COSMIC-RAY PROPAGATION IN EXTRAGALACTIC SPACE AND SECONDARY MESSENGERS

Lecture 1:

- **General introduction**
- **UHECR protons**

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Foundations of Cosmic Ray Astrophysics

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MAIN REFERENCES

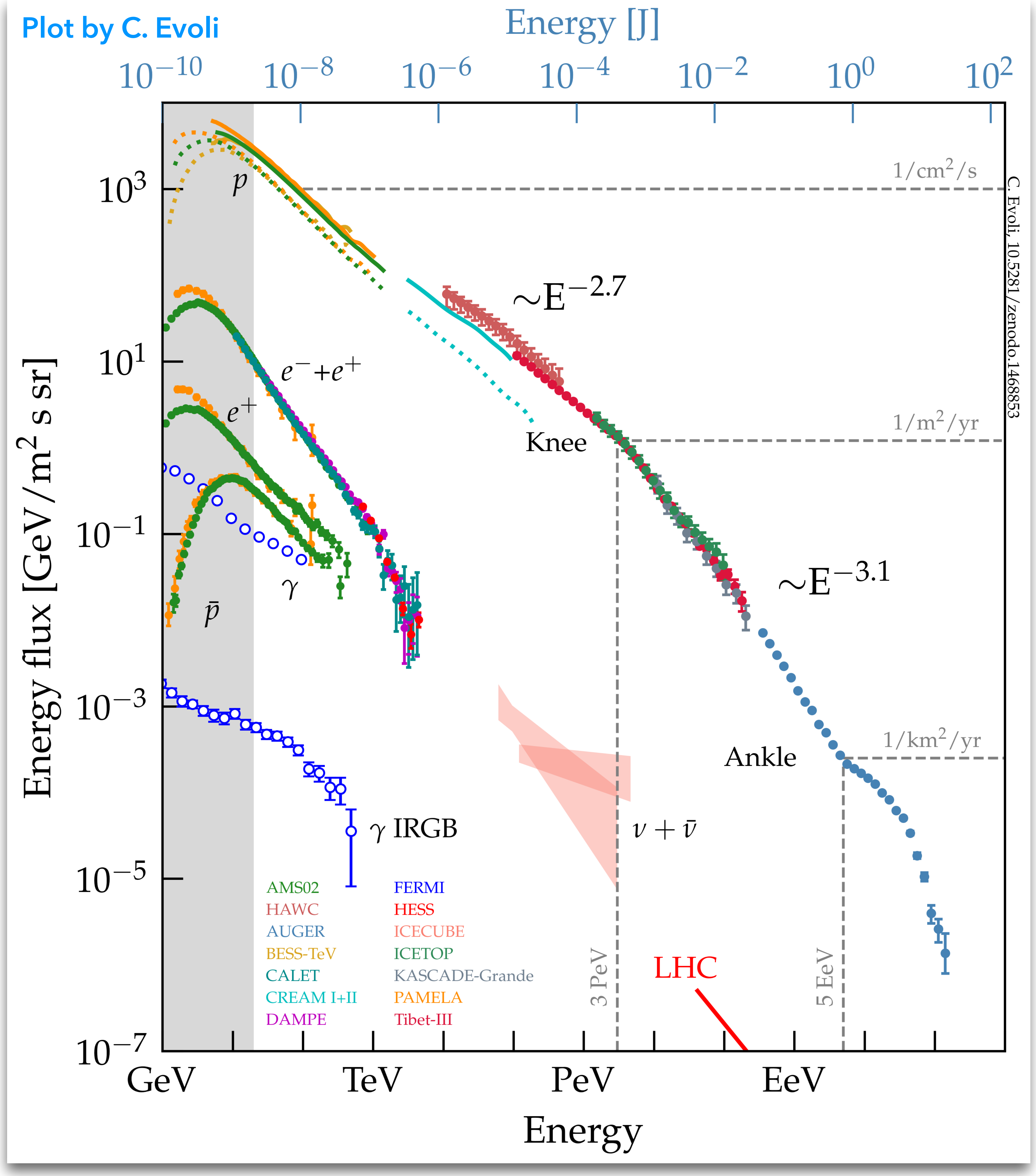
- T. Gaisser, R. Engel & E. Resconi, "Cosmic Rays and Particle Physics", Cambridge University Press
- R. Schlickeiser, "Cosmic Ray Astrophysics", Springer

- V. Berezinsky & S.I. Grigorieva, "A bump in the ultra-high energy cosmic ray spectrum" Astron. Astrop. 199, 1 (1988)
- V. Berezinsky, A.Z. Gazizov& S.I. Grigorieva, "Dip in UHECR spectrum as signature of proton interaction with CMB", *Phys.Lett.B* 612 (2005) 147-153
- V. Berezinsky, A.Z. Gazizov & S.I. Grigorieva, "On astrophysical solution to ultra-high energy cosmic rays", *Phys.Rev.D* 74 (2006) 043005
- R. Aloisio, V. Berezinsky, P. Blasi, A.Z. Gazizov & S.I. Grigorieva, "A dip in the UHECR spectrum and the transition from galactic to extragalactic cosmic rays", *Astropart.Phys.* 27 (2007) 76-91

- For a general introduction to the state of the art about UHECRs: arxiv: 2205.05845

INTRODUCTION

THE COSMIC-RAY ENERGY SPECTRUM



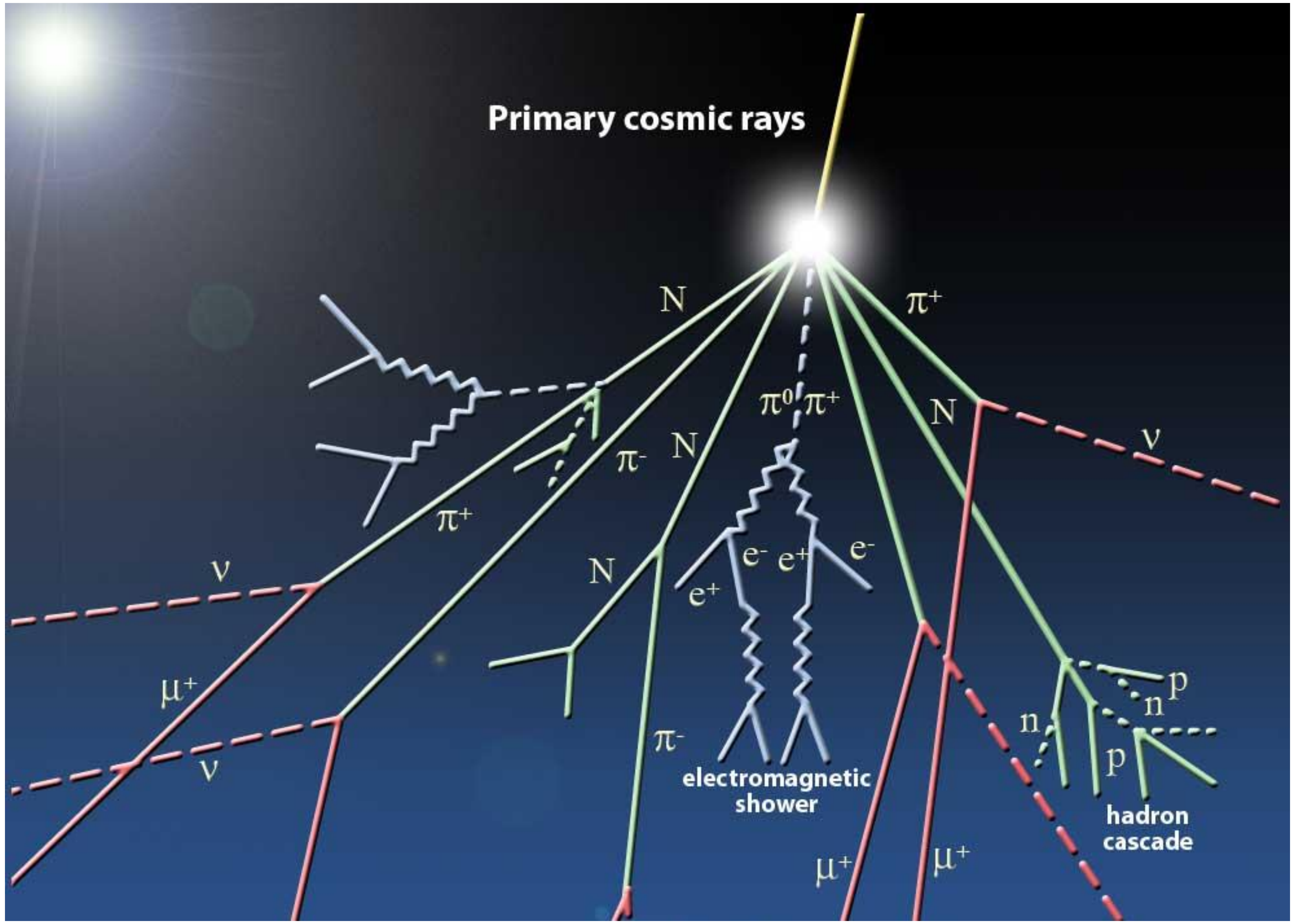
- Collection of measurements, indicating a power-law spectrum, with a few changes of spectral index
- <u>Focus on UHE particles</u>
  - above 10^{17} eV, 8 orders of magnitude larger than the rest mass of the proton… relativistic particles!
  - "Ankle", suppression at the highest energies

- 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

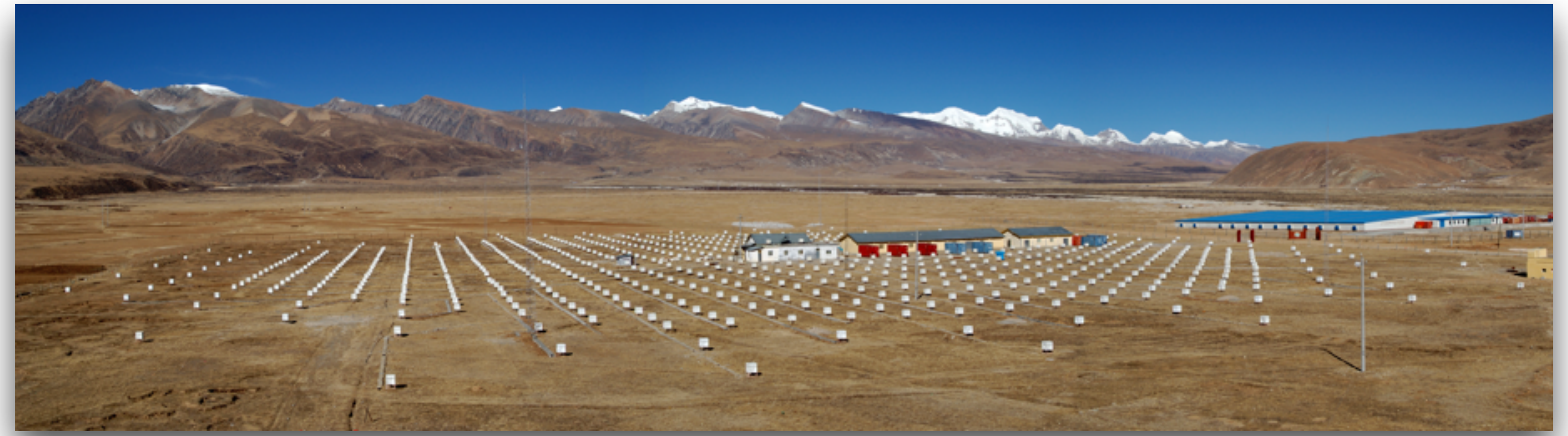
EXTENSIVE AIR SHOWERS



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

MEASUREMENTS AT UHE

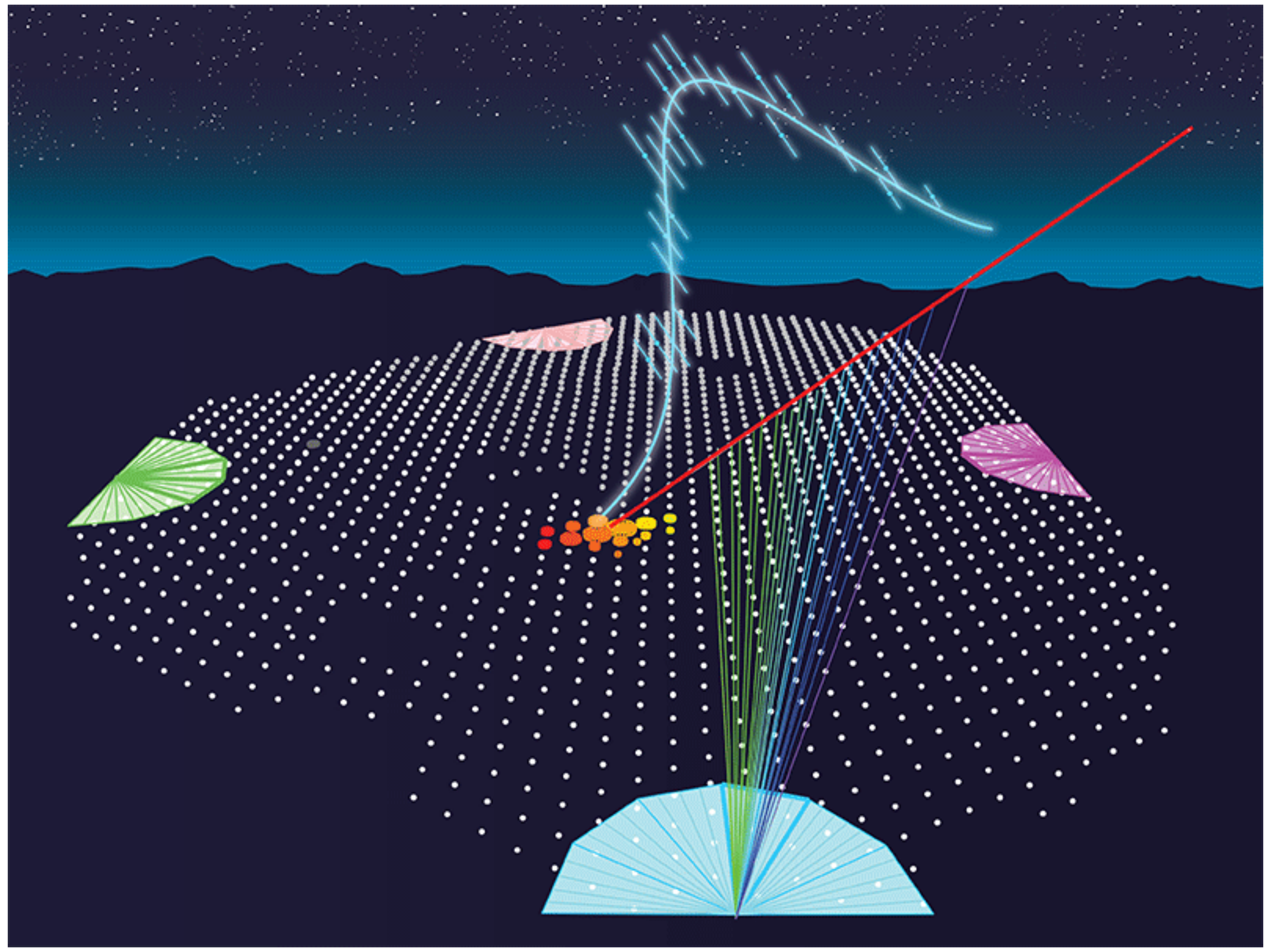
PARTICLE DETECTOR ARRAYS

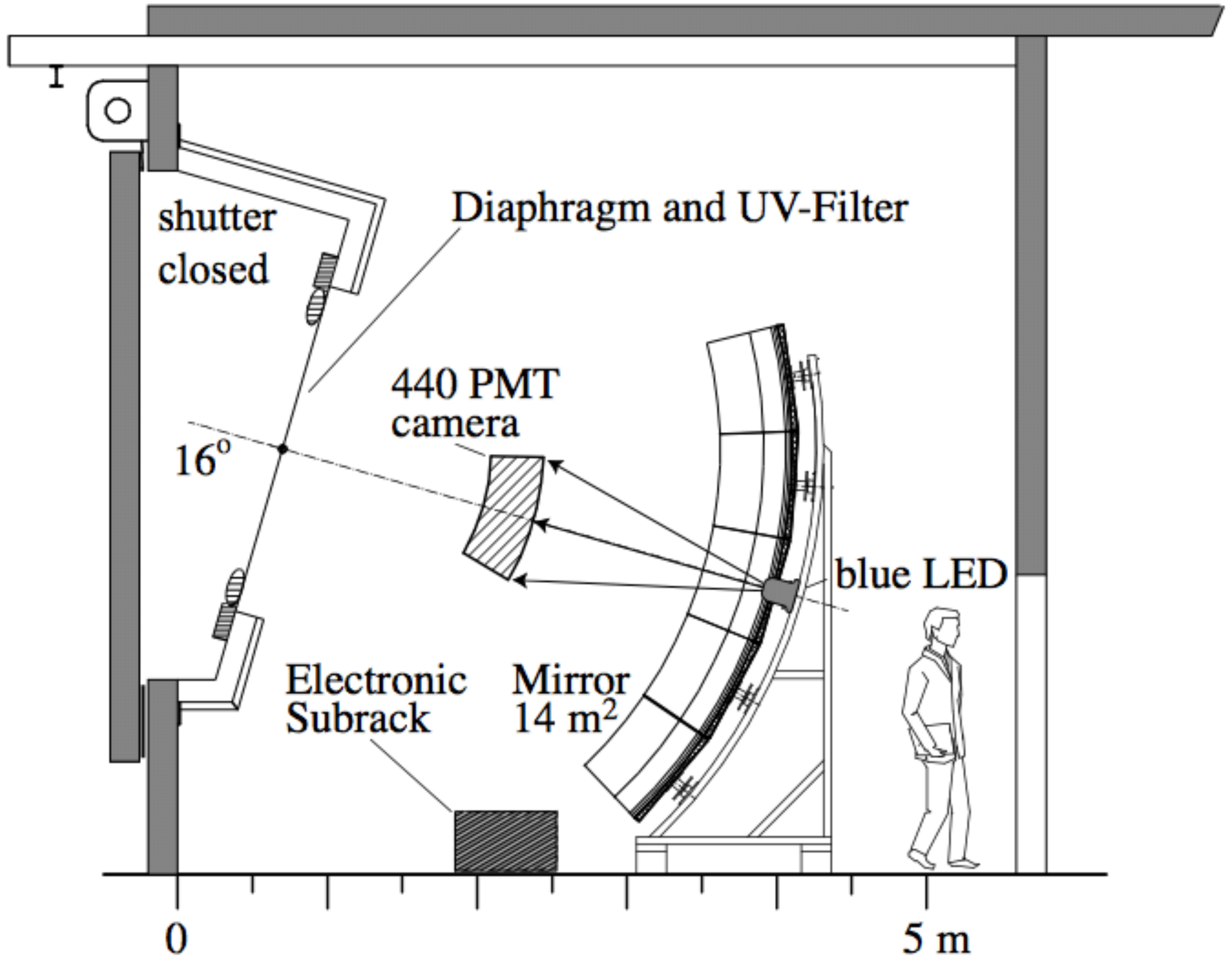


- Set of detectors arranged in a regular pattern
- Showers detected by searching for time coincidences of signals in neighbouring stations
- Depending on the energy range of interest, the distance between the detector stations can vary from tens of m to km

MEASUREMENTS AT UHE

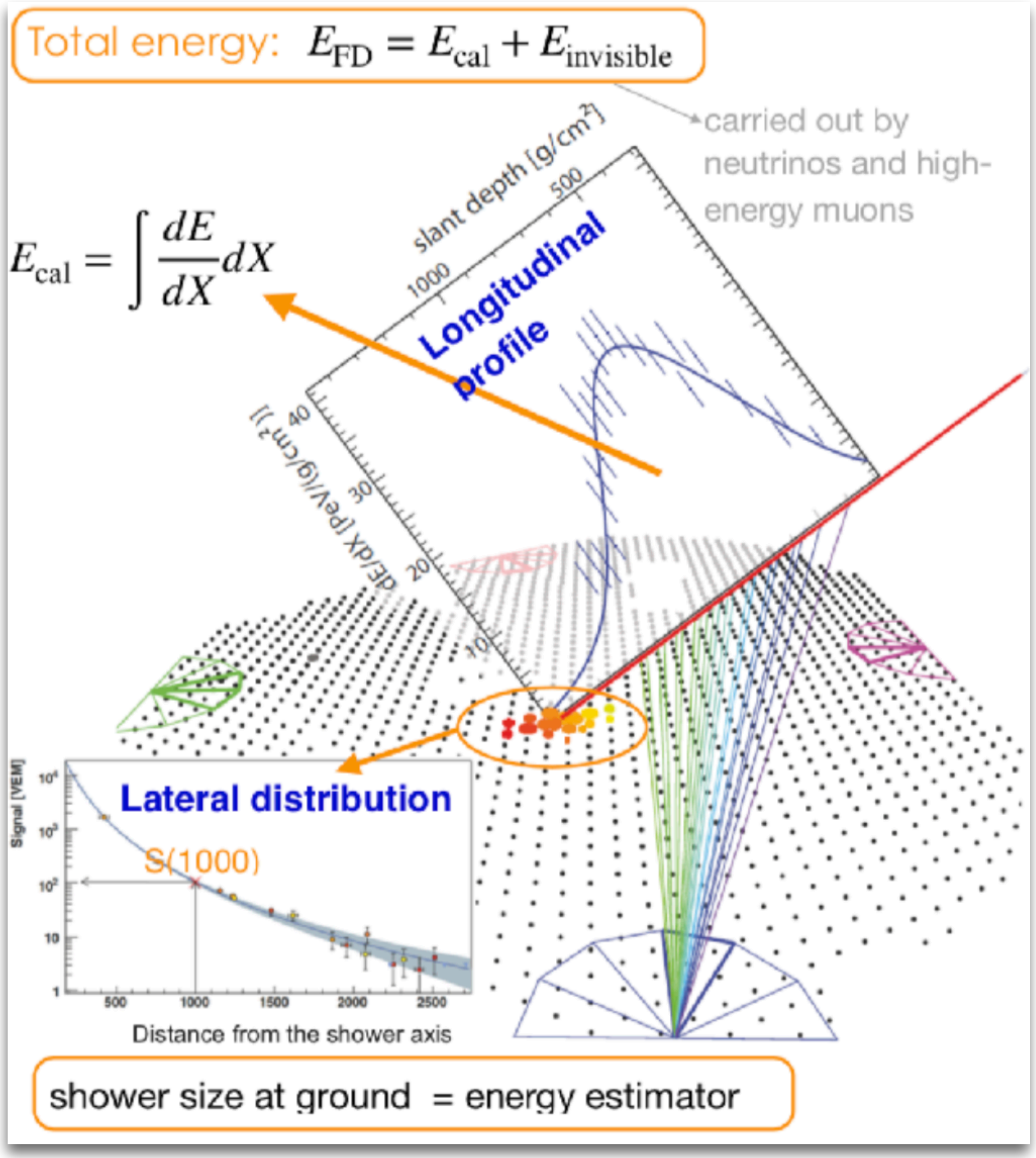
FLUORESCENCE DETECTORS





- 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

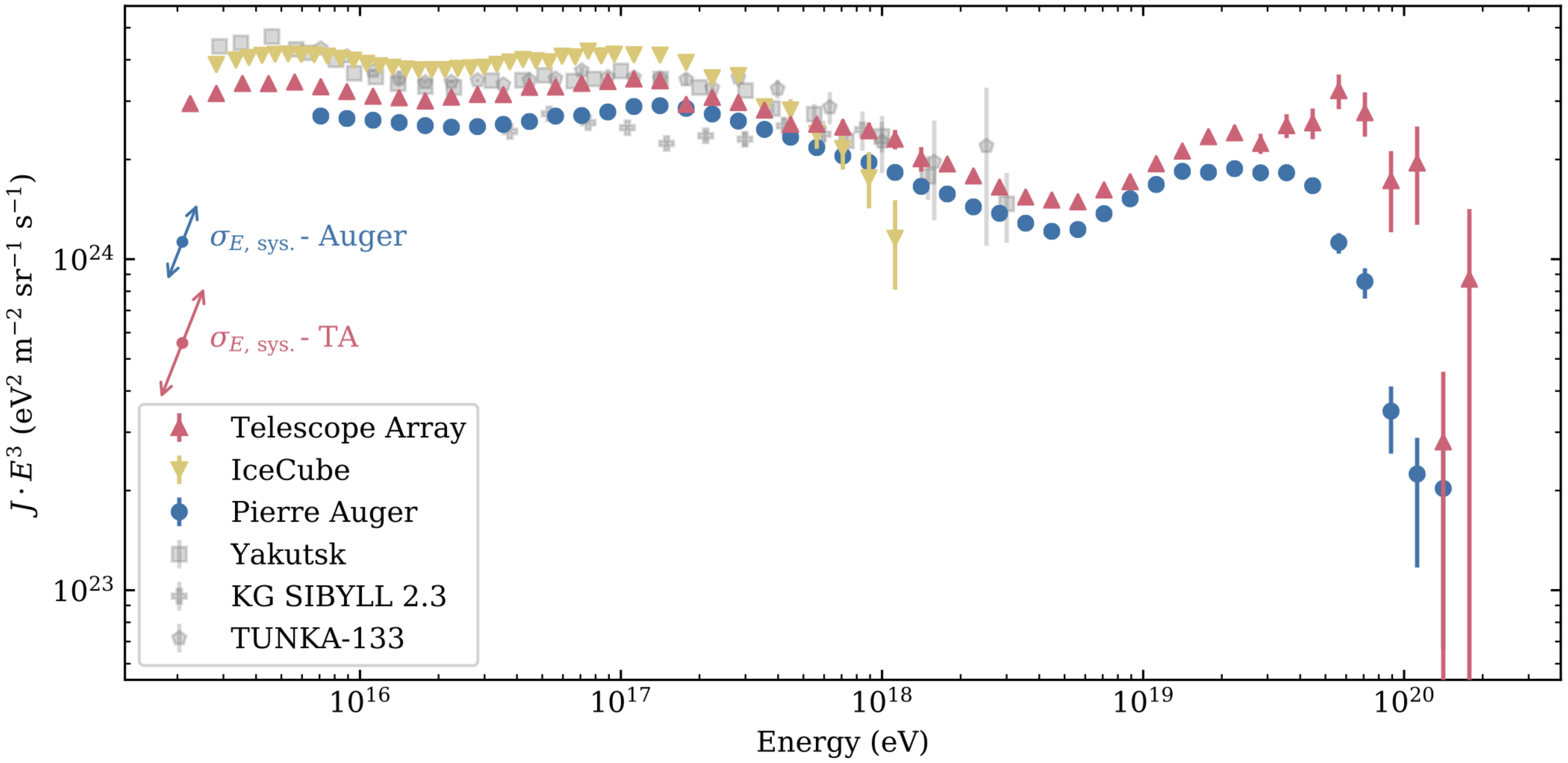


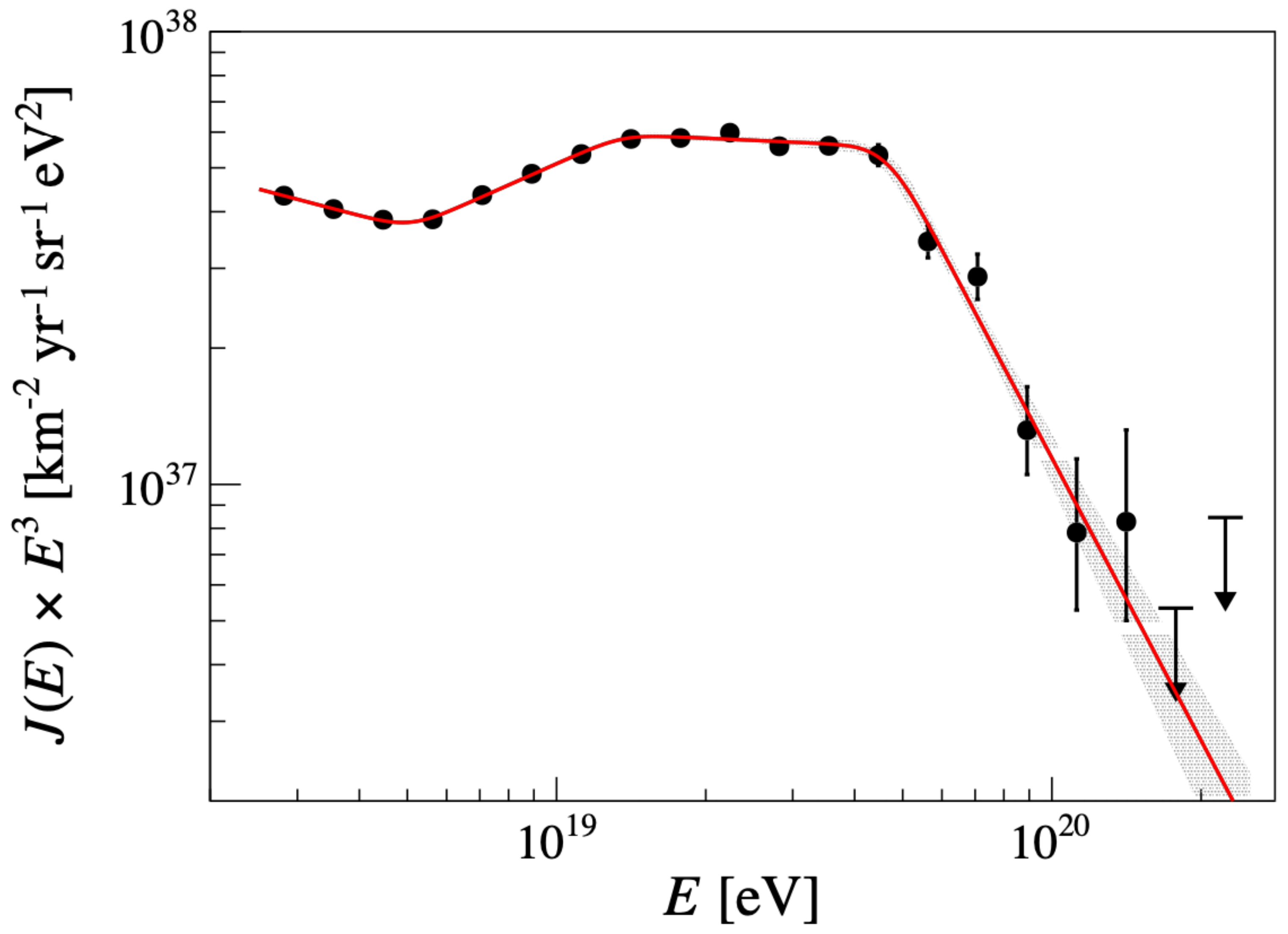
Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km²
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km²
27 fluorescence telescopes

STATE-OF-THE-ART

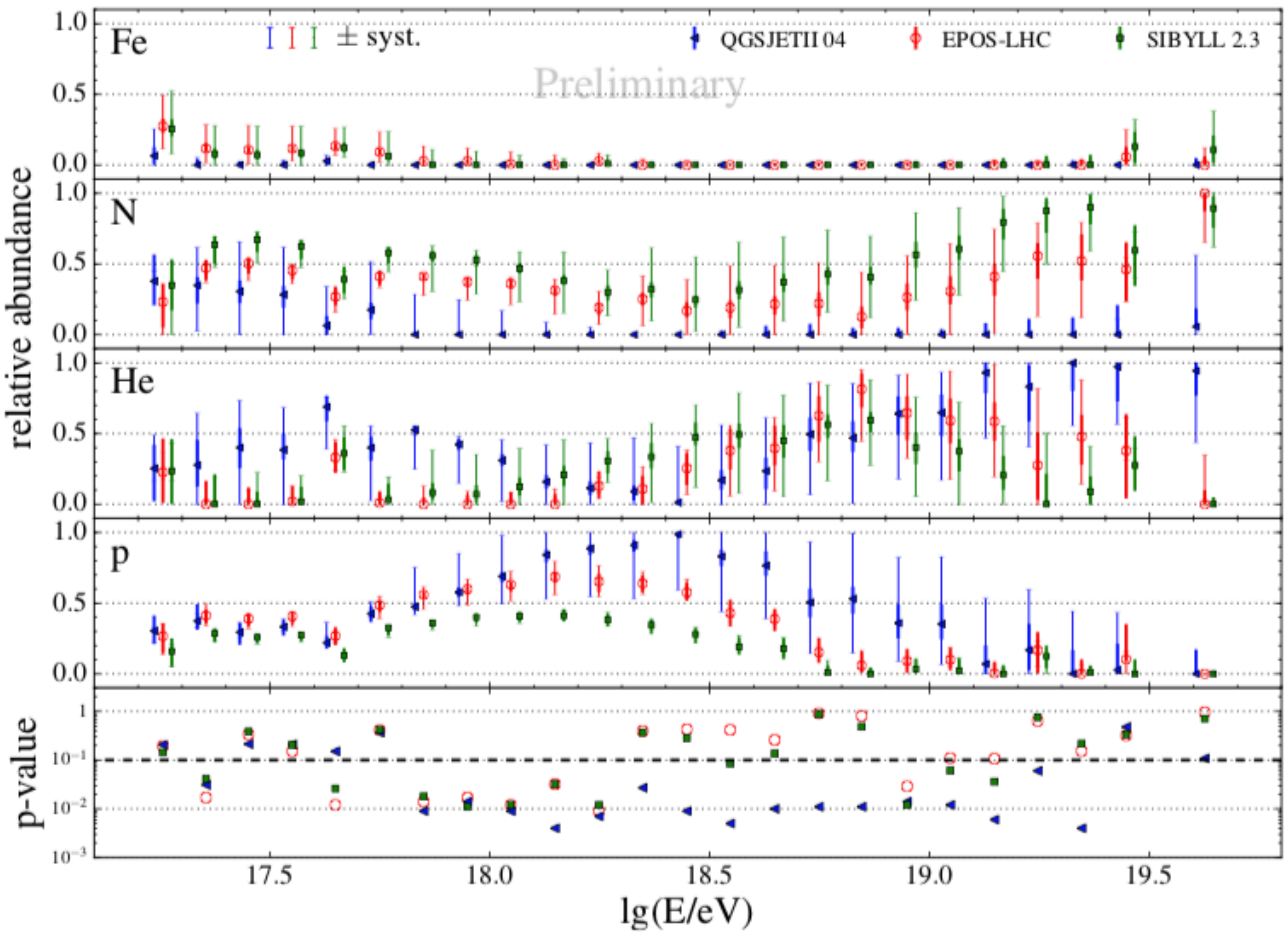
arxiv: 2205.05845

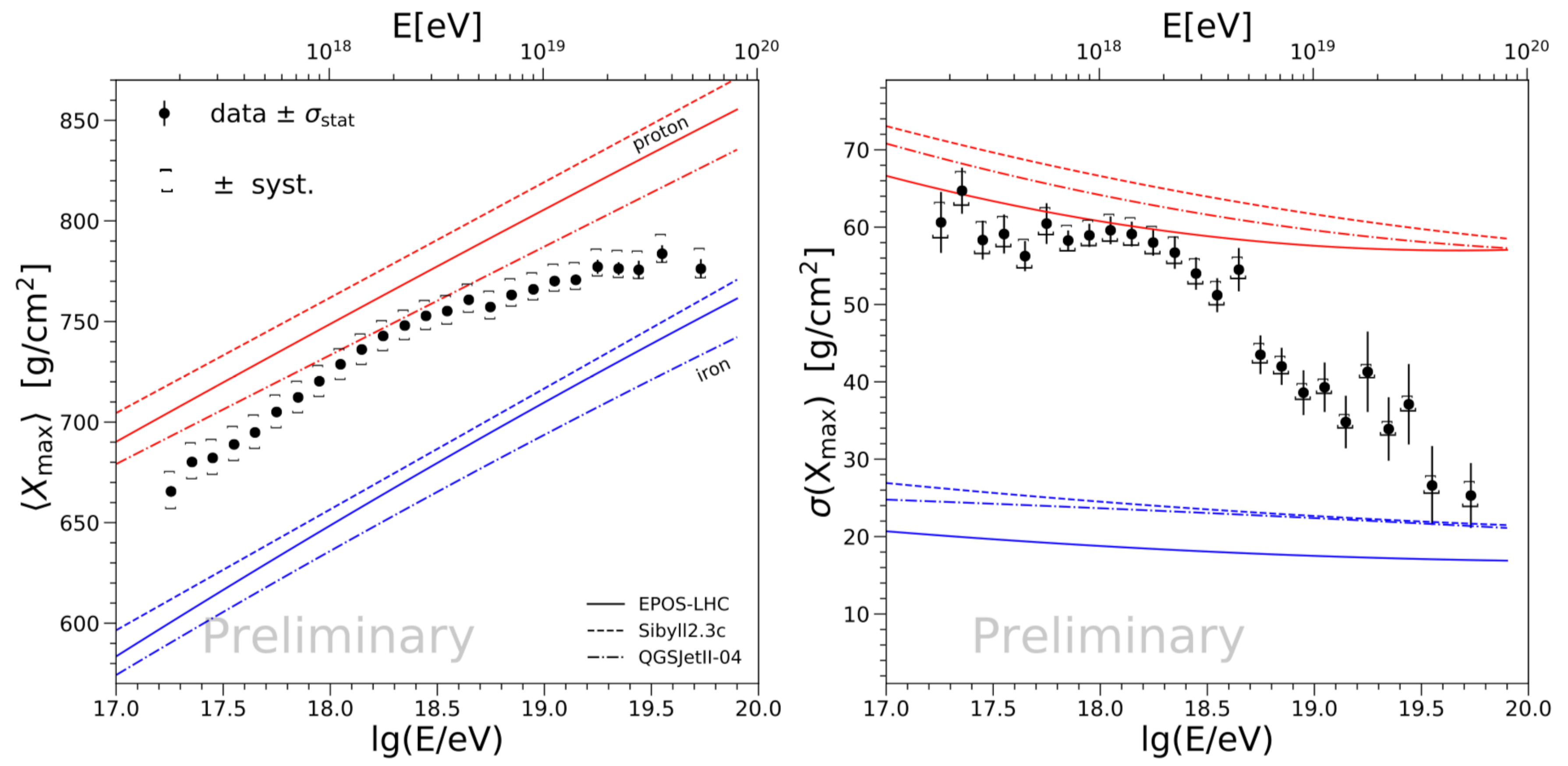




- Features of the energy spectrum
- Transition from Galactic to extragalactic cosmic rays

STATE-OF-THE-ART





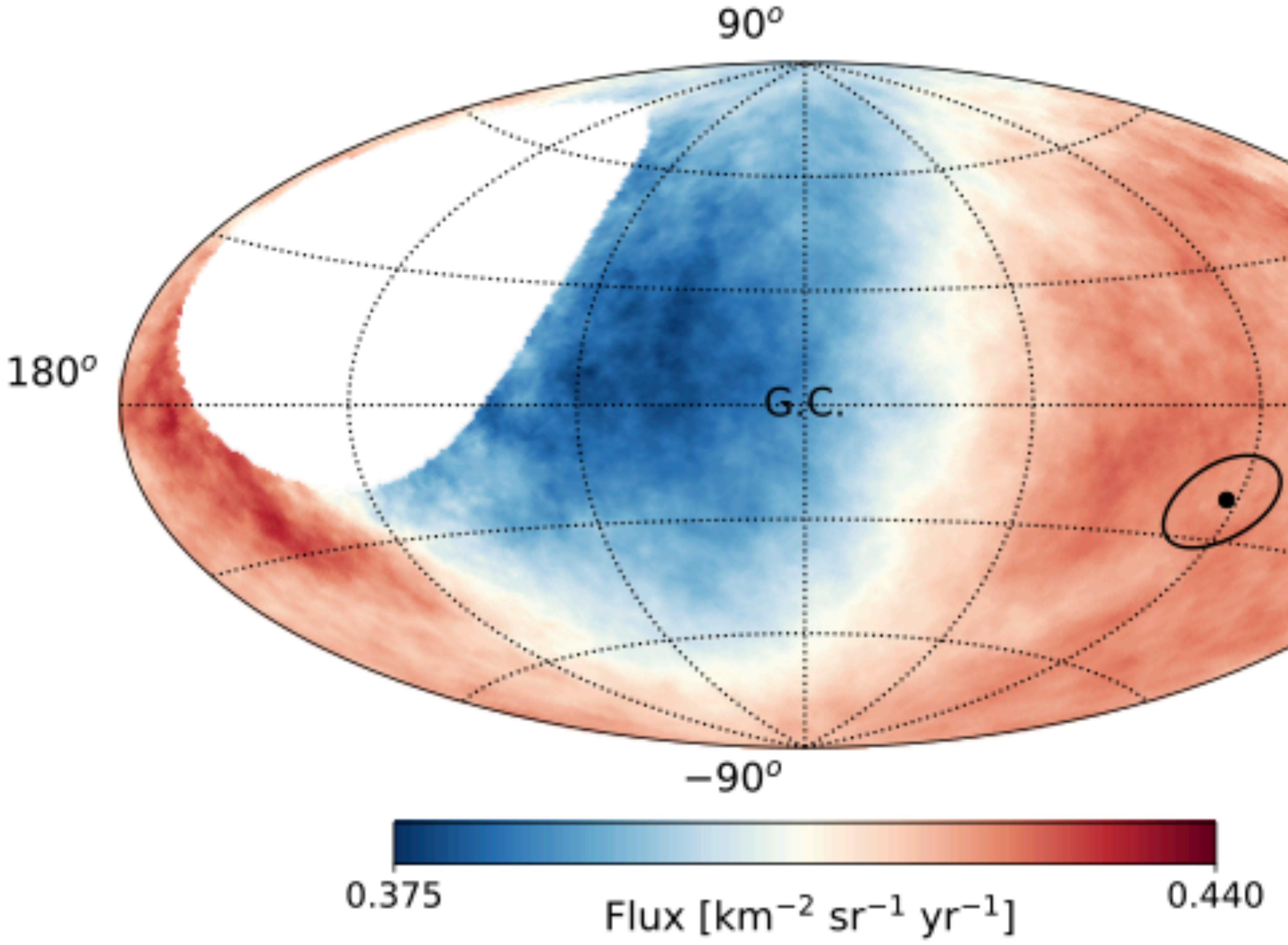
- Increase of mass with energy
- Hadronic interactions (?)
- Proton fraction at high energy (?)

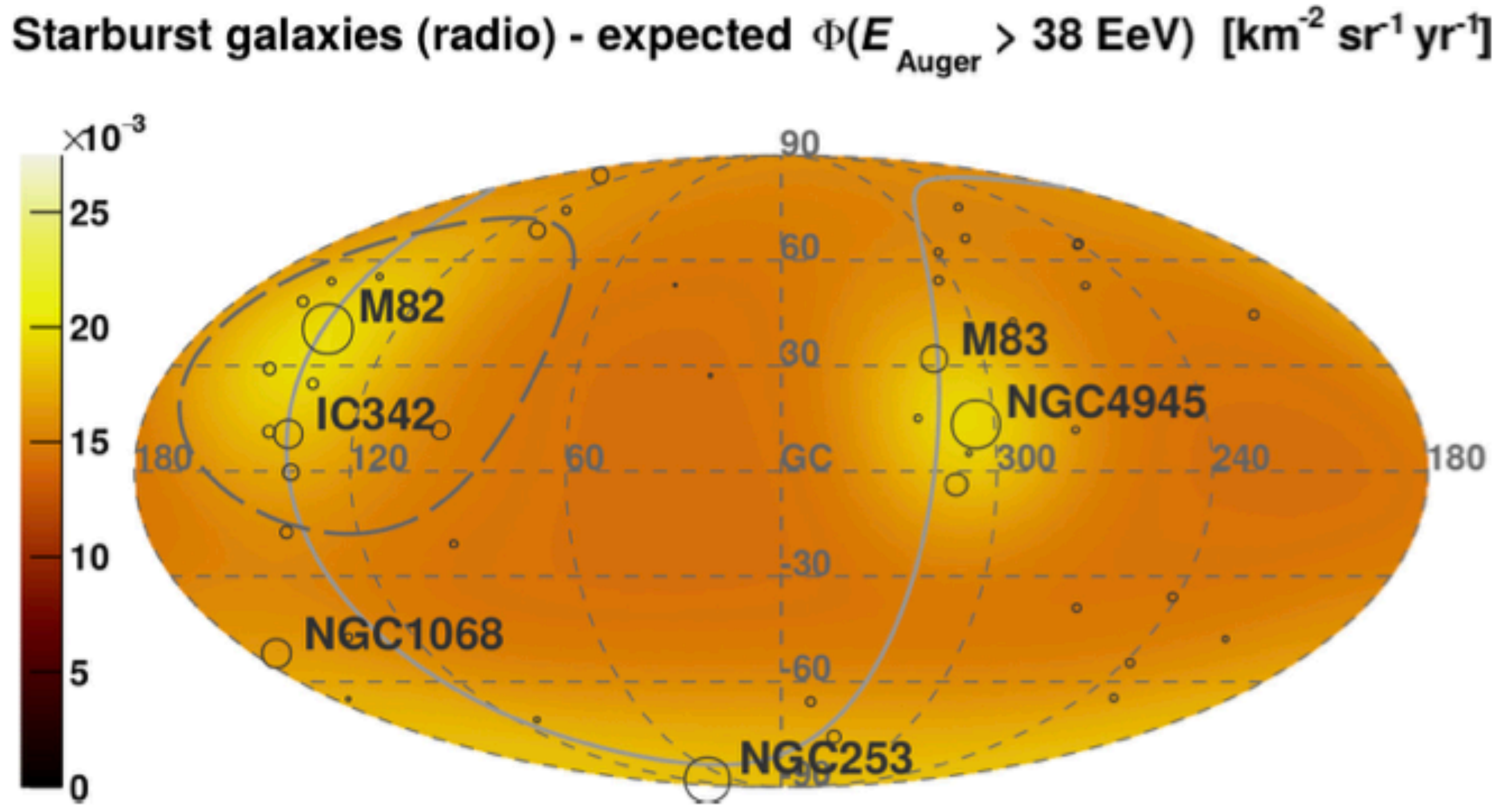
The Pierre Auger Collaboration, ICRC 2017-2019

- More details about mass composition in Lecture 2

STATE-OF-THE-ART

arxiv: 2205.05845





- > 6sigma measurement of large scale dipole anisotropy above 6 EeV

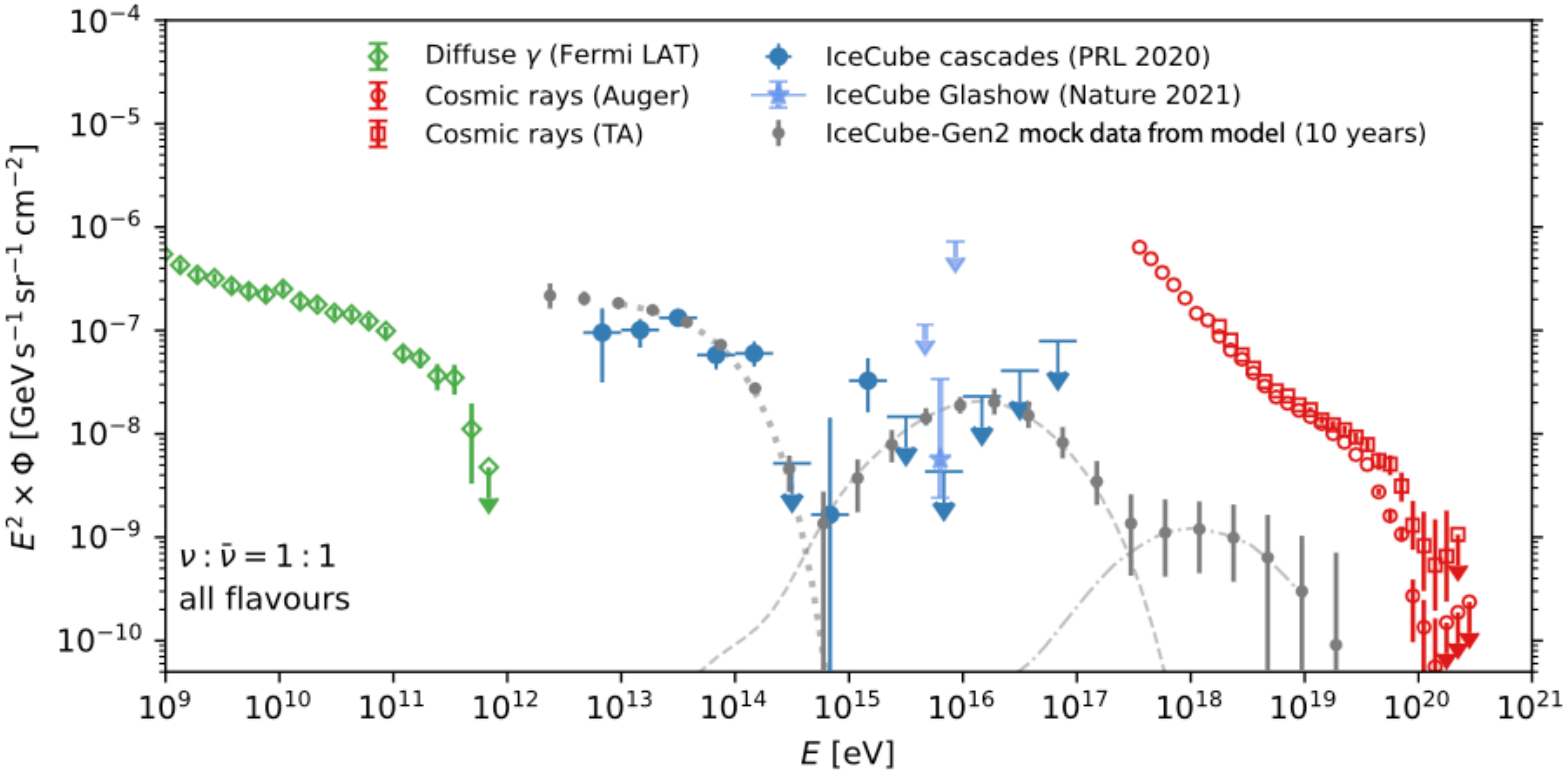
  -> evidence of extragalactic origin of UHECRs above this threshold

- 4sigma significance correlation of UHECR events with starburst galaxies

- Magnetic deflections?

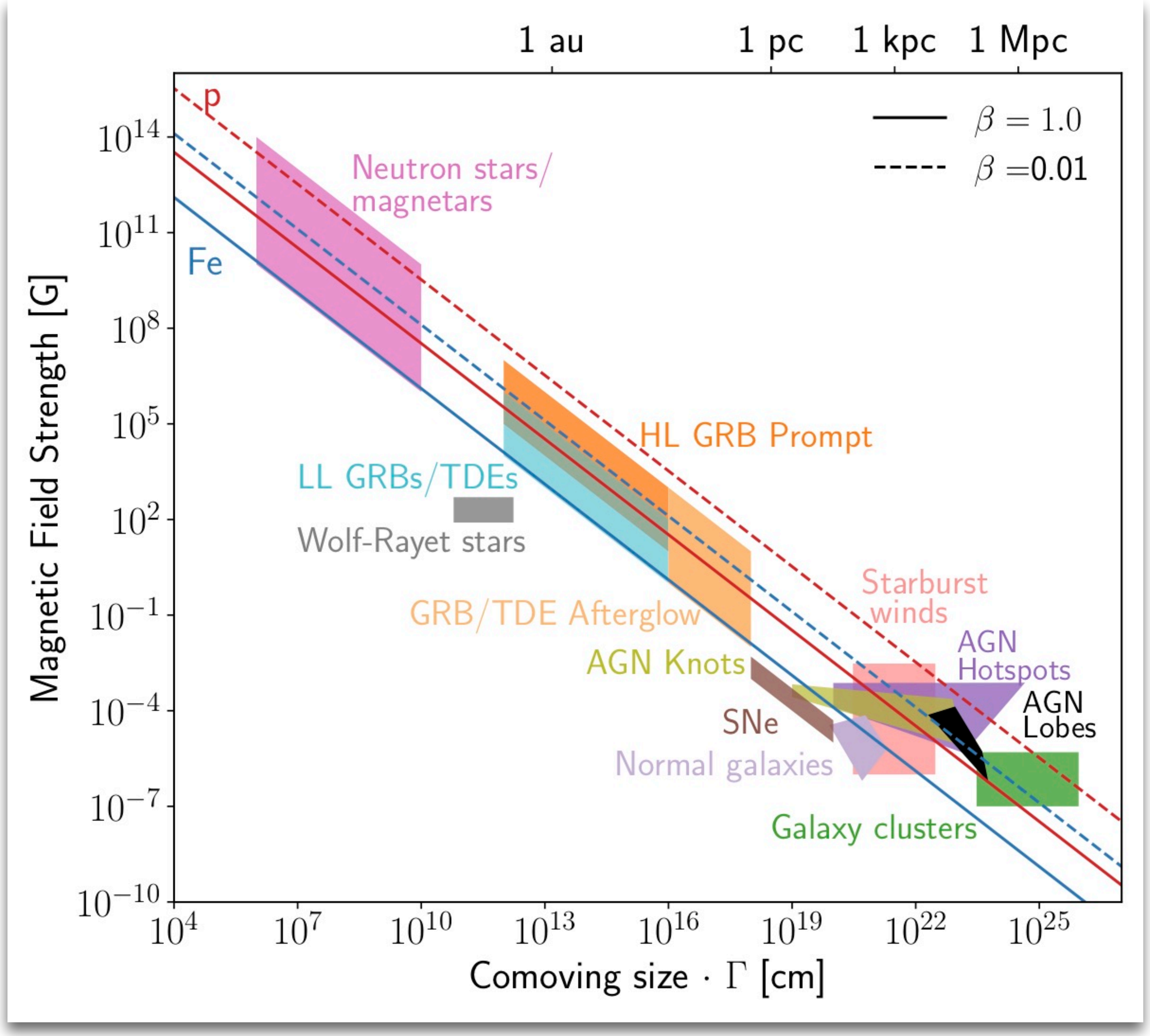
STATE-OF-THE-ART

arxiv: 2205.05845



- Connections with other messengers

THE COSMIC-RAY ACCELERATORS



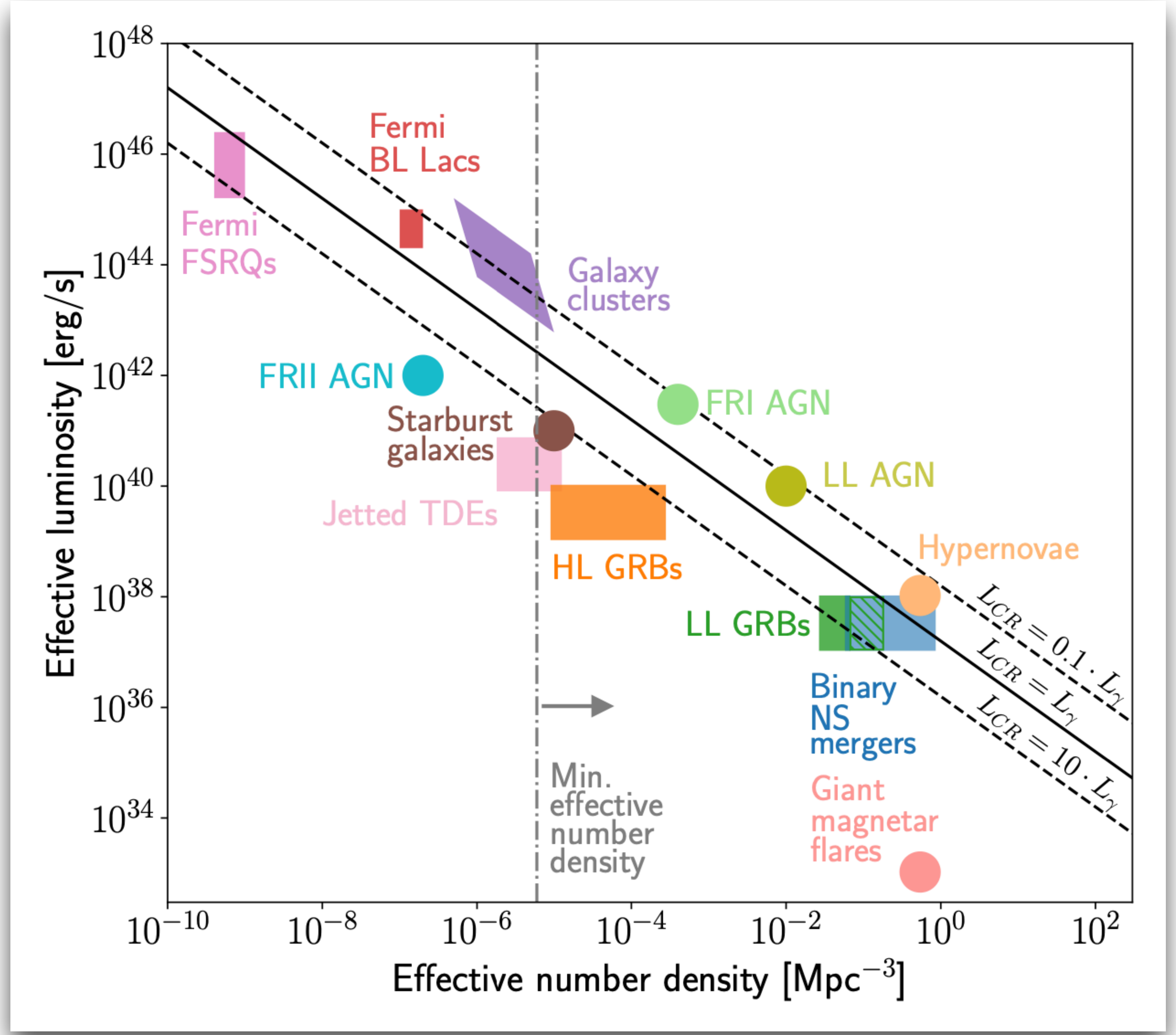
Alves Batista et al, 2019

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

Hillas 1984

- Max energy is limited by the gyroradius of the accelerator
- (Candidate) accelerators can be classified thanks to magnetic field and size

THE COSMIC-RAY ACCELERATORS

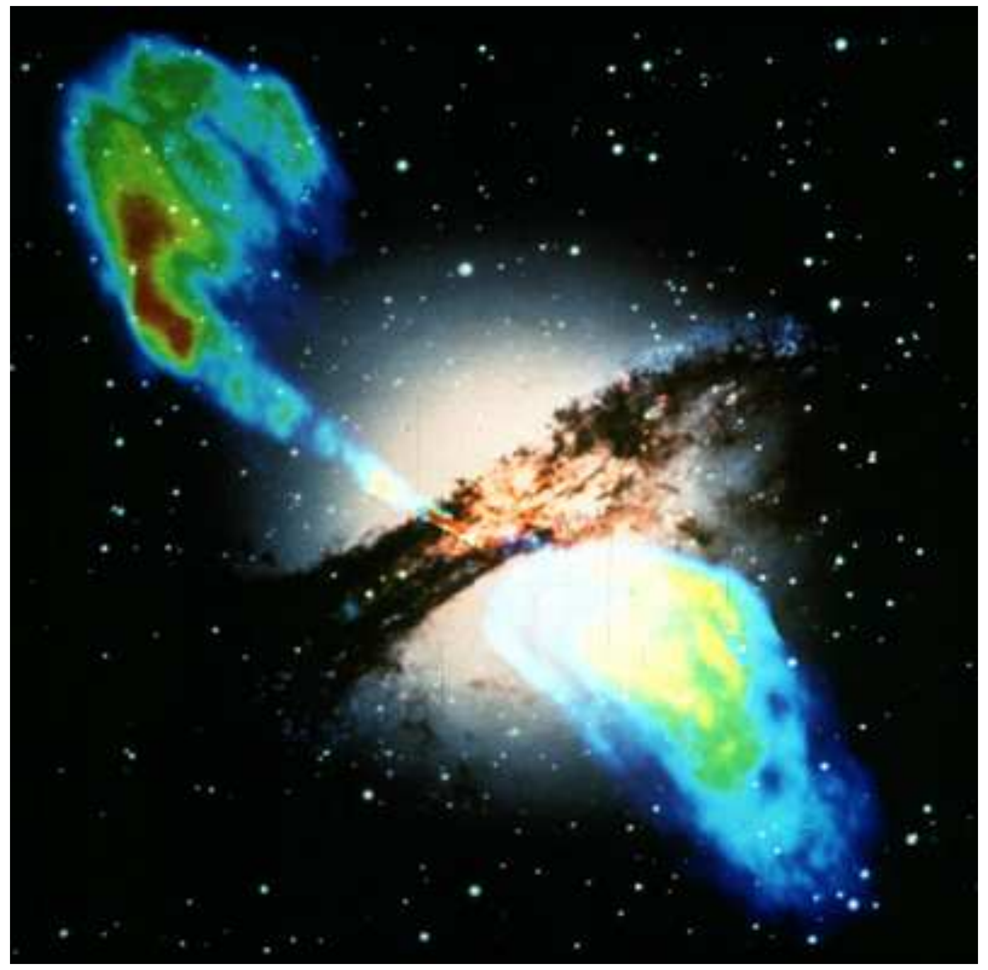


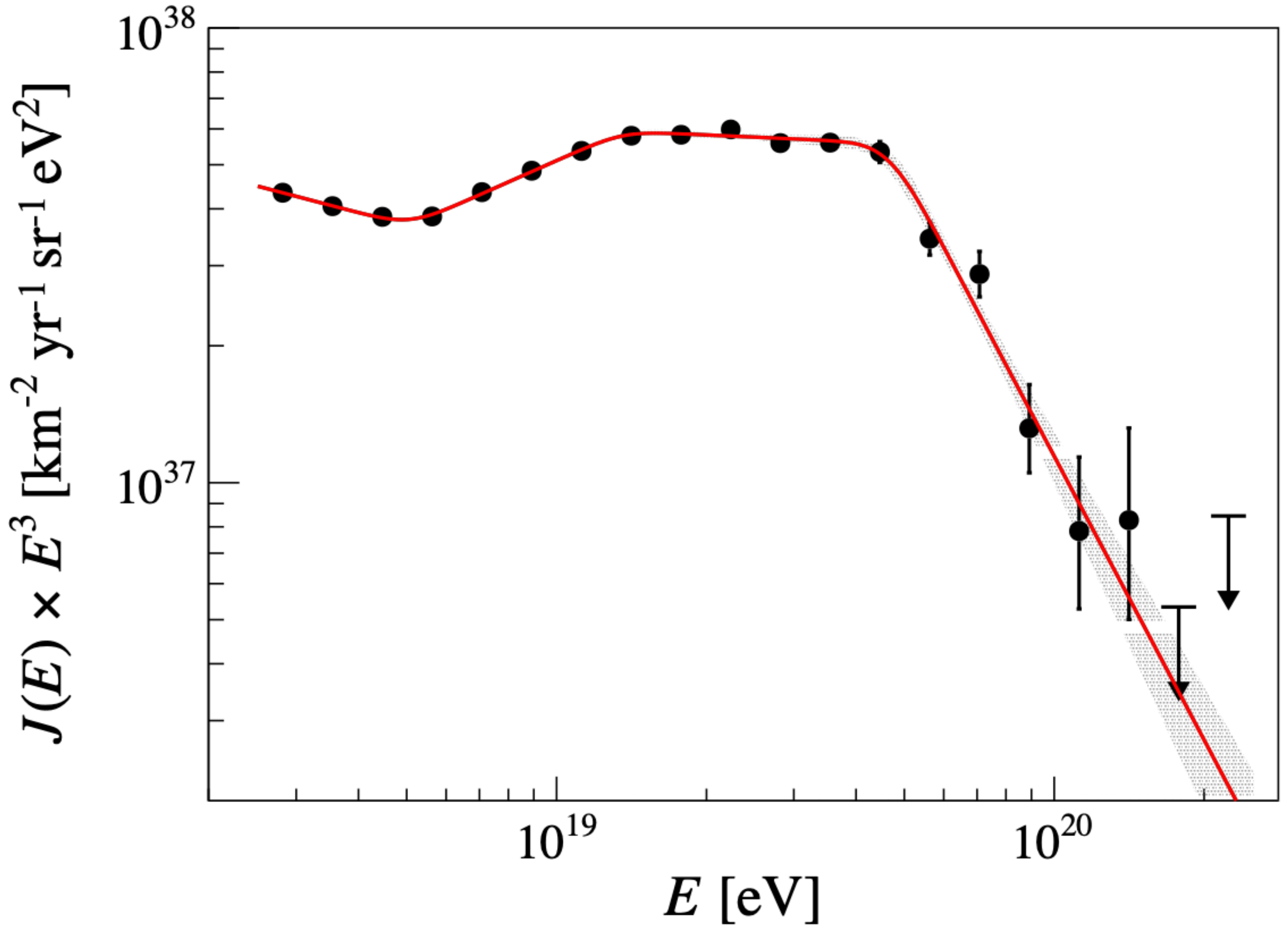
Alves Batista et al, 2019

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

- Required energy budget to produce observed UHECRs

WHY ?





- Extragalactic propagation of UHECRs
  - Features of UHECR spectrum
  - UHECR astronomy (?)
  - Connection to other messengers
- UHECR interactions (in-source and propagation)

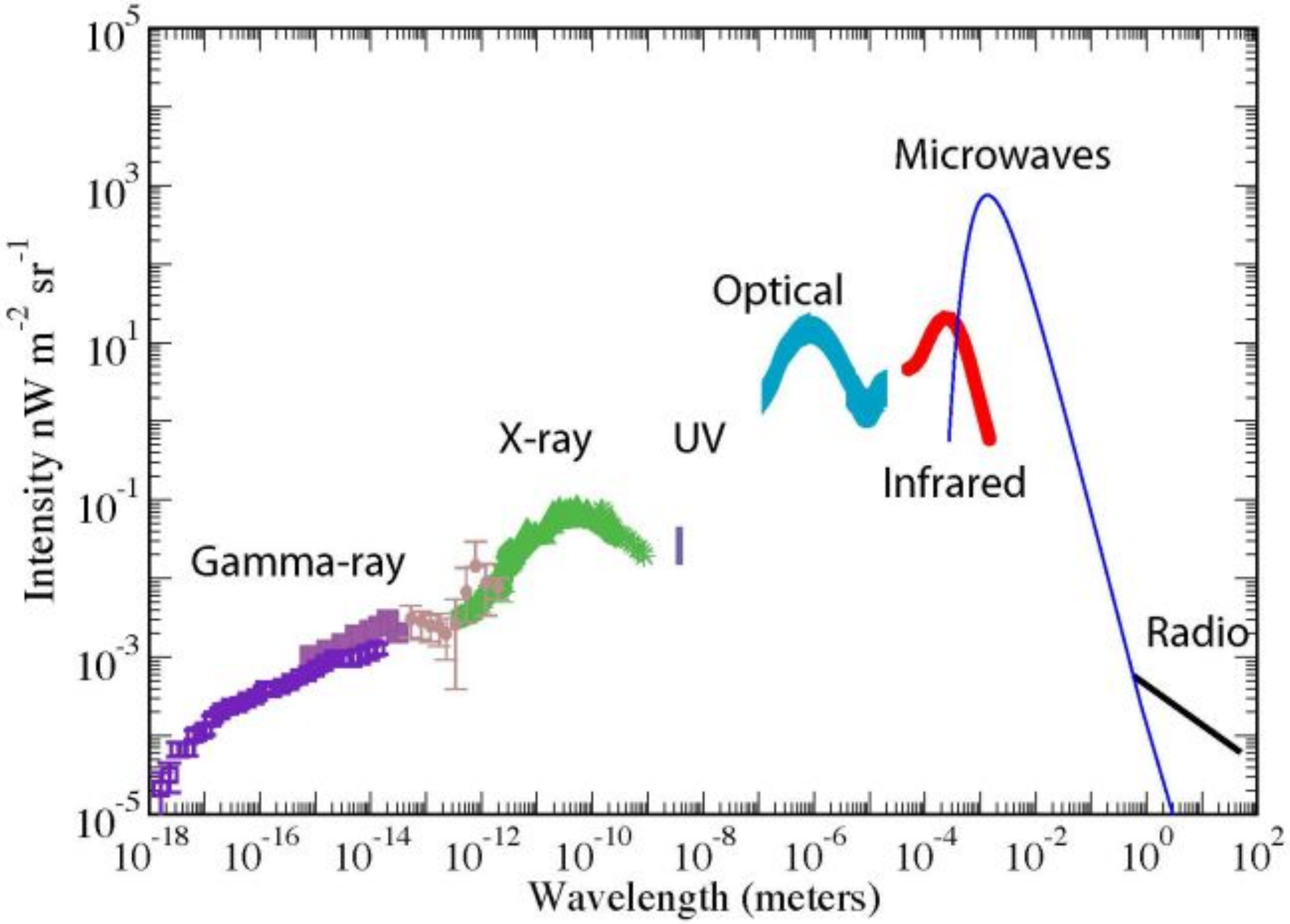
RATES OF INTERACTIONS

INGREDIENT (1): ASTROPHYSICS

- Photons of various energies and densities pervade the Universe

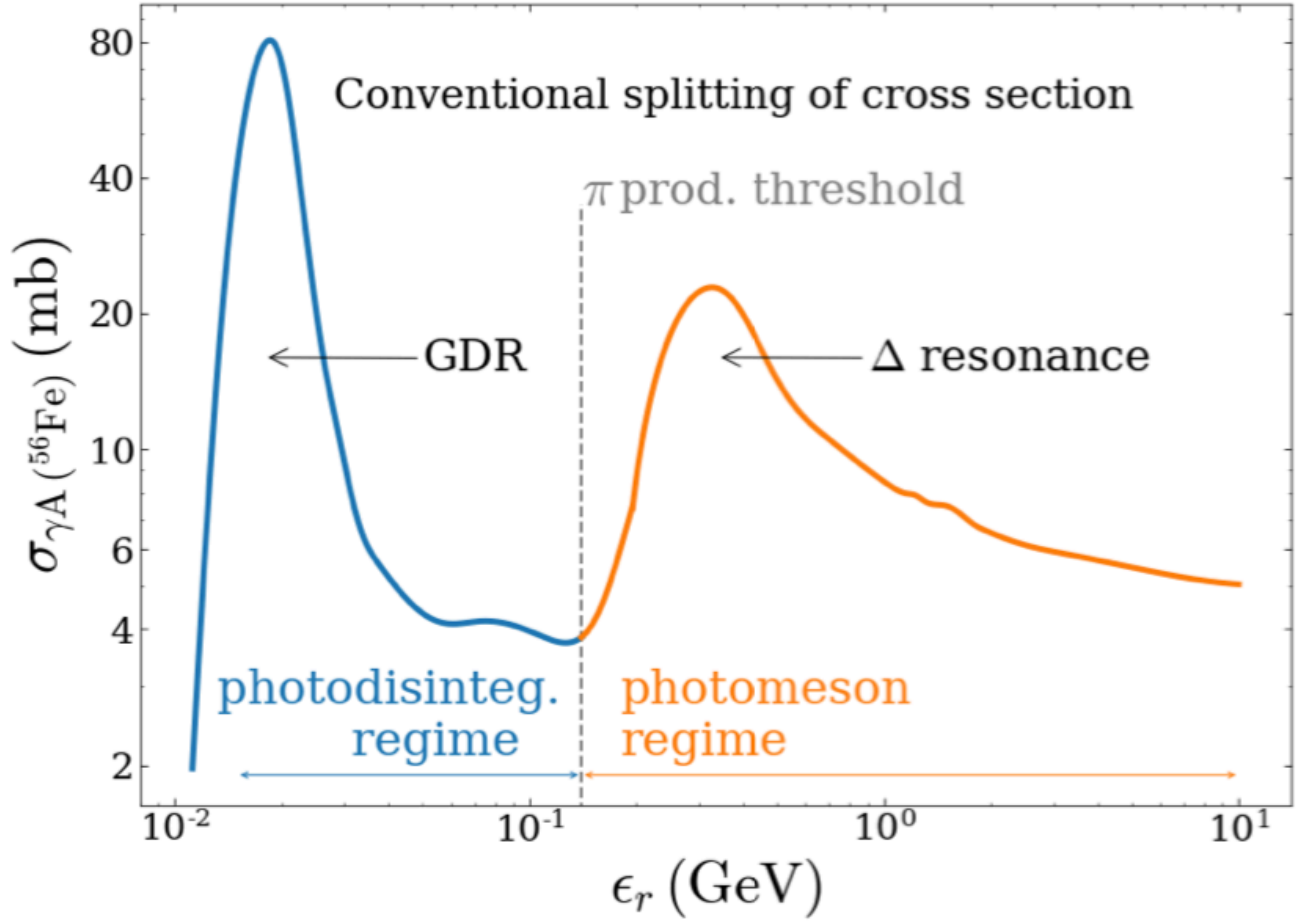
- For the energies of the UHECRs, relevant photon fields are:
  - Cosmic Microwave Background (**CMB**)
    - Discovered by Penzias and Wilson in 1965, is a relic radiation from the Big Bang; **black body** at temperature 2.7 K
  - UV-optical-IR (also called Extragalactic Background Light, **EBL**)
    - 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

https://ned.ipac.caltech.edu



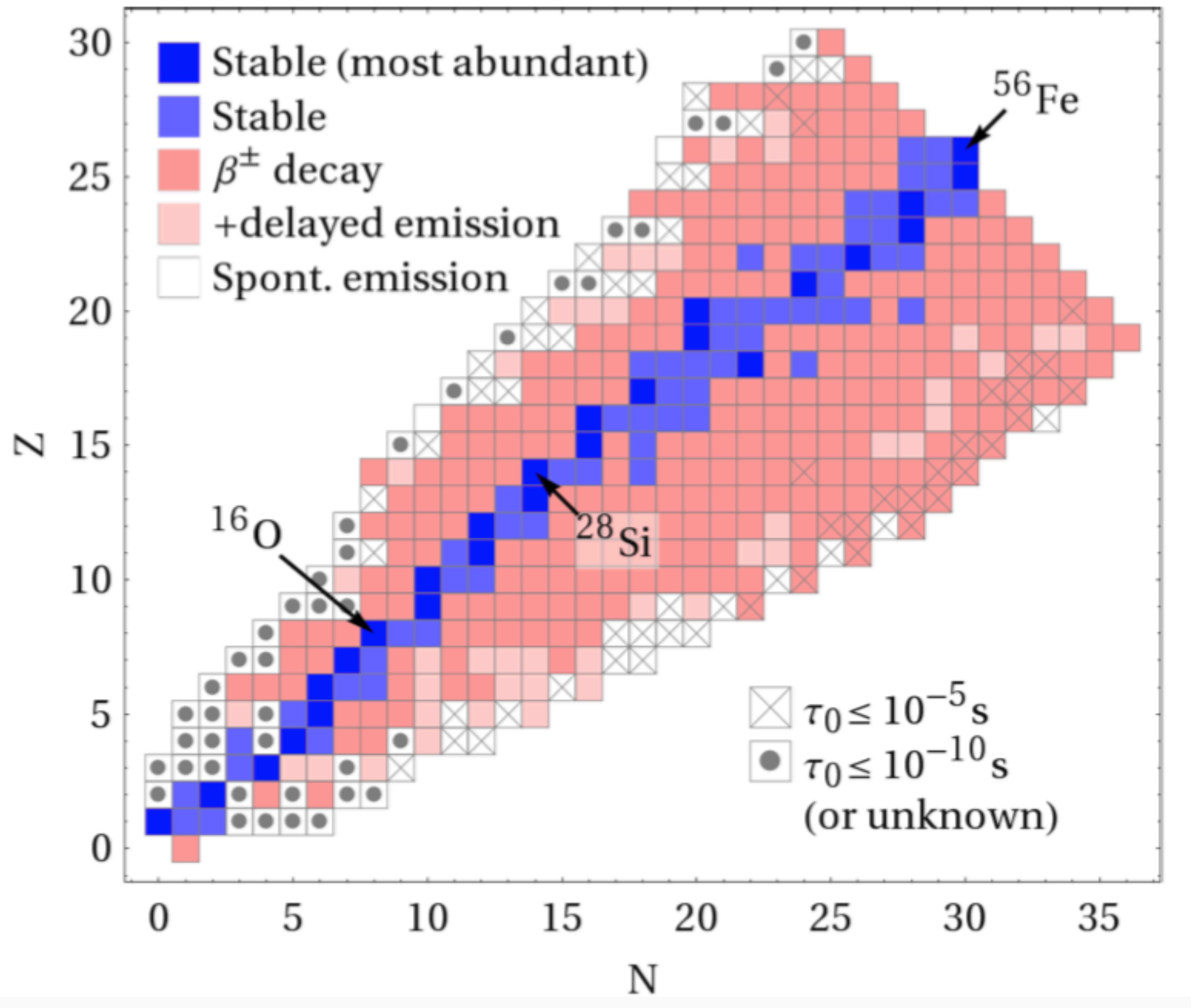
INGREDIENT (2): NUCLEAR PHYSICS

- Main reactions:
  - **Photo-disintegration** (through excitation of Giant Dipole Resonance)
  - **Photo-meson production** (through excitation of Delta resonance)



Morejon, Fedynitch, **DB**, Biehl & Winter 2019

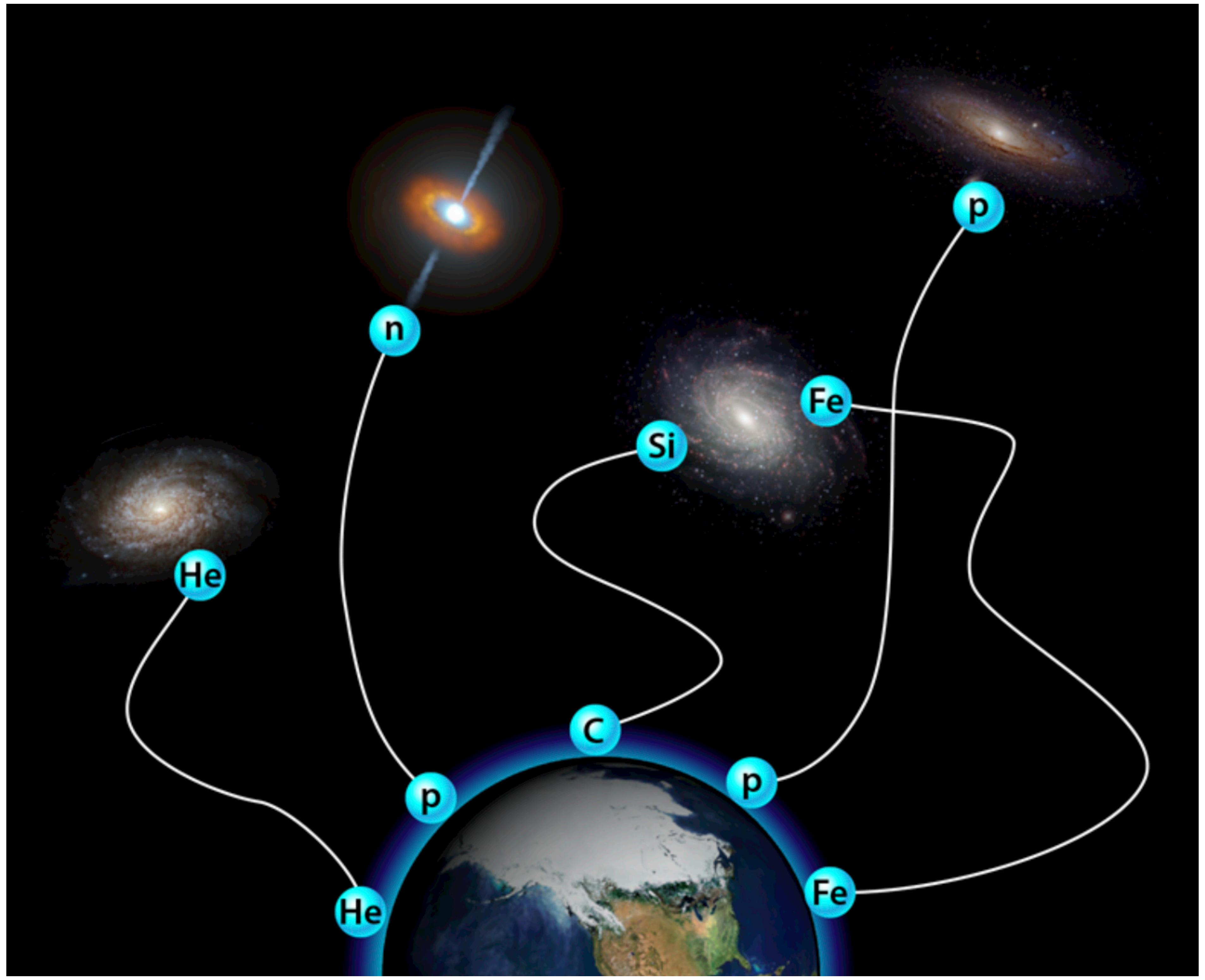
Interactions of **nuclei** (and not only protons!) must be taken into account, due to evidences from **measurements of CR mass composition**



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

KINEMATICS

- Special relativity
- Four-vector algebra
- Lorentz invariant quantity: scalar product of four-vectors is an invariant
  - Energy-momentum vector will be taken into account in the following

$$P_i = \left(\frac{E_i}{c}, \overrightarrow{p_i}\right)$$

$$a + b \rightarrow c + d$$

$$s = (E_a + E_b)^2 - (\overrightarrow{p}_a + \overrightarrow{p}_b)^2 = (E_c + E_d)^2 - (\overrightarrow{p}_c + \overrightarrow{p}_d)^2$$

$$s_{\text{th}} = (E_a + E_b)^2 - (\overrightarrow{p}_a + \overrightarrow{p}_b)^2 = (m_c + m_d)^2$$

KINEMATICS - PHOTO-PION REACTIONS

- 1965, discovery of CMB
- Greisen, Zatsepin and Kuzmin: cosmic ray particles interact with CMB photons through

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

  - Energy loss of protons -> end of the CR flux at the highest energies?

Greisen, PRL 1966;

Zatsepin & Kuzmin, JETP Lett 1966

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

$$= m_p^2 + 2E_{\rm th}\varepsilon(1 - \beta_p \cos\theta)$$

$$= m_p^2 + 2m_p\Gamma\varepsilon(1 - \beta_p \cos\theta)$$

$$= m_p^2 + 2\varepsilon' m_p$$

$$E_p = \Gamma m_p \quad p_p \approx E_p$$

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

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

KINEMATICS - PHOTO-PION REACTIONS

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

$$\gamma p \to \pi^0 p$$

- Energy of the photon in the nucleus rest frame has to be sufficient to produce pion(s) !
  - Energies of hundred(s) of MeV

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

$$\langle\varepsilon\rangle \approx 7 \times 10^{-4}\,\mathrm{eV}$$

For the case of CMB

$$\Gamma_{\mathrm{th}} \approx 7 \times 10^{10}$$

KINEMATICS - PHOTO-PION REACTIONS

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

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$$\varepsilon' \approx \varepsilon\Gamma \qquad \langle\varepsilon\rangle \approx 7 \times 10^{-4}\,\mathrm{eV}$$

For the case of CMB

$$\Gamma_{\mathrm{th}} \approx 7 \times 10^{10}$$

- If average **energy of the photon field is larger**, **lower energy particles** can trigger the same reaction -> e.g. infrared photon fields
- If nuclei heavier than protons are involved, the **threshold energy** is larger (threshold Lorentz factor is the same, superposition model can be used in first approximation)

KINEMATICS - PAIR PRODUCTION

- Bethe-Heitler pair production

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

Blumenthal, PRD 1970

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

$$= m_p^2 + 2E_{\rm th}\varepsilon(1 - \beta_p \cos\theta) \quad = (m_p + 2m_e)^2$$

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

Exercise: derive the energy threshold for pair production

INTERACTION RATES

- Rate of interactions of a particle propagating through CMB

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

INTERACTION RATES

- Rate of interactions of a particle propagating through CMB

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

$$\frac{dN_\gamma}{dVd\varepsilon} = n_\gamma(\varepsilon) = \frac{1}{\pi^2(\hbar c)^3}\frac{\varepsilon^2}{\exp(\varepsilon/k_BT)-1}$$

- Energy density of CMB photons, black body
  - We assume isotropy

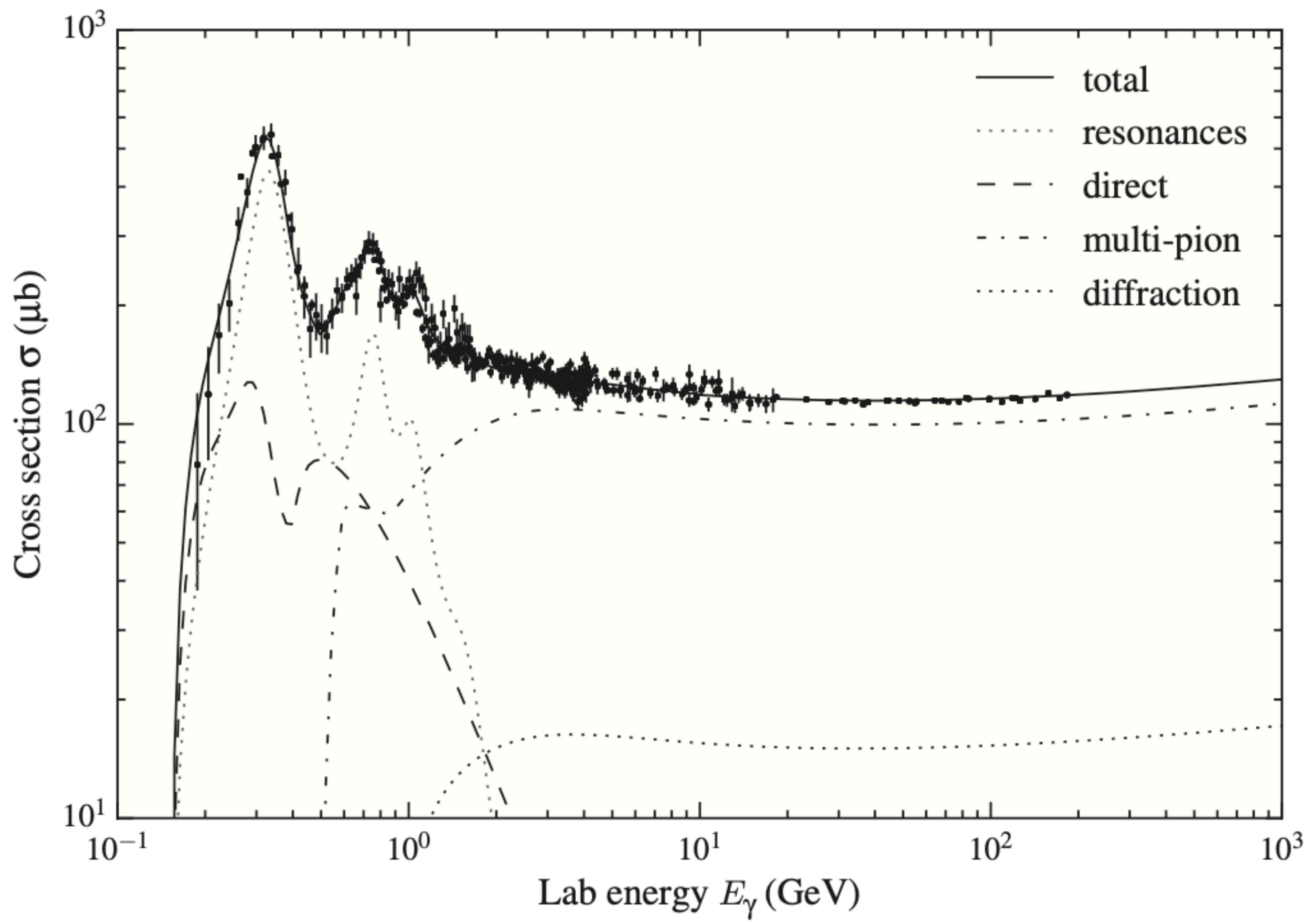
$$n_\gamma(\varepsilon, \cos\theta) \approx n_\gamma(\varepsilon)$$

INTERACTION RATES

- Rate of interactions of a particle propagating through CMB

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

- Cross section results in superposition of resonances, formed in the absorption of the photon
  - Delta is the main resonance, decaying in pion and proton
- For heavier nuclei, the **superposition model** can be used as first approximation



INTERACTION RATES

Gaisser, Engel & Resconi

Berezinsky, Grigorieva & Gazizov 2006

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

- In order to compute the integral we take into account:
  - The relation between the photon energy in the lab and the photon energy in the proton rest frame
  - The transformation:

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

$$d\varepsilon' = -\Gamma\varepsilon\, d\cos\theta$$

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

INTERACTION RATES

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

- If we take into account the CMB photon field, the second integral is analytical
  - suggested transformation $y = e^{\varepsilon/k_B T} - 1$

$$\frac{dN_{\rm int}}{dt} = \frac{c k_B T}{2\pi^2(\hbar c)^3\Gamma^2}\int_{\varepsilon'_{\rm th}}^{\infty} \varepsilon'\sigma(\varepsilon')\left\{-\ln\left[1-\exp\left(-\frac{\varepsilon'}{2\Gamma k_B T}\right)\right] d\epsilon'\right\}$$

Exercise: derive the energy loss length in the case of CMB

Berezinsky, Grigorieva & Gazizov 2006

ENERGY LOSS LENGTH

The fractional **energy loss rate (for an arbitrary photon field)** is then:

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

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

The trajectory of a particle can be followed as: $$\frac{dE}{ds} = -\frac{E}{l_{\rm loss}}$$

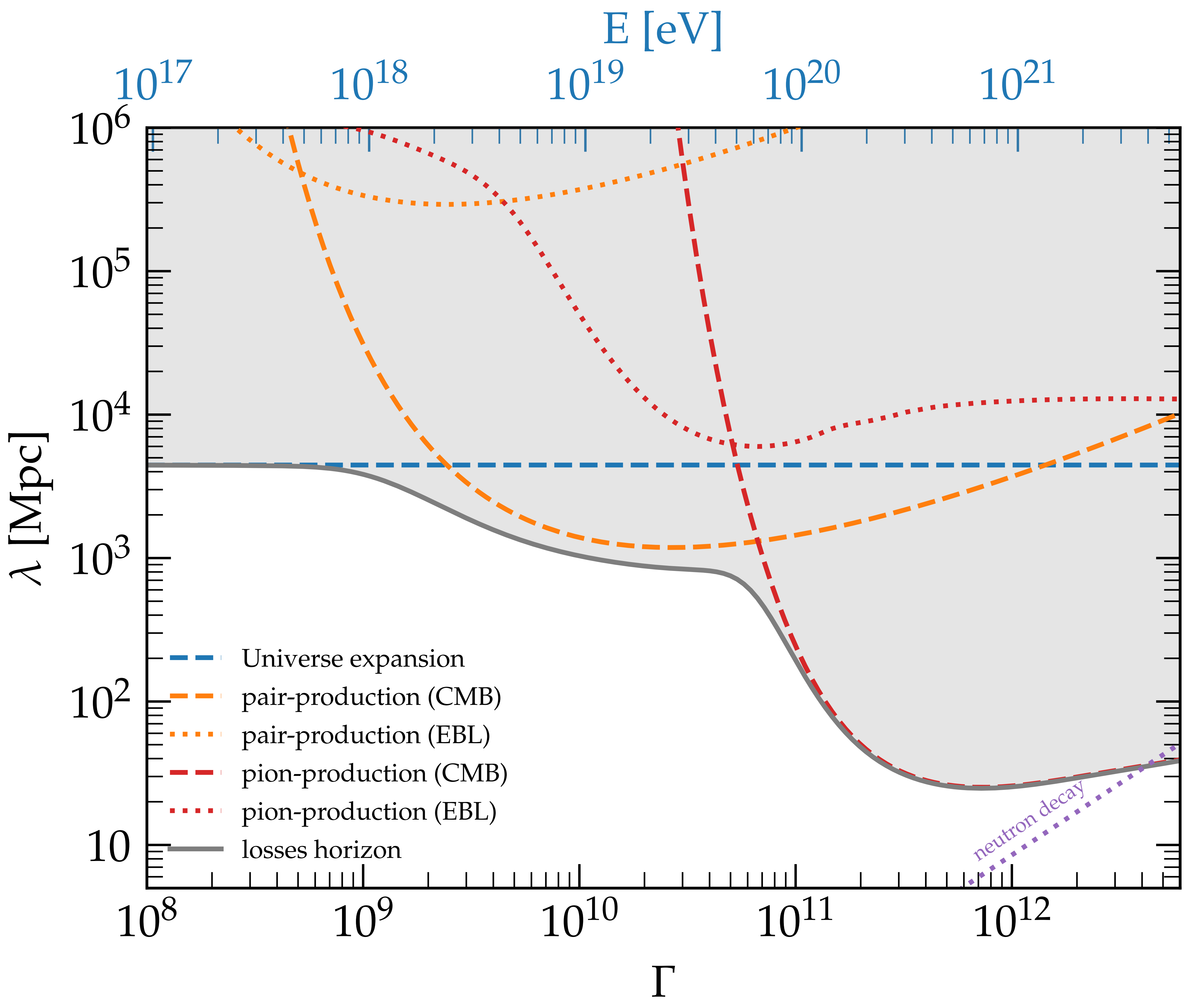
Gaisser, Engel & Resconi

ENERGY LOSS LENGTH

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

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

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



Plot by C. Evoli

FLUX AT EARTH

METRICS

Robertson-Walker metrics $$ds^2 = dt^2 - c^2R^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right)$$

Scale factor $R(t)$

Cosmological redshift $$1 + z = \frac{R(t_0)}{R(t_1)}$$

$$\frac{dt}{dz} = -\frac{1}{H_0(1+z)\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}}$$

FLUX FROM A SINGLE SOURCE

Source at cosmological distance, z_g emitting $Q(E_g(E,z))$

$$I(E)dE = \frac{Q(E_g(E,z))}{(1+z_g)4\pi(R(t_0)r)^2}dE_g$$

$$J(E,z) = \frac{1}{(4\pi)^2}\frac{Q(E_g(E,z))}{(1+z_g)(R(t_0)r)^2}\frac{dE_g}{dE}$$

FLUX FROM A SINGLE SOURCE

Energy loss rate

$$\beta(E) = -\frac{1}{E}\frac{dE}{dt}$$

$$b(E) = -\frac{dE}{dt} = E\beta(E)$$

Dependence on redshift

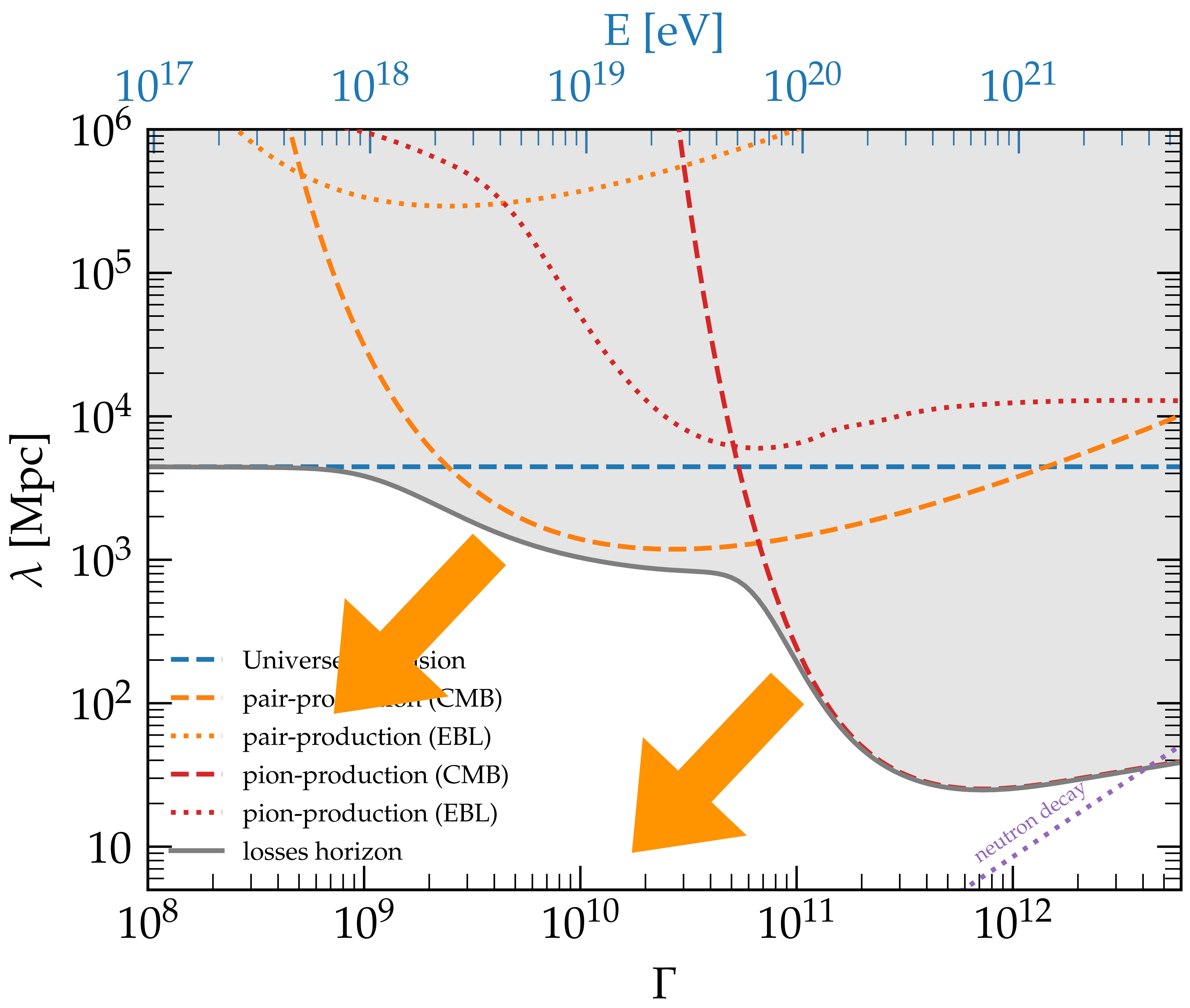
$$\beta(E, z) = (1+z)^3 \beta_0((1+z)E)$$

$$b(E, z) = (1+z)^2 b_0((1+z)E)$$

- Temperature of CMB $T(z) = T_0(1+z)$
- Density of photons $n_\gamma(z) = n_{\gamma,0}(1+z)^3$
  - Larger density of photons in the past, larger probability of interaction

ENERGY LOSS LENGTH - DEPENDENCE ON REDSHIFT

$$l_{\rm loss}(E, z) = (1+z)^{-3} l_{\rm loss}((1+z)E, z=0)$$



FLUX FROM A SINGLE SOURCE

Evolution of energy as a function of time/redshift

$$-\frac{1}{E_g}\frac{dE_g}{dt} = -\frac{1}{E_g}\frac{dE_g}{dz}\frac{dz}{dt} = \beta(E_g, z(t))$$

$$\frac{dE_g}{dz} = -E_g\frac{dt}{dz}\beta(E_g, z(t))$$

$$\frac{dE_g}{dz} = E_g\left\{\frac{(1+z)^2\beta_0(E_g, z)}{H_0\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}} + \frac{1}{1+z}\right\}$$

$$\left(\frac{dt}{dz}\right)^{-1} = -H_0(1+z)\sqrt{(1+z)^3\Omega_m + \Omega_\Lambda}$$

Energy loss rate as a function of time/redshift

$$\beta(E, z) = -\frac{1}{E}\frac{dE}{dz}\left(\frac{dt}{dz}\right)^{-1}$$

FLUX FROM A SINGLE SOURCE

$$E_g(z) = E + \int_t^{t_0} dt \left[\left(\frac{dE}{dt}\right)_{ad} + \left(\frac{dE}{dt}\right)_{int} \right]$$

$$dz = -H(z)(1+z)dt$$

$$b(E,z) = -\frac{dE}{dt} = (1+z)^2 b_0((1+z)E)$$

$$E_g(z) = E + \int_0^z dz' \frac{E_g(z')}{1+z'} + \int_0^z dz' \frac{1+z'}{H(z')} b_0((1+z')E_g(z'))$$

$$y(z) = 1 + \int_0^z dz' \frac{y(z')}{1+z'} + \int_0^z dz' \frac{1+z'}{H(z')} \frac{db_0((1+z')E_g(z'))}{dE} = 1 + \int_0^z dz' \frac{y(z')}{1+z'} + \int_0^z dz' \frac{(1+z')^2}{H(z')} \frac{db_0((1+z')E_g(z'))}{d((1+z')E_g(z'))} y(z')$$

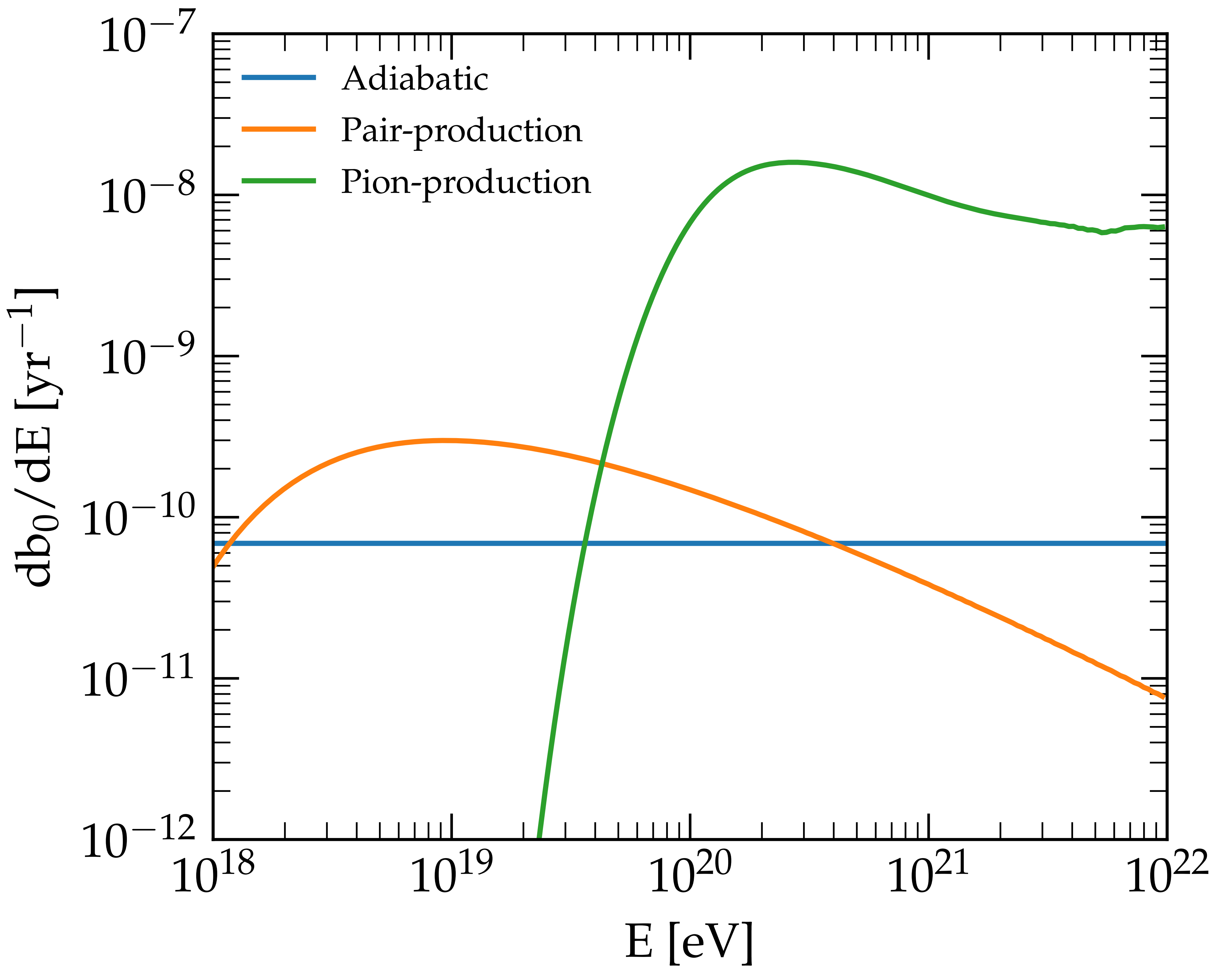
$$\frac{1}{y}\frac{dy}{dz} = \frac{1}{1+z} + \frac{(1+z)^2}{H(z)} \frac{db((1+z)E_g(z))}{d((1+z)E_g(z))}$$

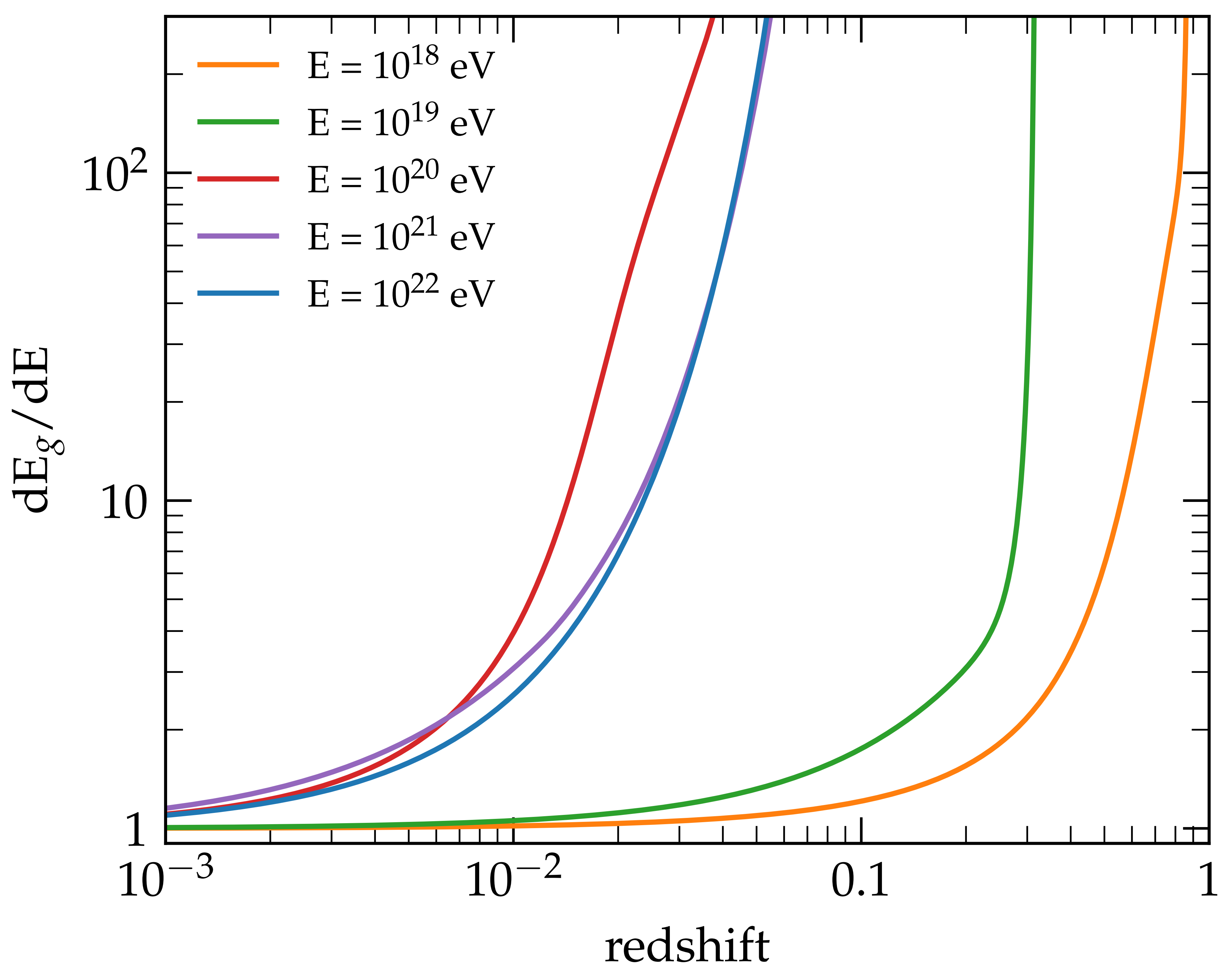
$$y(z) = (1+z)\exp\left\{ \frac{1}{H_0} \int_0^z dz' \frac{(1+z')^2}{\sqrt{(1+z')^3\Omega_m + \Omega_\Lambda}} \frac{db_0((1+z')E_g(z'))}{d((1+z')E_g(z'))} \right\}$$

Berezinsky & Grigorieva 1988

FLUX FROM A SINGLE SOURCE

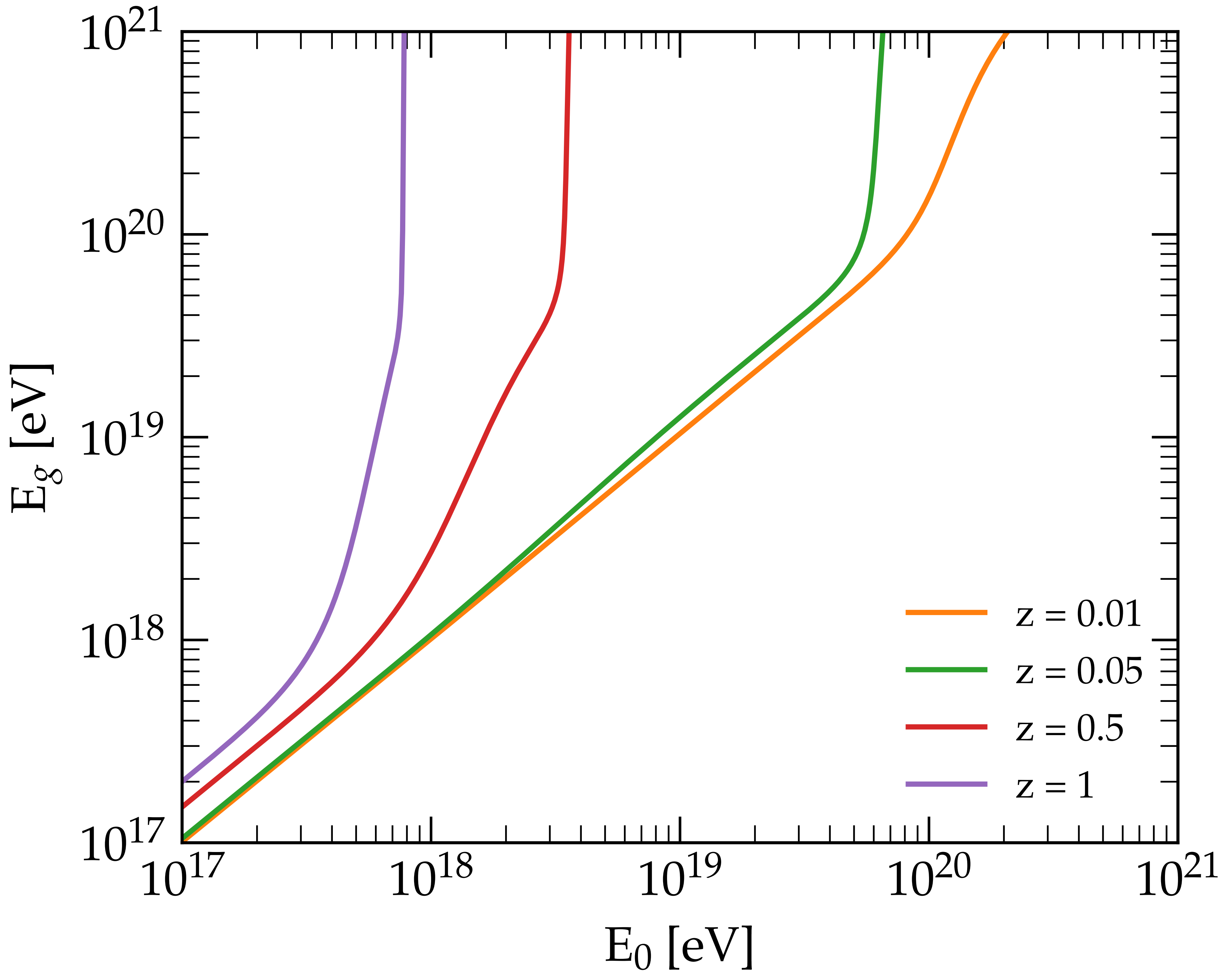
$$y(z) = (1+z)\exp\left\{\frac{1}{H_0}\int_0^z dz'(1+z')^3\left|\frac{dt}{dz}\right|\left(\frac{db_0}{dE}\right)_{(1+z)E_g(E,z)}\right\}$$

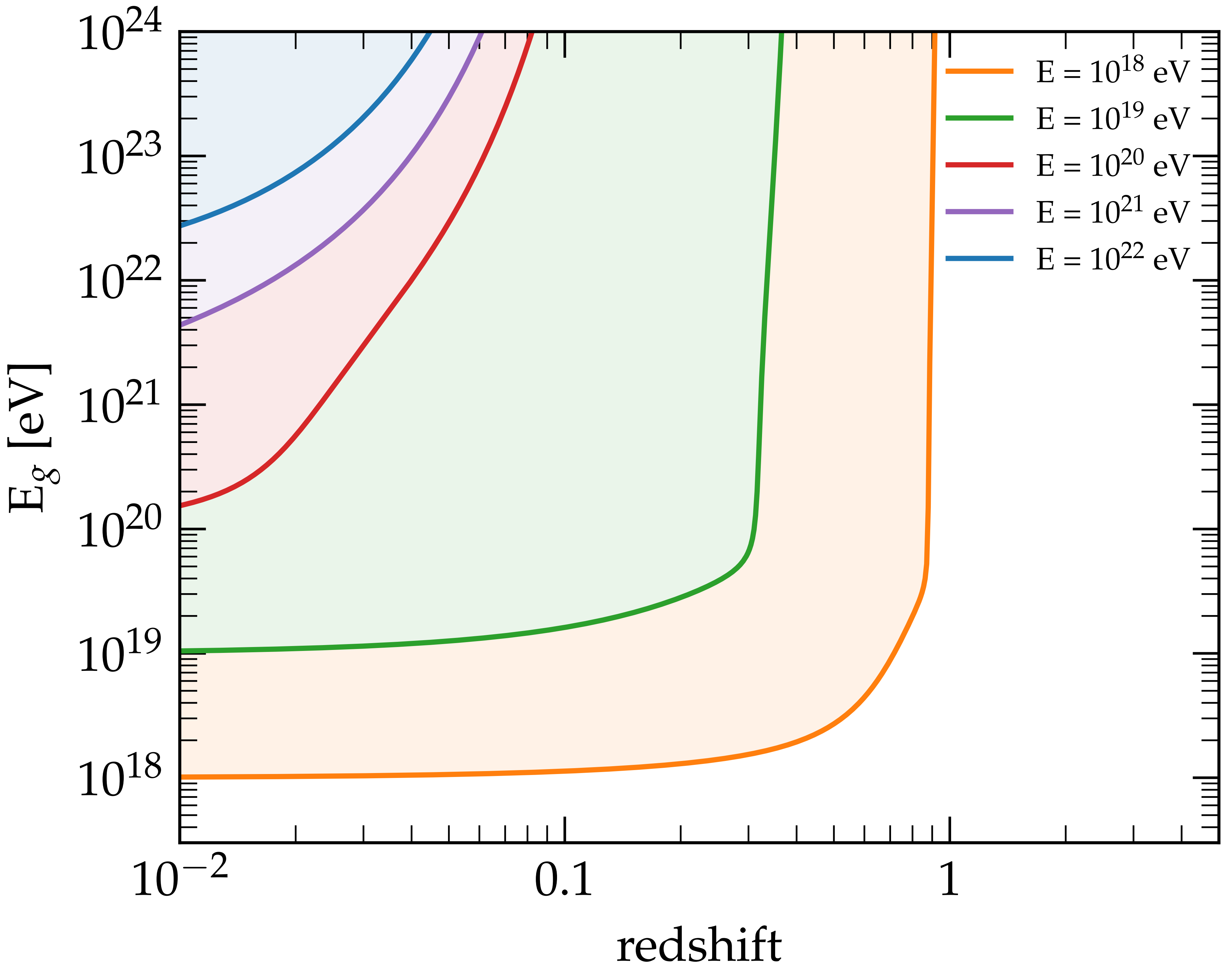




Plots by C. Evoli

FLUX FROM A SINGLE SOURCE





Plots by C. Evoli

FLUX FROM A DISTRIBUTION OF SOURCES

Single source

$$J(E,z) = \frac{1}{(4\pi)^2} \frac{Q(E_g(E,z))}{(1+z_g)(R(t_0)r)^2} \frac{dE_g}{dE}$$

$$\frac{1}{4\pi}\frac{dV}{dz} = (1+z)^3 c d_A^2 \left|\frac{dt}{dz}\right|$$

Distribution of sources

$$J(E) = \frac{1}{(4\pi)^2} \int dV \, \frac{\tilde{Q}(E_g(E,z))}{(1+z)(rR(t_0))^2} \frac{dE_g}{dE}$$

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

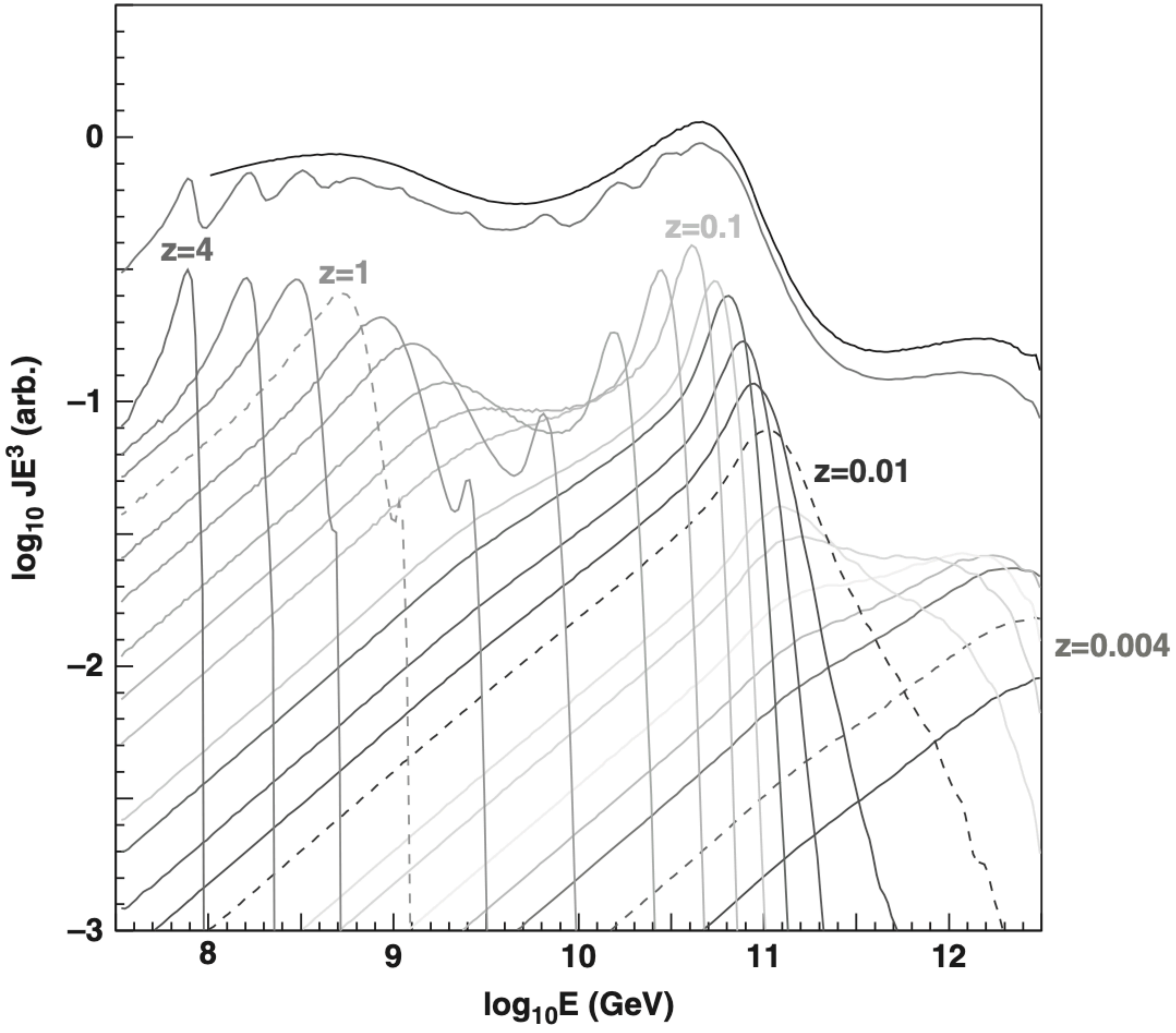
$$\tilde{Q} = n_0 Q$$

$$Q(E) \propto E^{-\gamma} \times f(E_{max})$$

$$L_{CR} = \int E \, Q_{inj}(E) \, dE$$

EXPECTED SPECTRUM AT EARTH

Gaisser, Engel & Resconi

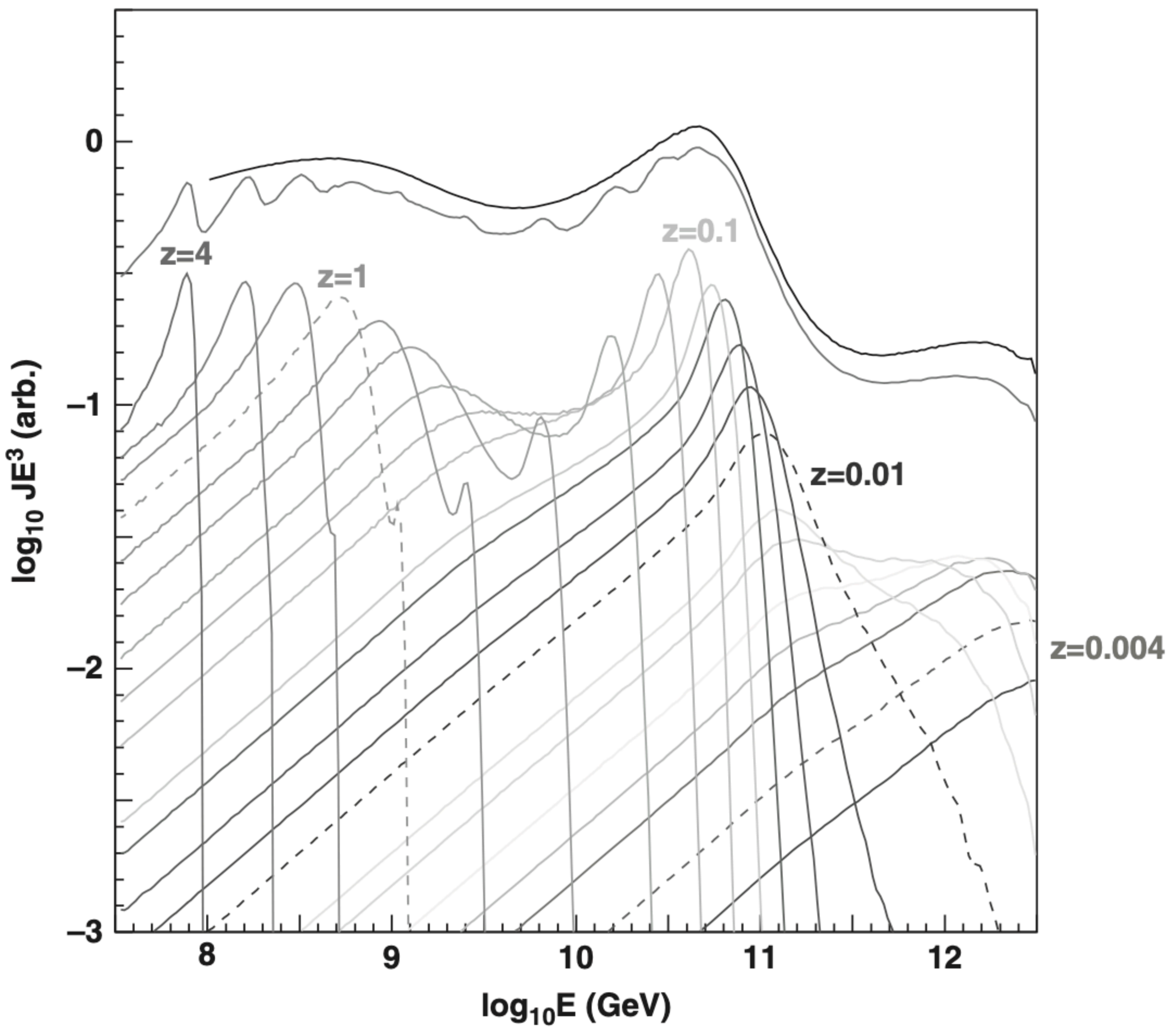


Expected spectrum at Earth (multiplied by E^3) from identical sources emitting protons with $E^{-2.38}$ spectra and cosmological evolution parameter $m = 2.55$

- Contribution of sources at different distances. From right to left we observe:
  - Closest sources: same slope as the one at injection
  - Bump feature: pile-up of protons below photo-pion production threshold
  - Dip
- Total spectrum
  - Bumps produce a flatter spectrum when summed up

EXPECTED SPECTRUM AT EARTH

Gaisser, Engel & Resconi

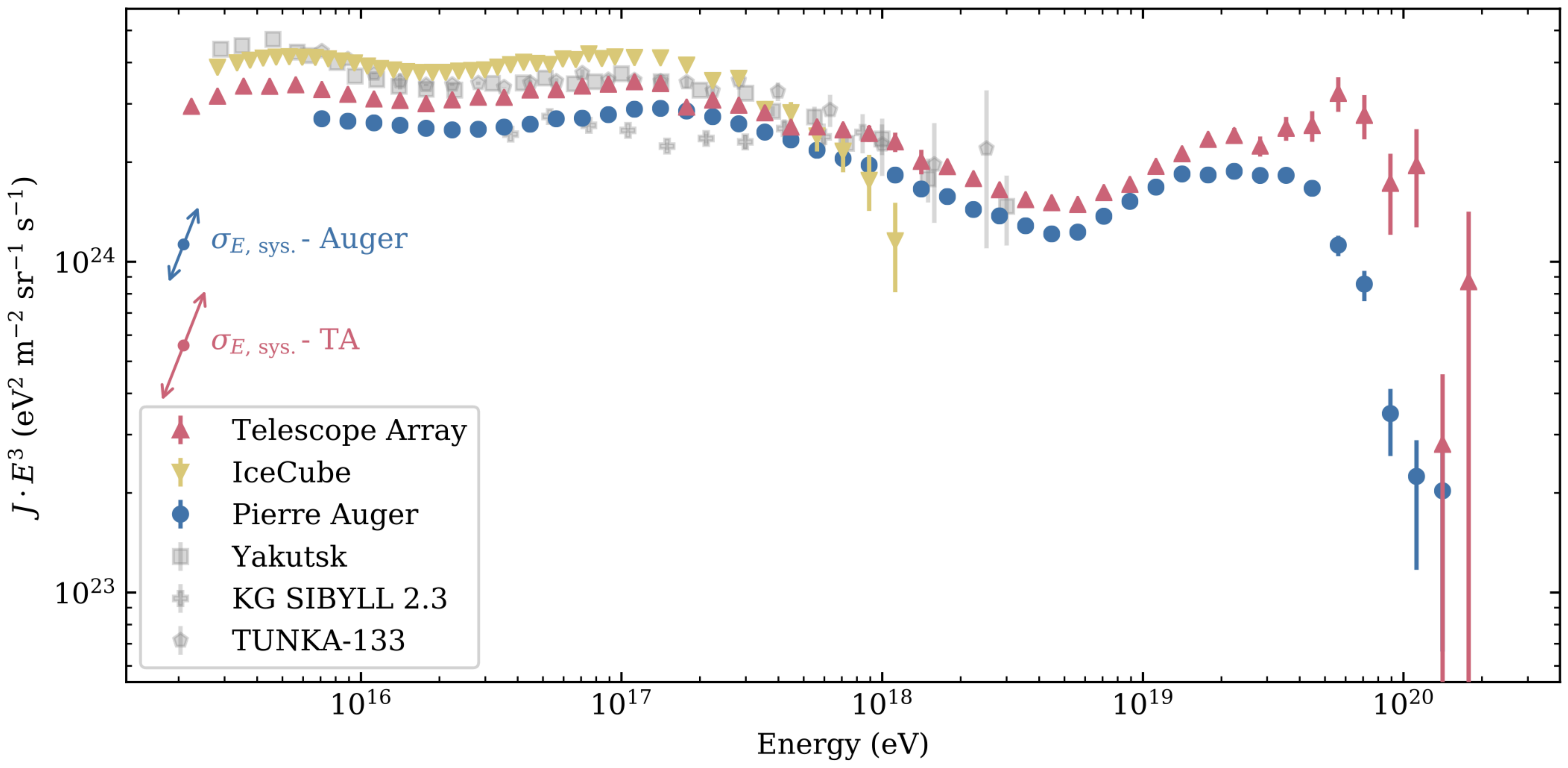


Dependence on details of injection

$$Q_{\rm inj}(E) \propto (1+z)^m E^{-\gamma} \times f(E_{\rm max})$$

INTERPRETATION

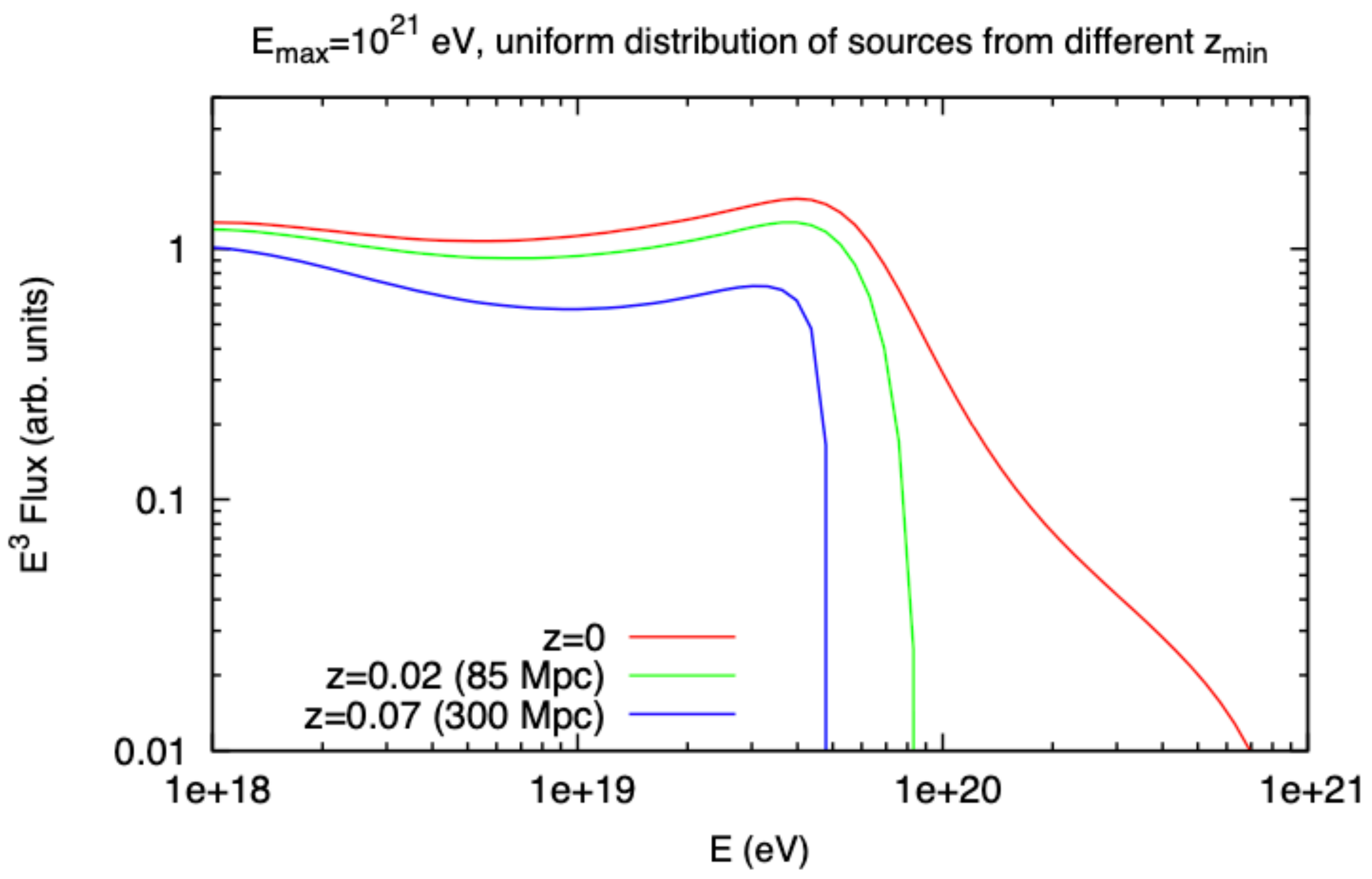
- Analytical (or Monte Carlo) computation of expected protons at Earth, under some assumptions:
    - Identical sources
    - Power-law spectrum at escape up to max energy
- Comparison to data
- Best parameters (at the source) that reproduce the spectrum at Earth (after propagation)

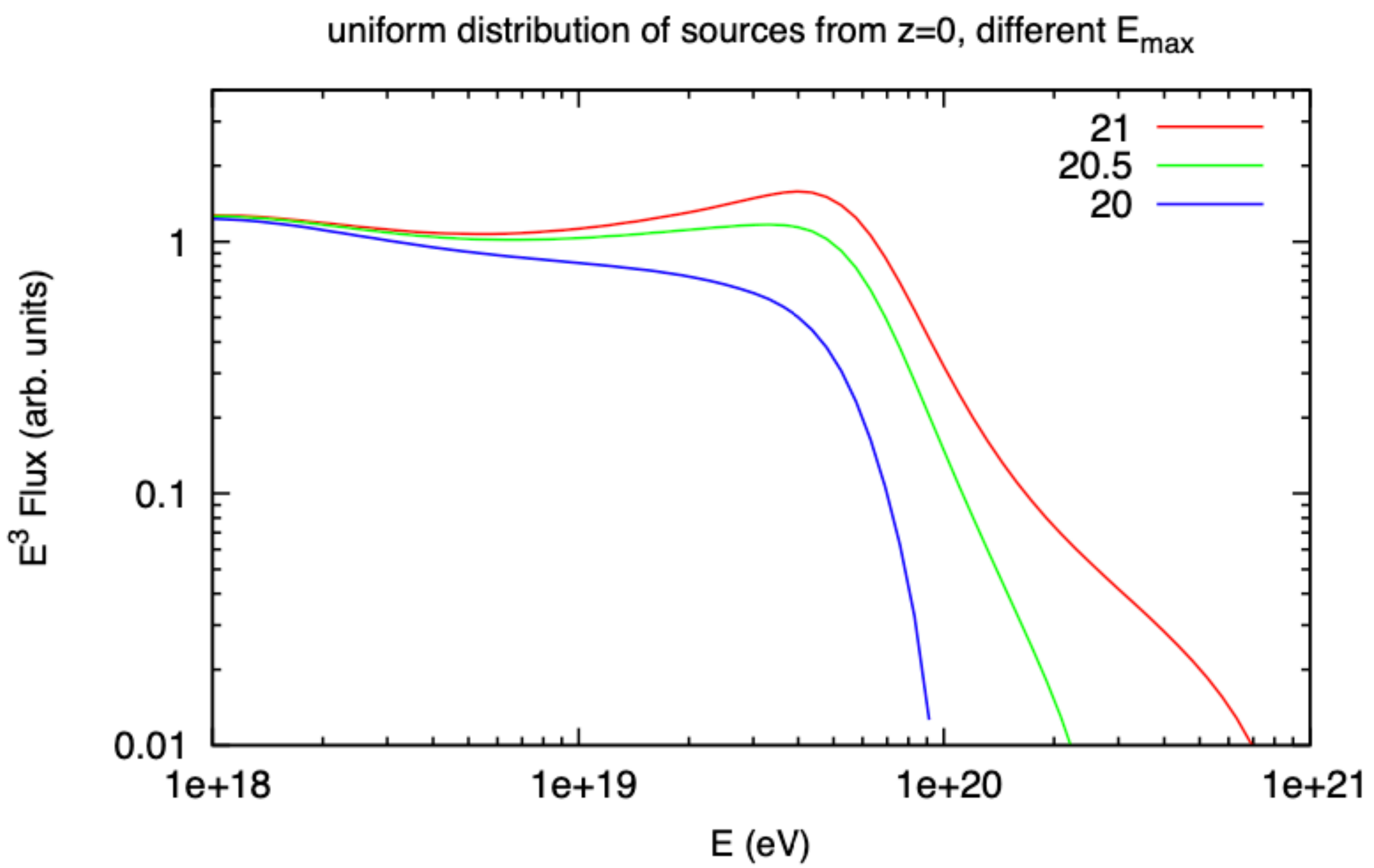


- High-energy region -> could constrain the maximum energy at the source (?)
- Low-energy region -> could constrain spectral index and cosmological evolution of sources (?)

INTERPRETATION

- Features of the spectrum at Earth might be connected to effects of propagation
  - pair-production energy losses -> dip
    - Not sensitive to details of local distribution of sources
  - photo-pion energy losses -> suppression
    - Sensitive to details of local distribution of sources (minimum redshift, density)
    - Sensitive to details of spectrum at source (maximum energy at the escape from sources)





INTERPRETATION

- Features of the spectrum at Earth might be connected to effects of propagation
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- Interpretation becomes even more uncertain if UHECRs are nuclei heavier than hydrogen !
  - **Lecture 2**