Unknowns in multimessenger high-energy astrophysics and their influence in the search for Lorentz invariance violation

Denise Boncioli

Università degli Studi dell'Aquila, Dipartimento di Scienze Fisiche e Chimiche
Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Gran Sasso

denise.boncioli@univaq.it

BridgeQG workshop
Bridging high-energy astrophysical modelling and Lorentz invariance violation
Annecy, 4-6 February 2026

Outline

- State-of-the-art of UHECR measurements and astrophysical interpretation
- Requests from data about source characteristics
  - What is the energy spectrum and mass composition of UHECRs at the escape from their sources?
    - accounting for extragalactic propagation
    - and for in-source interactions

    -> where could the **proton fraction in UHECRs** come from
- How does **LIV (modified kinematics in interactions)** affect UHECR characteristics?
- Example of LIV search and unknown from UHECR characteristics

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- Example of LIV search and unknown from UHECR characteristics

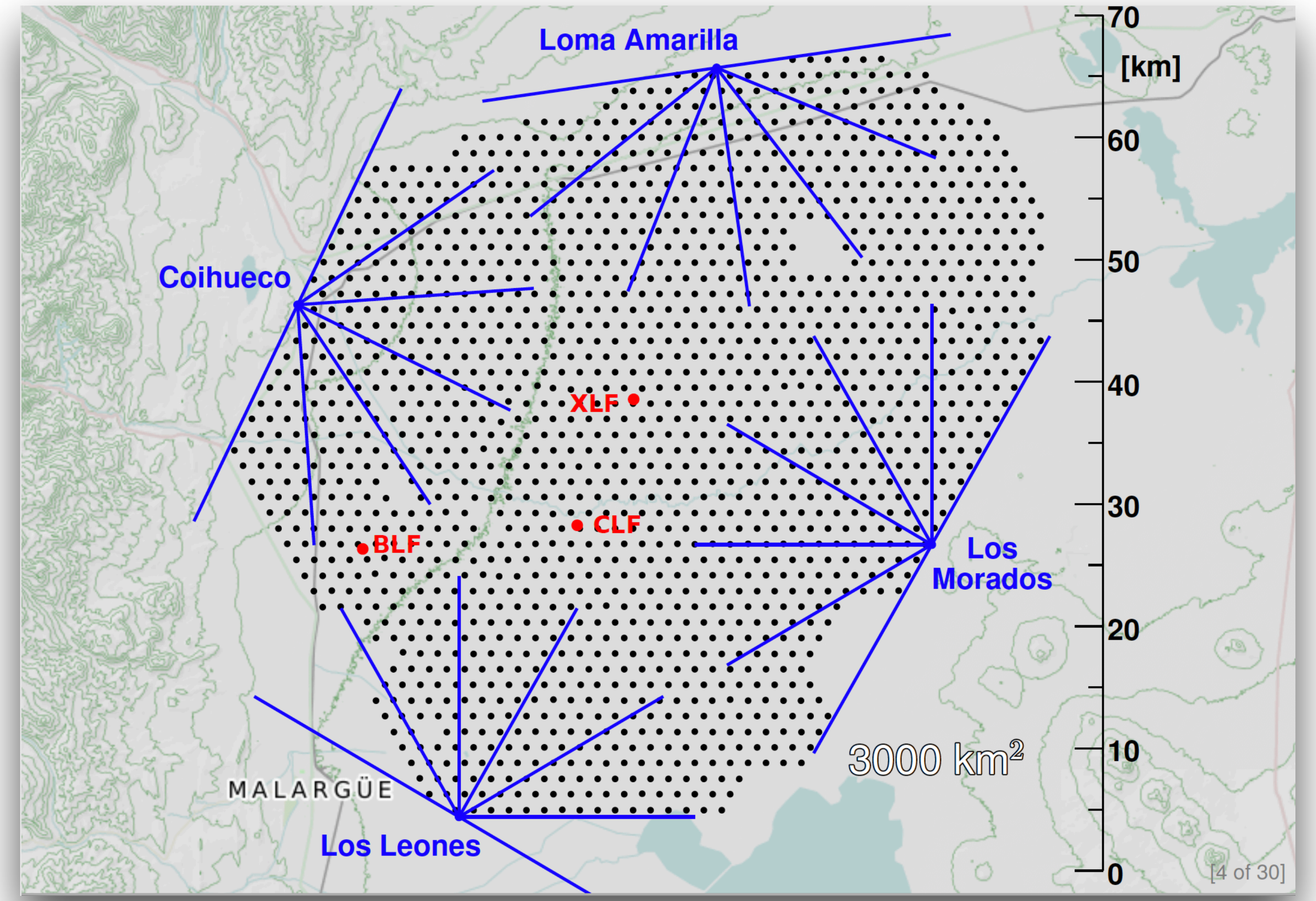
- Simple view:
  - LIV searches with UHECRs would benefit from:
    - Large energy;
    - High intensity of flux (below the "ankle")

  -> the knowledge of the proton component in UHECRs is crucial

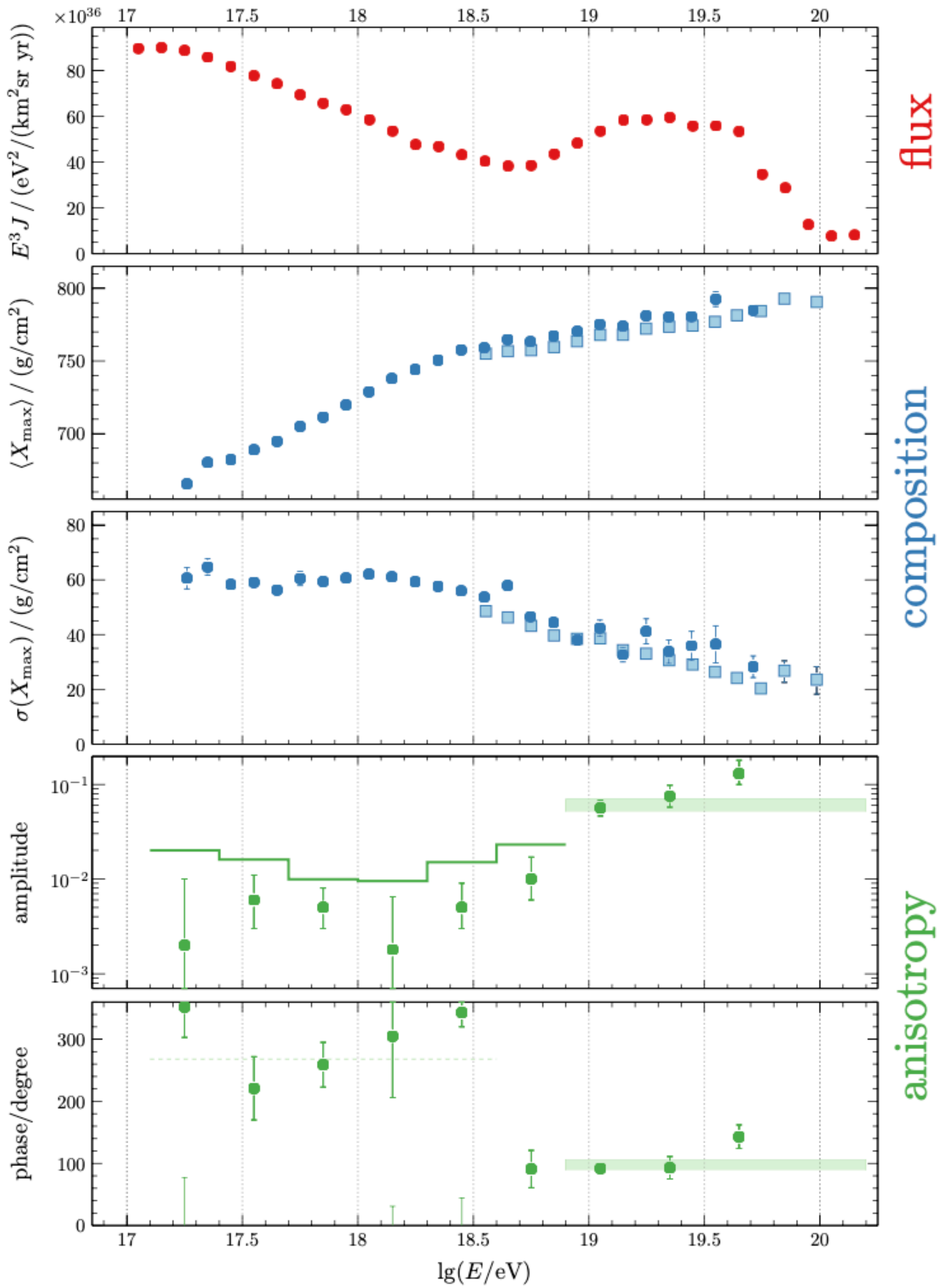
STATE-OF-THE-ART: MEASUREMENTS

State-of-the-art of the latest UHECR measurements

- Features in the energy spectrum
- Changes in mass composition
- Extragalactic origin from anisotropy signal



+ upgrade of Auger detectors (AugerPrime)



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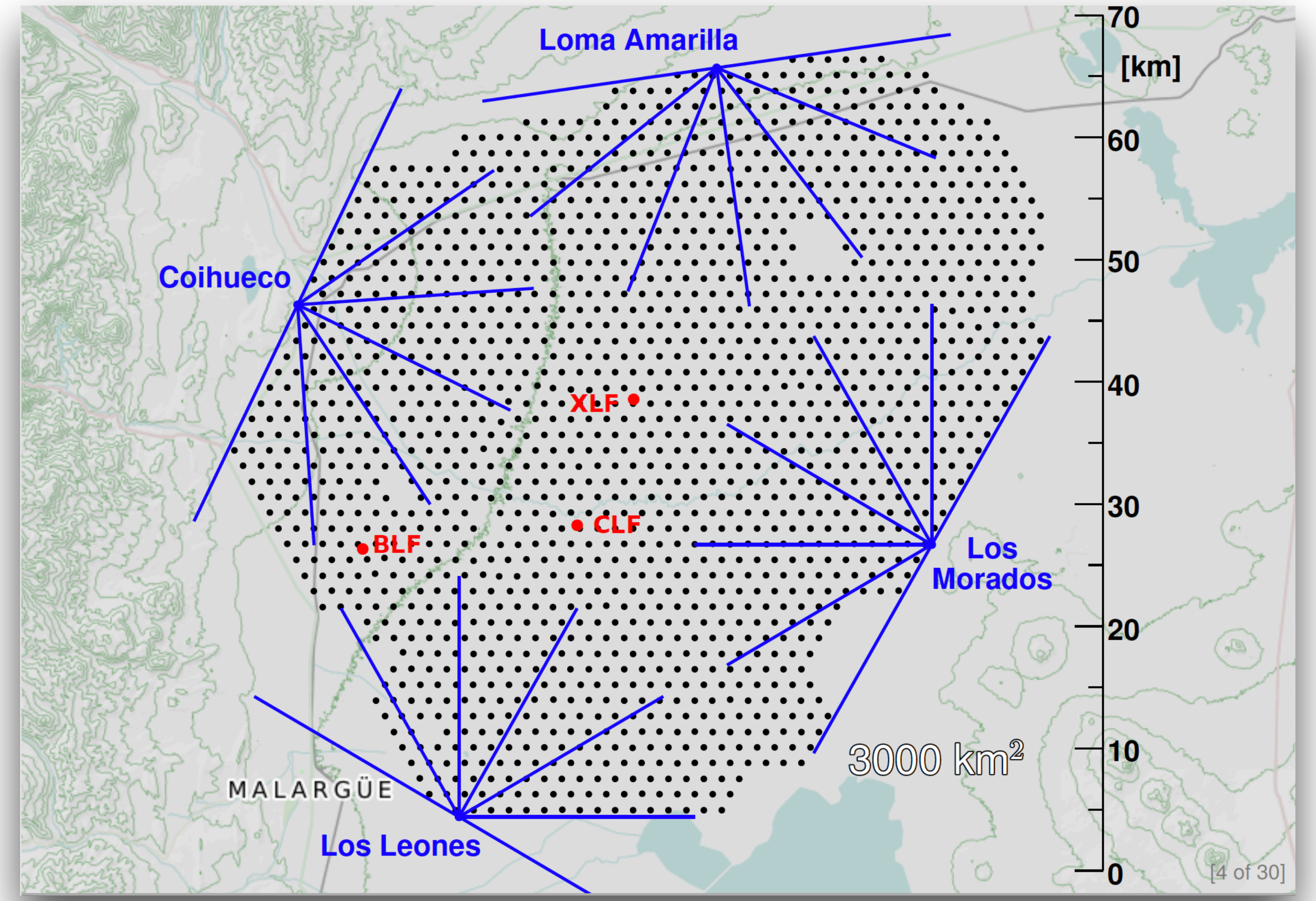

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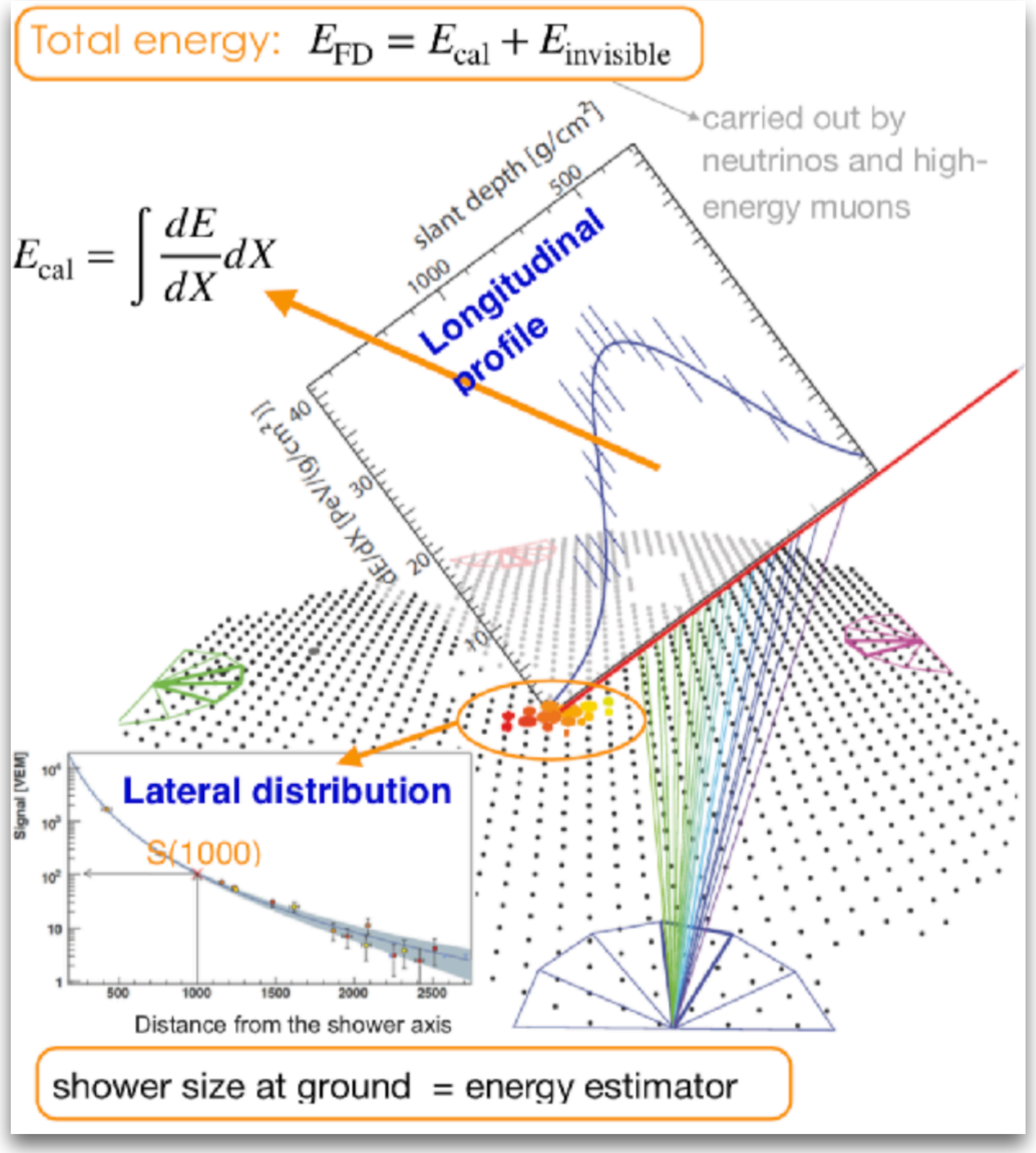
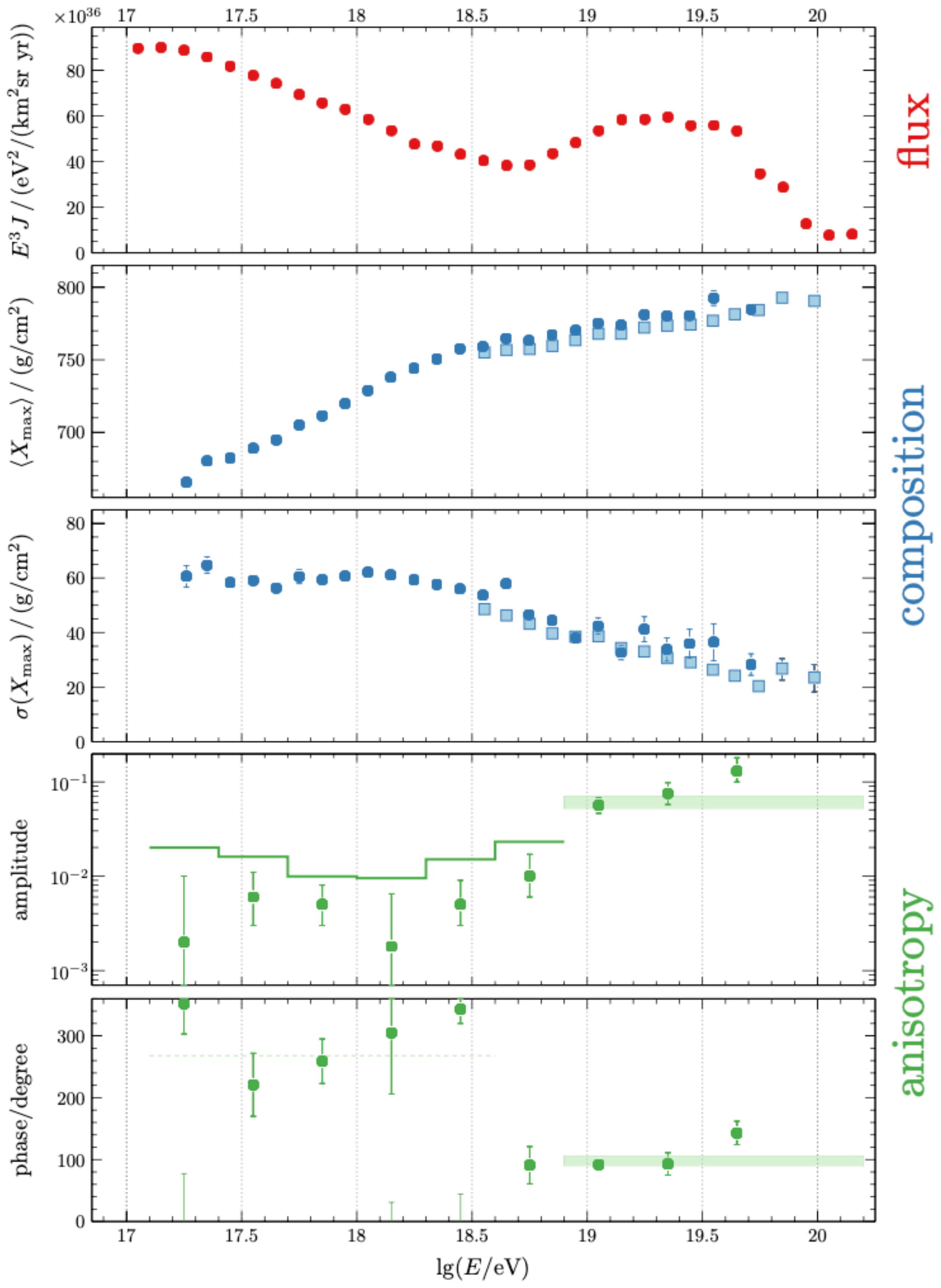
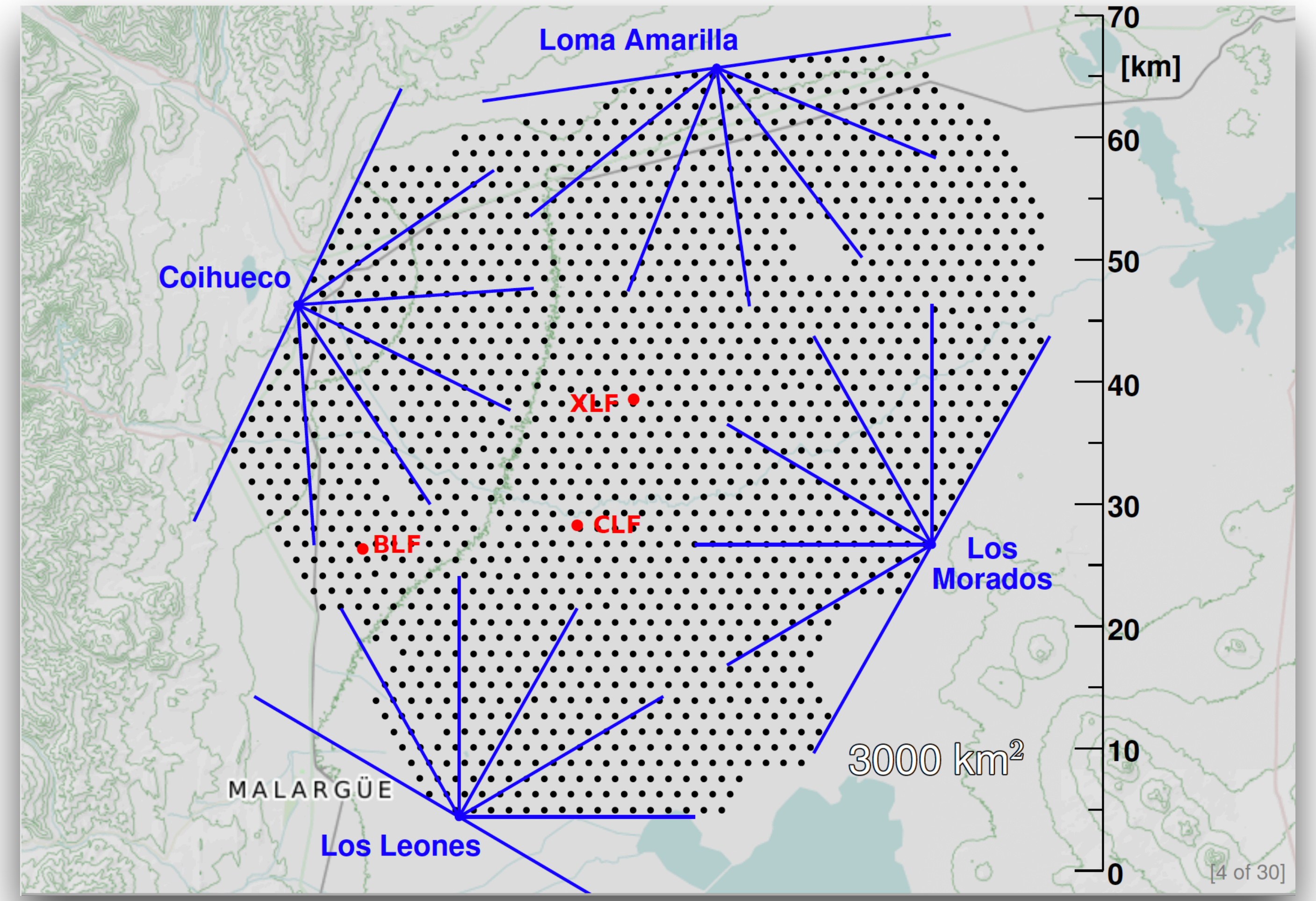




The Pierre Auger Collab. ICRC25

State-of-the-art of the latest UHECR measurements

- Features in the energy spectrum
- Changes in mass composition
- Extragalactic origin from anisotropy signal
- Coherent results with non-observation of cosmogenic particles



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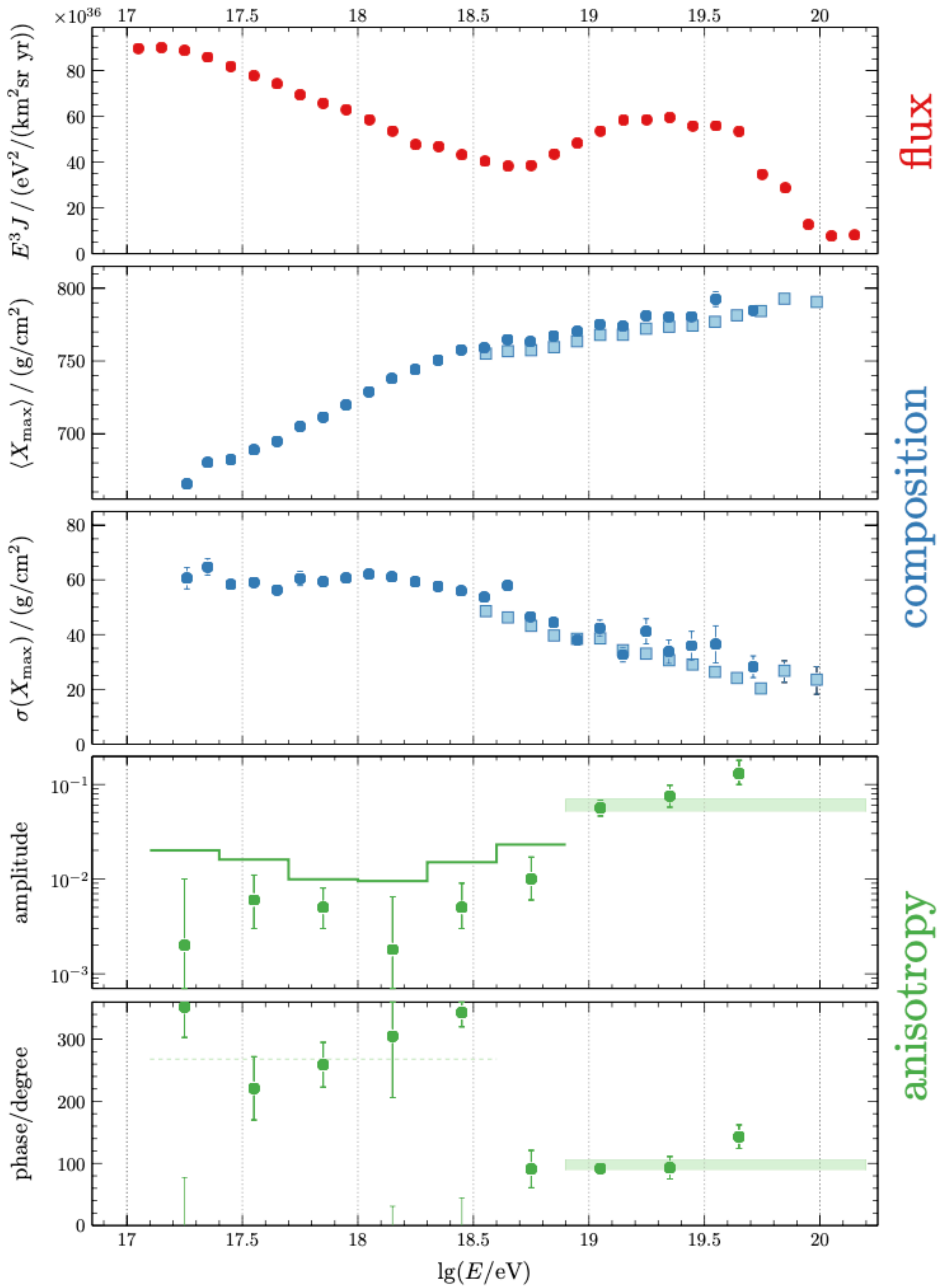

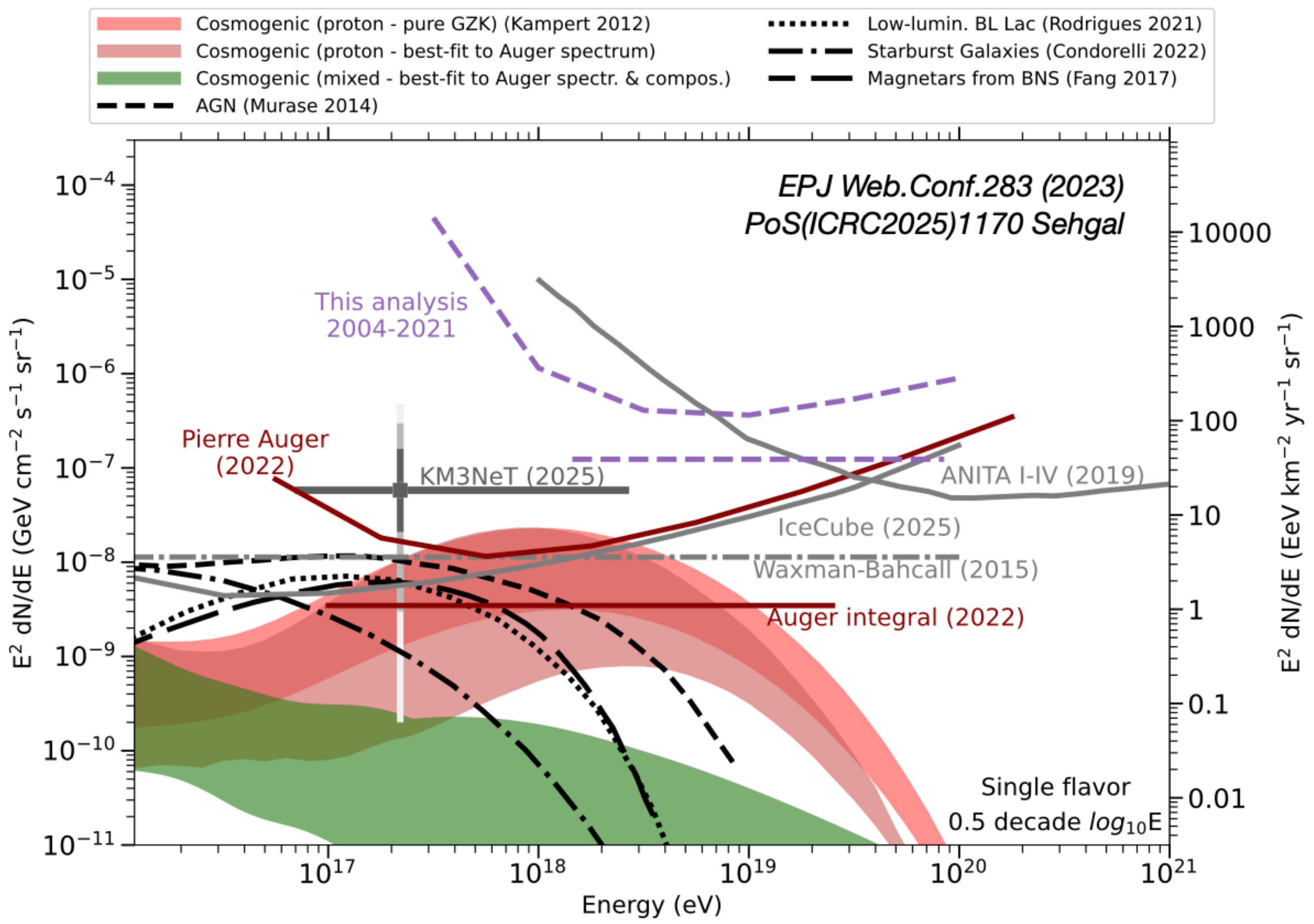

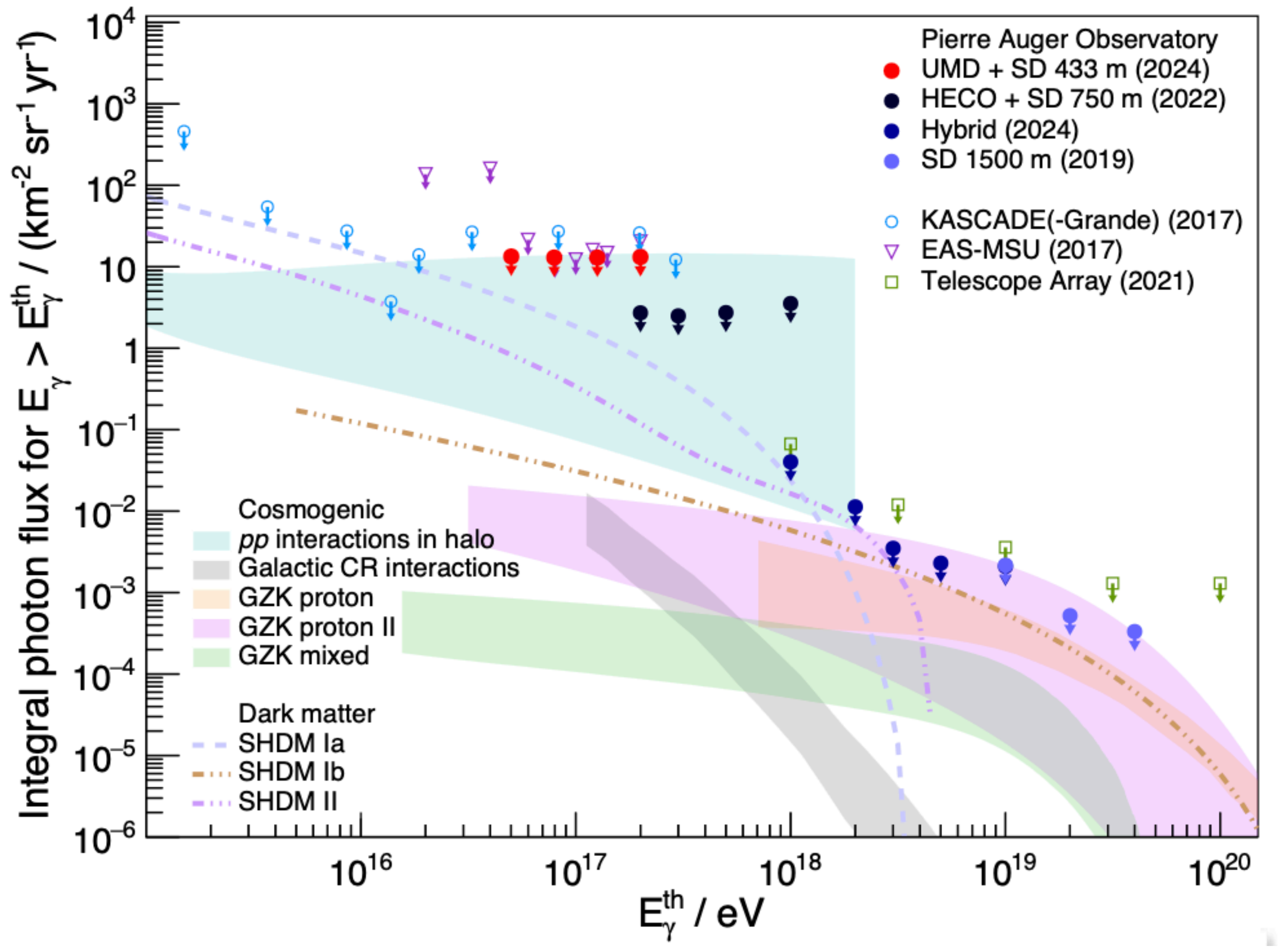

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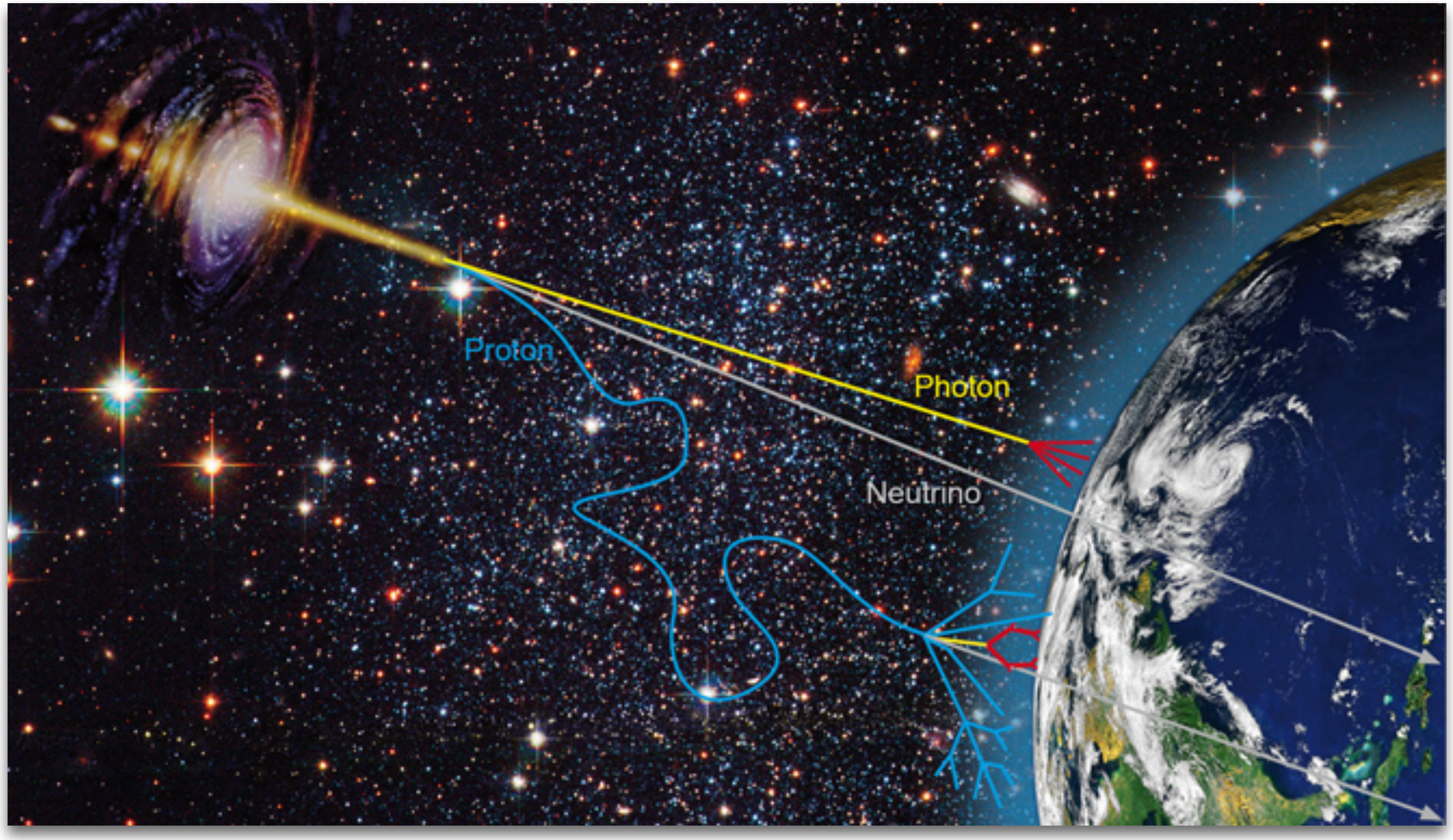
STATE-OF-THE-ART OF ASTROPHYSICAL INTERPRETATION

State-of-the-art: astrophysical scenarios



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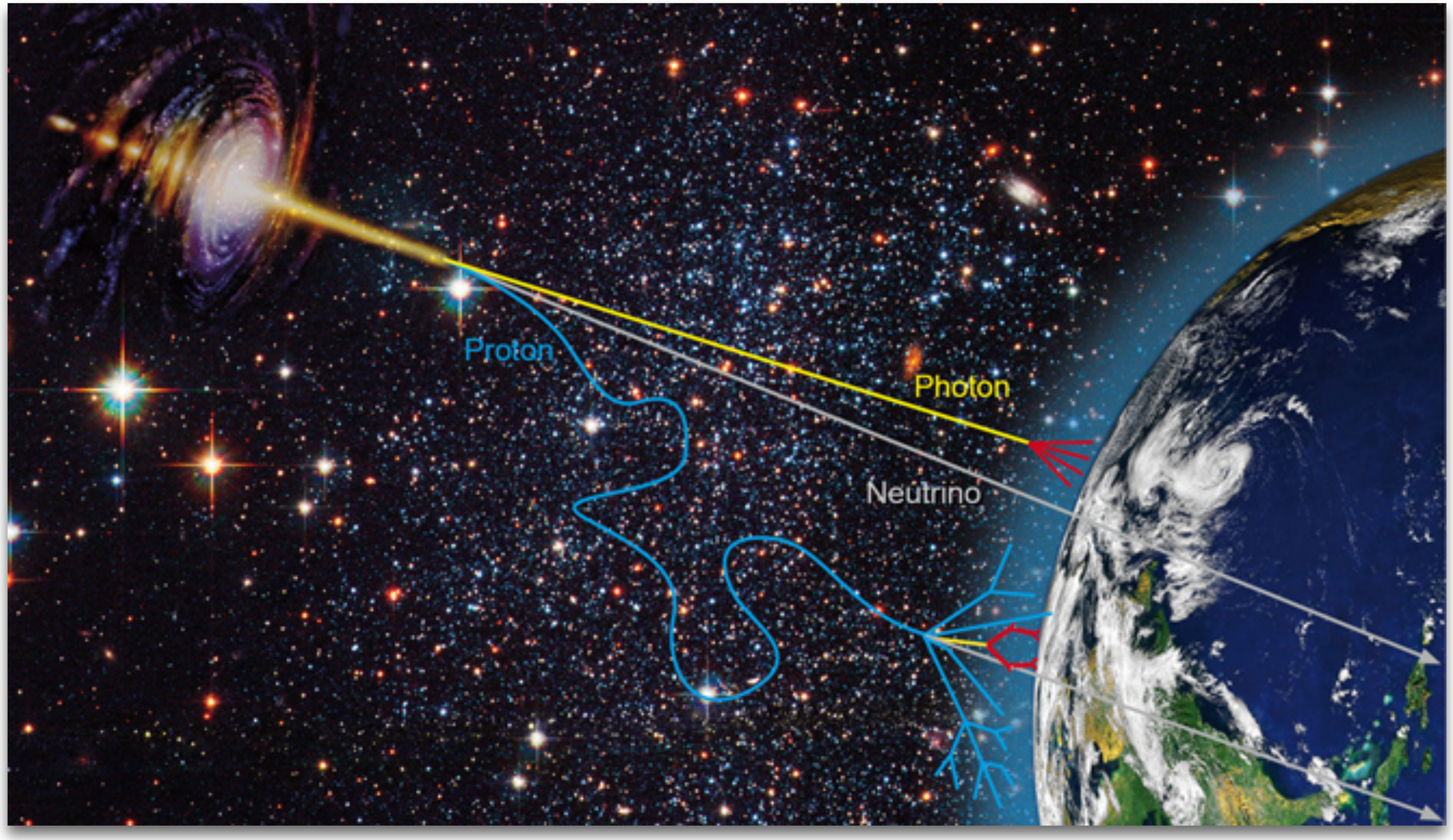

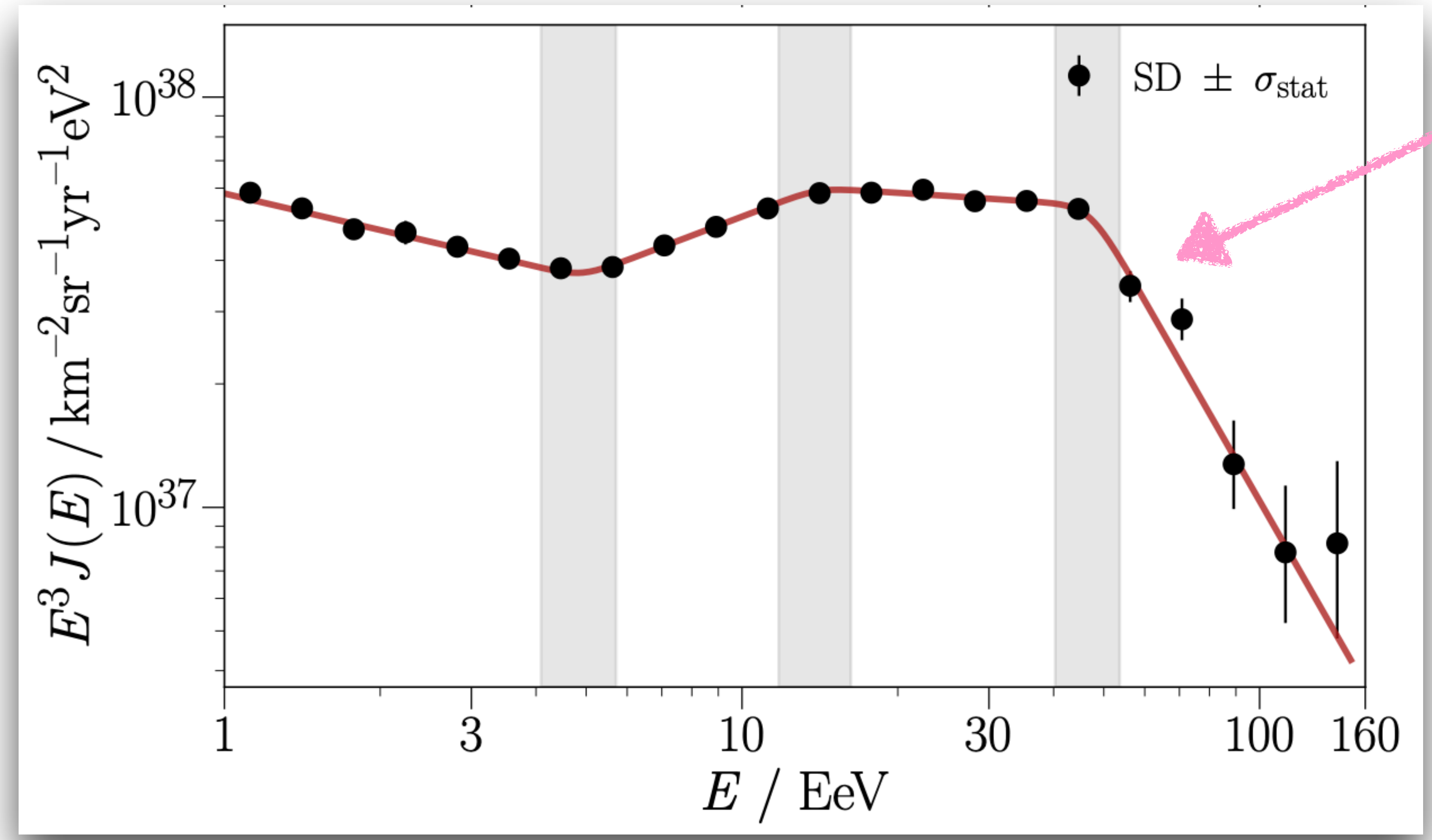

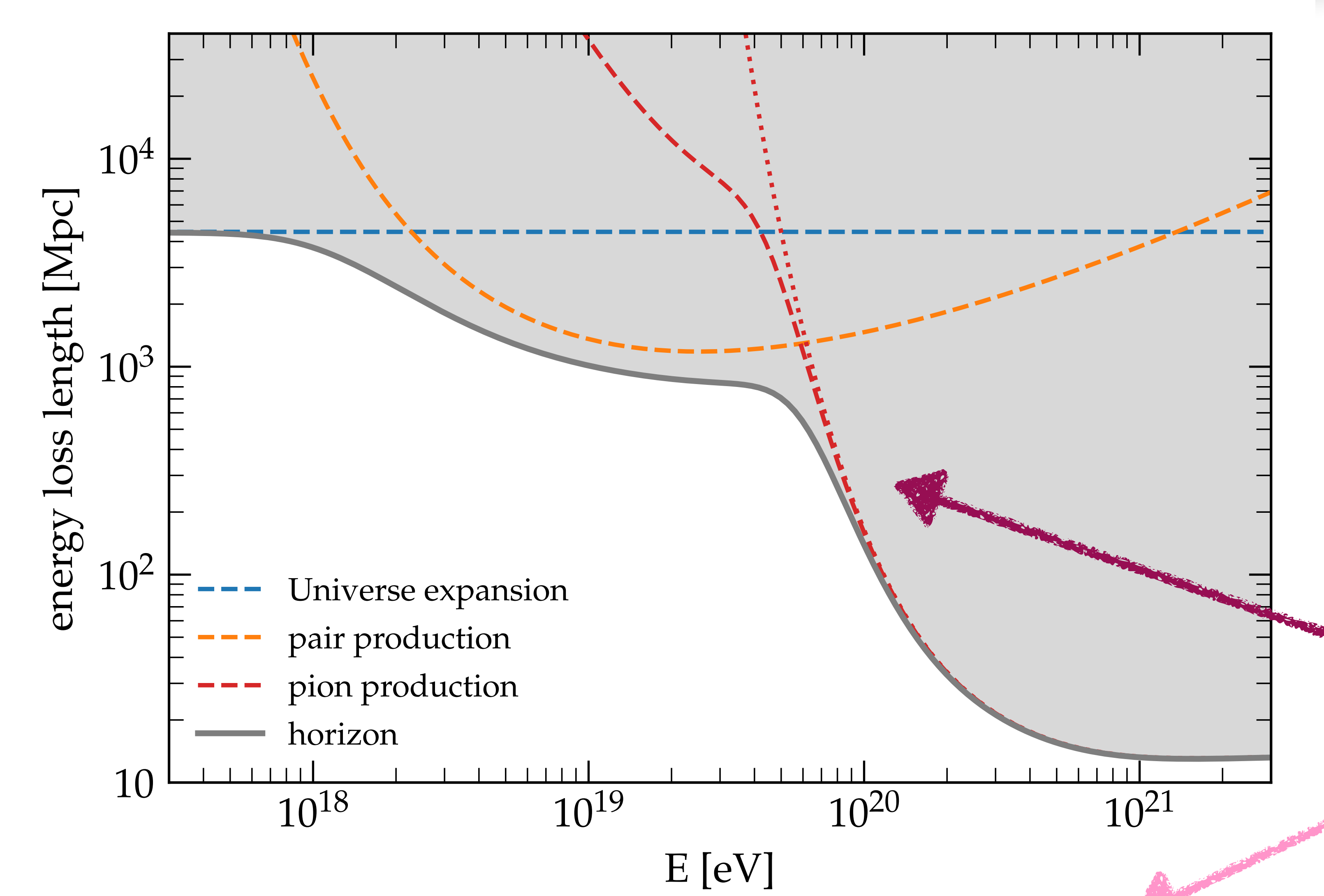

- Basic example (dip model, Berezinsky et al PRD 2006: the suppression of the spectrum could be explained with propagation effects (protons losing energy because of photopion production: **GZK effect**)

$$p + \gamma_{\rm bkg} \rightarrow p + \pi$$

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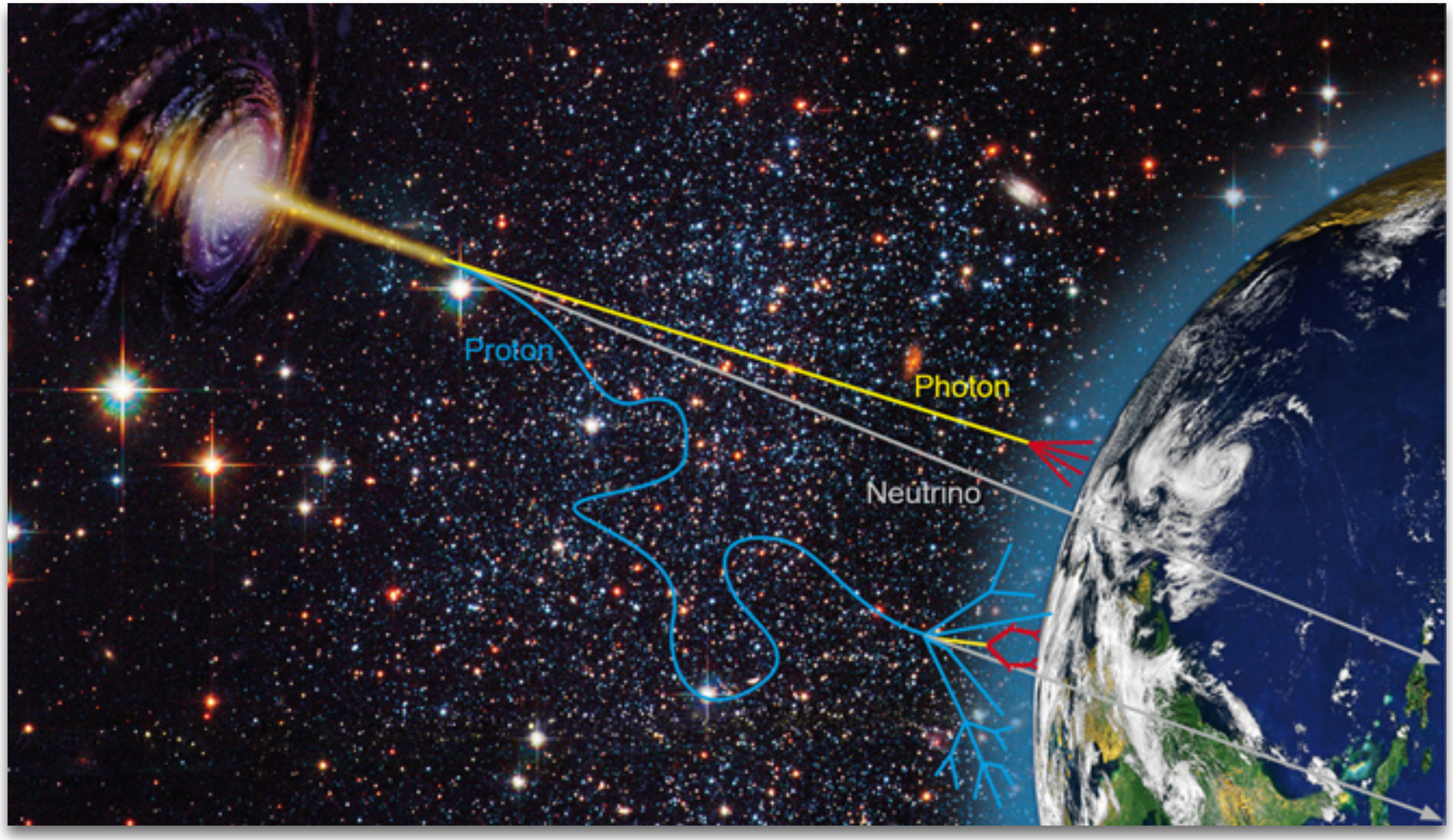

$$A + \gamma \rightarrow A' + (m)n + (A - A' - m)p$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$

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$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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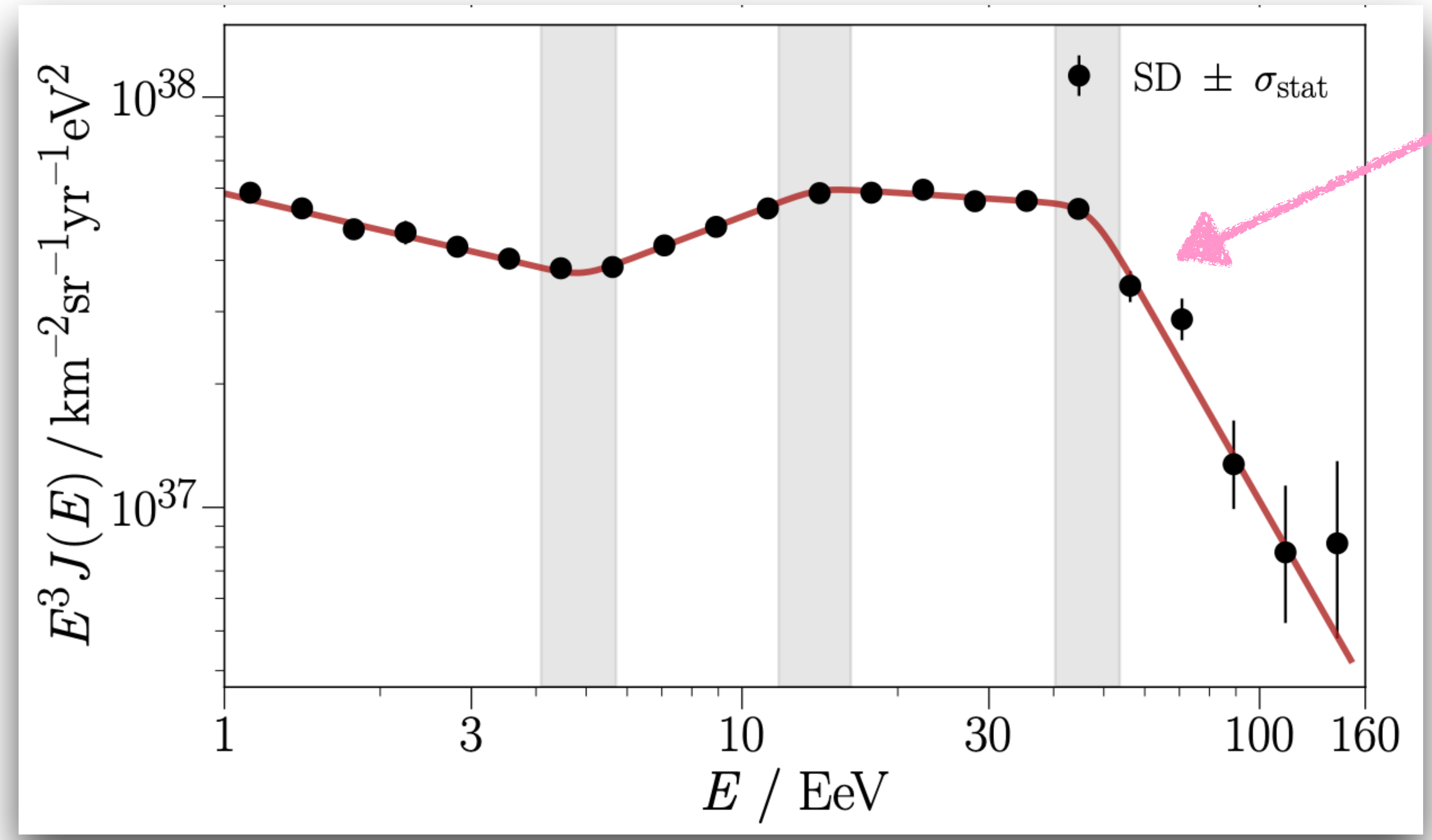
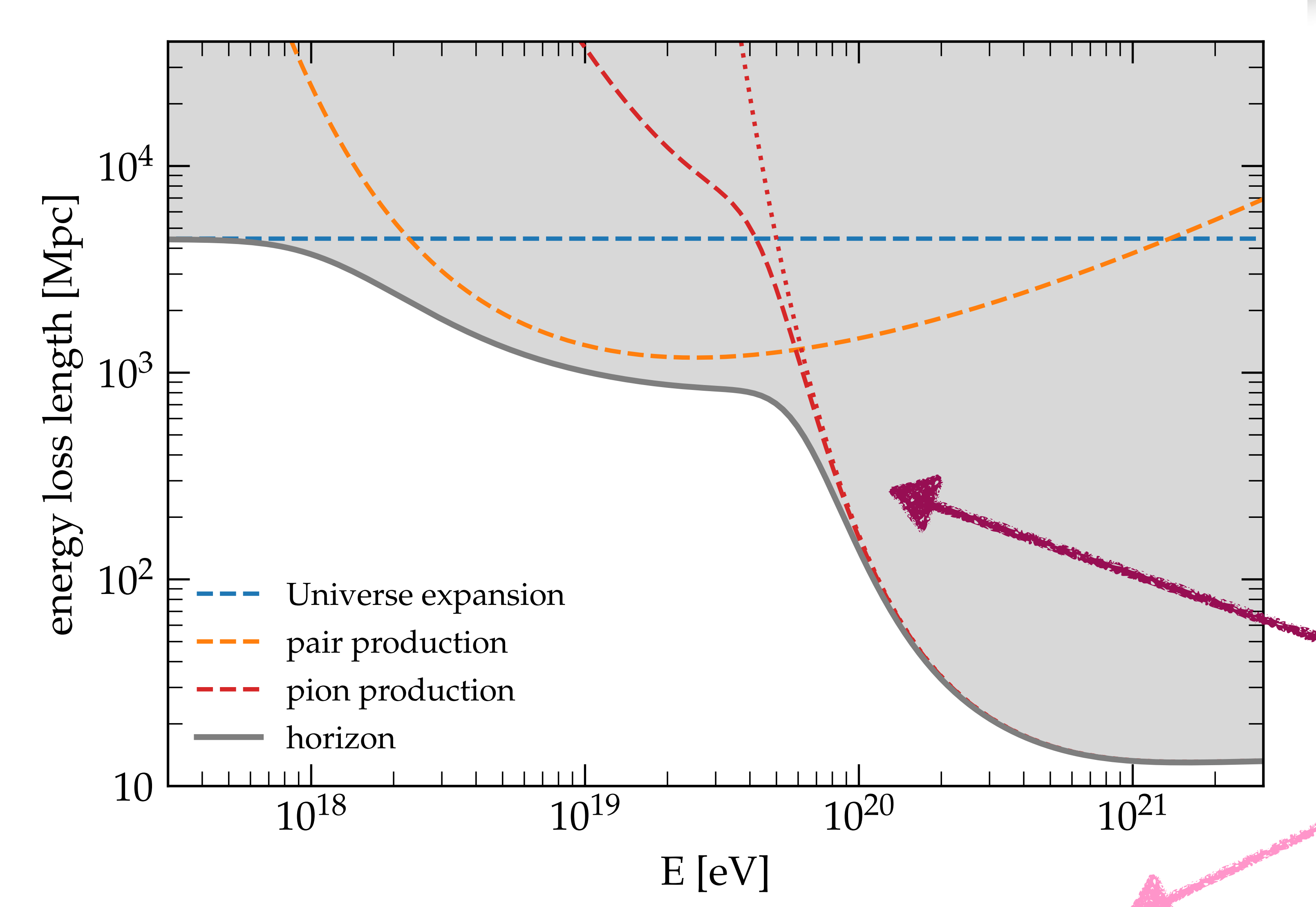
$$\pi^0 \rightarrow 2\gamma$$





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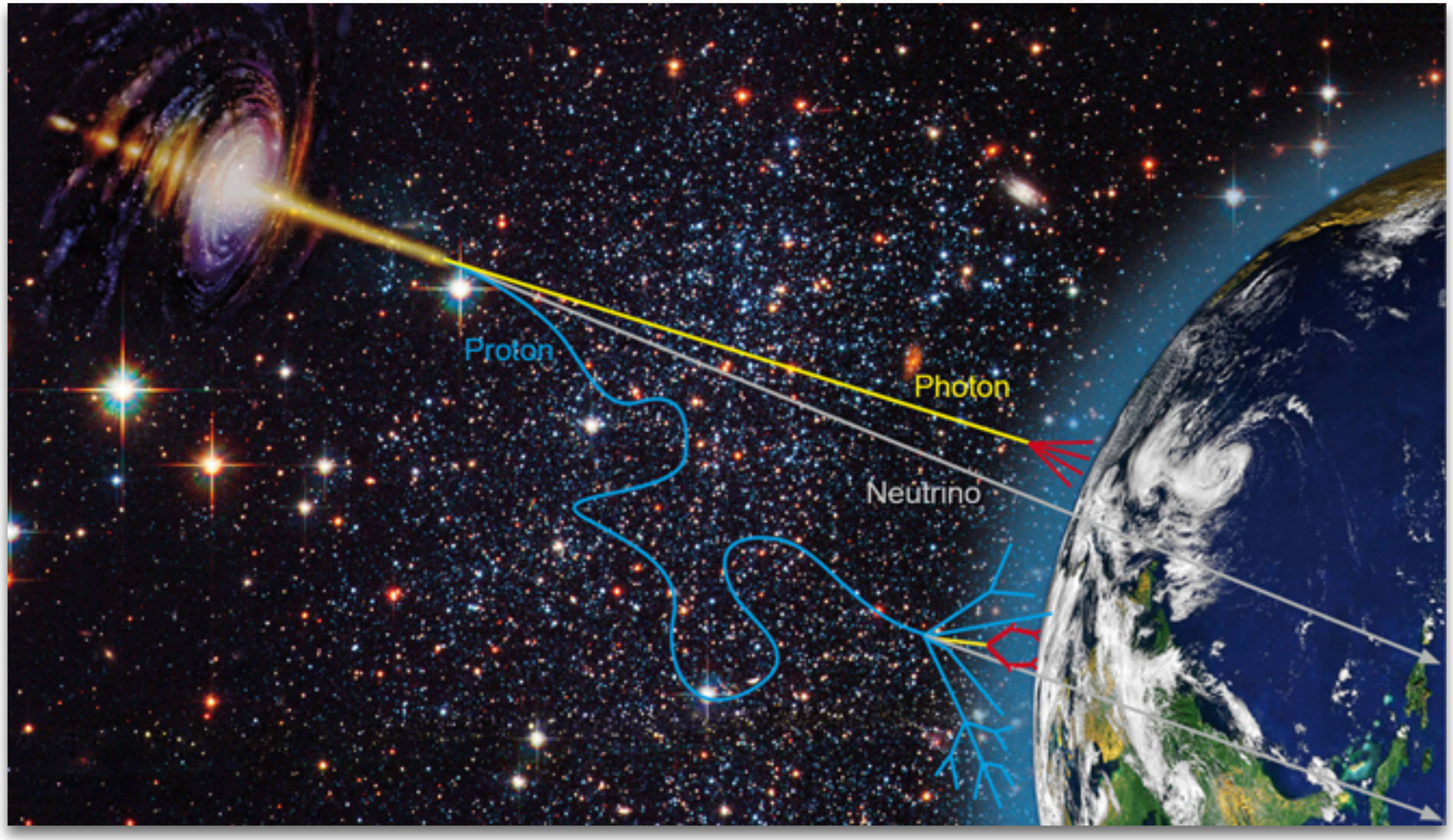

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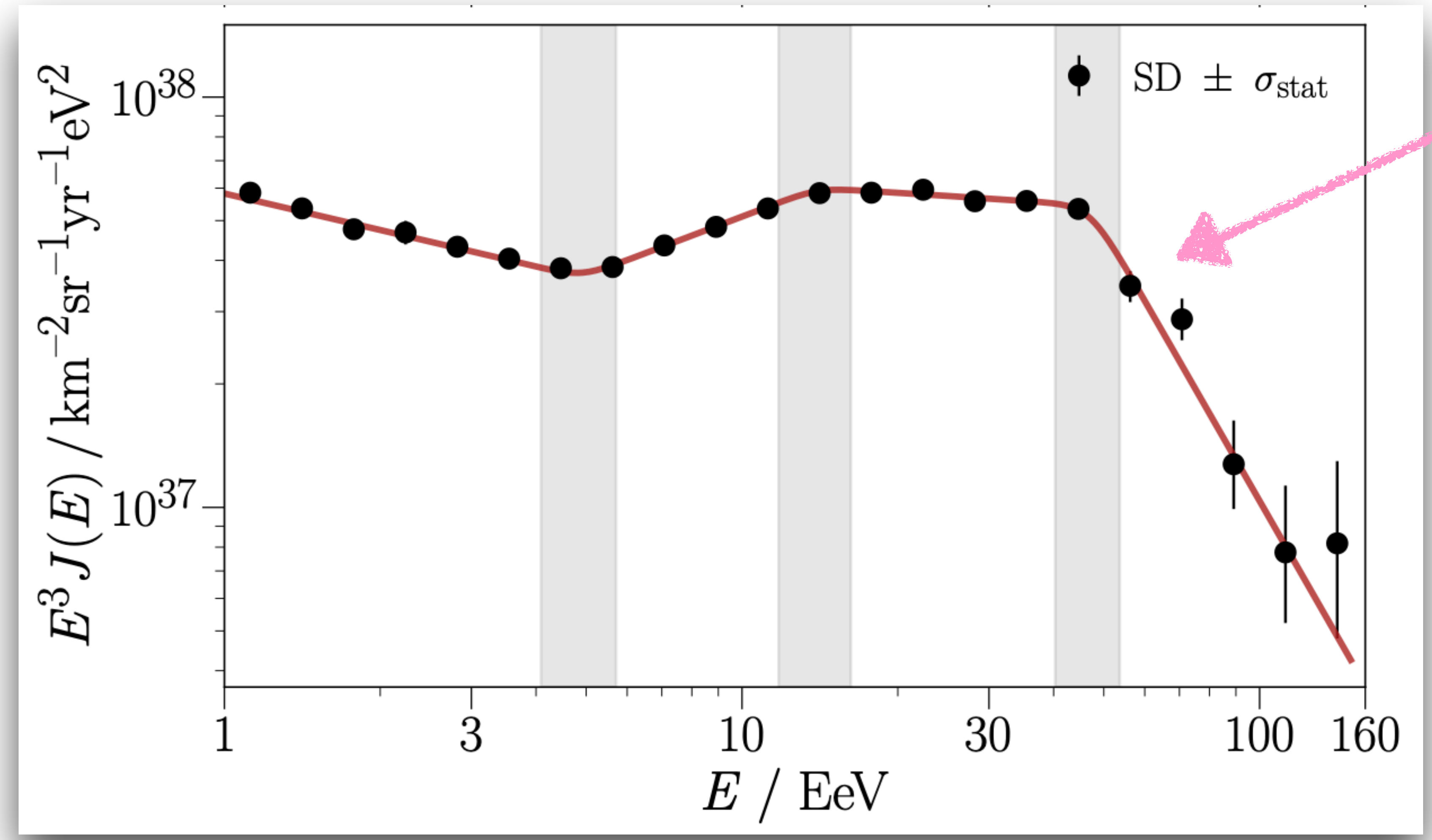
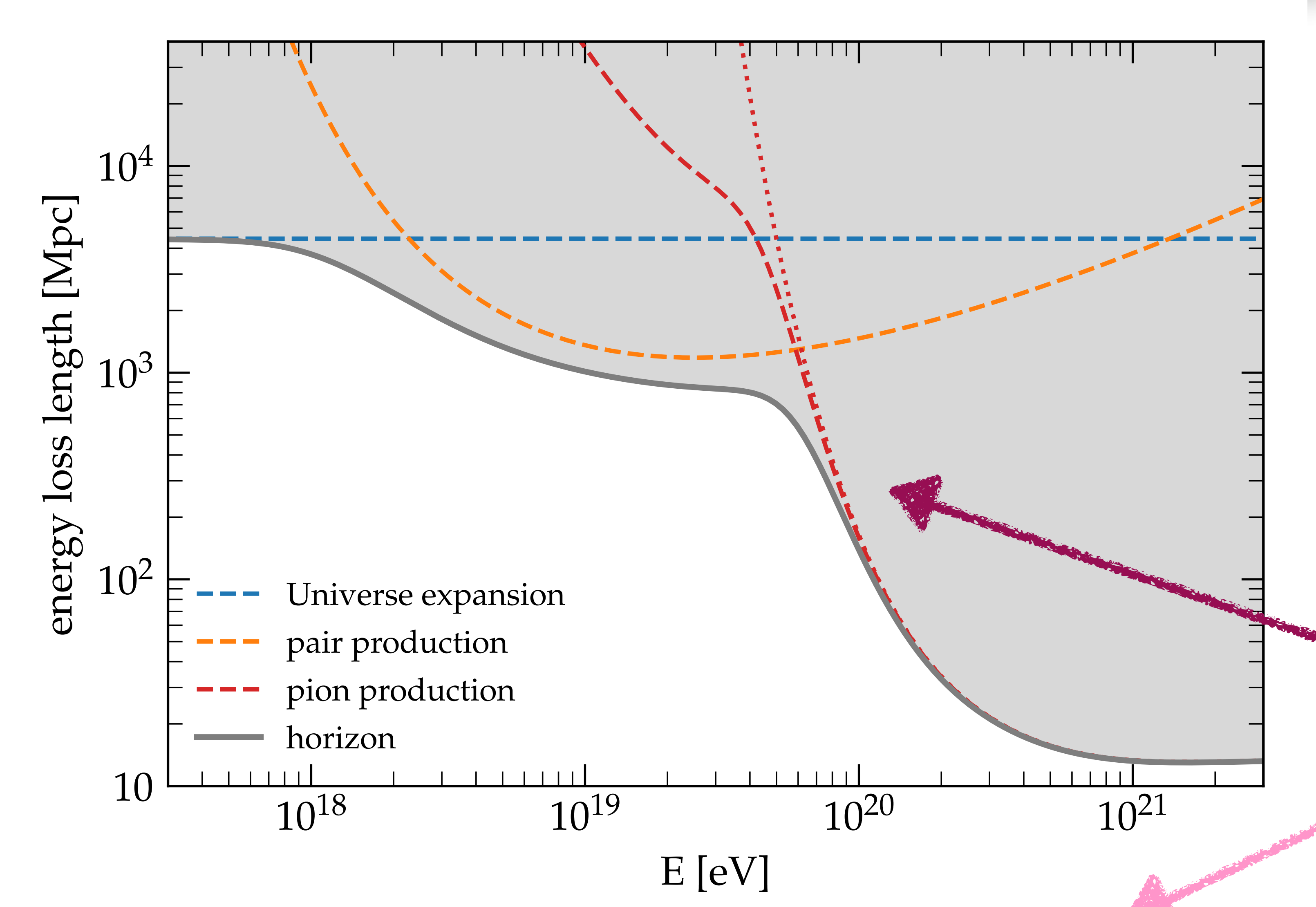
- In terms of secondary messengers:
  - The energy threshold for UHECR nuclei for photo-pion production is proportional to the mass
  - The heavier the UHECR mass composition, the smaller the expected cosmogenic flux





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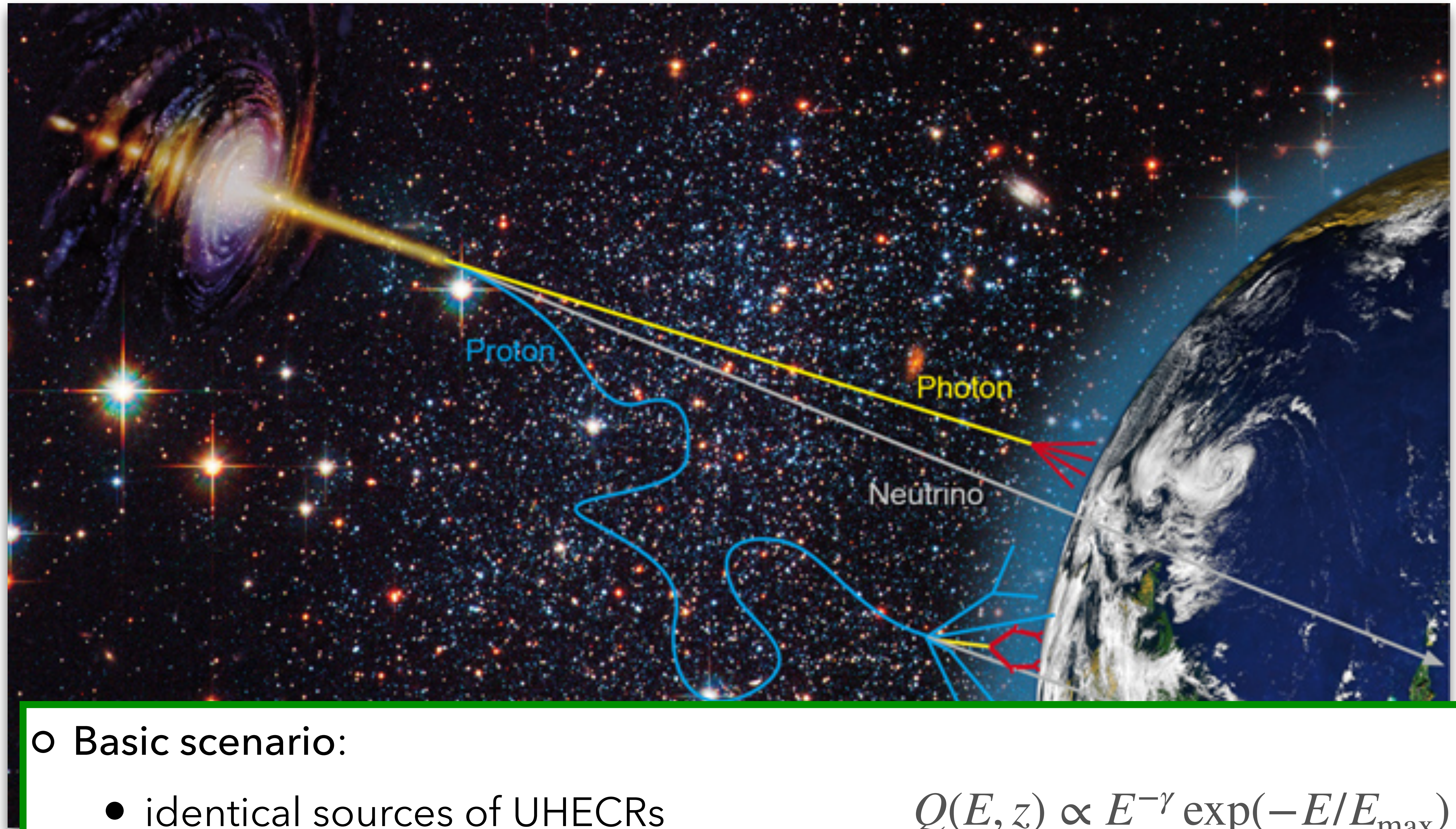
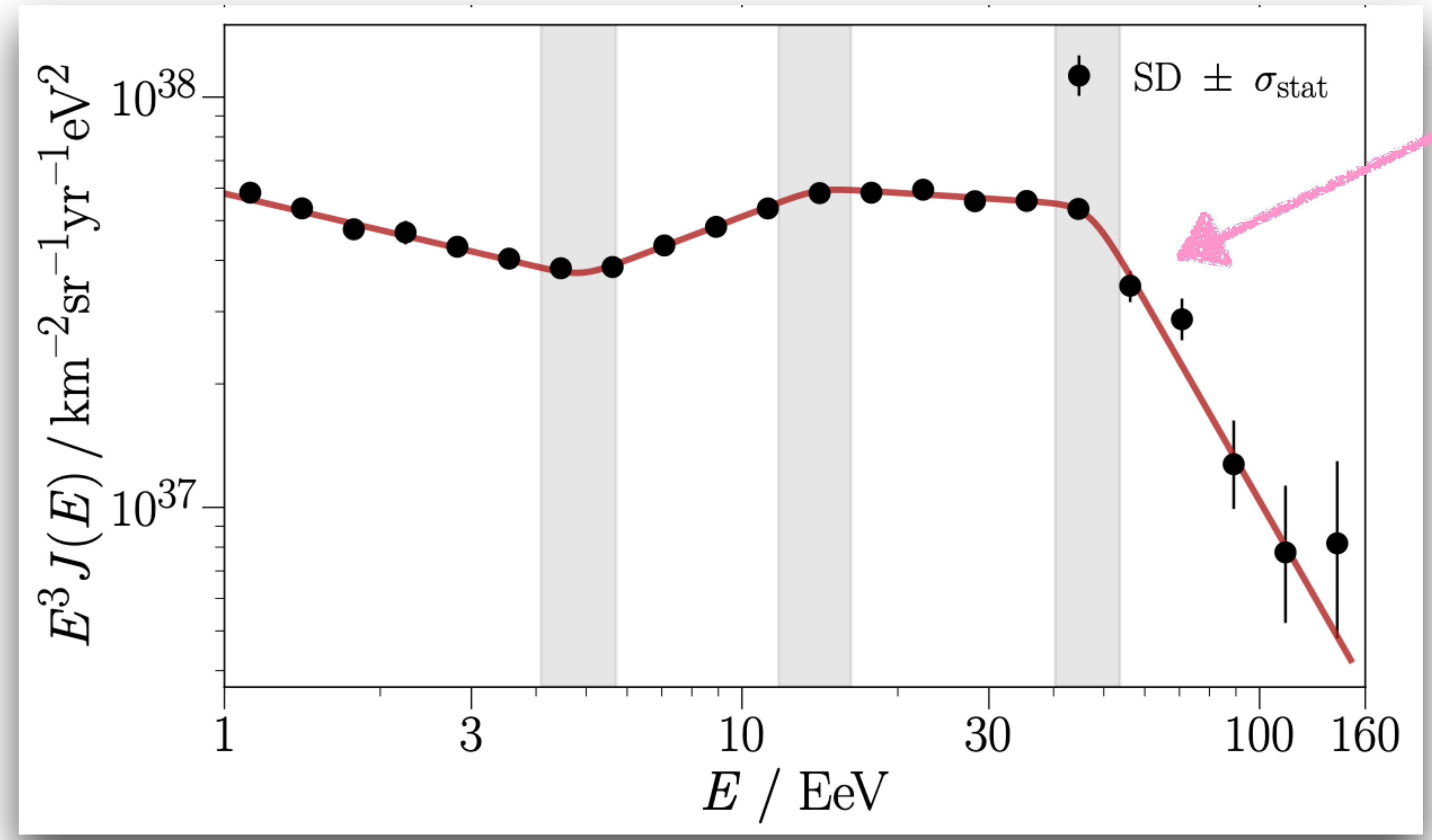
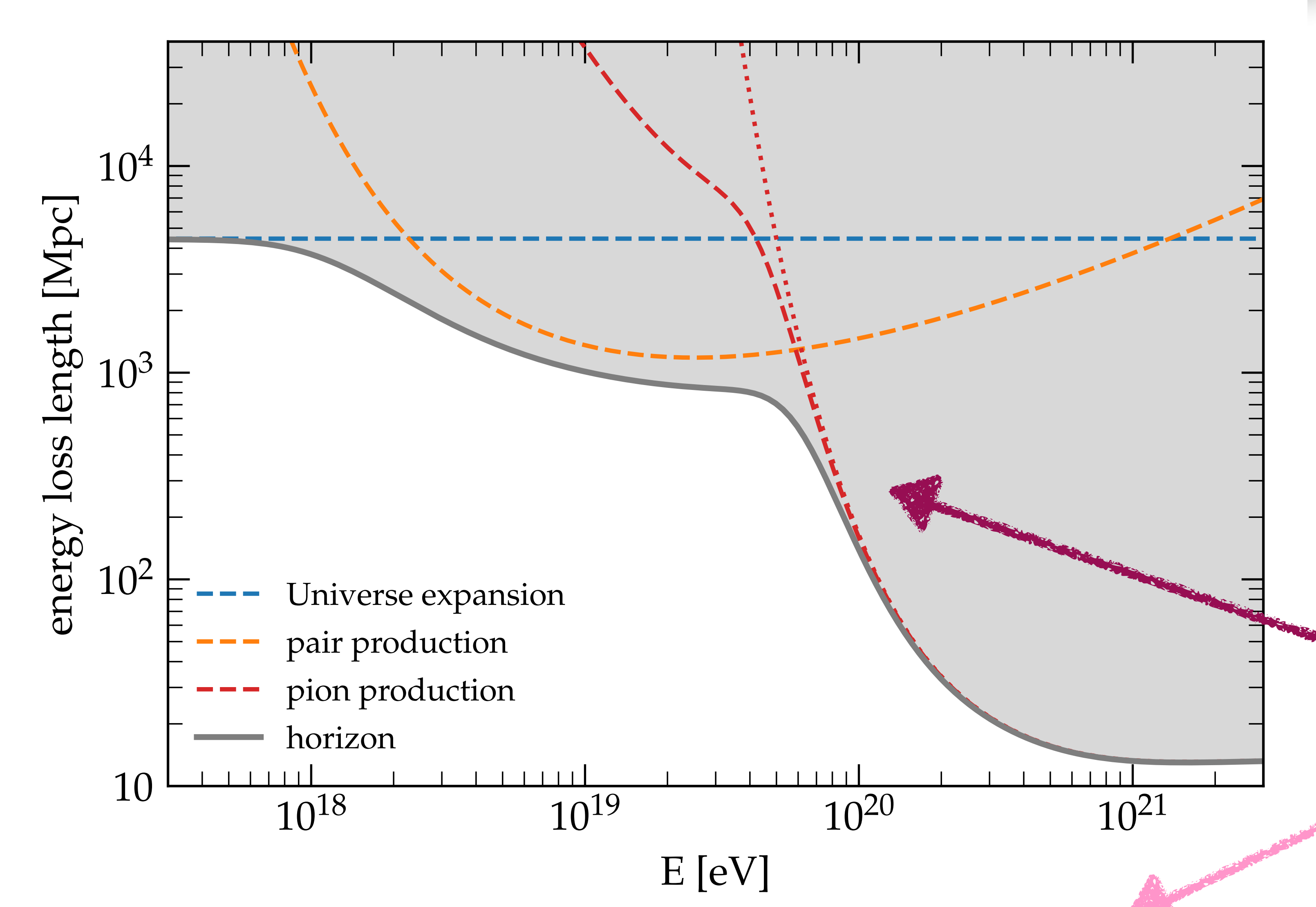


- Basic scenario:
  - identical sources of UHECRs $Q(E,z) \propto E^{-\gamma} \exp(-E/E_{max})$
  - power-law spectra at escape, with <u>rigidity dependence</u> for **UHECR nuclei**
    - <u>Peters cycle:</u> Peters, Nuovo Cimento 1961
- **Extragalactic propagation** taken into account:
  - **SimProp**, Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017
  - **CRPropa**, R. Alves Batista et al, JCAP 2022; A. Saveliev et al. ICRC 2025
- Comparison to UHECR data on energy spectrum and mass composition





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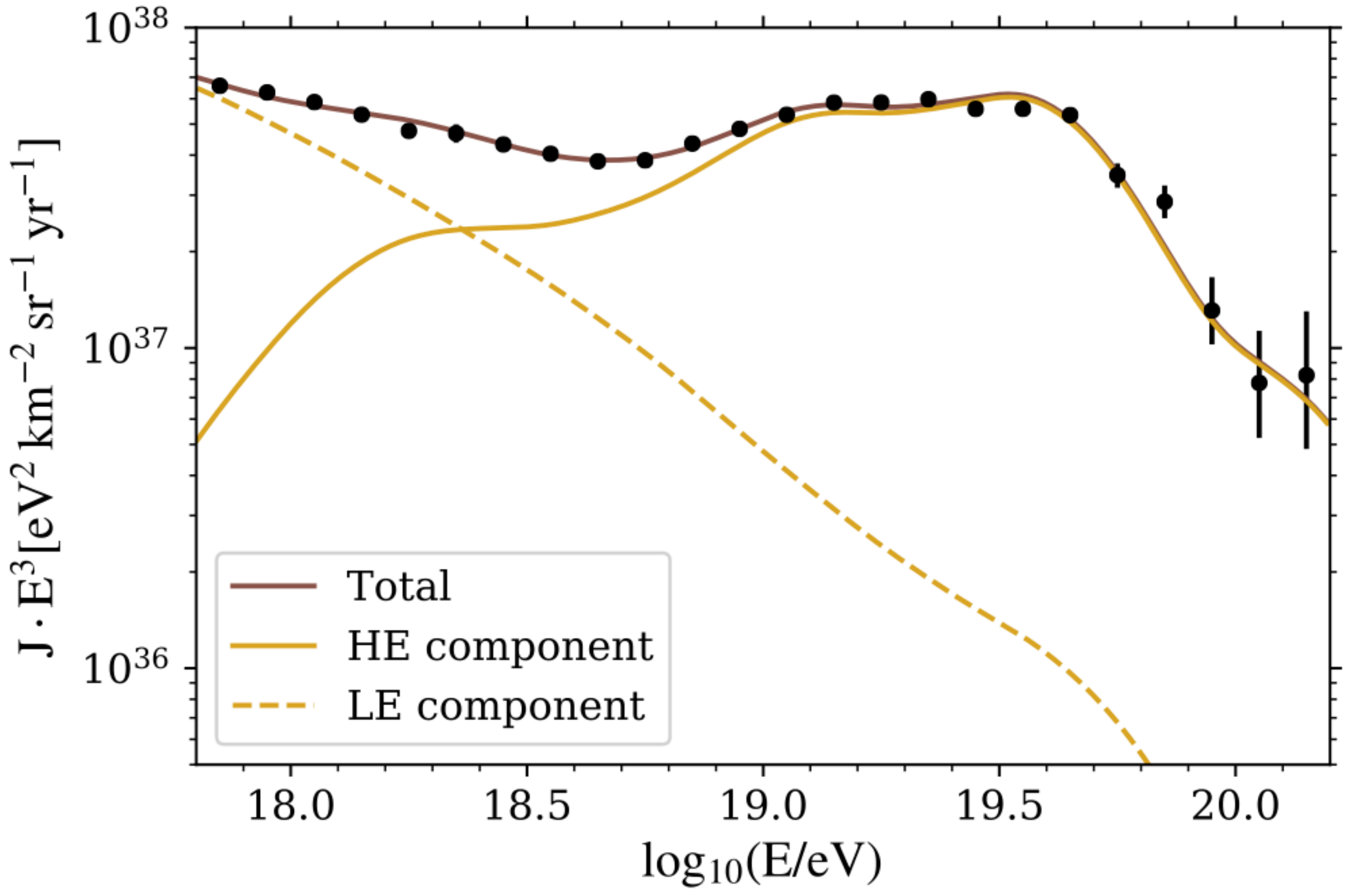

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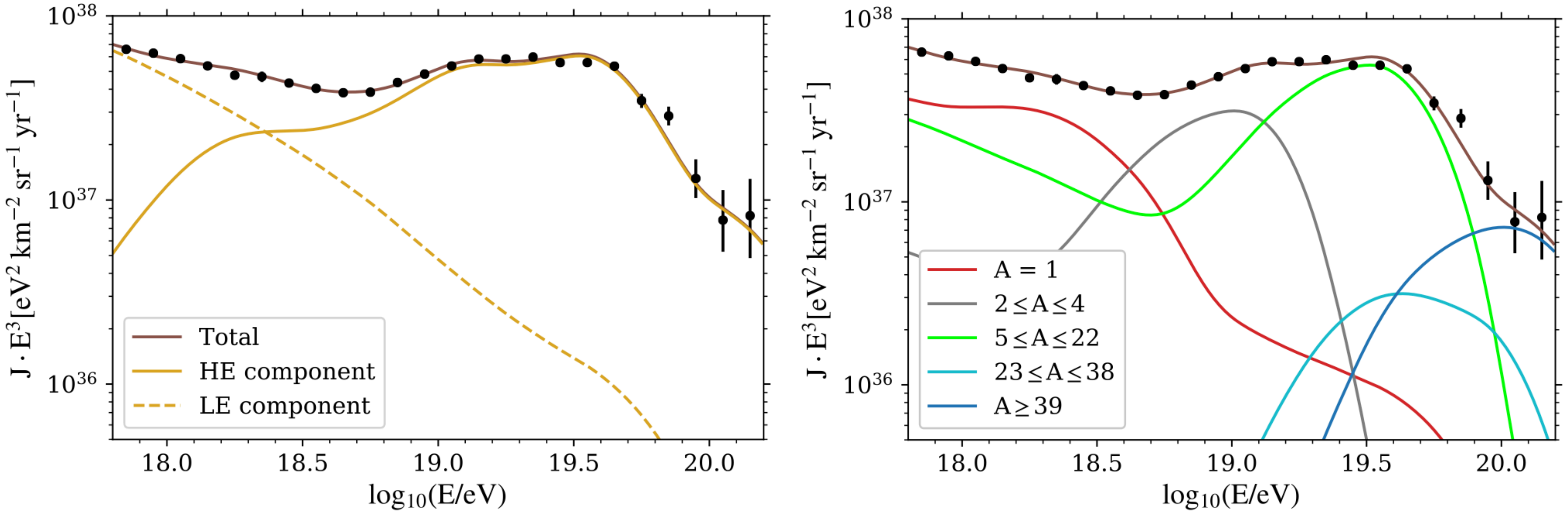
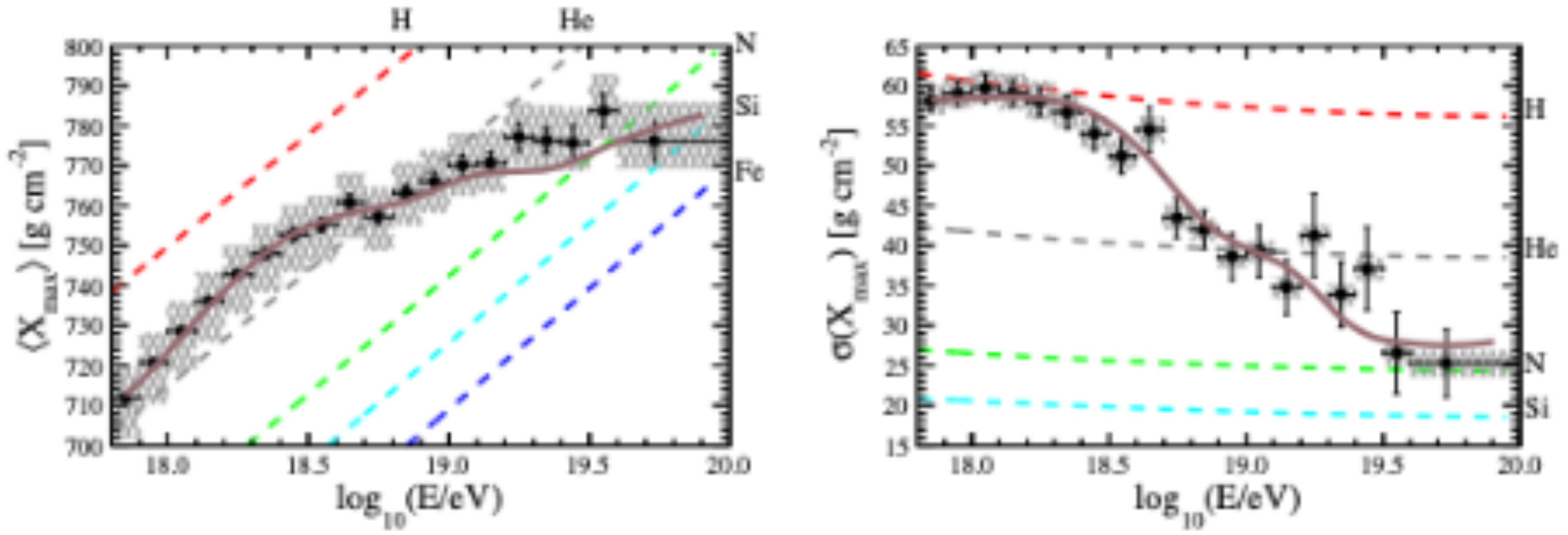
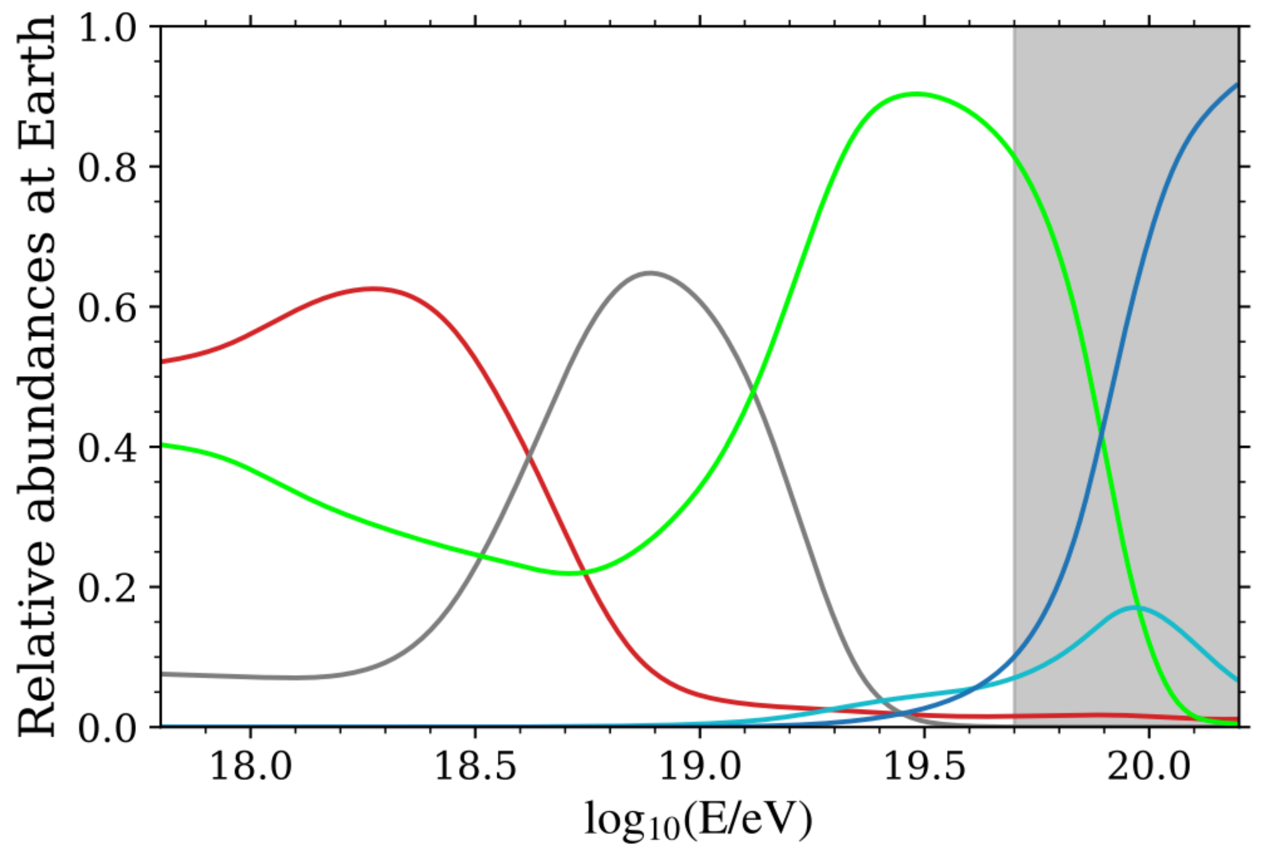




Different contributions needed at LE and HE: $Q(E,z) \propto E^{-\gamma} \exp(-E/E_{\max})$



- Different populations of sources Aloisio et al, JCAP 2014; Mollerach & Roulet PRD 2020; Das et al, Eur.Phys.J. 2021; **The Pierre Auger Collab. JCAP 2023**
- One population of sources (softer spectrum of protons due to in-source interactions) Unger et al. PRD 2015

Contribution from heavier particles below the ankle needed to account for mixed composition

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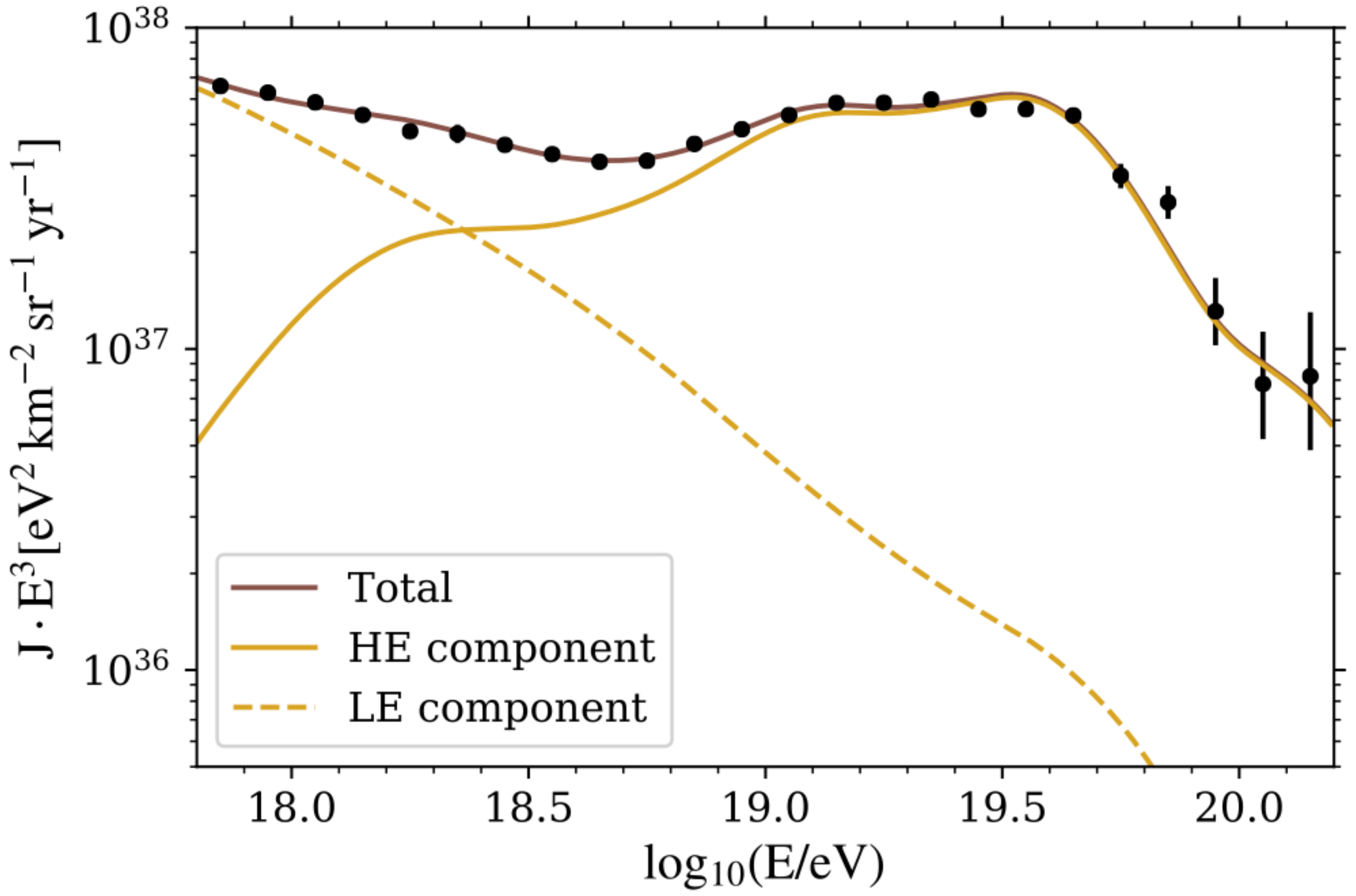

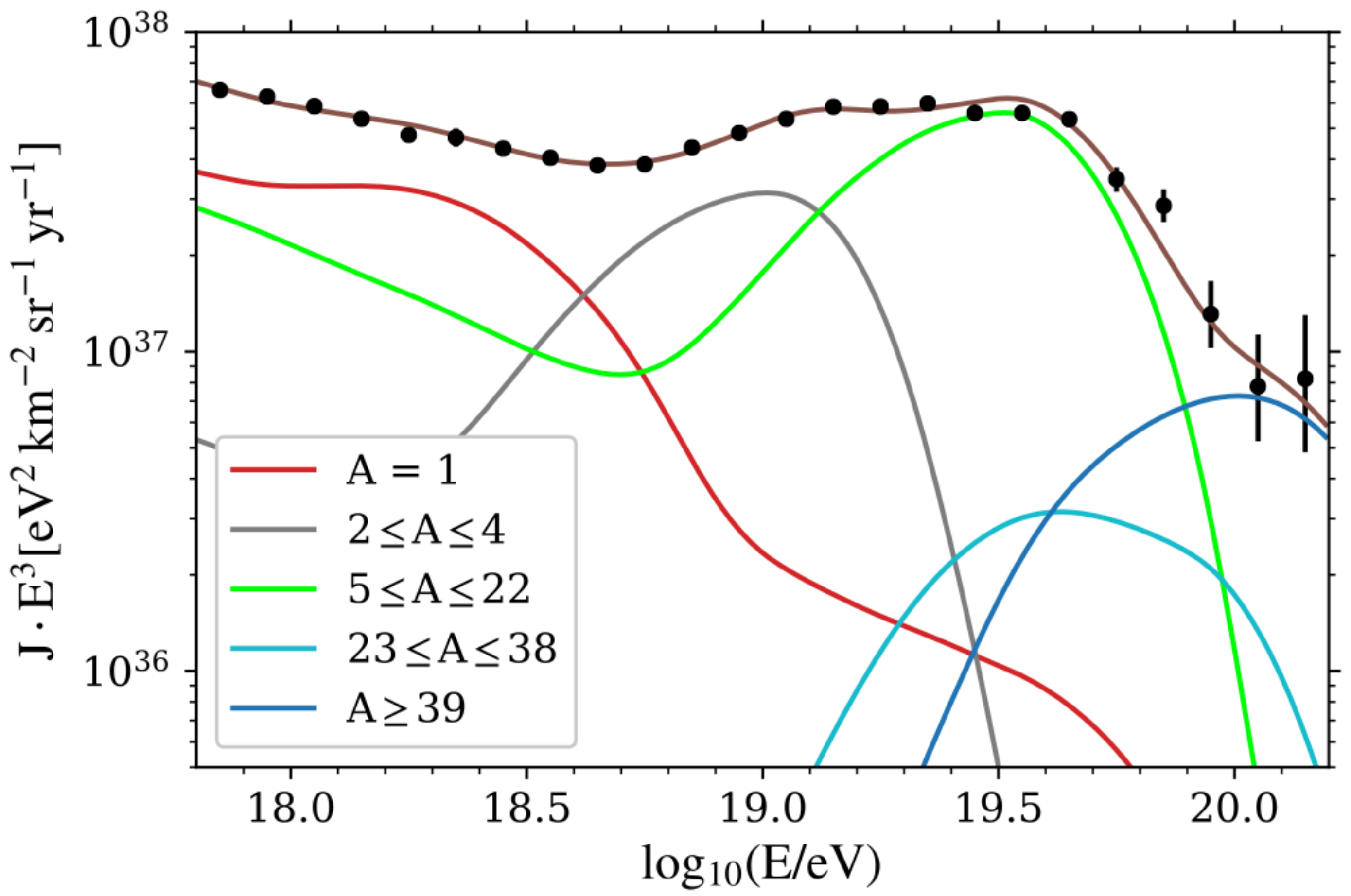

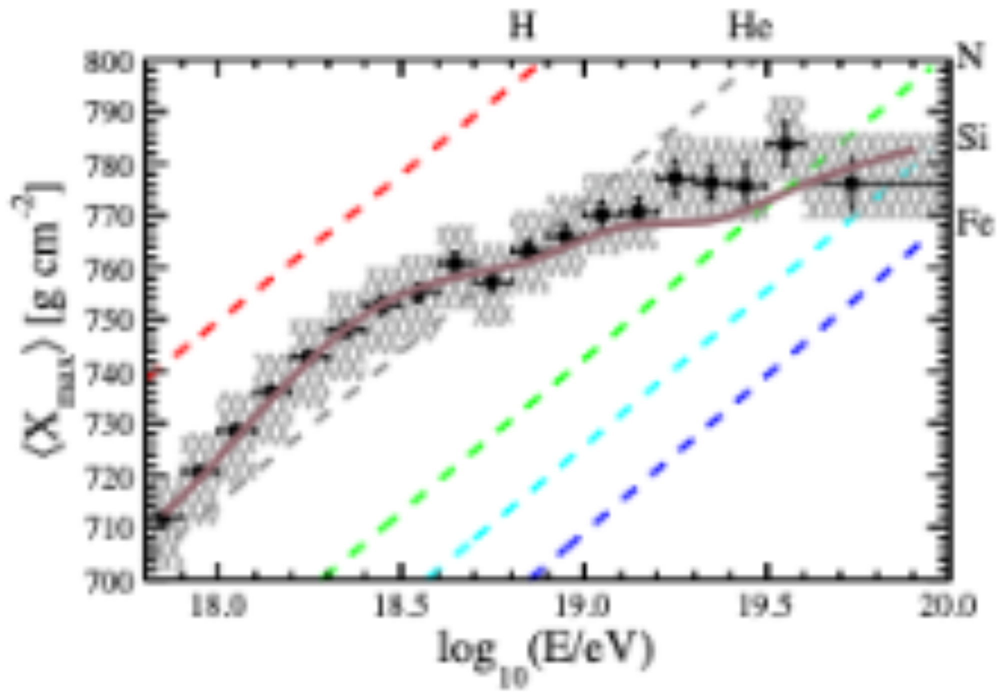

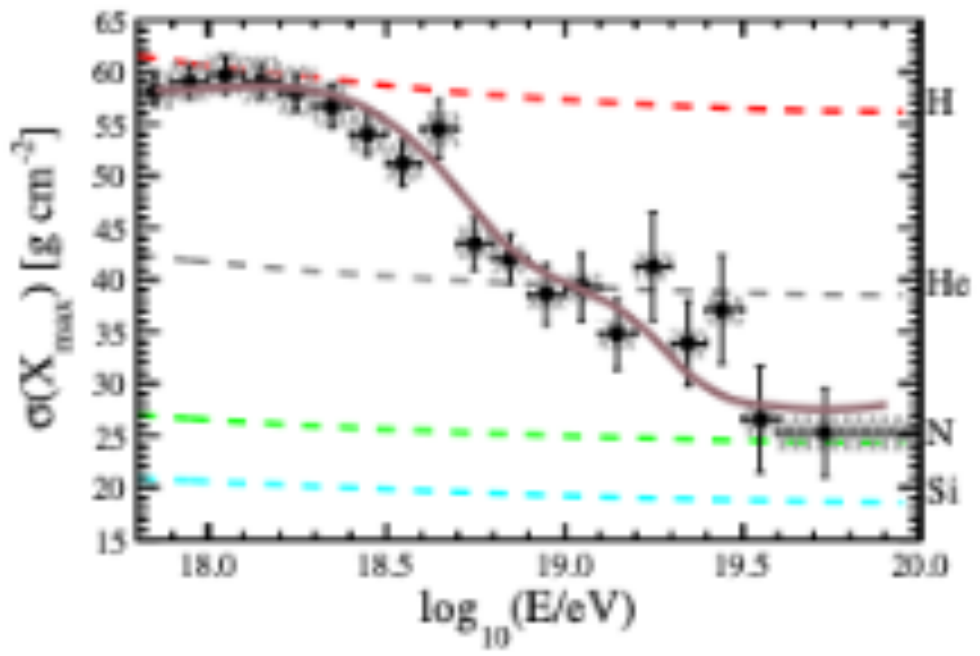

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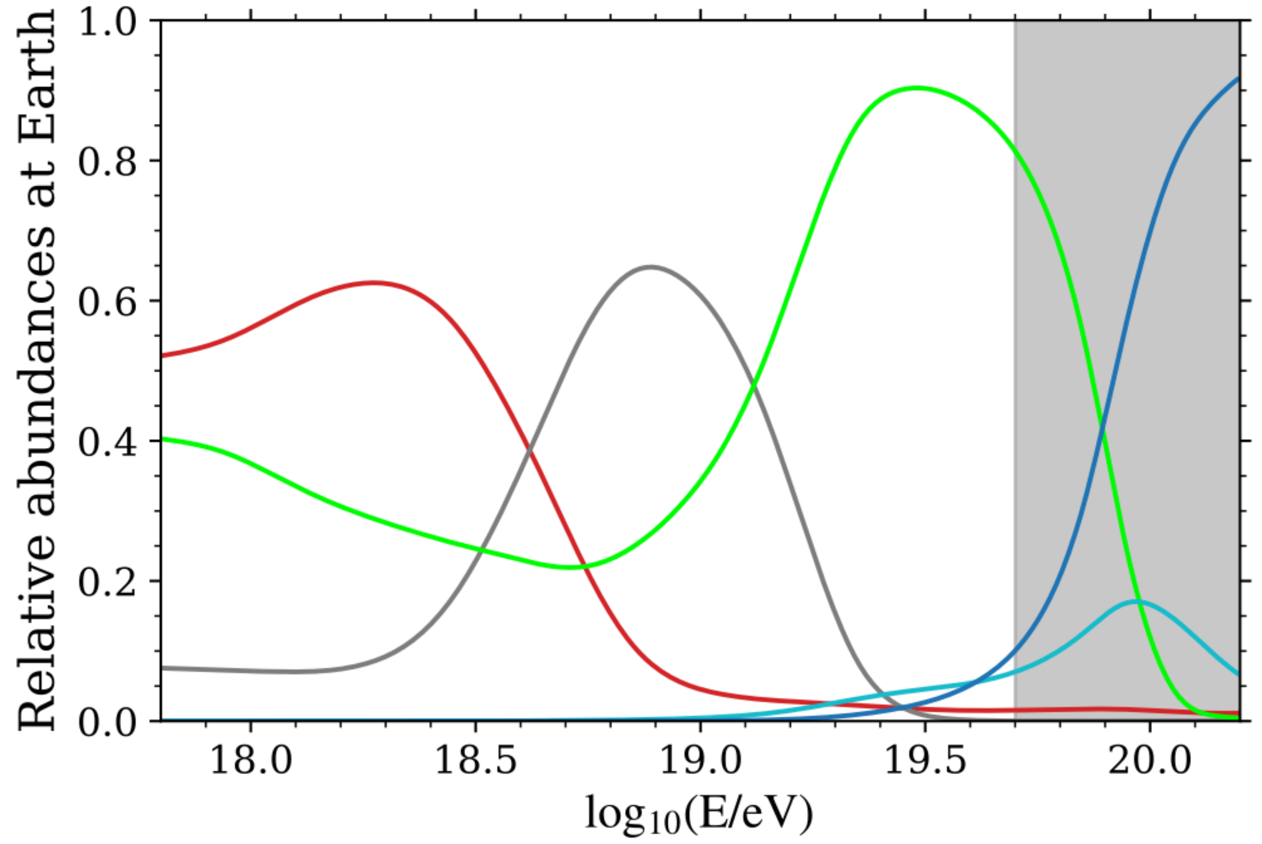


- Independently of the scenario, decreasing fluctuations of Xmax can be found corresponding to **limited mixing of spectra of different nuclear species at HE**, meaning
  - HE: hard spectra + low rigidity cutoff
  - LE: soft spectra + less constrainable rigidity

In terms of interpretation the **suppression**,

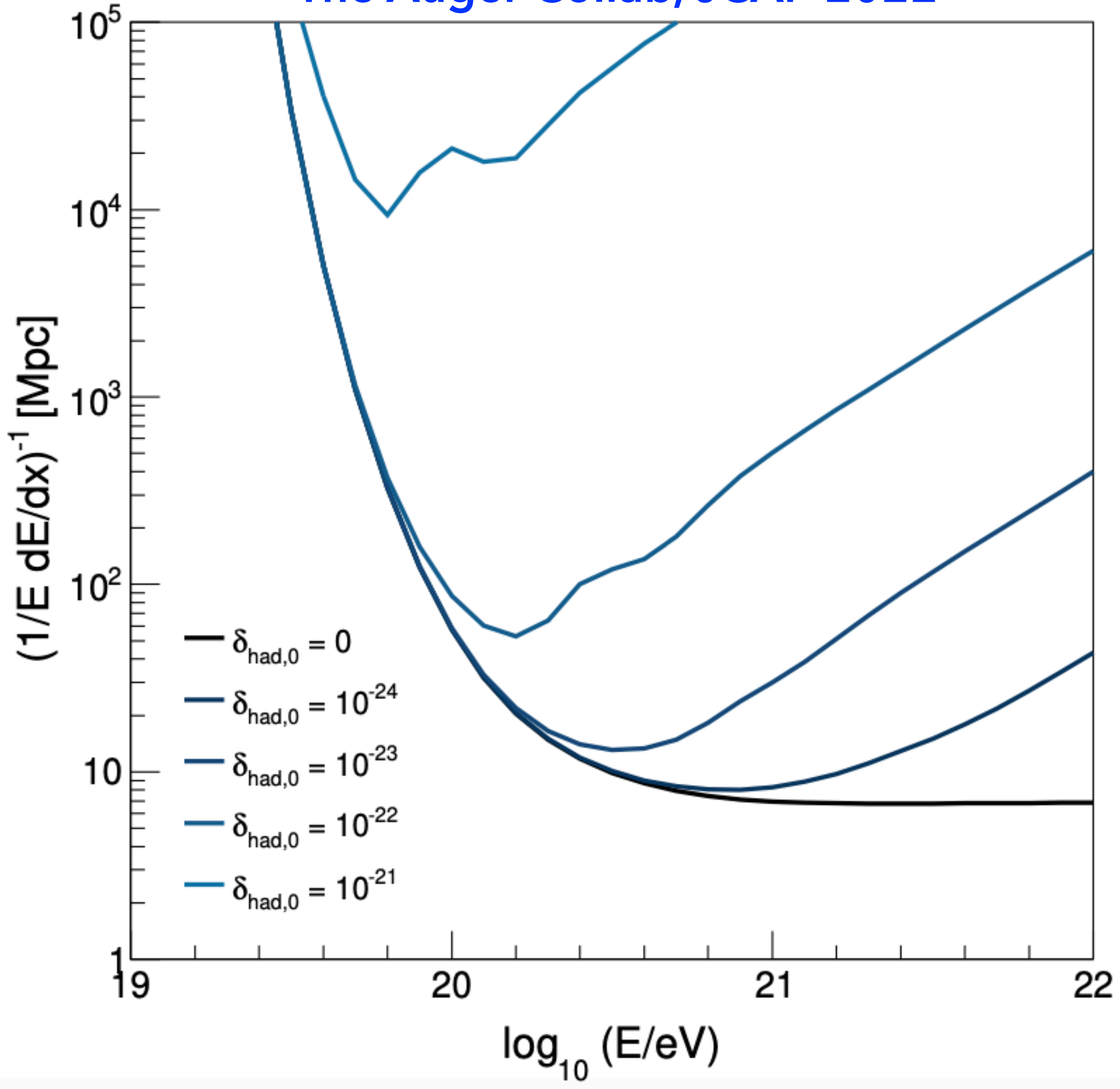
- Propagation effect
- Indication of source power

Not pure GZK !

State-of-the-art: astrophysical scenarios… **and LIV**

- With UHECRs we can test kinematic effects in their extragalactic propagation due to LIV

The Auger Collab, JCAP 2022



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

$$\frac{dN_{\rm int}}{dt} = \frac{c}{2\Gamma^2} \int_{\varepsilon'_{\rm th}}^{\infty} \sigma(\varepsilon')\varepsilon' \int_{\varepsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\varepsilon)}{\varepsilon^2} d\varepsilon d\varepsilon'$$

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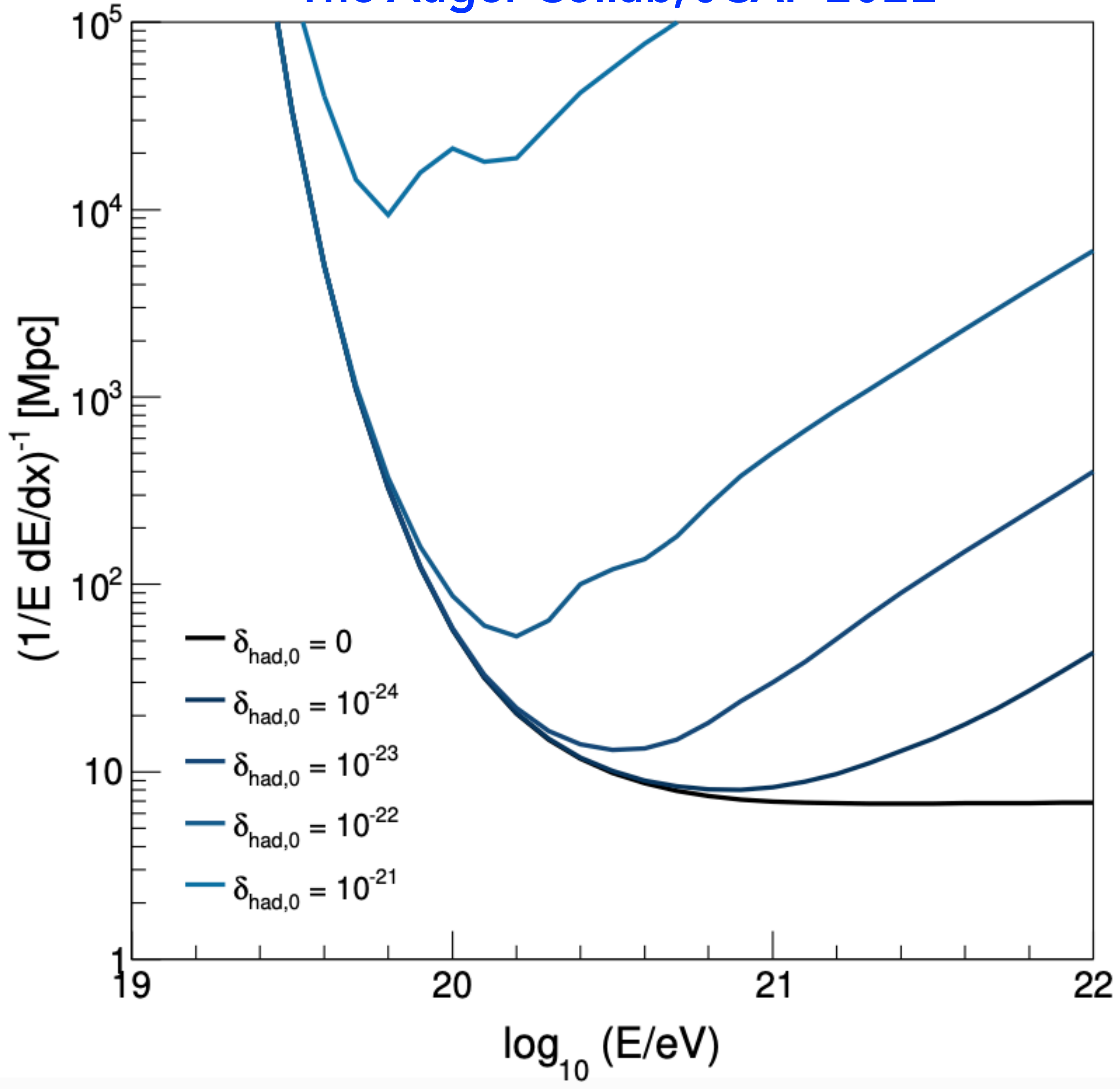

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- Similar effect is expected for interactions of nuclei
- What matters is the energy -> the higher the better to test LIV
- Expected behaviour at the source: $R_{A,max} = R_{p,max}$

$$E_{A,max} = Z(A) R_{p,max}$$

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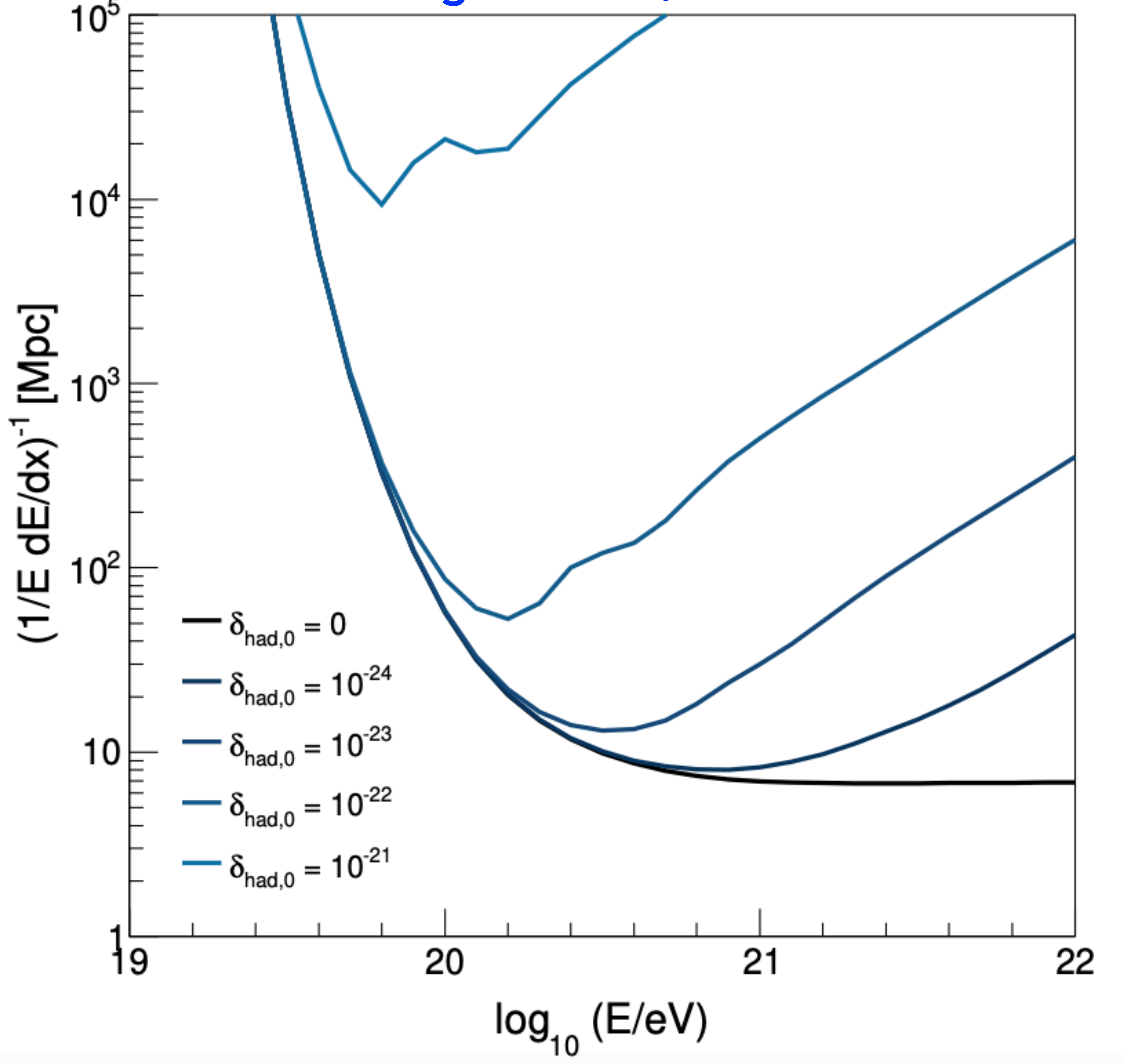

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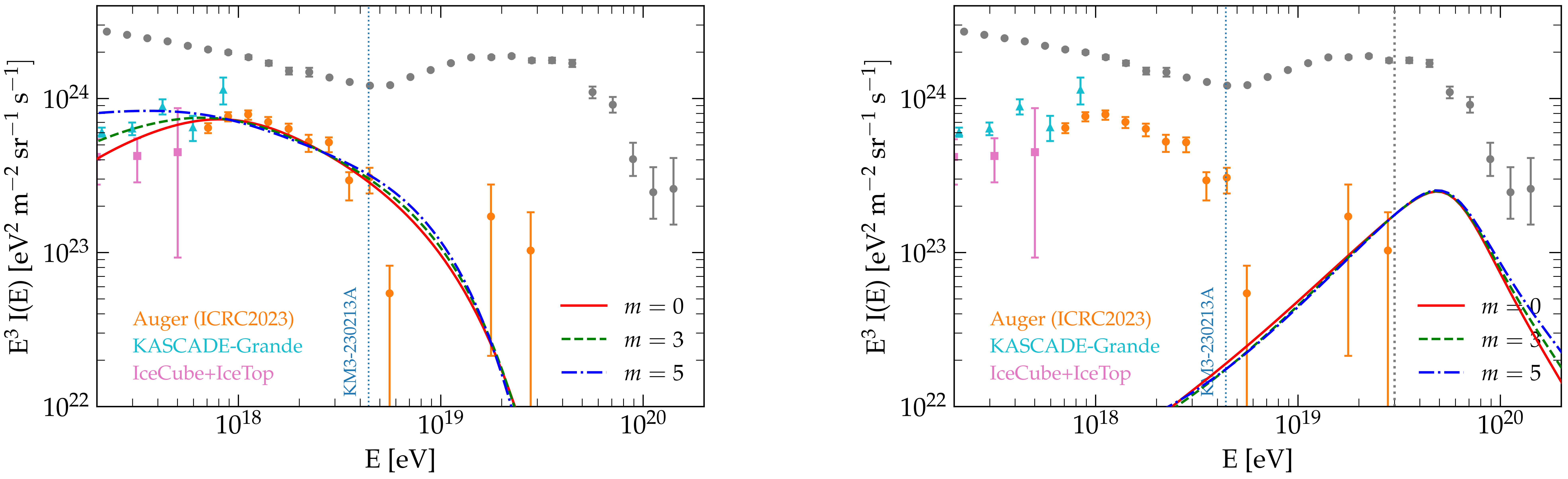
- UHECR nuclei
  - reach larger energies at the sources with respect to protons
  - imply smaller amounts of cosmogenic particles with respect to protons
    - Cosmogenic particles can be used to test LIV effects

- Preferred scenario to test LIV kinematic effects in propagation of UHECRs:
  - Large energy
  - Light mass

State-of-the-art: astrophysical scenarios… **and LIV**

Is a subdominant population of UHECR protons still compatible with UHECR data?

Cermenati, Ambrosone, Aloisio, **DB**, Evoli arxiv:2507.11993

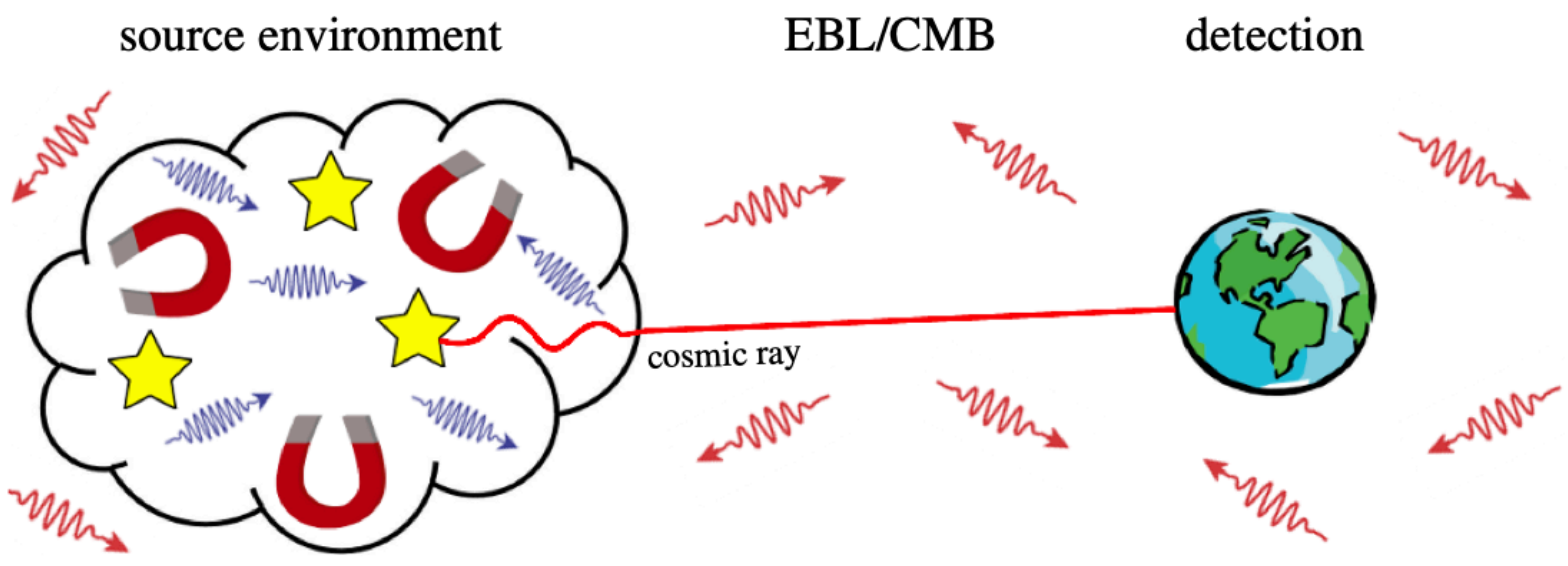


- The subdominant component of protons can have extremely large energy at the sources (modified by propagation)
- It can account for most of the expected cosmogenic fluxes; see also Ehlert et al JCAP 2024; Kuznetsov et al arxiv:2509.09590

What determines the proton component in the UHECRs at the escape from sources?

INSIGHTS ON IN-SOURCE INTERACTIONS

A toy-model to investigate the spectral shape and mass composition at the escape of a source environment



- Accelerator within an environment where cosmic rays can be confined by magnetic fields and interact with radiation and matter fields
- A cosmic ray either
  - escapes without changing energy,
  - or interacts one or more times before escaping;
- Typical lengths are independent of position in the source environment and depend only on E, A, Z

Unger et al, PRD 2015

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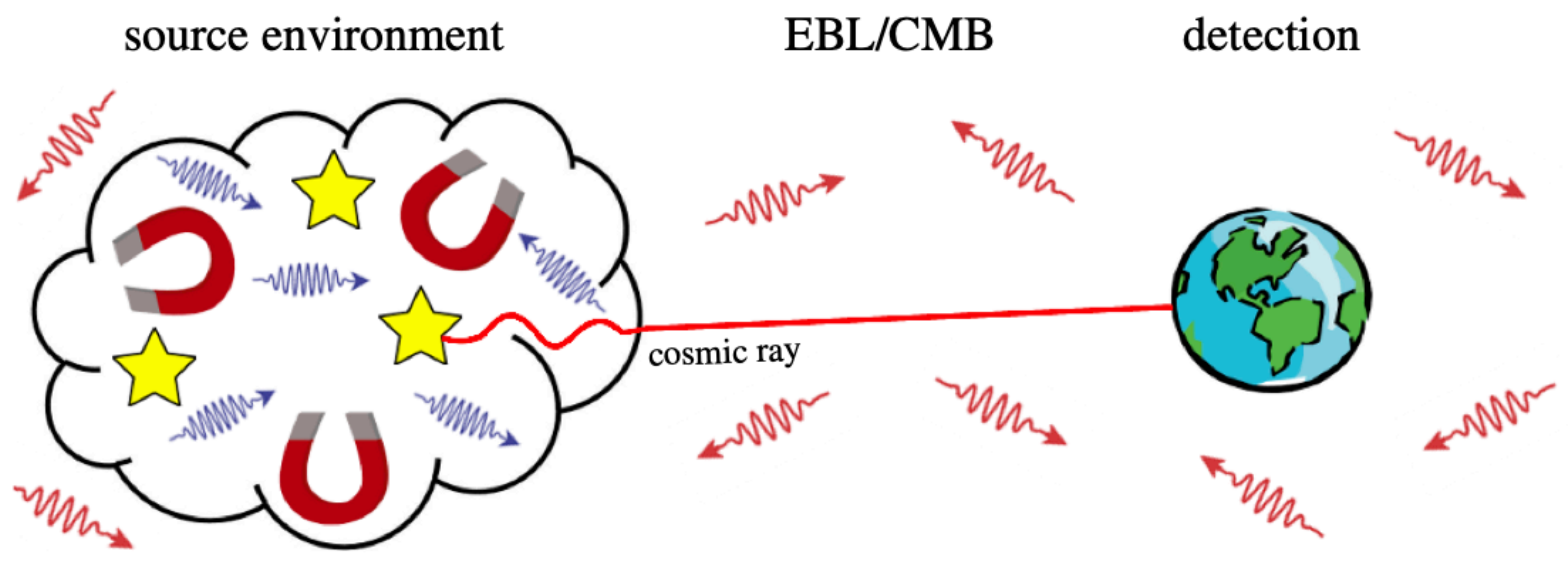

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Number of particles of a certain species is decreasing exponentially with time

$$\eta_{esc} = (1 + \tau_{esc}/\tau_{int})^{-1}$$

Particles escaping without interacting

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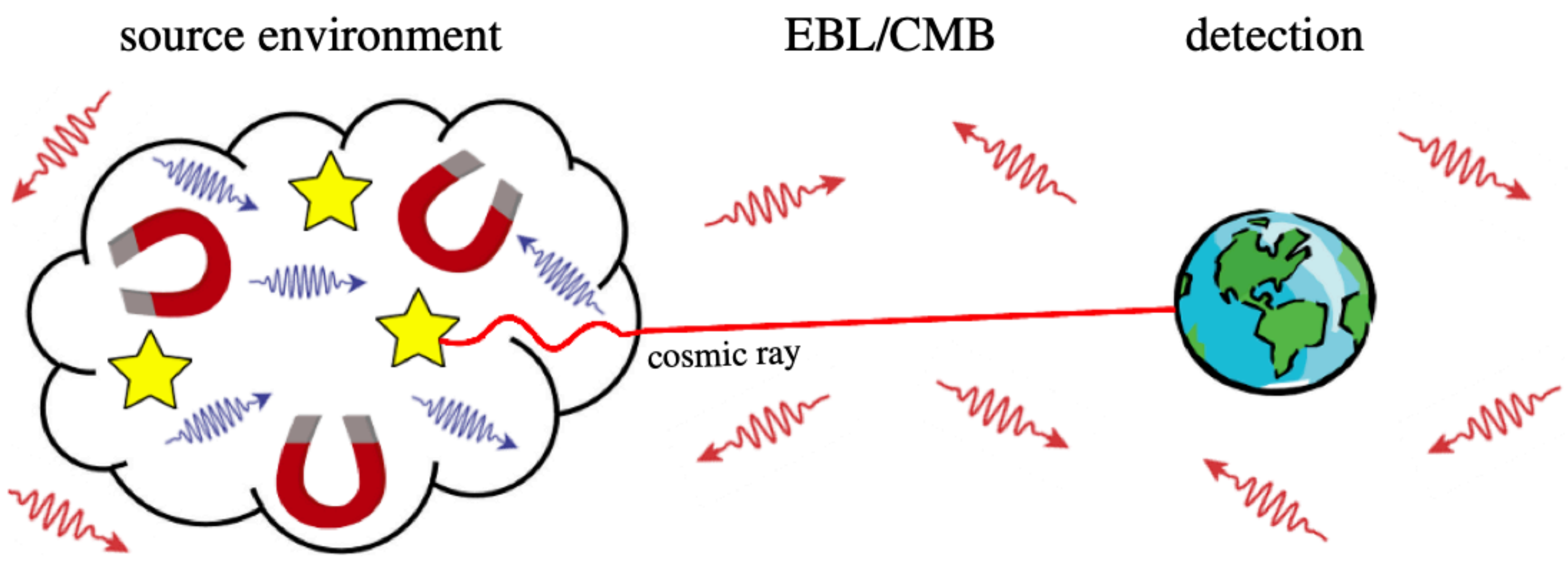

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$$\eta_{\rm int} = 1 - \eta_{\rm esc}$$

$$\tau_{\rm esc} = a(E/E_0)^{\delta} \qquad \tau_{\rm int} = b(E/E_0)^{\zeta}$$

$$\eta_{\rm esc} = (1 + R_0(E/E_0)^{\delta-\zeta})^{-1}$$

Only the ratio between escape and interaction is relevant

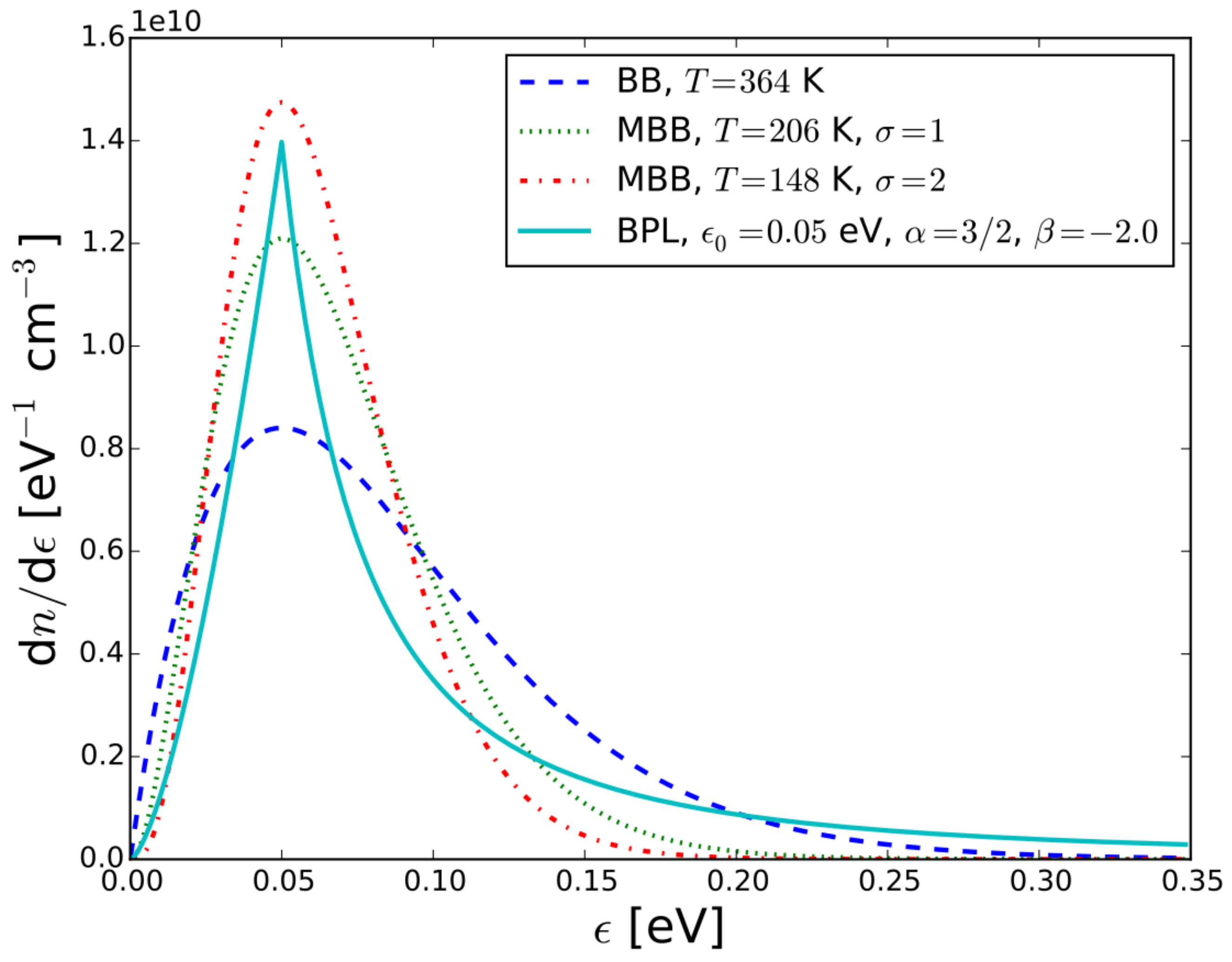
$\delta > \zeta$ — Low-pass filter

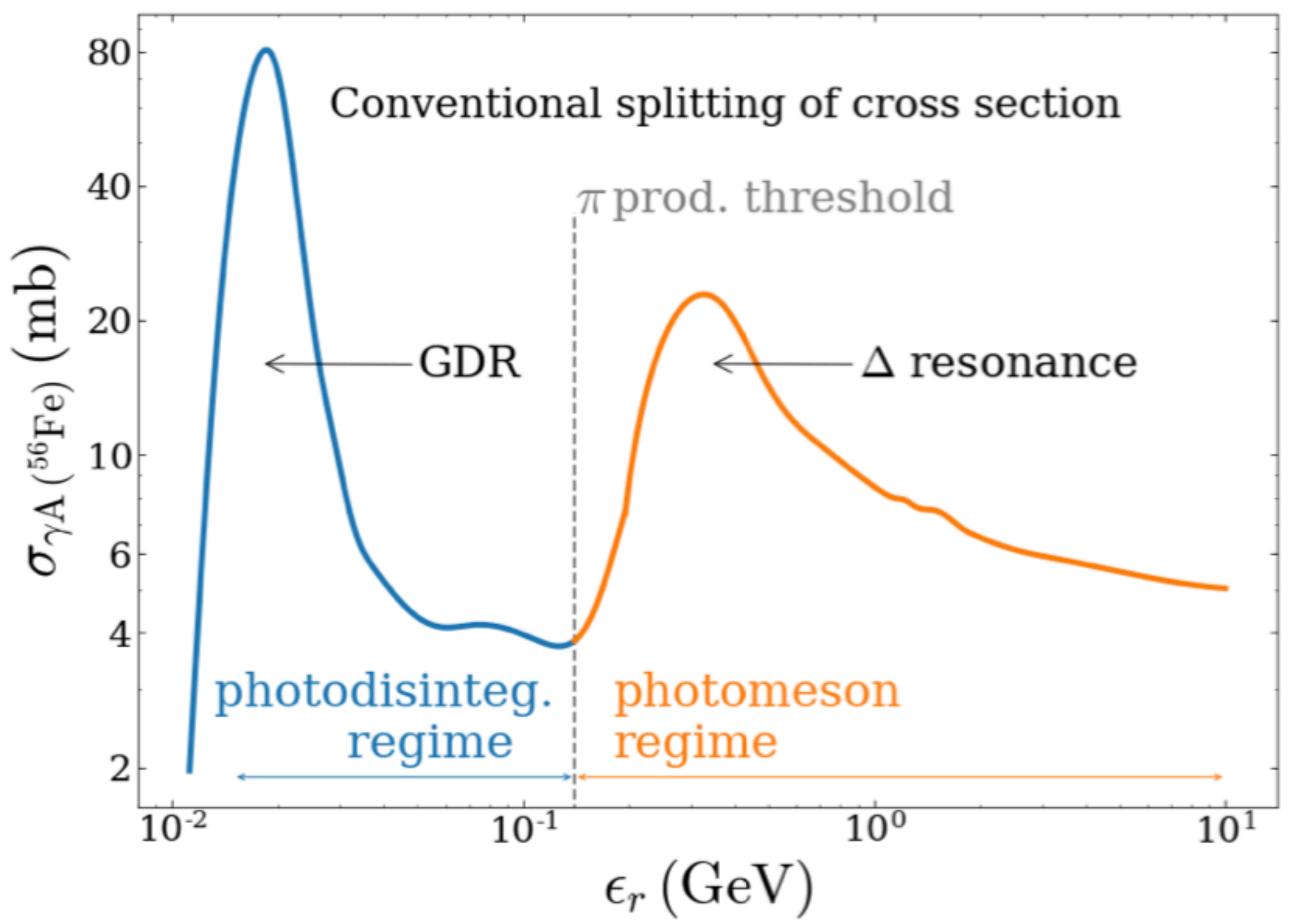
$\delta < \zeta$ — High-pass filter

Unger et al, PRD 2015

A toy-model to investigate the spectral shape and mass composition at the escape of a source environment

- Black body or power-law radiation field (peaked spectrum)
- Photopion production and/or photo-disintegration (resonances)





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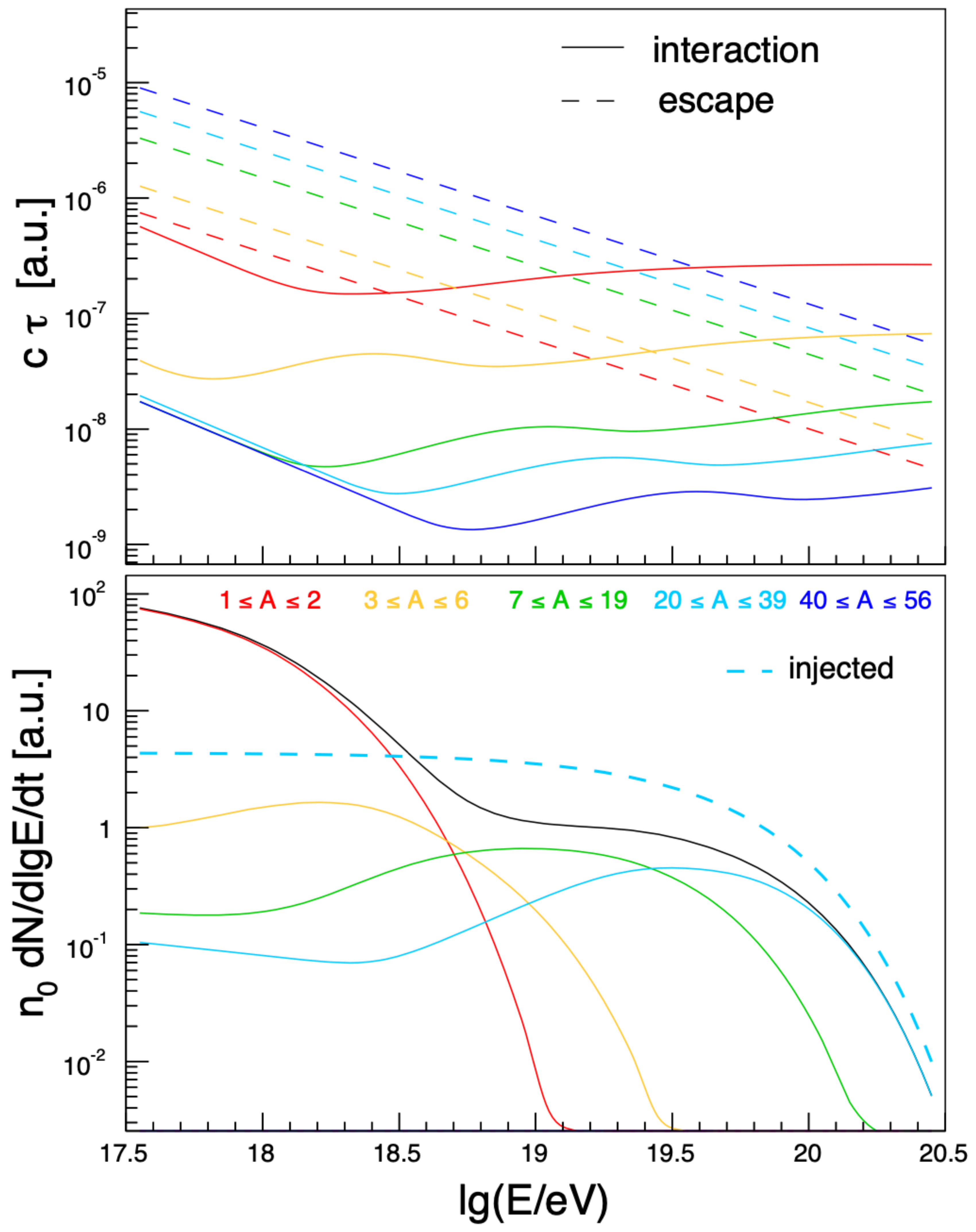
$$\varepsilon' \approx \varepsilon\Gamma$$

- Low CR energy -> high energy of the photon (above the peak) needed to reach the resonance energy -> steep spectrum -> time decreases
- High CR energy -> low energy of the photon (below the peak) needed -> time increases

- The lower the energy, the more time the nuclei have to interact before escaping
  - hardening of the spectrum and
  - lightening of the composition

- The high-pass filter scenario leads naturally to an **ankle-like feature** separating the nucleonic fragments from the remaining nuclei



Unger et al, PRD 2015

What do we learn from modelling?

- Cosmic-ray observatories can provide us with diffuse spectra
- Not ideal, but we can derive some basic requirements for sources
  - The proton component has a different slope with respect to the other nuclear species , which can be connected to in-source properties
  - Its intensity (as well as the neutrinos associated to it) is linked to the efficiency of interactions

What do we learn from modelling?

Example from a source-propagation model in the nucleus of a starburst galaxy, Condorelli, **DB**, Peretti & Petrera PRD 2023

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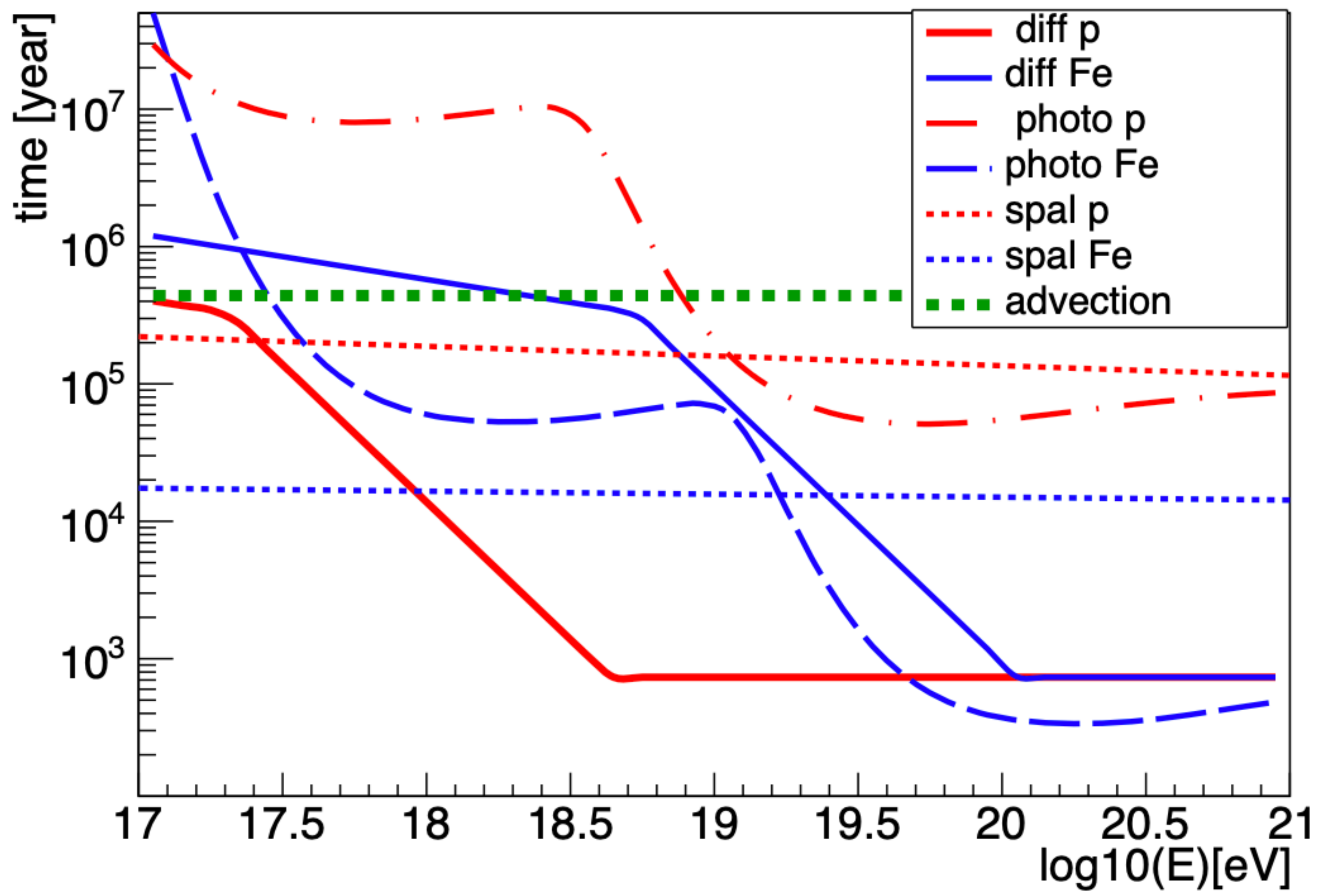
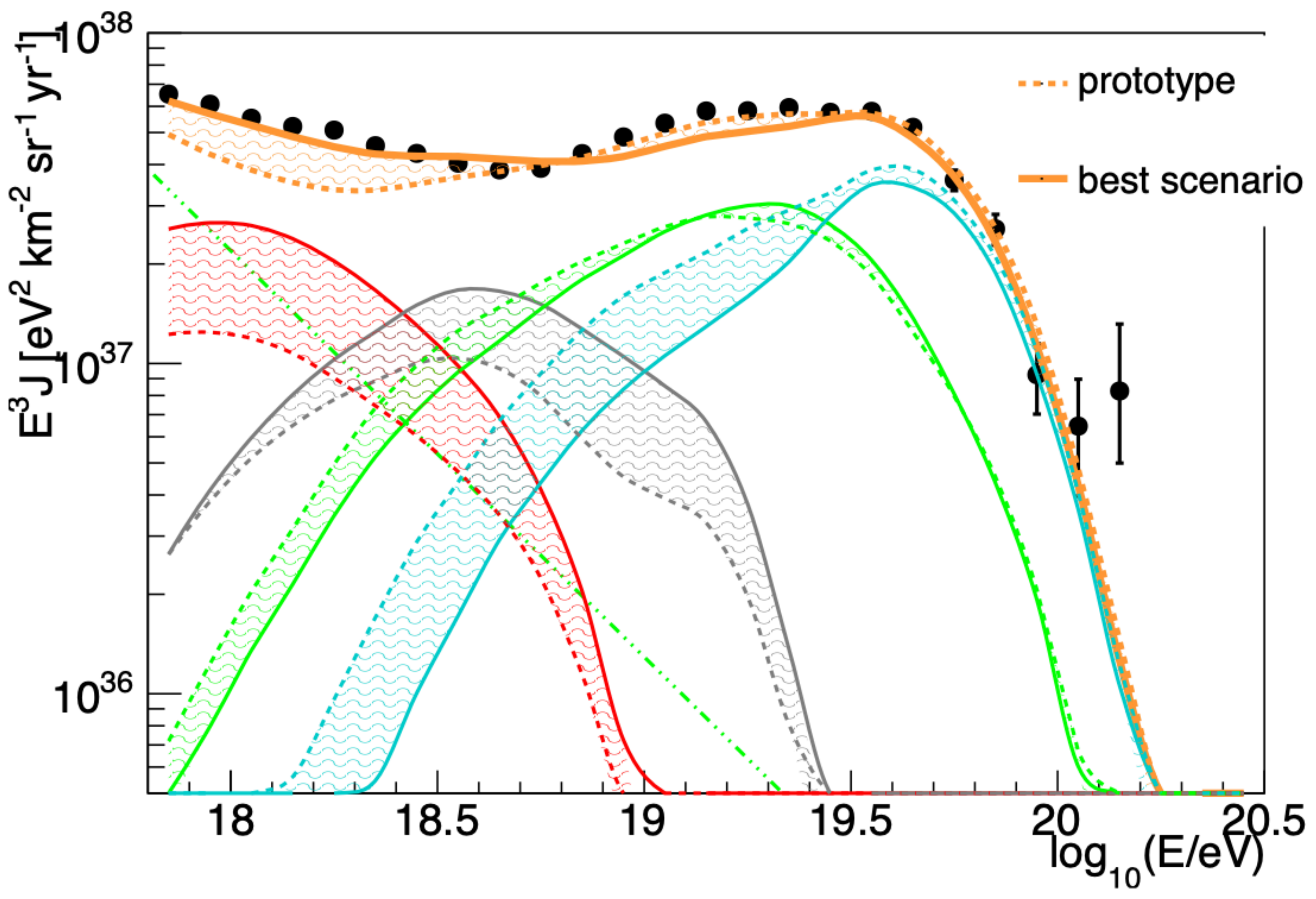
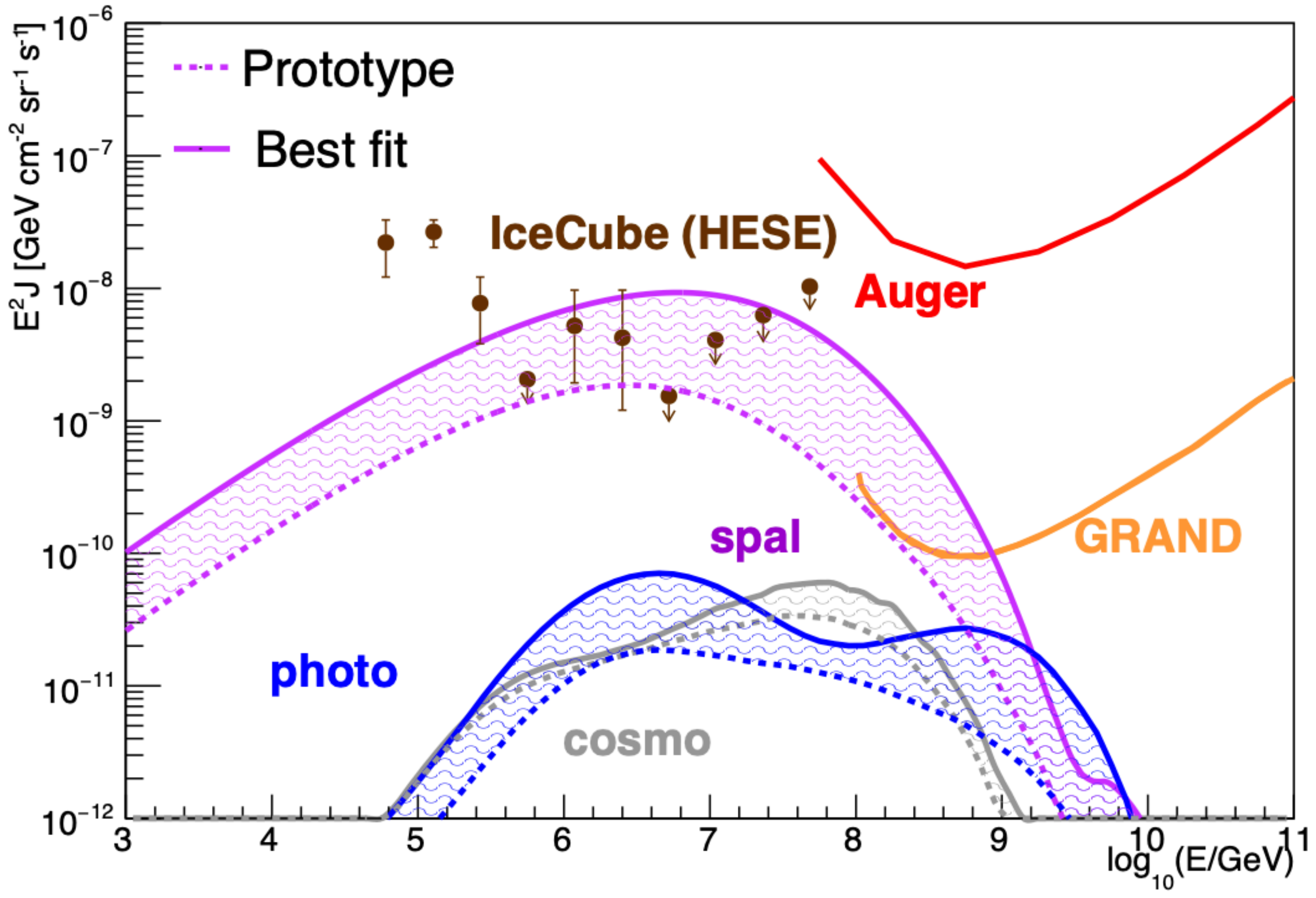
  - The proton component has a different slope with respect to the other nuclear species , which can be connected to in-source properties
  - Its intensity (as well as the neutrinos associated to it) is linked to the efficiency of interactions







What do we learn from modelling?

Example from a source-propagation model in the nucleus of a starburst galaxy, Condorelli, **DB**, Peretti & Petrera PRD 2023

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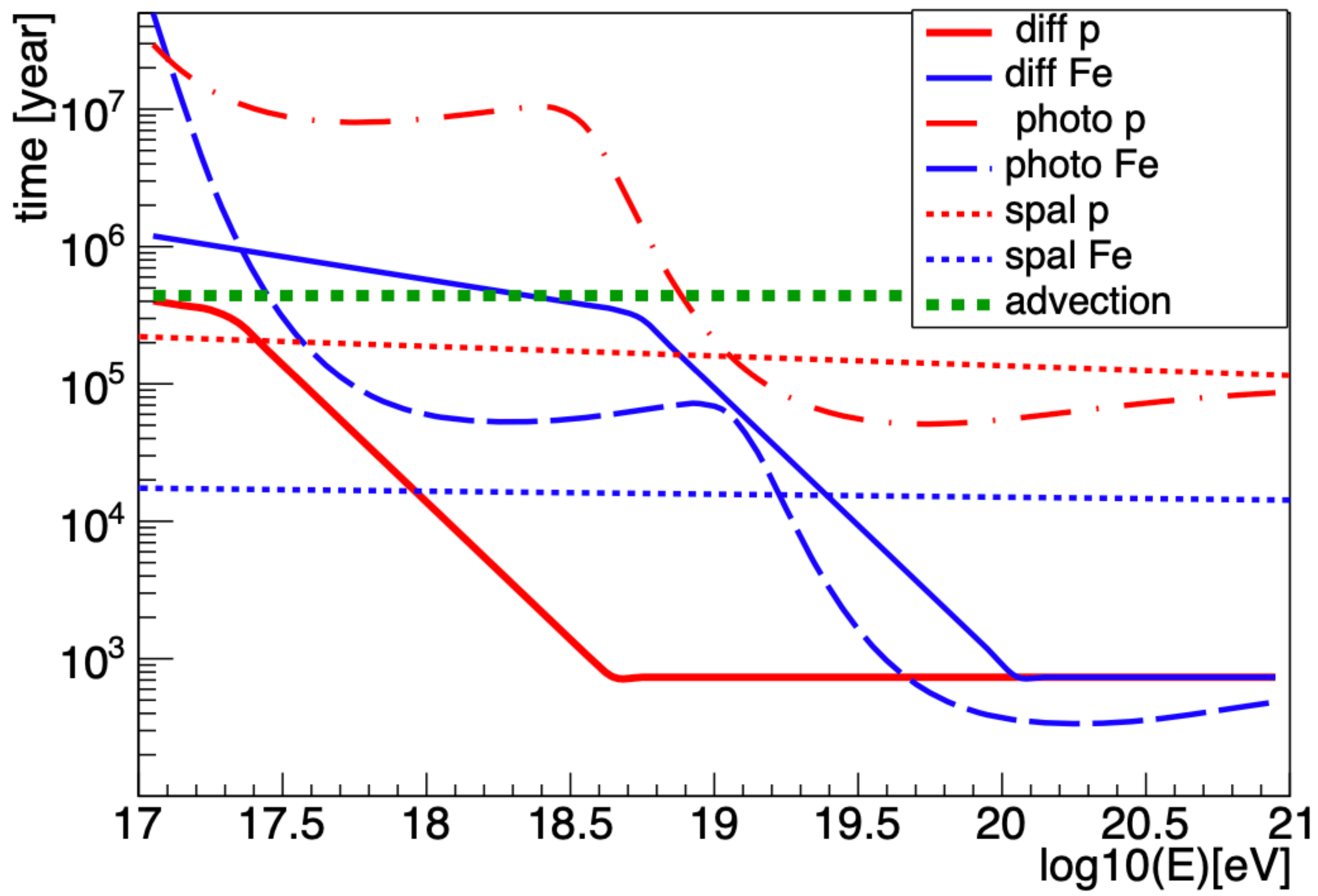
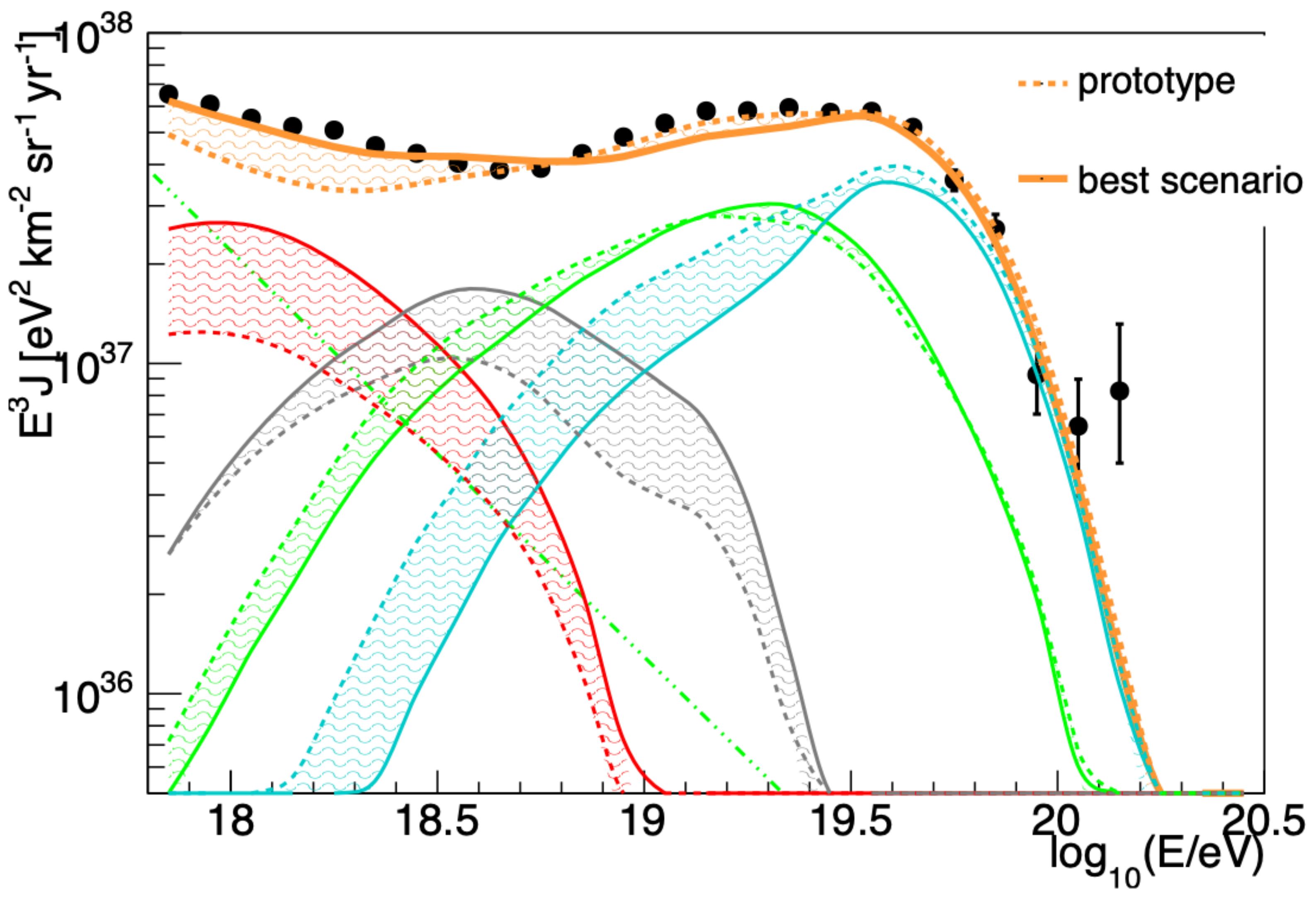
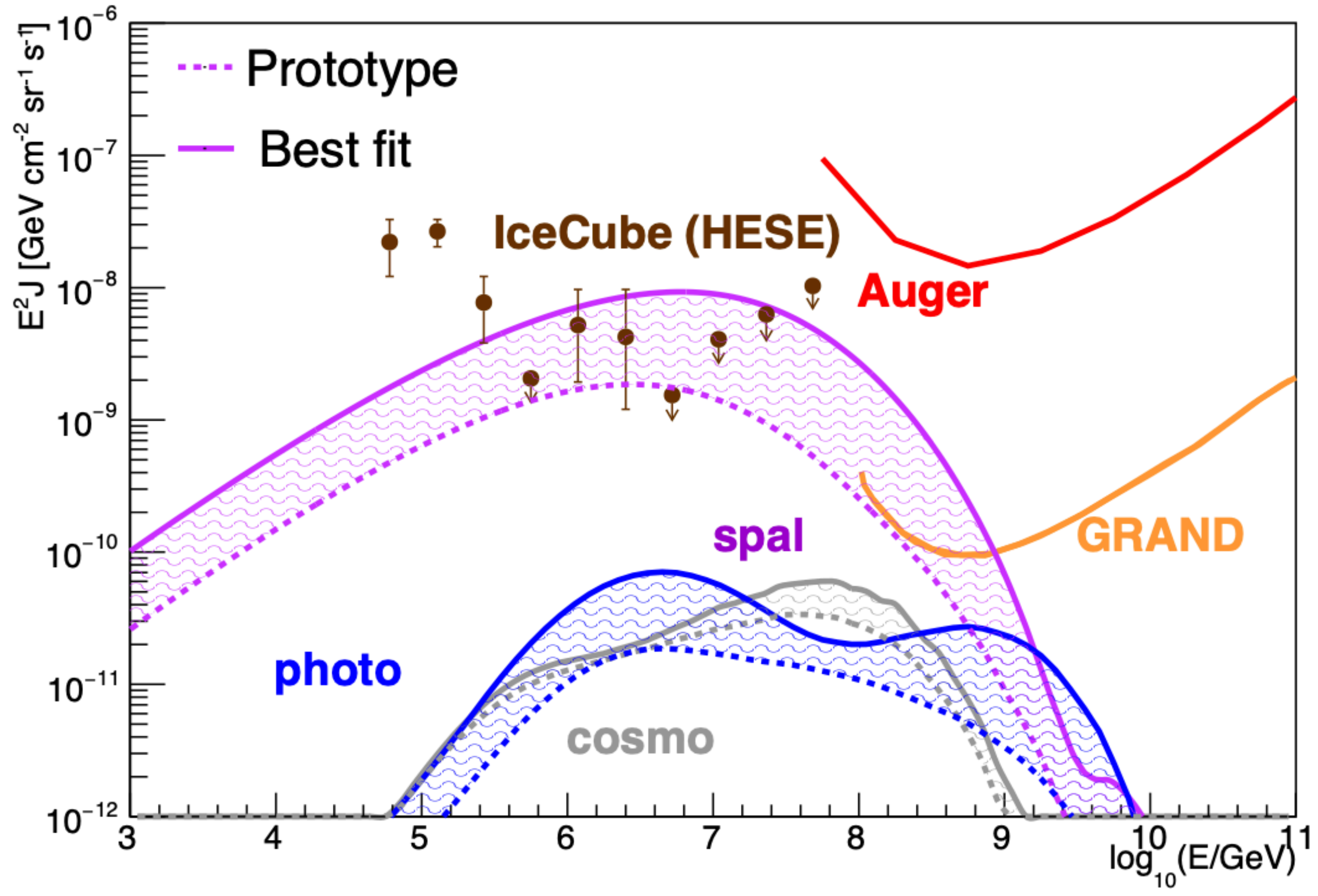


- The more efficient the interactions, the larger the proton component below the ankle (and the associated neutrinos from in-source interactions) -> the larger the sensitivity to LIV with UHECRs, cosmogenic and astrophysical secondary neutrinos





HOW DOES LIV IN EXTRAGALACTIC PROPAGATION OF UHECRS AFFECT THE INTERPRETATION OF UHECR DATA IN TERMS OF ASTROPHYSICAL SCENARIOS?

How does LIV affect UHECR characteristics in extragalactic propagation?

- It makes UHECRs at the escape from the sources:
  - Appear lighter
  - Have a softer spectrum
  - Have a larger maximum energy

With respect to the LI case

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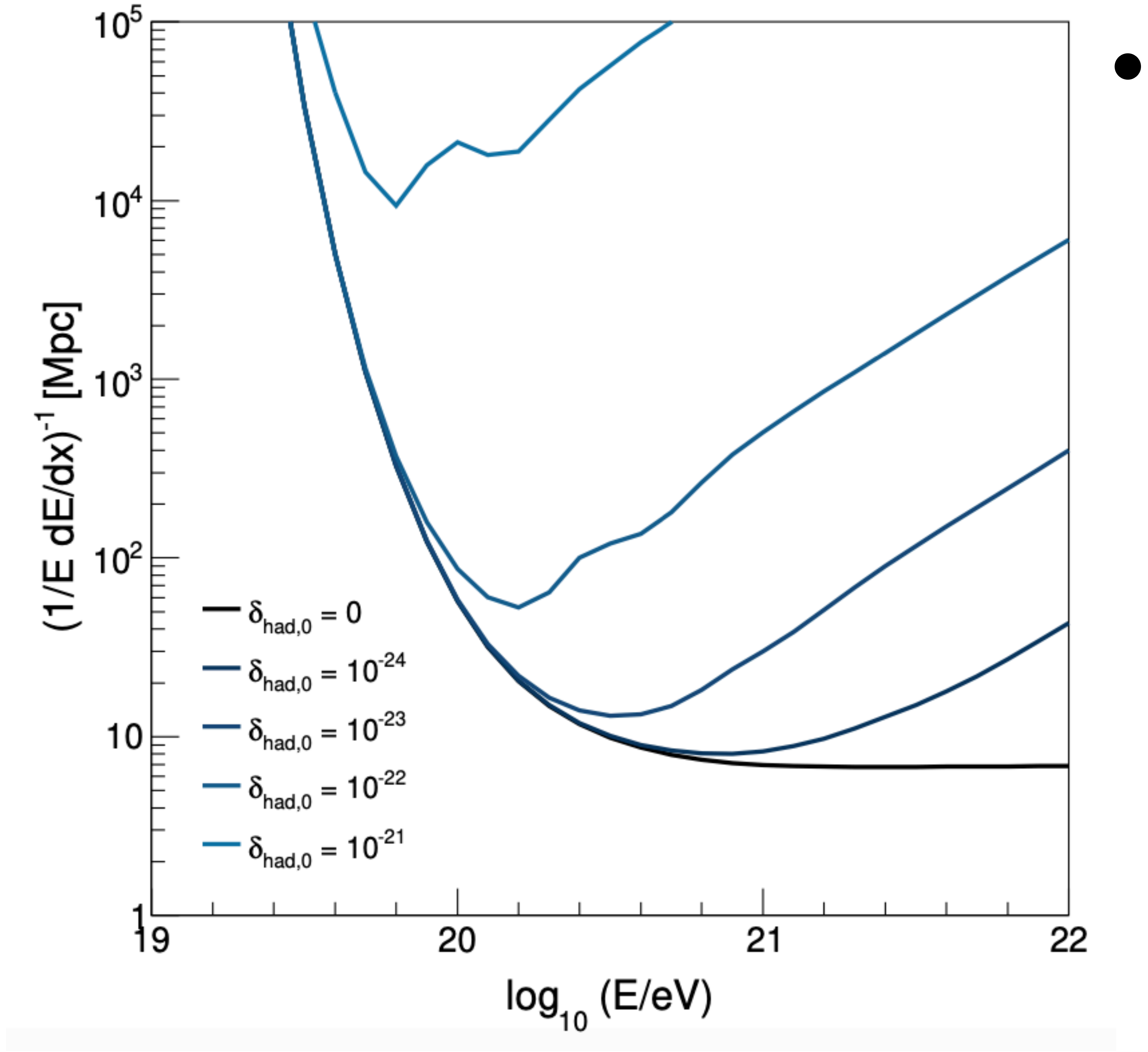
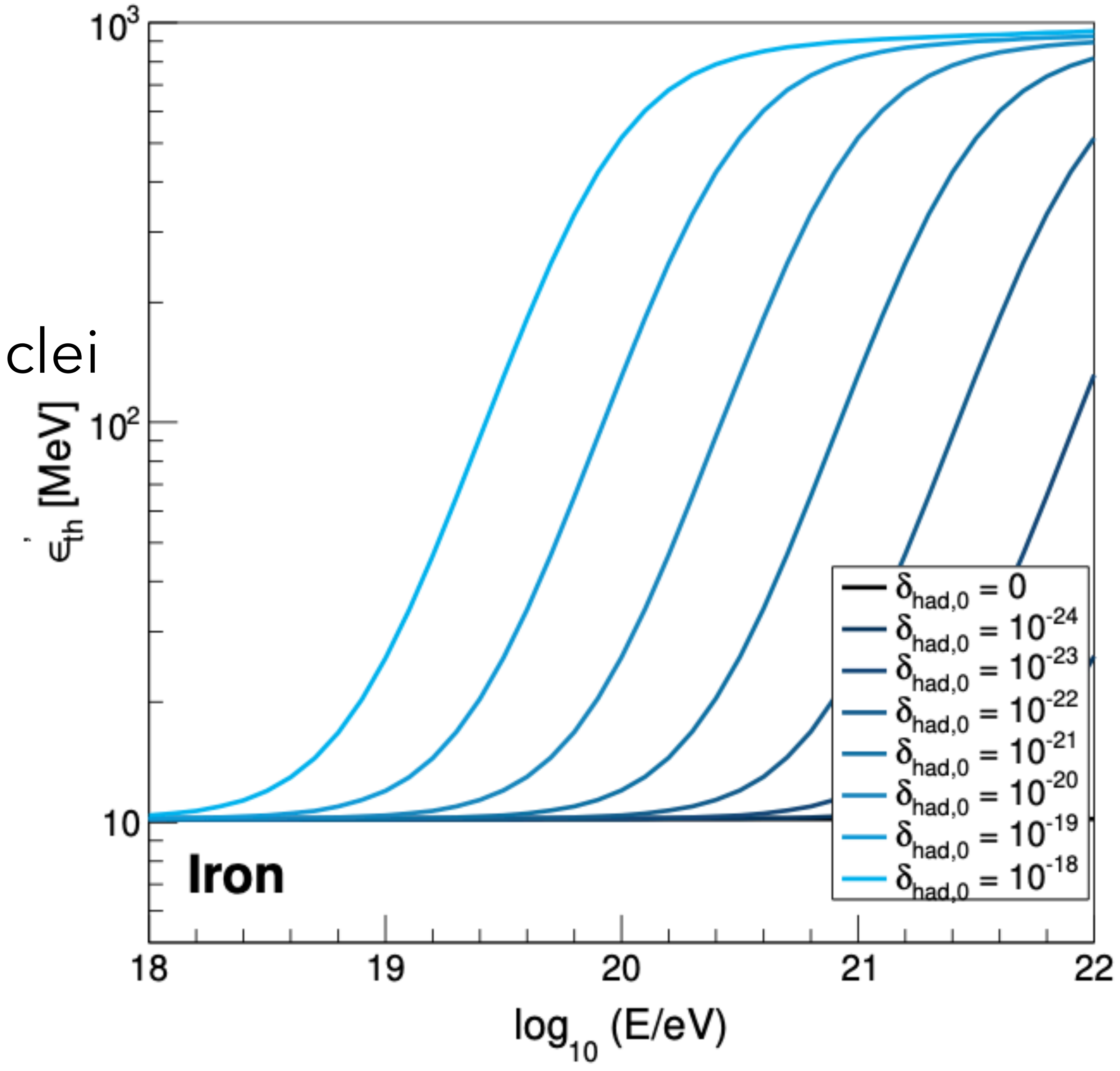
With respect to the LI case

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

$$\frac{dN_{\rm int}}{dt} = \frac{c}{2\Gamma^2} \int_{\epsilon'_{\rm th}}^{\infty} \sigma(\epsilon')\epsilon' \int_{\epsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon d\epsilon'$$



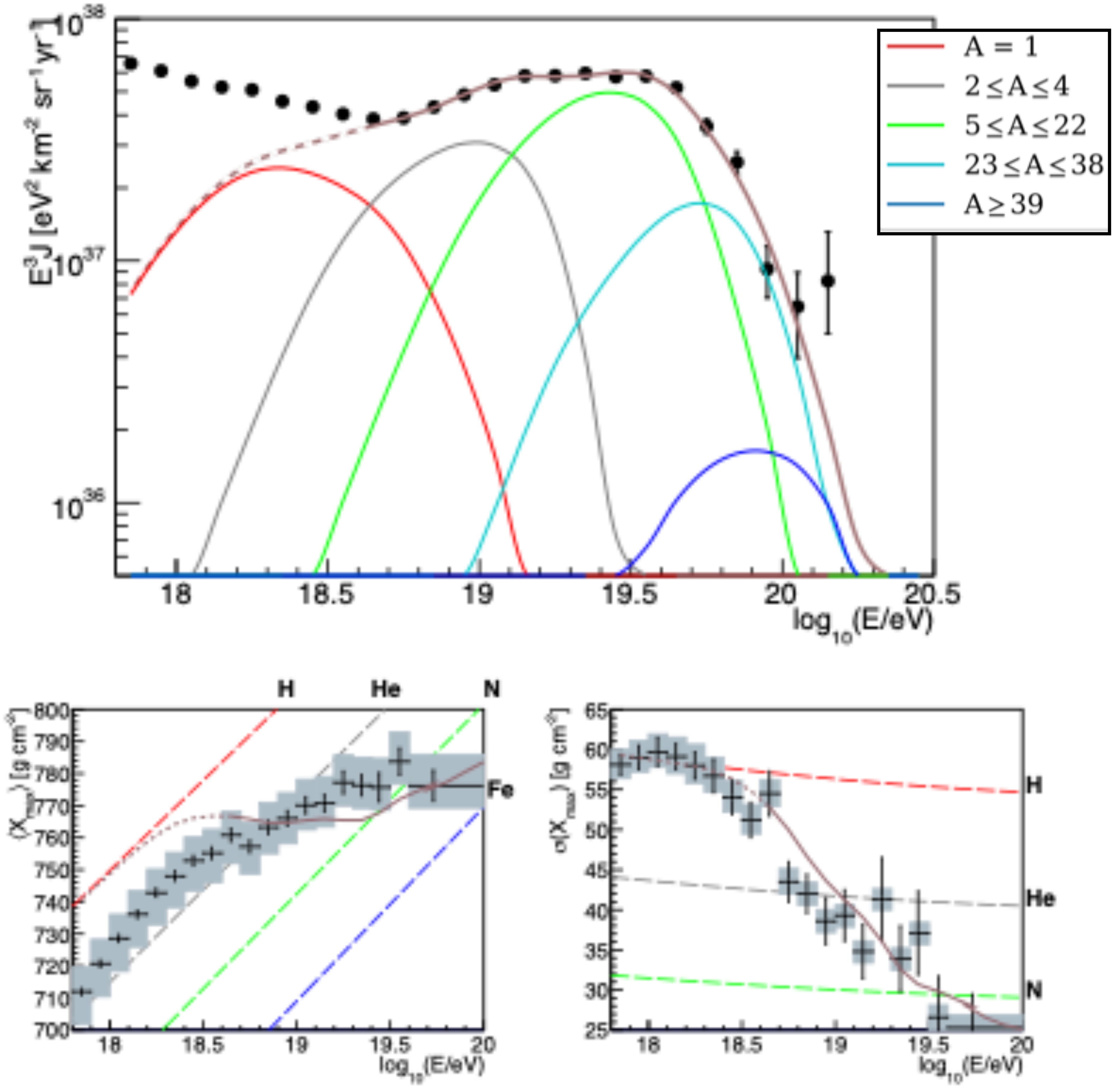
- Threshold effect in photopion production of protons
- Threshold effect in photodisintegration of nuclei
- Threshold increases -> interaction length is larger while LIV increases

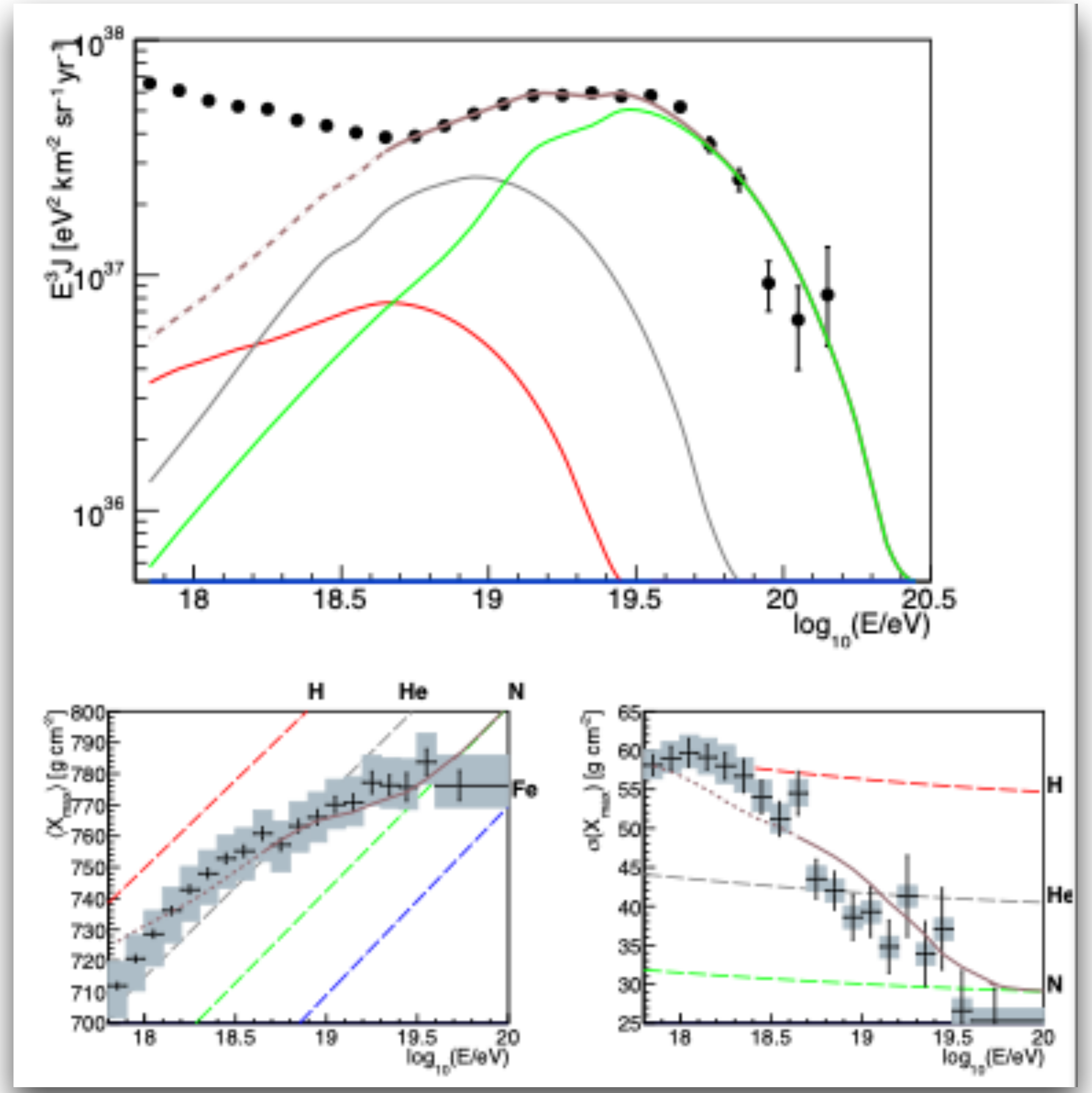


Effect on interpretation of mass composition

The Auger Collab, JCAP 2022

LI scenario





LIV scenario

- Threshold energy increases -> less interactions -> if LIV, lighter nuclear species are needed at the sources in order to reproduce the observed composition at Earth

Effect on interpretation of spectral index and max energy

- Astrophysical assumption: nuclear species are accelerated with charge Z ordering at their sources
- Photodisintegration conserves the Lorentz factor $E_{A'} = \frac{A'}{A} E_A,\ A' < A$
- Spectra of different nuclei are ordered in terms of mass A at Earth
- Heavy masses at source are discarded by LIV -> lighter masses must have larger maximum energy
- Maximum energy and spectral index at the escape from sources are correlated

$R_{A,max} = R_{p,max}$

$E_{A,max} = Z(A) R_{p,max}$

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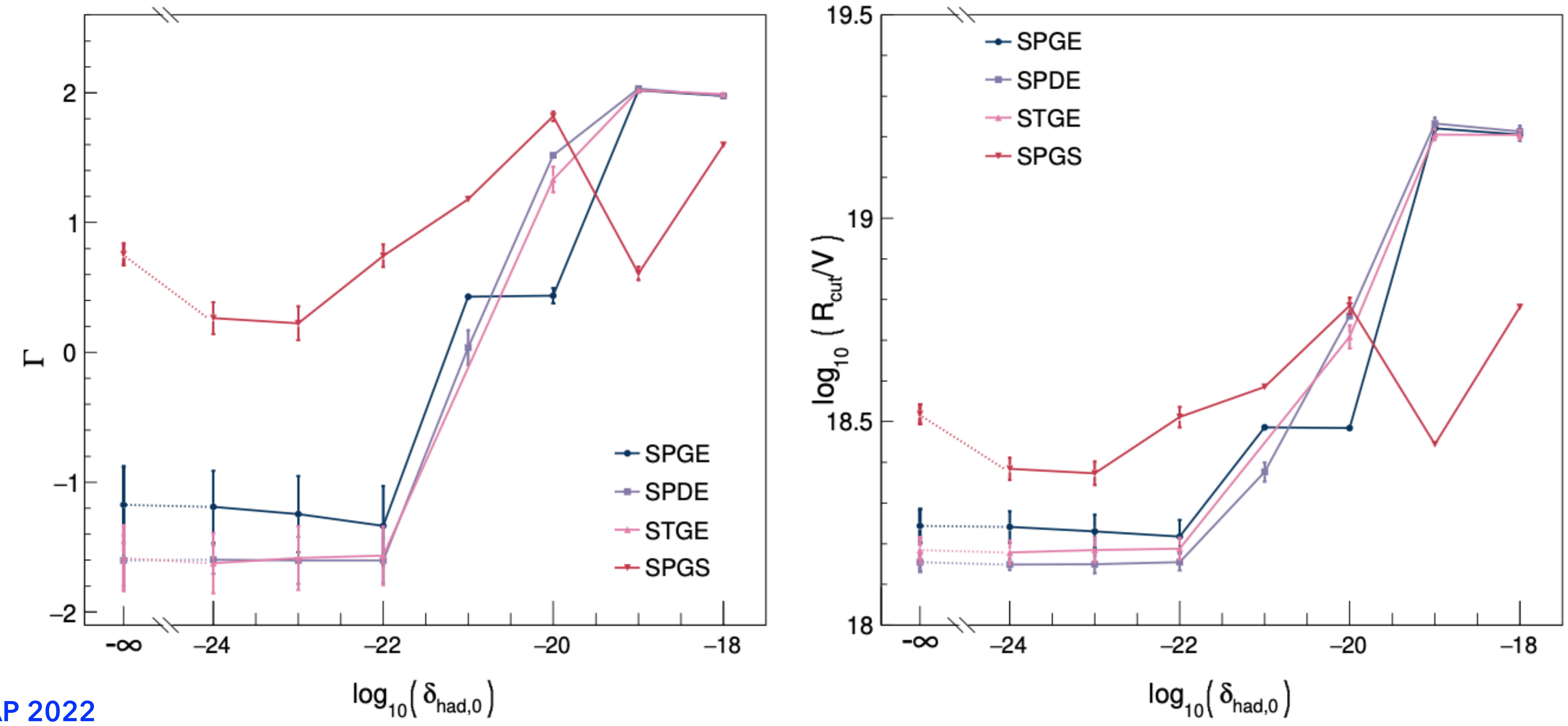

The Auger Collab, JCAP 2022

What do we learn from including LIV in propagation?

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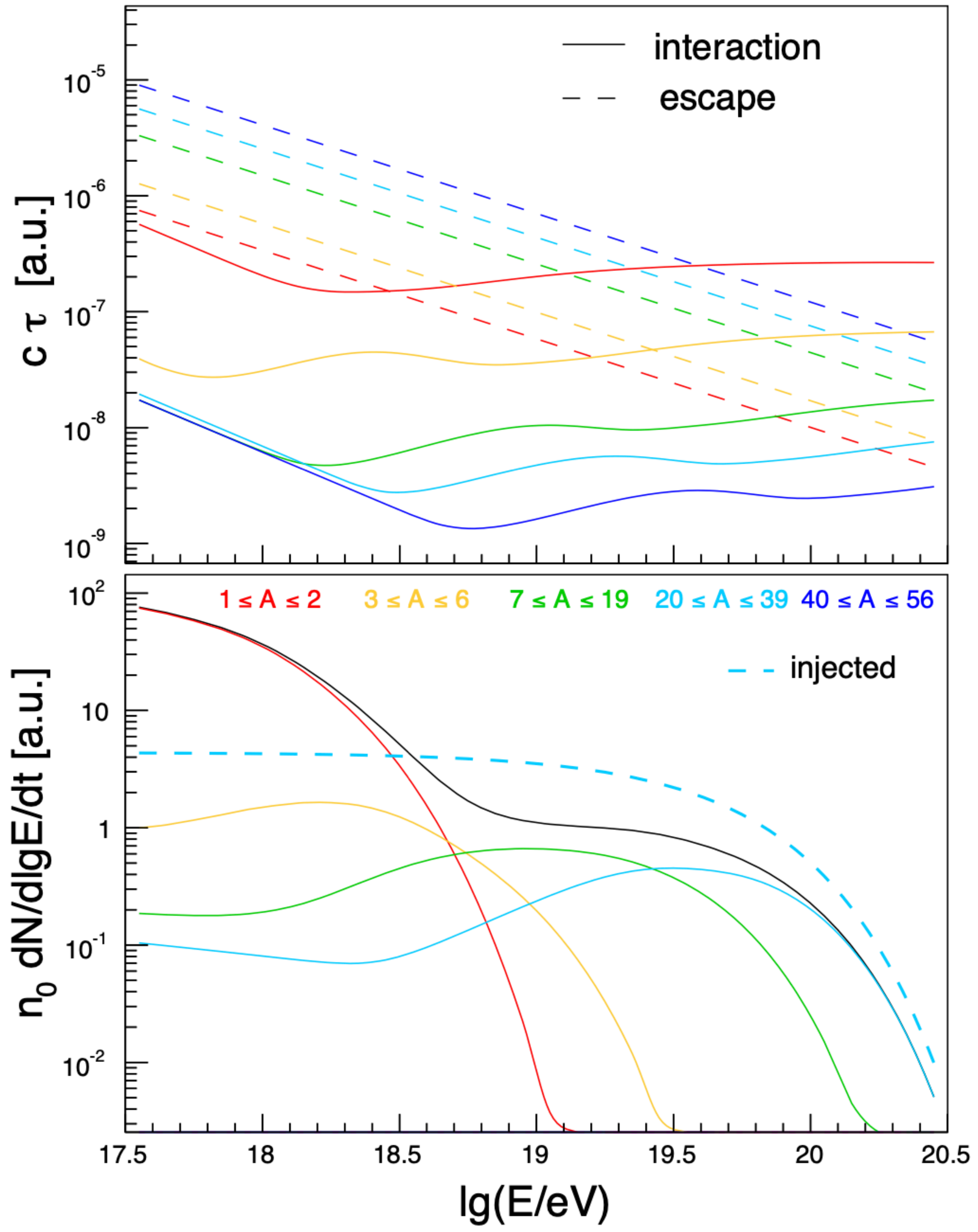

What if we add LIV in source?

- Toy model from Unger, Farrar & Anchordoqui PRD2015:
  - If interactions are affected, the typical time increases with LIV
  - CRs escape more easily
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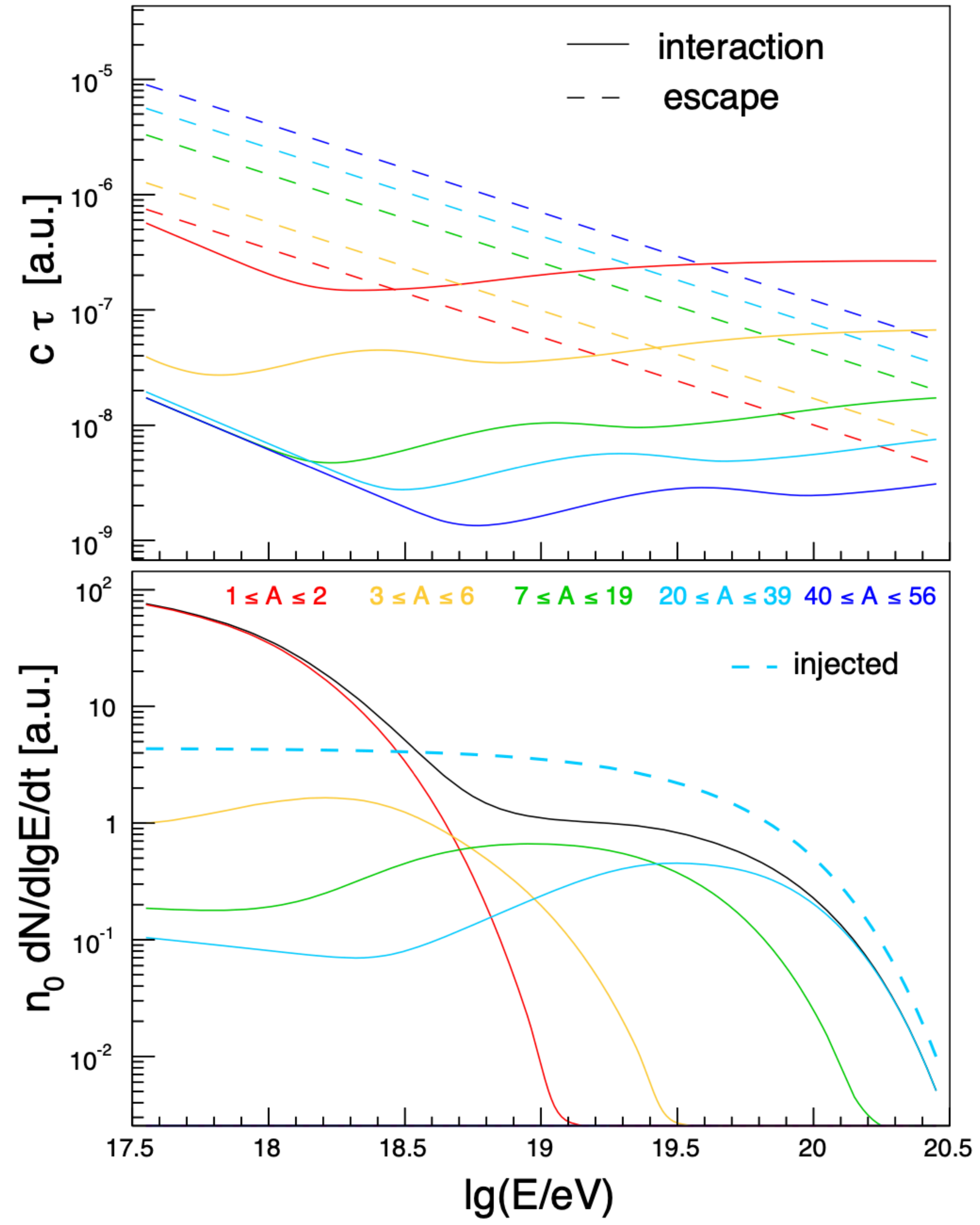

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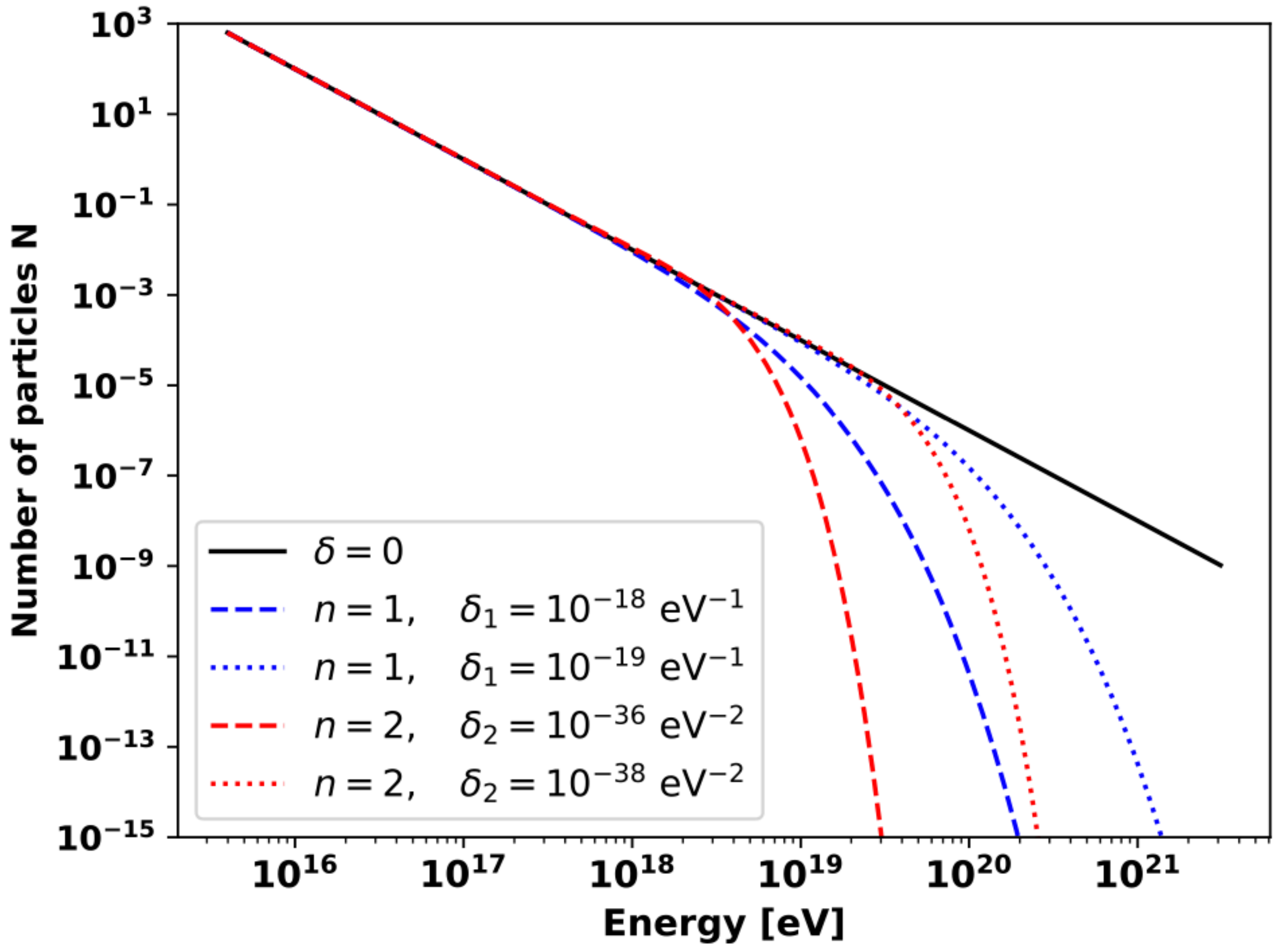

- First order Fermi acceleration can be modified as in Duarte & de Souza, JCAP2024
- Maximum energy is smaller with respect to the LI case
- Escape effects might be dominant anyway

What do we learn from including LIV in propagation?

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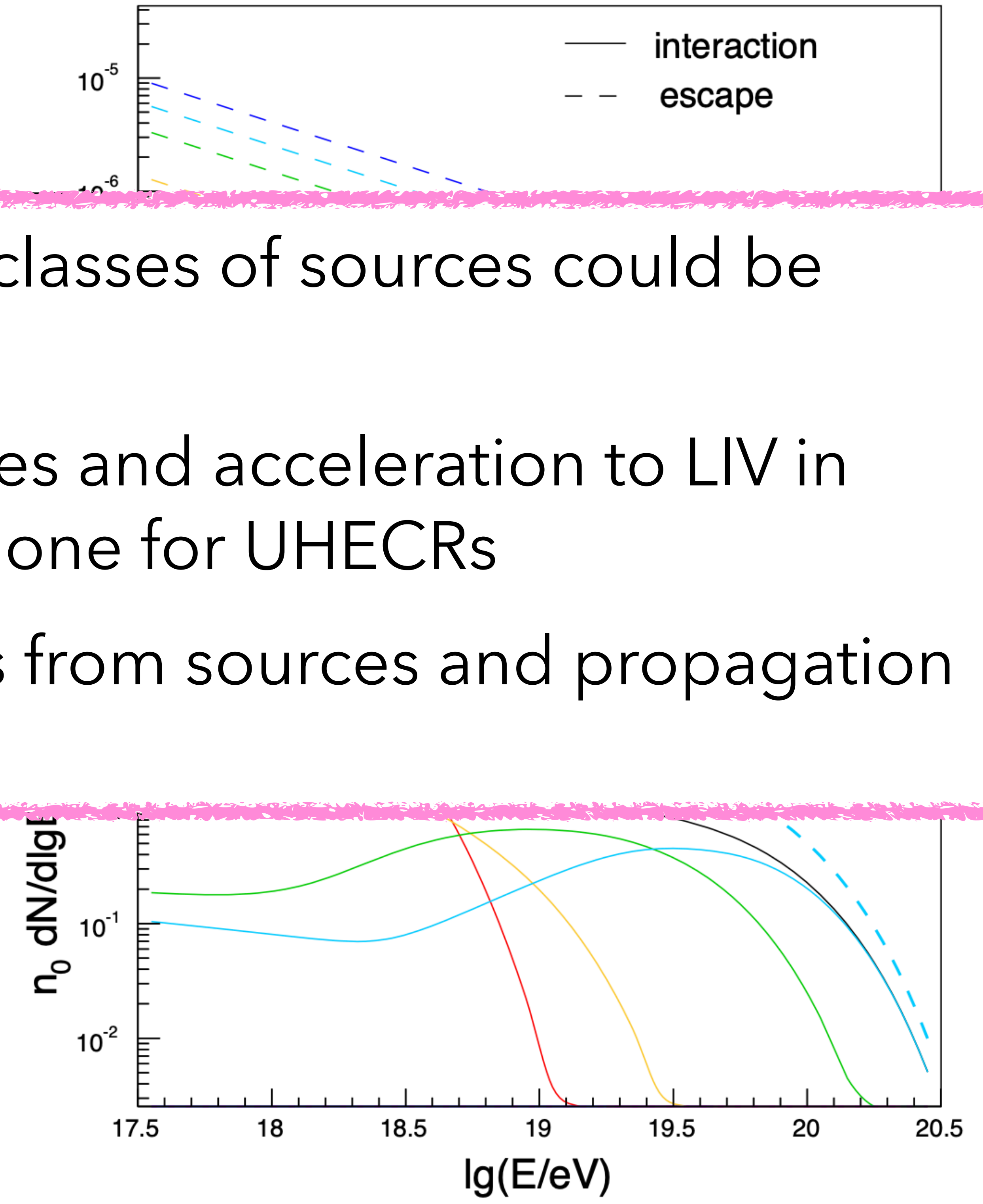
With respect to the LI case

- The characteristics of specific classes of sources could be altered by LIV
- Coupling interactions in sources and acceleration to LIV in propagation has never been done for UHECRs
- Effects for secondary particles from sources and propagation have not been investigated



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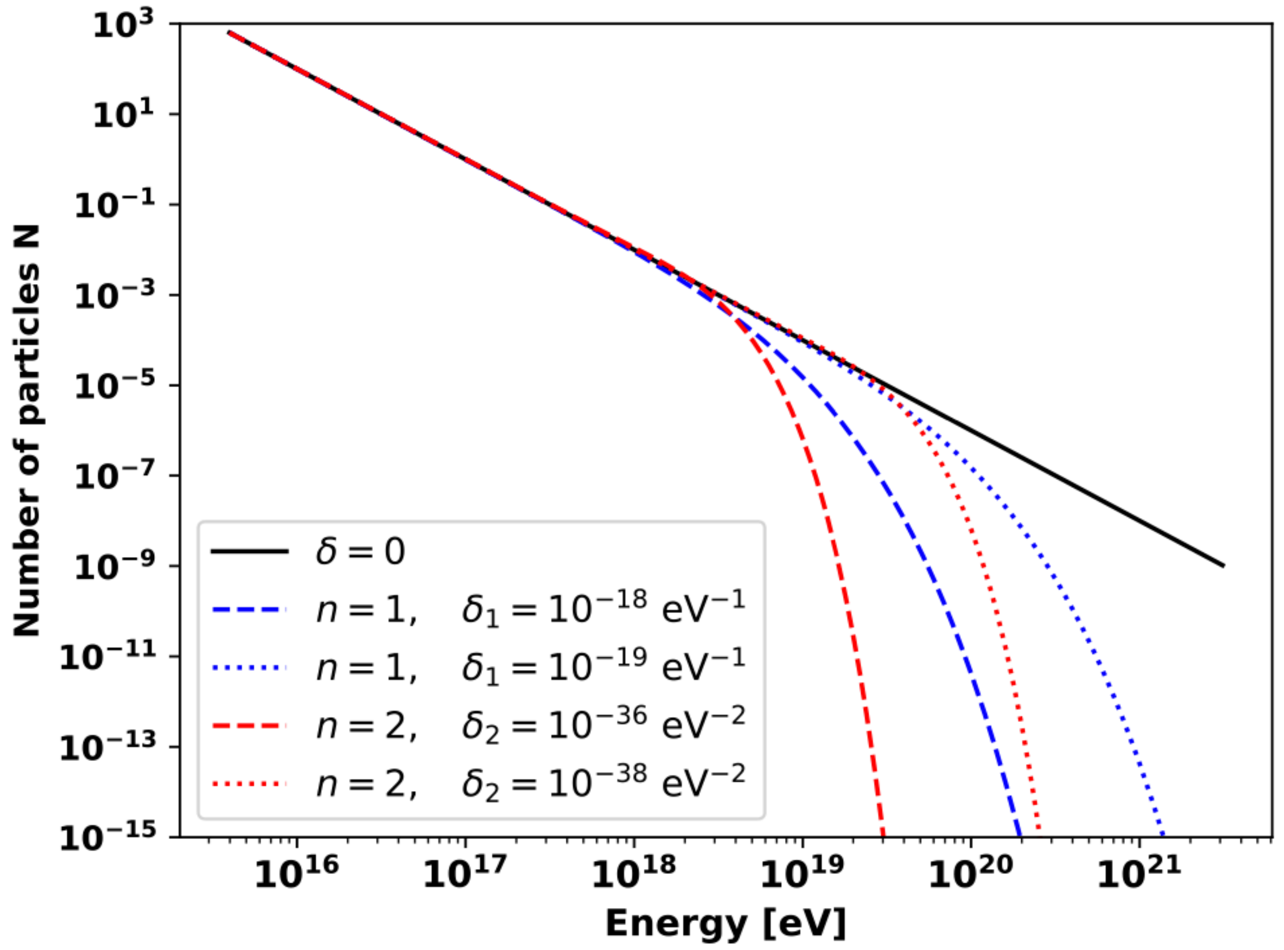


UNKNOWNS IN UHECRS AND HOW THEY AFFECT ALSO OTHER MESSENGERS

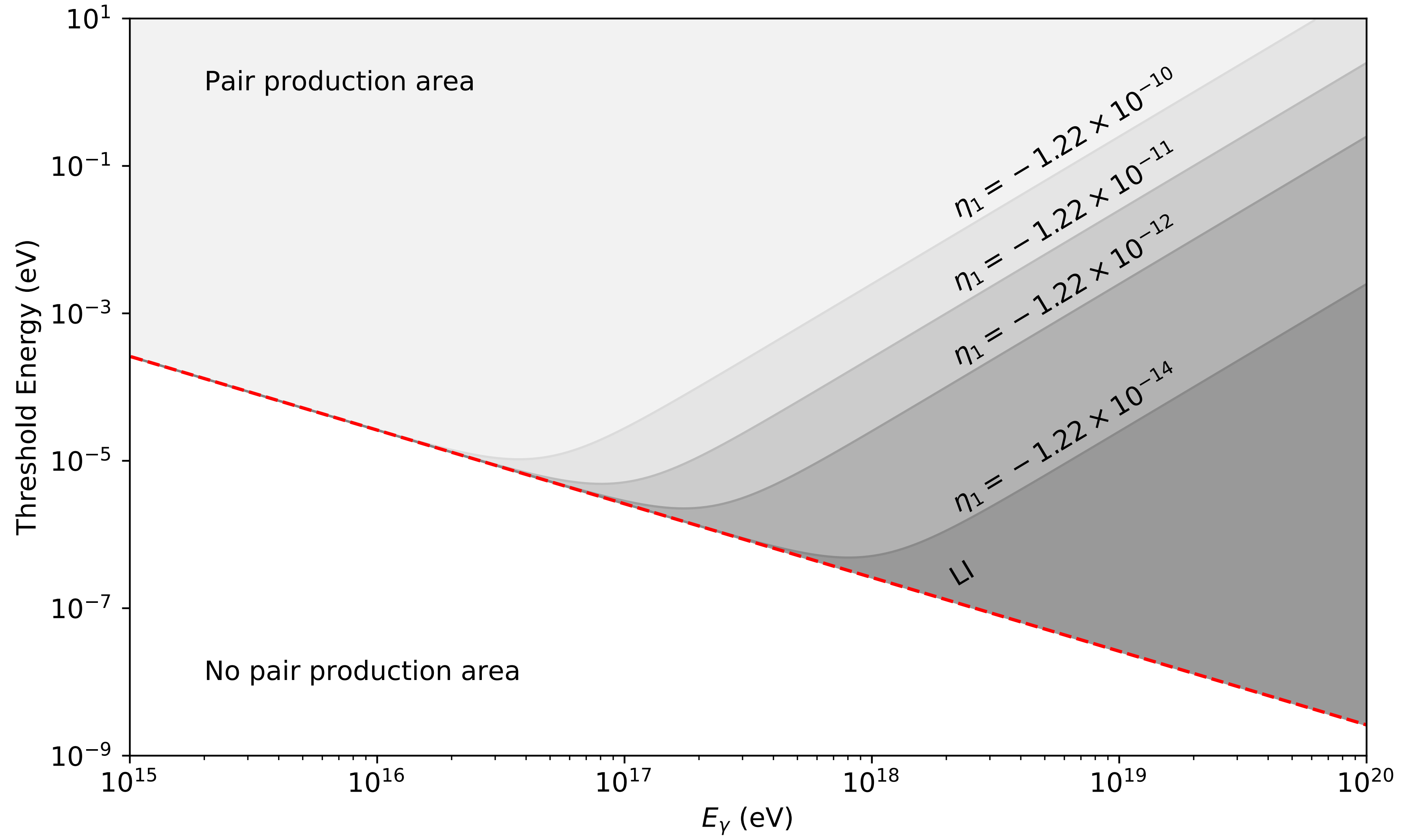
Example from non-observation of UHE photons

LIV in extragalactic propagation of photons

DB, Bezerra, Giammarco, Lobo, Morais & Salamida ICRC 2025

- Modification of threshold (focus on subluminal case, so the threshold increases with LIV), as reported in Lang+ ApJ 2018

$$\epsilon \geq \frac{4m_e^2 - m_{\rm eff}^2}{4E_\gamma}$$



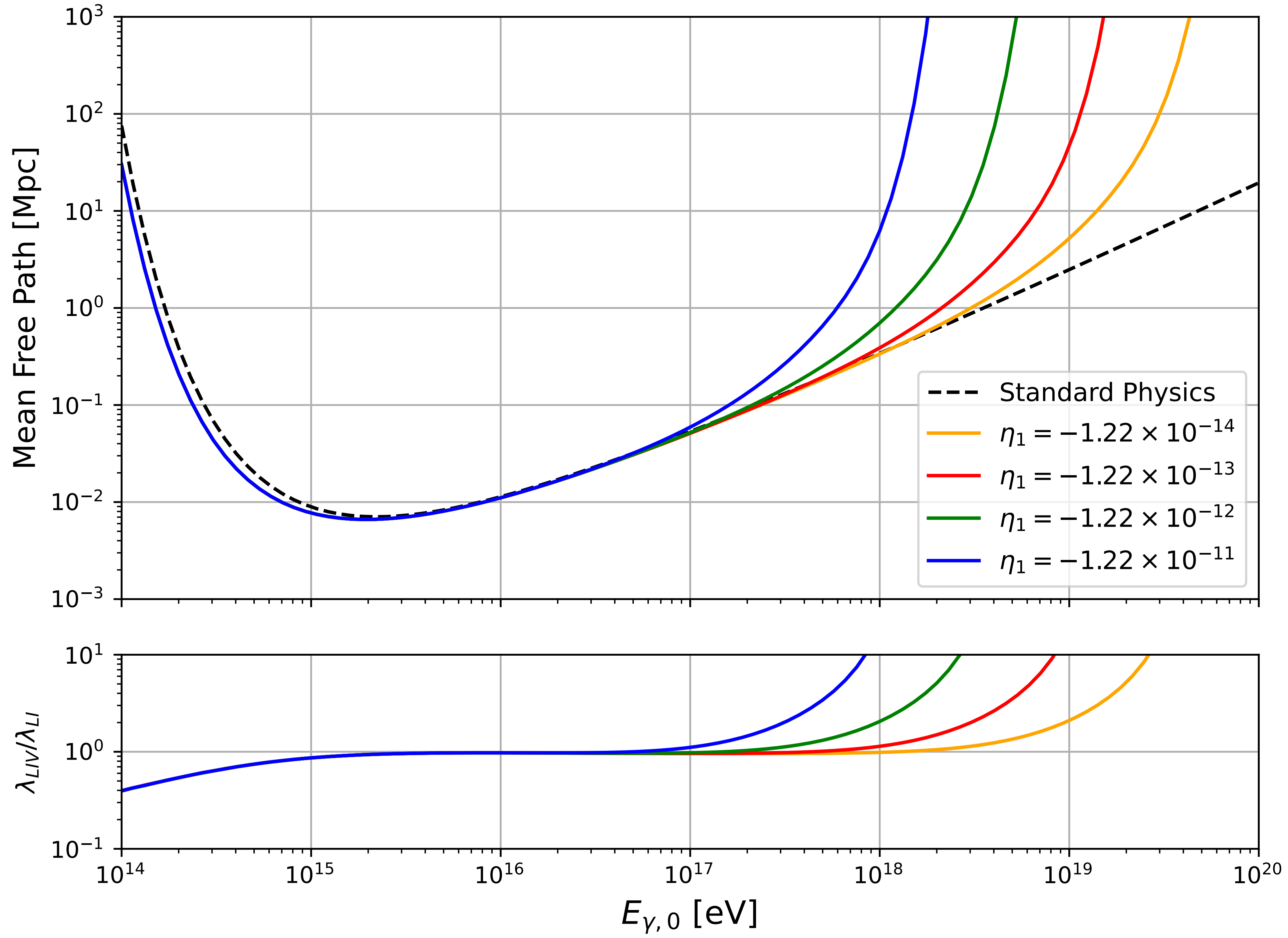
$$\gamma + \gamma_{\rm bkg} \rightarrow e^+ + e^-$$

- See also Carmona+ PRD 2024 for a refined treatment of cross section modifications

$$\frac{1}{\lambda(E)} = \frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty} \sigma(\varepsilon')\varepsilon' \int_{\varepsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\varepsilon)}{\varepsilon^2} d\varepsilon d\varepsilon'$$

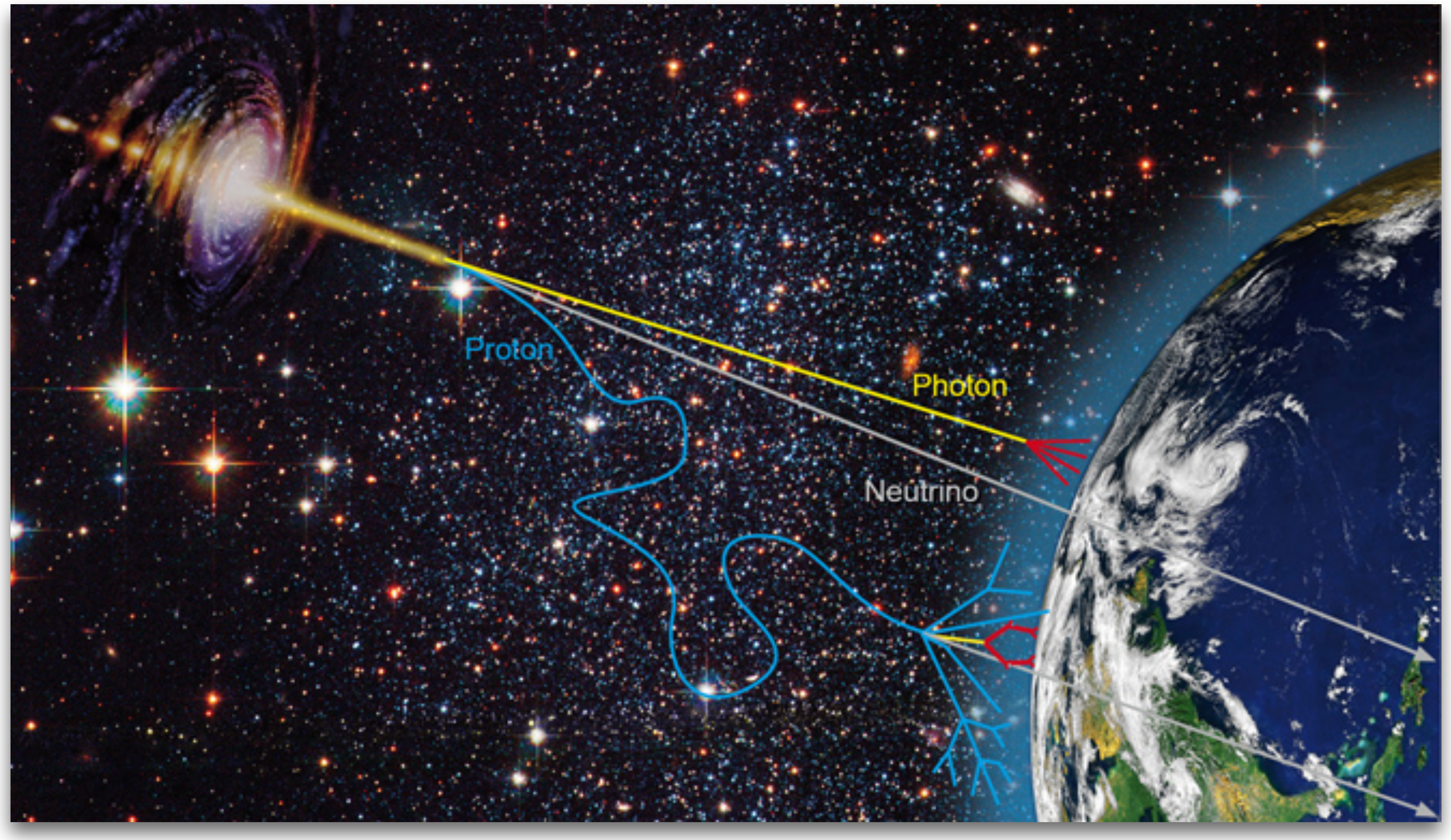
$$P_{prop}(E, d_s(z)) \approx \exp(-d_s/\lambda(E))$$

Modified mean free path



LIV in extragalactic propagation of photons

DB, Bezerra, Giammarco, Lobo, Morais & Salamida ICRC 2025



$$A + \gamma \rightarrow A' + (m)n + (A - A' - m)p$$

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p \quad / \quad \pi^+ + n$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^0 \rightarrow 2\gamma$$

- Redshift and energy of **cosmogenic photons** (as produced by interactions of UHECRs with background photons) computed with *SimProp*
- Mass composition and spectral characteristics of UHECRs at their sources determined through the fit of measured spectrum and mass composition, see Auger JCAP 2017; JCAP 2023
  - Additional proton component (as allowed from Auger data) to increase the production of cosmogenic particles (see Muzio+ PRD 2019 for details)
  - The normalisation of the photon flux is fixed by the comparison of the parent UHECR flux to data

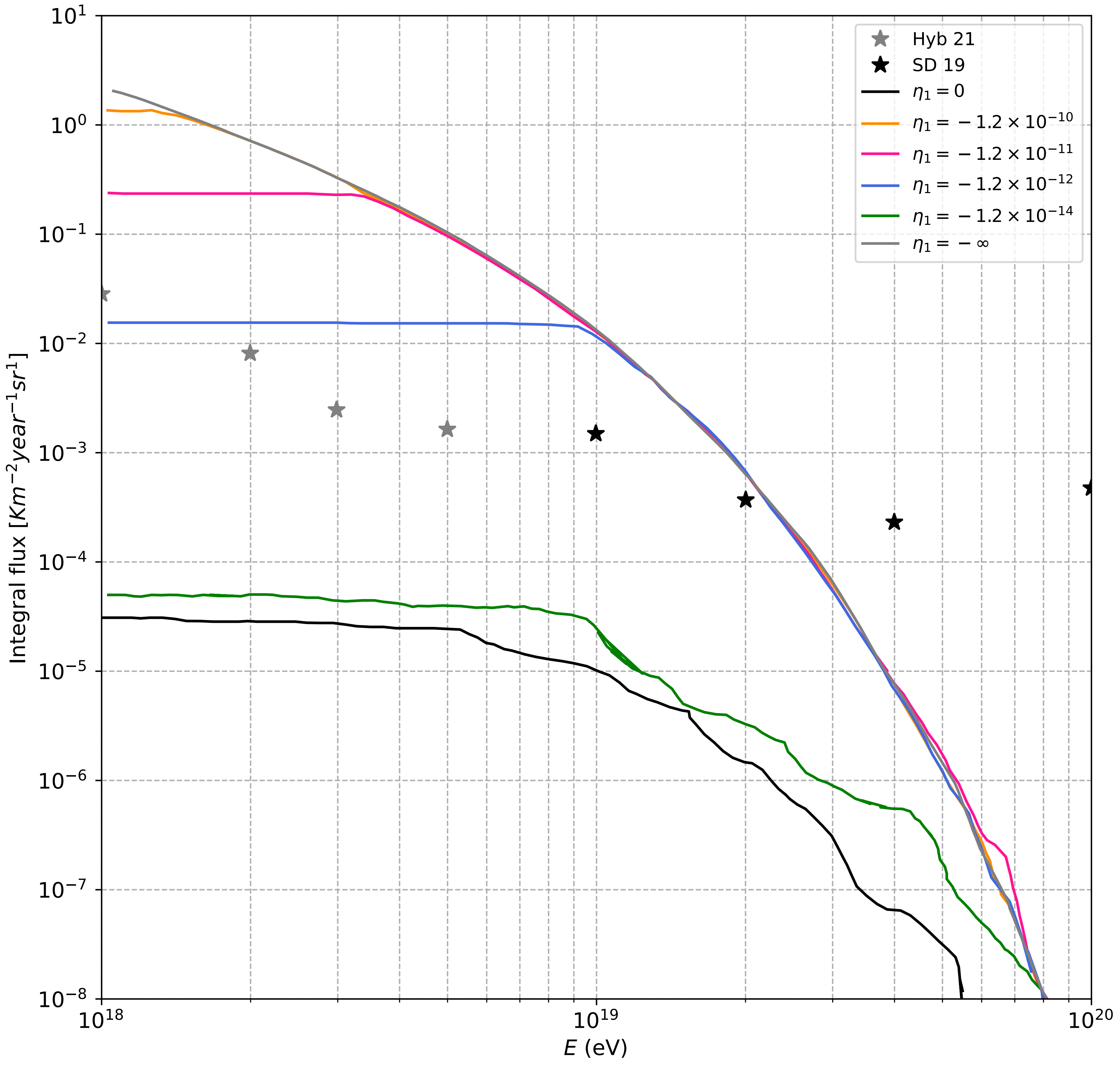
$$\left(\frac{dn_\gamma(E, z=0,\eta)}{dE}\right)_{top-of-atm} = \sum_{z_i} P_{prop}(E, z_i, \eta)\frac{dn_\gamma(E, z_i)}{dE}$$

→ Cosmogenic photons, as produced with SimProp

- LIV modifications allow for a larger photon flux to reach the top of the atmosphere
- LIV parameters corresponding to fluxes larger than the upper limits (as set by Auger, see Auger PRD 2024) can be excluded

LIV in extragalactic propagation of photons

DB, Bezerra, Giammarco, Lobo, Morais & Salamida ICRC 2025



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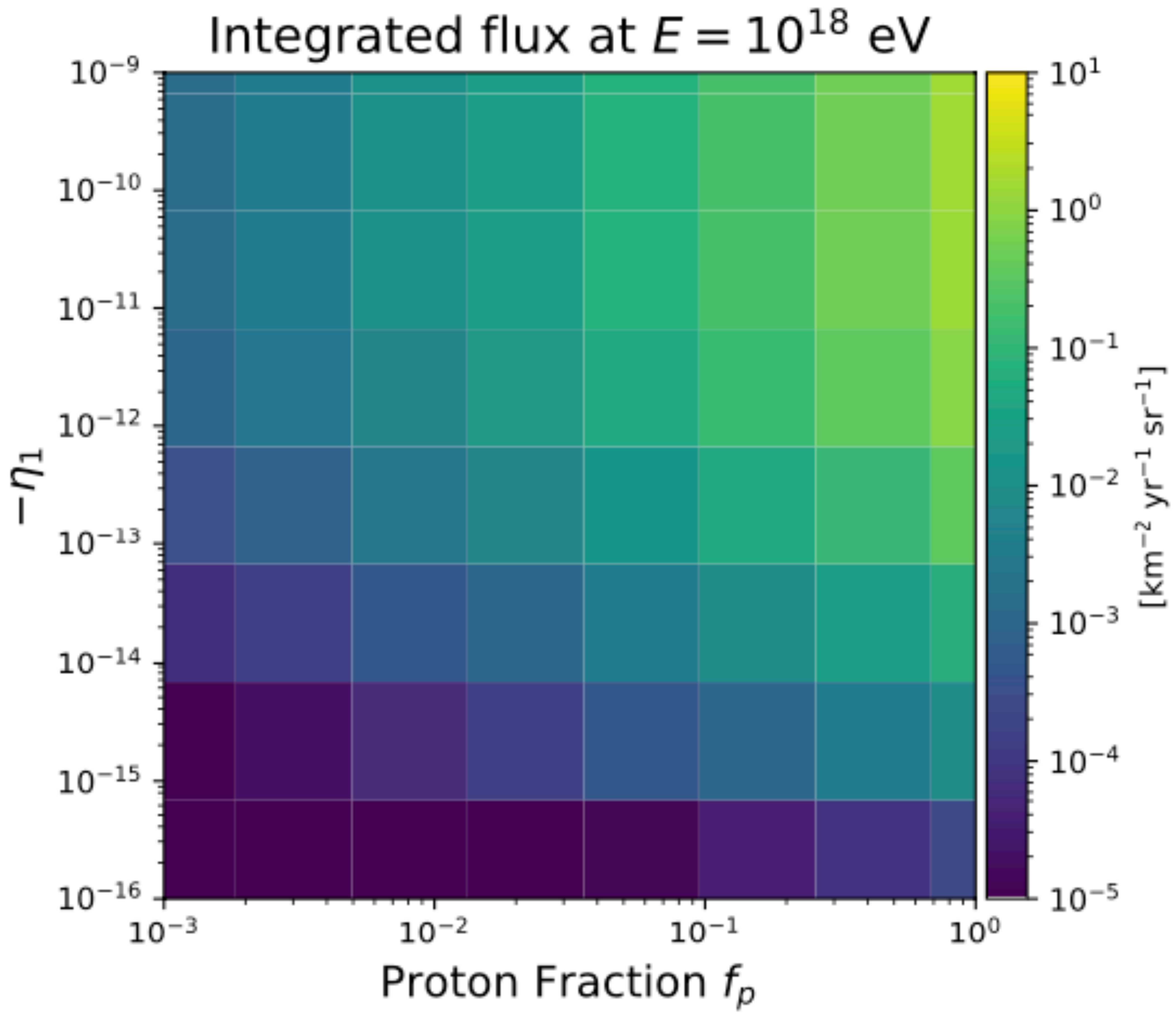
LIV in extragalactic propagation of photons

DB, Bezerra, Giammarco, Lobo, Morais & Salamida ICRC 2025

- Attempt of coupling astrophysical uncertainties with LIV searches

- While fixing the other astrophysical parameters linked to the UHECR flux (spectral index, maximum energy of acceleration, mass composition), a scan over the proton fraction in UHECRs and LIV parameter can be performed
- Large proton fraction as well as large LIV parameter increase the expected photon flux



- A similar approach as the one proposed here can be used also to **test DSR**
- Observation of UHE photons happens through the development of showers in atmosphere
  - The same effect allows for more photons to reach the Earth surface -> a lower flux is expected

SUMMARY

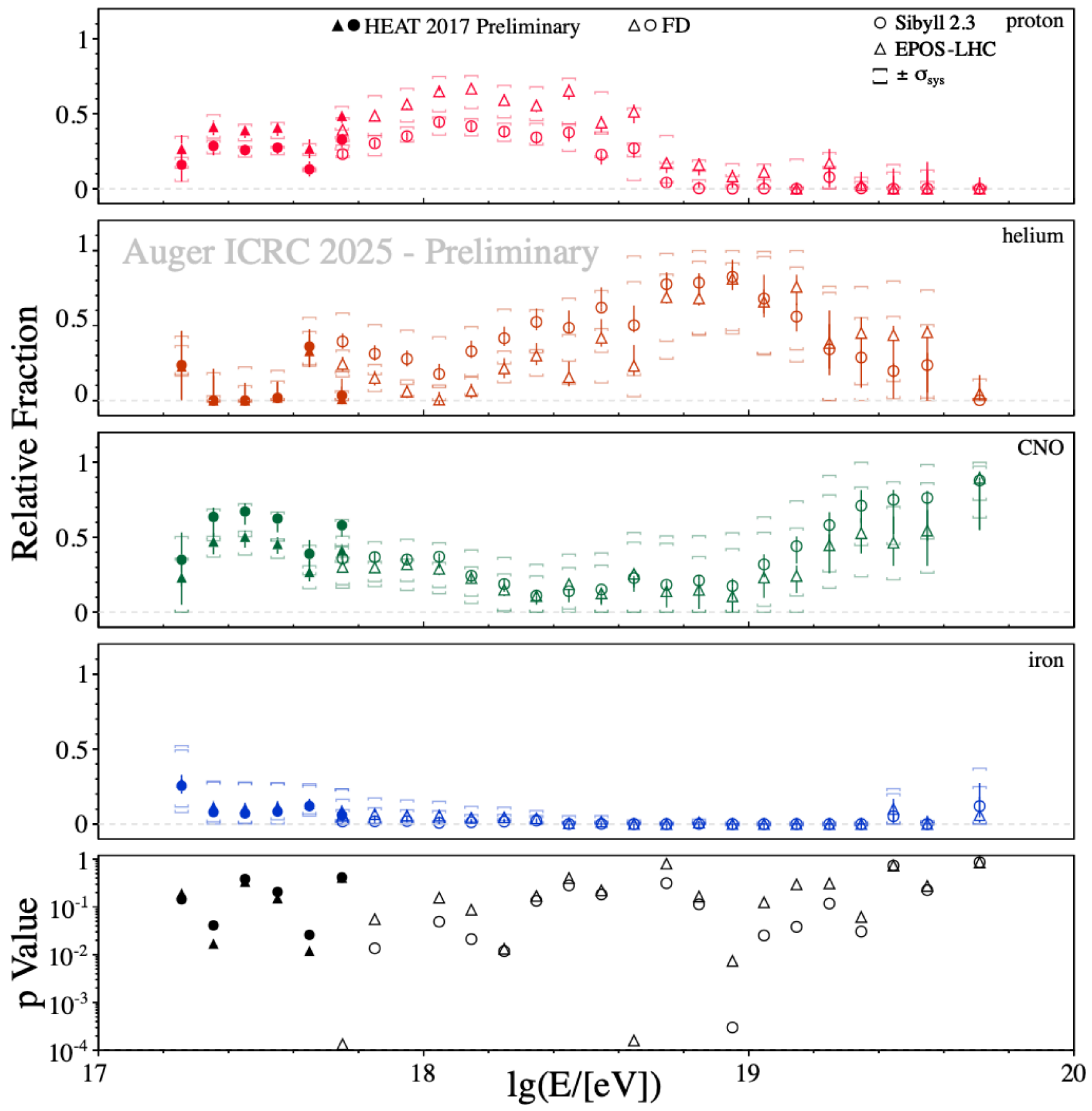
Summary

- Astrophysical scenarios from UHECRs data -> generic description of source properties through diffuse fluxes
  - Insights from basic source modelling on the origin of the proton component
- LIV can modify UHECR interactions, and therefore
  - our perception of the characteristics of UHECRs at the escape from sources; similarly, LIV can be considered in
    - in-source interactions -> expected effect: more particles escape before interacting
    - acceleration: -> expected effect: if 1st order Fermi acceleration is accounted for, the typical time has a stronger dependence on energy and therefore more particles could escape before reaching the highest energies
  - cosmogenic fluxes can be altered (depending on strength of violation and astrophysical unknowns)

Summary

- The preferred scenario to test LIV with UHECR in extragalactic propagation and in sources is the one predicting light mass & high energy
  - **Deciphering the proton fraction in UHECRs is crucial**
    - Experimental challenges for the determination of the proton fraction in UHECRs -> discrimination of electromagnetic and muonic component in the shower
      - Upper limit at about 20% above the ankle
    - Modelling challenges
      - Modelling of interactions in atmosphere: hadronic interaction models are extrapolated to the highest energies for the interpretation of the mass composition
      - Modelling of in-source interactions:
        - Dependence of proton fraction on source details and on acceleration (maximum energy has to match the UHECR data)
        - No theory predicts acceleration to UHE for CRs

The Pierre Auger Collab. ICRC25



- Other systematics should be considered for LIV searches with UHECRs
  - Uncertainty in the determination of the energy of UHECRs (as in the calorimetric measurement)
  - Uncertainty in the component of the showers (as in the number of muons, see C. Trimarelli for the Auger Collab, ICRC 2021)

BACKUP SLIDES

The Pierre Auger Observatory at a glance

Southern hemisphere: Malargüe, Province Mendoza, Argentina

Surface detector (SD)

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

Fluorescence detector (FD)

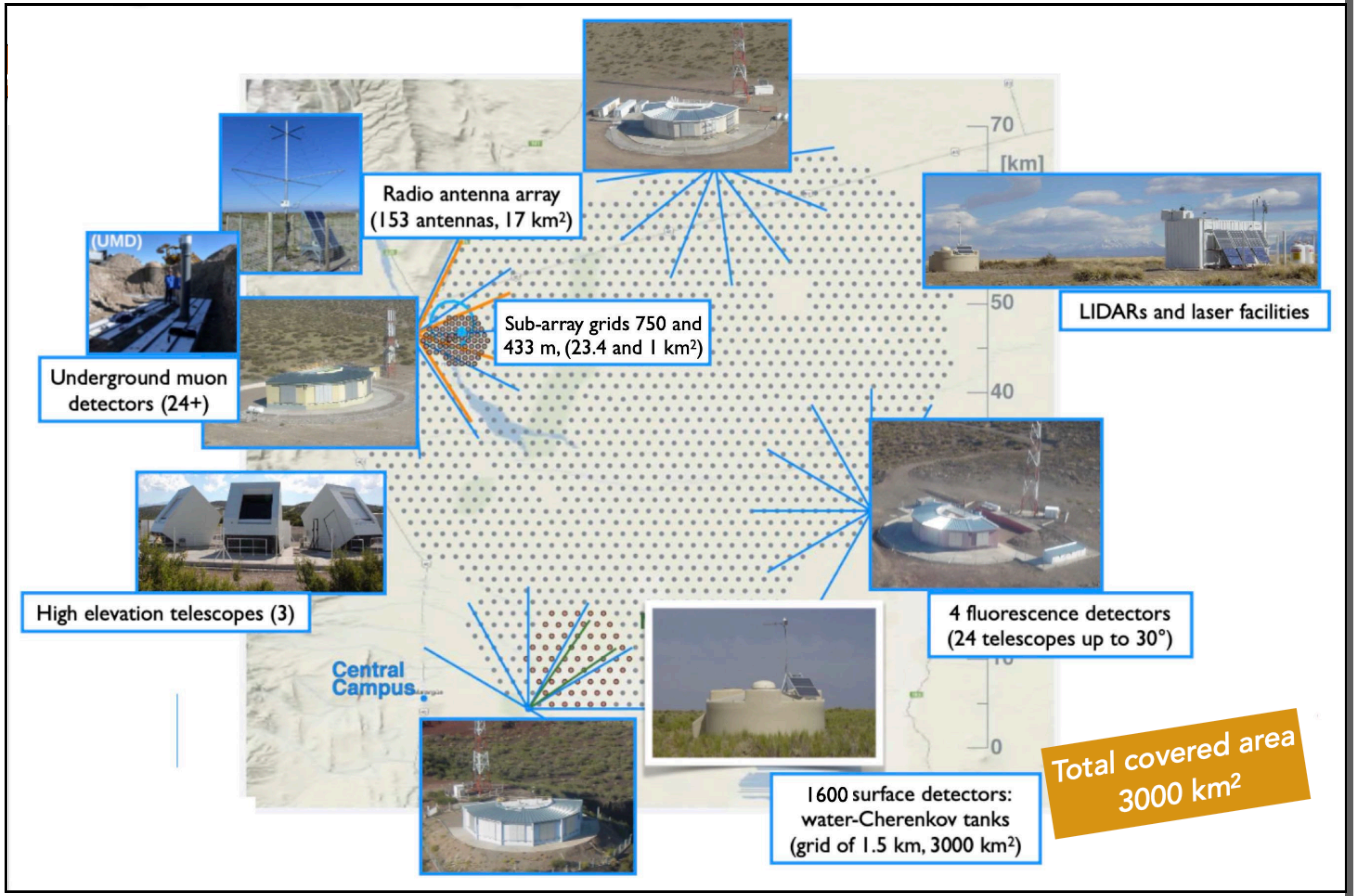
- 24 telescopes in 4 sites, FoV: 0-30°, E > 10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60°, E > 10^{17} eV

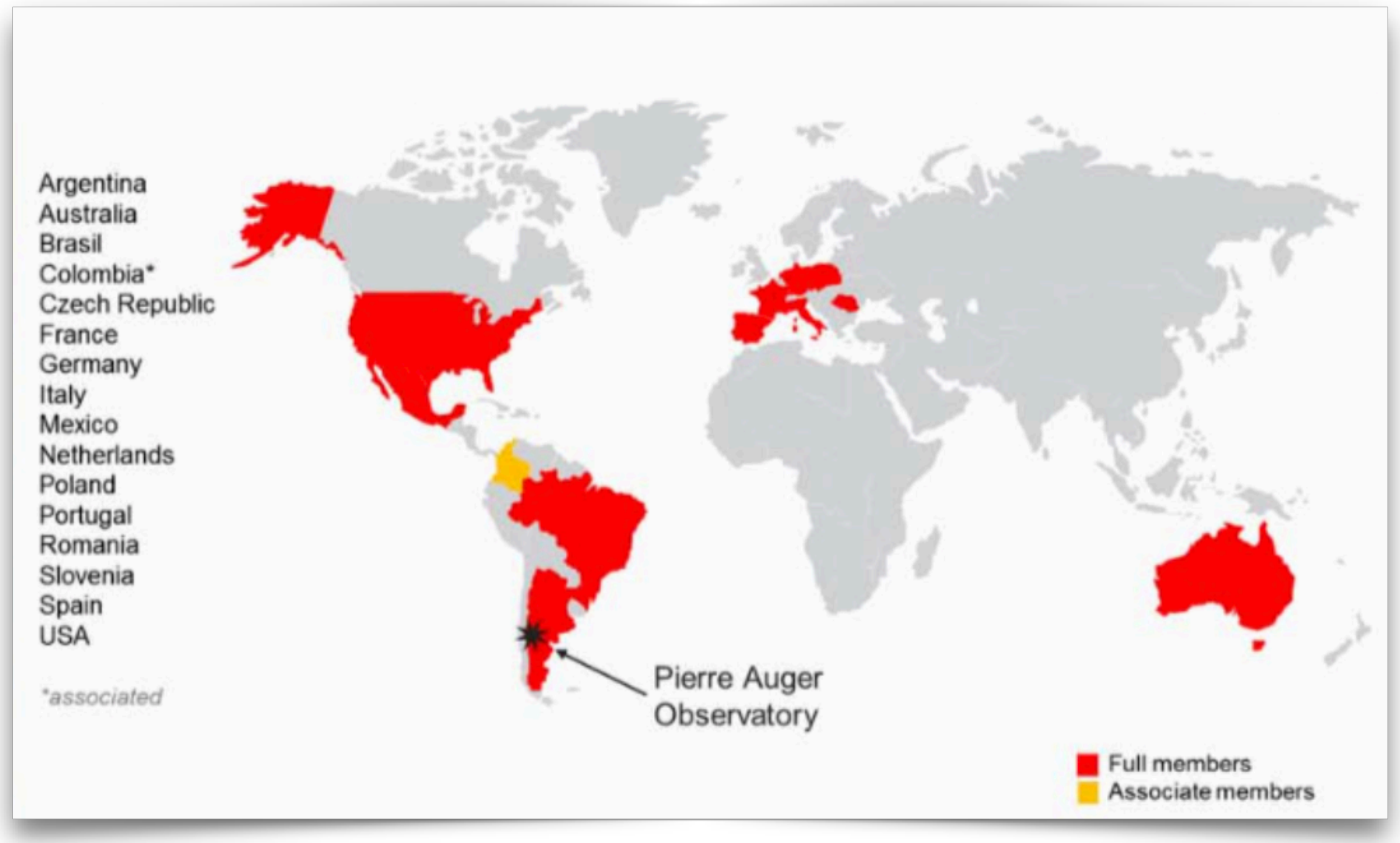
Auger Engineering Radio Array (AERA)

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

Underground muon detector

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





17 countries, more than 400 members

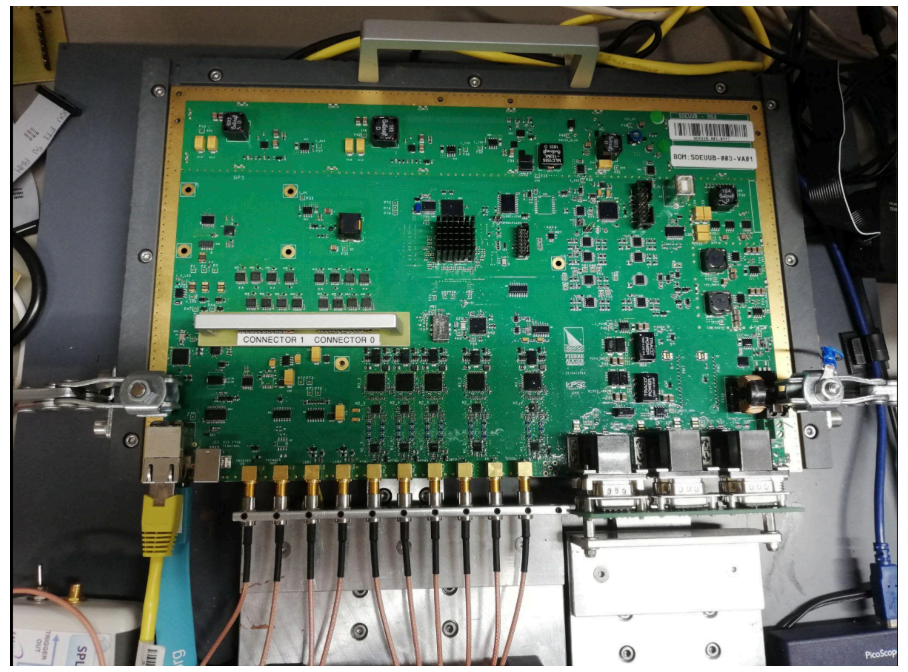
AugerPrime

- The SSDs complement the WCDs to provide enhanced electromagnetic-muonic shower component separation up to a zenith angle 60○
- The RDs extend this sensitivity to inclined showers above 60○ by measuring the electromagnetic component, while the WCDs measure the muons, which alone survive to the ground at these high inclinations
- An additional small PMT has also been installed in each station to enhance the WCD dynamic range.
- SD electronics have been upgraded to run all these detectors and provide improved timing resolution.

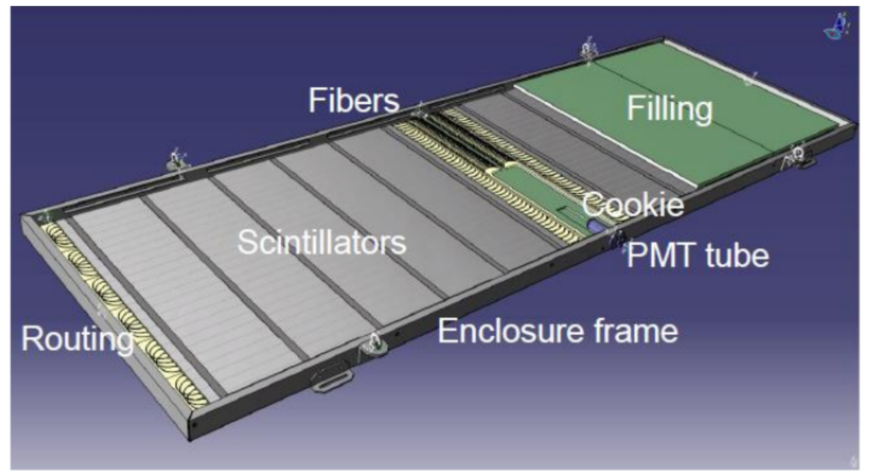
Towards multi-hybrid observations of extensive air showers with **AugerPrime!**

Radio upgrade

New electronics



Scintillators

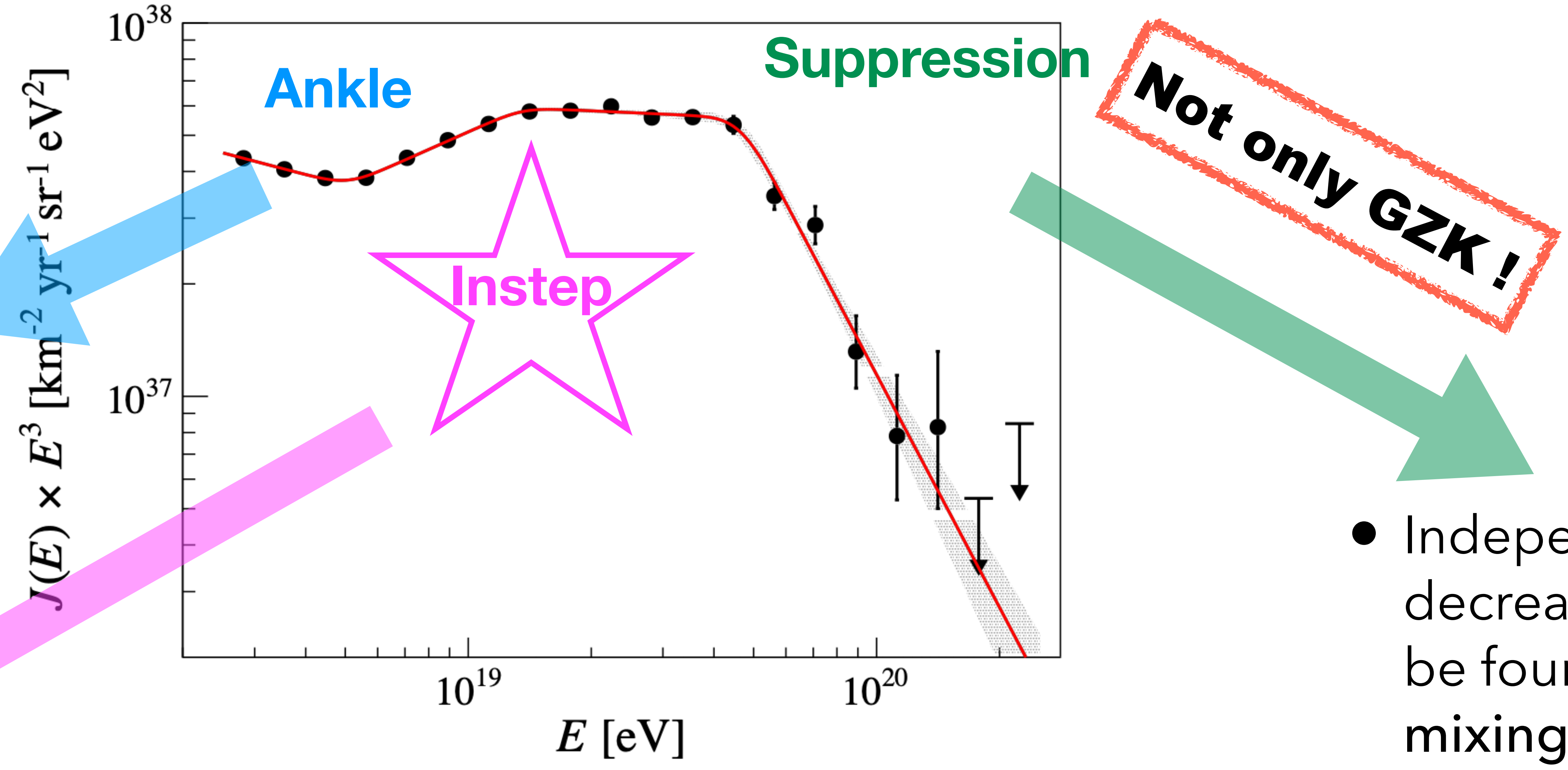


Underground muon detectors

High-dynamic range PMTs

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

The Pierre Auger Collab. JCAP 2023

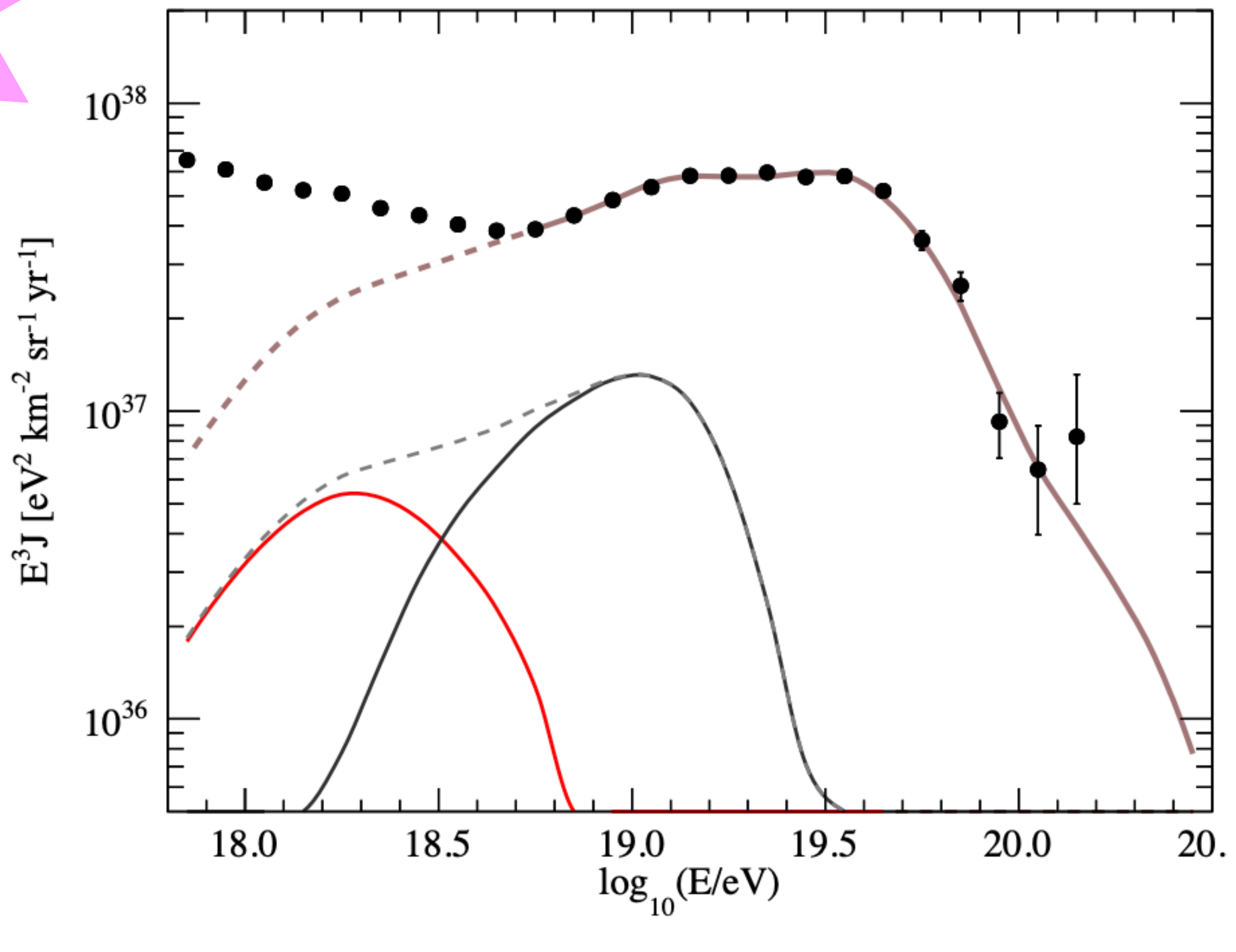


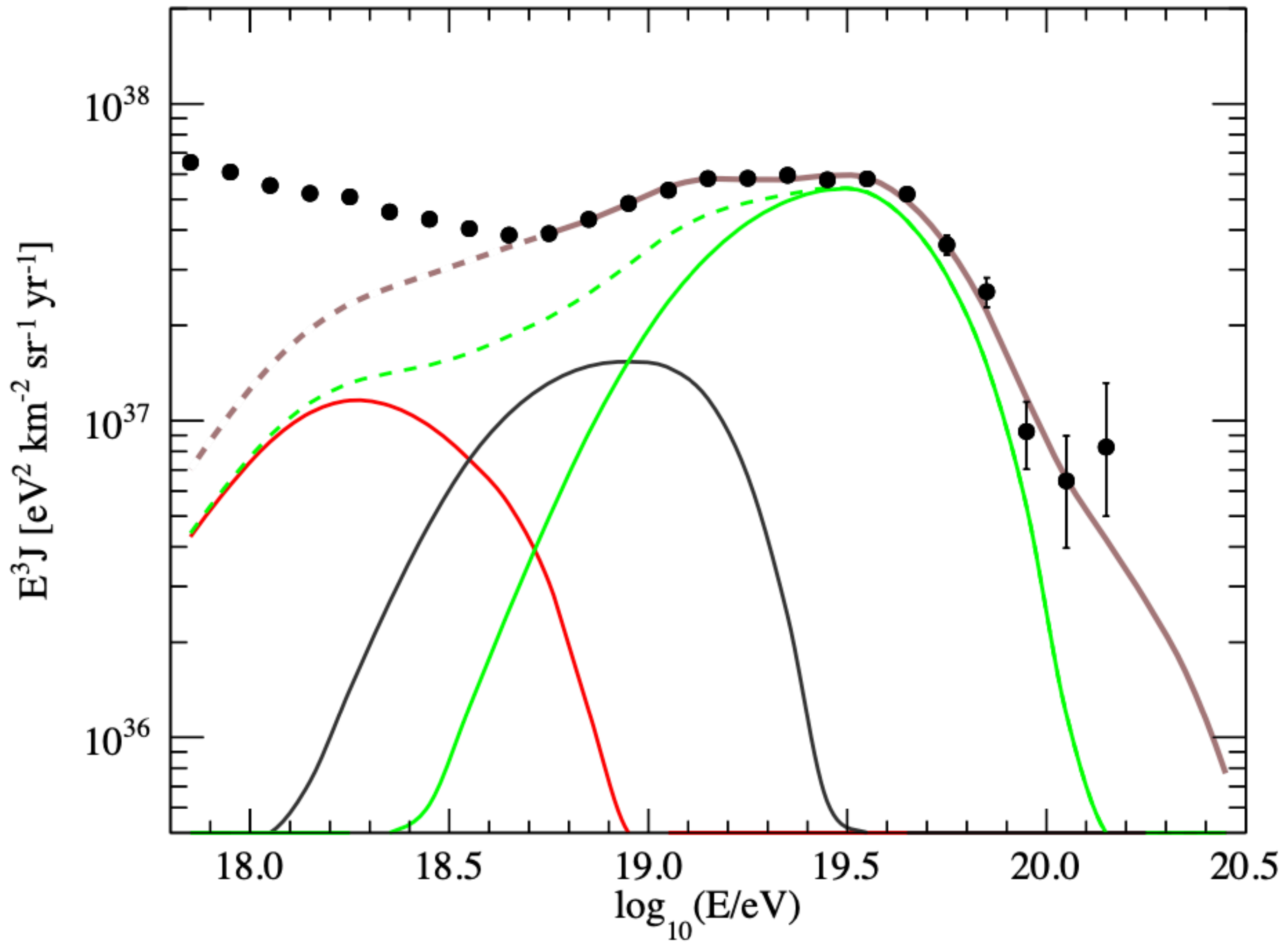
Ankle: interplay between (soft) LE and (hard) HE components

- Different populations of UHECR sources
- In-source interactions

- 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 + less constrainable rigidity

Instep: interplay between the flux contributions of the He and CNO components





In terms of interpretation, the **suppression is a combination of effects**

- Propagation effect
- Indication of source power

Mass composition observables from air-showers

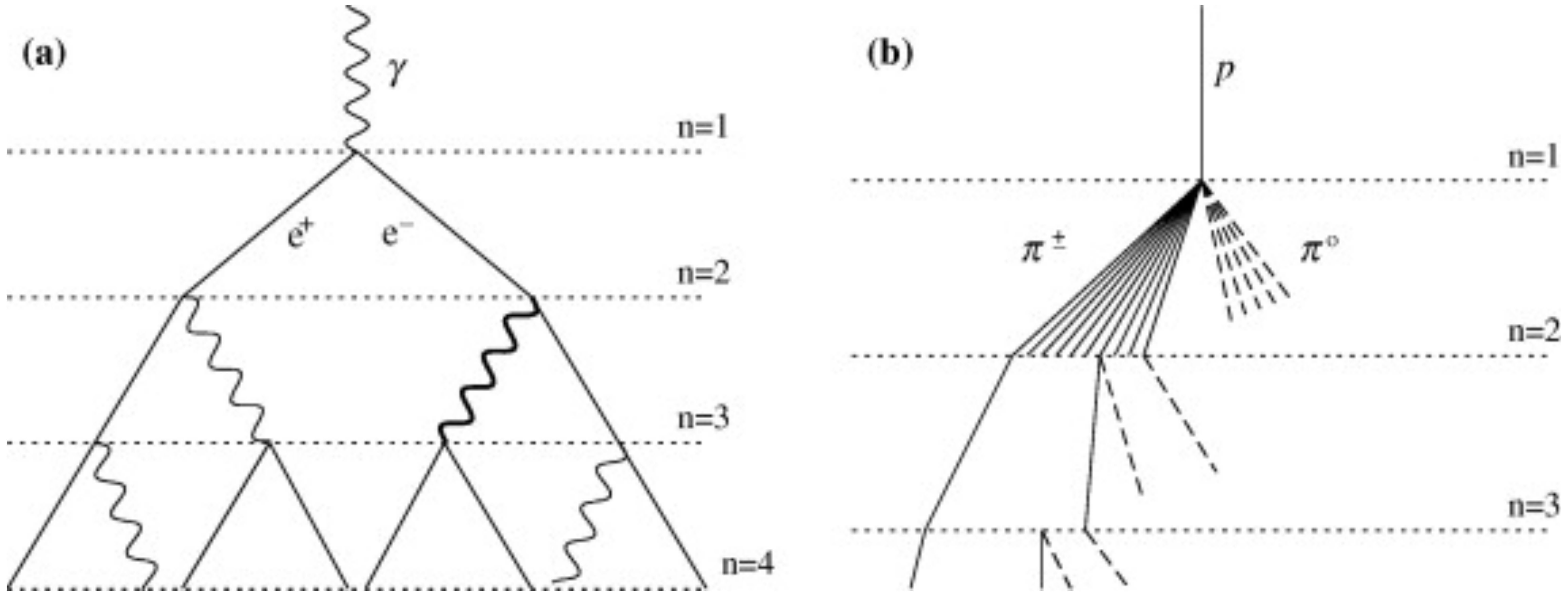
Heitler (and generalised-Heitler) model for EAS

$$N(X) = 2^{X/\lambda} \qquad E(X) = \frac{E_0}{N(X)}$$

$$N(X_{\rm max}) = \frac{E_0}{E_c} \qquad X_{\rm max} \propto \ln(E_0/E_c)$$

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

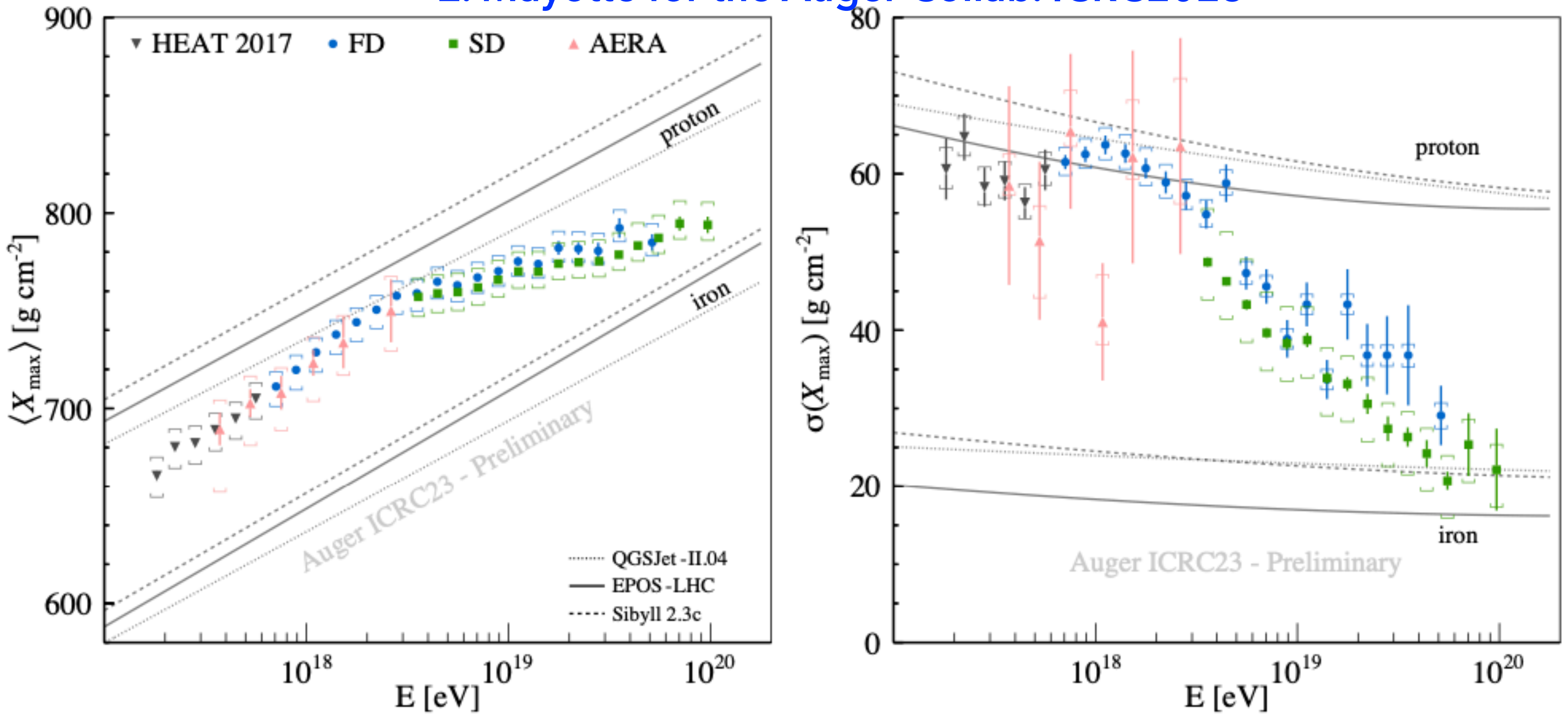
$$X^{A}_{\rm max} \propto X_{\rm max}(E_0/A)$$



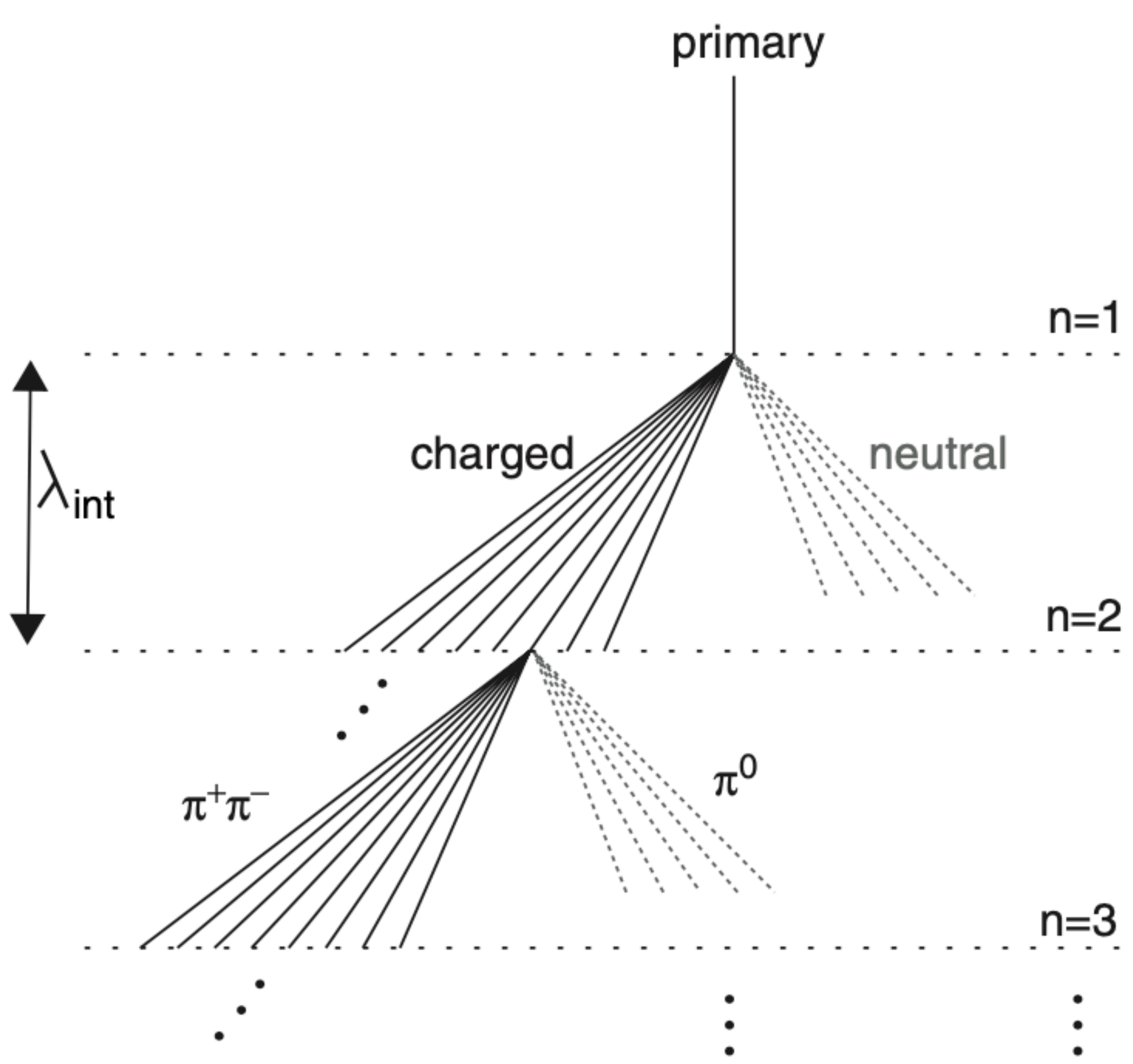
- Composition information (mainly) from the longitudinal development of the shower
- The number of muons (and its fluctuations) is also sensitive to the mass of the primary (from the measurements at ground)

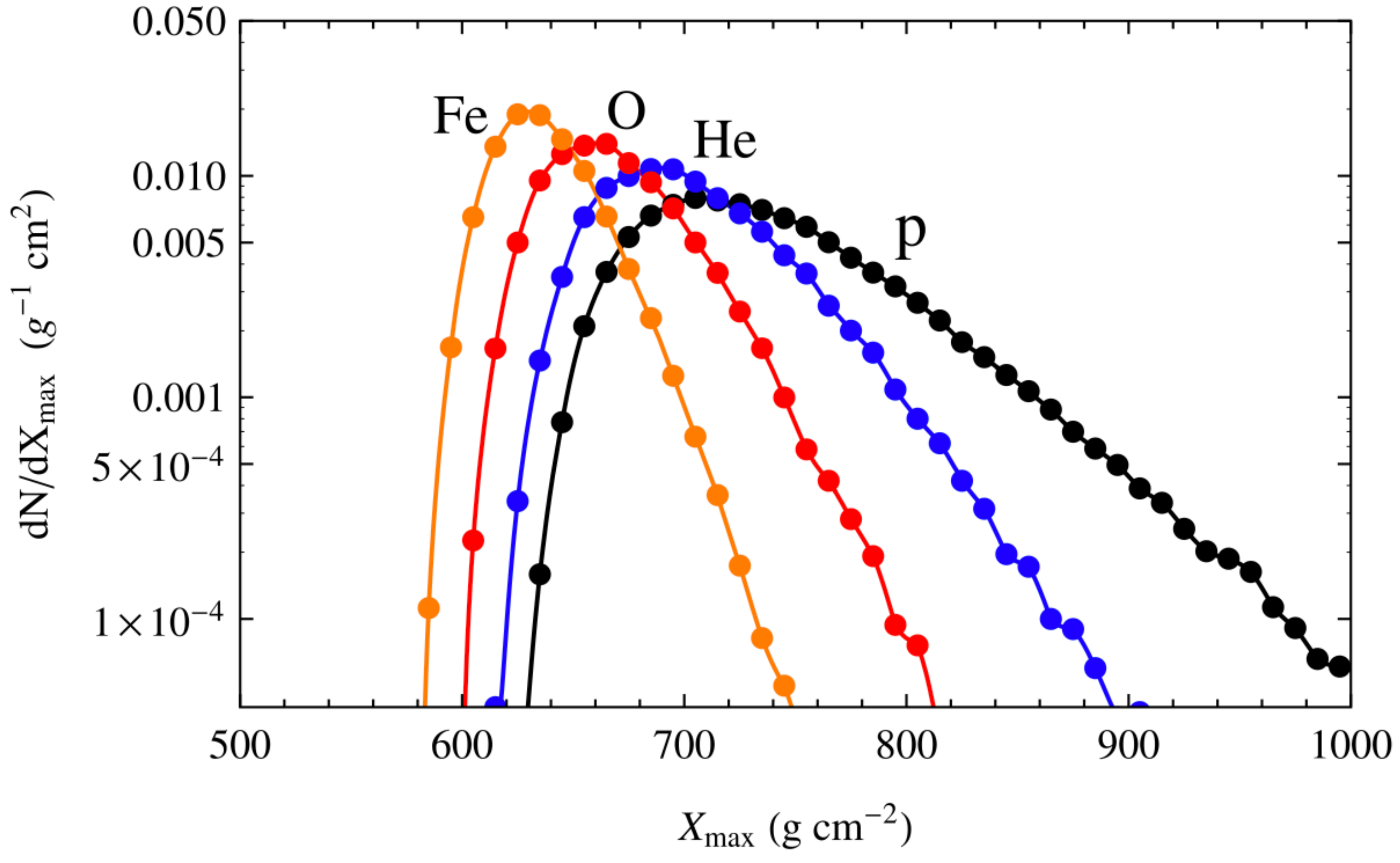
$$N^{A}_{\mu}(X_{\rm max}) = A\left(\frac{E_0/A}{E_{dec}}\right)^{\alpha} = A^{1-\alpha}N^{p}_{\mu}(X_{\rm max})$$

E. Mayotte for the Auger Collab. ICRC2023

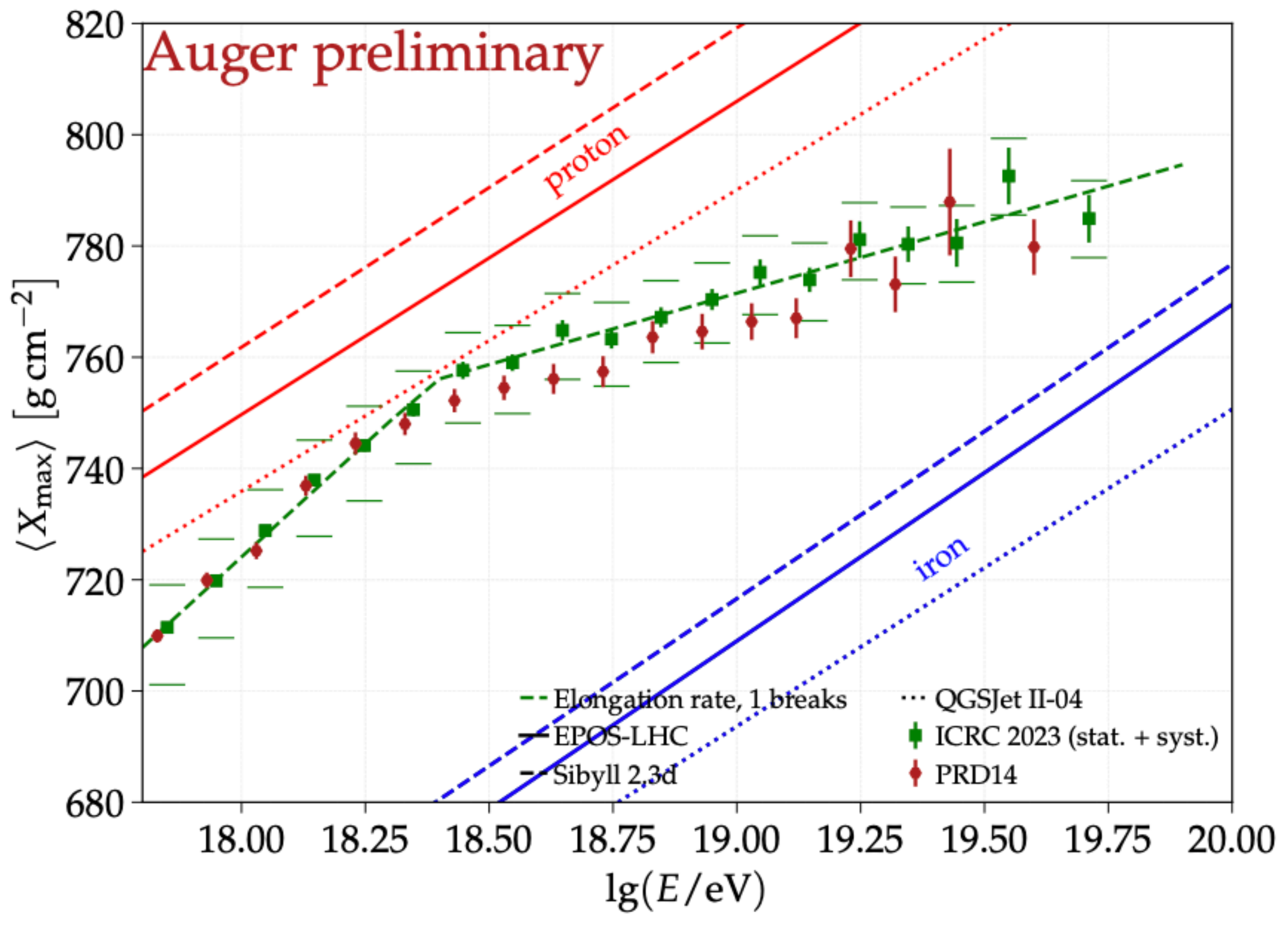


THE **MASS COMPOSITION MEASUREMENTS**





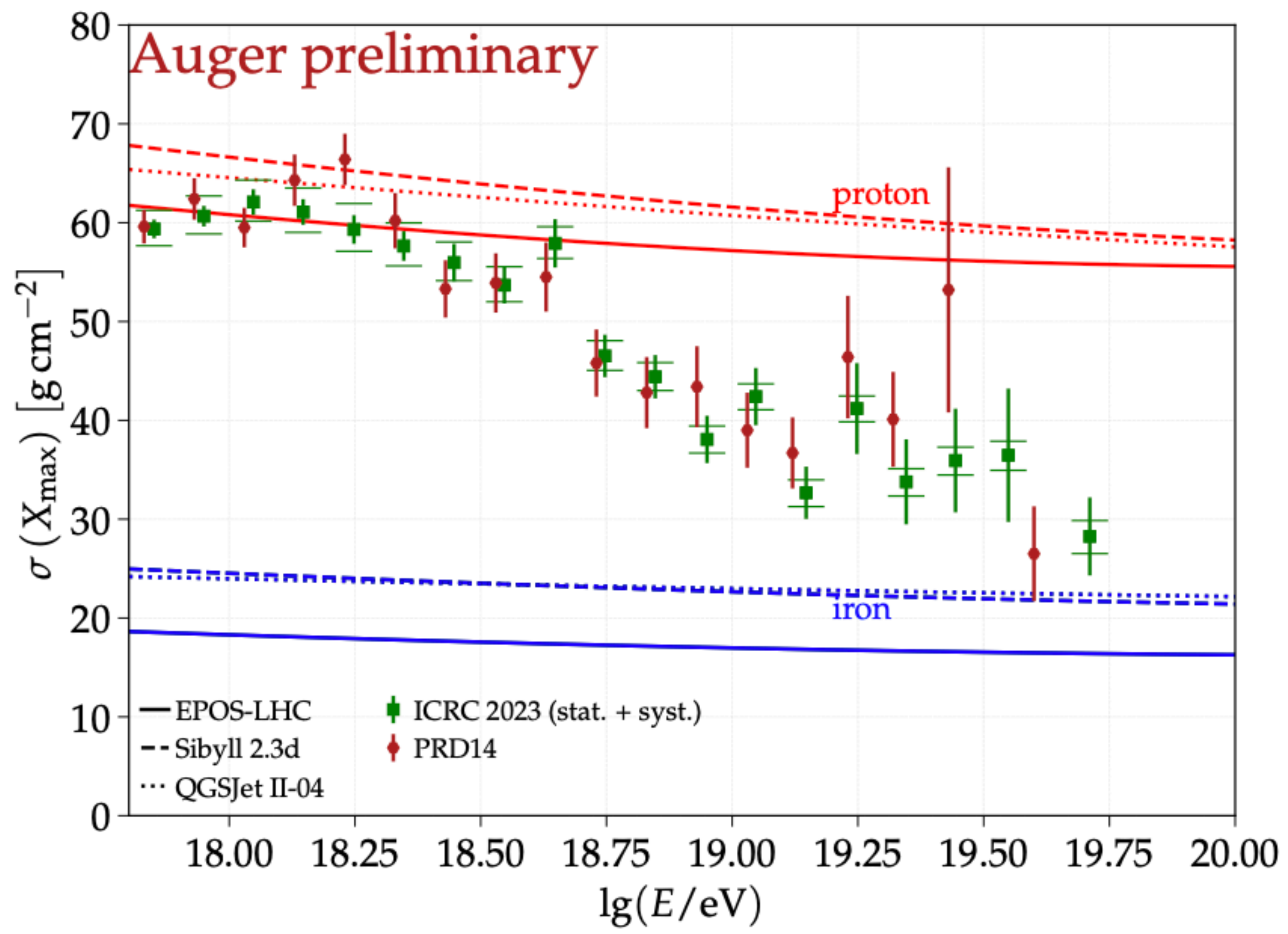
The Pierre Auger Collab. ICRC23



Evidences:

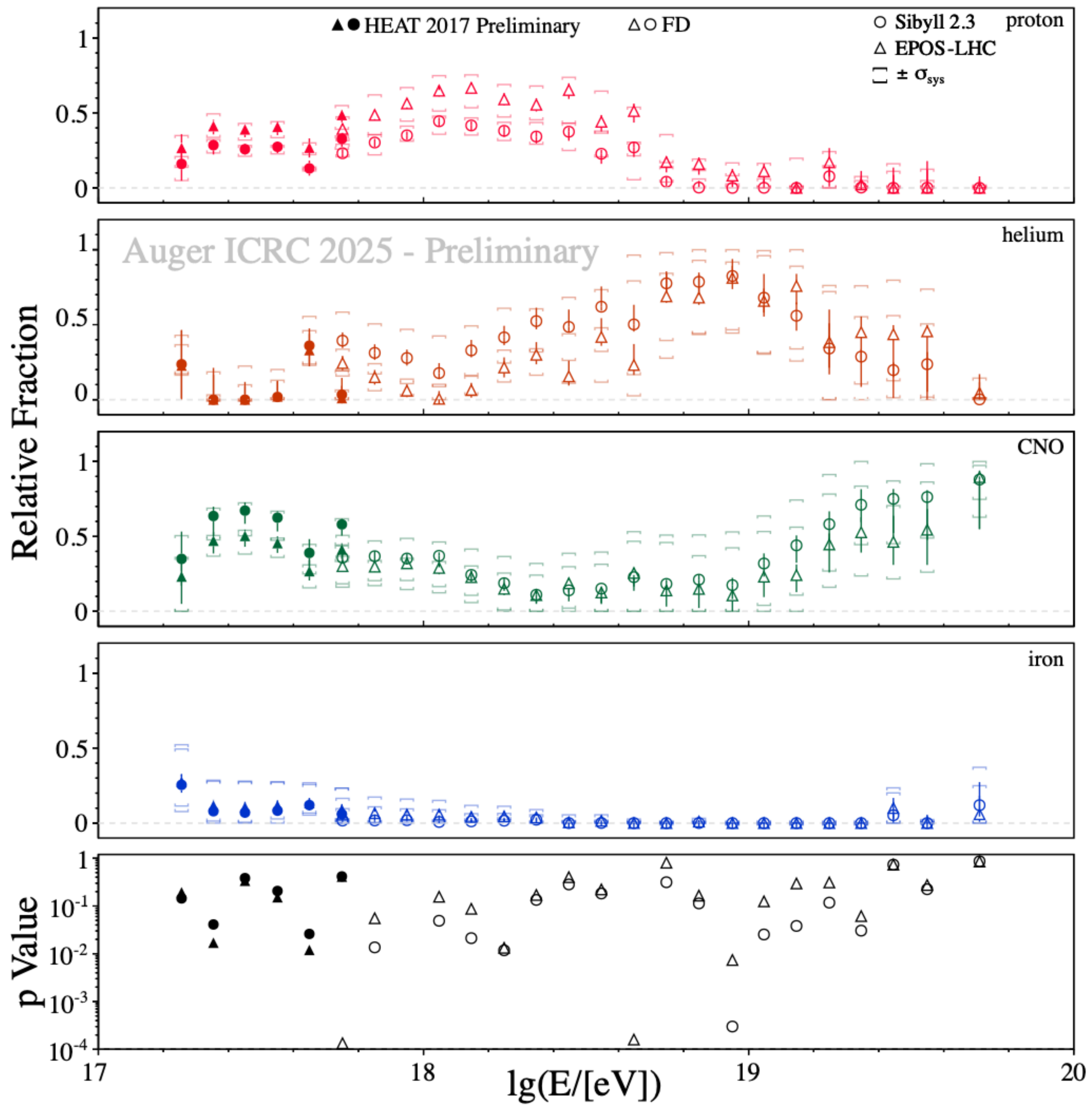
- First momentum: elongation rate is not constant
  -> see also The Auger Collab arxiv:2406.06315 and arxiv:2406.06319

- Second momentum: fluctuations decrease



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

THE **MASS COMPOSITION MEASUREMENTS**



The Pierre Auger Collab. ICRC25

- The first and second moments of Xmax provide a clear summary of the overall UHECR composition
- they do not offer a clear picture of the individual contributions of distinct mass groups.
    - By generating templates of the Xmax distributions for proton, helium, CNO, and iron with different hadronic interaction models, and then fitting a superposition of these templates to the measured Xmax distributions at each energy, estimates of the fractional abundances of each mass group can be extracted

WHAT DO WE LEARN FROM THE MASS COMPOSITION OBSERVABLES?

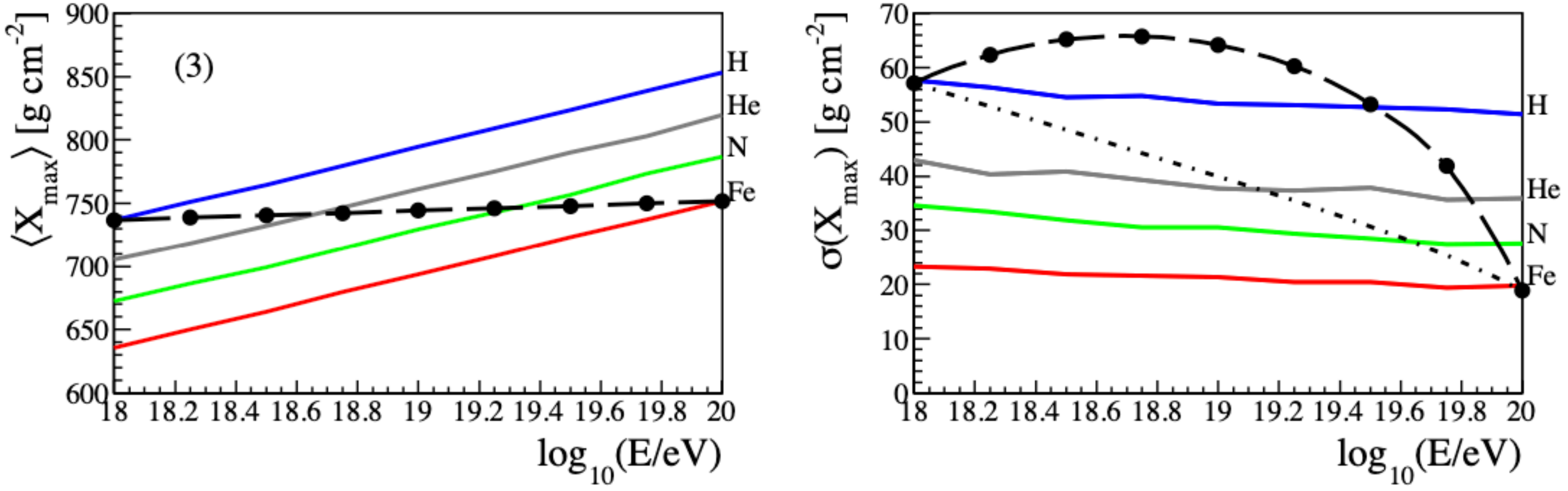
$\langle X_{max} \rangle = \langle X_{max} \rangle_p + f \langle \ln A \rangle$ $\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f^2 \sigma^2(\ln A)$

Focusing on the second momentum: 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

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

The Pierre Auger Collab. JCAP 2013



- Dispersion of the masses in the case of two components:

$$\sigma^2(X_{max}) =$$

$$f\sigma_1^2 + (1-f)\sigma_2^2 + f(1-f)(\Delta(\langle X_{max} \rangle))^2$$

WHAT DO WE LEARN FROM THE MASS COMPOSITION OBSERVABLES?

Focusing on the second momentum: it contains

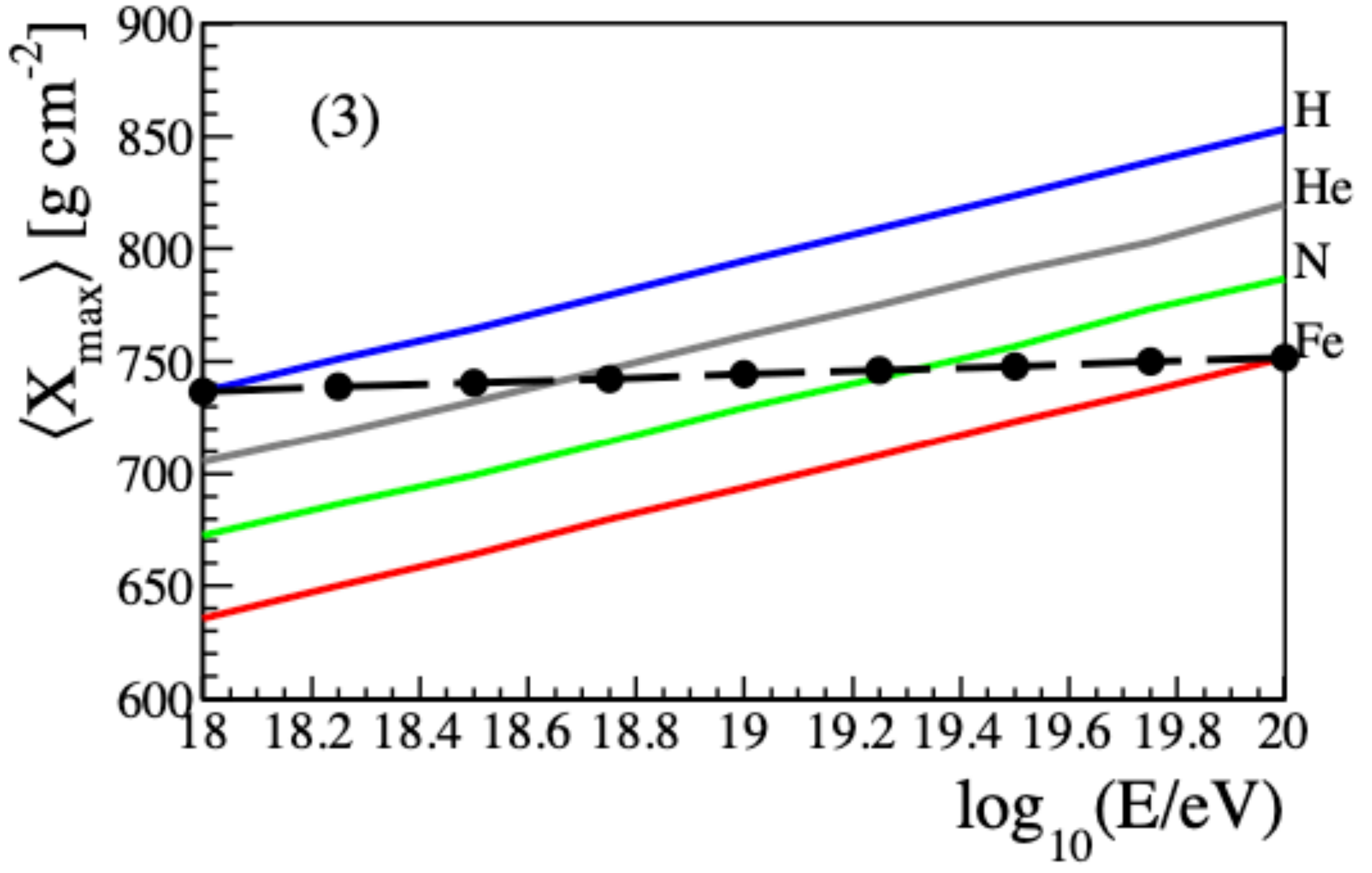
- the shower-to-shower fluctuations (first term) AND
- the dispersion of the masses as they hit the Earth atmosphere:
  - spread of nuclear masses at the sources
  - modifications that occur during their propagation to the Earth

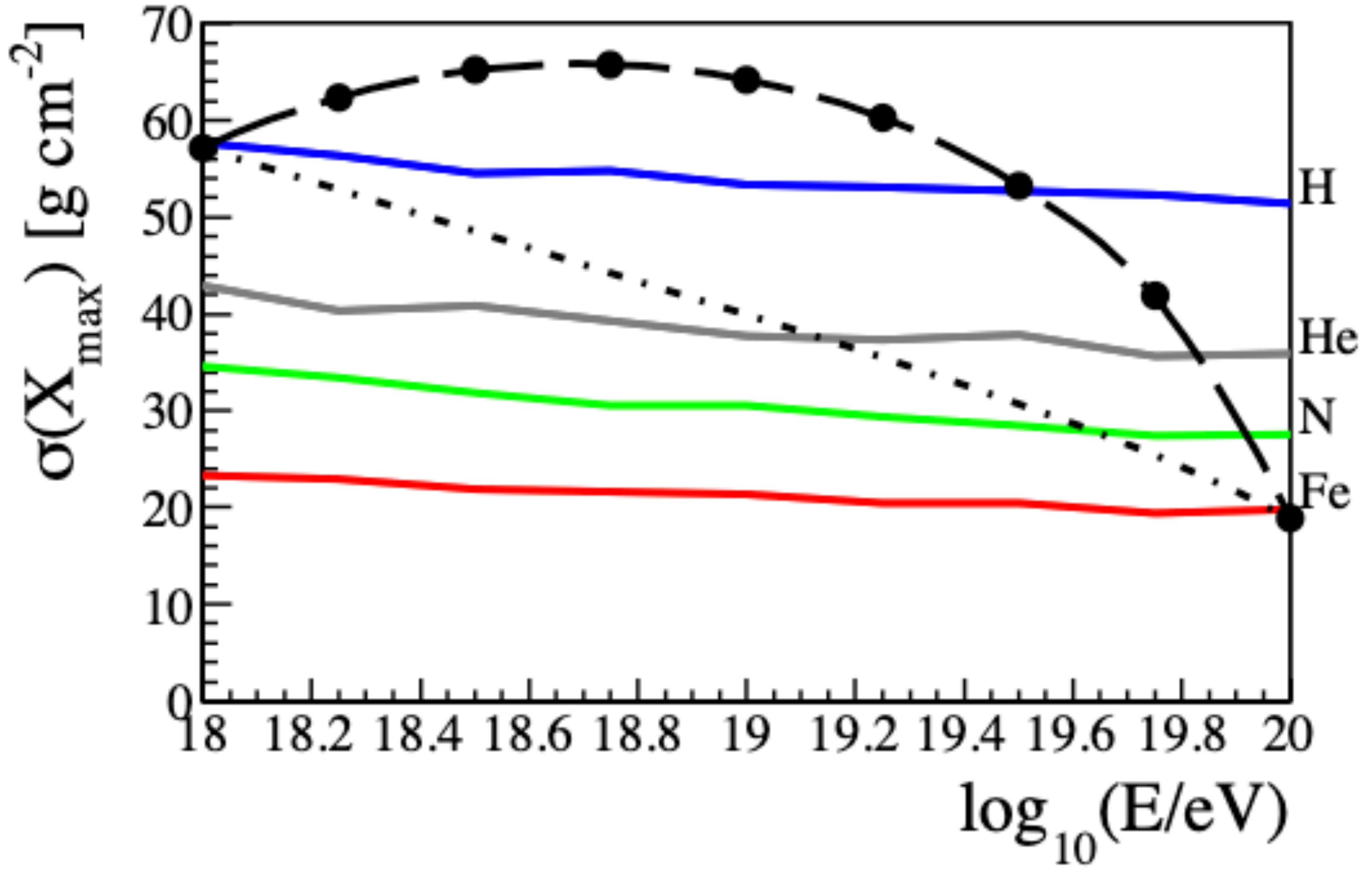
- Example for two components: H and Fe masses, fraction of H decreasing linearly with energy

Requirements from the mass composition measurements, in terms of astrophysical scenarios:

- Average mass increasingly heavy after the ankle
- Minimal superposition of different nuclear species

The Pierre Auger Collab. JCAP 2013





- Dispersion of the masses in the case of two components:

$$\sigma^2(X_{max}) =$$

$$f\sigma_1^2 + (1-f)\sigma_2^2 + f(1-f)(\Delta(\langle X_{max}\rangle))^2$$

The dipole

- Searches for large-scale anisotropies are conventionally made by looking for nonuniformities in the distribution of events in right ascension because, for arrays of detectors that operate close to 100% efficiency, the total exposure as a function of this angle is almost constant.
- The nonuniformity of the detected cosmic-ray flux in declination imprints a characteristic nonuniformity in the distribution of azimuth angles in the local coordinate system of the array

- Standard approach for studying large scale anisotropy in arrival directions: harmonic analysis in right ascension
- To recover the three-dimensional dipole, we combine the first-harmonic analysis in right ascension with a similar one in the azimuthal angle φ

$$a_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \cos \alpha_i, \qquad b_\alpha = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} w_i \sin \alpha_i.$$

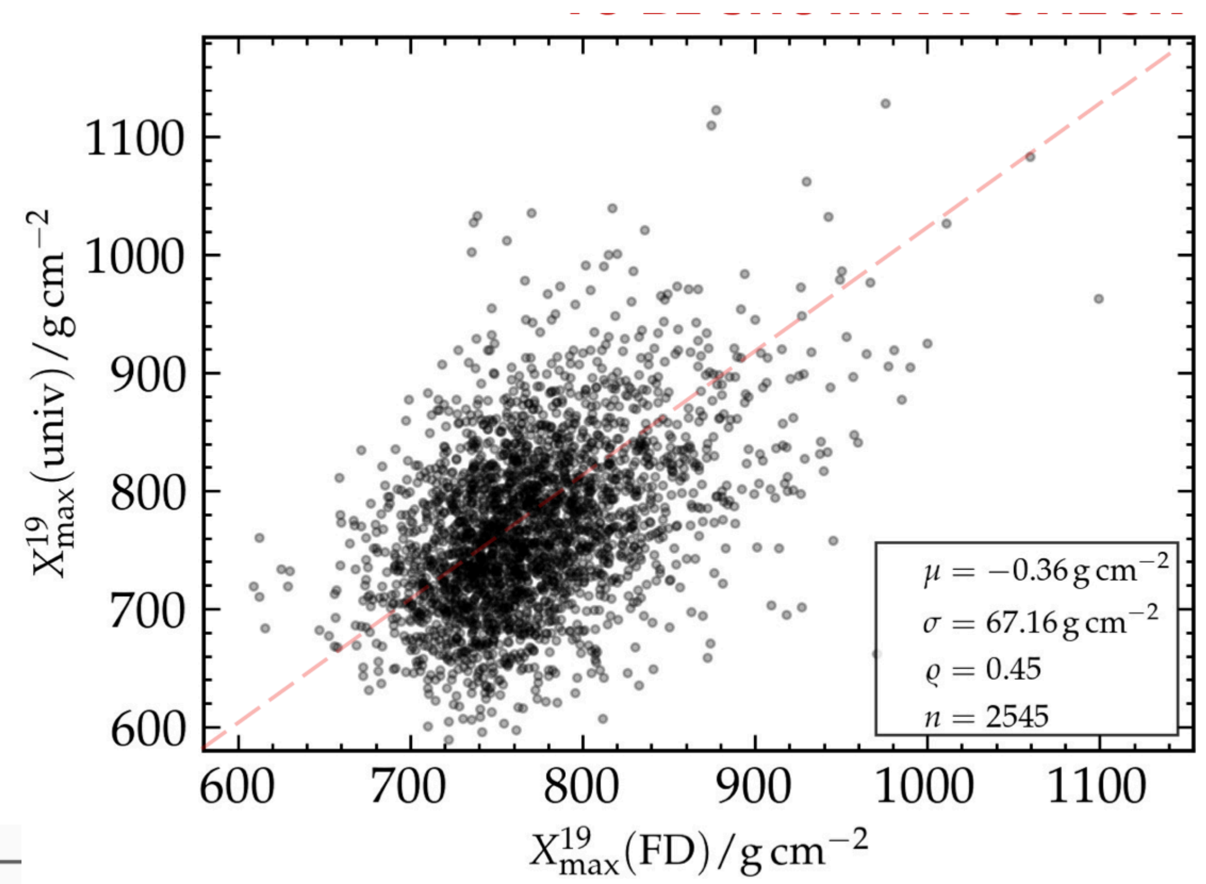
first-harmonic Fourier components

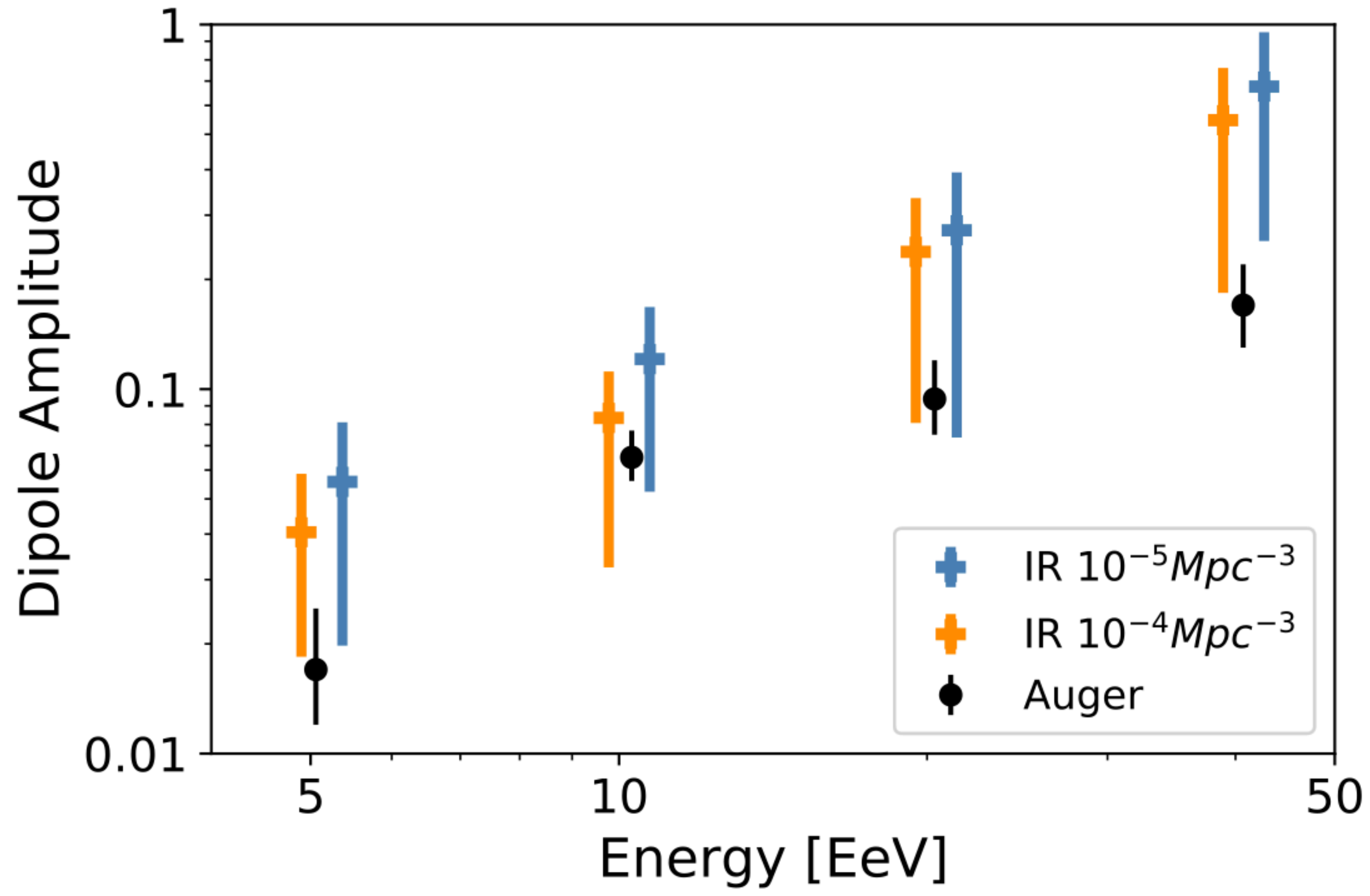
$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}, \qquad \tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}.$$

Amplitude and phase

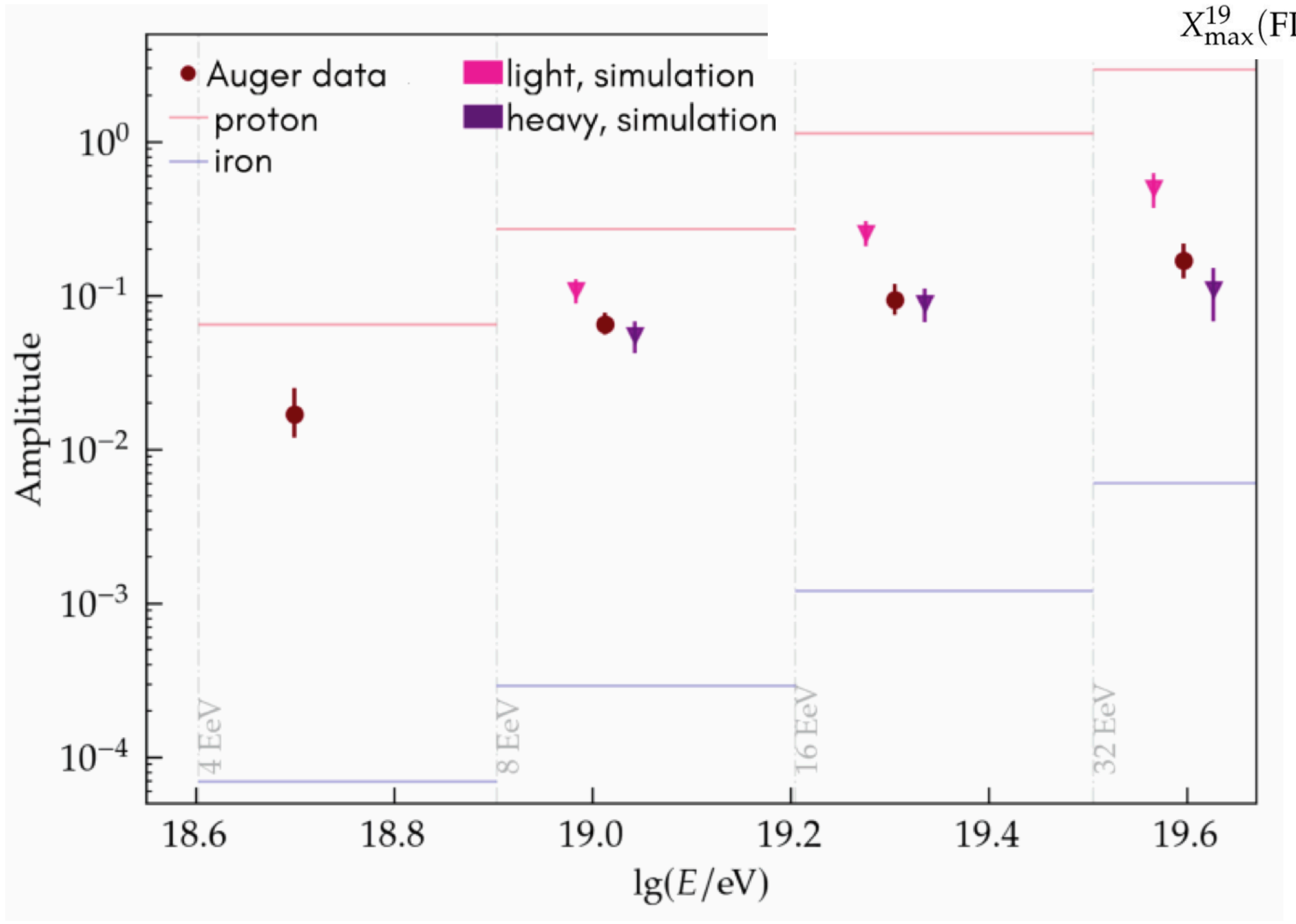
The dipole

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





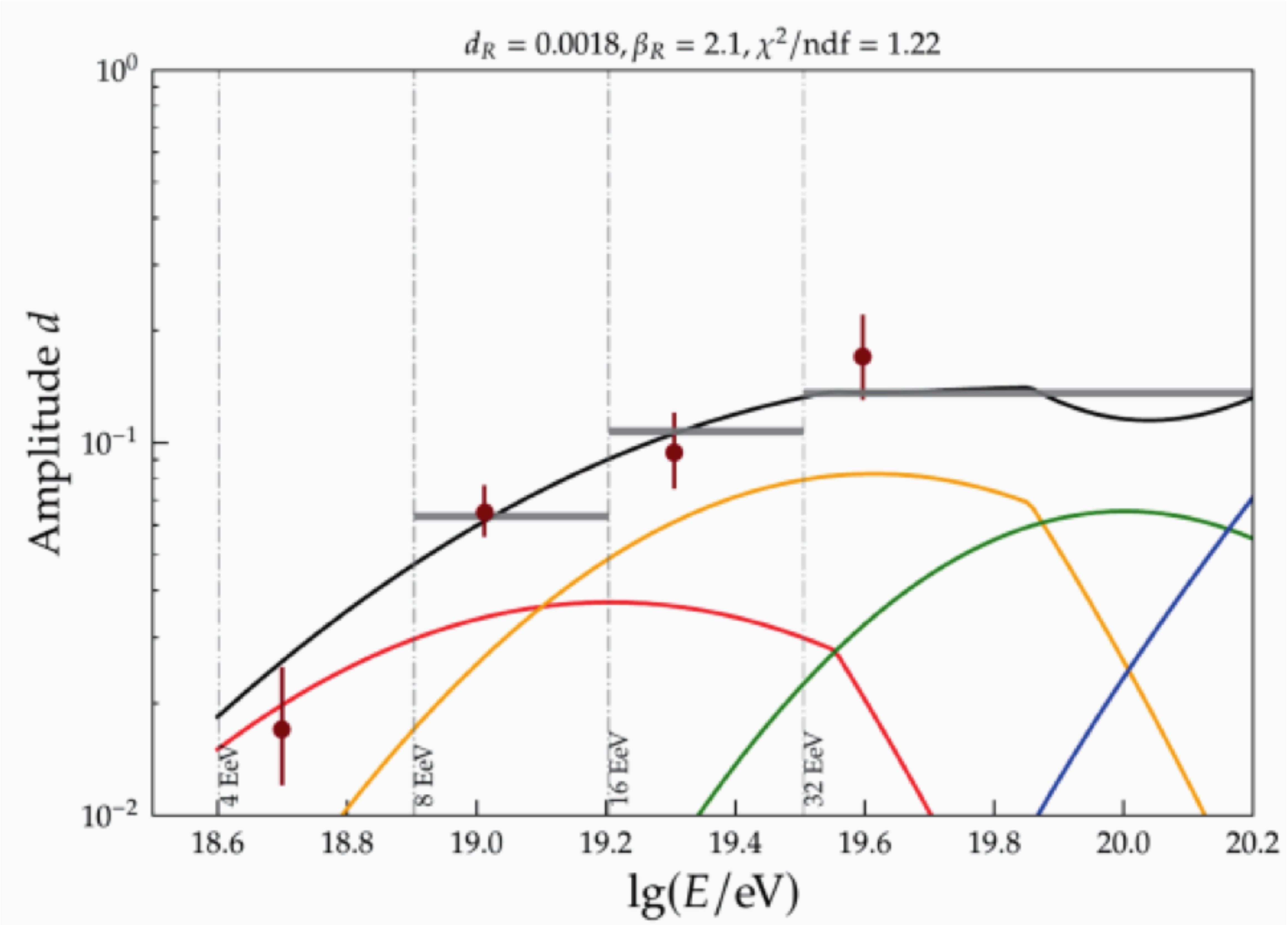
Comparison to expectations for astrophysical scenarios obtained from spectrum + composition interpretation -> if UHECR have a non-protonic mass composition, the dipole is compatible with the matter distribution of the large scale structure

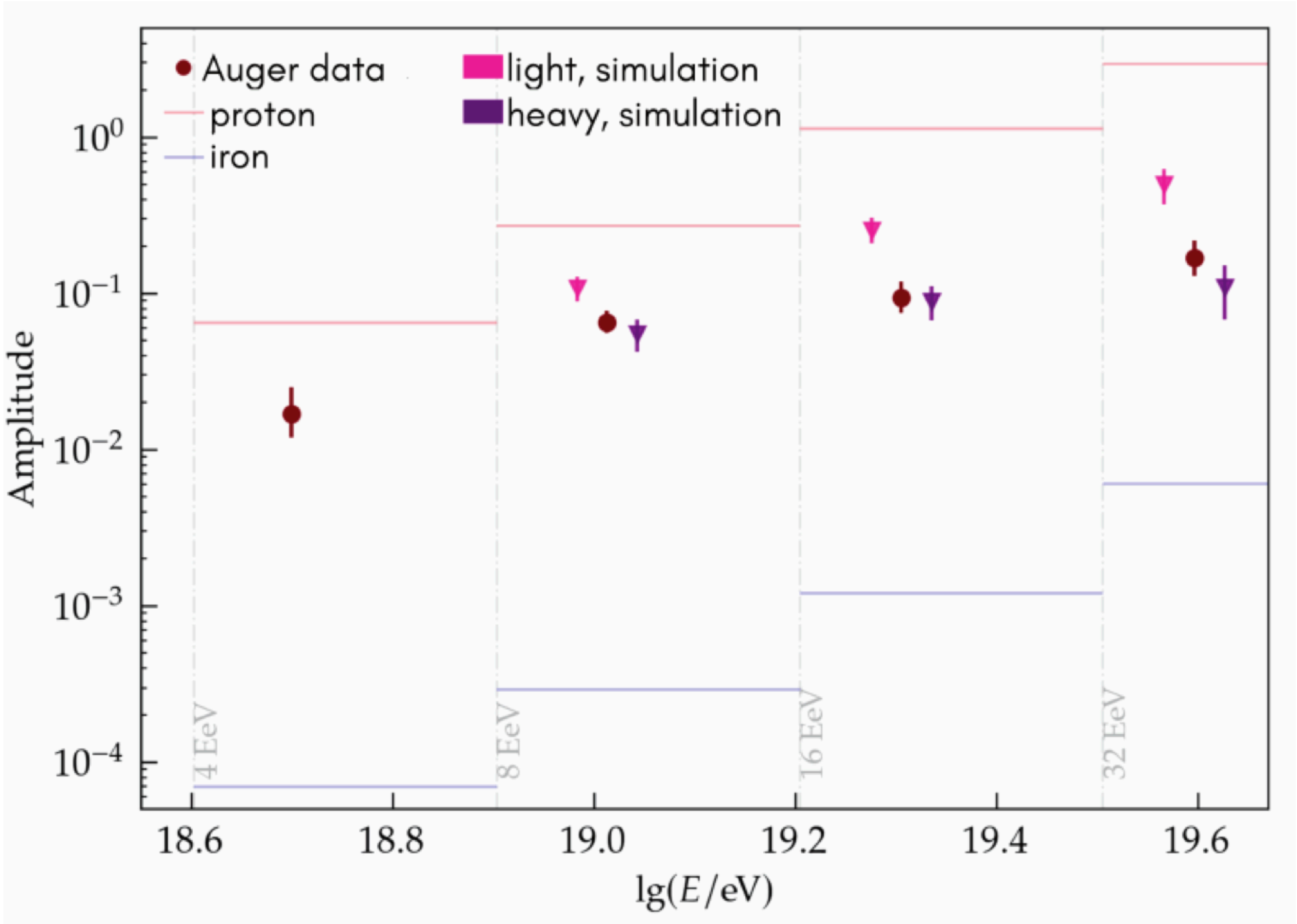


Defining light and heavy populations, through a mass estimator with universality -> potential to observe a separation in total amplitude in mass-selected subsets of data (probed on simulations)

The composition-informed dipole

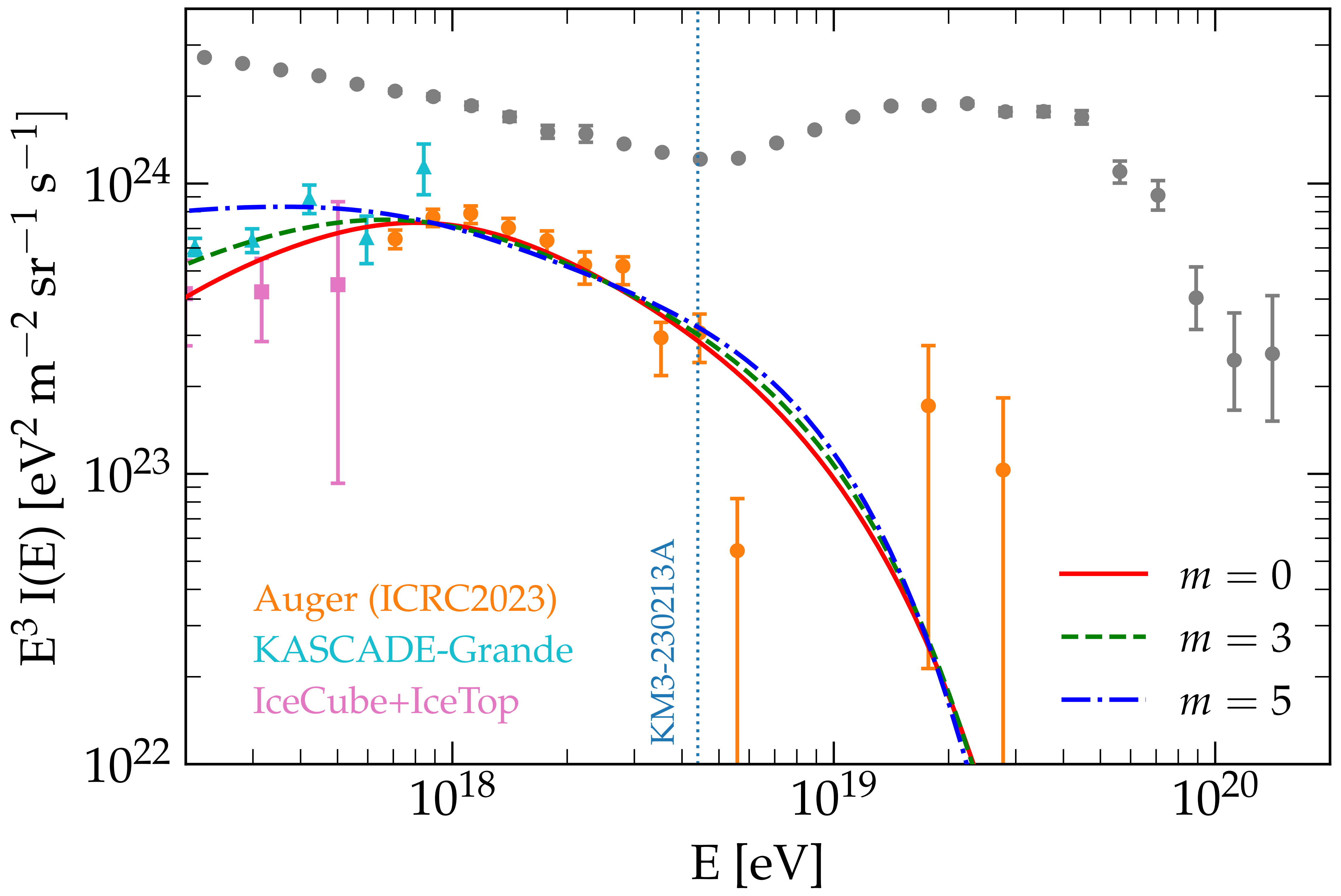
- Mass estimator with universality, using Xmax and relative-to-proton-shower muon number



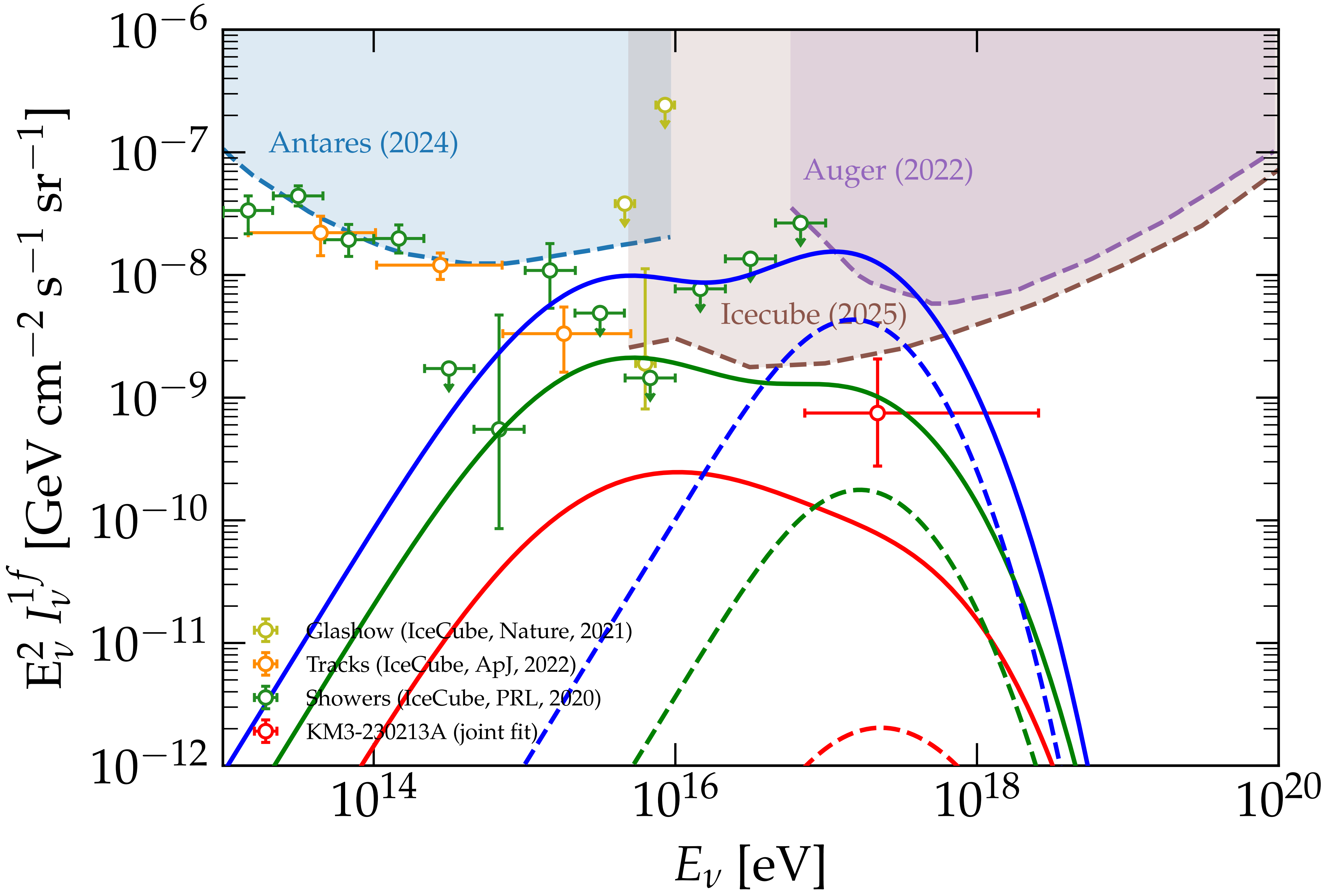


UHECR protons below the ankle -> implications on neutrino flux

$$Q_p(E,z) \propto (1+z)^m E^{-\gamma} \exp(-E/E_{\max})$$



Cermenati, Ambrosone, Aloisio, DB, Evoli arxiv:2507.11993

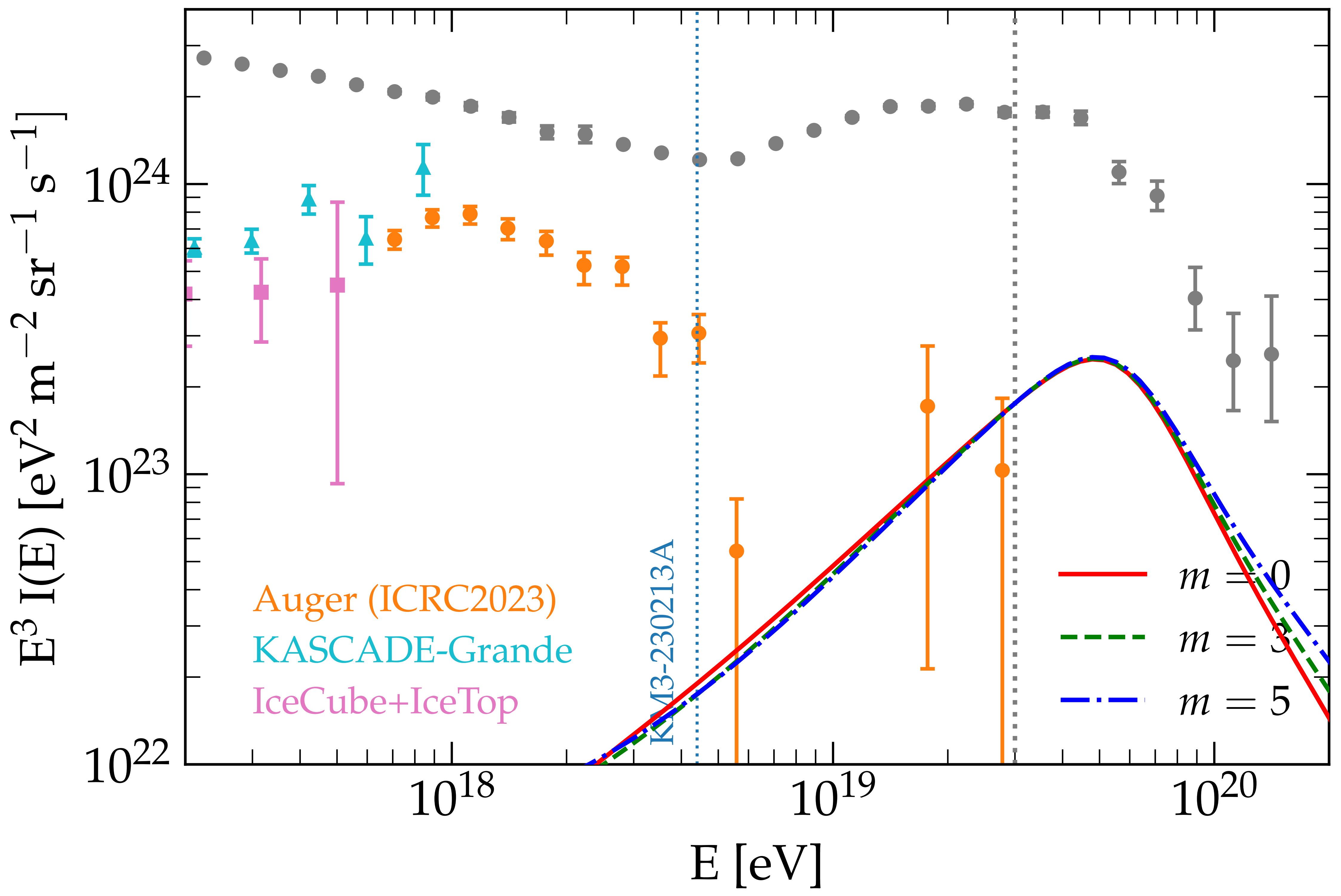


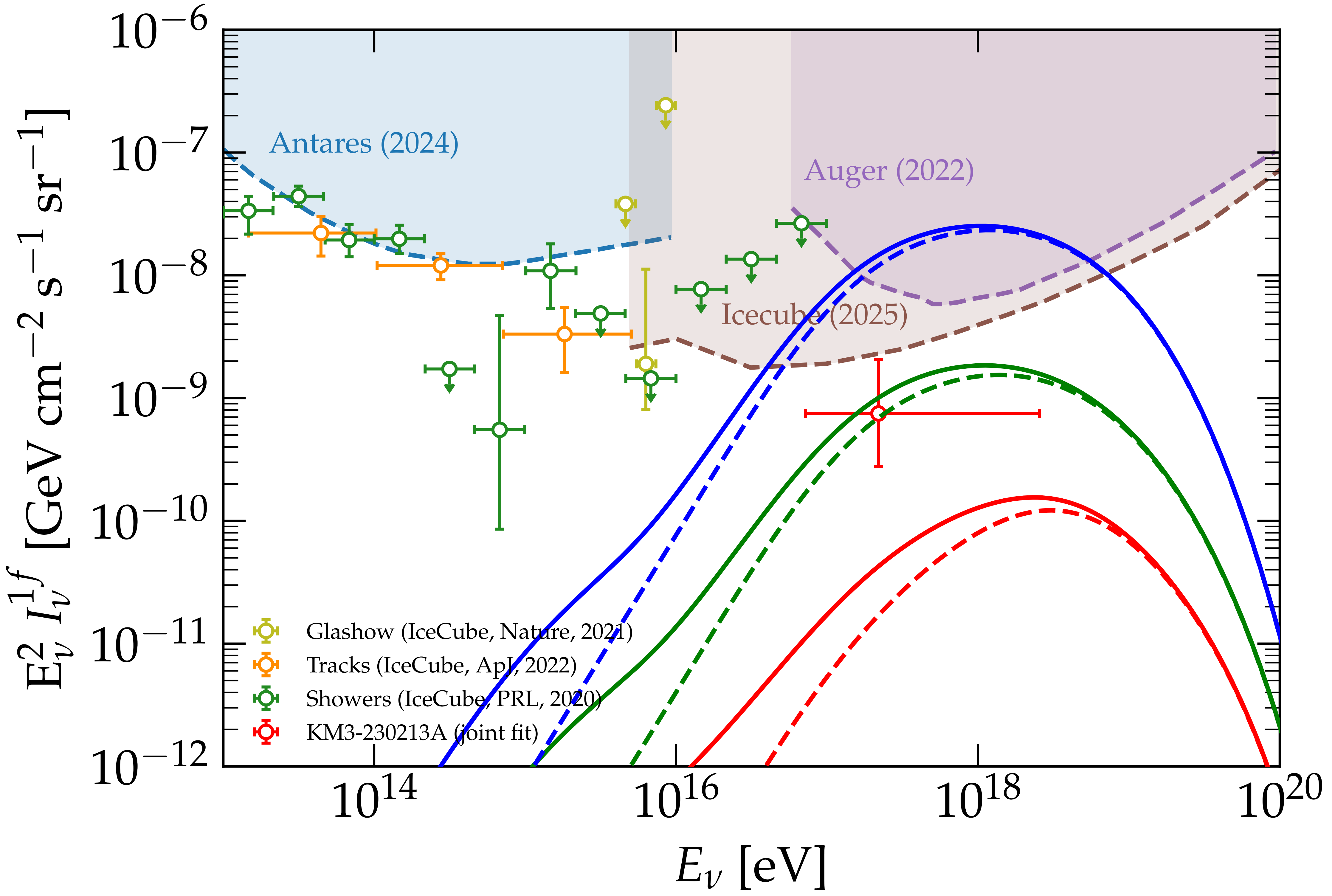
- Source emissivity of LE population normalised to match the proton spectrum obtained from the proton fraction (as from Auger ICRC 2023, multiplied by the all-particle spectrum from Auger ICRC 2023)
- Various combinations of source parameters (spectral index, maximum energy, source evolution) are used (results being in agreement with what found for instance in Heinze, DB, Bustamante & Winter ApJ 2016)
- Because of the softness of the spectral index and the limited maximum energy of the proton population, the neutrino flux is mostly due to proton interactions off EBL
- Source evolution m=3 of the LE population can account for the KM3Net neutrino flux

UHECR protons above the ankle -> implications on neutrino flux

$Q_p(E,z) \propto (1+z)^m E^{-\gamma} \exp(-E/E_{\max})$

Cermenati, Ambrosone, Aloisio, DB, Evoli arxiv:2507.11993



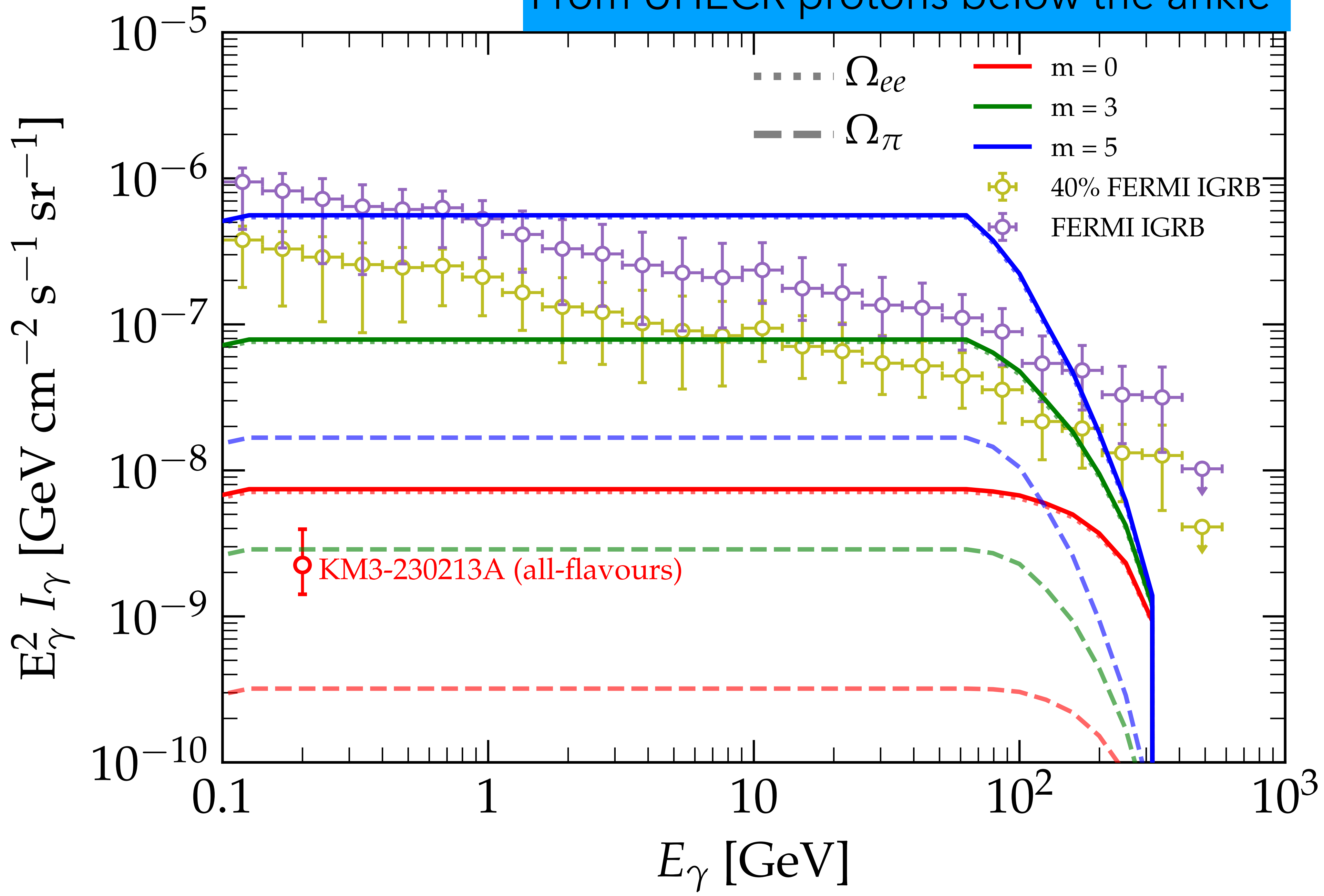


- Source emissivity of HE population normalised to match 10% of the all-particle spectrum at approximately 3×10^{19} eV

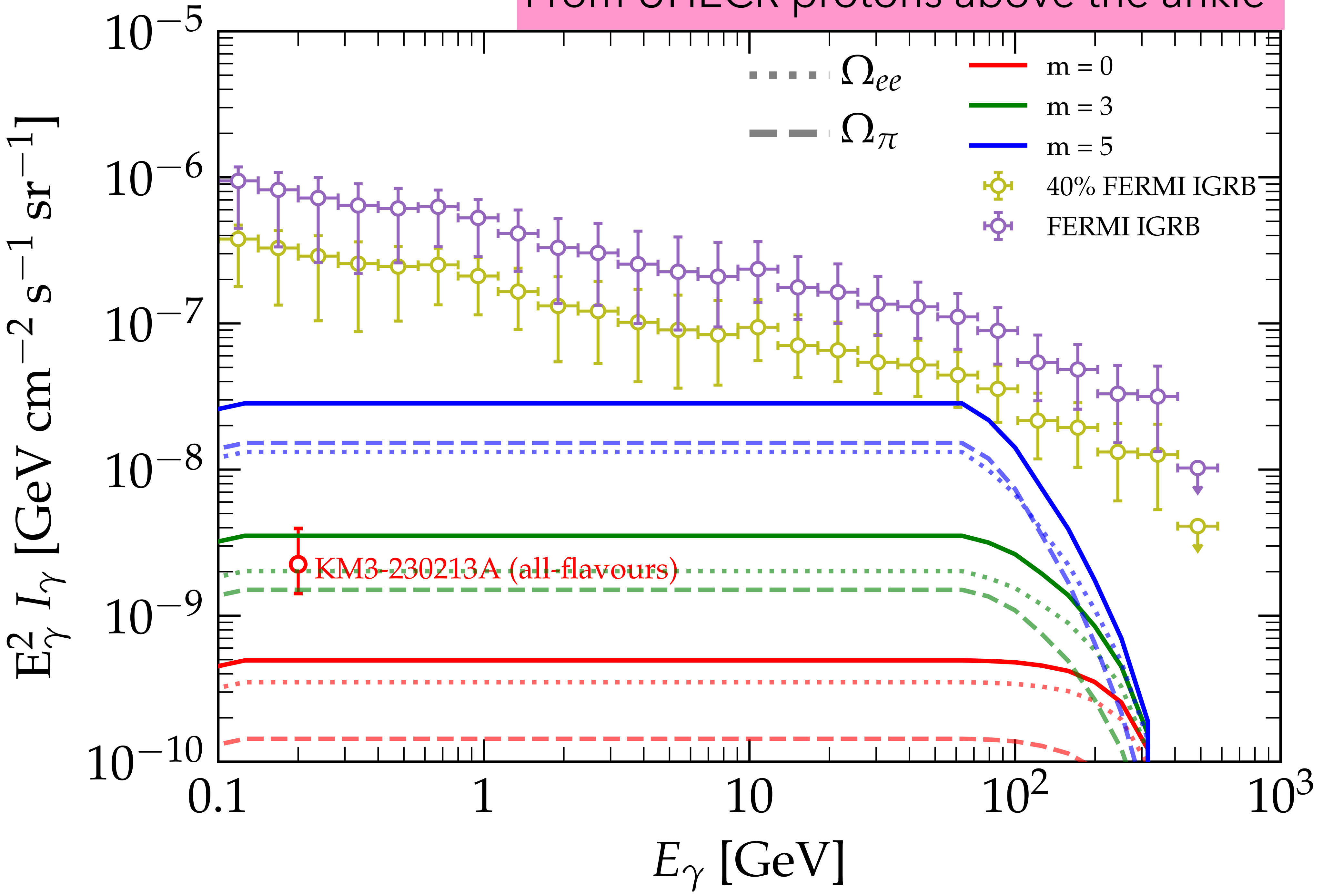
- Because of the hardness of the spectral index and the larger maximum energy of the proton population, the neutrino flux is mostly due to proton interactions off CMB
- Source evolution m=3 of the LE population can account for the KM3Net neutrino flux

Diffuse gamma rays

From UHECR protons below the ankle



From UHECR protons above the ankle



- Separate contributions of photo-pion and pair production processes are shown, obtained as in Berezinsky & Kalashev PRD 2016
- KM3Net neutrino flux corresponds to photo-pion contribution in gamma rays

- The contribution from pair production is dominant, due to the softness of the spectral index of the LE proton population
- Strong source evolutions are disfavoured by Fermi data

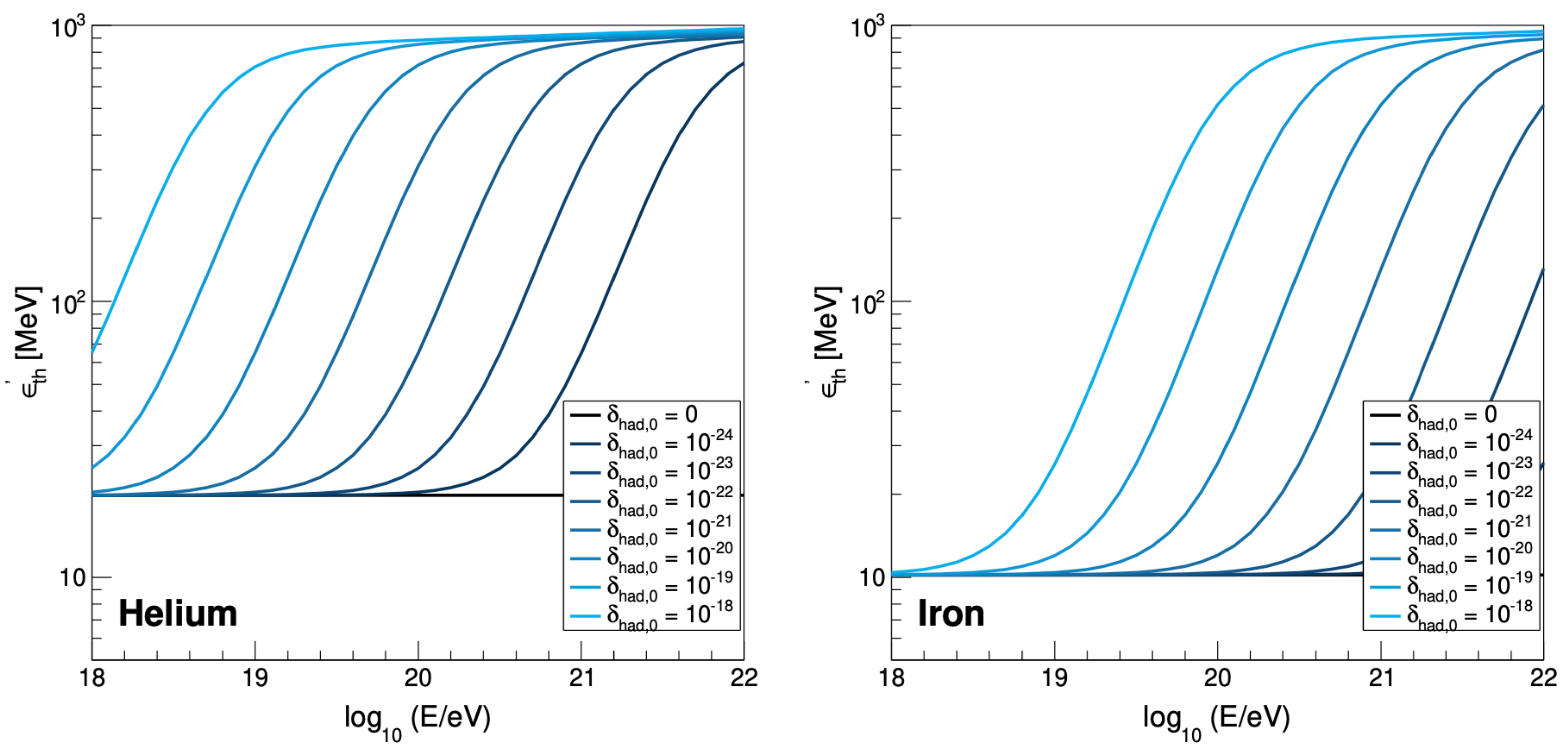
- The variations among different contributions are smaller, due to the hardness of the spectral index of the HE proton population
- Even strong source evolution is allowed

Cermenati, Ambrosone, Aloisio, DB, Evoli arxiv:2507.11993

BACKUP SLIDES:
LIV

MODIFIED CR PROPAGATION

The Pierre Auger Collaboration, JCAP 2022



$$E_A^2 = p_A^2 + m_A^2 + \sum \delta_{A,n} E_A^{2+n}$$

$$A^2 E_p^2 = A^2 p_p^2 + A^2 m_p^2 + A^2 \sum \delta_{A,n} A^n E_p^{2+n}$$

$$E_p^2 = p_p^2 + m_p^2 + \sum \delta_{A,n} A^n E_p^{2+n}$$

$$\delta_{A,n} = \delta_{p,n} / A^n$$

- Interactions of nuclei -> modified photo-disintegration
- Consider a nucleus as composed by A nucleons
- LI case: the photo-dis threshold depends only on the nuclear species
- LIV case: a dependence of the photo-dis threshold on the energy appears

MODIFIED FIRST ORDER FERMI ACCELERATION

Duarte & de Souza, JCAP 2024

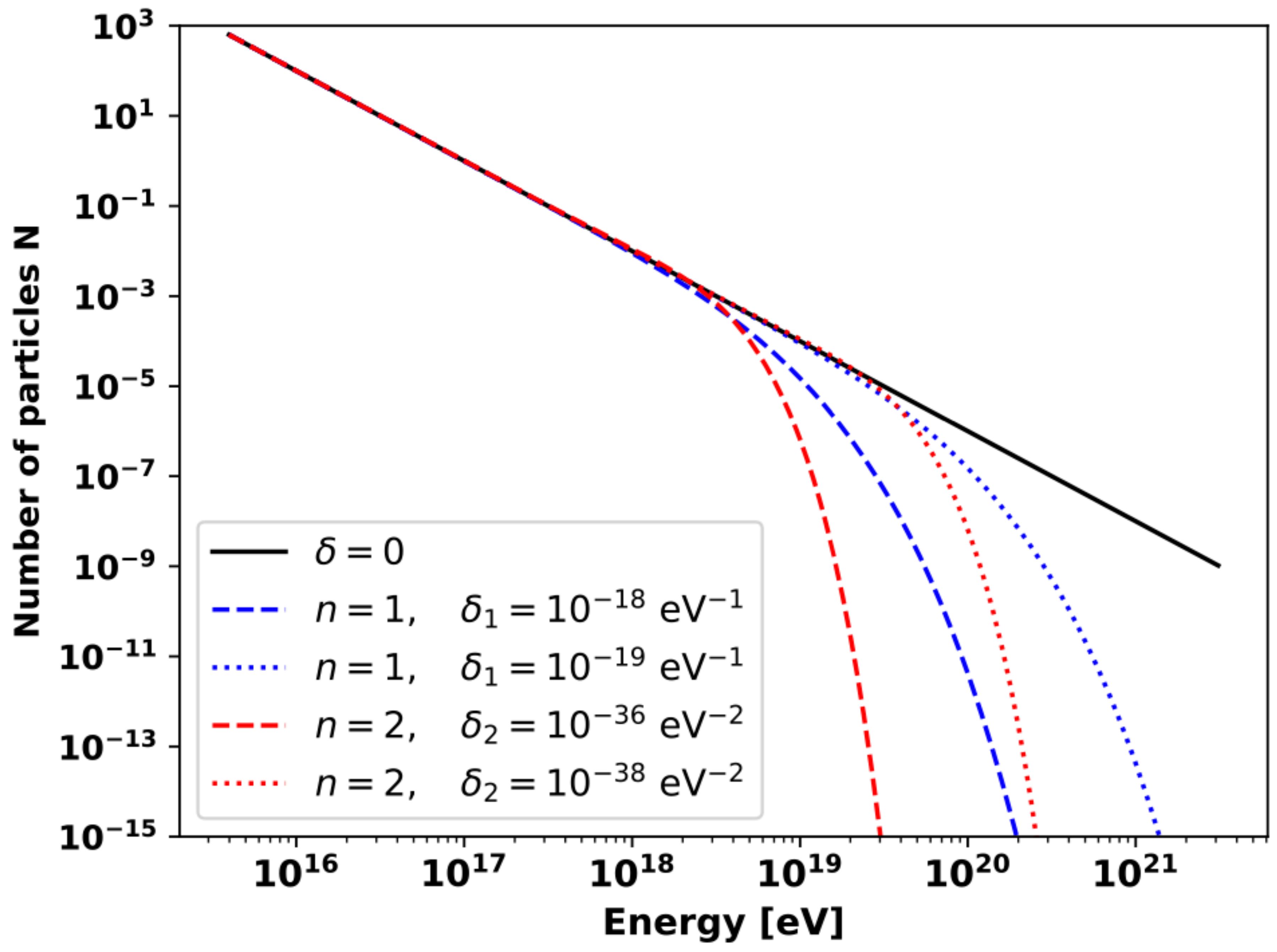
$$E^2 = p^2 + m^2 + \sum \delta_{p,n} p^{2+n}$$

$$p = \frac{E}{\sqrt{1 + \delta_{p,n} E^n}}$$

$$\langle \frac{\Delta E}{E} \rangle = \frac{4}{3\sqrt{1 + \delta_{p,n} E^n}} V$$

$$\frac{dN}{dE} = -\left[1 + \frac{2(1 + \delta_{p,n} E^n) - n\delta_{p,n} E^n}{2(1 + \delta_{p,n} E^n)}\right] \frac{\sqrt{1 + \delta_{p,n} E^n} N}{E}$$

$$t_{LIV} = \frac{5}{9} \frac{E(1 + \delta_{p,n} E^n)}{ZeBV^2}$$

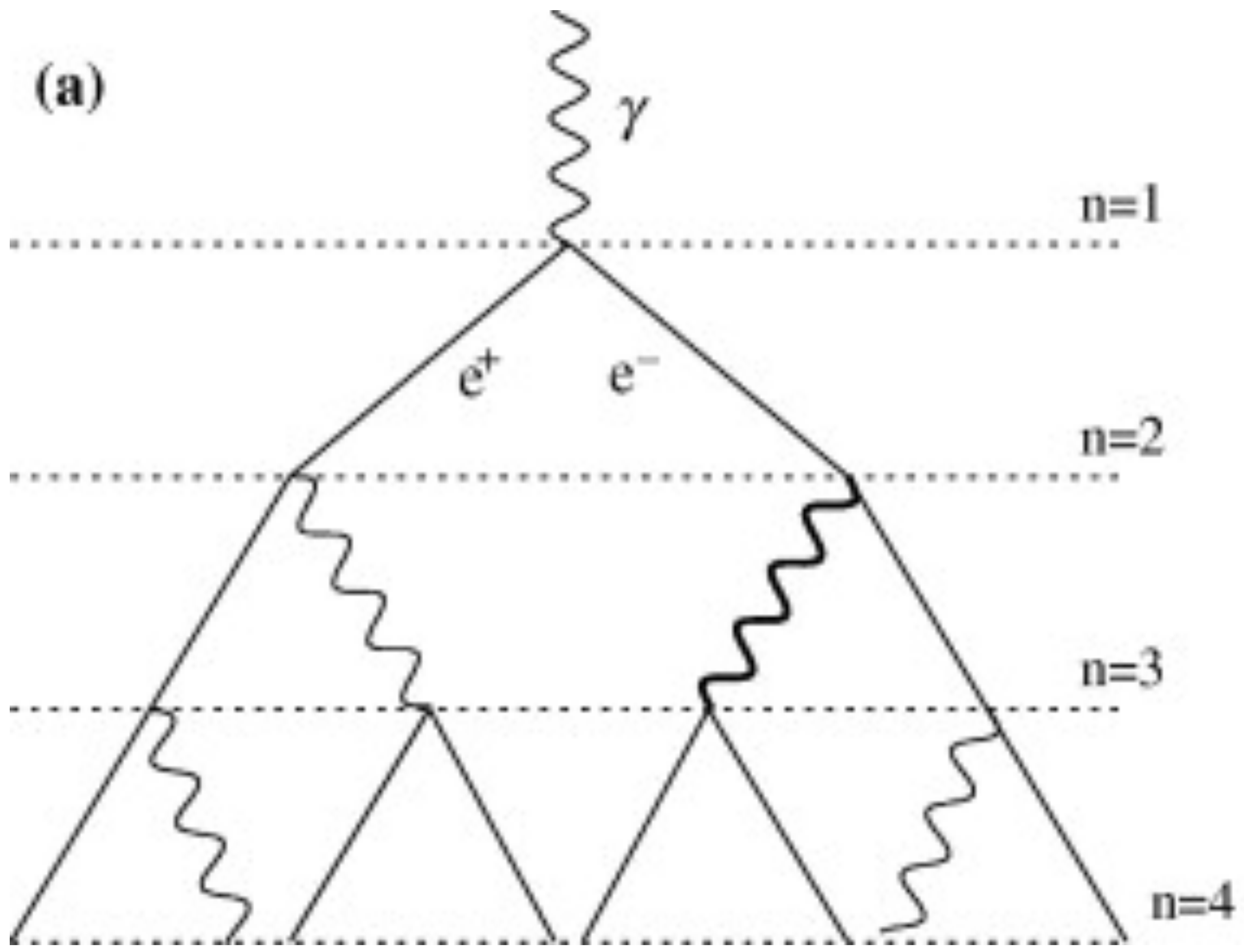


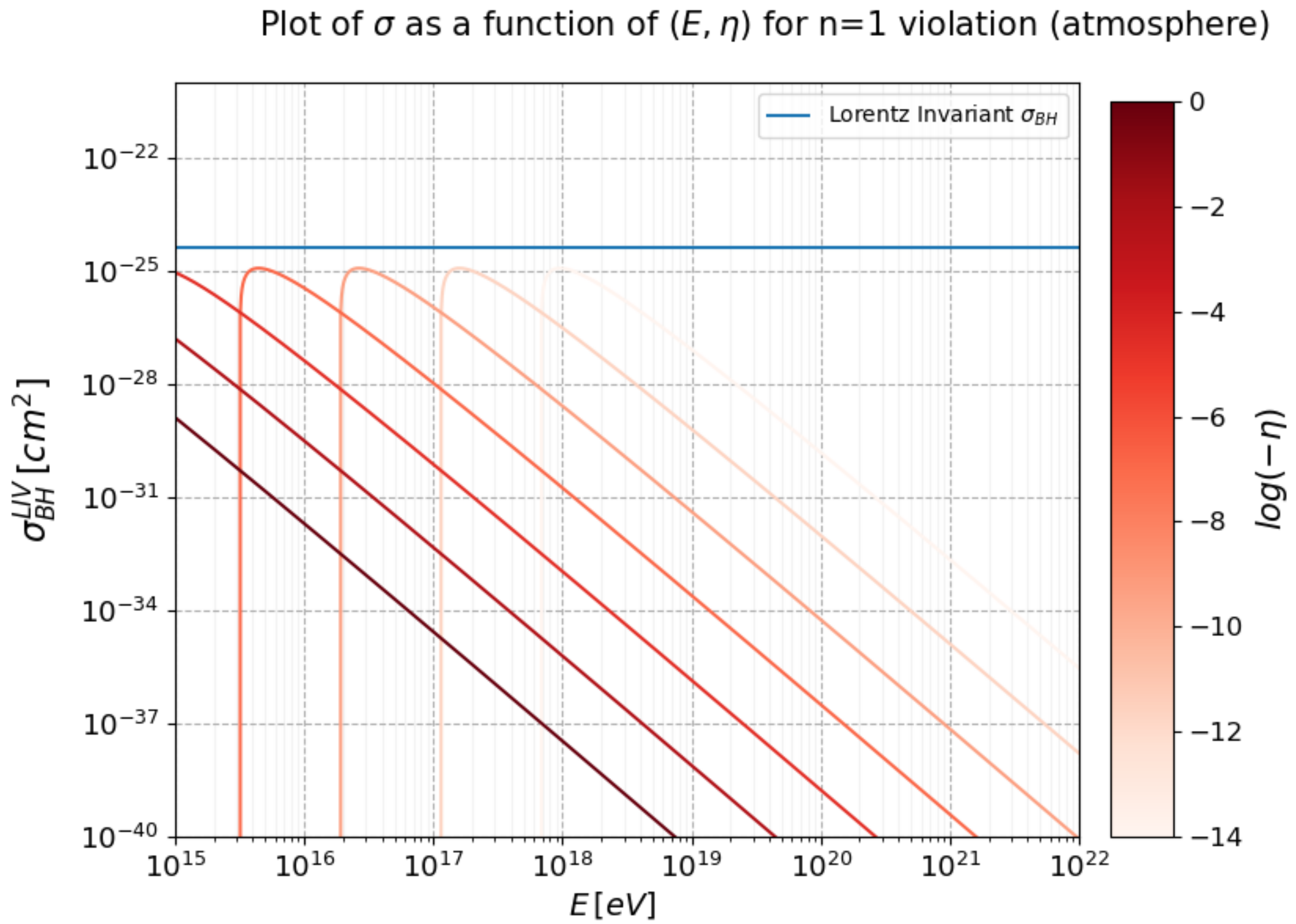
- for the first-order mechanism, the necessary time to gain energy increases rapidly, resulting in the significant flux suppression of particles

Cascade of particles initiated by photons in the atmosphere

Morais, DB, Salamida, Lobo & Bezerra, UHECR24

M. Giammarco





$$P = \int_0^{X_{\rm atm}} dX_0 \frac{e^{-X_0/\langle X_0\rangle_{\rm LIV}}}{\langle X_0\rangle_{\rm LIV}} = 1 - e^{-X_{\rm atm}/\langle X_0\rangle_{\rm LIV}}$$

$$\langle X_0\rangle_{\rm LIV} = \frac{\sigma^{\rm LI}}{\sigma^{\rm LIV}}\langle X_0\rangle_{\rm LI}$$

$$|\eta| \gg m_e^2 \frac{M_{Pl}^n}{E^{n+2}}$$

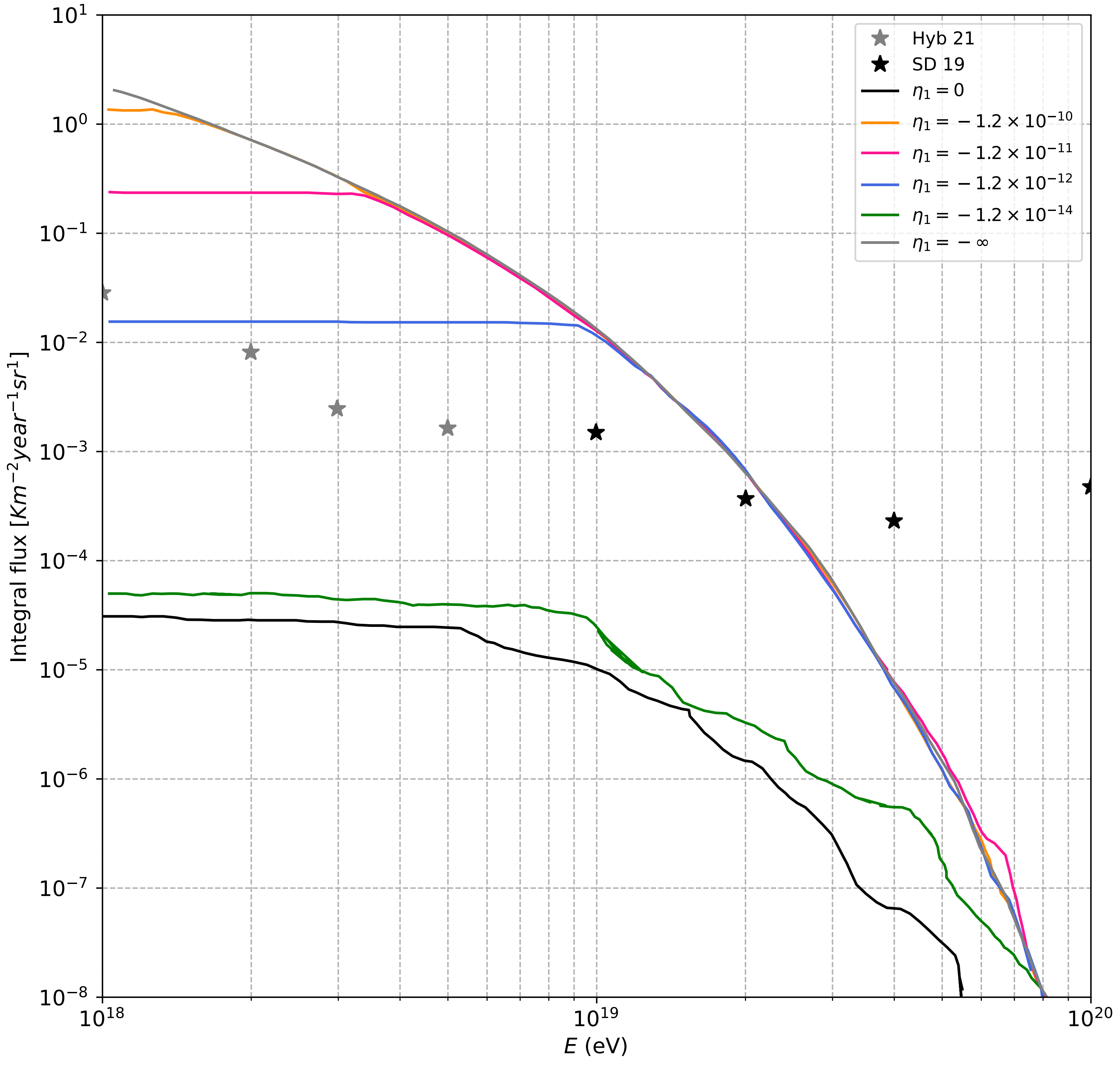
$$\sigma_{BH} = \frac{28Z^2\alpha^3}{9m_e^2}\left(\log\frac{183}{Z^{\frac{1}{3}}} - \frac{1}{42}\right) \qquad \sigma_{BH}^{LIV} = \frac{8Z^2\alpha^3}{3\,|m_{\gamma,\rm eff}^2|}\log\frac{1}{\alpha Z^{\frac{1}{3}}}\log\frac{|m_{\gamma,\rm eff}^2|}{m_e^2}$$

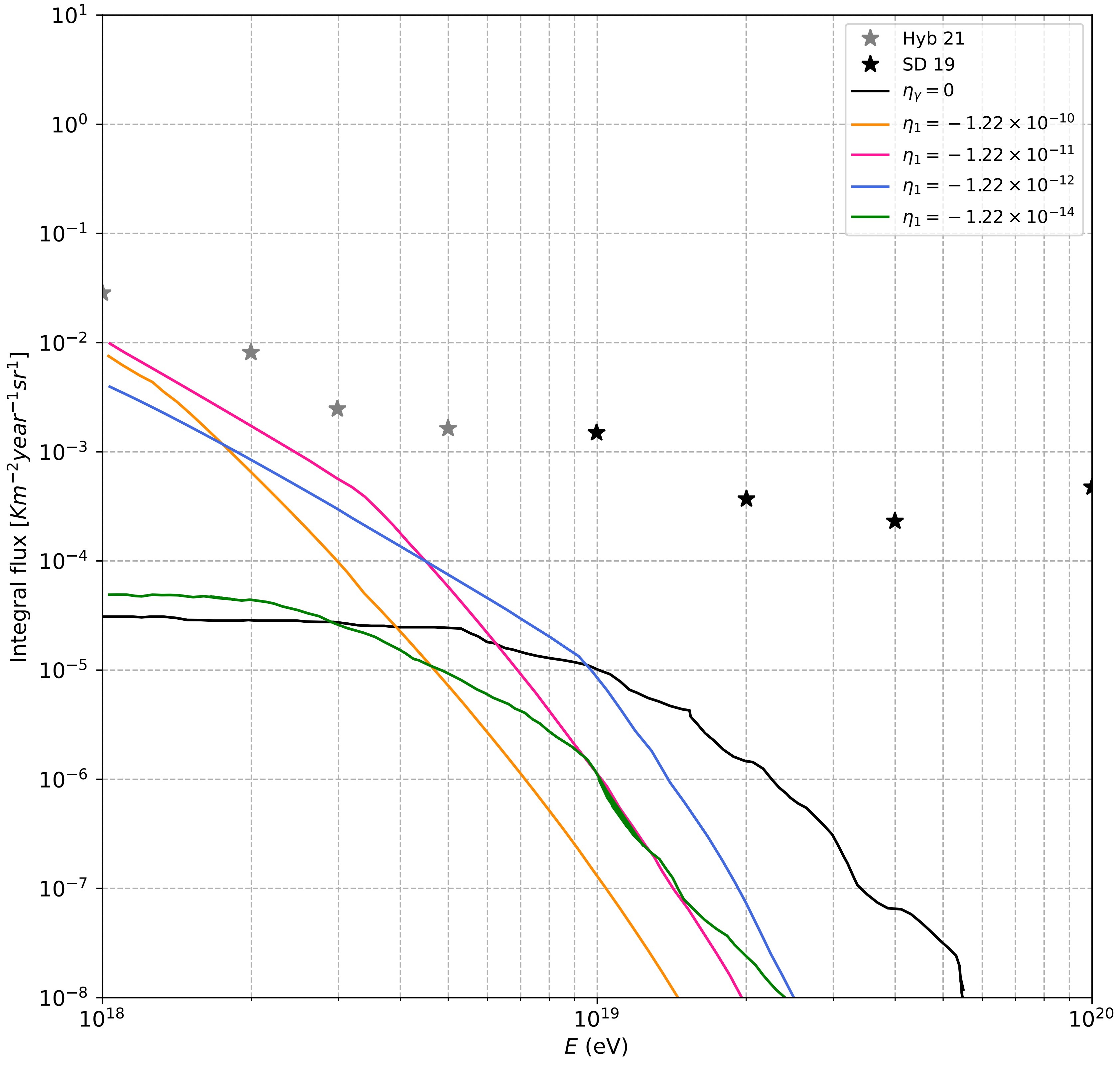
- At fixed energy: the larger the LI violation, the smaller cross section
- At fixed eta: the larger the energy, the smaller the cross section

- For other tests of LIV in atmosphere: see
  - Duenkel, Niechciol & Risse PRD 2023; PRD 2021; Klinkhamer, Niechciol & Risse PRD 2017

Rubtsov, Satunin & Sibiryakov, PRD 2012, 2014

Effect of LIV in extragalactic propagation and in the atmosphere





- LIV modifications -> increase the threshold for pair production
  - allows for more photons to reach the top of the atmosphere
  - allows for more photons to reach the Earth surface

$$\left(\frac{d\Phi(E,\eta)}{dE}\right)_{\text{LIV,i}} = P(E,\eta)_i \left(\frac{d\Phi(E,\eta)}{dE}\right)_{\text{top-of-atm}}$$

- First attempt of connecting different stages of the life of an astroparticle for constraining LIV → Less optimistic result, but more realistic!

Morais, DB, Salamida, Lobo & Bezerra, UHECR24

Modification of mass observables

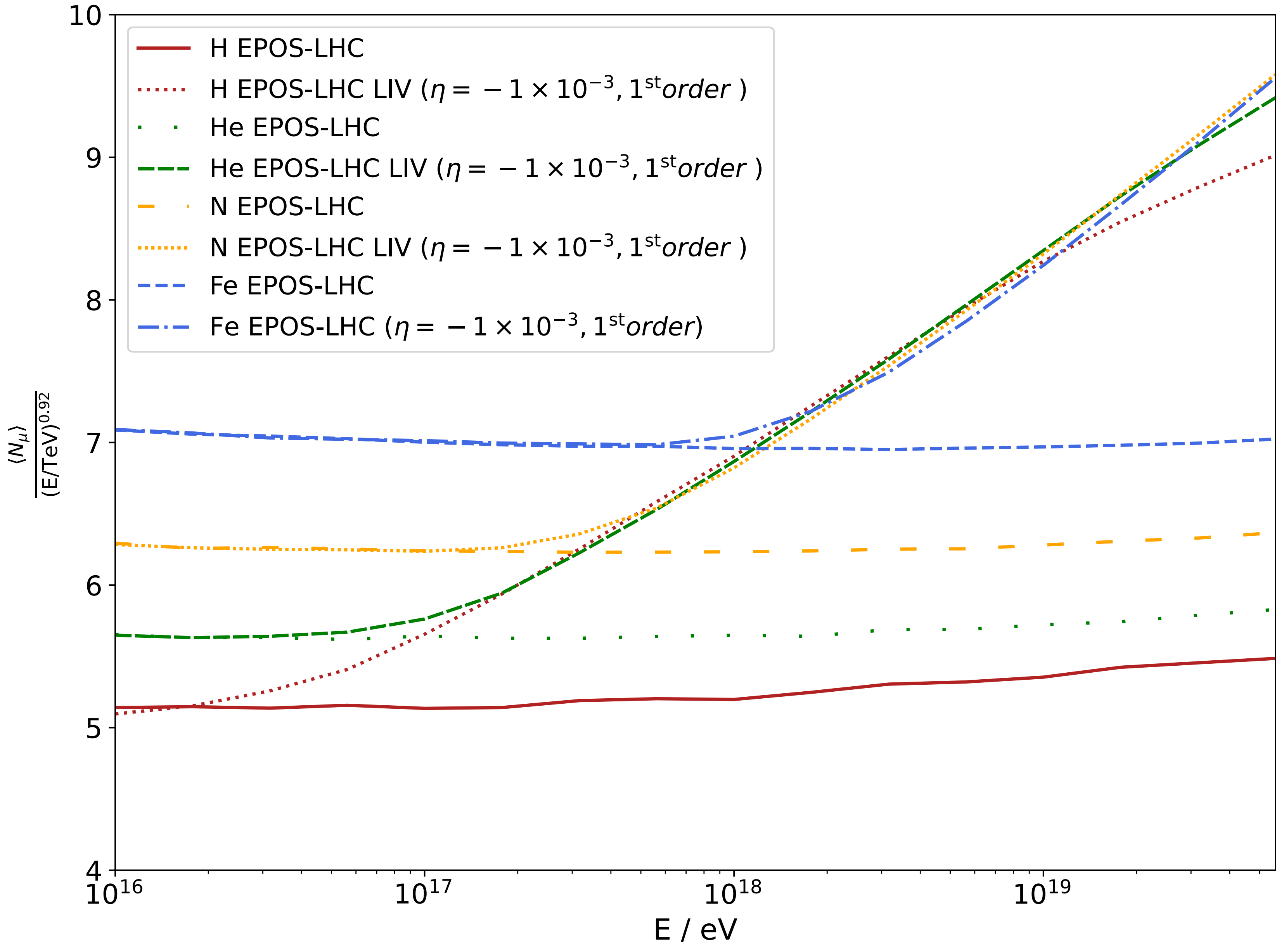
- Primary hadron transfer a fraction of energy to the secondary charged particles and the remaining to neutral ones
- Charged pions further interact while neutral ones promptly decay -> hadronic and electromagnetic sub-showers are generated
- Number of charged pions grows until the energy is depleted -> muons
- Fluctuations in the number of muons arise from variations in the fraction of energy from the parent particle
  - At large generation number, the fluctuation decrease because the fraction is averaged over many interactions -> <u>the fluctuations from the first interaction dominate</u>

$$N_\mu = \frac{E_0}{\xi_c} \prod_{i=1}^{c} f_i$$

$$\left(\frac{\sigma(N_\mu)}{\langle N_\mu \rangle} \right)^2 = \sum_{i=1}^{c} \left(\frac{\sigma(f_i)}{\langle f_i \rangle} \right)^2 .$$

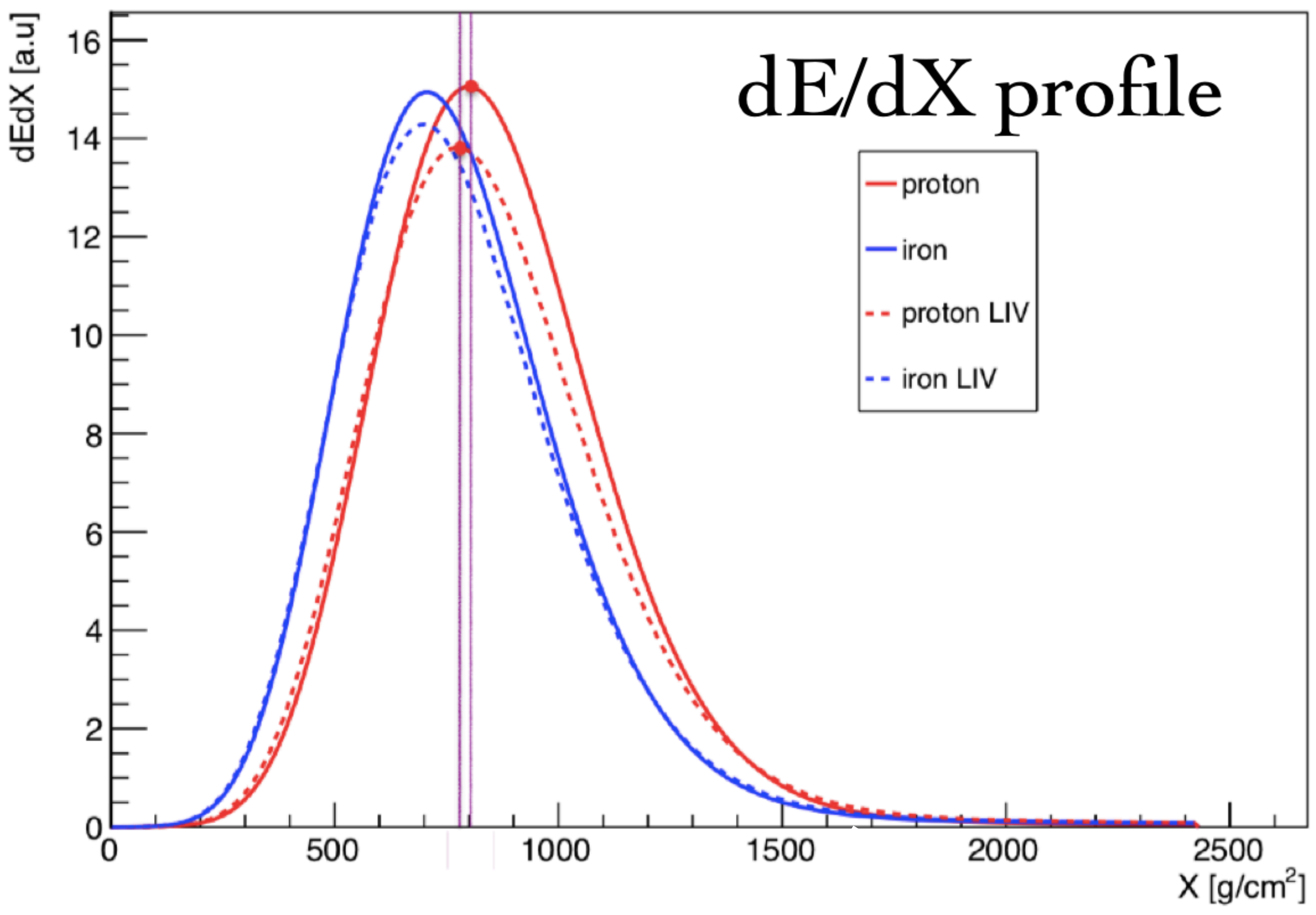
- **LI scenario**: A larger number of muons is expected for cascades initiated from heavy nuclei with respect to light ones
- With LIV,
  - hadronic sub-showers are created instead of electromagnetic ones;
  - the fraction of energy transferred to muons is maximal;

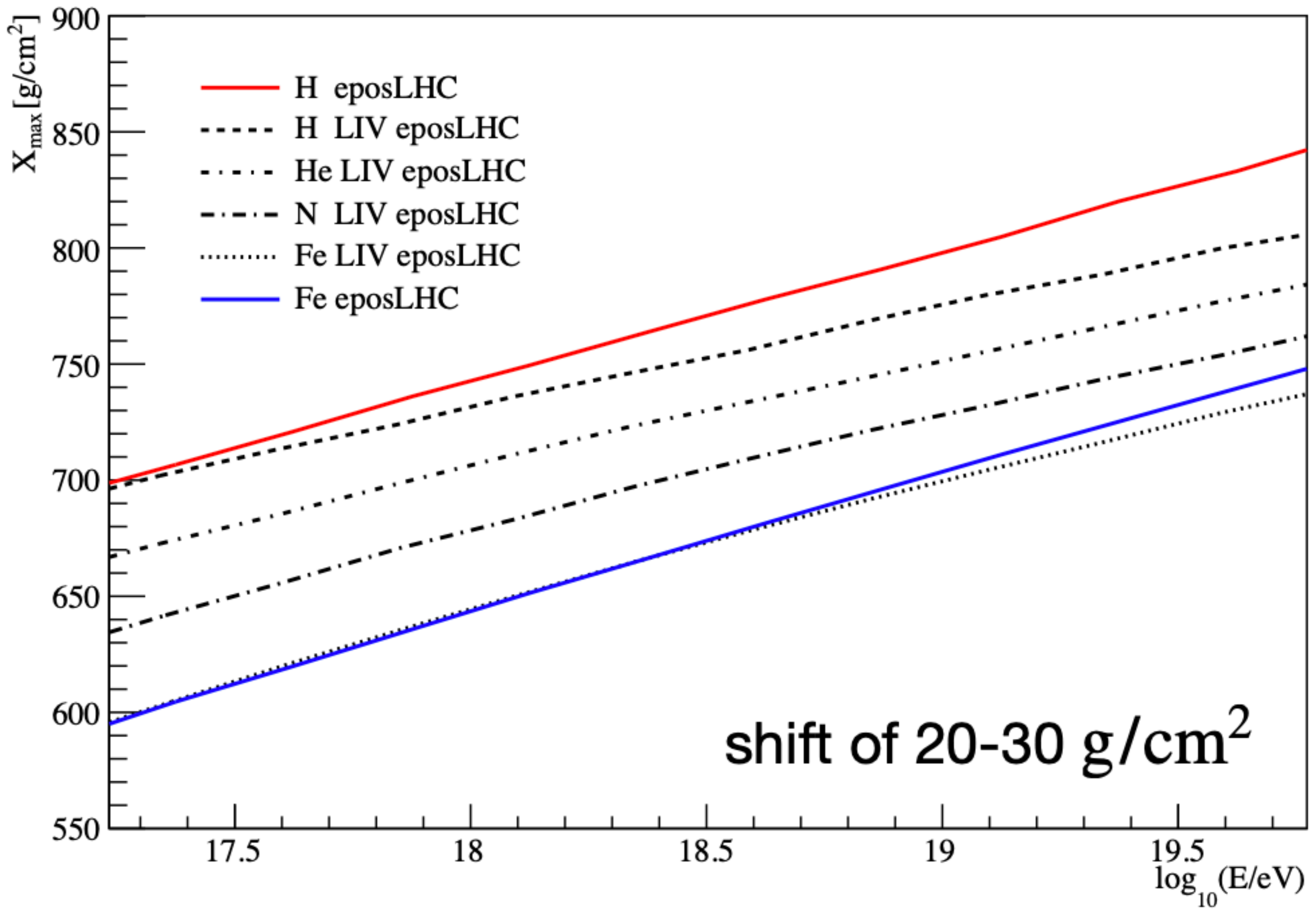
F. Salamida



The Auger Collab, in preparation

Modification of mass observables (electromagnetic component of the shower)





- 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

Modification of mass observables

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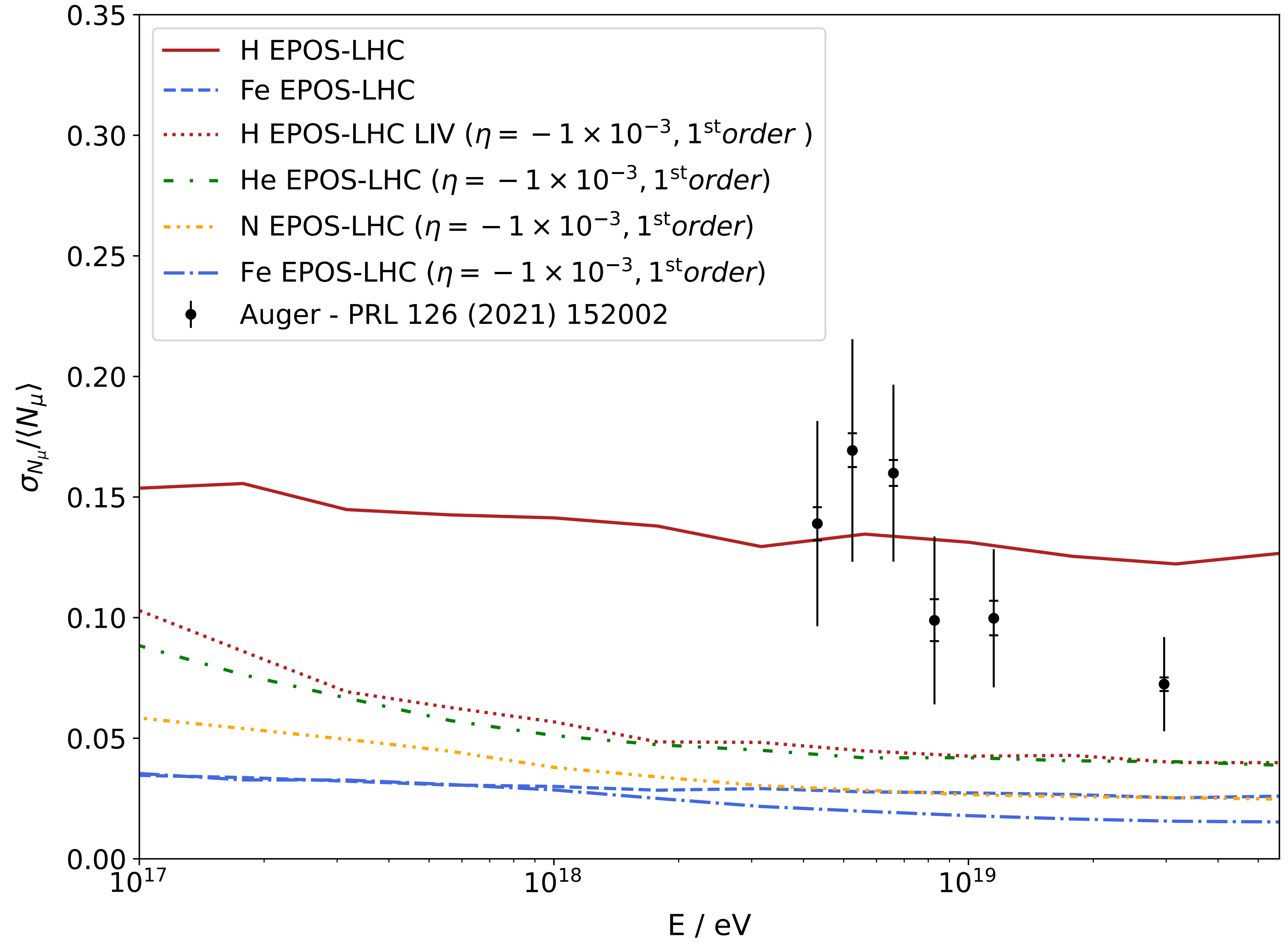
- **LI scenario**: A larger number of muons is expected for cascades initiated from heavy nuclei with respect to light ones
- With LIV,
  - hadronic sub-showers are created instead of electromagnetic ones;
  - the fraction of energy transferred to muons is maximal;
  - fluctuations are minimal, due to a limited stochastic leakage in the first interaction

F. Salamida



The Auger Collab, in preparation

F. Salamida

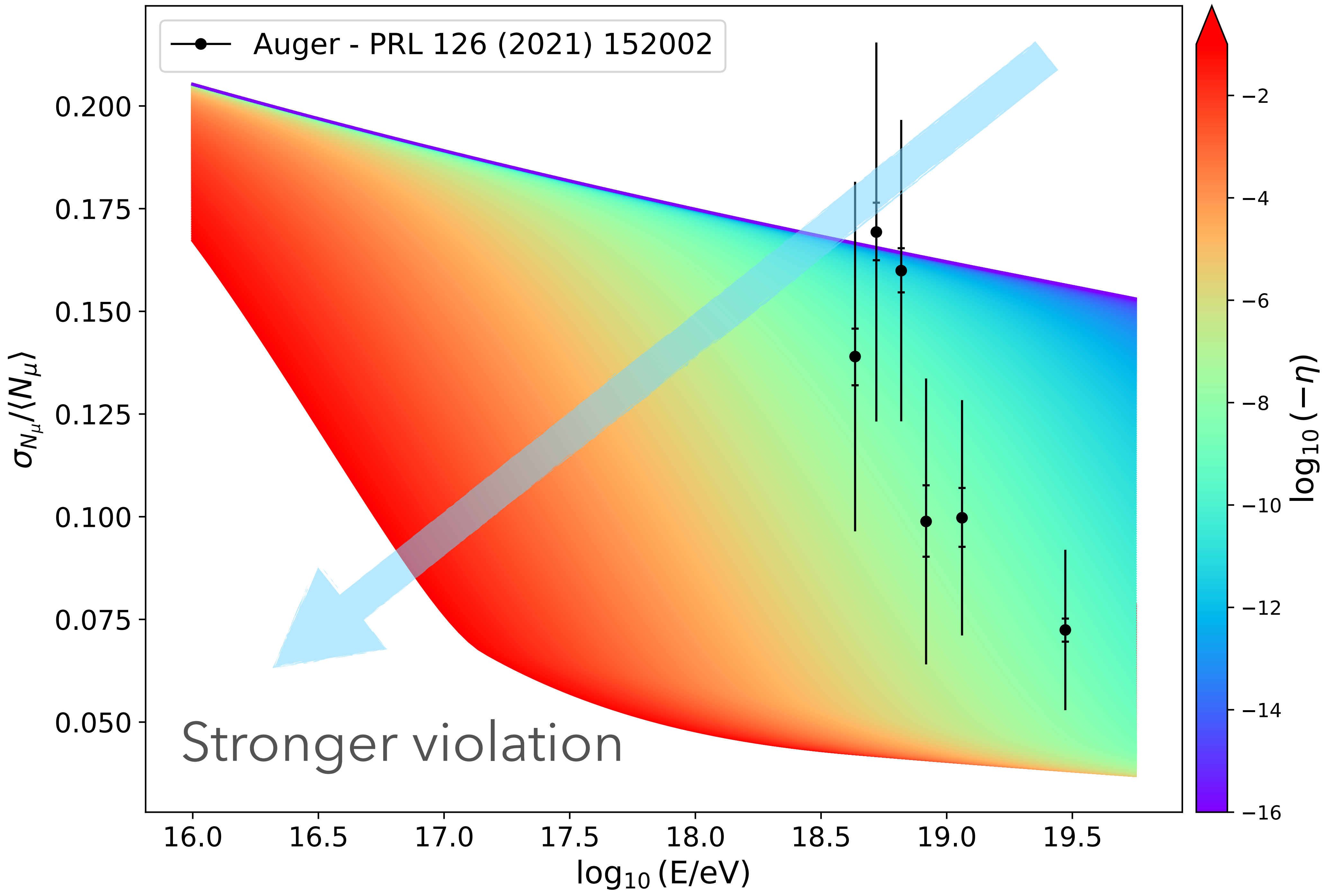
Constraints

- <u>Warning</u>: muon fluctuations are connected to UHECR mass composition

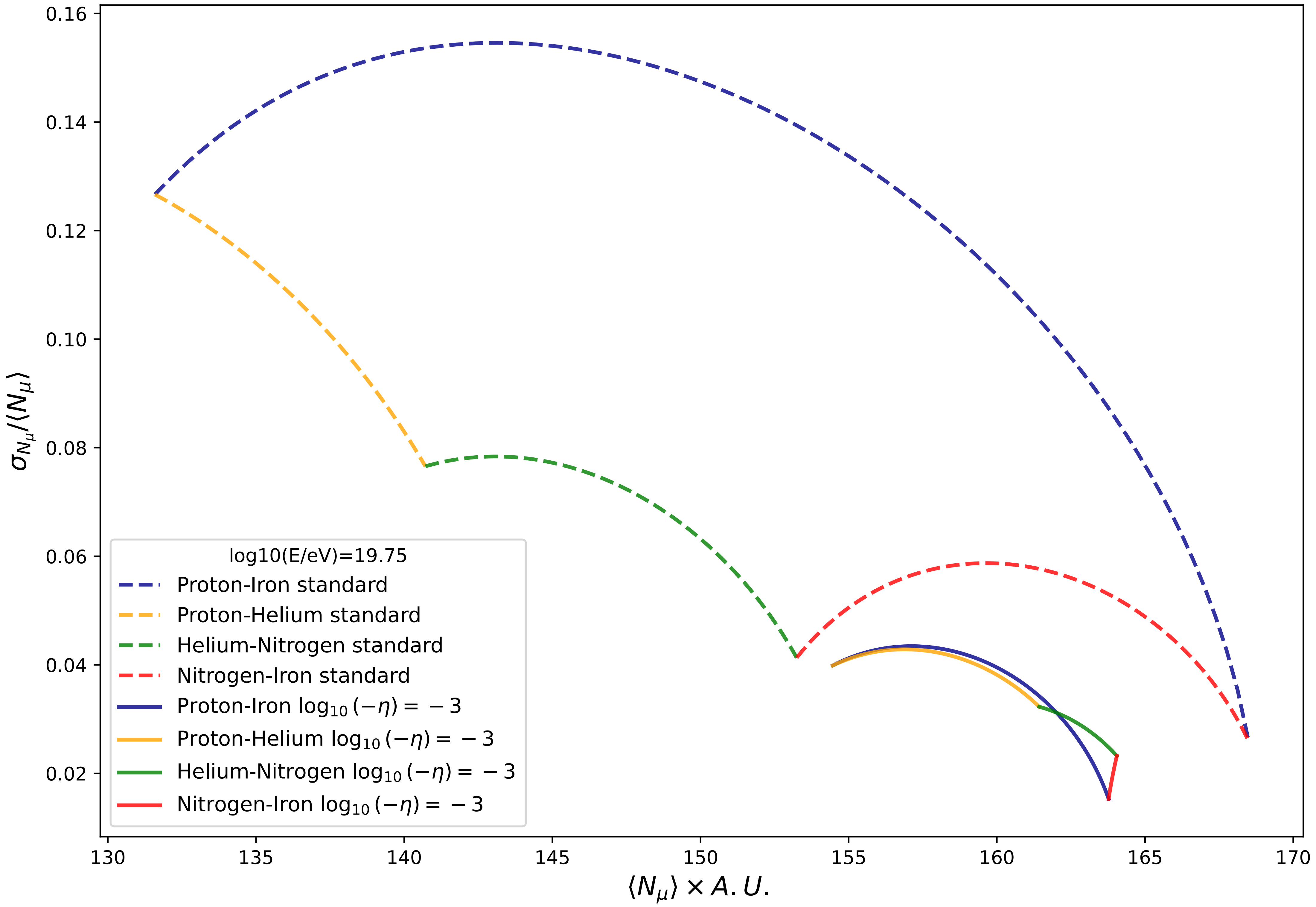
$$\langle N_\mu \rangle_{\mathrm{mix}}(\alpha;\eta) = (1-\alpha)\langle N_\mu \rangle_p + \alpha \langle N_\mu \rangle_{Fe}$$

$$\sigma^2_{\mathrm{mix}}(N_\mu)(\alpha;\eta) = (1-\alpha)\sigma^2(N_\mu)_p + \alpha\sigma^2(N_\mu)_{Fe} + \alpha(1-\alpha)(\langle N_\mu \rangle_p - \langle N_\mu \rangle_{Fe})^2$$

$$\frac{\sigma_\mu}{\langle N_\mu \rangle}(\alpha;\eta) = \frac{\sqrt{\sigma^2_{\mathrm{mix}}(N_\mu)(\alpha;\eta)}}{\langle N_\mu \rangle_{\mathrm{mix}}(\alpha;\eta)}$$



The Auger Collab, in preparation



- The number of muons and fluctuations are parametrised so that we have, for any given value of eta, the specific mixture that maximises the fluctuations at each energy
- <u>The most conservative LIV model corresponds to the alpha(E) which maximises the fluctuations, provided that the corresponding curve of the LIV fluctuations remains below the data</u>

C.L.	**90.5%**	**95.5%**	**99.9%**
$\log_{10}(-\eta)$	$-7.31^{+0.11}_{-0.17}$	$-7.14^{+0.11}_{-0.17}$	$-6.67^{+0.11}_{-0.17}$

BACKUP SLIDES:
DETAILS OF SOURCE-PROPAGATION MODELS

Source-propagation model

$$\frac{\partial N_i(E)}{\partial t} = \frac{\partial}{\partial E}(-b(E)N_i(E)) - \frac{N_i(E)}{t_{\rm esc}} + Q_{ji}(E)$$

$b(E) = E/t_{\rm loss}$

$Q_i(E)$ Injection of CRs (accelerated spectrum)

$Q_{j\to i}(E)$ Production of secondary cosmic rays

Coupled system of equations, arising because:

$Q_{ji} = Q_i(E) + Q_{j\to i}(E)$

$$Q(E,z) = Q_0 \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{E_{\rm max}}\right) f(z)$$

$$Q_0 = \frac{L}{\int_{E_0}^{\infty} dE'\, E' \left(\frac{E'}{E_0}\right)^{-\gamma} \exp\left(-\frac{E'}{E_{\rm max}}\right)}$$

- Accelerated spectrum Q in the source
  - Interactions and escape in the source environment
- Spectrum at the escape -> injection in the extragalactic space
  - Interactions in the extragalactic space
- Spectrum at detection
- Secondary messengers can be computed (from source and from extragalactic propagation)

Source-propagation model

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Multimessenger connections:

$$L_{\text{CR}} = \int Q_{\text{CR}}(E) E\, dE \approx \eta\, L_\gamma \qquad L_\nu \approx f_\pi L_{\text{CR}} \approx f_\pi \eta\, L_\gamma$$

η baryonic loading, unknown

Corresponding quantities for transient sources can be also described

Source-propagation model

$$\frac{\partial N_i(E)}{\partial t} = \frac{\partial}{\partial E}(-b(E)N_i(E)) - \frac{N_i(E)}{t_{\rm esc}} + Q_{ji}(E)$$

$$b(E) = E/t_{\rm loss}$$

$Q_i(E)$ Injection of CRs (accelerated spectrum)

$Q_{j\to i}(E)$ Production of secondary cosmic rays

Coupled system of equations, arising because:

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  - Interactions in the extragalactic space
- Spectrum at detection
- Secondary messengers can be computed (from source and from extragalactic propagation)

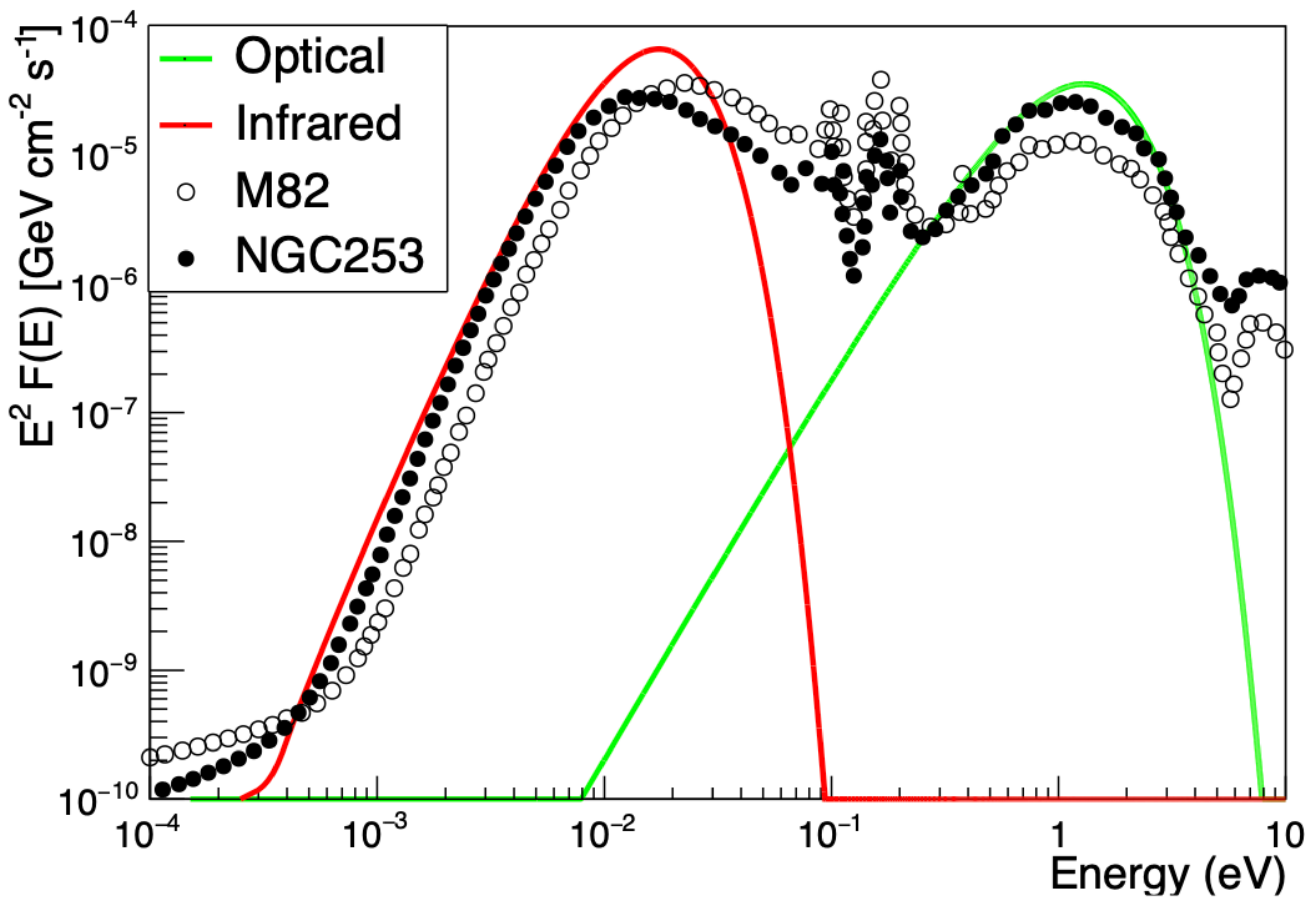
- **Cosmic Ray Injection**
  - Mass of primary particles
  - Maximum energy of CR spectra
  - Slope of CR spectra
  - Source evolution
  - Maximum distance of sources

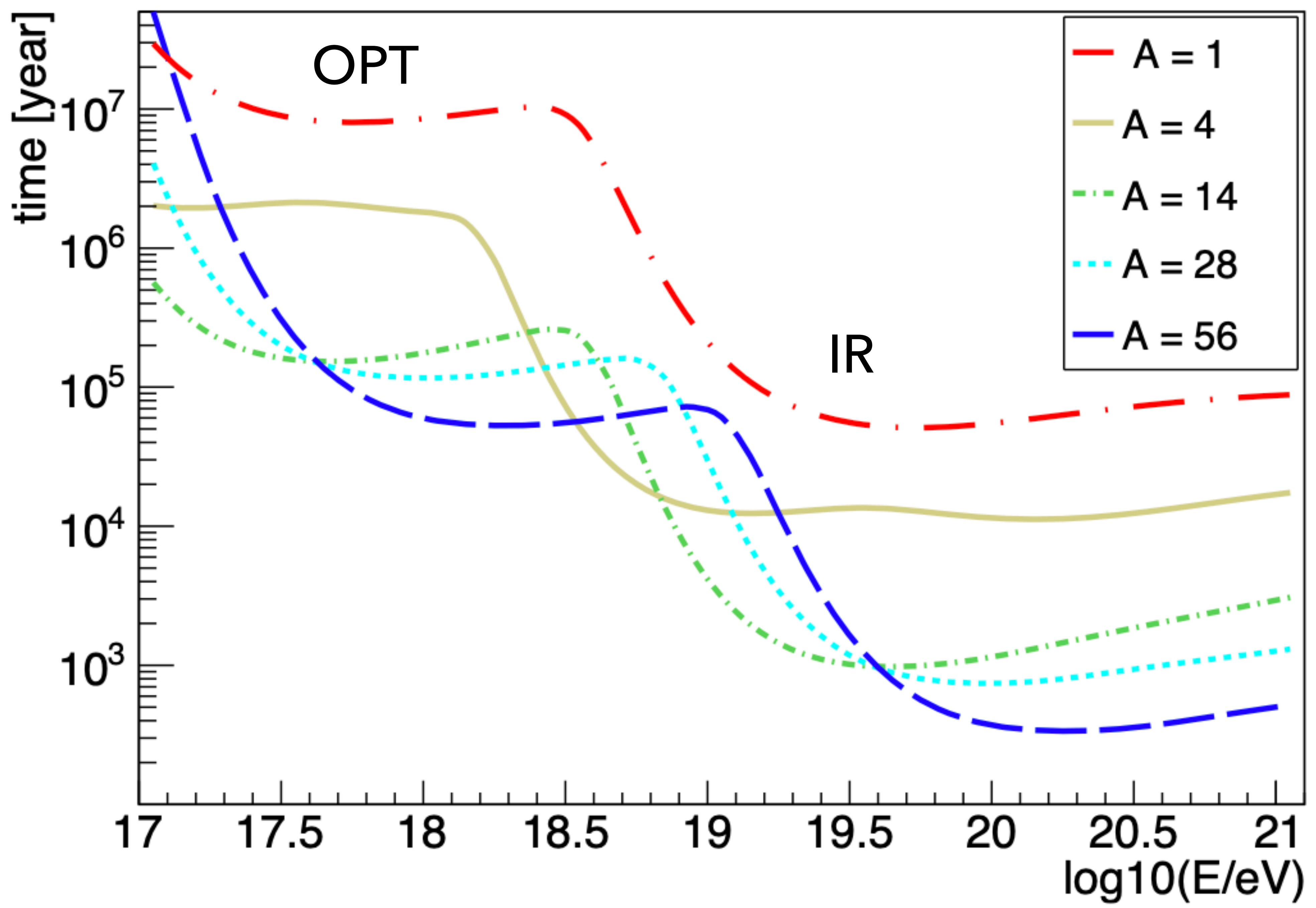
Not possible to be constrained only with UHECRs! Multimessenger approach needed; see for example:

- Heinze, **DB**, Bustamante & Winter, ApJ 2016
- Alves Batista, de Almeida, Lago & Kotera, JCAP 2019
- Heinze, Fedynitch, **DB** & Winter, ApJ 2019
- van Vliet, Alves Batista & Hoerandel, PRD 2019
- The Auger Collab. JCAP 2023; update in ICRC2023
- IceCube Collab. arxiv:2502.01963

Application to Starburst galaxies

- **Example** from Condorelli, DB, Peretti & Petrera PRD 2023: CR interactions in starburst galaxies





Characteristic time for photo-meson production and photodisintegration

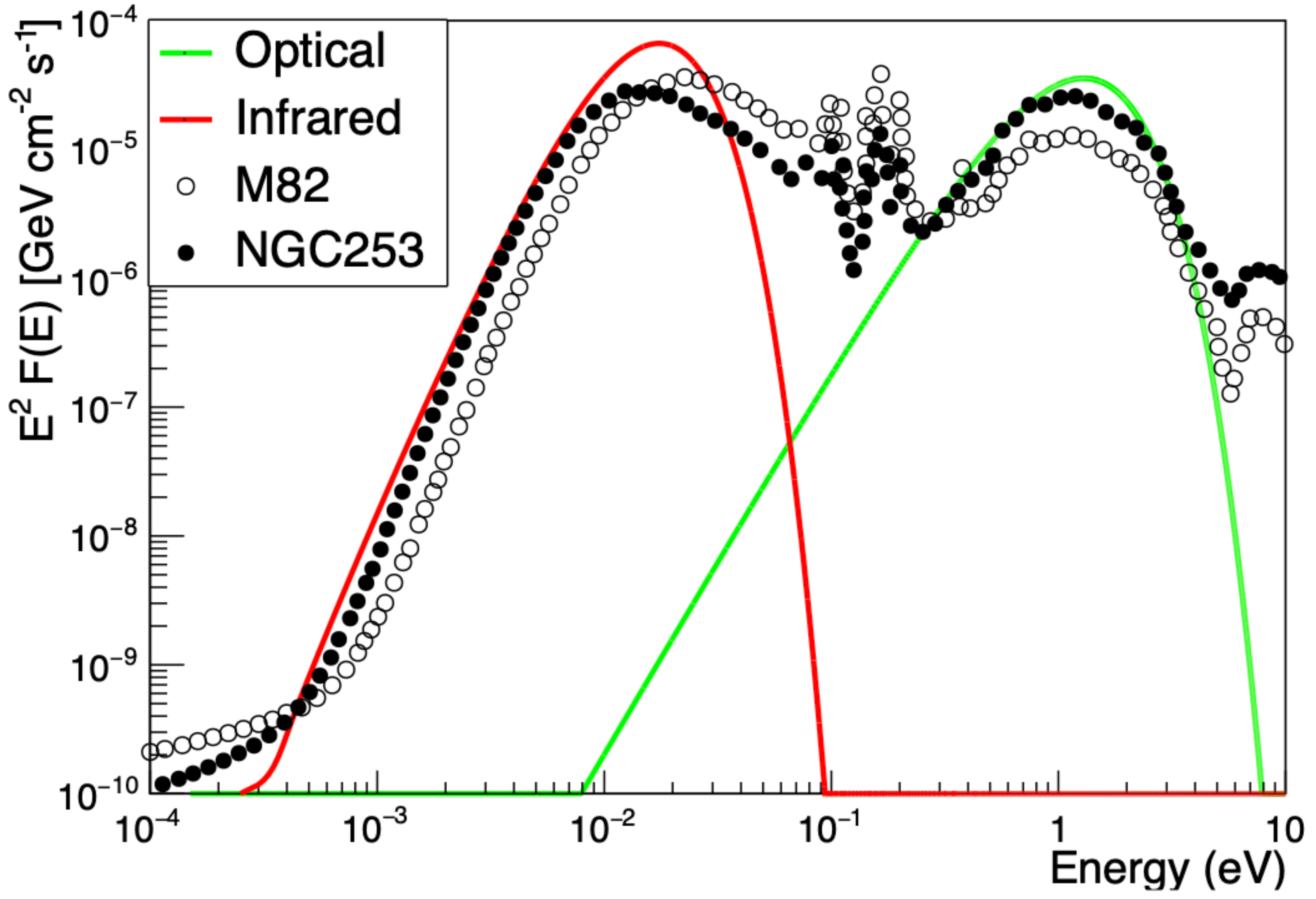
- **Radiation field (or matter density)**:
  - Intensity -> increase interaction rate
  - Min and max energy -> define range of interaction rate
  - Power law, energy break (if broken power law) or energy peak (if black-body radiation) -> change shape and/or shift interaction rate
  - Size -> interplay with escape/diffusion

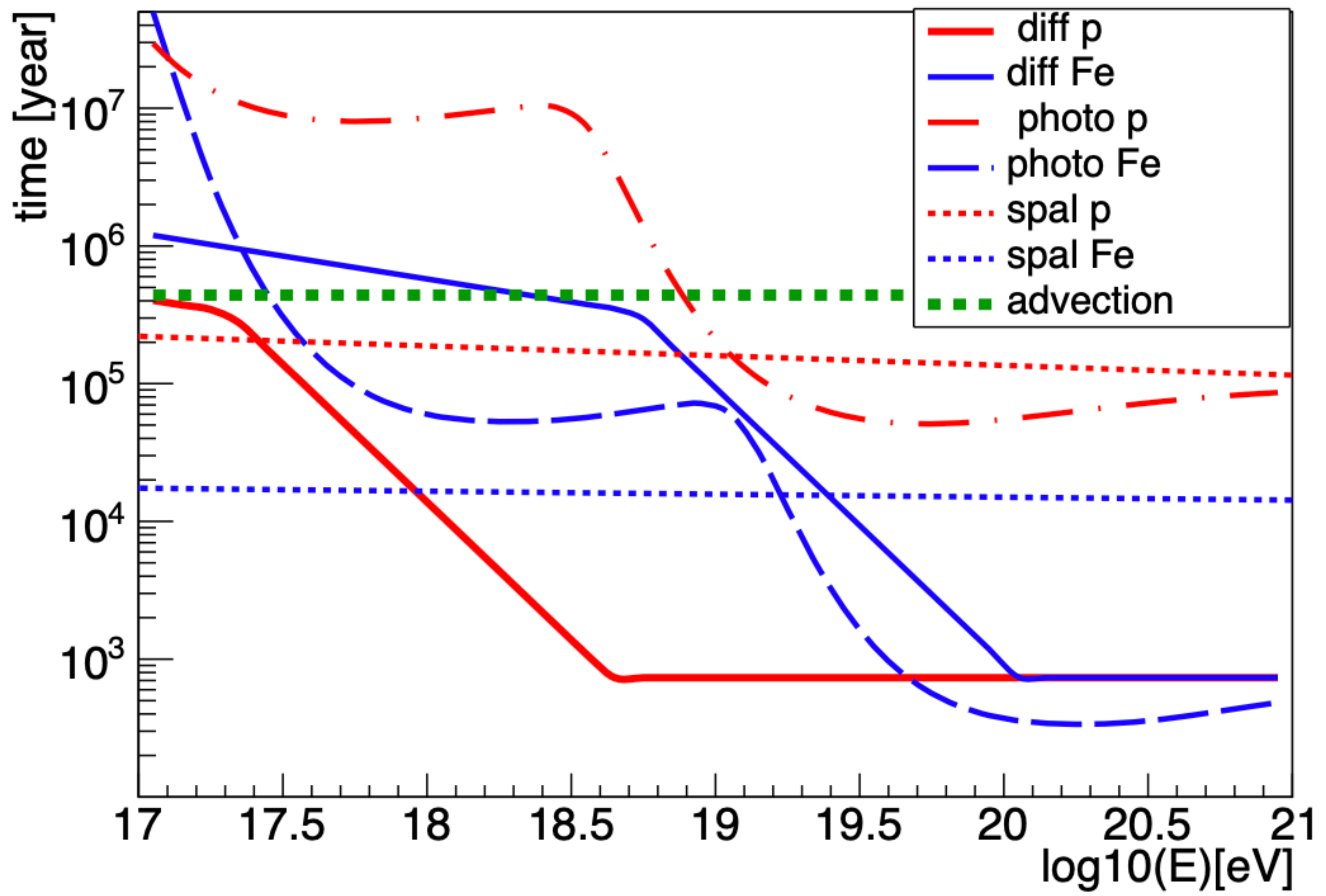
$$\frac{dN_{\rm int}}{dt} = \frac{c}{2\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty} \sigma(\varepsilon')\varepsilon' \int_{\varepsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\varepsilon)}{\varepsilon^2} d\varepsilon d\varepsilon'$$

$$\varepsilon' \approx \varepsilon\Gamma$$

Application to Starburst galaxies

- **Example** from Condorelli, DB, Peretti & Petrera PRD 2023: CR interactions in starburst galaxies





- **Radiation field (or matter density)**:
  - Intensity -> increase interaction rate
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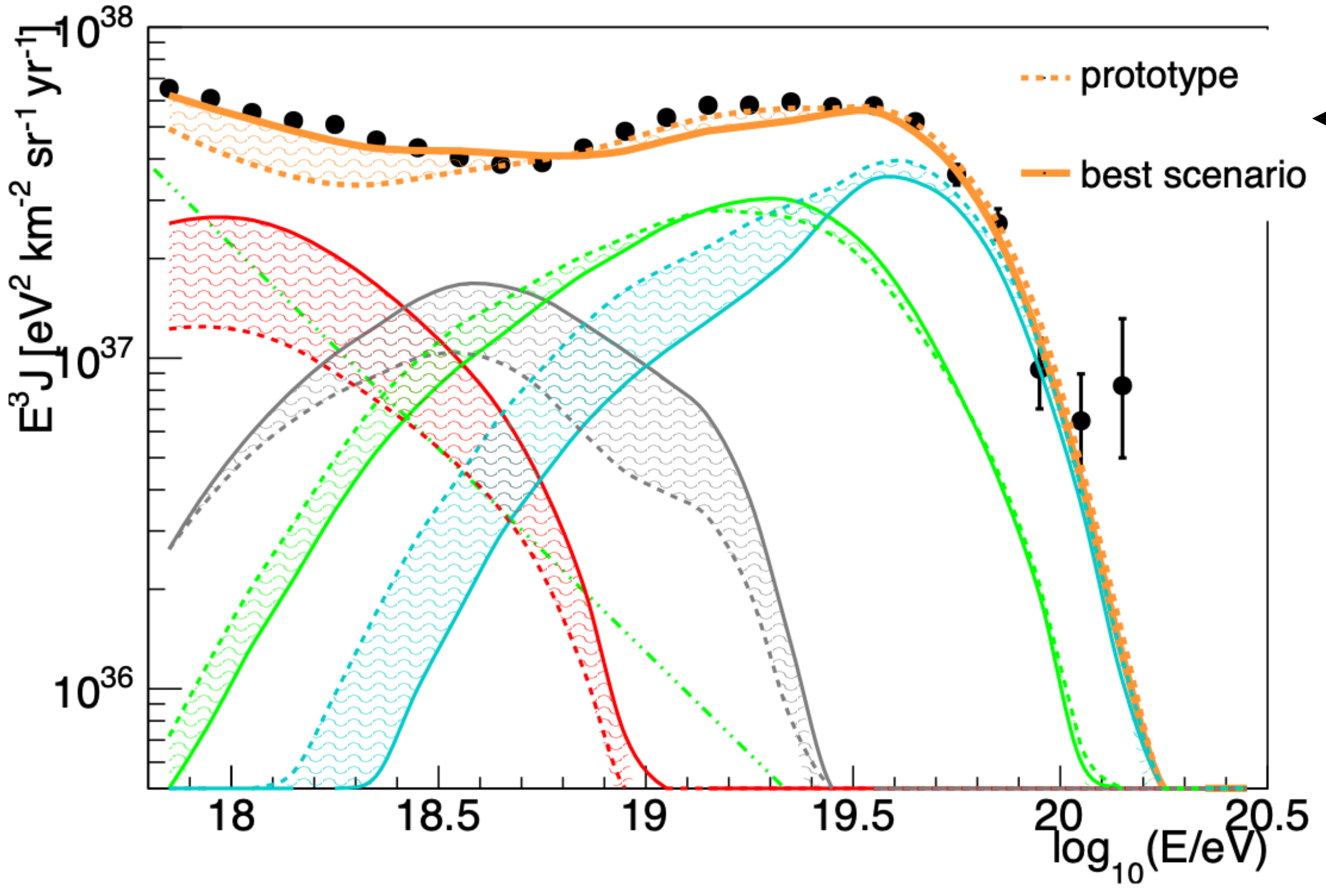
Characteristic time for diffusion compared to spallation and photonuclear interactions

$$t_{\rm adv} = \frac{R}{v_W} \qquad t_{\rm D} = \frac{R^2}{D(E)} \qquad t_{\rm esc} = \min[t_{\rm adv}, t_{\rm D}]$$

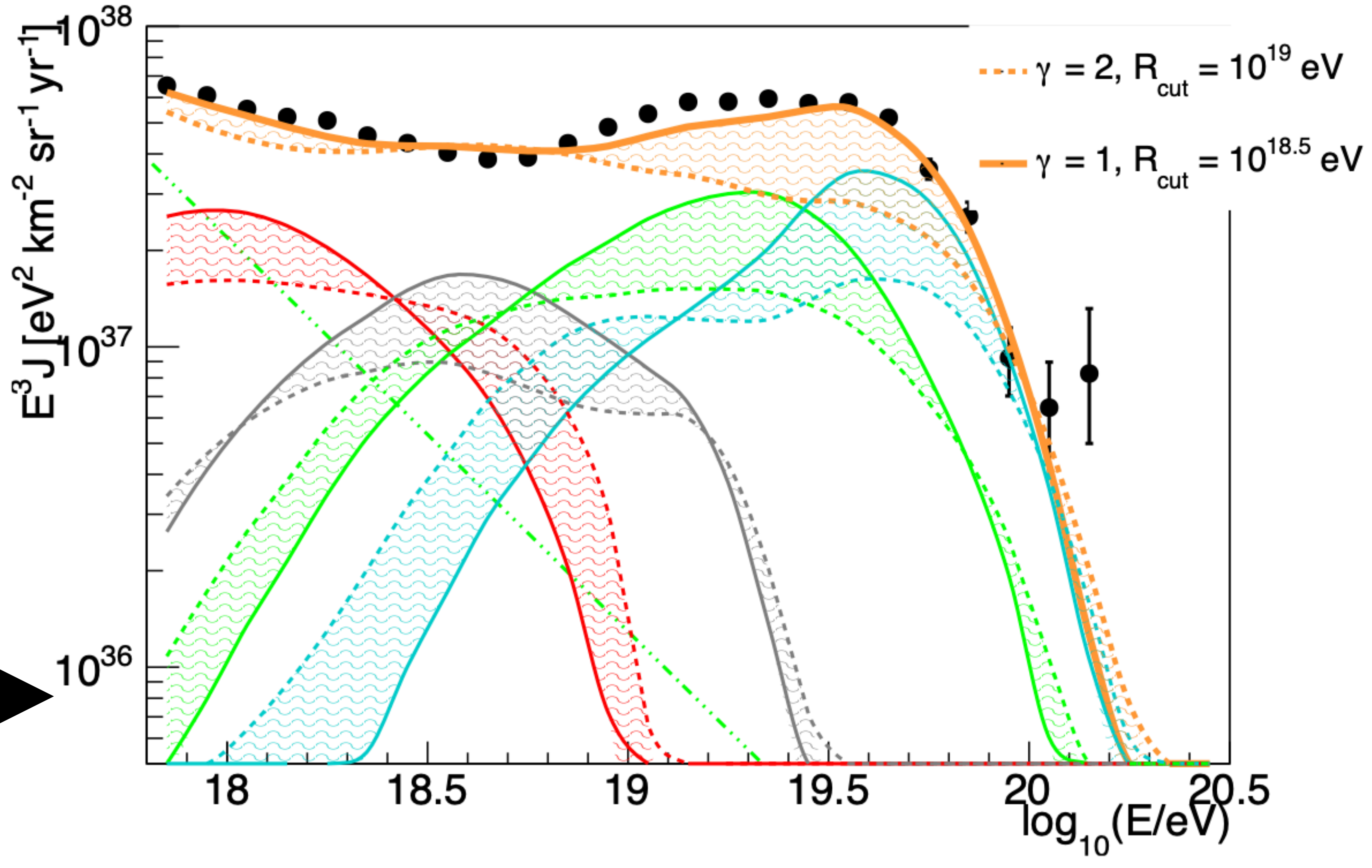
Maximum energy is not just defined by acceleration!

Application to Starburst galaxies



Effect of increased interaction efficiency

Effect of change of CR spectrum



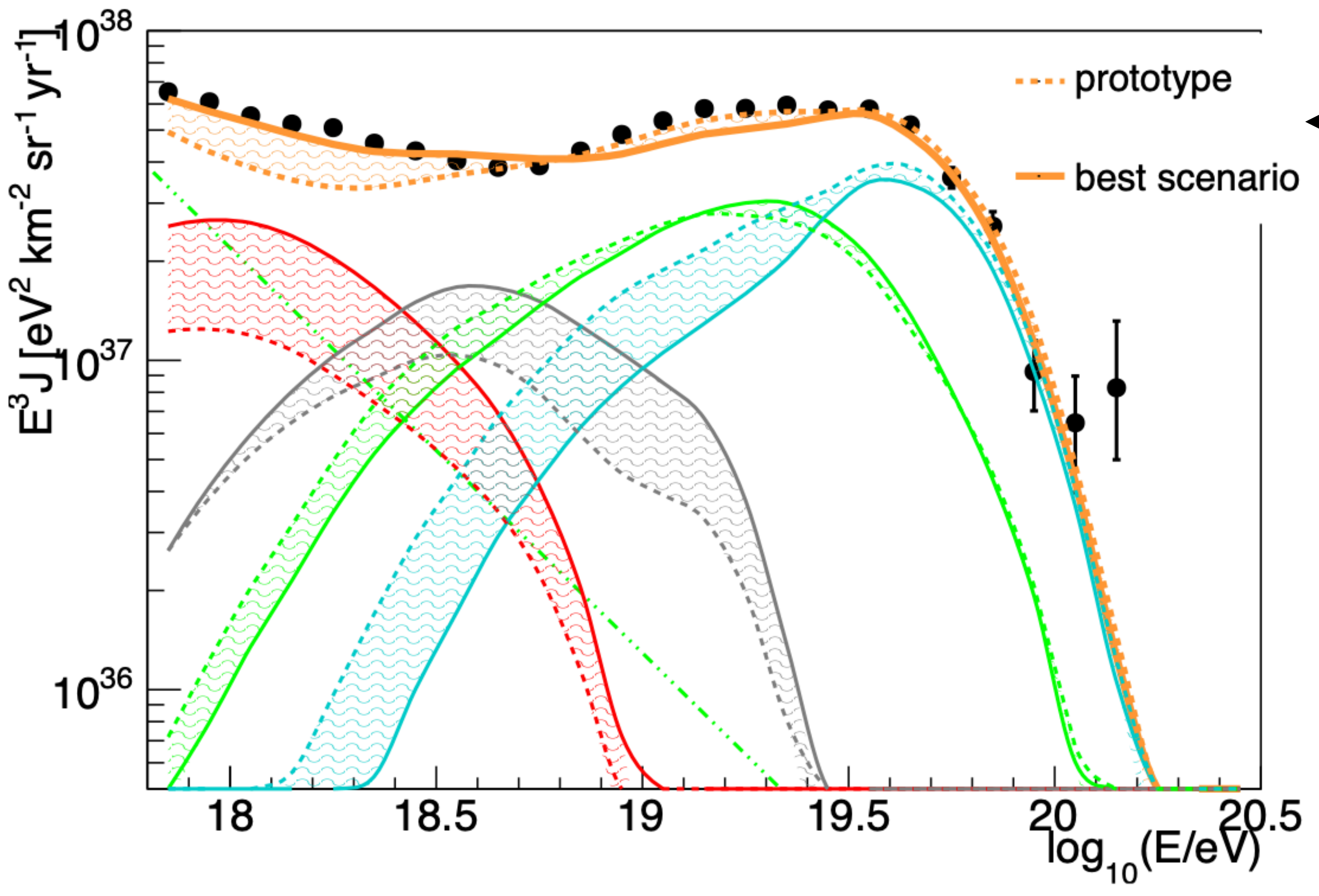
Condorelli, DB, Peretti & Petrera PRD 2023

- Denser photon field
  - heavier nuclei interact more efficiently
  - Lighter nuclei are more abundant

- Harder spectrum at acceleration
  - Larger number of particles at high energy with respect to low energy

- Extragalactic propagation computed with:
  - **SimProp**, Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017
  - **CRPropa**, R. Alves Batista et al, JCAP 2022

Application to Starburst galaxies + neutrinos



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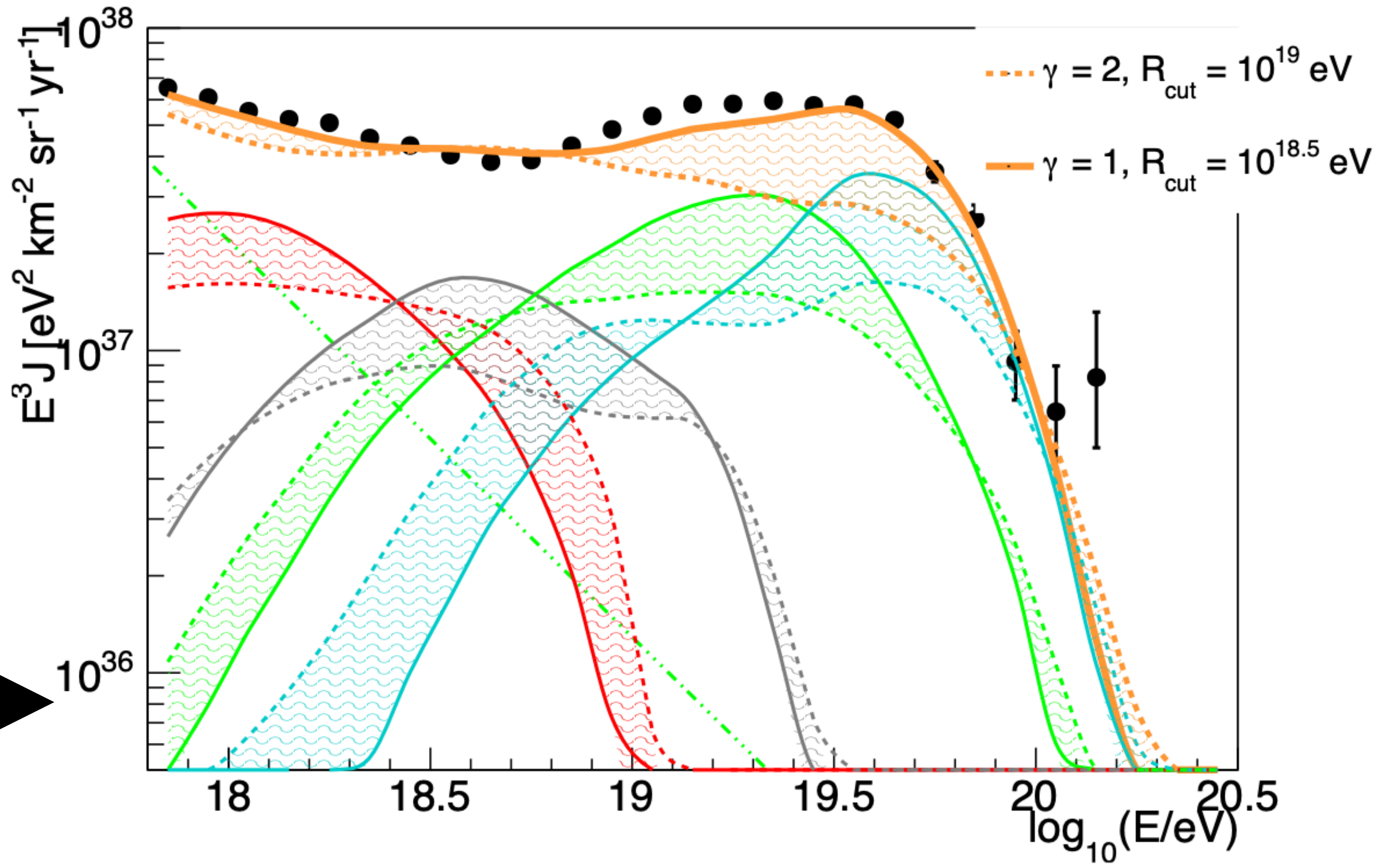
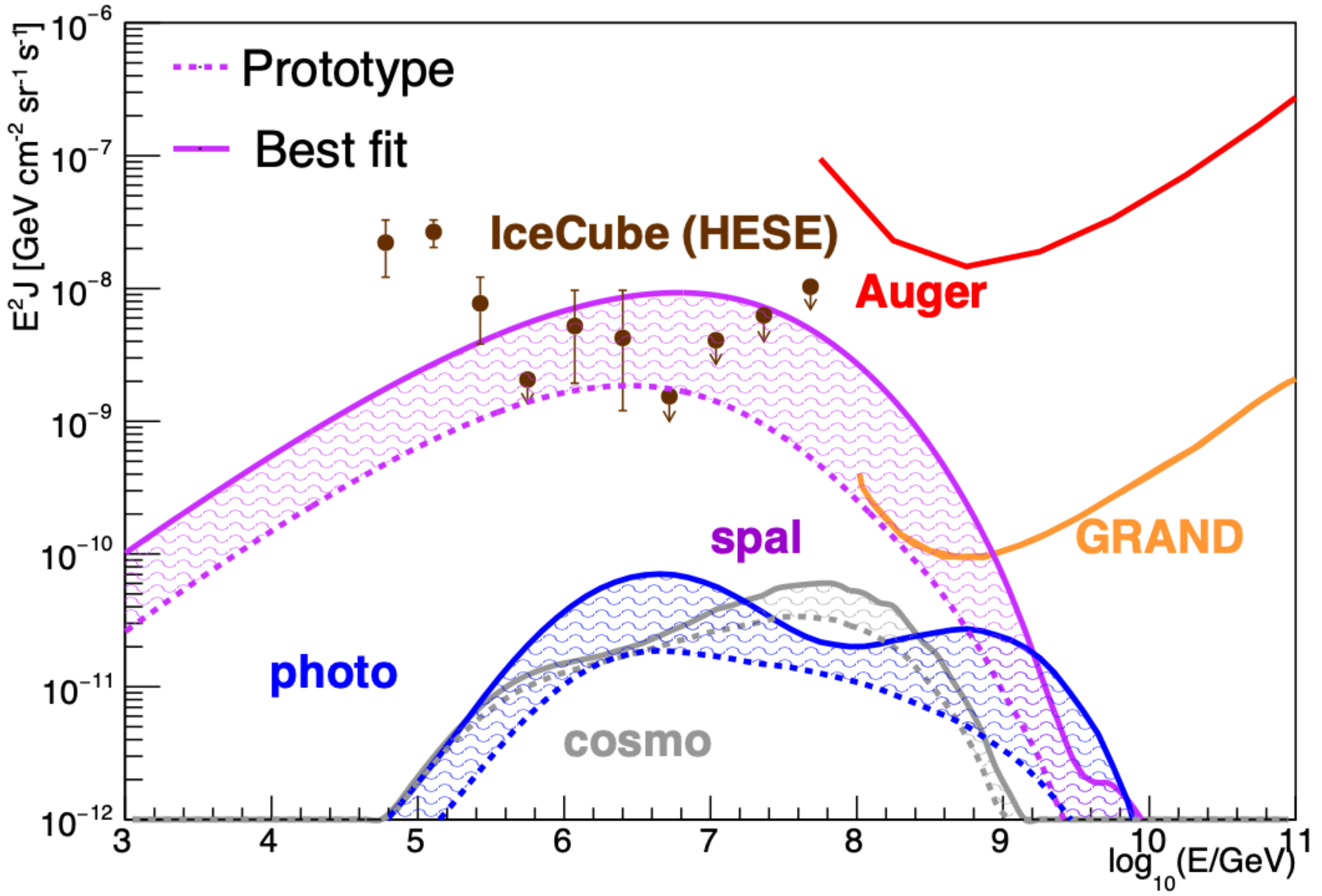


Condorelli, DB, Peretti & Petrera PRD 2023



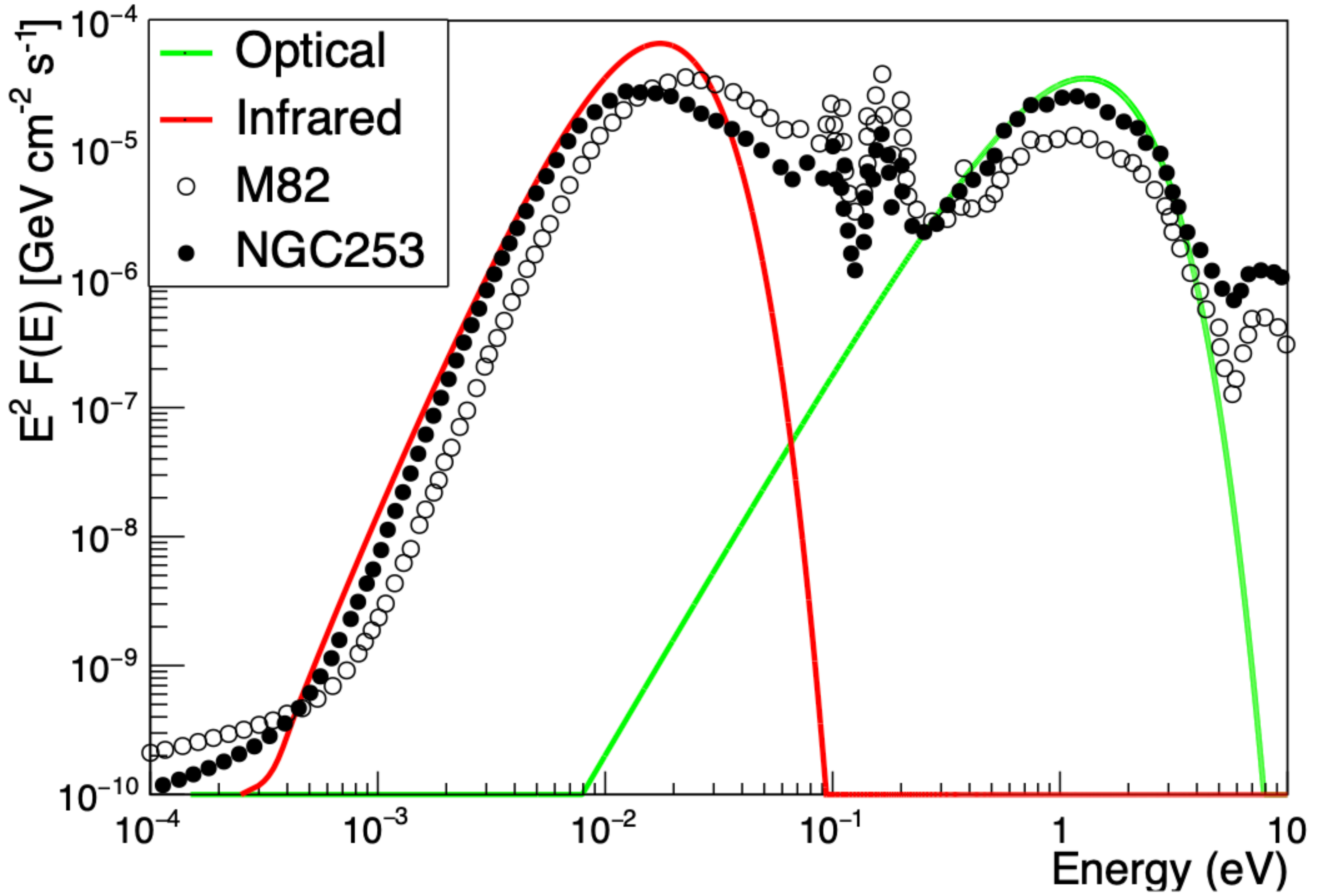
Neutrinos computed from in-source interactions and extragalactic propagation

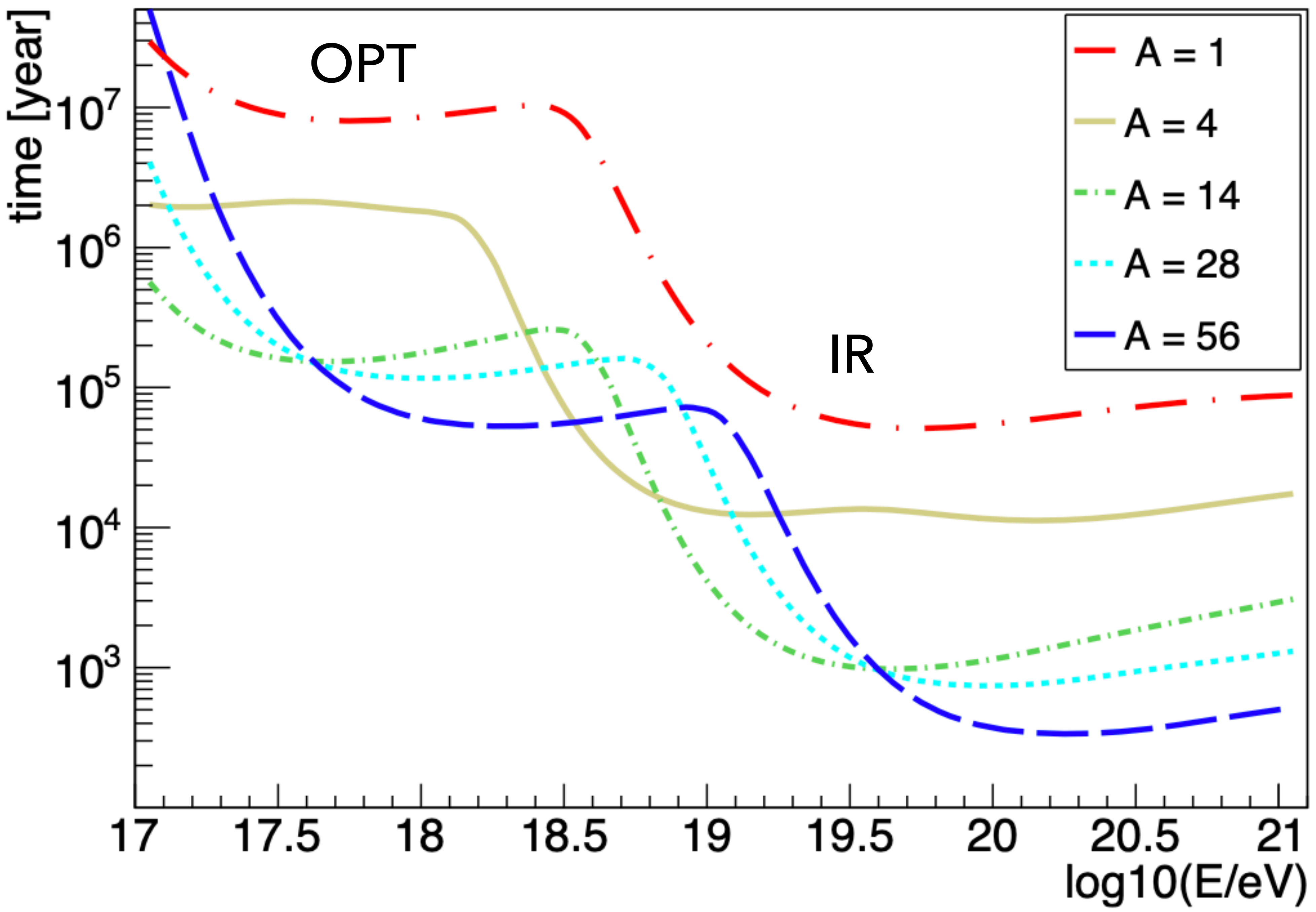
The importance of a **multimessenger approach, within a source-model scenario**:

- The cosmogenic neutrinos cannot reach the measurement level
- The contribution of in-source interactions can be investigated
  - the intensity of the photon field can be related to the neutrino flux, as well as the sub-ankle nucleons
  - The interactions responsible for the neutrino flux can be distinguished

Which source characteristics influence the neutrino flux?

- **Example** from Condorelli, DB, Peretti & Petrera PRD 2023: CR interactions in starburst galaxies





Characteristic time for photo-meson production and photodisintegration

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$$\frac{dN_{\mathrm{int}}}{dt} = \frac{c}{2\Gamma^2}\int_{\varepsilon'_{\mathrm{th}}}^{\infty}\sigma(\varepsilon')\varepsilon'\int_{\varepsilon'/2\Gamma}^{+\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'$$

$$\varepsilon' \approx \varepsilon\Gamma$$

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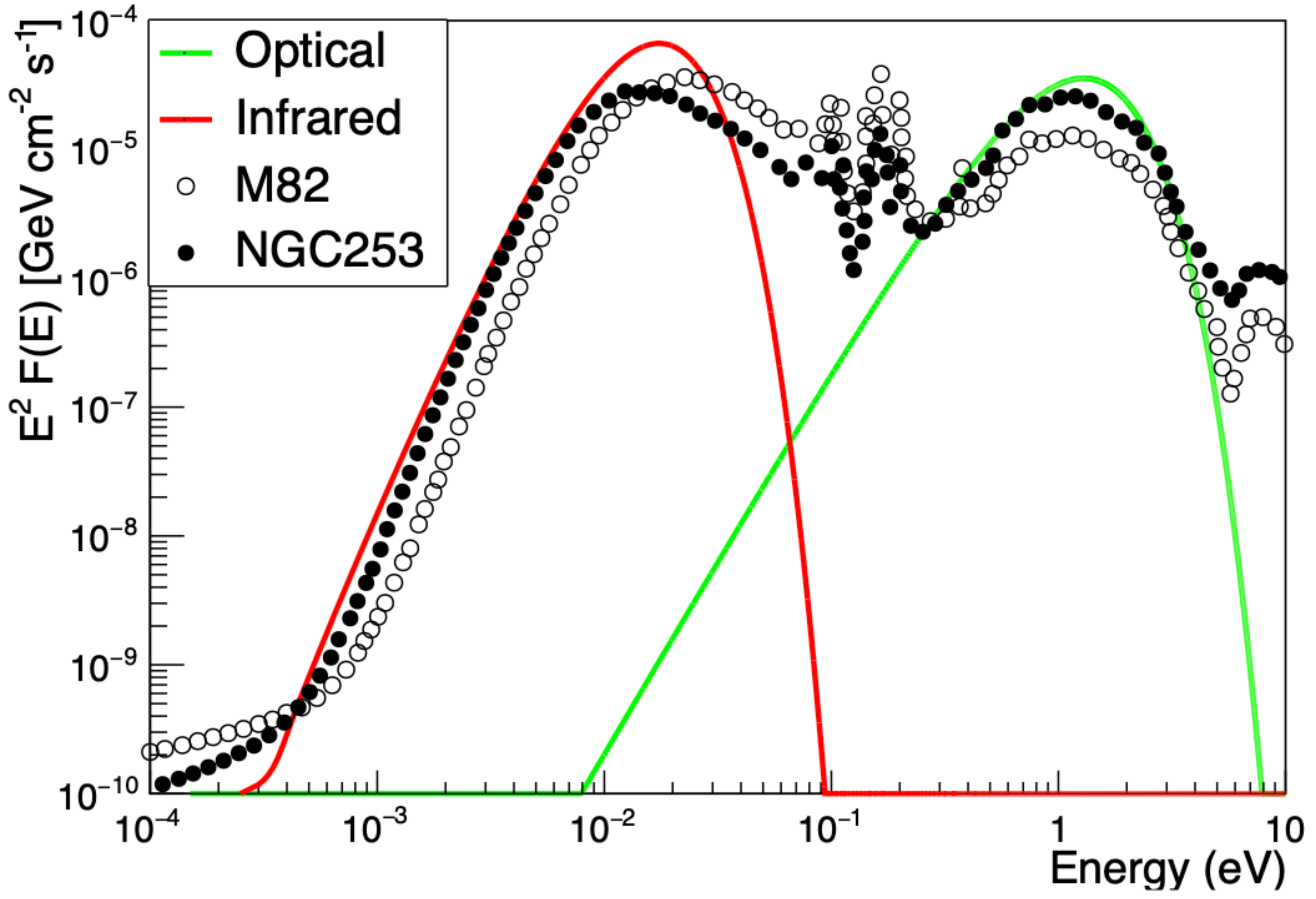

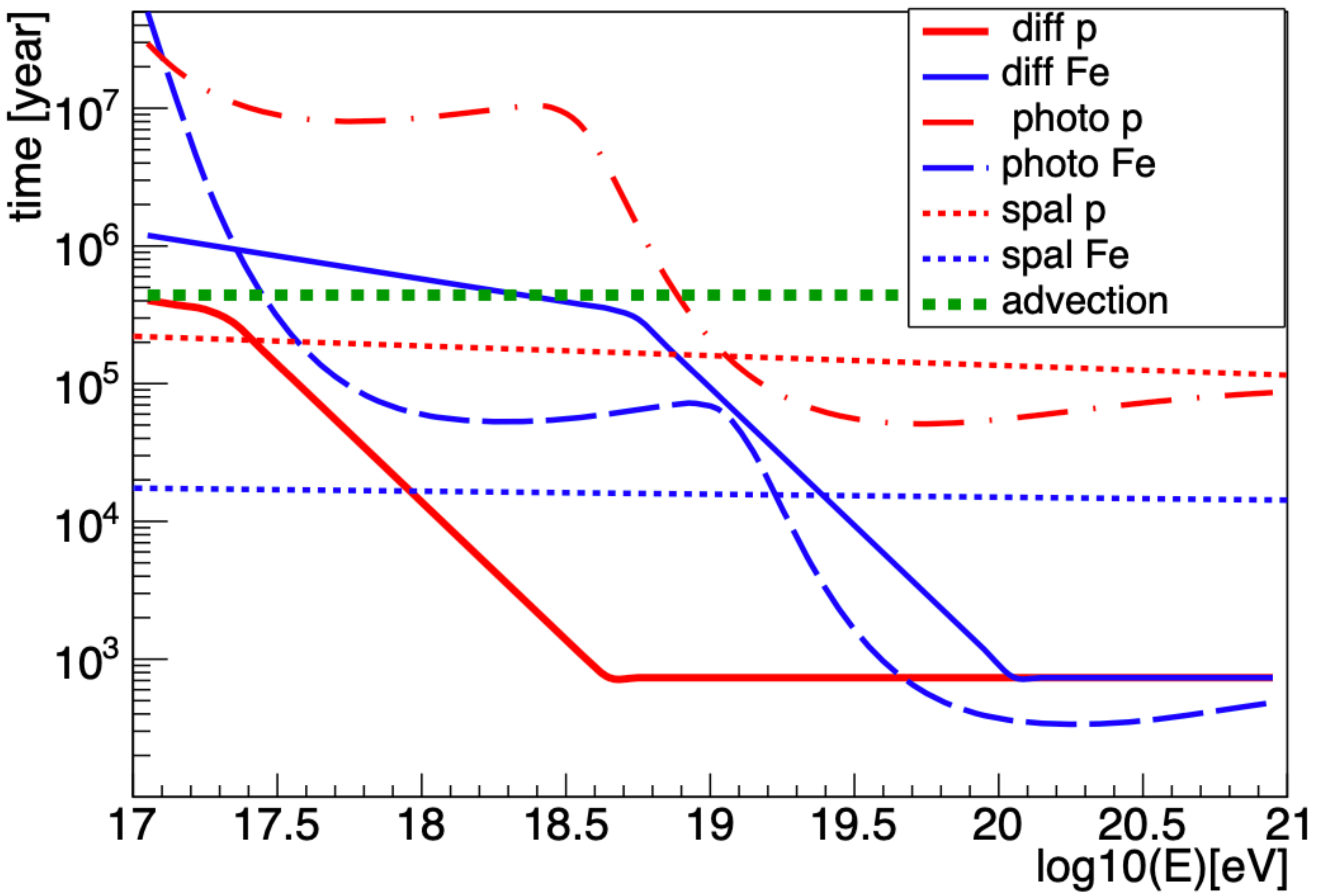

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