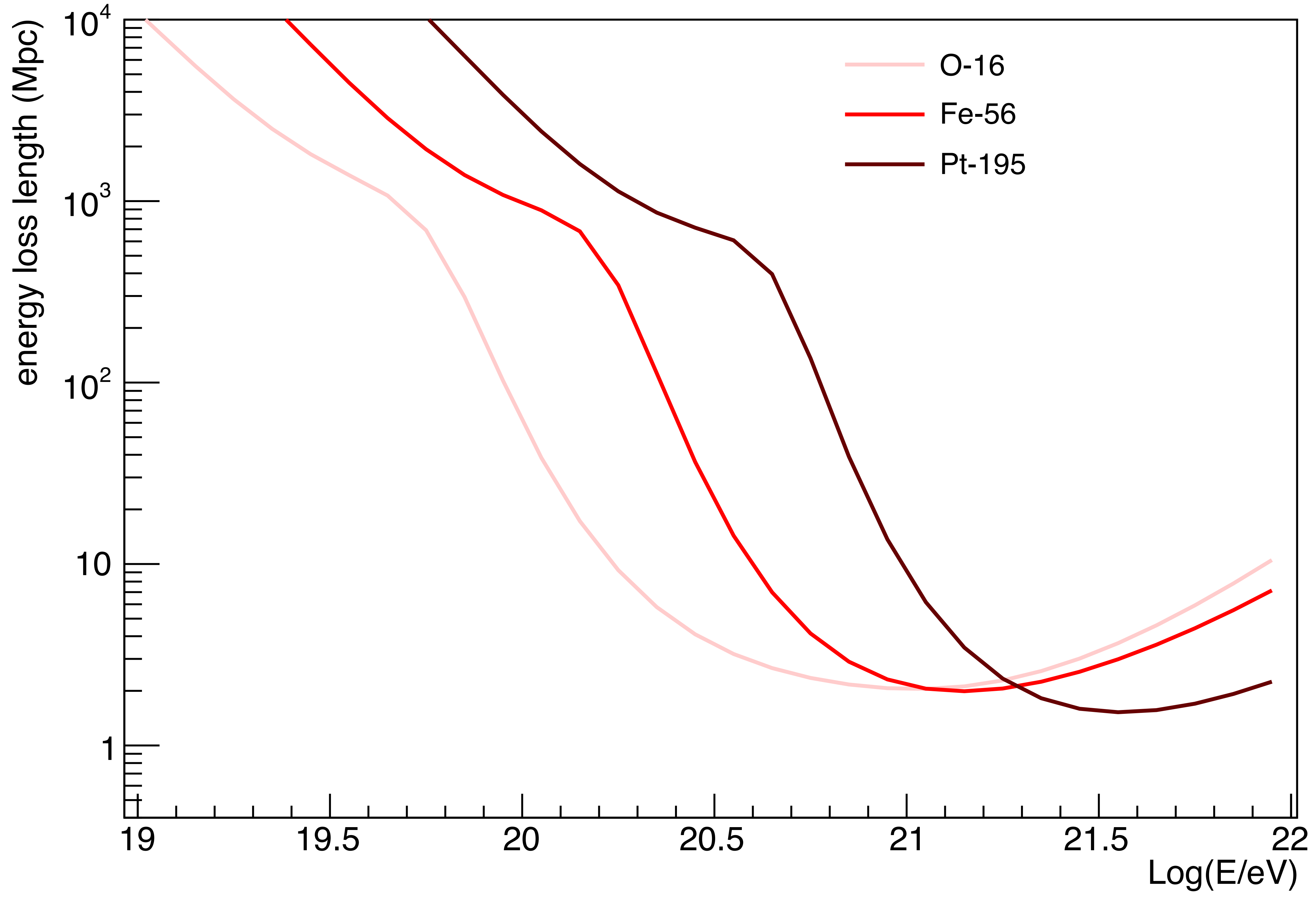
- The heavier is the nucleus
  - the peak of the cross section is shifting to lower energies
  - the cross section at the peak becomes larger

- **SimProp v2r4**, several cross section models implemented
  - Puget, Stecker & Bredekamp, ApJ 1976, PSB model (single, double and multiple nucleon ejection with tabulated branching ratios)
  - Fit of TALYS cross sections for single, double and multiple nucleon ejection with PSB branching ratios
  - Fit of TALYS cross sections for one-nucleon + alpha particle ejection
  - Interpolation of TENDL cross sections, from an extended list of nuclei (beyond A=56)

ENERGY LOSS LENGTH

$$\mathrm{ELL} \approx A\left(\frac{c}{2\Gamma^2}\int_{\varepsilon'_{\mathrm{th}}}^{\infty}\varepsilon'\sigma(\varepsilon')\int_{\varepsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'\right)^{-1}$$

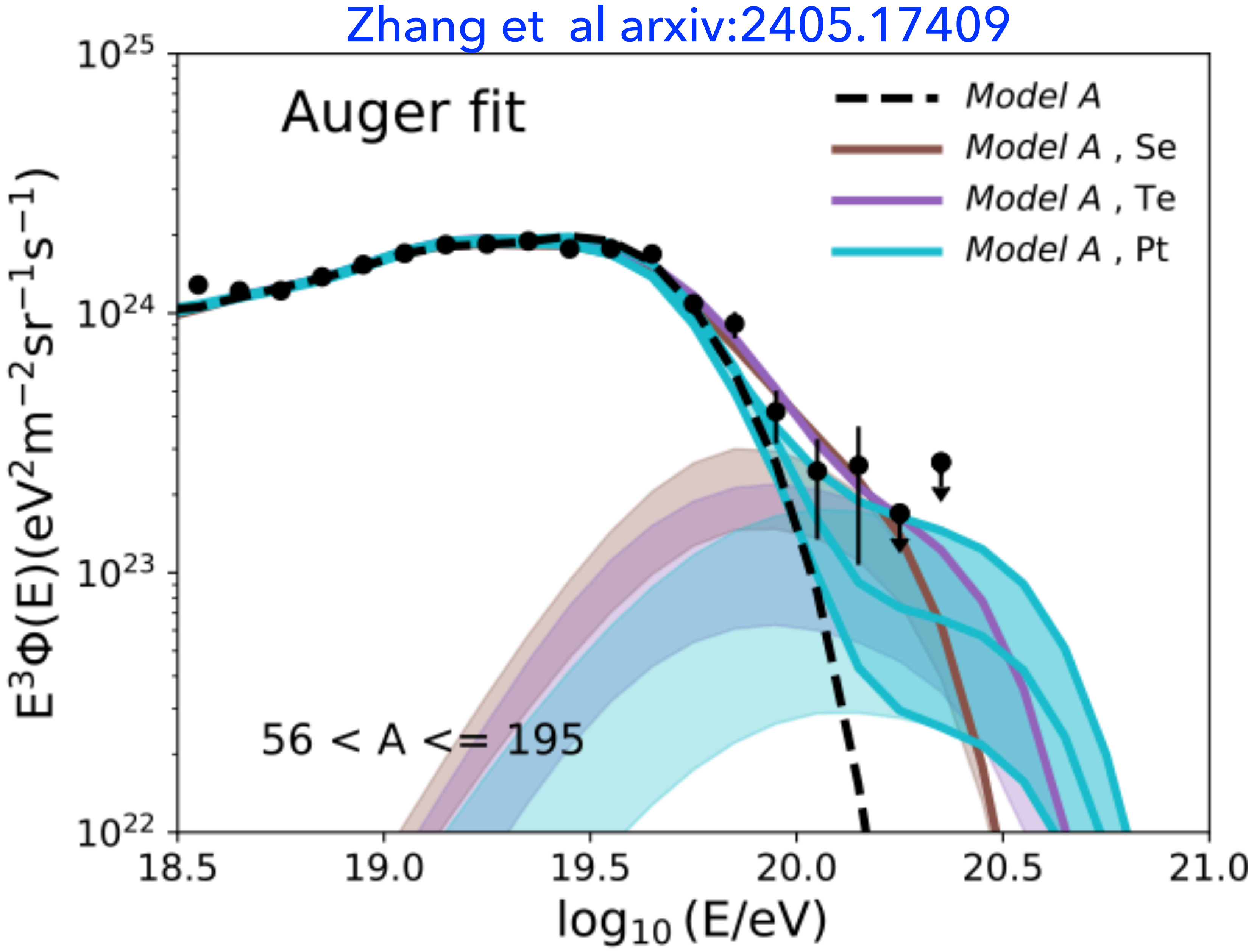
- At the minimum, the ELL are similar to each other
  - The increase in the maximum of the cross section is roughly compensated by the multiplicity
- If the ELL as a function of the Lorentz factor is taken into account,
  - The rapid decrease of the ELL has similar behaviour for each nucleus

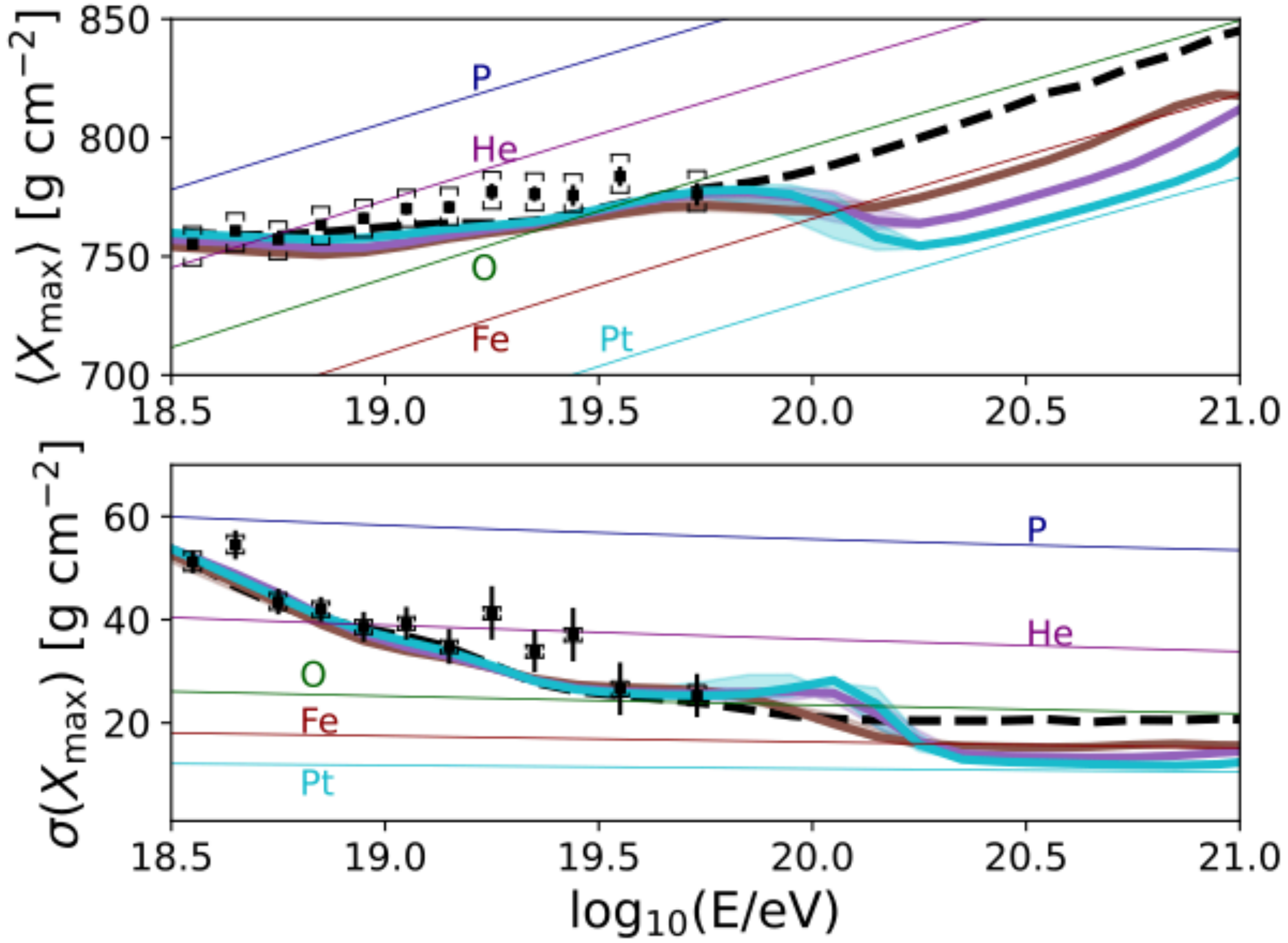


- At a fixed energy, the ELL increases with A
  - A larger portion of the Universe is available if nuclei with large A are considered

What can we learn from the highest energy CRs?

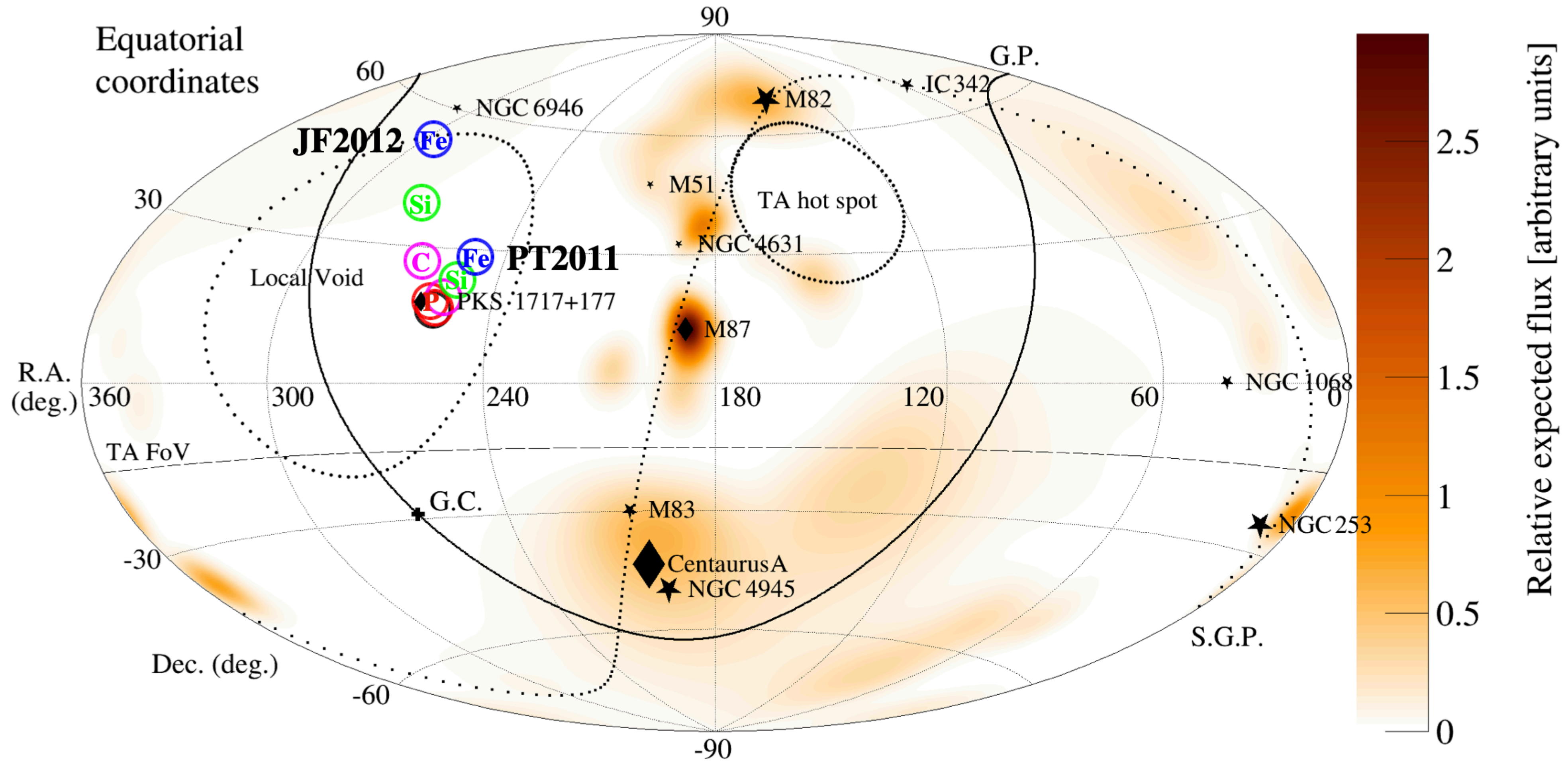
Zhang et al arxiv:2405.17409





$\Delta \ln A \approx 1.2$

- Combination of nuclear species up to A=56 + ultra-heavy nuclei
- Ultra-heavy nuclei
  - can reach larger energies with the same rigidity at the sources, compared to heavy nuclei
  - can be used to test the trend of the mass observables at the highest energies



Telescope Array Collab, Science 2023

- Amaterasu event, 244 EeV -> coming from a local void?
- Lack of a nearby source for Amaterasu
  - larger magnetic deflections than predicted by the GMF models?
  - Primary particle heavier than the ones considered?
- See Unger & Farrar ApJL 2024

SUMMARY

- Nuclear species up to A=56 are usually taken into account in UHECRs
- Among UHECR candidate sources, there can be conditions to have nuclei heavier than A=56
- At the highest energies, UHECR mass composition observables indicate that the mass composition is heavy… **how heavy?**
- The universe accessible with UHECRs depends on the nuclear species
- Among the open issues in UHECR physics: **how are they accelerated?** Example of acceleration of iron nuclei in young fast-rotating pulsars, see Blasi et al ApJL 2000; Kotera et al JCAP 2015. Can this be extended to heavier nuclei?

- SimProp, work in progress:
  - Increased list of stable nuclei (from A=56 to A=195)
  - TENDL2021 cross sections (TALYS) with one-nucleon emission
- Cross section models for heavy nuclei less affected by uncertainties with respect to lighter ones (?) -> example: the E1 function (electric dipole excitation mainly responsible for the giant dipole resonance) has been studied for the mass region above A=90, where nuclei exhibit lesser dependence on the shell structure
- Input from air-shower simulations needed to design a science case

- SimProp-Sirente, work in progress:
  - New Cross section models, Poster at UHECR24