Ultra high energy photons as probes of Lorentz symmetry violations in stringy space-time foam models

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The time delays between gamma-rays of different energies from extragalactic sources have often been used to probe quantum gravity models in which Lorentz symmetry is violated. It has been claimed that these time delays can be explained by or at least put the strongest available constraints on quantum gravity scenarios that cannot be cast within an effective field theory framework, such as the space-time foam, D-brane model. Here we show that this model would predict too many photons in the ultra-high energy cosmic ray flux to be consistent with observations. The resulting constraints on the space-time foam model are much stronger than limits from time delays and allow for Lorentz violations effects way too small for explaining the observed time delays.

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Introduction: Recent years have witnessed a growing interest in possible small deviations from the exact local Lorentz Invariance (LI) of general relativity. On the theoretical side, ideas in the scientific community of Emergent Gravity and partly in that of Quantum Gravity (QG) led to admit that Lorentz invariance may not be an exact local symmetry of the vacuum [1–4]. On the experimental side, the recent discovery of time delays on arrival of high energy γ-rays [5, 6], a phenomenon naturally predicted in a Lorentz violating (LV) framework, led to a novel interest of the scientific community in LV. Due to several tight constraints placed on some realizations of LV, not all generic models of LV can reproduce the observed time delays. Up to now, the only fully developed LV model able to explain the observed time delays has a string theory origin.[1] Furthermore, this model might also lead to a consistent explanation of the dark energy content of the Universe, which makes it even more appealing [8]. In this Letter we show that experimental data on the photon content of Ultra-High-Energy Cosmic Rays (UHECR) lead, for the first time, to strong constraints on this D-brane LV model, making it unsuitable to consistently explain the observed time delays and probably unnatural from a theoretical point of view. As we will argue in the following, due to suppression of UHE photon absorption on intergalactic radiation fields, the fraction of photons in UHECRs predicted within this model would be so large as to violate present experimental limits.

Time delays: Although it might seem hopeless to look for effects in principle suppressed by the Planck scale $M_{\rm Pl} = 1.22 \times 10^{19}$ GeV, it is possible that in some peculiar situations these tiny effects be magnified and become sizable. In order to identify these situations, it is necessary in general to work within a well defined theoretical framework, where to describe particle dynamics and compute reaction rates. A natural choice would be to work in the effective field theory (EFT) framework, extended with LV operators [9–12]. Indeed, Standard Model extensions including LV have been strongly constrained both in the case of renormalizable LV operators [1] and in the case of non-renormalizable, mass dimension 5 and 6, LV operators [4, 13–16].

The above mentioned framework is not however the only possible choice. In particular, string-theory space-time foam inspired models involving D-branes, as the one presented in [8, 17–23], do not lend themselves to an EFT description, and are hence able to evade most of the constraints that EFT models must obey.

Indeed, in the model [8, 17–23] only purely neutral particles, such as photons or Majorana neutrinos, possess LV modified dispersion relations. For the photon this has the very simple form

$$E_\gamma^2 = p^2 - \xi \frac{p^\alpha}{M^{\alpha-2}} , \tag{1}$$

with the free parameter (to be constrained) $\xi > 0$, meaning that only subluminal photons are present in the theory, and photon propagation in vacuum is not birefringent (indeed, the theory preserves CPT). In particular, the model outlined in [8, 17–23] predicts $\alpha = 3$, hence we will fix $\alpha = 3$ in the following. Moreover, exact energy-momentum conservation during interactions does not hold in this model, due to stochastic losses in interactions with the D-brane foam. This is possible if interactions with the D-brane foam have much shorter timescales with respect to particle interactions. This last

[1] Also other LV models, envisaging a deformation rather than a breaking of the Lorentz symmetry [3, 7], can explain the observed time delays. However, their dynamics is not fully developed to date, hence the present analysis cannot be applied to them yet.

phenomenon is controlled by the free parameter (again to be constrained) ξ_I [17], in a way which we will clarify below. Notice that both ξ and ξ_I are dimensionless, hence natural values for them are $O(1)$, and constraints stronger than $O(1)$ mean that some extra suppression of the LV effects has to be invoked in the model.

This model evades most of the present constraints. The electron and birefringence constraints discussed in [4] do not apply, because the theory has LV only in the photon (and Majorana neutrino) sector, it is not birefringent, and LV applies only to real (on shell) particles [23]. UHECR constraints [13, 24–28] do not apply as well.

However, Eq. (1) implies that photons with different energy travel at different speeds, meaning that if two photons at energy $E'_1 \neq E'_2$ started at the same time from a source located at redshift $\bar{z}$, after propagation they will be observed on Earth with a time delay

$$\Delta t \simeq \xi \frac{\Delta E}{M} \frac{1}{H_0} \int_0^{\bar{z}} dz \frac{1+z}{\sqrt{\Omega_\Lambda + (1+z^3)\Omega_\mathrm{M}}} \,, \qquad (2)$$

where ΔE is the observed energy difference and the integral on redshift accounts also for redshift of the energy [29, 30]. Time-of-flight constraints are then viable for this model, even though they lead at most to constraints on ξ, because ξ_I is not effective in this context.

Rather intriguingly, the FERMI Collaboration has recently reported the detection of delays on arrival of γ-ray photons emitted by distant GRBs, in particular GRB 080916C [5] and GRB 090510 [6] (see however [30] for an updated review). A thorough analysis of these delays in the energy range 35 MeV – 31 GeV allowed to place for the first time a constraint of order $\xi \lesssim 0.8$ [6] on LV effects expressed as in Eq. (1), hence also on the space-time foam model [17]. This is the best constraint so far available on the theory. On the other hand, FERMI results can be interpreted in terms of LV assuming slightly lower values of ξ (of the order of 10^{-1}) and a possible evolution of the D-particle density with redshift [8].

Photon absorption in D-brane models: In order to constrain the LV model under consideration, we exploit the process of $\gamma\gamma \to e^+e^-$. This reaction is effective in many contexts in astrophysics. We are concerned in particular with its effects on the absorption of UHE photons produced in GZK interactions [31, 32]. Indeed, if GZK energy losses affect the propagation of UHECR protons in the intergalactic medium, then a large amount of UHE photons is generated by the decay of the π^0's copiously produced in such interactions. UHE photons however are attenuated by pair production onto the CMB and Radio background during their travel to Earth, leading to their fraction in the total UHECR flux being reduced to less than 1% at 10^{19}eV and less than 10% at 10^{20} eV [33, 34]. It was already shown in a framework with modified dispersion relations for both photons and e^+/e^- and standard energy/momentum conservation, that pair production could be effectively inhibited at high energy, due to the presence of an upper threshold [14],[2] and therefore the fraction of photons present in UHECRs on Earth would violate the present experimental upper limits. Hence, the *non* observation of a large fraction of UHE photons in UHECRs implies a constraint of order $|\xi| < O(10^{-14})$ in the EFT framework [15, 16].

We want to address here the problem whether the same argument can be applied in the space-time foam model with energy non conservation. First, we observe that γ-rays are indeed generated by π^0 decay, i.e. that π^0 decay is not affected by LV in our working scenario because LV in the D-brane models acts as an energy dependent modification of the background space-time metric (in fact, the new metric is of Finslerian type [23, 35]), and hence it can only act on real particles. But in order to decay, π^0s must excite modes of the electromagnetic vacuum, i.e. virtual photons, which then are not affected by LV and do not lead to significant modifications of π^0 decay. In other words, the LV effects described in D-brane models are the result of multiple interactions between photons and D-branes, hence cannot be relevant in the mere process of photon production.[3] Moreover, π^0 is not a structureless particle, and its constituents are charged, hence they do not interact with D-particles.

Now that we established that ultra-high energy photons are to be expected in the considered model, we can then start, following [17], with the threshold equations

$$\begin{aligned} E_1 + \omega &= E_2 + E_3 + \delta E_D \\ p_1 - \omega &= p_2 + p_3 \,, \end{aligned} \qquad (3)$$

where ω is the energy of the low energy background photon ($\omega \simeq 6 \times 10^{-4}$ eV for a CMB photon), $E_1 \simeq p_1 - \xi/M \cdot p_1^2/2$ is the energy of the high energy photon and $E_j \simeq p_j + m_e^2/(2p_j)$, with $j = 2, 3$ are the energies of the outgoing electron and positron. The symbol δE_D represents the energy lost in the stochastic interactions with the D-branes. The above equation is already written in the threshold configuration (head-on collision and collinear outgoing particle momenta) [36]. We can exploit momentum conservation and the ultrarelativistic limit, to get (we use that $p_1 = \omega + p_2 + p_3$)

$$2\omega - \frac{m_e^2}{2p_2} - \frac{m_e^2}{2p_3} = \delta E_D^{(4)} + \frac{\xi}{M}\left(\omega^2 + \omega(p_2+p_3) + p_2 p_3\right) \qquad (4)$$

[2] An upper threshold is an energy above which it is not possible to simultaneously conserve energy and momentum in an interaction. If Lorentz symmetry is exact then upper thresholds do not exist, while they might well exist if it is violated [36].

[3] In fact, this seems to justify a more general theorem, stating that only reactions with photons in the *initial* state can be affected by LV in this model. Note that the resulting violation of time reversal invariance is due to LV in this scenario. We thank N. Mavromatos for bringing this argument to our attention.

where $\delta E_D^{(4)}$ is the amount of energy violation in a four-particle interaction, and corresponds to the sum of the corresponding violations in each of the two three-body interactions described by Eq. (27) in [17]

$$\delta E_D^{(4)} \equiv \delta E_D + \frac{\xi}{2M}\left(p_2^2 + p_3^2 - \omega^2\right) \simeq \frac{\xi_I}{2M} E_{\rm th}^2 \; , \qquad (5)$$

where according to [17] we assume the last equality to hold, with ξ_I different from ξ in principle. A comment is in order here: While it is natural that $\delta E_D^{(4)}$ depend only on $E_{\rm th}$ and M, as they are the only energy scales present in the problem, the effect of the quantum fluctuations δE_D is less clear. We shall assume that this effect only amounts to a redefinition of the unknown parameter ξ_I, and check that our conclusions remain unchanged if we let ξ_I fluctuate in the interaction up to 10 times its central value. The threshold equation can then be derived by putting $p_2 = p_3 = (p_1 - \omega)/2$ (the threshold configuration of the e^+/e^- momenta is symmetric in this context) and $p_1 \equiv E_{\rm th}$. Introducing $x \equiv E_{\rm th}/M$ one obtains

$$-\frac{\xi_I + \xi/2}{2} x^3 + \frac{\xi_I - \xi/2}{2}\frac{\omega}{M} x^2 + \left(2 + \frac{\xi}{4}\frac{\omega}{M}\right)\frac{\omega}{M} x - 2\frac{\omega^2 + m_e^2}{M^2} + \frac{\xi}{4}\left(\frac{\omega}{M}\right)^3 = 0 \; . \qquad (6)$$

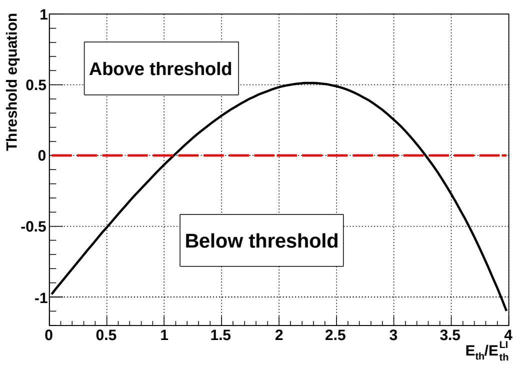

FIG. 1. Equation 7 is drawn for $\xi/2 + \xi_I = 10^{-5}$. Positive values on the y-axis mean that the reaction is allowed, while negative values mean that it is forbidden. In this case both lower and upper thresholds are present.

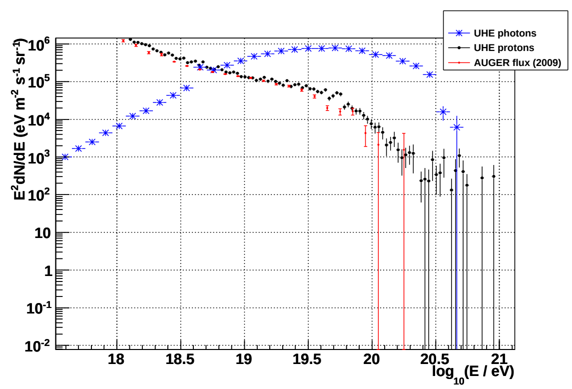

FIG. 2. UHE proton and photon simulated spectra assuming that pair production is inhibited for $z < 0.2$ and $z > 1$ for a proton injection spectrum $\propto E^{-2.5}$ up to 10^{21} eV and source density redshift evolution as in [39]. Error bars on the simulated fluxes correspond to the statistical error of the MonteCarlo simulation. Measured UHECR flux is from [40].

Constraints: If we now neglect all the terms more than linear in either ξ or ω/M, we recover eq. (32) in [17]

$$-\frac{\xi_I + \xi/2}{2} x^3 + 2\frac{\omega}{M} x - 2\frac{m_e^2}{M^2} + \cdots = 0 \; . \qquad (7)$$

We represent (up to factors) Eq. (7) in Fig. 1, for $\xi/2 + \xi_I = 10^{-5}$. Equation (7) has in general a lower and an upper threshold ($E_{\rm low}$ and $_{\rm up}$, respectively). From the observational requirement that $E_{\rm up} > 10^{19}$ eV, with ξ_I and ξ varying independently (and setting $M = M_{\rm Pl}$, $\omega = 6 \times 10^{-4}$ eV and $m_e = 0.511$ MeV), we obtain that values of ξ_I, $\xi > 10^{-12}$ are excluded by the *non* observation of a significant photon fraction in the UHECR spectrum by the Pierre Auger experiment [37].

It was recently proposed in [8] that the evolution with redshift of the D-particle/D-void background might allow to understand why significant delays compatible with $\xi \simeq O(1)$ are present in some GRBs, while in other GRBs the delays are much smaller and imply $\xi < O(1)$. Since the effect of time delay (as well as the one of energy non-conservation) is expected to be proportional to the density of D-particles, the scenario envisaged by data requires the density of D-particles to be large for redshift $z > 1$, to drop at $z \sim 1$ and to raise again for $z < 1$. This evolution might in principle affect our constraints, which depend on the effectiveness of pair production at least up to $z \sim 3$. To address this issue, we modified the public UHECR propagation code CRPropa [38].

Following [8], we assume that for $0.2 < z < 1$ LV effects are suppressed (then, pair production is allowed as if LI were exact and UHE photons are effectively absorbed), while outside this redshift range we assume that the LV effects are strong and then that pair production absorption is inhibited (i.e., we switch it off). Because UHE photons are mainly of local origin, this assumption is conservative: Moving the suppression of LV effects to more distant epochs would indeed increase the photon fraction on Earth. We found that even in this case the photon fraction would violate experimental limits for values of $\xi,\ \xi_I > 10^{-12}$ (see Fig. 2). We therefore conclude that the limit is robust against this test.

In [23] it was noticed that the interactions between photons and D-particles might be suppressed in the case that the momentum Δp transferred to the D-particle is large compared to its mass $M_D = M_s/g_s$, where M_s is the string scale and g_s is the coupling. Normally, in standard string framework, M_D is expected to be at least of order $M_{\rm Pl}$ [8], therefore this would not be an issue for our constraint. However, in some compactification schemes, lower values of M_D cannot be excluded [23]. In the case $\Delta p \gg M_D$, g_s is replaced by an effective coupling $g_s^{\rm eff} = g_s/\Gamma$, where $\Gamma \sim \Delta p/M_D$, and given that the unknown coefficients ξ and ξ_I are proportional to the scattering cross section, which in turn is proportional to g_s^2, they both receive a natural suppression $1/\Gamma^2$. In order to explain the observed time delays in the GeV-TeV energy range within the model [23], M_D has to be substantially larger than the TeV scale. Although Δp is not fixed by kinematics, it is possible to estimate its maximum value for the case of two body scattering $\gamma D \to \gamma D$, finding that, even for $M_D \sim 1$ GeV, $\Delta p \lesssim 10^{-5} E_{{\rm UHE}\gamma}$. Therefore, our constraints are weakened by only a factor 10^{10}, and we remark that the weakening is less strong with increasing M_D.

Hence, we conclude that present D-particle explanations of GRB time delays are in conflict with data on the photon fraction in UHECRs.

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