lecture 7. astroparticle propagation

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Advanced Astroparticle Physics

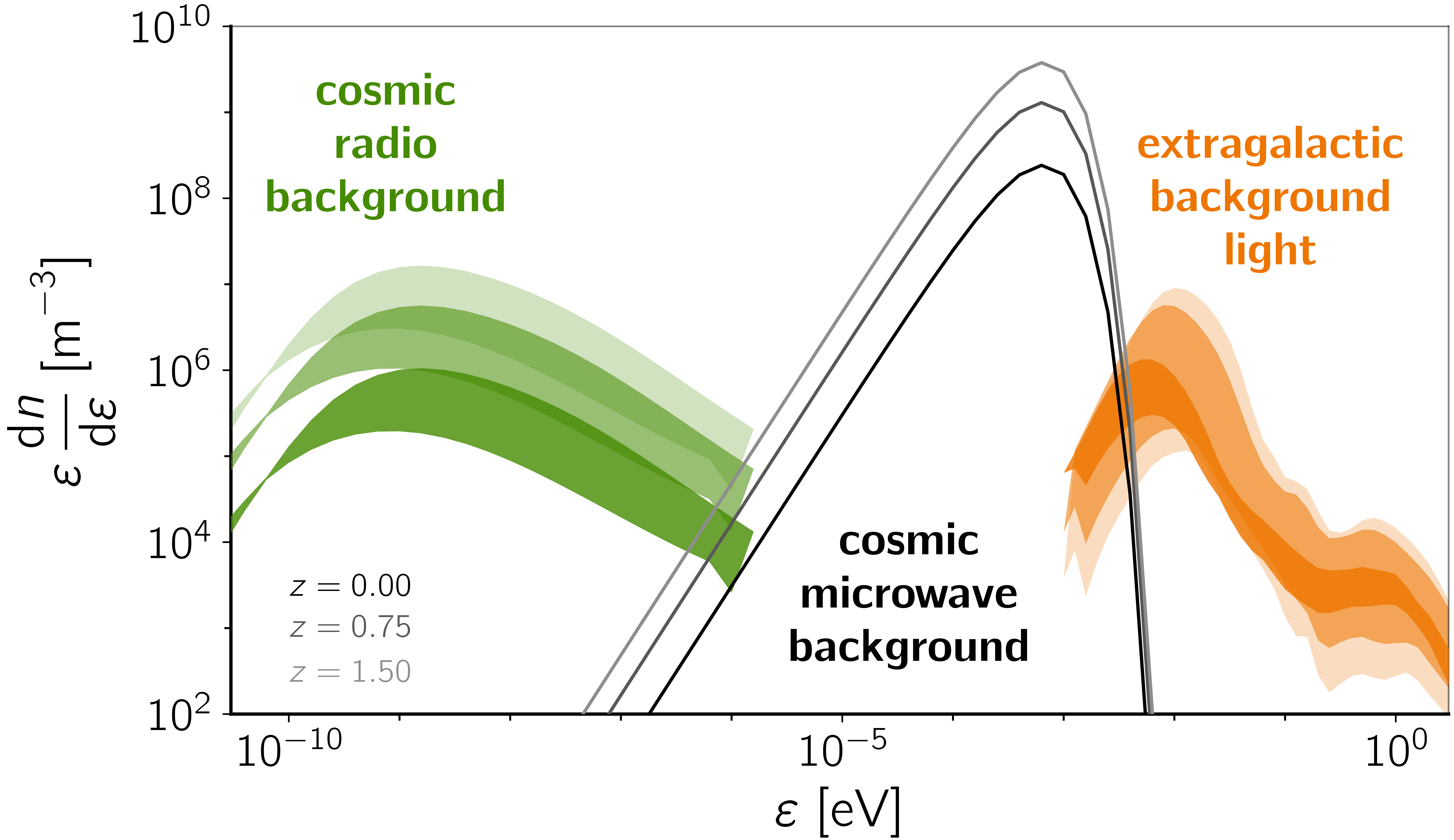
NPAC M2

2024-2025

in today's class...

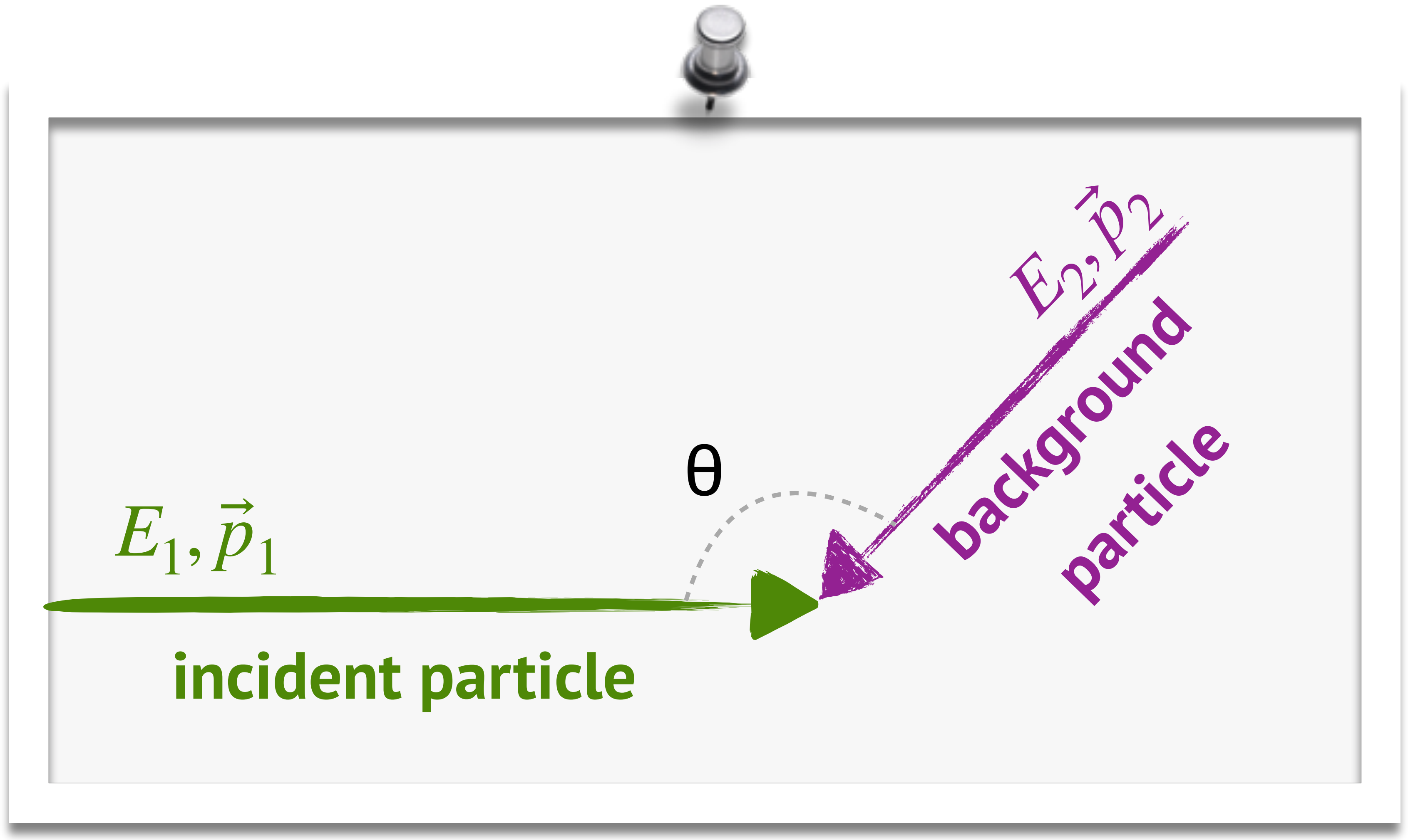
- **propagation of cosmic particles**
  - gamma rays
  - UHECRs
  - neutrinos

astroparticle propagation: basics



cosmic
radio
background
extragalactic
background
light
cosmic
microwave
background
z = 0.00
z = 0.75
z = 1.50
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{-10}
10^{-5}
10^{0}
$\varepsilon \frac{dn}{d\varepsilon}$ [m^{-3}]
ε [eV]

interaction between two particles



centre of mass energy

$$s = m_1^2 c^4 + m_2^2 c^4 + 2E_1 E_2 (1 - \beta_1 \beta_2 \cos\theta)$$

relative velocity

$$\beta_{\text{rel}} = \sqrt{\frac{(P_1 \cdot P_2)^2 - (m_1 m_2 c^2)^2}{(P_1 \cdot P_2)^2}}$$

interaction length

for particle of type 1
interacting with (isotropic)
background of type 2

$$\lambda^{-1} = \frac{1}{2} \iint \mathrm{d}p_2 \, \mathrm{d}\cos\theta \;\; \sigma(s) \; \beta_{\text{rel}}(P_1, P_2) \; \left(1 - \beta_1 \beta_2 \cos\theta\right) \frac{\mathrm{d}n_2(\vec{p}_2)}{\mathrm{d}p_2}$$

$\sigma(s)$: cross section

$\beta_{\text{rel}}(P_1, P_2)$: relative velocity between the projectile and the target

$\frac{\mathrm{d}n_2(\vec{p}_2)}{\mathrm{d}p_2}$: photon density distribution

$$\lambda^{-1}(E,z) = \frac{1}{8\beta E^2} \int_{\varepsilon_{\min}(E)}^{+\infty} \frac{1}{\varepsilon^2} \frac{dn(\varepsilon,z)}{d\varepsilon} \int_{s_{\min}}^{s_{\max}(E,\varepsilon)} (s - m^2c^4)\sigma(s) ds d\varepsilon$$

Exercise. Let E be the energy of the projectile, and ε the energy of a background photon. From the more general equation for the mean free path for any two particles (see previous slide), derive this equation.

$$\max s_\text{i} = \min s_\text{f}$$

$$s_\text{i} = m_1^2c^4 + m_2^2c^4 + 2E_1E_2(1 - \beta_1\beta_2\cos\theta_\text{i})$$

$$s_\text{f} = m_3^2c^4 + m_4^2c^4 + 2E_3E_4(1 - \beta_3\beta_4\cos\theta_\text{f})$$

$$\max s_\text{i} = m_1^2c^4 + m_2^2c^4 + 2E_1E_2(1 + \beta_1\beta_2)$$

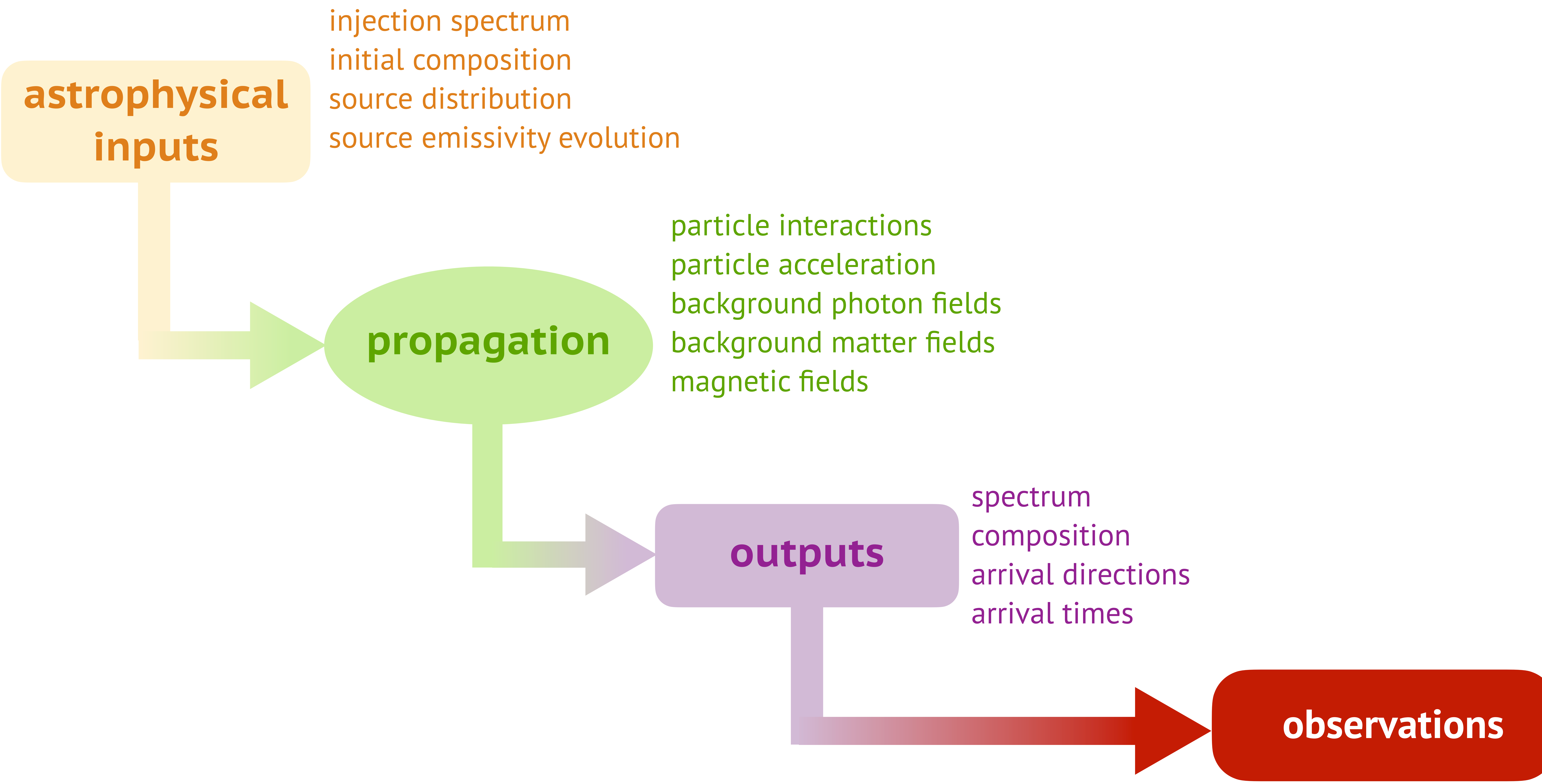
$$\min s_\text{f} = m_3^2c^4 + m_4^2c^4 + 2E_3E_4(1 - \beta_3\beta_4)$$

$$\min s_\text{f} \approx m_3^2c^4 + m_4^2c^4$$

$$E_{2,\text{thr}} = \frac{(m_3^2 + m_4^2 - m_1^2 - m_2^2)c^4}{2(1 + \beta_1\beta_2)E_1}$$

- the invariant mass of the initial state should be at least the same as that of the final state
- for 2-to-2 scattering
  - max(s_i): head-on collisions ($\theta_i=\pi$)
  - min(s_f): parallel momenta ($\theta_f=0$)
- in the ultrarelativistic limit (or if photons), $\beta_3 \sim \beta_4 \sim 1$
  - if this is not the case, threshold depends on the energy/ momentum of the final state

recipe for astroparticle propagation



propagation of extragalactic cosmic rays

decays

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

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

$\mu^+ \rightarrow e^+ + \underline{\nu_\mu} + \nu_e$

$n \rightarrow p + e^- + \underline{\nu_e}$

photodisintegration

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1, Z) + n$

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1, Z\text{-}1) + p$

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A, Z) + \gamma$

photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$

$p + \gamma_{bg} \rightarrow n + \pi^+$

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \ldots + \pi^0 + \pi^+$

nuclear decays

$\text{nucleus}(A, Z) \rightarrow \text{nucleus}(A\text{-}4, Z\text{-}2) + \alpha$

$\text{nucleus}(A, Z) \rightarrow \text{nucleus}(A, Z\text{+}1) + e^- + \underline{\nu_e}$

$\text{nucleus}(A, Z) \rightarrow \text{nucleus}(A, Z\text{-}1) + e^+ + \nu_e$

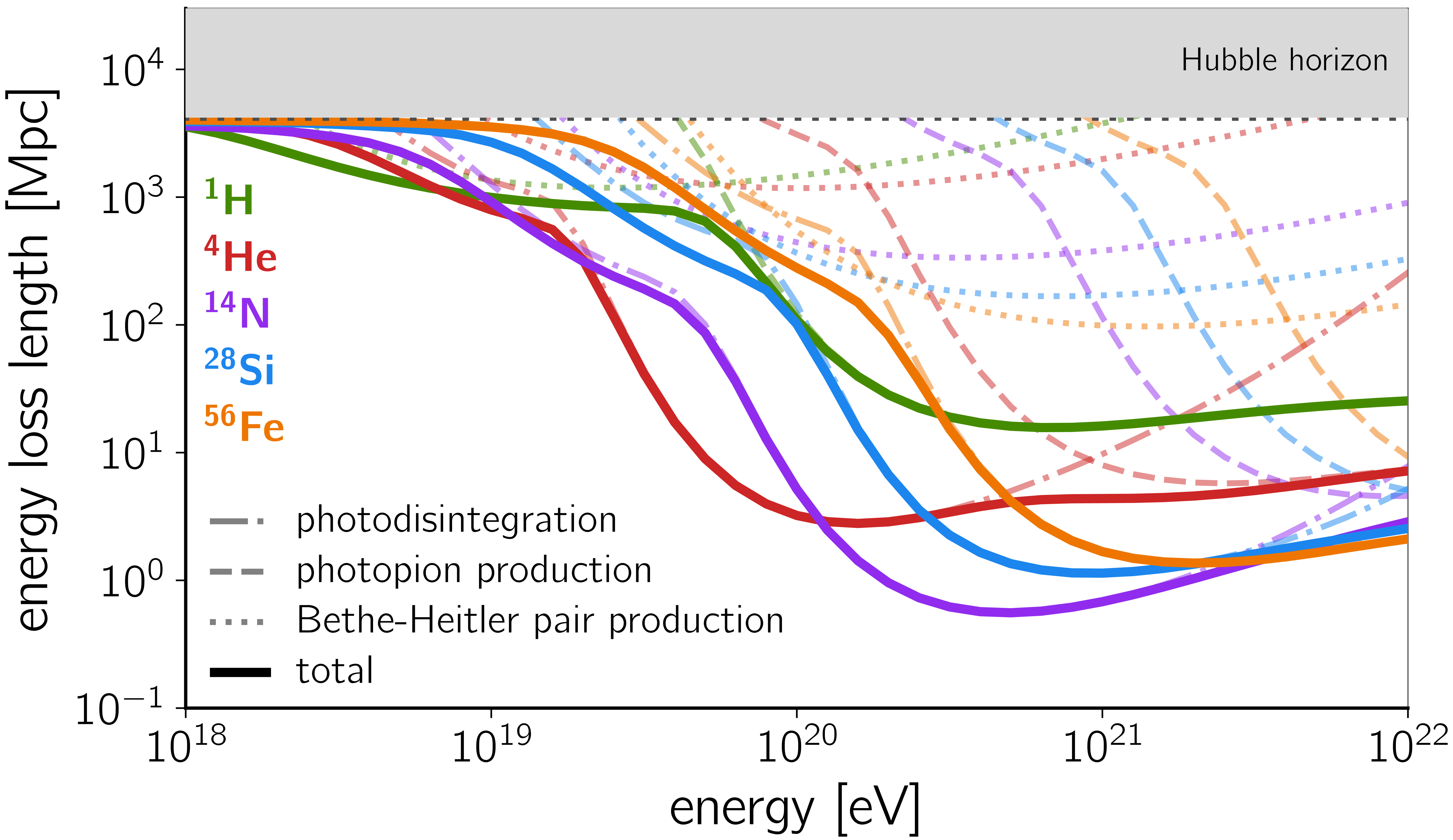
$\text{nucleus}(A, Z)^* \rightarrow \text{nucleus}(A, Z) + \gamma$

Bethe-Heitler pair production

$\text{nucleus}(A, Z) + \gamma_{bg} \rightarrow \text{nucleus}(A, Z) + e^+ + e^-$

UHECRs: interactions during cosmological propagation

Alves Batista. arXiv:2412.17201



photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$ $\qquad \pi^0 \rightarrow \gamma + \gamma$

$p + \gamma_{bg} \rightarrow n + \pi^+$ $\qquad \pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

(similar for nuclei)

Bethe-Heitler pair production

nucleus(A, Z) + $\gamma_{bg} \rightarrow$ nucleus(A, Z) + e^- + e^+

photodisintegration

nucleus(A, Z) + $\gamma_{bg} \rightarrow$ nucleus(A-1, Z) + n

nucleus(A, Z) + $\gamma_{bg} \rightarrow$ nucleus(A-1, Z-1) + p

...

nuclear decays

nucleus(A, Z) $\rightarrow$ nucleus(A-4, Z-2) + α

nucleus(A, Z) $\rightarrow$ nucleus(A, Z+1) + e^- + $\underline{\nu_e}$

nucleus(A, Z) $\rightarrow$ nucleus(A, Z-1) + e^{-+} + ν_e

nucleus(A, Z)* $\rightarrow$ nucleus(A, Z) + γ

UHECRs: interactions during cosmological propagation

photodisintegration

nucleus(A, Z) + γ_{bg} → nucleus(A-1, Z) + n

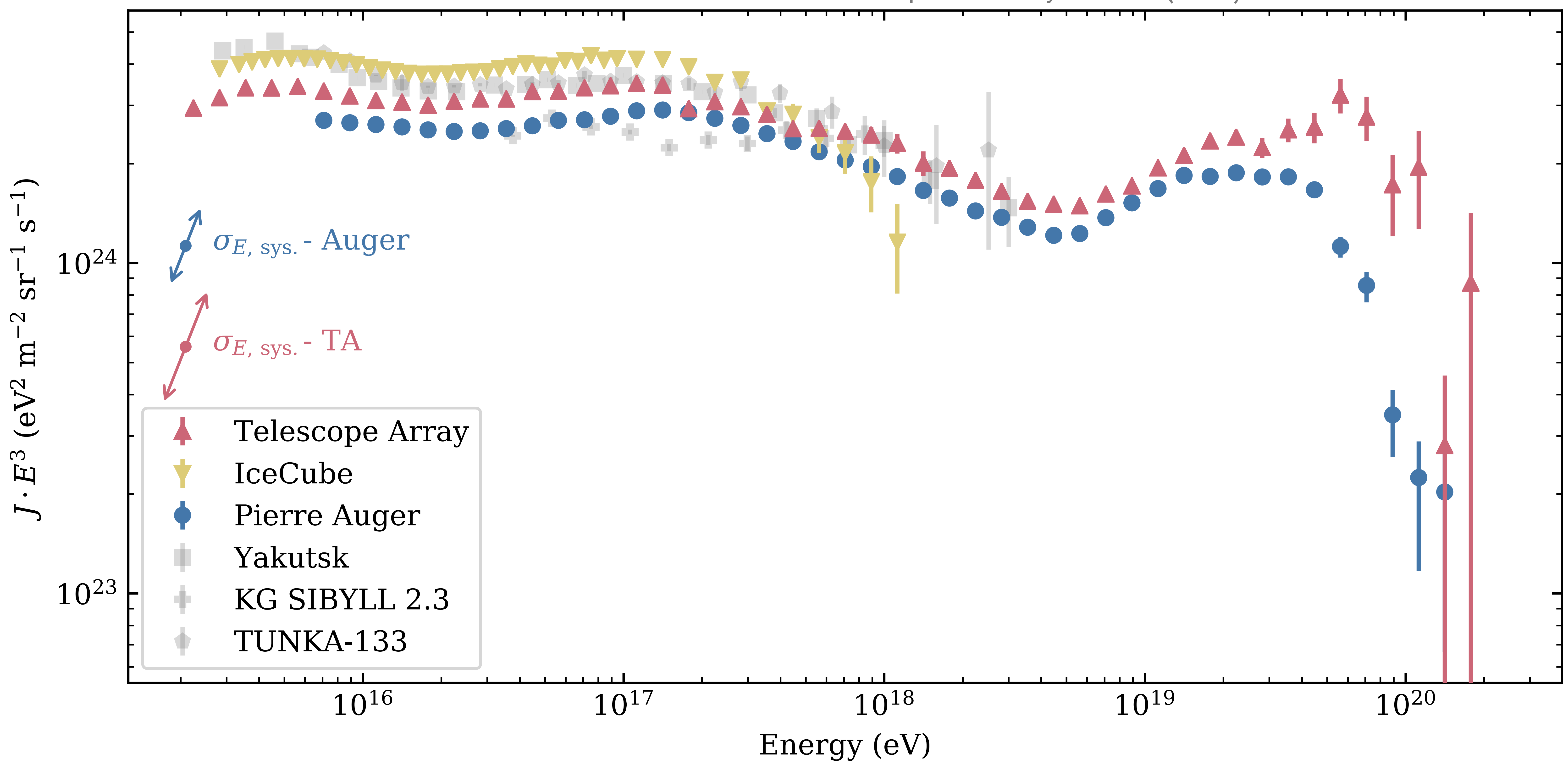
nucleus(A, Z) + γ_{bg} → nucleus(A-1, Z-1) + p

pion production

p + γ_{bg} → p + π^0

p + γ_{bg} → n + π^+

Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845



Discussion. Look at the UHECR spectrum shown in the figure. Suppose neutrons are not detected at all.

a) What can be concluded about the sources of these particles?

b) If a neutron from a cosmologically distant source is detected, what would that imply?

UHECRs: interactions during cosmological propagation

pion production

$p + \gamma_{bg} \rightarrow p + \pi^0$

$p + \gamma_{bg} \rightarrow n + \pi^+$

Bethe-Heitler pair production

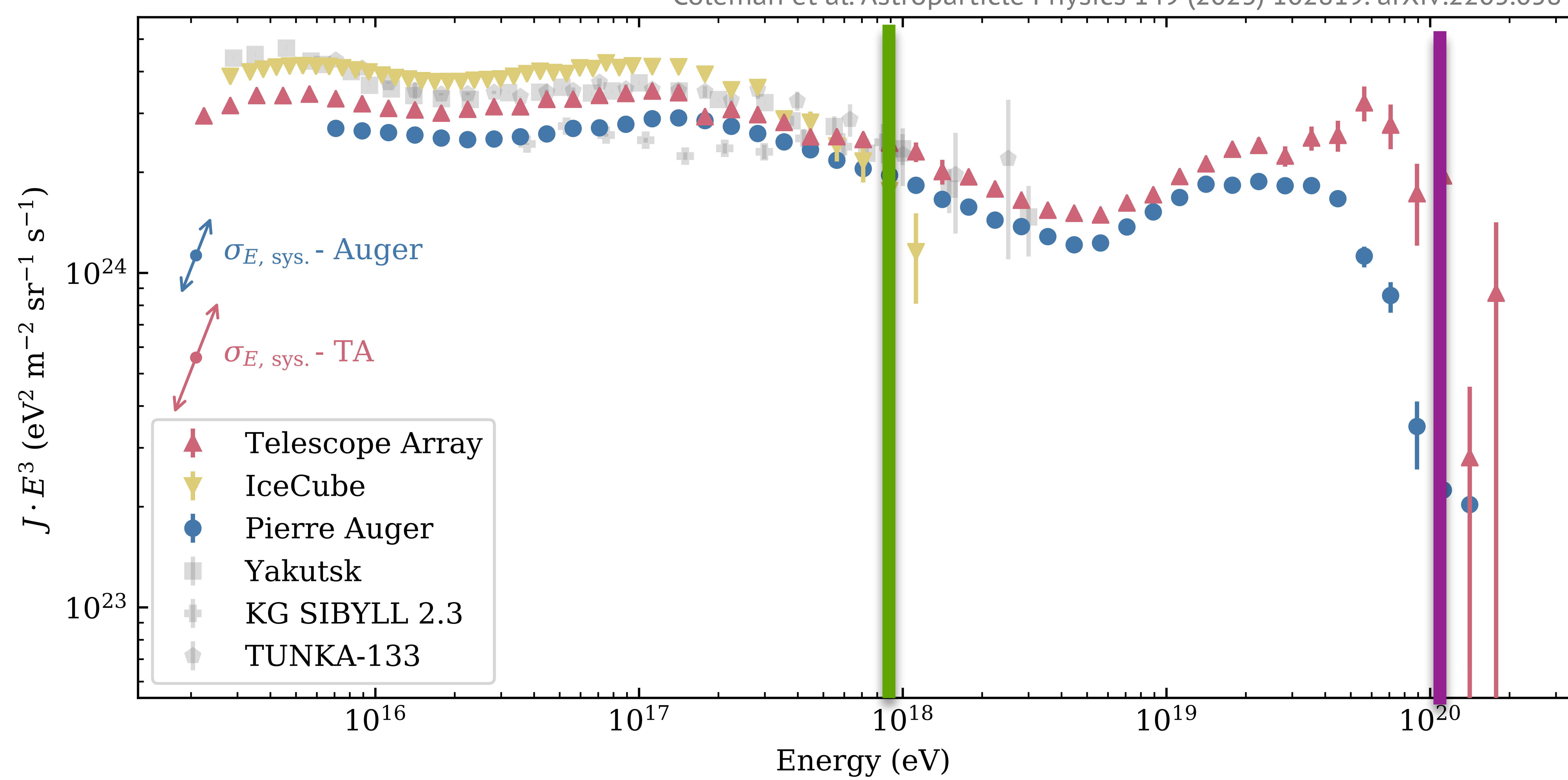
$p + \gamma_{bg} \rightarrow p + e^- + e^+$

- *hypothesis*: spectral features due to proton propagation (if extragalactic sources)
- *expectation*: spectral features at corresponding energies

computing thresholds...

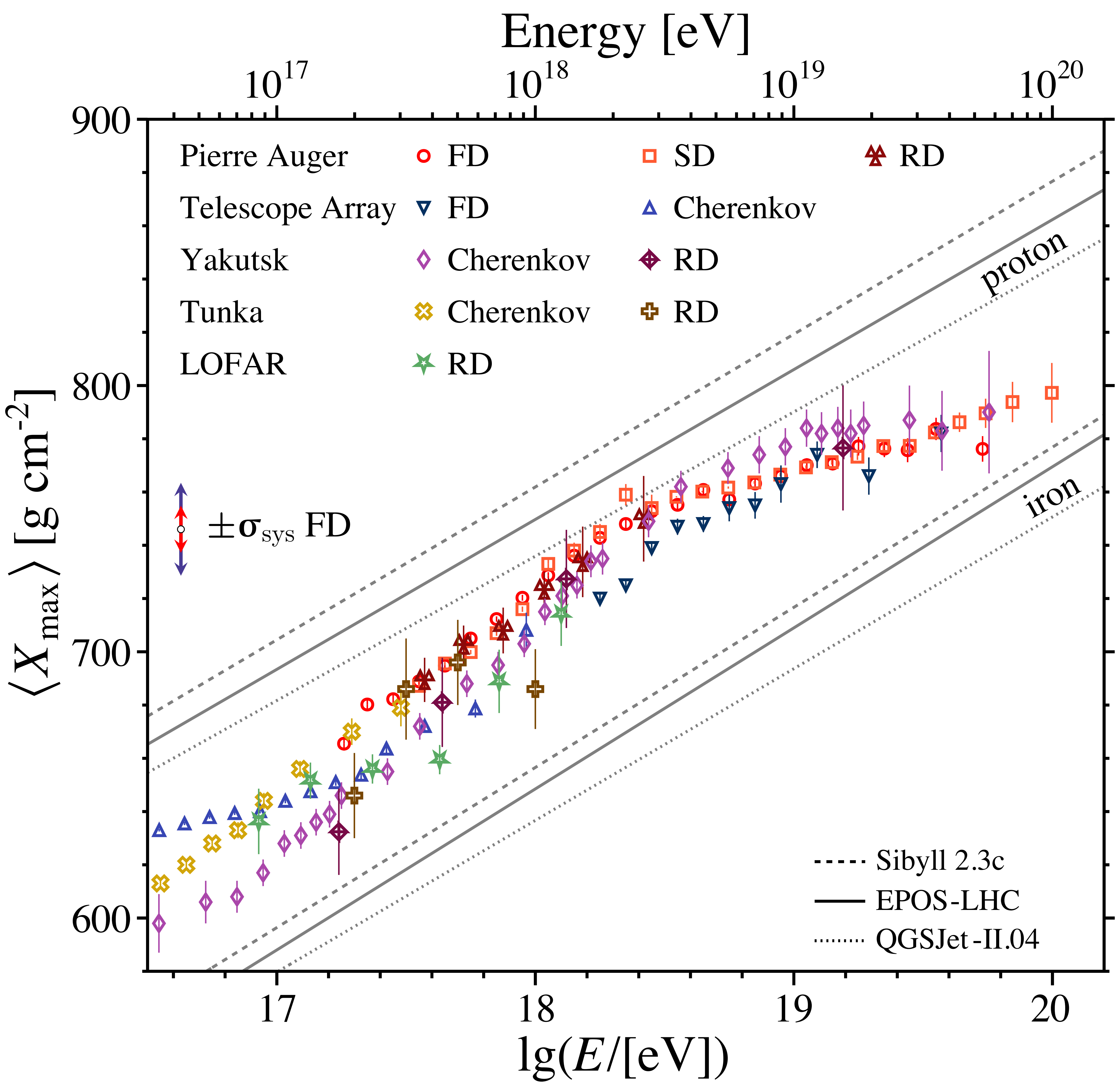
	CMB	EBL
pion production	10^{20} eV	$10^{18.7}$ eV
Bethe-Heitler	10^{18} eV	$10^{16.5}$ eV

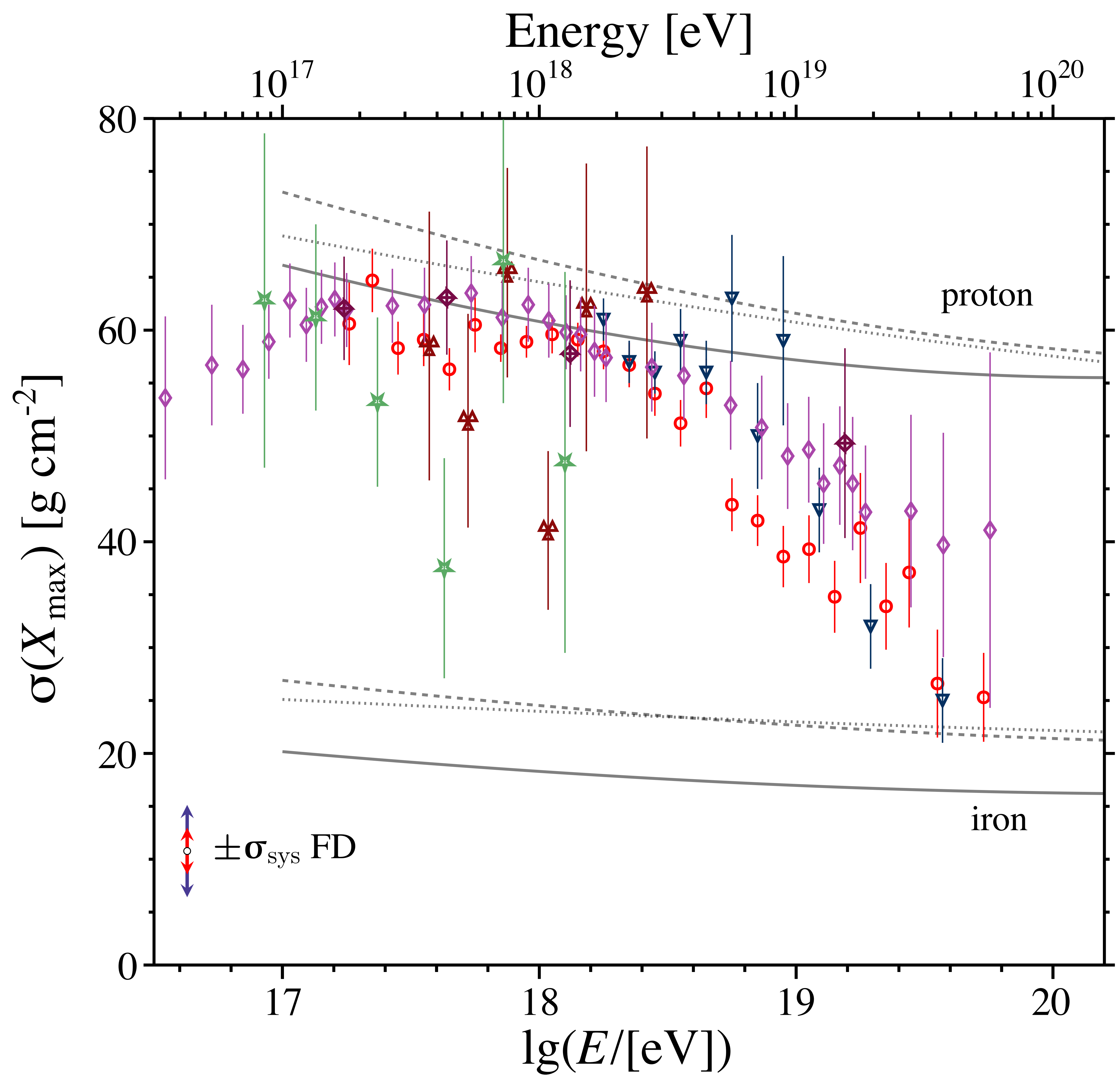
Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845



UHECRs: interactions during cosmological propagation

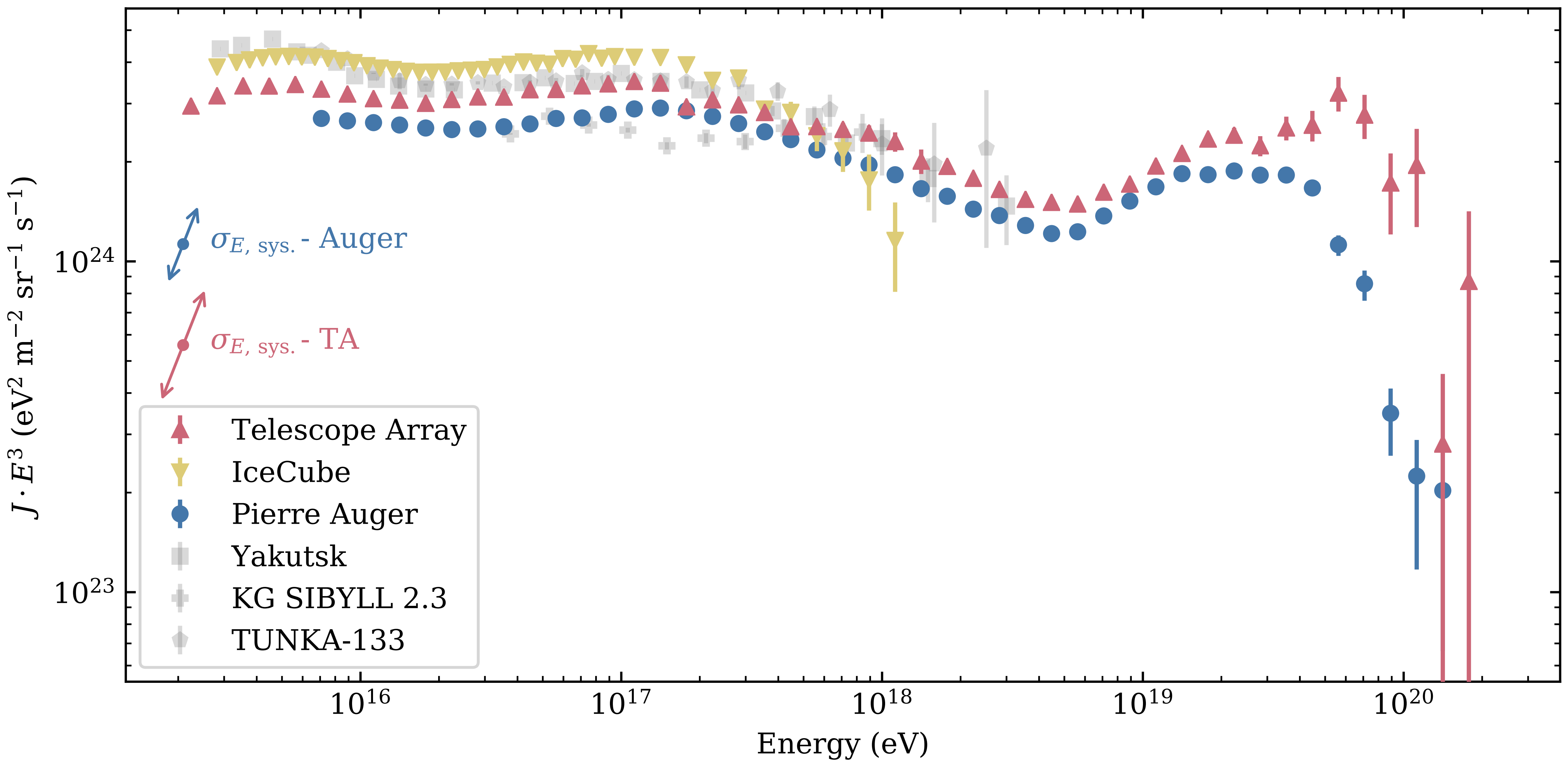
Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845





the GZK cut-off

Coleman et al. Astroparticle Physics 149 (2023) 102819. arXiv:2205.05845



$$p + \gamma_{\text{bg}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$$

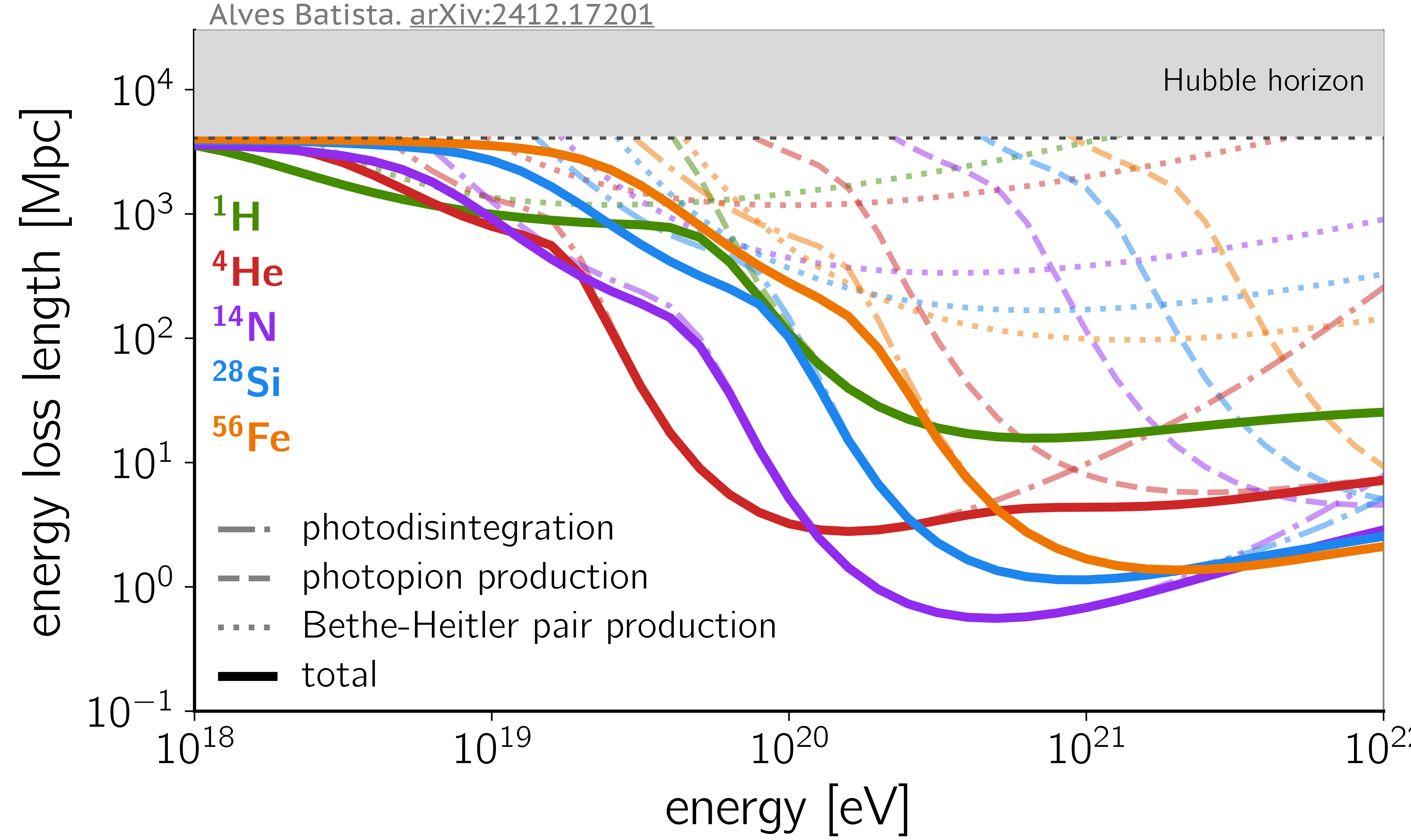
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Alves Batista. arXiv:2412.17201



Auger

Selected for a Viewpoint in *Physics*
PRL **101,** 061101 (2008) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2008

Observation of the Suppression of the Flux of Cosmic Rays above 4×10^{19} eV

The energy spectrum of cosmic rays above 2.5×10^{18} eV, derived from 20 000 events recorded at the Pierre Auger Observatory, is described. The spectral index γ of the particle flux, $J \propto E^{-\gamma}$, at energies between 4×10^{18} eV and 4×10^{19} eV is $2.69 \pm 0.02(\mathrm{stat}) \pm 0.06(\mathrm{syst})$, steepening to $4.2 \pm 0.4(\mathrm{stat}) \pm 0.06(\mathrm{syst})$ at higher energies. The hypothesis of a single power law is rejected with a significance greater than 6 standard deviations. The data are consistent with the prediction by Greisen and by Zatsepin and Kuz'min.

DOI: 10.1103/PhysRevLett.101.061101 PACS numbers: 98.70.Sa, 95.85.Ry, 96.50.sb, 96.50.sd

HiRes

PRL **100,** 101101 (2008) PHYSICAL REVIEW LETTERS week ending 14 MARCH 2008

First Observation of the Greisen-Zatsepin-Kuzmin Suppression

The High Resolution Fly's Eye (HiRes) experiment has observed the Greisen-Zatsepin-Kuzmin suppression (called the GZK cutoff) with a statistical significance of five standard deviations. HiRes' measurement of the flux of ultrahigh energy cosmic rays shows a sharp suppression at an energy of 6×10^{19} eV, consistent with the expected cutoff energy. We observe the ankle of the cosmic-ray energy spectrum as well, at an energy of 4×10^{18} eV. We describe the experiment, data collection, and analysis and estimate the systematic uncertainties. The results are presented and the calculation of the statistical significance of our observation is described.

DOI: 10.1103/PhysRevLett.100.101101 PACS numbers: 98.70.Sa, 95.85.Ry, 96.50.sb, 96.50.sd

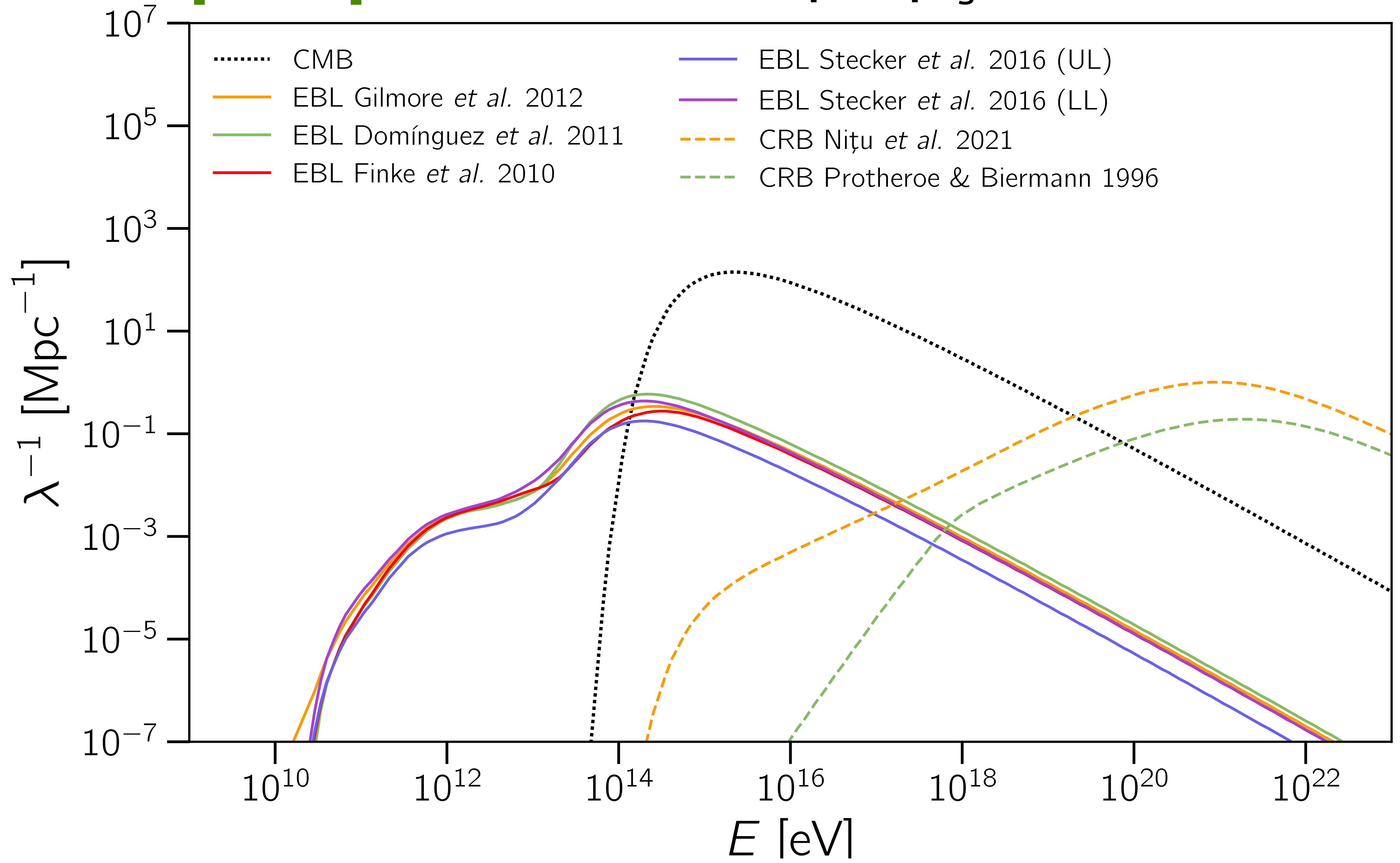
- *is the suppression at E > 50 EeV due to the GZK effect?*
- necessary conditions:
  - either:
    - (i) source spectrum very well understood
    - (ii) source $E_{max} > E_{GZK}$
  - dominant proton composition

propagation of gamma rays

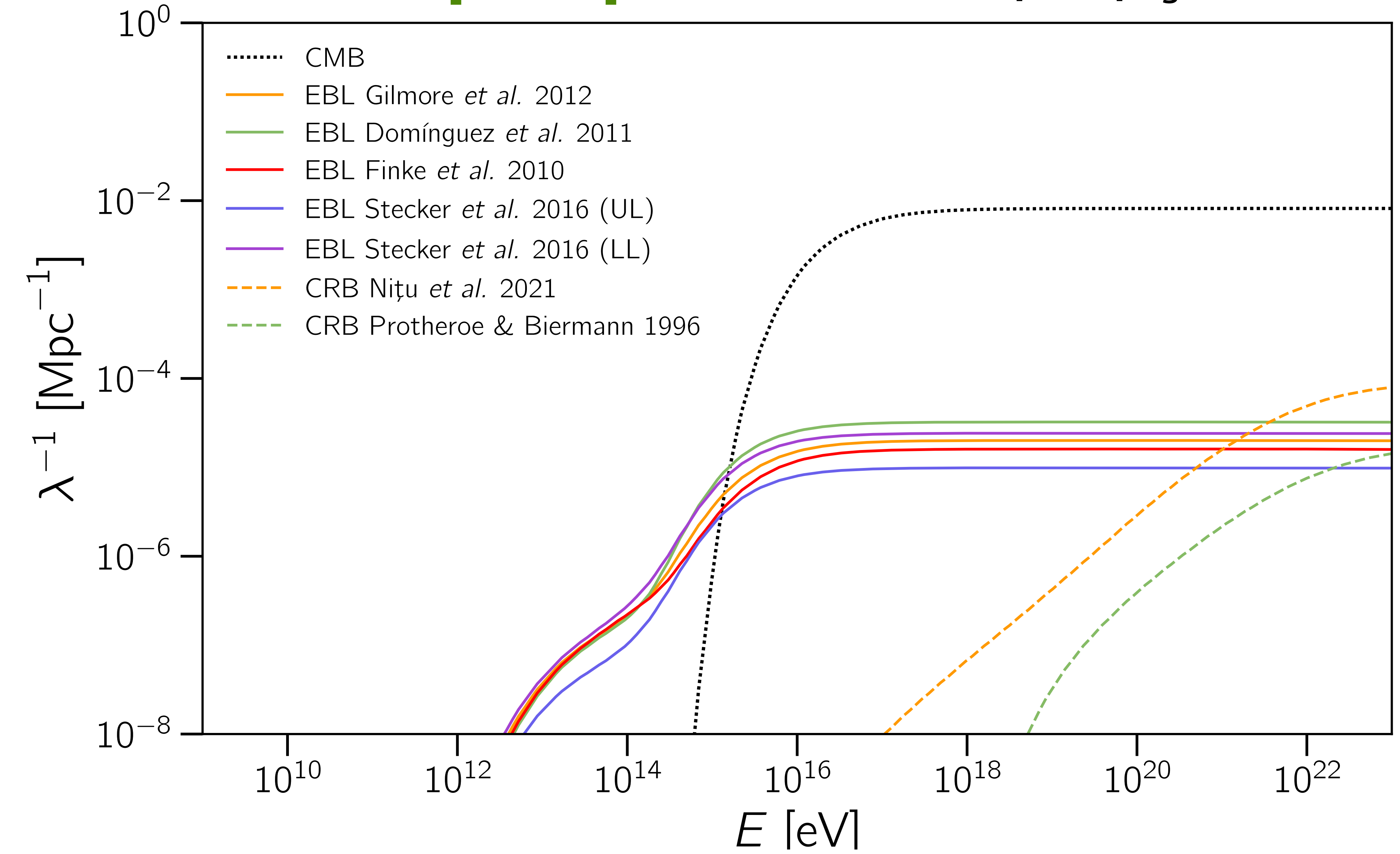

pair production
$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$
inverse Compton scattering
$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$
γ
e⁻
e⁺
γ
γ
e⁺
e⁻

cosmological propagation of gamma rays and electrons

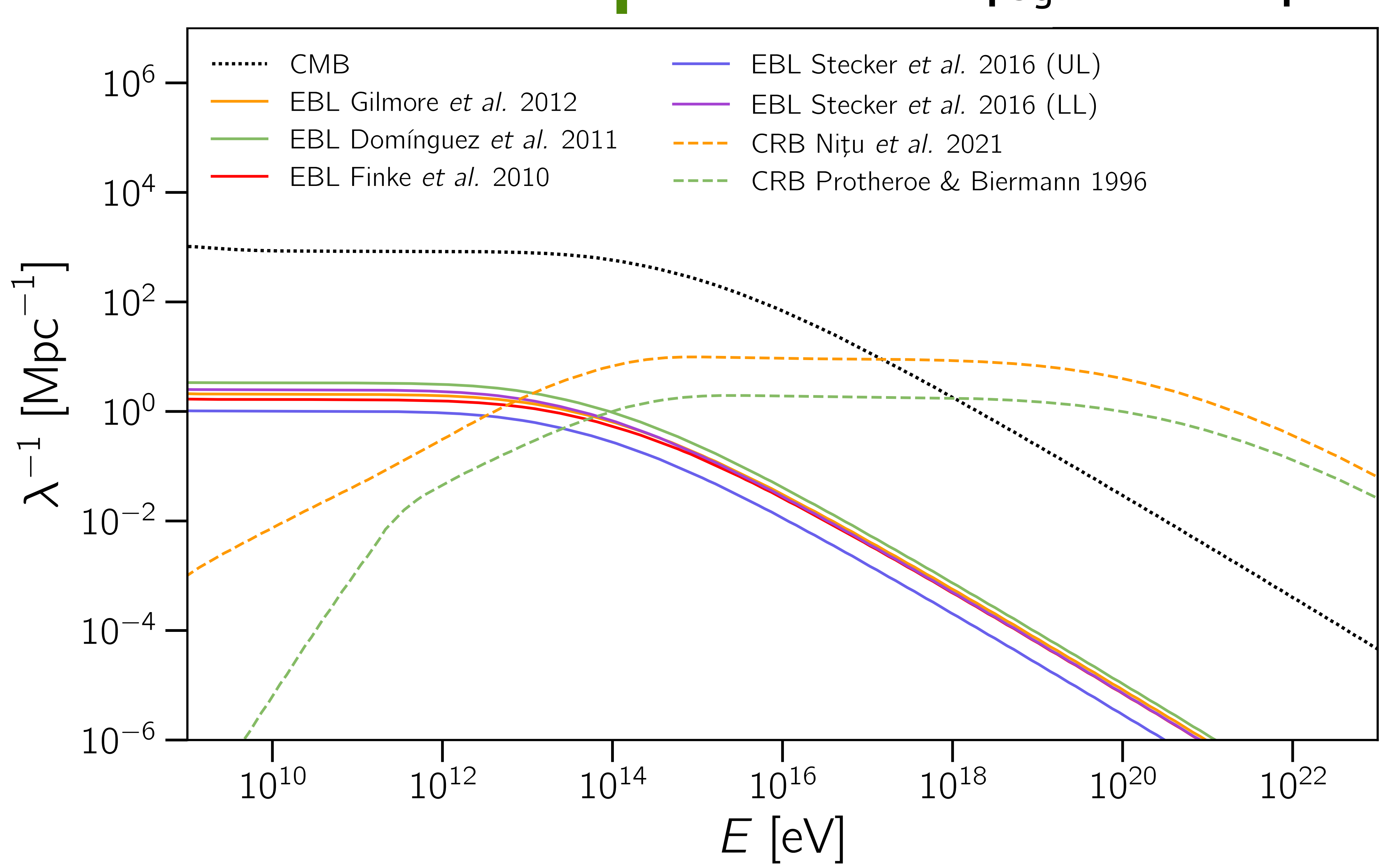
pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+$



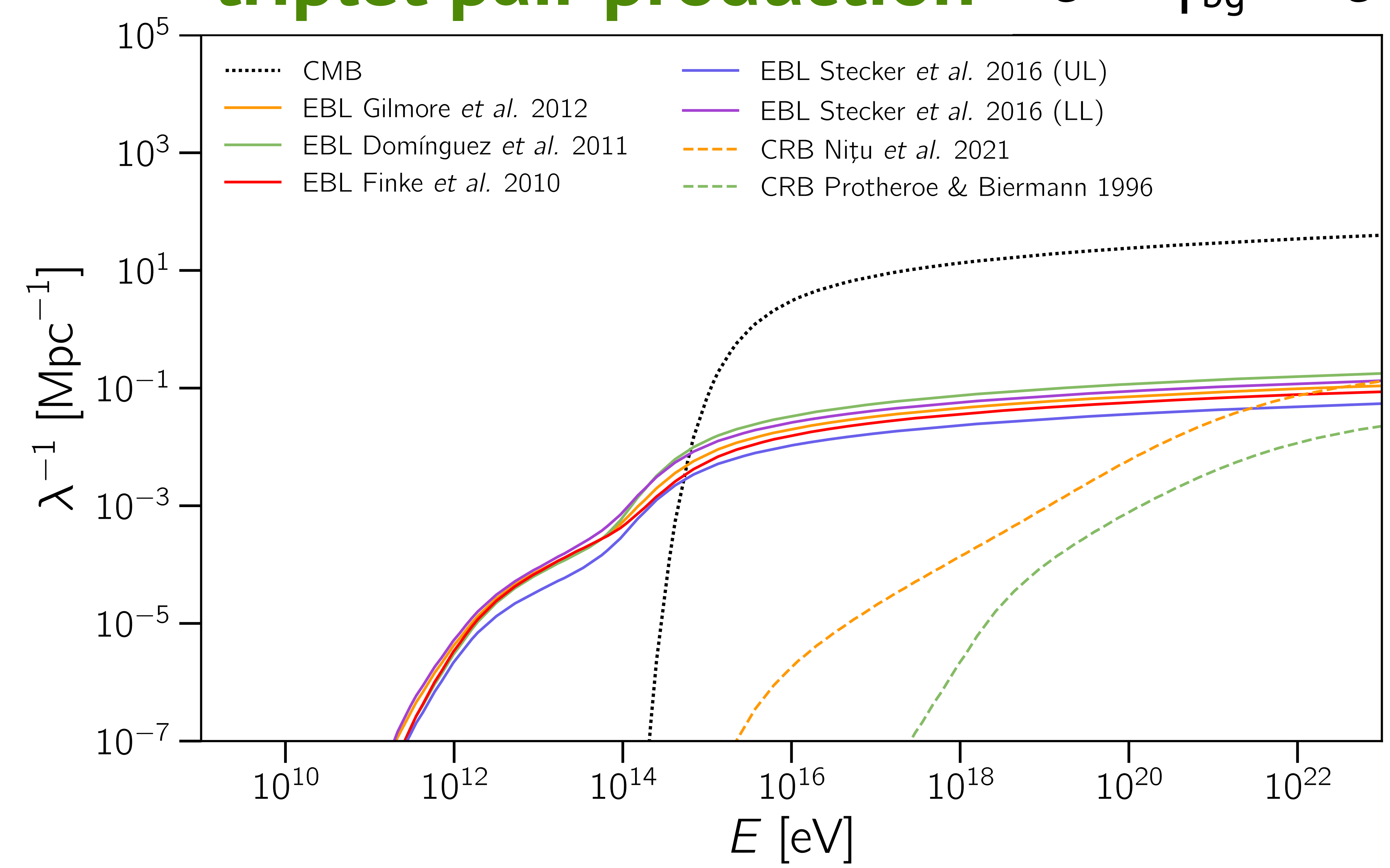
double pair production $\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$



inverse Compton $e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$



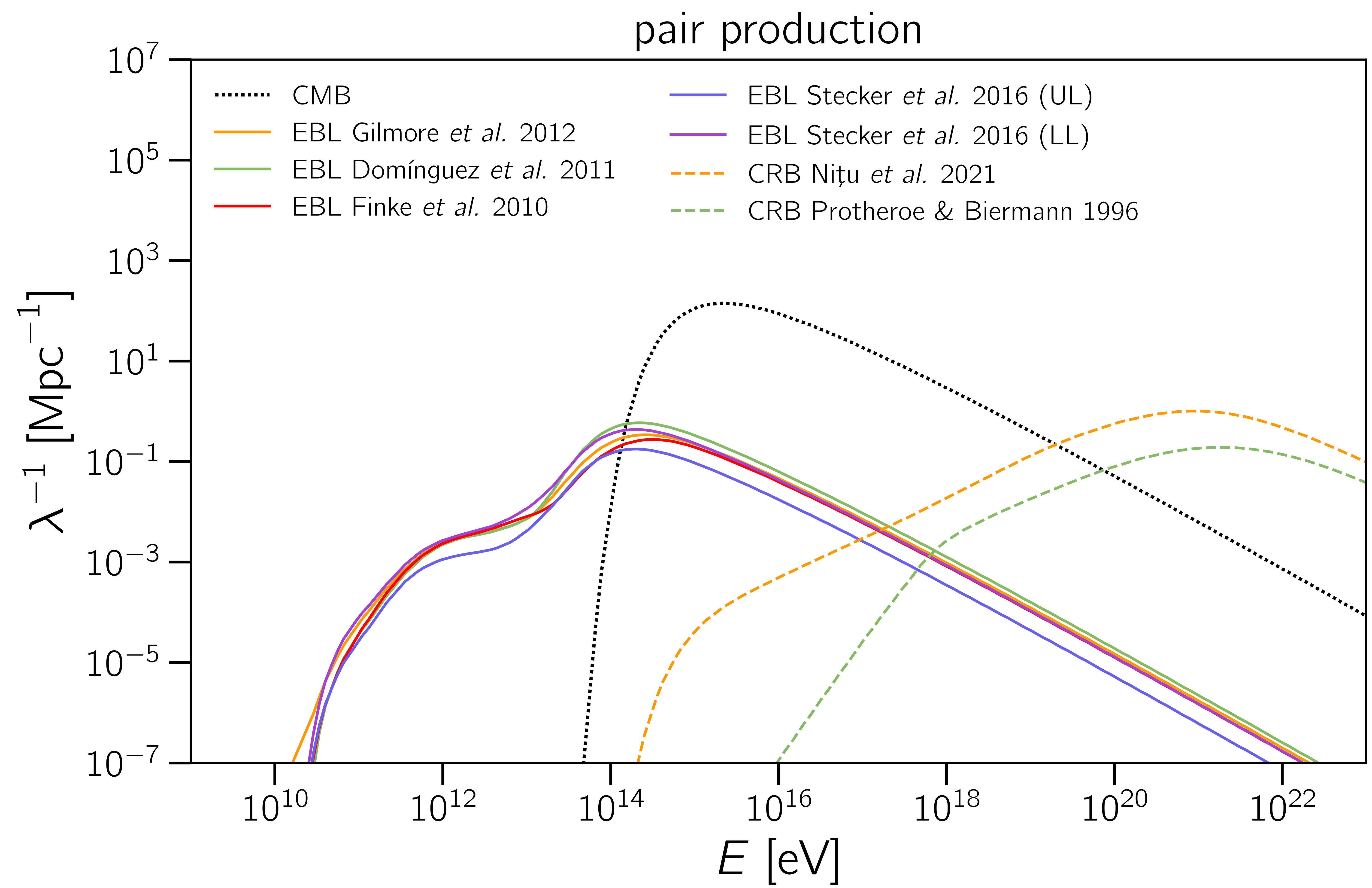
triplet pair production $e^\pm + \gamma_{bg} \rightarrow e^\pm + e^- + e^+$



$$\gamma + \gamma_{bg} \rightarrow e^+ + e^-$$

$$s_{min} = 4 m_e^2 c^4$$

$$E_{thr} = \frac{m_e^2 c^4}{\varepsilon}$$



the brightest-ever gamma-ray burst: GRB 221009A

Science RESEARCH ARTICLE

Cite as: LHAASO Collaboration, *Science* 10.1126/science.adg9328 (2023).

A tera-electron volt afterglow from a narrow jet in an extremely bright gamma-ray burst

LHAASO Collaboration†*

†LHAASO Collaboration authors and affiliations are listed in the supplementary materials.

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Some gamma-ray bursts (GRBs) have a tera–electron volt (TeV) afterglow, but the early onset of this has not been observed. We report observations with the Large High Altitude Air Shower Observatory of the bright GRB 221009A, which serendipitously occurred within the instrument field of view. More than 64,000 photons >0.2 TeV were detected within the first 3000 seconds. The TeV flux began several minutes after the GRB trigger, then rose to a peak about 10 seconds later. This was followed by a decay phase, which became more rapid ~650 seconds after the peak. We interpret the emission using a model of a relativistic jet with half-opening angle ~0.8°. This is consistent with the core of a structured jet and could explain the high isotropic energy of this GRB.

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Very high-energy gamma-ray emission beyond 10 TeV from GRB 221009A

The LHAASO Collaboration*†

The highest-energy gamma-rays from gamma-ray bursts (GRBs) have important implications for their radiation mechanism. Here we report the detection of gamma-rays up to 13 teraelectronvolts from the brightest GRB 221009A by the Large High Altitude Air-shower Observatory (LHAASO). The LHAASO-KM2A detector registered more than 140 gamma-rays with energies above 3 teraelectronvolts during 230 to 900 seconds after the trigger. The intrinsic energy spectrum of gamma-rays can be described by a power-law after correcting for extragalactic background light absorption. Such a hard spectrum challenges the synchrotron self-Compton scenario of relativistic electrons for the afterglow emission above several teraelectronvolts. Observations of gamma-rays up to 13 teraelectronvolts from a source with a measured redshift of $z = 0.151$ hints more transparency in intergalactic space than previously expected. Alternatively, one may invoke new physics such as Lorentz invariance violation or an axion origin of very high-energy signals.

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GCN Circular 32677

Subject LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
Date 2022-10-11T09:21:54Z (2 years ago)
From Judith Racusin at GSFC <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Yao and Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642), Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above 100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d., where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy band between 10^11 and 10^15 eV) and cosmic ray measurements.

flux attenuation

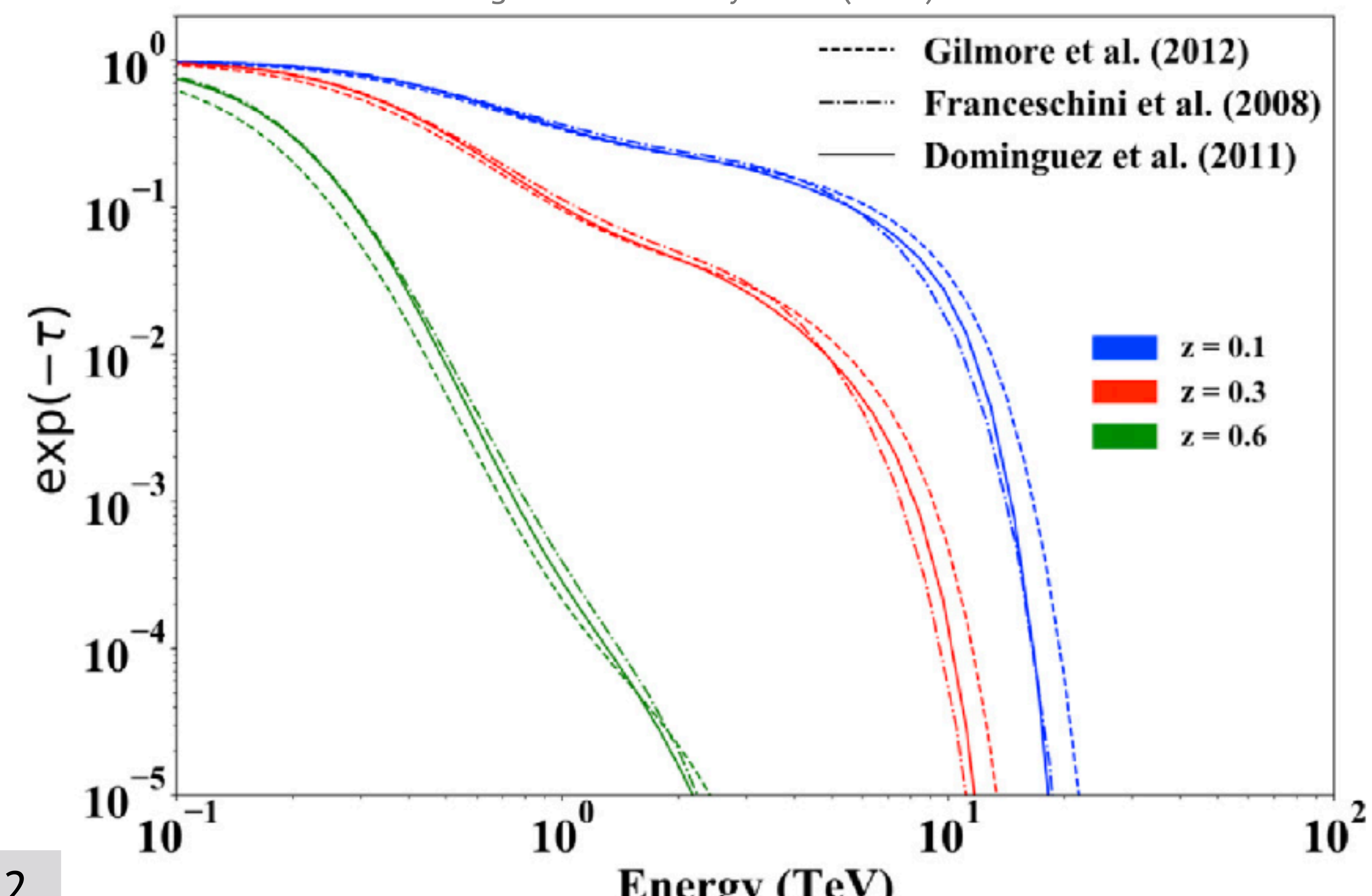
$$\Phi_\mathrm{o}(E_\mathrm{o}; z_\mathrm{s}) = \Phi_\mathrm{s}(E_\mathrm{o,s}) \exp\left[-\tau(E_\mathrm{o}, z_\mathrm{s})\right]$$

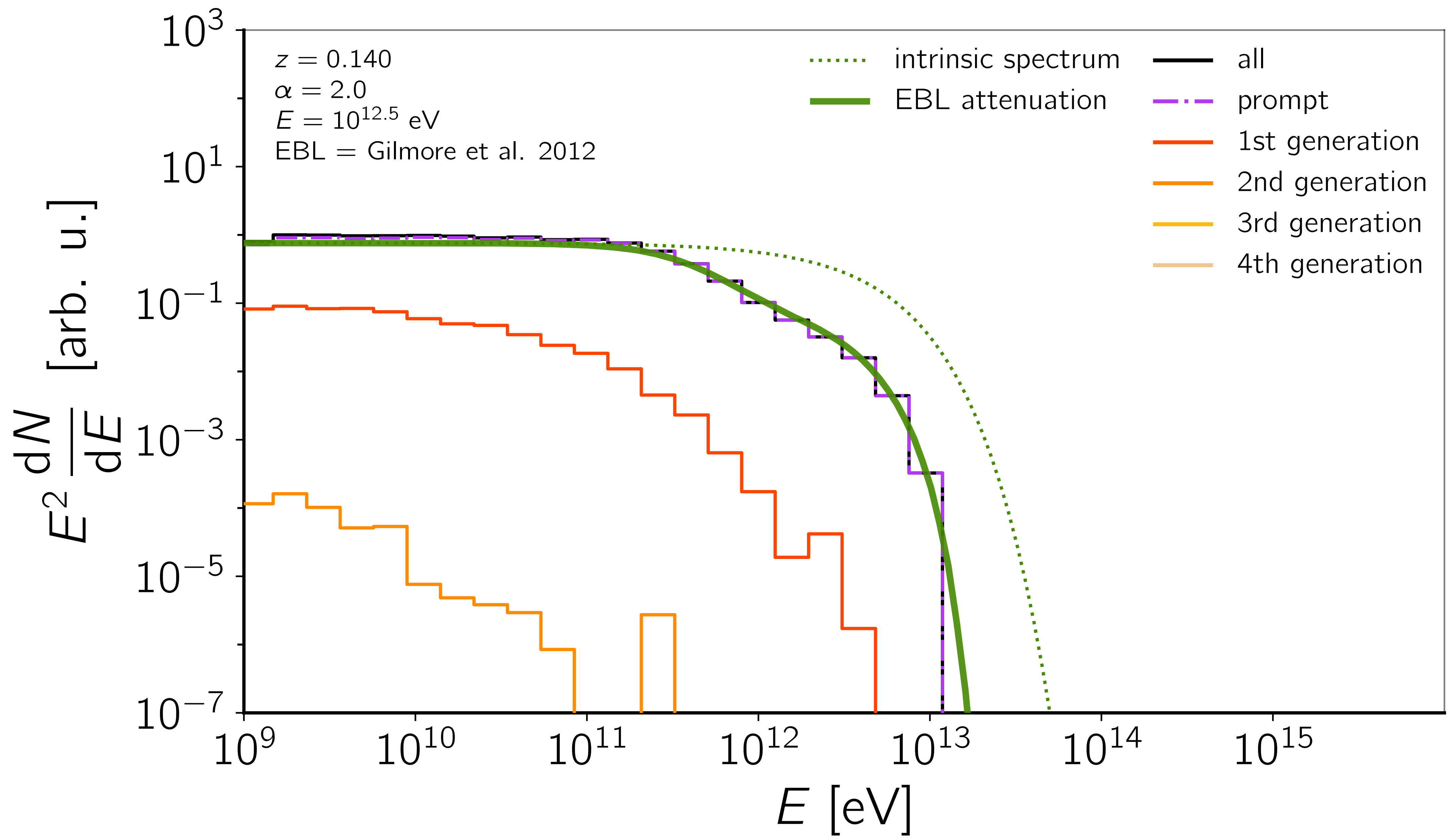
optical depth

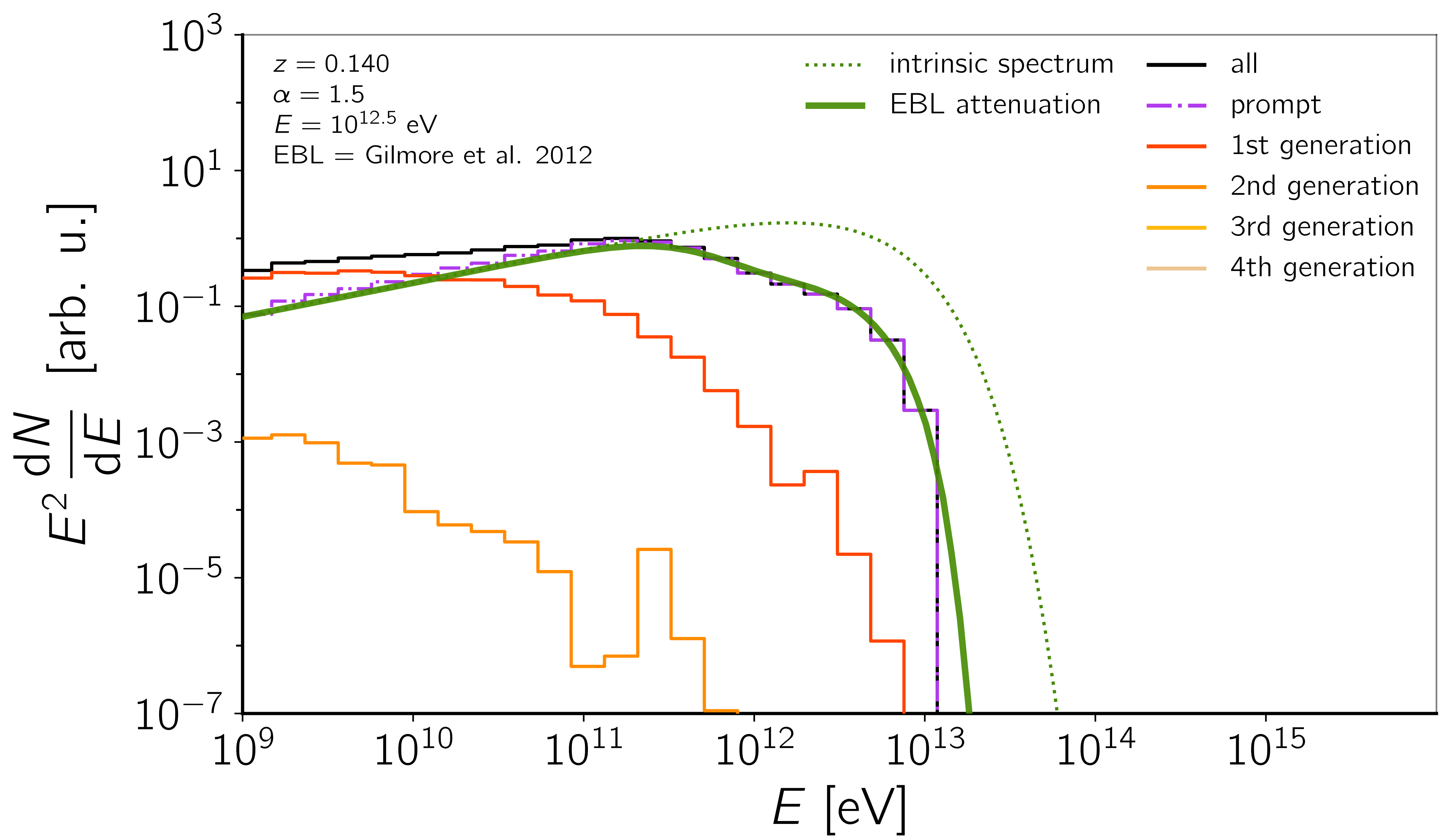
$$\tau(E_\mathrm{o}, z_\mathrm{s}) = \int_0^{z_\mathrm{s}} \mathrm{d}z\, \lambda^{-1}\left(\frac{E_\mathrm{o,s}}{1+z}, z\right) \frac{\mathrm{d}\ell}{\mathrm{d}z}$$

how good is this approximation?

Addazi et al. Prog. Part. Nucl. Phys. 125 (2022) 103948. arXiv:2111.05659







A&A 528, L3 (2011)
DOI: 10.1051/0004-6361/201016175

Astronomy & Astrophysics

LETTER TO THE EDITOR

First evidence of a gravitational lensing-induced echo in gamma rays with *Fermi* LAT

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ABSTRACT

Aims. This article shows the first evidence ever of gravitational lensing phenomena in high energy gamma-rays. This evidence comes from the observation of an echo in the light curve of the distant blazar PKS 1830-211 induced by a gravitational lens system.

Methods. Traditional methods for estimating time delays in gravitational lensing systems rely on the cross-correlation of the li[illegible] curves from individual images. We used the 300 MeV–30 GeV photons detected by the *Fermi*-LAT instrument. I[illegible] separ[illegible] images of known lenses, so the observed light curve is the superposition of individual image light curves. T[illegible]*ermi*-L[illegible]ent has the advantage of providing long, evenly spaced, time series with very low photon noise. This allows [illegible] to use Fourier [illegible]sform methods directly.

Results. A time delay between the two compact images of PKS 1830-211 has been searched for by bot[illegible] the autocorrelation [illegible]ethod and the "double power spectrum" method. The double power spectrum shows a 4.2σ proof of a time delay [illegible]27.1±0.6 days, c[illegible]sistent with others' results.

27 days!

gamma-ray propagation. gravitational lensing

propagation of neutrinos

neutrino propagation

neutrino as probes of the cosmos

Ackermann et al. arXiv:1903.04333

what can we learn from neutrinos