

Testing Lorentz invariance with photons

Based on

- The Auger Collab, JCAP 01 (2022)
- Morais, DB, Lobo, Salamida & Bezerra PoS UHECR2024;
- DB, Bezerra, Giammarco, Lobo & Salamida arxiv:2509.14753v1 (ICRC2025);
- Master Thesis, M. Giammarco, Oct 2025, University of L'Aquila

Ongoing work: A. Bakalova, DB, M. Giammarco, F. Salamida

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PEPS workshop
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LORENTZ INVARIANCE VIOLATION AND ASTROPARTICLES

- The need for a unified theory of gravity has led to several models, some of which automatically imply the breaking of Lorentz invariance
- The concept of continuous space-time can be profoundly changed by quantum gravitational effects
- The validity of what we define as fundamental theories, as Lorentz invariance, can be put under experimental scrutiny
- The violation could appear in the invariant mass, through modifications of the dispersion relation

$$E^2 - p^2 - m^2 = p^2 f\left(\frac{p}{M_{Pl}}\right)$$

The Planck mass parametrizes the violation of Lorentz invariance, or an essential discreteness of space-time

$$m \ll p \ll M_{Pl} \quad \text{In the interesting regime, after a Taylor expansion ->} \quad E_i^2 - p_i^2 = m_i^2 + \sum \eta_{i,n} \frac{E_i^{2+n}}{M_{Pl}^n} \quad \delta_{i,n} = \frac{\eta_{i,n}}{M_{Pl}^n}$$

PRD2000 Coleman & Glashow, PRD 1999; Aloisio, Blasi, Ghia & Grillo, PRD 2000

- Observationally, high energy astrophysics is providing a range of opportunities to probe energies (i.e. Lorentz factors, or speeds) much larger than the ones obtainable in accelerator experiments
 - High-energy photons could be exploited to scrutinize the Lorentz invariance

See [Addazi+ Prog.Part.Nucl.Phys. 125 \(2022\)](#) for a review on multimessenger probes of quantum gravity

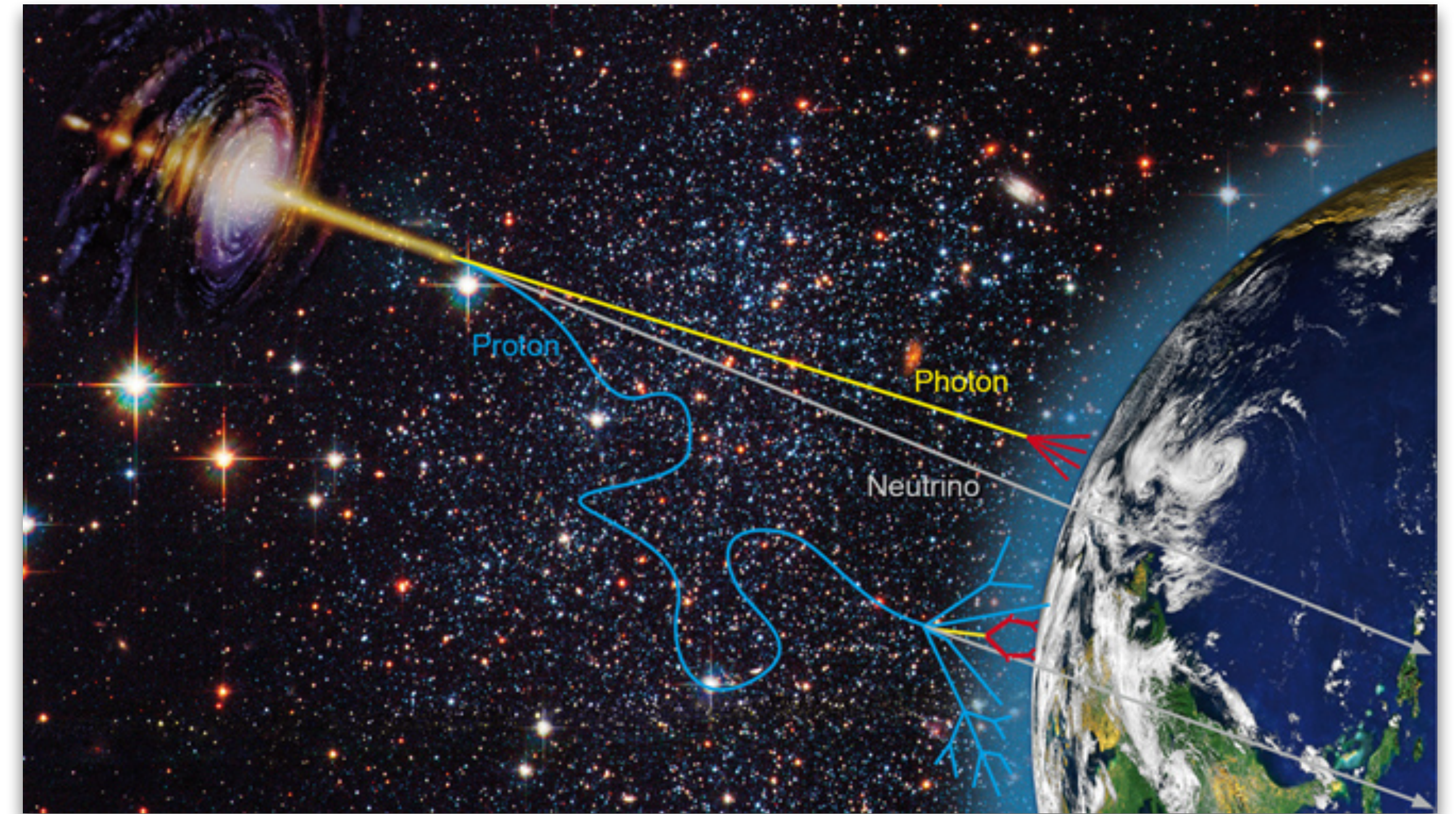
Photons at UHE

- Origin of diffuse photon fluxes at UHE
 - Interactions:
 - Photo-hadronic \rightarrow Cosmogenic
 - Hadronic \rightarrow Galactic
 - Dark matter decay
 - Primordial black hole evaporation

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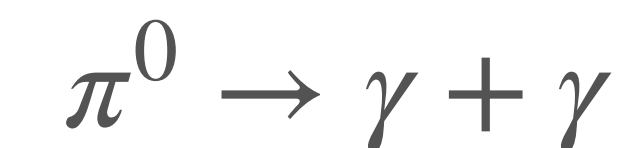
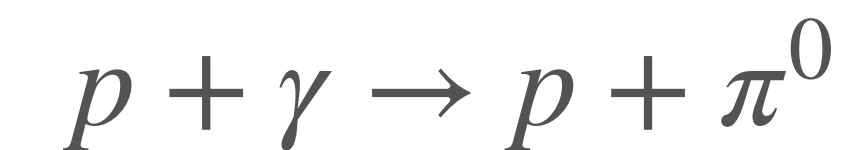
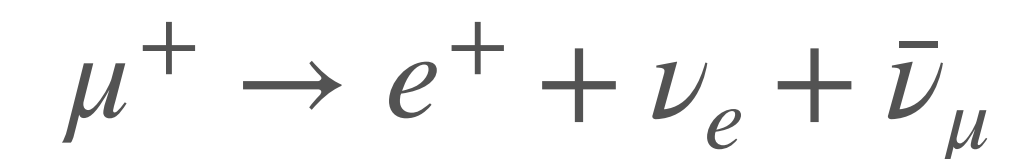
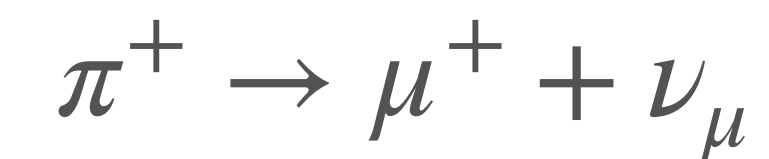
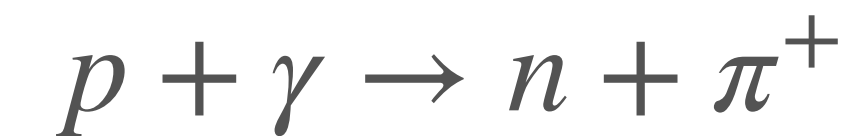
- We focus on cosmogenic photons (for testing Lorentz invariance)
 - originated in the decay of neutral pions from photo-hadronic interactions
 - their flux depends on
 - astrophysical parameters linked to UHECRs
 - interactions with photon backgrounds



$$\varepsilon' > 150 \text{ MeV}$$

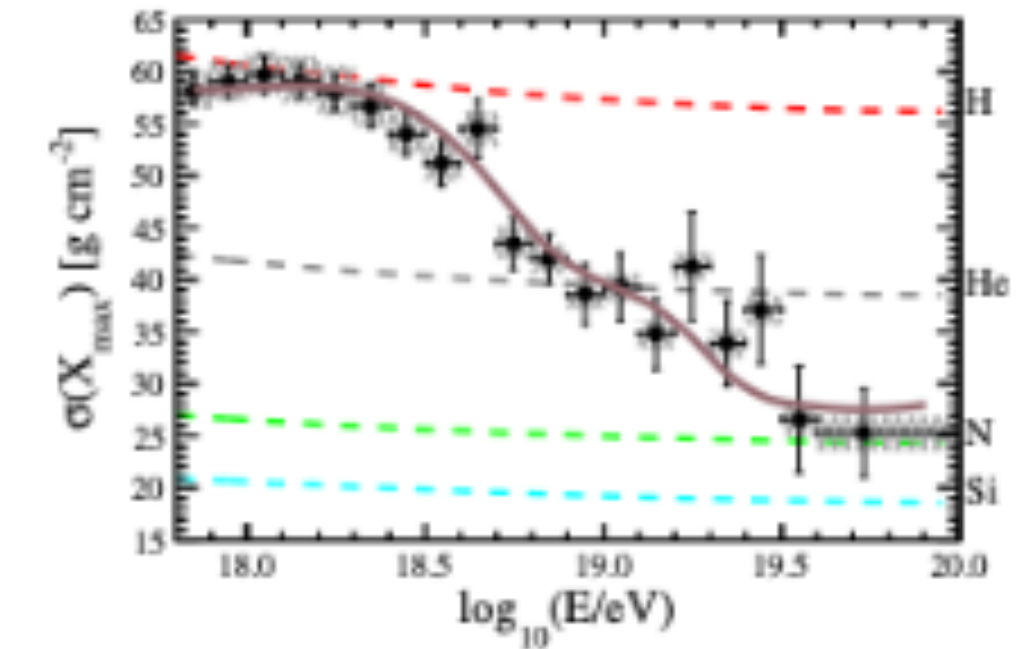
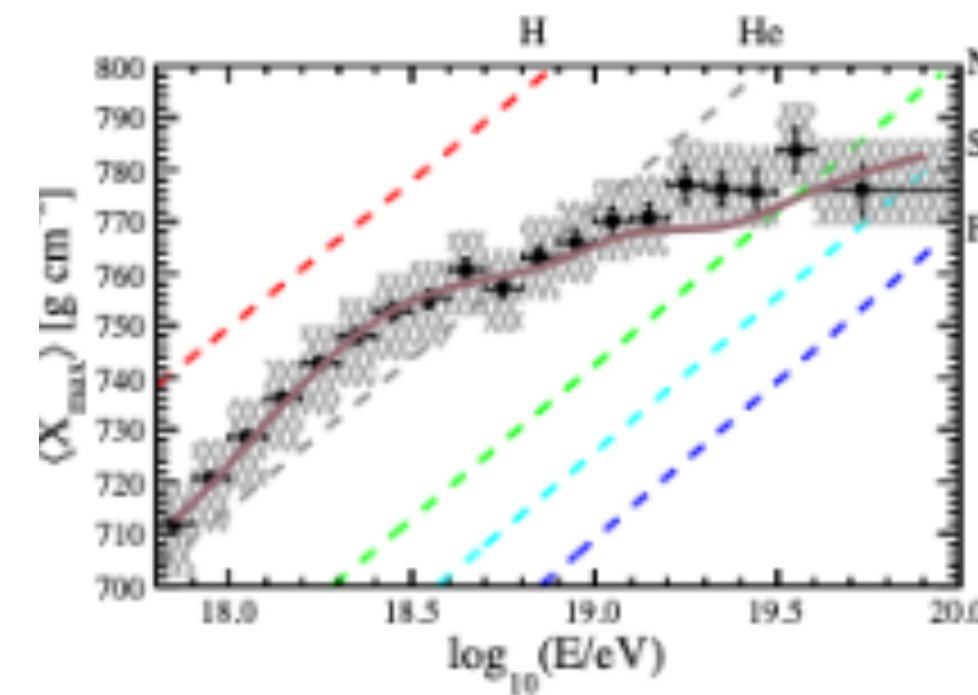
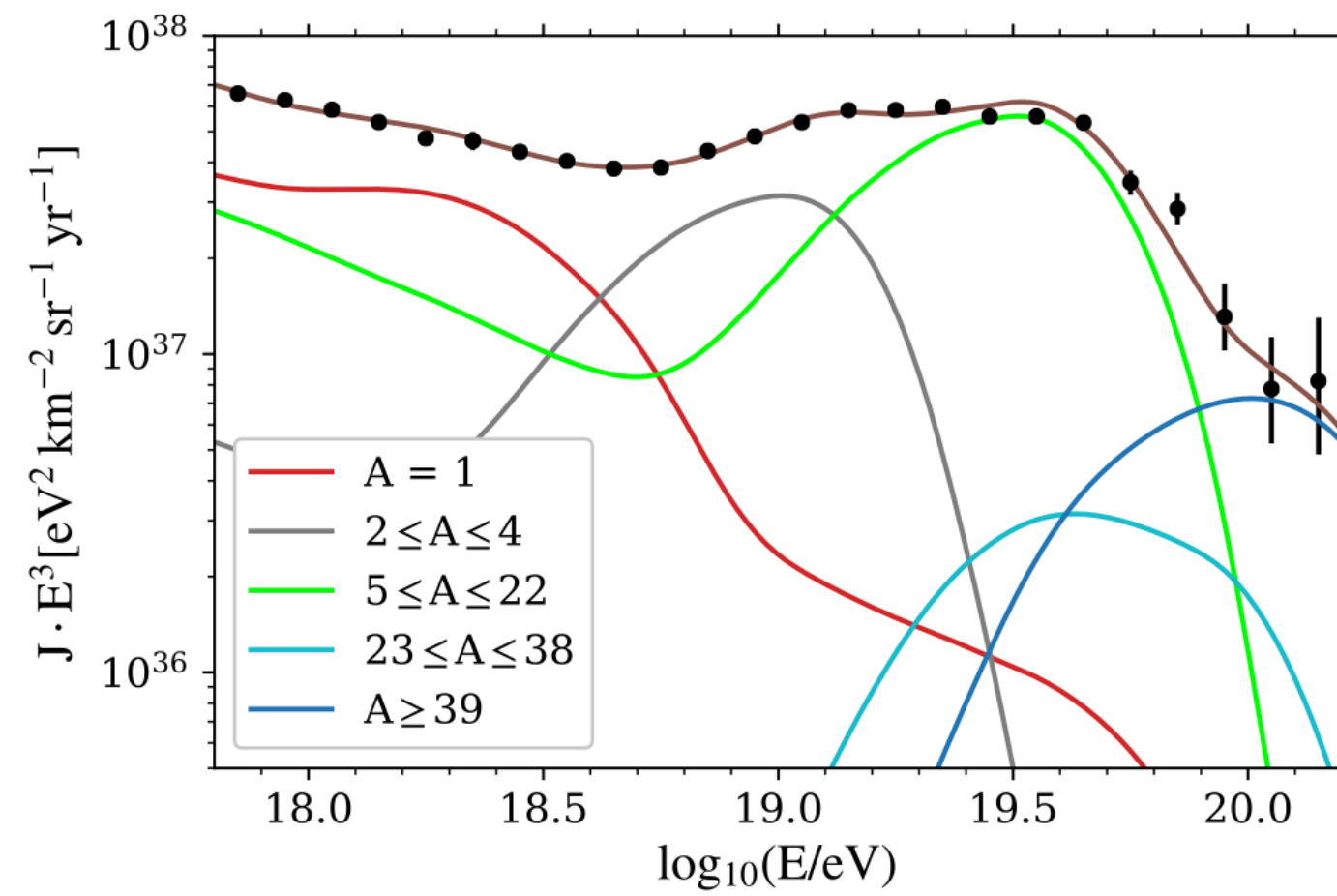
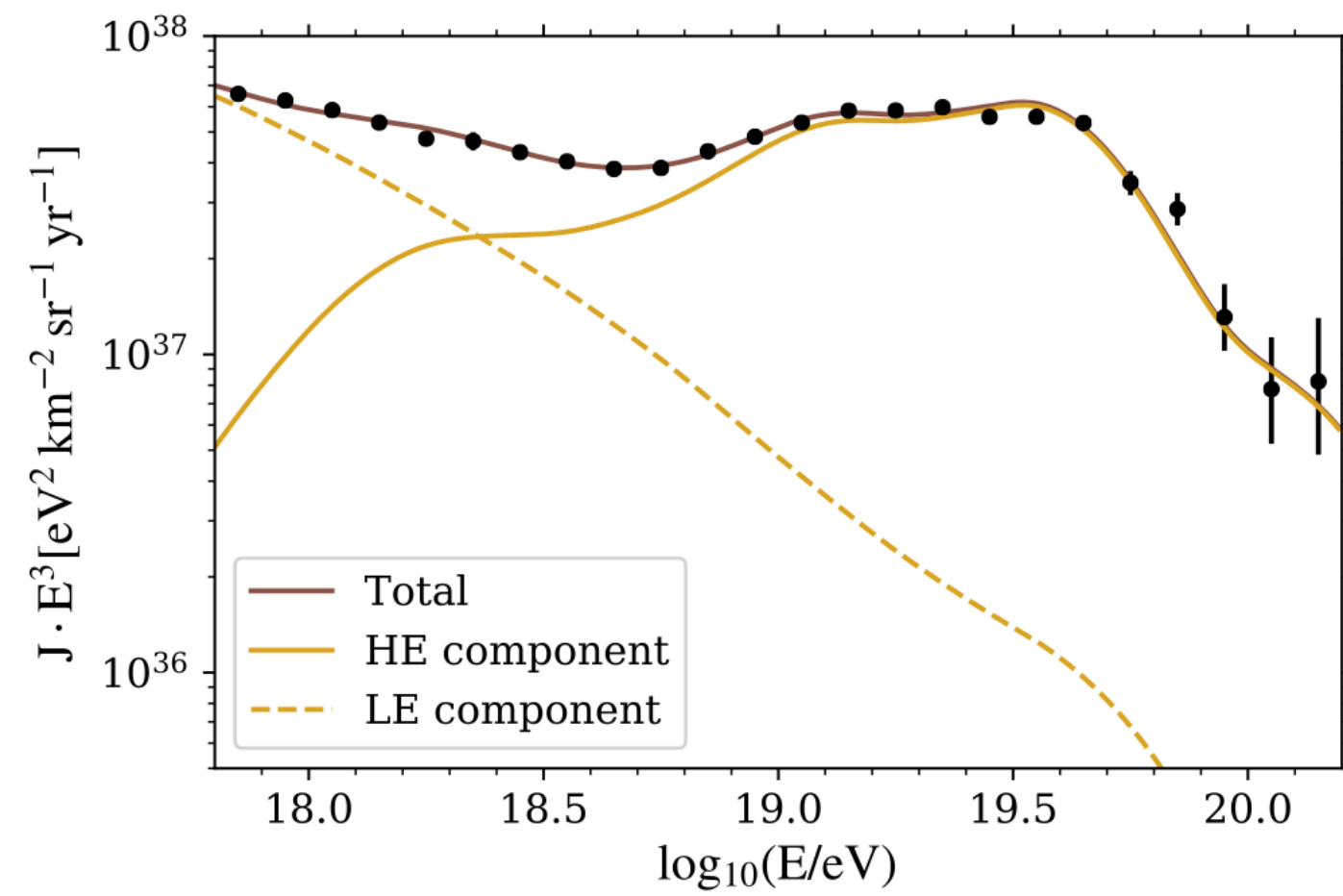
- Pion production

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



Photons at UHE

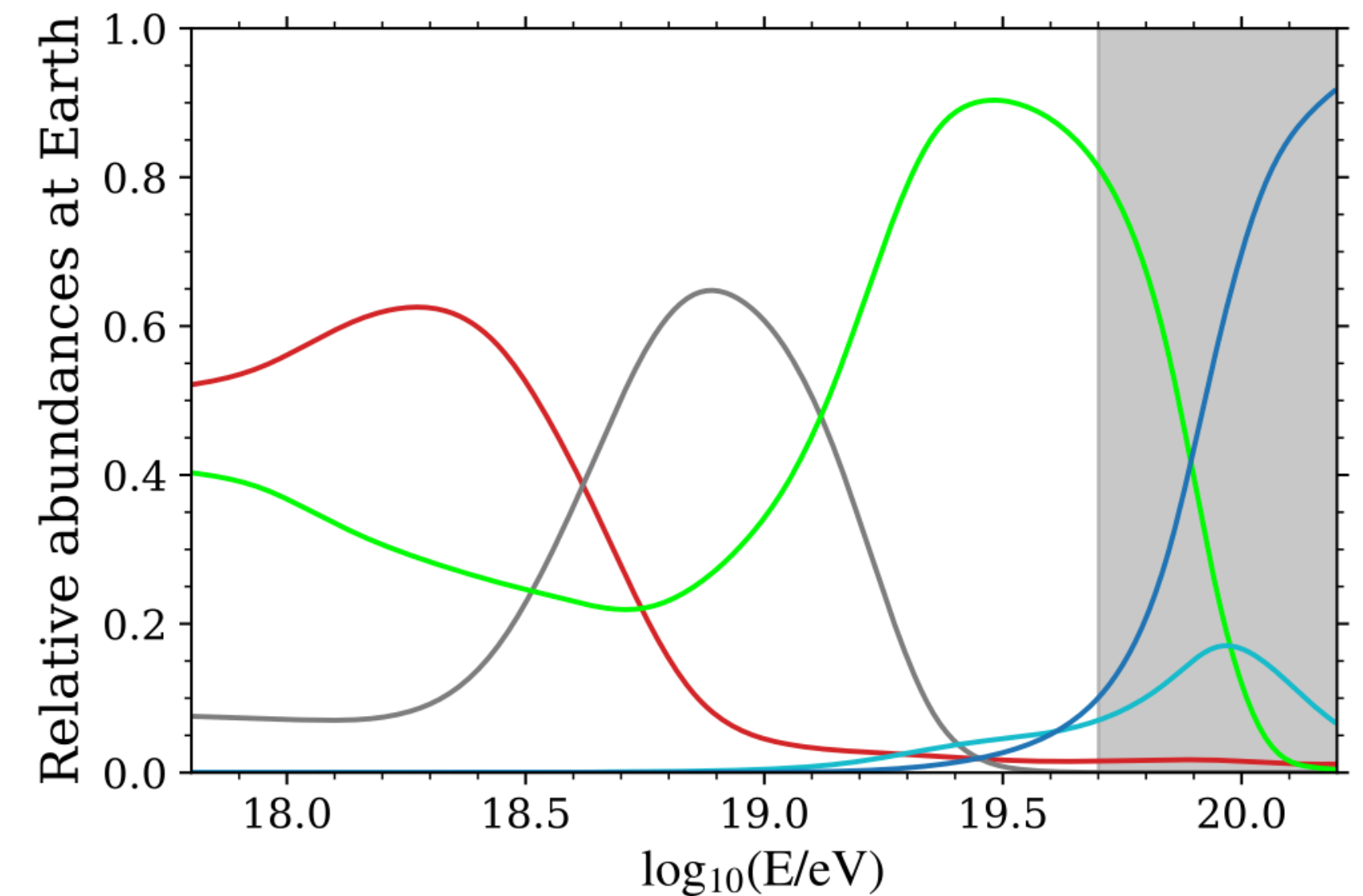
- UHECR data require a limited mixing of spectra of different nuclear species at the escape from sources, implying low rigidity cutoff



The Auger Collab. JCAP 2023

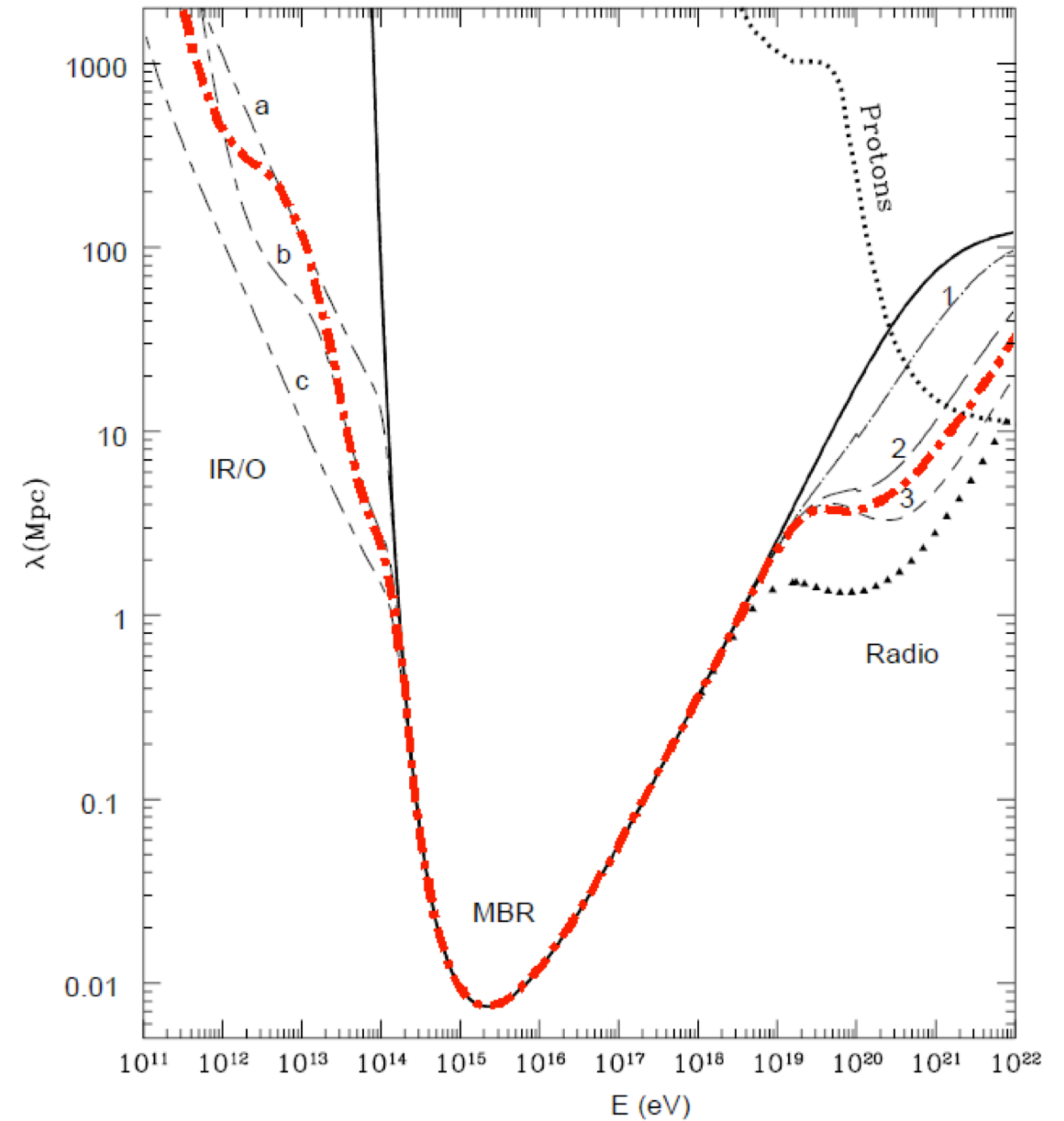
- Independently of the scenario, decreasing fluctuations of X_{max} can be found corresponding to limited mixing of spectra of different nuclear species at HE, meaning

- HE: hard spectra + low rigidity cutoff
- LE: soft spectra + less constrainable rigidity



Photons at UHE

- Due to the characteristics of photopion production and to the interactions of photons, the cosmogenic flux (of photons) mostly depends on the
 - Maximum rigidity of UHECRs at the escape from their sources
 - Proton fraction
- and just mildly depends on the cosmological source evolution and on the maximum redshift (unlikely the cosmogenic neutrino flux)



De Angelis, Galanti & Roncadelli, MNRAS 2013

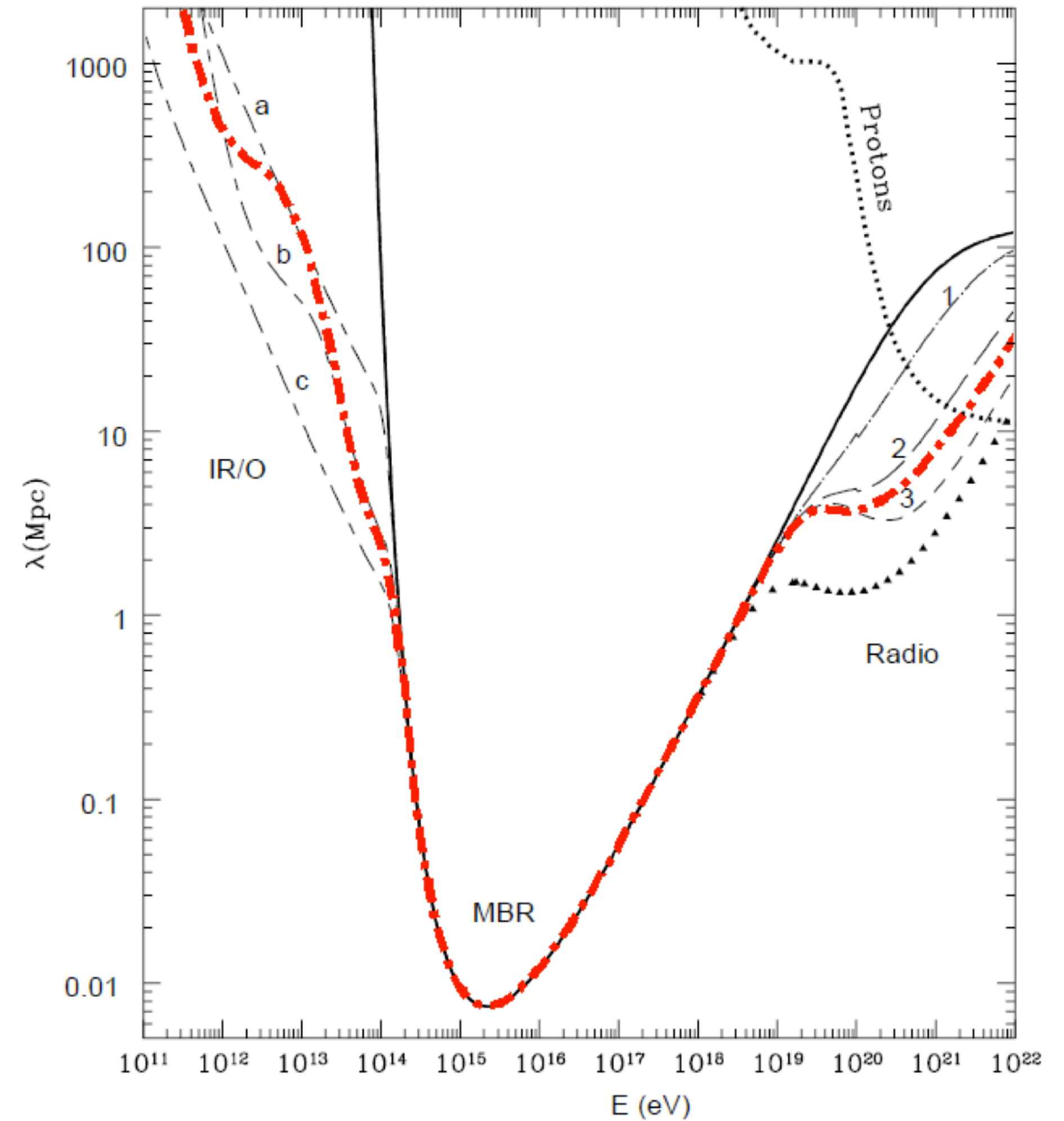
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-> This is valid also when Lorentz invariance is violated

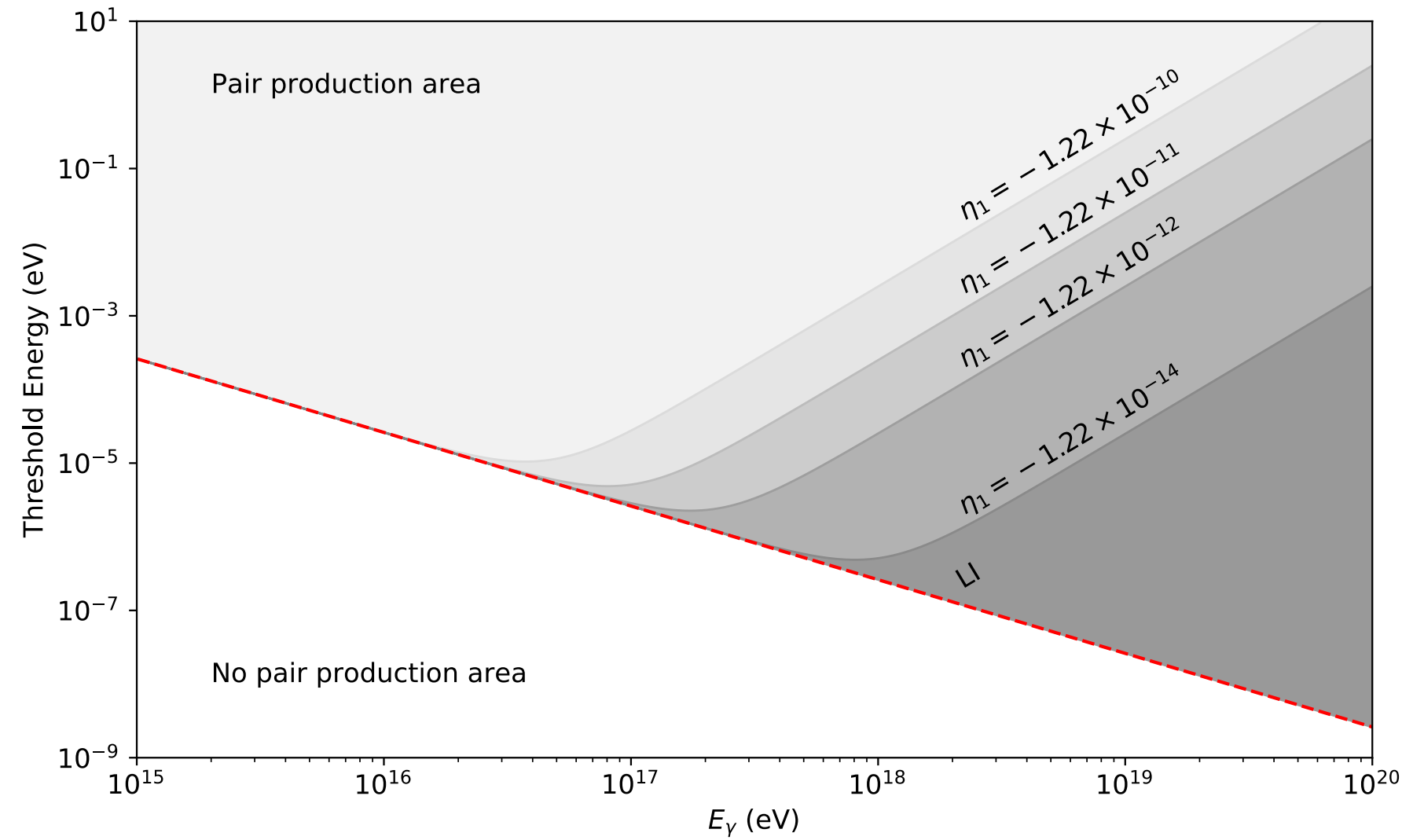


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Photons at UHE and LIV

- Modification of threshold (focus on subluminal case, so the threshold increases with LIV), as reported in [Lang+ ApJ 2018](#)

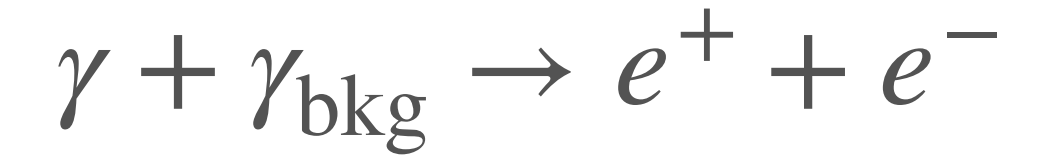
$$\epsilon \geq \frac{4m_e^2 - m_{\text{eff}}^2}{4E_\gamma}$$



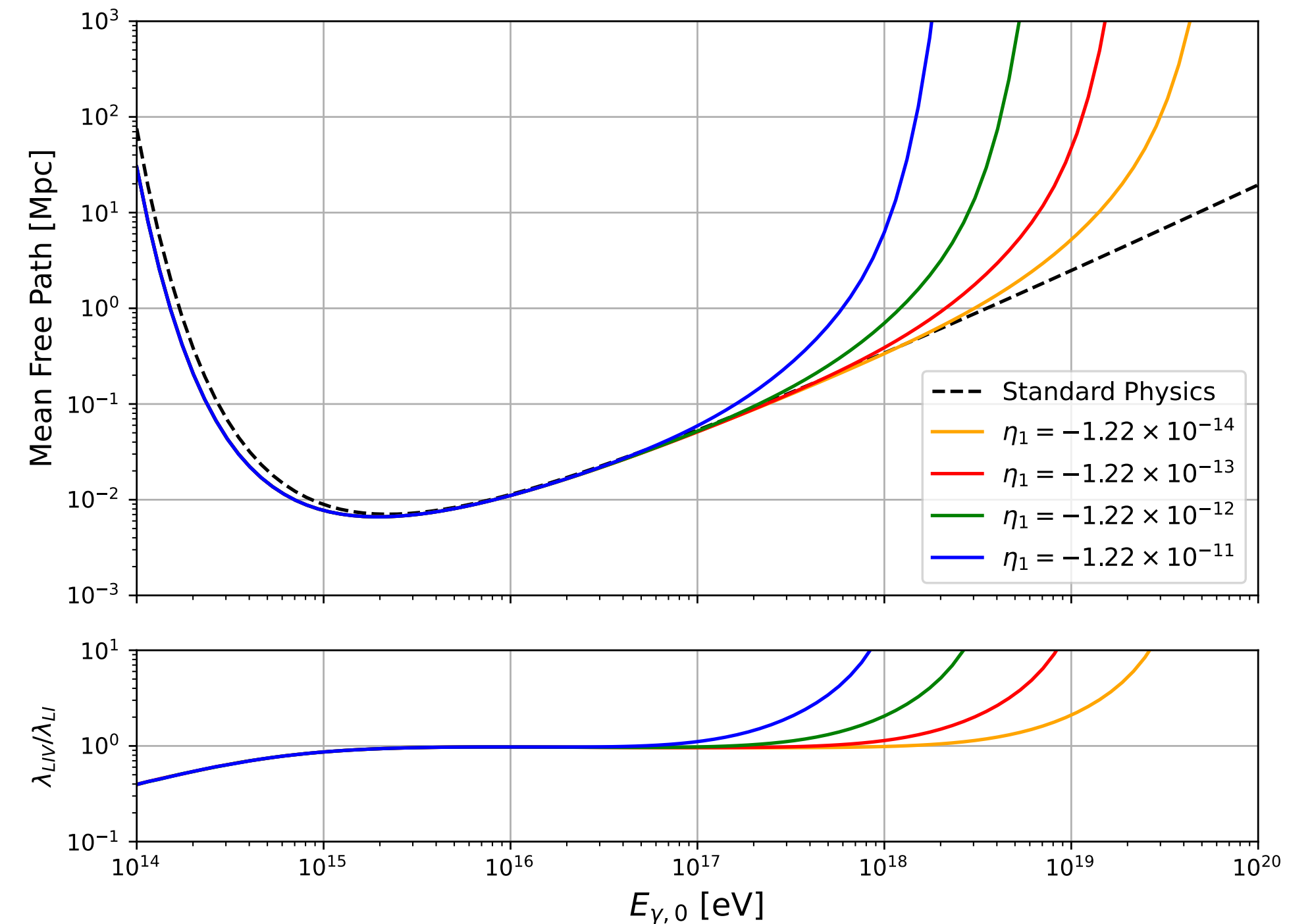
- See also [Carmona+ PRD 2024](#) for a refined treatment of cross section modifications

$$\frac{1}{\lambda(E)} = \frac{c}{2\Gamma^2} \int_{\epsilon'_{\text{th}}}^{\infty} \sigma(\epsilon') \epsilon' \int_{\epsilon'/2\Gamma}^{+\infty} \frac{n_\gamma(\epsilon)}{\epsilon^2} d\epsilon d\epsilon'$$

$$P_{\text{prop}}(E, d_s(z)) \approx \exp(-d_s/\lambda(E))$$



Modified mean free path

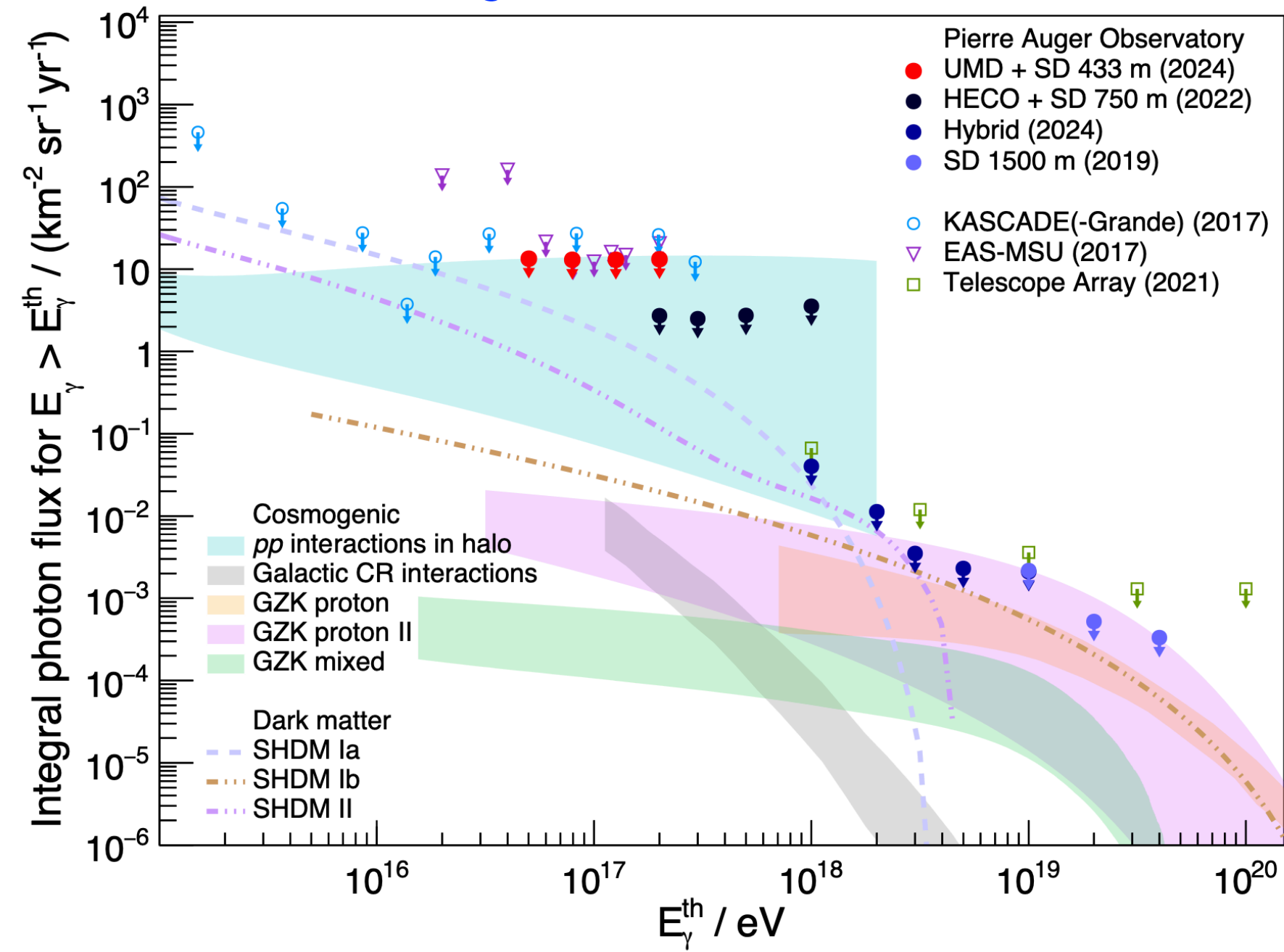


Framework

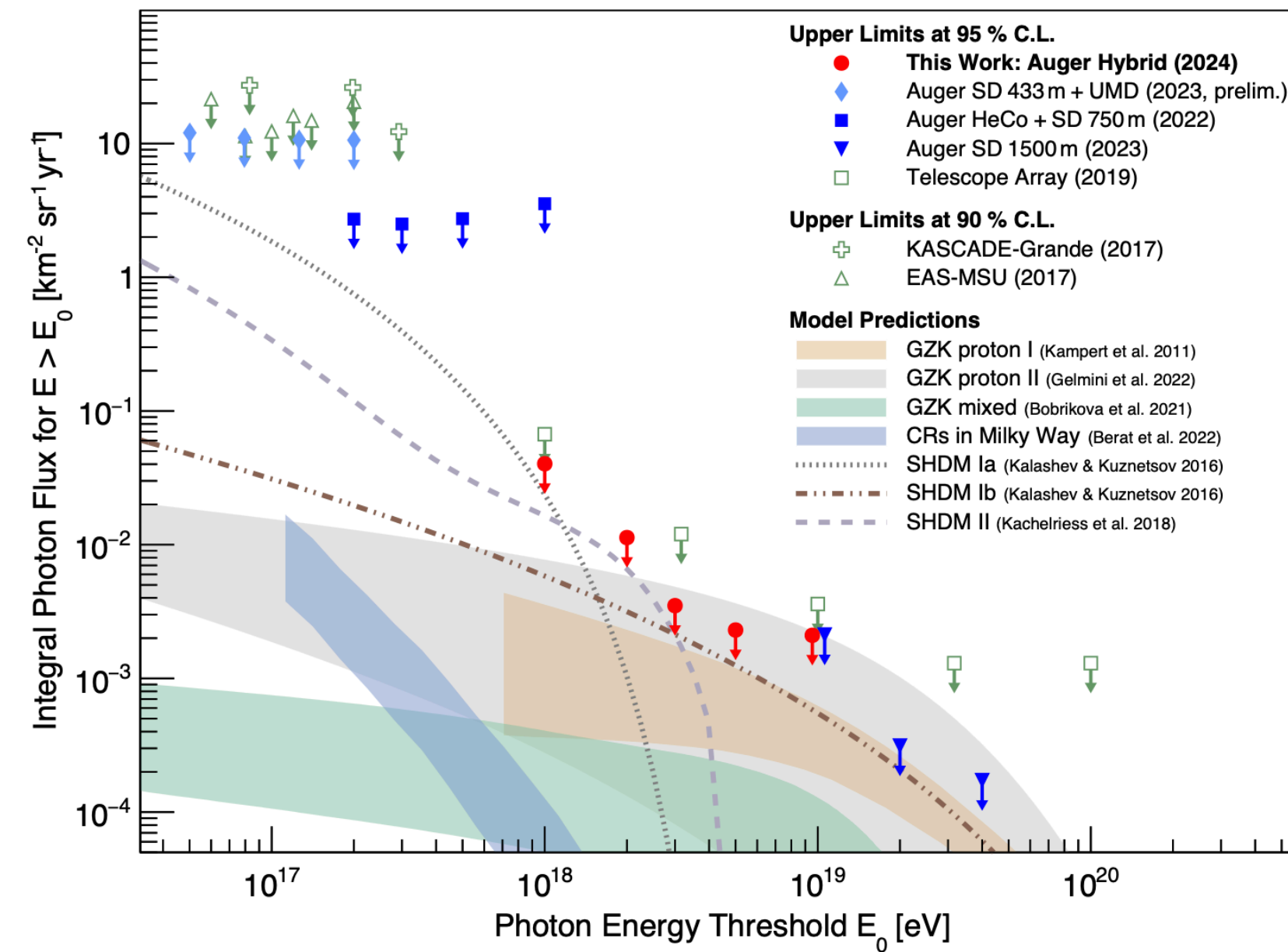
- How to constrain LIV?
 - We compute
 - the typical interaction length
 - the probability of interacting in a medium
 - the modified flux
 - We compare the modified propagated flux (model) to the measured energy spectrum - or to existing limits

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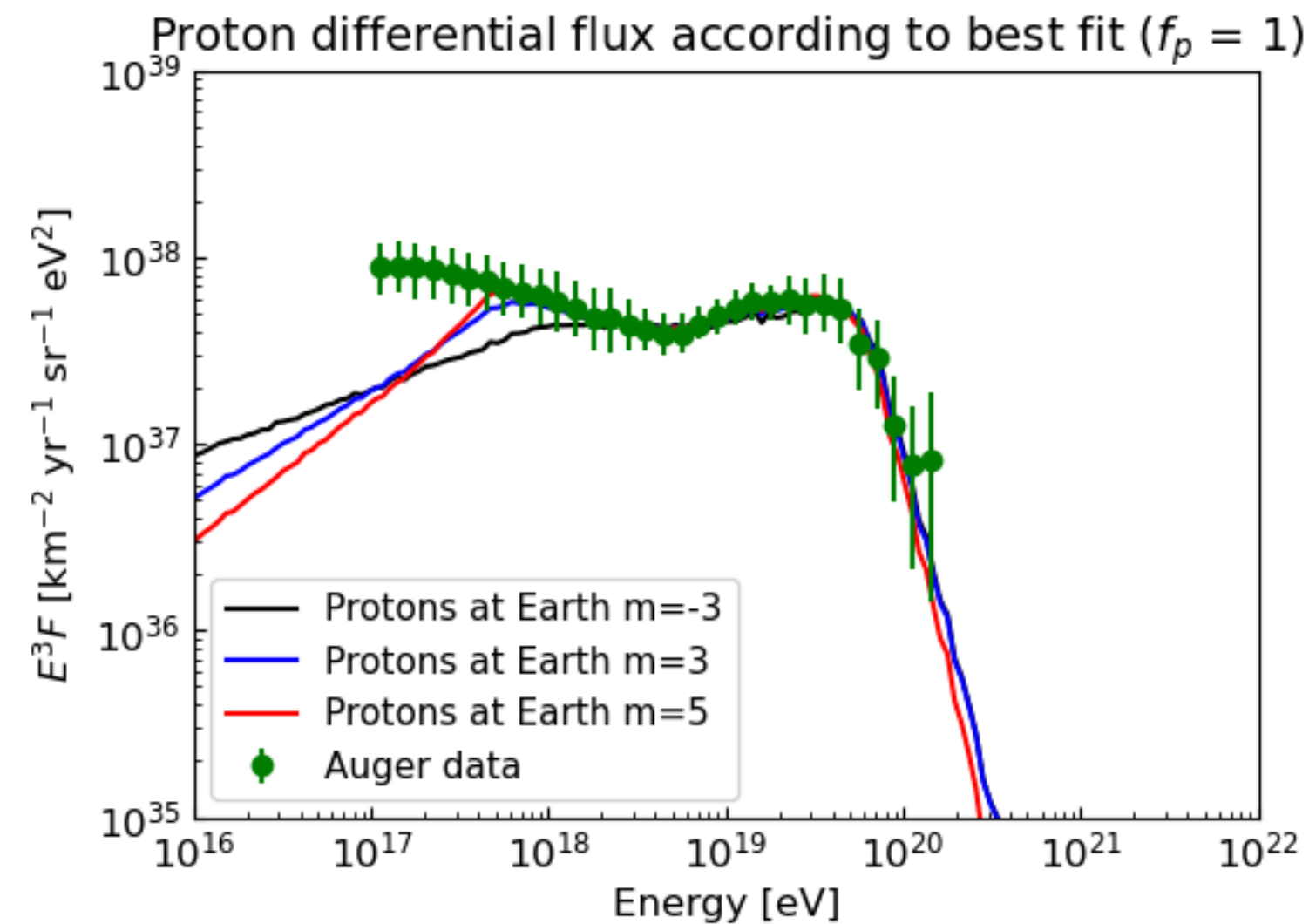
Low-energy range



High-energy range

LIV in extragalactic propagation of photons

- Redshift and energy of cosmogenic photons (as produced by interactions of UHECRs with background photons) computed with *SimProp*, Aloisio, DB, di Matteo, Grillo, Petrera & Salamida JCAP 2017
- Simplified approach:
 - fit the measured UHECR spectrum with pure propagated protons (fit parameters: normalisation, spectral index at source, maximum energy at source)
 - The normalisation of the photon flux is fixed by the comparison of the parent UHECR flux to data

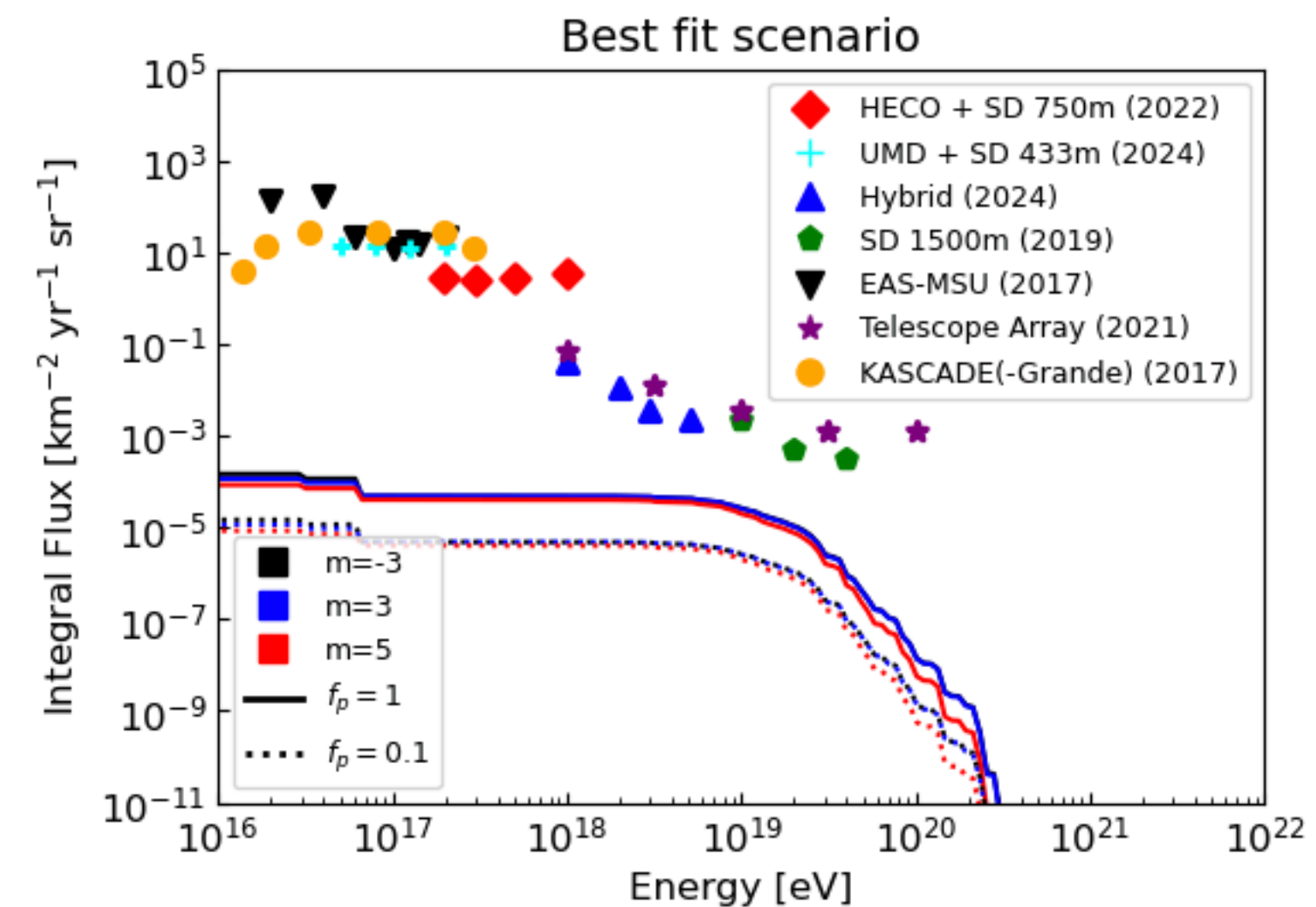
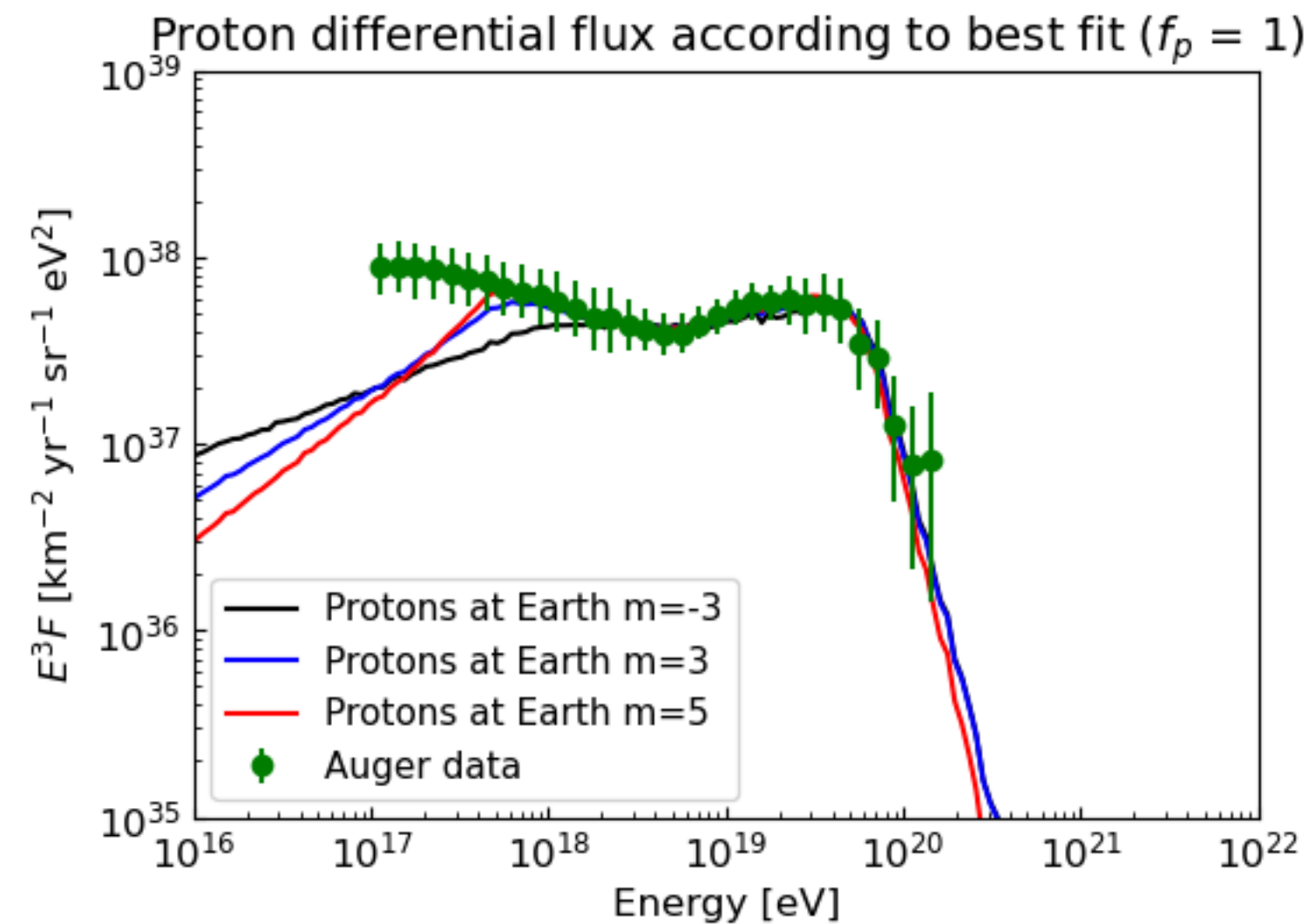


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- Compute the attenuated photon flux

$$\left(\frac{dn_\gamma(E, z=0, \eta)}{dE} \right)_{top-of-atm} = \sum_{z_i} P_{prop}(E, z_i, \eta) \frac{dn_\gamma(E, z_i)}{dE} \rightarrow \text{Cosmogenic photons, as produced with SimProp}$$

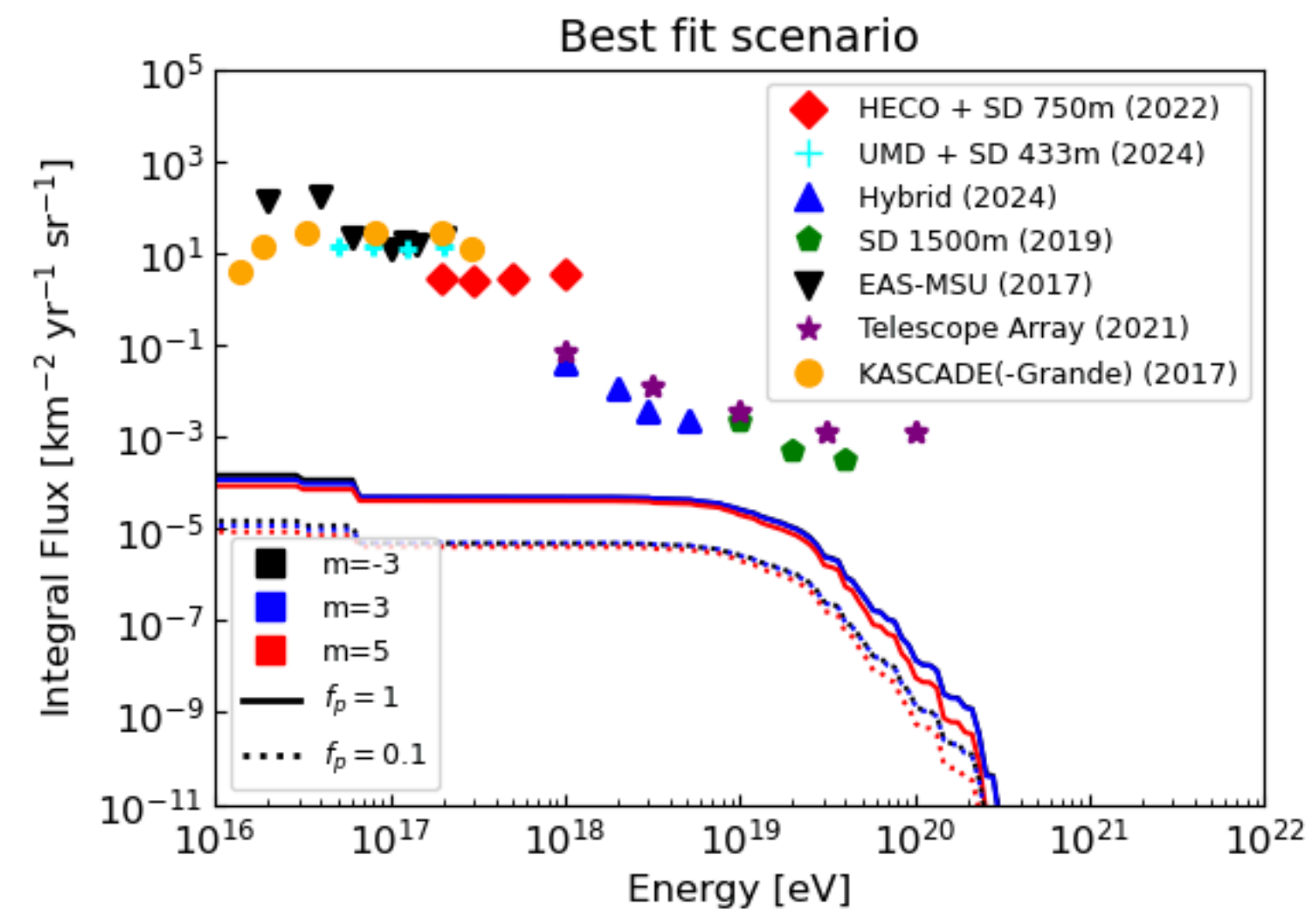
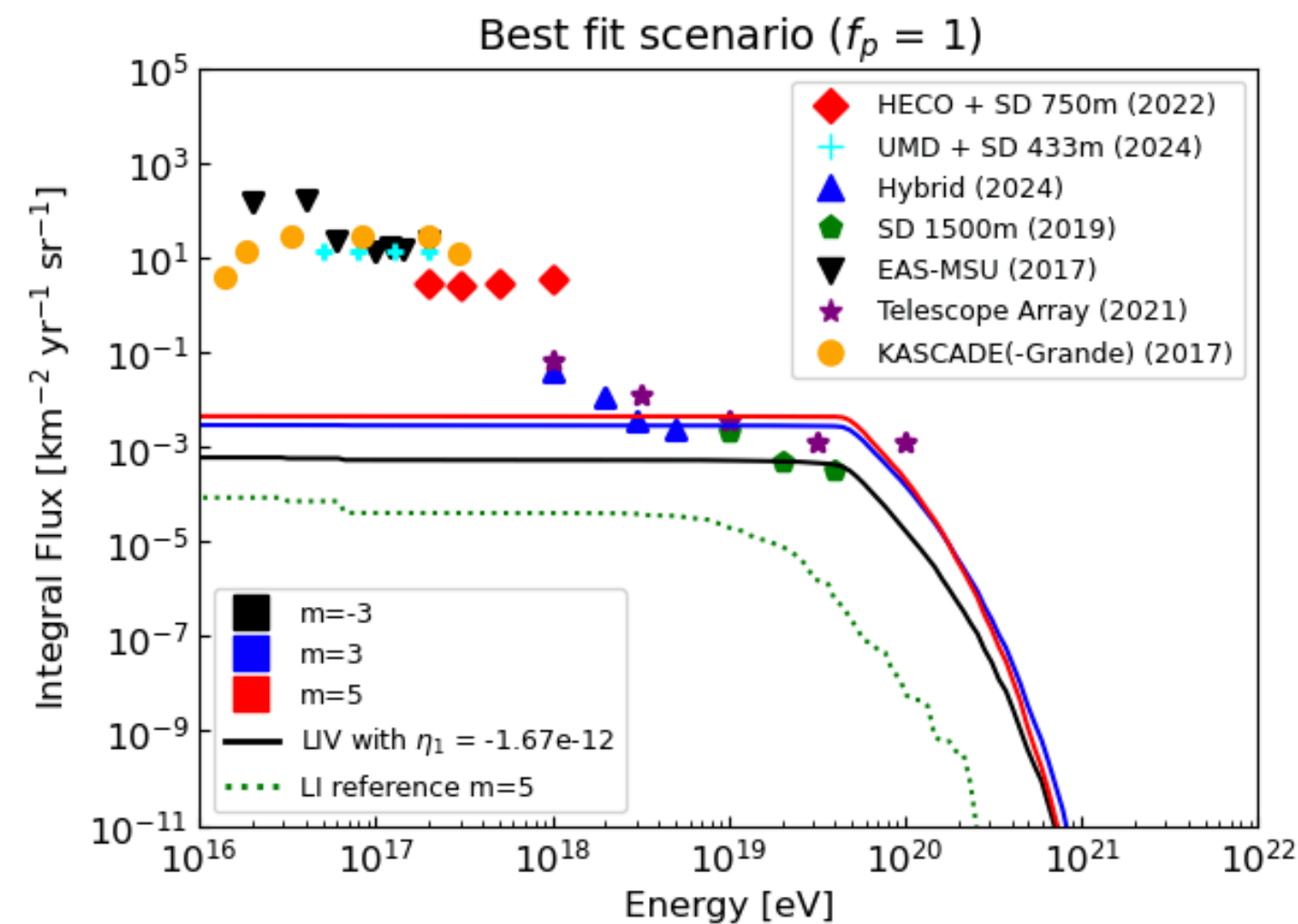


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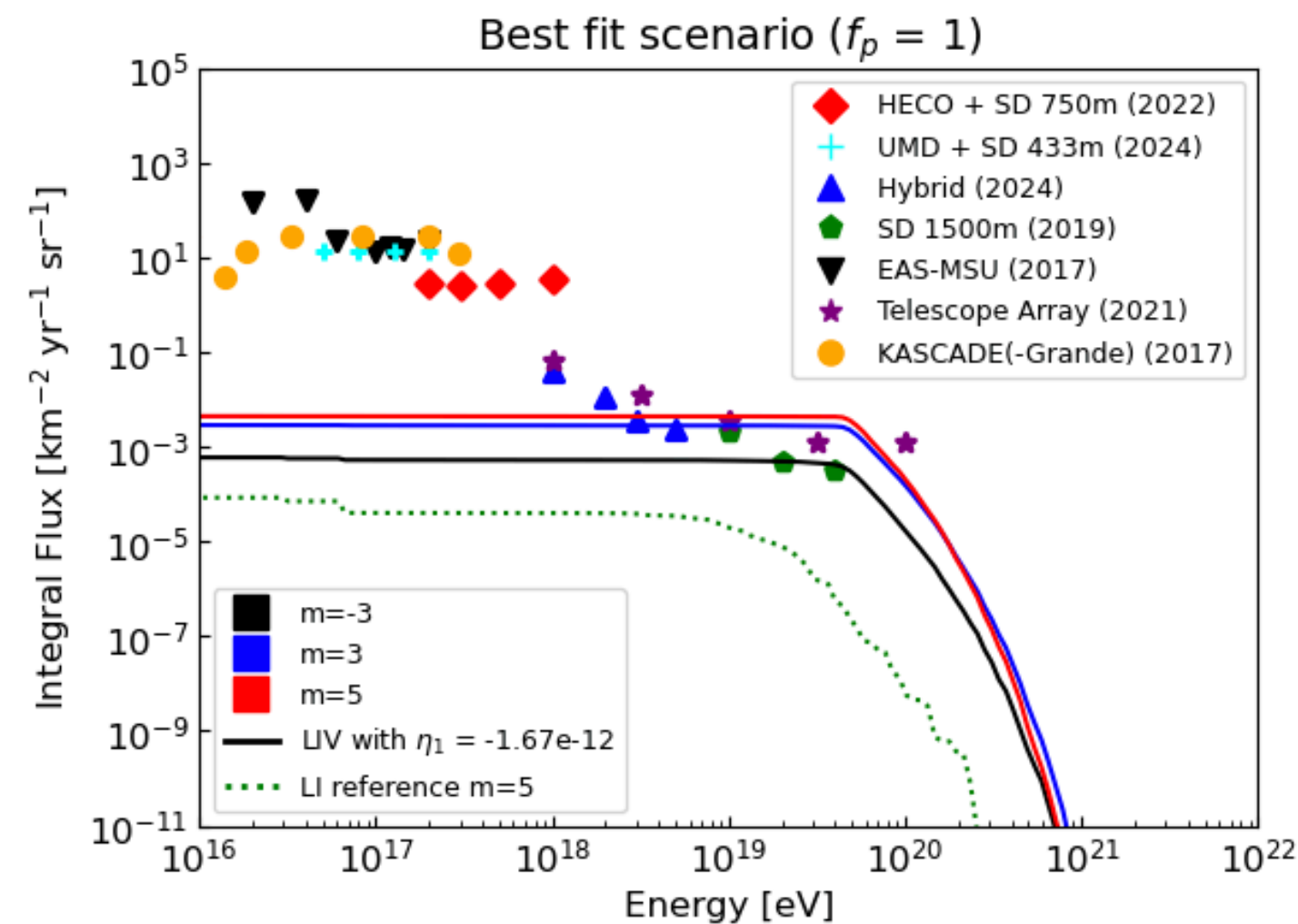


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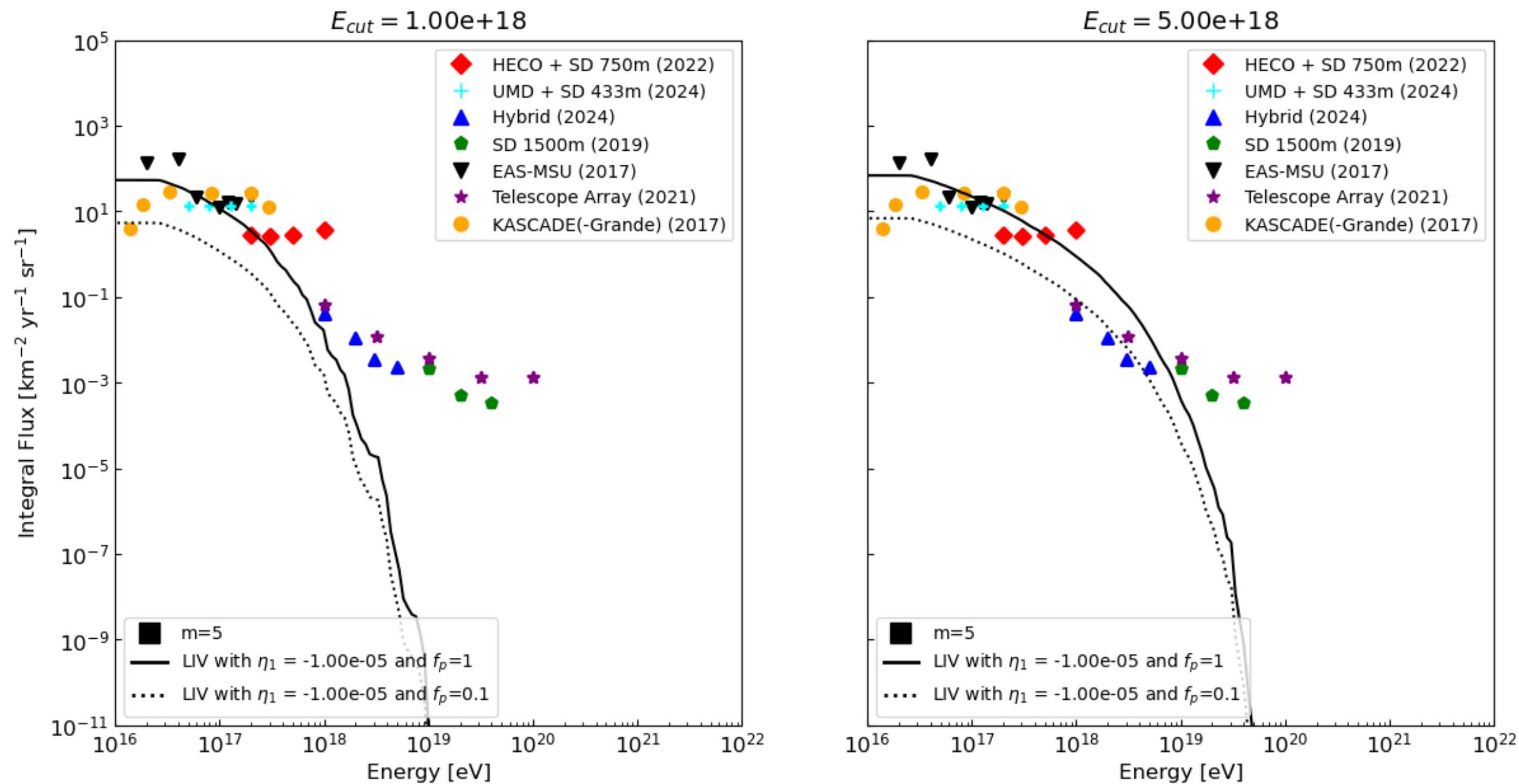


- LIV modifications allow for a larger photon flux to reach the top of the atmosphere
- LIV parameters corresponding to fluxes larger than the upper limits (as set by Auger, see Auger PRD 2024) can be excluded

LIV in extragalactic propagation of photons

- Sensitivity to LIV tests corresponding to the photon energy range (which corresponds to maximum energy of protons and their fraction with respect to the other nuclear species)
 - The larger the E_{max} , the more sensitive to the LIV parameter at the highest energies
 - The smaller the E_{max} , the more sensitive to the LIV parameter at the lowest energies

Photon integral flux with LIV and with CRB (broken exponential cutoff)



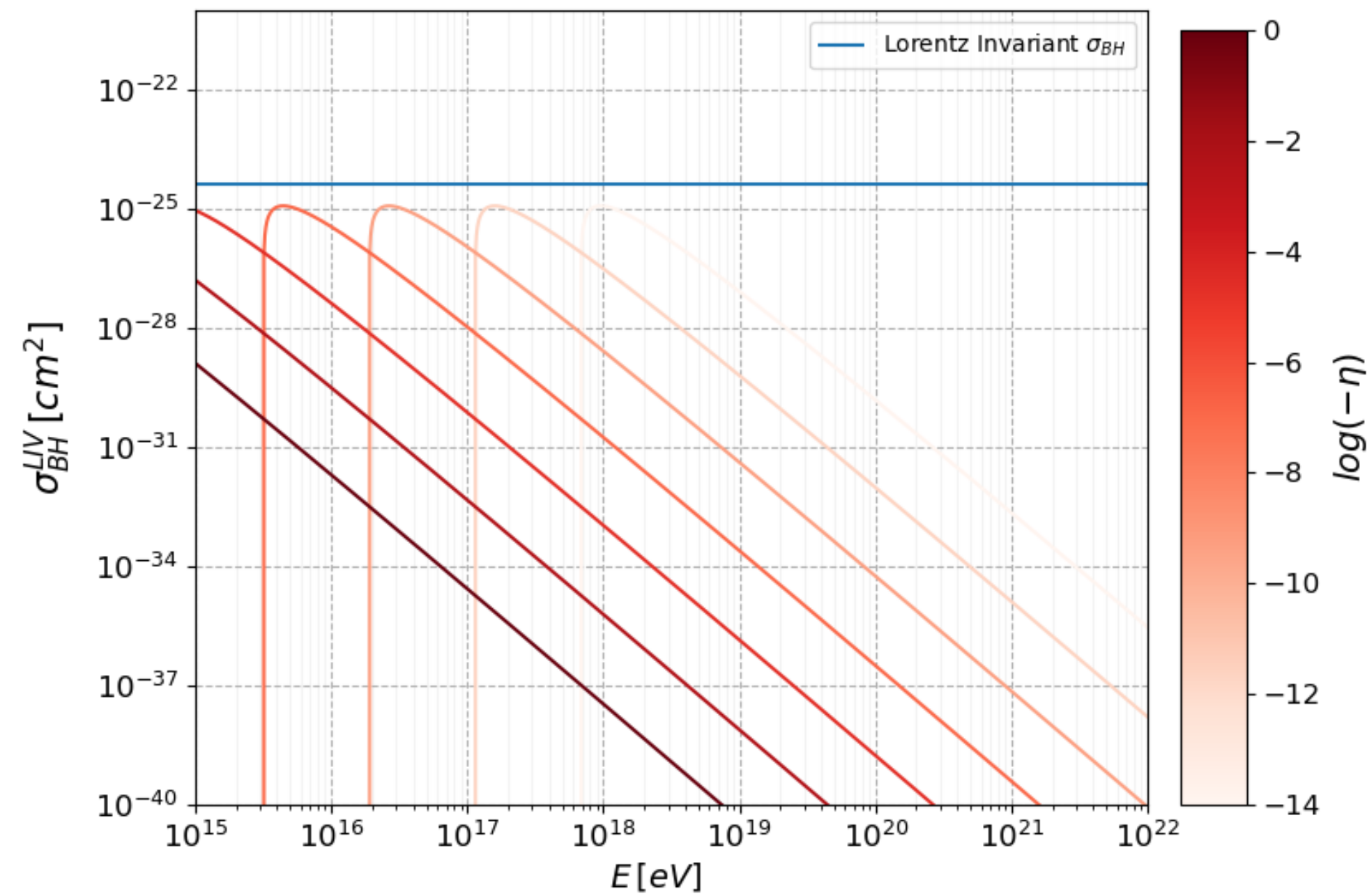
- **Work in progress** -> To be optimised to enhance the expected photon flux at 10^{16} eV as a function of proton fraction and LIV parameter that can be investigated

LIV in development of atmospheric showers initiated by photons

- Modification of cross section as reported in [Rubtsov, Satunin & Sibiryakov, PRD 2012; 2014](#)



Plot of σ as a function of (E, η) for $n=1$ violation (atmosphere)



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

Validity of modification

$$P_{\text{atm}}(E, \eta) = \int_0^{X_{\text{atm}}} dX_0 \frac{e^{-X_0/\langle X_0 \rangle_{\text{LIV}}}}{\langle X_0 \rangle_{\text{LIV}}} = 1 - e^{-X_{\text{atm}}/\langle X_0 \rangle_{\text{LIV}}}$$

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

Probability to produce a pair in atmosphere

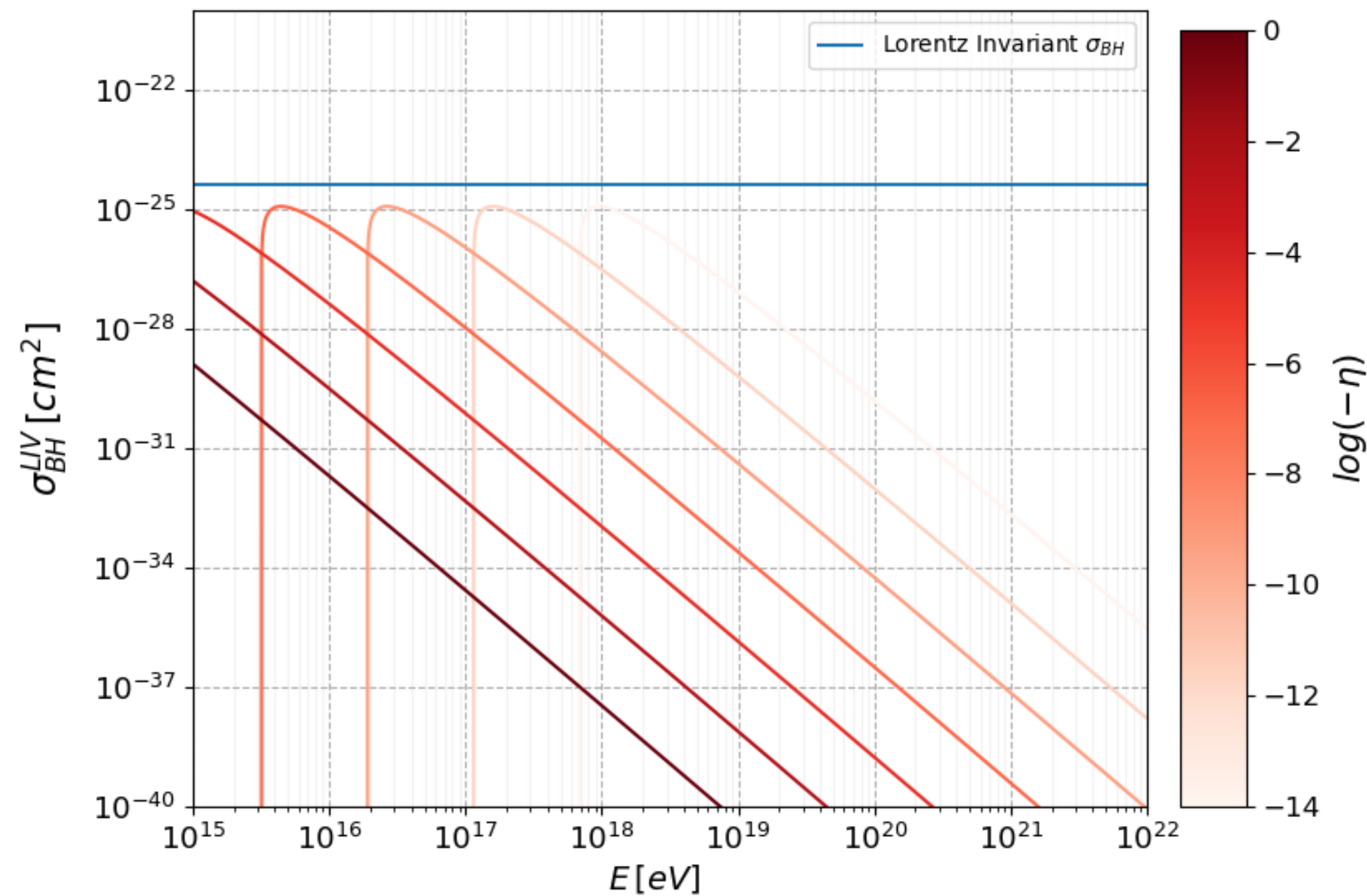
- For other tests of LIV in atmospheric showers: see
 - Photon sector: [Duenkel+ PRD 2023; PRD 2021; Klinkhamer+ PRD 2017](#)
 - Effects in X_{max} predictions: [DB+ ICRC2015](#)
 - Fluctuation of the number of muons: [Auger, accepted in PRL](#)

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Probability to produce a pair in atmosphere

- LIV modifications -> increase the threshold for pair production
 - allows for more photons to reach the top of the atmosphere
 - allows for more photons to reach the Earth surface
 - Caveat: photons which do not produce a pair, could interact through photopion production, inducing hadronic showers -> under investigation (with CONEX) to check if it could compensate the absence of pair production

$$\left(\frac{dn_\gamma(E, z=0, \eta)}{dE} \right)_{\text{Earth}} = P_{\text{atm}}(E, \eta) \left(\frac{dn_\gamma(E, z=0, \eta)}{dE} \right)_{\text{top-of-atm}}$$

Summary

- LIV can be tested with astroparticles at UHE
 - See also [Auger JCAP 2021](#) for LIV in UHECR propagation
- Focus on photons:
 - the propagation and detection stages (first study to account for LIV effects in both stages)
 - main uncertainties for the expected photon flux at 10^{16} eV:
 - from UHECRs:
 - proton fraction
 - maximum energy of this component at source
 - from photon interactions:
 - mild effect of radio background
 - electromagnetic showering to be considered

For a roadmap about quantum gravity phenomenology see [Alves Batista+ Class.Quant.Grav. 42 \(2025\)](#)