TESTING **LORENTZ INVARIANCE WITH UHECRS** IN EXTRAGALACTIC SPACE AND EARTH'S ATMOSPHERE WITH THE PIERRE AUGER OBSERVATORY

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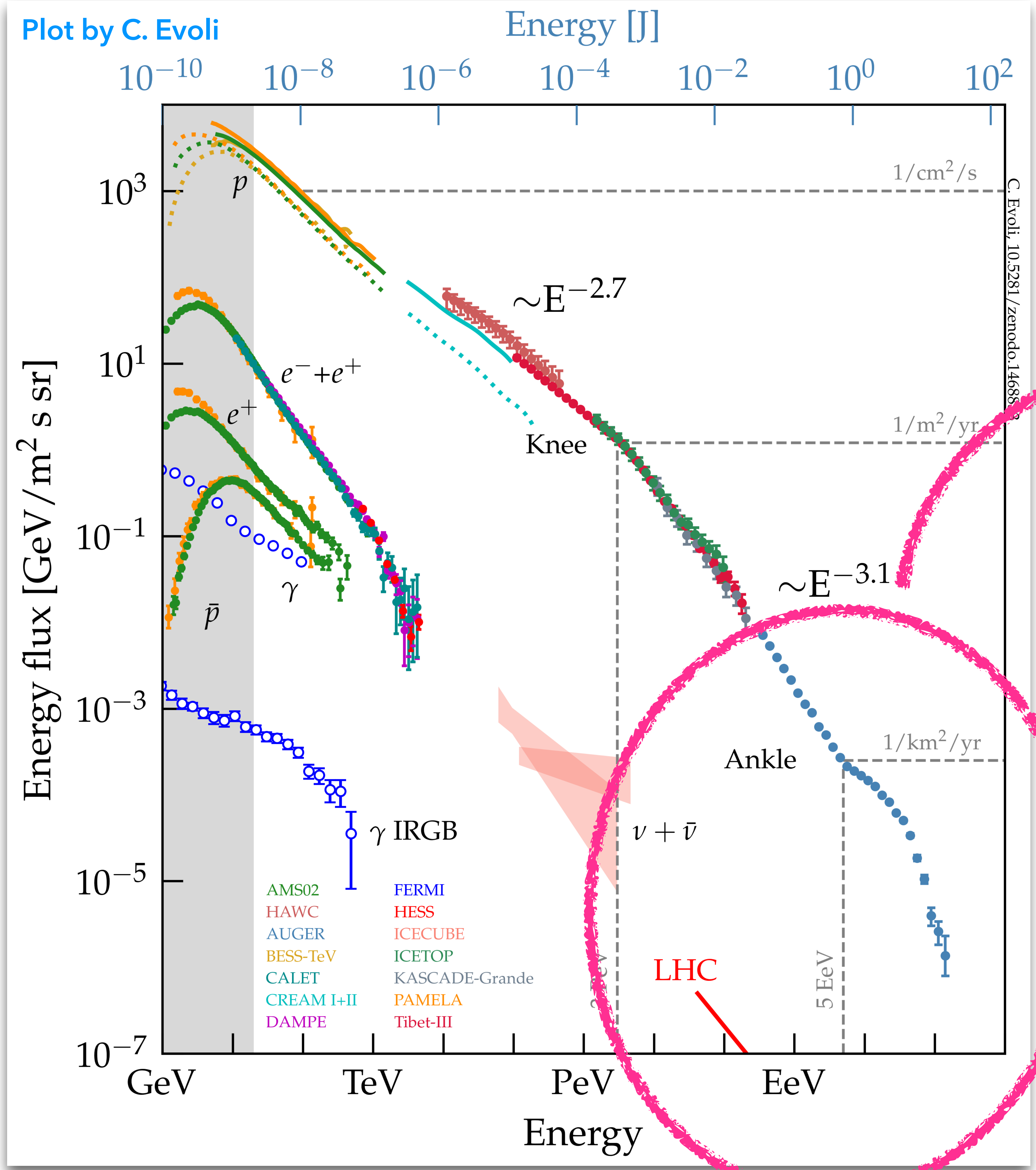
Quantum Gravity Phenomenology in the Multi-messenger Approach
13-15 July 2022, Naples, Italy

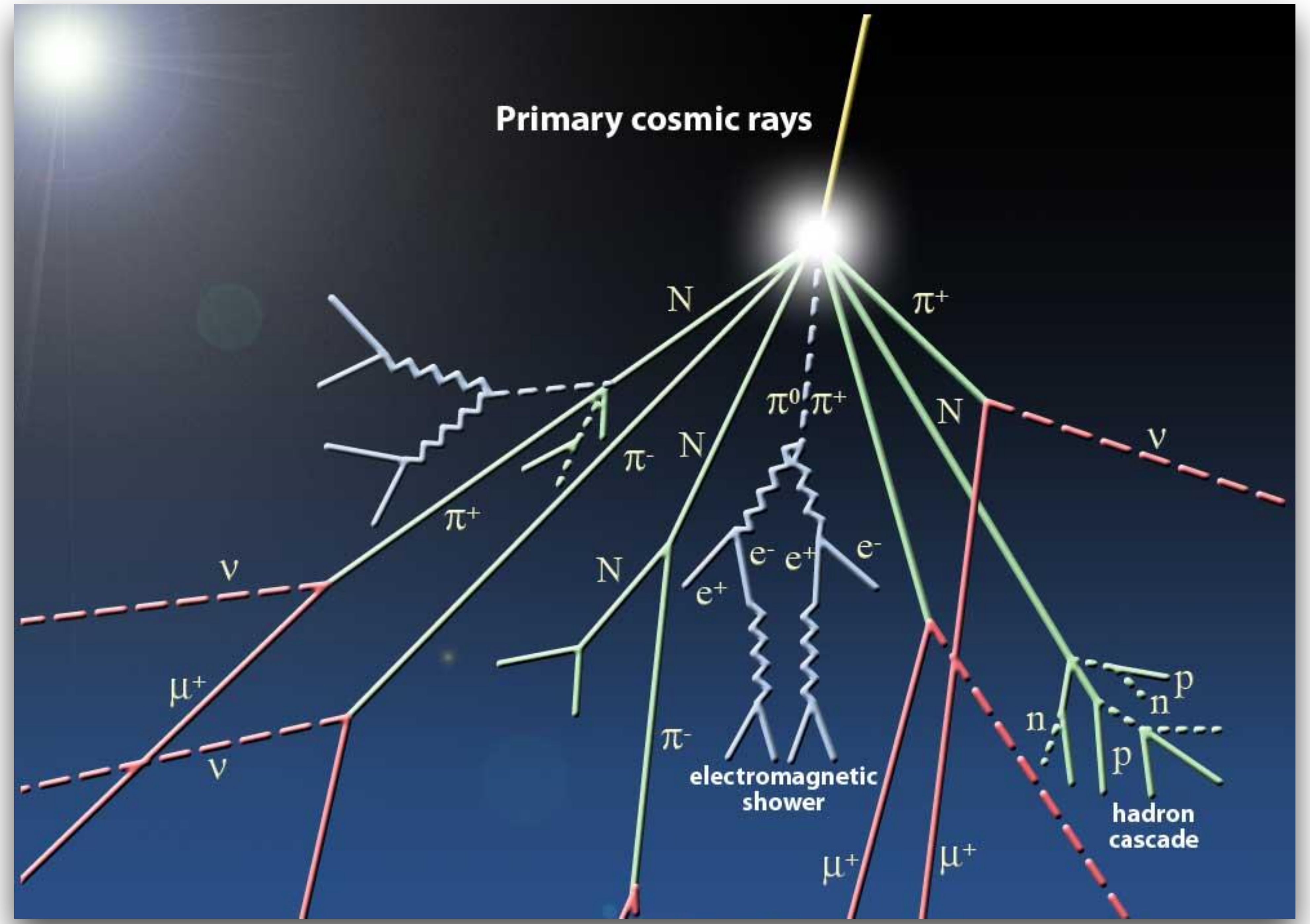
MAIN REFERENCES

- The Pierre Auger Collaboration, "**Testing effects of Lorentz invariance violation in the propagation of astroparticles with the Pierre Auger Observatory**", JCAP 2022
  - D. Boncioli et al, "Future prospects of testing Lorentz invariance with UHECRs" ICRC2015
  - D. Boncioli for the Pierre Auger Collaboration, "Probing Lorentz symmetry with the Pierre Auger Observatory" ICRC 2017
  - R. G. Lang for the Pierre Auger Collaboration, "Testing Lorentz Invariance Violation at the Pierre Auger Observatory" ICRC2019
- C. Trimarelli for the Pierre Auger Collaboration, "**Constraining Lorentz Invariance Violation using the muon content of extensive air showers measured at the Pierre Auger Observatory**", ICRC2021

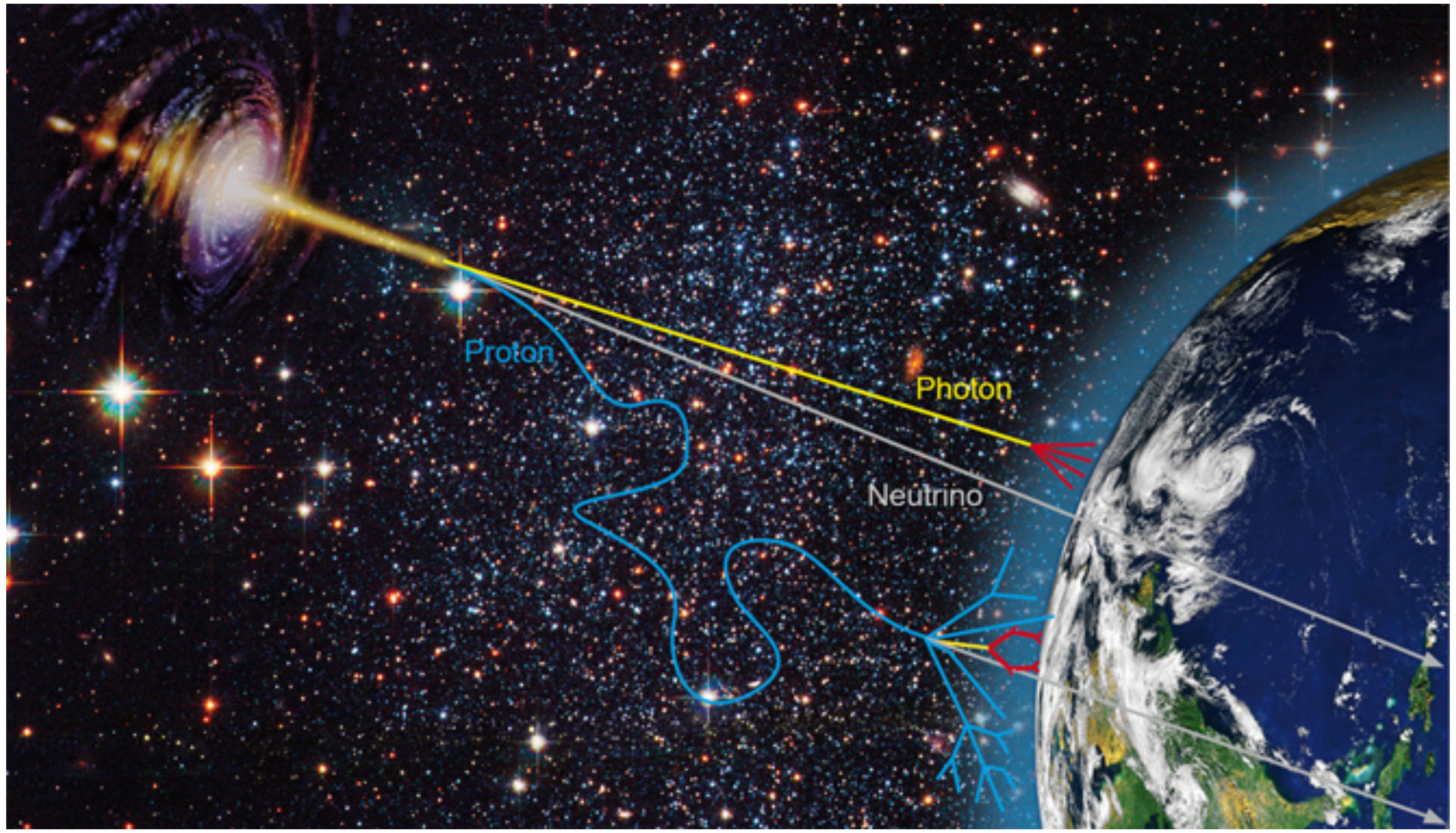
THE COSMIC-RAY ENERGY SPECTRUM

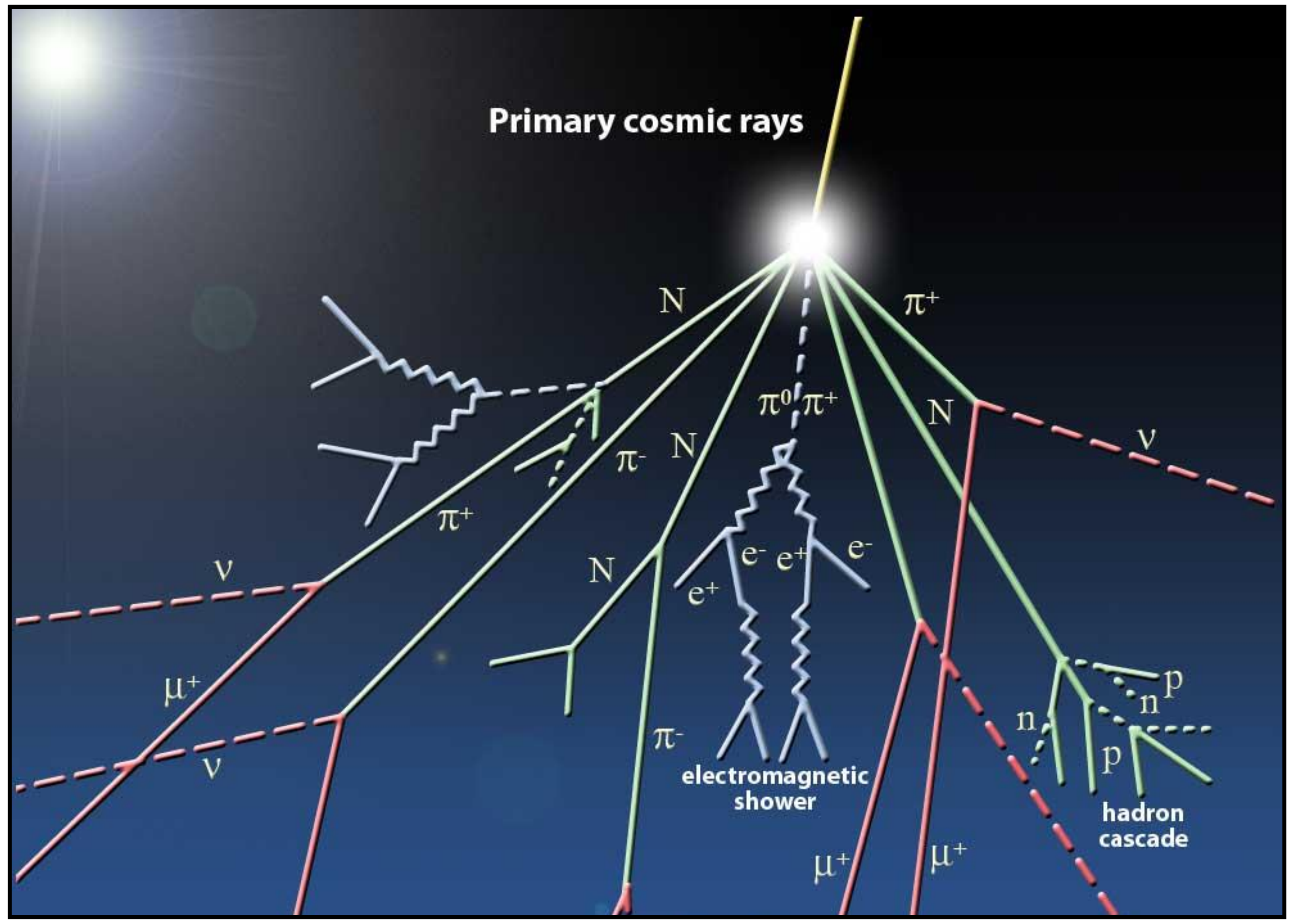


UHECRs in the Earth's atmosphere



UHECRs and Lorentz Invariance Violation

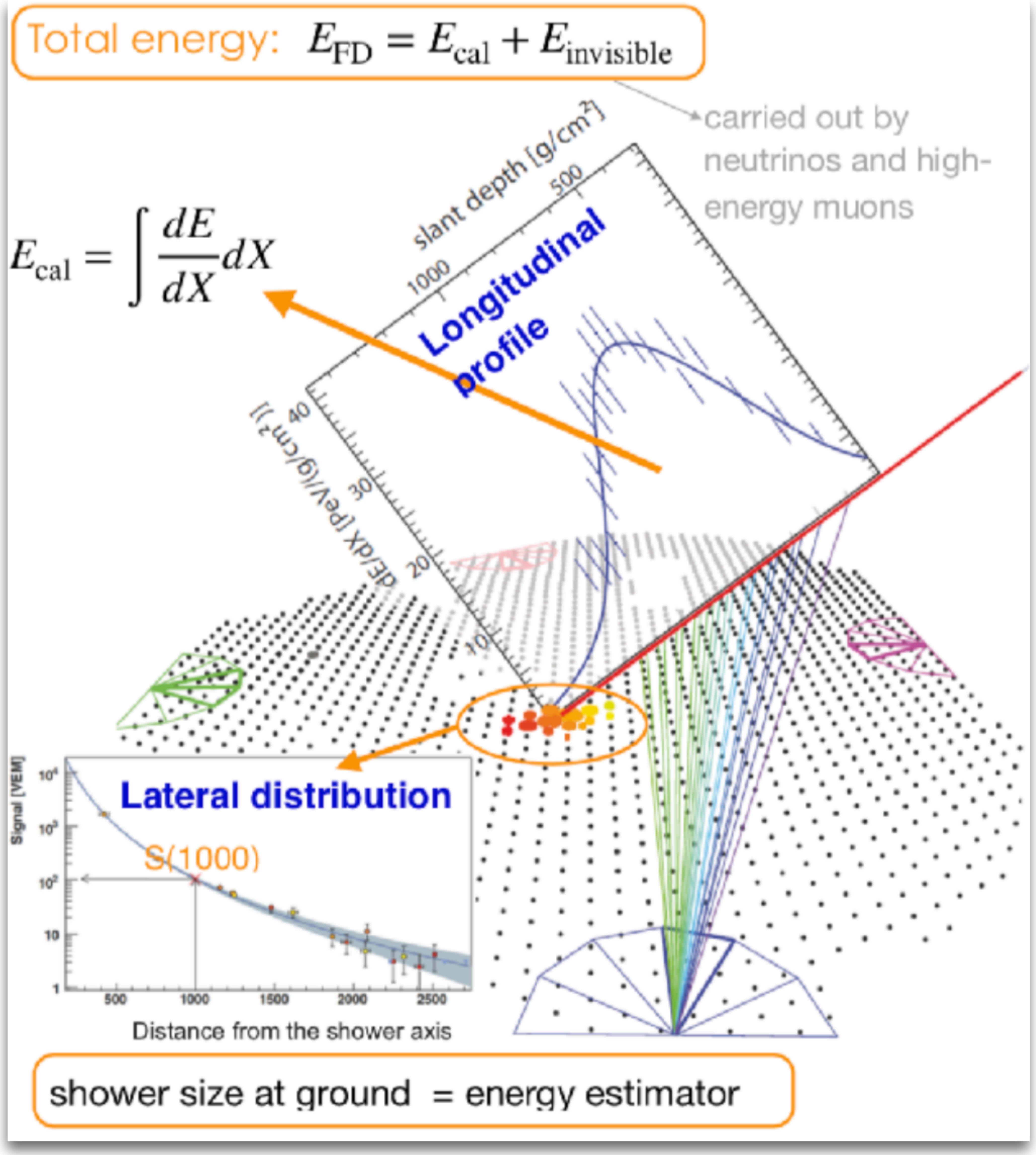


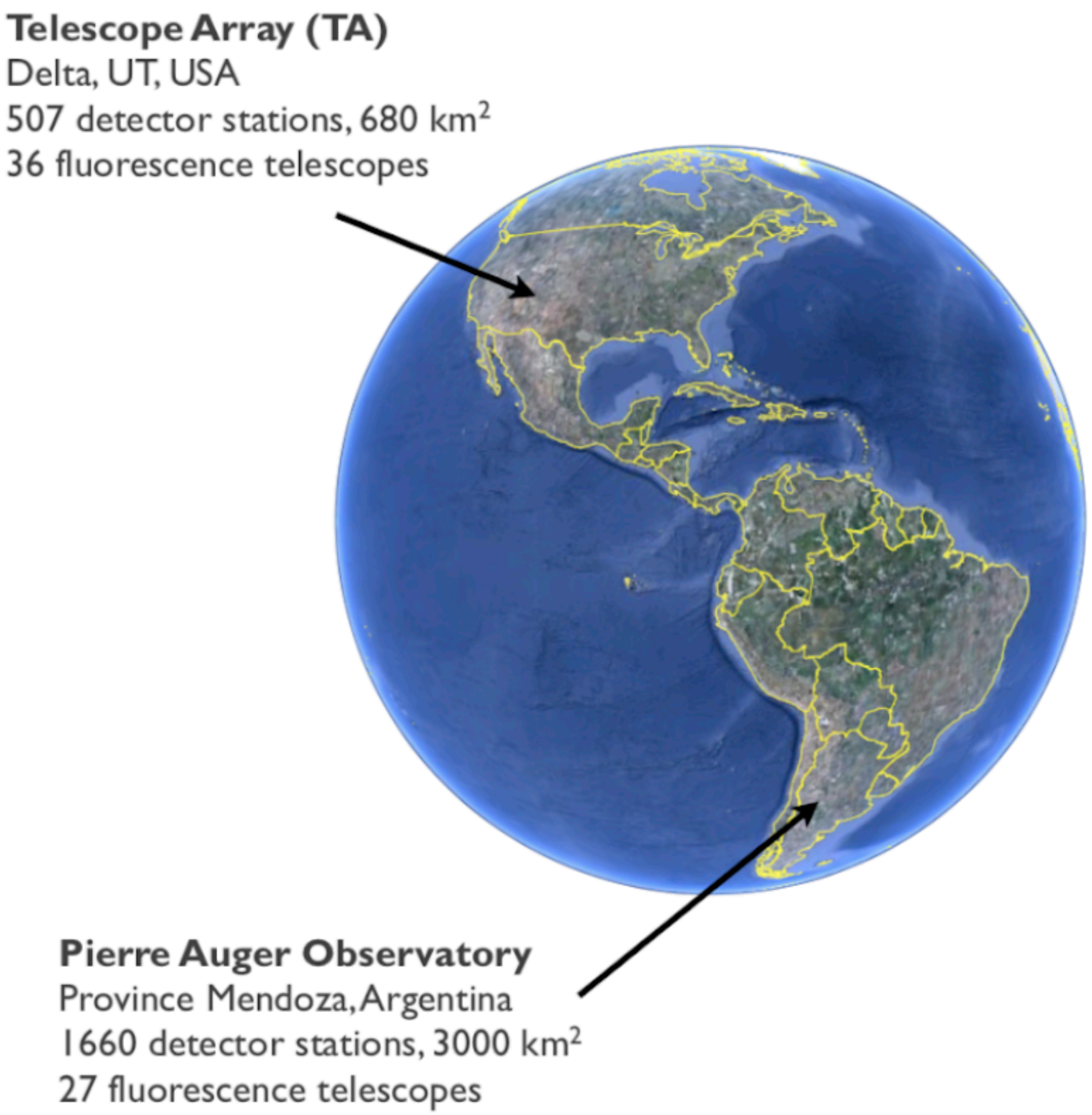


- The **extragalactic propagation of UHECRs** as well as the **development of the cascade in the atmosphere** can be modified by violation of Lorentz invariance
  - Suppression of pion production in propagation
  - Suppression of nuclear disintegration in propagation
  - Suppression of UHE photon absorption by photons of the background
  - Suppression of pion decay in atmosphere
- Data measured at Earth can contain imprints of LIV

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

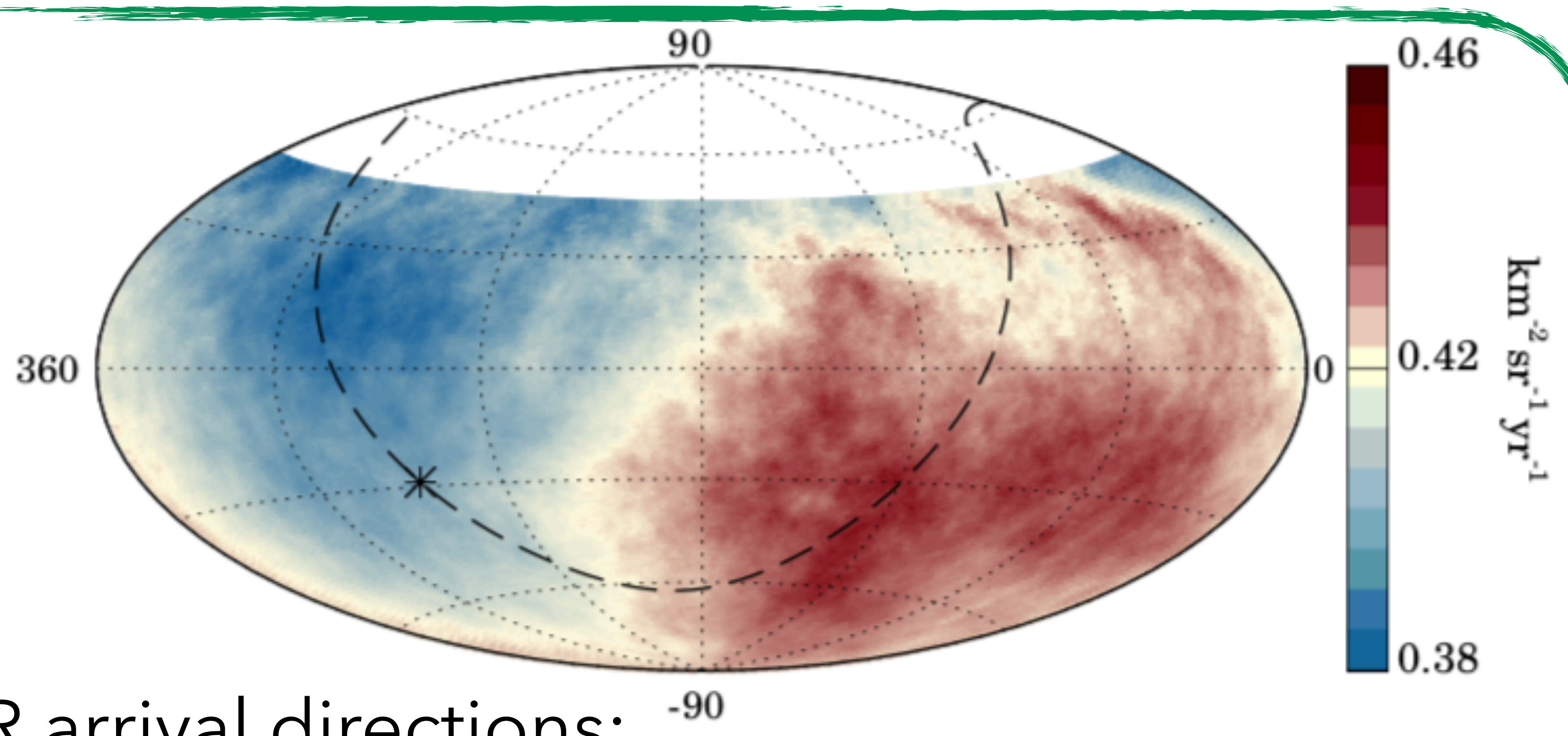
MEASUREMENTS AT UHE





UHECRs at the Pierre Auger Observatory

Collection of results from ICRC 2021

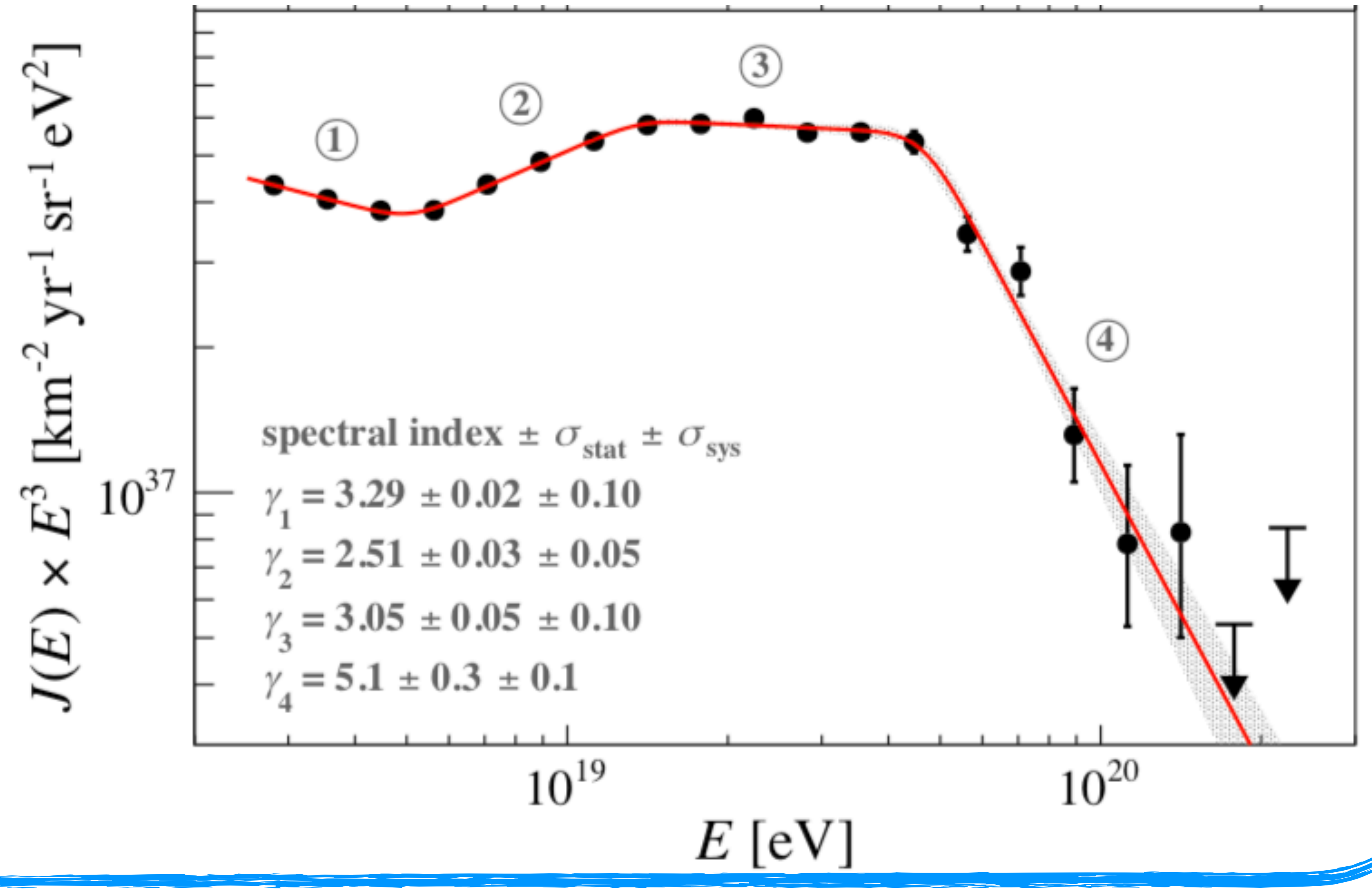


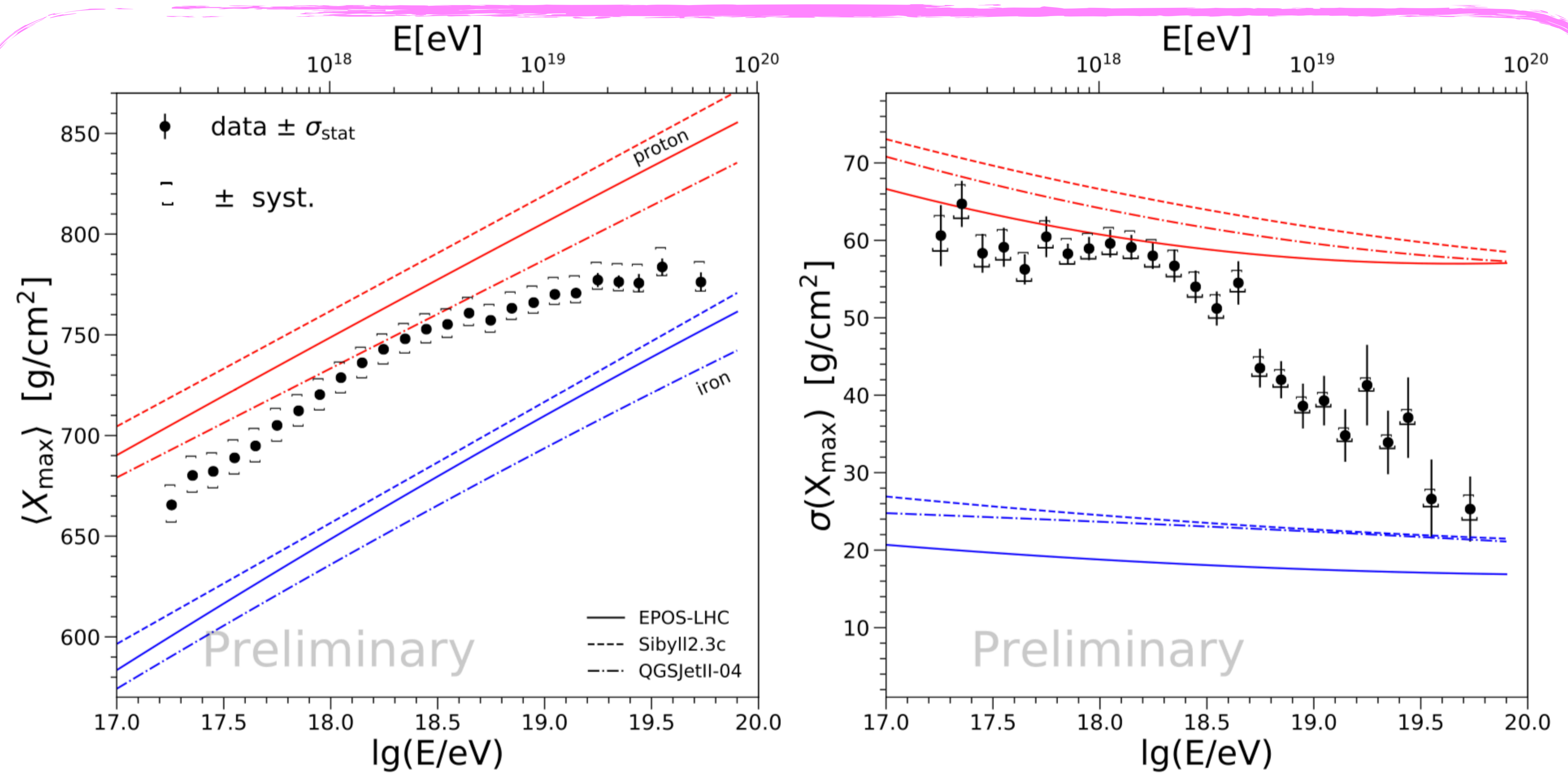
UHECR arrival directions;

- Evidence of extragalactic origin
- Signal of correlation with starburst galaxies

UHECR spectrum;

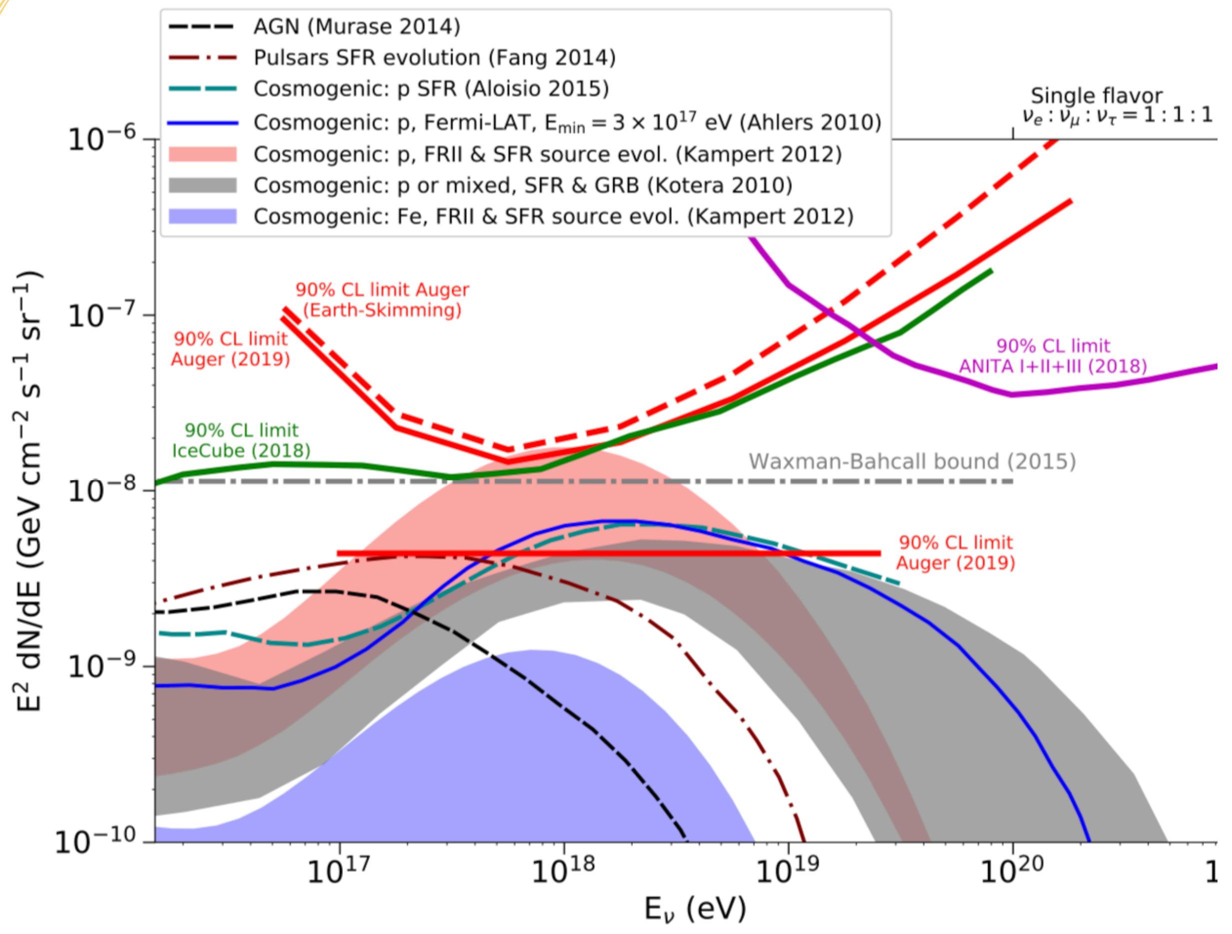
- changes of slope
- suppression

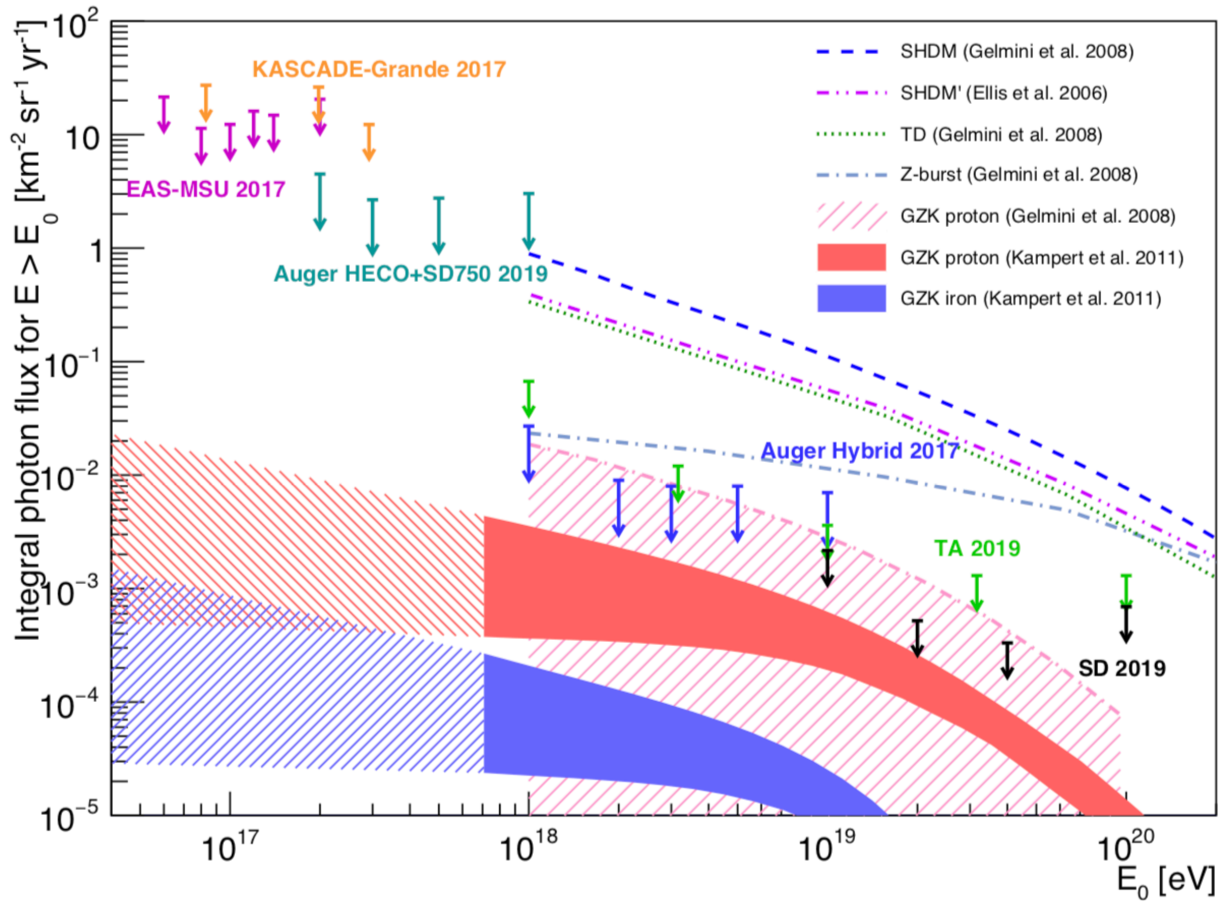




UHECR mass composition;

- Mass composition changes with energy
- Fluctuations decrease

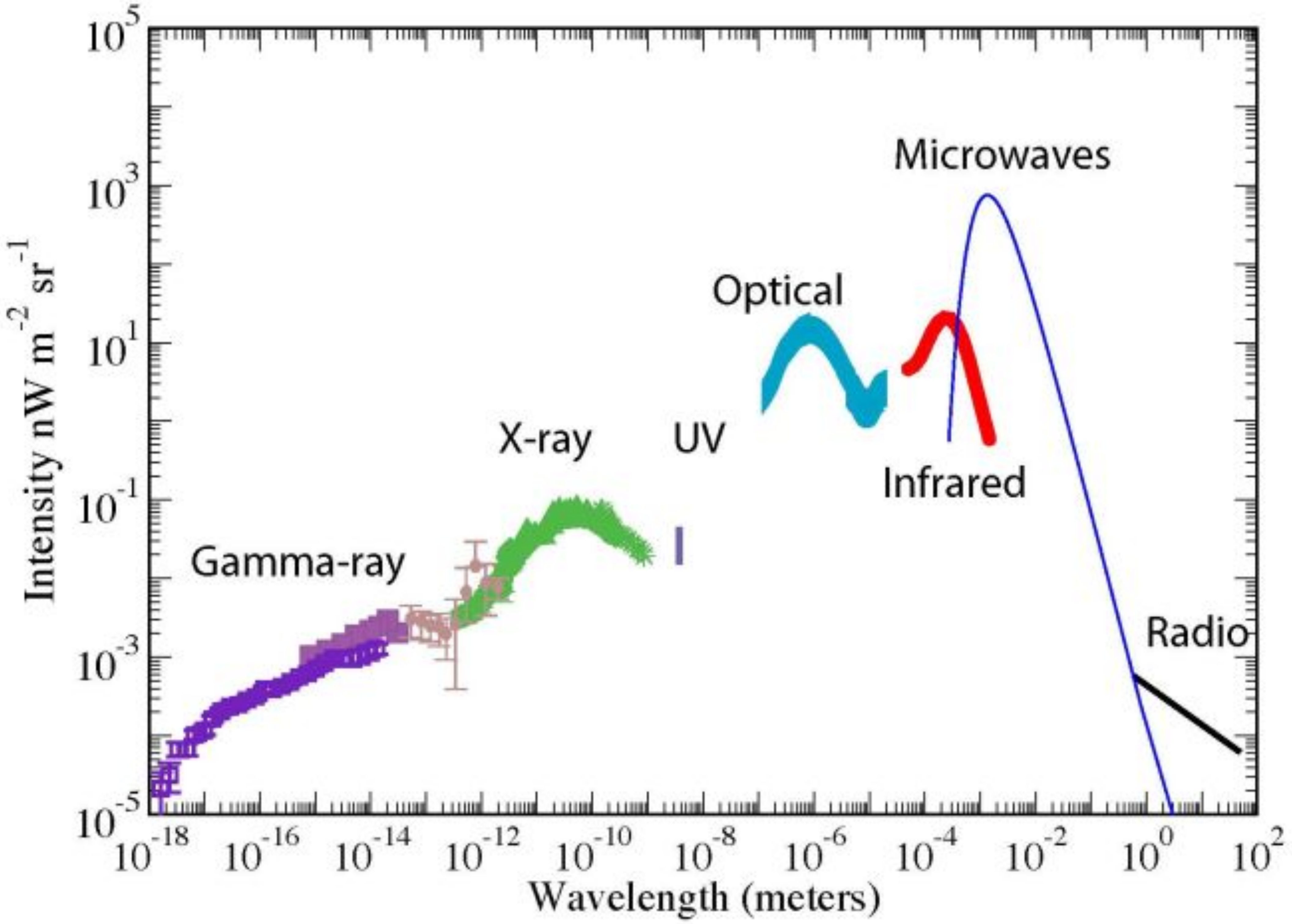




Limits on secondary messengers

LIV AND ASTROPARTICLES

UHECR PROPAGATION



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

$$A + \gamma_{\rm bkg} \rightarrow \ldots$$

$$\gamma + \gamma_{\rm bkg} \rightarrow \ldots$$

- For the energies of the UHECRs, relevant photon fields are:
  - Cosmic Microwave Background (**CMB**)
    - relic radiation from the Big Bang; **black body** at temperature 2.7 K
  - UV-optical-IR (Extragalactic Background Light, **EBL**)
    - UV, optical and near IR is due to direct starlight
    - From mid IR to submm wavelengths, EBL consists of re-emitted light from dust particles
  - Dependence on redshift to be considered

- Relevant energy scale:

$$\varepsilon' = \varepsilon\Gamma(1 - \cos\theta)$$

UHECR PROPAGATION

- Pair production $\varepsilon' > 1\,\mathrm{MeV}$

$$p + \gamma \rightarrow p + e^+ + e^-$$

- Pion production $\varepsilon' > 150\,\mathrm{MeV}$

$$p + \gamma \rightarrow n + \pi^+$$

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

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

Source of cosmogenic neutrinos

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

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

Source of cosmogenic gamma rays

UHECR nucleons & nuclei

- Disintegration $\varepsilon' > 8\,\mathrm{MeV}$

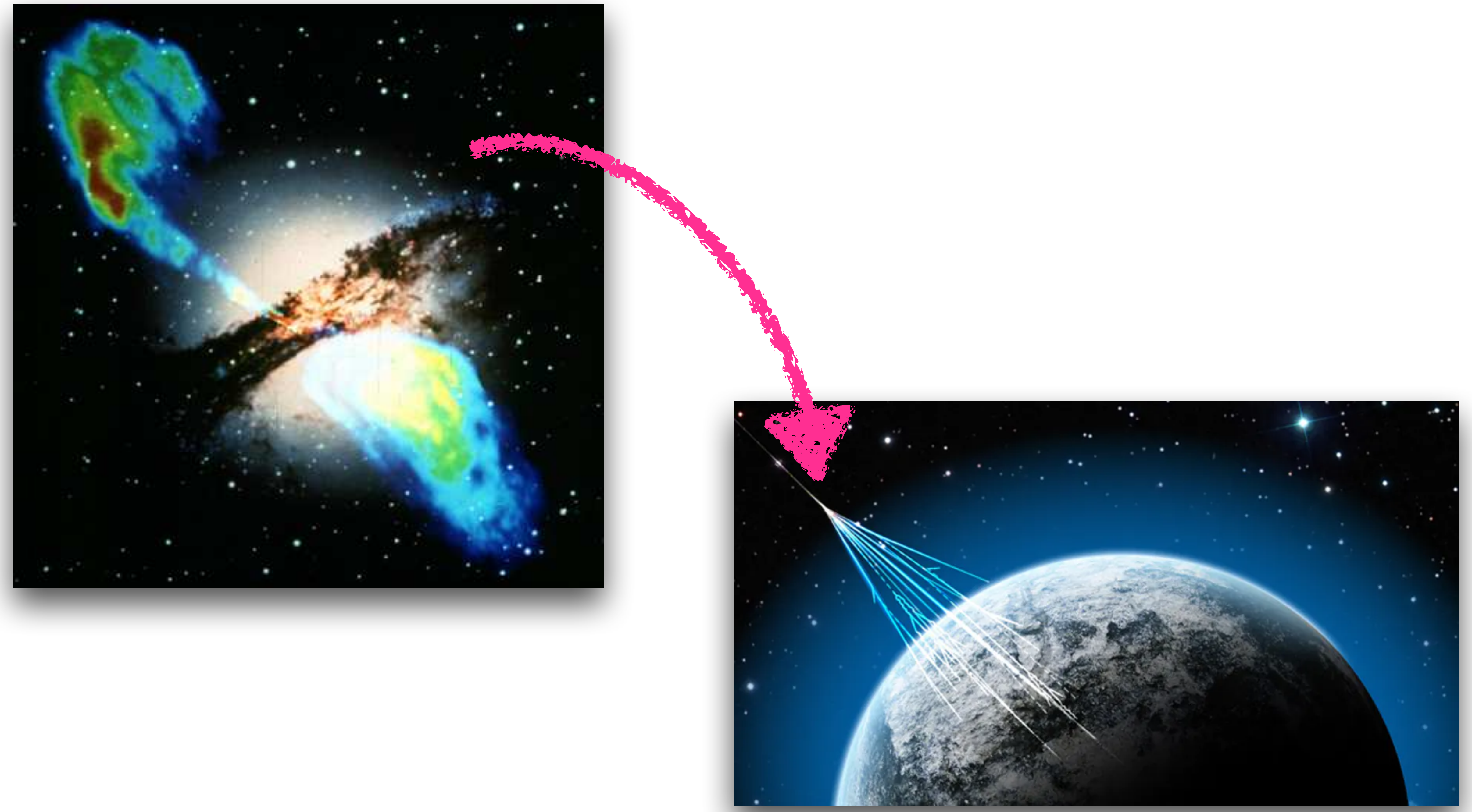
$$^A_ZX + \gamma \rightarrow ^{A-1}_{Z-1}X' + p$$

$$^A_ZX + \gamma \rightarrow ^{A-1}_{Z}X' + n$$

$$^A_ZX + \gamma \rightarrow ^{A-2}_{Z-2}X'' + \alpha$$

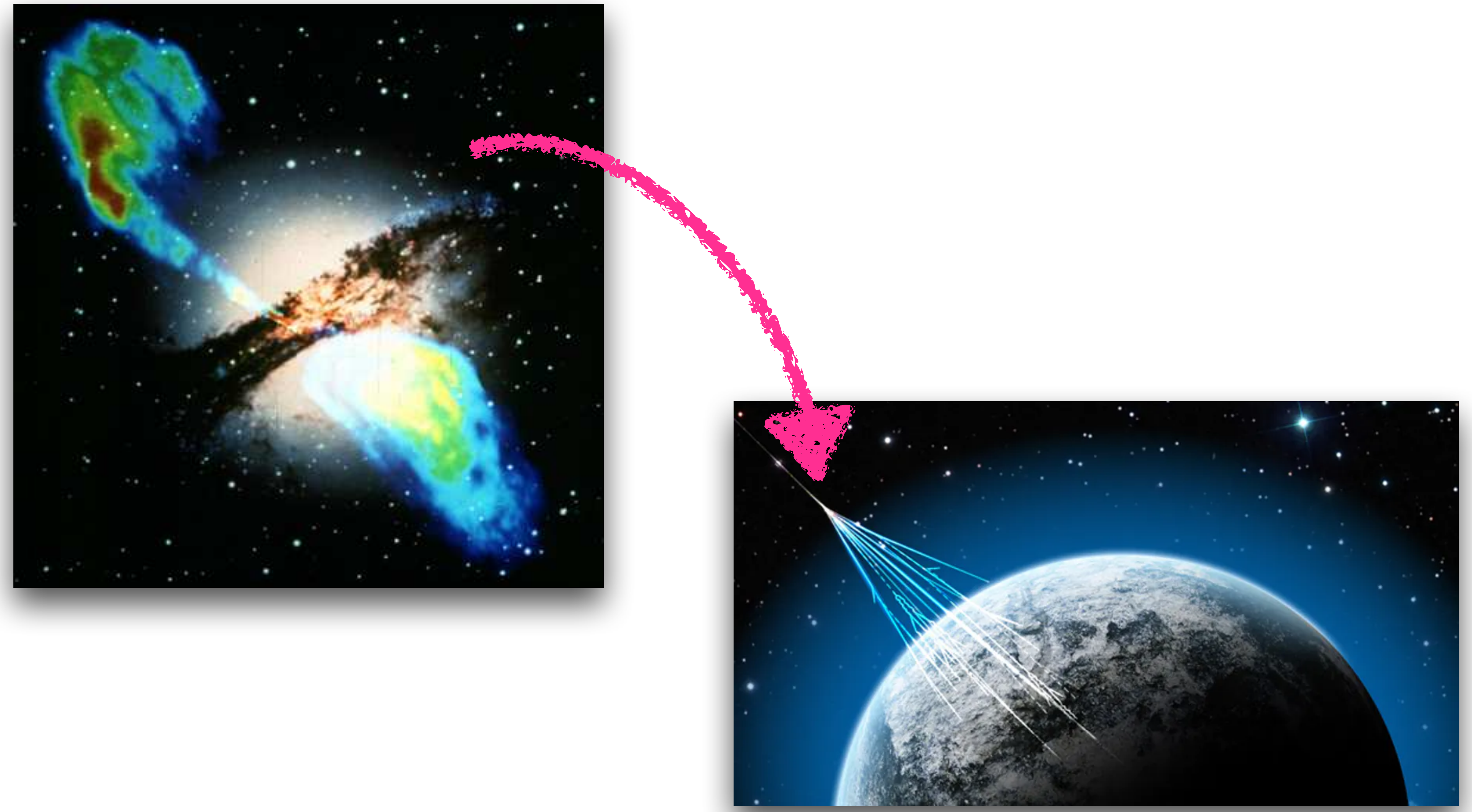
UHECR nuclei

ASTROPHYSICAL SCENARIOS



- **What is measured**: energy spectrum at Earth, mass composition…
- **What do we want to know**: energy spectrum at the sources, mass composition at the sources, properties of the distribution of sources…
  - Spectrum at Earth $\neq$ spectrum at source (…), due to interactions !

ASTROPHYSICAL SCENARIOS



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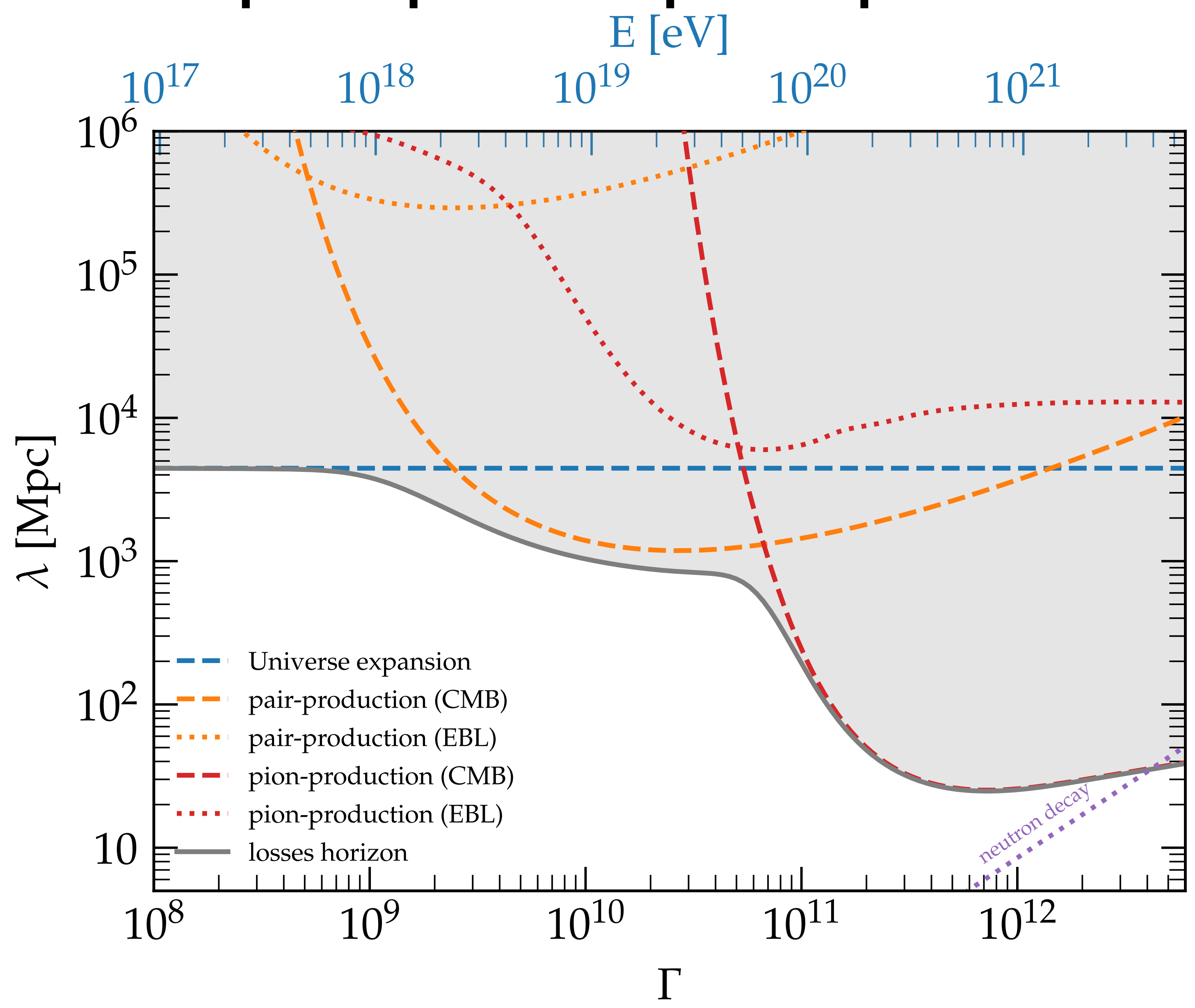
Example: photo-pion production

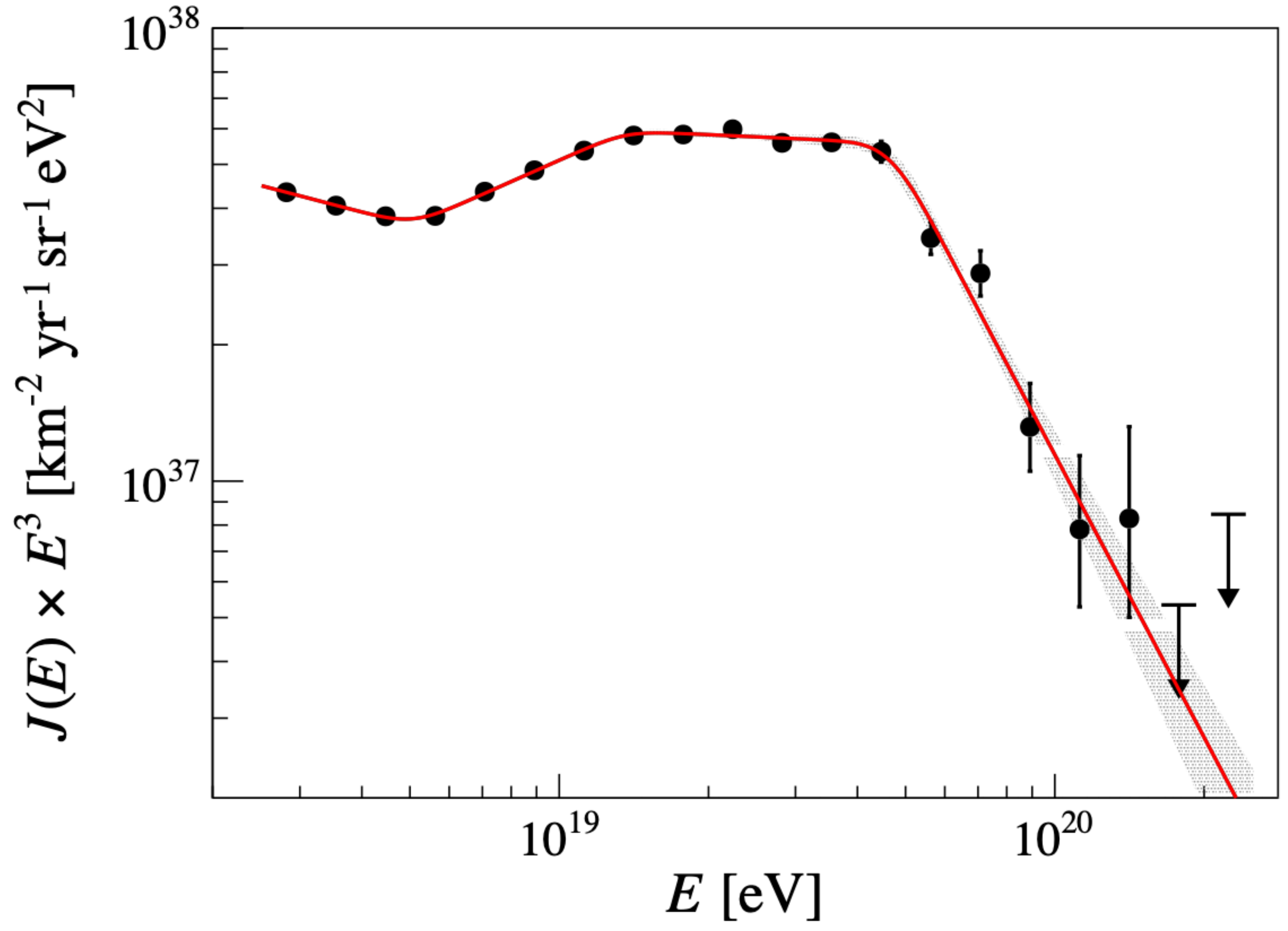


- Typical interaction length: order of 10 Mpc
- Typical energy loss in one interaction: 15-20 %
  - Protons above 10^{20} eV are expected only from close sources
  - Origin of the **suppression of the UHECR spectrum at the highest energies (?) - GZK effect**

ASTROPHYSICAL SCENARIOS

Why LIV ???

- Violation of LI could modify the kinematics of interactions
  - The photo-pion production could be inhibited
  - The shape of the **expected** UHECR spectrum at the highest energies could be different
- Experimental evidence: the suppression of the UHECR spectrum **is observed**
- Limits on LIV parameters influencing the UHECR propagation can be derived by **comparing the expected spectrum with the measured one**



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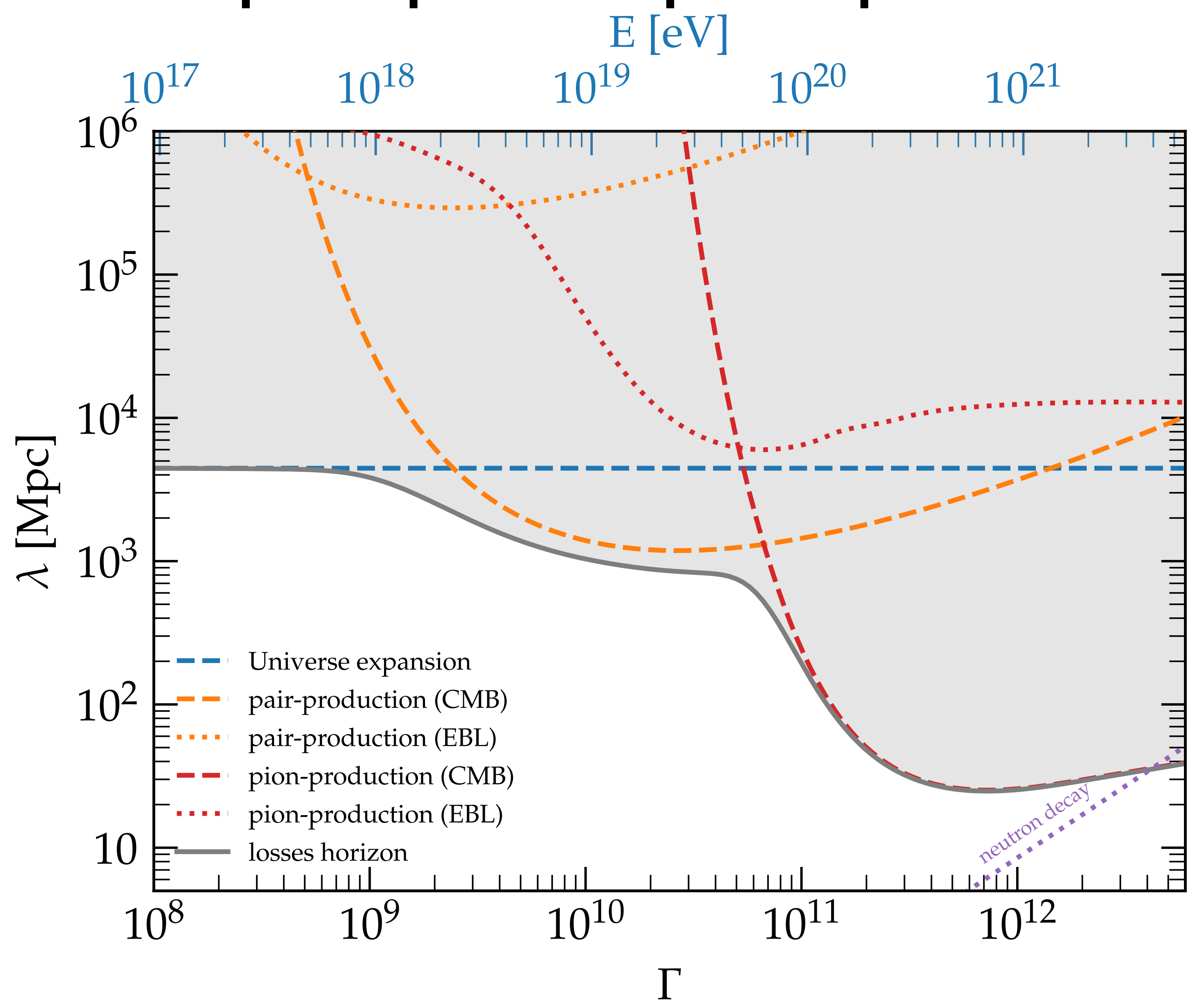

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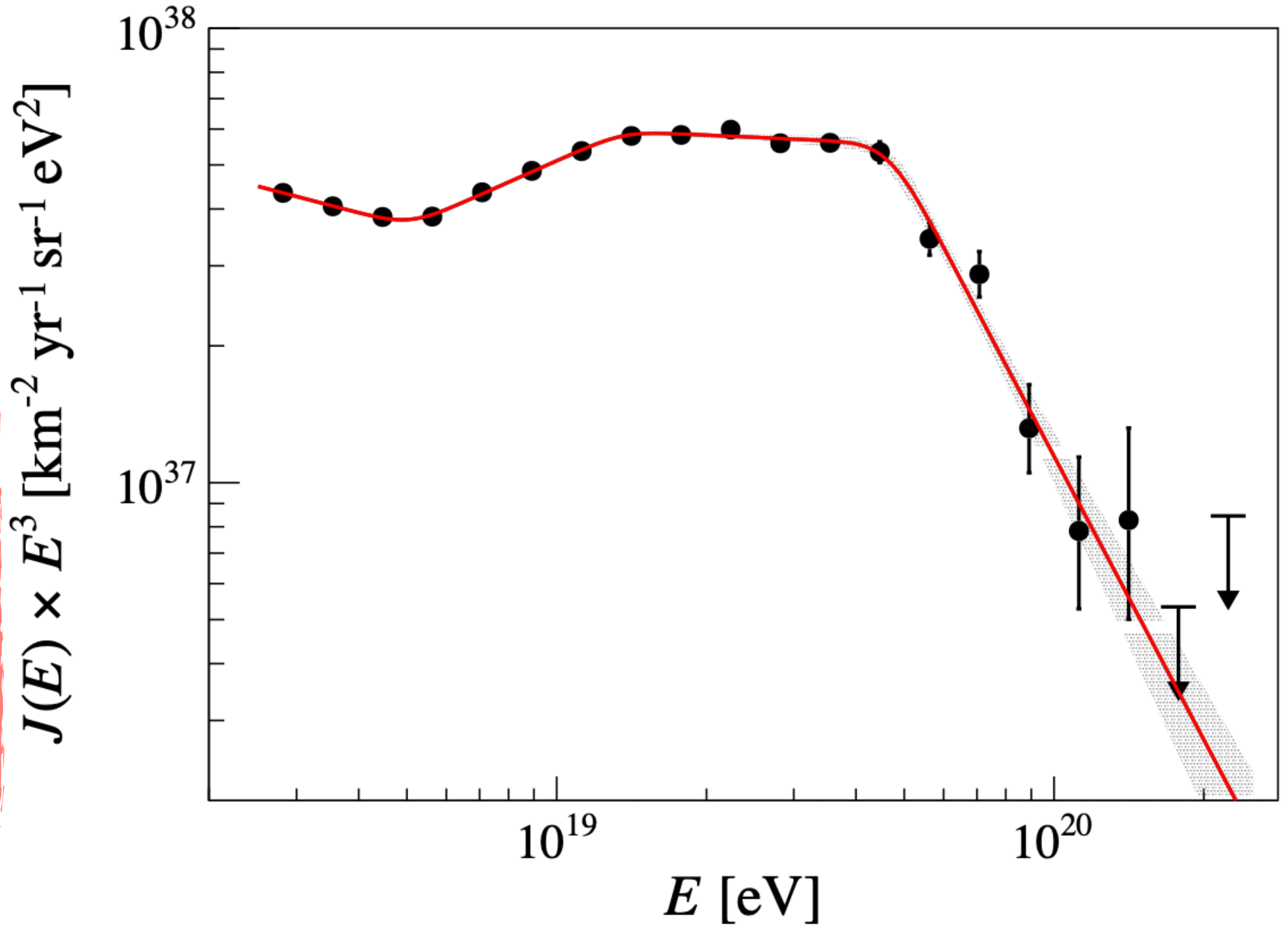

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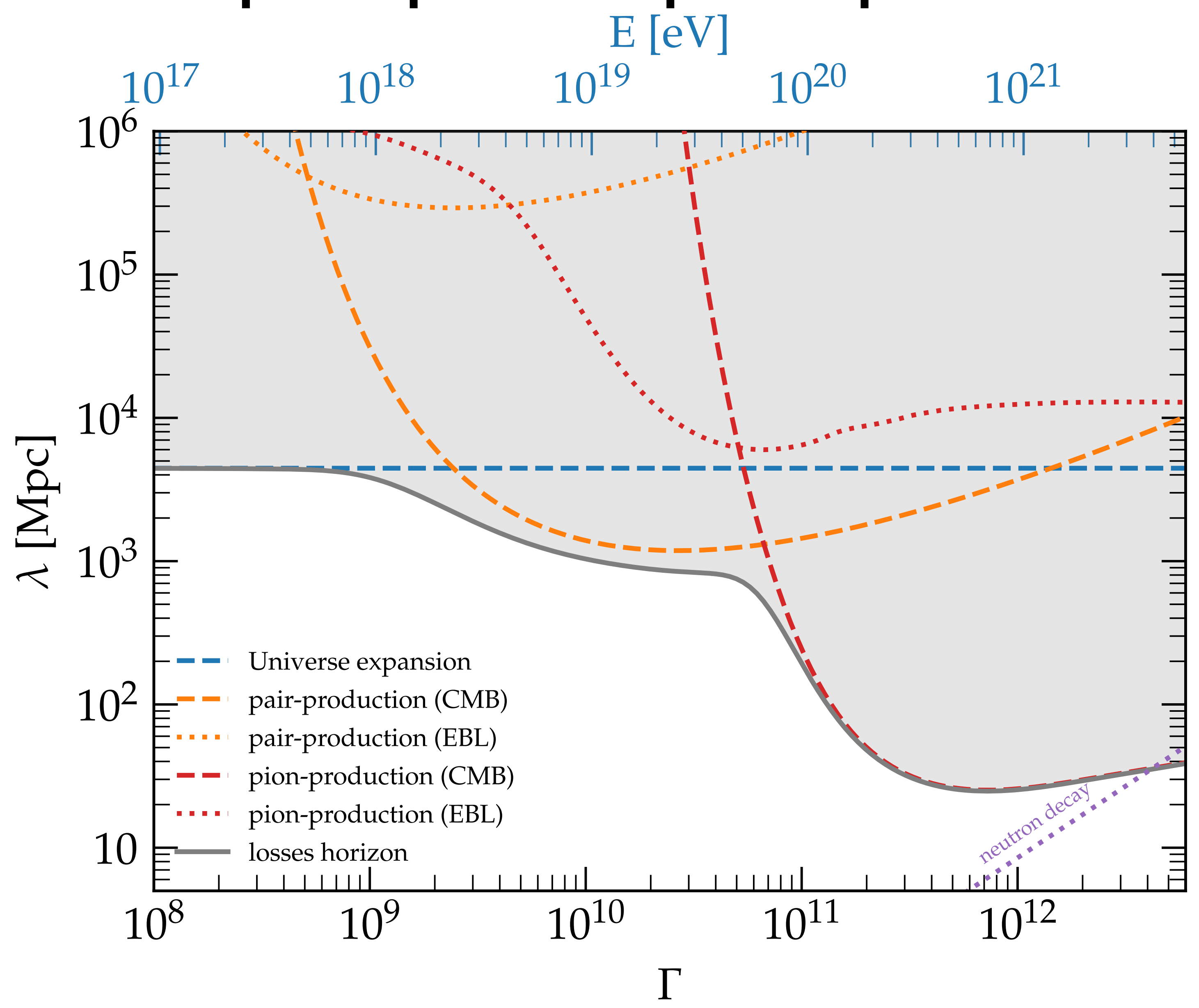
Great idea, too optimistic though...

Example: photo-pion production



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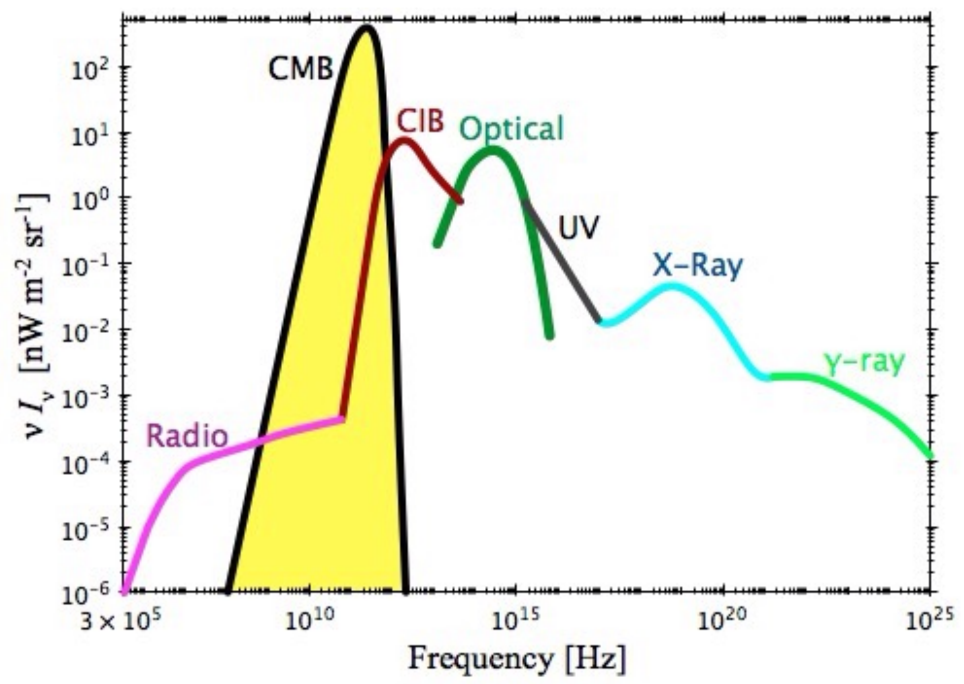
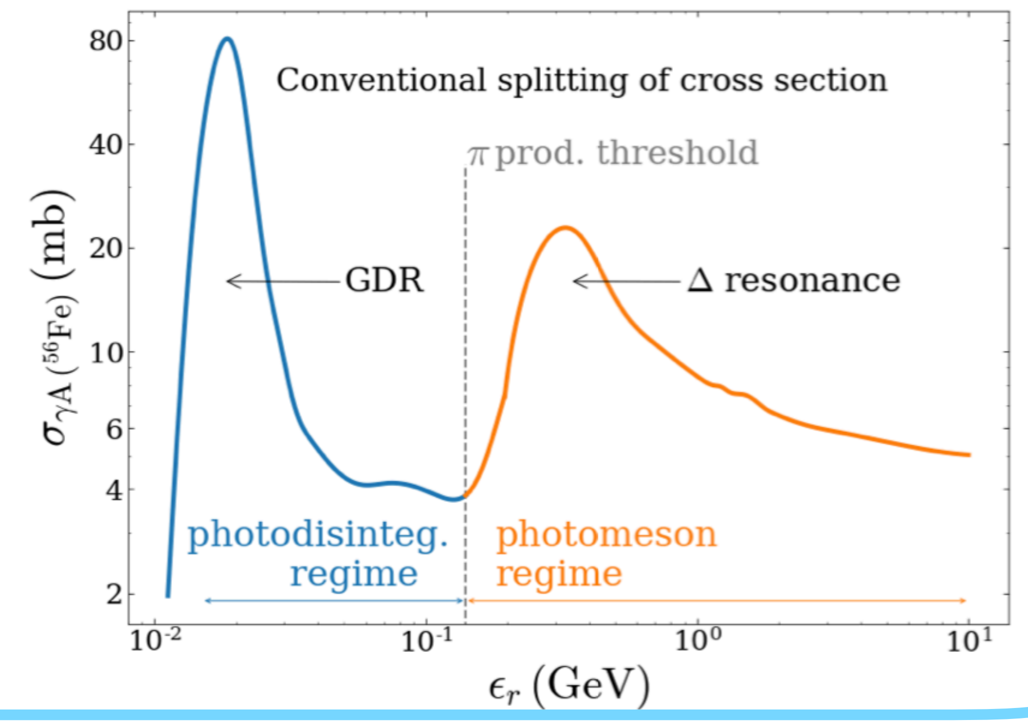
COMBINED SPECTRUM AND COMPOSITION FIT

Astrophysical scenarios to investigate the UHECR origin

$$\frac{\mathrm{d}N_A}{\mathrm{d}E} = J_A(E) = f_A J_0 \left(\frac{E}{10^{18}\ \mathrm{eV}}\right)^{-\gamma} \times f_{\mathrm{cut}}(E, Z_A R_{\mathrm{cut}});$$

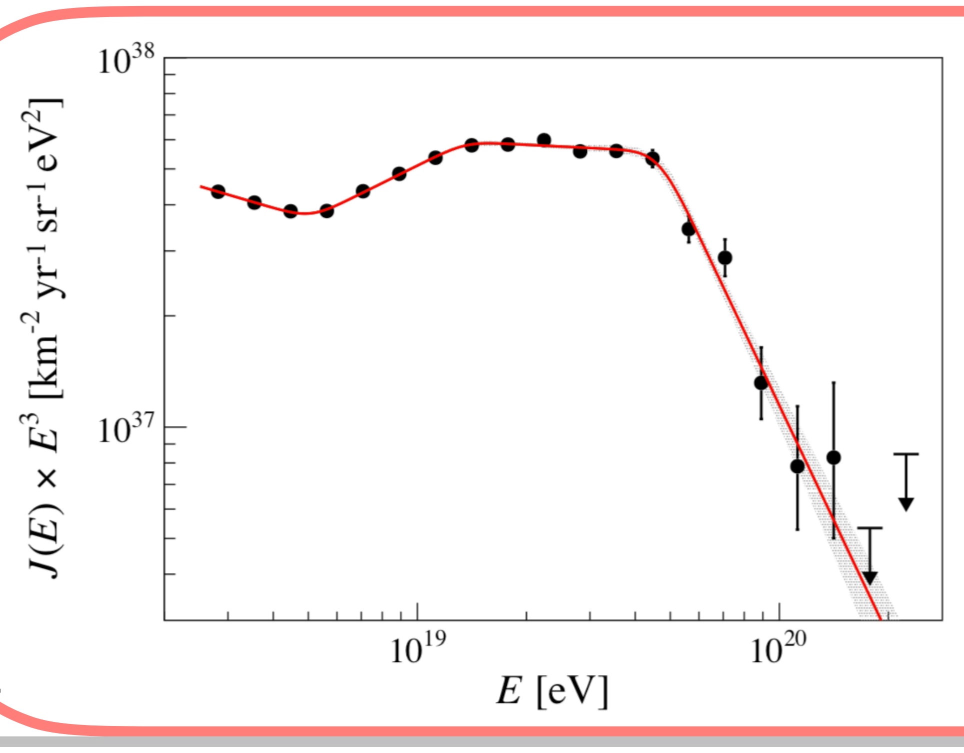
- Simple astrophysical model:
  - identical sources, uniformly distributed in co-moving volume
  - Power-law spectra at escape, up to max energy, rigidity dependence assumption

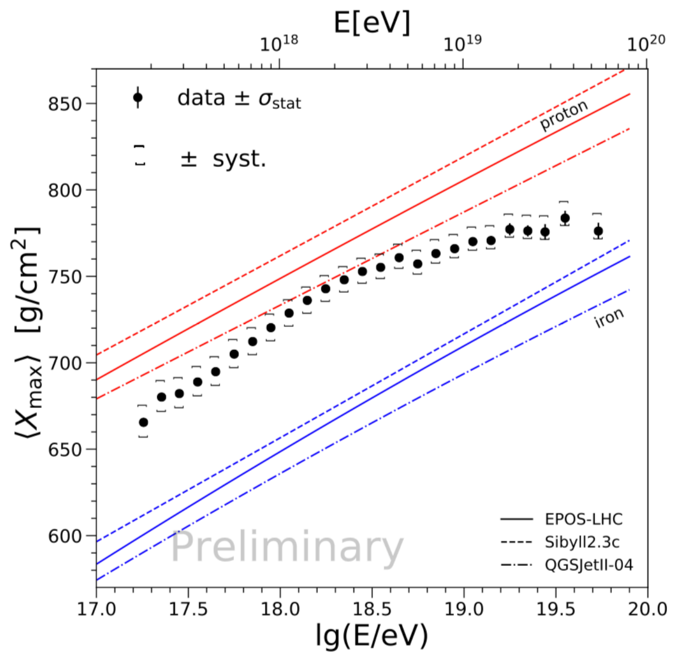


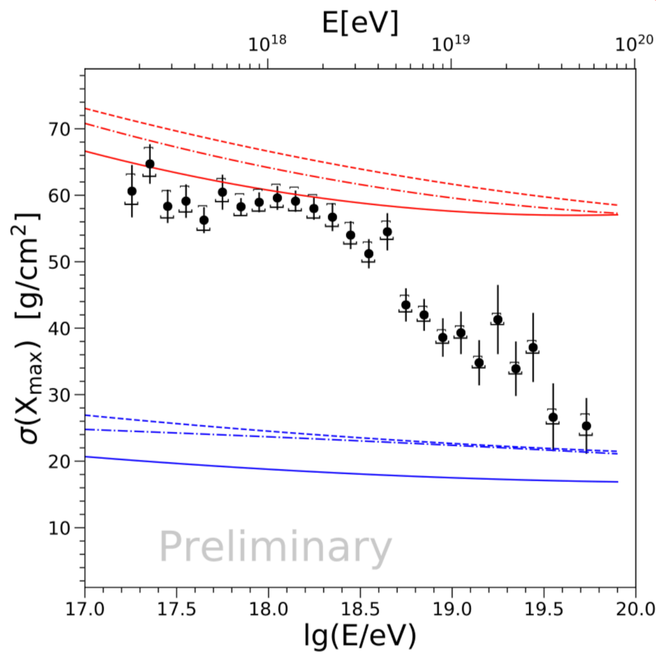


- Simulation of extragalactic propagation, taking into account:
  - Extragalactic photon fields
  - Photo-hadronic cross sections

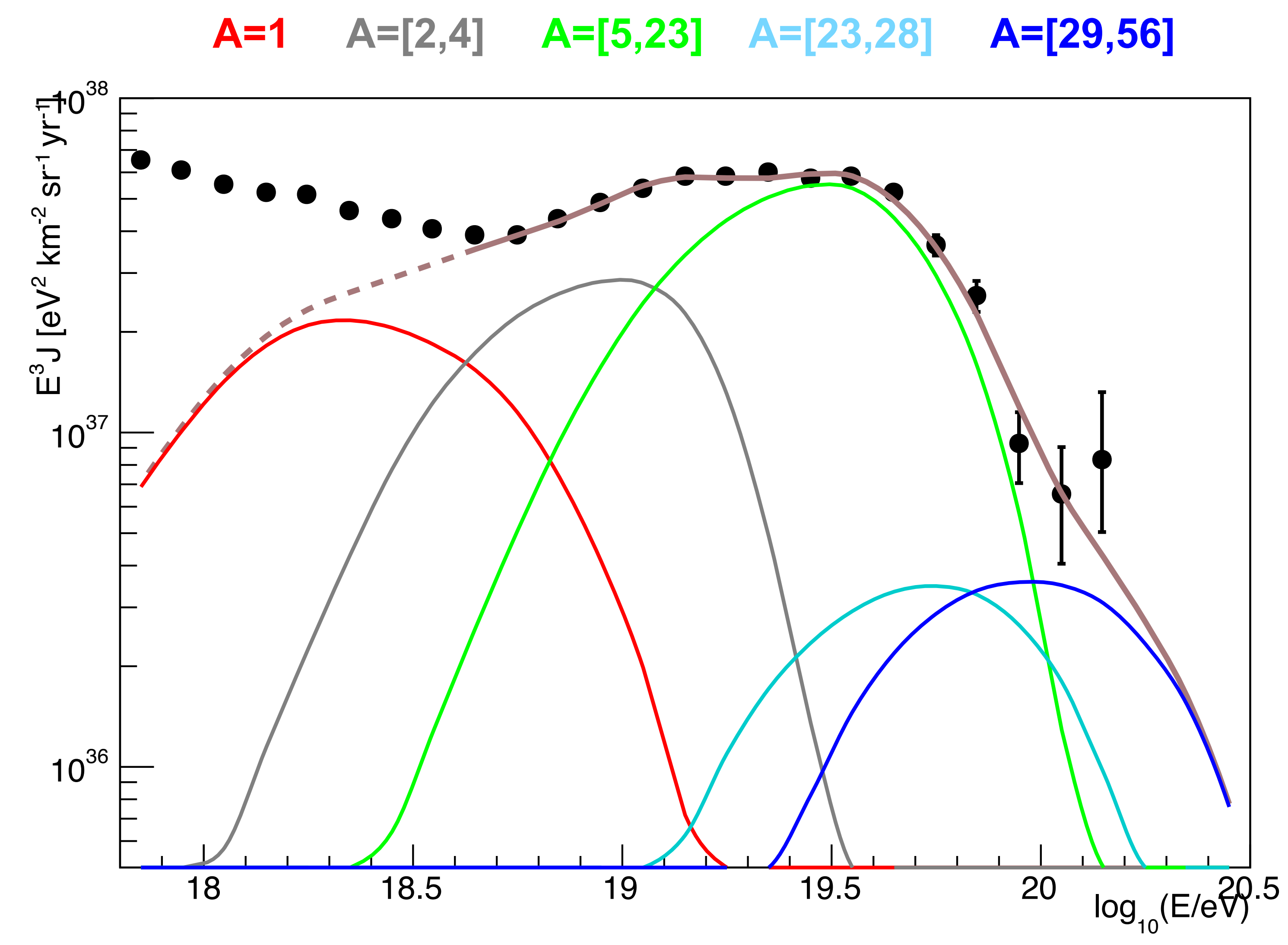
- Fit of energy spectrum and composition





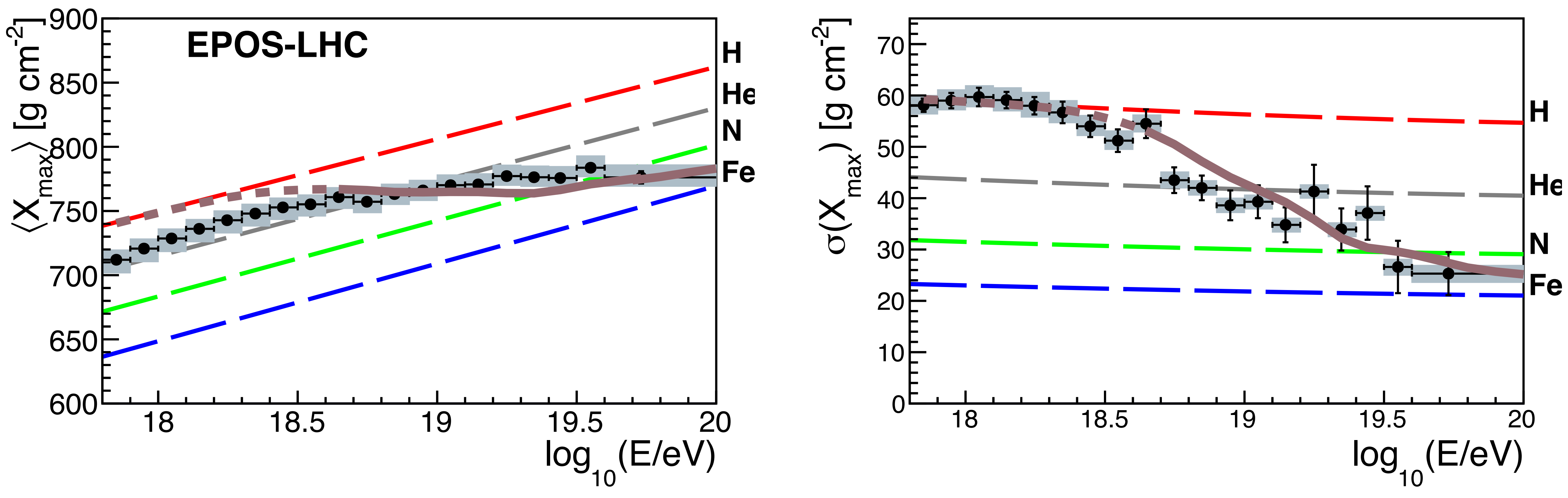


COMBINED SPECTRUM AND COMPOSITION FIT



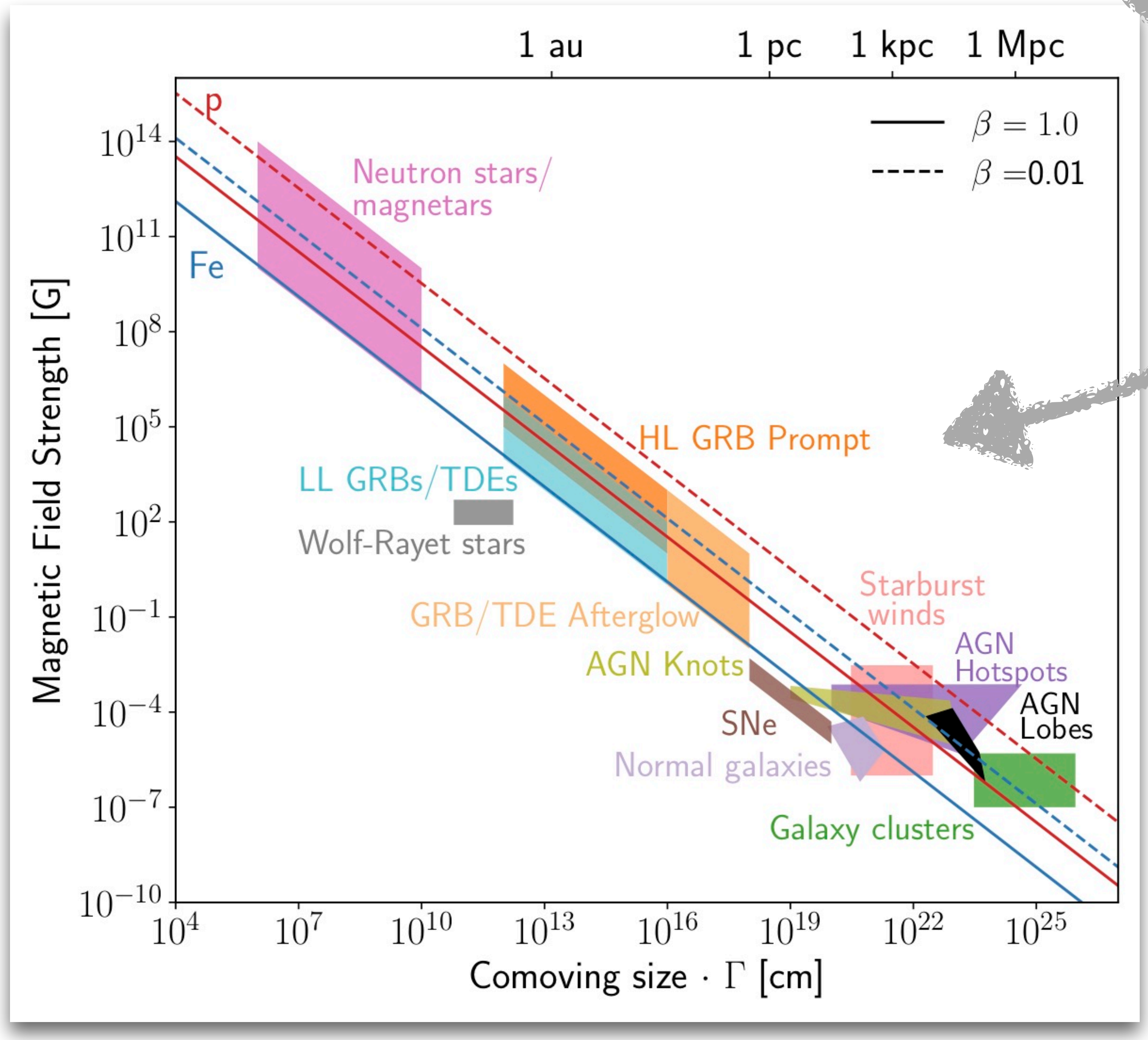
- Implications for characteristics of UHECRs <u>at their sources</u>
  - Small spectral index -> acceleration/interaction processes in the sources
  - Small rigidity -> power of the sources, <u>Hillas condition</u>?
  - CNO nuclear species dominate at source -> nature of the sources
  - <u>Consequences on secondary messengers</u>

$$E_{\max} \propto \beta_{\mathrm{sh}} ZeBR$$

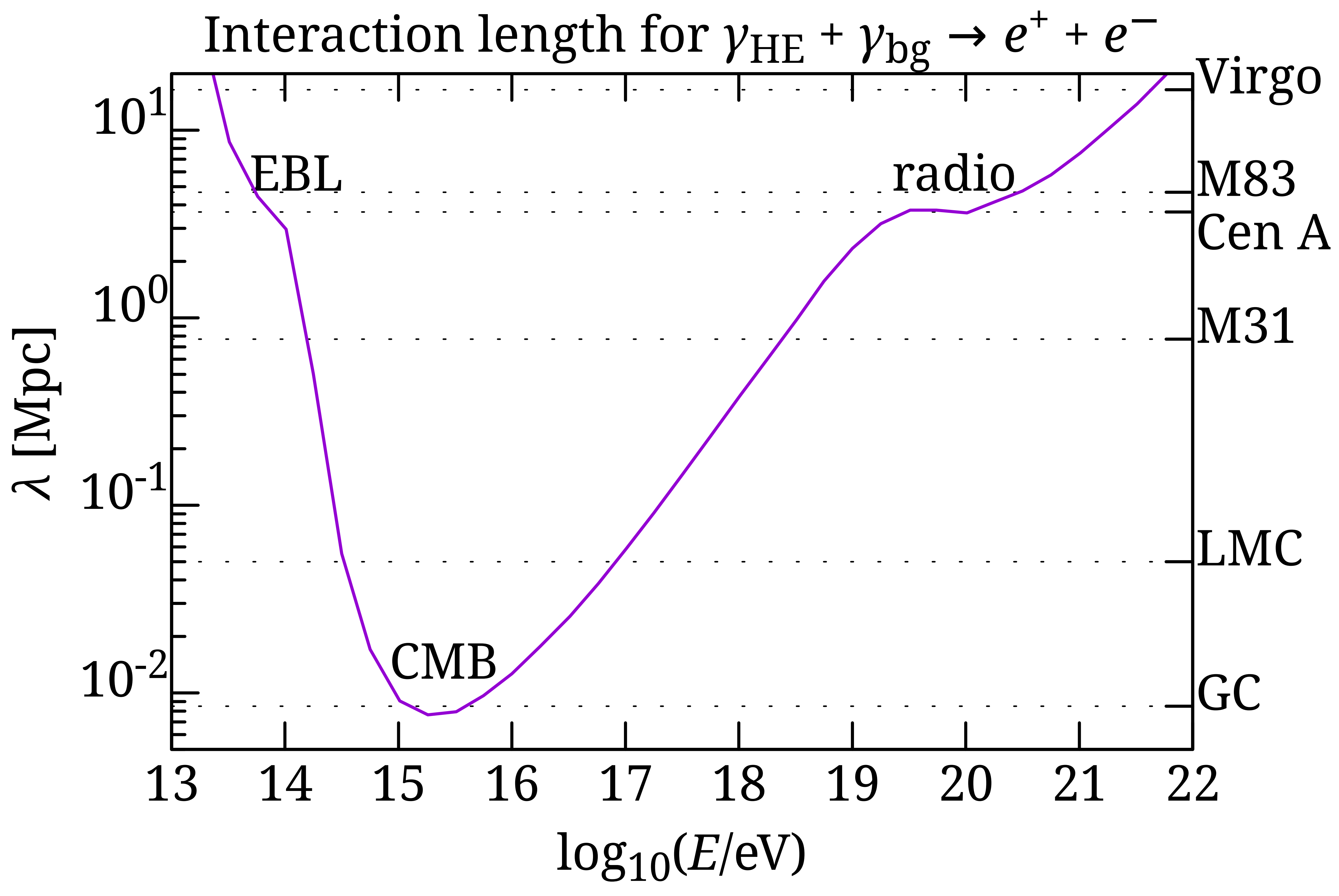


Similar to Auger JCAP 2017, with updated spectrum and composition (ICRC 2019)

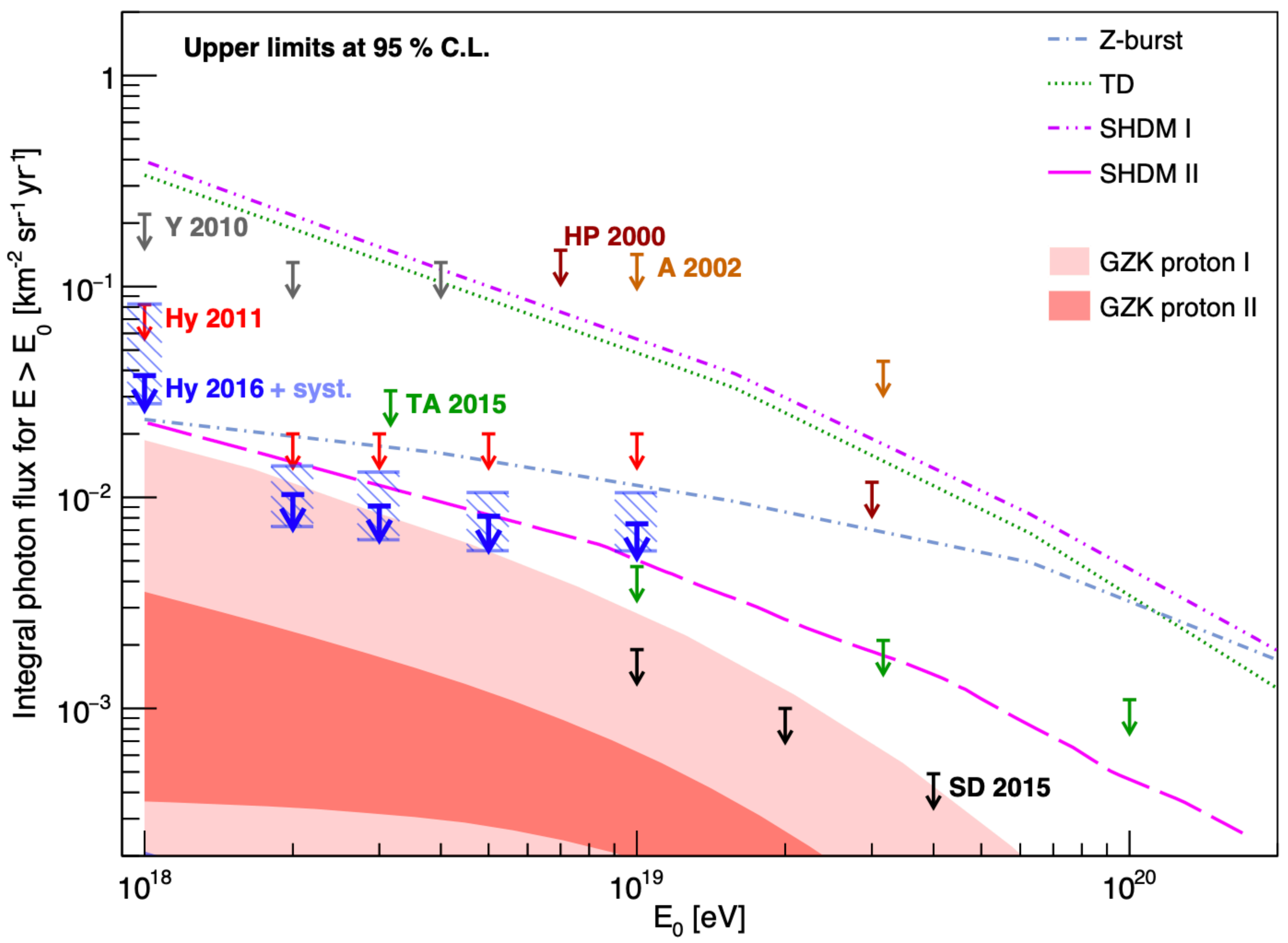
Alves Batista et al, 2019



PHOTON PROPAGATION



- Neutral pion decay contributes to electron/positron pair production
- Electrons/positrons undergo inverse Compton
  - Energy is transferred below 10^{14} eV



The Pierre Auger Collaboration, JCAP 2020

- UHE photons can be expected in connection with
  - Close UHECR sources
  - Top-down models
  - LIV modified photon propagation ?

MODIFIED PHOTON PROPAGATION

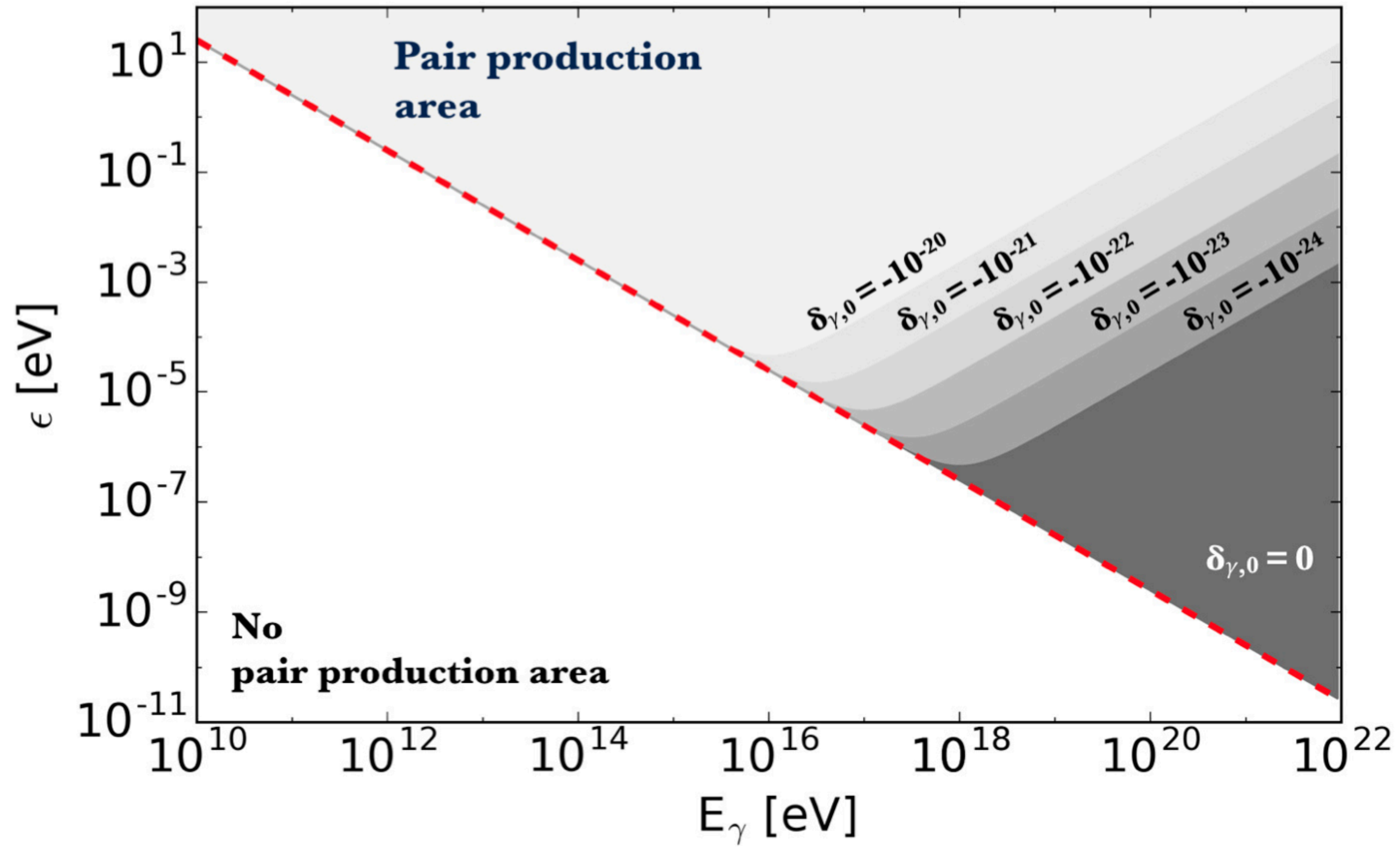
$$E_i^2 - p_i^2 = m_i^2 + \sum \delta_{i,n} E_i^{2+n}$$

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

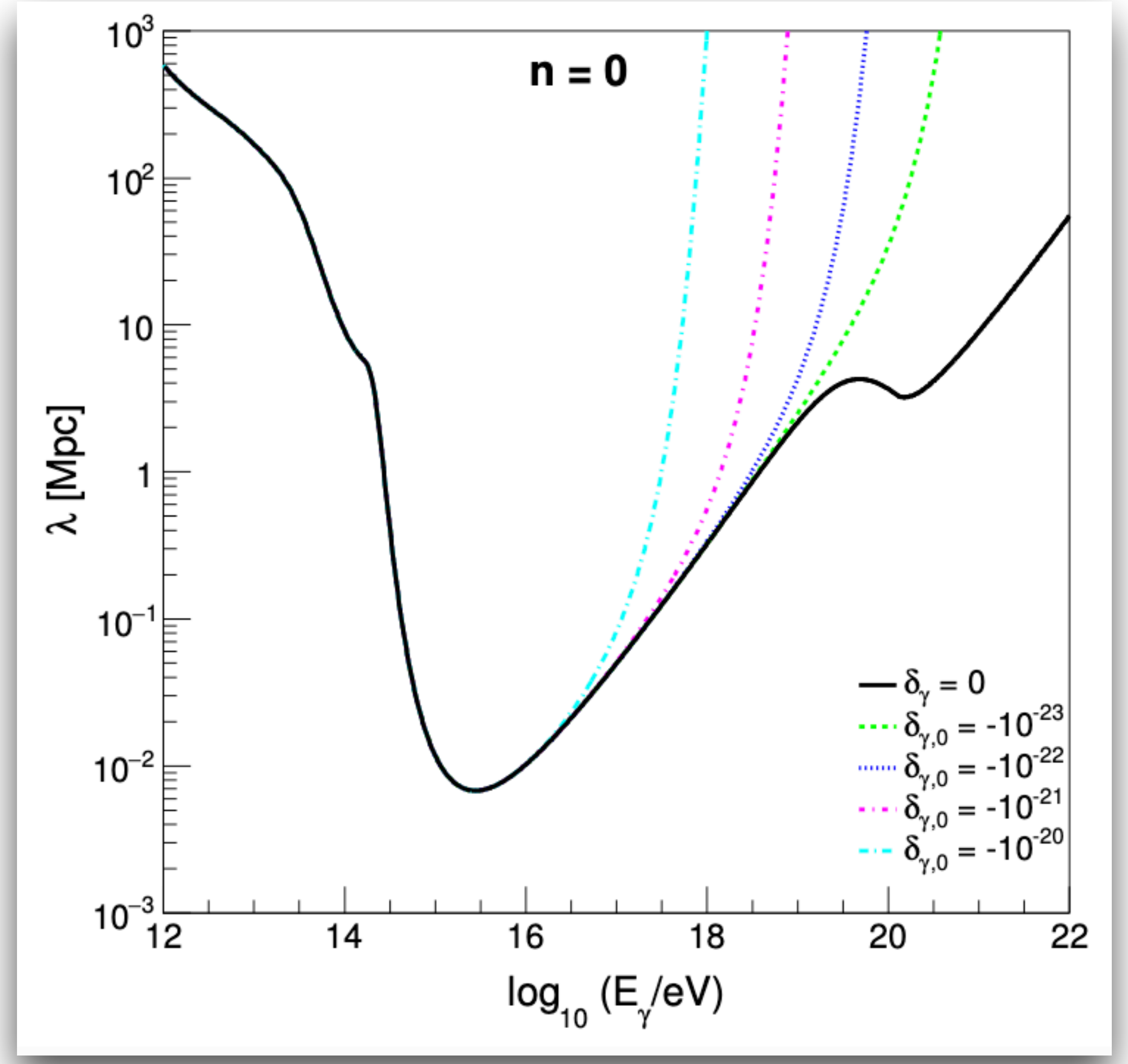
Effect on photon propagation:

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

- Modifications of propagation: **CRPropa/Eleca code**

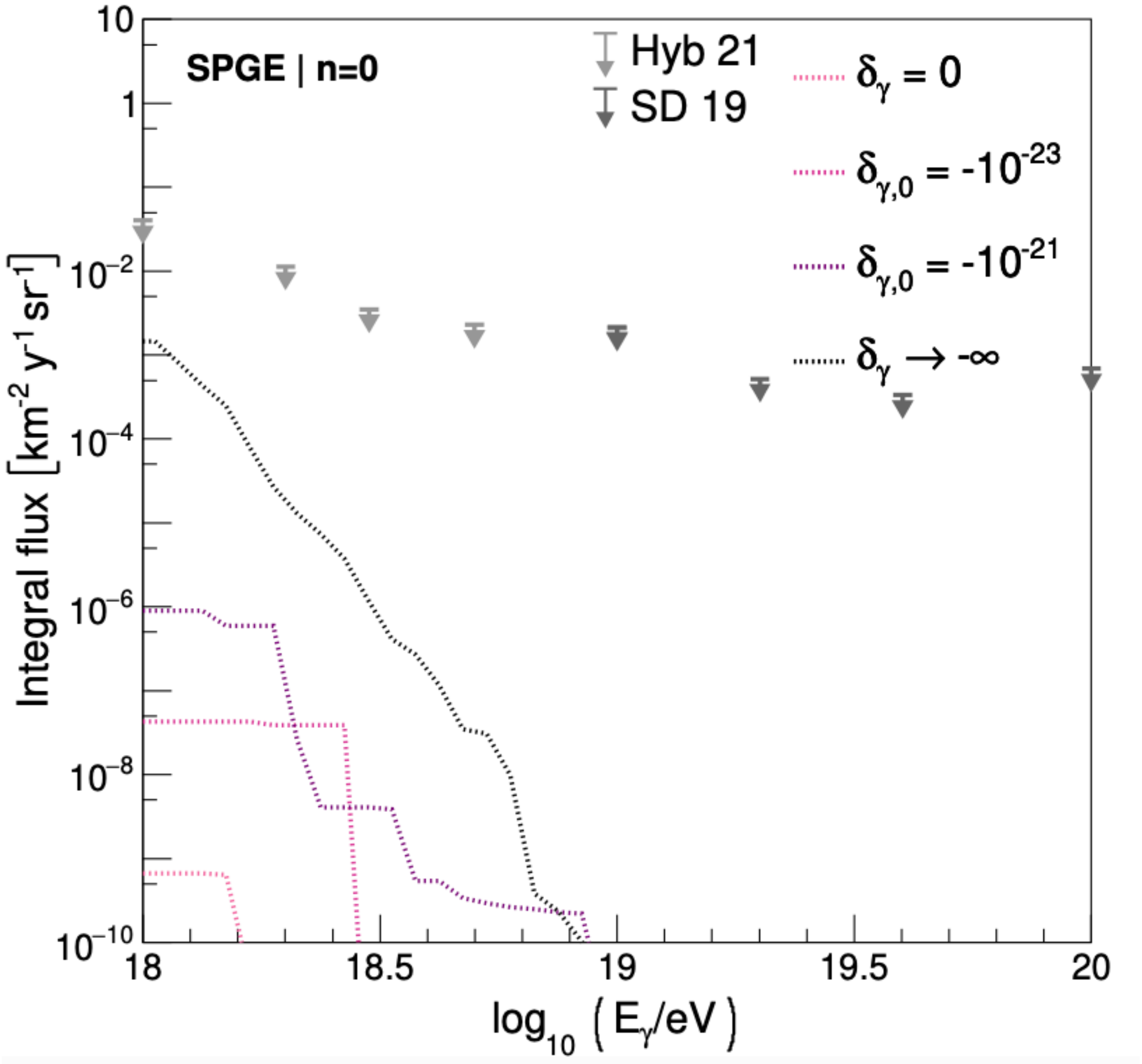


Lang, Martinez-Huerta & de Souza, ApJ 2018



EXPECTED PHOTON FLUX

The Pierre Auger Collaboration, JCAP 2022



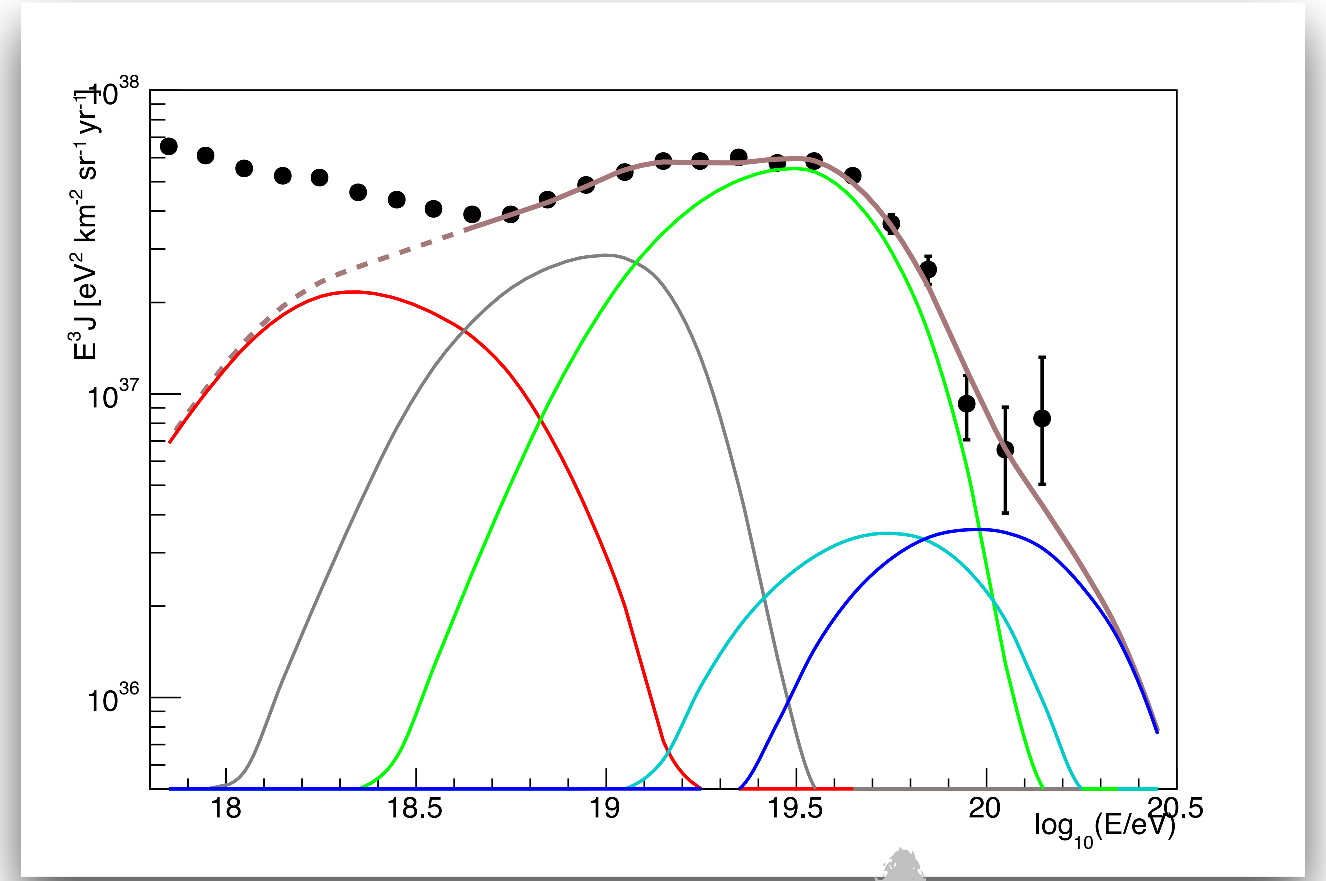
Effect on photon propagation:

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

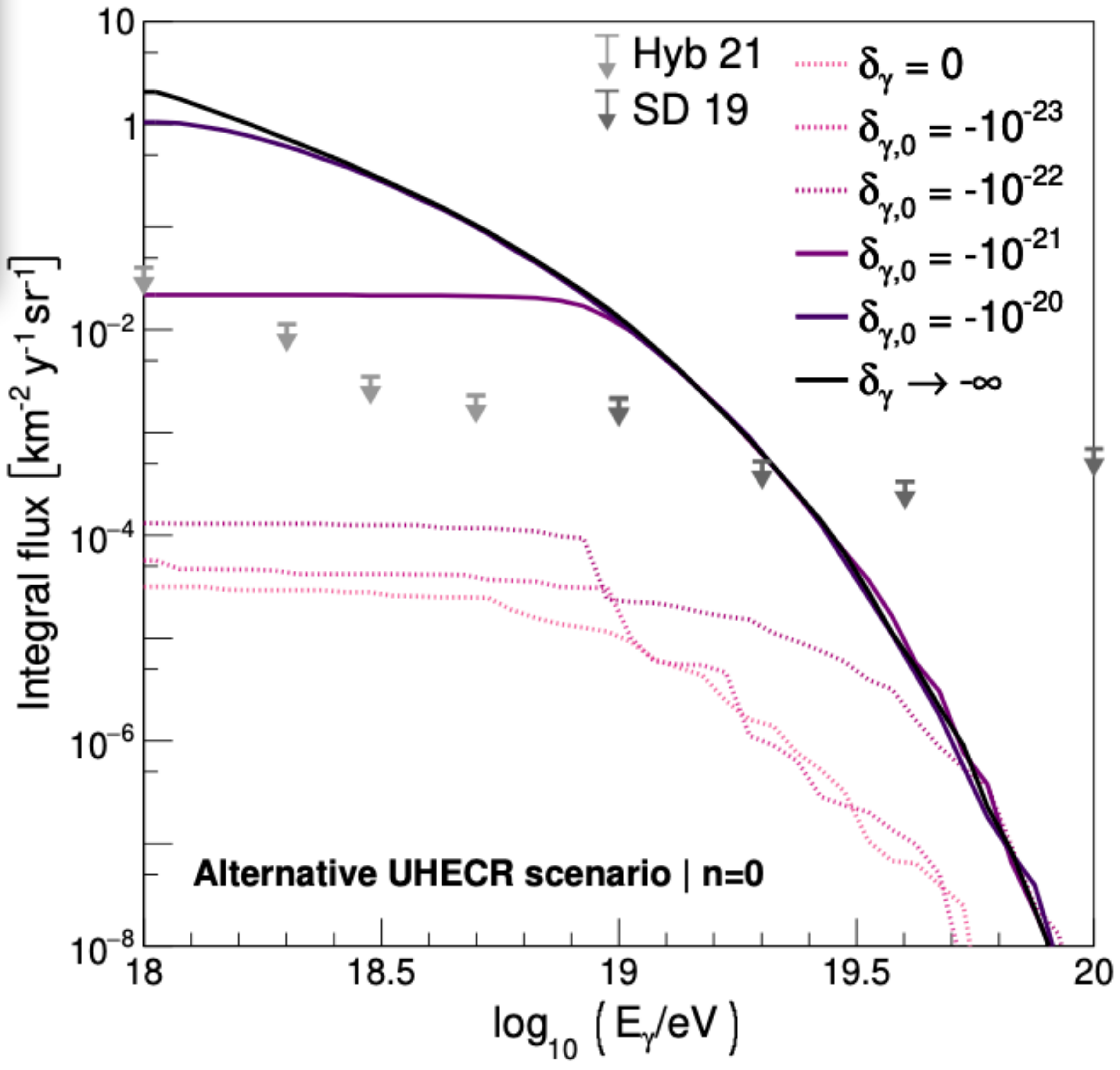
- Problem: favoured UHECR astrophysical scenarios imply parameters at the sources (for the spectrum and composition) that minimise the expected photon flux!
- Why?
  - Photons from neutral pion decay -> Pions from photo-pion production -> Threshold for photo-pion production is shifted at A times the one for protons

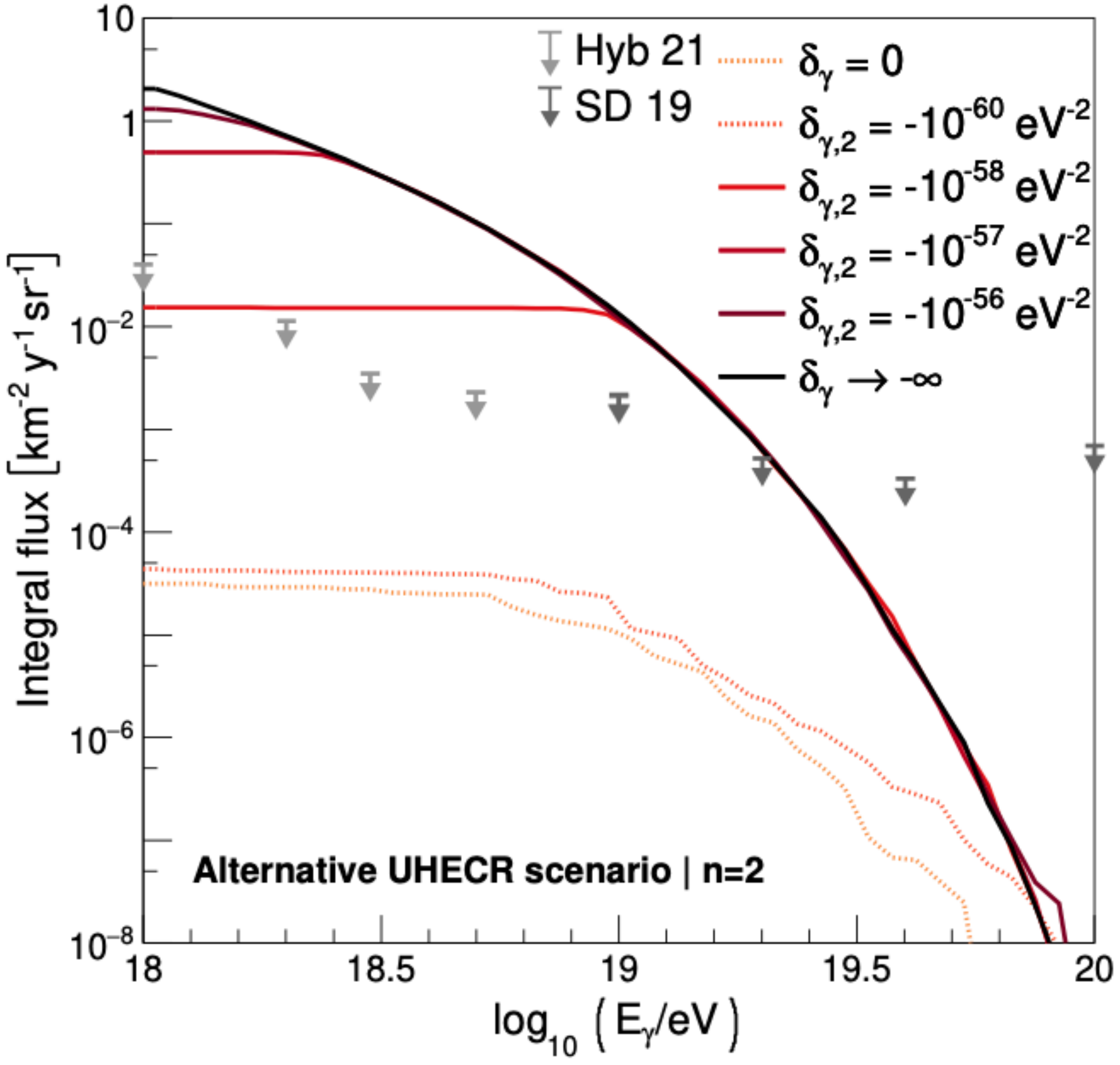
EXPECTED PHOTON FLUX

The Pierre Auger Collaboration, JCAP 2022



Photons produced in extragalactic propagation by UHECRs with **additional proton component** at high energy!



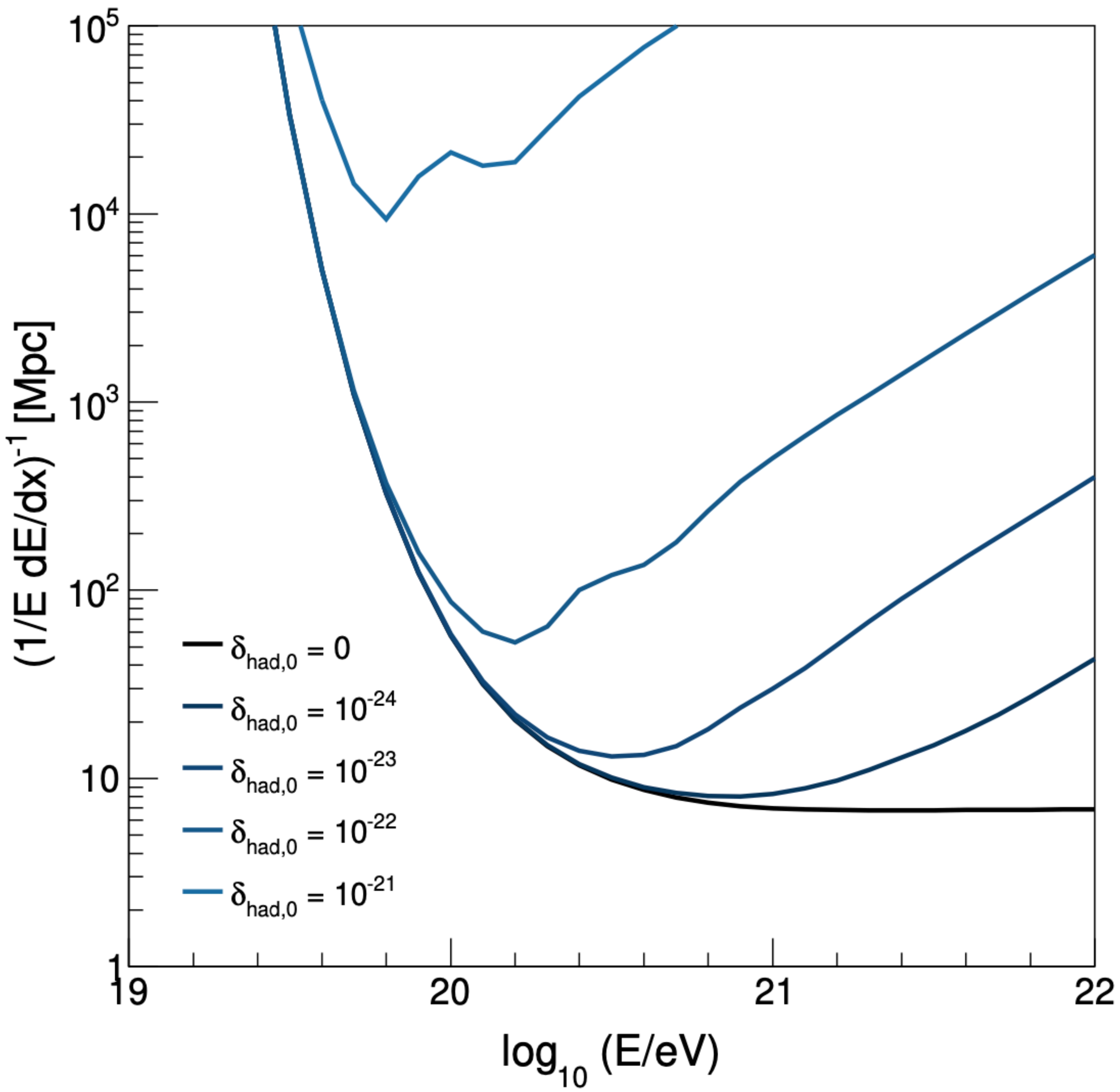


$\delta^{(0)} > -10^{-21}$ $\delta^{(1)} > -10^{-40}\,\mathrm{eV}^{-1}$ $\delta^{(2)} > -10^{-58}\,\mathrm{eV}^{-2}$

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)

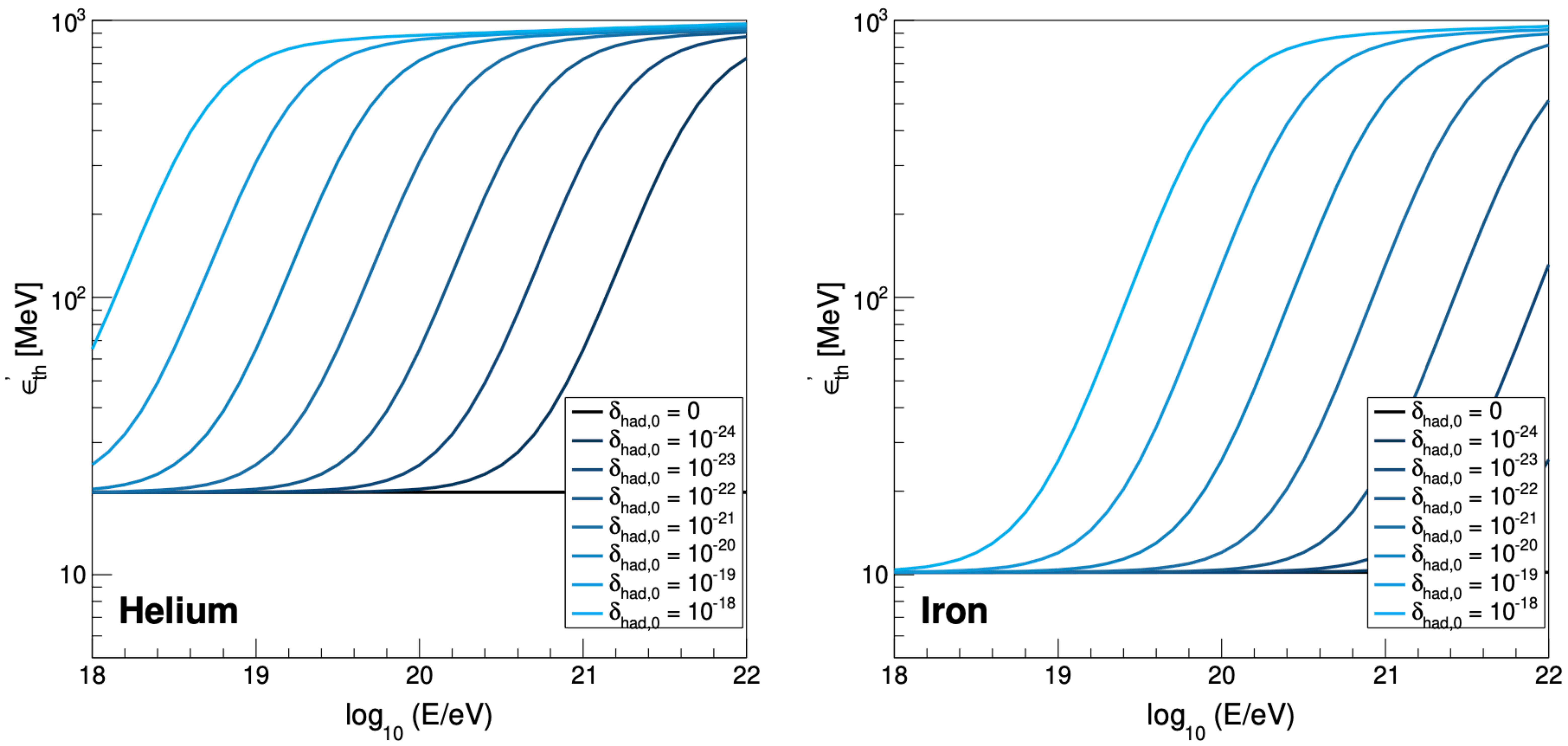


- Effect of recovering of the spectrum is expected
  - But not observed!

- 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

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

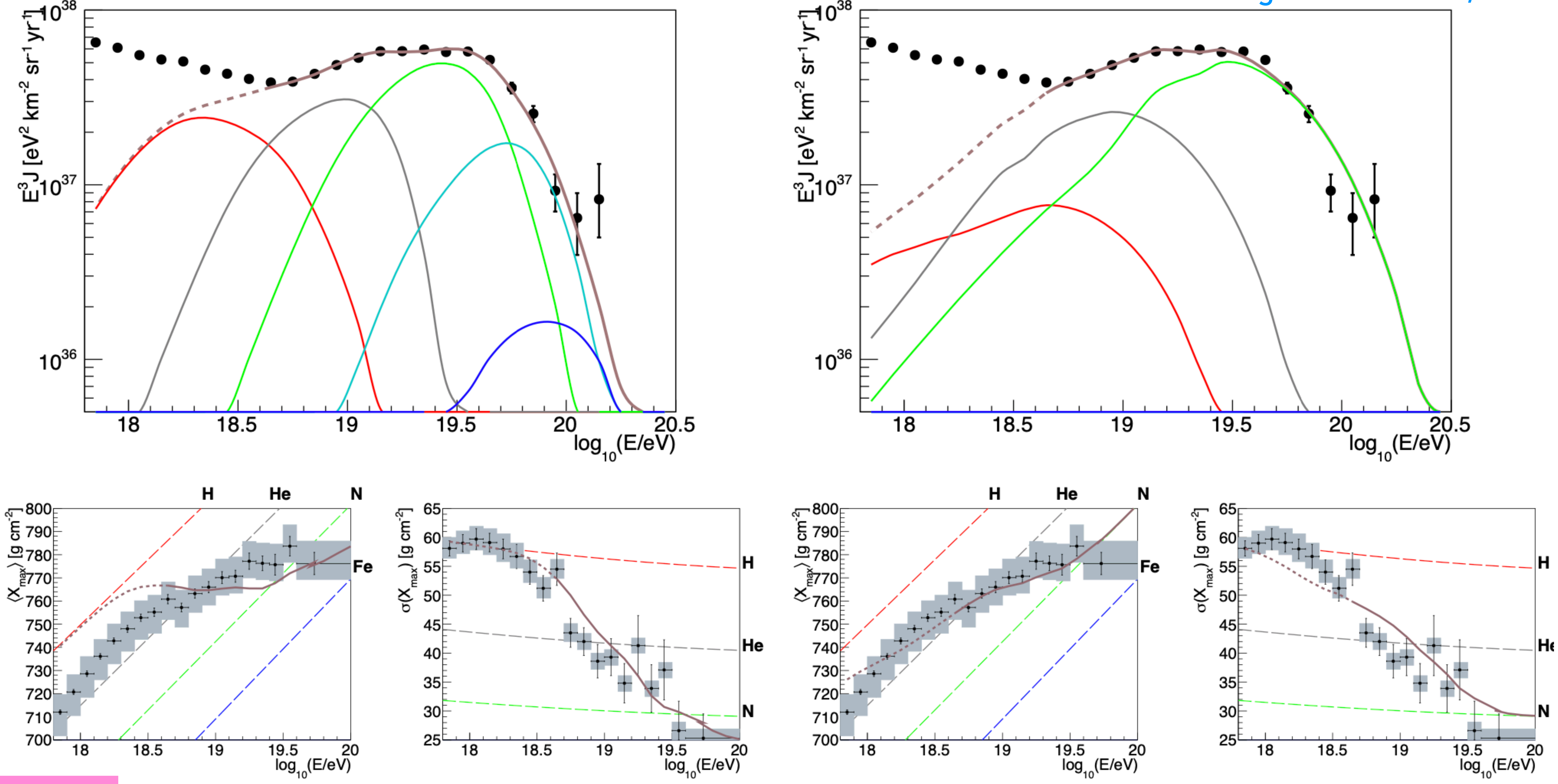
$$A^2 E_p^2 = A^2 p_p^2 + A^2 m_p^2 + A^2 \sum \delta_{A,n} A^n E_p^{2+n}$$

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

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

EXPECTED CR SPECTRUM AND COMPOSITION

The Pierre Auger Collaboration, JCAP 2022

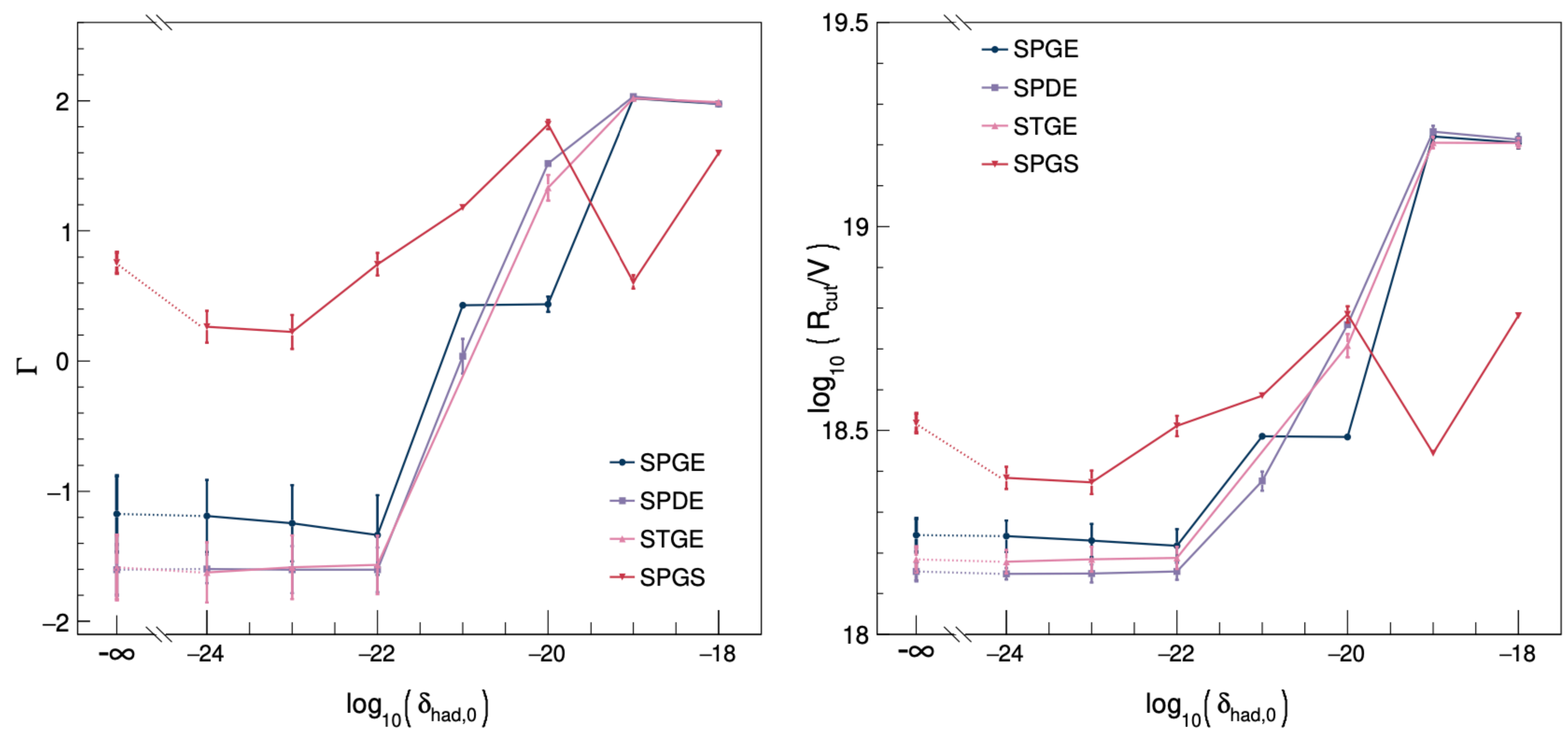


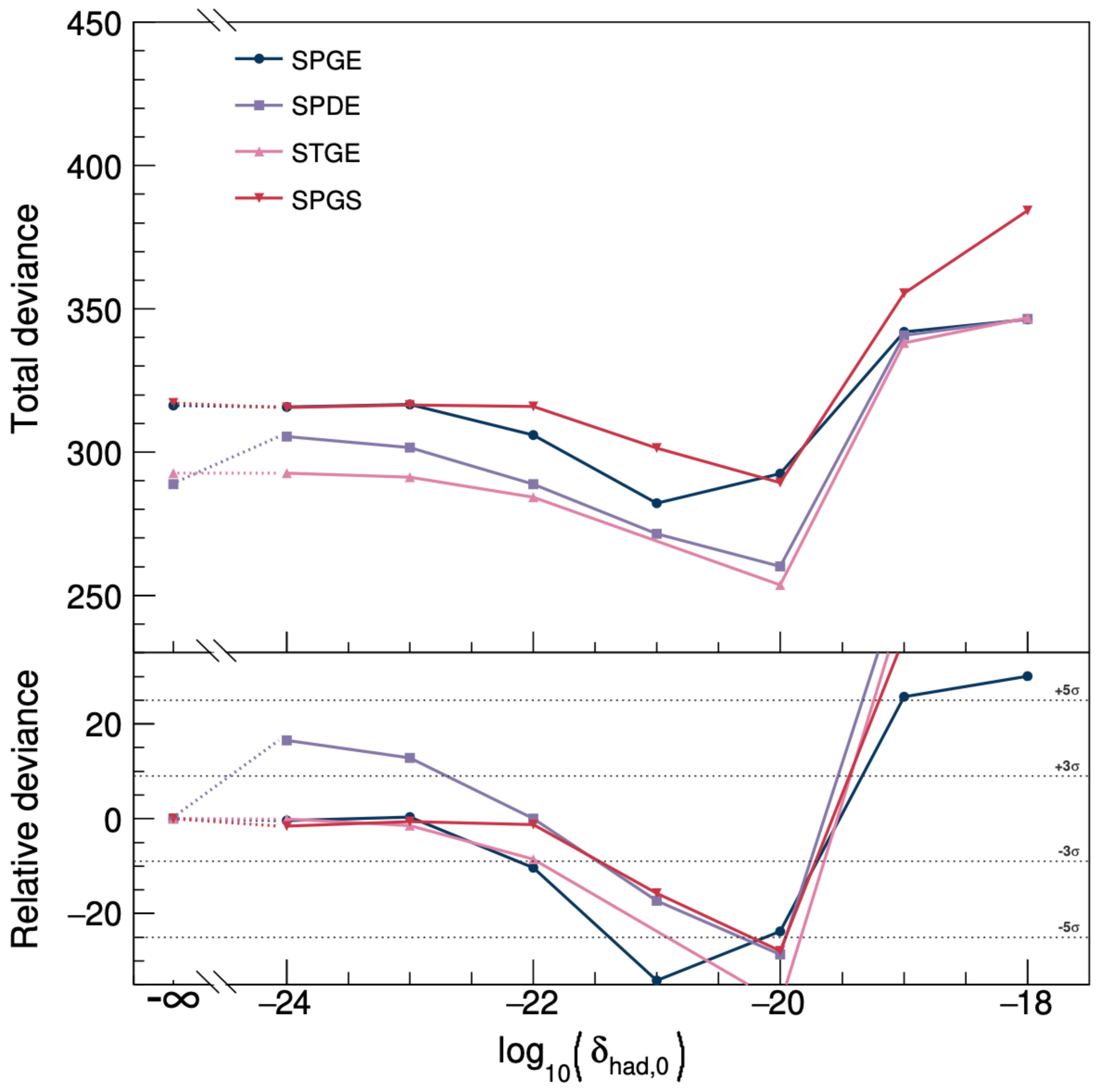
Effect on CR propagation:

- 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

LIV AND ASTROPARTICLES

- Wish list for studying LIV with astroparticles
  - Extremely energetic cosmic rays
  - Light cosmic rays (photo-pion production processes might have the largest modifications due to LIV)
  - High energy + light particles -> photo-pion reactions are more efficient -> large cosmogenic gamma-ray and neutrino fluxes might be expected

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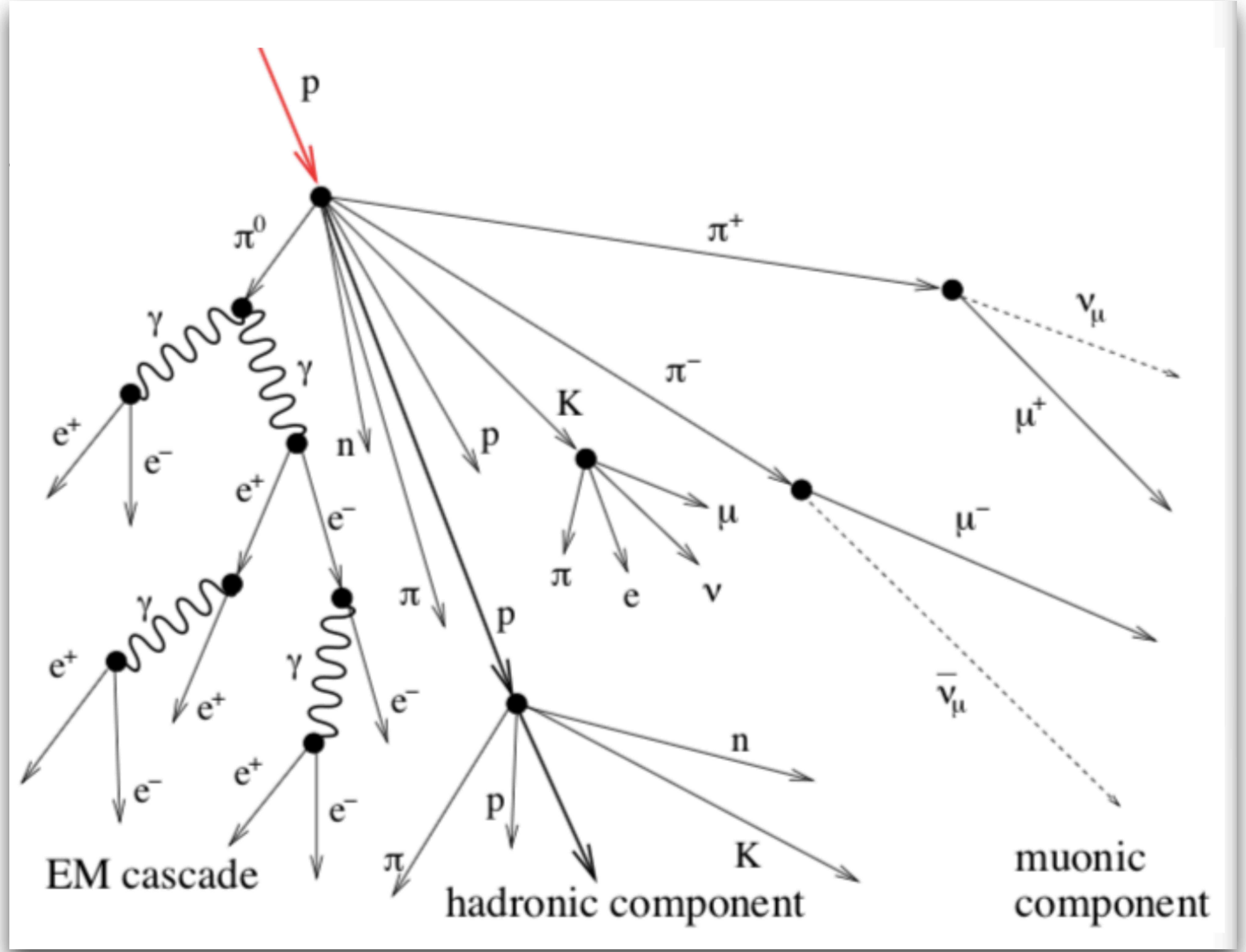
- What we have
    - Low rigidity found with UHECR astro scenarios
        - The suppression of the CR flux cannot be due only to propagation: source power is involved
    - Heavier species found at the highest energies
        - Implications for secondary messengers

What about the development of the cascade of particles in the Earth's atmosphere?

LIV AND EXTENSIVE AIR SHOWERS

EXTENSIVE AIR SHOWERS



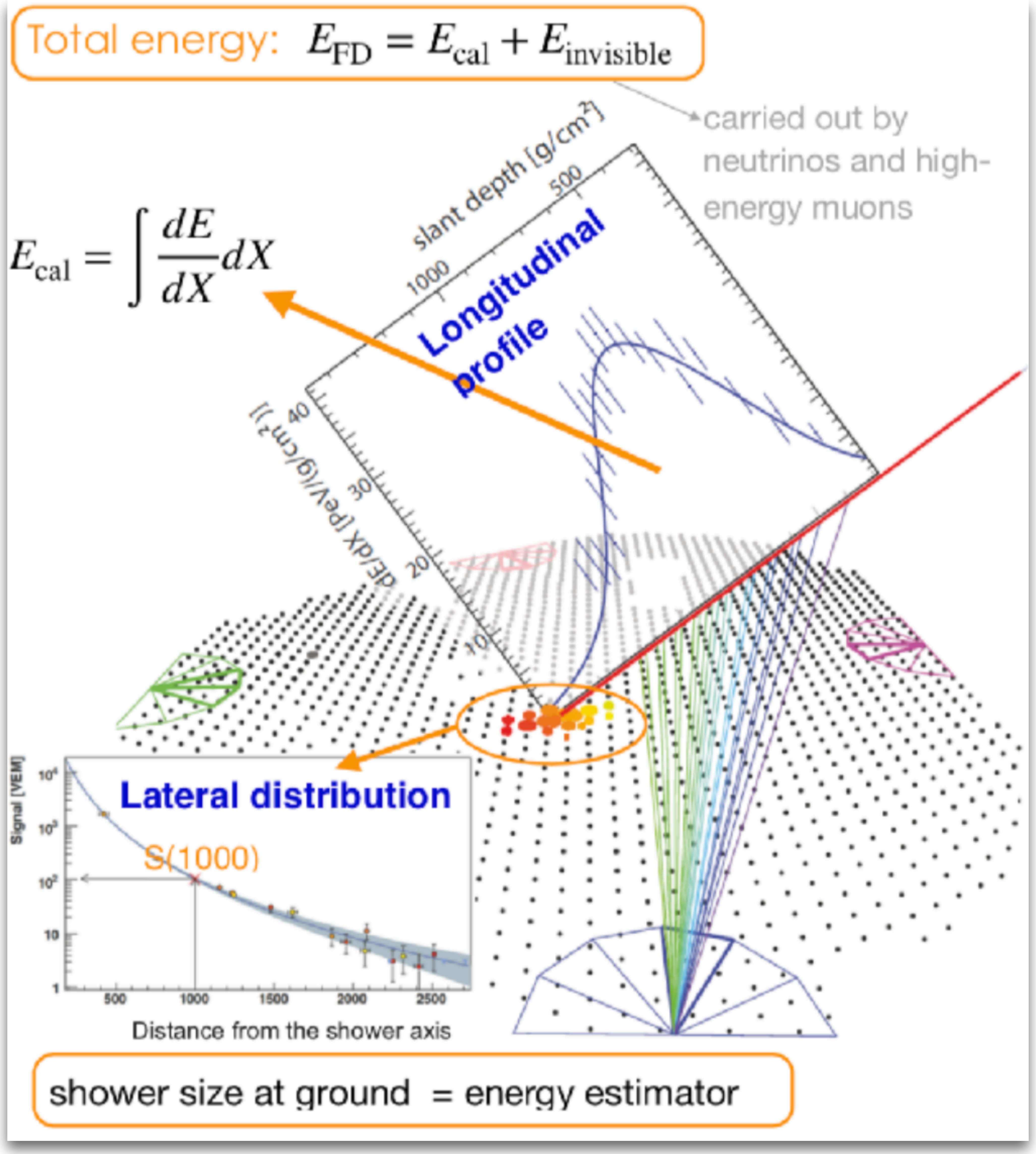
- **Pions** drive the development of <u>electromagnetic and muonic components</u> of EAS
  - Early stages: pions interact
  - Late stages: pions decay

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

EXTENSIVE AIR SHOWERS

- **Longitudinal profile of the EAS (integrate energy losses in atmosphere)**
  - Electromagnetic component

- **Lateral distribution of the EAS (look at particles at ground)**
  - Muonic component



MASS COMPOSITION FROM EL-MAG COMPONENT OF EAS

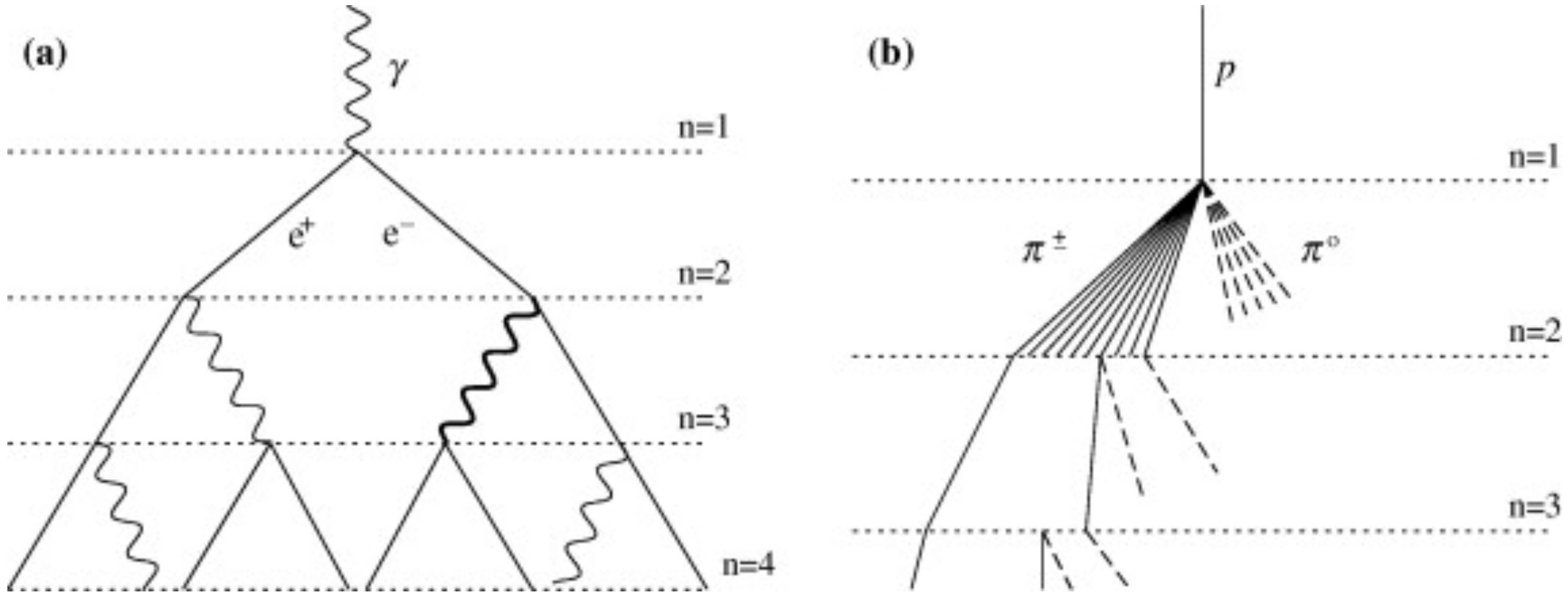
Heitler model for EAS

$$N(X) = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{N(X)}$$

$$N(X_{\max}) = \frac{E_0}{E_c}$$

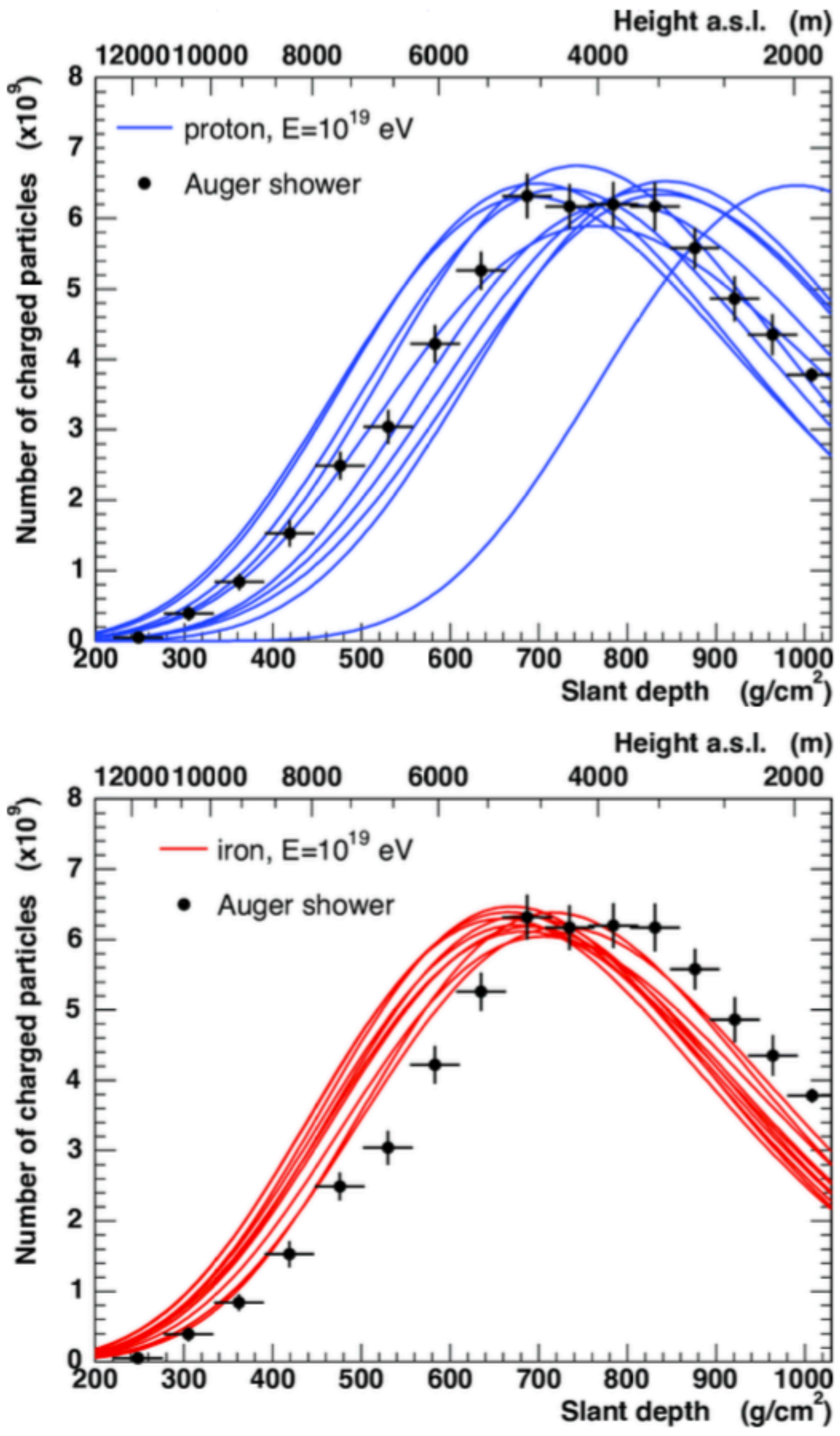
$$X_{\max} \propto \ln(E_0/E_c)$$



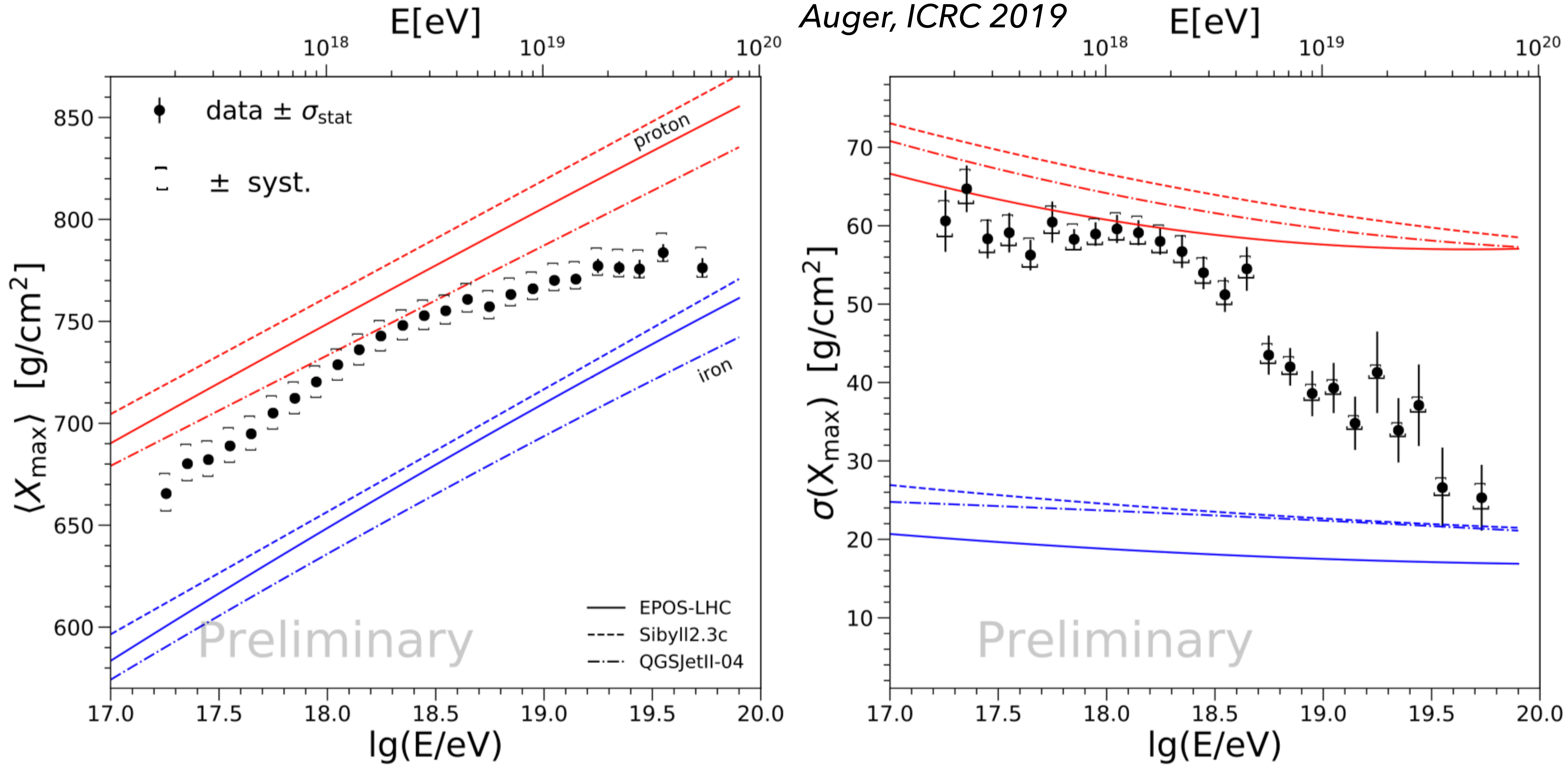
Superposition model: ${}^{A}X, E_0 \leftrightarrow A \times n, E_0/A$

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

MASS COMPOSITION FROM EL-MAG COMPONENT OF EAS

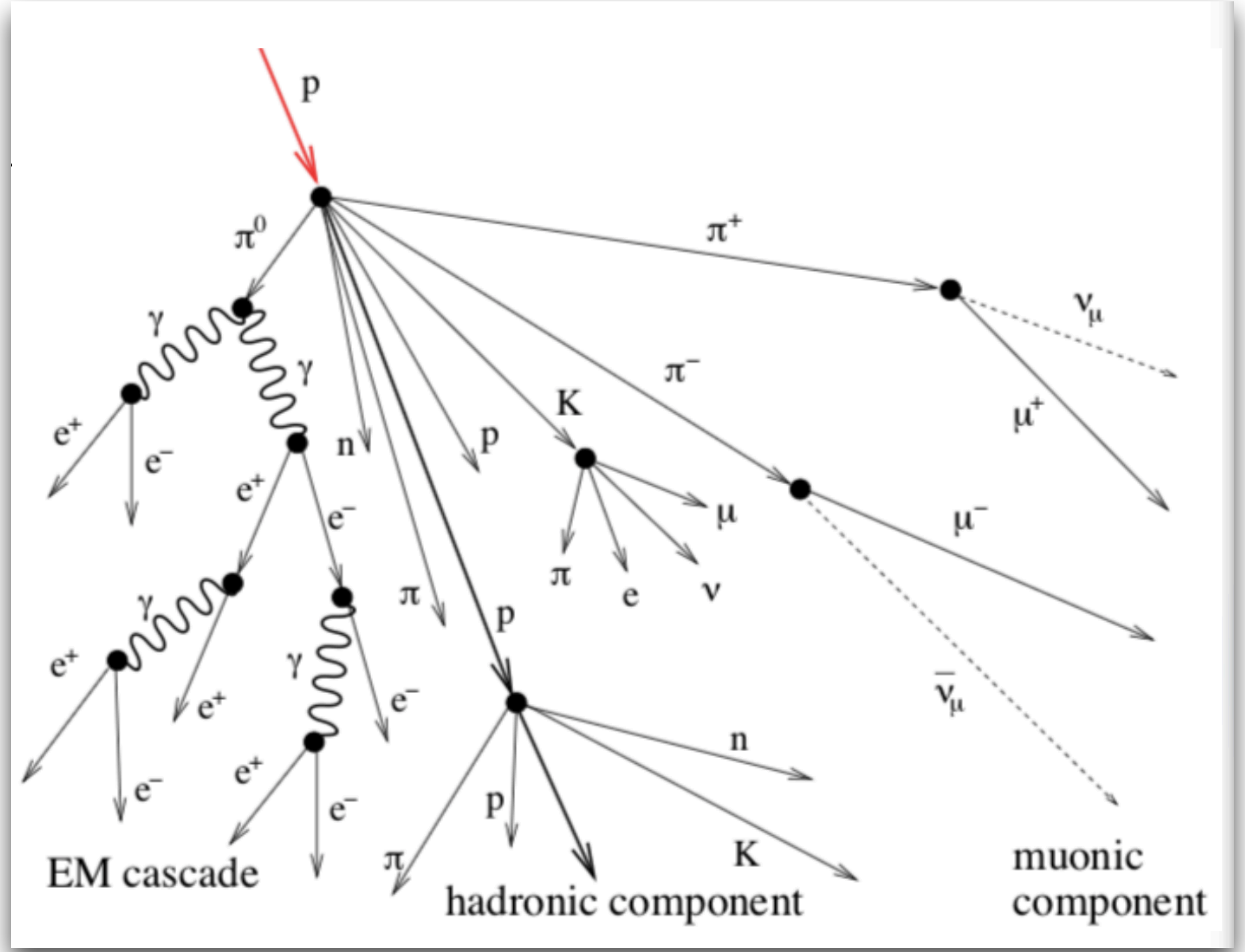


Auger, ICRC 2019



- Composition information (mainly) from the longitudinal development of the shower
- Break in <Xmax> at energy of the ankle
- Fluctuations decreasing with increasing energy

LIV IN EXTENSIVE AIR SHOWERS

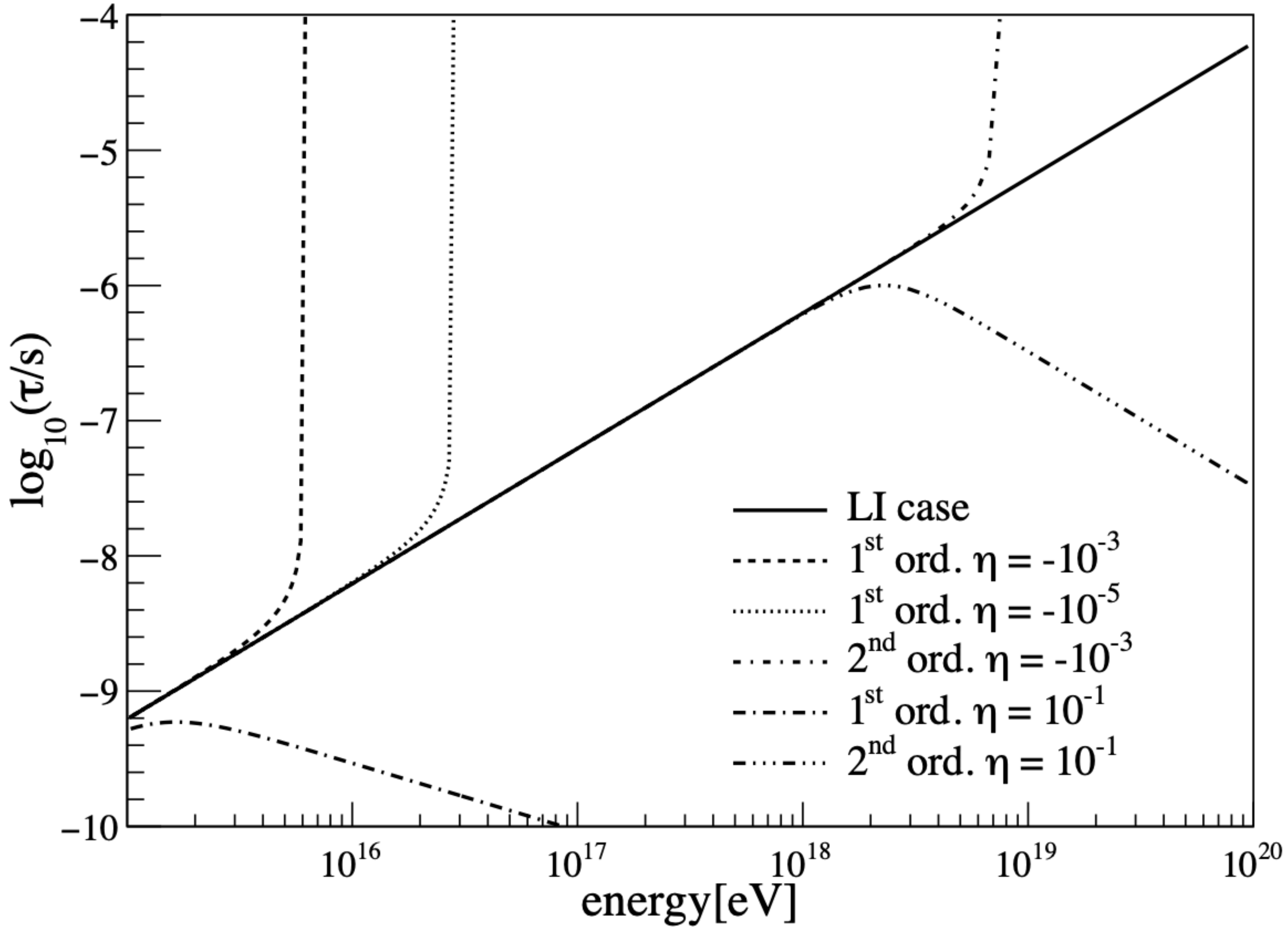


- Heavy primary CRs with respect to light primary CRs with same energy
  - EAS develops earlier in atmosphere (smaller Xmax)
  - Position of Xmax fluctuates less
  - Contain more muons
  - Number of muons fluctuates less
- LIV can affect kinematics
  - Example:
    - Pions do not decay -> neutral pions interact
    - More muons are produced
    - Electromagnetic vs muonic component of the shower are affected

MODIFICATIONS TO EAS DEVELOPMENT

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

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



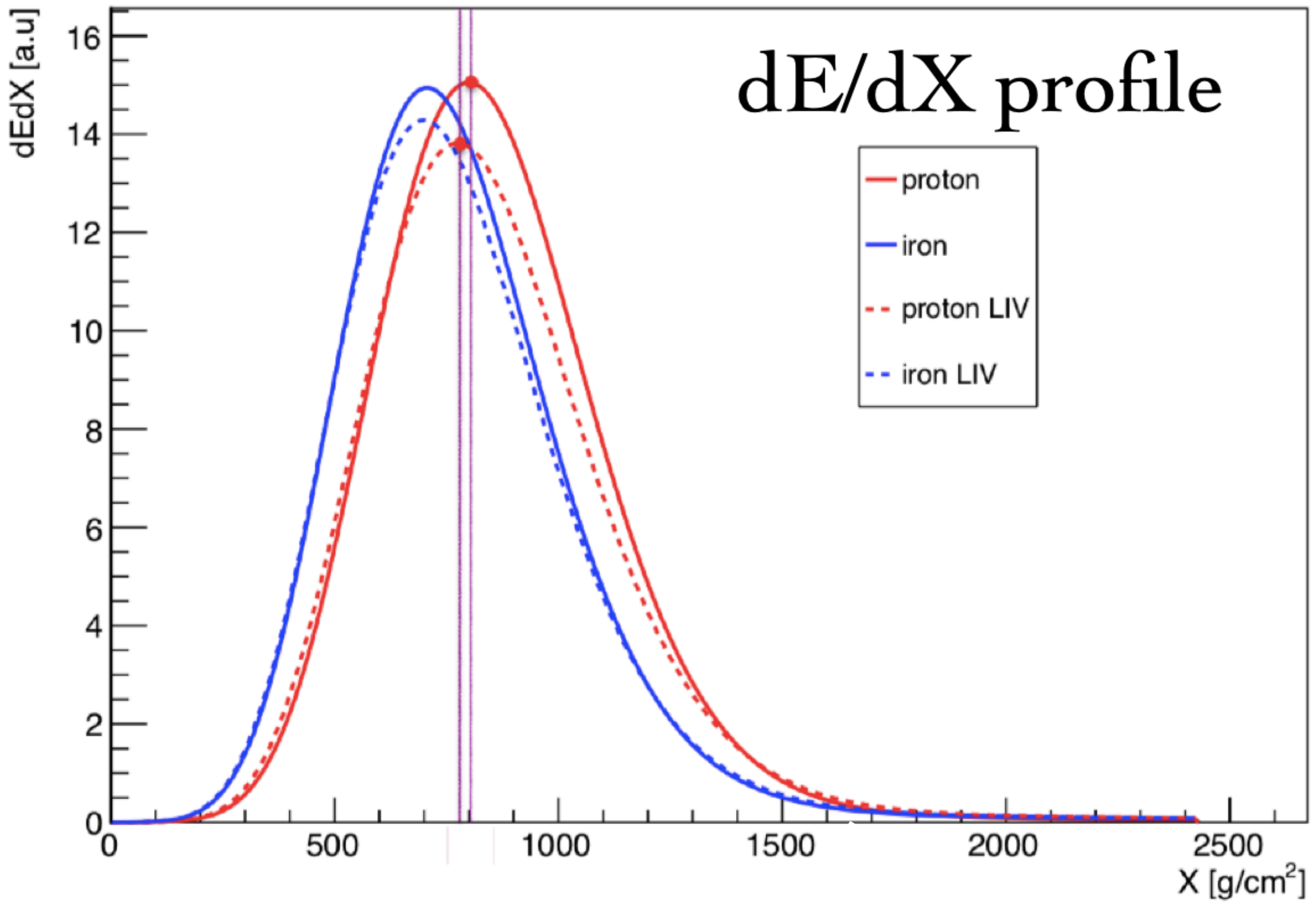
$$\Gamma = \frac{E}{m_{\mathrm{LIV}}} \qquad \tau = \Gamma \tau_0$$

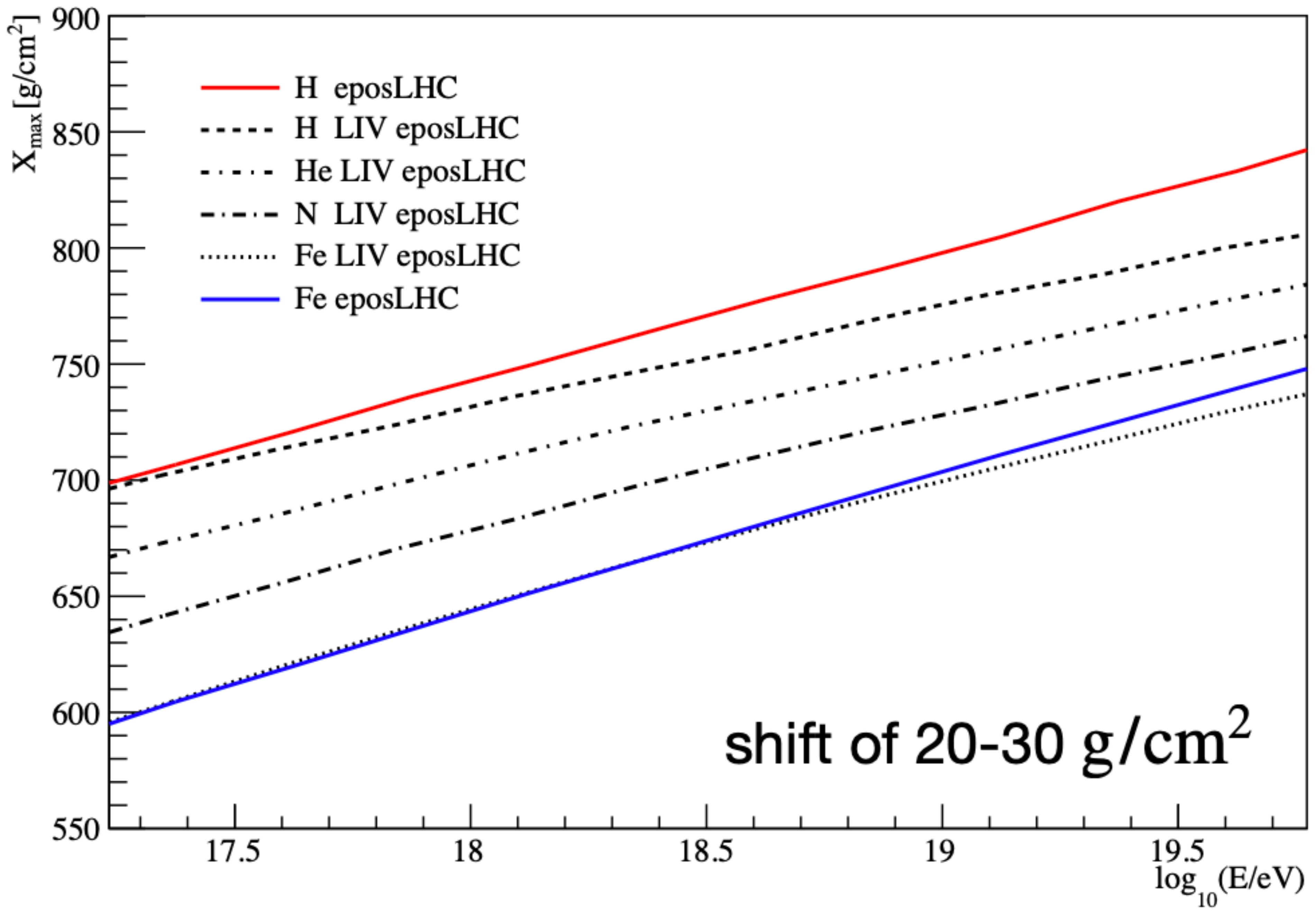
1. Positive eta: negligible effects
2. Negative eta: forbidden neutral pion decay if…

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

MODIFICATIONS TO MASS OBSERVABLES

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

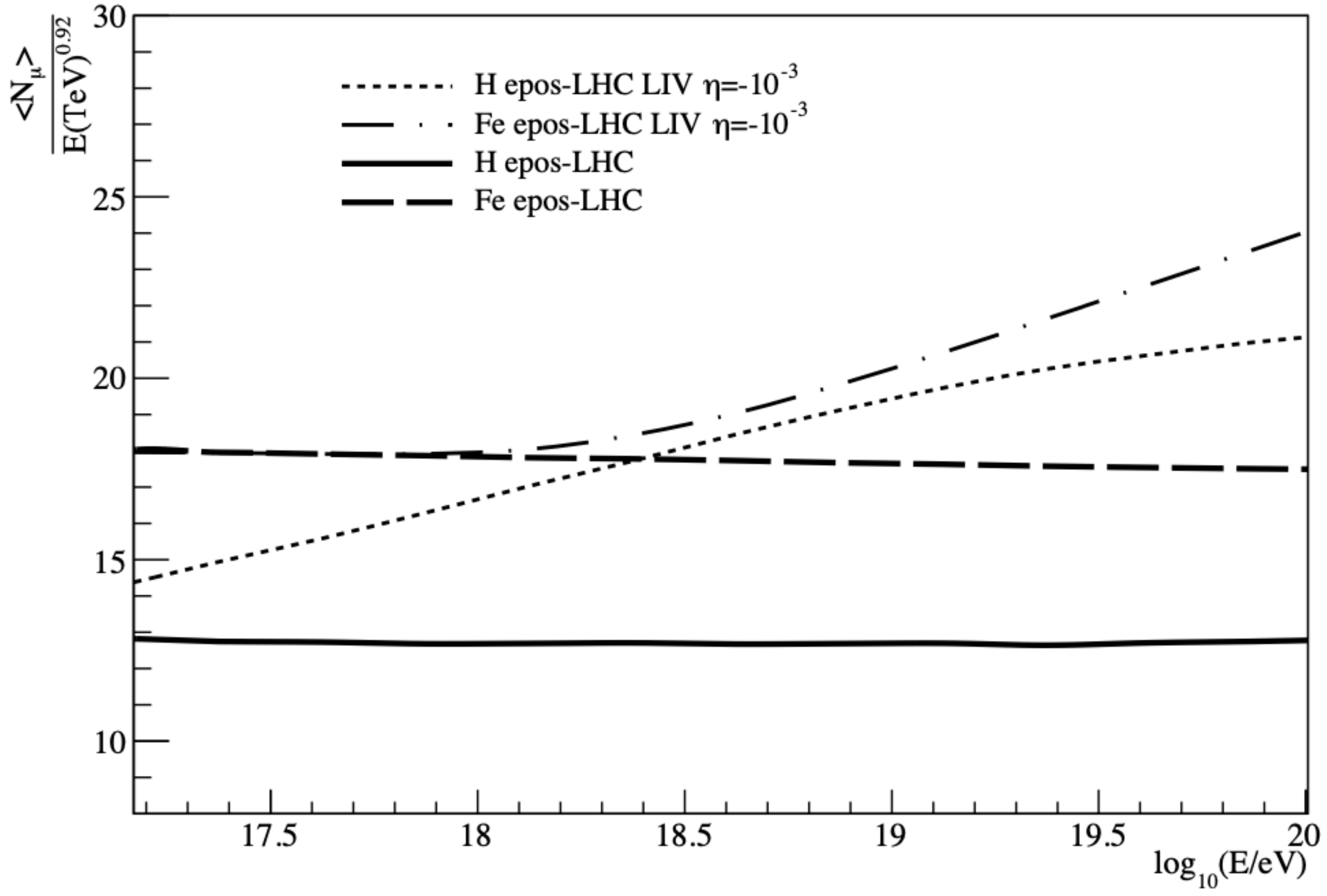


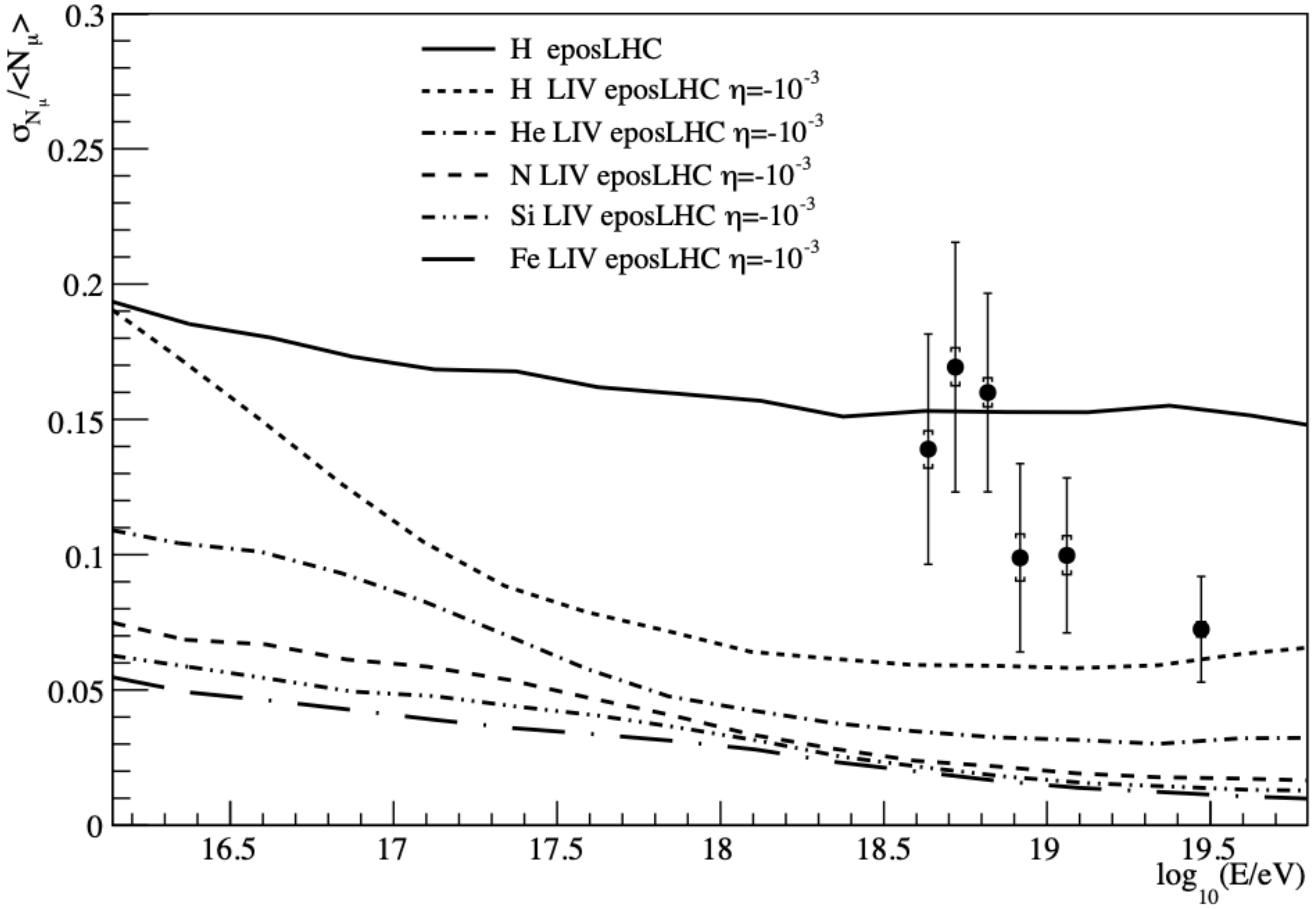


- If neutral pion does not decay, it can interact
  - Calorimetric energy is smaller than in the LI case
  - Predictions for Xmax decrease with energy with respect to the LI case

MODIFICATIONS TO MASS OBSERVABLES

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021





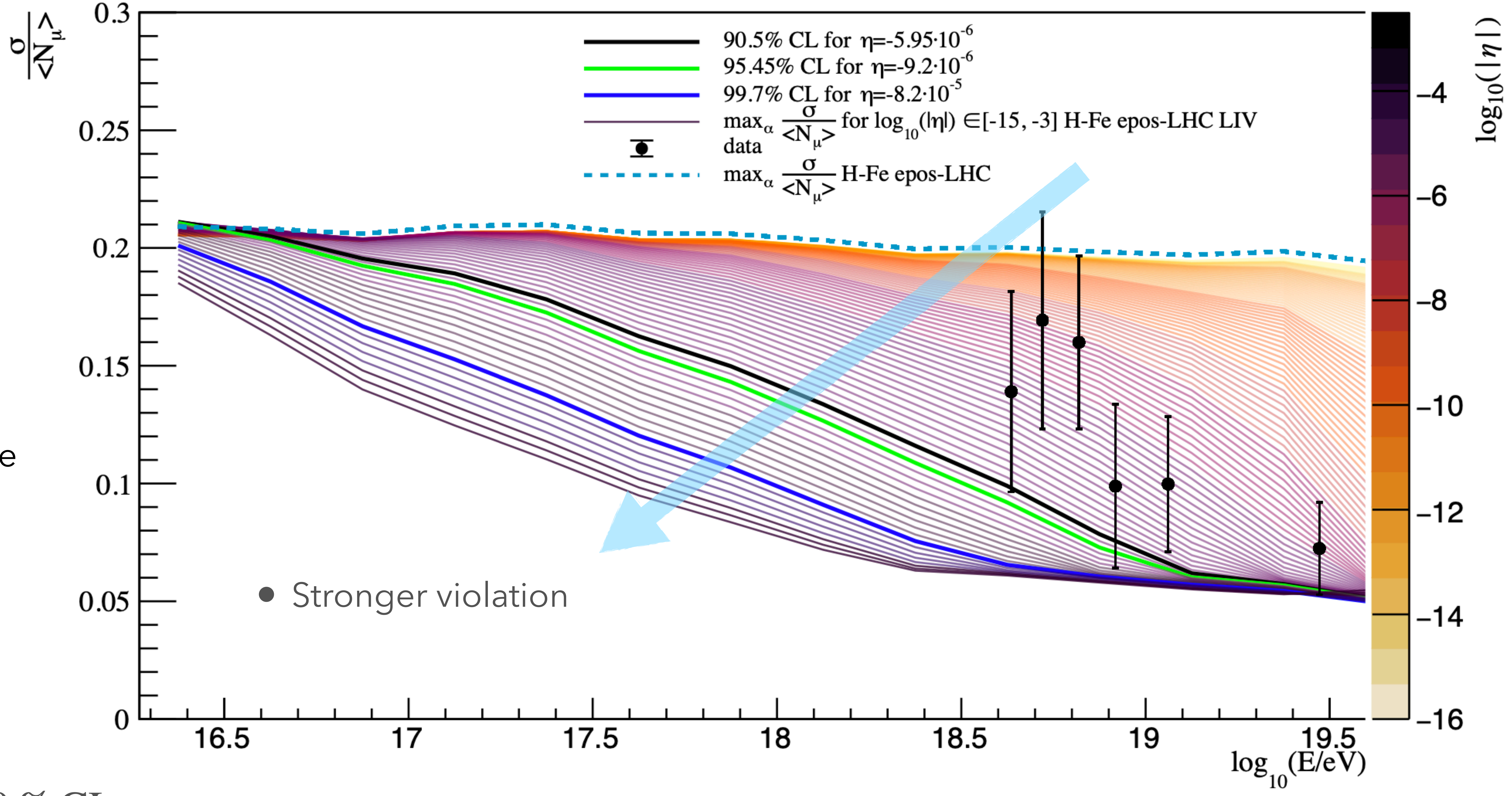
- LI case:
  - number of muons larger (and less fluctuations) in showers initiated by heavy nuclear species with respect to protons
- LIV case:
  - Fluctuations decrease with respect to the LI case

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

CONSTRAINTS FROM MUON FLUCTUATIONS

C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021

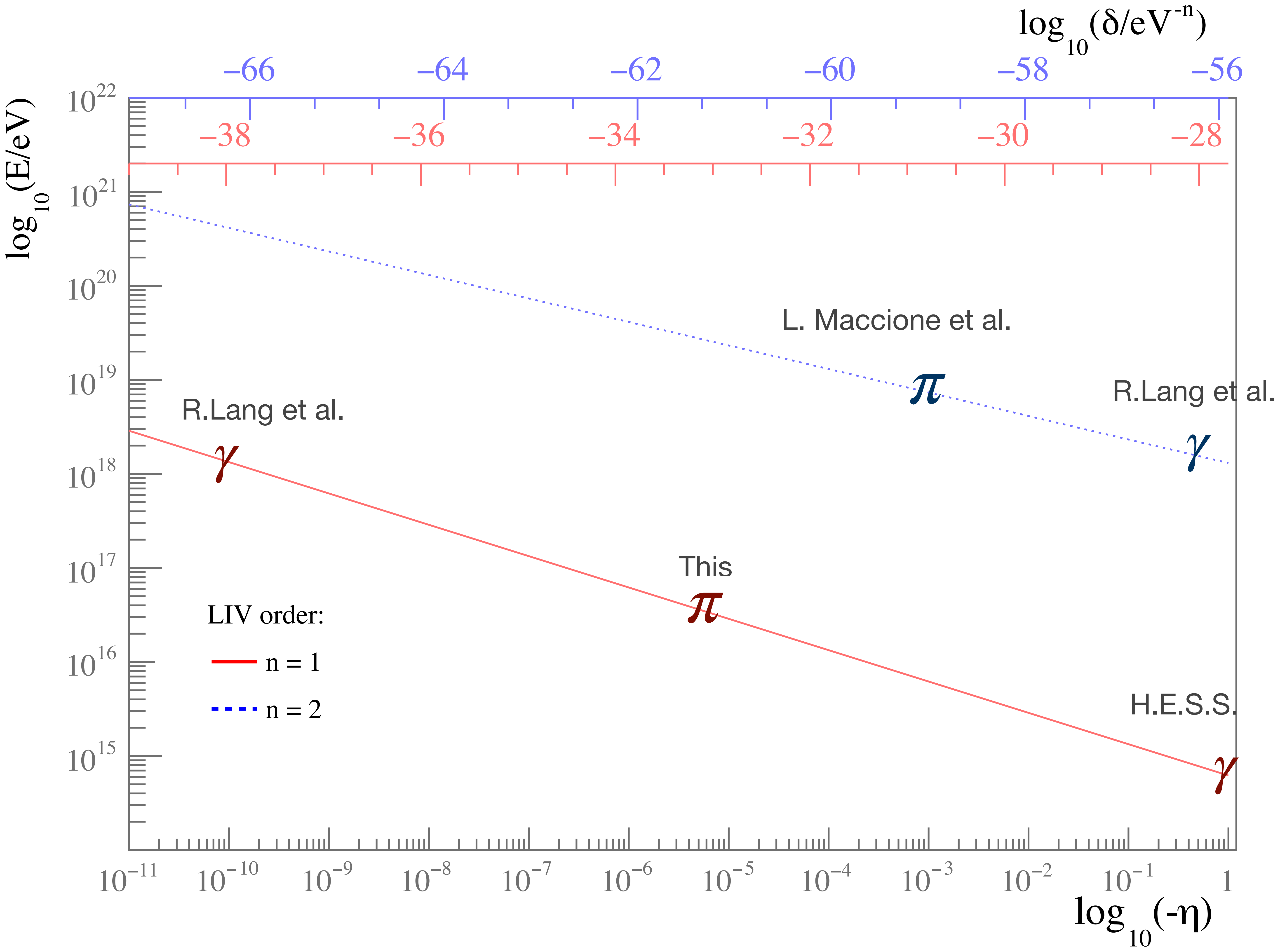
- Procedure:
  - Combine masses as a function of energy and LIV strength in order to have the largest fluctuation for each LIV parameter
  - Compare the data to the predictions corresponding to LIV parameters



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

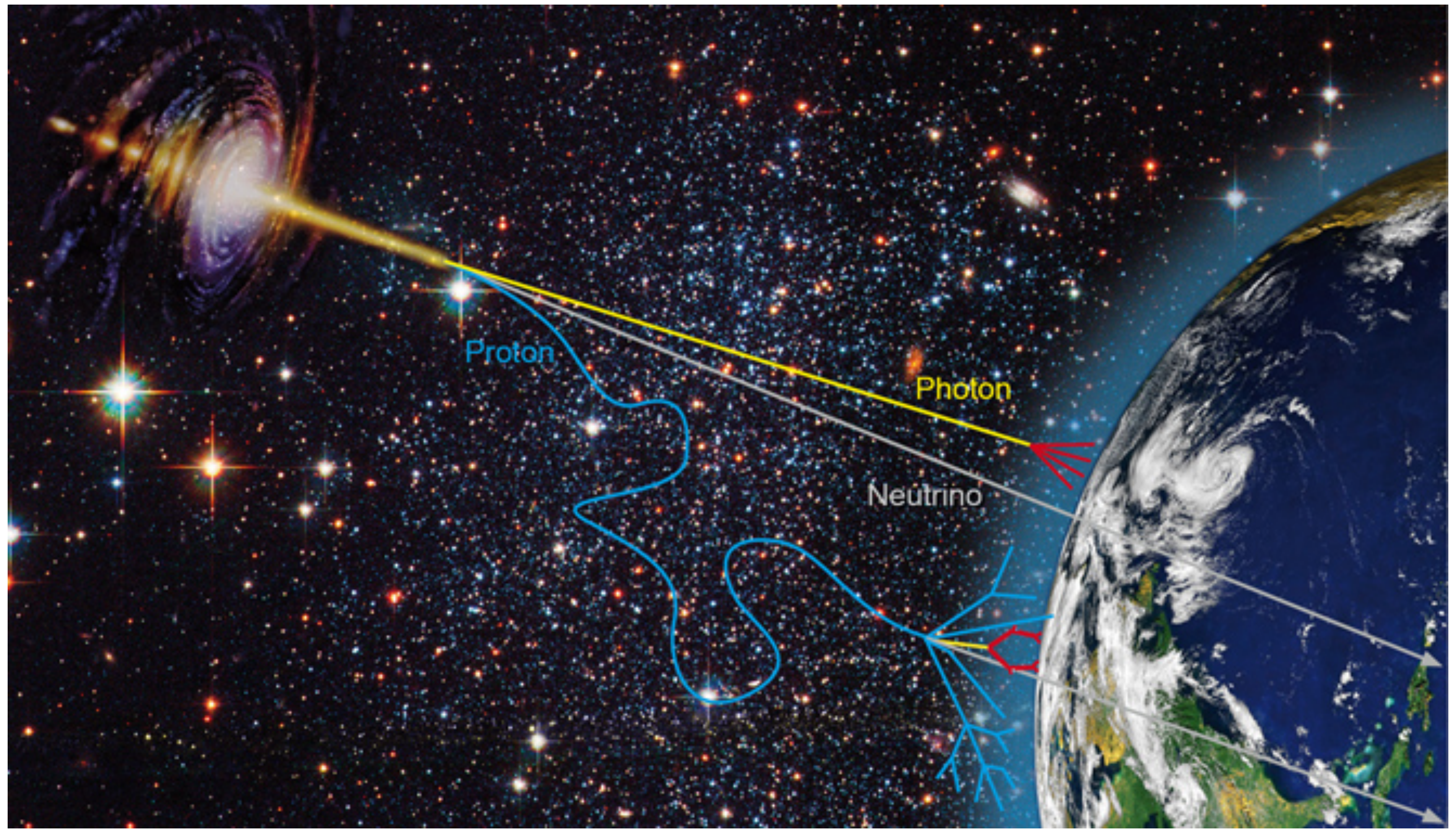
CONSTRAINTS FROM MUON FLUCTUATIONS

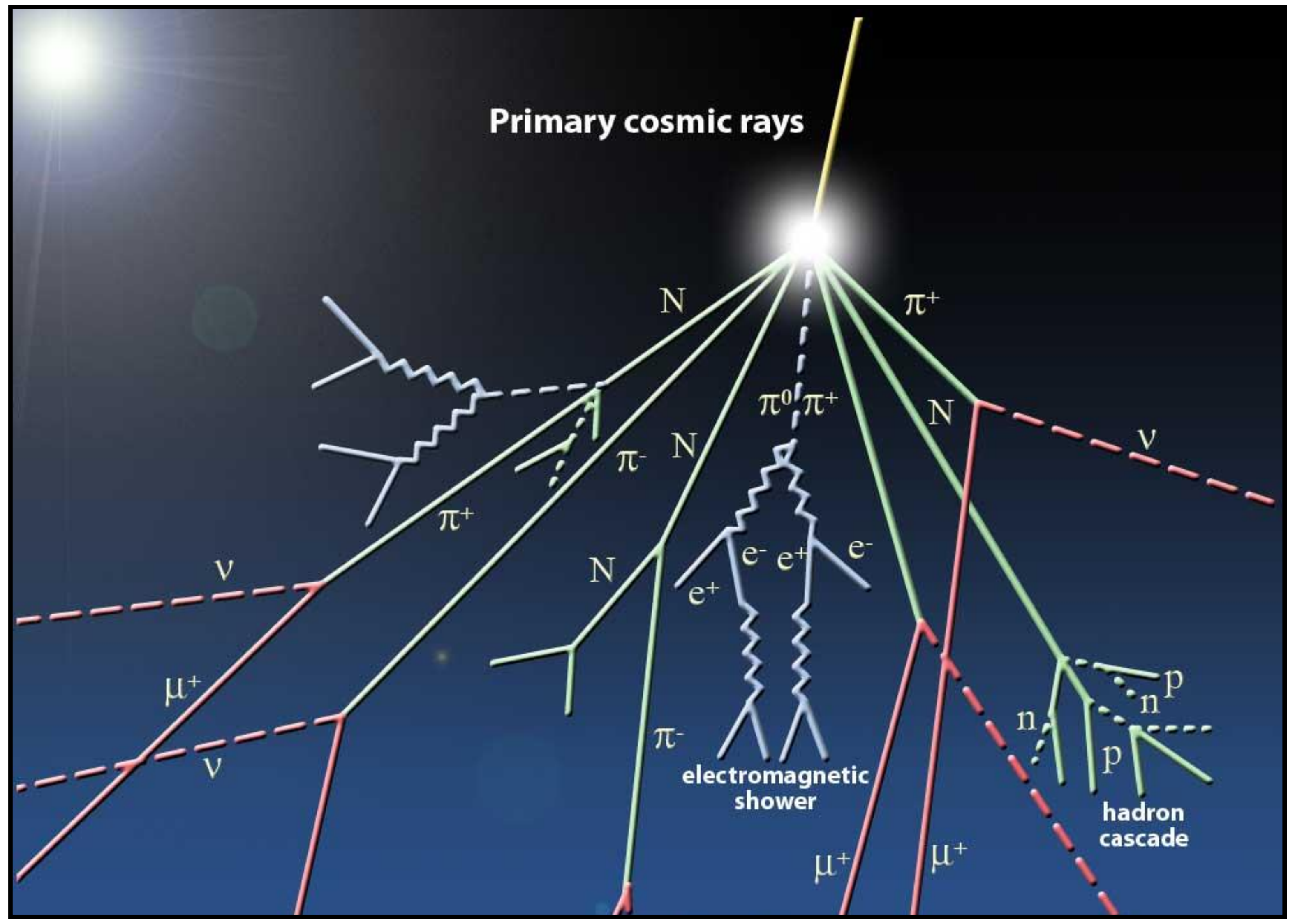
C. Trimarelli for the Pierre Auger Collaboration, ICRC 2021



CONCLUSIONS

- **LIV can be tested with UHECRs**
- Extragalactic propagation of UHECRs
  - Astrophysical scenarios predict low maximum energy at the sources and mixed composition
    - Not optimal for LIV tests with UHECRs and/or cosmogenic photons
- Development of cascade of particles in atmosphere
  - Fluctuations of number of muons used for the first time to constrain LIV





FUTURE PERSPECTIVES

- Upgrade of Pierre Auger Observatory
  - Can provide better discrimination between muonic and electromagnetic component of the shower
    - Possible proton fraction at highest energy can be better constrained
      - Astrophysical models could be reconsidered and LIV limits could be improved

- OPEN QUESTIONS:
  - **Origin of flux suppression and other spectrum features**:
    - propagation and/or source effects
    - in-source interactions
  - **Proton fraction at the highest energies**:
    - charged particle astronomy?
    - secondary messengers (neutrino and photons) ?
  - **UHECR composition and hadronic interactions**
    - Muonic component of air showers
    - New physics

FUTURE PERSPECTIVES

- Upgrade of Pierre Auger Observatory
    - Can provide better discrimination between muonic and electromagnetic component of the shower
        - Possible proton fraction at highest energy can be better constrained
            - Astrophysical models could be reconsidered and LIV limits could be improved

Many analyses still inspired from previous works and discussions with Aurelio Grillo

- OPEN QUESTIONS:
    - **Origin of flux suppression and other spectrum features**:
        - propagation and/or source effects
        - in-source interactions
    - **Proton fraction at the highest energies**:
        - charged particle astronomy?
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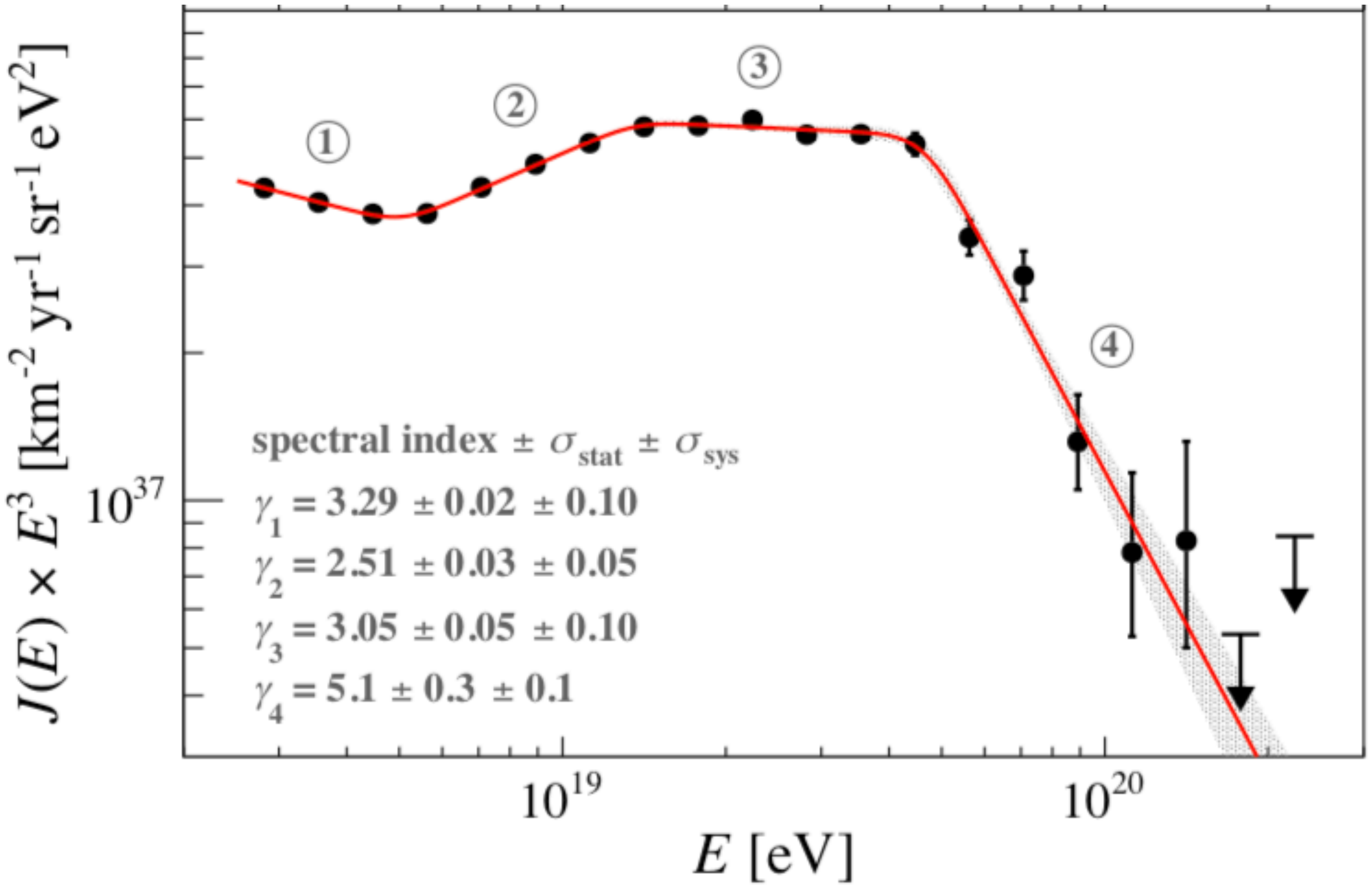
    - **UHECR composition and hadronic interactions**
        - Muonic component of air showers
        - New physics

BACKUP SLIDES

MEASUREMENT OF THE ENERGY SPECTRUM

- Change of slope between 1 and 2 ("ankle", already known, reconfirmed)
- Change of slope between 2 and 3 (new feature!!!)
- Change of slope between 3 and 4 ("suppression", already known, reconfirmed)

Auger, PRL 2020



MASS COMPOSITION

The Pierre Auger Collaboration, PRD 2014

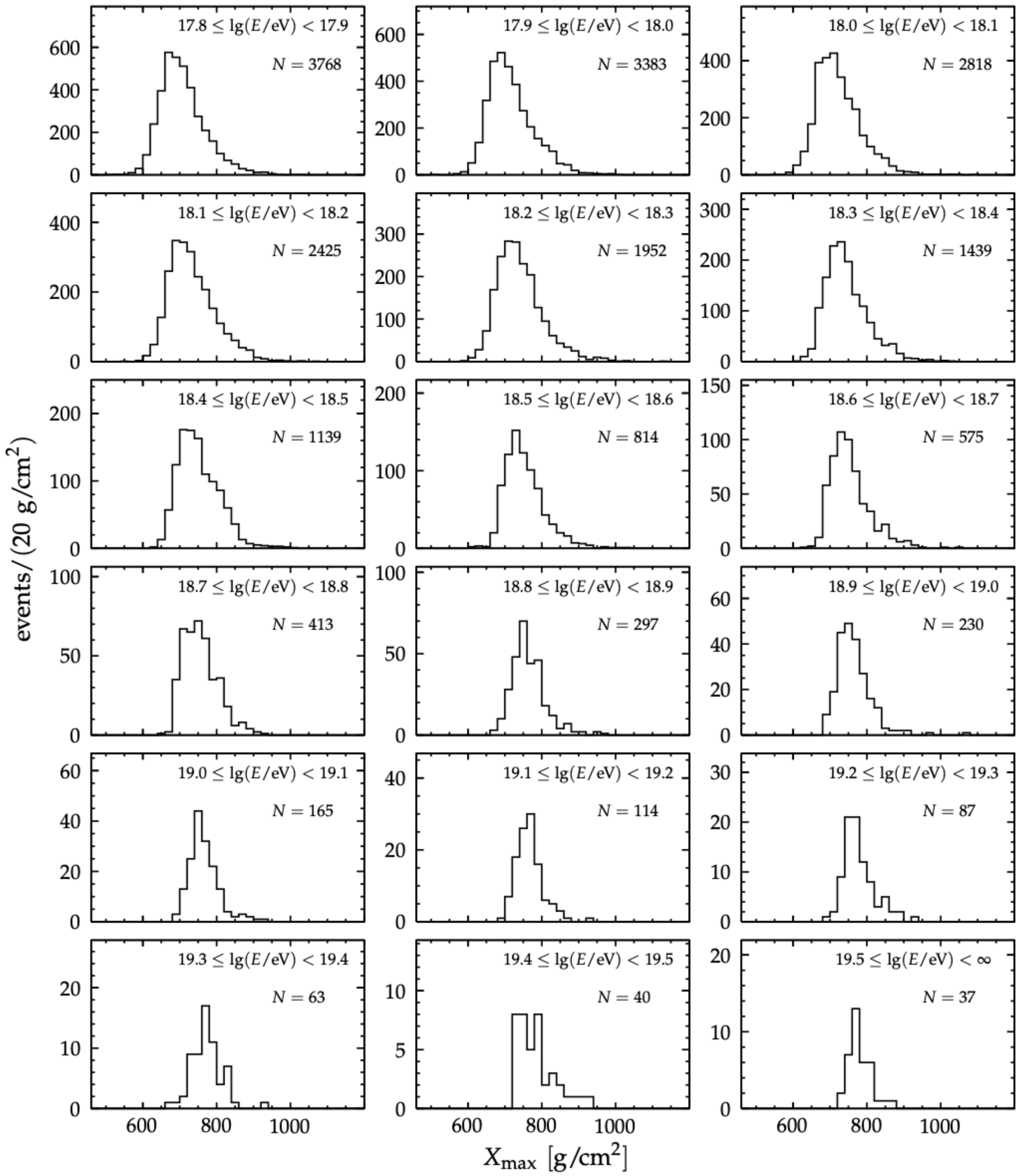
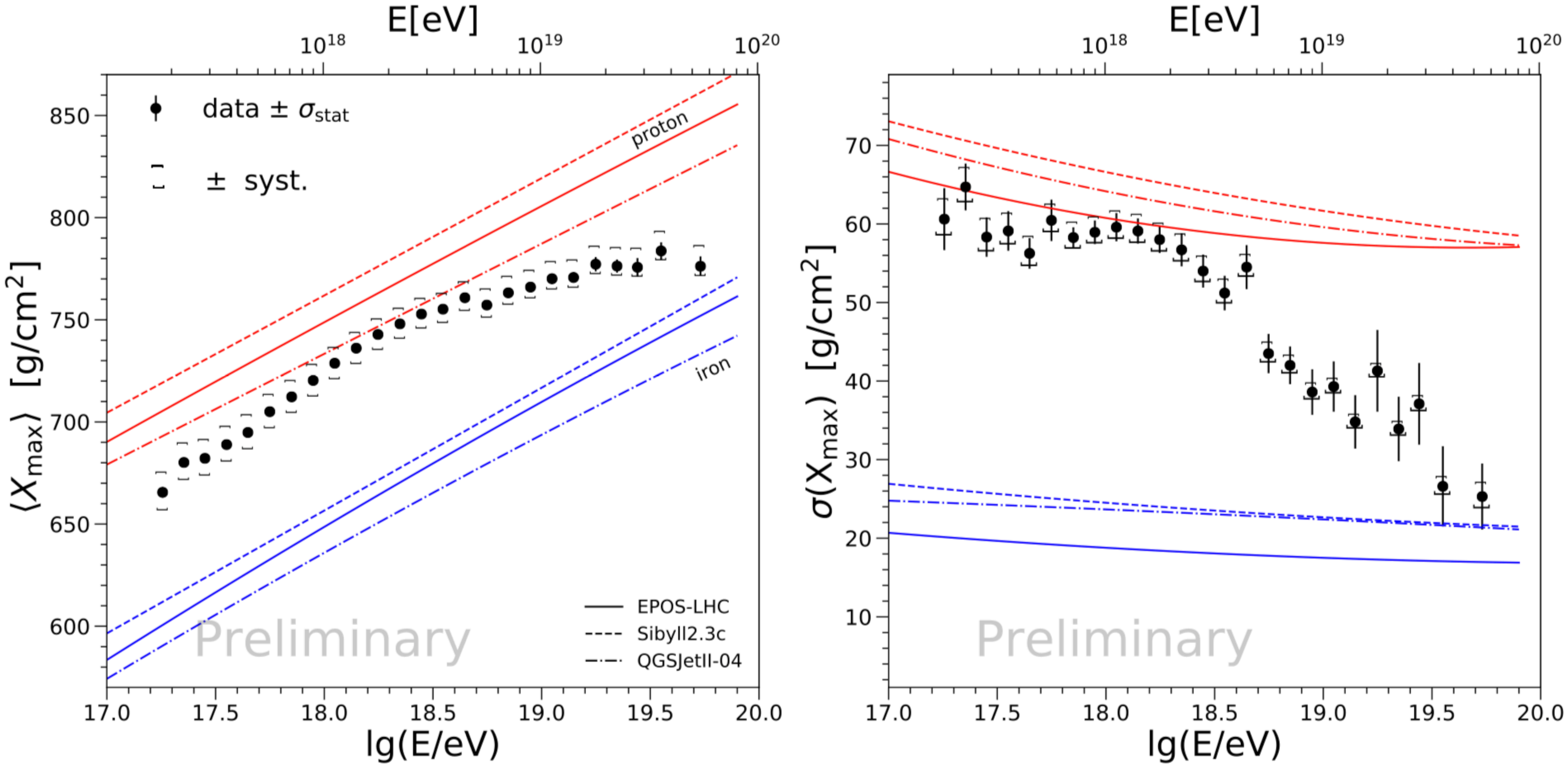


Figure 12: $X_{\max}$ distributions for different energy intervals.

MASS COMPOSITION

The Pierre Auger Collaboration, ICRC 2019

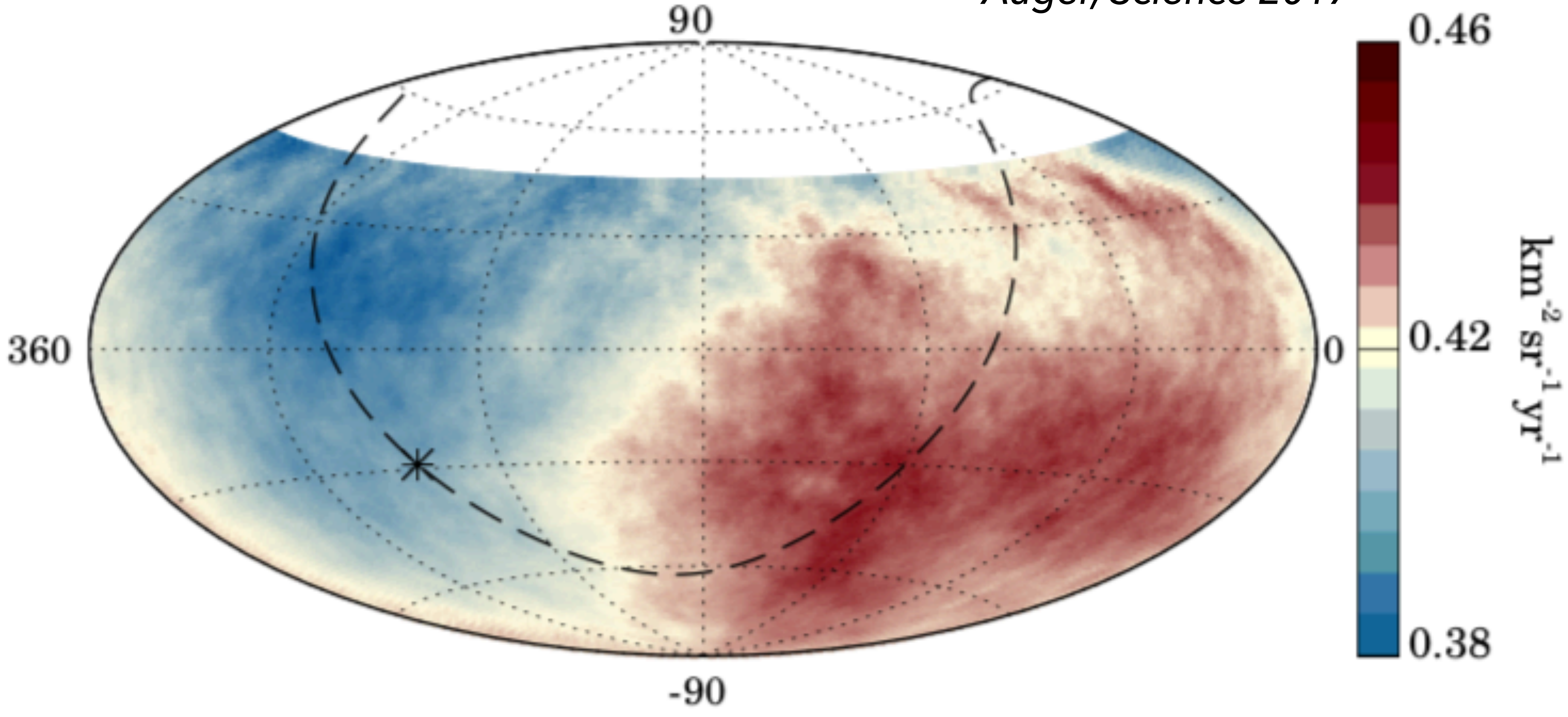


- Composition information (mainly) from the longitudinal development of the shower
- Break in <Xmax> at energy of the ankle
- Fluctuations decreasing with increasing energy

ANISOTROPY

- 114000 SD events
- 76800 km^2 sr yr exposure, 85% sky coverage
- Analysis of first harmonic in right ascension:
  - 4-8 EeV -> compatible with isotropy
  - >8 EeV: 3D dipole of amplitude 6.5% at 5.2 sigma

Auger, Science 2017

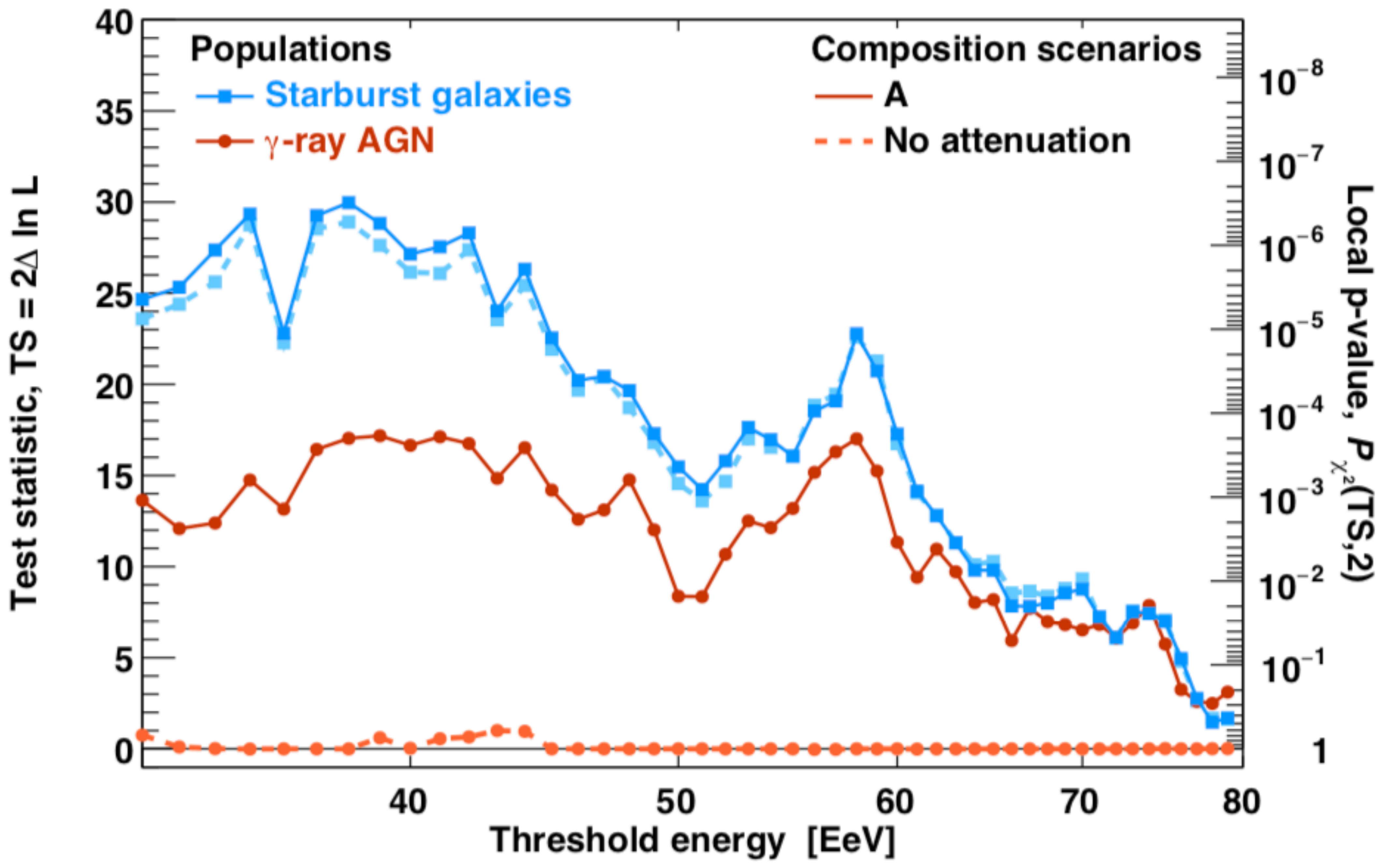


Magnitude and direction of the anisotropy support the hypothesis of extragalactic origin of UHECRs !

COMPARISON WITH EXTRAGALACTIC GAMMA-RAY CATALOG

- Events above 20 EeV, collected between Jan 2004 and April 2017, total exposure 89720 km^2 yr sr.
- Fermi-LAT sources above 50 GeV (D<250 Mpc)
  - 17 AGN + 23 starburst galaxies

- Assumption: UHECR flux proportional to photon flux
- The attenuation of UHECRs due to propagation effects is taken into account (scenario A corresponds to combined spectrum composition fit, Auger JCAP 2017), but no Galactic/extragalactic magnetic fields are included



Auger, ICRC 2019

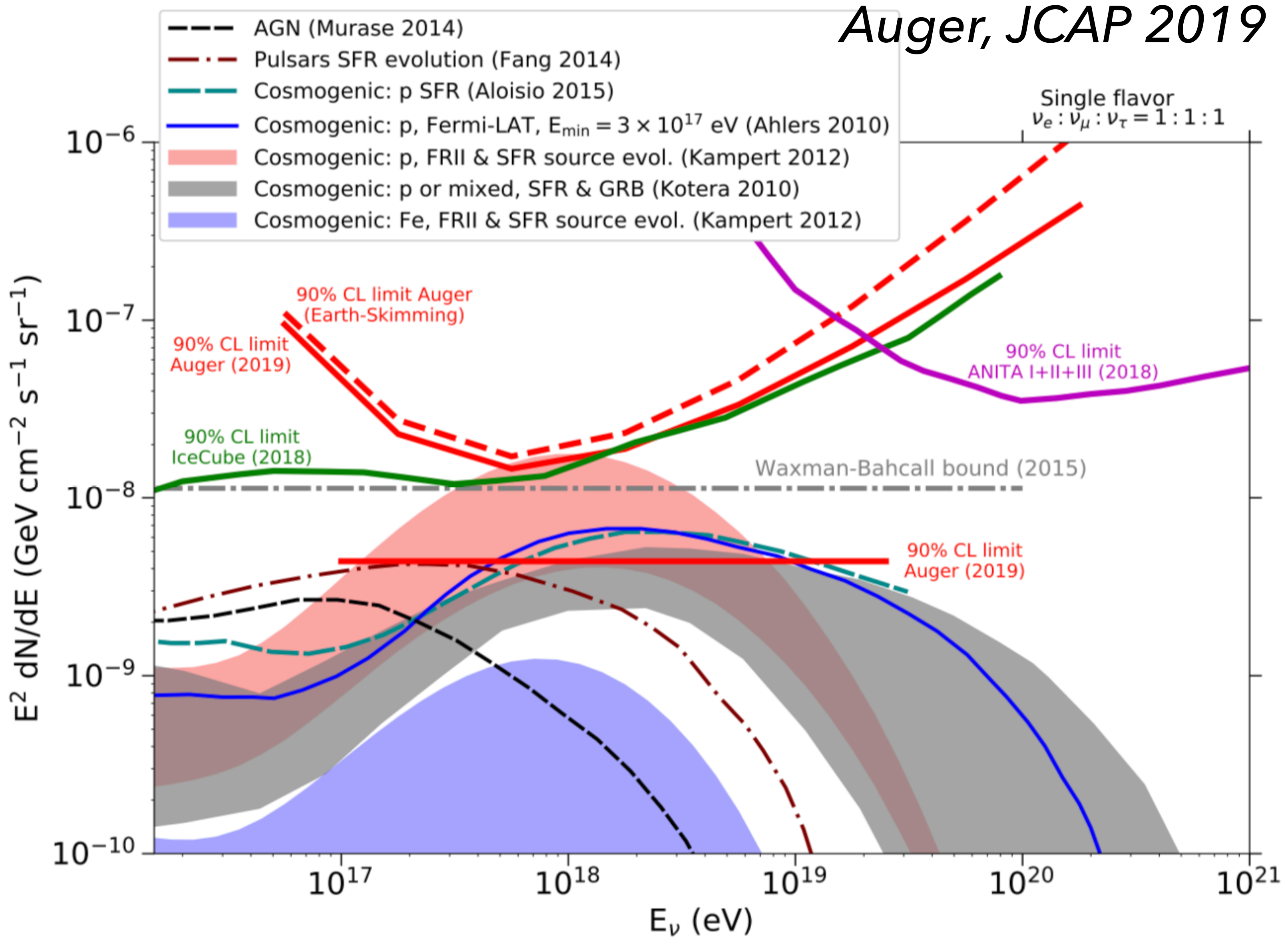
- Maximum signal for **Starburst Galaxies** found above 38 EeV

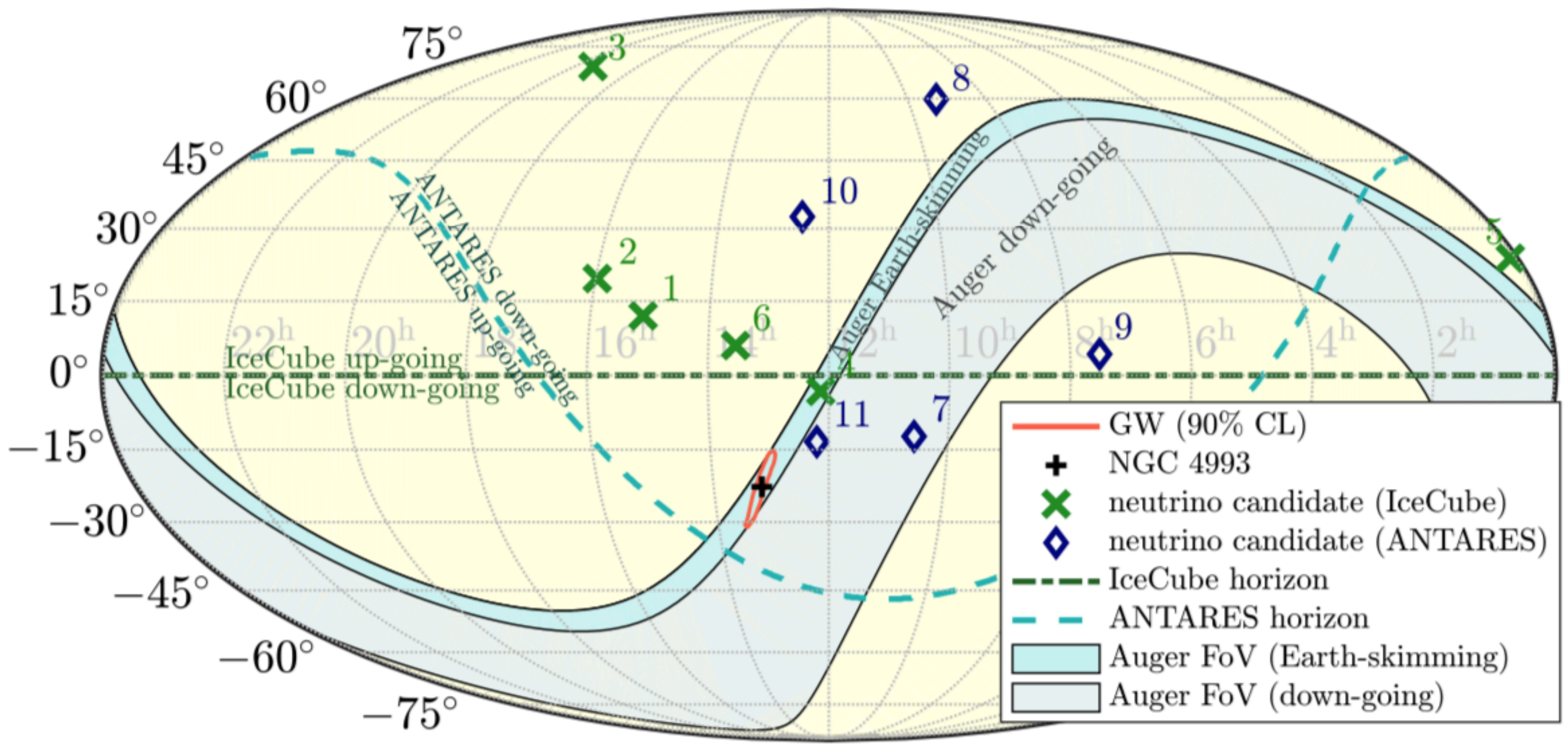
MULTIMESSENGER SEARCHES

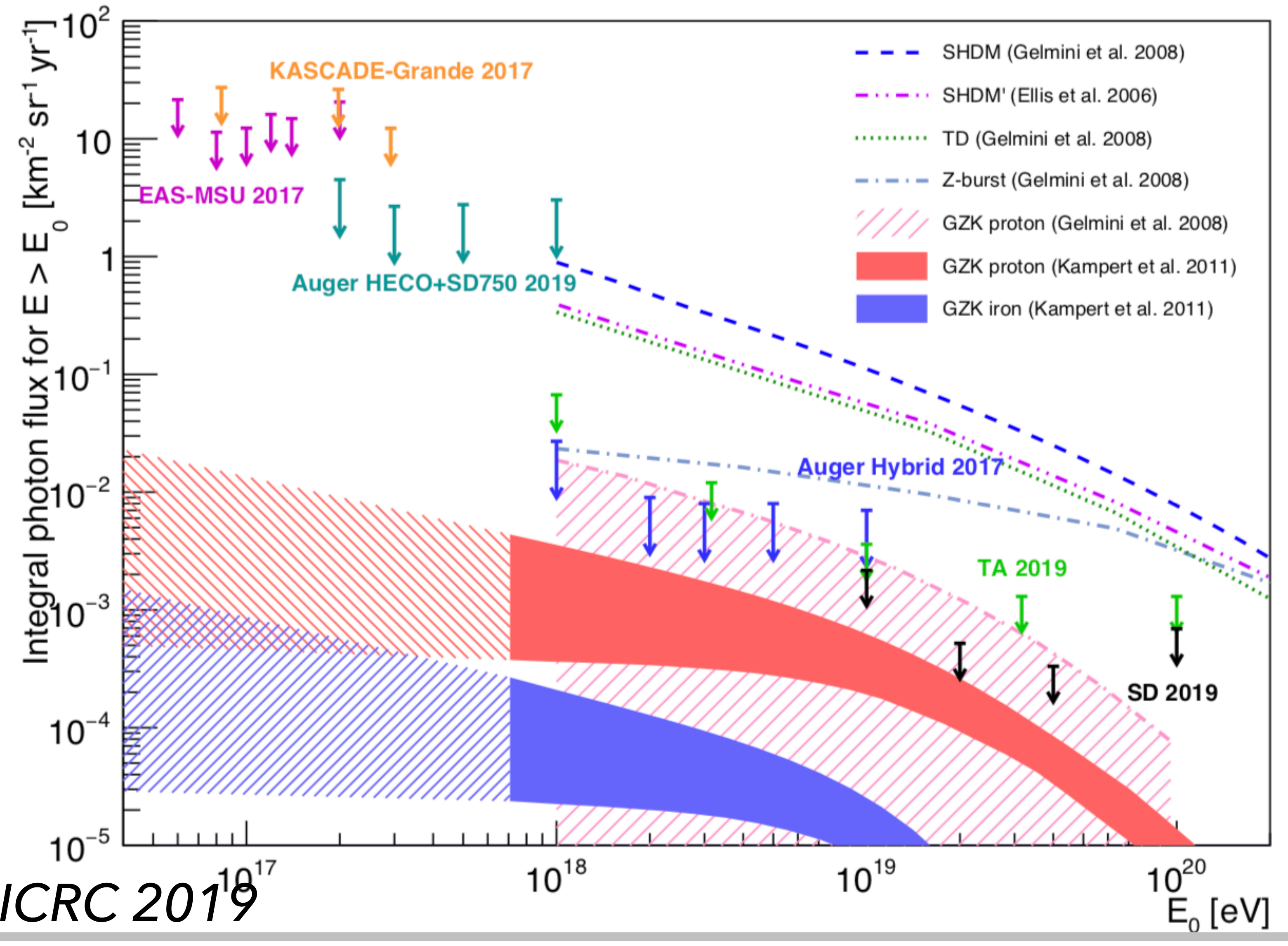
- Sensitivity to neutrinos above 100 PeV, by looking for inclined showers with SD
- Sensitivity to photons with SD

- Searches for neutrinos in coincidence with transient events:
  - Neutrinos associated with GW150914 and GW151226, ***Auger PRD 2016***
  - Neutrinos associated with GW170817, together with Antares and IceCube, ***Apj 2017***
  - Neutrinos associated to TXS, ***ApJ 2020***

Auger, JCAP 2019







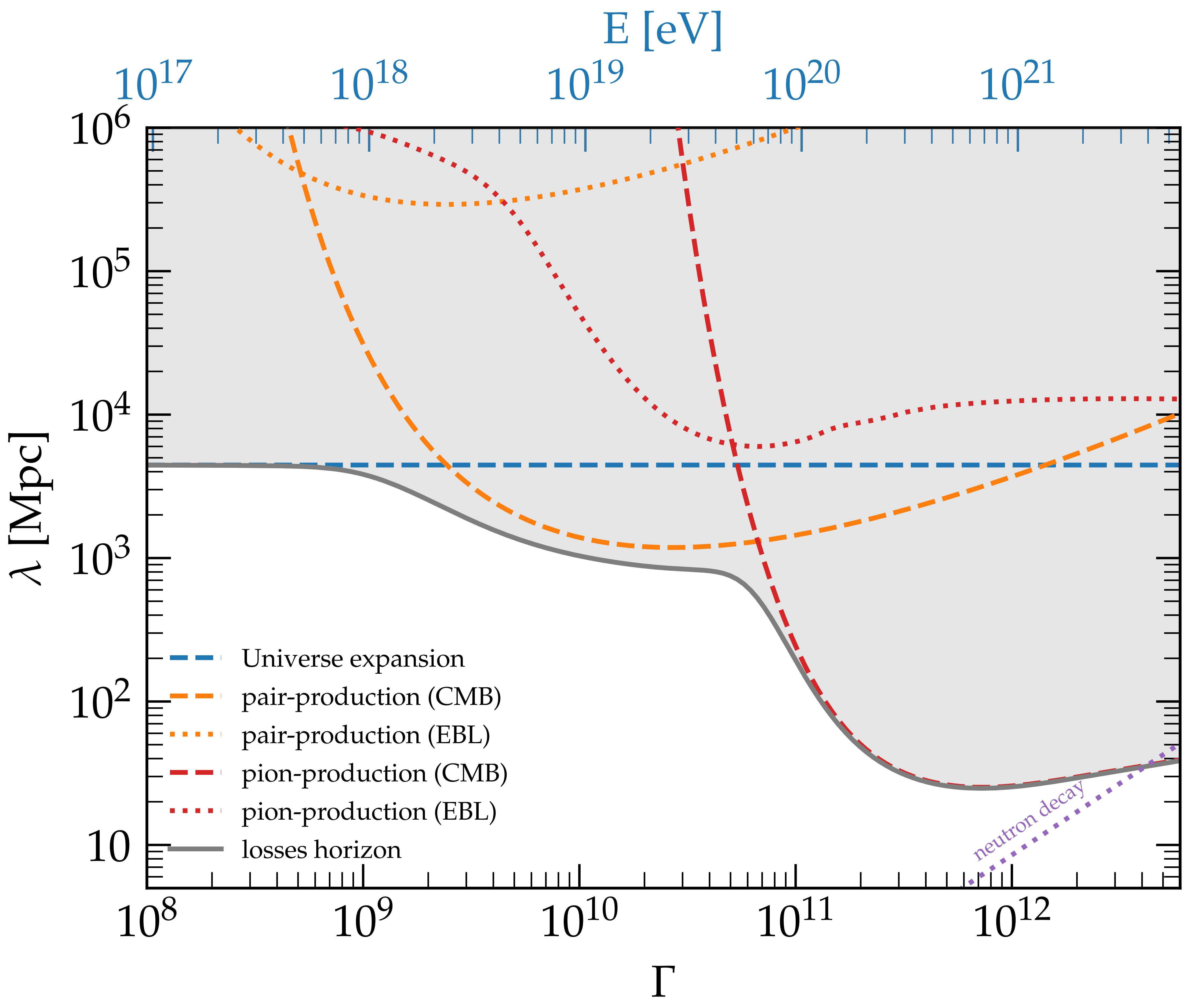
Auger, ICRC 2019

ENERGY LOSS LENGTH

$$l_{\text{loss}} = -c\left(\frac{1}{E}\frac{dE}{dt}\right)^{-1} = -E\frac{ds}{dE}$$

$$\frac{1}{E}\frac{dE}{dt} = -H_0$$

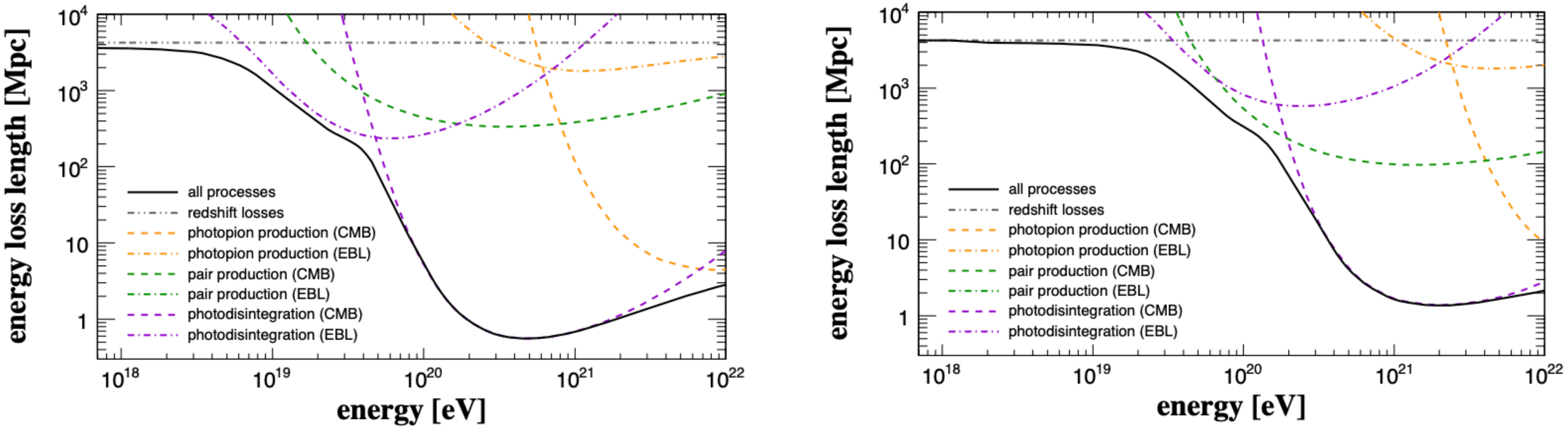
$$\frac{1}{E}\frac{dE}{dt} = -\frac{c}{2\Gamma^2}\int_{\varepsilon'_{\text{th}}}^{\infty}\varepsilon' f(\varepsilon')\sigma(\varepsilon')\int_{\varepsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'$$



Plot by C. Evoli

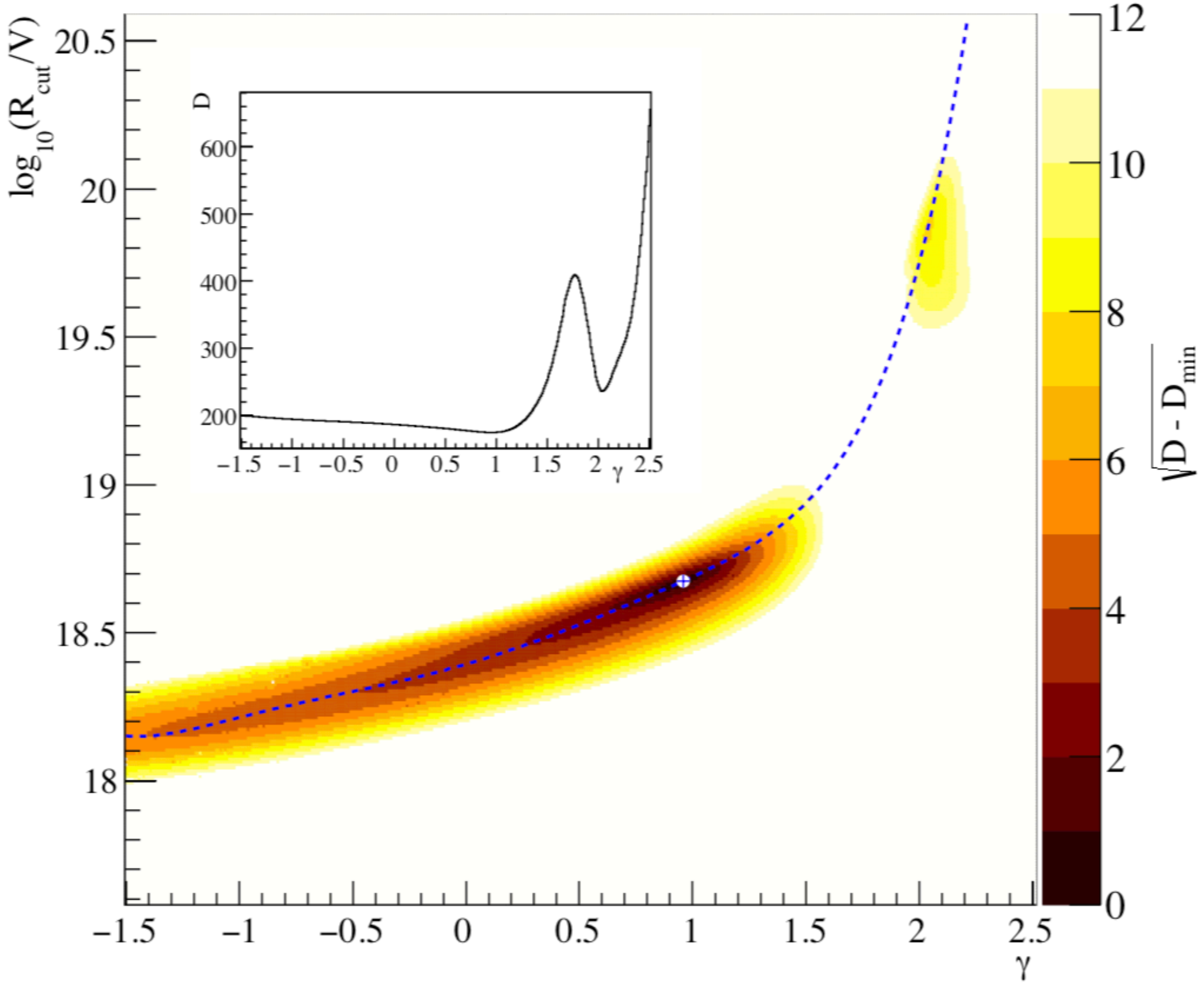
INTERACTIONS OF COSMIC RAY NUCLEI

Alves Batista, **DB**, di Matteo, van Vilet & Walz JCAP 2015

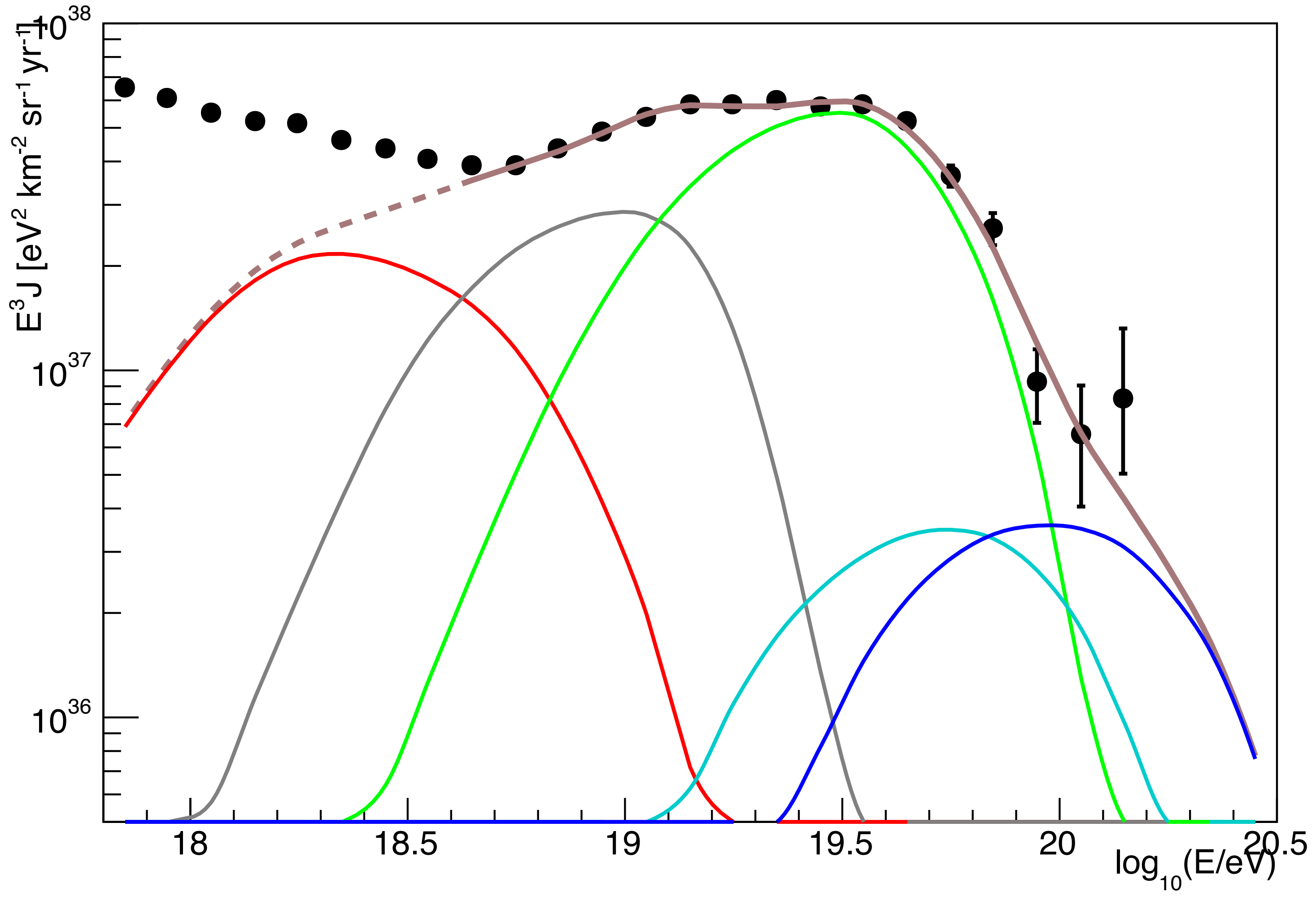


COMBINED SPECTRUM AND COMPOSITION FIT

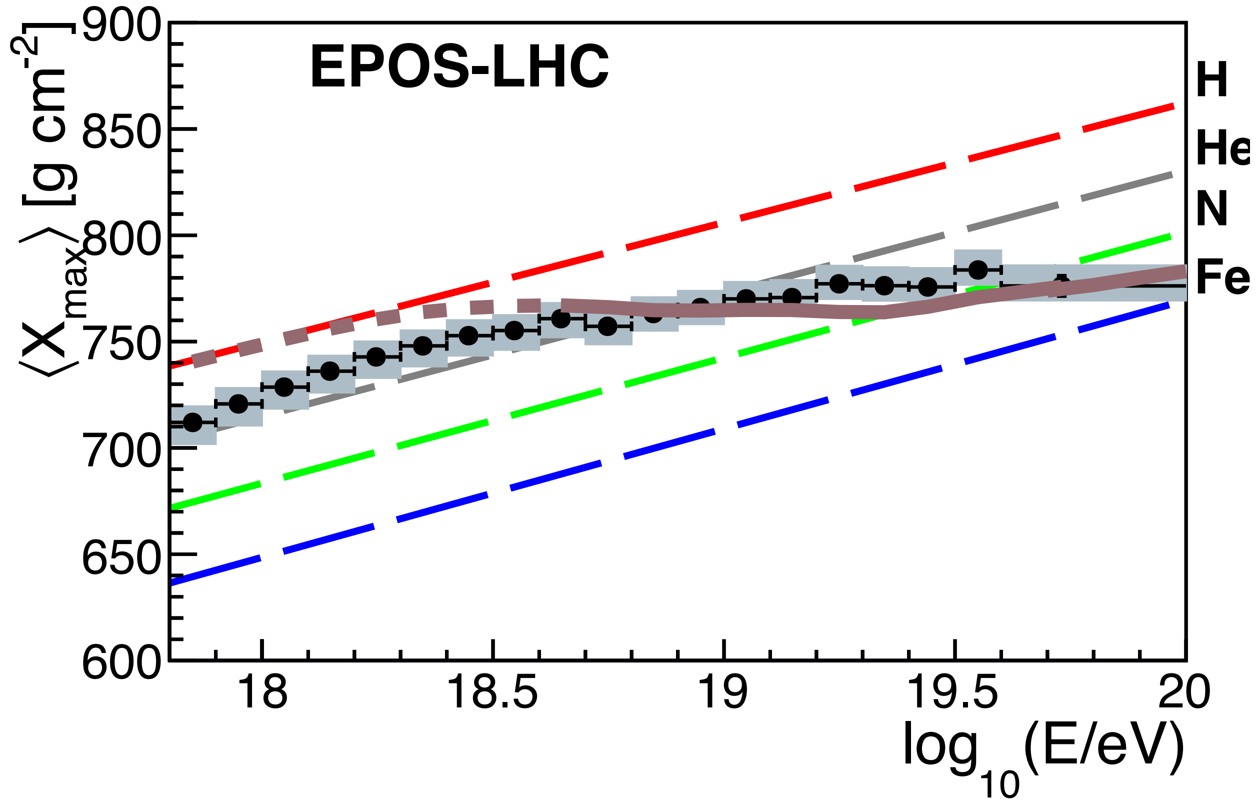
Auger, JCAP 2017

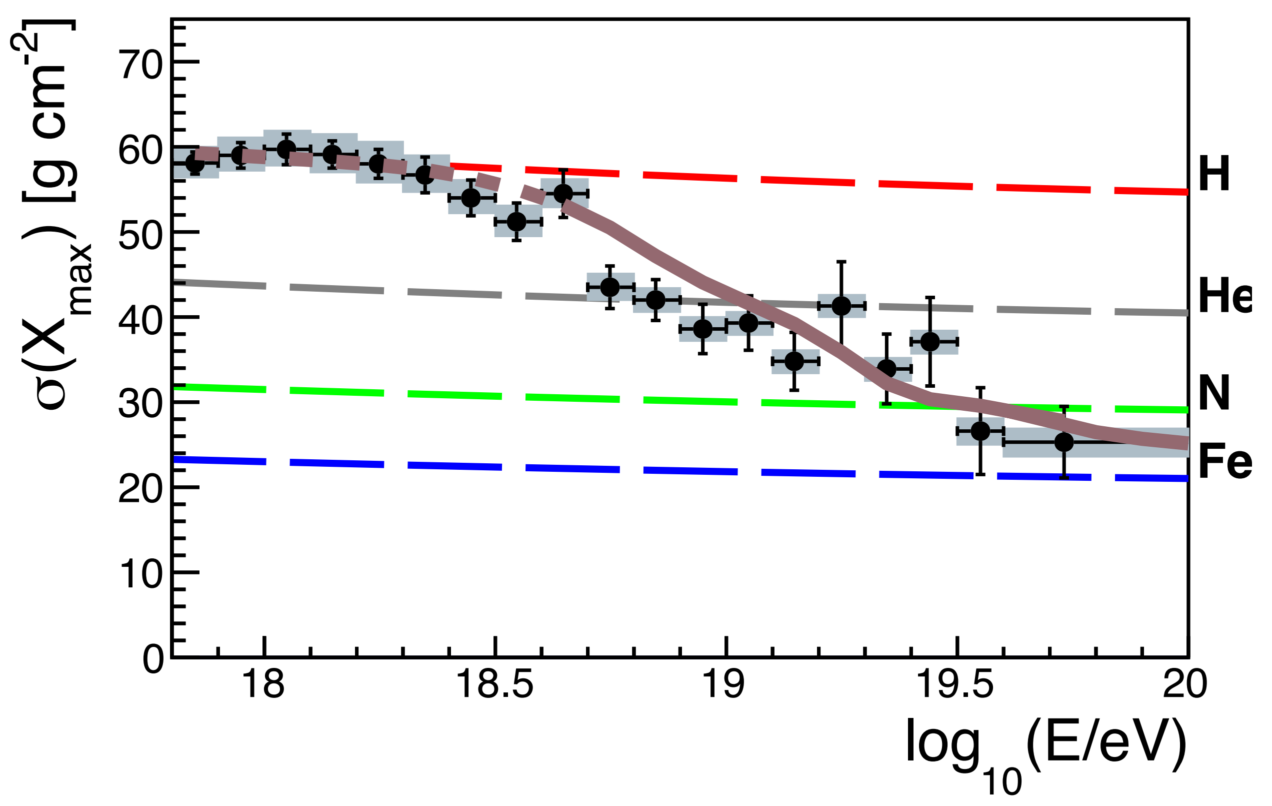


- Using **SimProp** MC code, Aloisio, **DB**, di Matteo, Grillo, Petrera, Salamida, JCAP 2017



- Groups of nuclei as they reach the Earth's atmosphere, according to their mass number

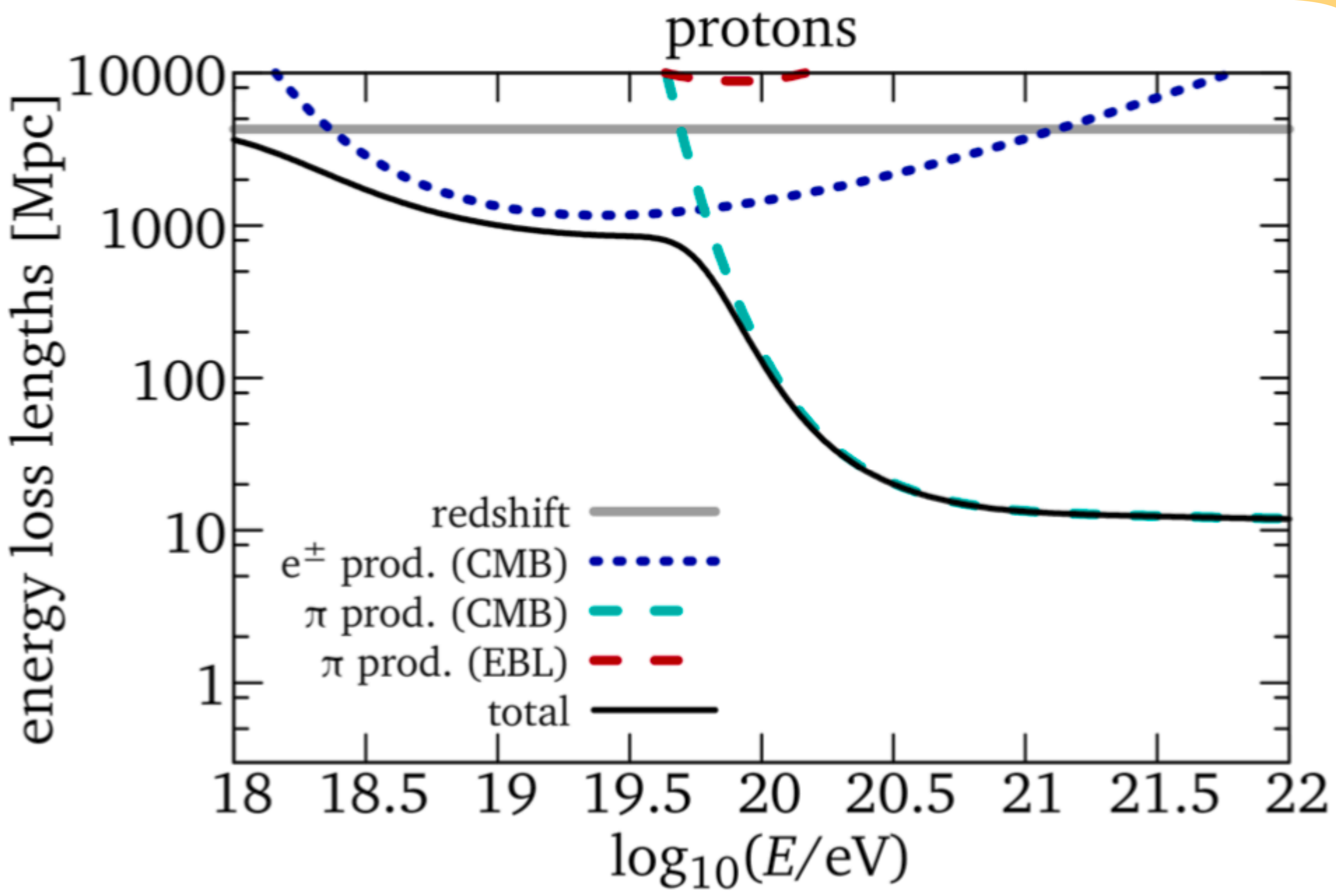




Similar to Auger JCAP 2017, with updated spectrum and composition (ICRC 2019)

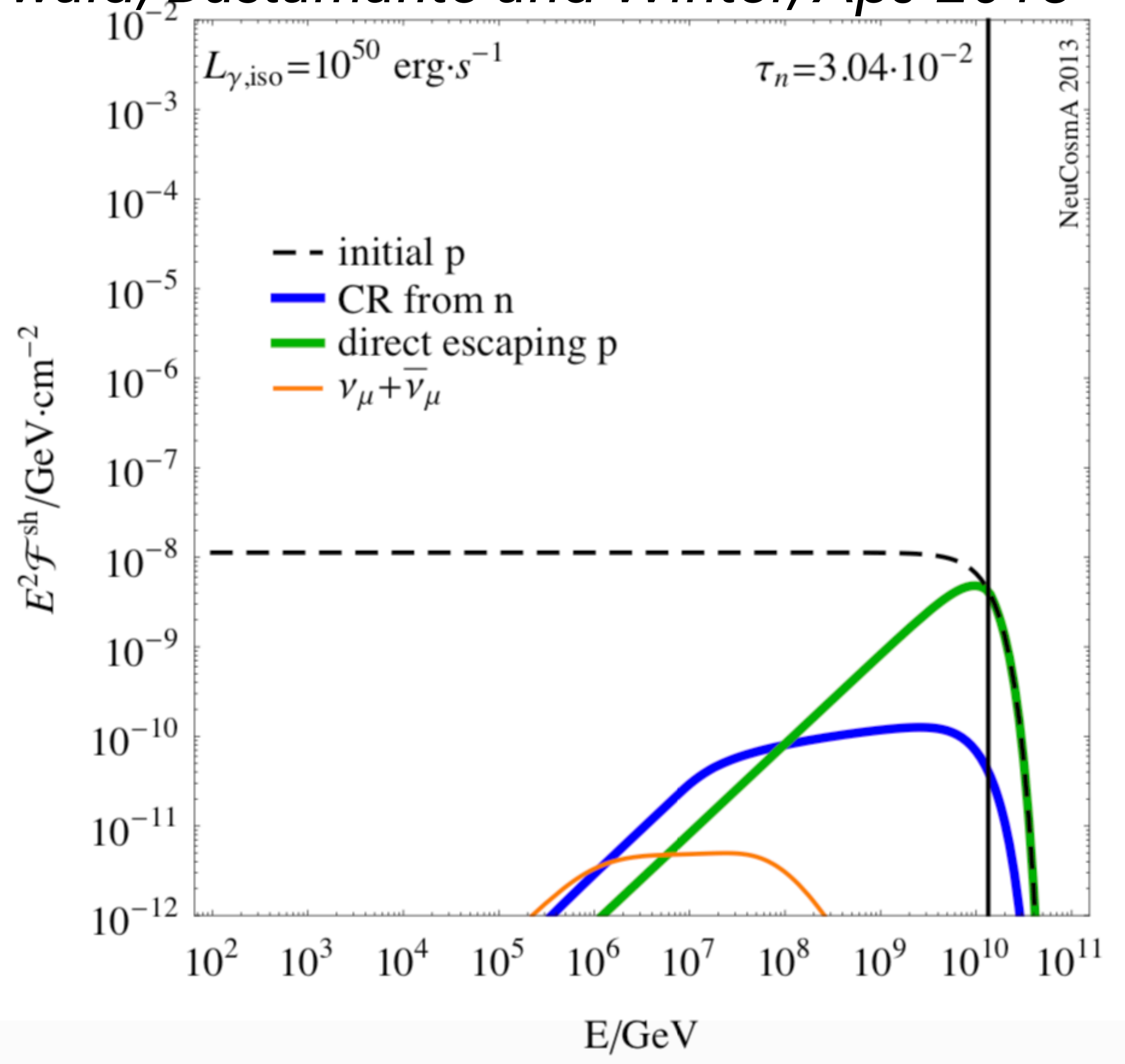
IMPLICATIONS ON SOURCE CHARACTERISTICS

- **Low-rigidity cutoff** at the sources:
  - Interpretation of **suppression** as due to lack of acceleration power at source is favoured with respect to propagation effects (i.e. "GZK effect"), independent of composition

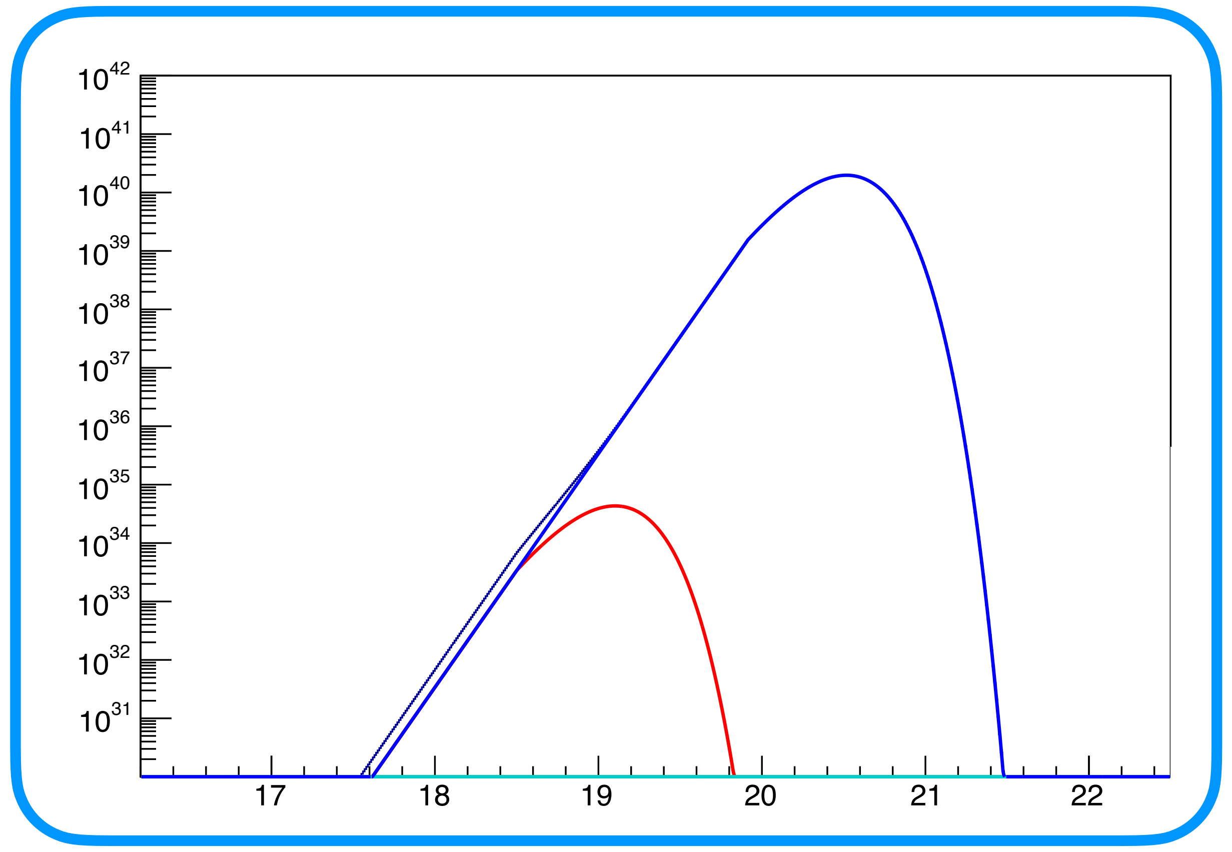


- **Small spectral index** (at odds with Fermi mechanisms):
  - Escape of high-energy (charged) particles from source environment is favoured, change of effective spectral index expected

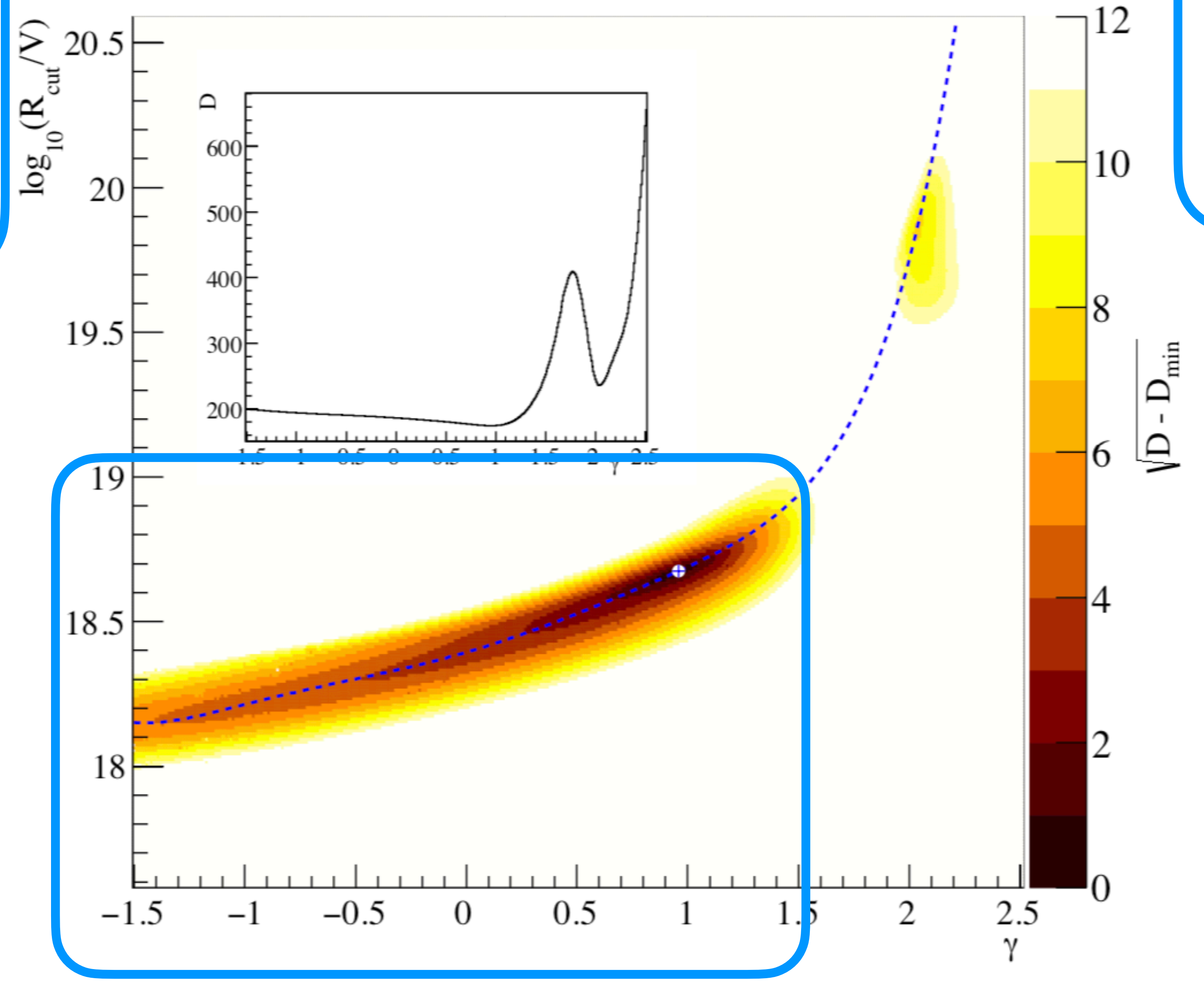
Baerwald, Bustamante and Winter, ApJ 2013

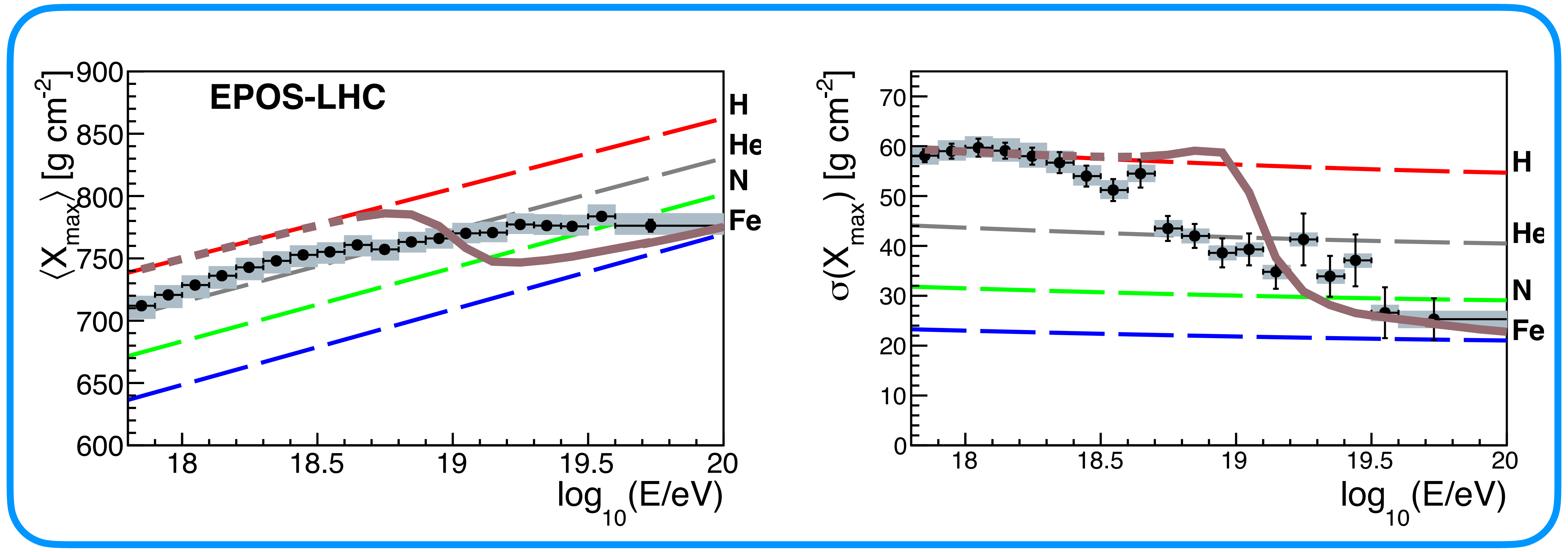


IMPLICATIONS ON SOURCE CHARACTERISTICS



Example: 50% H + 50% Fe at source





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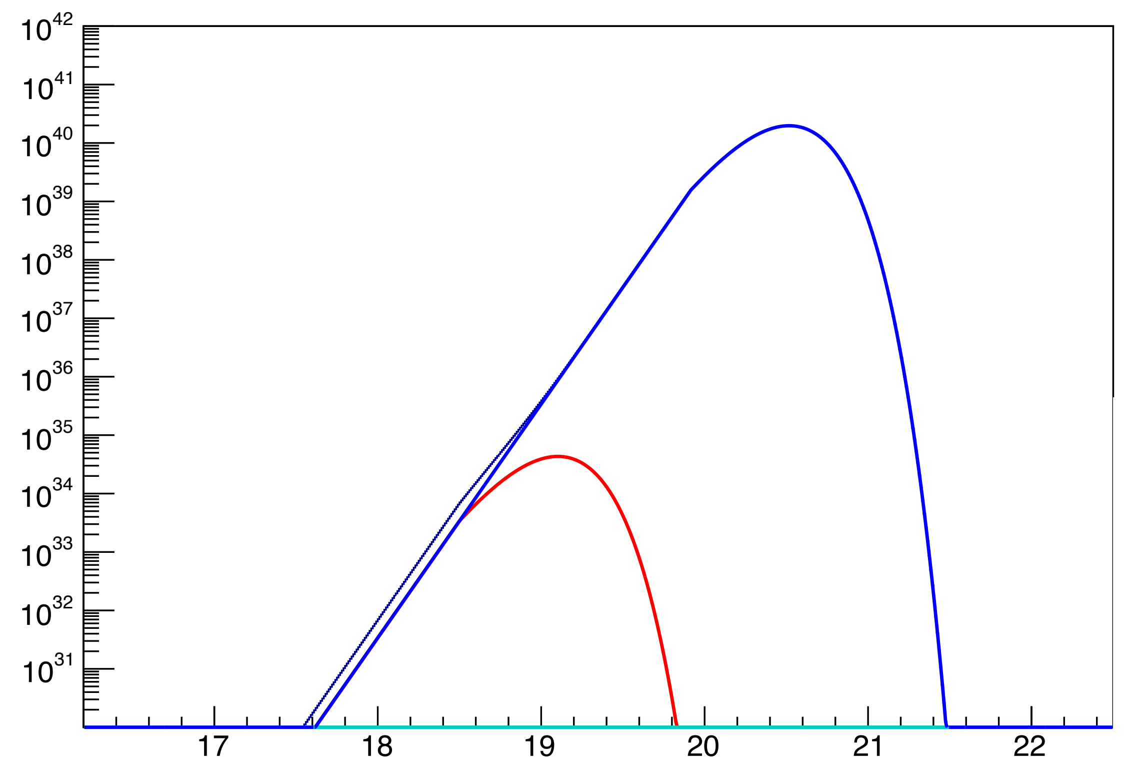

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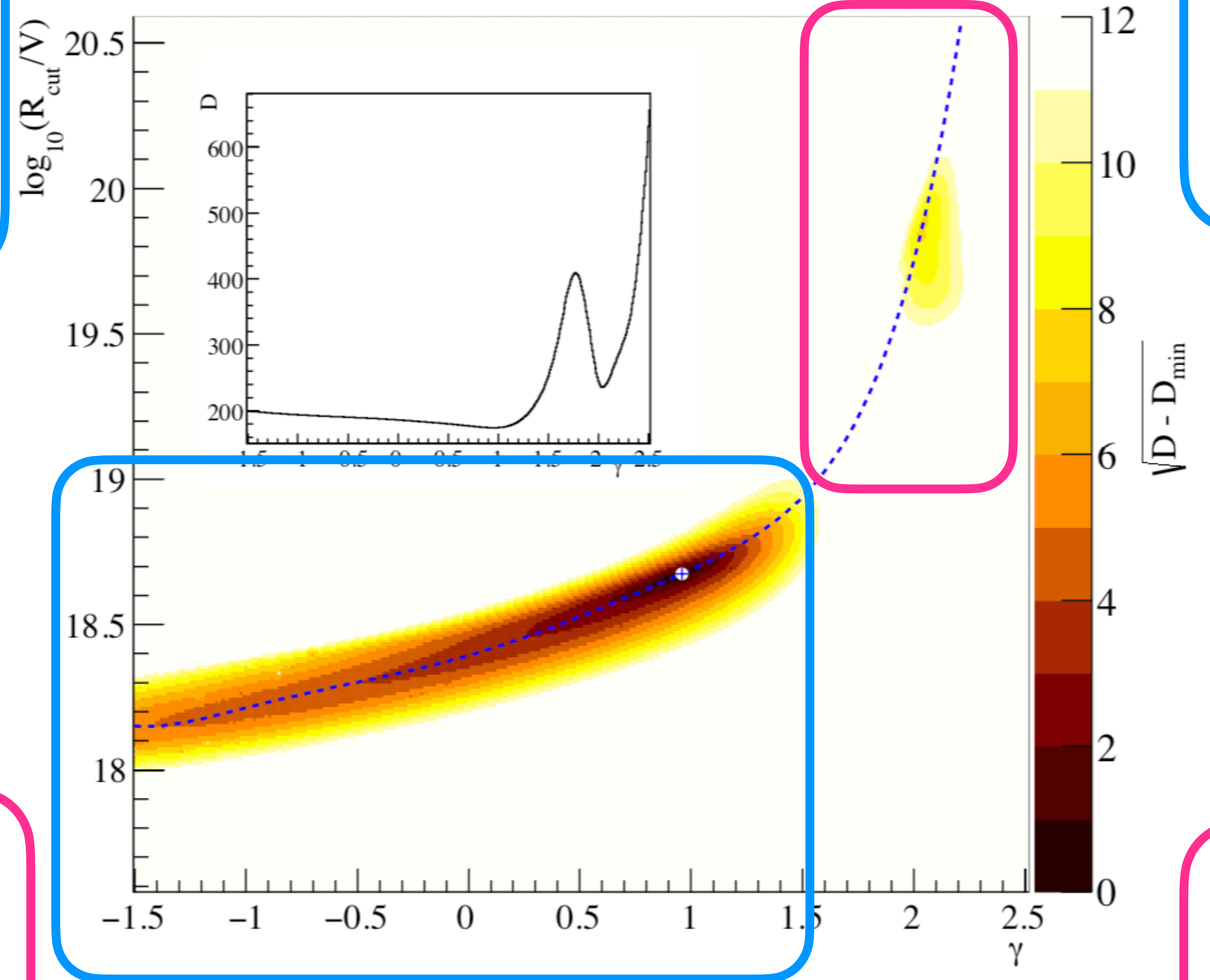
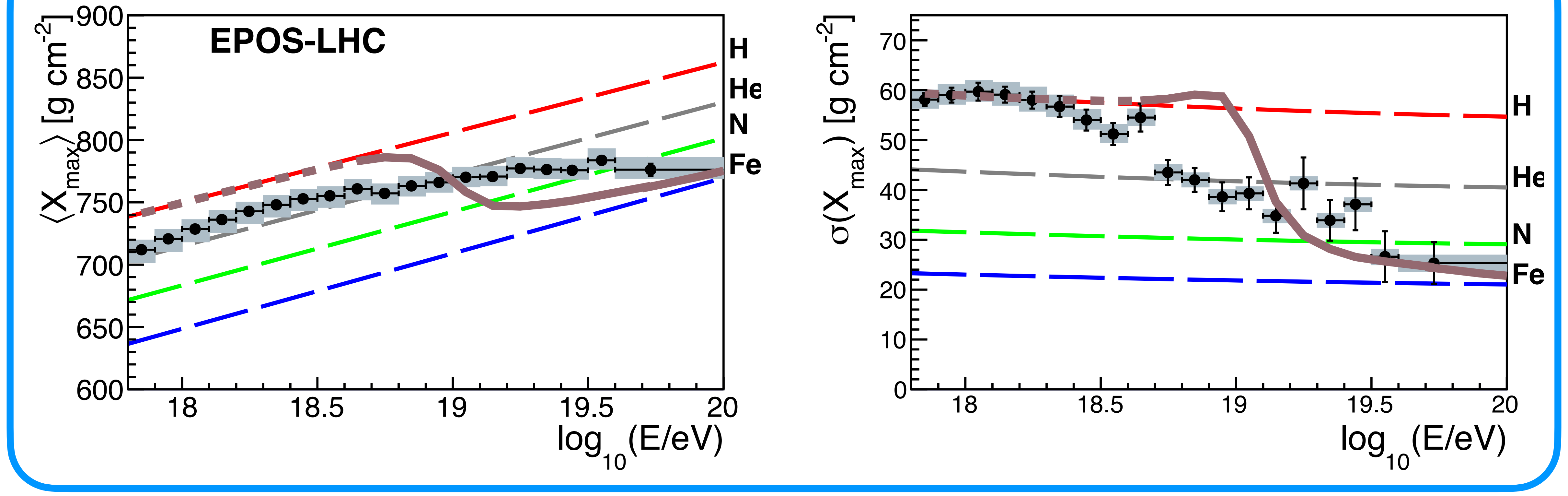
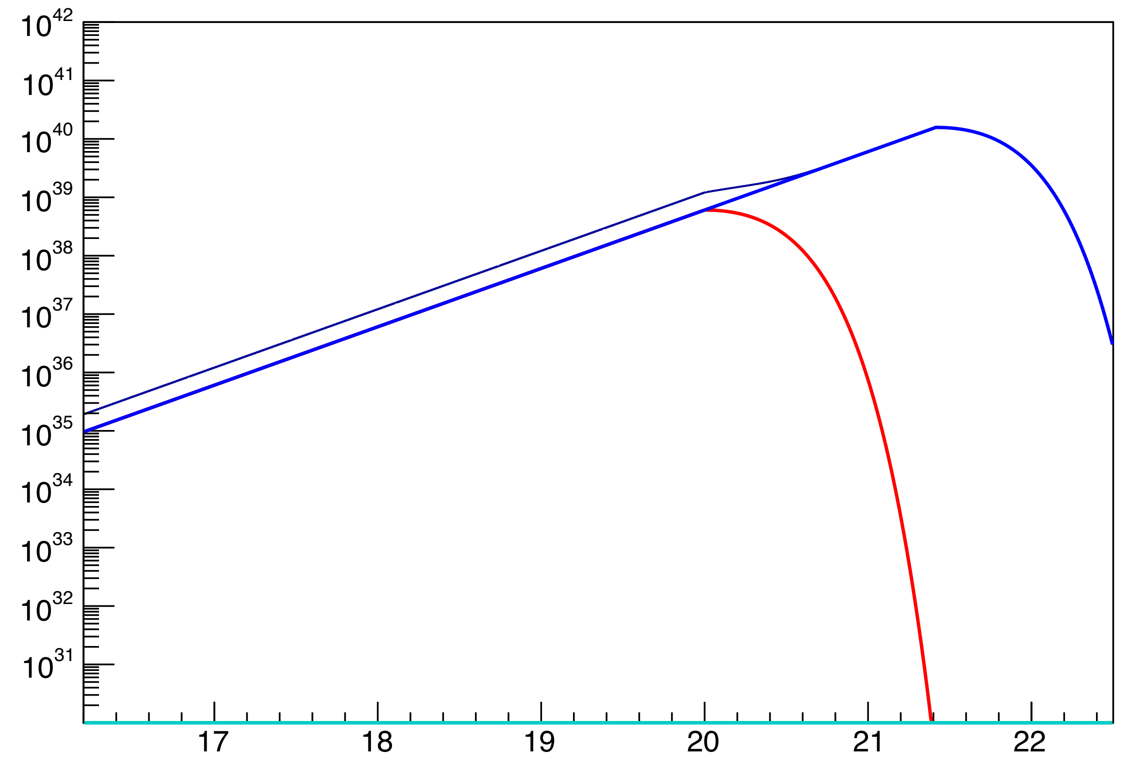
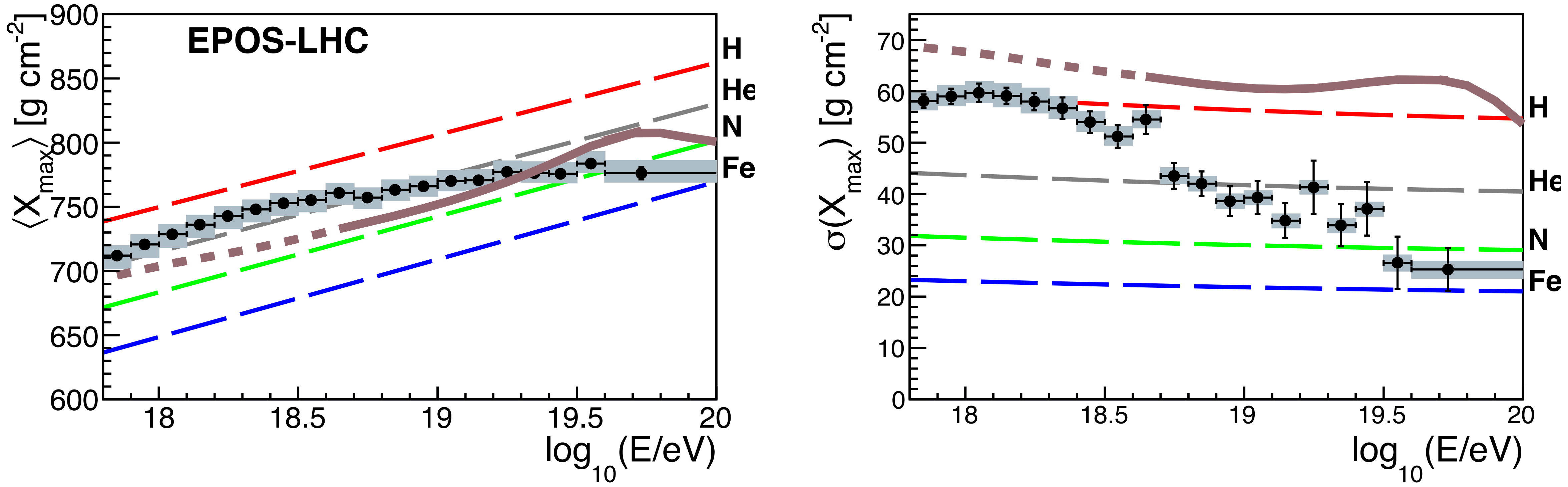
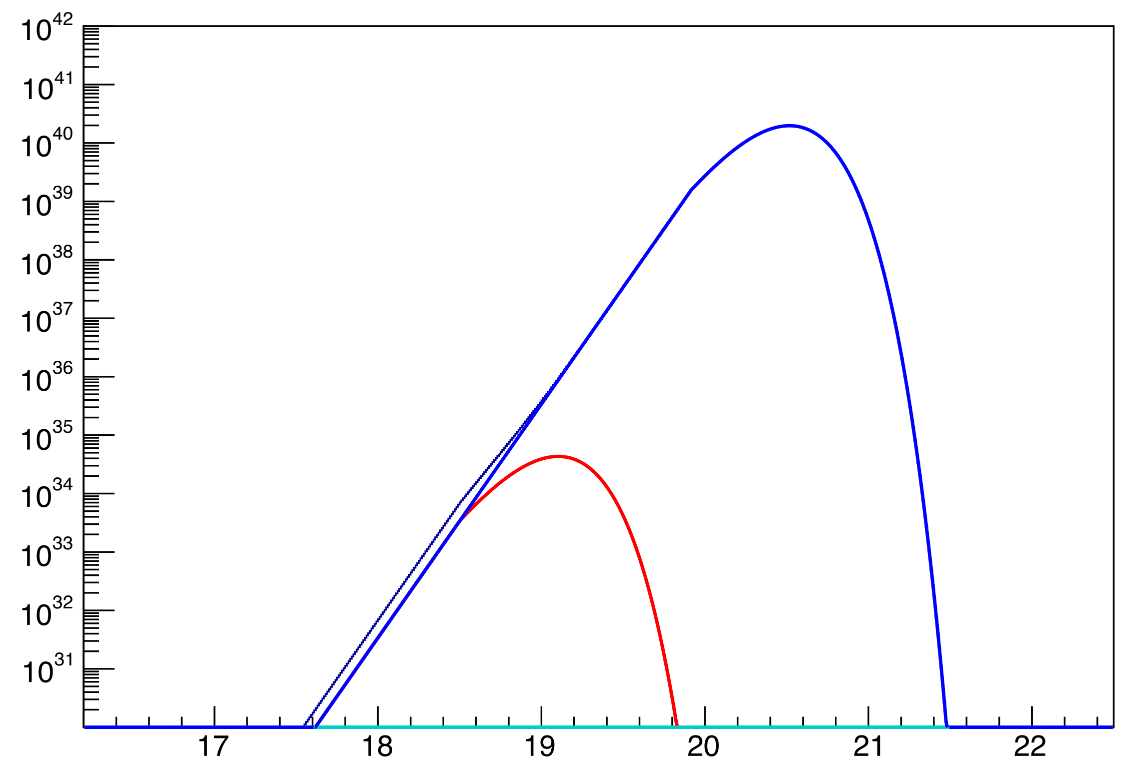




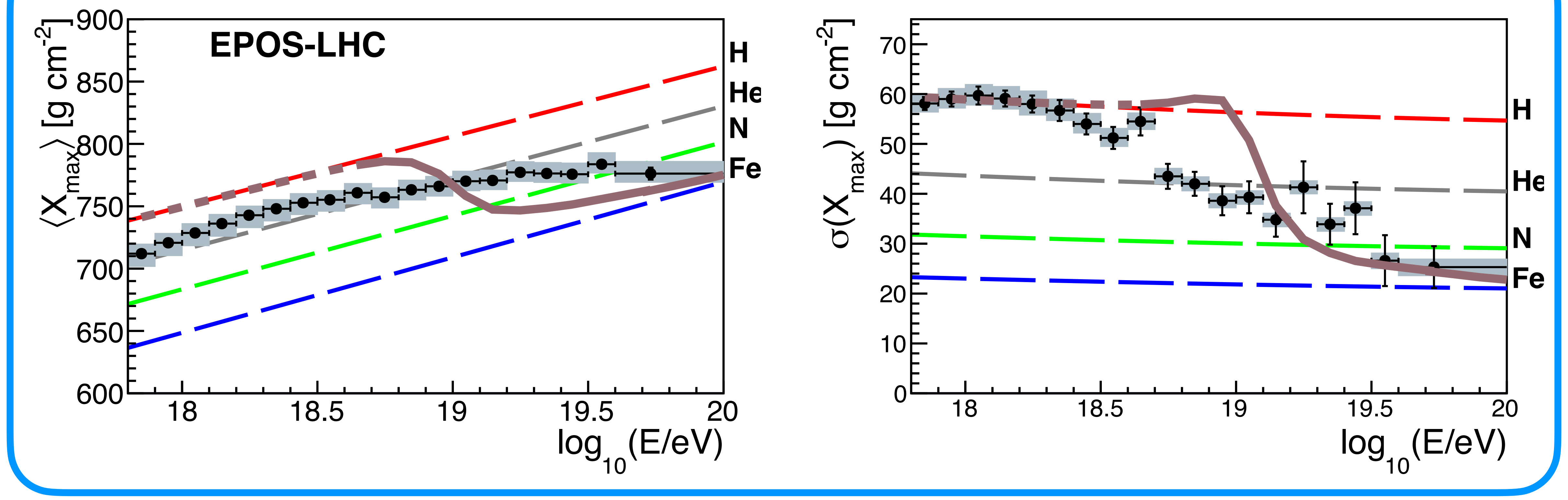




IMPLICATIONS ON SOURCE CHARACTERISTICS



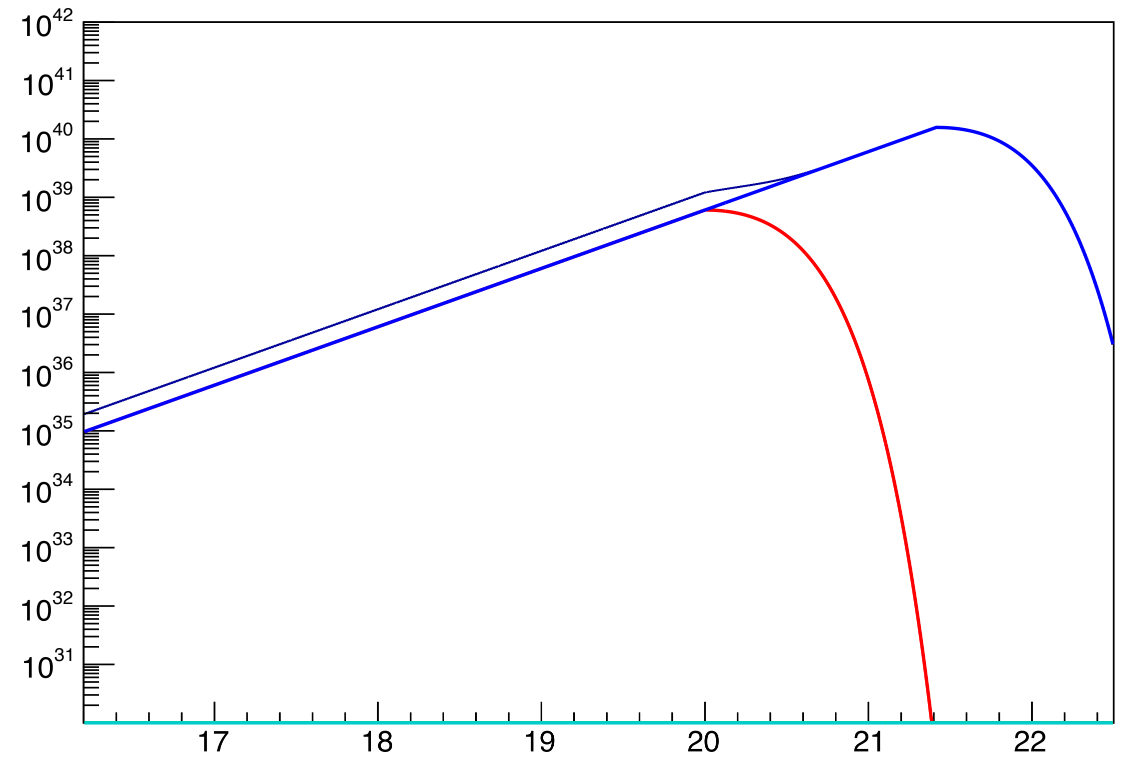
Example: 50% H + 50% Fe at source



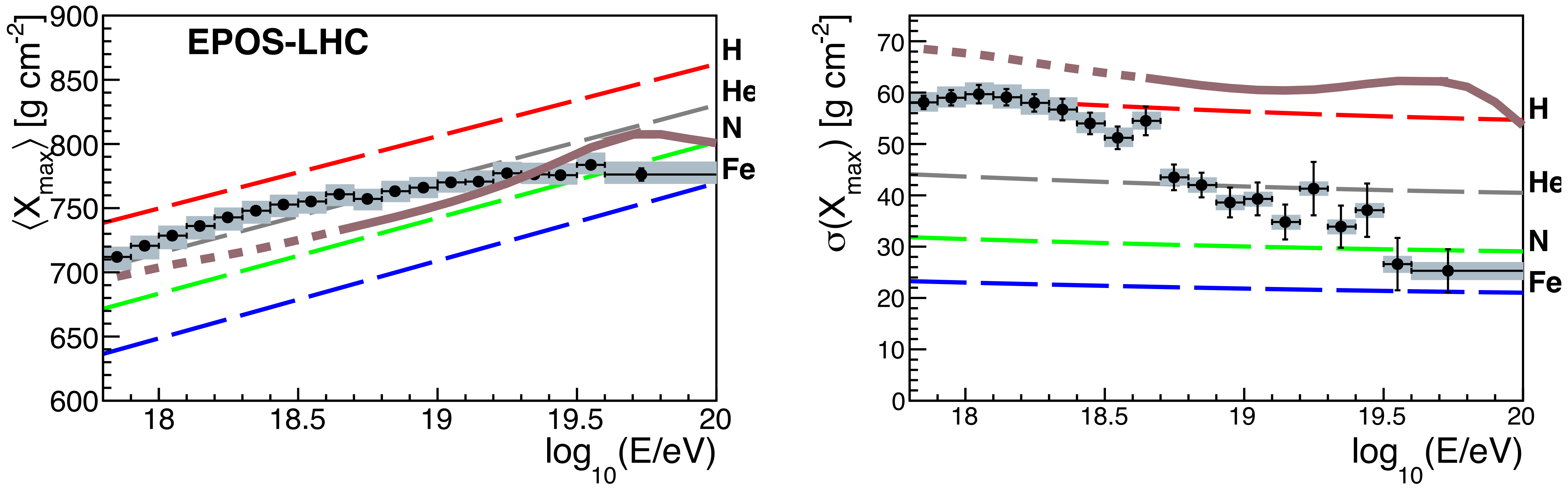
- The sigma(Xmax) is a measurement of the spread of the mass composition, due to
  - Mixed composition at source
  - Spectral parameters
  - Propagation of UHECRs in the extragalactic space

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

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

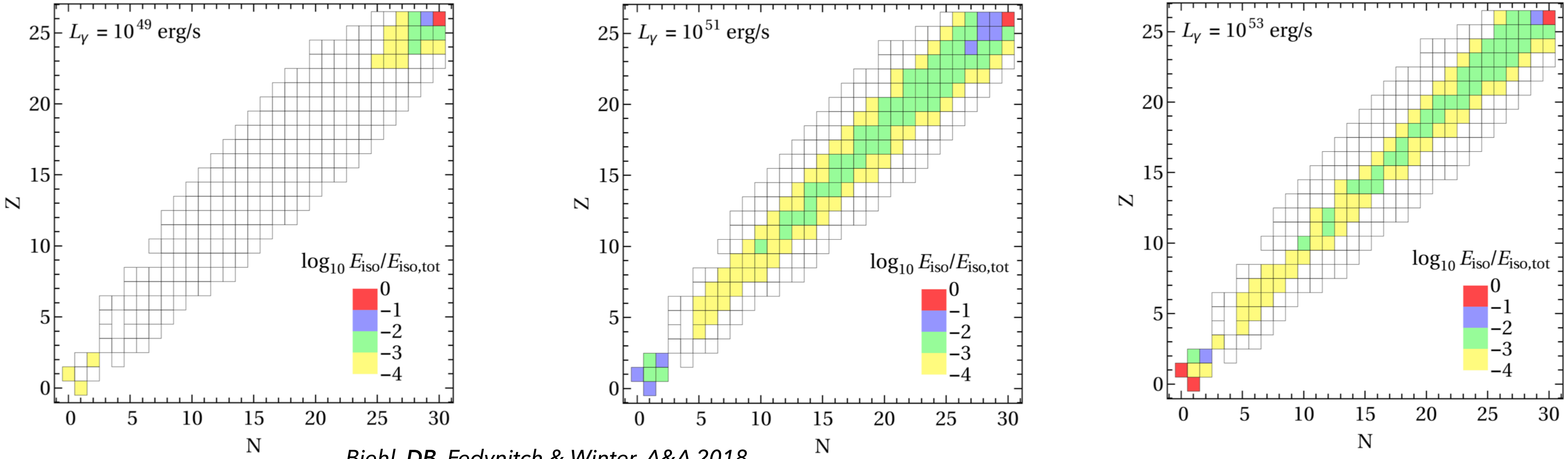


See Auger, JCAP 2013 for more details on this topic



IMPLICATIONS ON SOURCE CHARACTERISTICS

- Mixed UHECR composition
  - Nuclei heavier than H must **exist** in the source environment, and **survive** the potential interactions with the present matter/radiation
  - The survival condition can be satisfied depending on the characteristics of the possible source (such as **density of radiation**, etc…)



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

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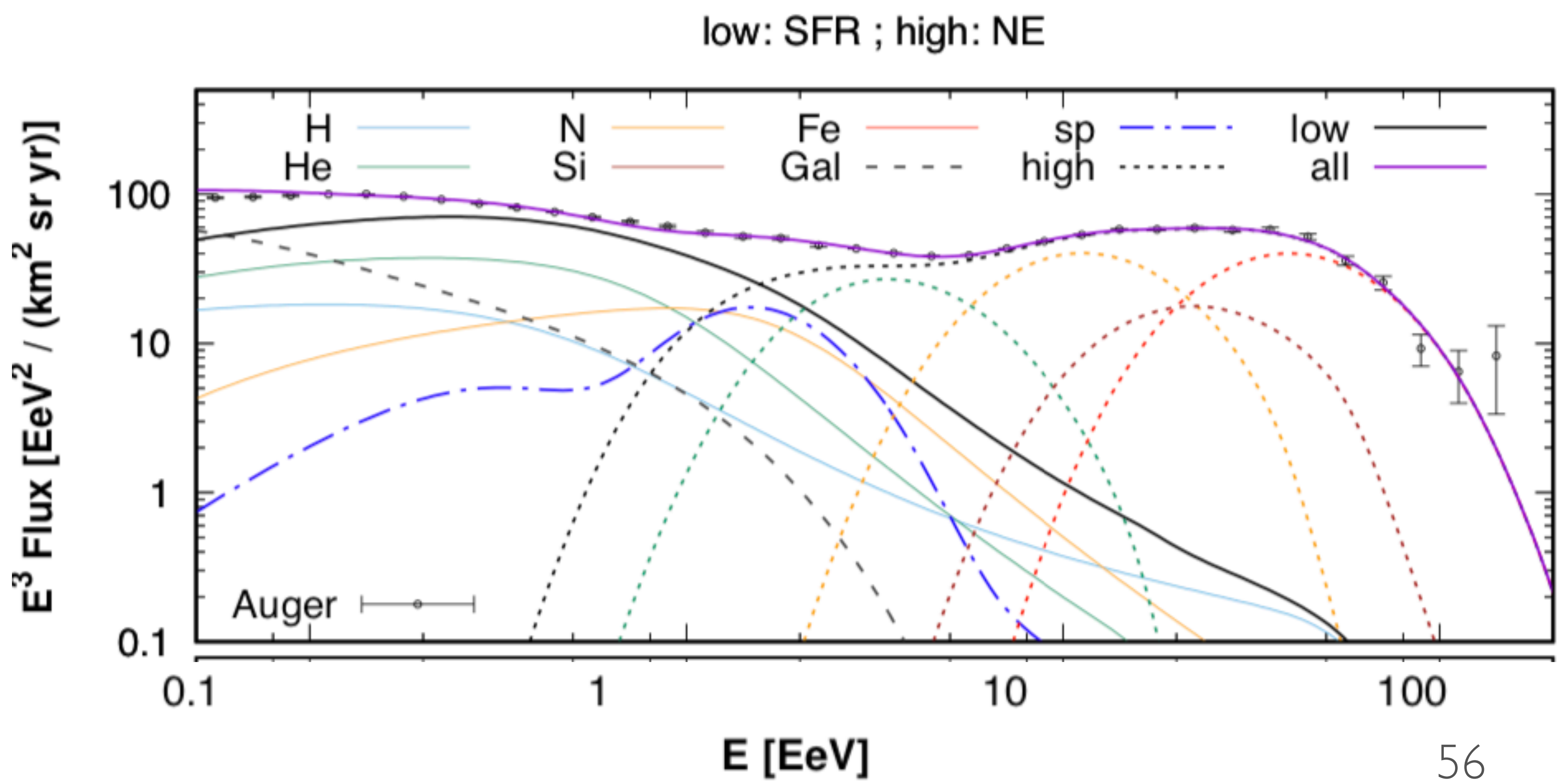
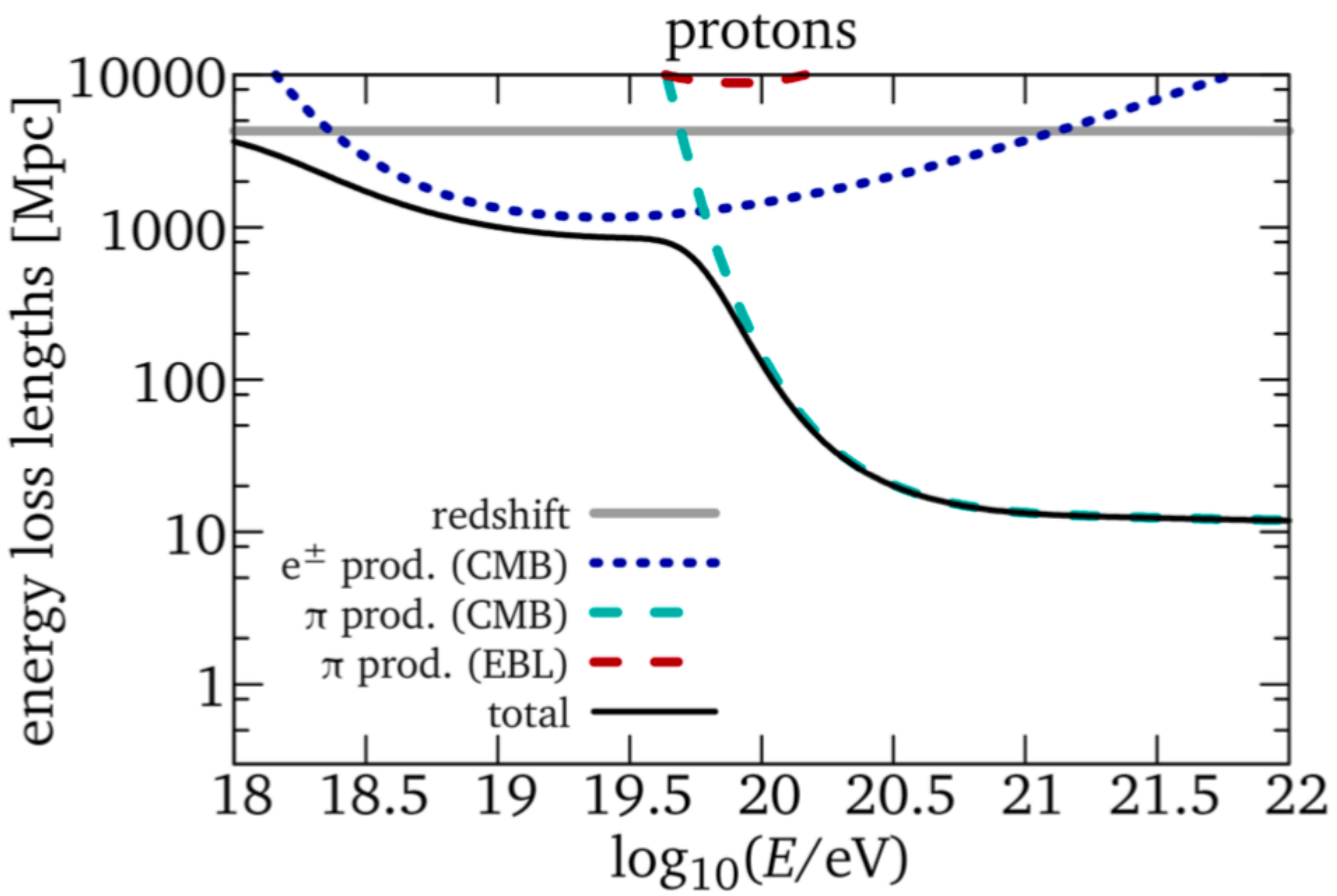
  - Nuclei heavier than H must **exist** in the source environment, and **survive** the potential interactions with the present matter/radiation
  - The survival condition can be satisfied depending on the characteristics of the possible source (such as **density of radiation**, etc…)
- What sources could provide mixed UHECR composition?
  - Neutron stars, ***Kotera, Amato & Blasi, JCAP 2015***
  - Wolf-Rayet stars, ***Thoudam et al. A&A 2016***
  - Binary Neutron Star mergers, ***Rodrigues, Biehl, DB & Taylor, Astropart. Phys. 2019; Decoene et al. JCAP 2020***
  - Tidal Disruption Events, ***Alves Batista & Silk, PRD 2017; Biehl, DB, Lunardini & Winter, Sci. Rep. 2018***
  - Gamma-Ray Bursts jets, ***Murase et al. PRD 2008; Biehl, DB, Fedynitch & Winter, A&A 2018;*** LL-GRB jets, ***Zhang et al, PRD 2018; DB, Biehl & Winter, ApJ 2019***
  - Blazars, ***Murase et al. PRD 2014***

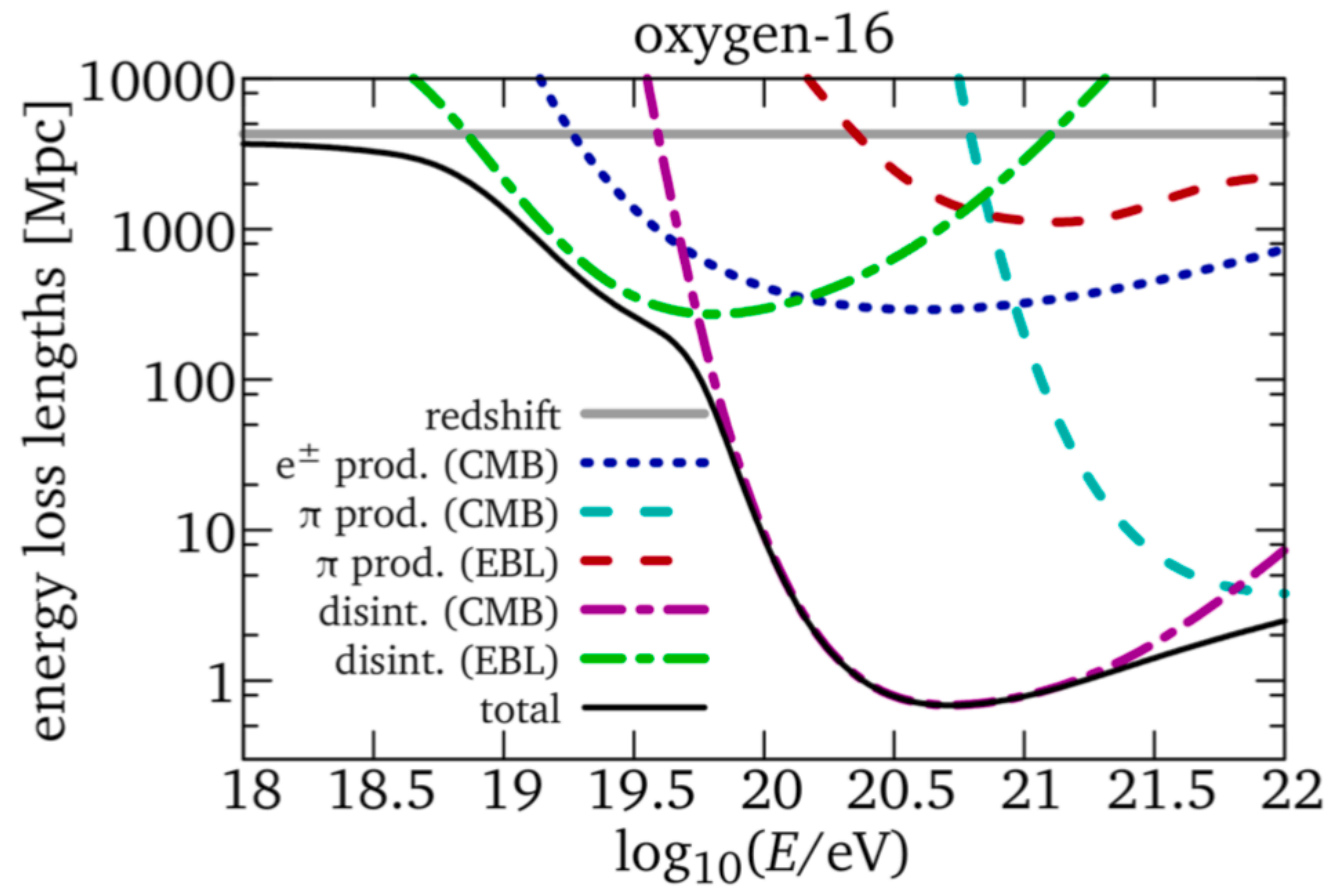
IMPLICATIONS ON SOURCE CHARACTERISTICS

- Mixed UHECR composition
    - The **ankle** cannot be interpreted as a propagation effect of the protons in the extragalactic space (dip model), due to pair-production
    - Other possible explanations:
        - ankle as **signature of in-source interactions**?
        - Interplay between contributions of **different populations**?

Mollerach & Roulet, PRD 2020





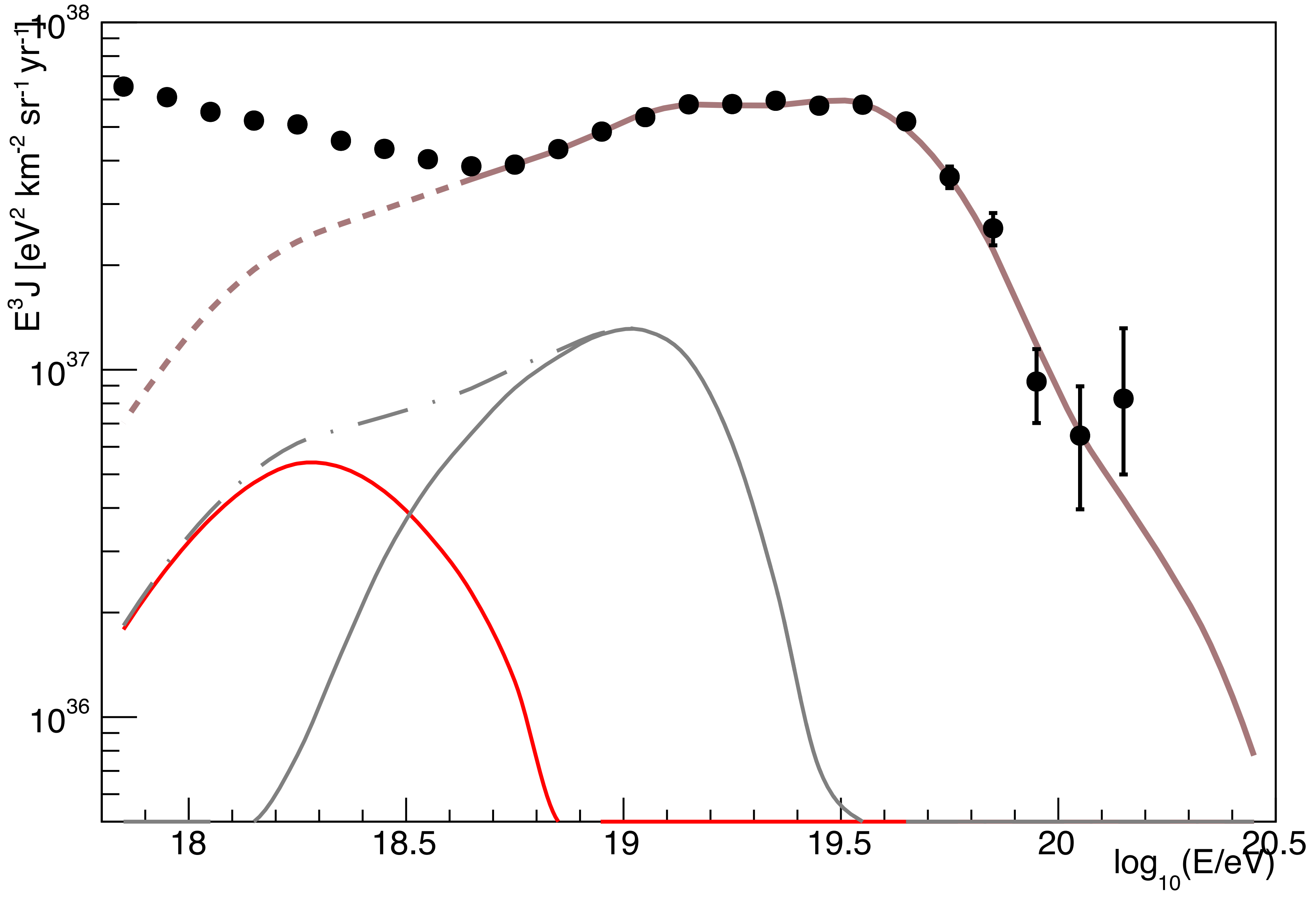


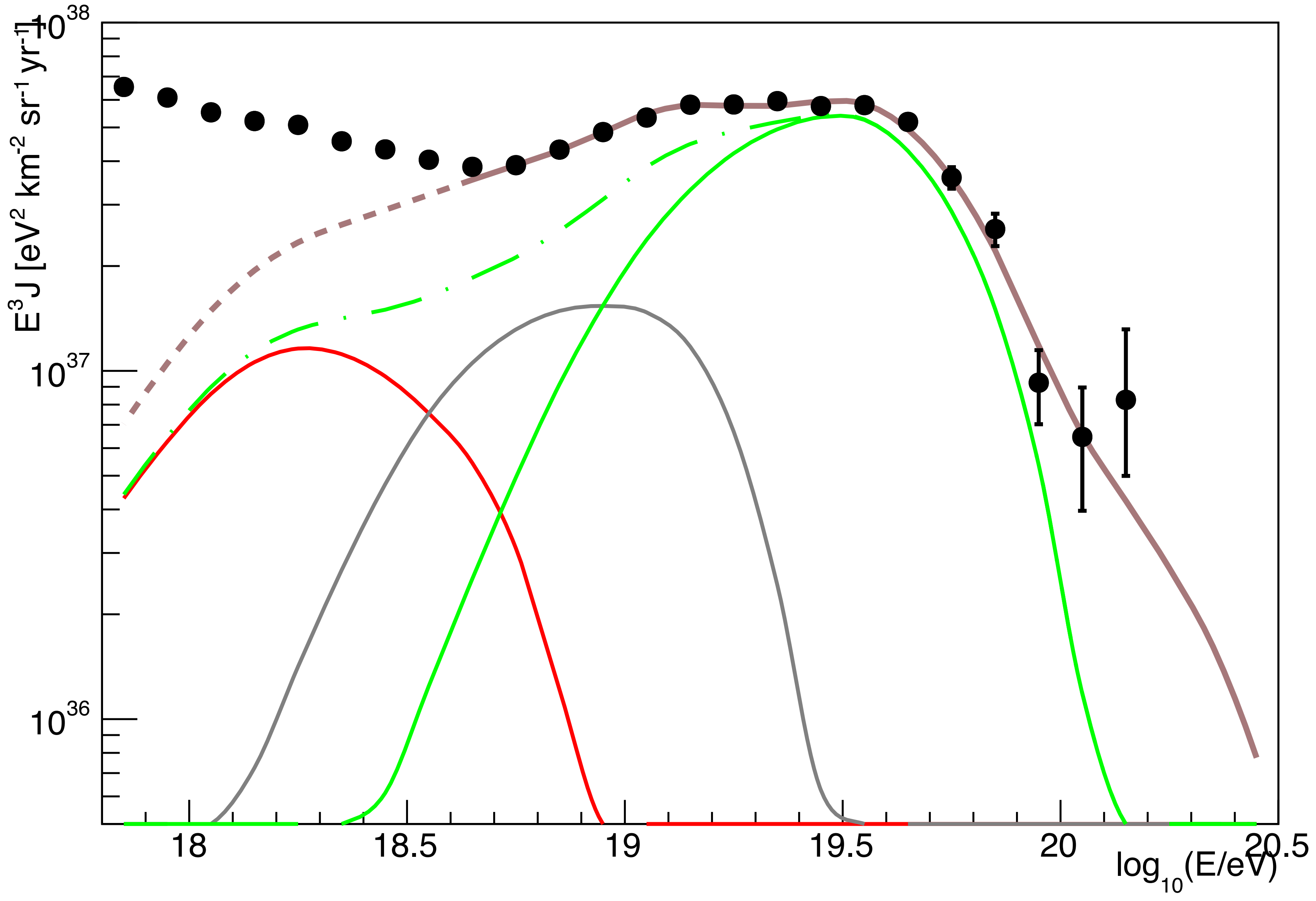
IMPLICATIONS ON SOURCE CHARACTERISTICS

- Mixed UHECR composition

- The **new feature at 13 EeV** might reflect the interplay between the flux contributions of the He and CNO components injected at the source with their distinct cut-off energies, shaped by photodisintegration during the propagation

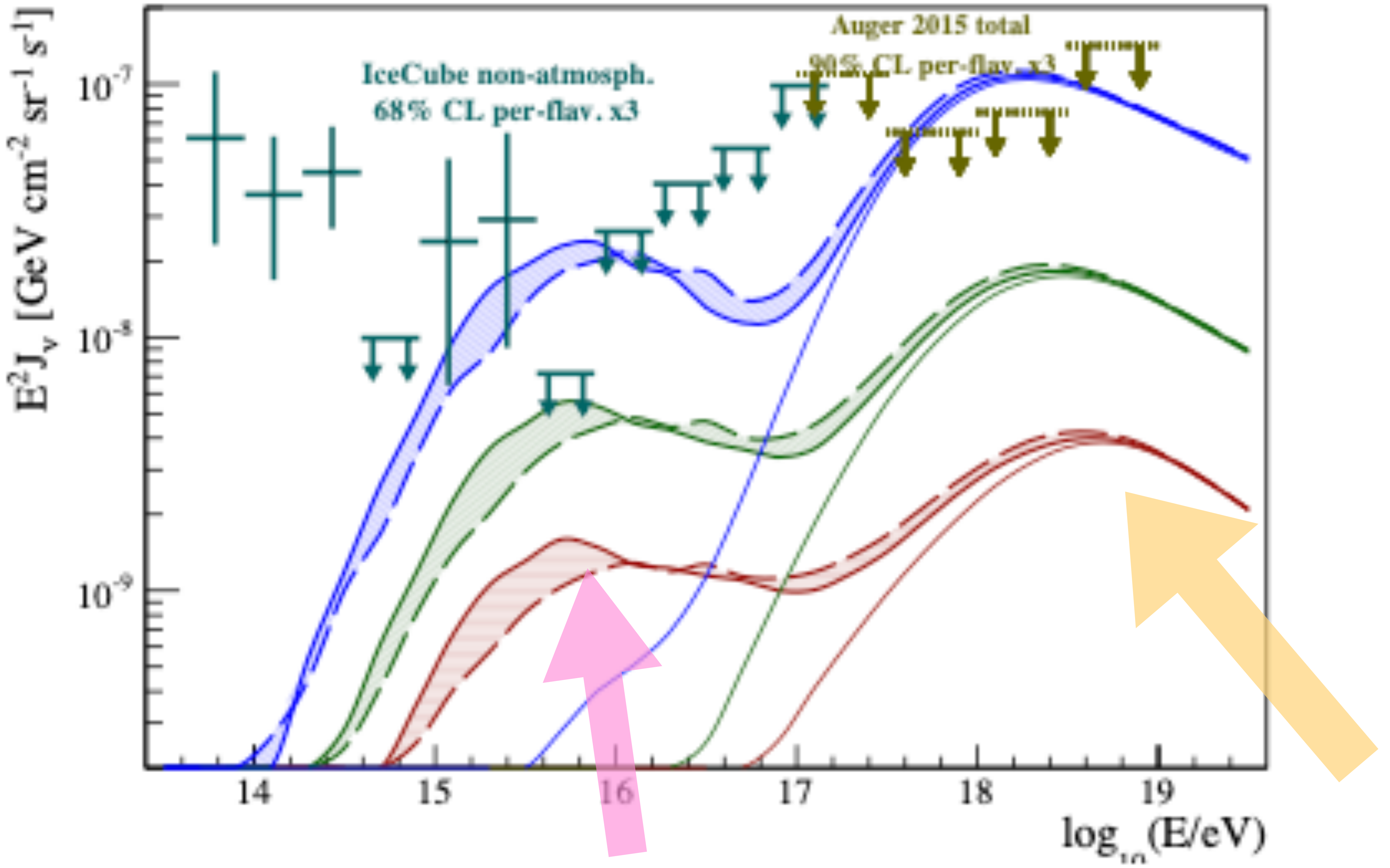
.





SECONDARY PARTICLES: NEUTRINOS

E^2 x flux



$\varepsilon' = \Gamma\varepsilon$ must be order of hundreds of MeV for producing pions

Neutrinos from interactions of protons with CMB (7×10^{-4} eV); for instance

- Proton with E=$10^{20.5}$ eV, Lorentz factor 3×10^{11} -> 2.2×10^8 eV photon energy in the nucleus rest frame, above threshold for pion production

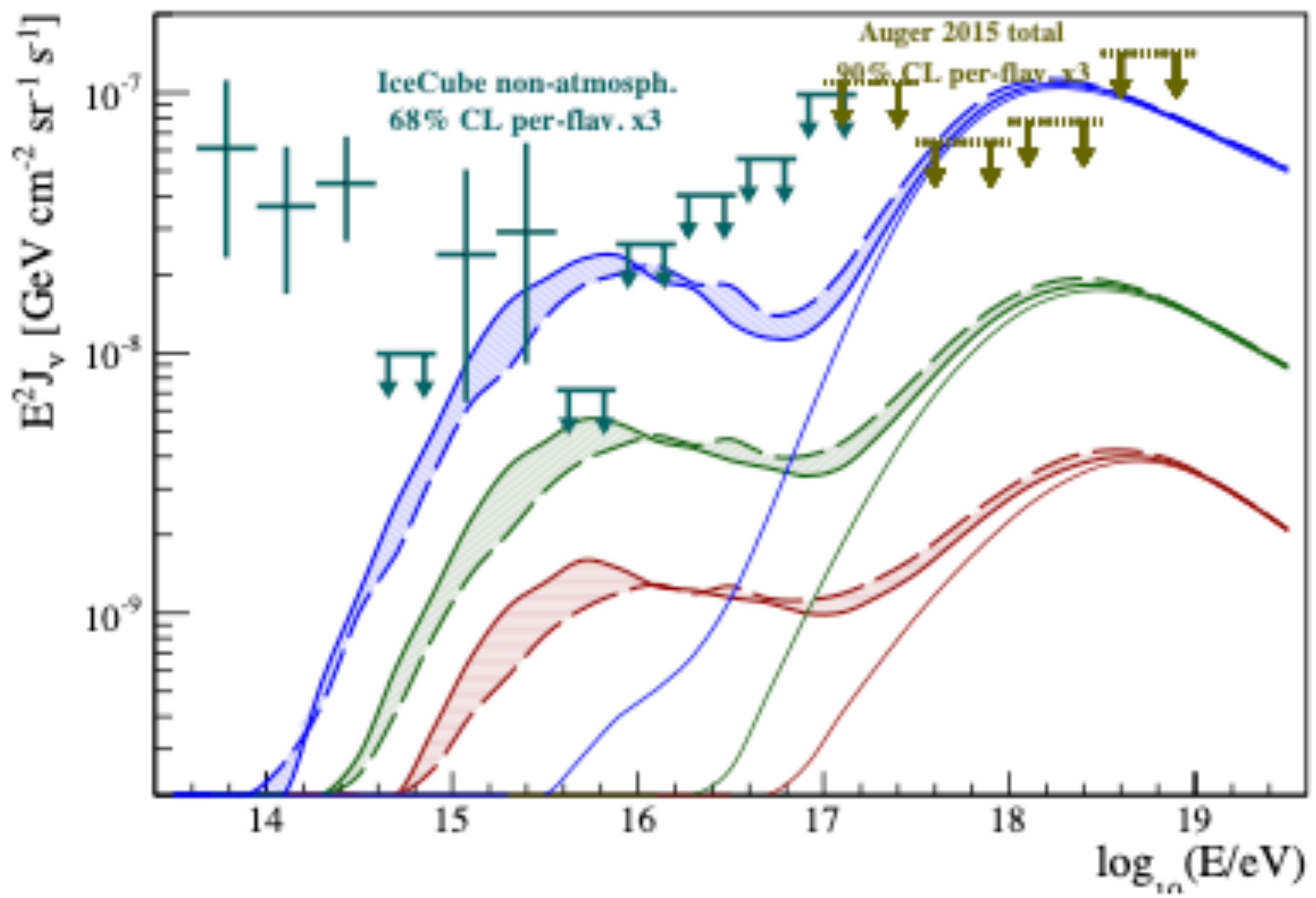
Neutrinos from interactions of protons with IR (10^{-2}-10^{-1} eV)

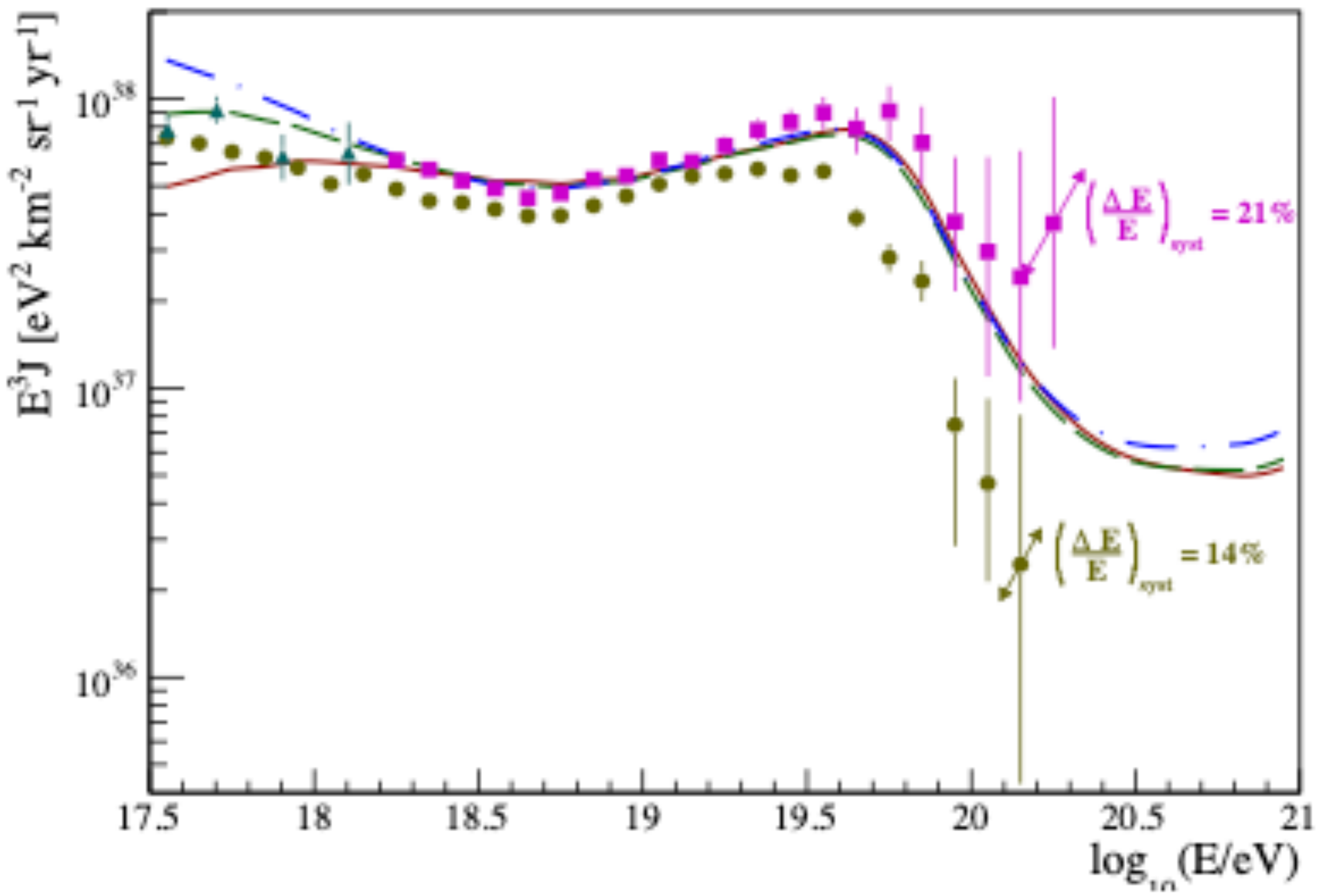
-> smaller energy of the protons is required to excite the Delta resonance;

-> neutrinos with smaller energy will be produced

Aloisio, DB, di Matteo, Grillo, Petrera, Salamida 2015

SECONDARY PARTICLES: NEUTRINOS





Effect of **cosmological evolution** of sources $(1+z)^m$

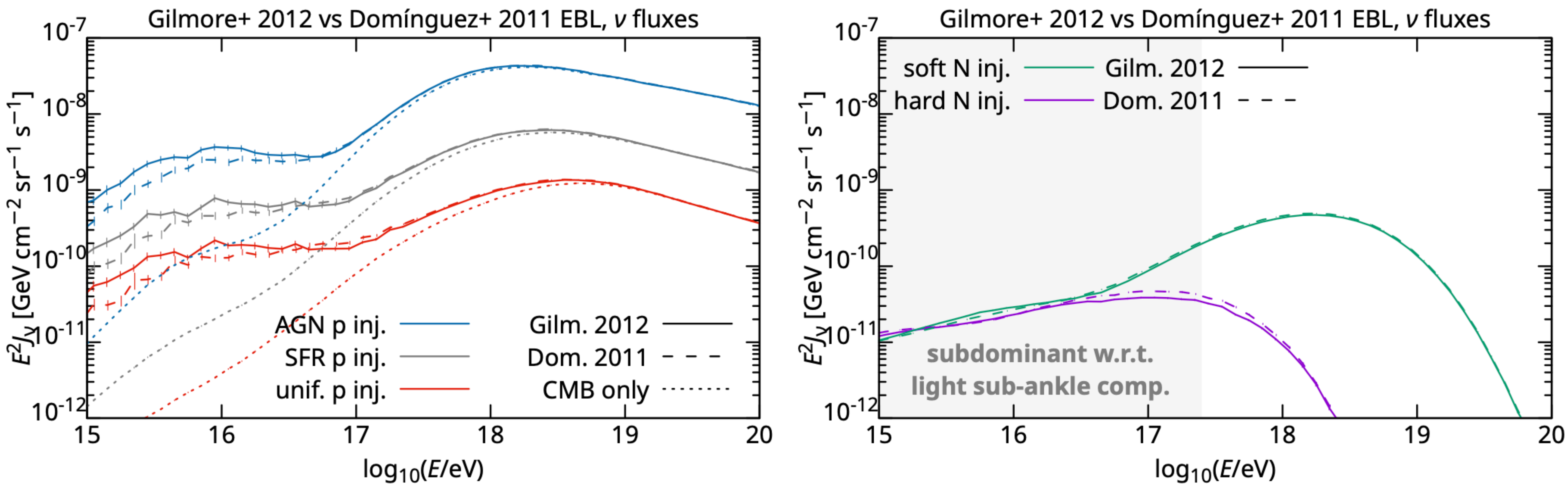
$$J(E) = \frac{c}{4\pi} \int dz \left| \frac{dt}{dz} \right| \tilde{Q}(E_g(E,z),z) \frac{dE_g}{dE}$$

Aloisio, DB, di Matteo, Grillo, Petrera, Salamida 2015

On cosmic-ray spectra the effect is much less relevant than for neutrinos!

- Cosmogenic neutrinos could improve the understanding of the distribution of UHECR sources

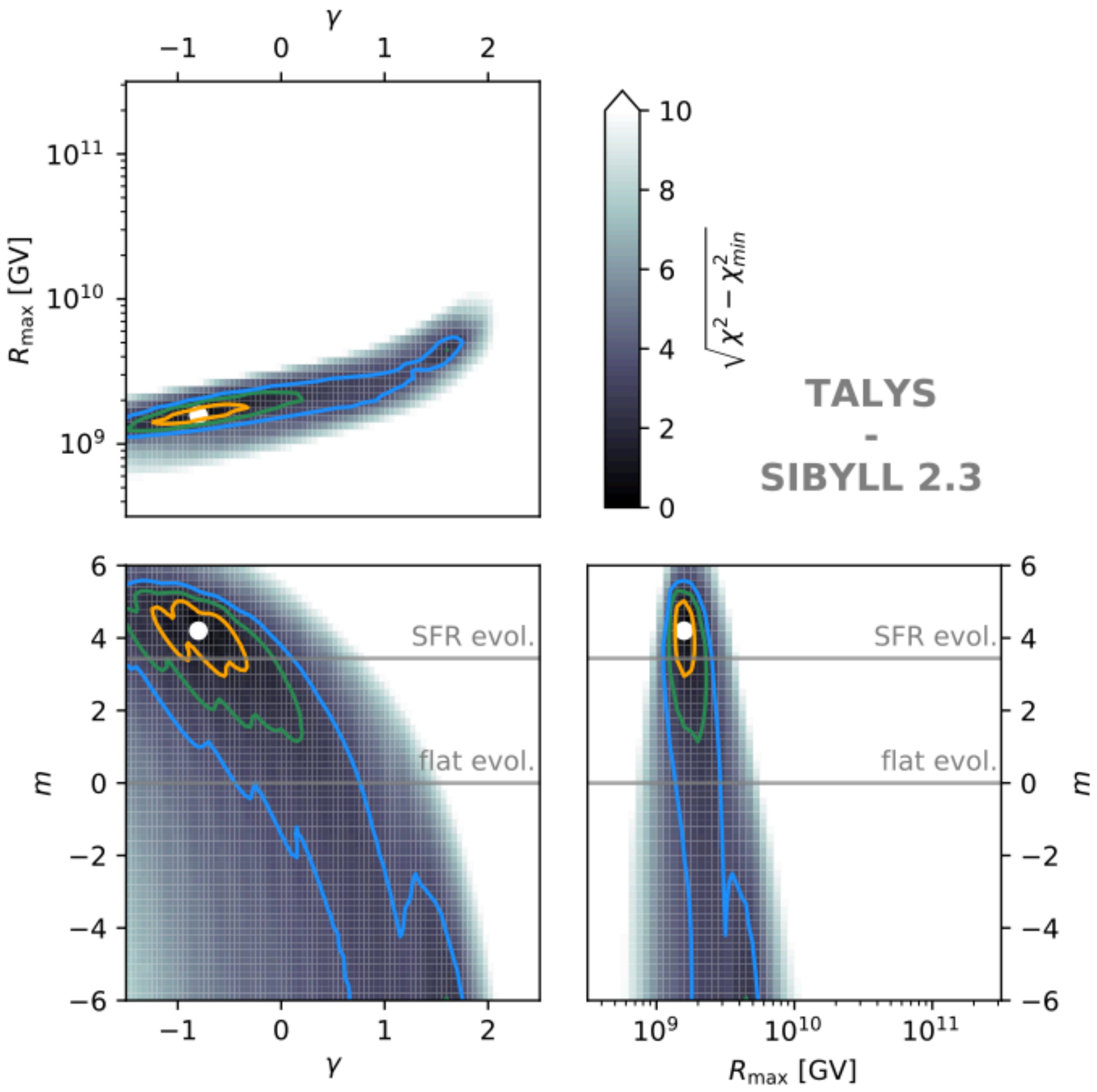
SECONDARY PARTICLES: NEUTRINOS

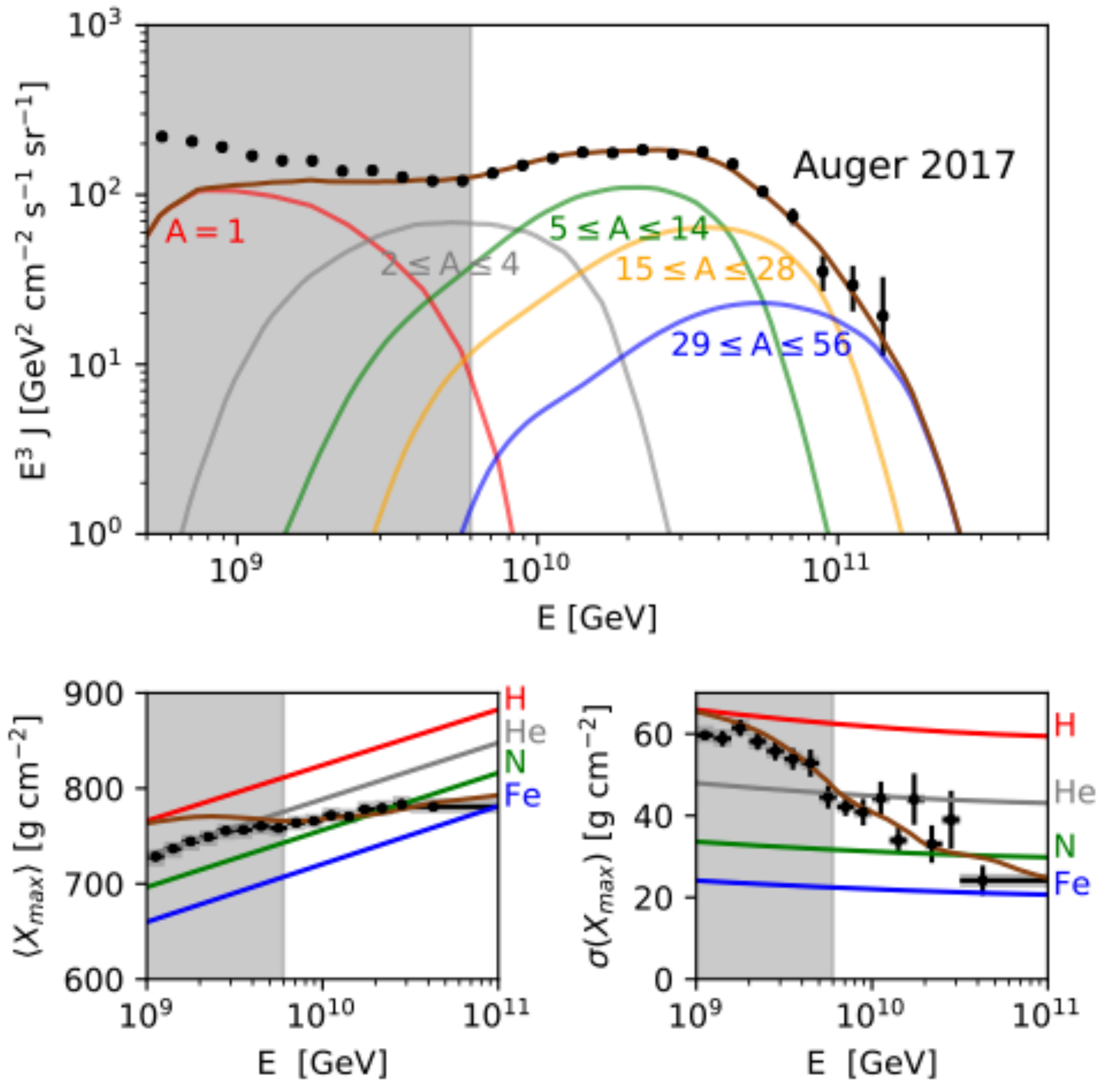


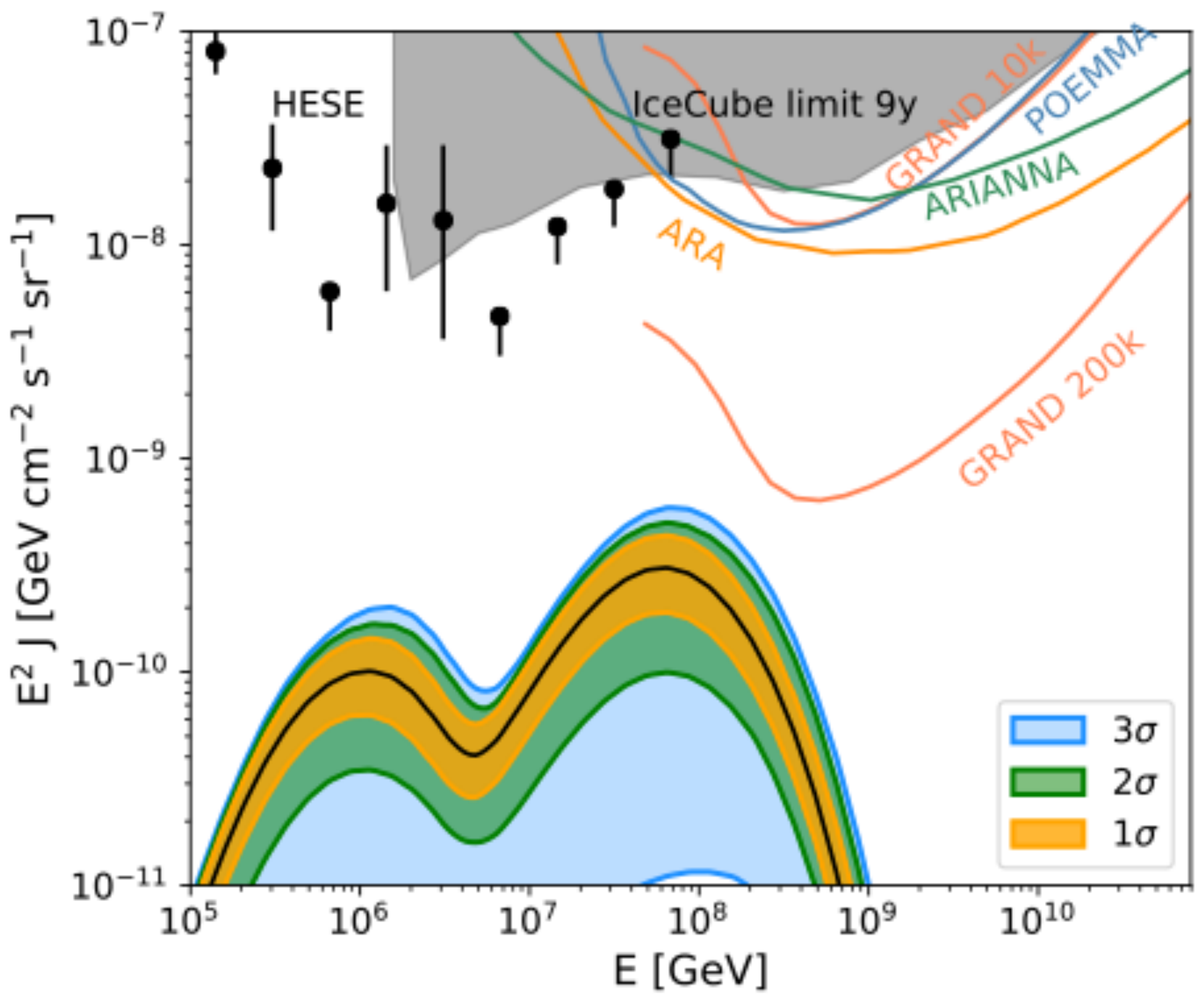
Cosmogenic neutrinos from UHECR protons/nuclei

Alves Batista, DB, di Matteo, van Vliet 2019

SECONDARY PARTICLES: NEUTRINOS



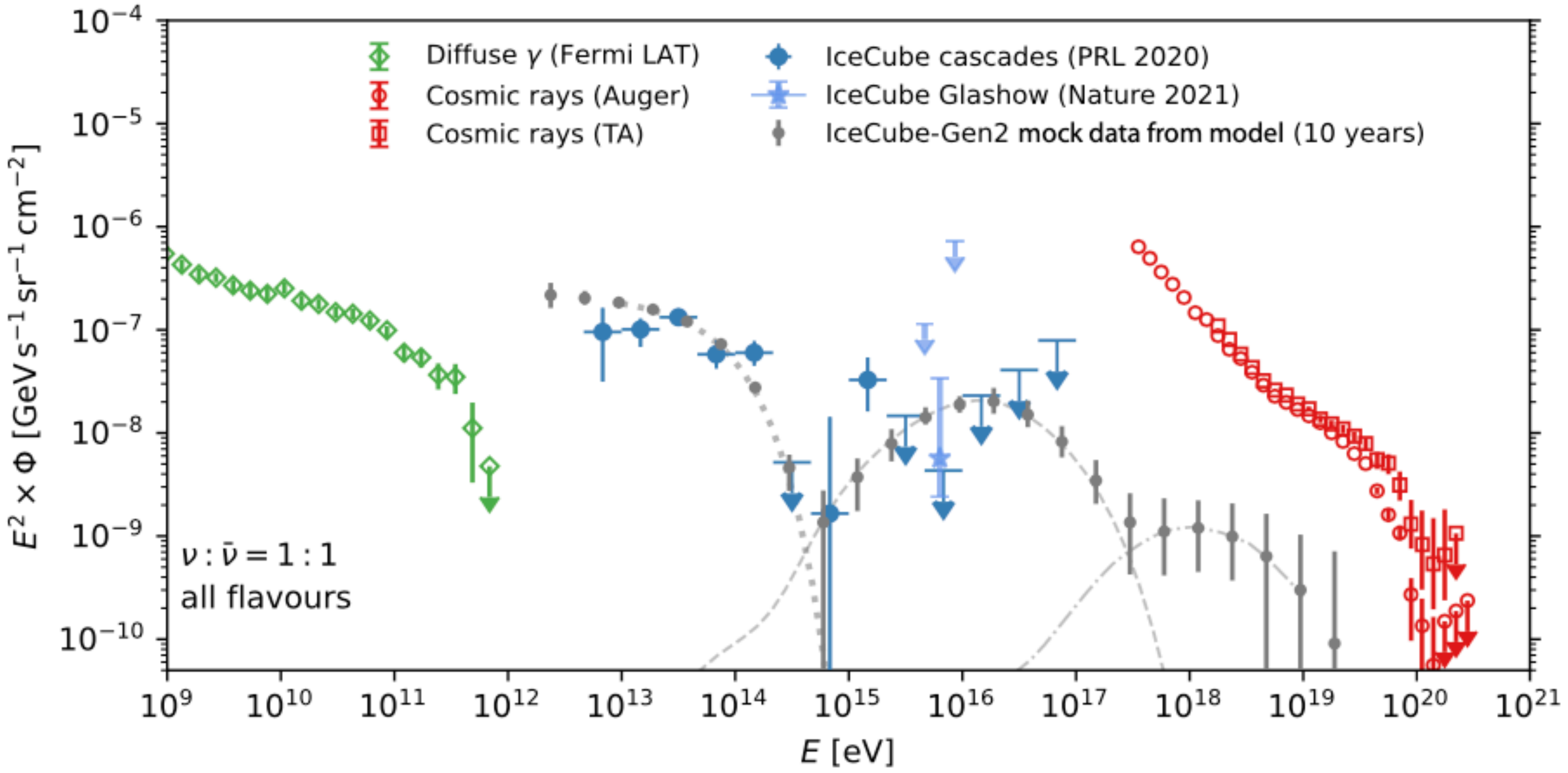




Heinze, Fedynitch, DB, Winter 2019

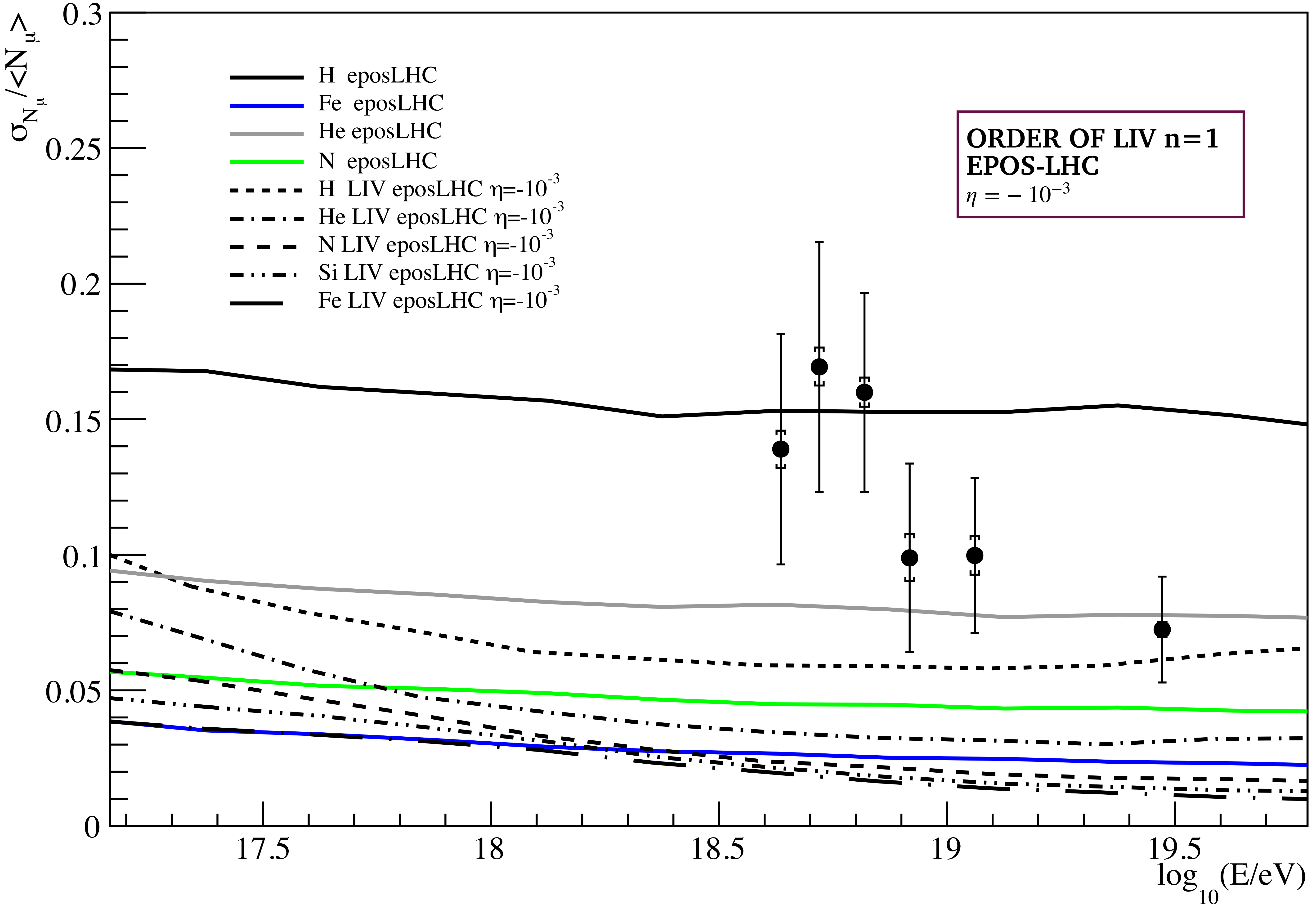
THE MULTI-MESSENGER PICTURE

arxiv: 2205.05845



Muon Fluctuations

- **<u>In the standard case:</u>** $\frac{N_\mu}{\langle N_\mu \rangle} = \alpha_1 \ldots$**—> for primary particle with mass A** $\frac{N_\mu}{\langle N_\mu \rangle} = \frac{\alpha_1}{A} \ldots$
- in the presence of LIV **<u>Reduction of Muon Fluctuations:</u>** the proton is behaving as a heavier nucleus and the fluctuations decrease



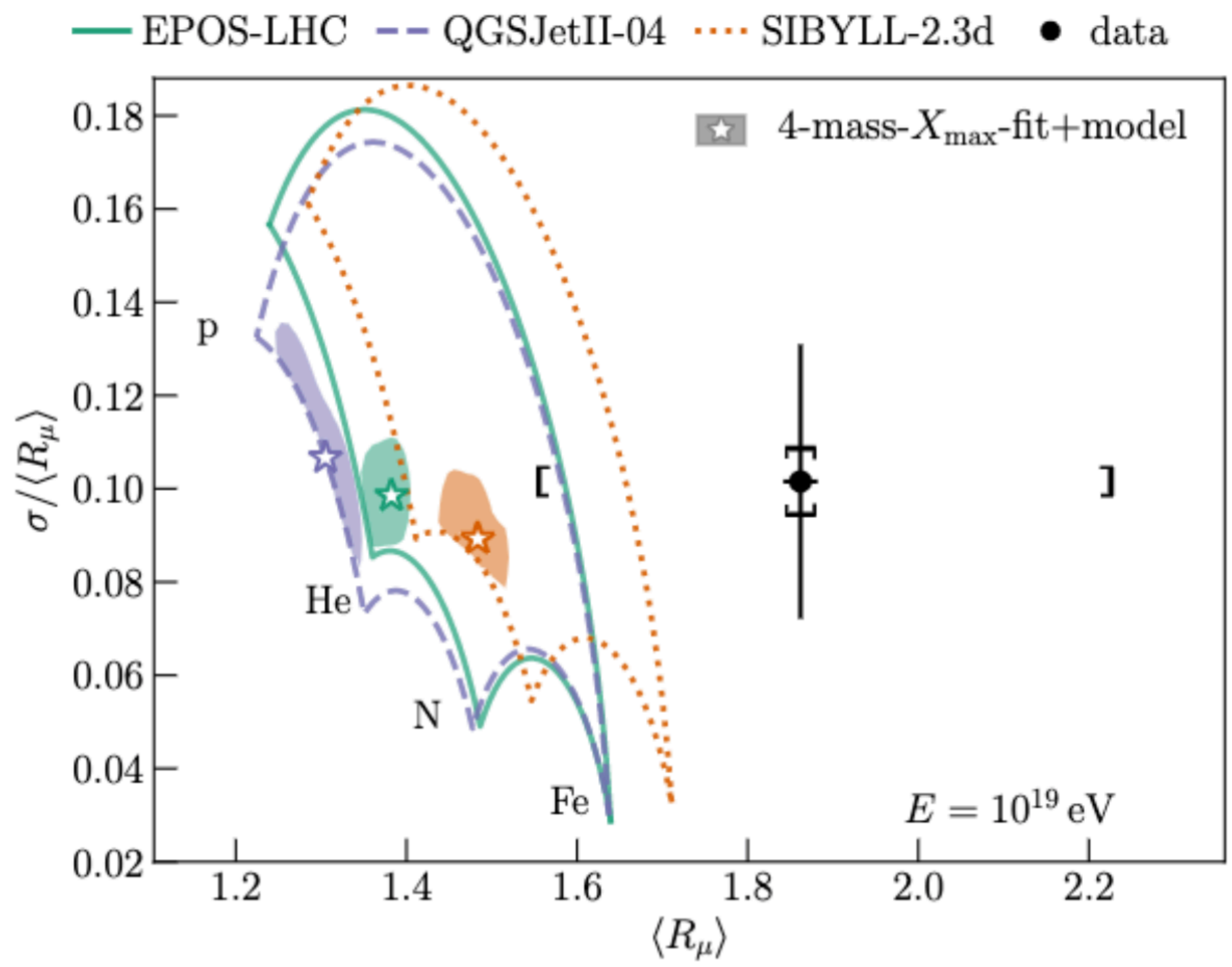
Relative Fluctuations

Effects of the different composition scenarios

A. Aab et al. [Pierre Auger] Phys. Rev. Lett. 126 (2021) no.15, 152002

The mixture of the two components p and Fe gives the maximum value of relative fluctuations.

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



Where

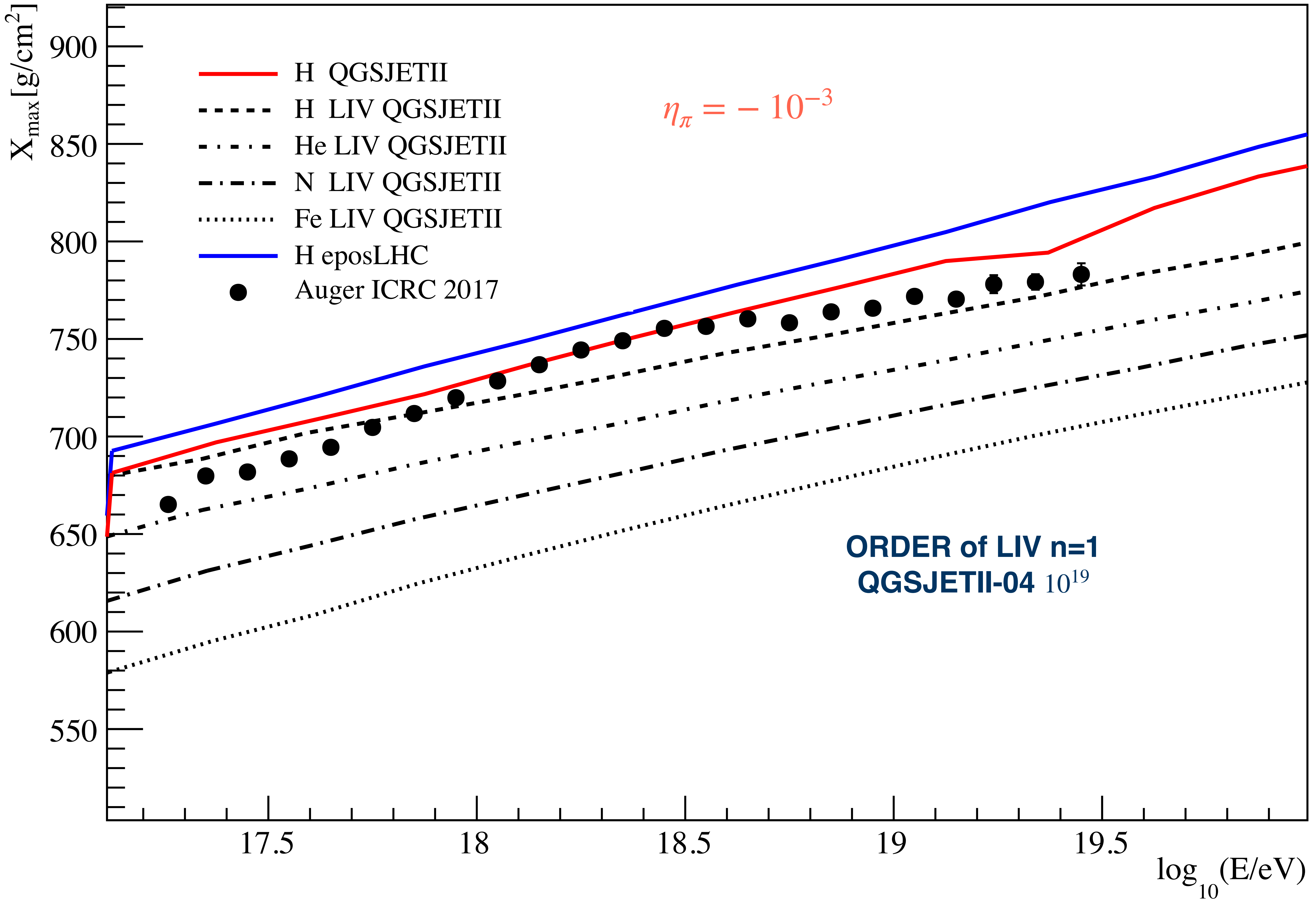
$$\langle N_\mu \rangle_{\text{mix}}(\alpha;\eta) = (1-\alpha)\langle N_\mu \rangle_p + \alpha \langle N_\mu \rangle_{Fe}$$

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

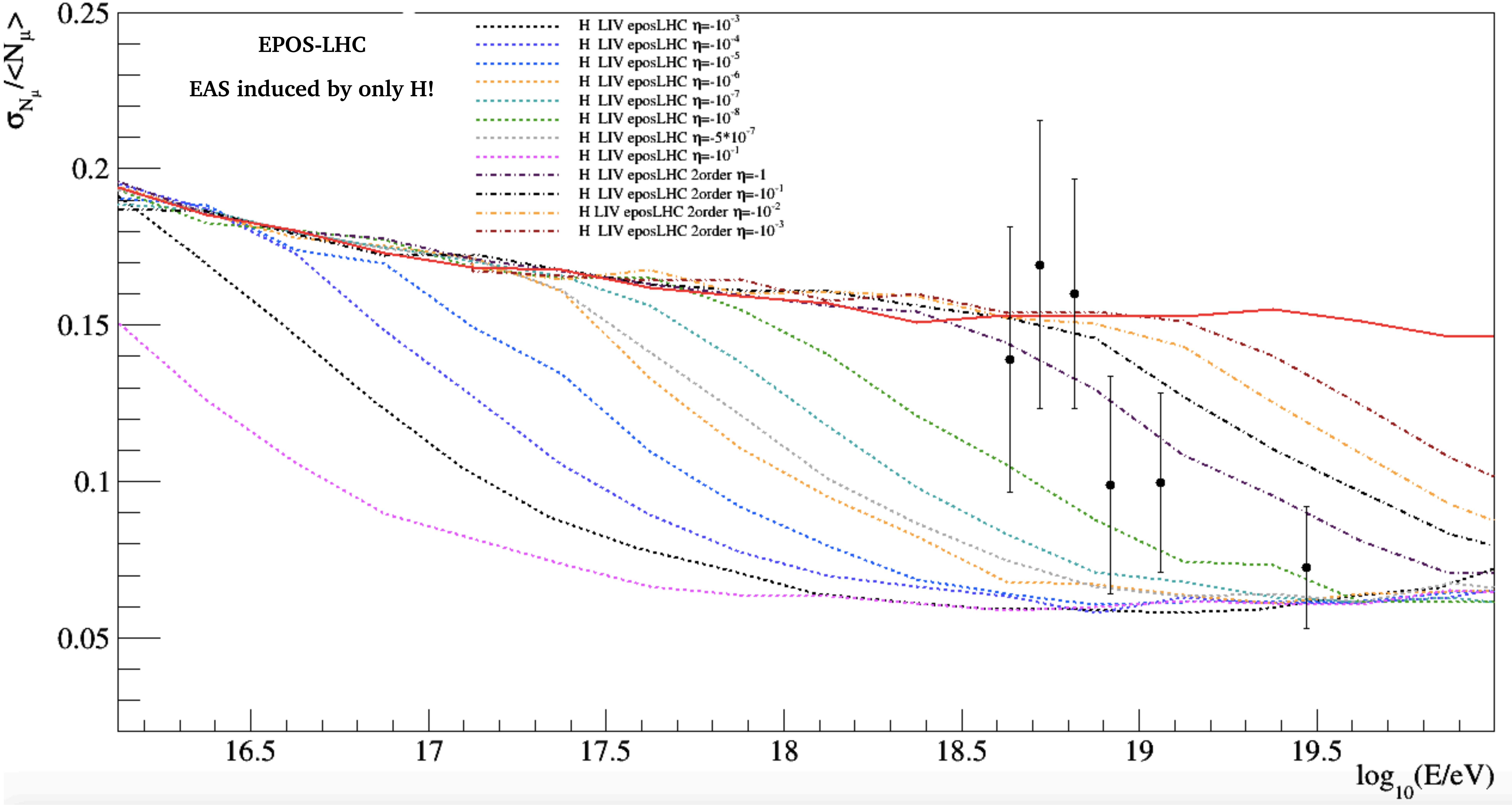
$1-\alpha$ is the fraction of proton

α is the fraction of iron

$\langle X_{max} \rangle$



Muon Fluctuations



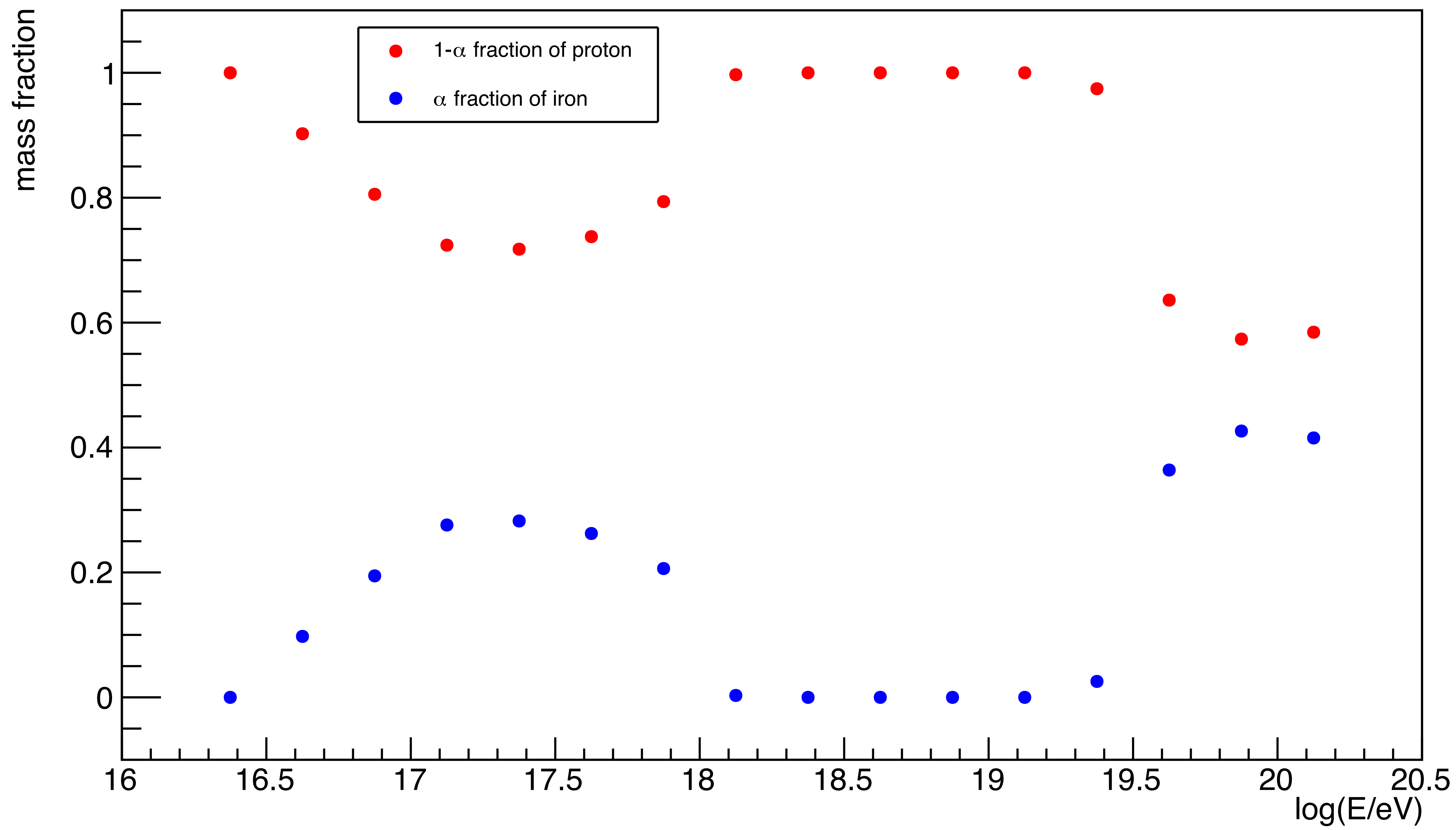
The most conservative case is produced by H-Fe mixture corresponding to <u>the maximum of the relative fluctuations wrt α</u>

<u>In presence of LIV</u>

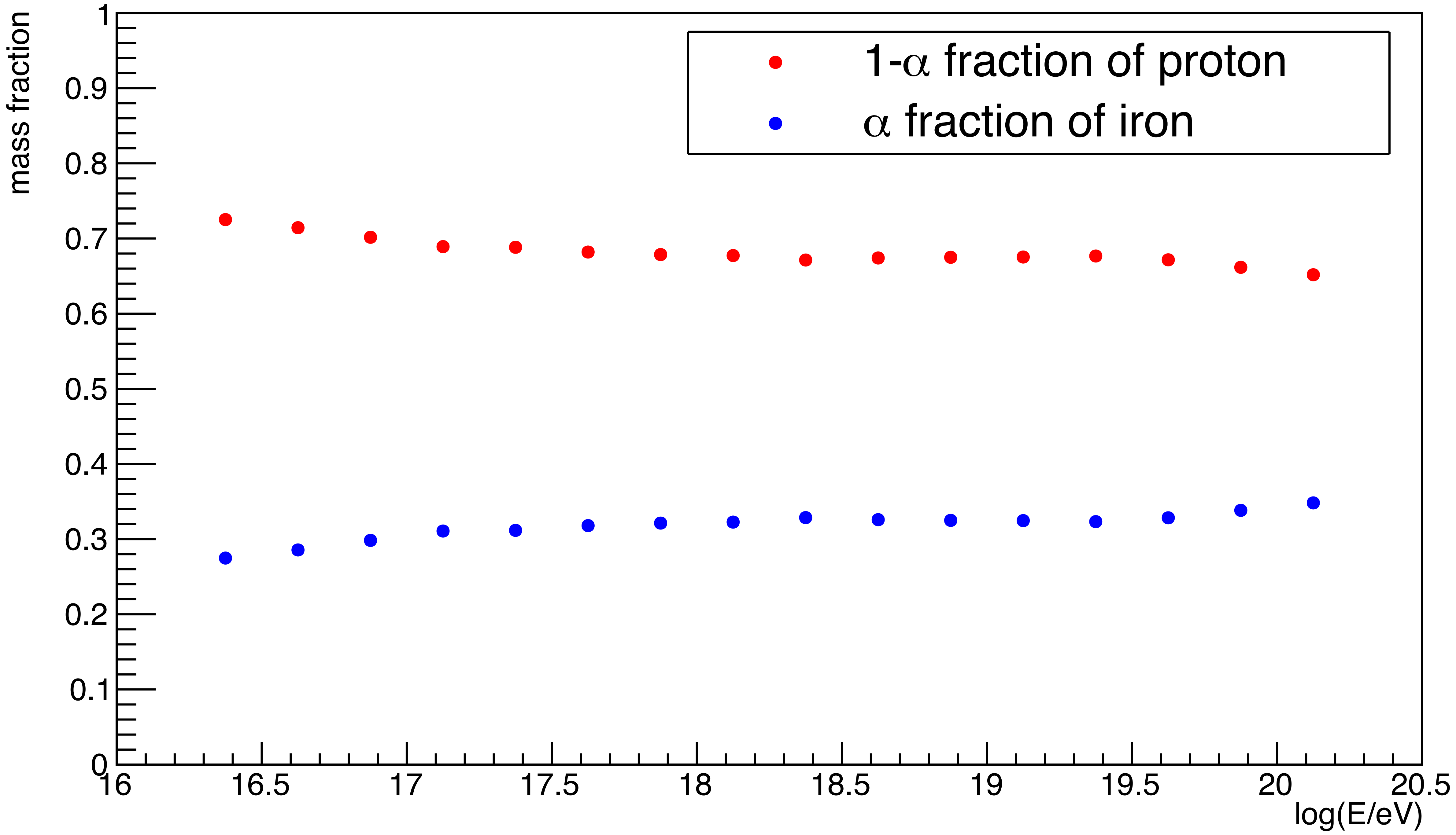
1- We have to parametrize: $\langle N_\mu \rangle_p$, $\langle N_\mu \rangle_{Fe}$, $RMS^2(N_\mu)_p$ and $RMS^2(N_\mu)_{Fe}$

2- We will find the maximum: $\max_\alpha \frac{\sigma_\mu}{\langle N_\mu \rangle} = \frac{\sqrt{RMS^2(N_\mu)(\alpha)}}{\langle N_\mu \rangle(\alpha)}$ $\forall$ energy bin

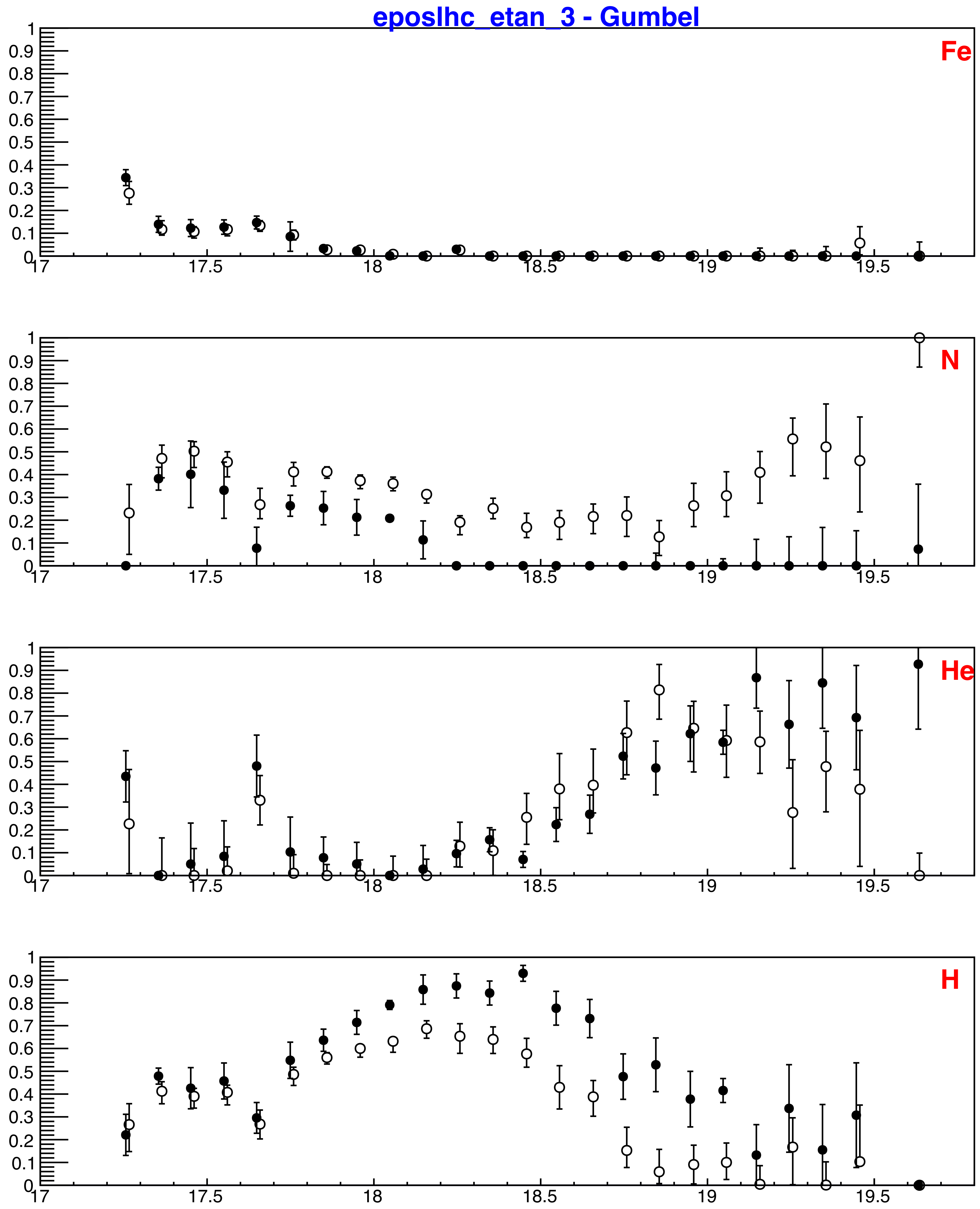
log(-η)=-3



log(-η)=-14



Mass fraction fit



- The mass fraction fit has been done again using the LIV models
- The Gumbel parametrization have been produced for the LIV models we have simulated

For LIV at 1st order the number of protons highest energies increases