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New stringent LIV limits from astrophysical gamma-ray sources

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Lorentz invariance violation (LIV) introduced as a generic modification to particle dispersion relation can change the photon energy threshold of pair-production, which modifies the extragalactic background light (EBL) absorption of gamma rays from astrophysical sources. In this note, we report an innovative data analysis that allows us to extract unprecedented information from the most updated data set composed of 111 energy spectra of 38 different sources measured by current gamma-ray observatories. The outcome technique and results maximize the chances to find or discriminate LIV signals in any future search and reduce the biases in current analyses. Therefore, we report stringent limits for the LIV energy scale at first and second leading order in high energy gamma-rays. These limits are better than the ones current available in the literature for subluminal searches of LIV, irrespectively of many tested uncertainties, such as, poor knowledge of the EBL, large uncertainties in the intrinsic energy spectra functional form, energy resolution, selection of spectra and the energy bins selection used in the calculation of the intrinsic energy spectra.

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1. Introduction

The possibility to violate Lorentz invariance (LIV) has been proposed as a possible departure from the relativity principle [1]. The invariance of physics laws under Lorentz's transformation has been tested and restrictive limits have been imposed [2]. Possible invariances are proposed to be present in extreme phenomena and, thus, astroparticle physics is a suitable area to search for LIV signals.

LIV physics could result in an energy-dependent speed of light, vacuum Cherenkov, photon decay, and changes in the kinematics of interactions [3–5]. These effects could change astroparticle physics data in a detectable way. This work discusses the results obtained by Lang *et al.* [6] by searching subluminal LIV signals in the energy spectra of TeV gamma-ray sources. It is also shown preliminary results of the possibility of testing superluminal signal.

2. Attenuation of gamma-rays including LIV

Along the extragalactic path toward Earth, TeV gamma rays and EBL photons interact creating electron-positron pairs: $\gamma + \gamma_{EBL} \rightarrow e^+ + e^-$ [7]. Successive interactions attenuate the primary emitted gamma-ray flux as described by

$$a(E,z) = e^{-\tau}(E,z) = \frac{J_{\rm meas}(E)}{J_{\rm int}(E,z)}, \tag{2.1}$$

where $J_{\rm meas}$ is the measured spectrum at Earth and $J_{\rm int}$ is the intrinsic spectrum emitted by the source. $a(E,z)$ is called attenuation and τ is the optical depth.

Under the LIV assumption, the energy threshold of the pair production is changed, and the attenuation modified by a change in the energy dispersion relation [5, 8]. Changing the photon dispersion relation changes the energy threshold of the pair production:

$$\varepsilon_{th}^{\rm LIV} = \frac{m_e^2}{4E_\gamma K(1-K)} - \frac{\delta_n^{\rm tot} E_\gamma^{n+1}}{4}, \tag{2.2}$$

where $\varepsilon_{th}^{\rm LIV}$ is the background photon energy threshold considering LIV, E_γ is the gamma-ray energy, m_e is the electron mass, K is the inelasticity, and $\delta_n^{\rm tot}$ is a linear combination of the LIV coefficients from the different particle types, $\delta_{a,n}$ [4]. Two cases are possible: subluminal ($\delta_n^{\rm tot} < 0$) and superluminal ($\delta_n^{\rm tot} > 0$) [9]. For simplicity, only LIV photons are considered and $|\delta_n| = 1/(\mathrm{E}_{\rm LIV}^{(n)})^{\rm n}$.

The subluminal case was discussed by Lang *et al.* [6]. Figure 1 shows the mean free path and the energy threshold of the superluminal case. The complete analysis of this effect in the detection of TeV gamma-rays is yet to be evaluated.

3. LIV limits for the subluminal case

The subluminal case was analyzed in detail in Lang *et al.* [6], and it is reviewed here. The analysis method was done in two steps (a) selection of the relevant measured spectra and (b) selection of the bins in each measured energy spectrum to be considered. This procedure minimized the systematic bias and resulted in a very robust result.

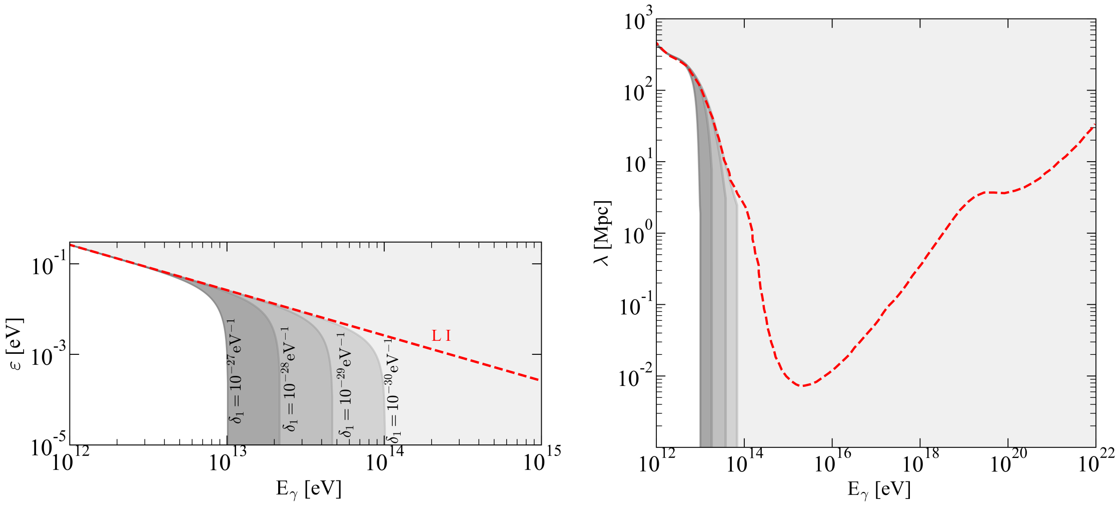

Figure 1: Mean free path for the pair production as a function of the photon energy. The red dashed continuous line represents the LI scenario. The left panel shows the background photon energy thresholds and the allowed pair production process configurations for the scenarios with the different LIV superluminal coefficients in the colored gray shades. The right panel shows the absolute mean free path for the same LIV scenarios, where the shaded regions are the none transparent universe as a function of the gamma-ray energy.

The method was applied to the most updated gamma-ray TeV data set. 111 measured energy spectra from 38 sources were analyzed from which 18 measured spectra from 6 sources were shown to contribute to restricting the LIV energy scale ($E_{LIV}^{(n)}$) beyond the current limits. The data set is best described by the LI assumption. Therefore, LIV energy scale limits were imposed as shown in Tab. 1 and Figure 2. The 5σ CL limits, using the reference EBL model (Franceschini [10]), are 3.3 times better than the best limits in the literature for LIV subluminal signatures in high-energy gamma rays using TeV spectra analysis [11] and 3.6 times better than the best limits based on energy-dependent time delay [3]. For comparison, Figure 2 also shows previous strong exclusion limits to the LIV energy scale by similar subluminal analysis and the best limits based on energy-dependent time delay.

	Franceschini			Dominguez			Gilmore		
	2σ	3σ	5σ	2σ	3σ	5σ	2σ	3σ	5σ
$E_{LIV}^{(1)}$ [10^{28} eV]	12.08	9.14	5.73	6.85	5.62	4.17	14.89	9.80	4.74
$E_{LIV}^{(2)}$ [10^{21} eV]	2.38	1.69	1.42	1.56	1.40	1.14	2.17	1.78	1.31

Table 1: Limits on the LIV energy scale imposed by this work using the EBL models Franceschini [10], Dominguez [12], and Gilmore [13].

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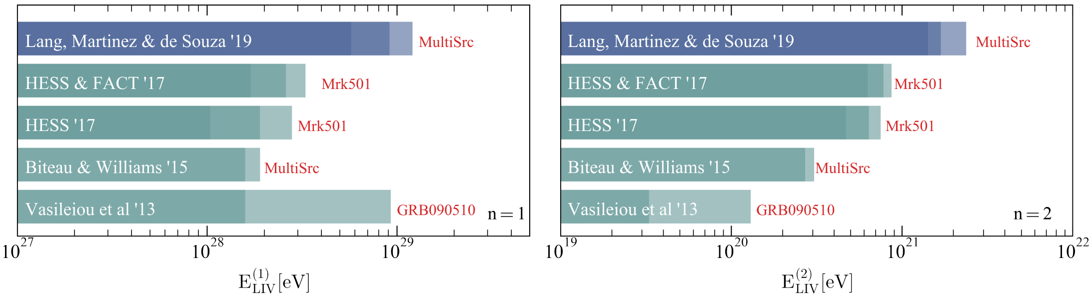

Figure 2: Comparison of the best limits imposed on the LIV energy scale. Left panel for $n = 1$ and right panel for $n = 2$. Shades of blue and green correspond to 2, 3, and 5 σ CL. *Lang, Martínez and de Souza'19* (this work) and *Biteau and Williams's 15* are based on multiple sources (MultiSrc), the latter of which are translated to the photon sector and the quadratic term. The other limits are based on specific measurements of one source as appointed. From top to bottom, see Refs. [6], [11], [14], [15], and [3].

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