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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

UNIVERSITÀ
DEGLI STUDI
DELL'AQUILA

ULTRA-HIGH-ENERGY COSMIC-RAY PROPAGATION IN EXTRAGALACTIC SPACE

Implications on UHECR source characteristics

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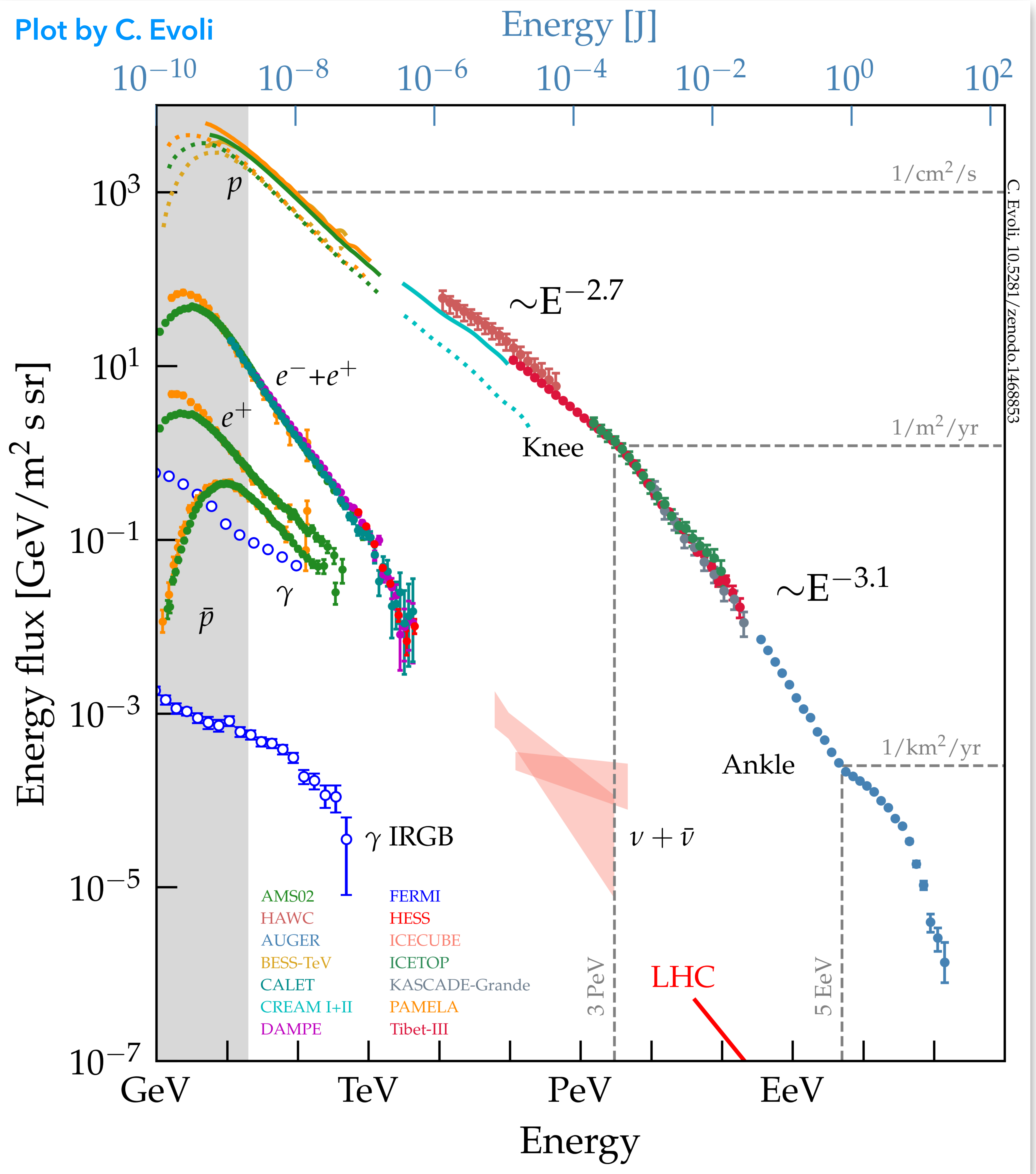
Hands-on the extreme universe with high-energy gamma-ray data
18-22 July 2022, Sexten, Italy

INTRODUCTION

THE COSMIC-RAY ENERGY SPECTRUM



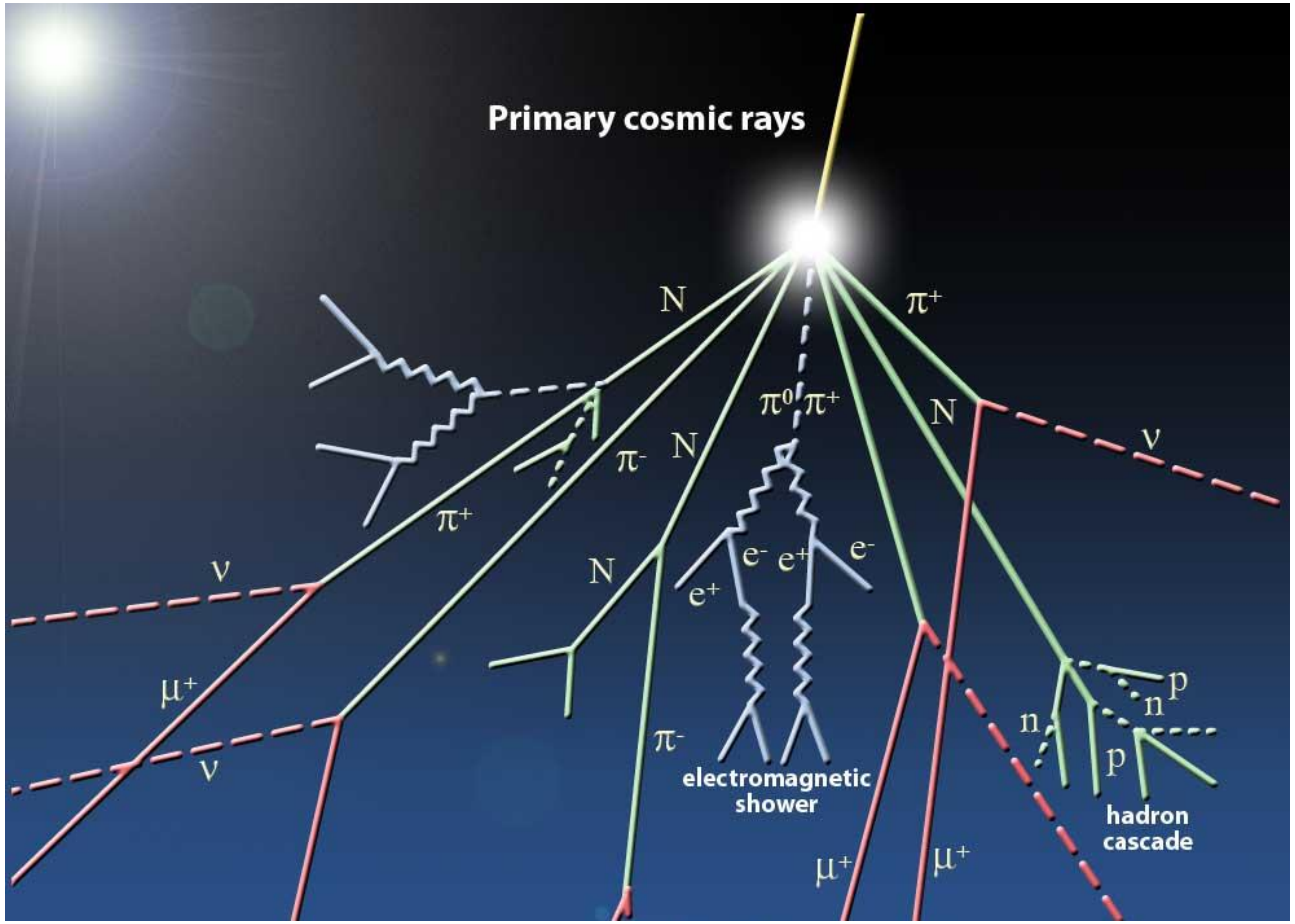
- Collection of measurements, indicating a power-law spectrum, with a few changes of spectral index
- Focus on UHE particles
  - above 10^{17} eV, 8 orders of magnitude larger than the rest mass of the proton… relativistic particles!
  - "Ankle", suppression at the highest energies

- Where do UHECRs come from?
- How are they accelerated to such high energies?
- What is the chemical composition of UHECRs?
- What is the origin of the changes in the spectral index?

- What do we learn about cosmic rays and their sources from current measurements?

MEASUREMENTS AT UHE

EXTENSIVE AIR SHOWERS

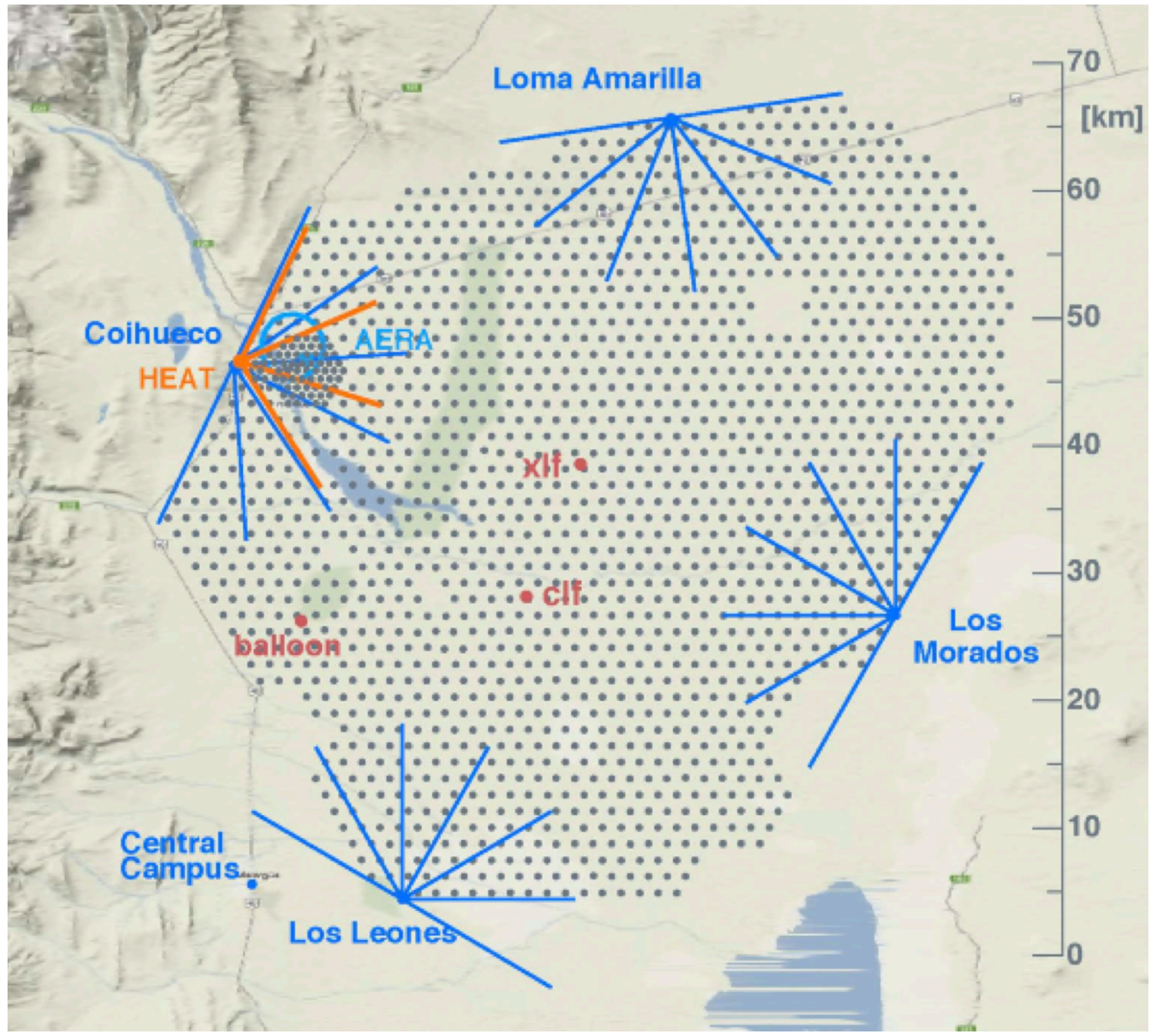


- Cosmic-ray induced cascade of particles in the atmosphere: Extensive Air Shower (EAS)
    - Electromagnetic component
    - Muonic component
    - Hadronic component

MEASUREMENTS AT UHE

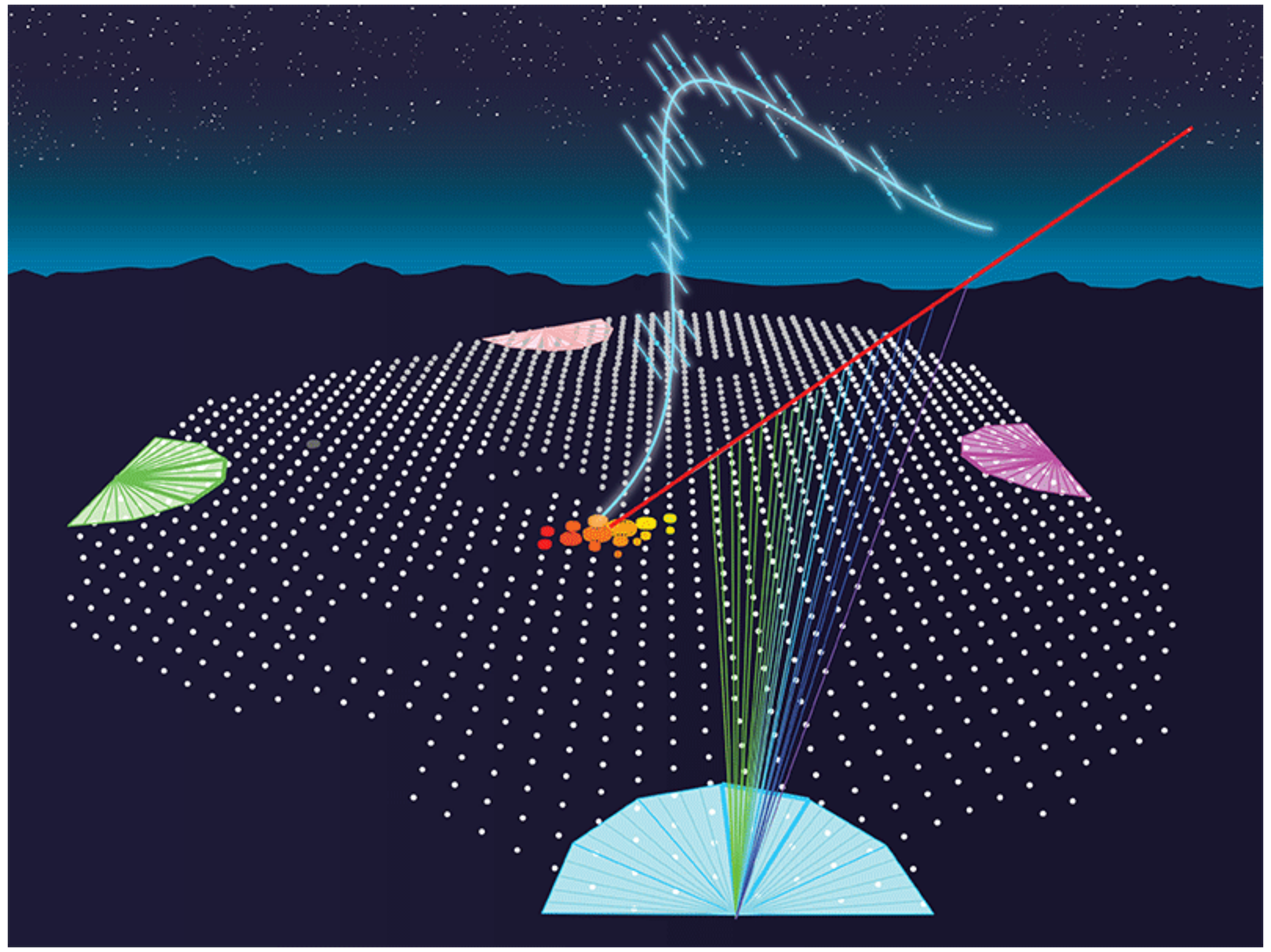
PARTICLE DETECTOR ARRAYS

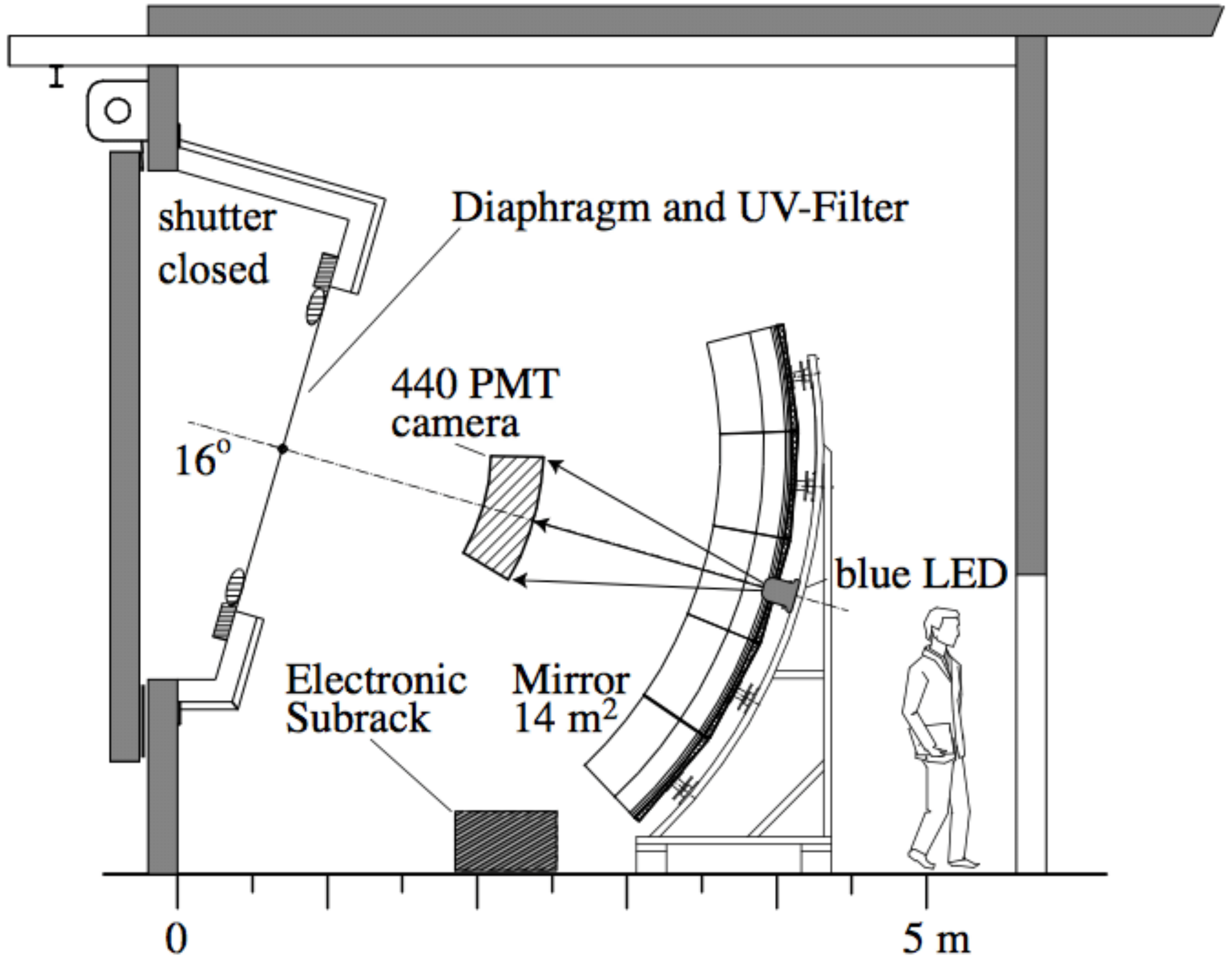
- Set of detectors arranged in a regular pattern
- Showers detected by searching for time coincidences of signals in neighbouring stations
- Depending on the energy range of interest, the distance between the detector stations can vary from tens of m to km



MEASUREMENTS AT UHE

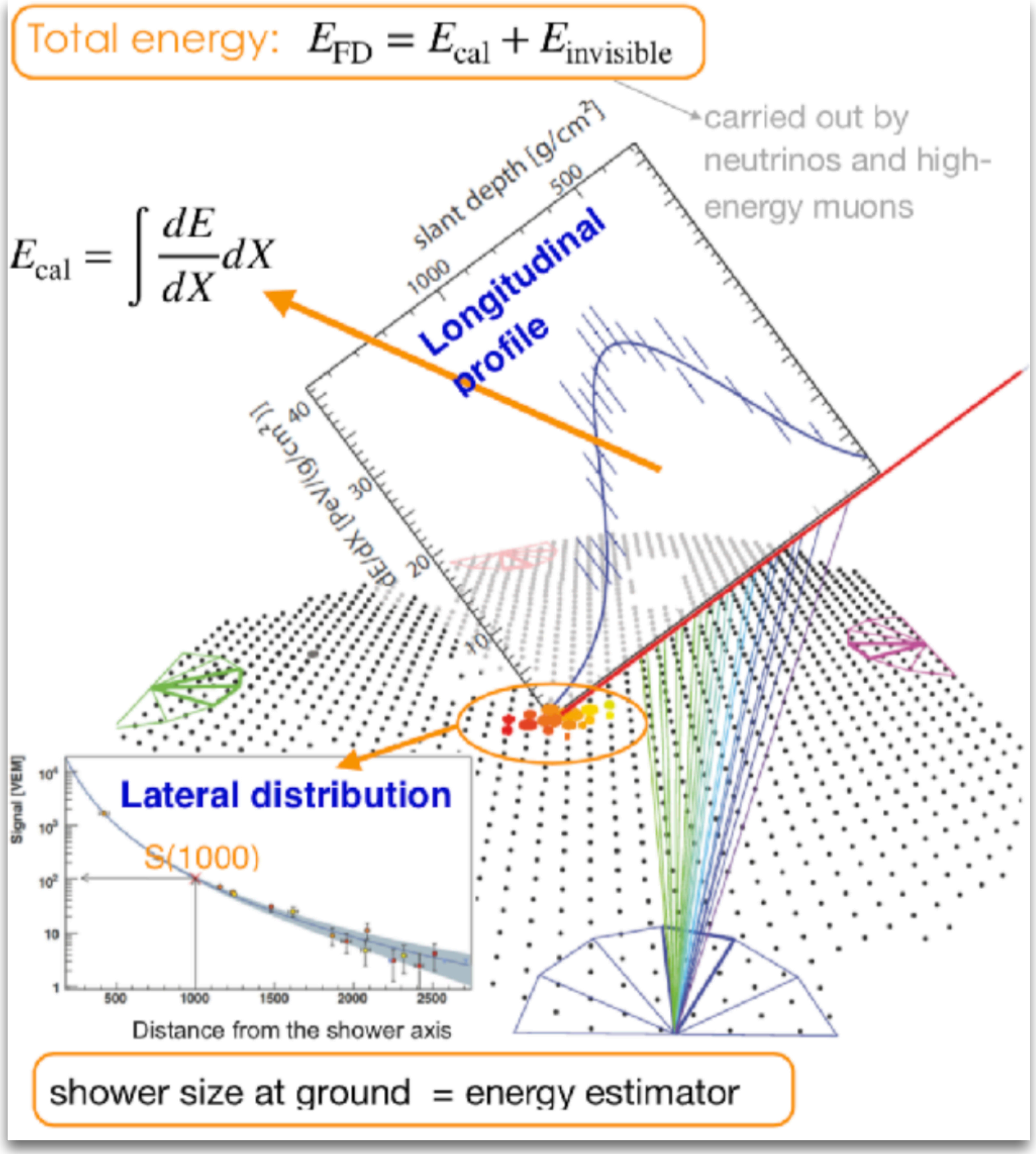
FLUORESCENCE DETECTORS





- Nitrogen molecules in the atmosphere are excited by charged particles in the shower
- De-excitation and change of vibrational and rotational states of the molecules lead to fluorescence emission

MEASUREMENTS AT UHE



Total energy: $E_{\mathrm{FD}} = E_{\mathrm{cal}} + E_{\mathrm{invisible}}$

carried out by neutrinos and high-energy muons

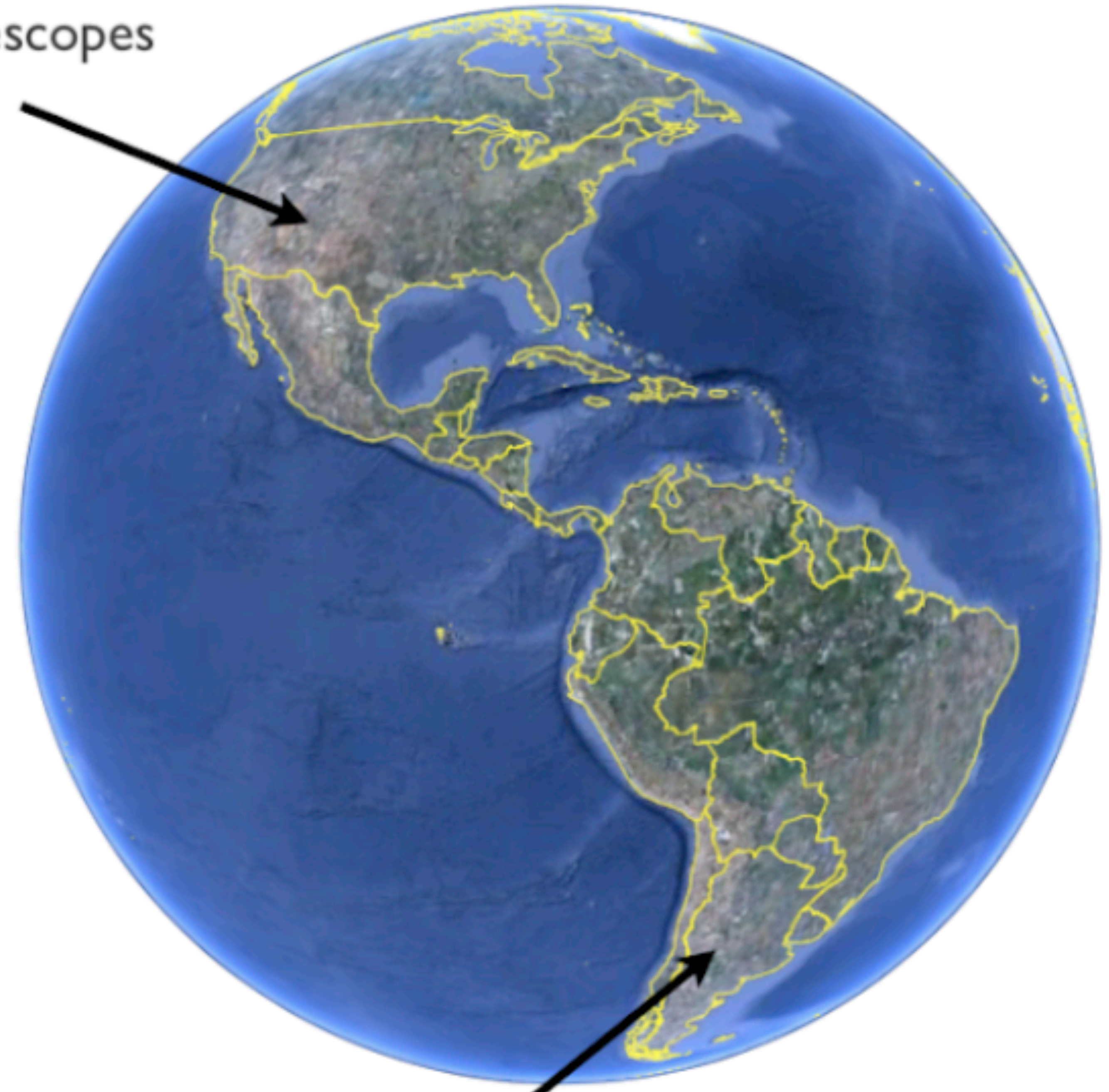
$$E_{\mathrm{cal}} = \int \frac{dE}{dX} dX$$

Longitudinal profile

Lateral distribution

shower size at ground = energy estimator

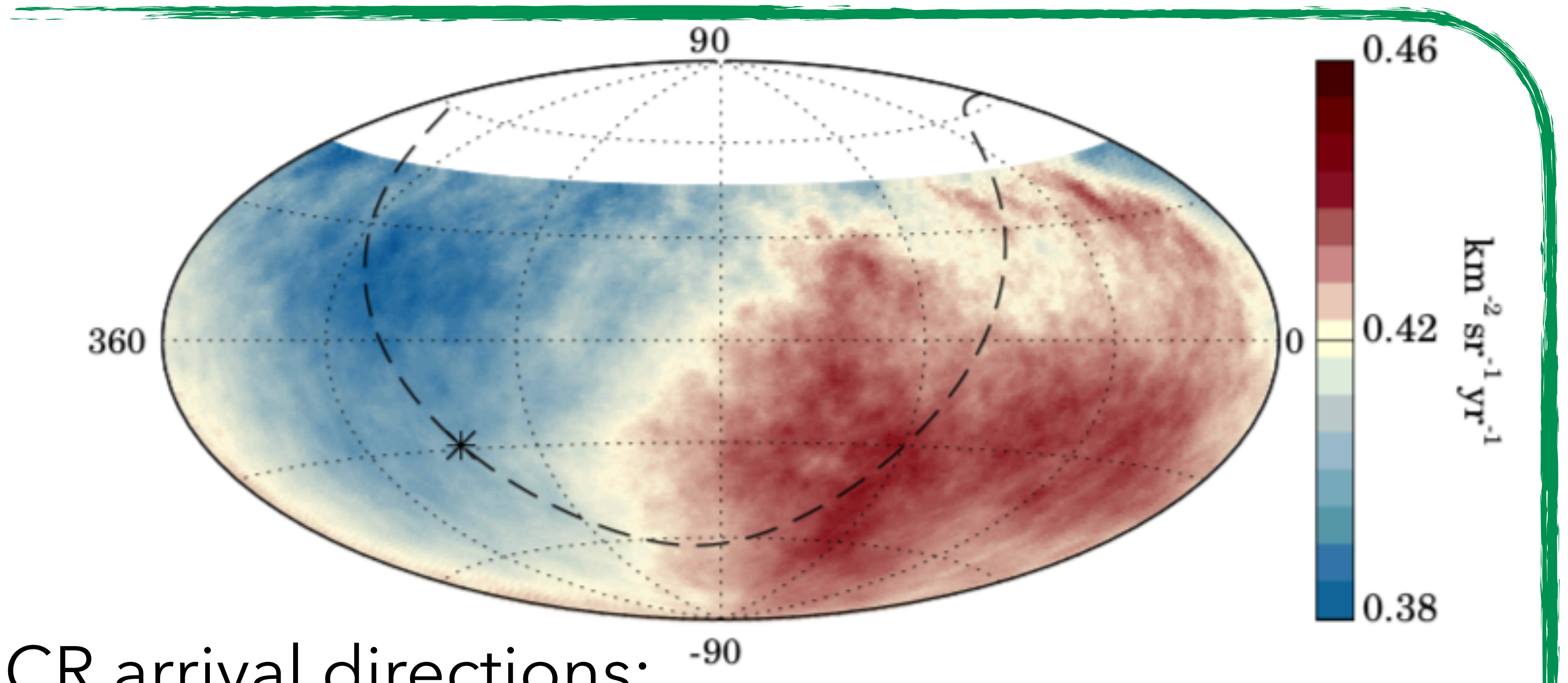
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes



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

UHECRs at the Pierre Auger Observatory

Collection of results from ICRC 2021

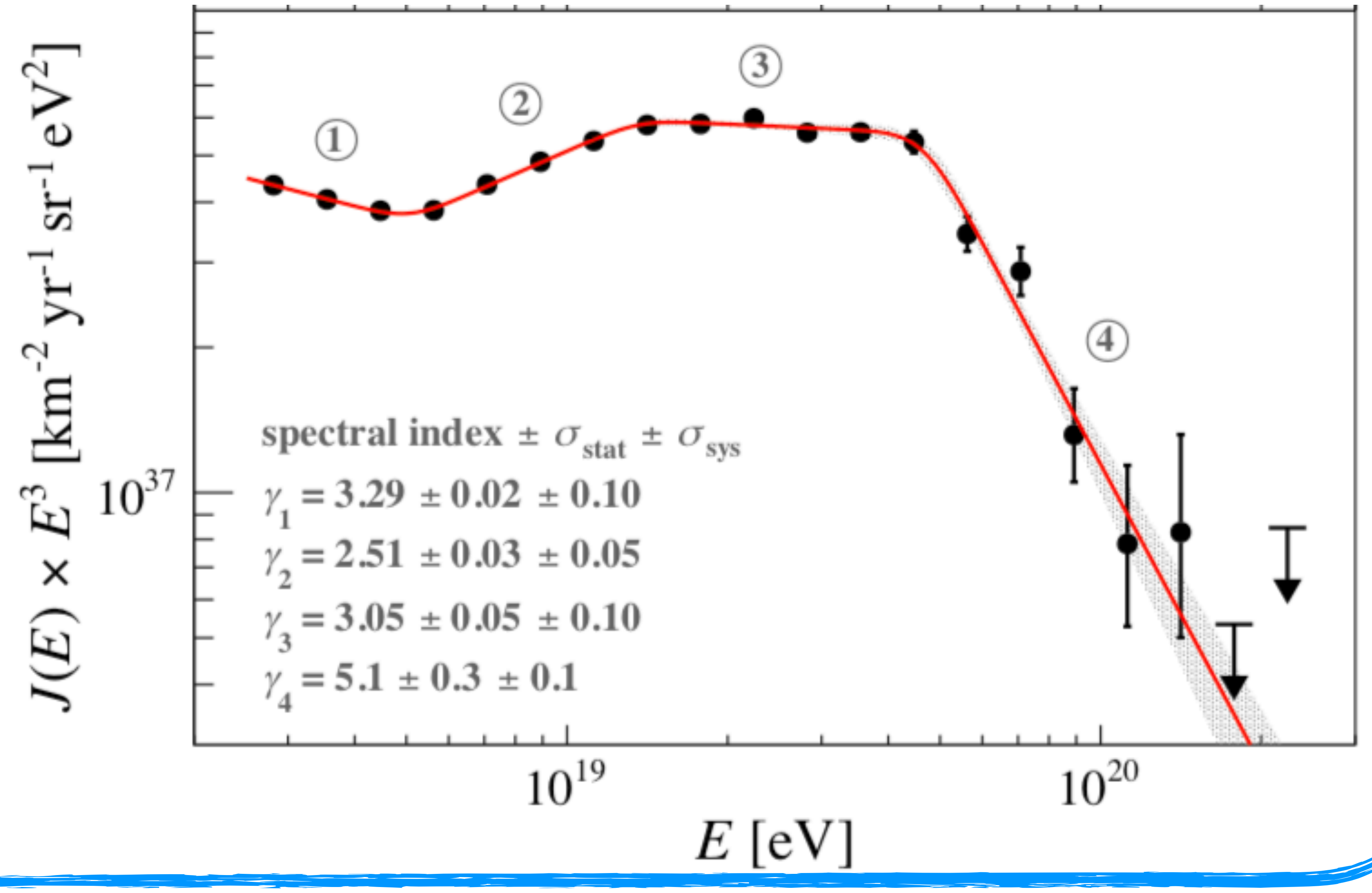


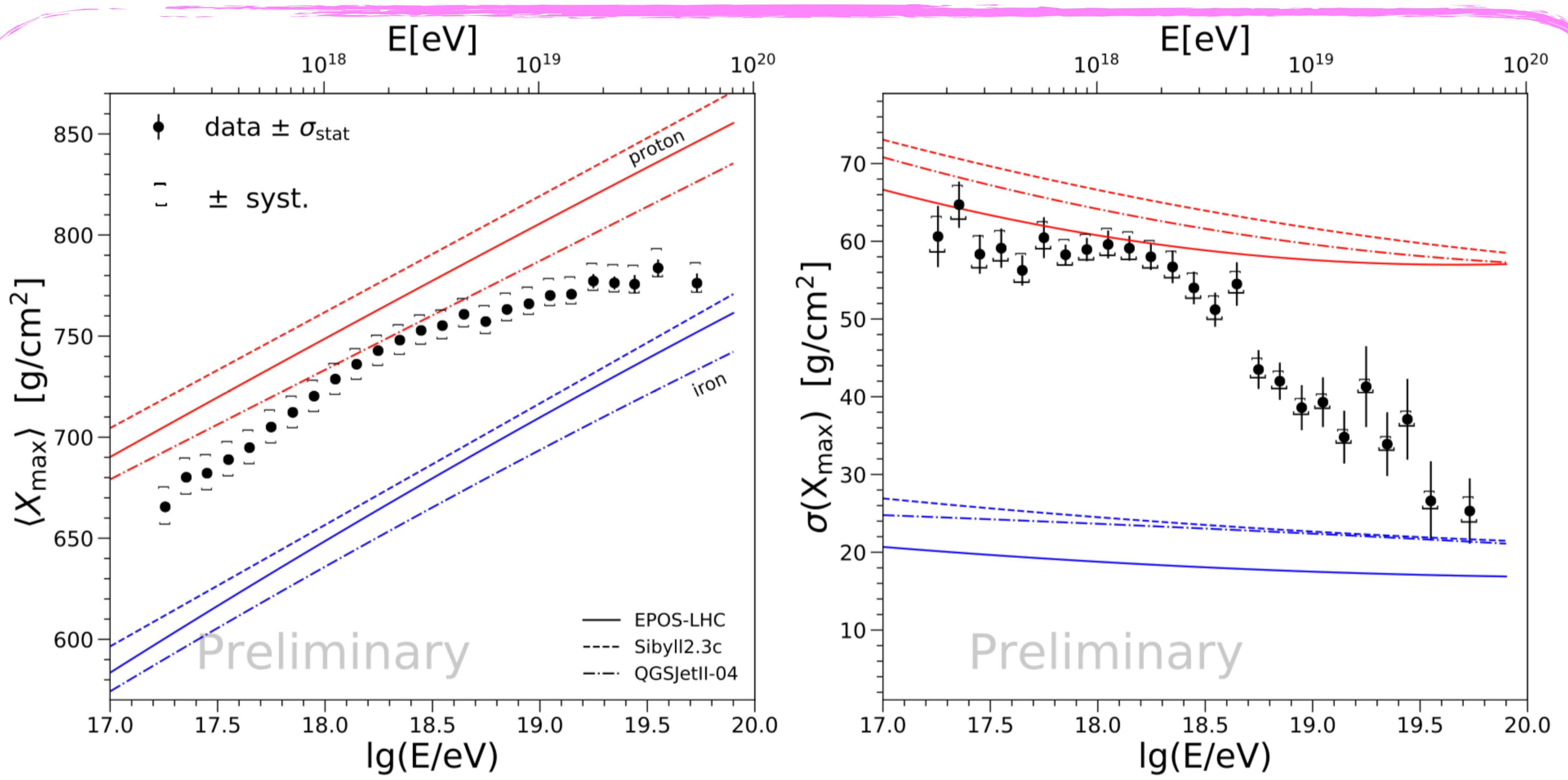
UHECR arrival directions;

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

UHECR spectrum;

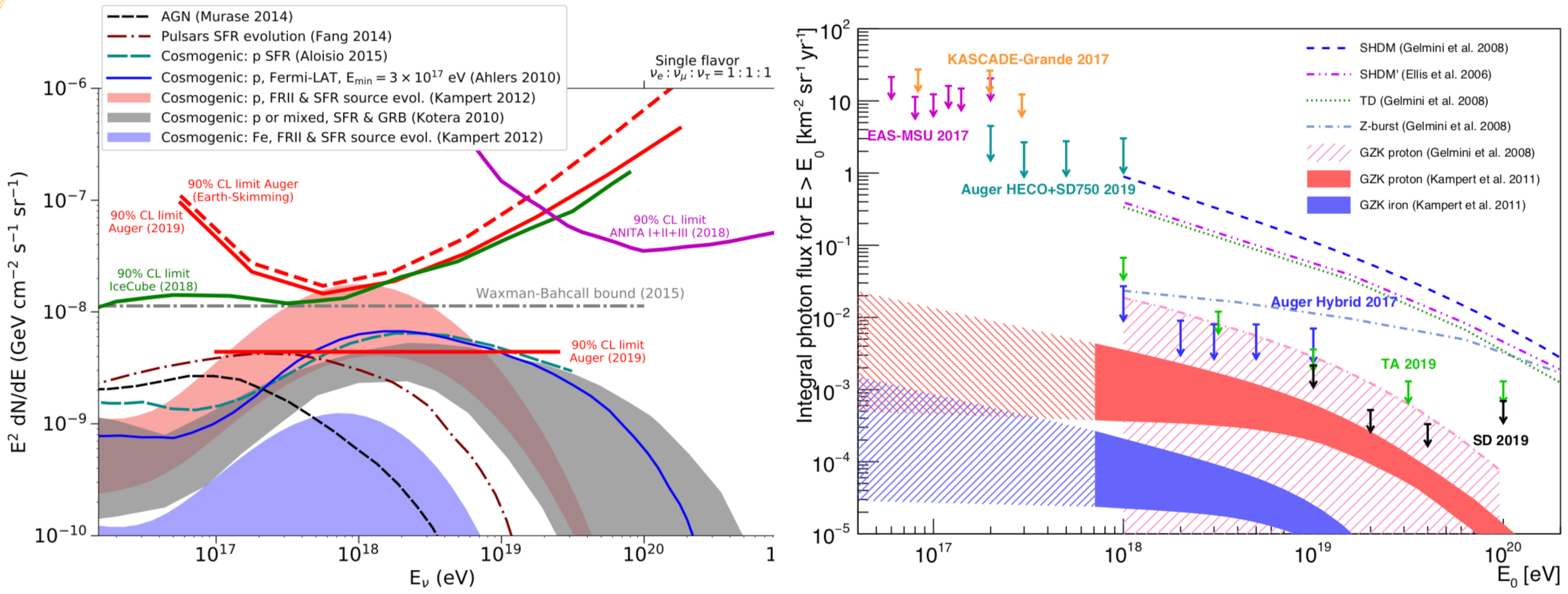
- changes of slope
- suppression





UHECR mass composition;

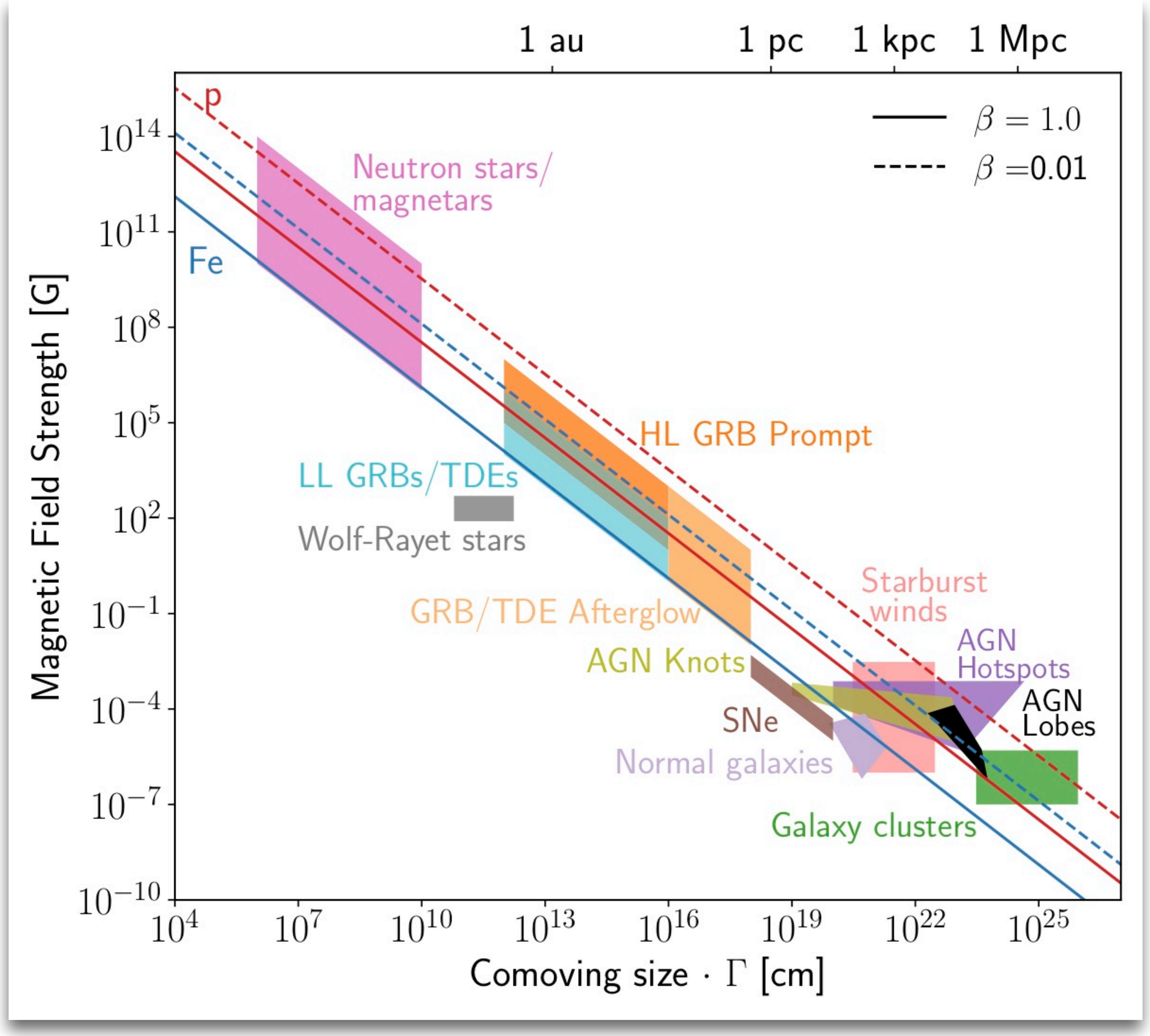
- Mass composition changes with energy
- Fluctuations decrease



Limits on secondary messengers

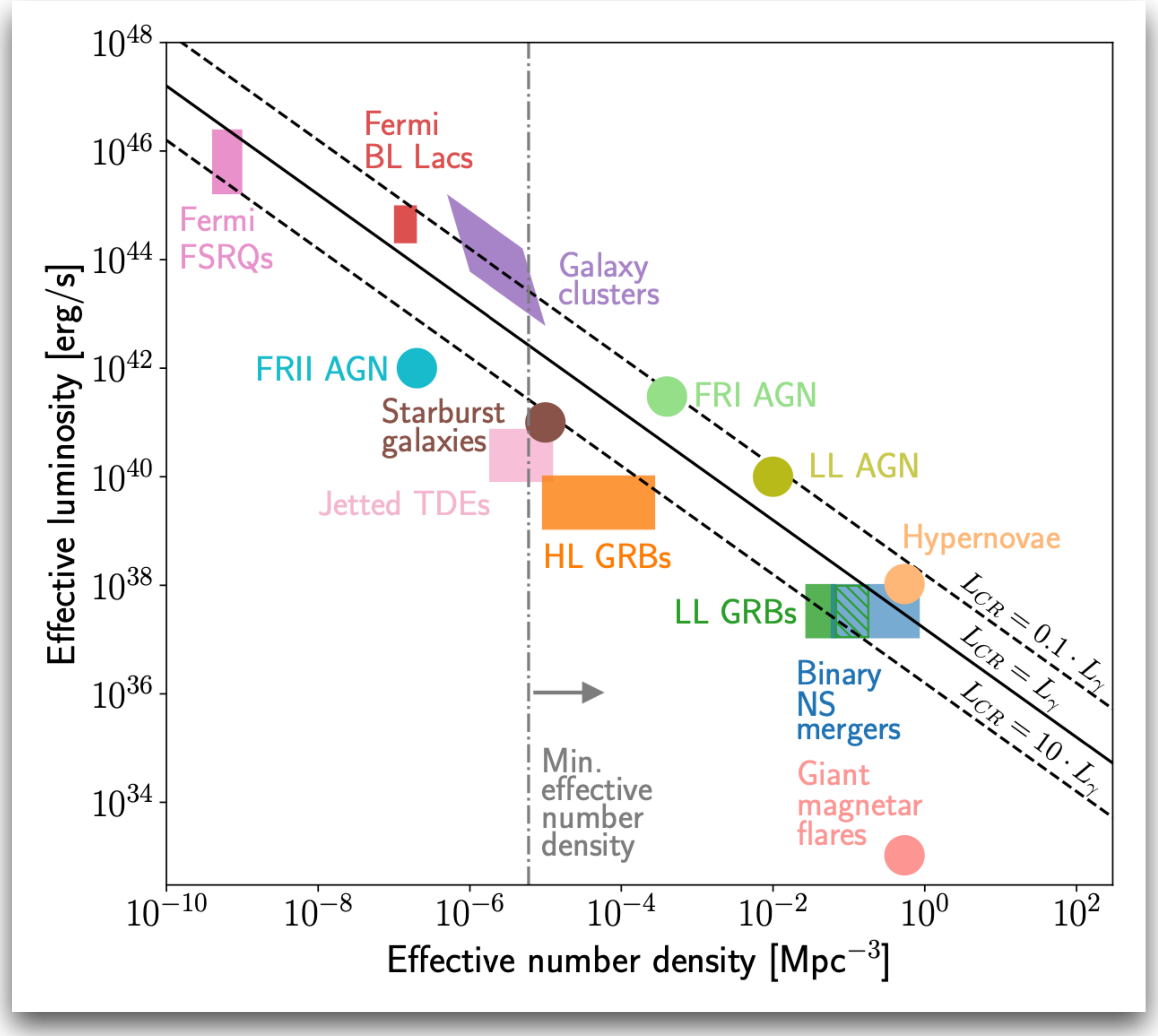
THE COSMIC-RAY ACCELERATORS

Alves Batista et al, 2019



- Required energy budget to produce observed UHECRs

$$\varepsilon = L_{\rm CR} n$$

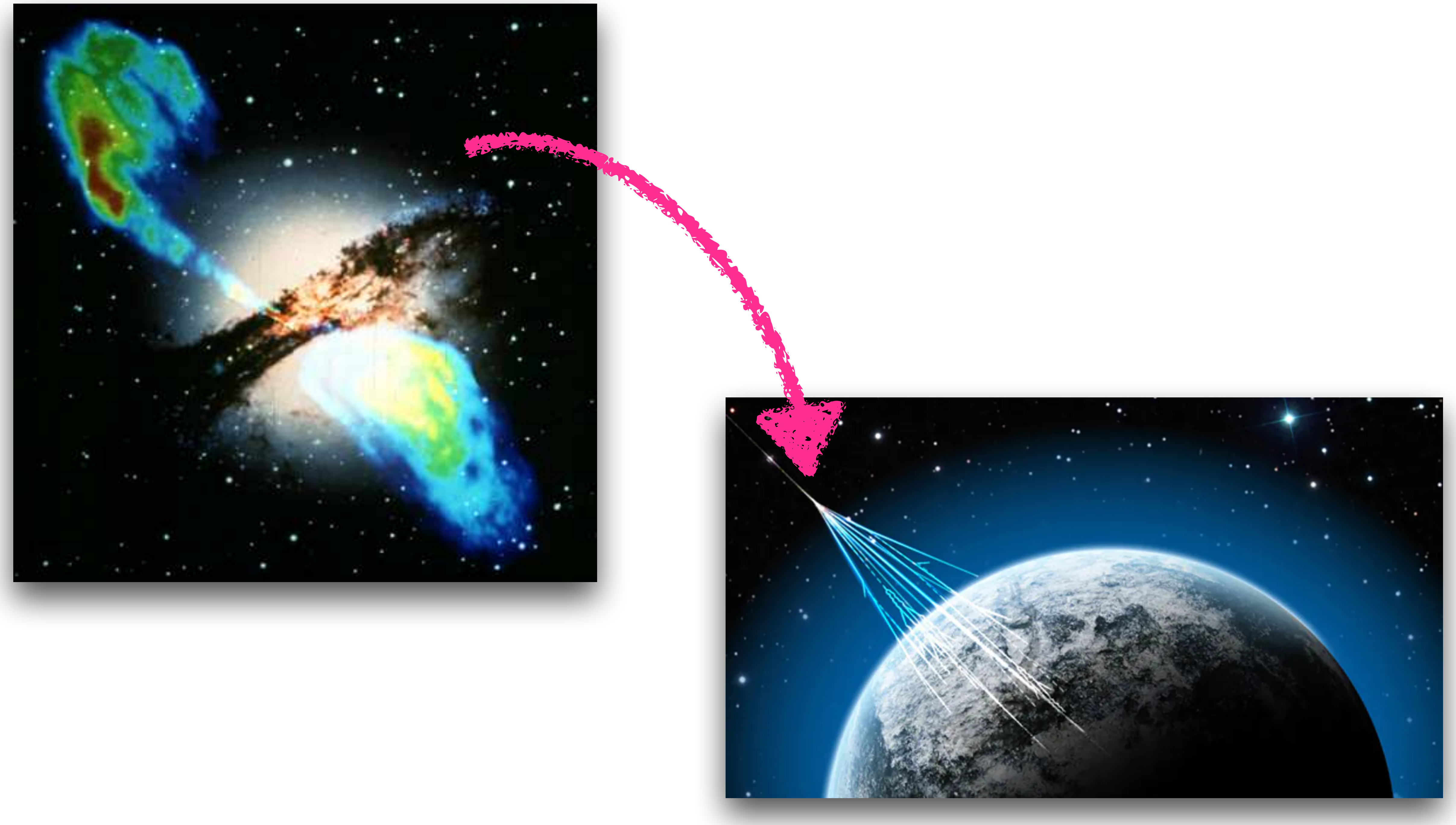


- Max energy is limited by the gyroradius of the accelerator
- Accelerators can be classified thanks to magnetic field and size

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

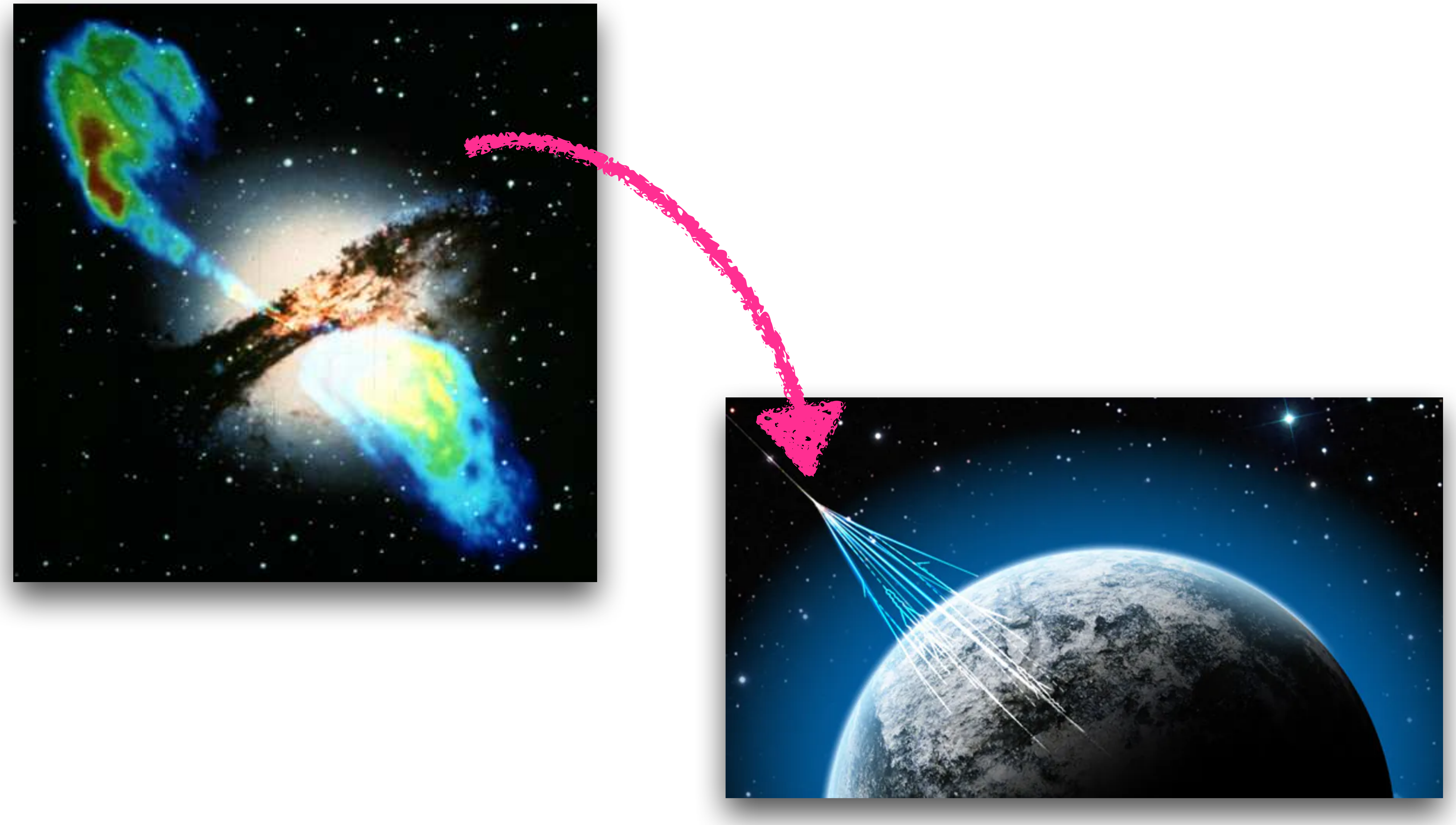
Hillas 1984

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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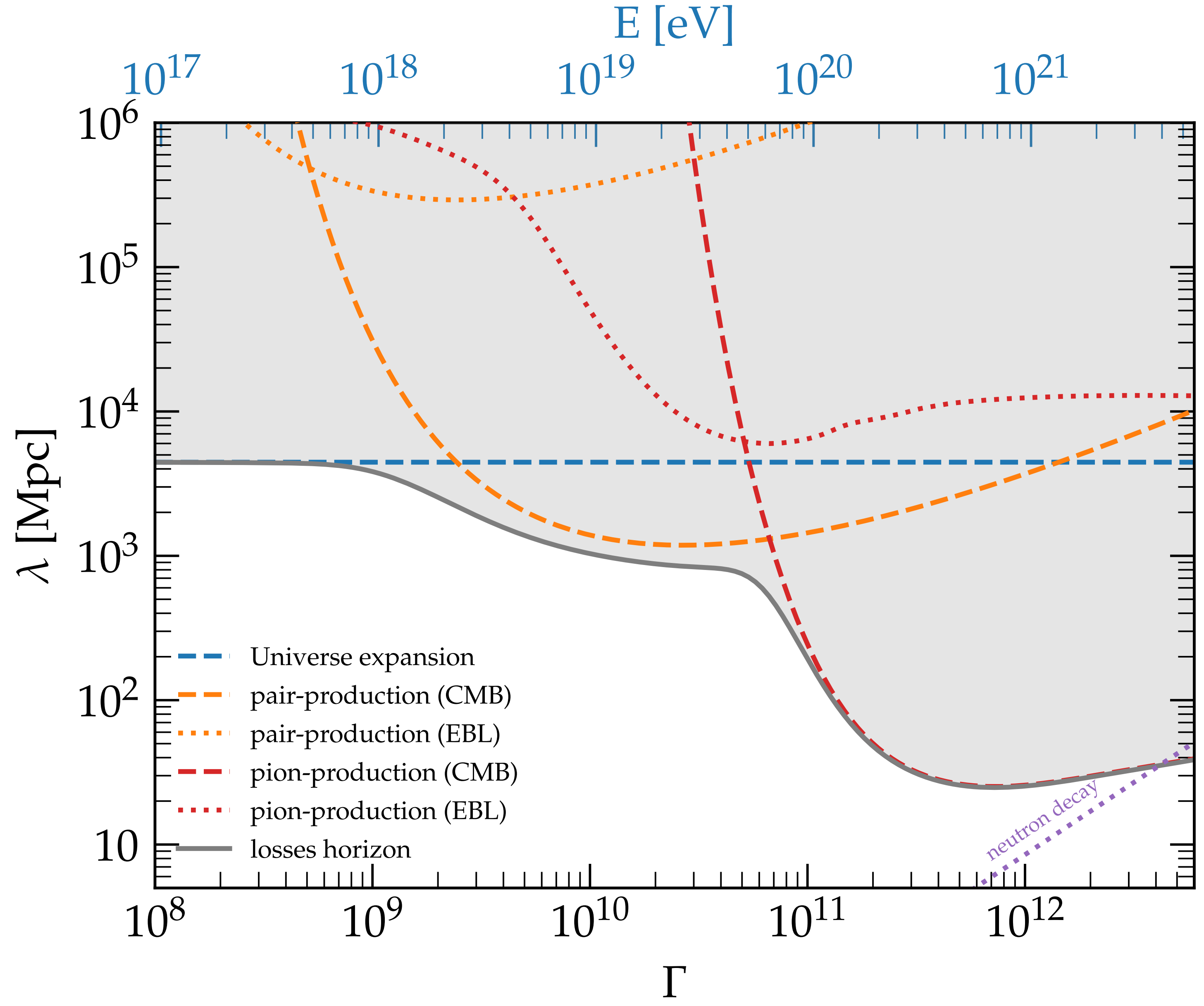
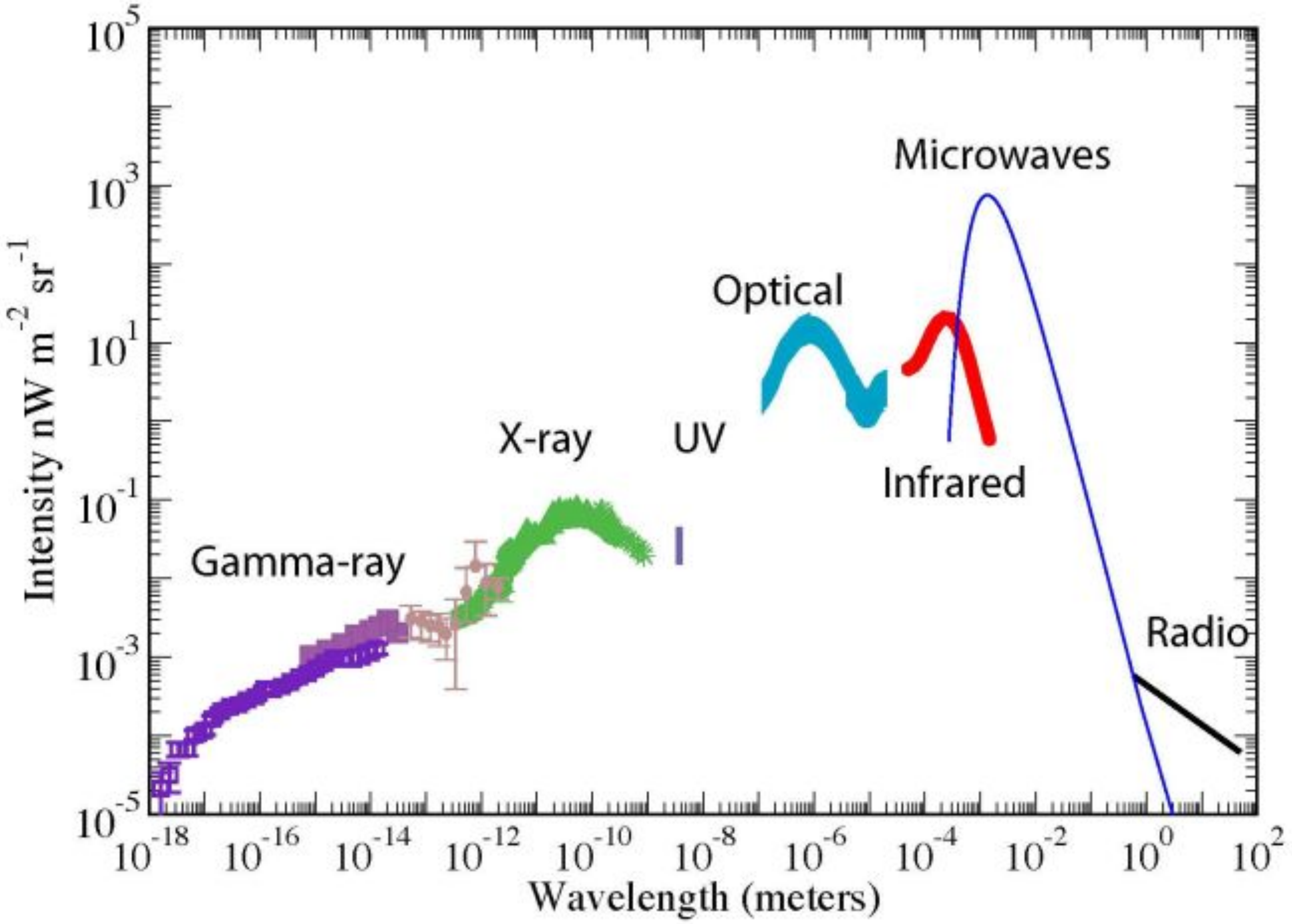
Example: photo-pion production



- 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**

UHECR PROPAGATION

INGREDIENT (1): ASTROPHYSICS



$$p + \gamma_{\mathrm{bkg}} \to \dots$$

$$A + \gamma_{\mathrm{bkg}} \to \dots$$

$$\gamma + \gamma_{\mathrm{bkg}} \to \dots$$

- 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:

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

INGREDIENT (2): NUCLEAR PHYSICS

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

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

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

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

$$\left.\begin{array}{l} \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{array}\right\}$$

Source of cosmogenic neutrinos

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

$$\left.\pi^0 \rightarrow \gamma + \gamma\right\}$$

Source of cosmogenic gamma rays

UHECR nucleons & nuclei

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

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

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

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

UHECR nuclei

INGREDIENT (2): NUCLEAR PHYSICS

- 1965, discovery of CMB
- Greisen, Zatsepin and Kuzmin: cosmic ray particles interact with CMB photons through $p + \gamma_{\rm bkg} \rightarrow \pi^0 + p$
  - Energy loss of protons -> end of the CR flux at the highest energies?

$$\boxed{E_{\rm th} = \frac{m_\pi^2 + 2m_\pi m_p}{2\varepsilon(1-\cos\theta)} \approx 7 \times 10^{19}\,{\rm eV}}$$

Greisen, PRL 1966;

Zatsepin & Kuzmin, JETP Lett 1966

The energy thresholds can be easily computed from the **s** of the reaction as:

$$s_{\rm th} = (\varepsilon + E_p)^2 - (\vec{p}_\gamma + \vec{p}_p)^2 = (m_p + m_\pi)^2$$

- Bethe-Heitler pair production

$$\boxed{E_{\rm th} = \frac{4m_e^2 + 8m_e m_p}{2\varepsilon(1-\cos\theta)} \approx 6 \times 10^{17}\,{\rm eV}}$$

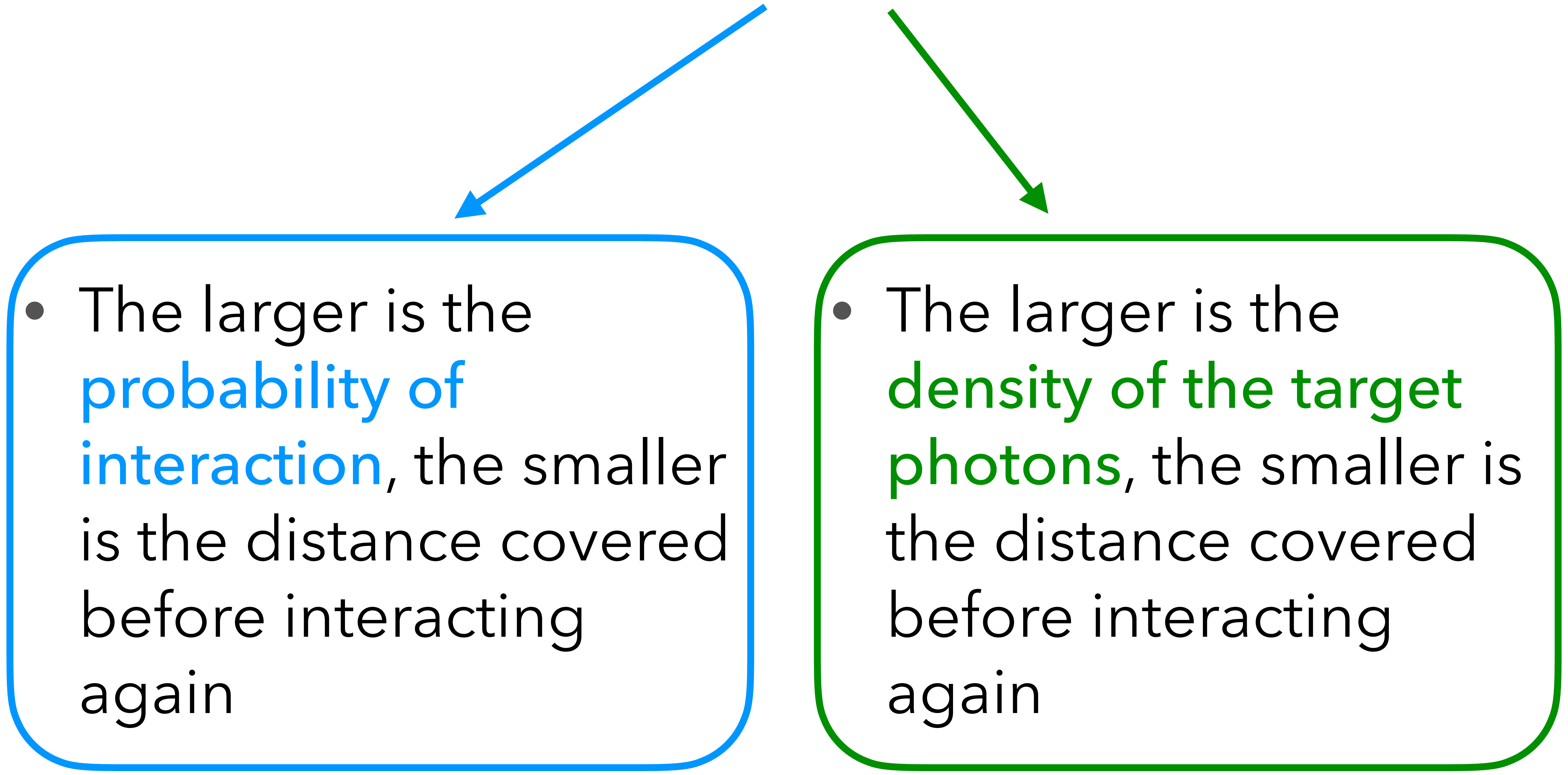
Blumenthal, PRD 1970

INTERACTIONS OF COSMIC-RAY NUCLEI

Relevant quantities for the computation of losses:

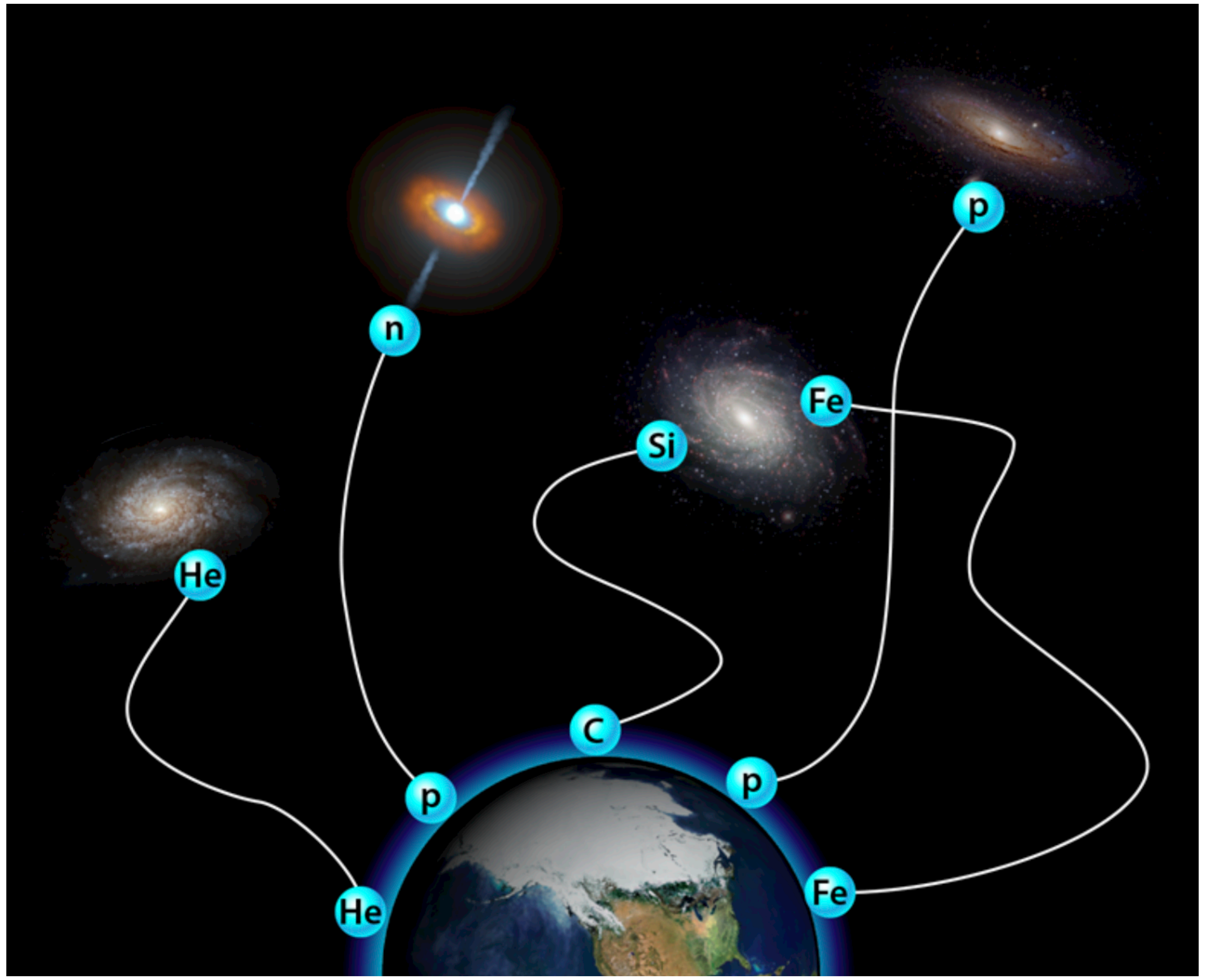
- Photon fields
- Cross sections

$$\tau \approx \frac{1}{c\,\sigma\,n}$$



- The larger is the probability of interaction, the smaller is the distance covered before interacting again

- The larger is the density of the target photons, the smaller is the distance covered before interacting again



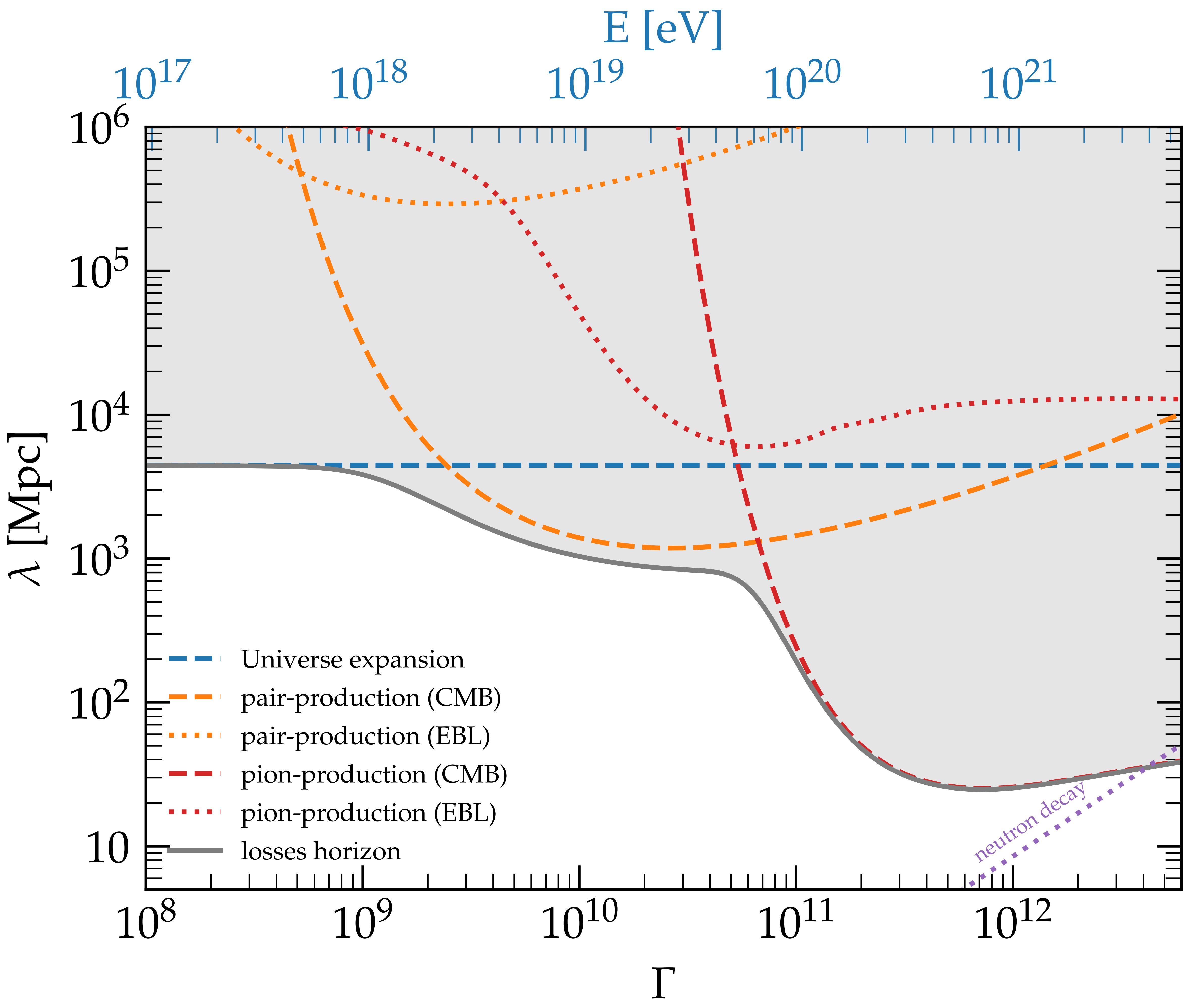
ENERGY LOSS LENGTH - PROTONS

$$\frac{dN_{\mathrm{int}}}{dt} = c\int (1-\cos\theta)\, n_\gamma(\varepsilon,\cos\theta)\,\sigma(\varepsilon')\, d\cos\theta\, d\varepsilon$$

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

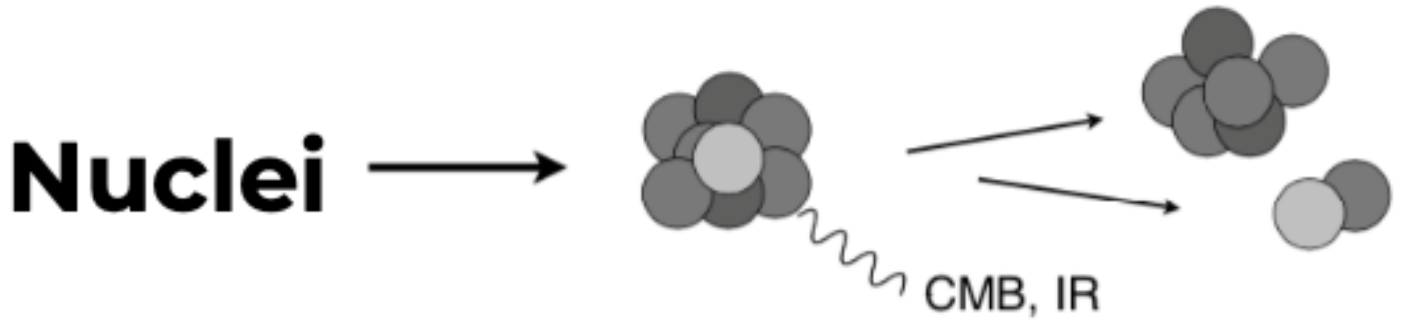
$$\frac{1}{E}\frac{dE}{dt} = -\,H_0$$

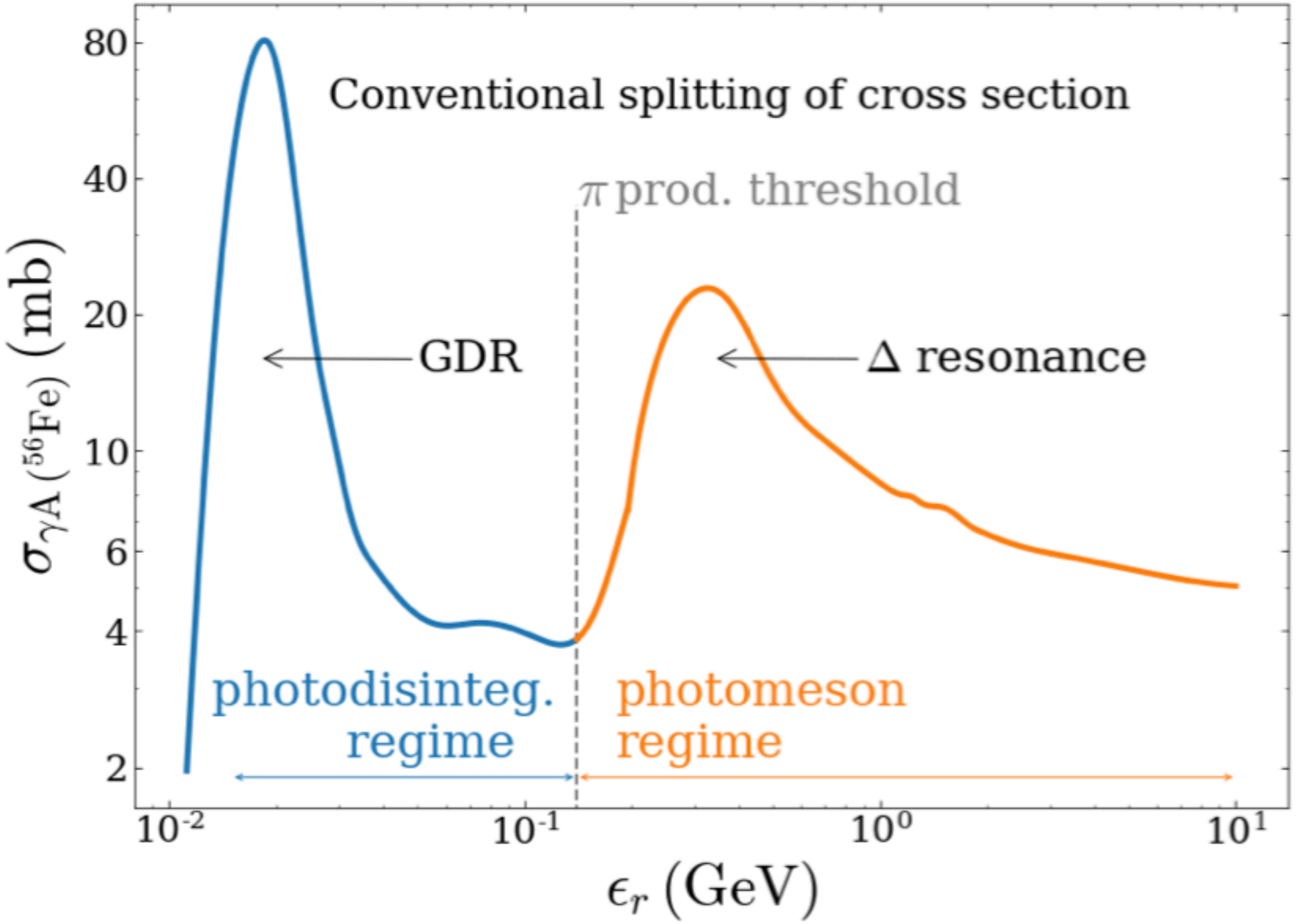
$$\frac{1}{E}\frac{dE}{dt} = -\,\frac{c}{2\Gamma^2}\int_{\varepsilon'_{\mathrm{th}}}^{\infty}\varepsilon' f(\varepsilon')\sigma(\varepsilon')\int_{\varepsilon'/2\Gamma}^{\infty}\frac{n_\gamma(\varepsilon)}{\varepsilon^2}d\varepsilon d\varepsilon'$$



Plot by C. Evoli

PHOTO-DISINTEGRATION

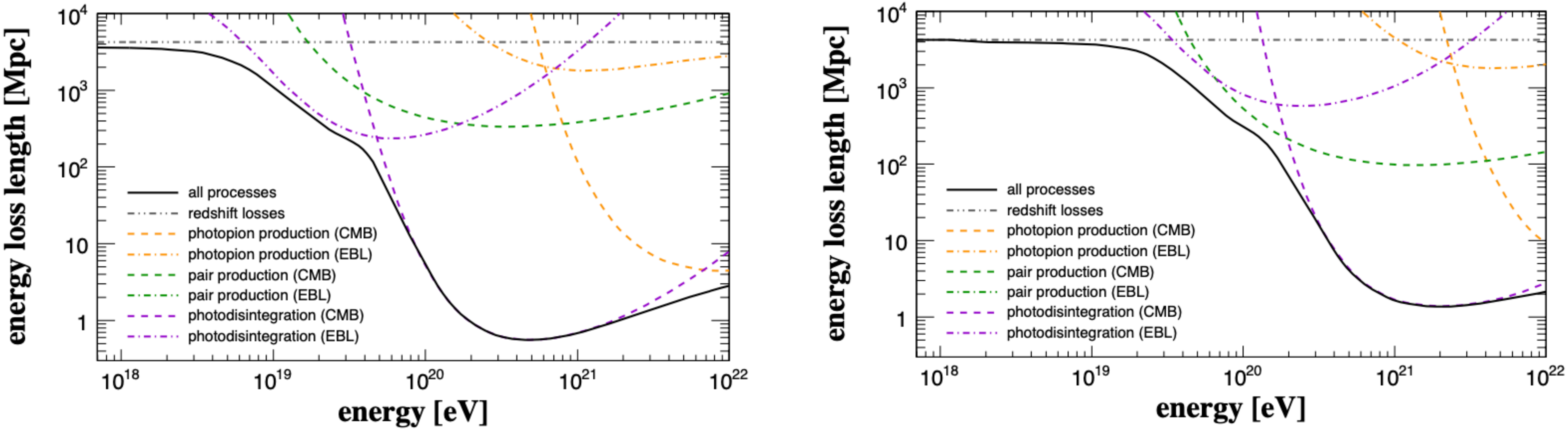




- Regimes
  - Giant Dipole Resonance (GDR): protons and neutrons can be considered as penetrating fluids; absorption of photons determines vibrations; 8 MeV; ejection of one/two nucleons
  - Quasi-Deuteron (QD), 20-150 MeV: the photon wavelength becomes comparable with the nuclear dimensions; photon interacts with nucleon pair; ejection of pair + possibly other nucleons
- Conservation of Lorentz factor

ENERGY LOSS LENGTH - NUCLEI

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



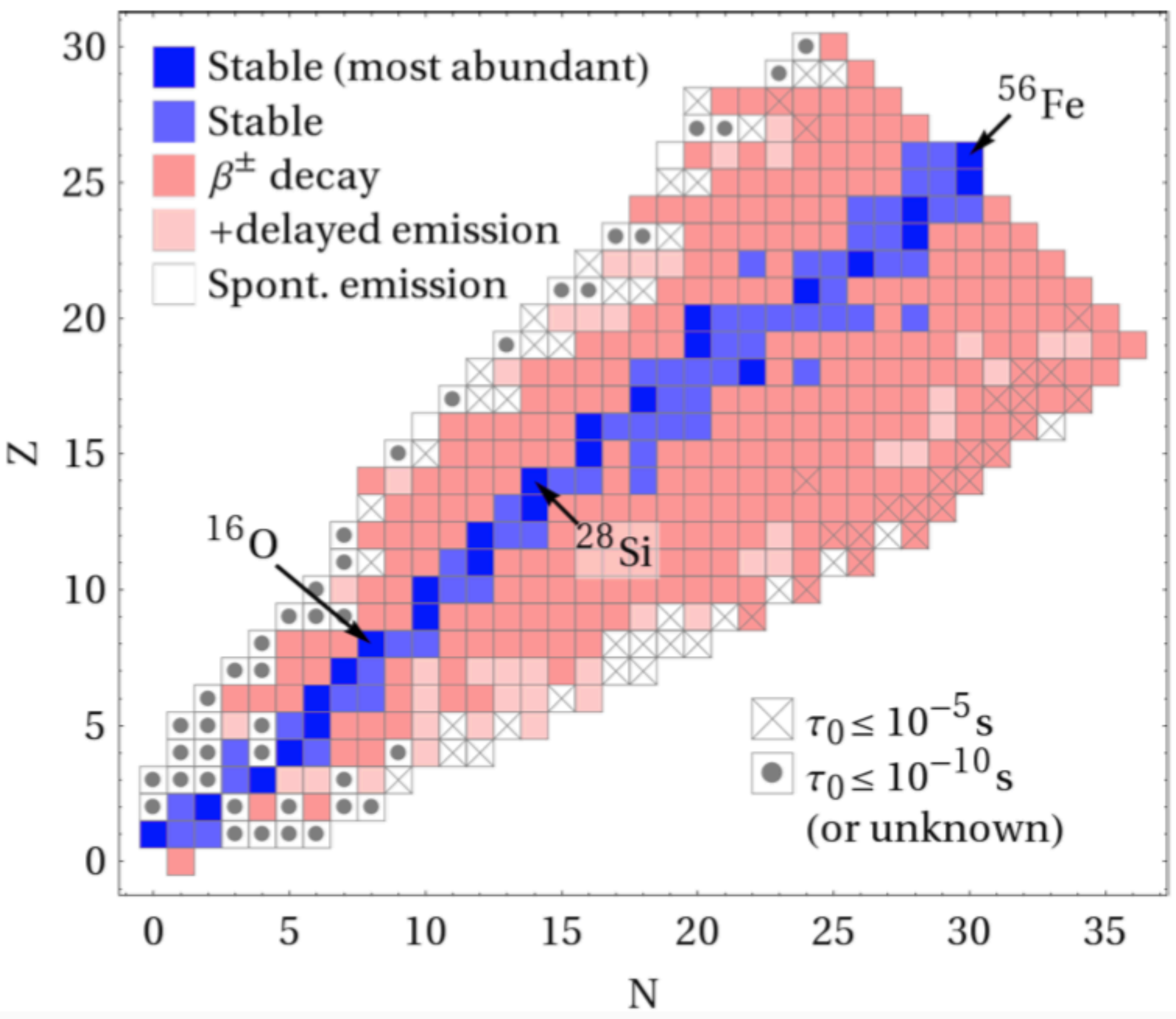
COMPUTING COSMIC-RAY PROPAGATION

Aloisio, Berezinsky & Grigorieva, Astropart.Phys. 2013

$$\frac{\partial n_{A_0}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}[n_{A_0}(\Gamma,t) b_{A_0}(\Gamma,t)] + \frac{n_{A_0}(\Gamma,t)}{\tau_{A_0}(\Gamma,t)} = Q_{A_0}(\Gamma,t)$$

$$\frac{\partial n_{A_0-1}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}[n_{A_0-1}(\Gamma,t) b_{A_0-1}(\Gamma,t)] + \frac{n_{A_0-1}(\Gamma,t)}{\tau_{A_0-1}(\Gamma,t)} = \frac{n_{A_0}(\Gamma,t)}{\tau_{A_0}(\Gamma,t)}$$

$$\frac{\partial n_{A}(\Gamma,t)}{\partial t} - \frac{\partial}{\partial \Gamma}[n_{A}(\Gamma,t) b_{A}(\Gamma,t)] + \frac{n_{A}(\Gamma,t)}{\tau(\Gamma,t)} = \frac{n_{A+1}(\Gamma,t)}{\tau_{A+1}(\Gamma,t)}$$



COMPUTING COSMIC-RAY PROPAGATION

Treatment of (extragalactic) propagation → analytical and MC codes available:

- **SimProp**, Aloisio, **DB**, di Matteo, Grillo, Petrera, Salamida (last update) JCAP 2017
- **CRPropa 3**, Alves Batista, Dundovic, Erdmann, Kampert, Kuempel, Müller, Sigl, van Vliet, Walz, Winchen, JCAP 2016
- **TransportCR**, Kalashev & Kido, J.Exp.Theor.Phys 2016
- **HERMES**, De Domenico, J.Exp.Theor.Phys 2013
- **PRINCE**, Heinze, Fedynitch, **DB** & Winter 2019
- Other (private) codes:
  - Allard, A&A 2005
  - Hooper, Sarkar, Taylor, Astropart. Phys. 2007
  - Aloisio, Berezinsky, Grigorieva, Astropart. Phys. 2013

Work in progress for updates and improvements !

IMPLICATIONS ON UHECR CHARACTERISTICS

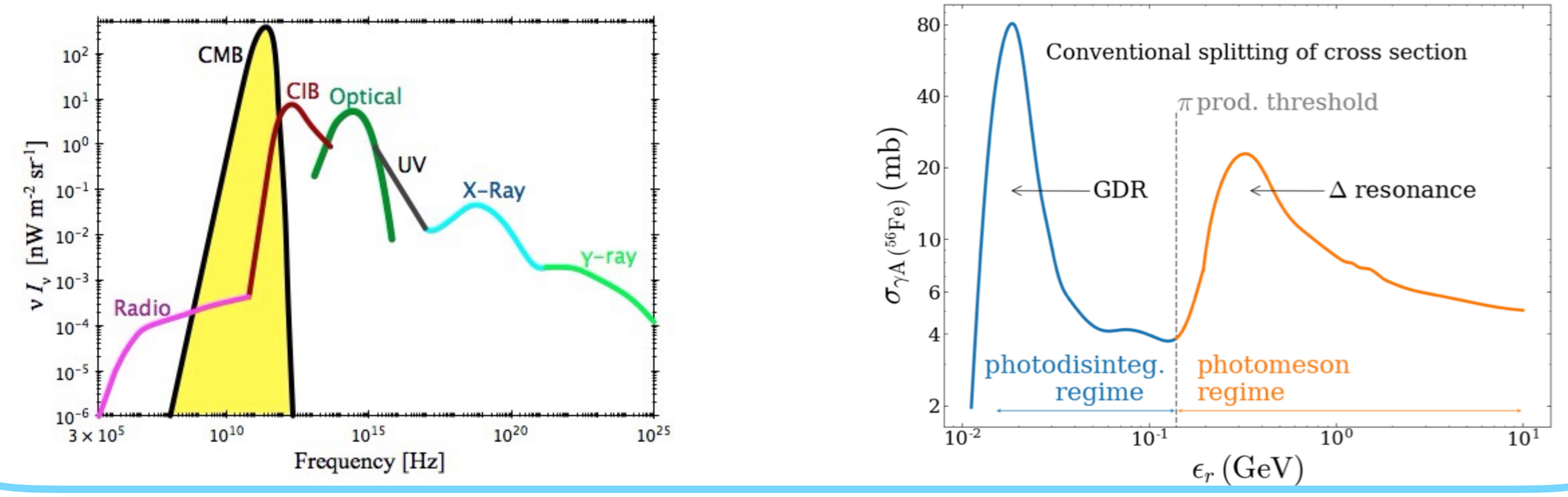
COMBINED SPECTRUM AND COMPOSITION FIT

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

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

×

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



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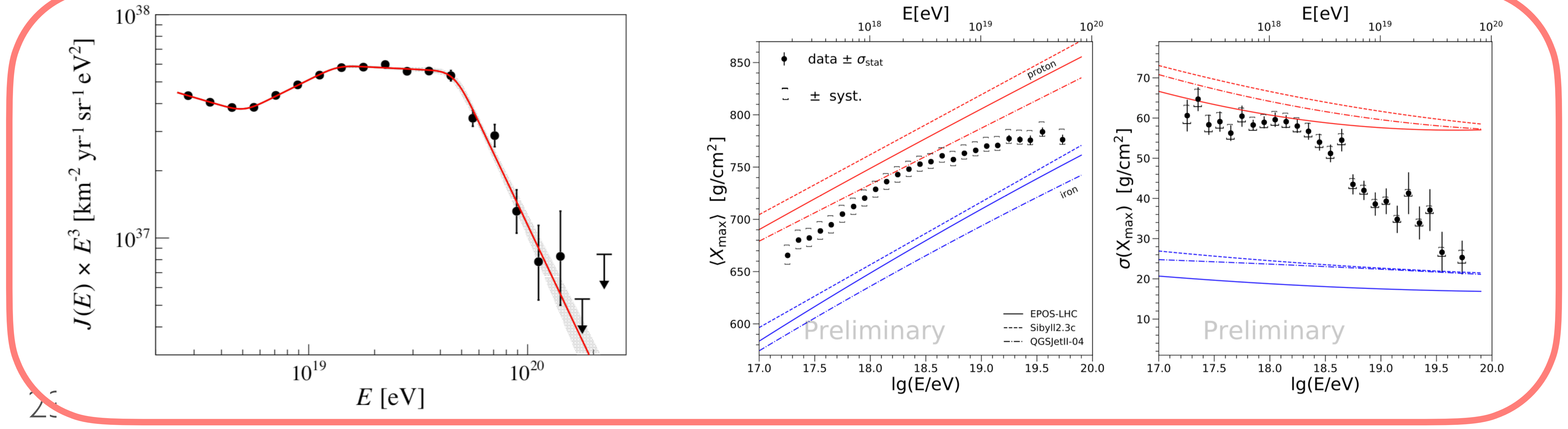
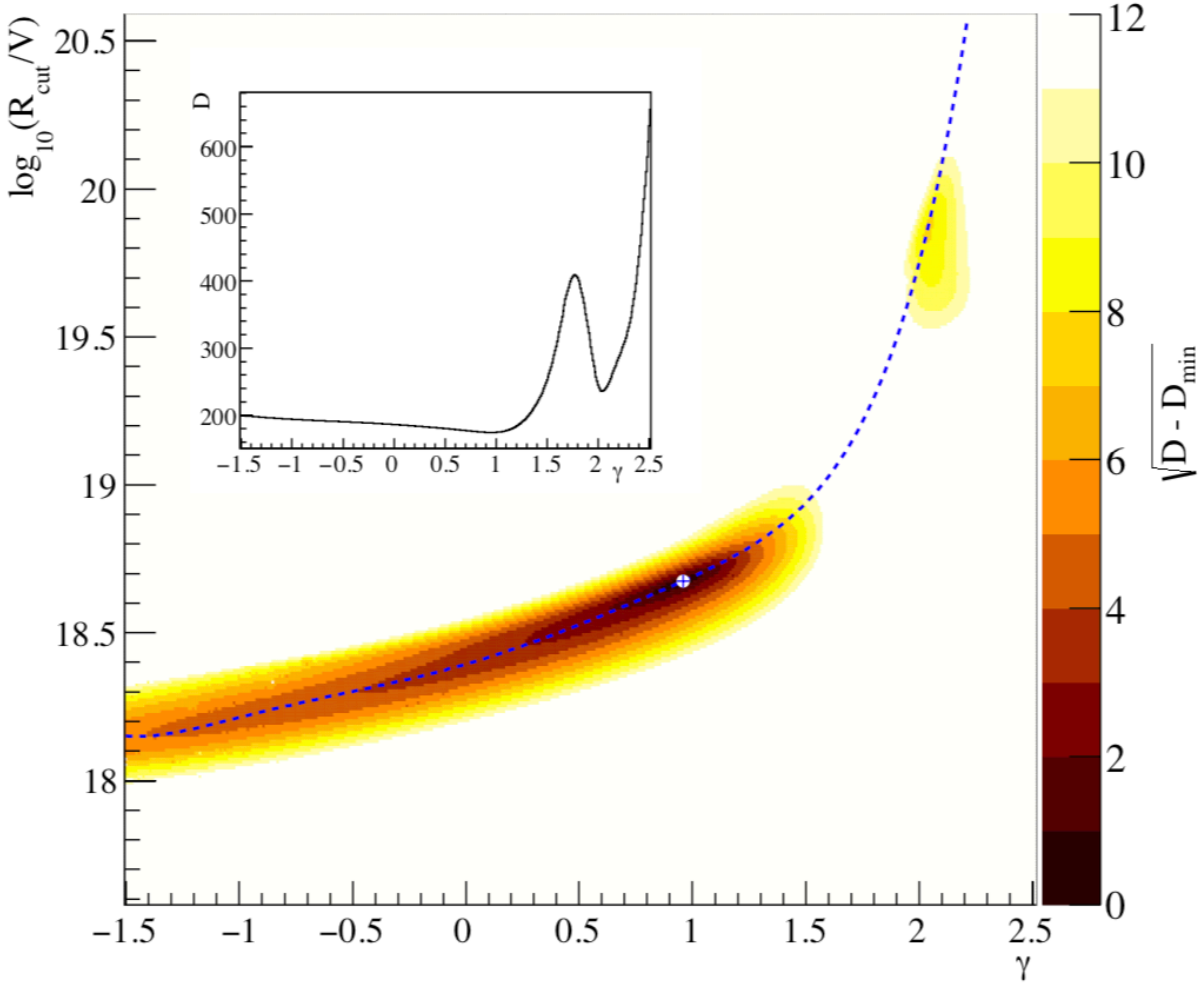
- Fit of energy spectrum and composition

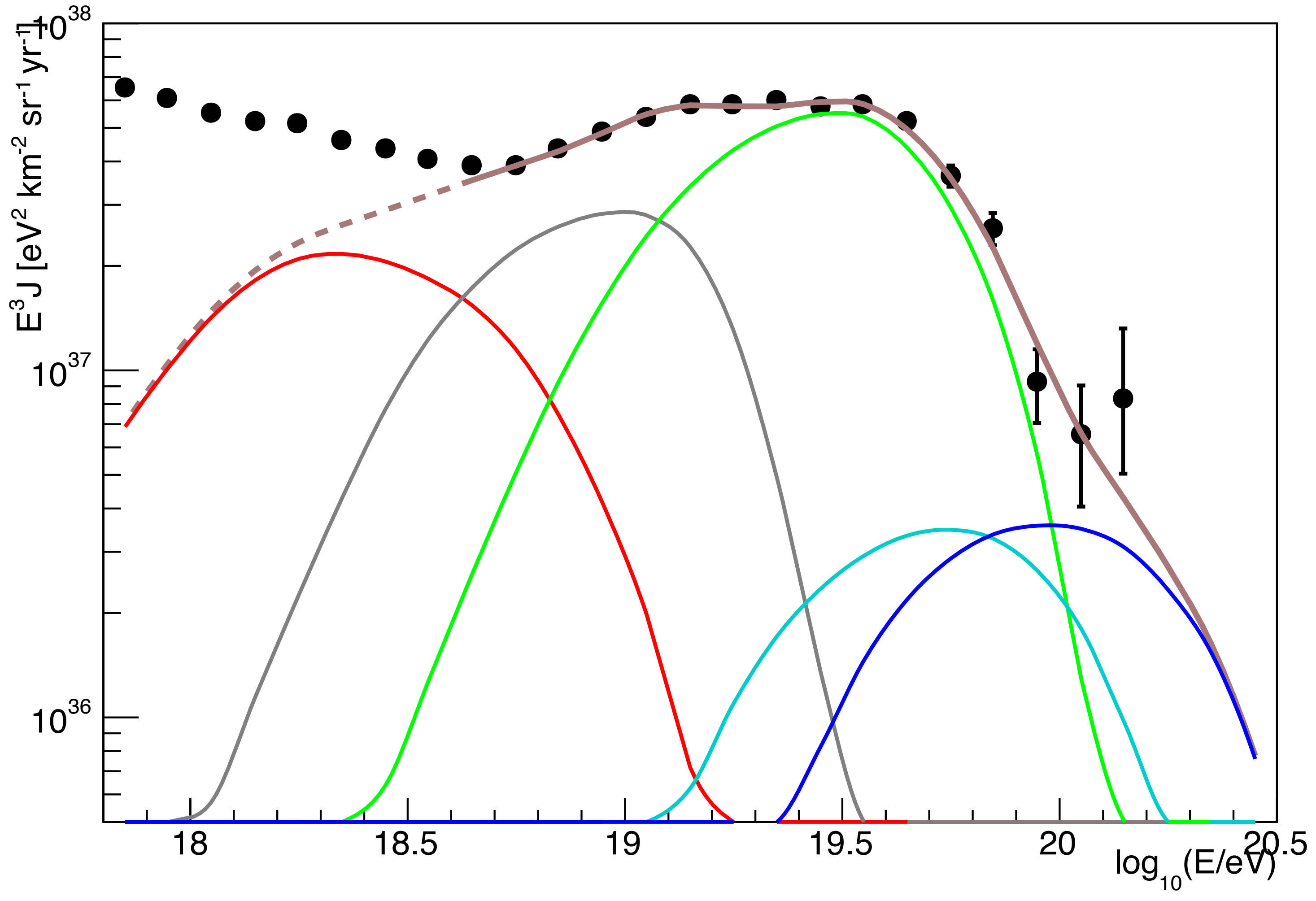


COMBINED SPECTRUM AND COMPOSITION FIT

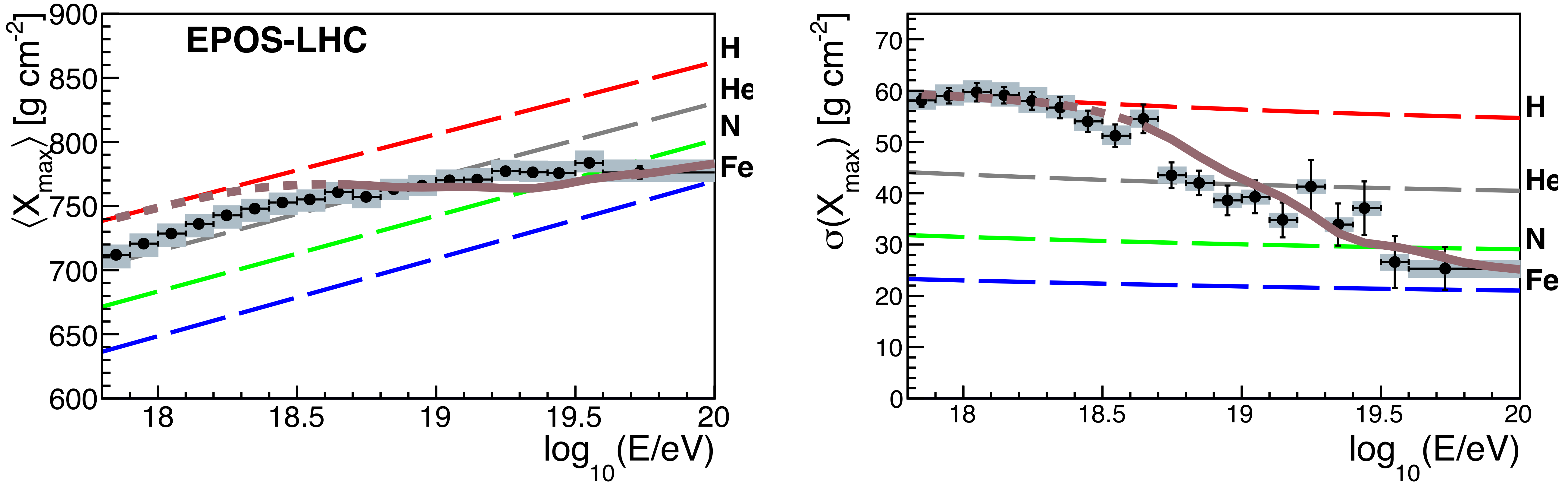
Auger, JCAP 2017



- 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)

COMBINED SPECTRUM AND COMPOSITION FIT

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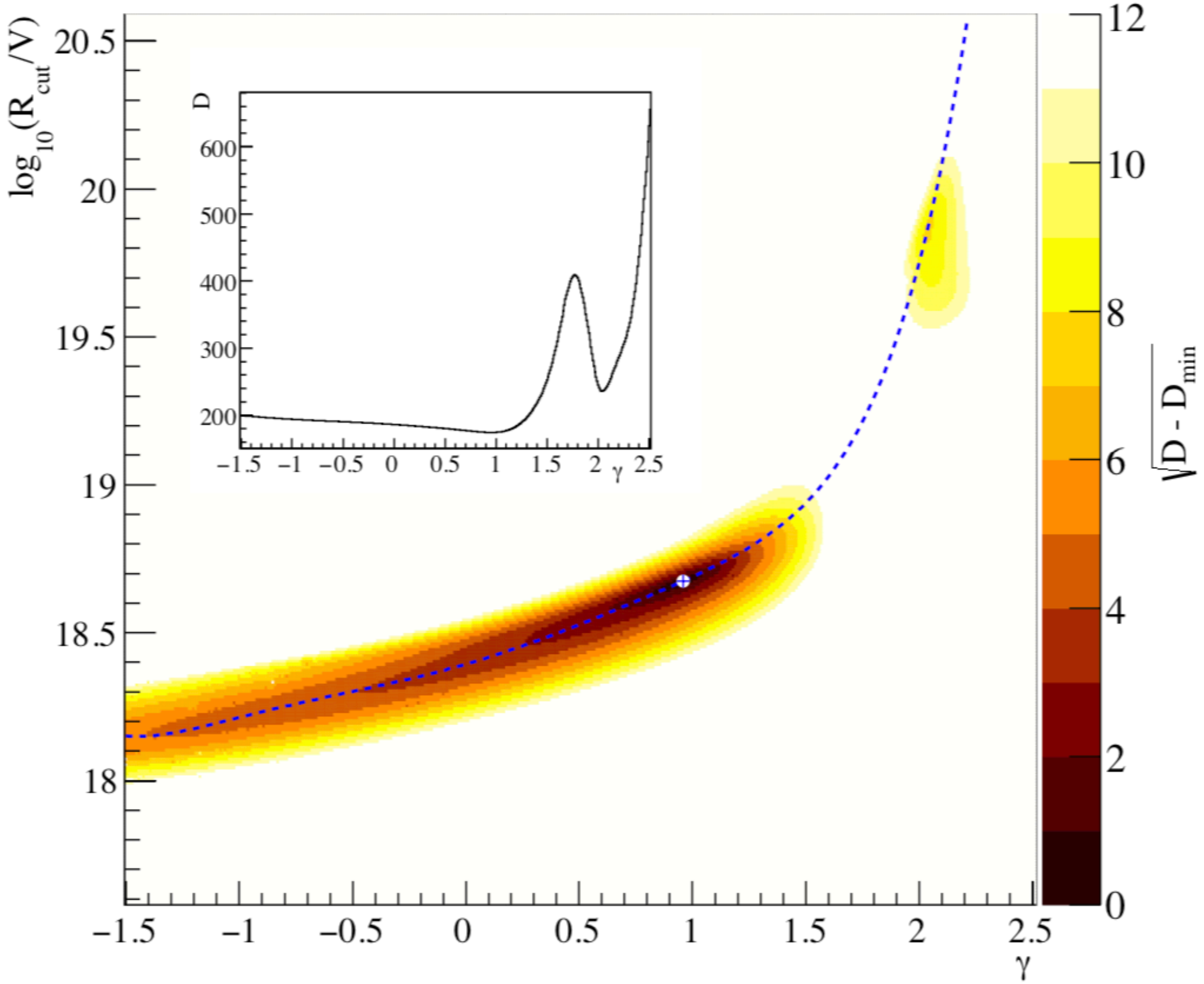

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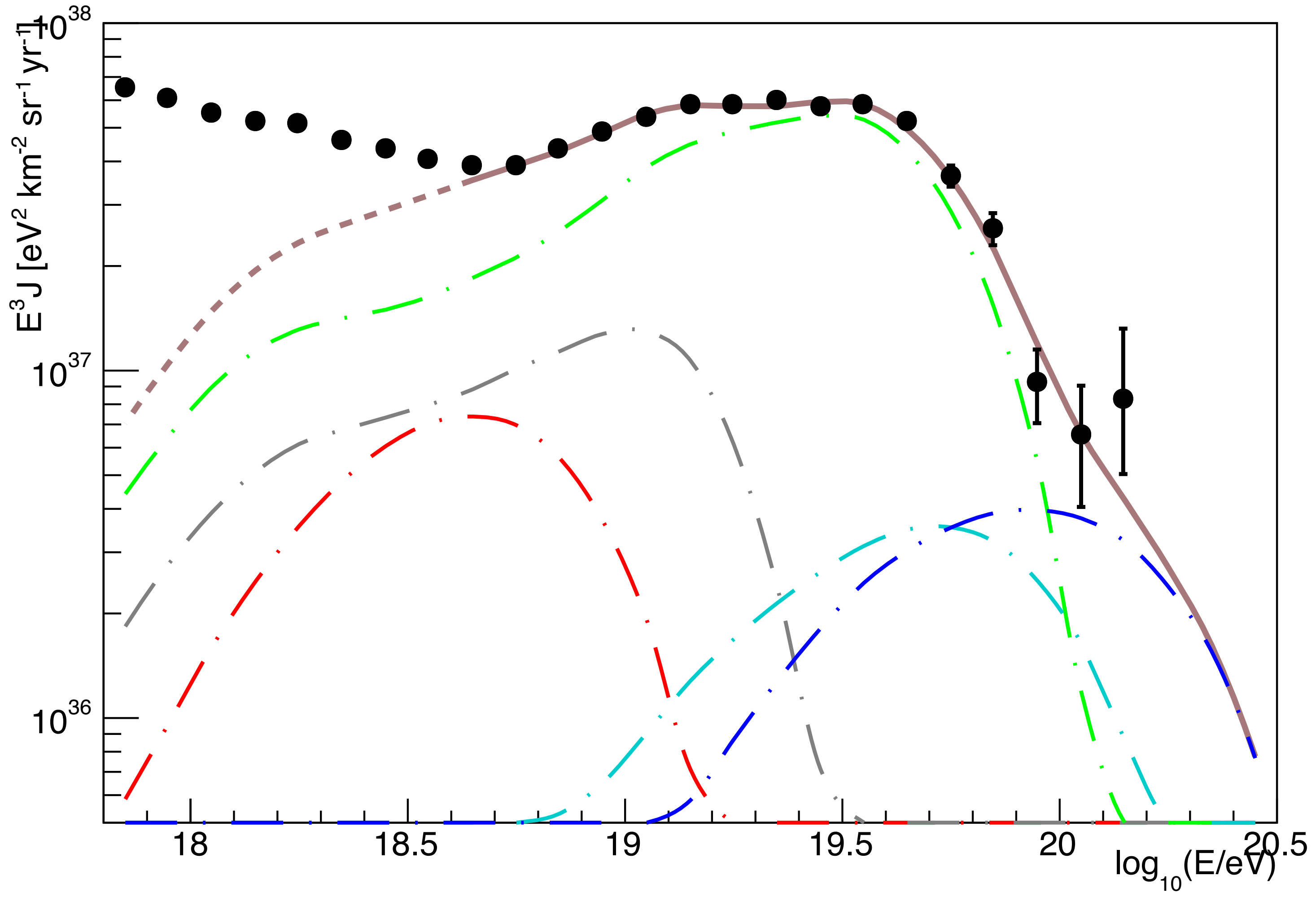
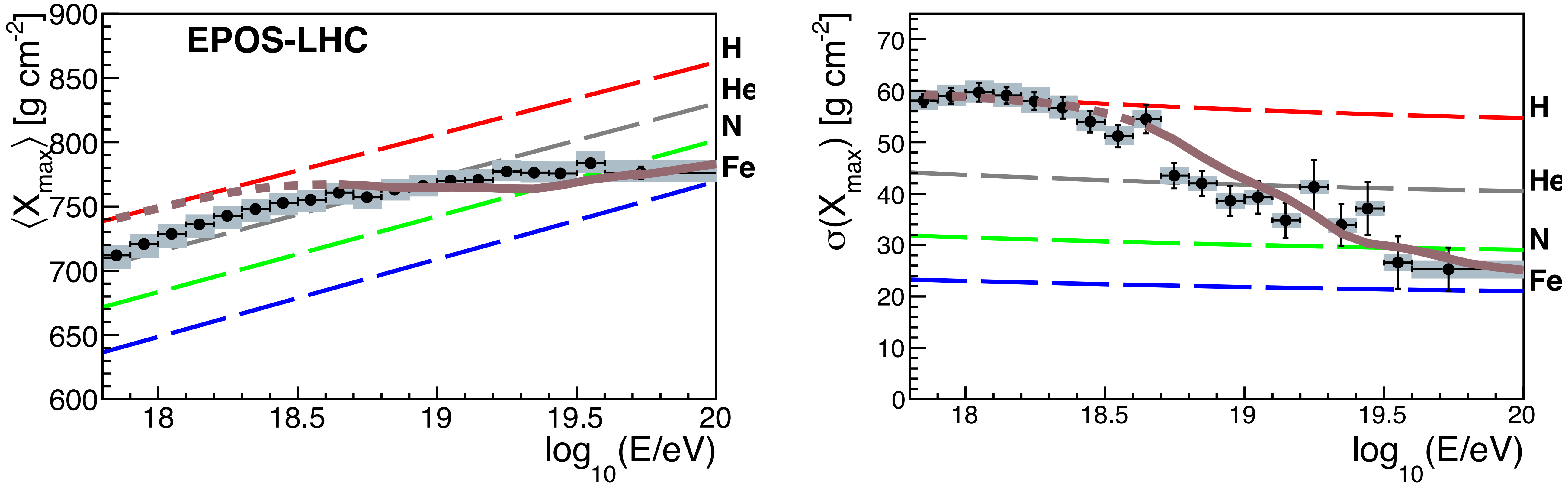


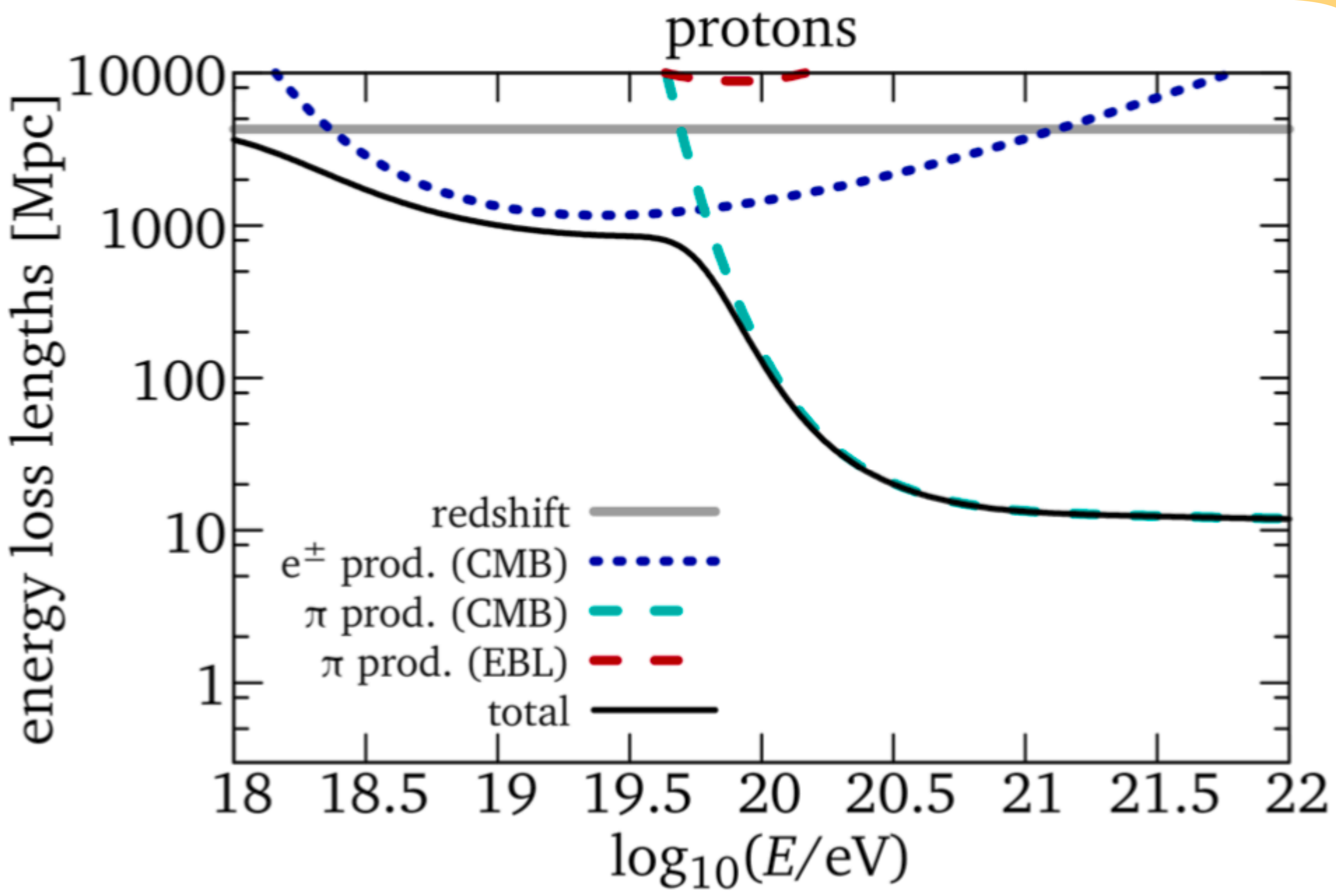
- Groups of nuclei with their partial contributions from the injected elements at the source



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

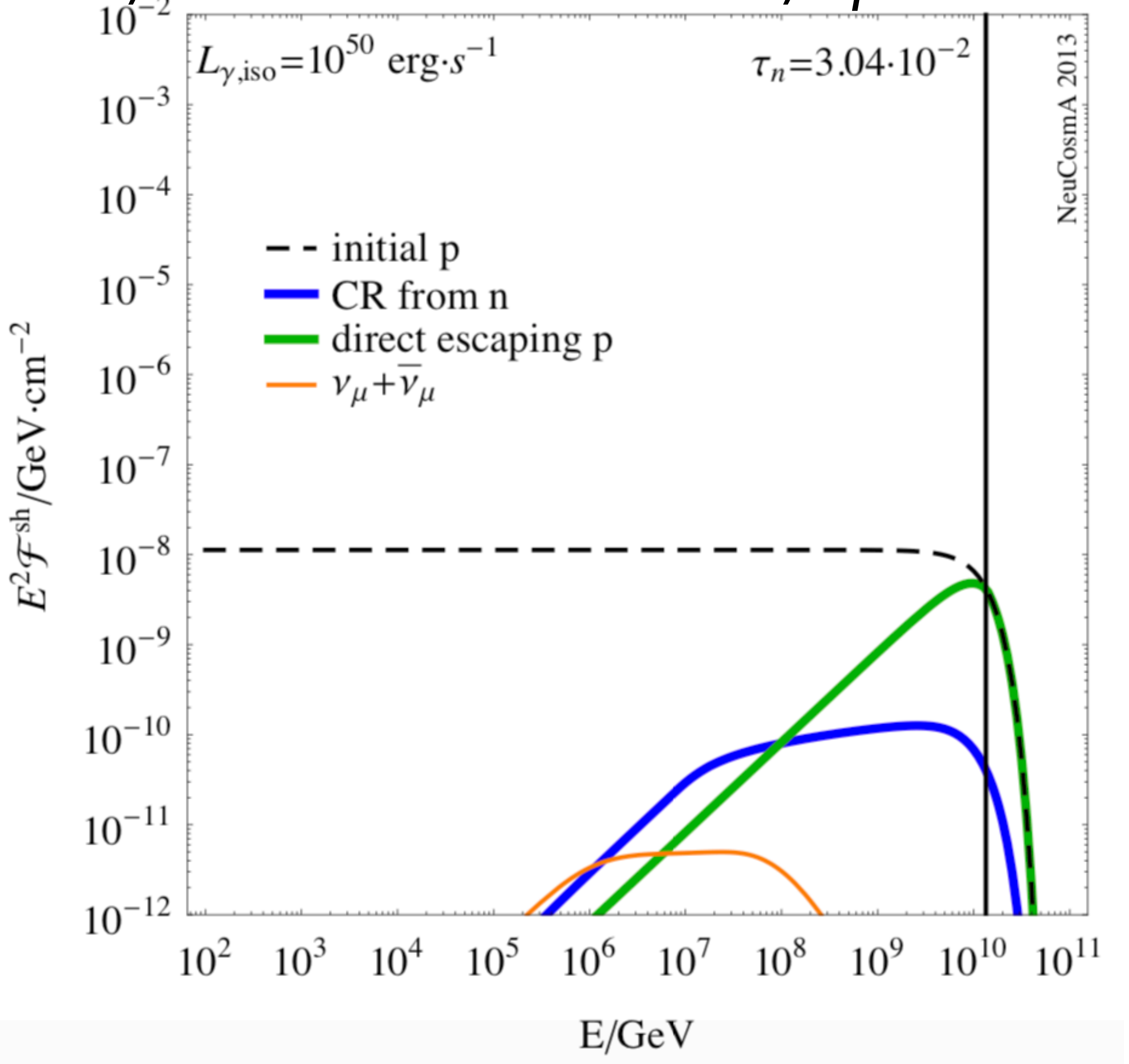
IMPLICATIONS ON SOURCE CHARACTERISTICS

- **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



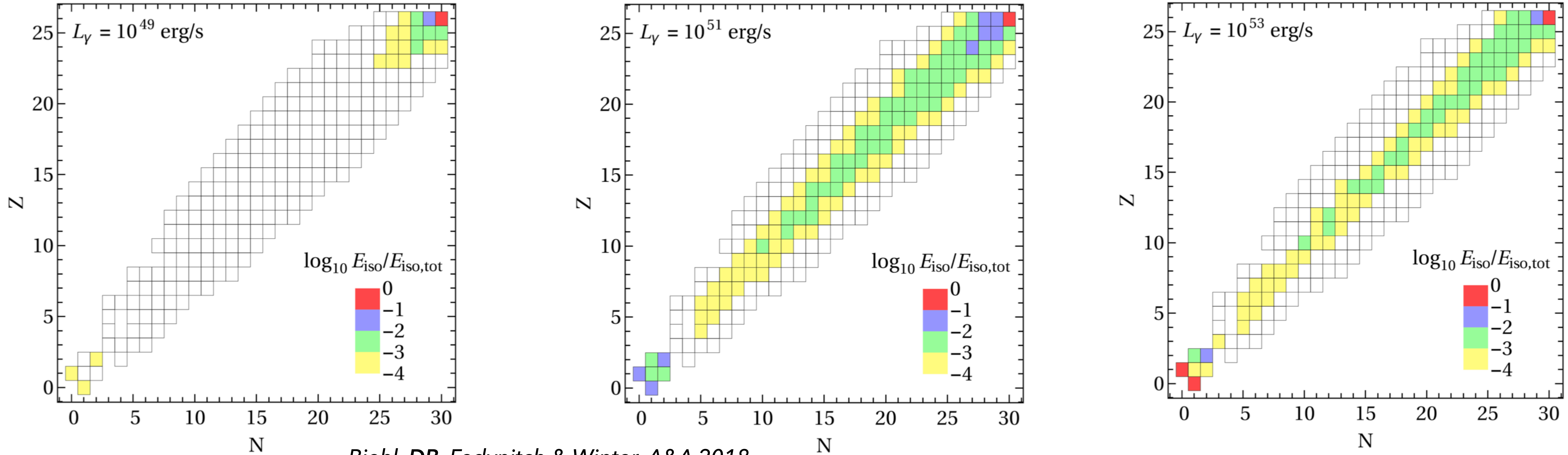
Baerwald, Bustamante and Winter, ApJ 2013

- **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



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

IMPLICATIONS ON SOURCE CHARACTERISTICS

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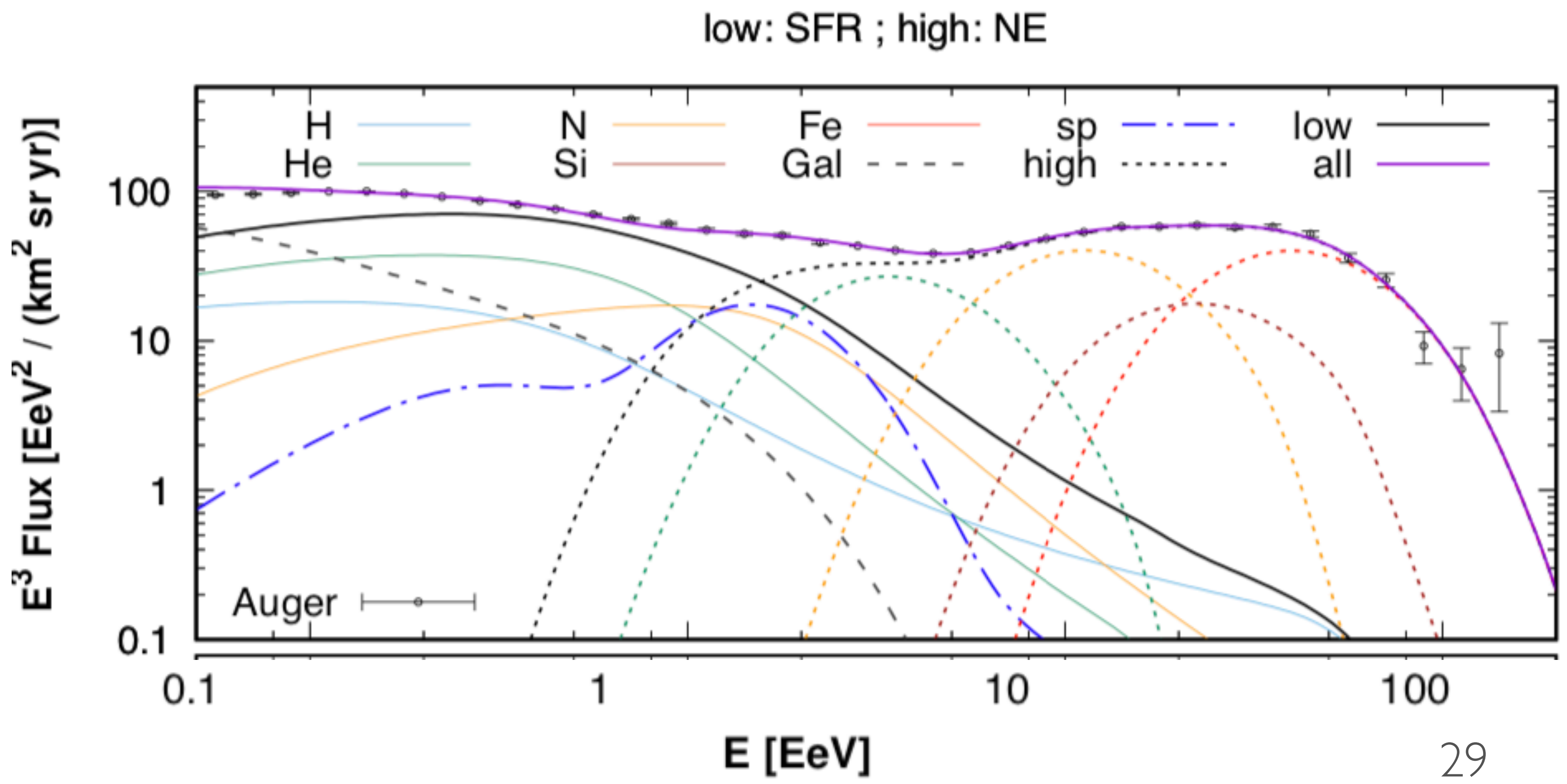
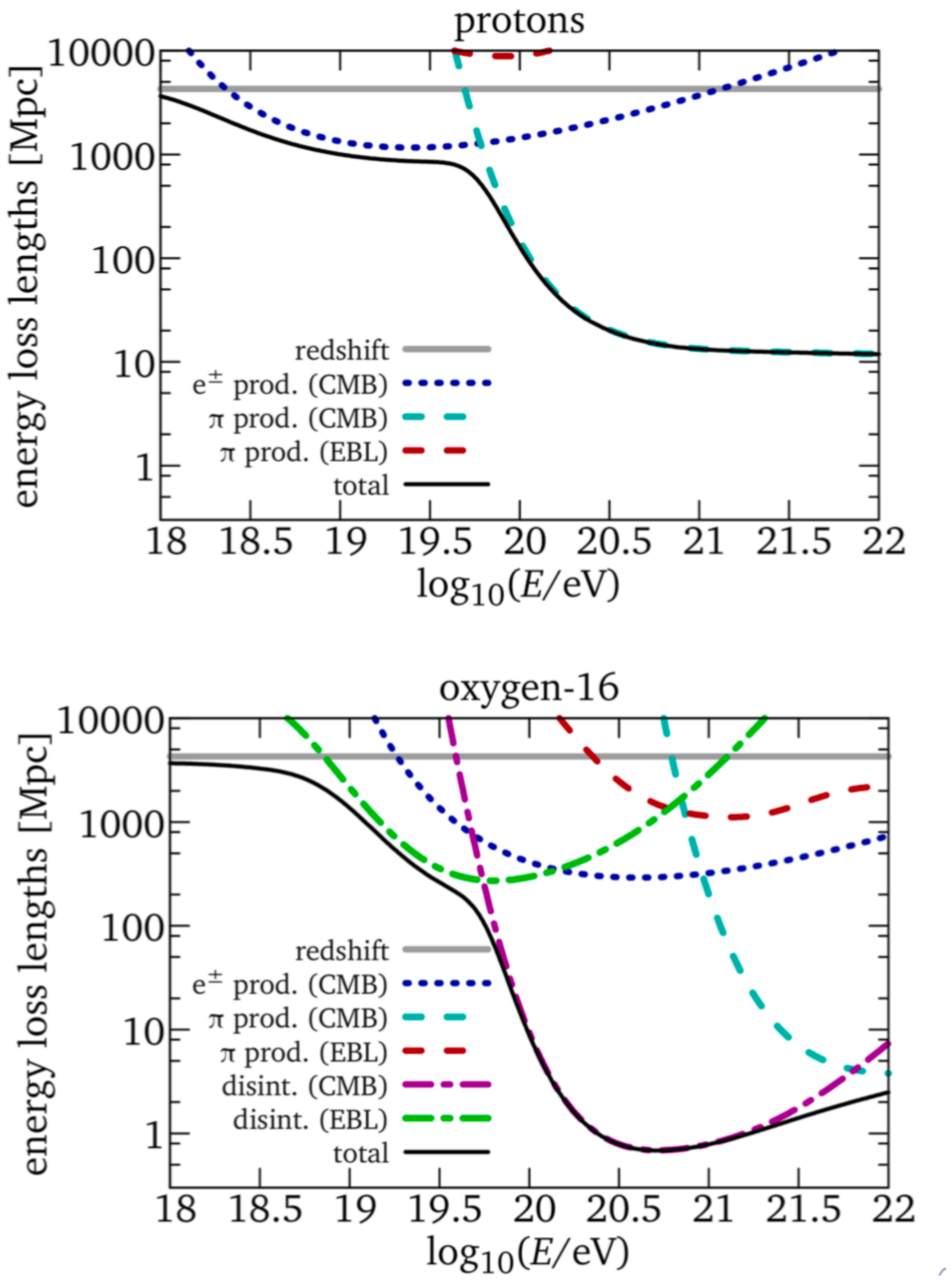
  - The survival condition can be satisfied depending on the characteristics of the possible source (such as **density of radiation**, etc…)
- <u>What sources could provide mixed UHECR composition?</u>
  - Neutron stars, ***Kotera, Amato & Blasi, JCAP 2015***
  - Wolf-Rayet stars, ***Thoudam et al. A&A 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



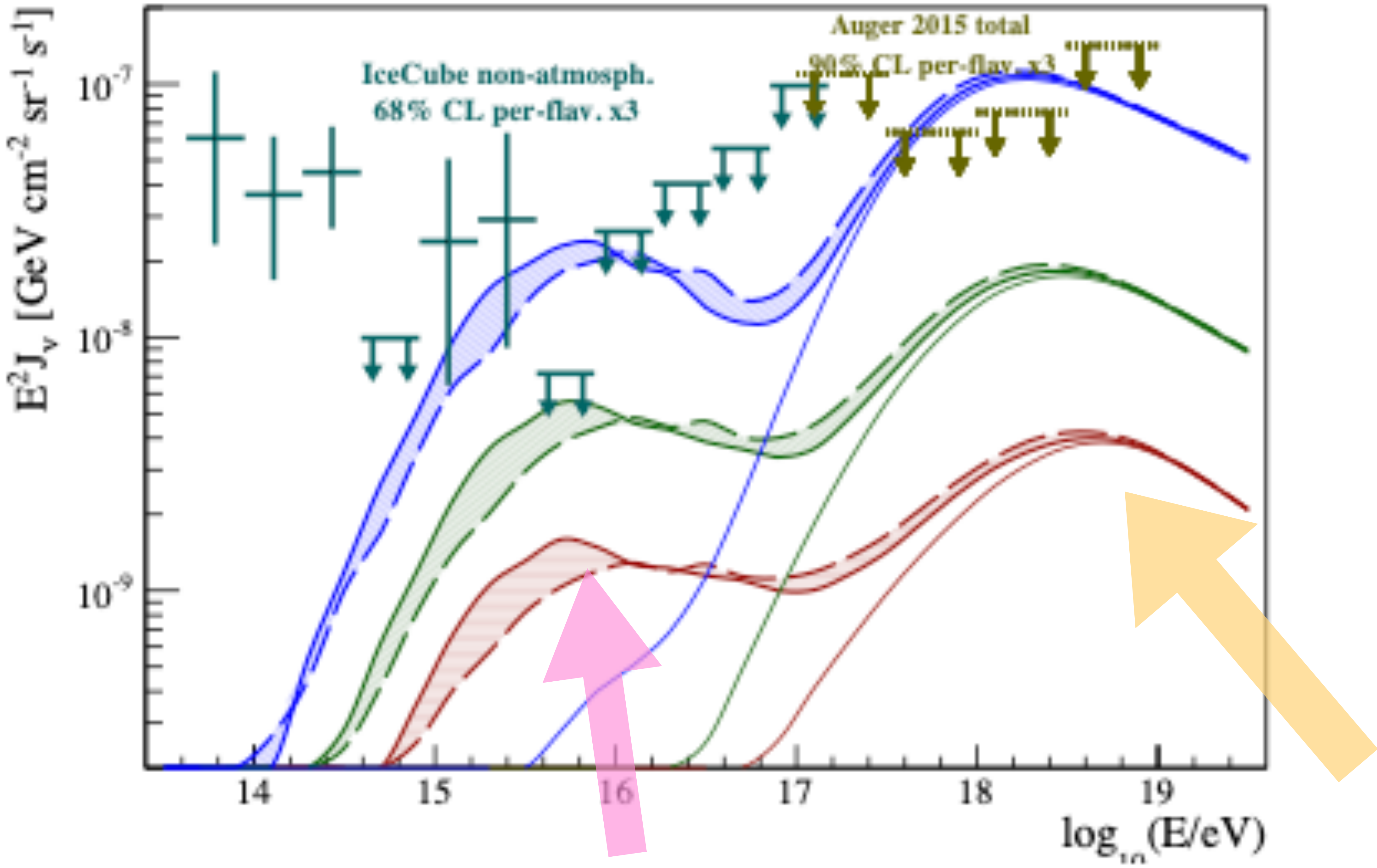


A MULTIMESSENGER VIEW

SECONDARY PARTICLES: NEUTRINOS

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

E^2 x flux



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

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

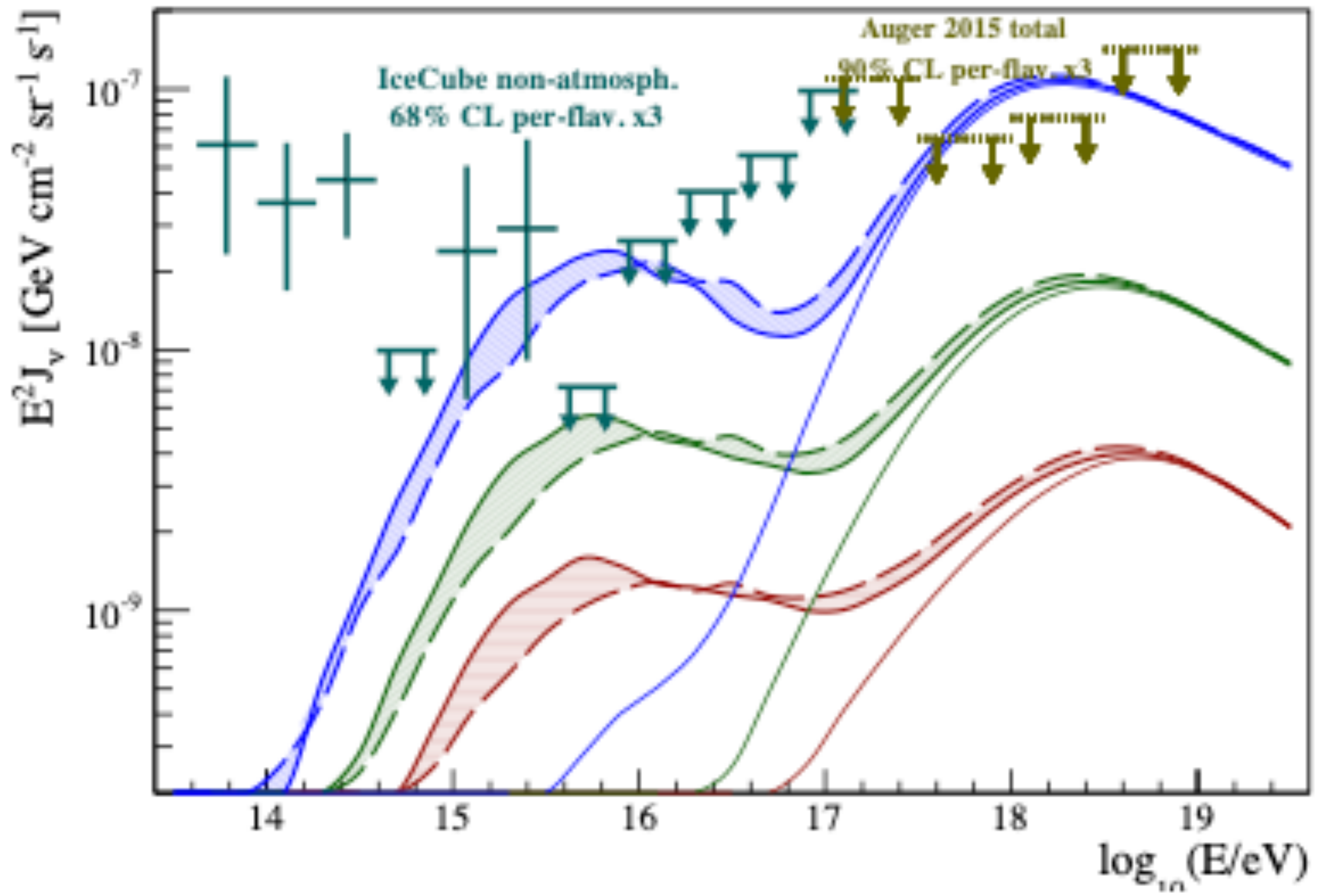
-> neutrinos with smaller energy will be produced

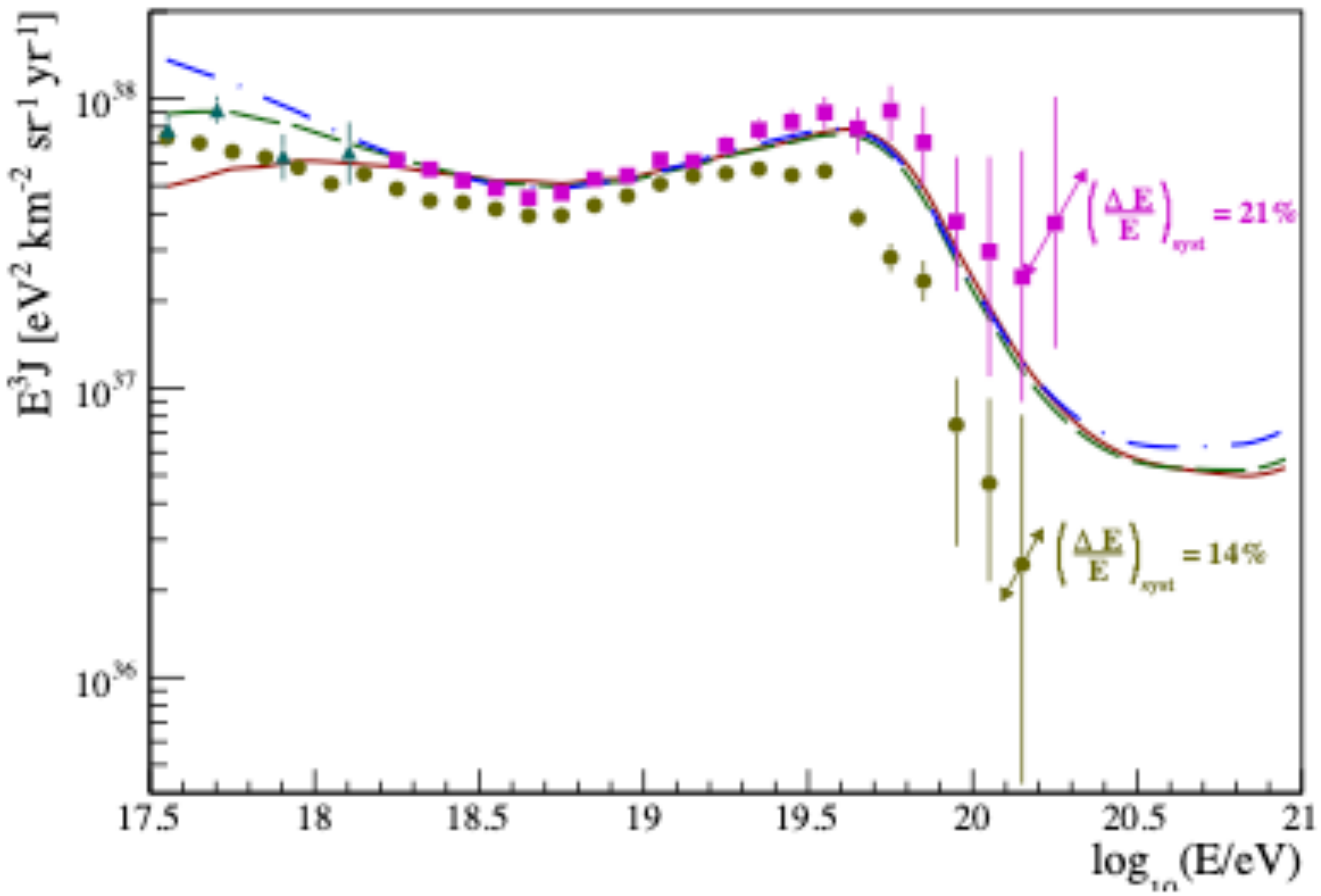
Neutrinos from interactions of protons with CMB ($7\text{x}10^{-4}$ eV); for instance

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

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

SECONDARY PARTICLES: NEUTRINOS





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

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

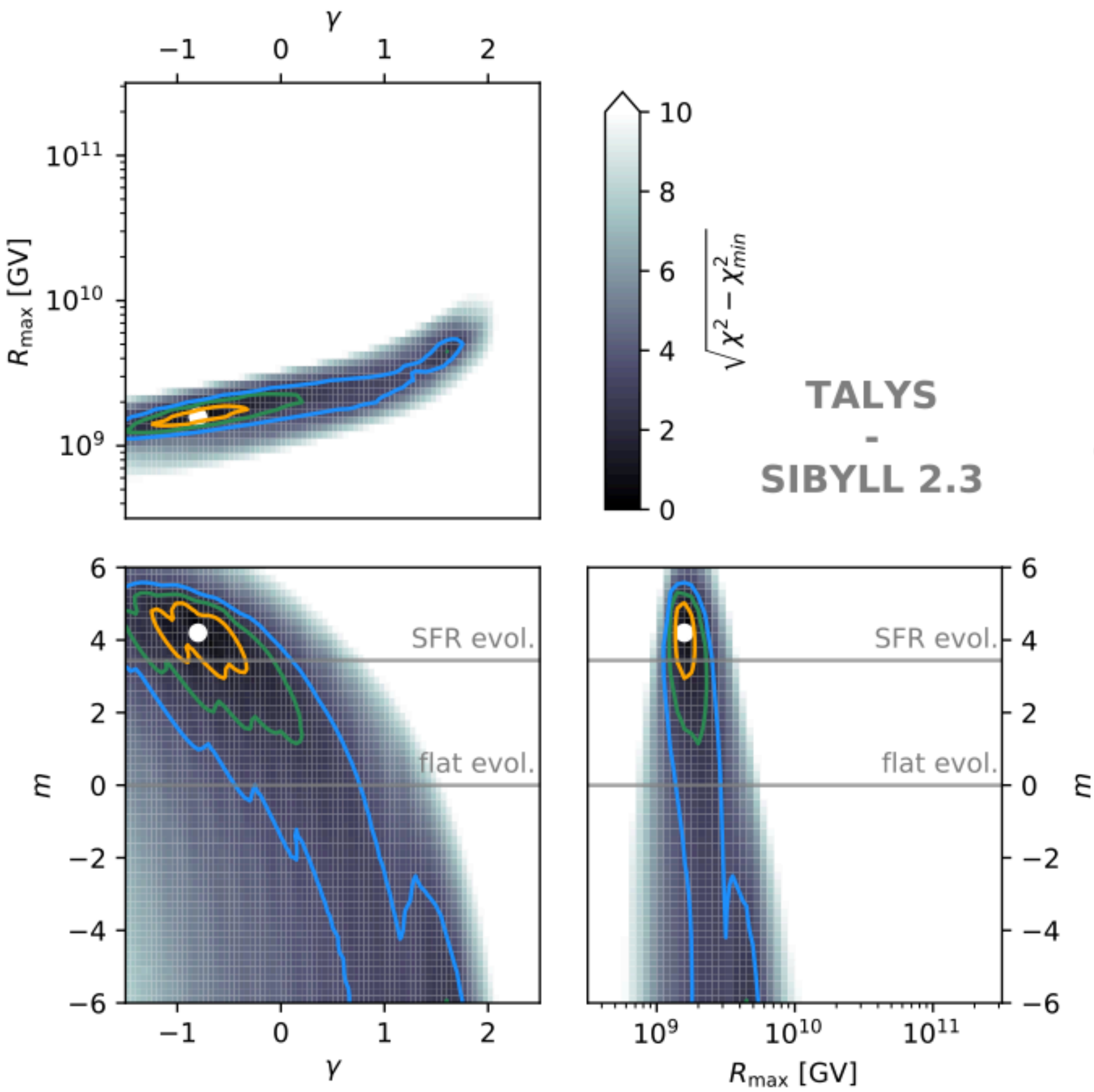
Aloisio, DB, di Matteo, Grillo, Petrera, Salamida 2015

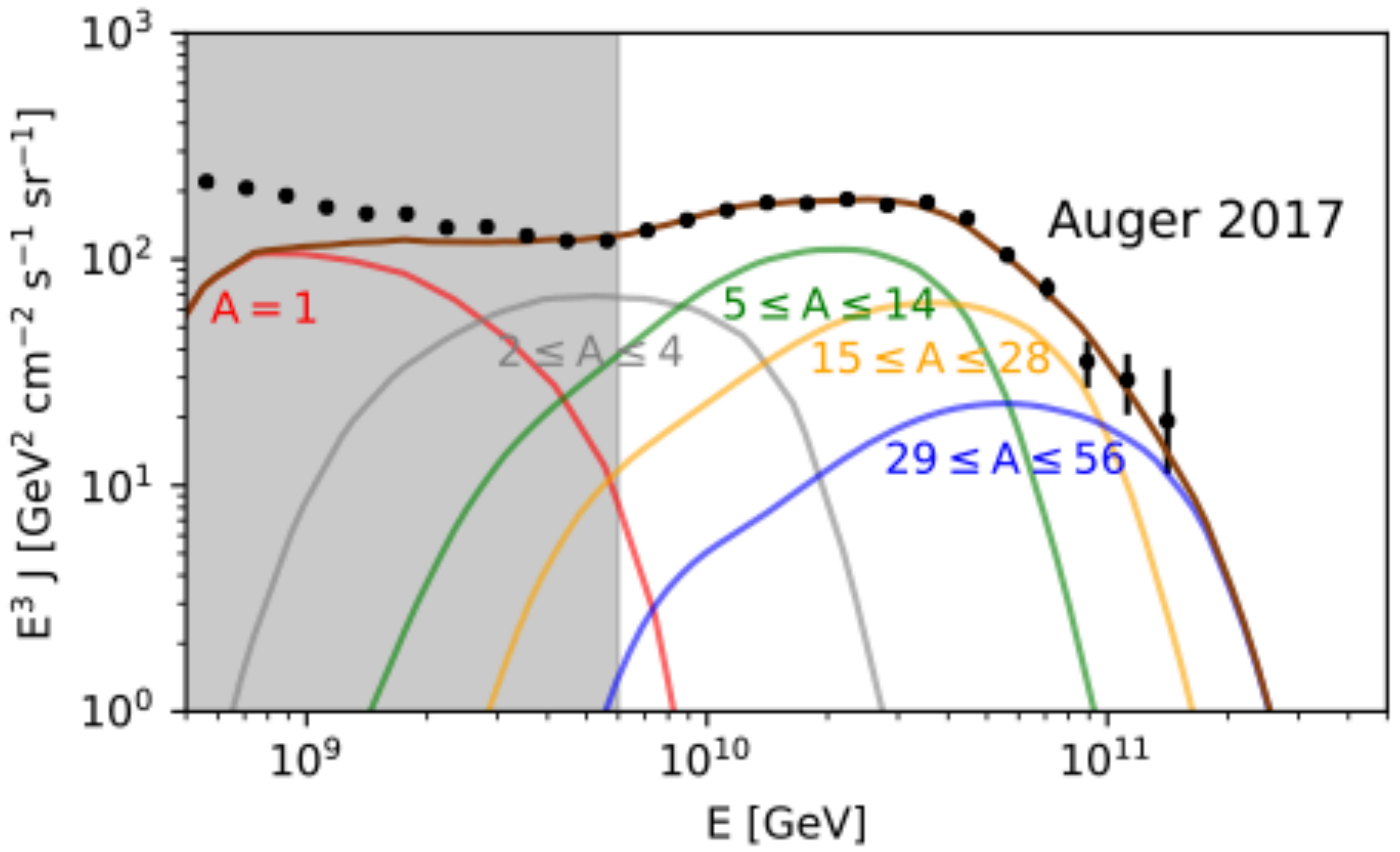
On cosmic-ray spectra the effect is much less relevant than for neutrinos!

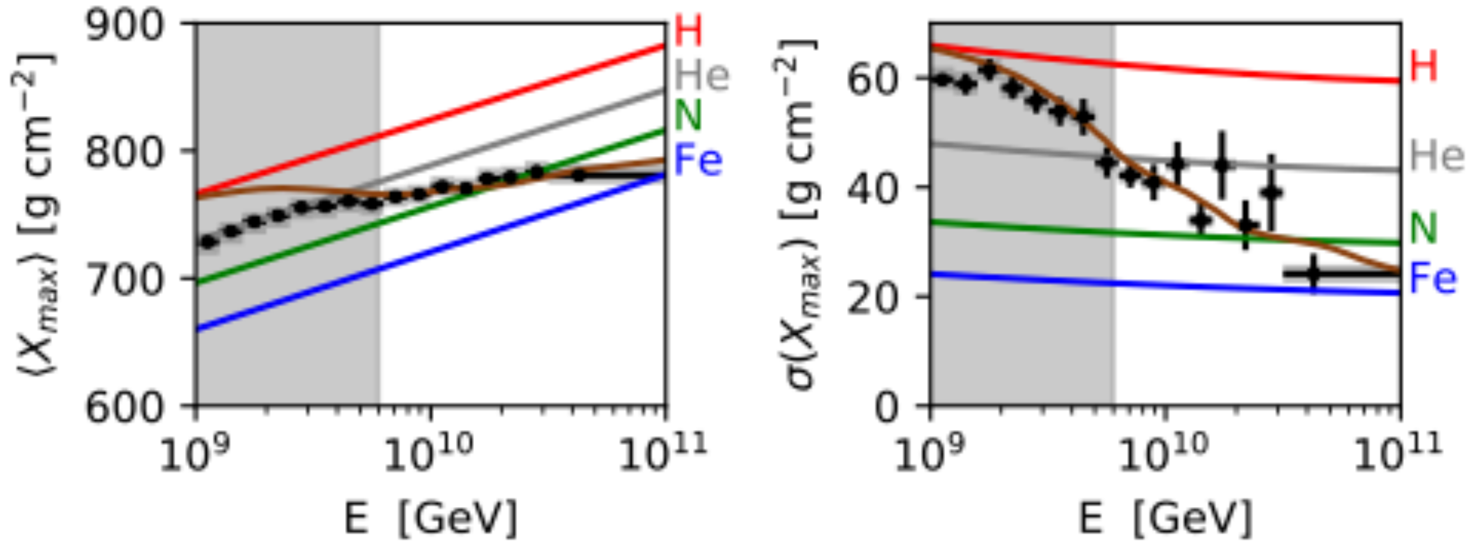
- Cosmogenic neutrinos could improve the understanding of the distribution of UHECR sources

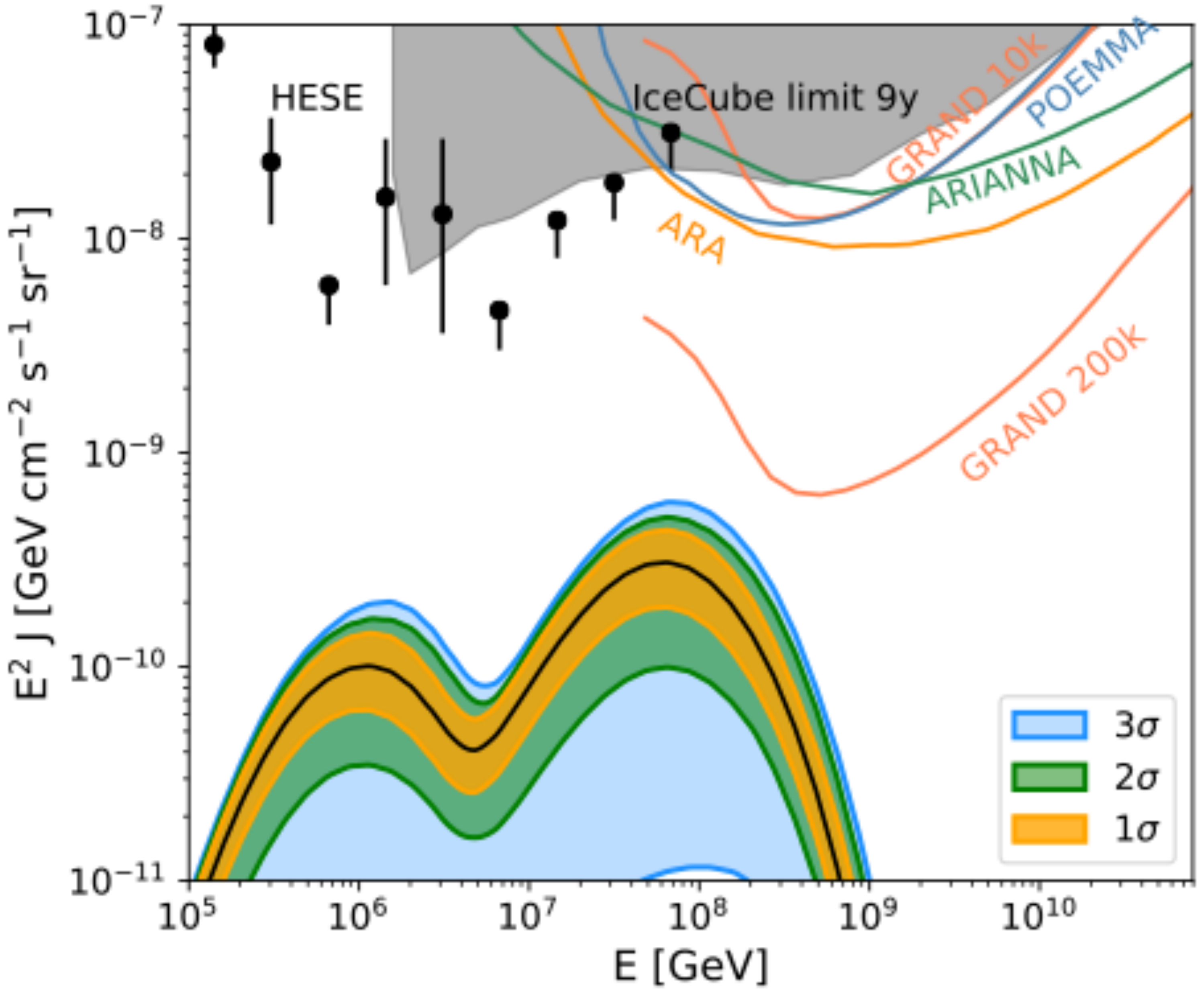
COMBINED SPECTRUM AND COMPOSITION FIT

Heinze, Fedynitch, DB, Winter 2019









- Improvements of these analyses include the sub-ankle region in the fit
- See E. Guido for the Pierre Auger Collaboration ICRC2021

SUMMARY

- UHECR interactions in the extragalactic space
  - Computation of interaction lengths
  - Computation of expected fluxes at Earth
- Secondary messengers

Necessary for interpretation of UHECR measurements

- **Origin of the suppression of the spectrum** -> not yet understood
  - Could be a propagation/source effect
  - Composition at UHE ?
- **Origin of the ankle**
  - If protons -> propagation effect
  - If nuclei -> need additional (Galactic? extragalactic?) component to be reproduced
- Secondary messengers might help, but:
  - If nuclei -> small (cosmogenic) neutrino flux is expected

} Source-modelling (+propagation) needed for improving multimessenger studies

SUMMARY

- 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 STEPS:
  - Higher UHECR statistics at the highest energies
  - Better composition sensitivity
  - Multi-messenger studies; source-propagation models
  - Hadronic interactions

AugerPrime