Effect of LIV in the propagation of UHE photons

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Introduction

This study examines how quantum gravity effects [1, 2], particularly Lorentz Invariance Violation (LIV), impact the propagation of ultra-high-energy (UHE) photons [3, 4]. LIV can affect fundamental parameters such as cross-section, threshold energy, and mean free path. The work focuses on the Breit-Wheeler process in the intergalactic medium and the Bethe-Heitler process in Earth's atmosphere, emphasizing how minor deviations from Lorentz invariance influence the expectation of UHE photon fluxes. photons

The Modified Dispersion Relation

The principal LIV modification is the Modified Dispersion Relation (MDR) [5, 6], which can be expressed in terms of energy as follows:

$$E^2 = m^2 + p^2 + m^2_{eff} \text{ where } m^2_{eff} = \sum_{n\geq 0} \eta_{i,n} \frac{E^{n+2}}{M^n_{Pl}}, \tag{1}$$

where $\eta_{i,n}$ represents the LIV coefficients, which in principle can be different for each type of particle, $M_{Pl} = 1.22 \times 10^{19}\,\text{GeV}^2$ is the Planck mass, the low-energy velocity of photons is normalized to 1, and the m^2_{eff} is the terms of effective momentum-dependent masses of the particles that provide significant insights into how these effective masses influence the kinematics of various reactions.

The effects of LIV in the extragalactic propagation of photons

Photons propagating in the extragalactic space interact with background photons, producing electron-positron pairs **Breit-Wheeler (BW) process**. The mean free-path for this process can be computed as

$$\frac{1}{\lambda_\gamma(E)} = \int_{-1}^{1} d(\cos\theta)\frac{1-\cos\theta}{2}\int_{\epsilon_{\text{th}}}^{\infty} d\epsilon n(\epsilon)\sigma(E,\epsilon). \text{ where } n_\gamma(\epsilon) = \epsilon/\pi^2(e^{\epsilon/kT_0}-1)^{-1} \tag{2}$$

where usually the modification from MDR can appear on **Threshold energy** and **Cross-Section**:

$$\epsilon_{\text{th}} = \frac{4m_e^2 - m^2_{\gamma eff}}{4E} \text{ and } \sigma^{LIV}_{\gamma\gamma CB} = \frac{\alpha^2\pi}{2E_\gamma\epsilon}\left(1 + \left(1 + \frac{m^2_{\gamma eff}}{E_\gamma\epsilon}\right)^2\right)\log\left(\frac{2E_\gamma\epsilon + m^2_{\gamma eff}}{m_e^2}\right). \tag{3}$$

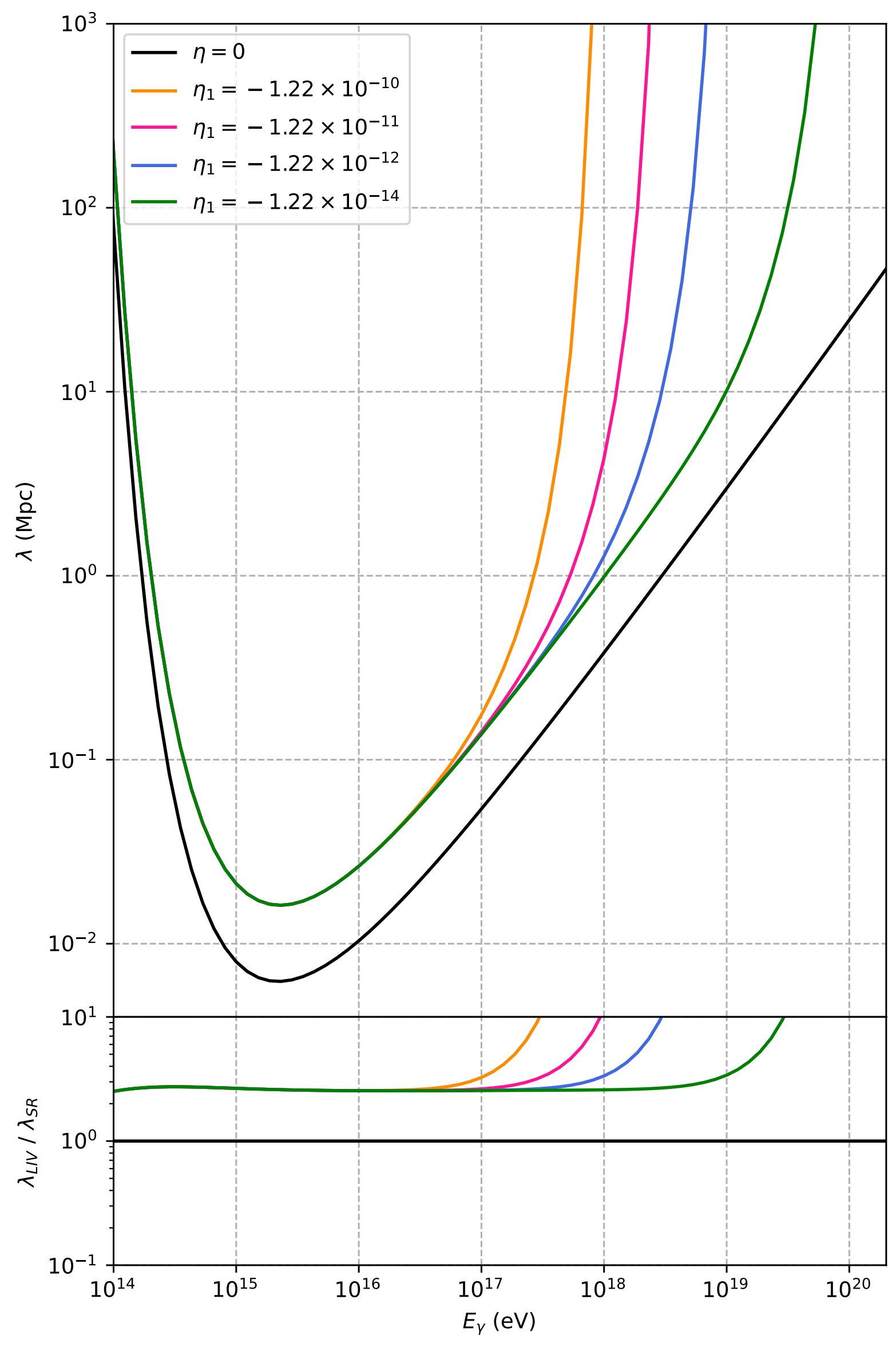


Figure 1. Mean free path for photons as a function of their energy in the range where the CMB is the relevant background. The black line curve corresponds to the mean free path in SR, and the colored curves represent the LIV scenarios with different values of η with $n = 1$.

The impact of LIV in photon-initiated EAS

When UHE photons reach the Earth atmosphere, they can initiate extensive air showers. At energies around 10^{18} to 10^{19} eV, the dominant mechanism is the **Bethe-Heitler (BH) process**, where electron-positron pairs are produced through interactions with atmospheric nitrogen nuclei. Under typical conditions, the cross-section for the BH process is energy-independent, as illustrated below:

$$\sigma_{BH} = \frac{28Z^2\alpha^3}{9m_e^2}\left(\log\frac{183}{Z^{1/3}} - \frac{1}{42}\right), \tag{4}$$

$$\sigma^{Liv}_{BH} = \frac{8Z^2\alpha^3}{3|m^2_{\gamma,eff}|}\log\frac{1}{\alpha Z^{1/3}}\log\frac{|m^2_{\gamma,eff}|}{m_e^2}, \tag{5}$$

In the Eq.(4) we have the standard case and the Eq.(5) is the LIV case from [5]

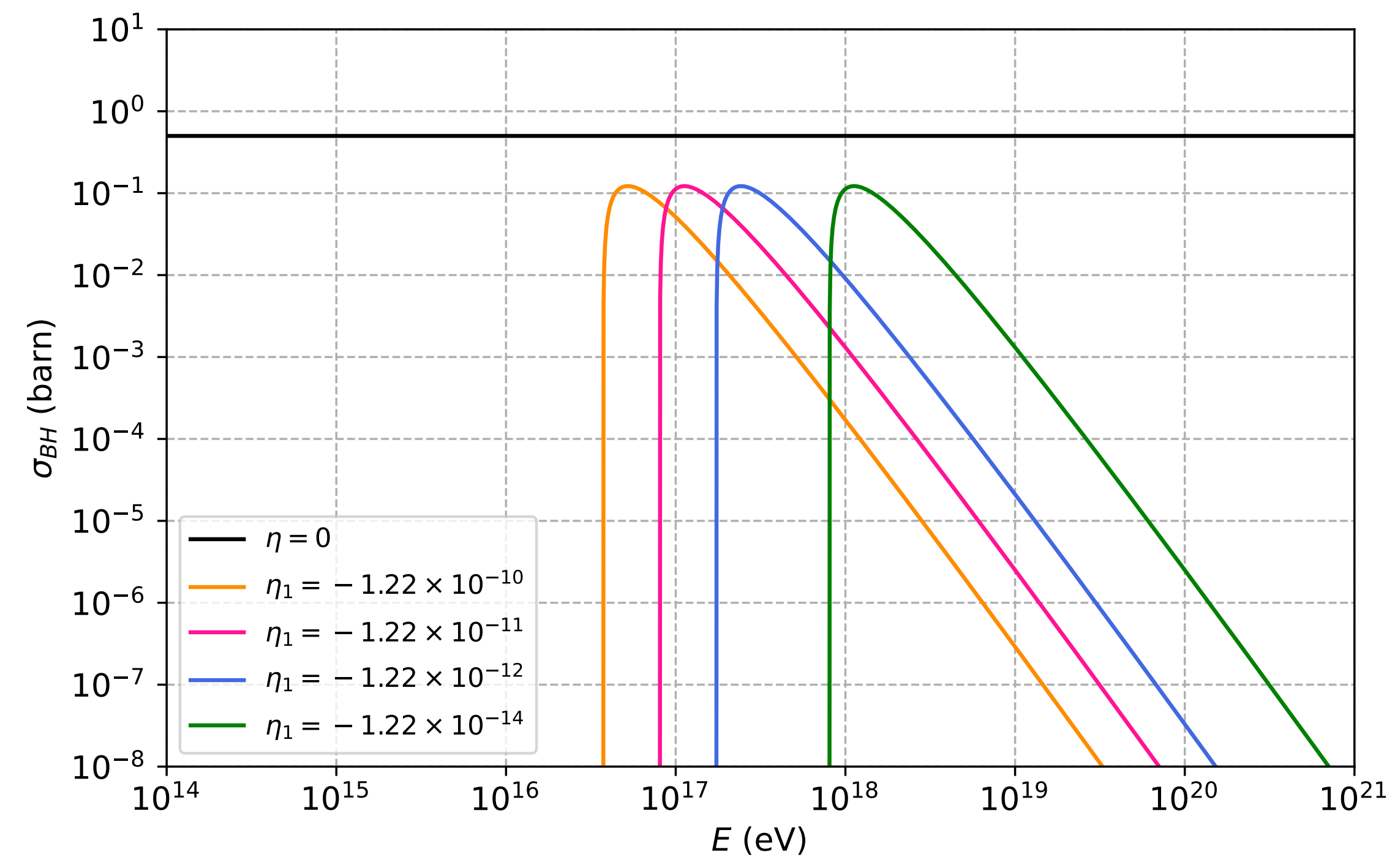


Figure 2. Comparison of the cross-section σ_{LIV} colored color and black color for SR (Bethe-Heitler) case. We consider a fixer energy of the low-energy photon, $\epsilon = 10^{-4}$ eV, a fixed angle $\theta = \pi$, fixed orders $n = 1$, and different values of η.

The survival probability

The probability for a photon to produce a pair in the atmosphere shown in [6] can be written as,

$$P = \int_0^{X_{\text{atm}}} dX_0 \frac{e^{-X_0/\langle X_0\rangle_{\text{LIV}}}}{\langle X_0\rangle_{\text{LIV}}} = 1 - e^{-X_{\text{atm}}/\langle X_0\rangle_{\text{LIV}}} \text{ where } \langle X_0\rangle_{\text{LIV}} = \frac{\sigma^{\text{LI}}}{\sigma^{\text{LIV}}}\langle X_0\rangle_{\text{LI}}, \tag{6}$$

where the mean depth of interactions $\langle X_0\rangle_{\text{LIV}}$ in the LIV case are expressed via the mean depth $\langle X_0\rangle_{\text{LI}} = 57\,\text{g}\,\text{cm}^{-2}$ in the LI case and the ratio of the cross-sections σ^{LIV} and σ^{LI}.

The probability $P(E_\gamma, \eta)$ is understood as a suppression factor to assess the potential for particle shower formation

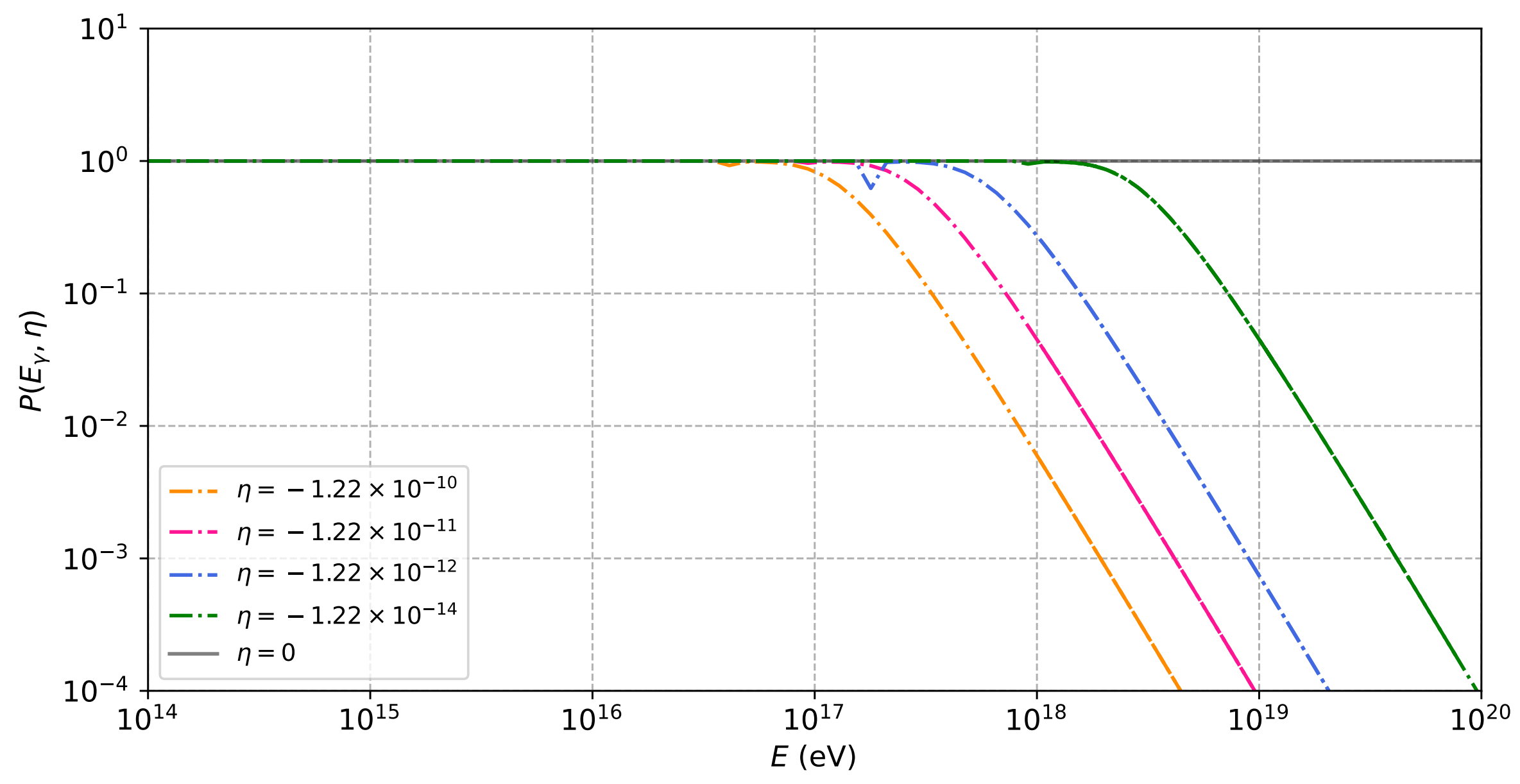
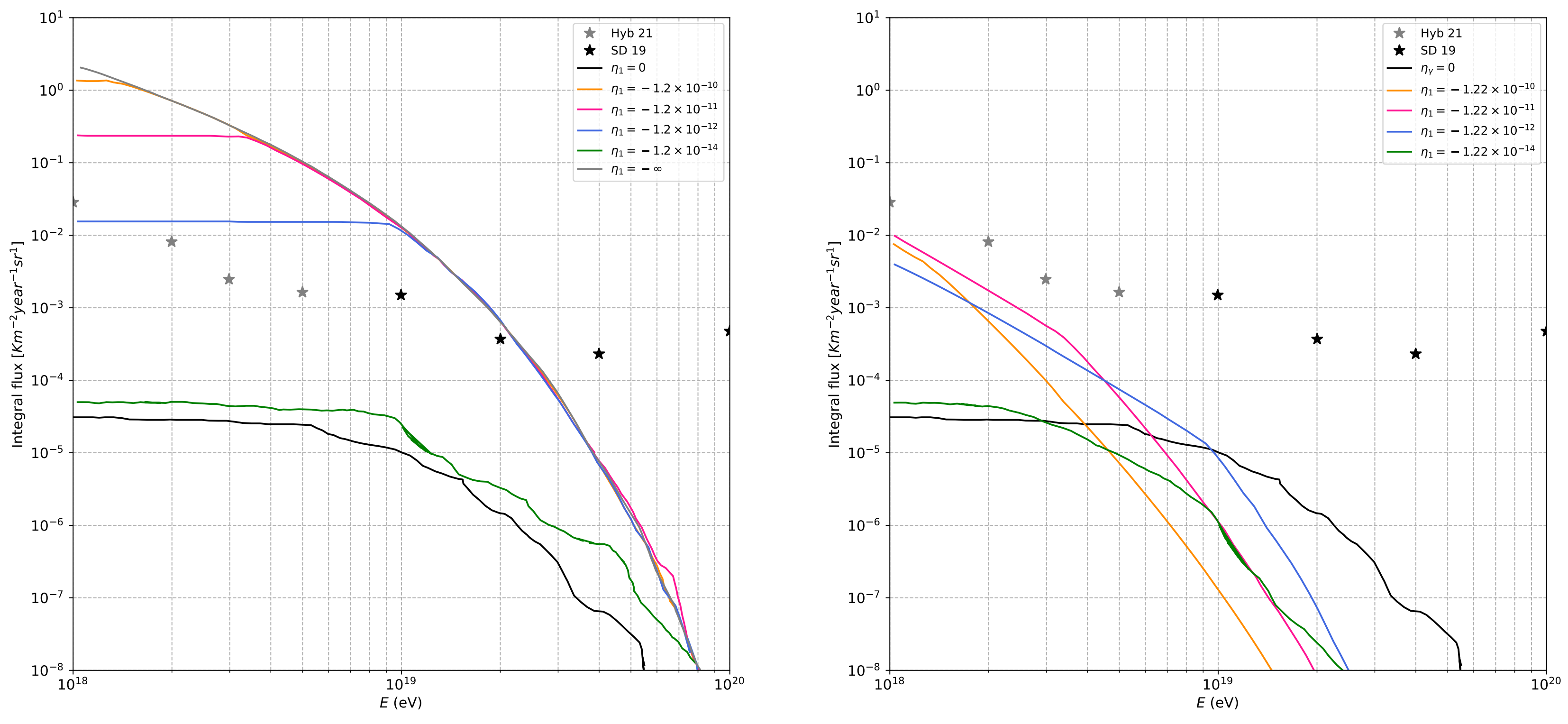


Figure 3. The suppression factor as a function of the energy for an alternative scenario with different values of the E_{LIV}.

The prediction for the observed flux that was formulated in [6] follows as:

$$\left(\frac{d\Phi}{dE}\right)_{\text{LIV}} = P(E_\gamma, \eta) \times \left.\frac{d\Phi}{dE}\right|_{\text{source}}, \tag{7}$$

where the suppression factor is given by eq. 6). The application of the atmospheric suppression on the simulated UHE photon flux is shown in Fig.(4b), to be compared to Fig.(4a), where the atmospheric suppression is not taken into account.



(a)   (b)

Figure 4. The simulated integral flux of UHE photons as a function of the energy. Left: simulated integral fluxes as taken from [3] with LIV effects only in the intergalactic propagation. Right: same simulated integral fluxes, including the atmospheric suppression as calculated in this work.

Conclusions:

In this work, we couple for the first time the LIV modifications in the extragalactic propagation of UHE photons and in the development of the shower they initiate in the atmosphere. To do so, we derive the modifications induced by LIV both in the cross-section and in the threshold for the BW and the BH processes, happening respectively in the extragalactic space and the development of photon-initiated showers. We demonstrate that, while the LIV in the extragalactic propagation might increase the expected UHE photons at Earth, the same effect in the atmosphere of the shower can inhibit the starting of the shower. Although the excluded region of LIV parameters is smaller if the atmospheric suppression is taken into account, the derived limits are more robust as they account for the LIV modifications in both the propagation and detection stage of the life of the UHE photon.

References

[1] G. Amelino-Camelia, C. Lammerzahl, A. Macias and H. Muller, *The Search for quantum gravity signals*, *AIP Conf. Proc.* **758** (2005) 30 [`gr-qc/0501053`].

[2] G. Amelino-Camelia, *Quantum-Spacetime Phenomenology*, *Living Rev. Rel.* **16** (2013) 5 [`0806.0339`].

[3] Pierre Auger collaboration, *Testing effects of Lorentz invariance violation in the propagation of astroparticles with the Pierre Auger Observatory*, *JCAP* **01** (2022) 023 [`2112.06773`].

[4] H. Martínez-Huerta, R.G. Lang and V. de Souza, *Lorentz Invariance Violation Tests in Astroparticle Physics*, *Symmetry* **12** (2020) 1232.

[5] G. Rubtsov, P. Satunin and S. Sibiryakov, *Prospective constraints on Lorentz violation from ultrahigh-energy photon detection*, *Phys. Rev. D* **89** (2014) 123011 [`1312.4368`].

[6] P. Satunin and A. Sharofeev, *Shower formation constraints on cubic Lorentz invariance violation parameters in quantum electrodynamics*, *Eur. Phys. J. C* **84** (2024) 793 [`2312.06307`].

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