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On the detectability of Lorentz invariance violation (LIV) in neutrino propagation

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Abstract. This work investigates the consequences of Lorentz invariance violation, proposing its influence on the dispersion relation and the flight time of astrophysical neutrinos in extreme scenarios. The technique involves analyzing delays in the flight time of ultra-high-energy particles, such as neutrinos, considering their mass and the expansion of the Universe.

Resumo. Este trabalho investiga as consequências da quebra da invariância de Lorentz, propondo sua influência na relação de dispersão e no tempo de voo de neutrinos astrofísicos em cenários extremos. A técnica consiste em analisar atrasos no tempo de voo de partículas de altíssima energia, como neutrinos, considerando sua massa e a expansão do Universo.

Keywords. Neutrinos – Relativistic processes – Cosmology: theory

1. Introduction

In the early 20th century, general relativity and the Standard Model of particle physics emerged as pillars of modern physics, describing gravity and quantum phenomena, respectively. However, their incompatibility has spurred the search for a quantum theory of gravity, including the hypothesis of Lorentz Invariance Violation (LIV), which posits variations in the speed of light under extreme conditions near the Planck scale. Studies on LIV include analyzing cosmic rays at high energies and investigating astrophysical neutrinos, such as those from gamma-ray bursts or supernovae, to explore correlations between their speed and energy.

2. Modified Dispersion Relation

Considering the existence of Lorentz Invariance Violation, there will be an additional term in the dispersion relation:

$$E^2 = m^2 + p^2 + \delta_n p^{n+2}, \tag{1}$$

as the dispersion term carries

$$\delta_n = \frac{1}{(E_n^{LIV})^n}. \tag{2}$$

In photons and charged particles traveling toward Earth in high-energy gamma rays, it is known that they originate from very distant sources and often interact along the way. Assuming the occurrence of LIV, even in just one of these interactions, the effect would be maximized due to the long distances traveled by the particles. This allows their energy to remain high and for multiple interactions to occur. LIV also implies a modification in the energy dependence of the flight velocity of these charged particles.

3. LIV in photons

Considering the cosmological effects caused by the expansion of the universe, including the comoving distances, we will have the equation for the time of flight of photons. It relates the time and the distance considering LIV in a redshift, as we can see in Figs. 1 and 2.

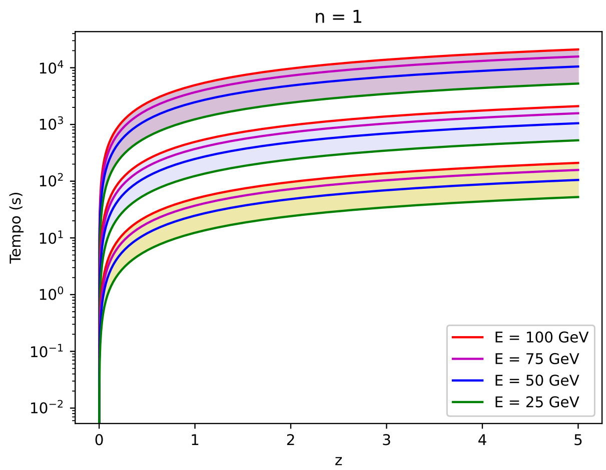

Figure 1. Time as a function of distance for different energy values and LIV energy for n=1. The energies of LIV used are 10^{25} eV in the purple filling, 10^{26} eV in the blue and 10^{27} eV in the yellow one.

In this way, we can see results that are in agreement with the reference Castilho (2019). Our next step is to follow the same analysis, but now considering the mass of the neutrino as different from zero.

4. LIV in neutrinos

Guided by Choubey & King (2003) and calculations based on the modified energy relation for neutrinos, it was possible to construct the equation for the neutrino's time of flight, considering the LIV energy and the effects of the universe's expansion, with the cosmological effects:

$$\Delta t \approx \frac{1}{2}\left(\frac{m_\nu c^2}{E}\right)^2 \int_0^z \frac{dz}{(1+z)^2 H(z)} - \frac{3}{2}\xi \frac{E}{E_{LIV}^n} \int_0^z \frac{dz}{(1+z)^{-1} H(z)}. \tag{3}$$

For a comparison between the time of flight of neutrinos with and without LIV, we can analyze the plots of the difference be-

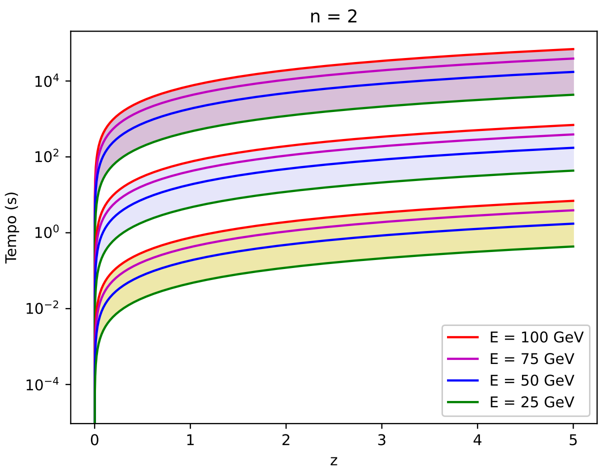

Figure 2. Time as a function of distance for different energy values and LIV energy for n=2. The energies of LIV used are 10^{25} eV in the purple filling, 10^{26} eV in the blue and 10^{27} eV in the yellow one.

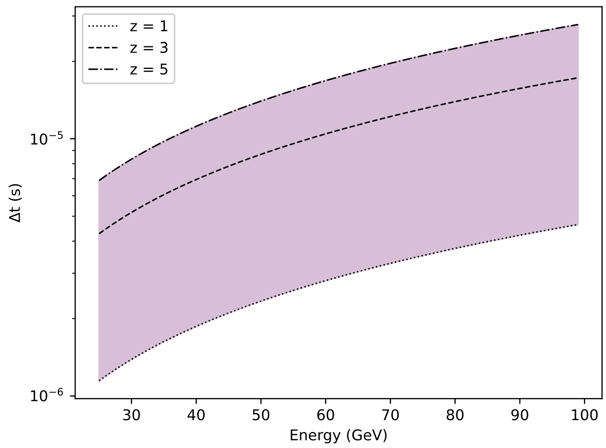

Figure 4. Difference between models for neutrino time of flight as a function of energy, using only $E_{LIV} = 10^{25}$ eV as stated in the color purple.

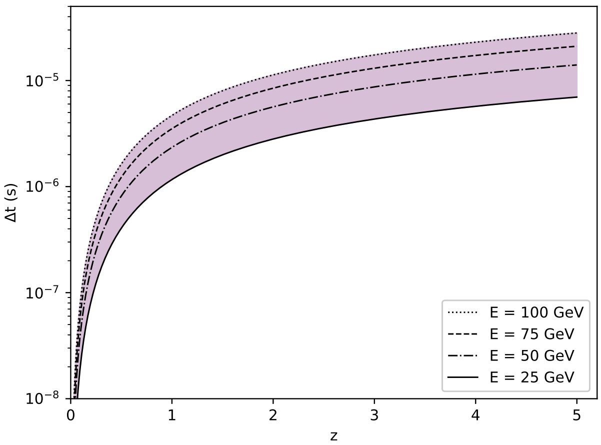

Figure 3. Difference between models for neutrino time of flight as a function of distance, using only $E_{LIV} = 10^{25}$ eV as stated in the color purple.

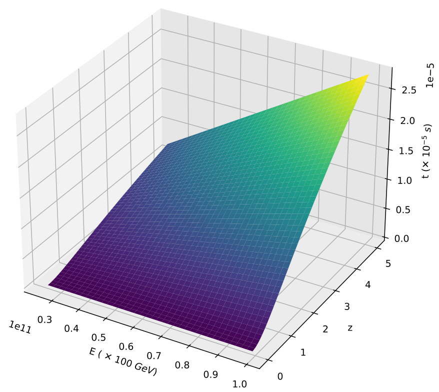

Figure 5. Three-dimensional graph of the difference between models.

tween the time and the distance and between the time and the energies of the neutrino, as it is set in Figs. 3 and 4.

A 3D plot of the scheme can be made, as it´s possible to visualize in Fig. 5.

5. Conclusions

This study examined Einstein's dispersion relation and its modification under the hypothesis of Lorentz Invariance Violation (LIV). The time of flight of astrophysical neutrinos was calculated considering Lorentz Invariance (LI) and the modified dispersion relation, incorporating LIV energy and the cosmological effects of the Universe's expansion. Numerical solutions were performed for LIV energies ranging from 10^{25} to 10^{27} eV, revealing significant differences in the time of flight between models with and without LIV.

The results indicated that, for high-energy neutrinos and long distances (from 1 to 5 redshifts), the presence of LIV could cause noticeable time delays, emphasizing the need to consider the expanding Universe. Despite consistency with the literature, factors such as neutrino mass variation, delays from the sources, and experimental errors could influence the results. The study achieved its objectives by analyzing the detectability of LIV in neutrino propagation, although further studies are needed to deepen the investigation.

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