When astroparticles arrive at Earth

new ways for investigating Lorentz invariance

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BridgeQG - first annual conference
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Outline

- Introduction
  - State-of-the-art of UHECR measurements
  - The life of an astroparticle - and where LIV can manifest itself
- Scenarios describing UHECR data
- LIV in propagation stage -> extragalactic propagation
- LIV in detection stage -> atmosphere and Earth crust
- Discussion of astrophysical and physical competing effects
- Conclusions

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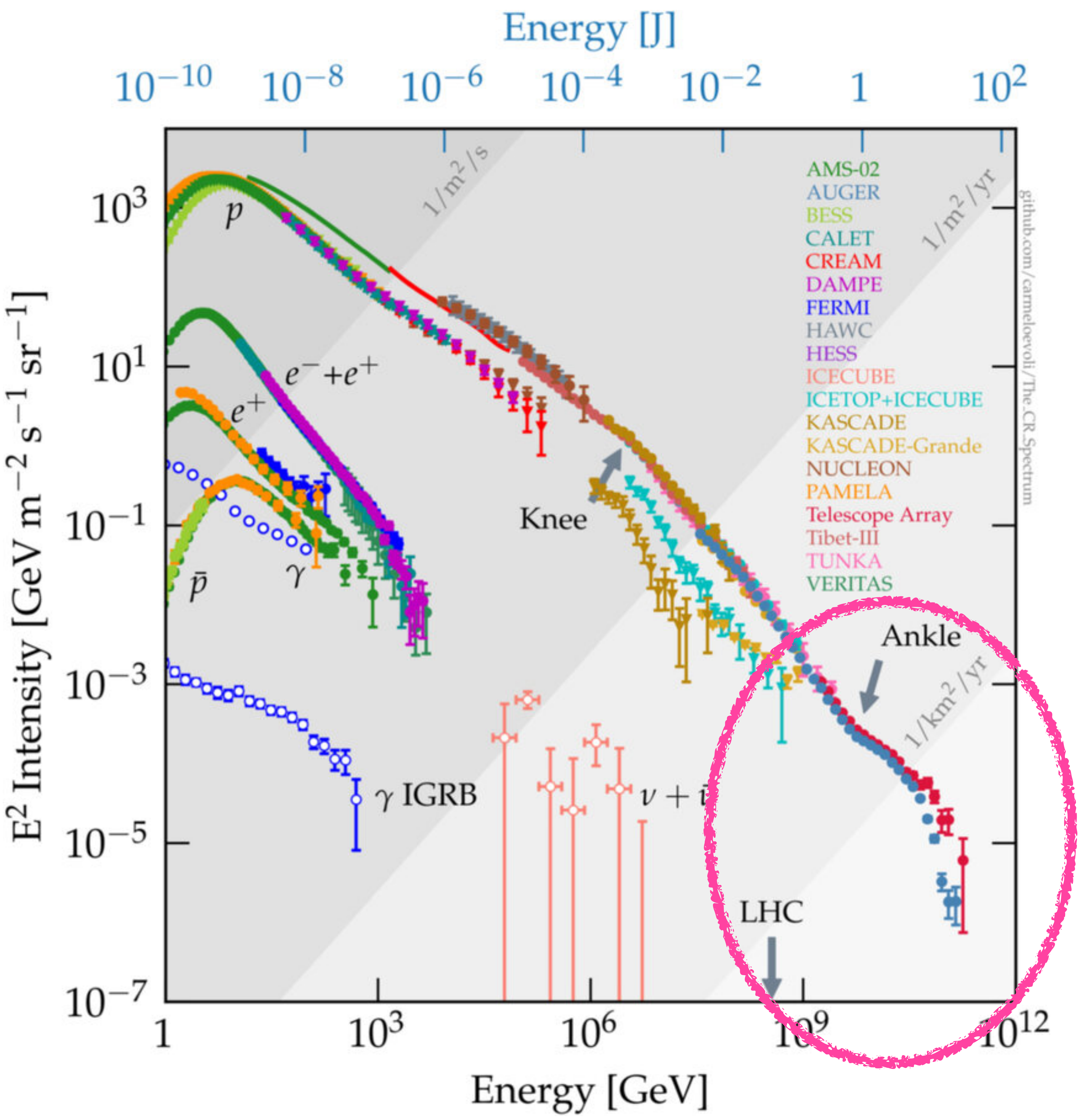
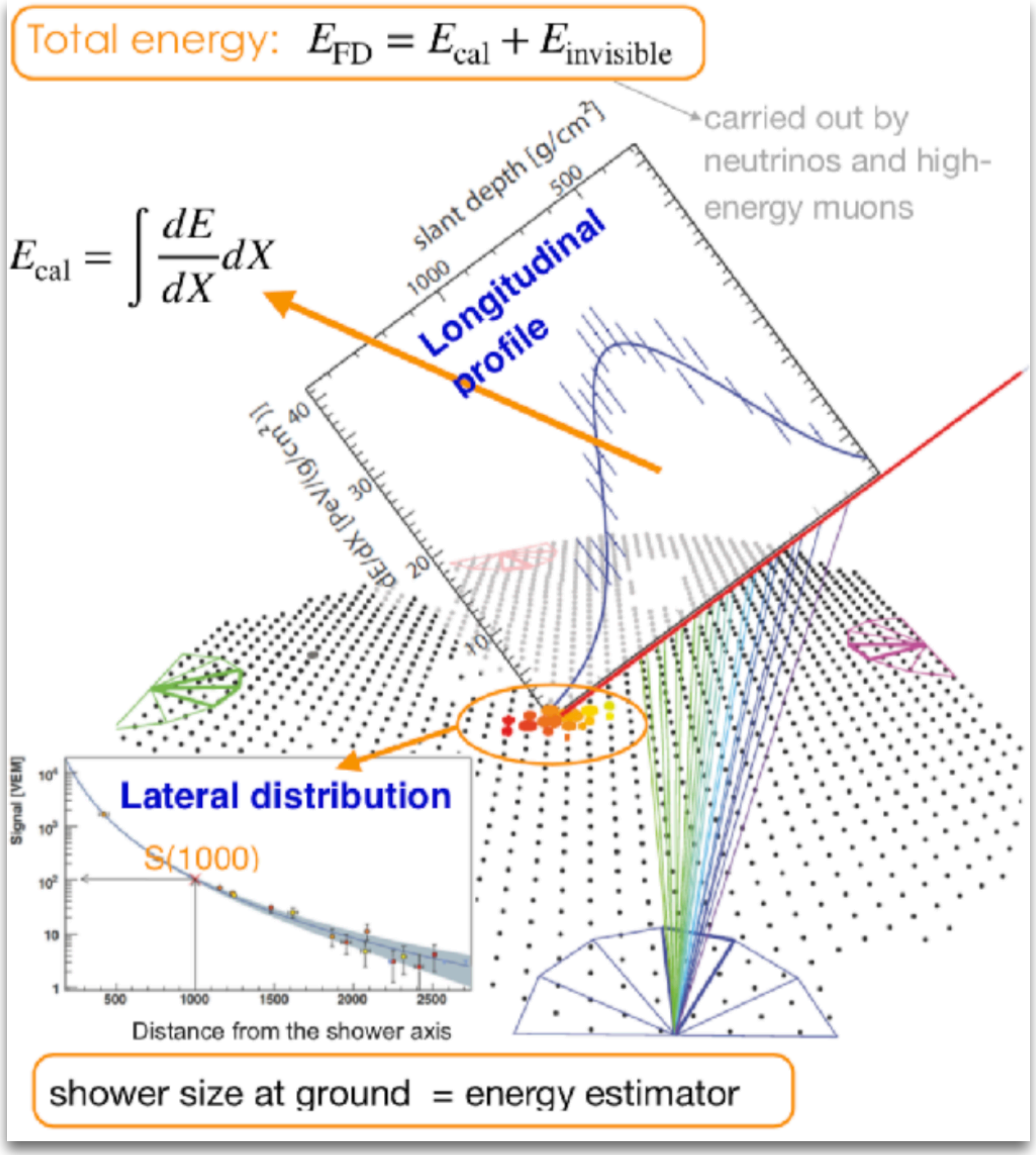


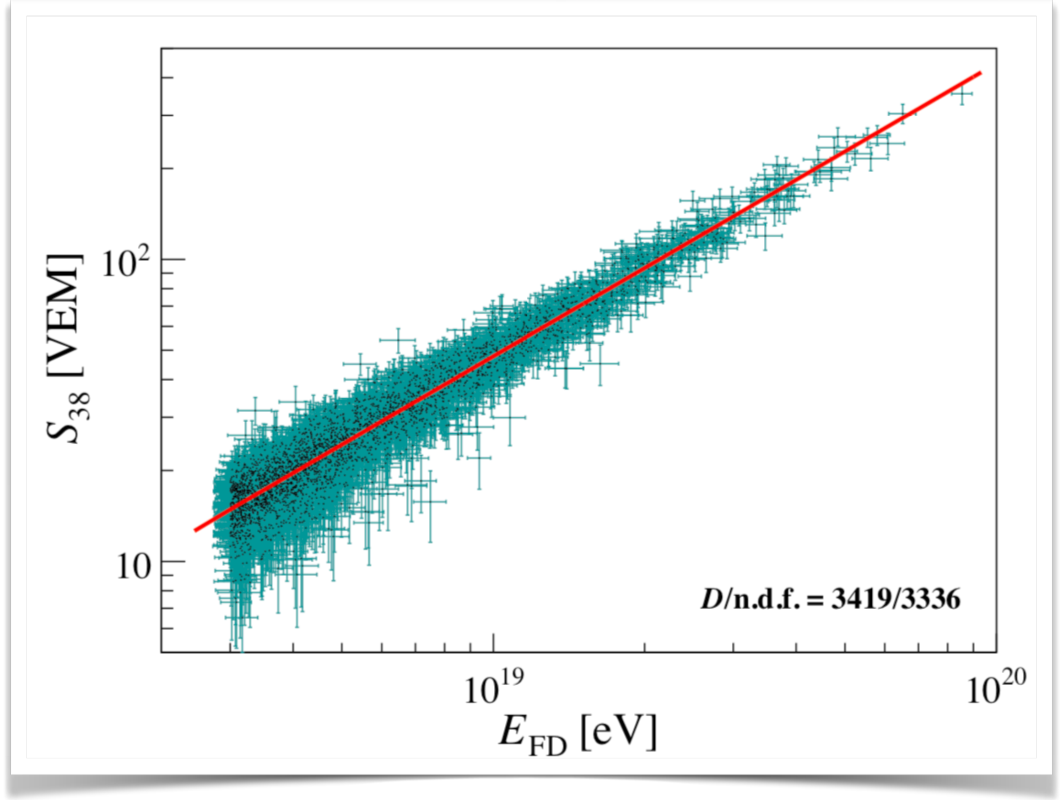
- At UHEs we rely on indirect techniques to measure the characteristics of astroparticles. For instance we exploit the atmosphere as a calorimeter;
  - **can we exploit the detection stage of astroparticles as a laboratory to test quantum-gravity effects?**

Measurements at the UHE

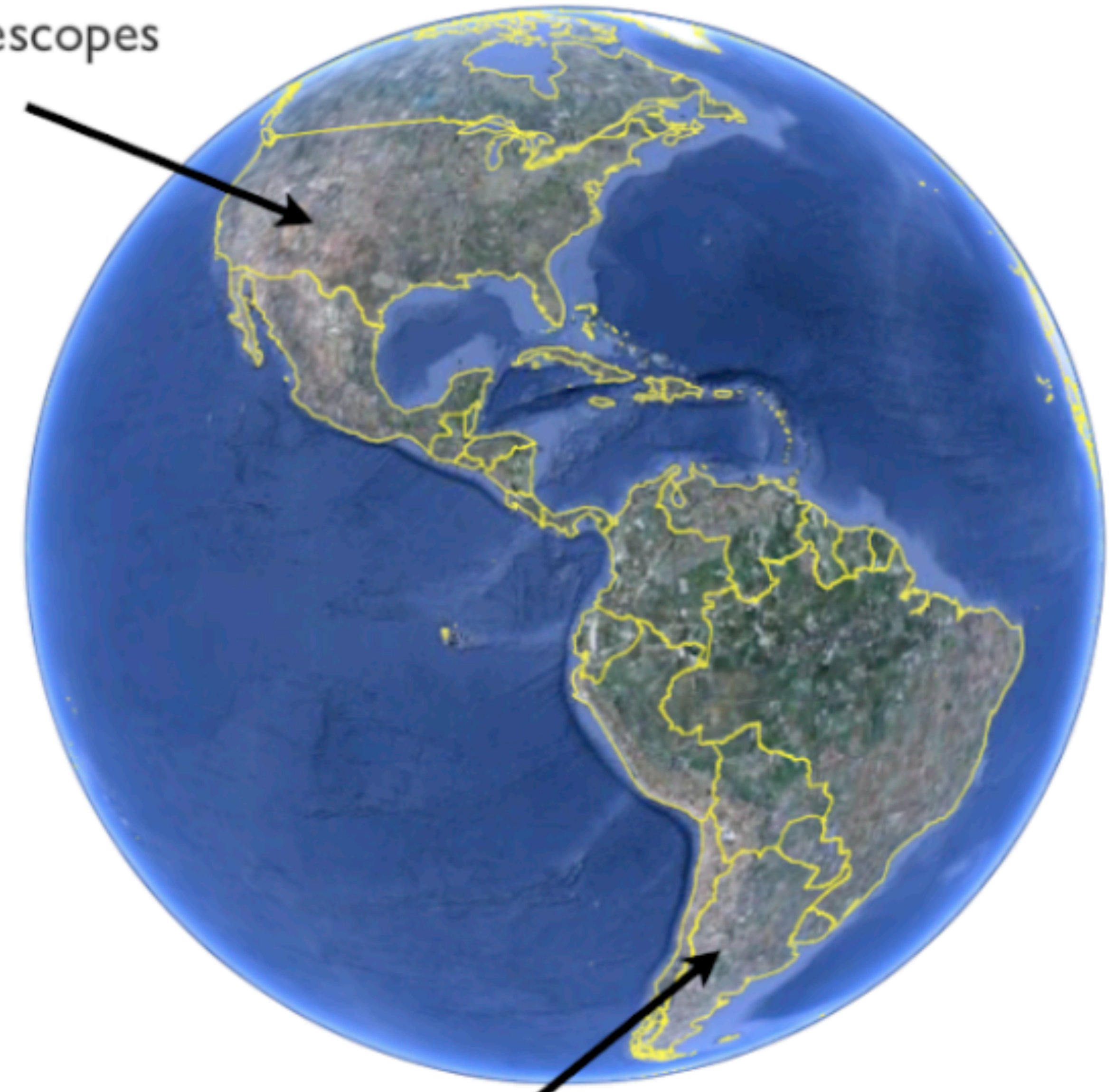


- **Longitudinal profile of the EAS (integrate energy losses in atmosphere)**
  - Electromagnetic component
- **Lateral distribution of the EAS (look at particles at ground)**
  - Muonic component

The Pierre Auger Collab. PRD2020

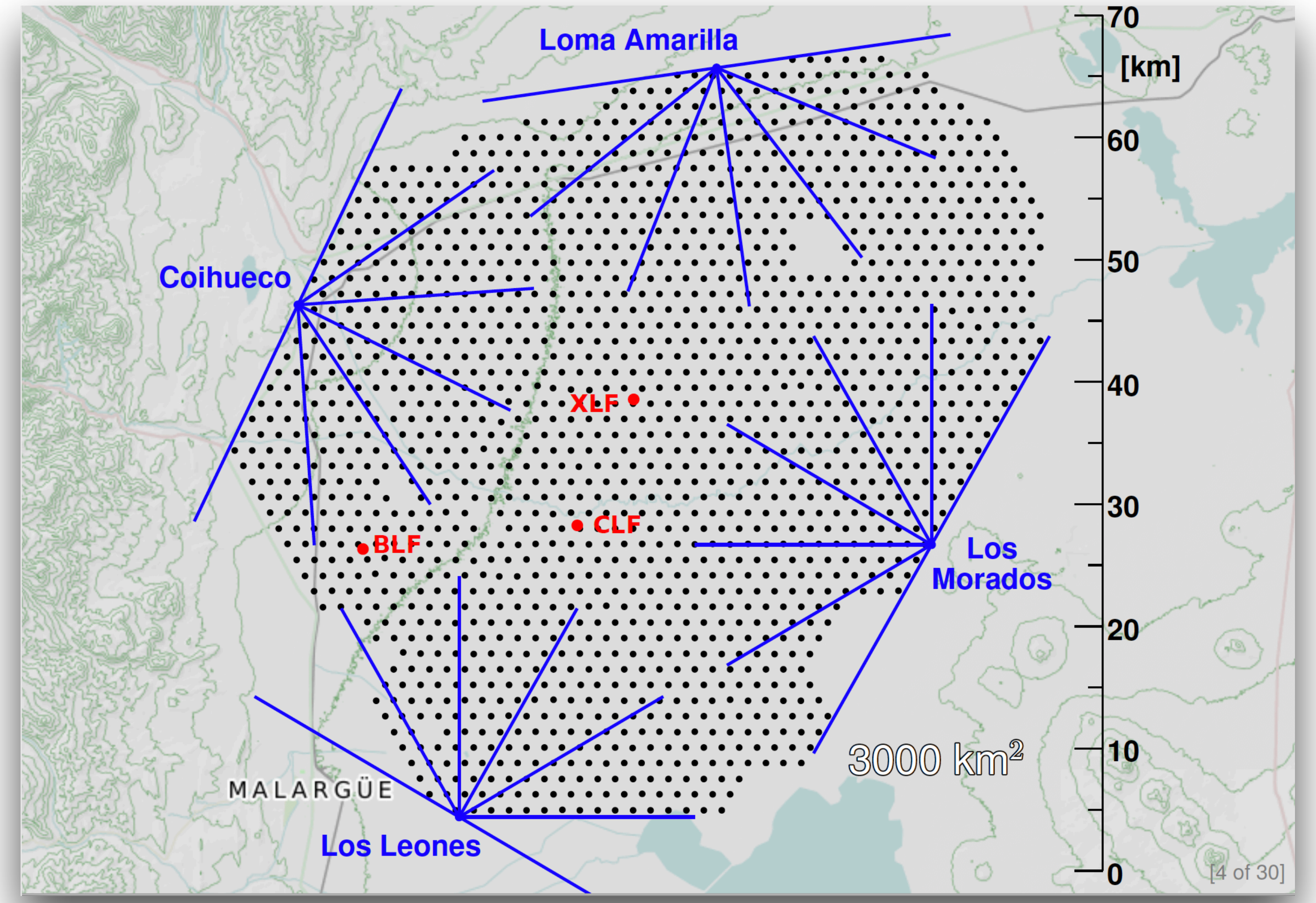


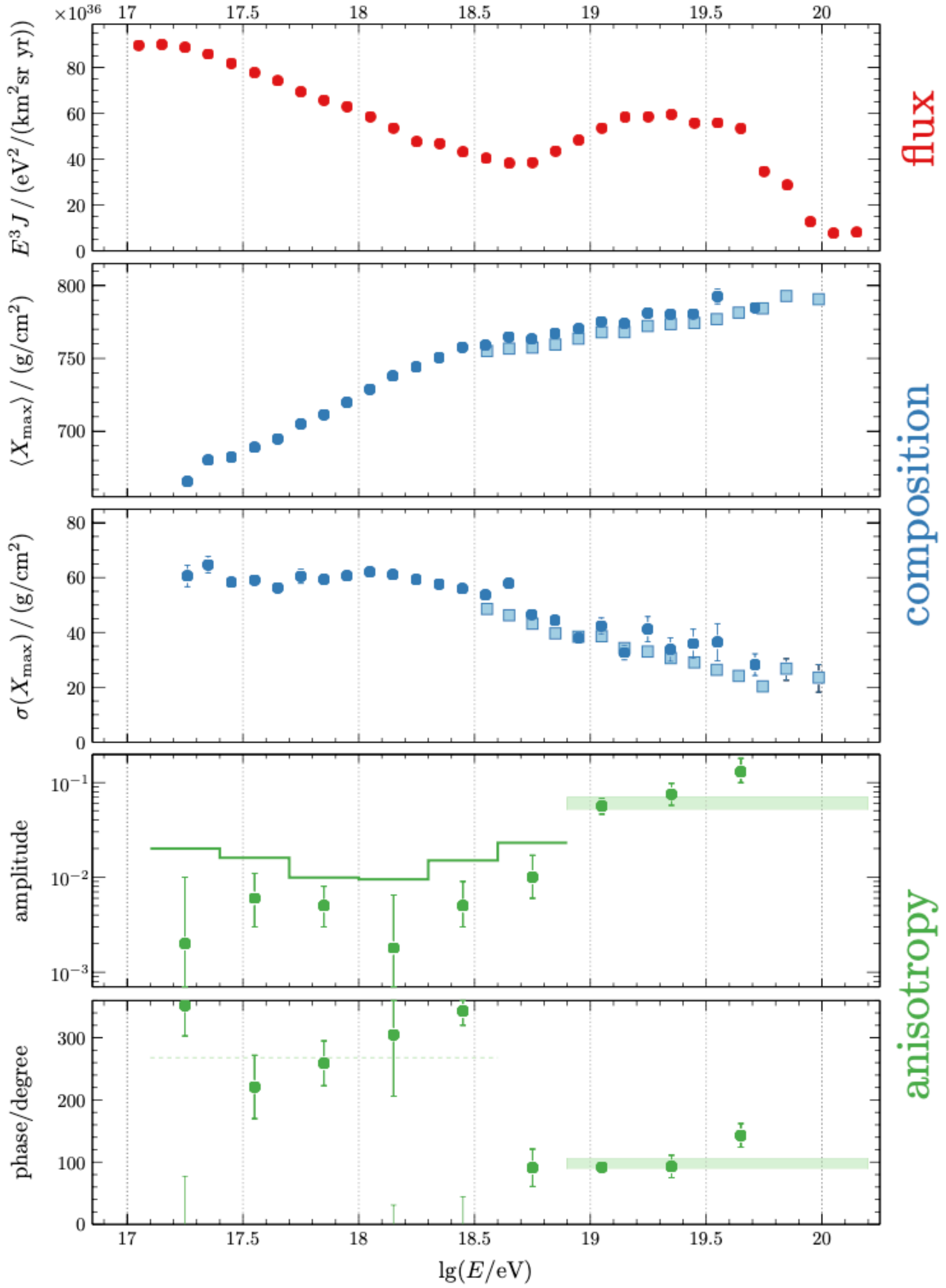
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes



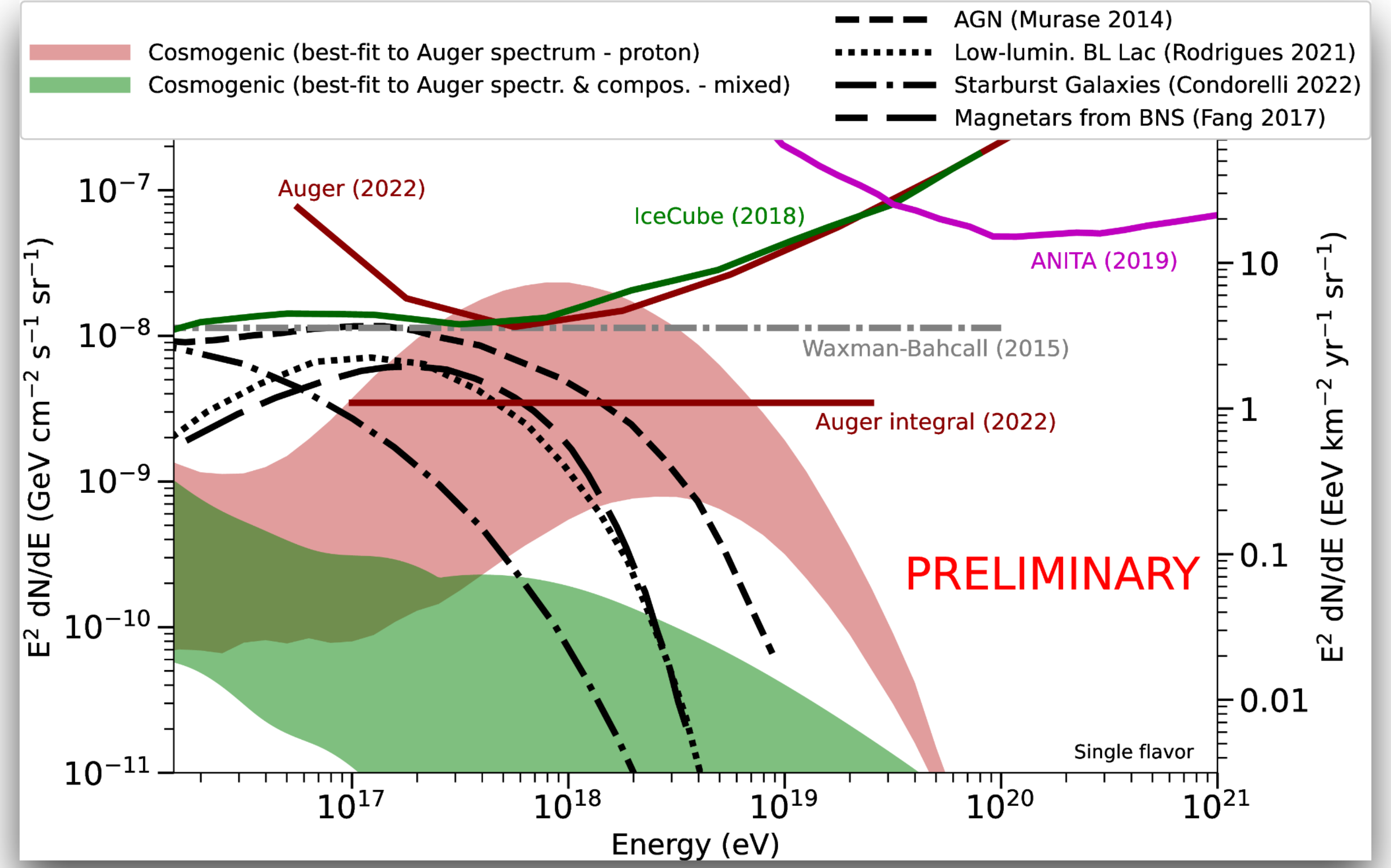
Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

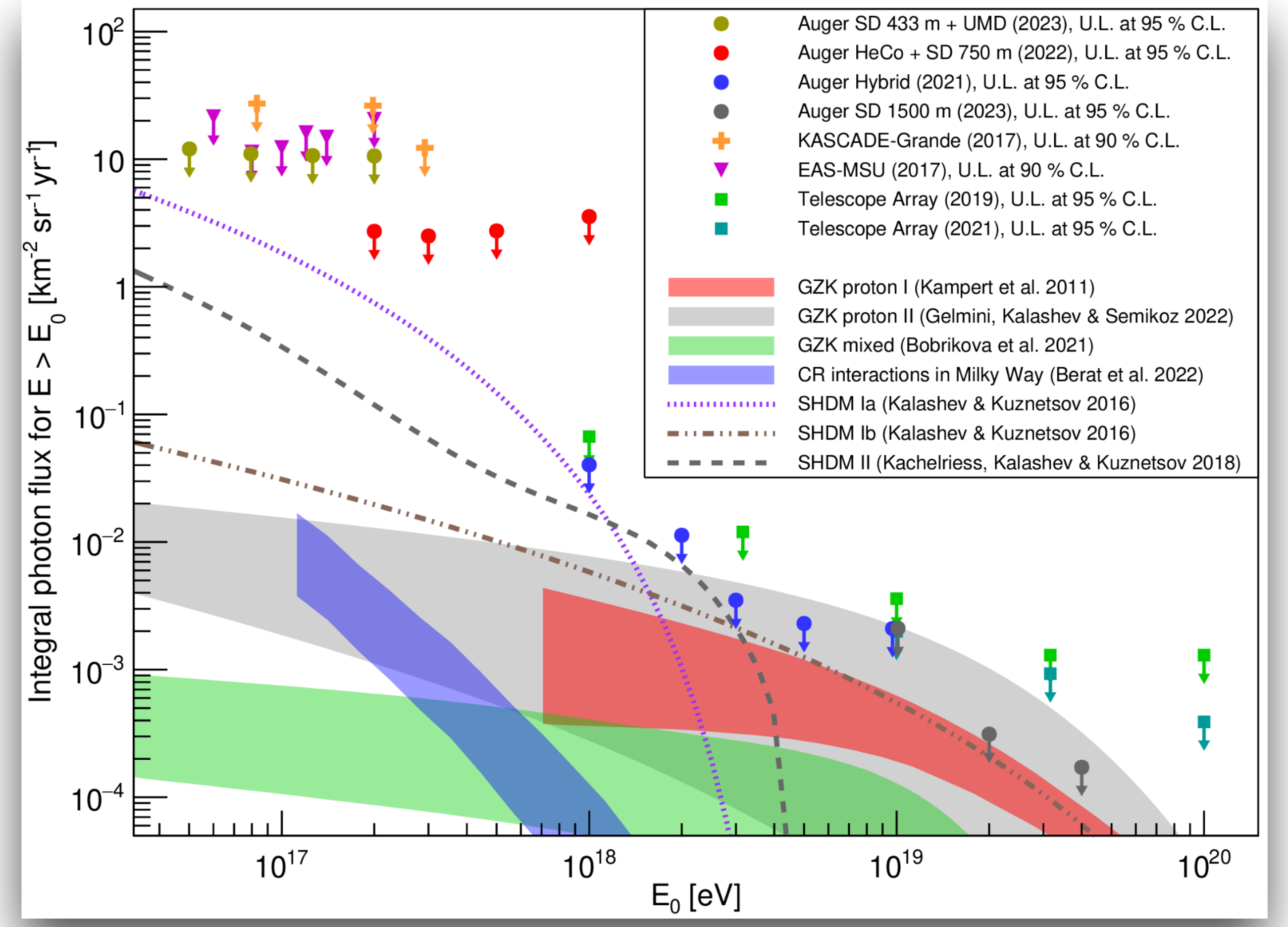
State-of-the-art of the latest UHECR measurements





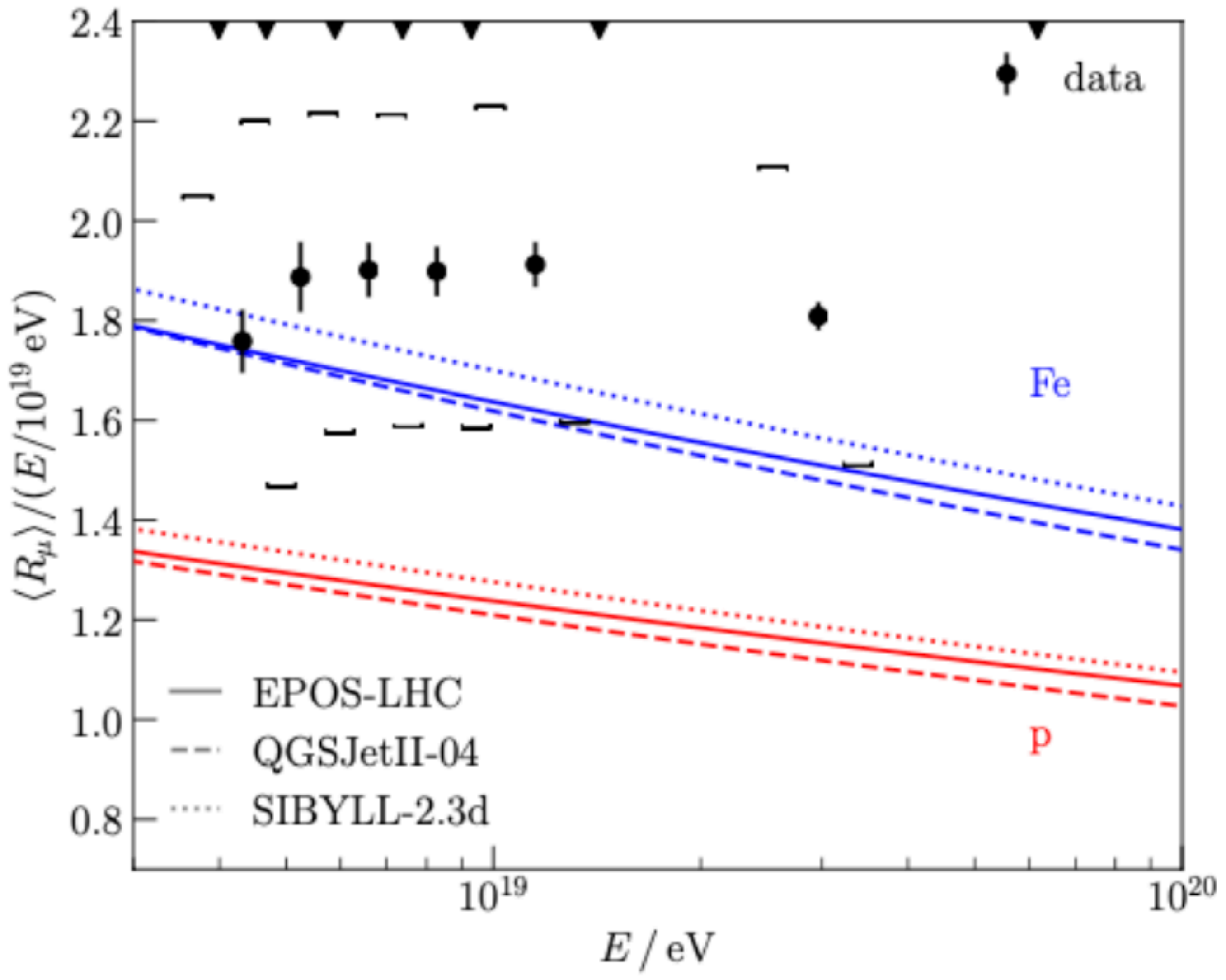
- Features in the energy spectrum
- Changes in mass composition
- Extragalactic origin from anisotropy signal
- Coherent results with non-observation of cosmogenic particles

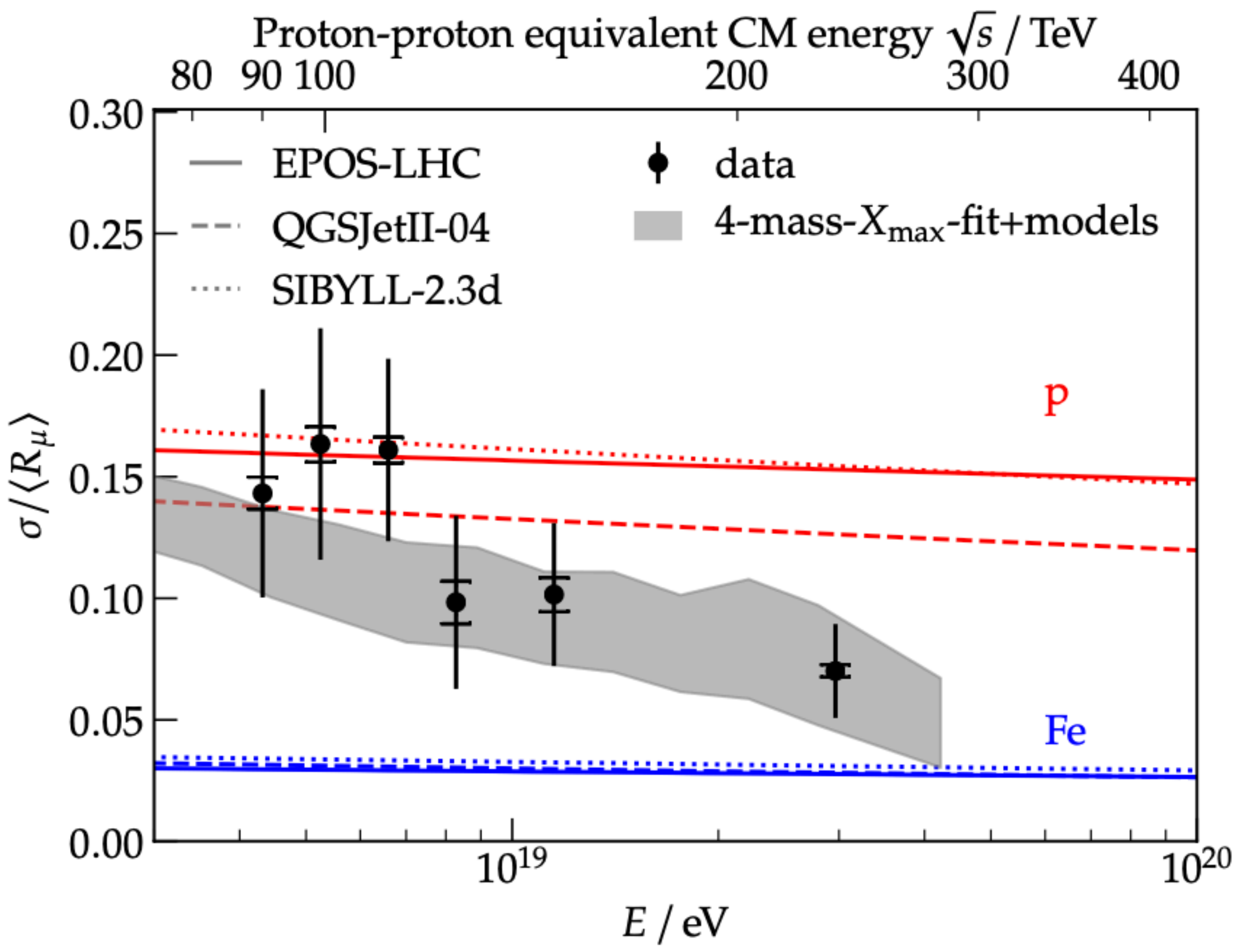




The Pierre Auger Collab. ICRC23

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



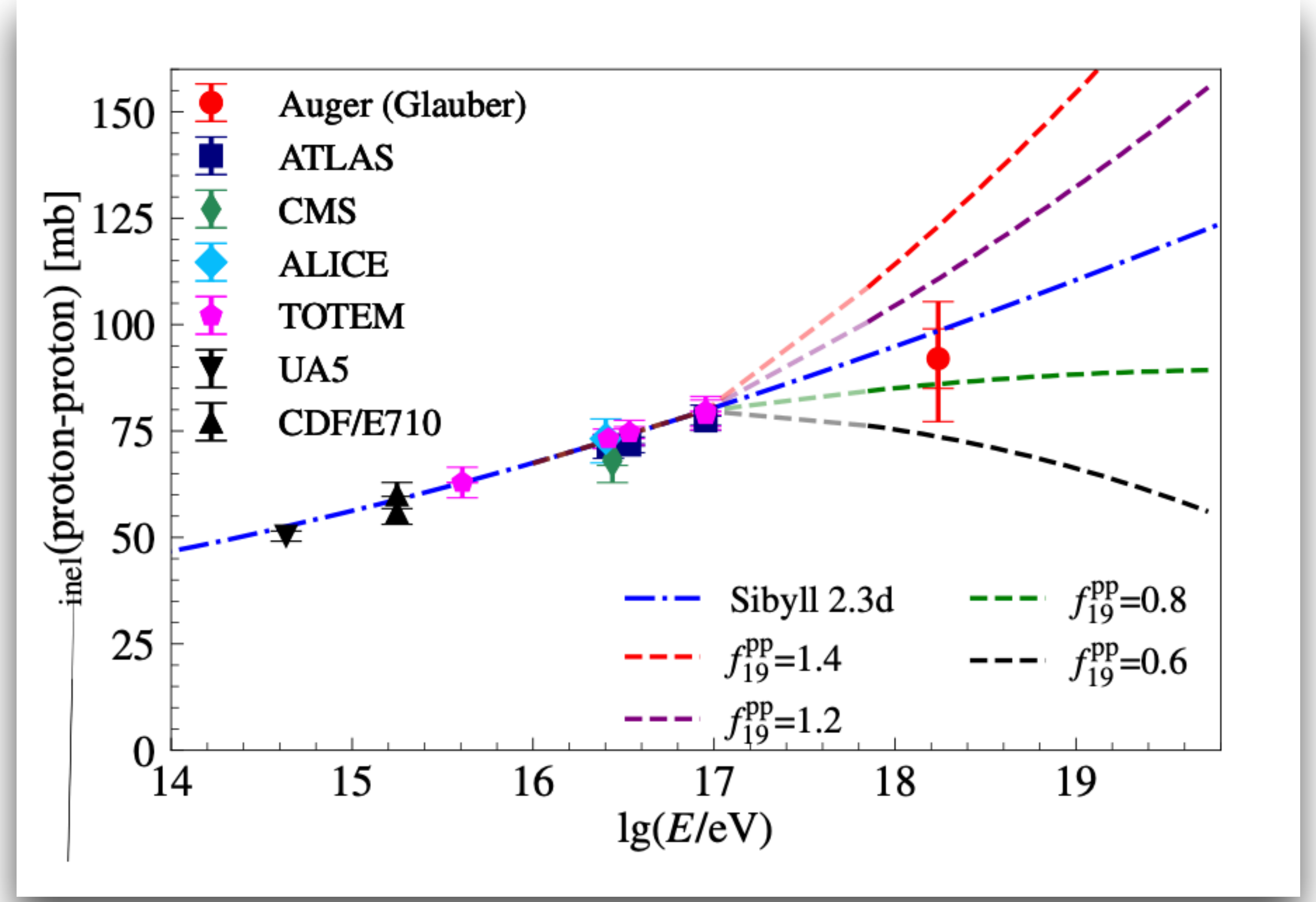


- A **deficit in the number of muons in simulations** with respect to measurements is observed
- The fluctuations of the number of muons are in good agreement with model predictions

Auger Collab. PRL 126 (2021)

- **Measurement of the pp cross section** beyond the energy range accessible to terrestrial accelerators

O. Tkachenko for the Auger Collab. ICRC23



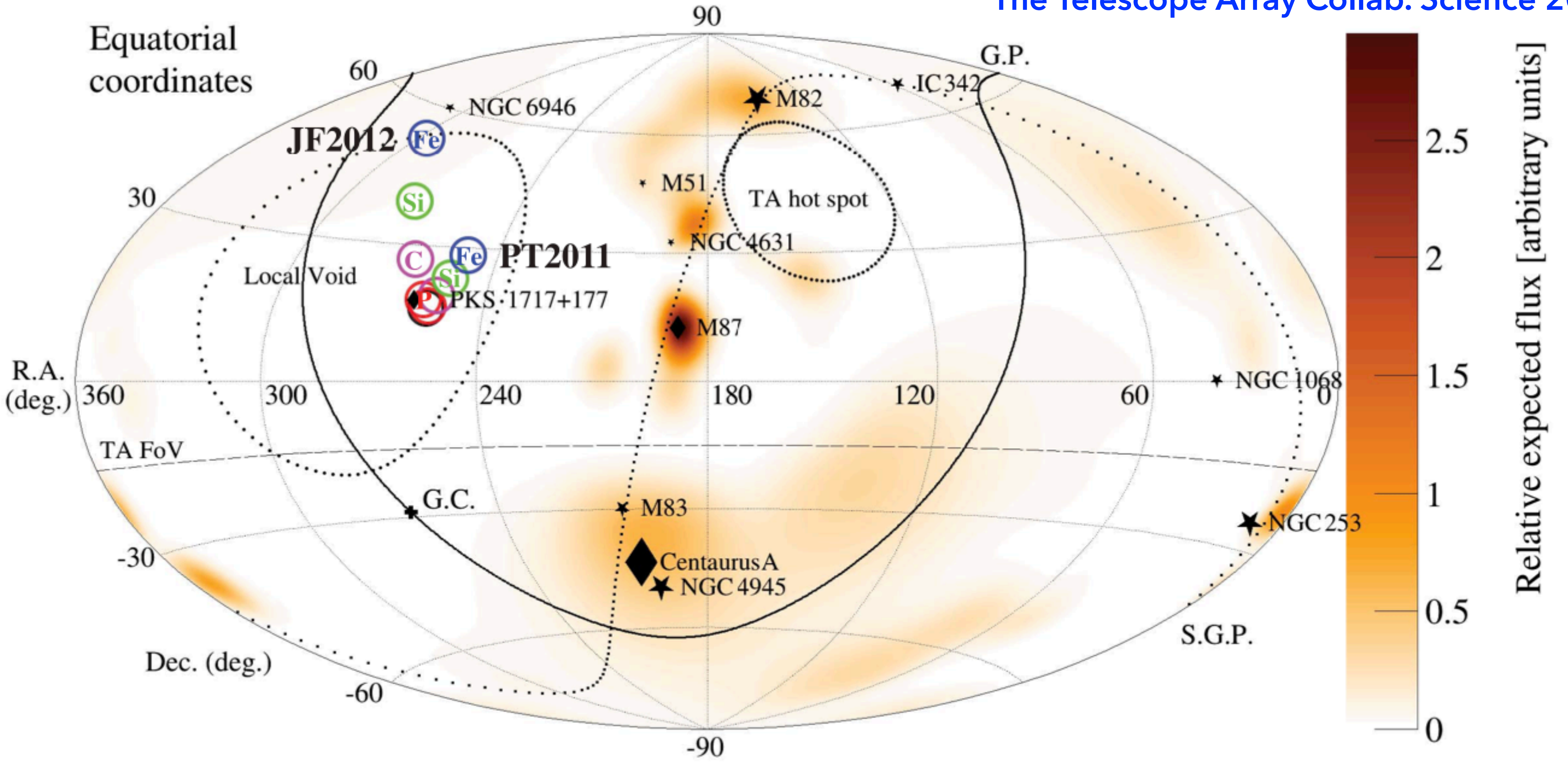
- Tests of non-standard physics
  - From non-observation of cosmogenic particles (LIV, **JCAP 2022**; super-heavy dark matter **PRD 2023, 2024**)
    - From non-observation of upward-going showers, **PRL 2025**
- Geophysics
- **AugerPrime** -> multi-hybrid observation of air showers has started!

D. Schmidt for the Auger Collab. UHECR24

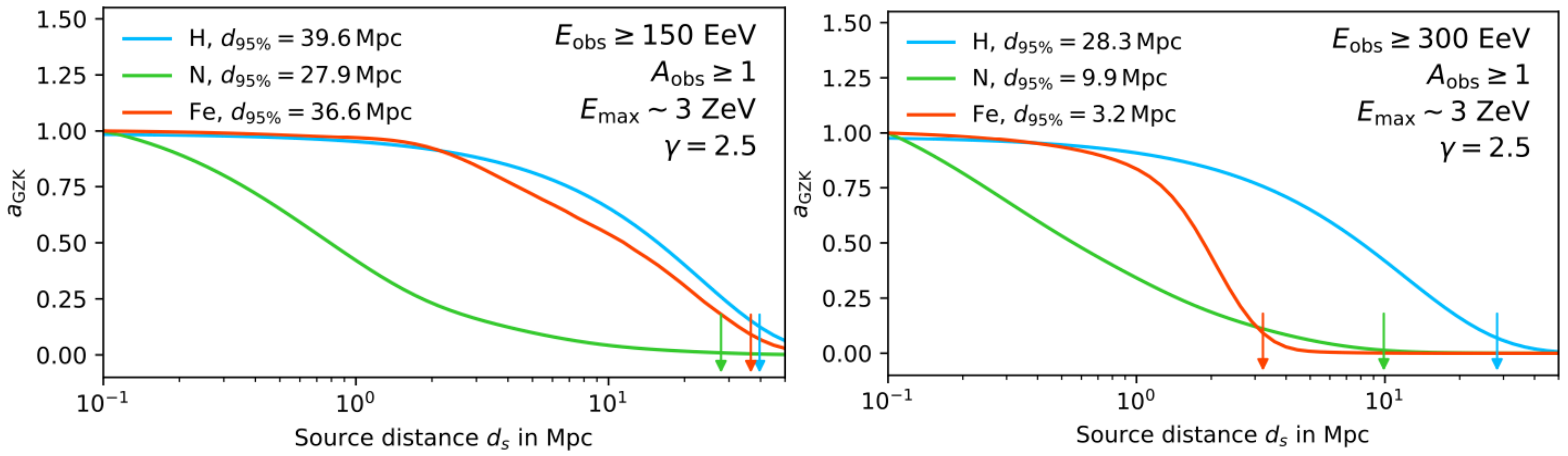
The extremely energetic cosmic ray observed by **Telescope Array**

The Telescope Array Collab. Science 2023

- May 27th, 2021, estimated energy: 244 EeV
- Back-tracked directions assuming two models of the Milky Way regular magnetic field, for <u>four primaries</u>
- The closest object to the proton backtracked direction in gamma rays is the active galaxy PKS 1717+177
  - Distance of 600 Mpc -> too large!



Globus et al, ApJ 2023



- Maximum source distance for this energy: 8-50 Mpc (the range reflects the <u>uncertainty in the energy assignment</u>); see Unger & Farrar ApJL 2023
  - Radio galaxies satisfying the luminosity criteria are not present in the localisation volume; no starburst galaxies within the source direction
  - Transient event in an otherwise undistinguished galaxy?

From sources to detection - the life of an astroparticle

- Source:
    - Acceleration, interactions, escape
- Extragalactic propagation
    - Interactions, magnetic fields
- Galactic propagation
    - Magnetic fields
- Atmosphere
- Earth

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Discussed in this talk

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Manifestations of LIV

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

- Threshold effects
- Cross section effects

- **Typical interaction rate** $$t^{-1} = cn\sigma$$

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- When the target density and cross section do not depend on energy
  - Atmosphere, Earth

$$t^{-1} = \frac{c}{2\Gamma^2} \int_{\varepsilon'_{\mathrm{th}}}^{\infty} \sigma(\varepsilon')\varepsilon' \int_{\varepsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\varepsilon)}{\varepsilon^2} d\varepsilon d\varepsilon'$$

- When the target density and cross section depend on energy
  - Extragalactic space

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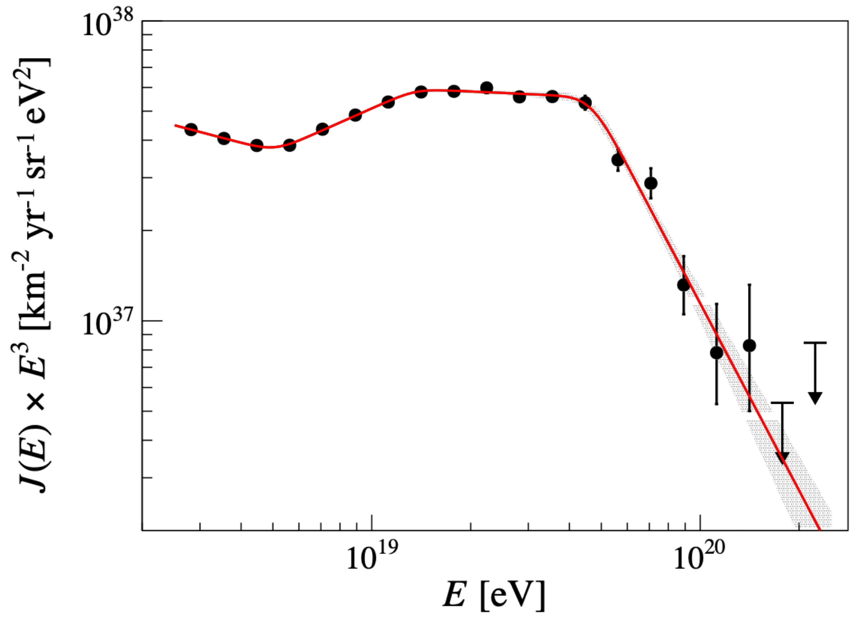
- **If LIV rate is smaller than LI one -> larger flux of particles expected**
  - Example: modified threshold for photopion production and observation of UHECR flux suppression
    - Aloisio, Biasi, Ghia & Grillo, PRD2000; Scully & Stecker, Astropart.Phys. 2009; DB et al ICRC2015; DB for the Auger Collab. ICRC2017; The Auger Collab. JCAP 2022



- **Problem: in terms of interpretation, the suppression of the spectrum at the highest energies cannot be attributed to propagation effects only -> indications of lack of source power (see The Auger Collab. JCAP 2023)**
- LIV effects are more difficult to be investigated in extragalactic propagation of UHECRs than what expected

Manifestations of LIV

- Modified dispersion relation

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

- Threshold effects
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- **Typical interaction rate**

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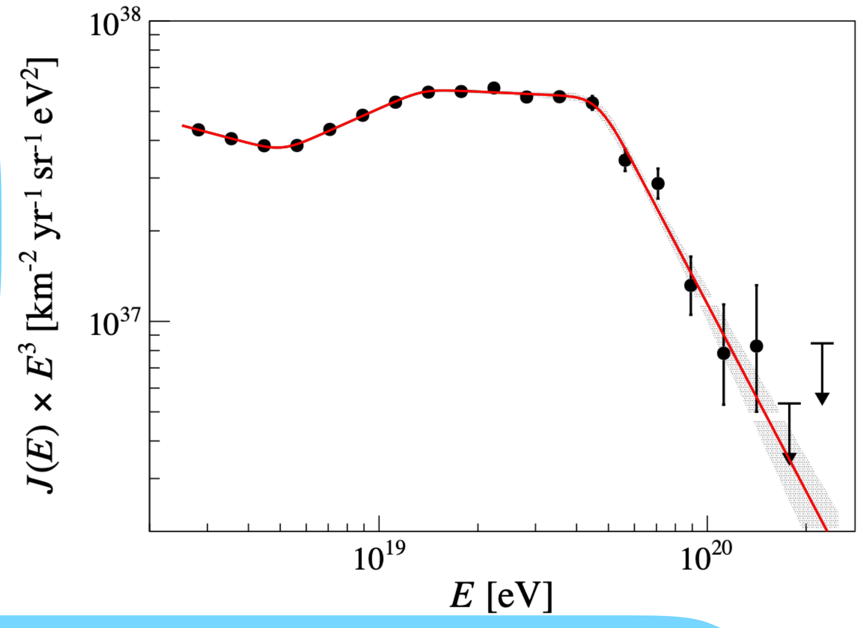
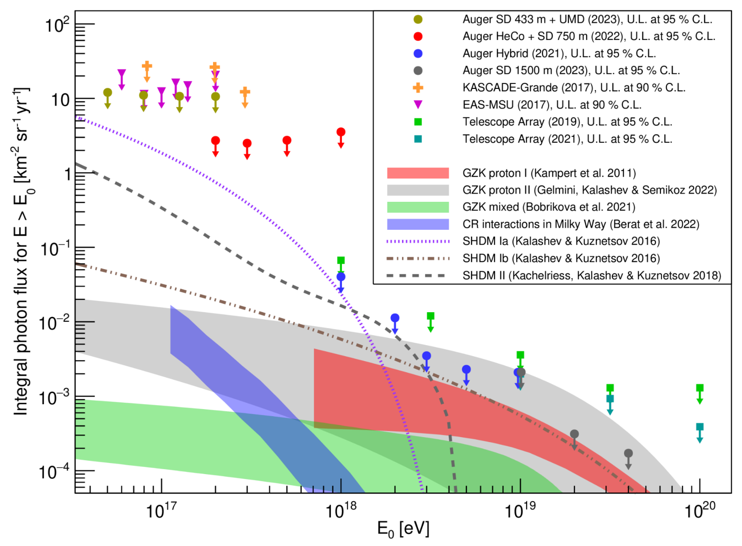




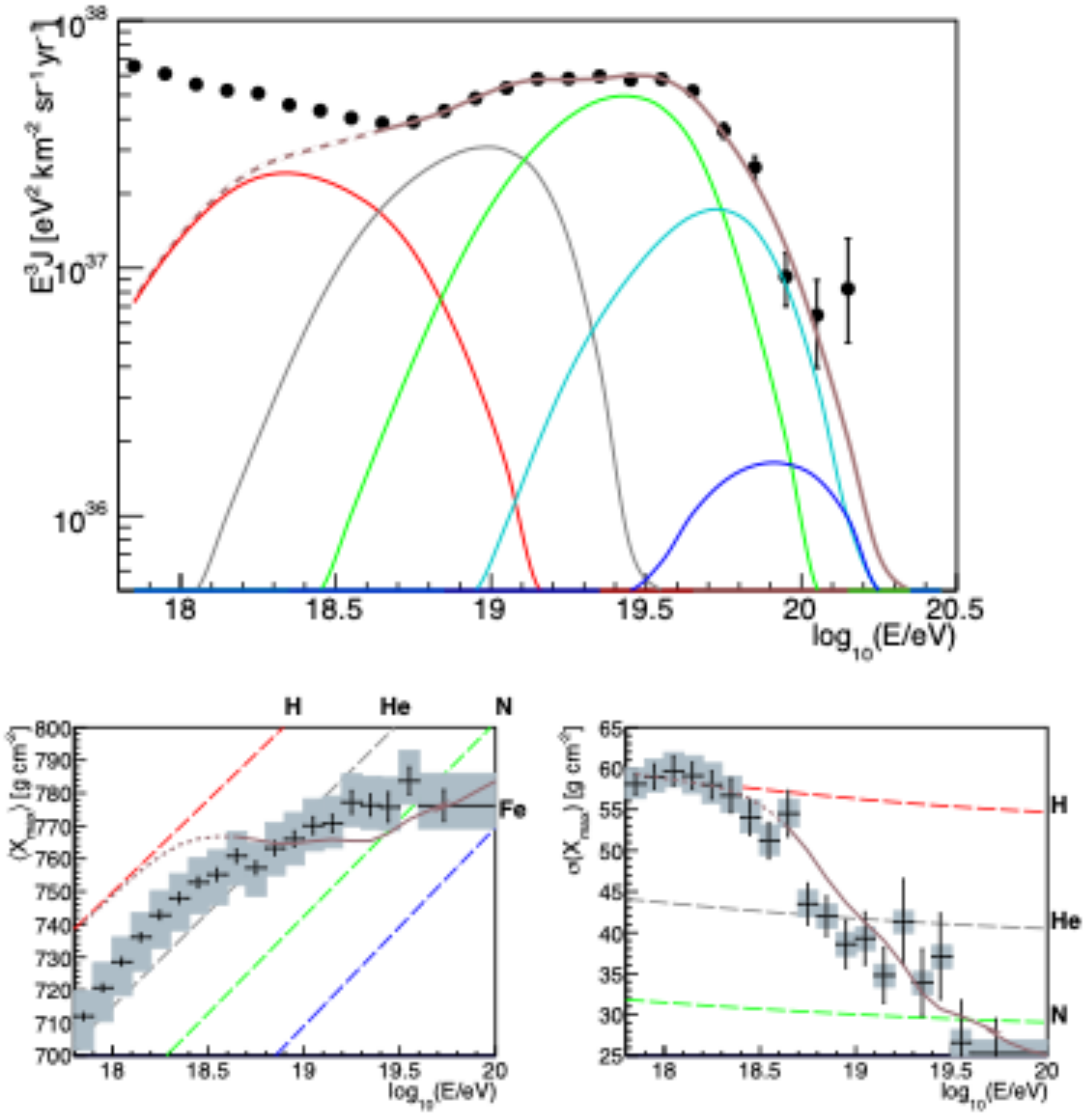
- **What if the probability of interaction also influences the detection stage?**
    - Example: cascade of photons in the extragalactic space and in the Earth atmosphere

LIV IN THE PROPAGATION STAGE

Expected CR spectrum and composition

The Auger Collab, JCAP 2022

LI scenario

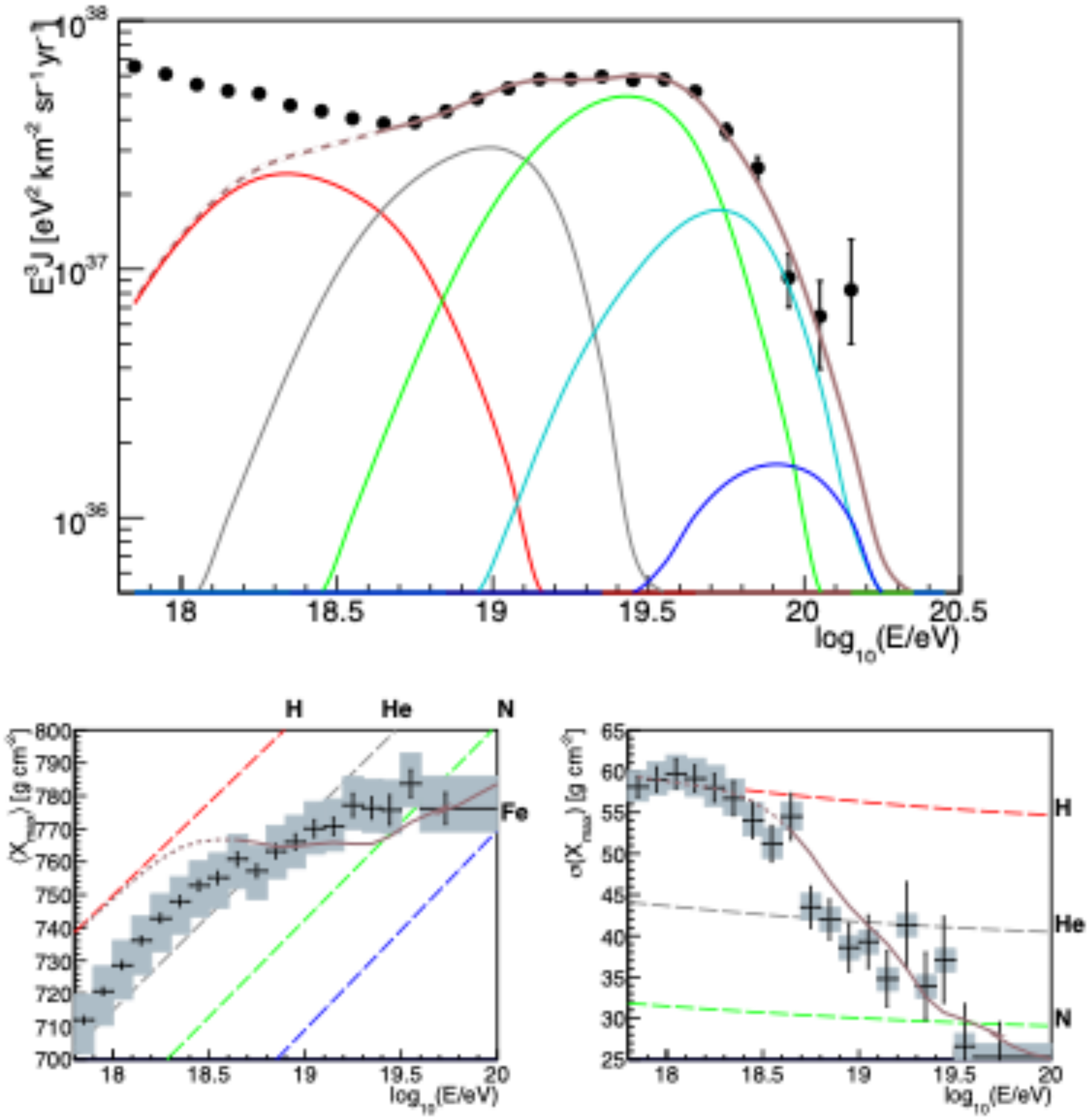


- For simplicity, we consider only the energy range above the ankle
- LIV modifications in the energy threshold of photopion and photo-disintegration happening during the extragalactic propagation
- <u>Warning</u>: the spectrum is mostly limited by source effects, so effect on propagation are less important than expected

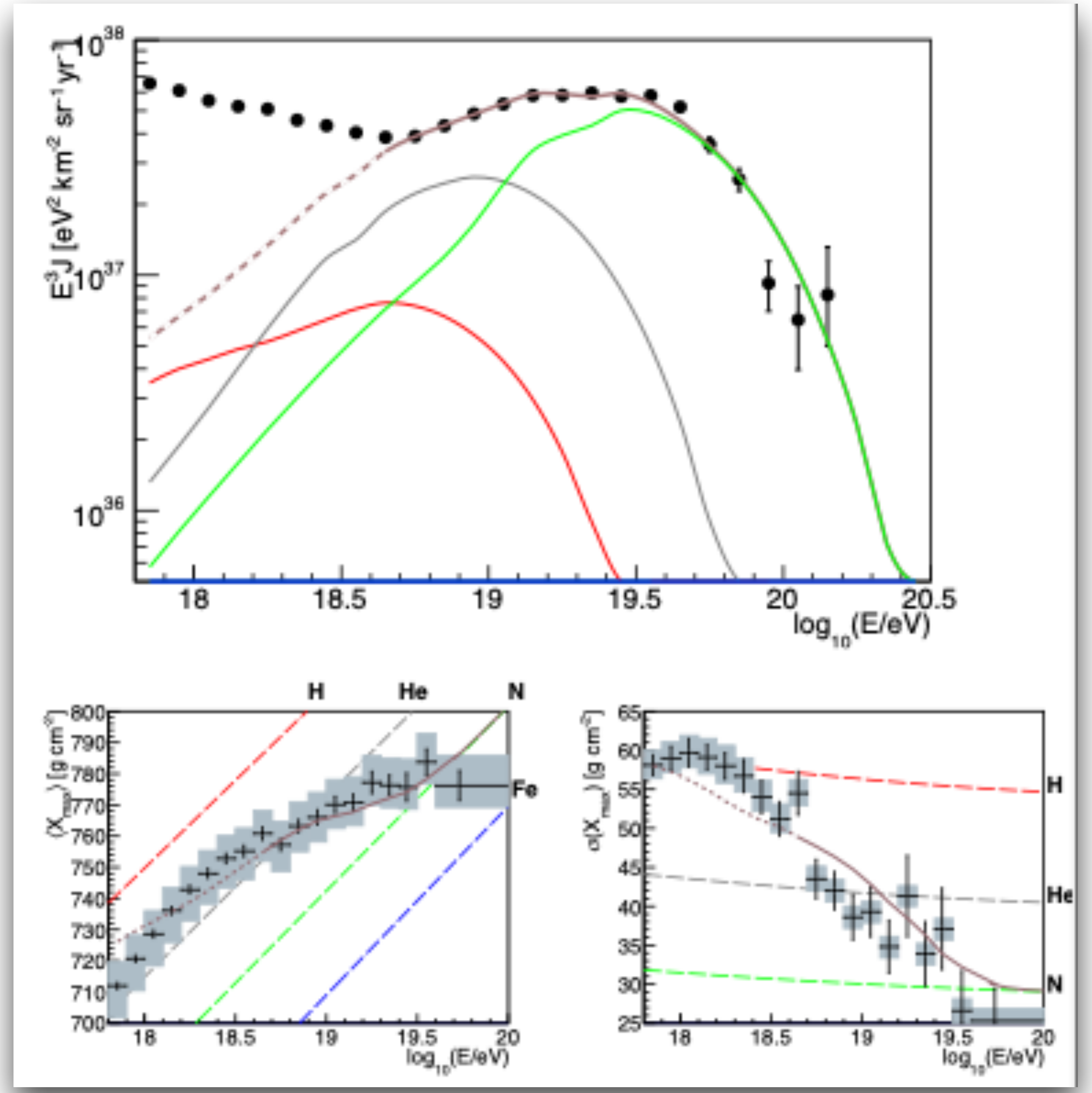
Expected CR spectrum and composition

The Auger Collab, JCAP 2022

LI scenario



LIV scenario



Effect on CR propagation:

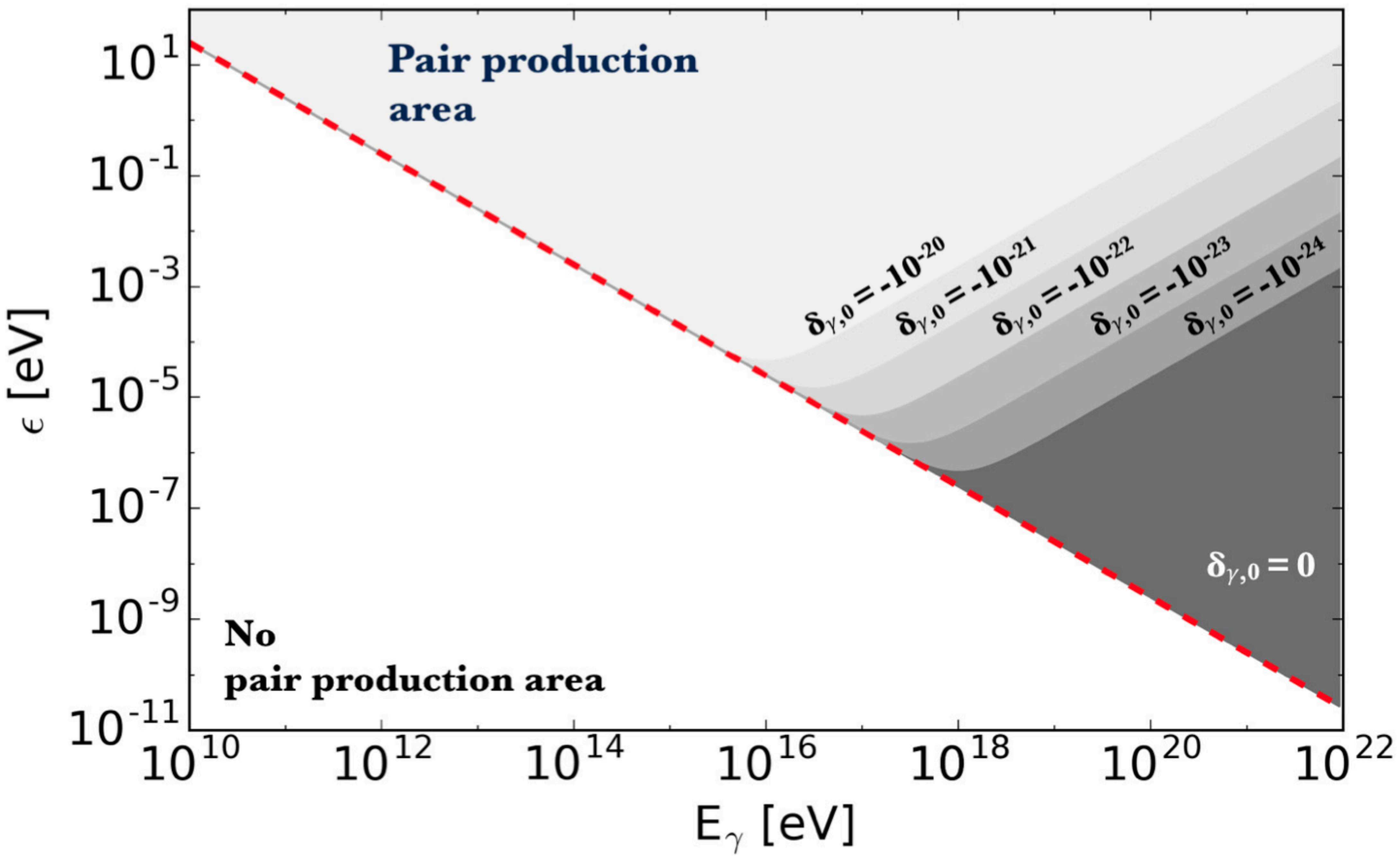
- Threshold energy increases -> less interactions -> if LIV, lighter nuclear species are needed at the sources in order to reproduce the observed composition

Modified photon propagation

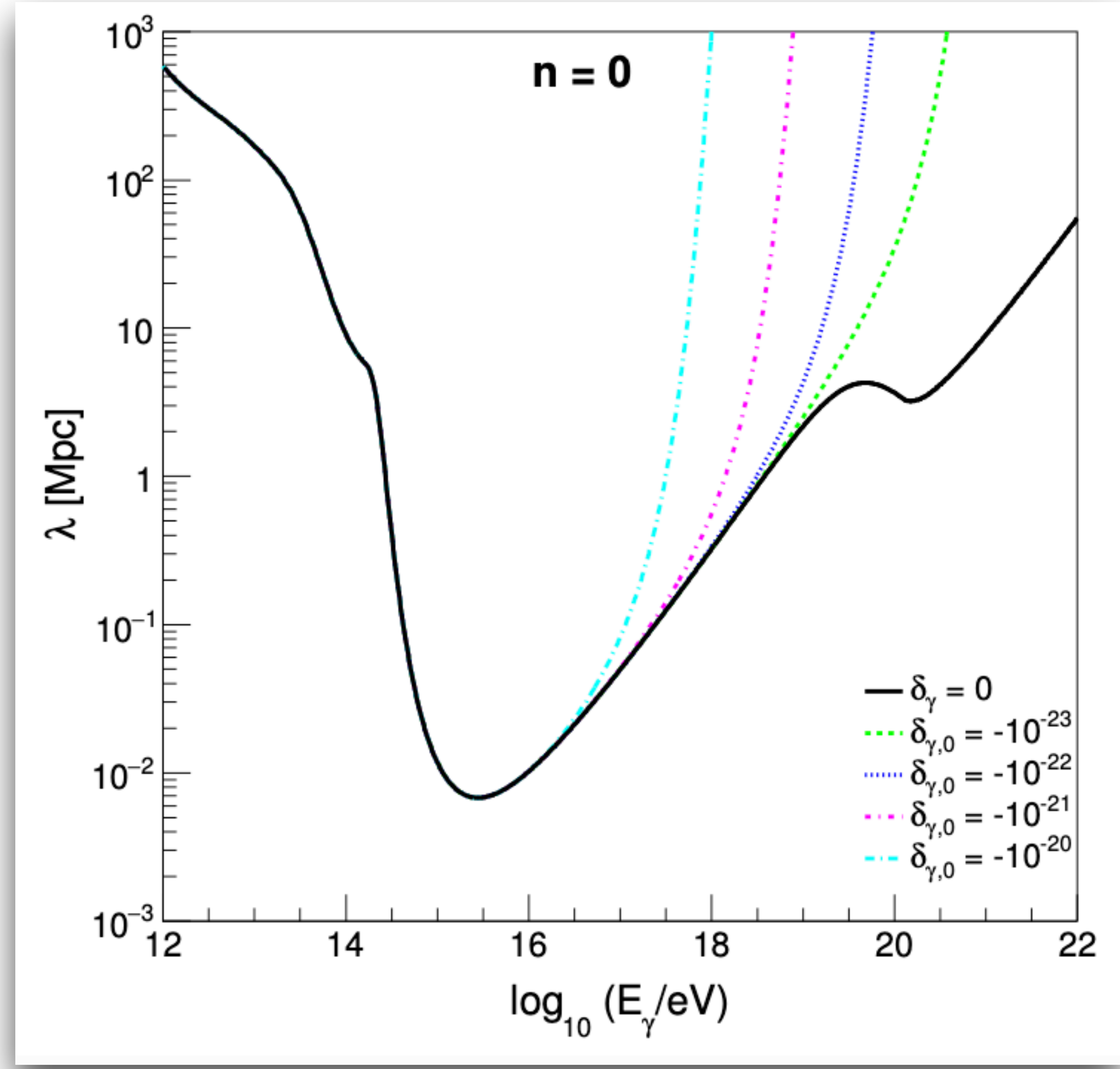
$$\gamma + \gamma_{\rm bkg} \to e^+ + e^-$$

$$E_i^2 - p_i^2 = m_i^2 + \sum \delta_{i,n} E_i^{2+n}$$

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



Lang, Martinez-Huerta & de Souza, ApJ 2018



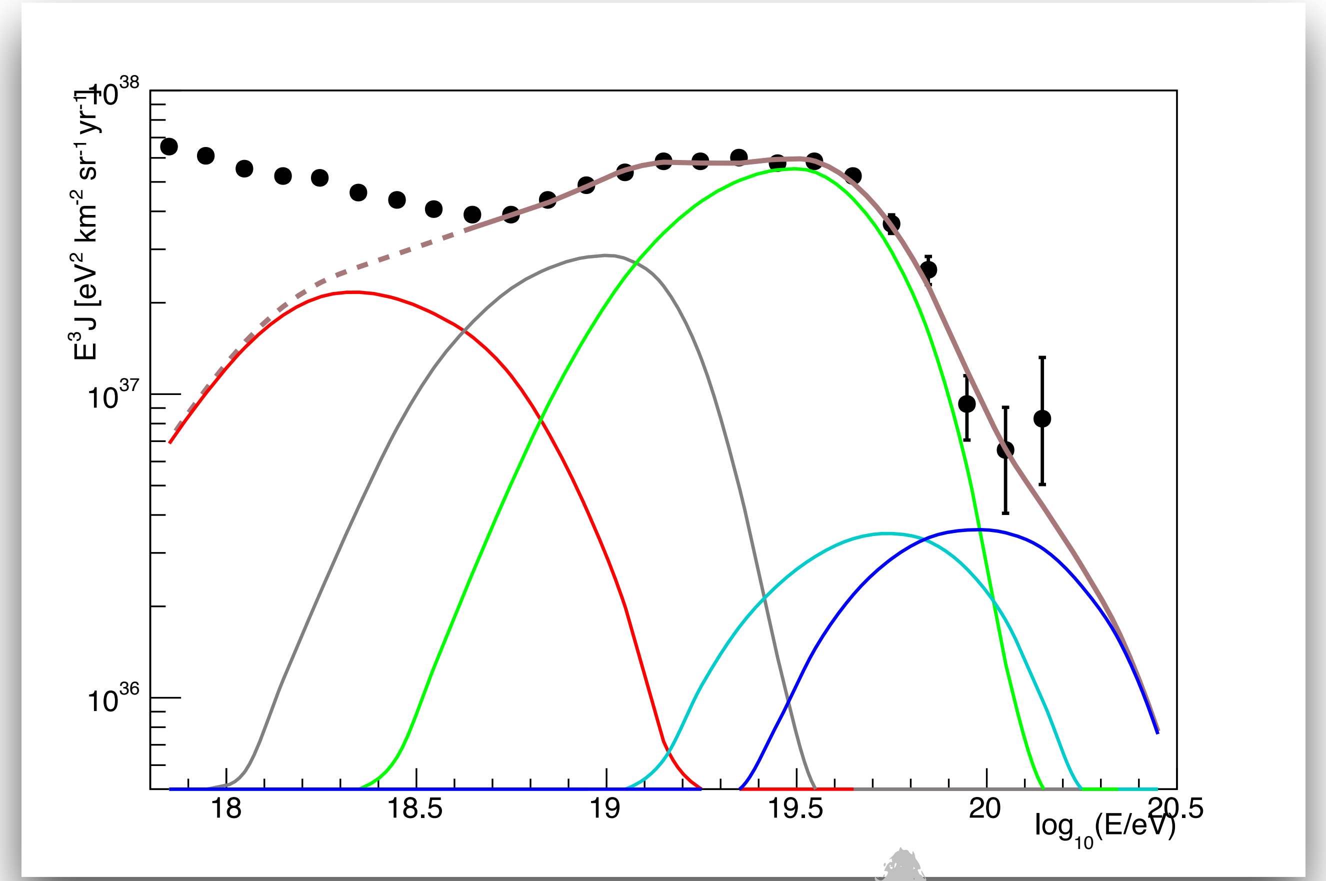
- Modifications of propagation: CRPropa/Eleca code
- More refined study in J.M. Carmona et al. PRD 2024

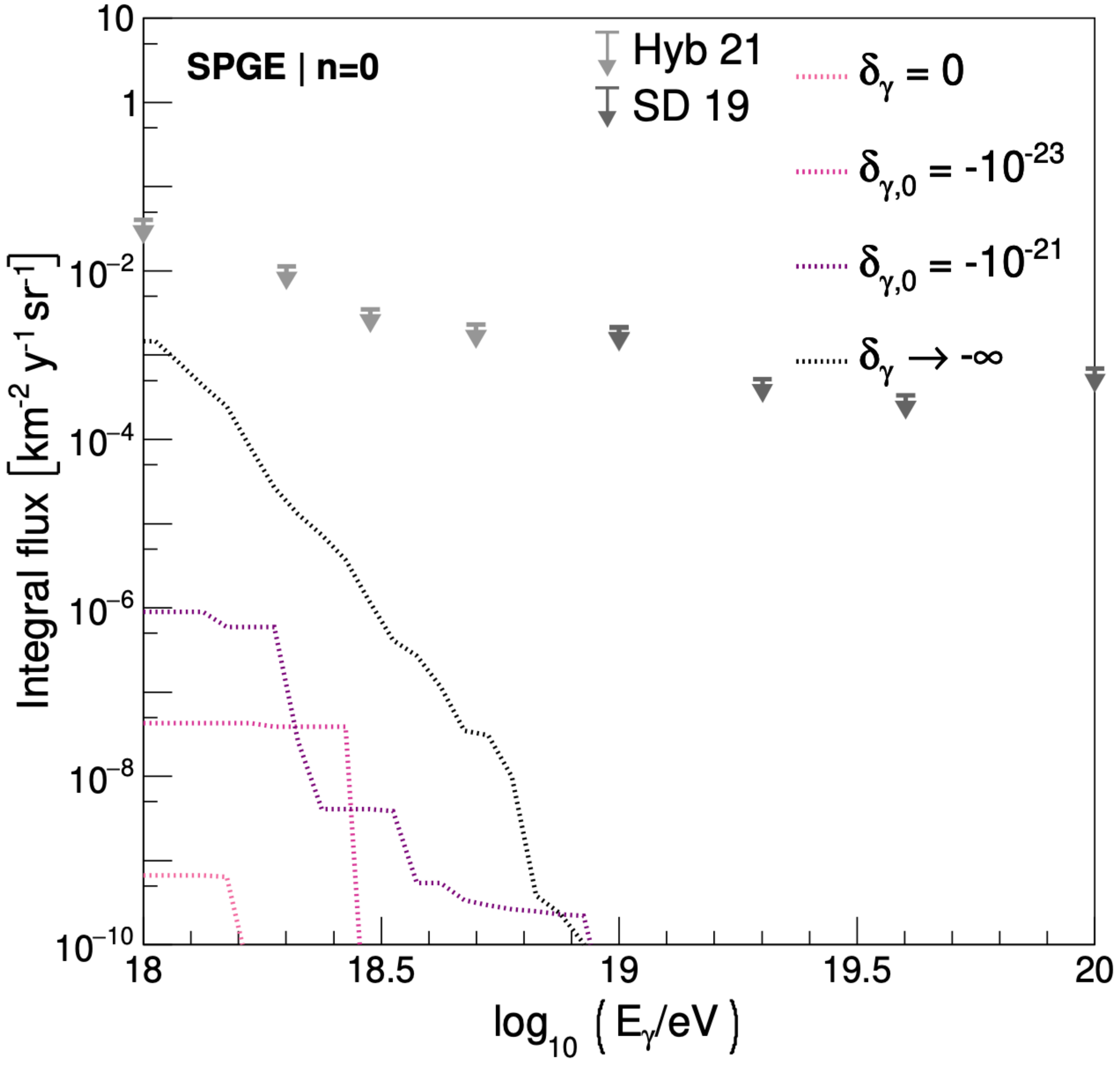
Effect on photon propagation:

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

Expected UHE photon flux

The Auger Collab, JCAP 2022



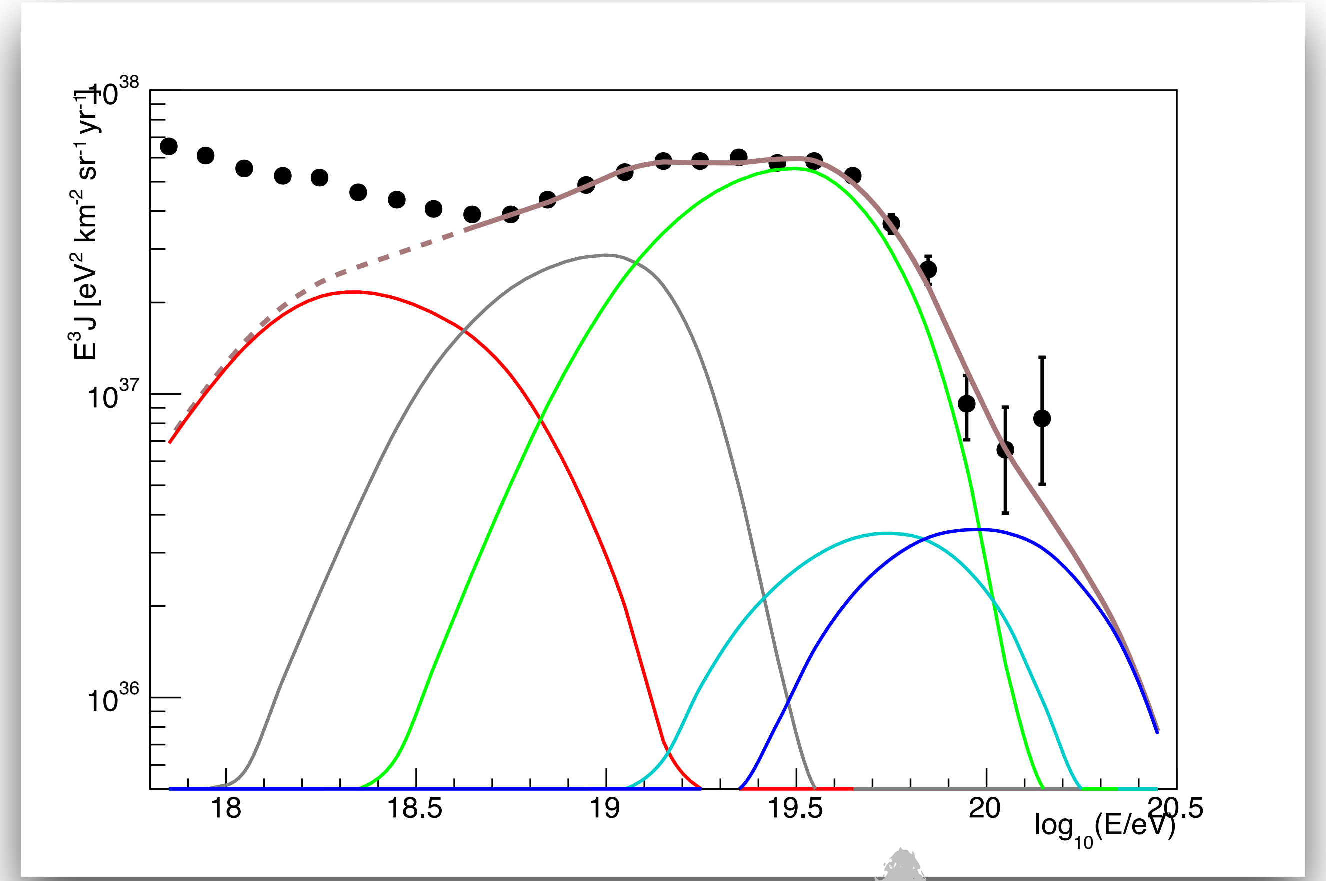


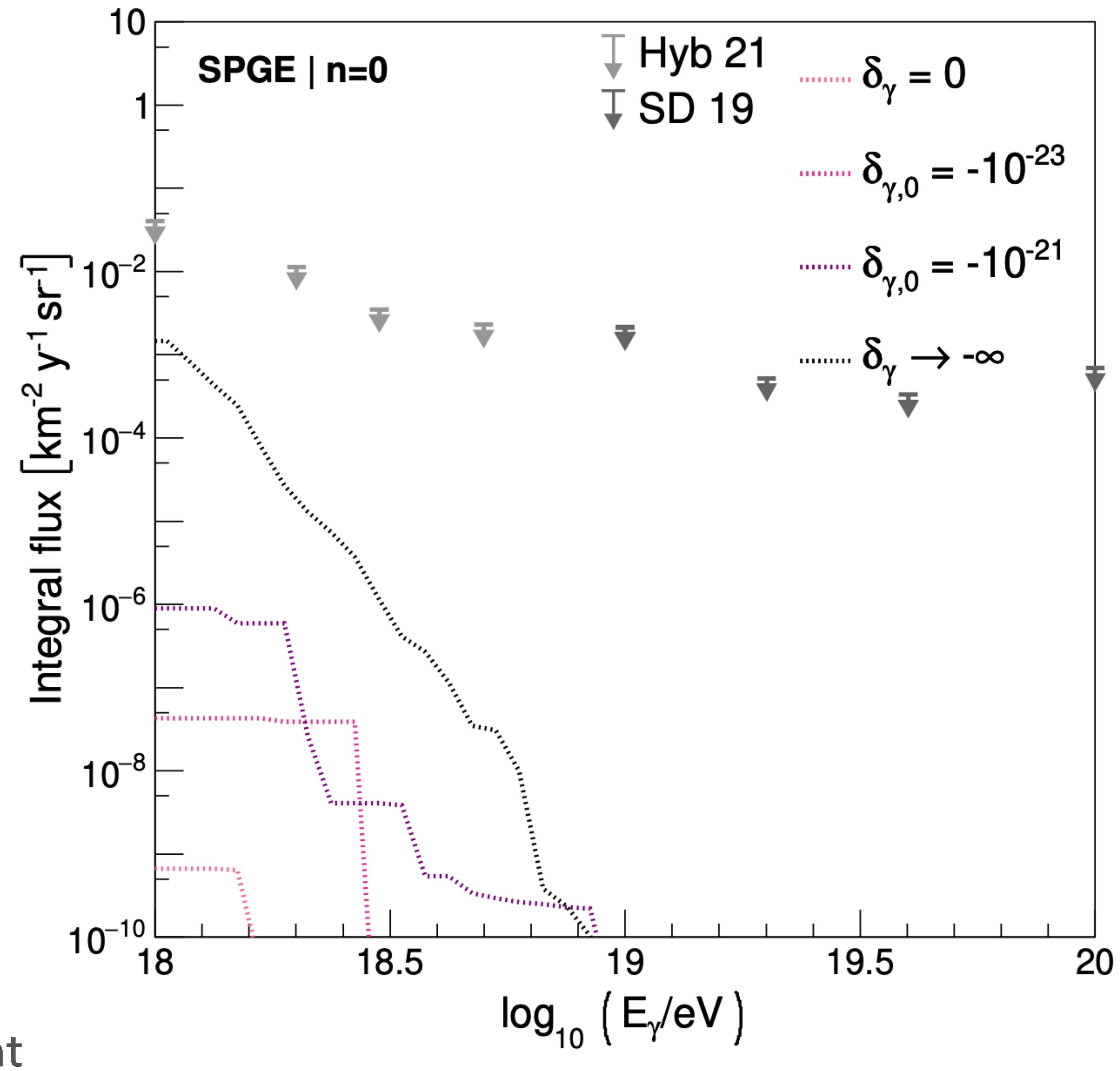
- **Photons** produced in extragalactic propagation by UHECRs;

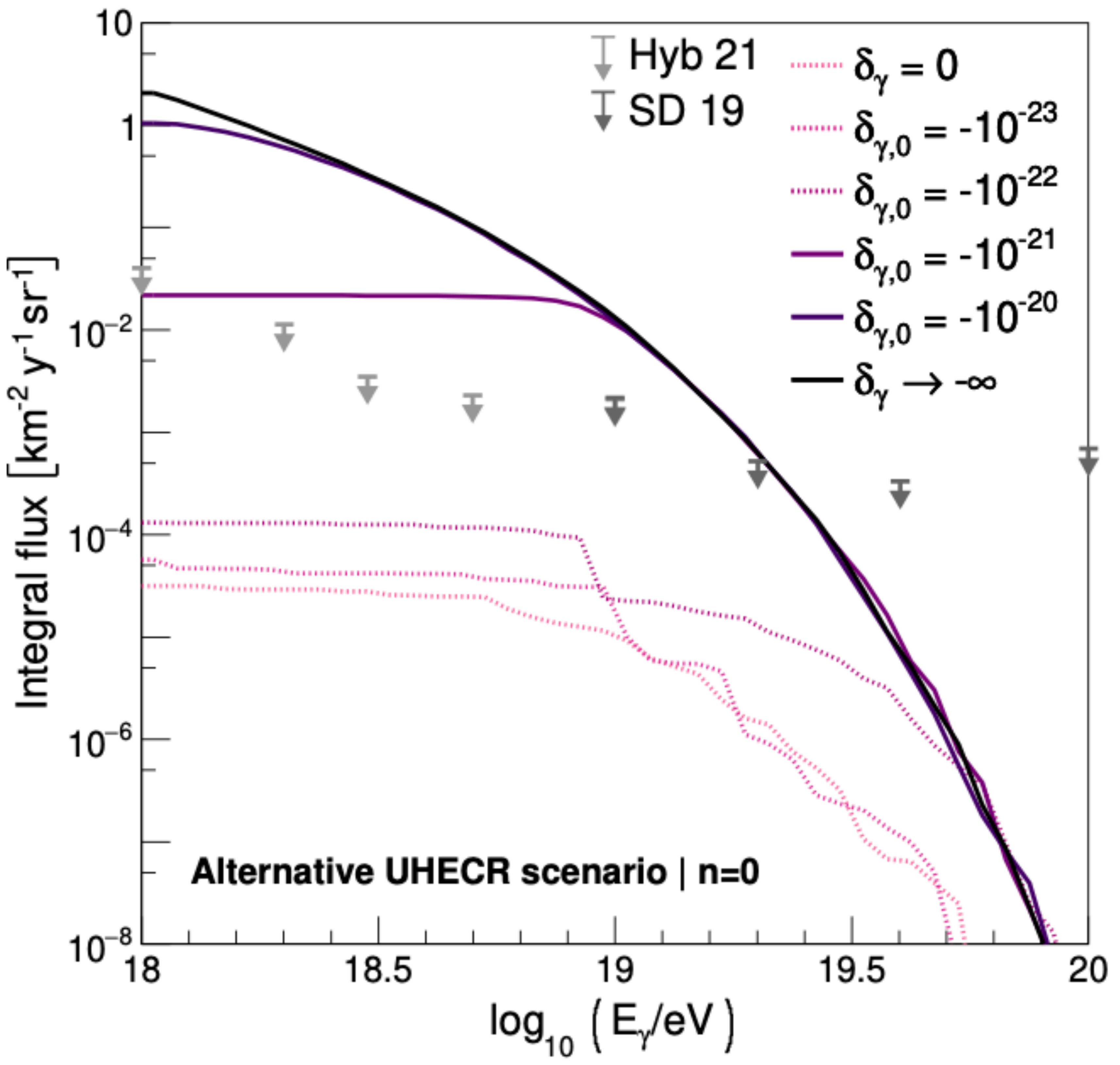
- Warning: photon production is connected to UHECR mass composition

Expected UHE photon flux

The Auger Collab, JCAP 2022







- **Photons** produced in extragalactic propagation by UHECRs;
  - **additional proton component** (compatible with mass composition data) is accounted for at high energy!

$\delta^{(0)} > -10^{-21}$ $\quad \delta^{(1)} > -10^{-40}\,\mathrm{eV}^{-1}$ $\quad \delta^{(2)} > -10^{-58}\,\mathrm{eV}^{-2}$

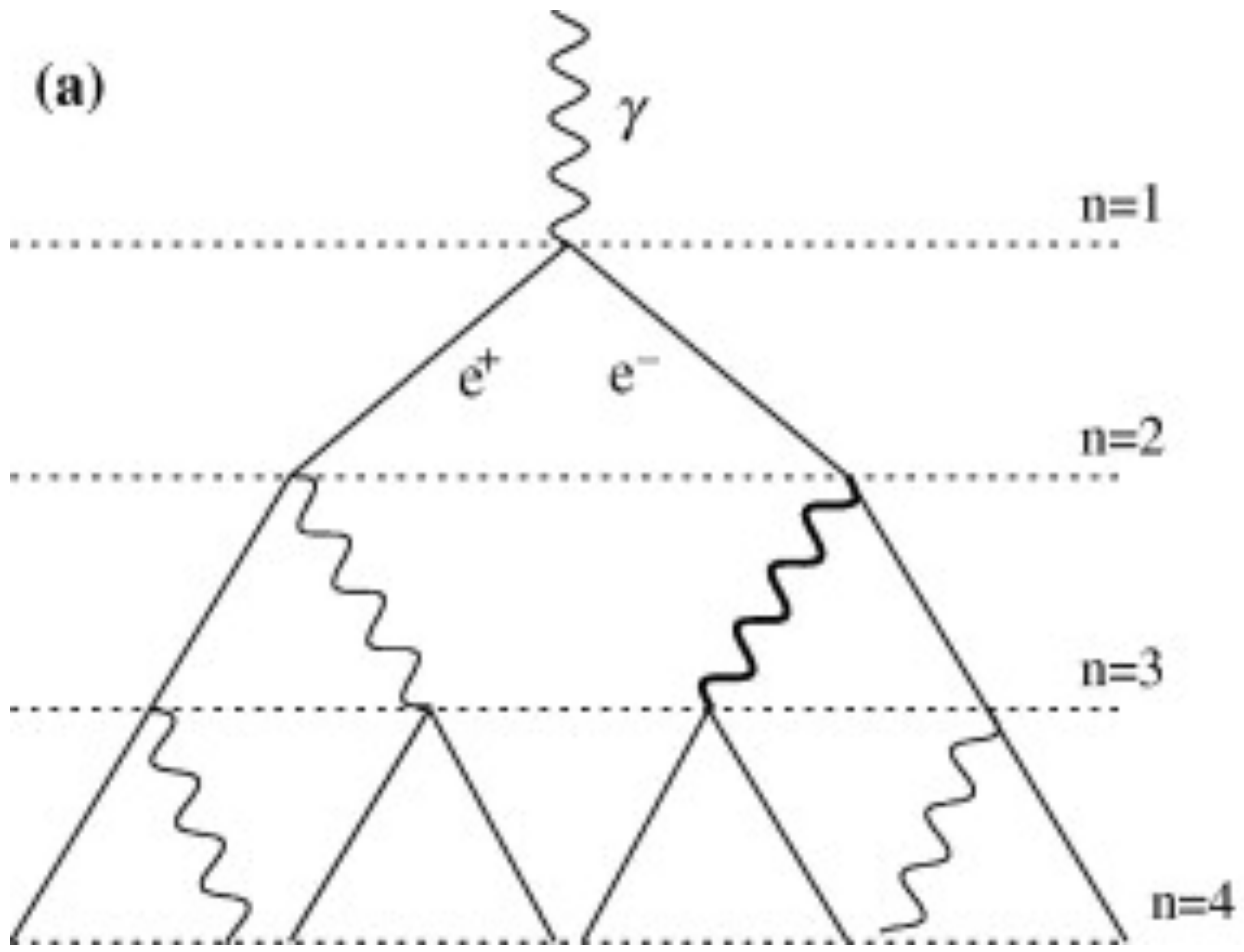
- Warning: photon production is connected to UHECR mass composition

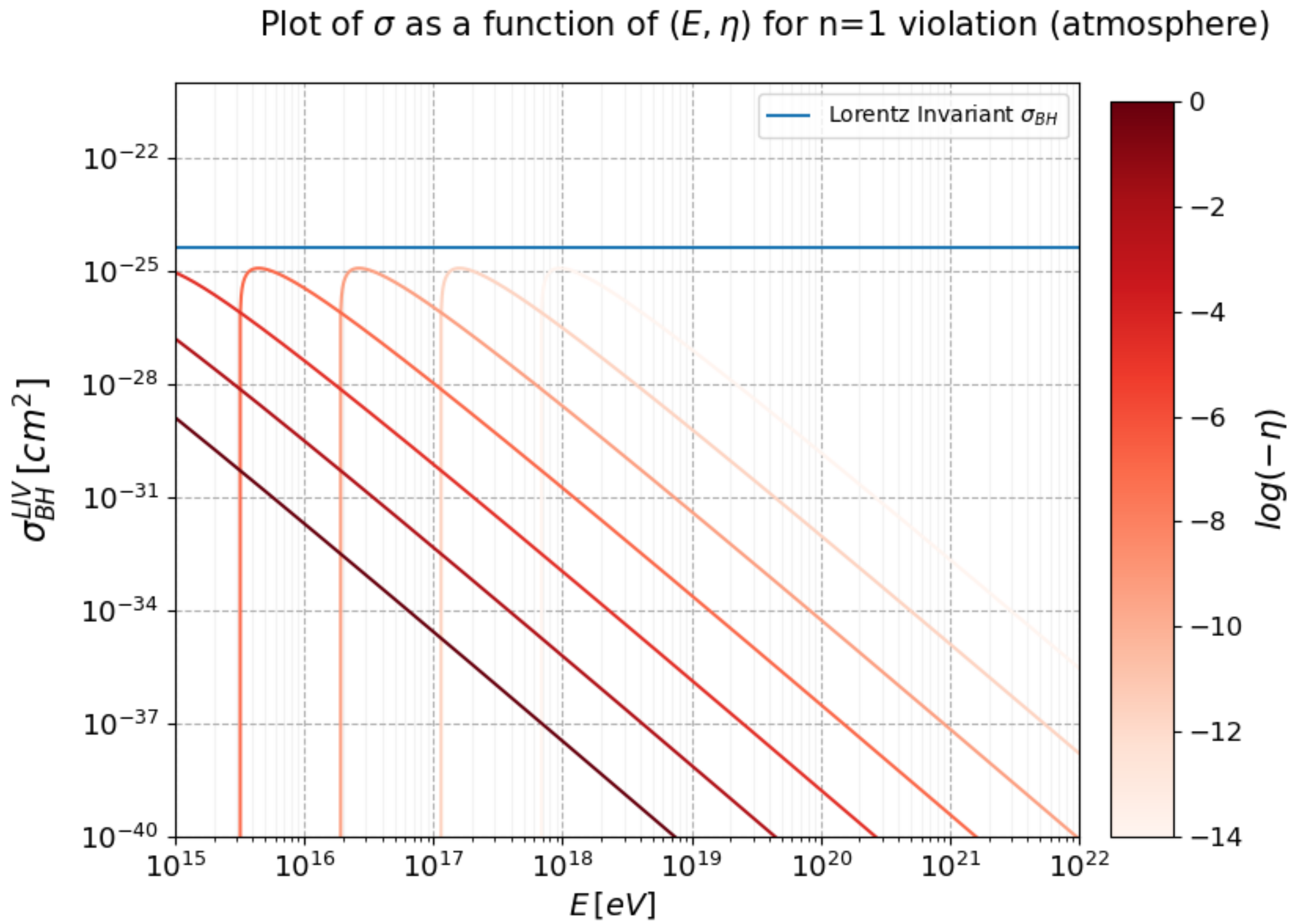
LIV IN THE DETECTION STAGE

LIV IN THE DETECTION STAGE:
FOCUS ON ELECTROMAGNETIC COMPONENT OF THE SHOWER

Cascade of particles initiated by photons in the atmosphere

Morais, DB, Salamida, Lobo & Bezerra, UHECR24
M. Giammarco





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

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

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

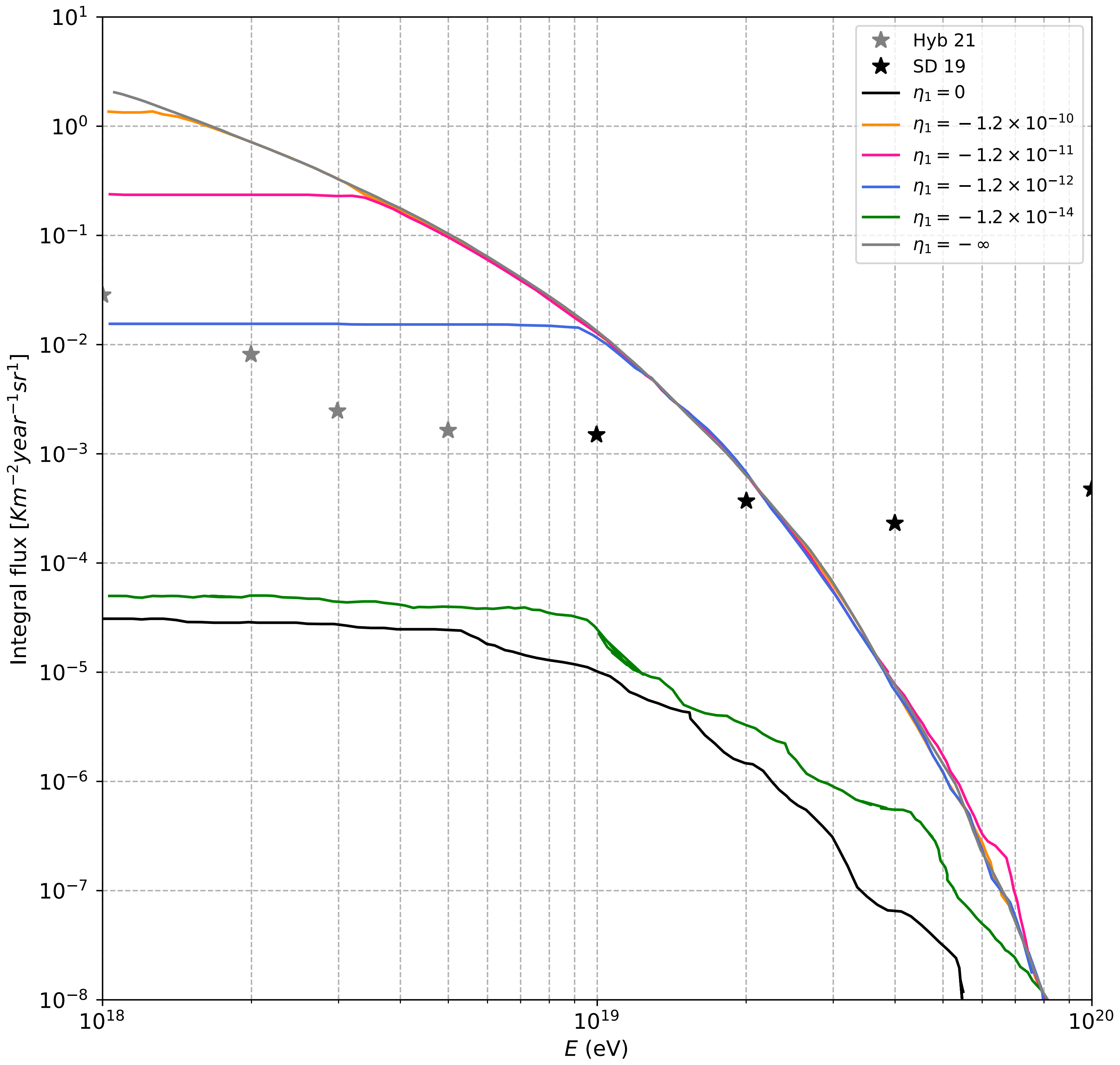
$$\sigma_{BH} = \frac{28Z^2\alpha^3}{9m_e^2}\left(\log\frac{183}{Z^{\frac{1}{3}}} - \frac{1}{42}\right) \qquad \sigma_{BH}^{LIV} = \frac{8Z^2\alpha^3}{3\,|m_{\gamma,\rm eff}^2|}\log\frac{1}{\alpha Z^{\frac{1}{3}}}\log\frac{|m_{\gamma,\rm eff}^2|}{m_e^2}$$

- 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

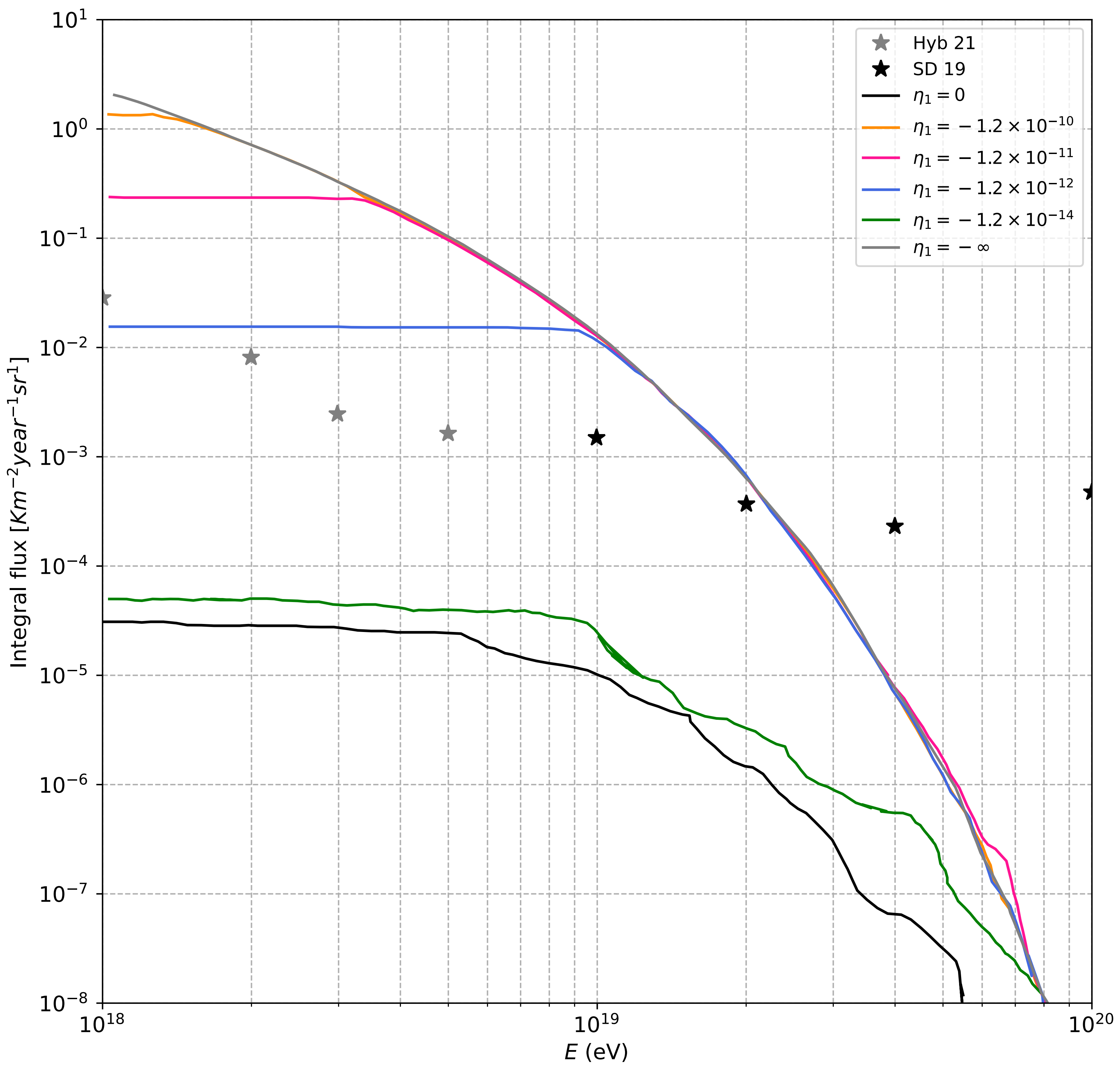
Effect of LIV in extragalactic propagation

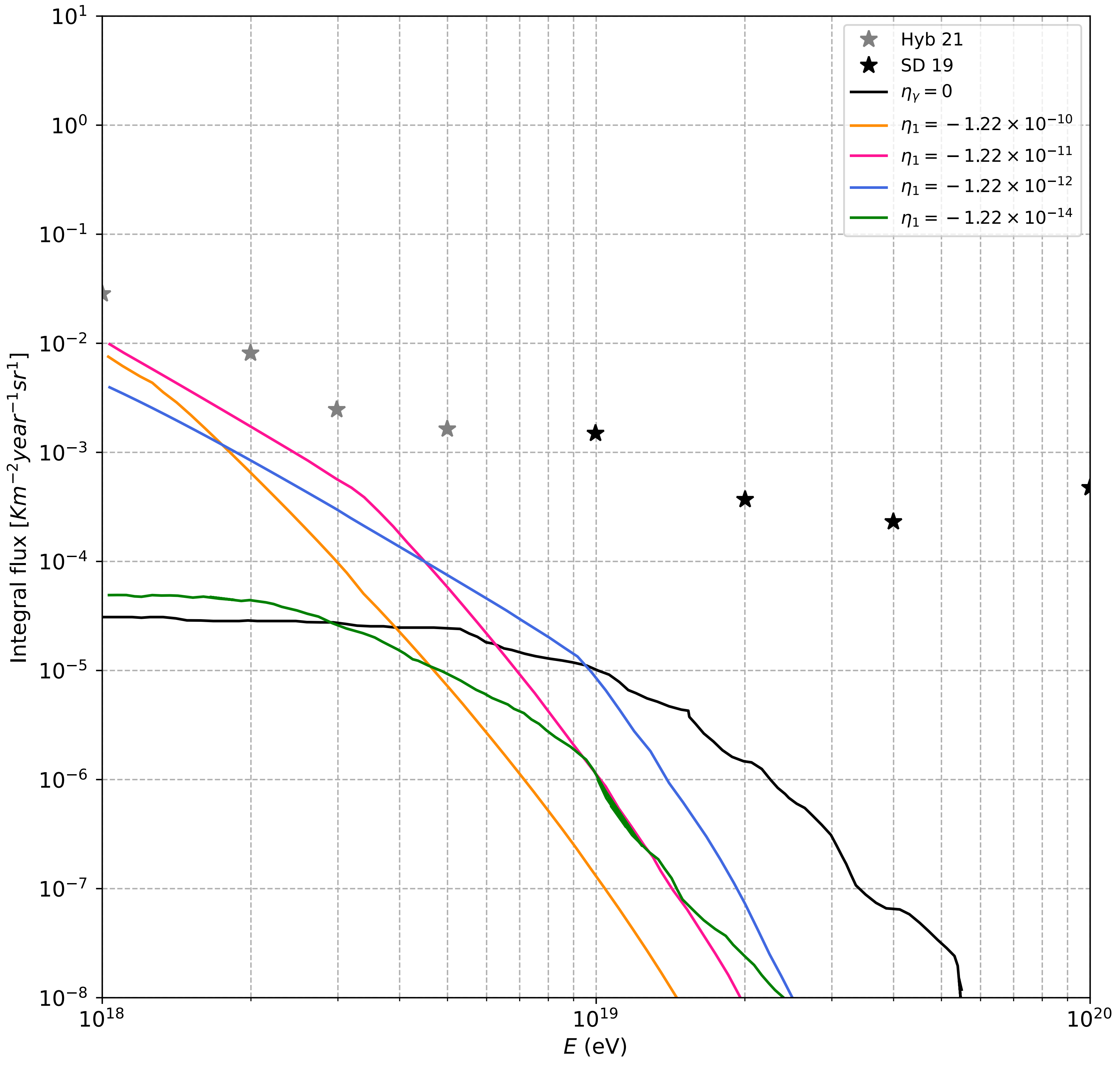


- LIV modifications -> increase the threshold for pair production
  - allows for more photons to reach the top of the atmosphere

Morais, DB, Salamida, Lobo & Bezerra, UHECR24

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

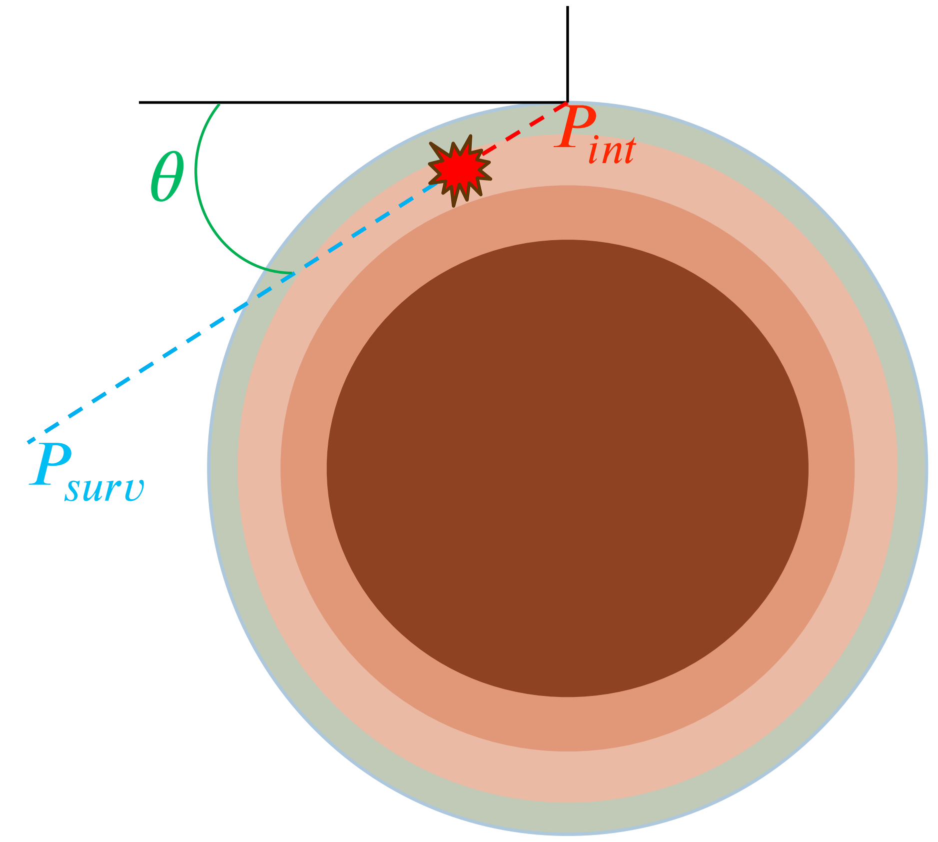
$$\left(\frac{d\Phi(E,\eta)}{dE}\right)_{\mathrm{LIV,i}} = P(E,\eta)_i \left(\frac{d\Phi(E,\eta)}{dE}\right)_{\mathrm{top-of-atm}}$$

- 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

Cascade of particles initiated by photons in the Earth



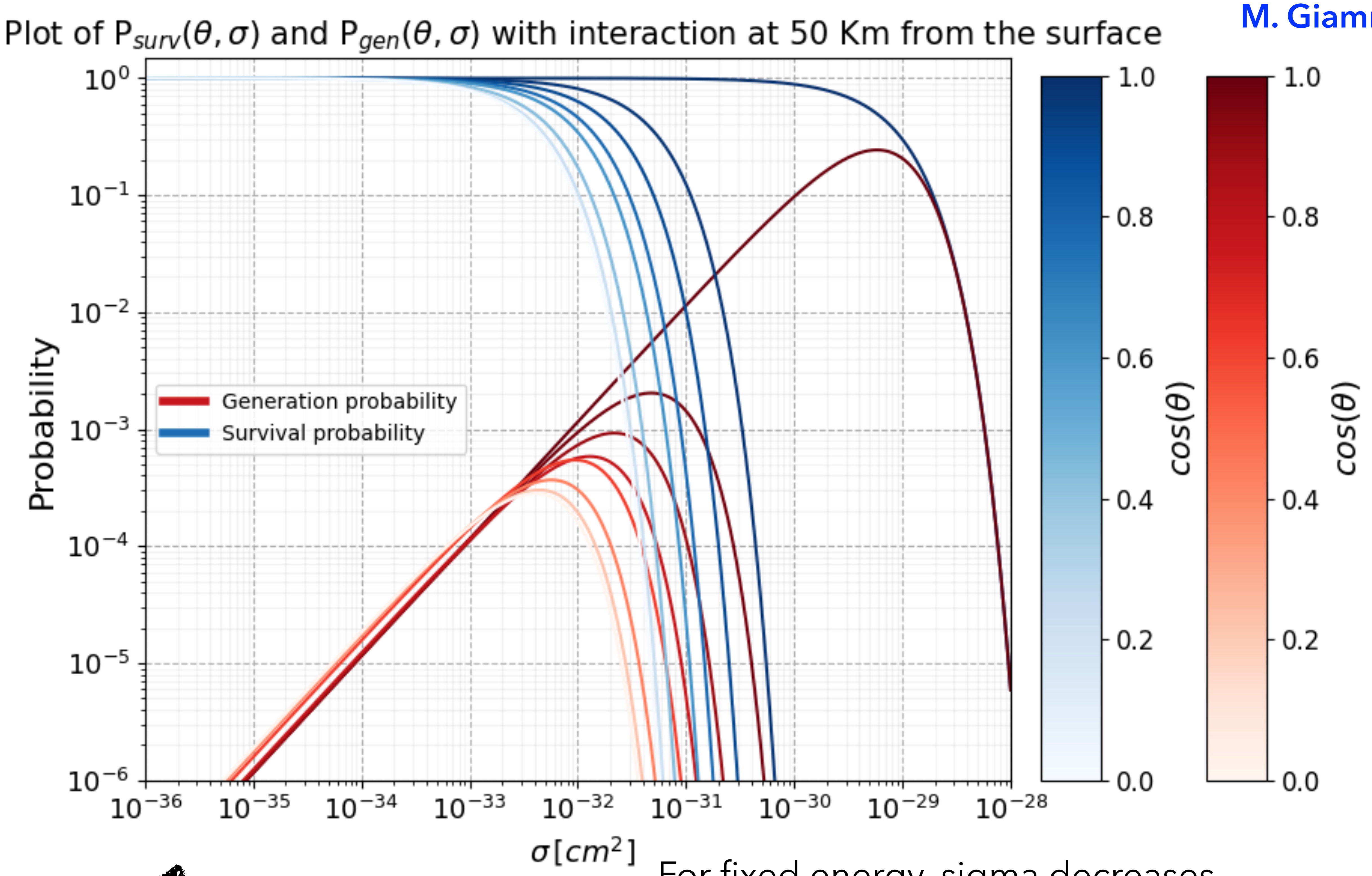
- Test of **pair production in the Earth** -> same cross section as in the atmosphere, different target nuclei
- Compute the survival of photons so that they can initiate showers next to the surface
  - **Upward-going showers**, as expected from neutrinos? (inspired to B. Yue for the Auger Collab. ICRC23)

$$P_{\text{surv,Earth}}(\theta) = \exp\left(-\frac{N_A \sigma_{\text{BH}}}{M} \sum_{i=1}^{n(\theta)} l_i(\theta)\rho_i\right)$$

$$P_{\text{int,Earth}} = 1 - \exp\left(-\frac{N_A \sigma_{\text{BH}}}{M} d\rho\right)$$

$$P_{\text{gen}}(\theta) = P_{\text{int,Earth}} P_{\text{surv,Earth}}(\theta)$$

M. Giammarco

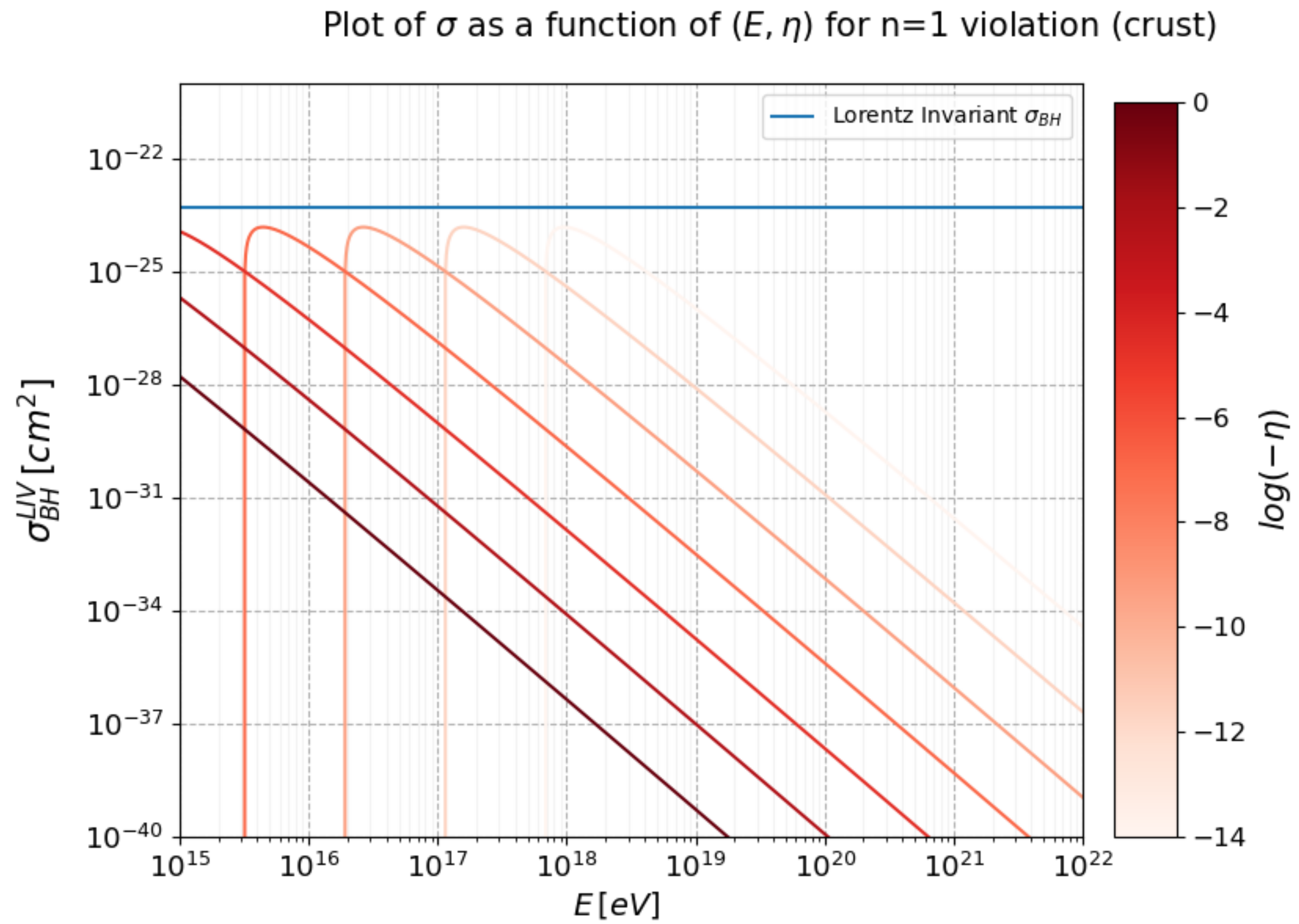


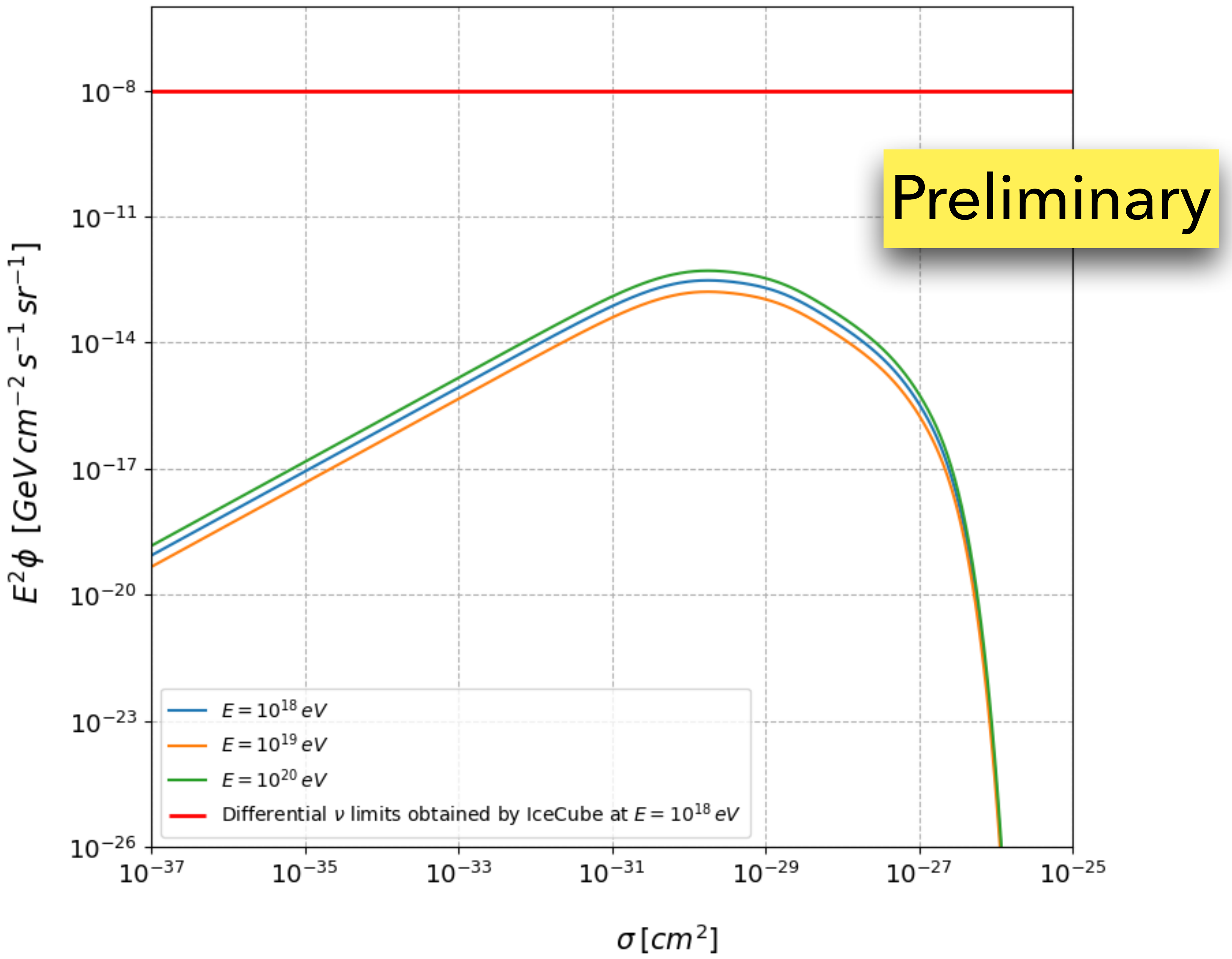
For fixed energy, sigma decreases while eta increases

DB, Bezerra, Giammarco, Lobo, Morais & Salamida, to be presented at ICRC2025

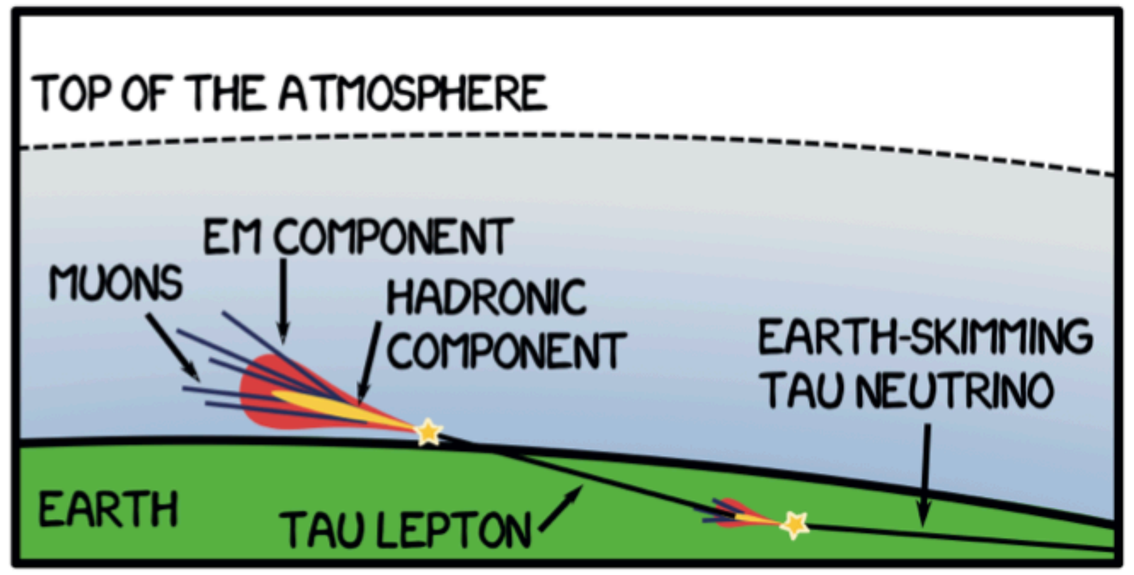
Cascade of particles initiated by photons in the Earth

M. Giammarco





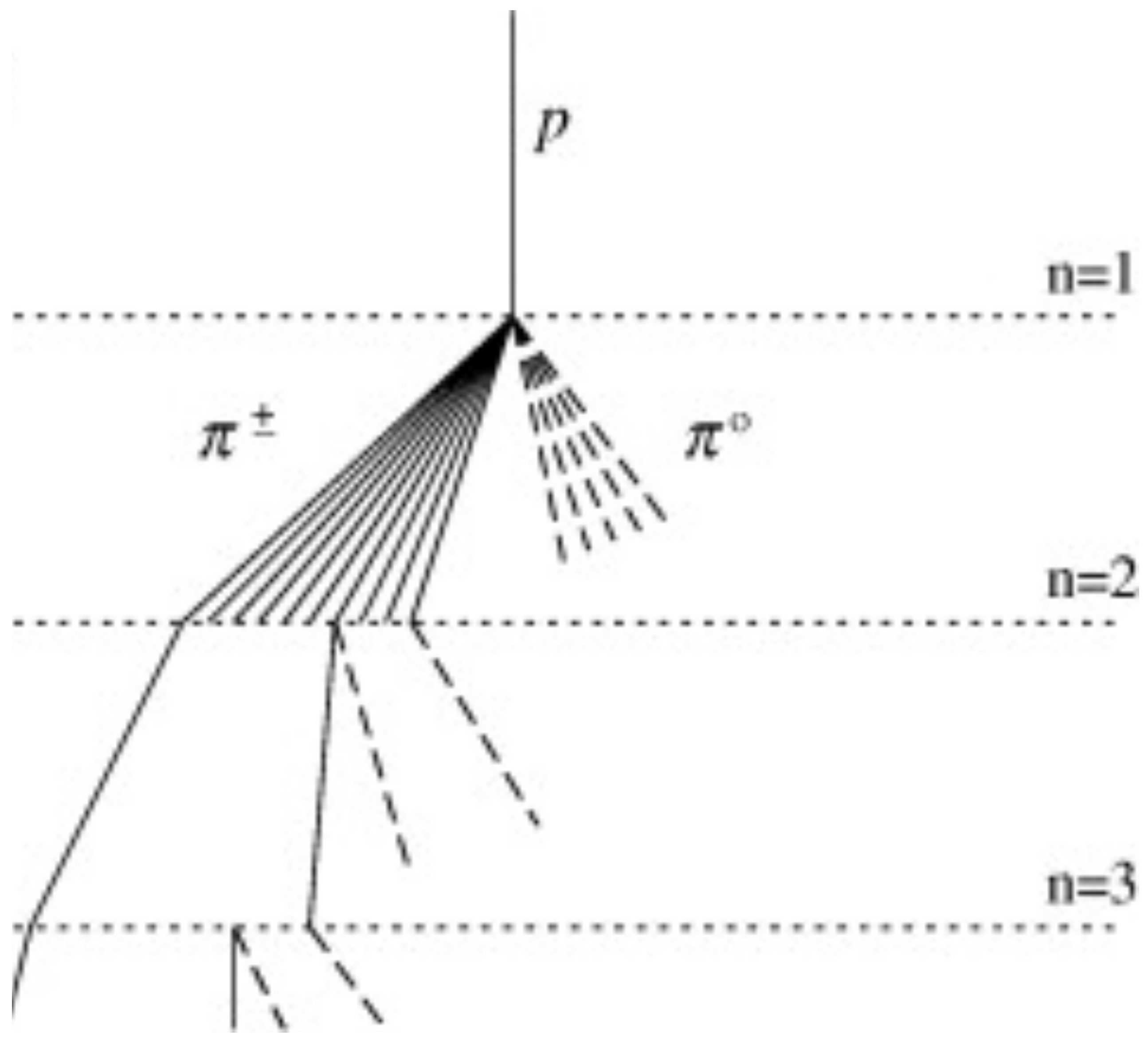
- As for the pair production in the atmosphere: the larger the energy, the more sensitive to LIV
- The expected flux as a function of the cross section is compared to the current UHE neutrino limits
  - A primary photon misinterpreted as a primary neutrino…



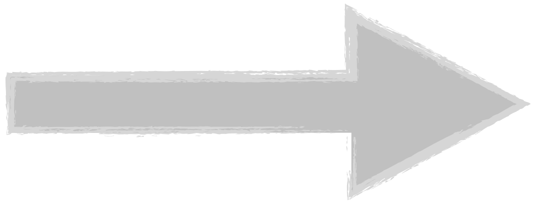
DB, Bezerra, Giammarco, Lobo, Morais & Salamida, to be presented at ICRC2025

LIV IN THE DETECTION STAGE:
FOCUS ON MUONIC COMPONENT OF THE SHOWER

Cascade of particles initiated by hadrons in the atmosphere

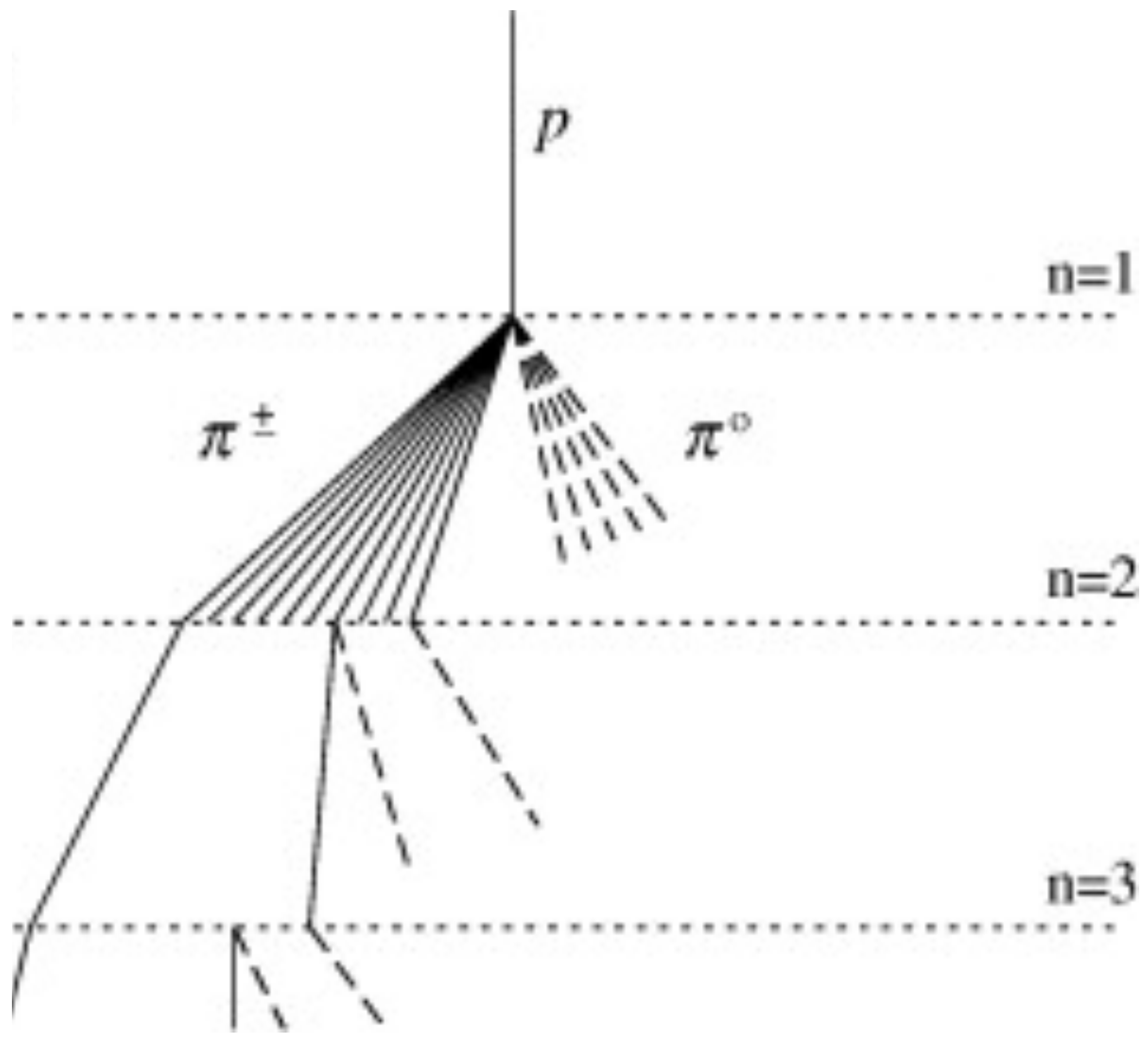


- **Pions** drive the development of <u>electromagnetic and muonic components</u> of EAS
  - Early stages: pions interact
  - Late stages: pions decay



Depending on pion energy (which depends on primary **energy per nucleon)**

Cascade of particles initiated by hadrons in the atmosphere



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Depending on pion energy (which depends on primary **energy per nucleon)**

Modified pion decay

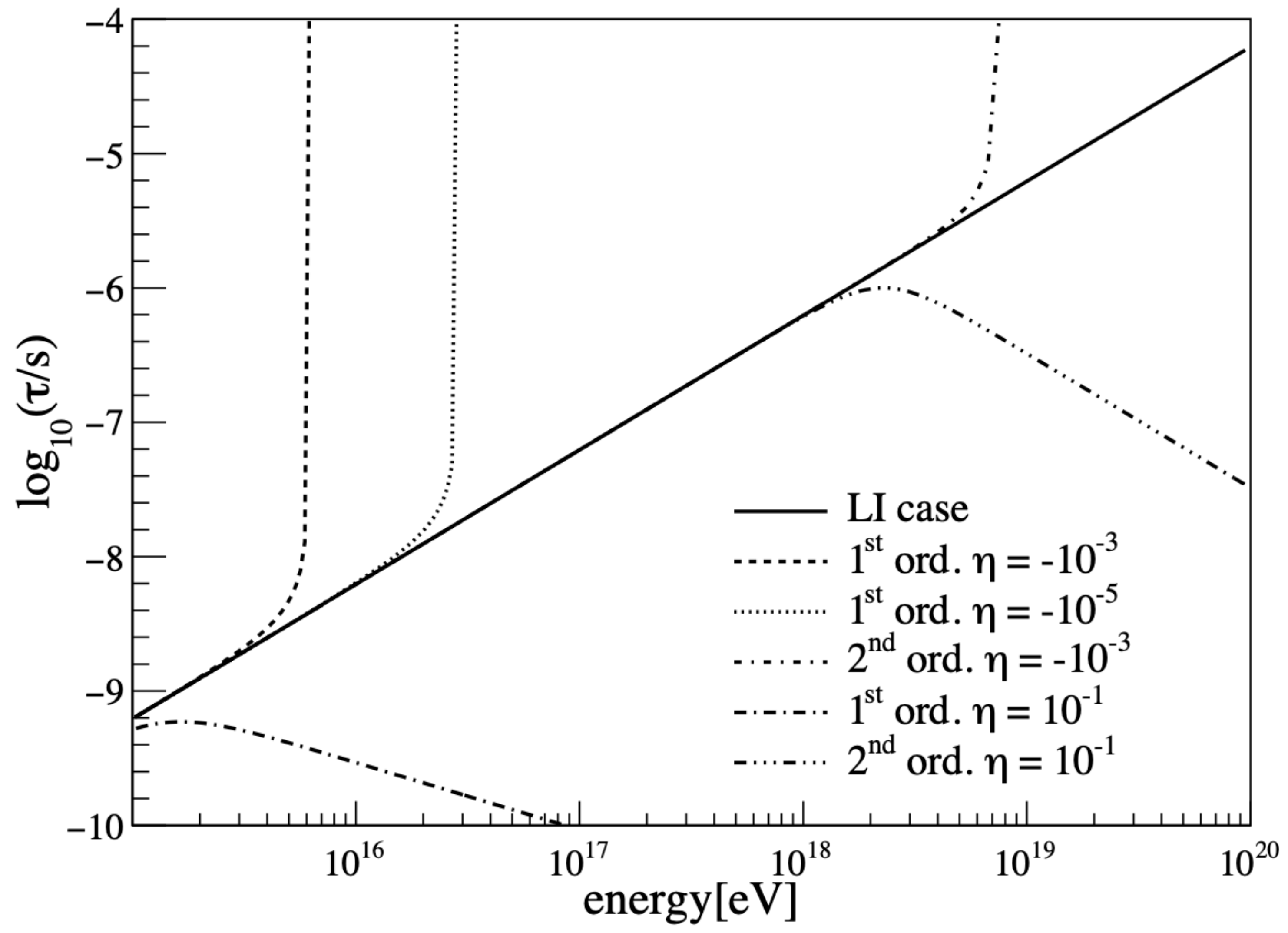
$$E_i^2 - p_i^2 = m_i^2 + \sum \eta_{i,n} \frac{E_i^{2+n}}{M_{Pl}^n}$$

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

- Positive eta: negligible effects
- Negative eta: forbidden neutral pion decay if

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

C. Trimarelli for the Auger Collab, ICRC 2021



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 -> the fluctuations from the first interaction dominate

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

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

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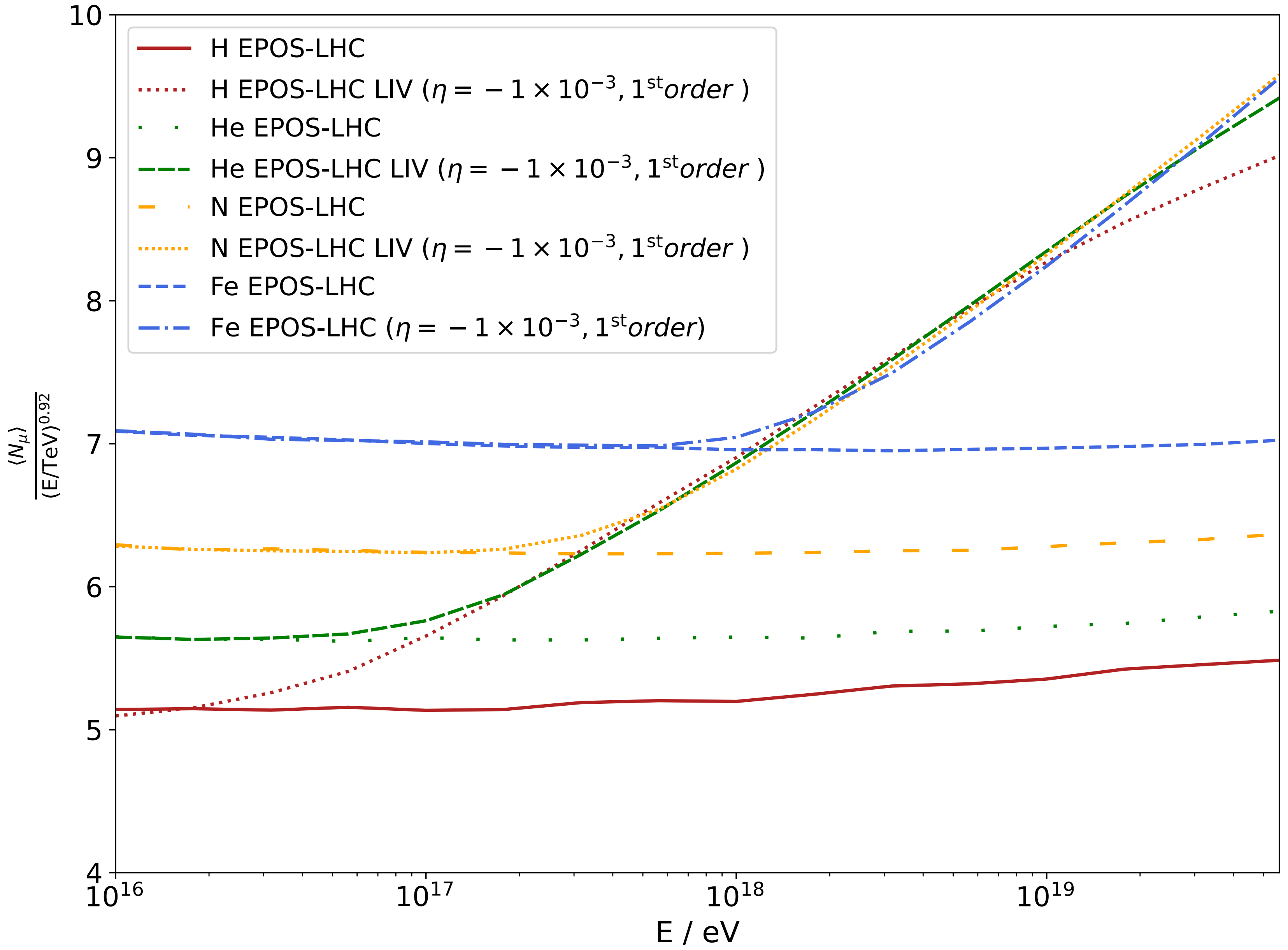
F. Salamida



The Auger Collab, in preparation

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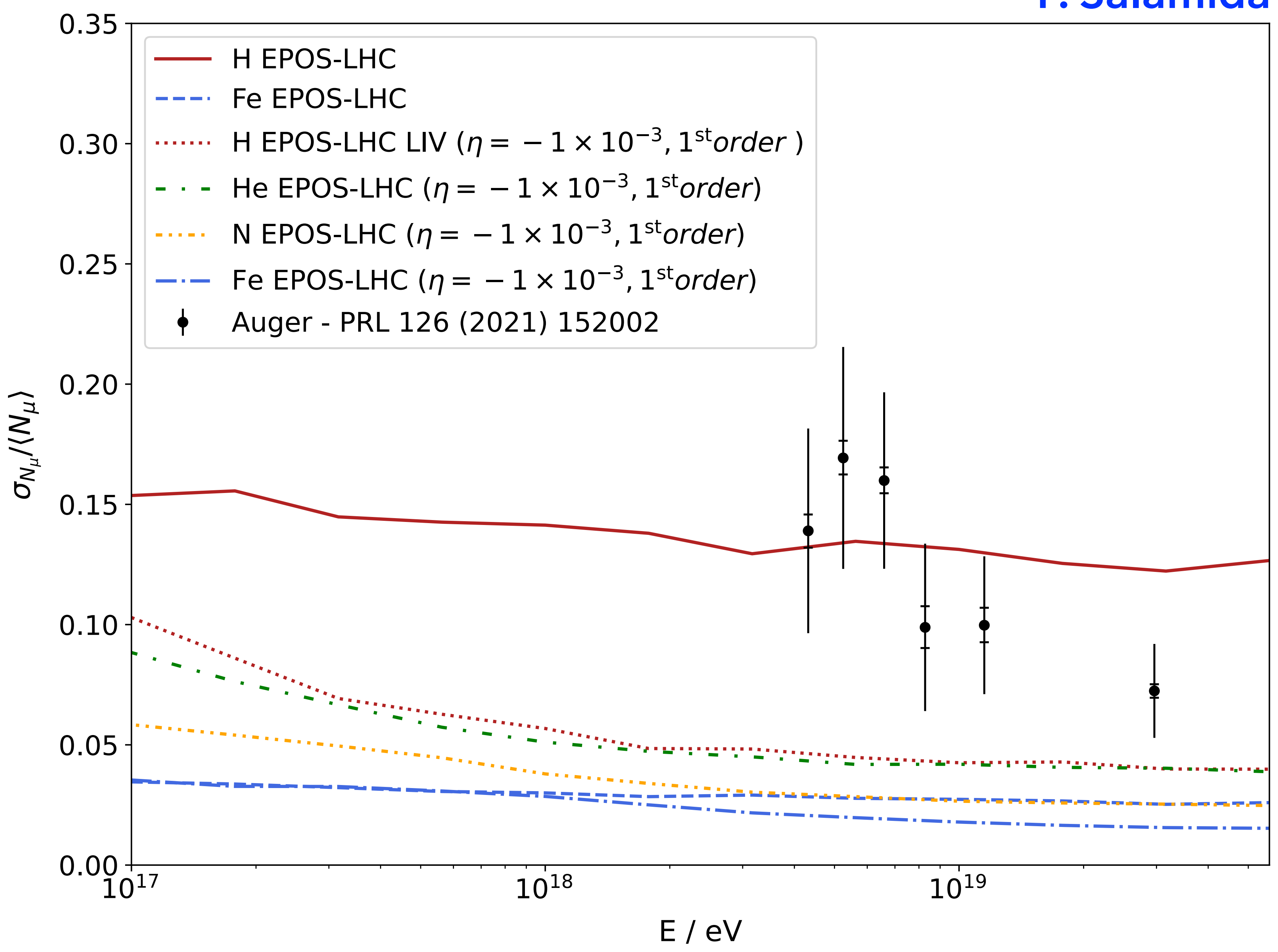
    - fluctuations are minimal, due to a limited stochastic leakage in the first interaction

F. Salamida



The Auger Collab, in preparation

Constraints

F. Salamida

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

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

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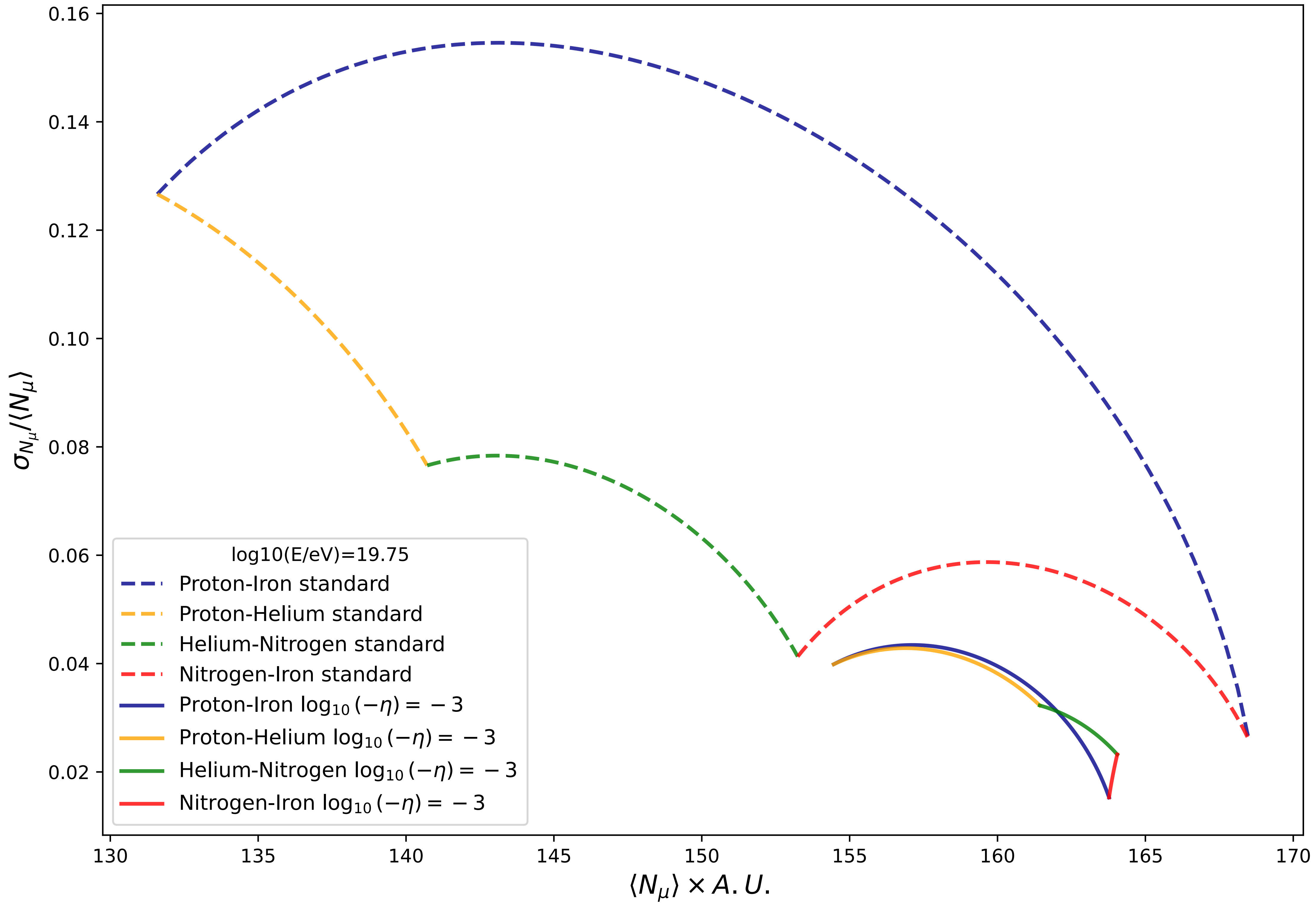

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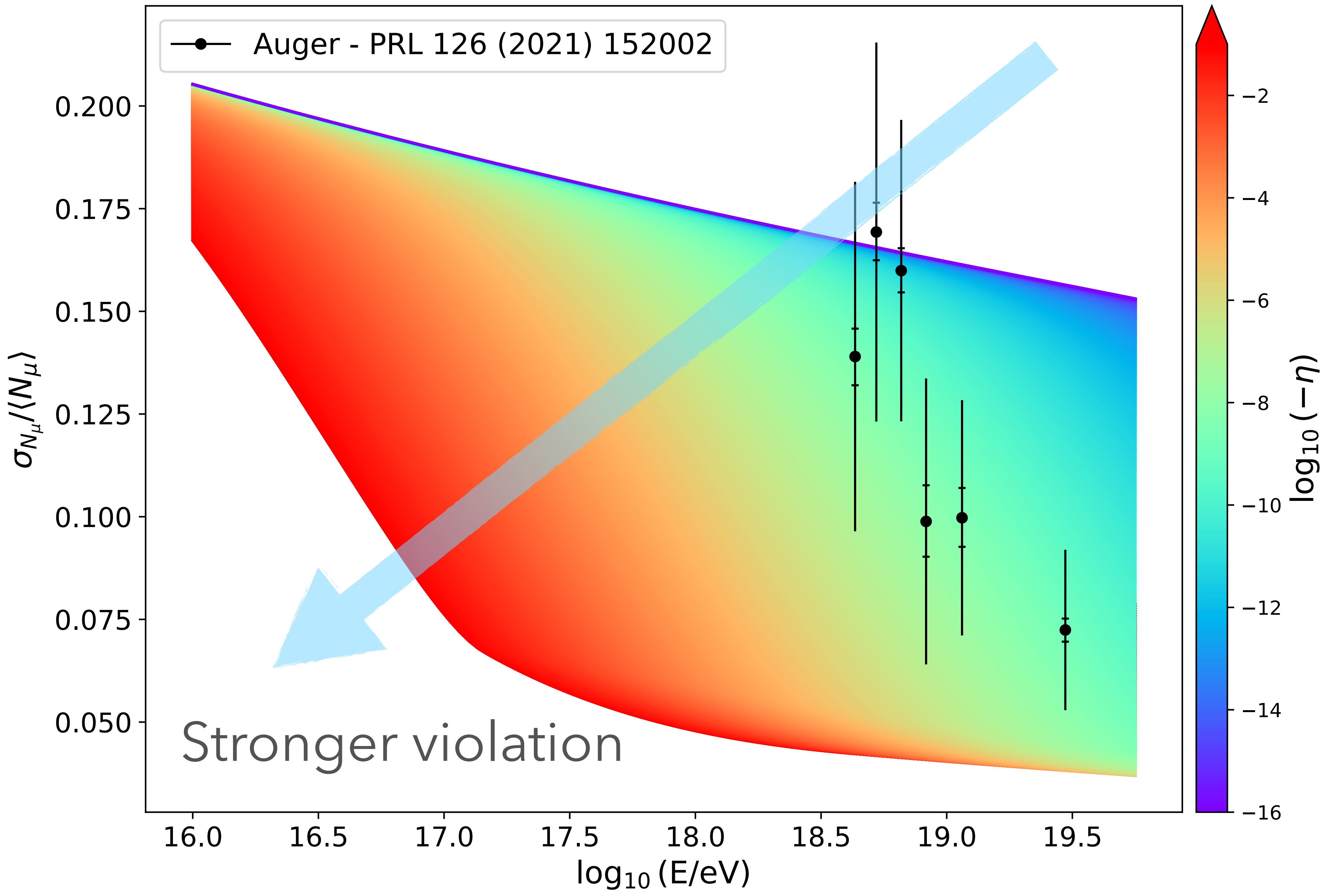
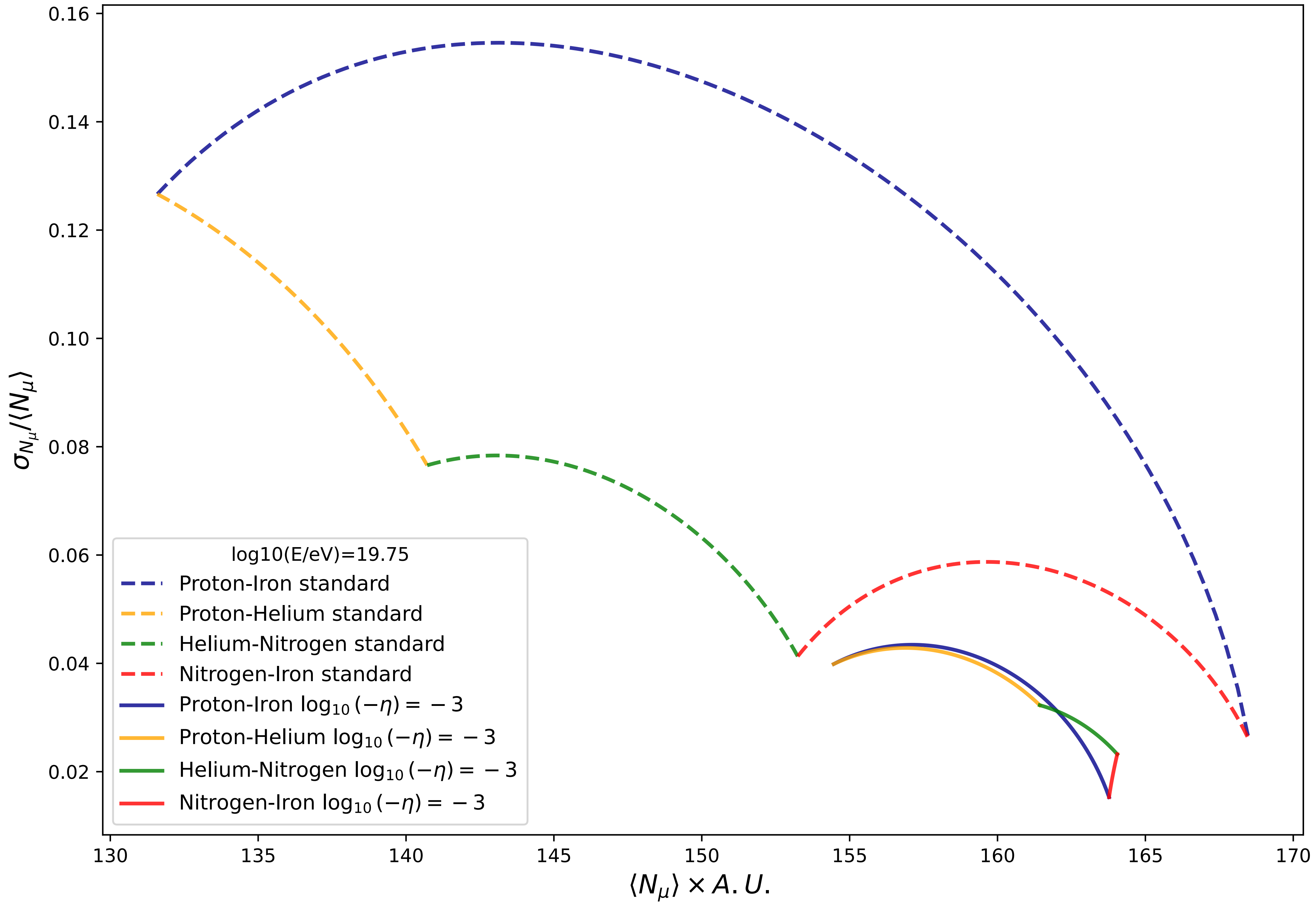


The Auger Collab, in preparation



- 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
- 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

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

SUMMARY

Summary

- LIV can be tested with UHECRs
- Focus on the detection stage
  - The case of photons: it is possible to test the same modifications of LI in different stages of the photon life
    - The LIV effect is responsible for
      - the increase of the photon flux in the extragalactic propagation, and
      - the decrease of the photon flux reaching Earth
        - What about showers initiated in the Earth crust?

Overall effect: smaller LIV parameter space is constrained, but it is more realistic than considering just one stage!

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New observable to constrain LIV!

  - **Could individual events be used to test non-standard physics (and not only data samples)?**

- We aim to improve investigating the detection stage of astroparticles in order to constrain (discover?) LIV

Summary

- Competing effects (from astrophysics and physics uncertainties) must be taken into account
    - The **indetermination on the mass composition of UHECRs** is the main responsible for the lack of precision in several non-standard physics analyses (not only for UHECR analyses -> multimessenger analyses can be also affected, see for instance Reyes, DB, Carmona & Cortes ICRC23 about cosmogenic neutrinos)
        - Improvements expected with **AugerPrime**

- Other ideas for constraining LIV with UHECRs (not only with diffuse flux information):
    - 3D correlation analyses with catalogs -> the **horizon of UHECRs** can account for LIV effects in the propagation
    - Search for multiplets

- Any hope to account for the different stages of the UHECR life for constraining LIV?

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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)

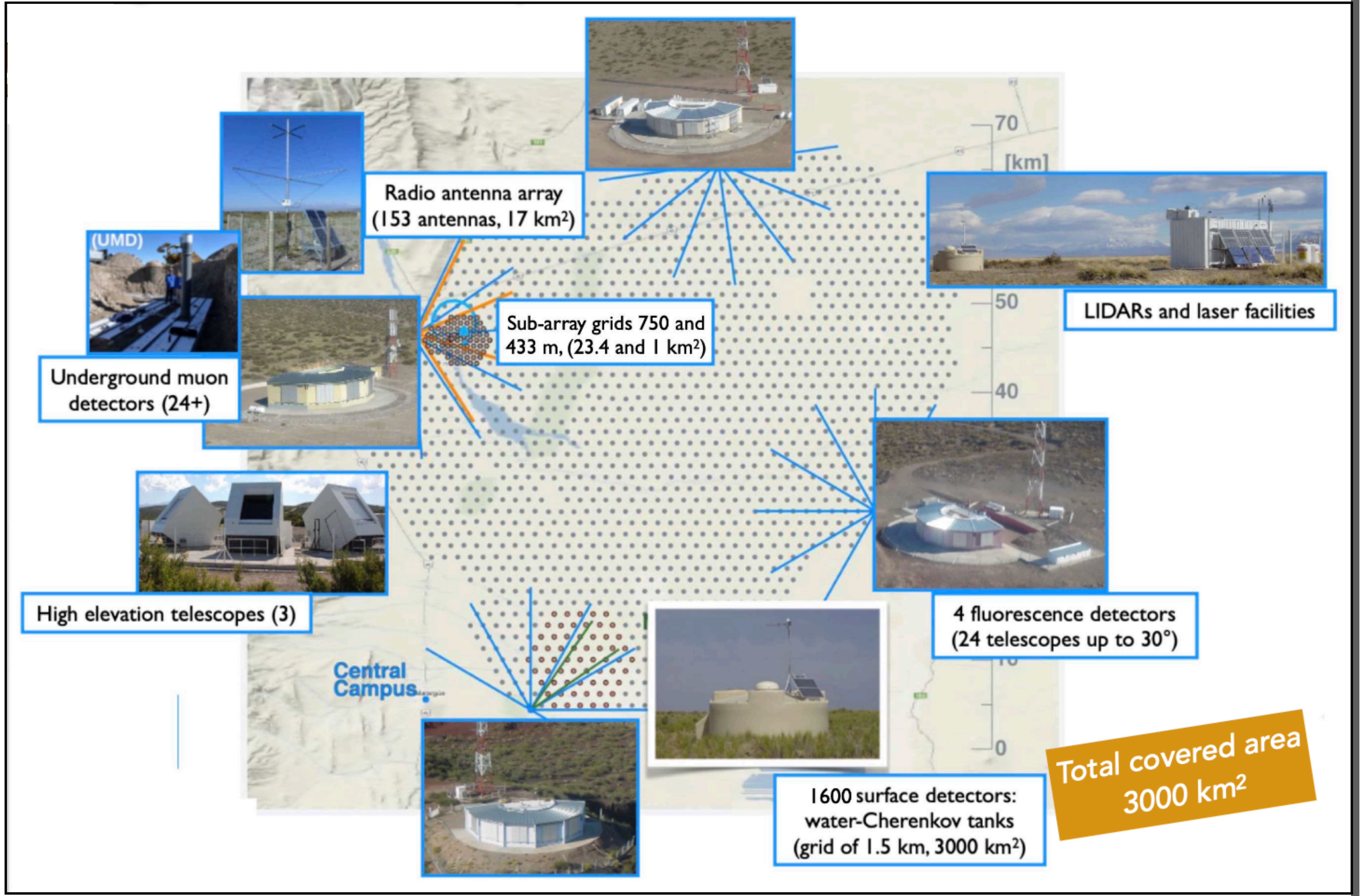
- 24 telescopes in 4 sites, FoV: 0-30°, E > 10^{18} eV
- HEAT (3 telescopes), FoV: 30 - 60°, E > 10^{17} eV

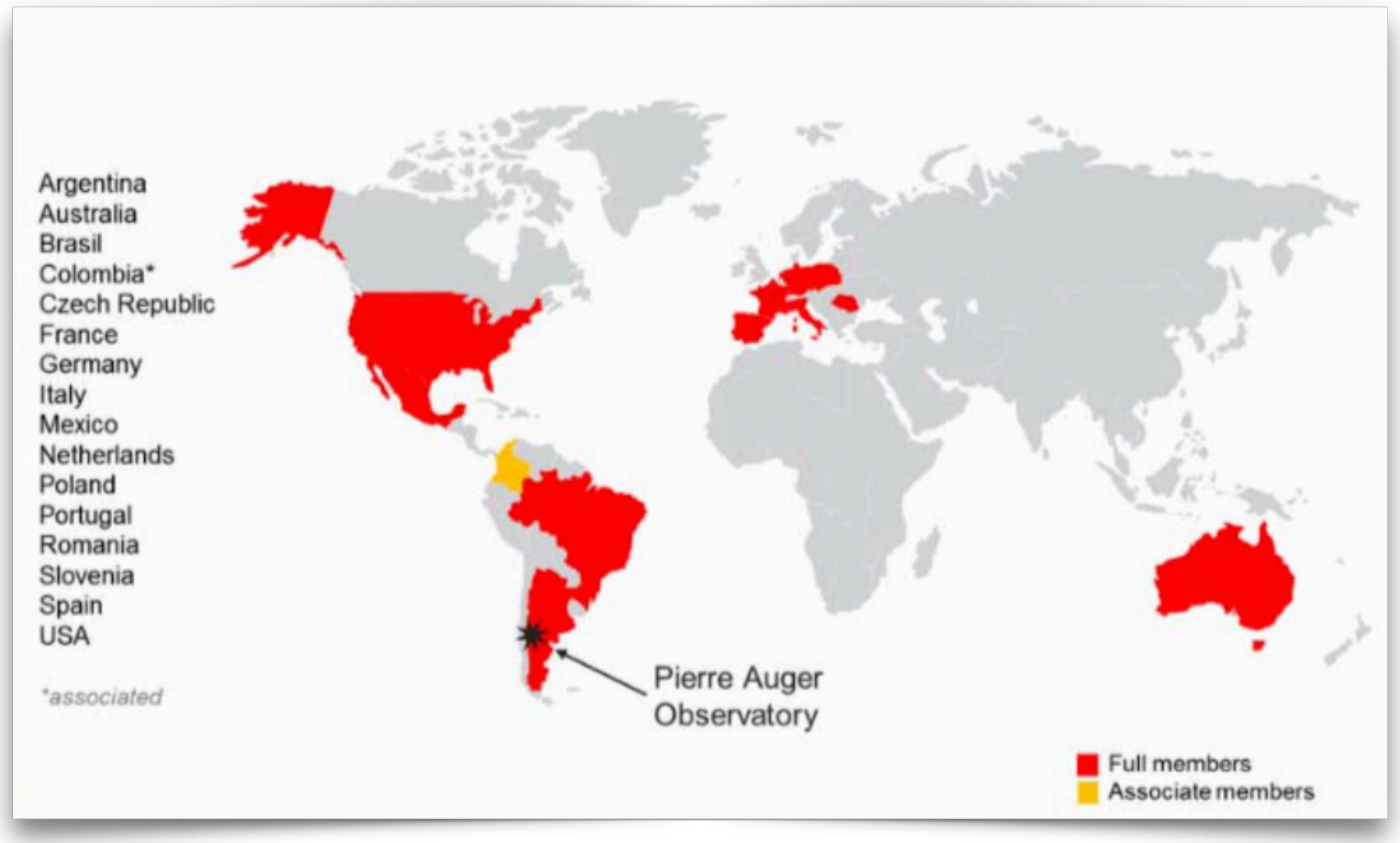
Auger Engineering Radio Array (AERA)

- 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

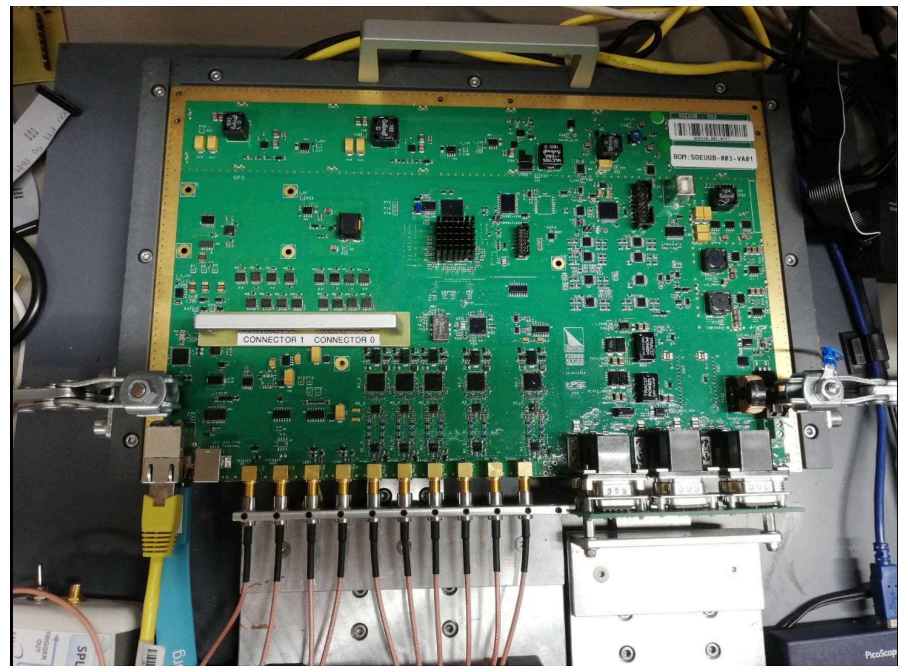
AugerPrime

- 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.

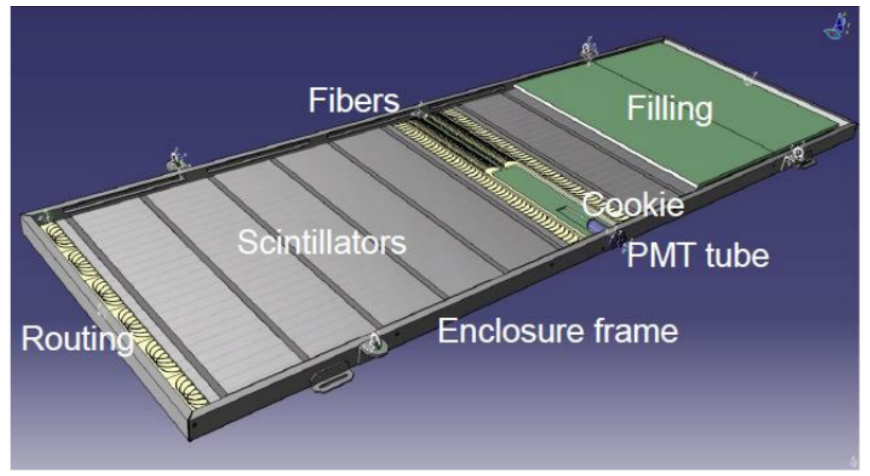
Towards multi-hybrid observations of extensive air showers with **AugerPrime!**

Radio upgrade

New electronics



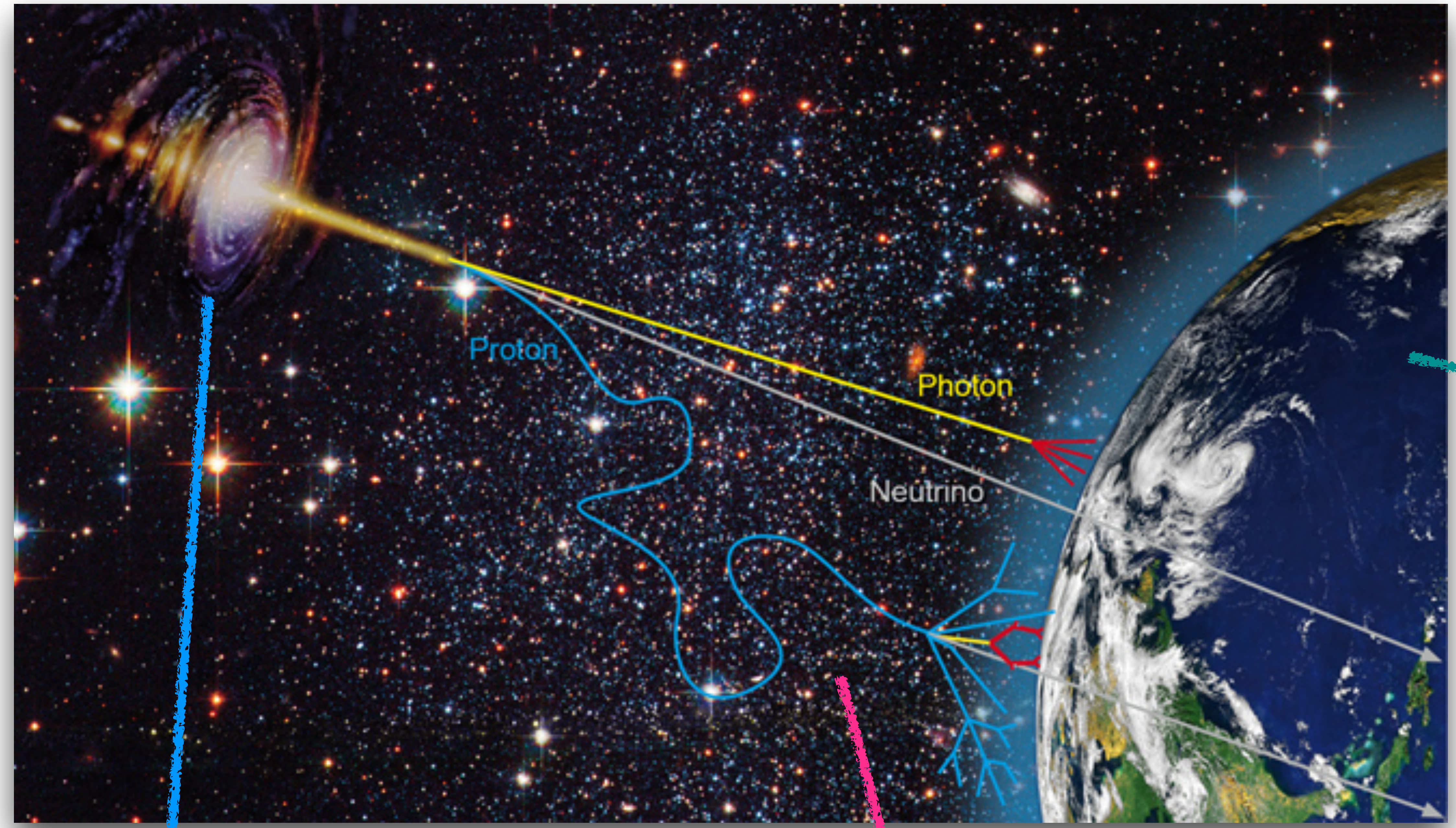
Scintillators



Underground muon detectors

High-dynamic range PMTs

State-of-the-art: astrophysical scenarios



Power law-spectra at emission from (identical) sources, up to a maximum energy

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} \pi^0 + p \\ \pi^+ + n \end{cases}$$

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

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

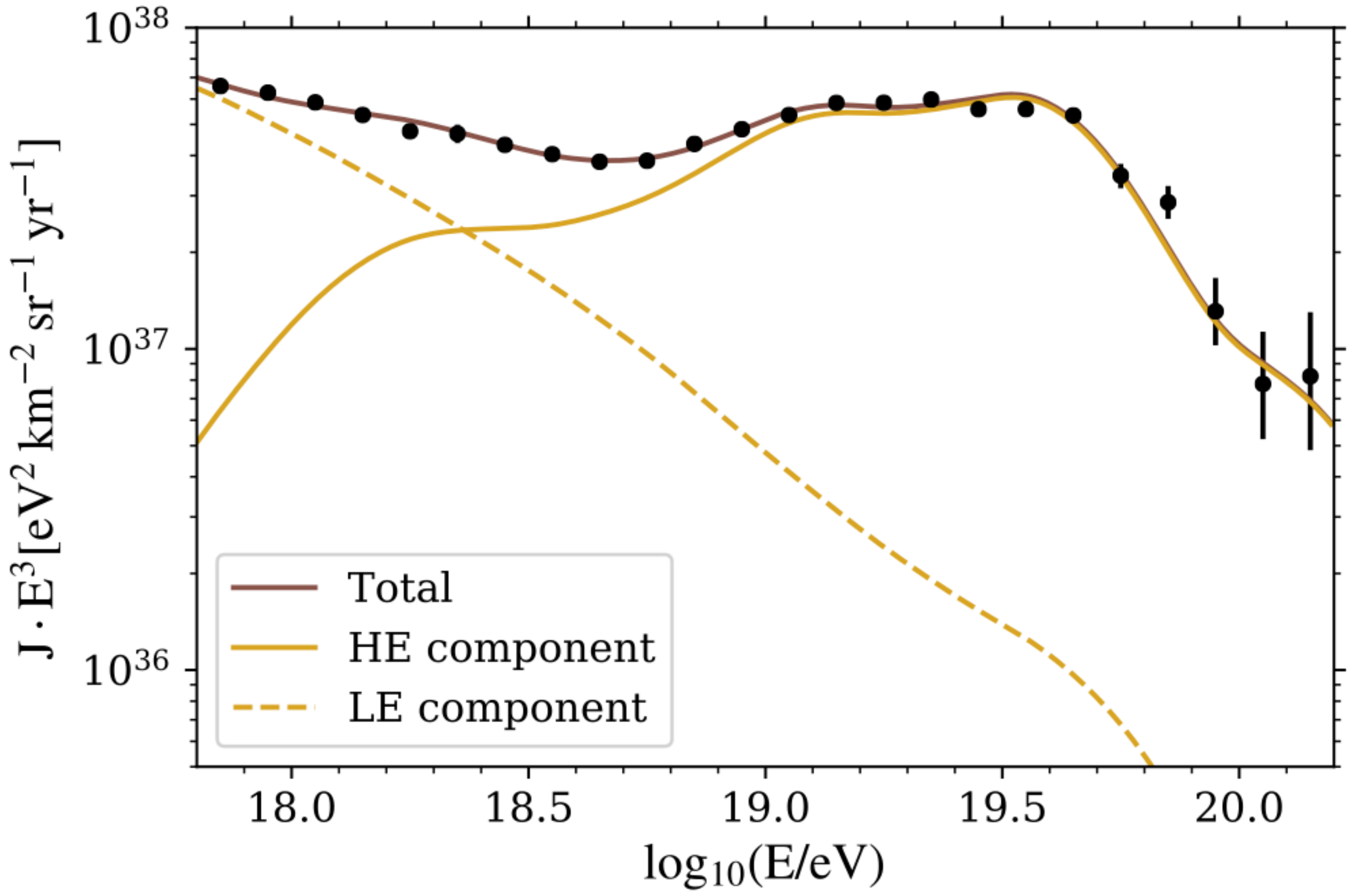
Basic scenario:

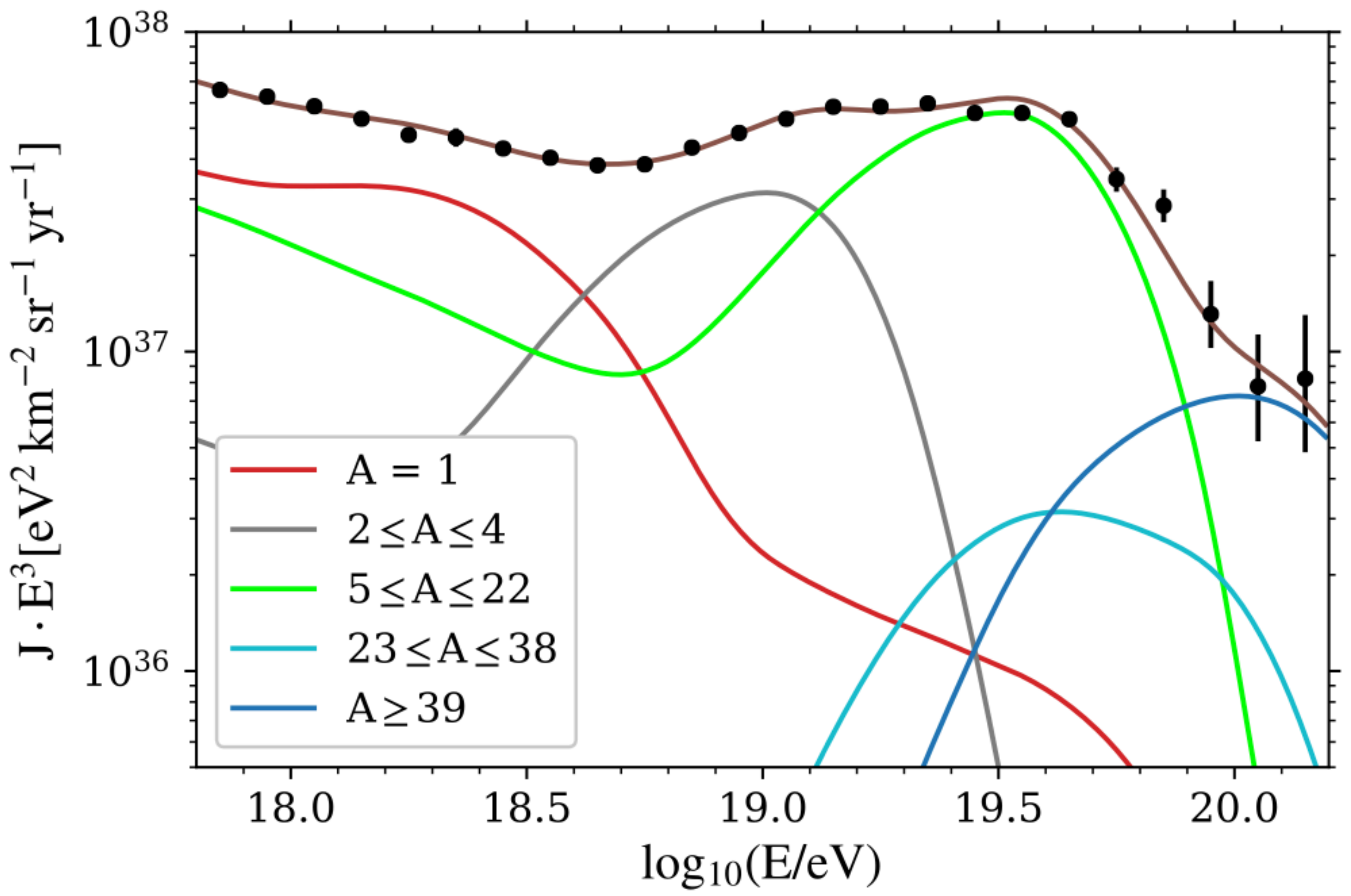
- identical sources
- power-law spectra at escape, with rigidity dependence

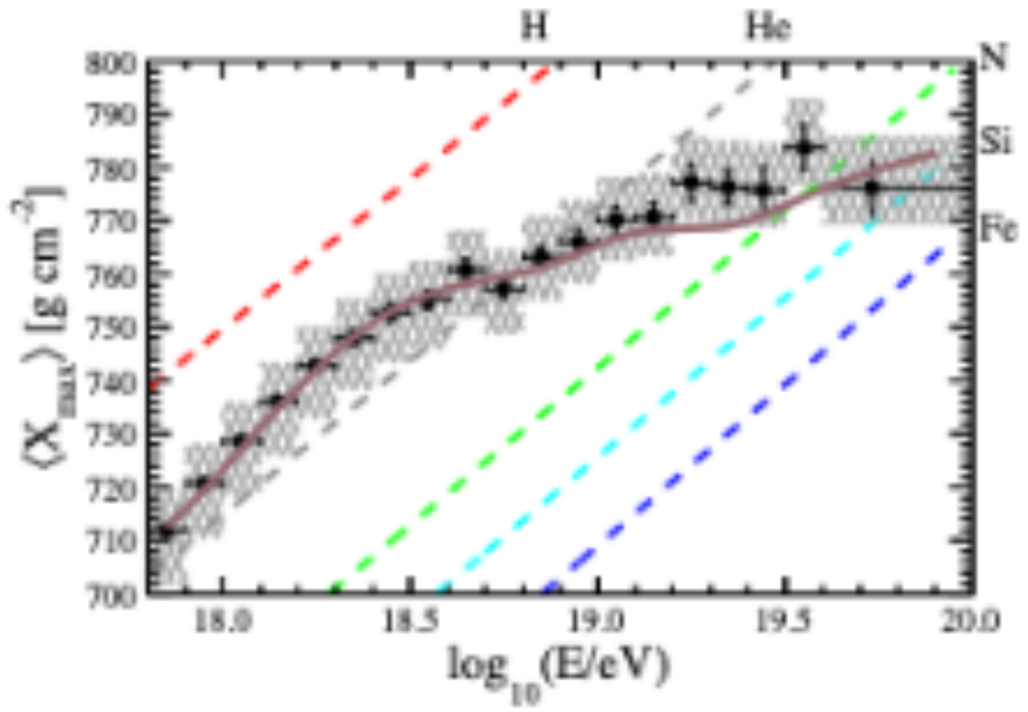
Extragalactic propagation taken into account, as from **SimProp**, Aloisio, **DB**, di Matteo, Grillo, Petrera & Salamida, JCAP 2017; **CRPropa**, R. Alves Batista et al, JCAP 2022

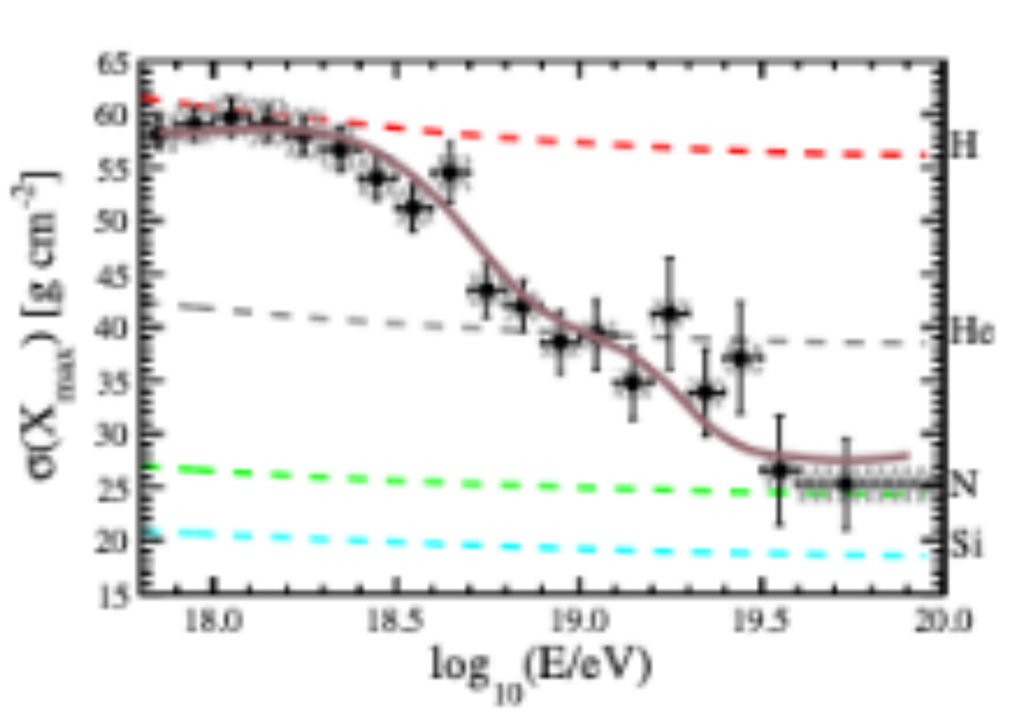
Fit of spectrum and mass composition; arrival directions can be also included

State-of-the-art: astrophysical scenarios





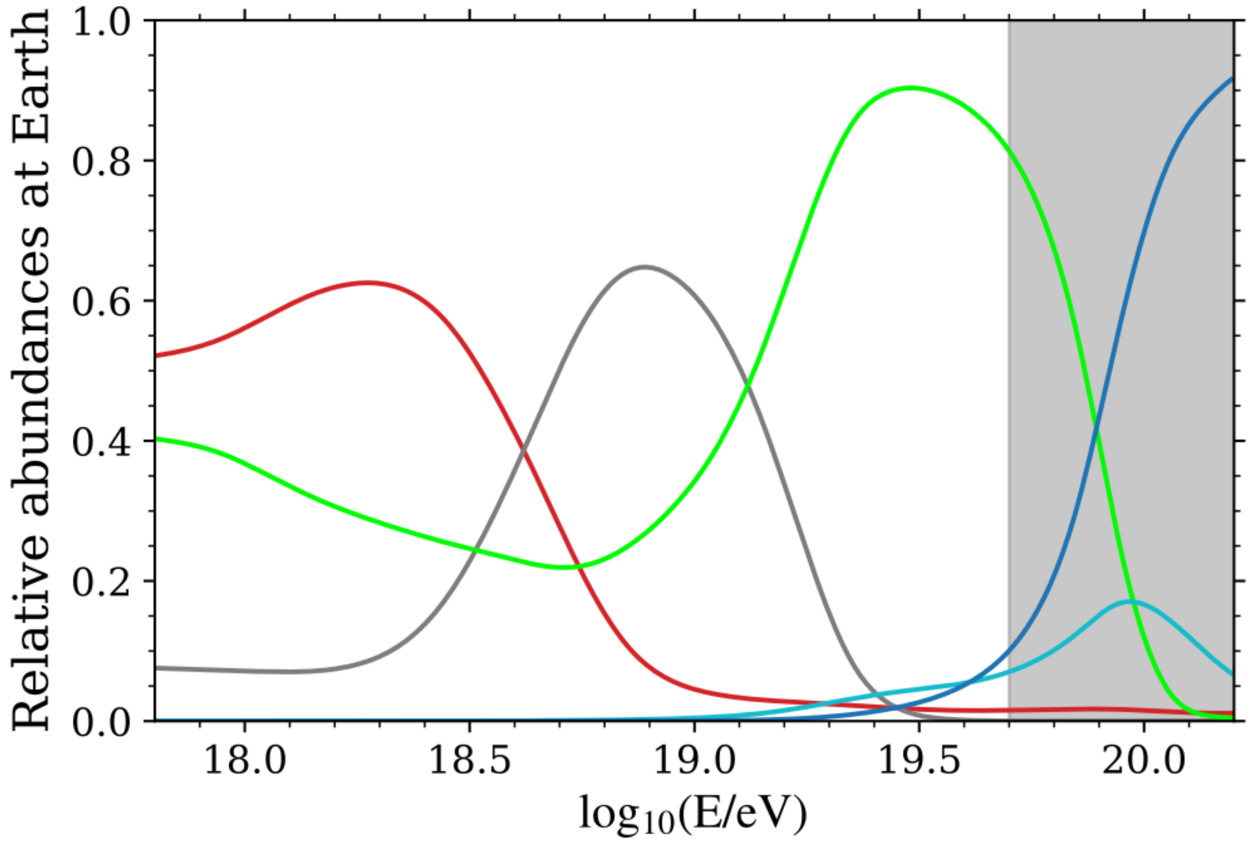




Different contributions needed at LE and HE:

- 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



- 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 !

Mass composition observables from air-showers

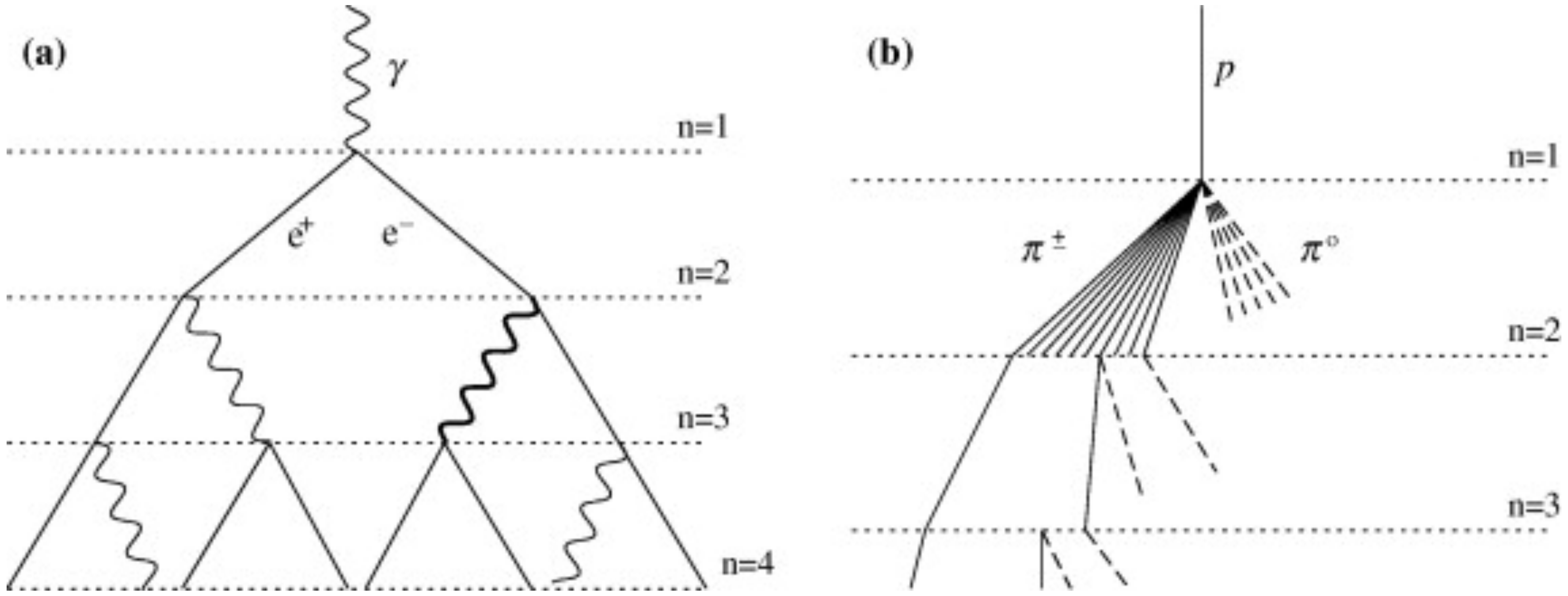
Heitler (and generalised-Heitler) model for EAS

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

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

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

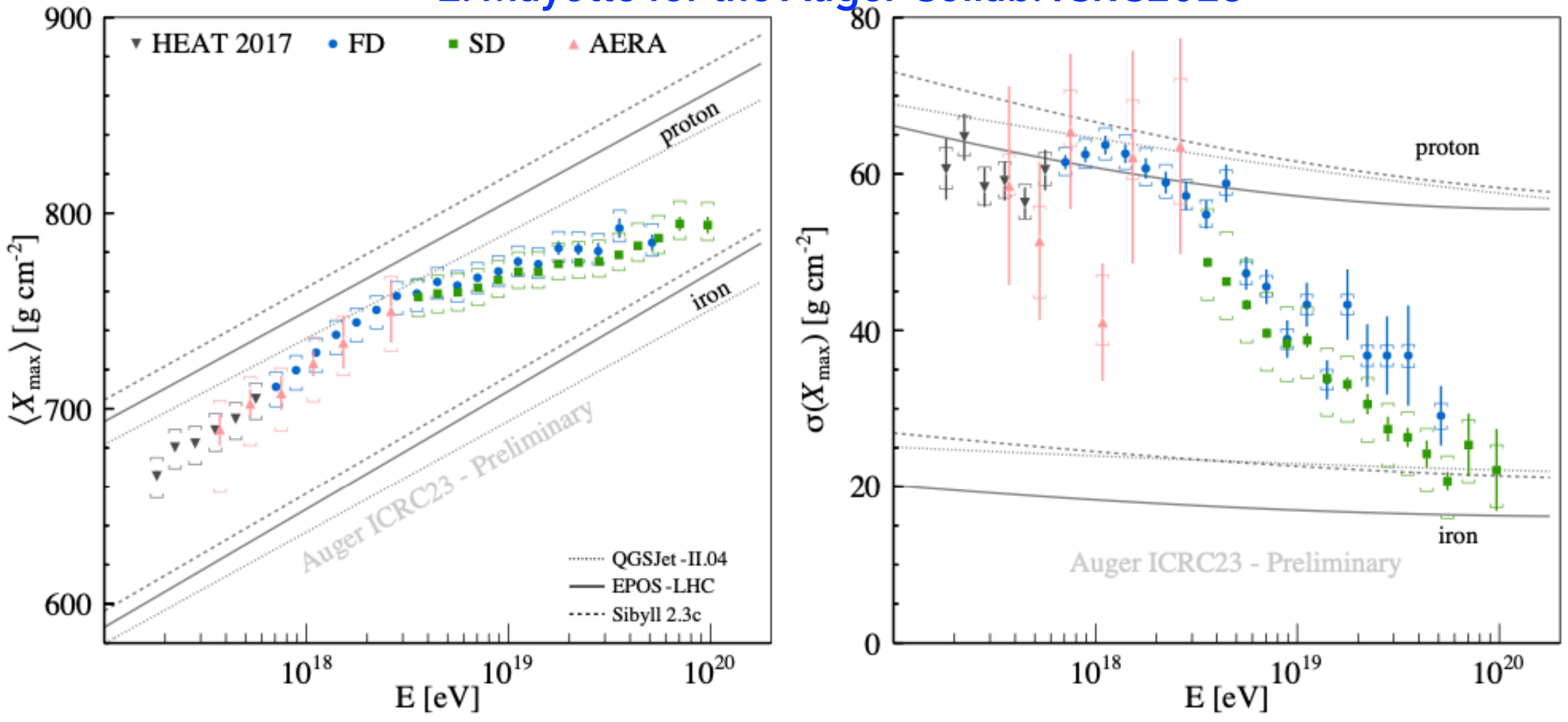
$$X^{A}_{\max} \propto X_{\max}(E_0/A)$$



- 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)

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

E. Mayotte for the Auger Collab. ICRC2023

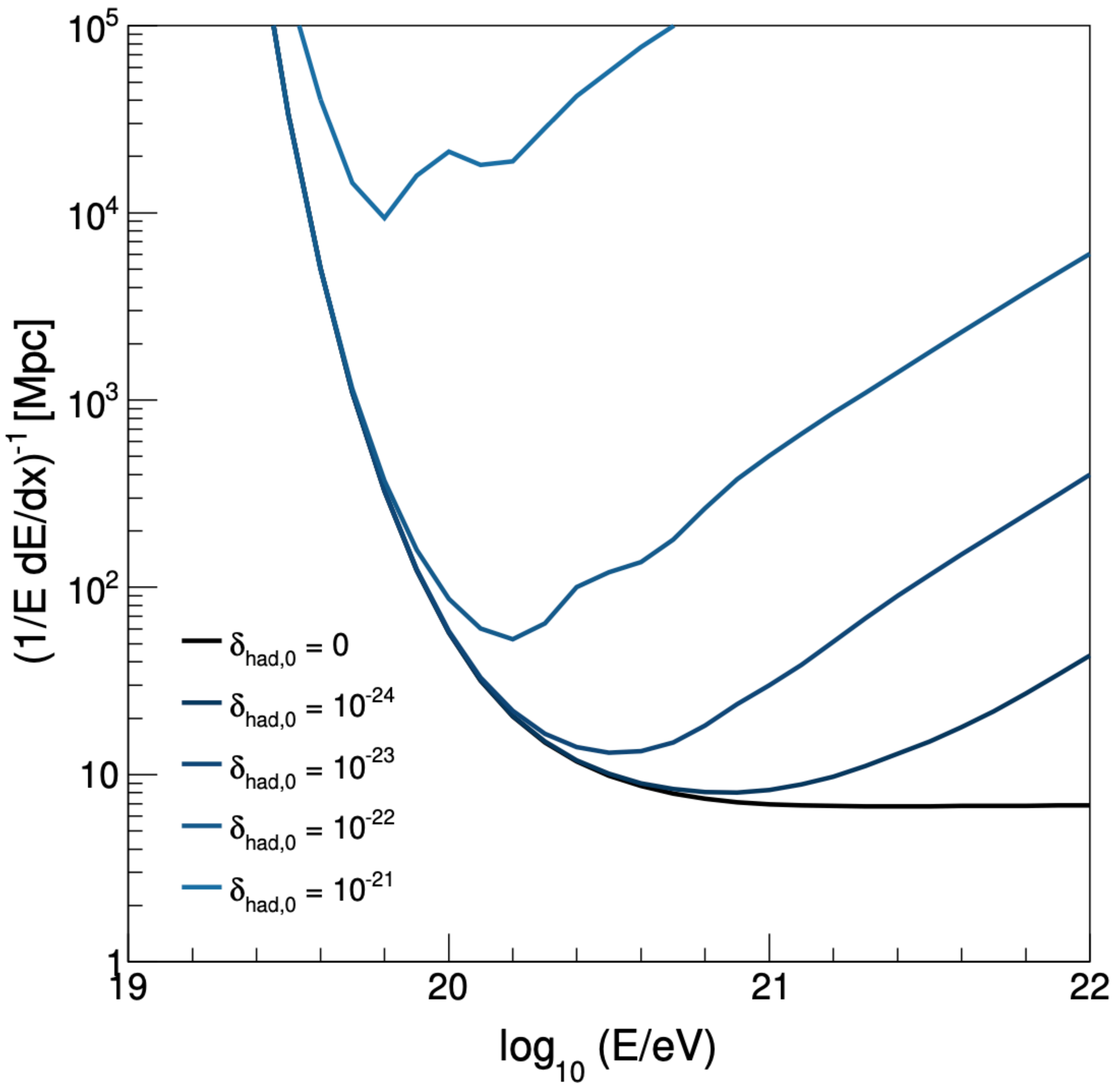


MODIFIED CR PROPAGATION

The Pierre Auger Collaboration, JCAP 2022

- Similar approach to the one used in **Scully & Stecker 2009**
  - In order to modify the effect of photo-pion production above the GZK energy, we must have delta_pion > delta_proton (**Coleman&Glashow 1999**)
  - For most of the allowed parameter space near threshold, delta_pion can be as much as one order of magnitude greater than delta_proton
  - delta_pion is considered (at or near threshold)

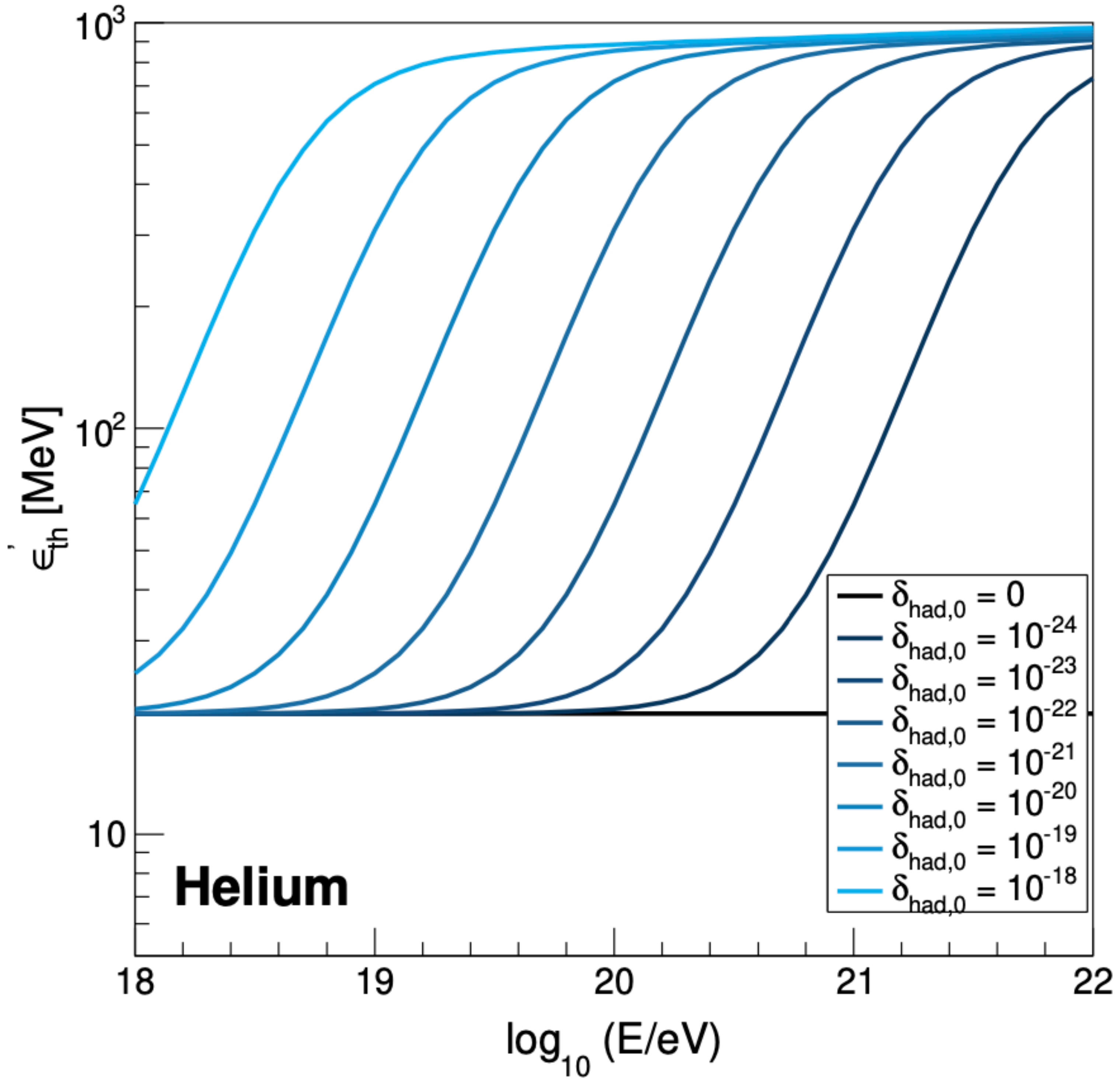
- Effect of recovering of the spectrum is expected
  - But not observed!

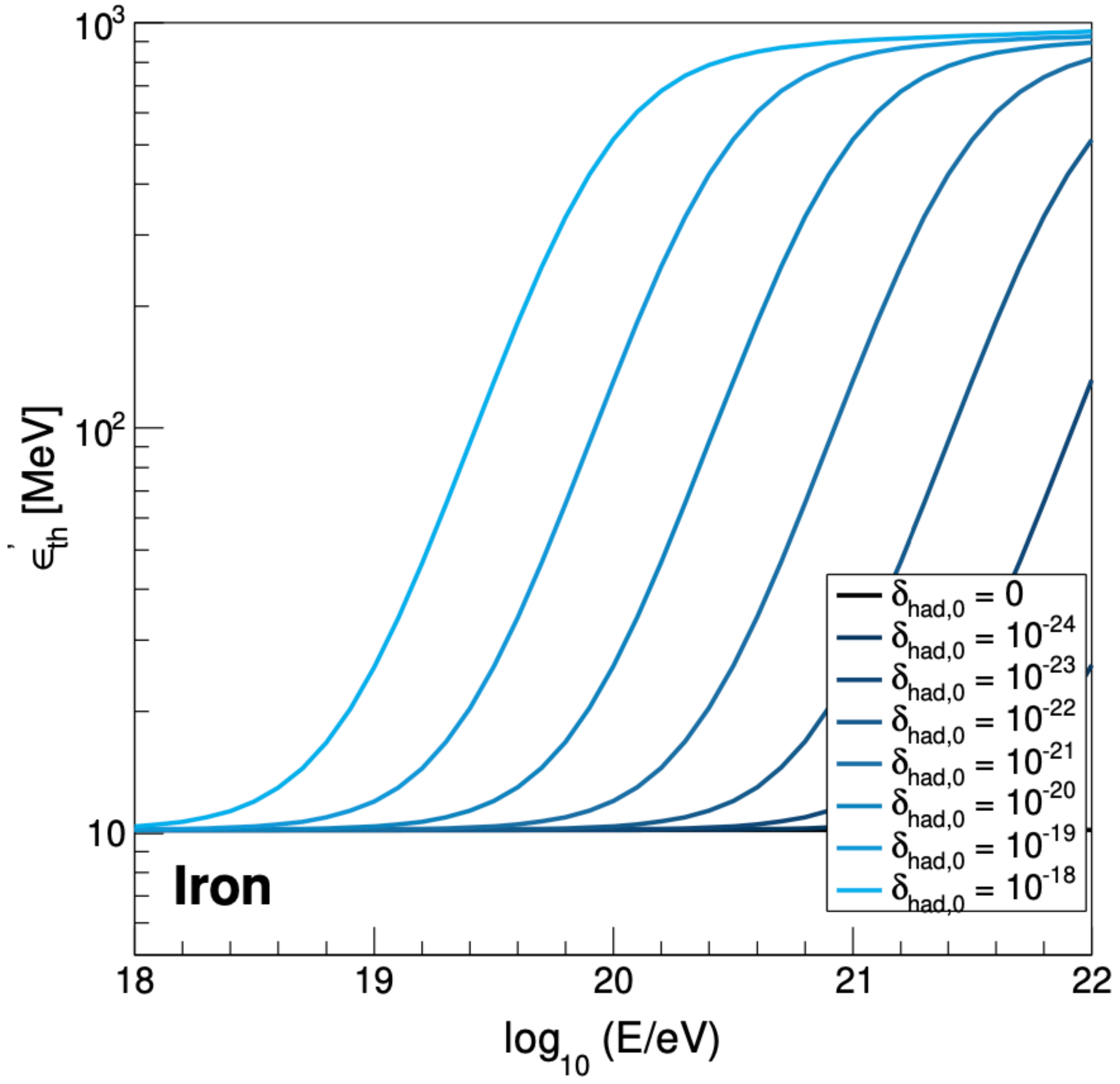


- Modifications of propagation: **SimProp code**

MODIFIED CR PROPAGATION

The Pierre Auger Collaboration, JCAP 2022





- 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

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

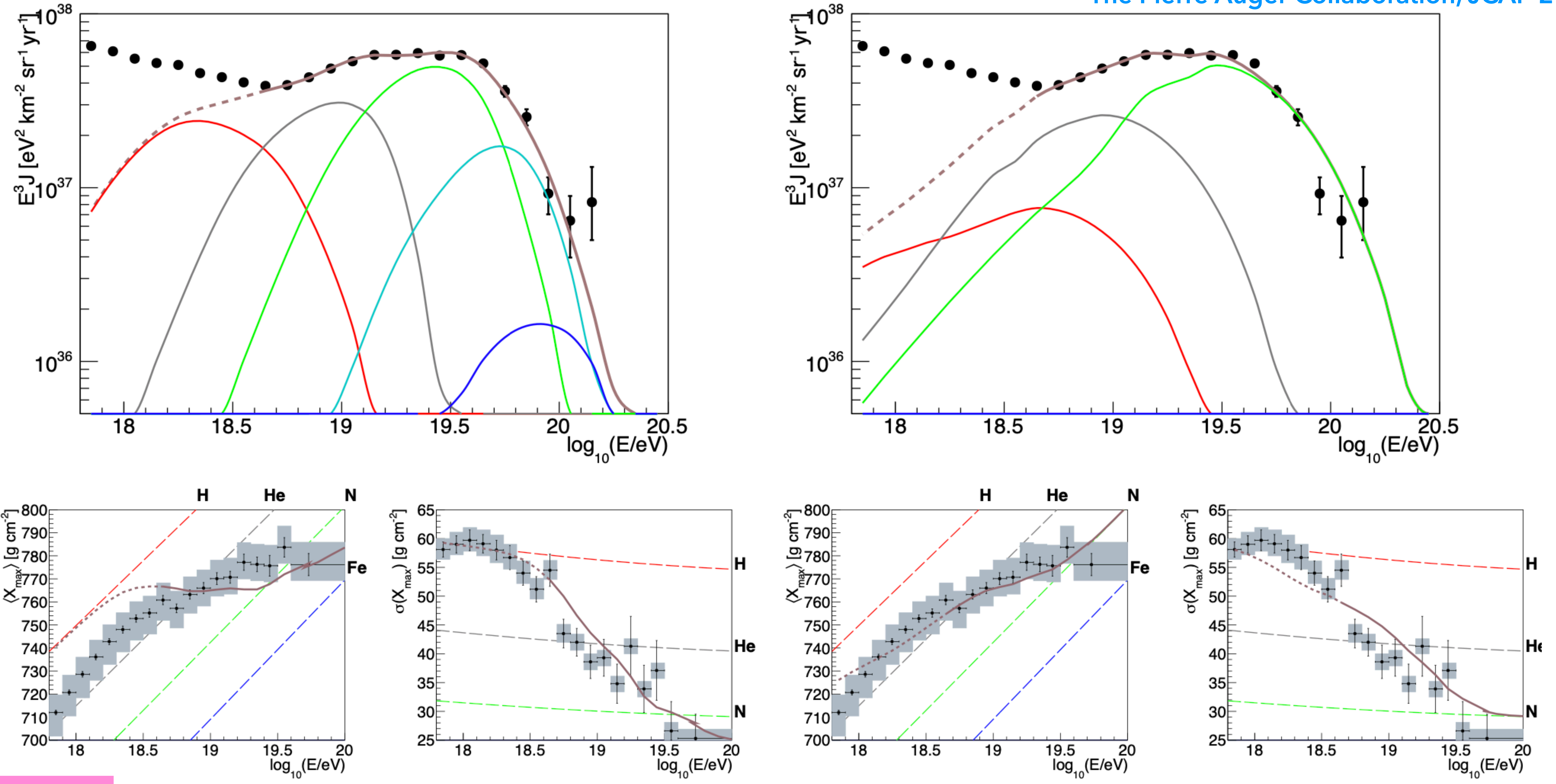
$$A^2 E_p^2 = A^2 p_p^2 + A^2 m_p^2 + A^2 \sum \delta_{A,n} A^n E_p^{2+n}$$

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

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

EXPECTED CR SPECTRUM AND COMPOSITION

The Pierre Auger Collaboration, JCAP 2022

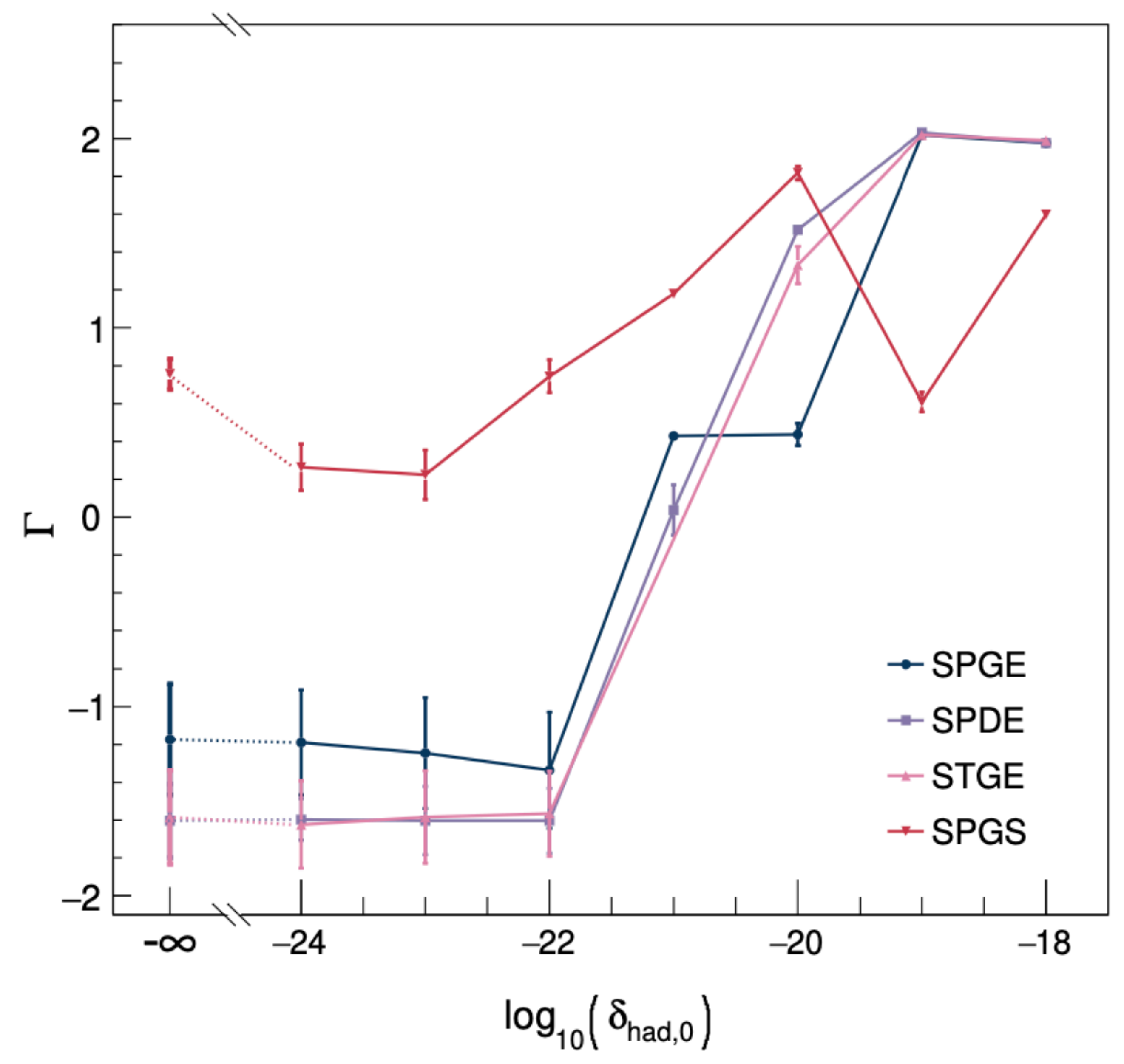


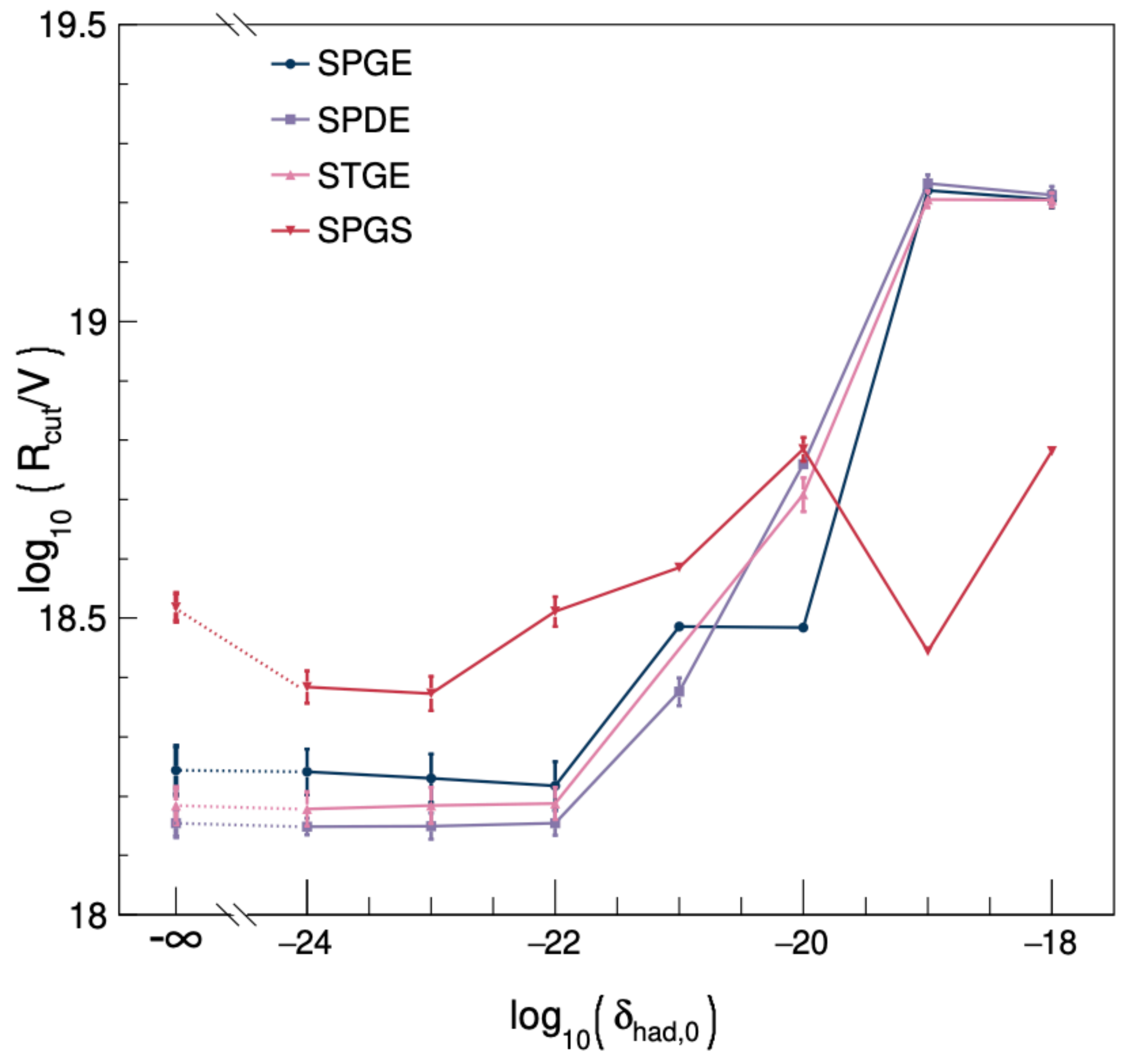
Effect on CR propagation:

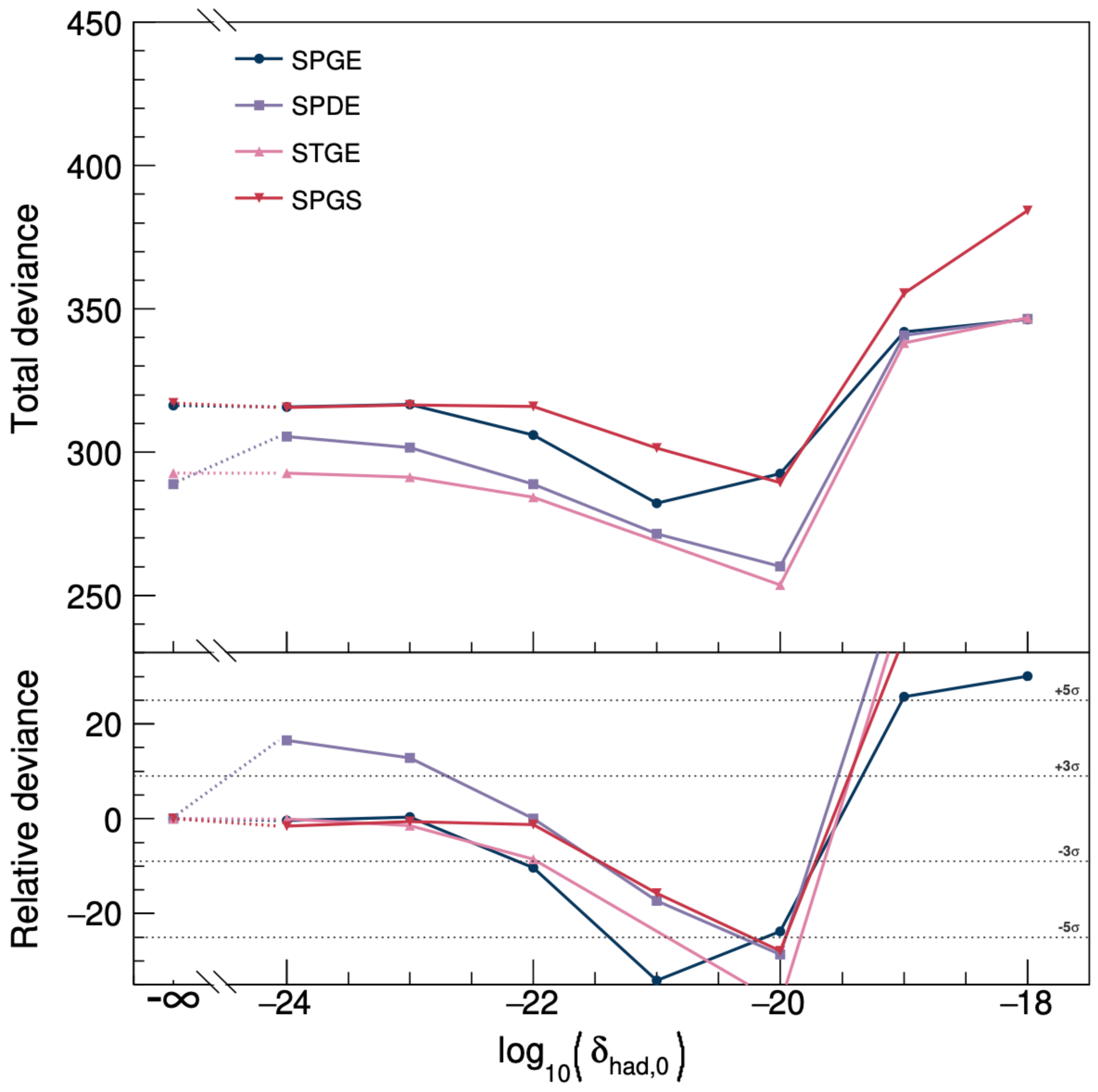
- Threshold energy increases -> less interactions -> if LIV, lighter nuclear species are needed at the sources in order to reproduce the observed composition

EXPECTED CR SPECTRUM AND COMPOSITION

The Pierre Auger Collaboration, JCAP 2022

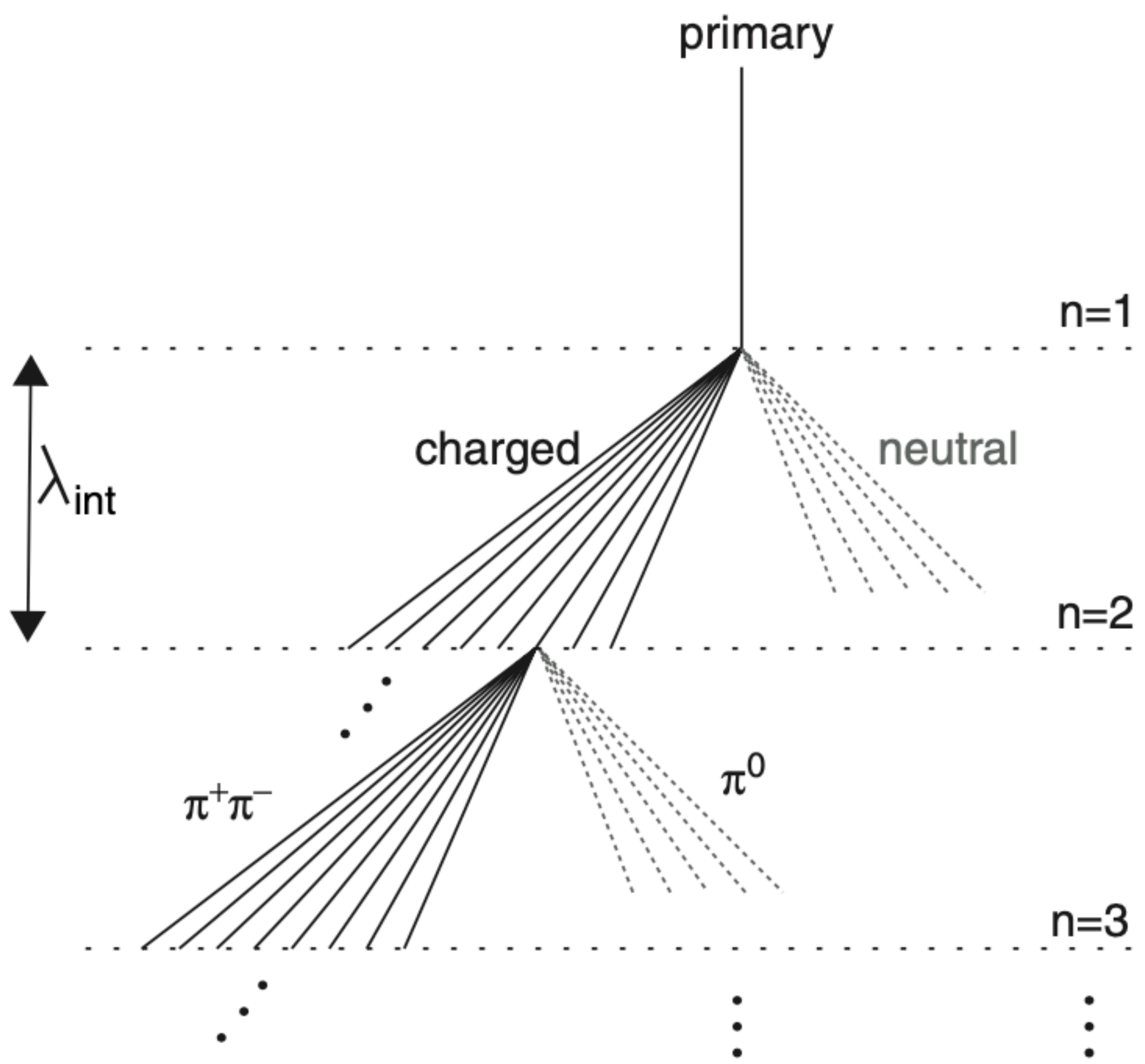


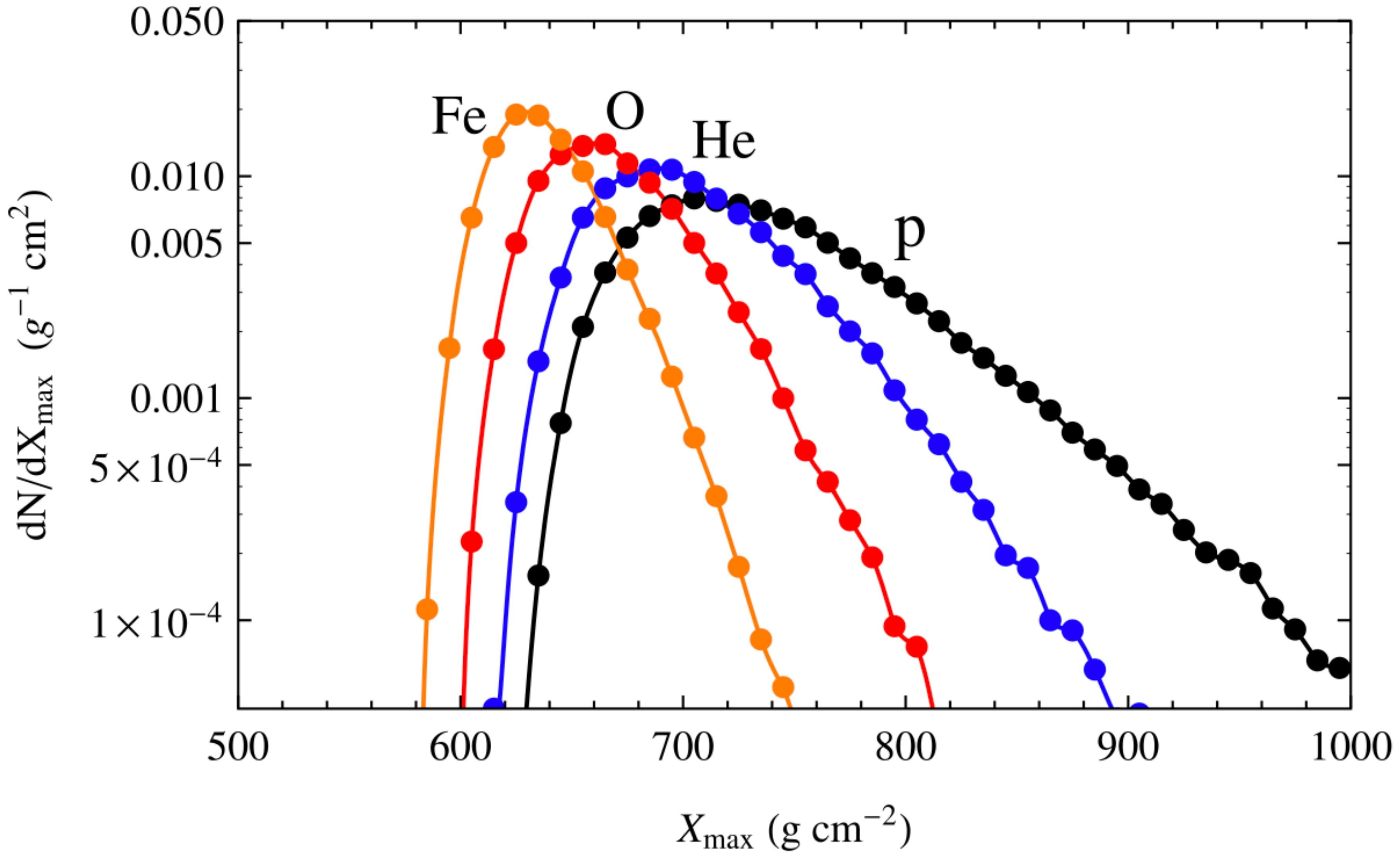




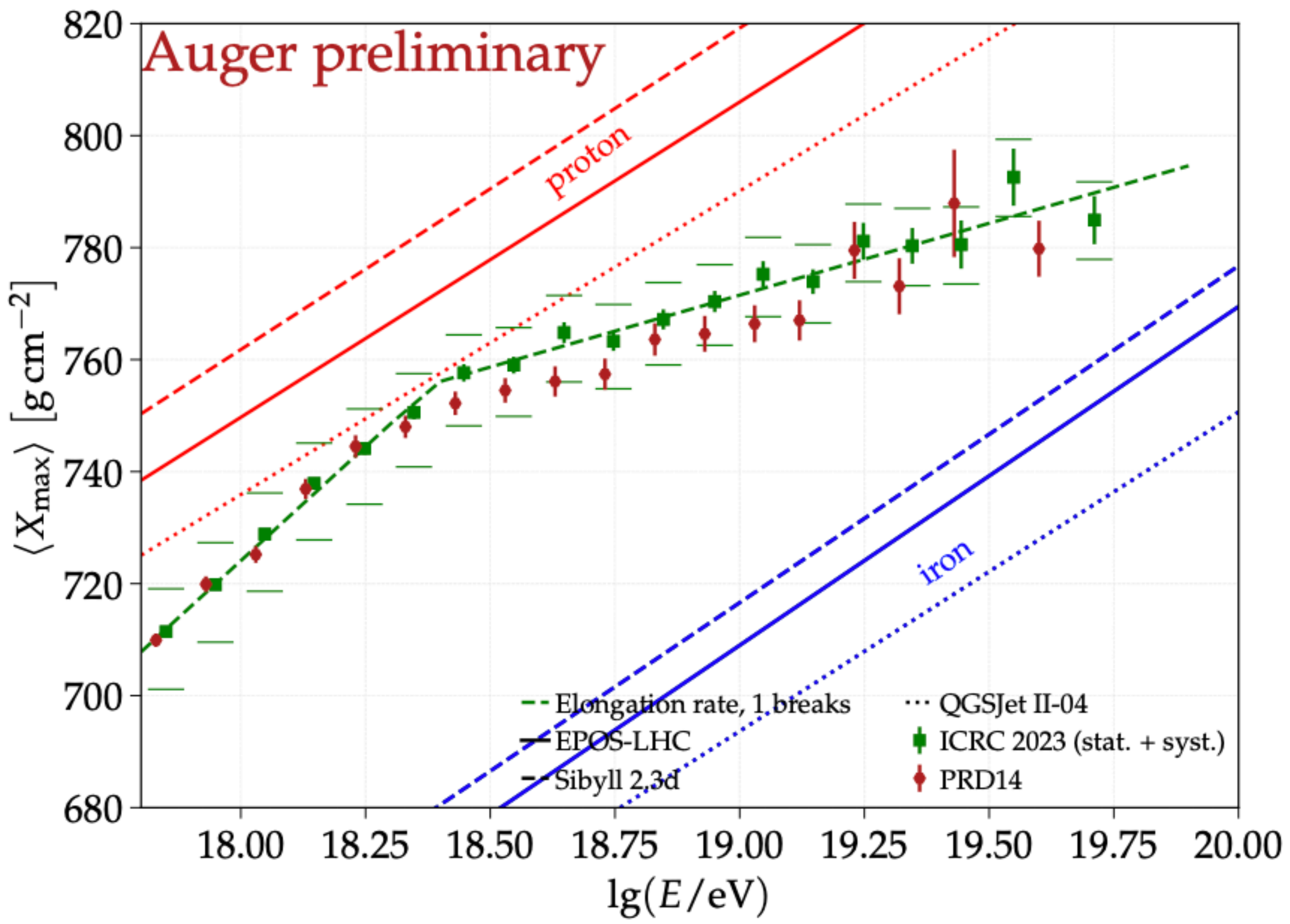
- Interpretation in terms of spectral parameters at the source is affected
  - Larger LIV effects -> less interactions -> softer spectra

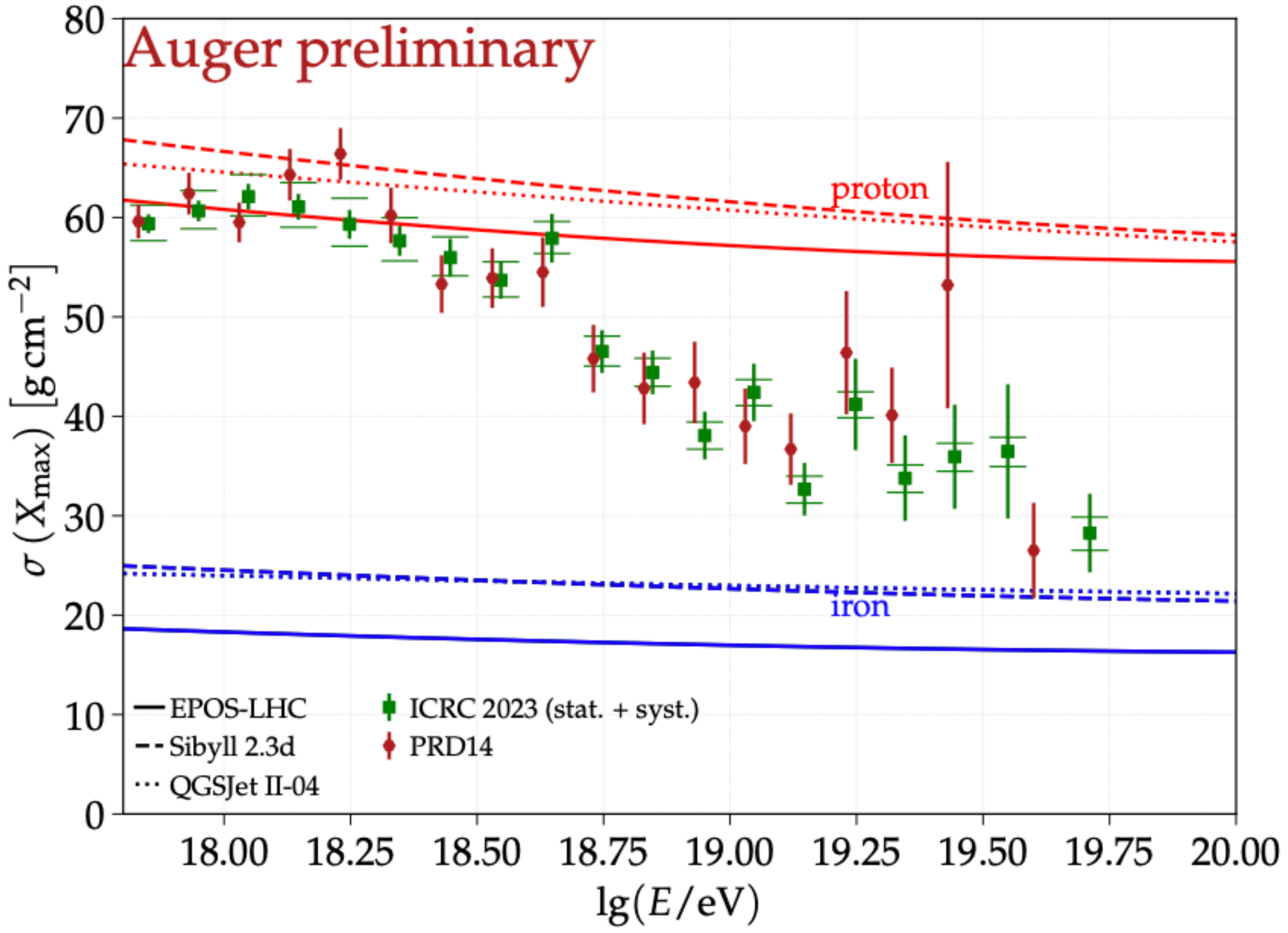
THE **MASS COMPOSITION MEASUREMENTS**





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

PARTICLE DETECTOR ARRAYS

DETERMINATION OF CR COMPOSITION

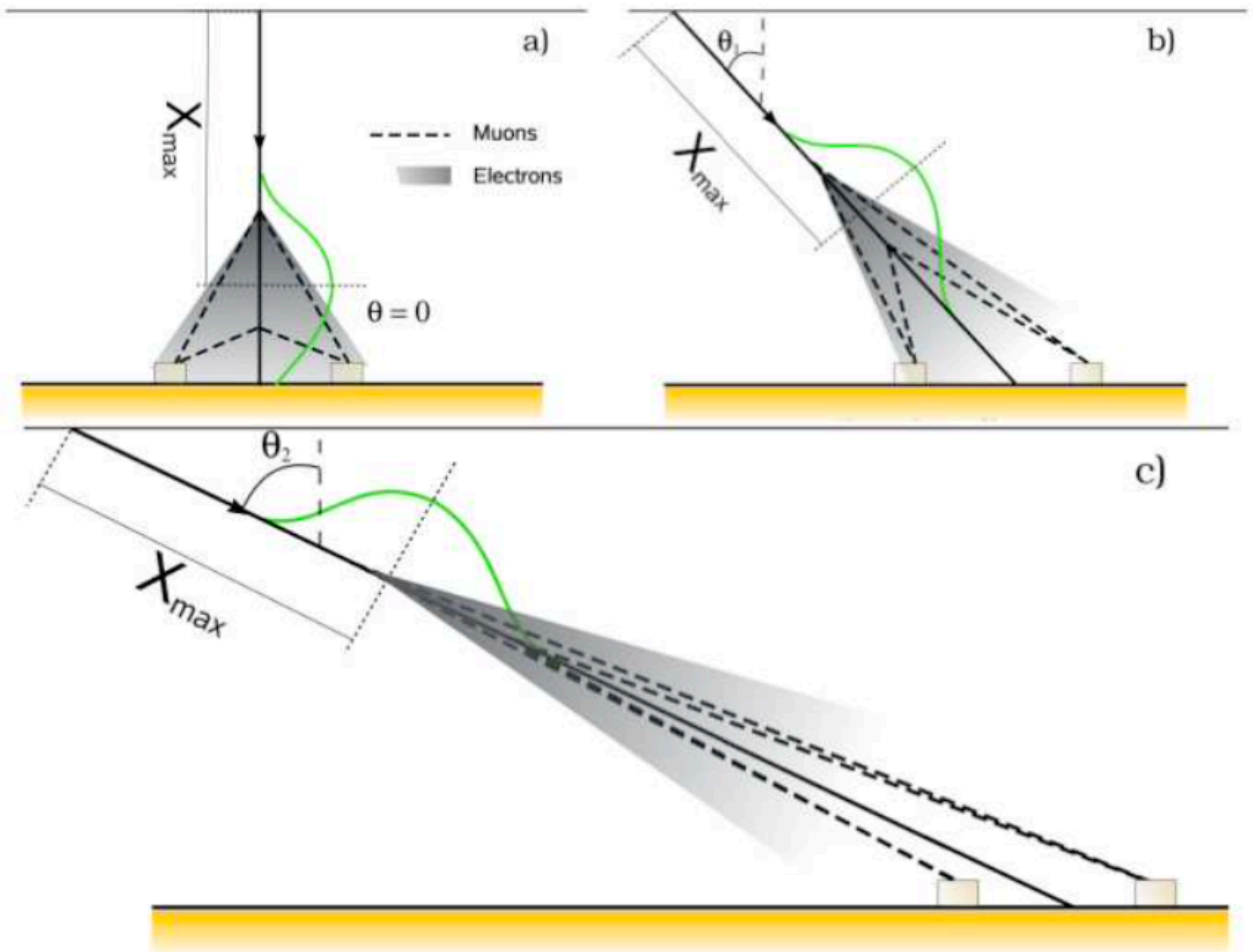
- Curved profile of the shower
  - Particles at distance r from the core are delayed with respect to the shower axis
    - Delay increases with r and decreases with h
    - Showers initiated from heavy (light) particles with same energy will be less (more) delayed

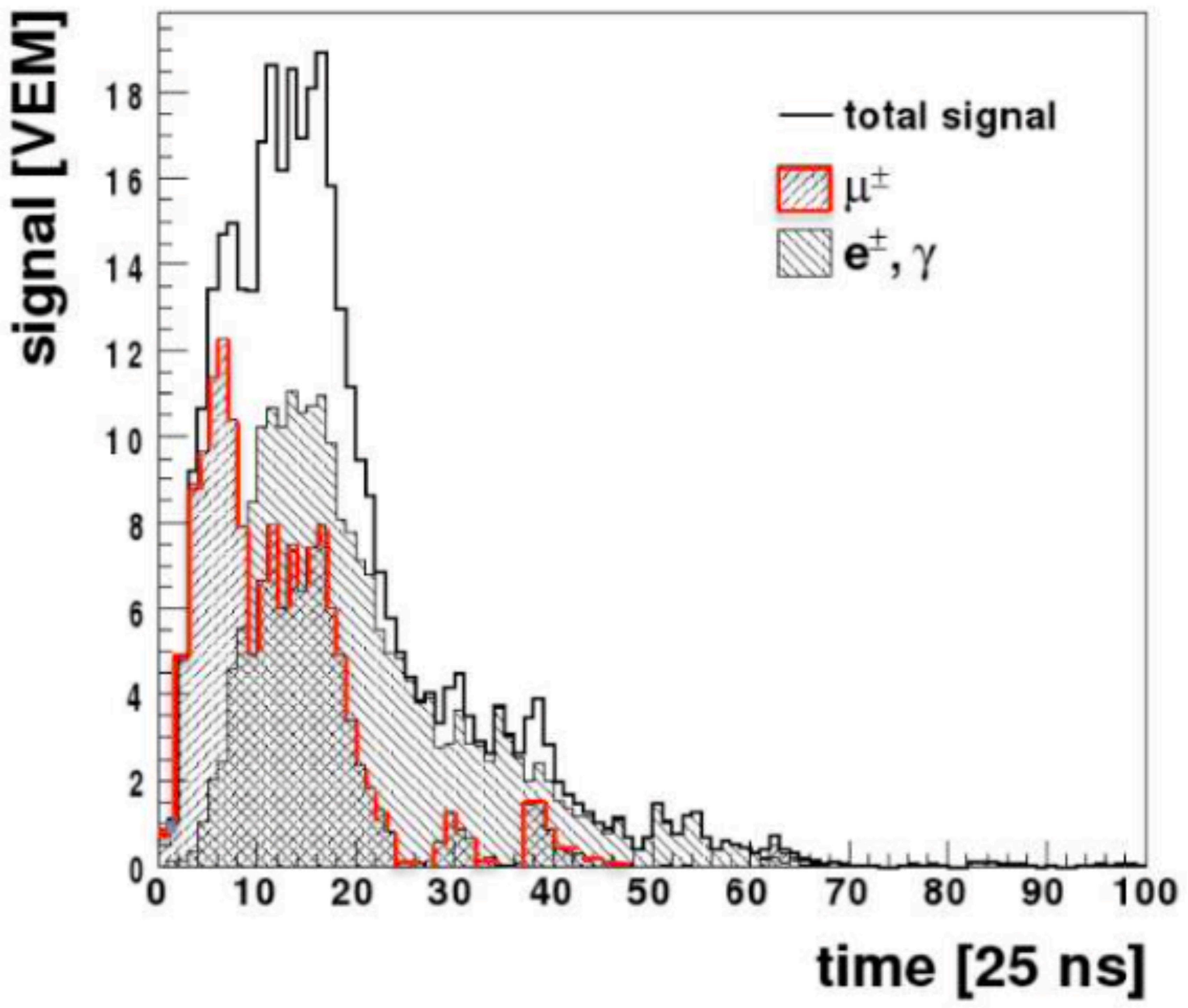
$$t = \frac{1}{c}\left(\sqrt{h^2 + r^2} - h\right) \propto \frac{r^2}{h}, \text{ if } r \ll h$$

PARTICLE DETECTOR ARRAYS

DETERMINATION OF CR COMPOSITION

- Muons dominate the early part of the signal in the particle detectors, and the signal is shorter
- At the increase of the zenith angle, an **early-late time asymmetry** might appear
  - At very large zenith angles, the EM component is more absorbed
  - Muon component does not have asymmetry





WHAT DO WE LEARN FROM THE MASS COMPOSITION OBSERVABLES?

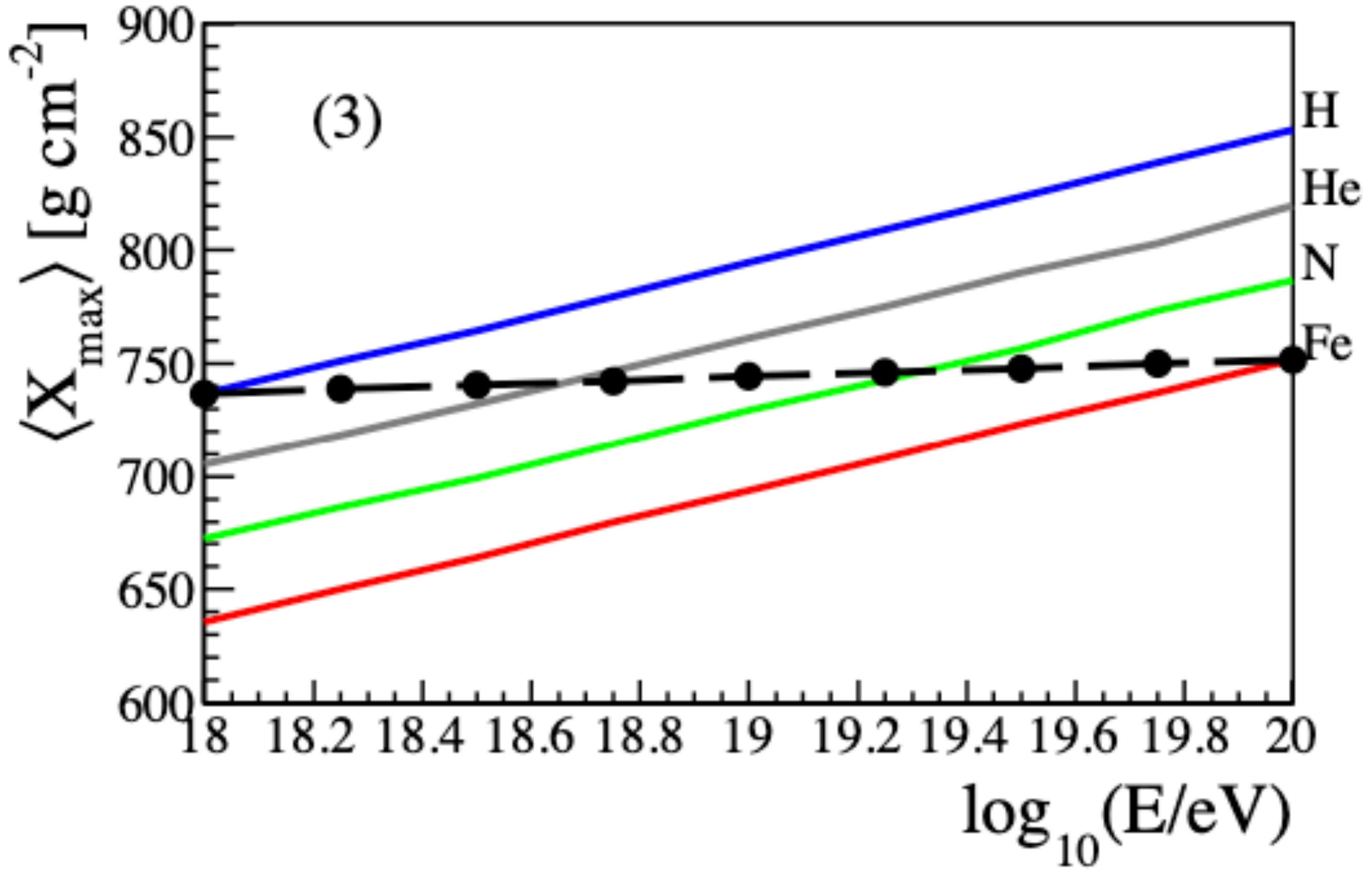
$\boxed{\langle X_{max} \rangle = \langle X_{max} \rangle_p + f \langle \ln A \rangle}$ $\boxed{\sigma^2(X_{max}) = \langle \sigma^2_{sh} \rangle + f^2 \sigma^2(\ln A)}$

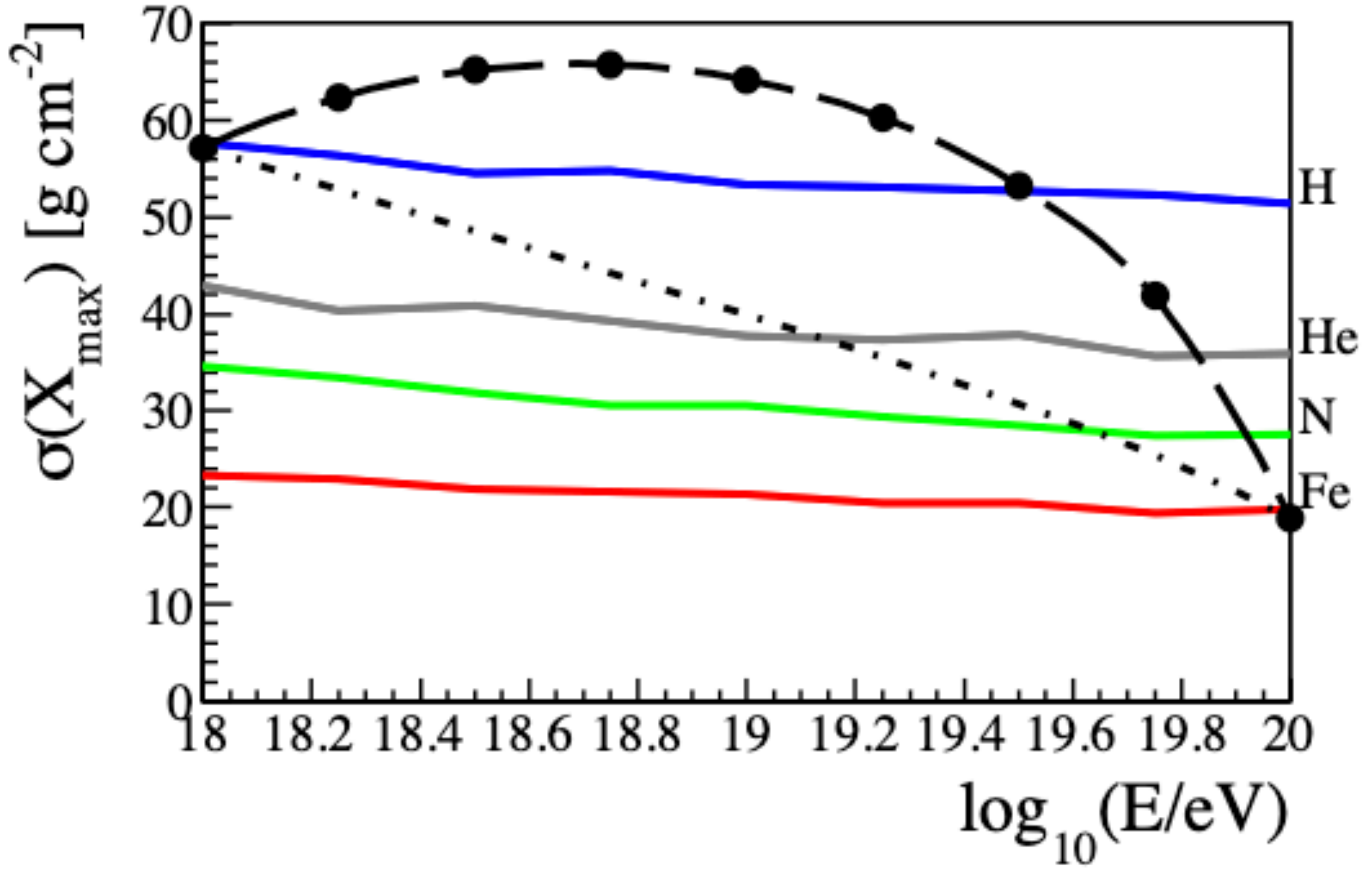
Focusing on the second momentum: it contains

- 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:

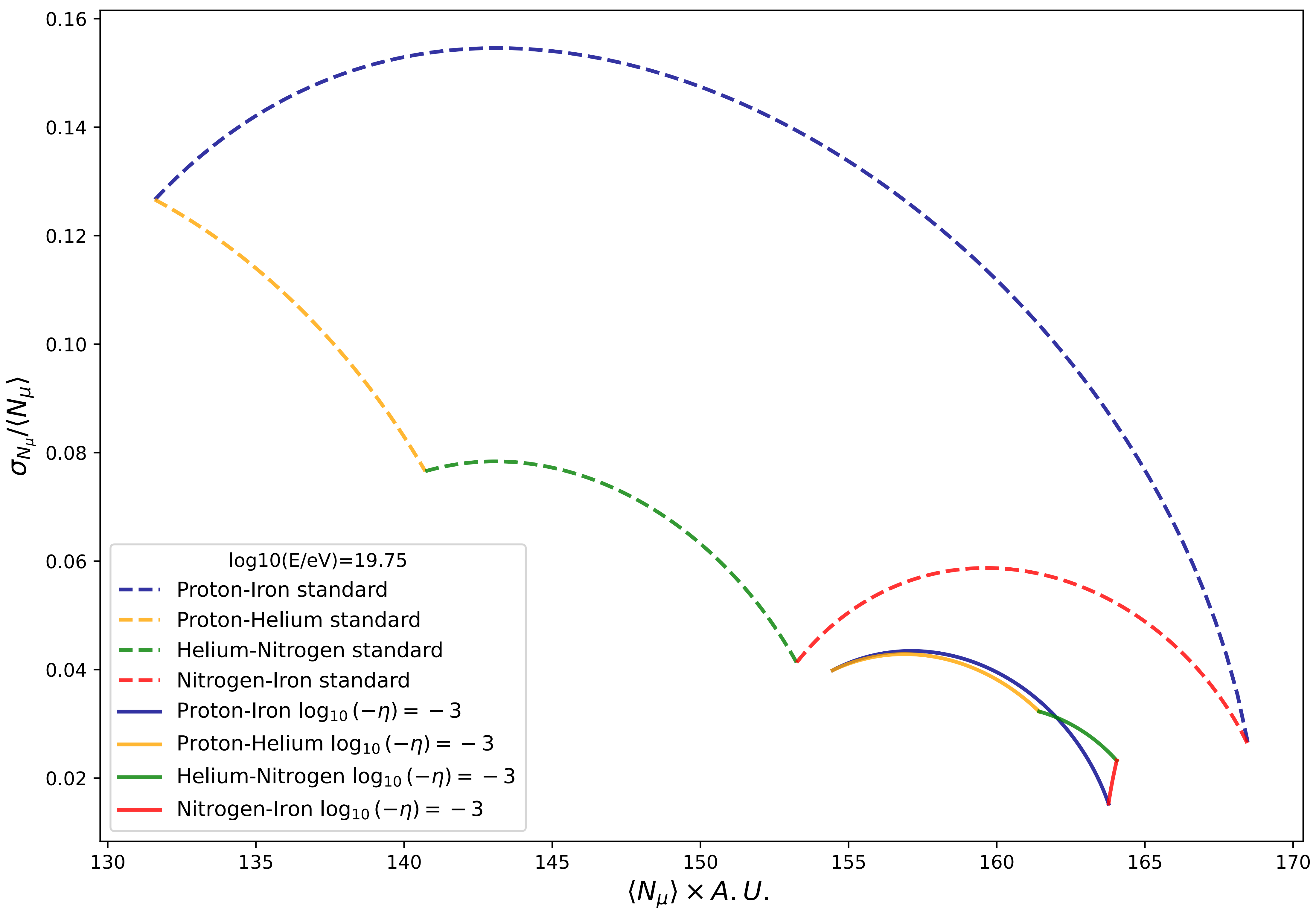
$$\sigma^2(X_{\rm max}) =$$

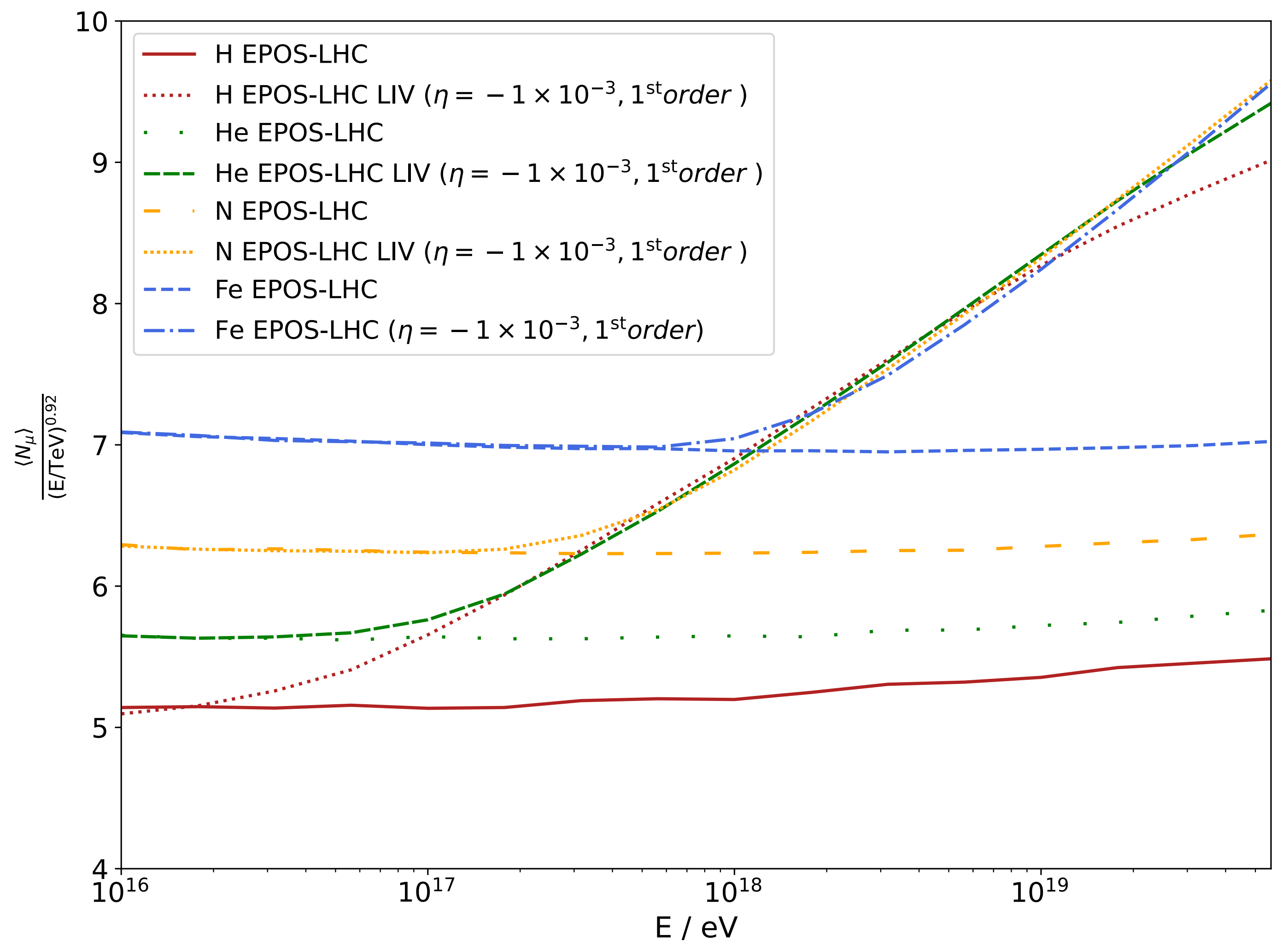
$$f\sigma_1^2 + (1-f)\sigma_2^2 + f(1-f)(\Delta(\langle X_{\rm max}\rangle))^2$$

Modification of mass observables

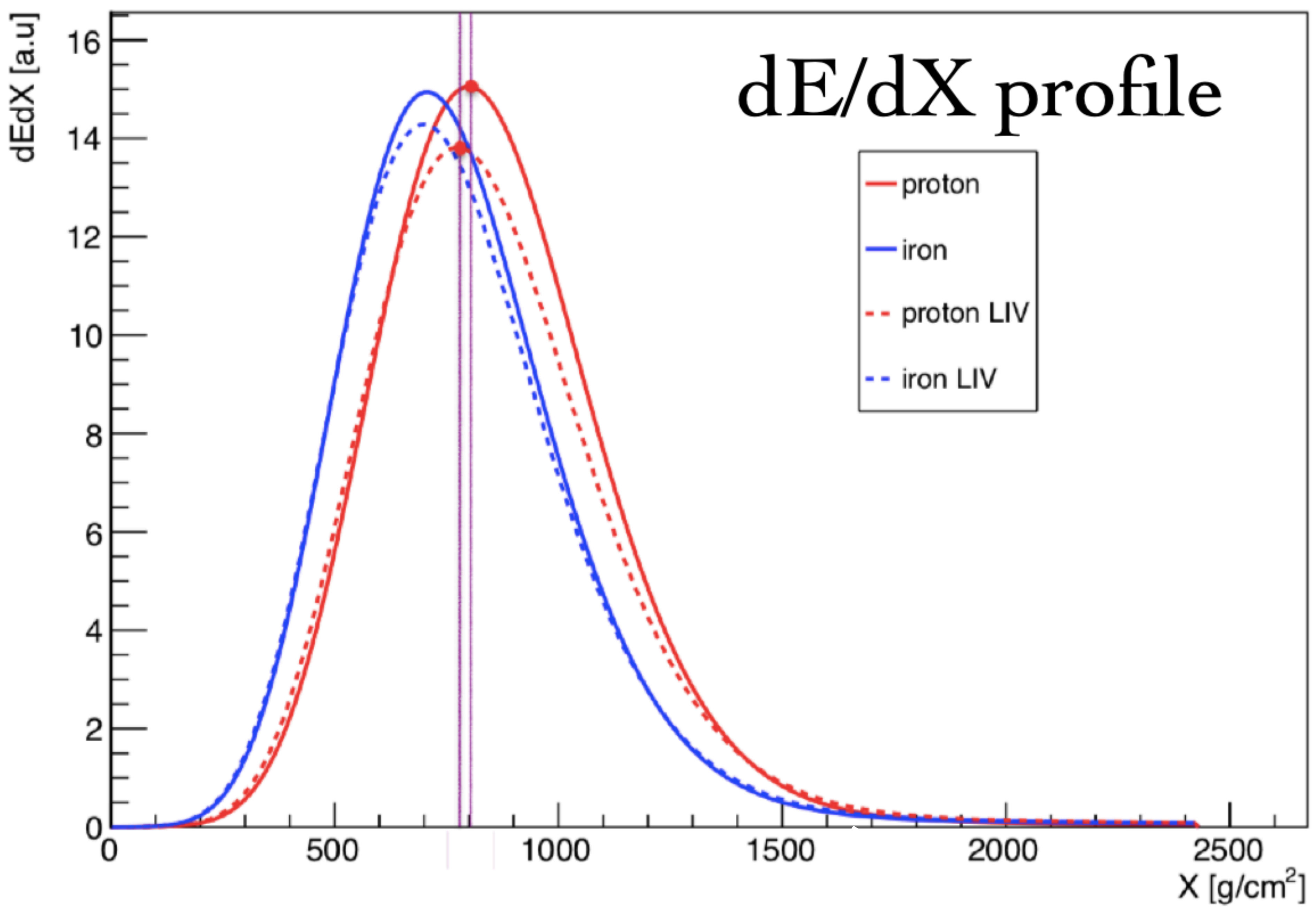
- Simulations of the longitudinal profile of the shower using the CONEX software for the LI and LIV cases. For the LIV scenario, the software has been modified by changing the lifetime of any unstable particle. The η(n) values considered in this study span the range from -10^{-1} to -10^{-6} in logarithmic steps, with order of violation n = 1.

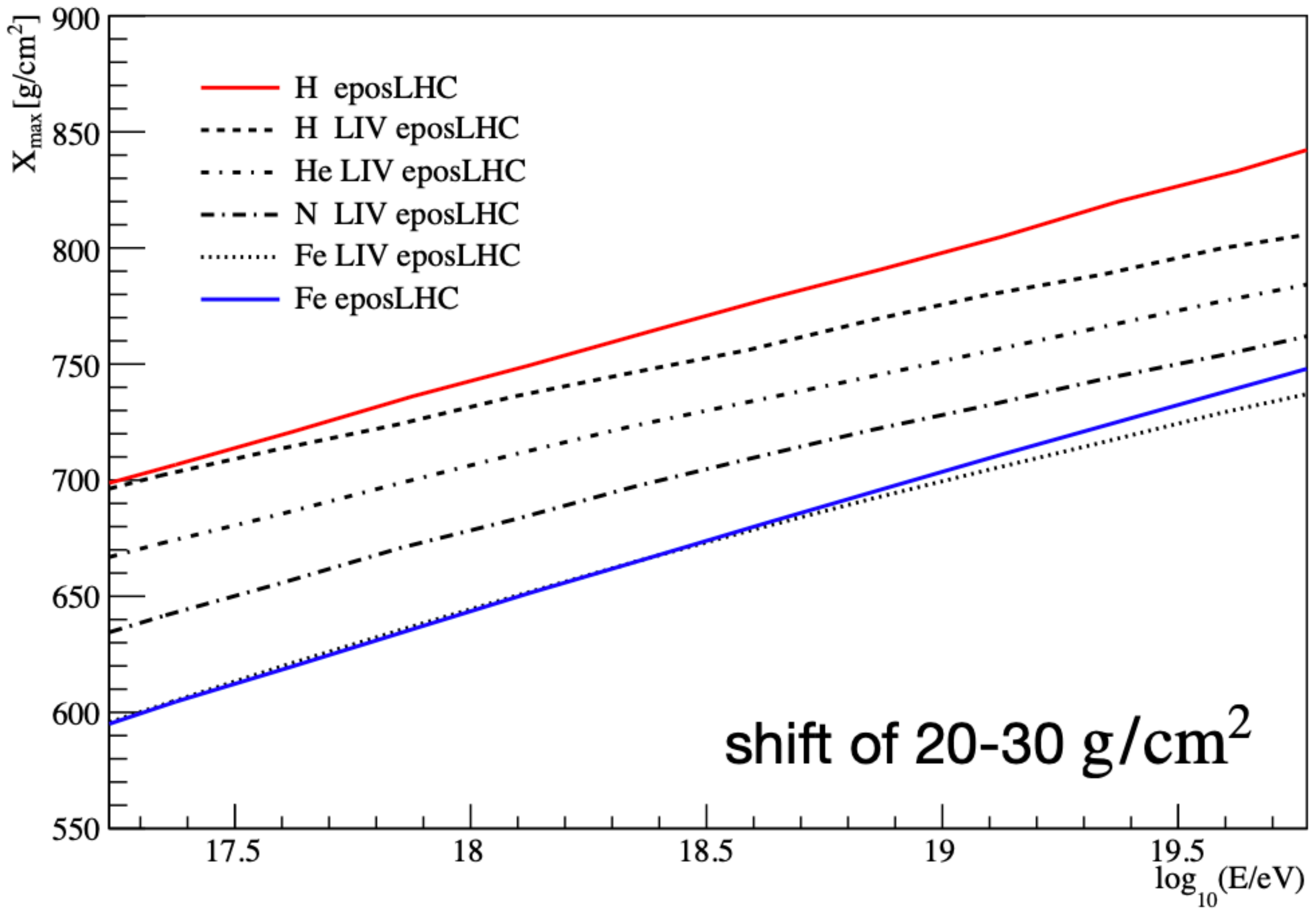
- For each value of η, 15000 primary cosmic-ray particles have been produced in the energy range between 1014 eV and 1021 eV, using EPOS-LHC and QGSJetII-04hadronic interaction models and for different primary particle types i.e. hydrogen, helium, nitrogen, silicon and iron nuclei





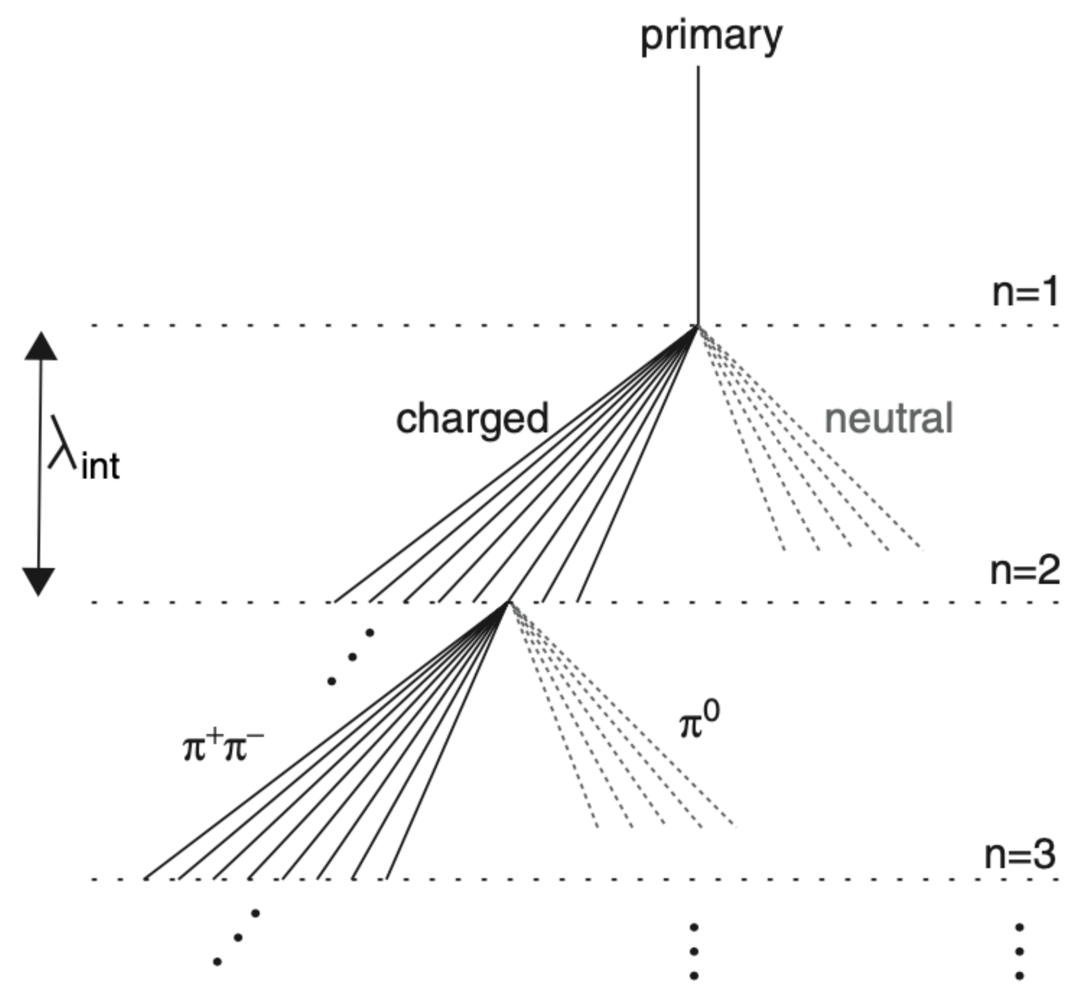
Modification of mass observables (electromagnetic component of the shower)





- 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

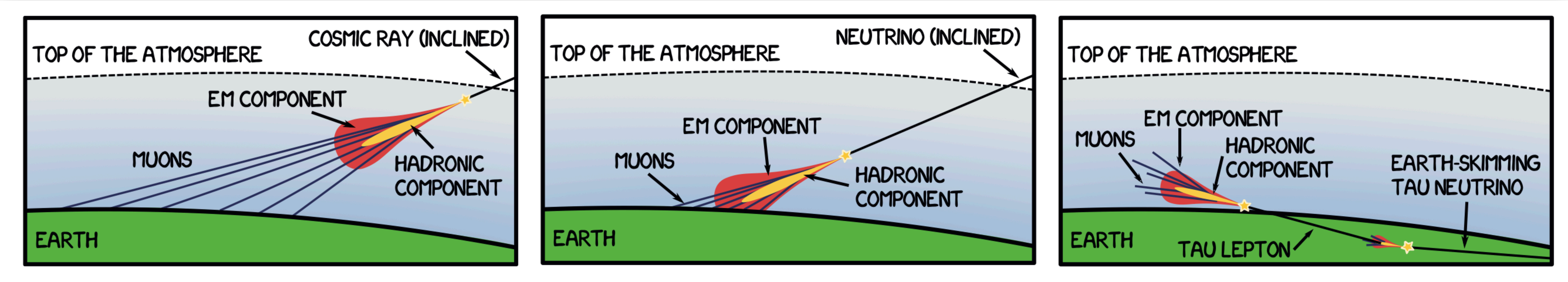
How to search for neutrinos



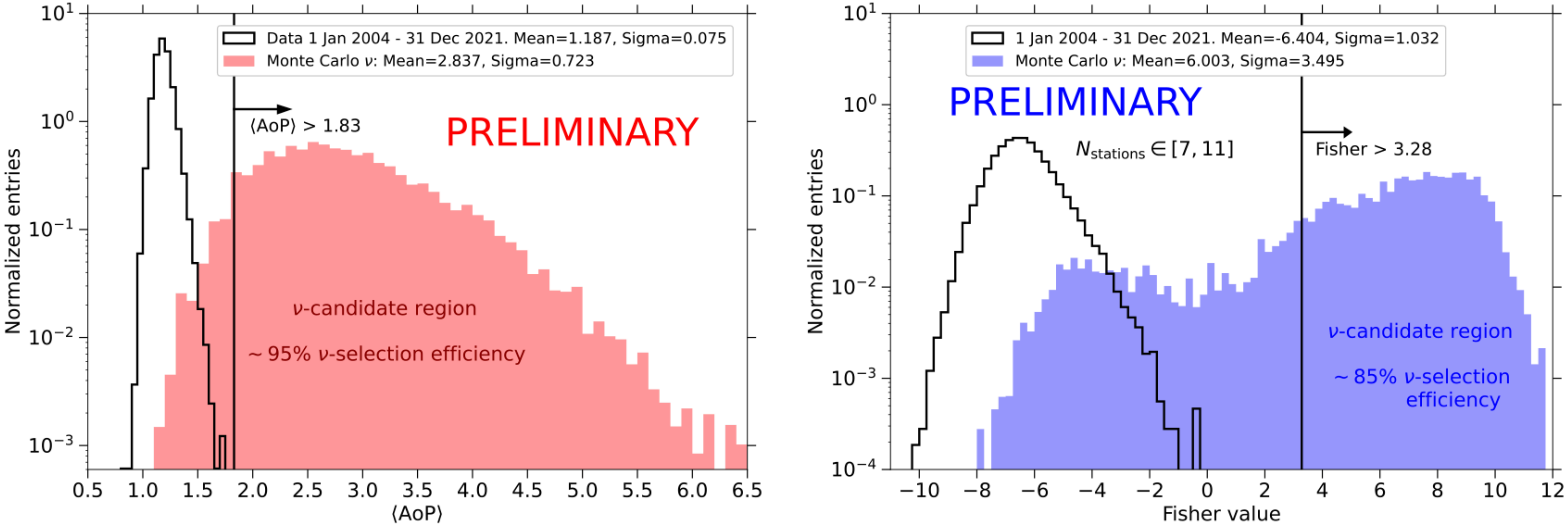
Measurements at UHE happen through the observation of extensive air showers (also for neutrinos and photons!)

How to search for neutrinos:

- **Inclined showers** with electromagnetic component (down-ward going **DG**)
- **Upgoing showers** from Earth-skimming tau neutrinos



How to search for neutrinos



- 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**

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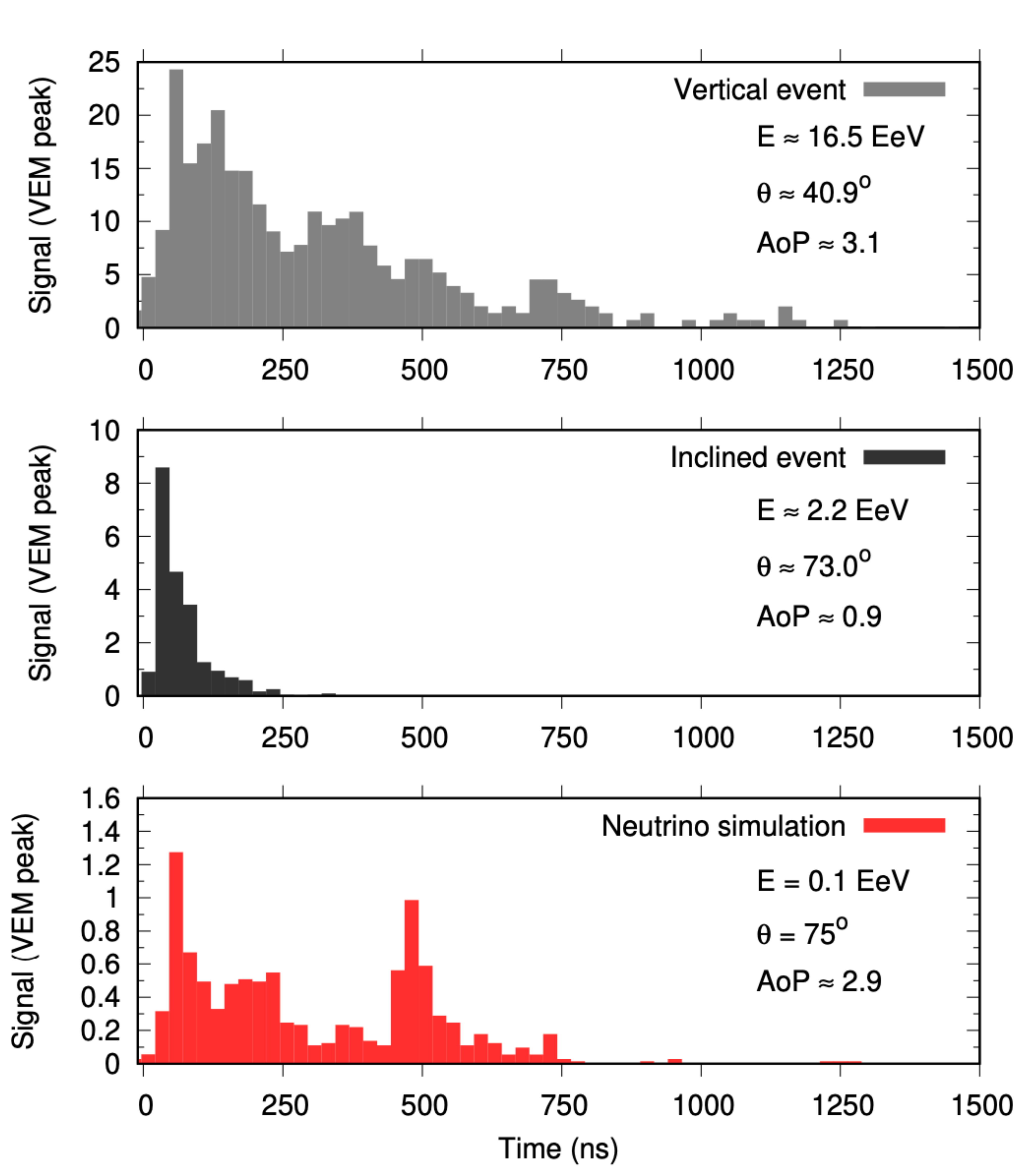
How to search for neutrinos



- Select showers that arrive at the SD array in the inclined directions and identify those that exhibit a broad time structure in the signals induced in the SD stations
- <u>Information from geometry</u>: in inclined events the pattern of the triggered SD stations exhibits an elliptical shape on the ground with the major axis of the ellipse along the azimuthal arrival direction
- <u>Information from timing</u>: several observables that contain information on the spread in time in the SD stations can be extracted from the time traces -> area over peak (AoP) can discriminate broad from narrow shower fronts

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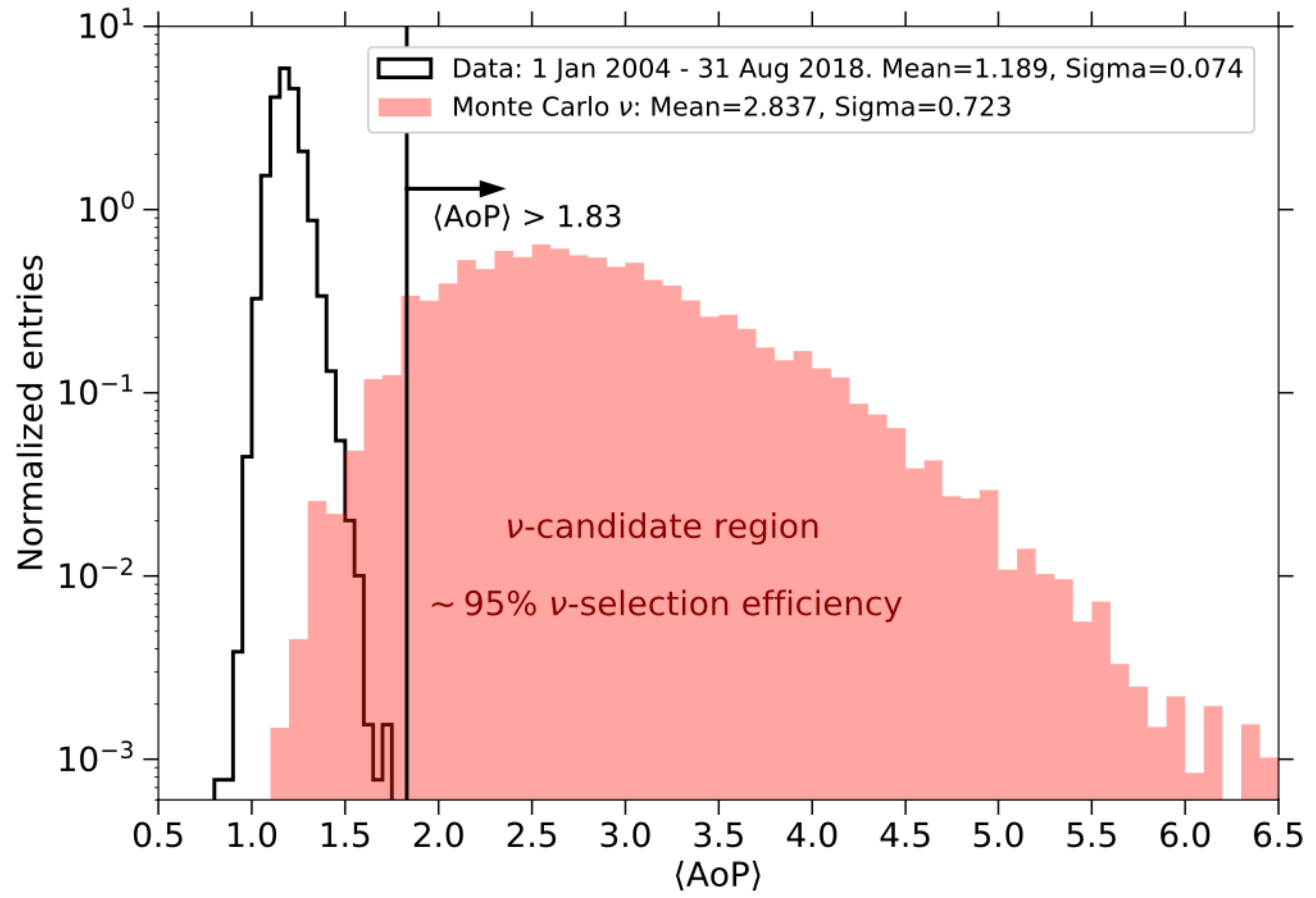
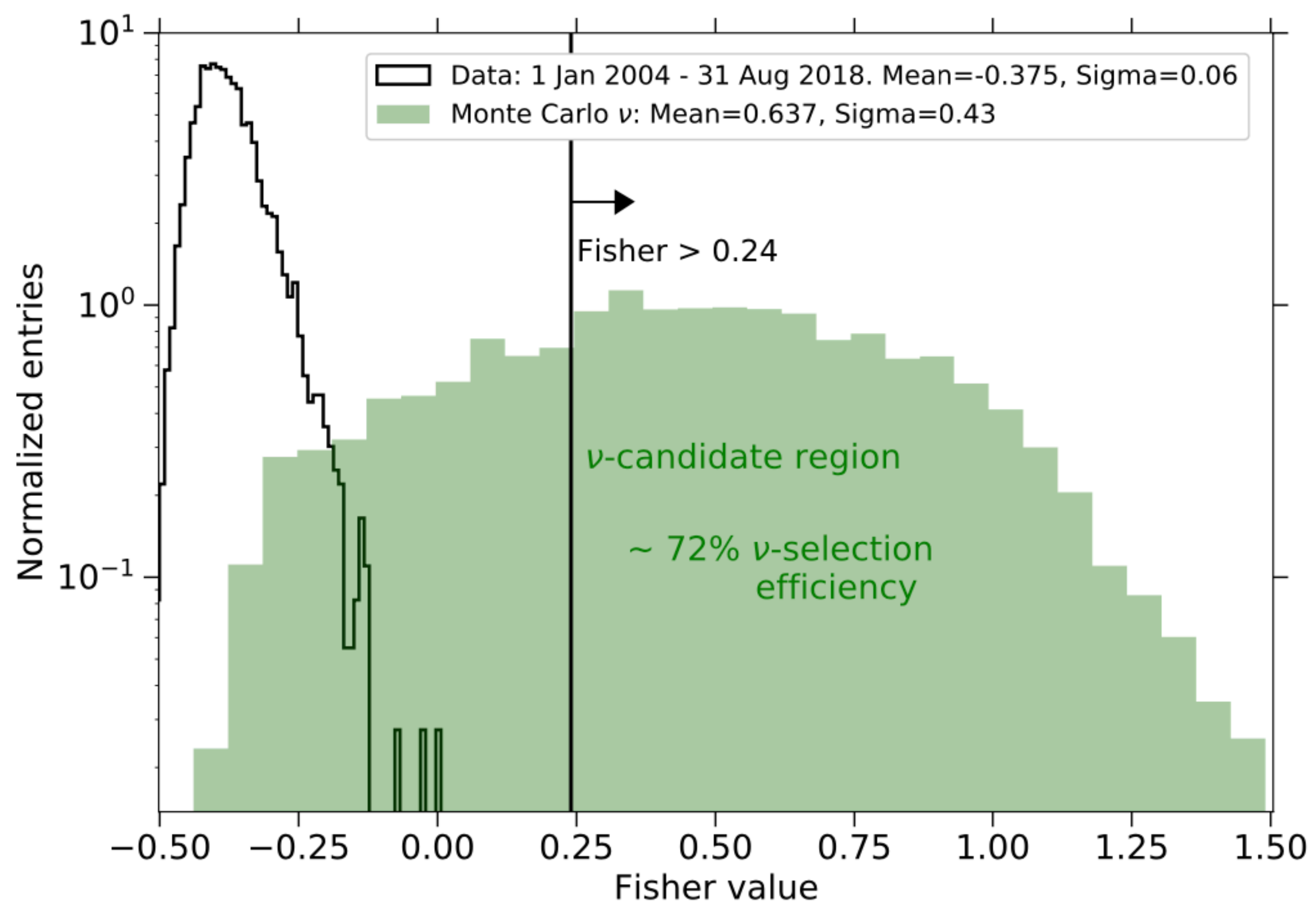
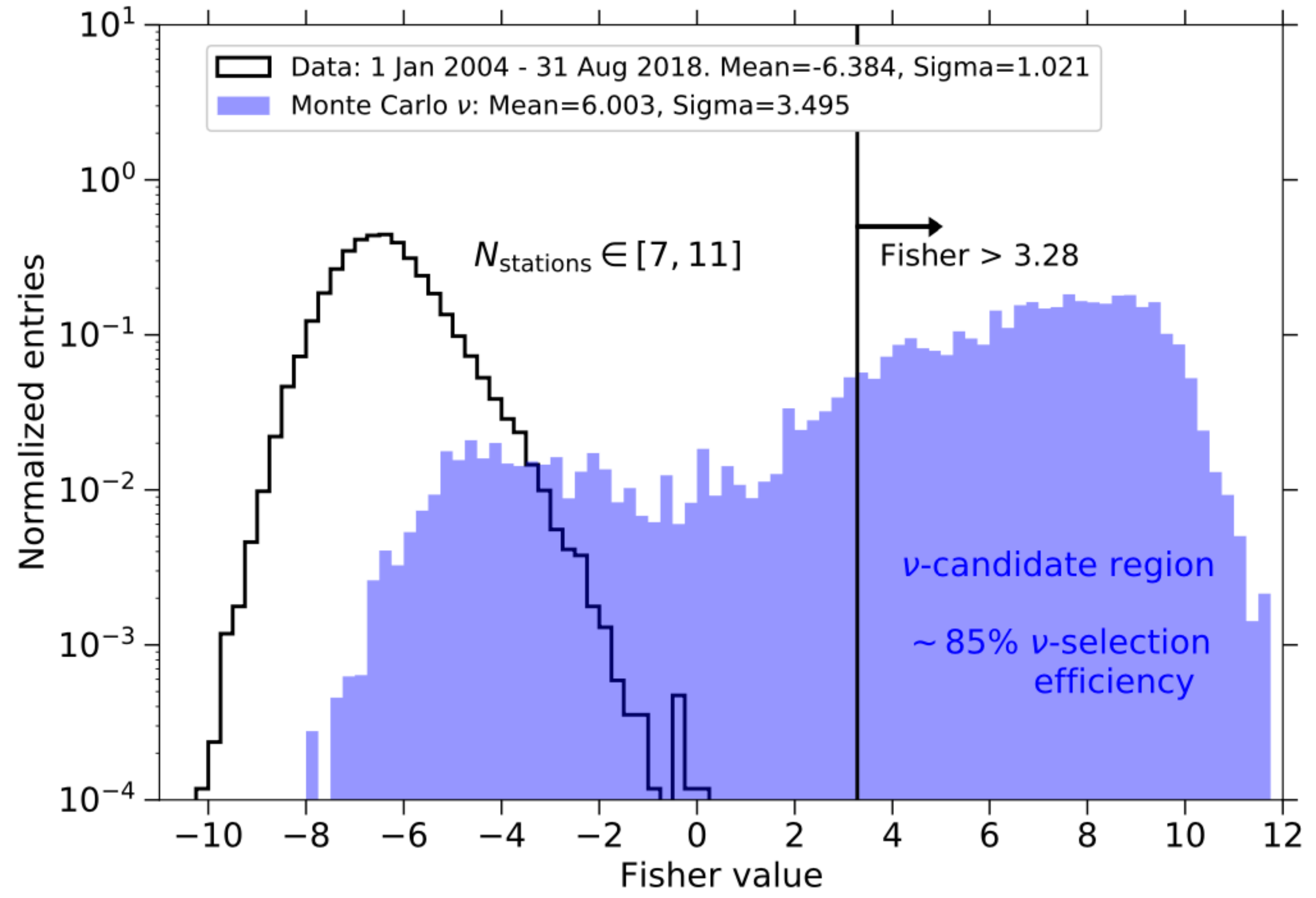
How to search for neutrinos



Earth-skimming



Downward (low zenith angle), 60<ϑ<75



Downward (high zenith angle) 75<ϑ<90

- The average value of AoP over all the triggered stations in the event is used as the only observable to discriminate between hadronic showers and ES neutrinos.
- The value of the cut on AoP is fixed using the tail of the distribution of AoP in real data, which is consistent with an exponential function

- Multivariate analysis to combine several observables that carry information on the time spread of the signals in the SD stations; observables are constructed from the AoP values of individual stations

- DWL: Selection more challenging due to the contamination from hadronic showers; the primary observables for inclined selection in the DGH case are the ratio L/W of the signal pattern of the shower at ground as well as the apparent average velocity of the signal, in addition to a simple estimate of the zenith angle

- DWH: The discriminants are constructed with ten variables that exploit the fact that, due to the large inclination of the shower, the electromagnetic component is less attenuated in the stations that are first hit by a deep inclined shower than in those that are hit last

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Upper limits on the diffuse flux of neutrinos

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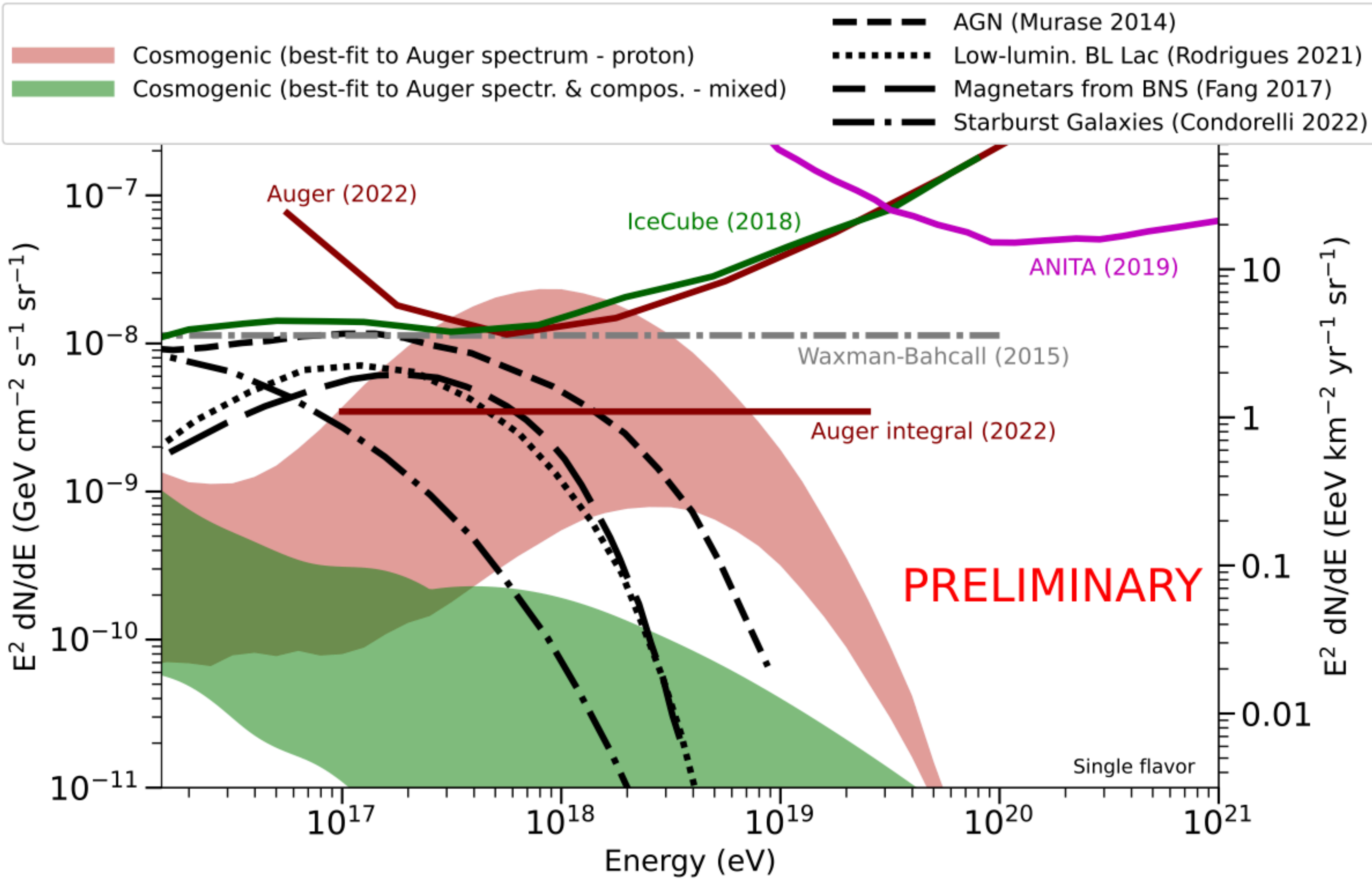
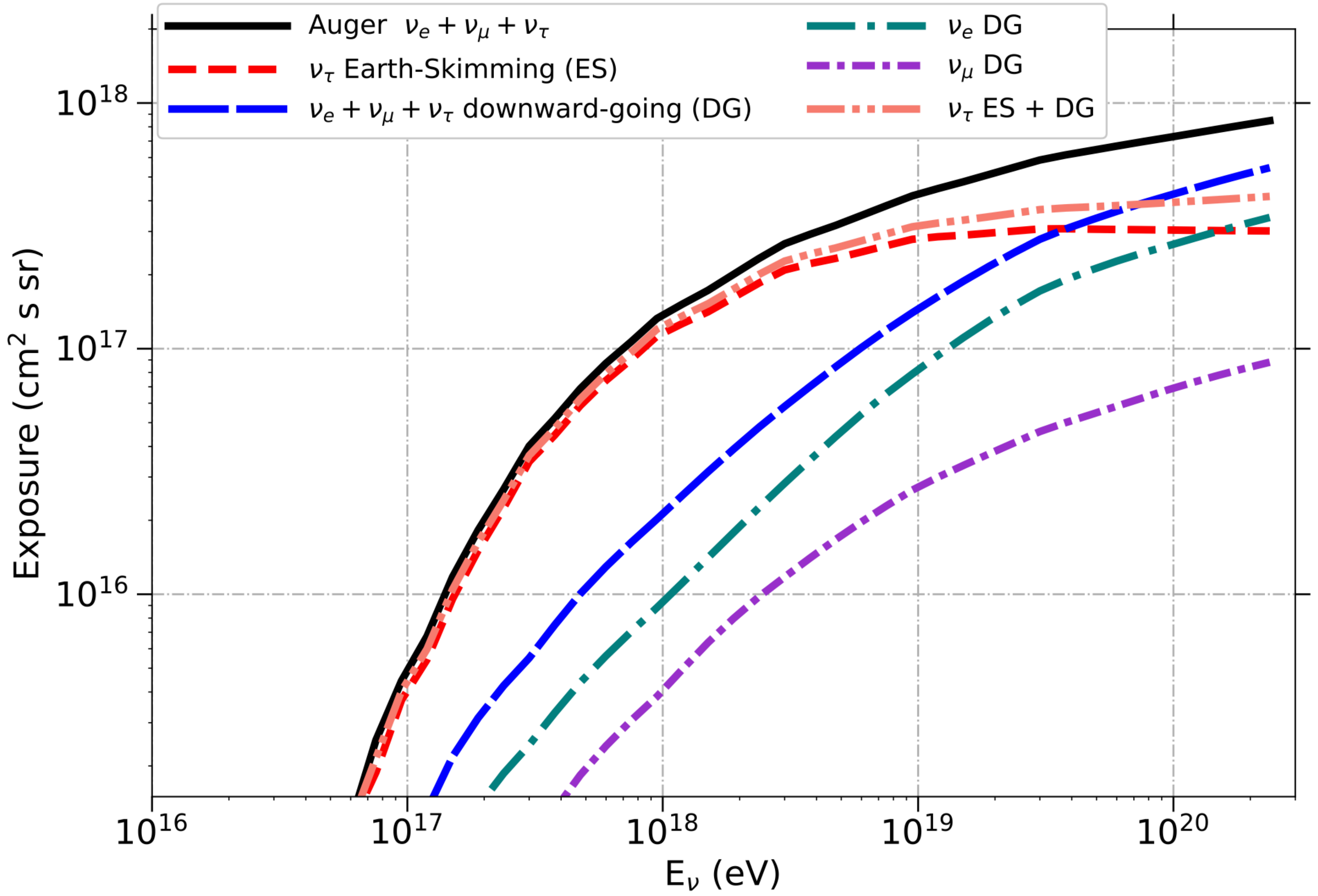
- Assumption: $\phi = k \cdot E_\nu^{-2}$ $\quad N_{\rm evt} = \int_{E_\nu} \mathcal{E}_{\rm tot}(E_\nu)\ \phi(E_\nu)\ {\rm d}E_\nu.$

$$k_{90} = \frac{2.39}{\int_{E_\nu} E_\nu^{-2}\ \mathcal{E}_{\rm tot}(E_\nu)\ {\rm d}E_\nu},$$





Several classes of models of neutrino production, both cosmogenic and astrophysical, can be constrained thanks to the upper limit

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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

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

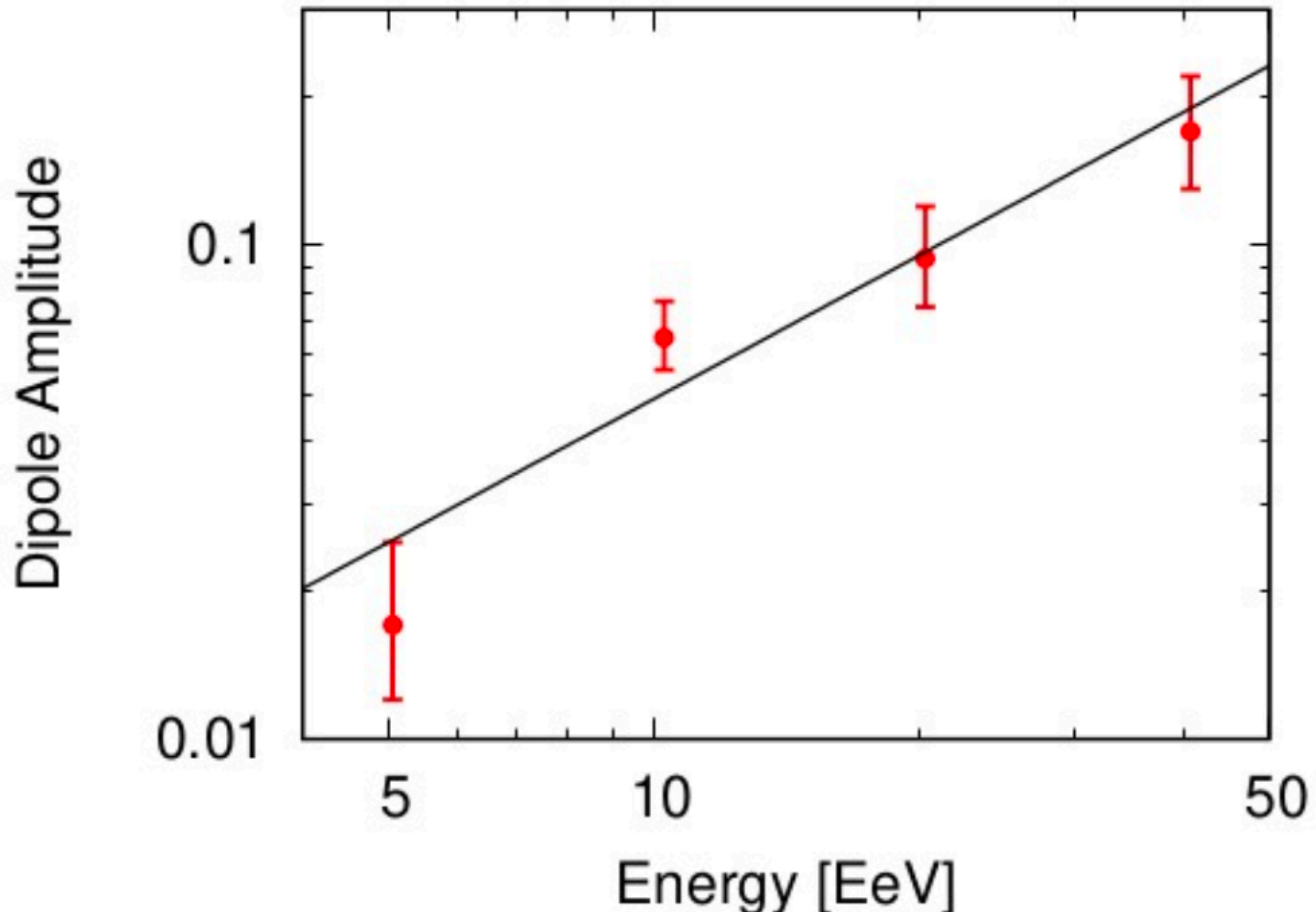
first-harmonic Fourier components

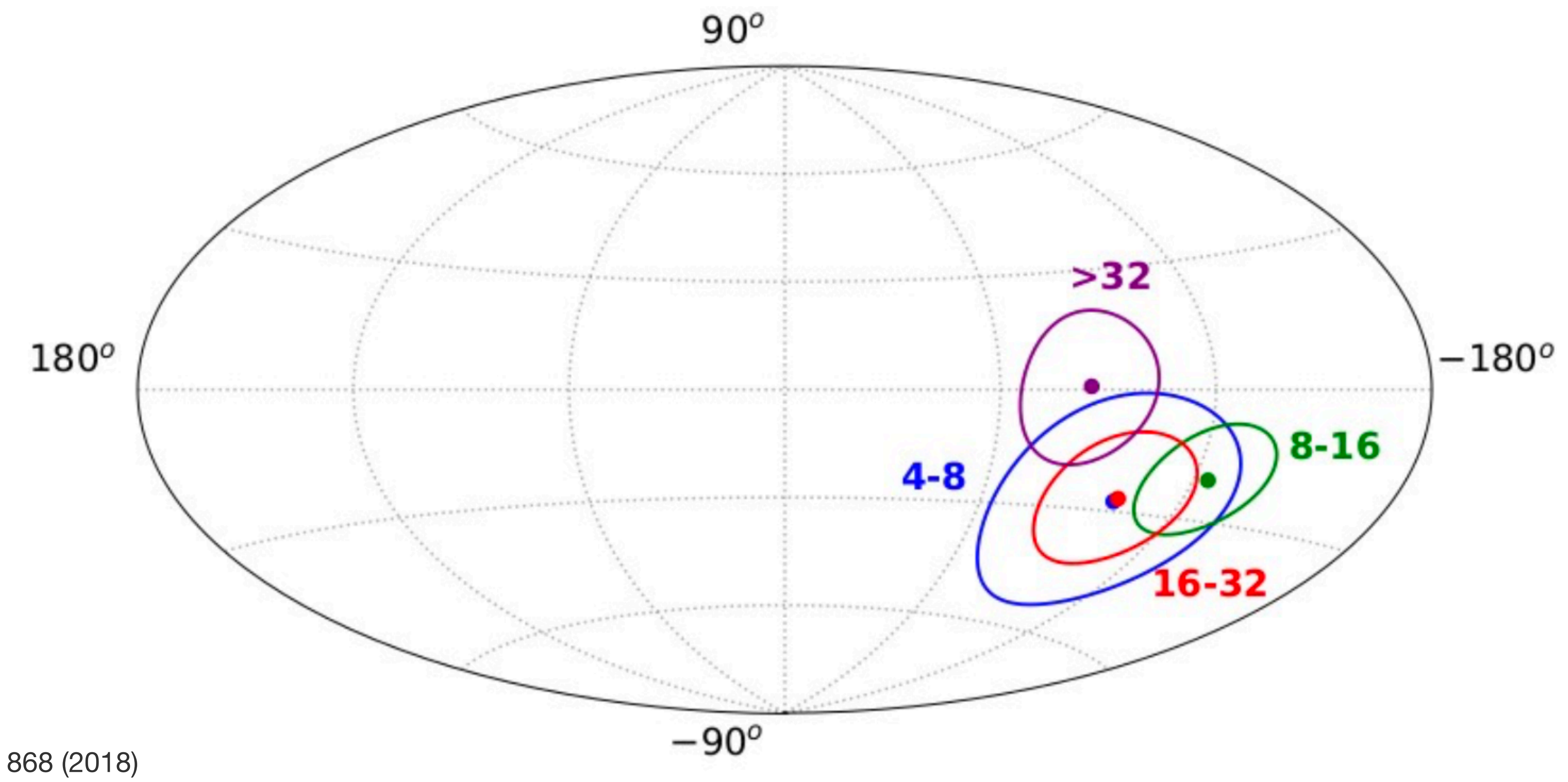
$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}, \qquad \tan \varphi_\alpha = \frac{b_\alpha}{a_\alpha}.$$

Amplitude and phase

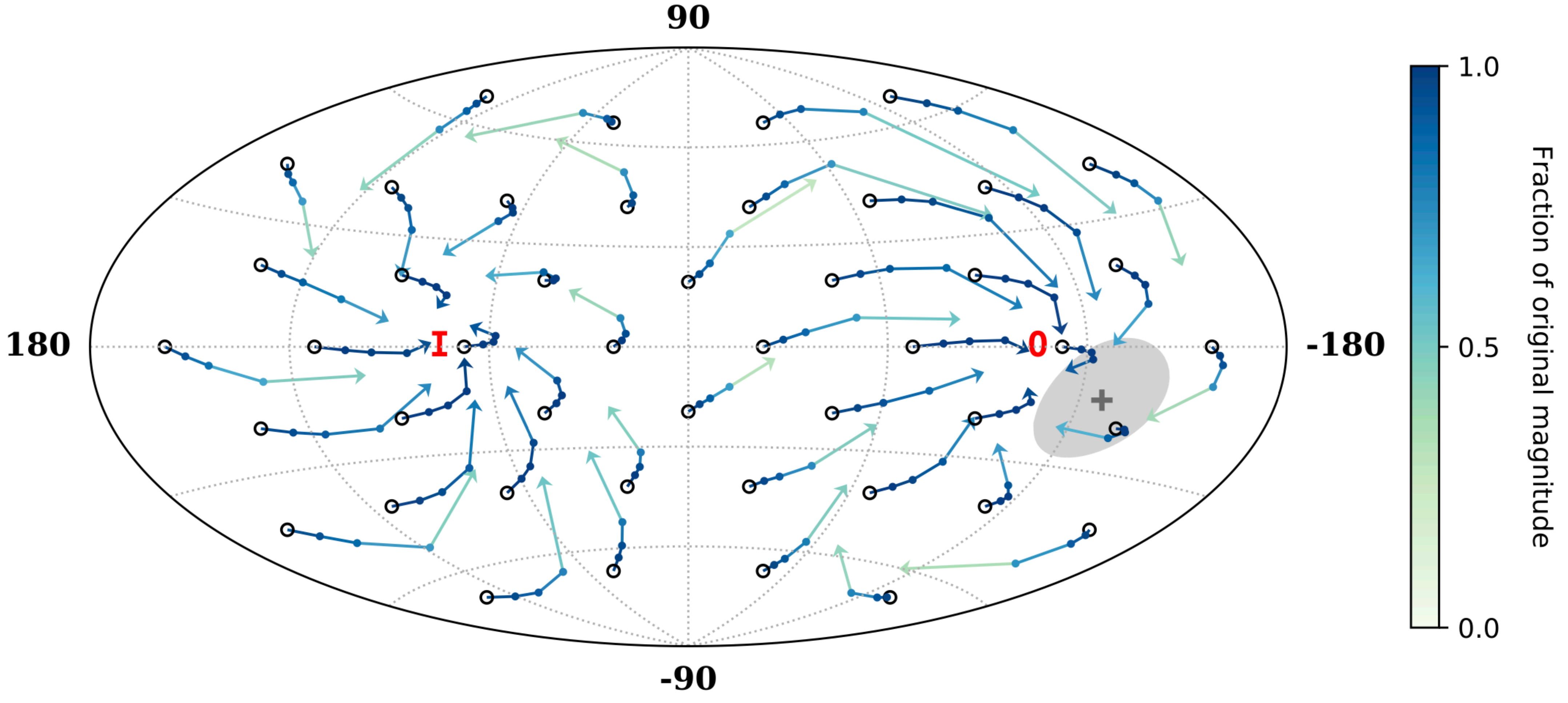
The dipole

arxiv:2408.05292, submitted to ApJ





Astrophys.J. 868 (2018)

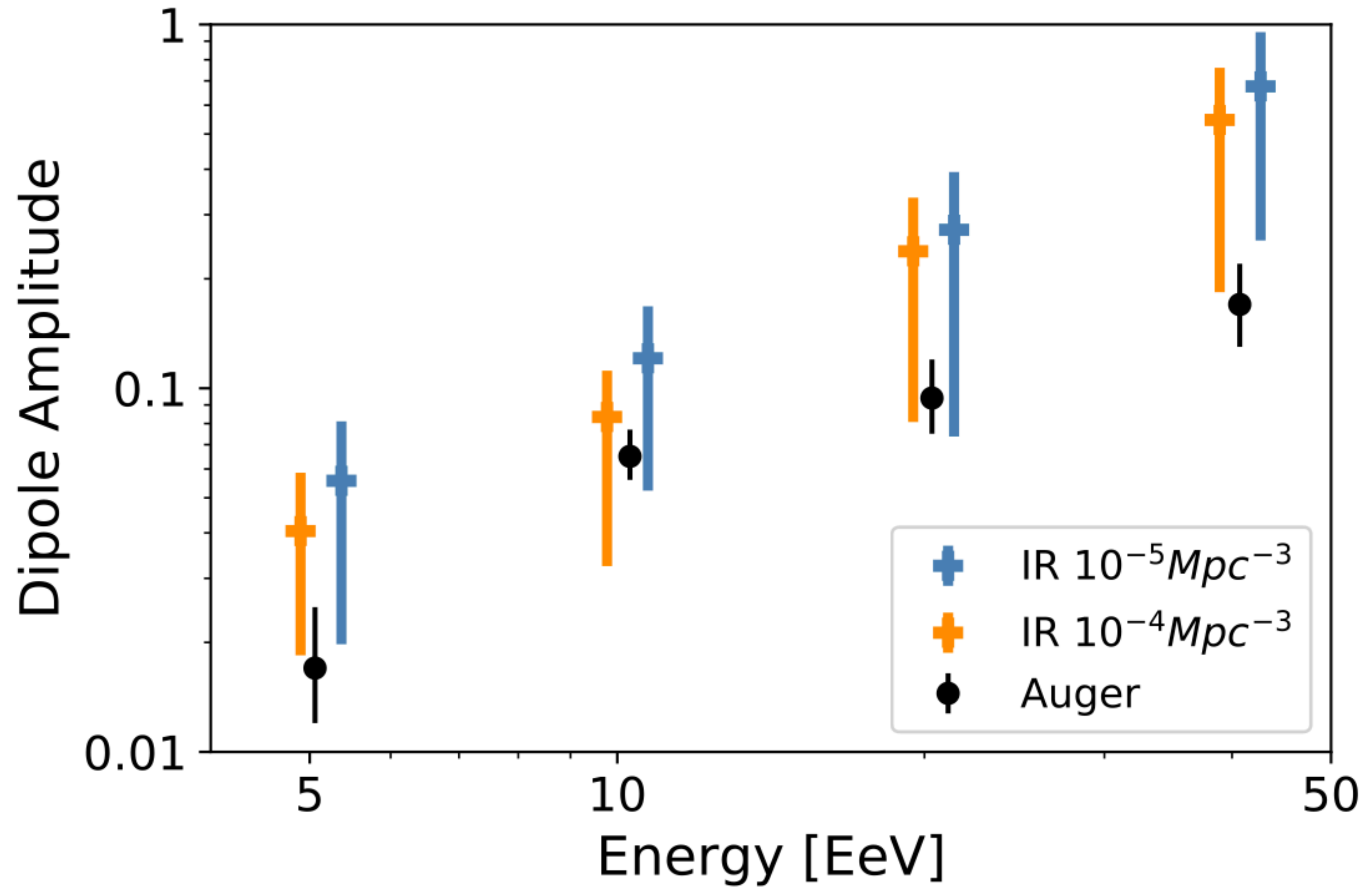


-> the change in the direction of an originally dipolar distribution after traversing a particular Galactic magnetic field. The arrows start in a grid of initial directions for the dipole outside the Galaxy and indicate the dipole directions that would be reconstructed at the Earth for different CR rigidities.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

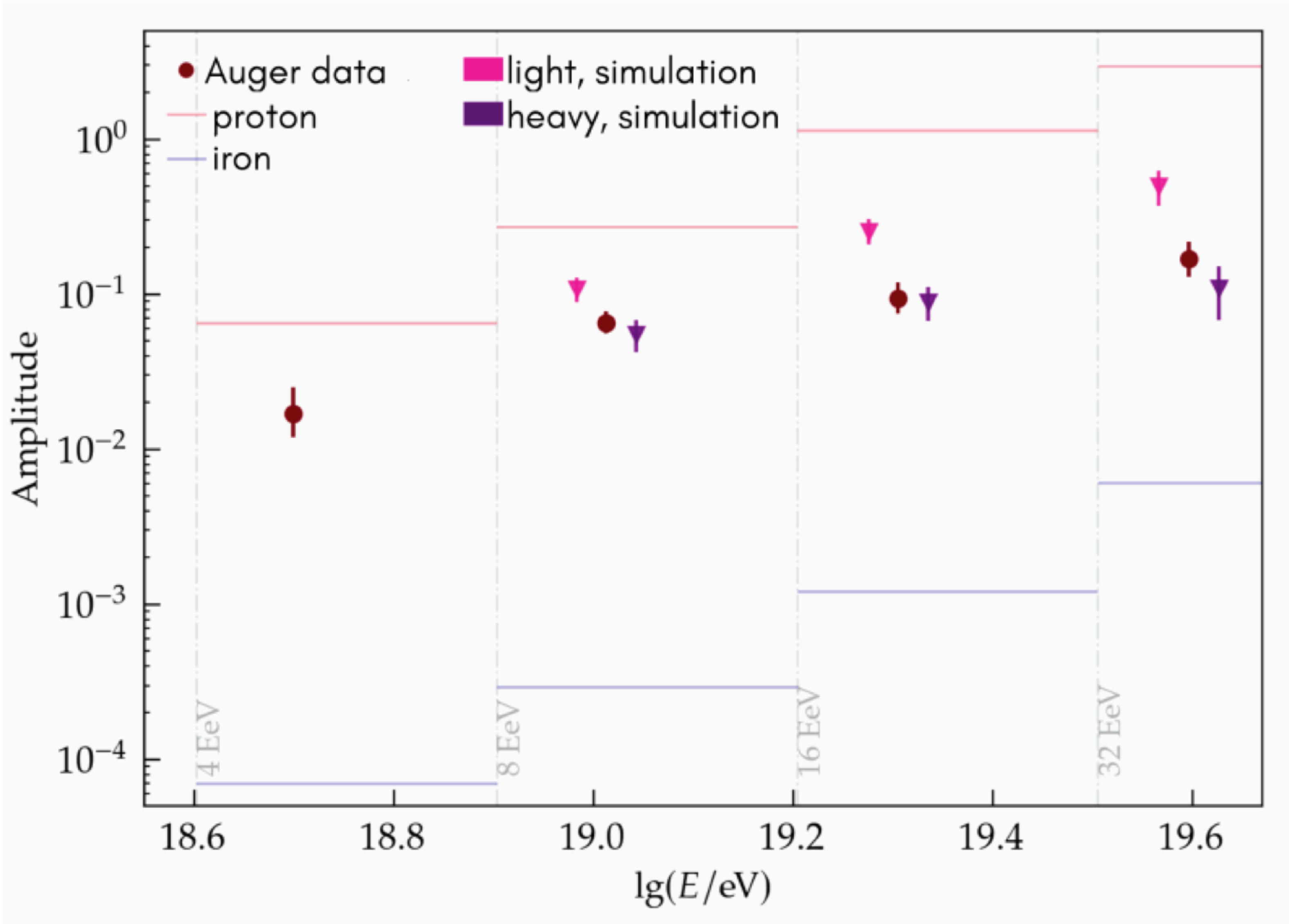
Astrophys.J. 868 (2018)

The dipole

- Focusing on the dipole: <u>the dipole amplitude increases with energy</u>, 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

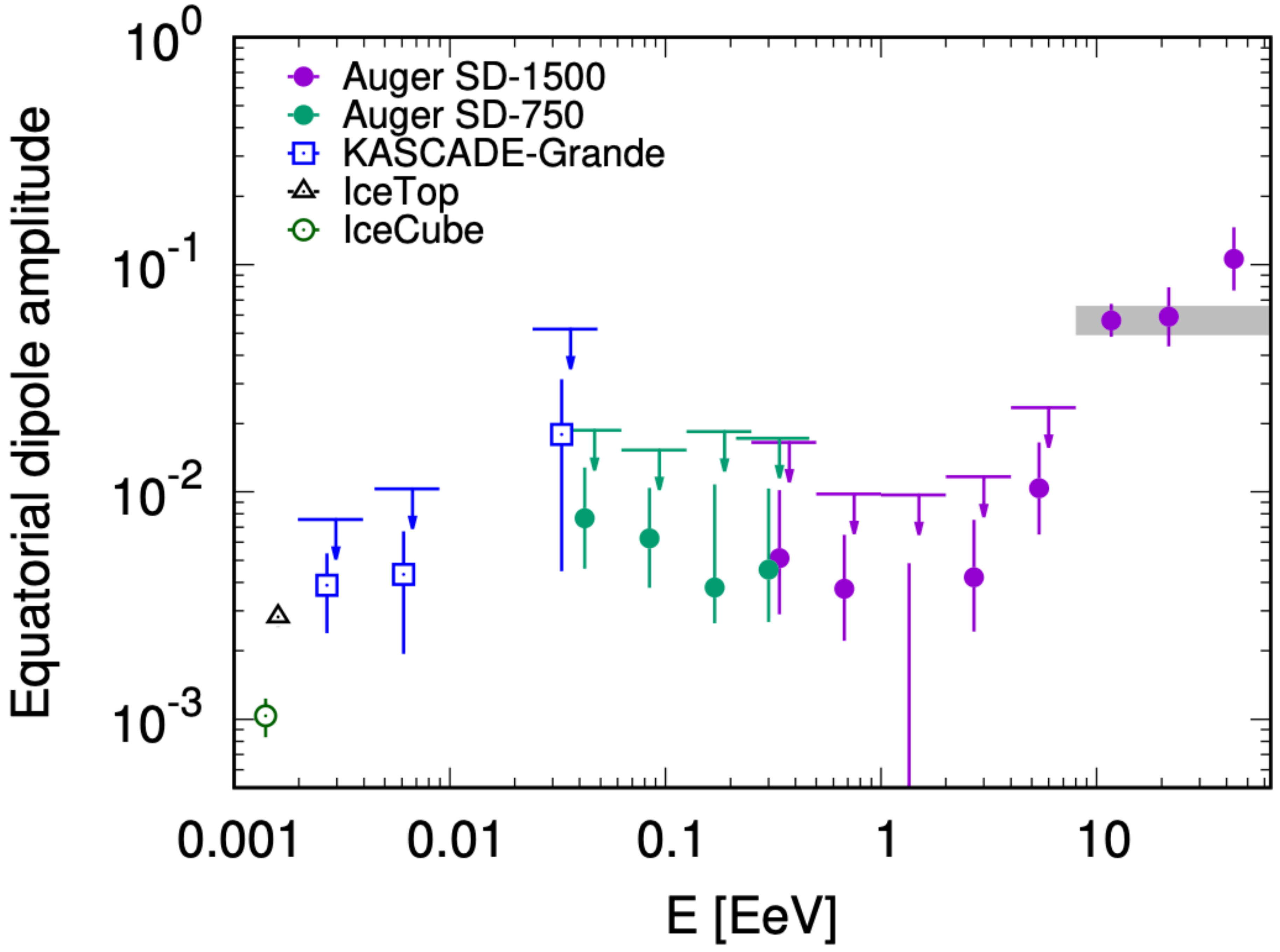


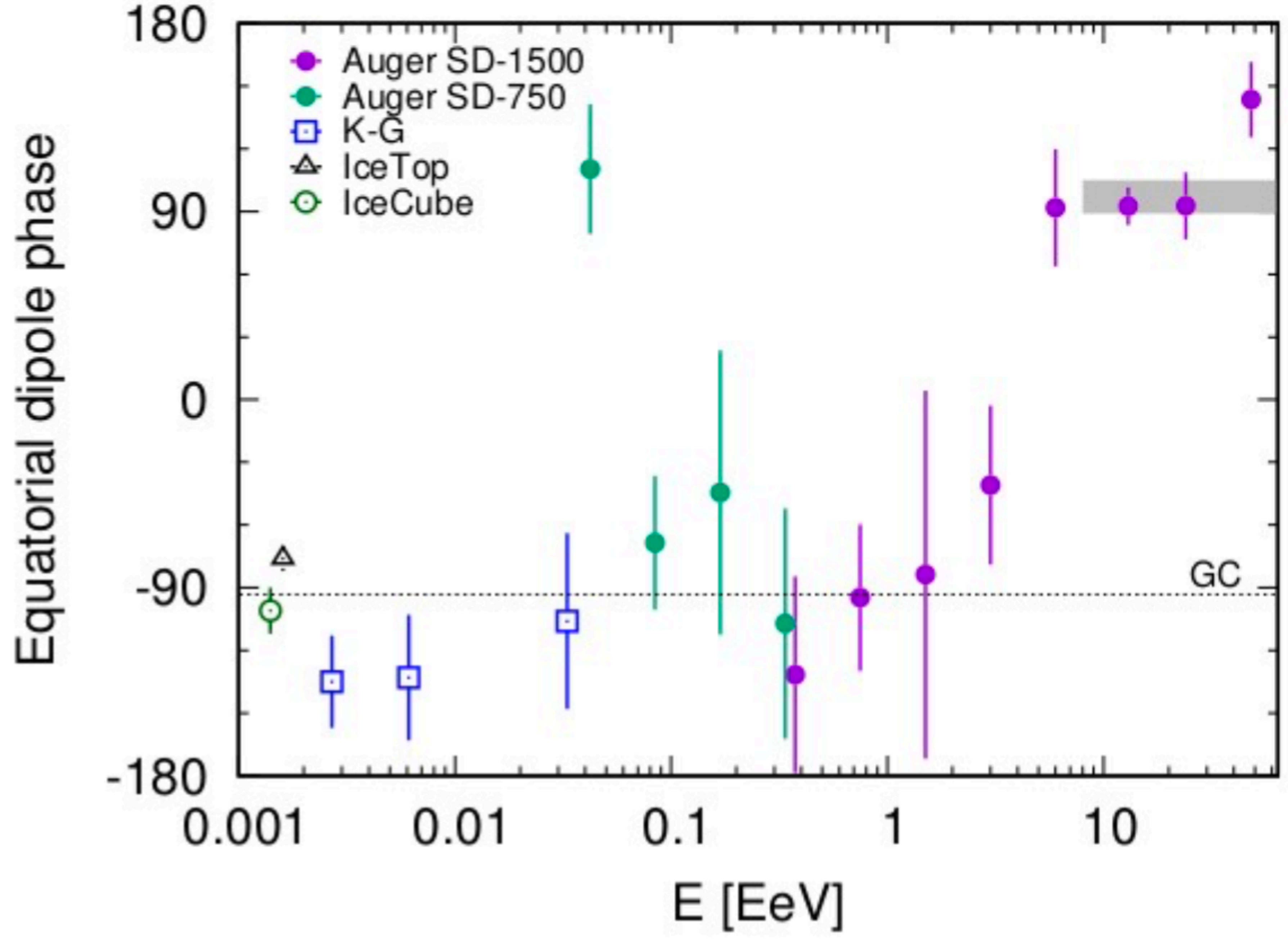
Comparison to expectations for astrophysical scenarios obtained from spectrum + composition interpretation -> if UHECR have a non-protonic mass composition, the dipole is compatible with the matter distribution of the large scale structure



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

The dipole at lower energies





Anisotropy dominated by Galactic contribution below a few EeV?

ApJ 2024