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Not only time delay. Ultra-high-energy cosmic rays as probes of quantum gravity scenarios

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Summary. — 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 violation effects way too small for explaining the observed time delays.

PACS 98.70.Sa – Cosmic rays (including sources, origin, acceleration, and interactions).
PACS 04.60.-m – Quantum gravity.
PACS 96.50.sb – Composition, energy spectra and interactions.
PACS 11.30.Cp – Lorentz and Poincaré invariance.

1. – 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 stemming from the Quantum Gravity (QG) community led to conjecture that LI may not be an exact local symmetry of the vacuum. On the observational side, high energy astrophysics observations played a leading role in constraining such models and in particular the recent detection of time delays on arrival of high energy γ-rays [1-3] led to renewed interest of the astrophysics community in QG-induced Lorentz violation (LV) effects. For a comprehensive review see, *e.g.* [4-7].

The observed time delays can be explained, and are actually expected, in standard astrophysical scenarios hence they can be readily used to place constraints on LV models. However, time delays are naturally predicted also in generic LV QG models.

It is now established that any LV model able to reproduce the observed delays and admitting an Effective Field Theory (EFT) formulation is in tension with other astrophysical observations (see, *e.g.* [7]). Up to now, the only fully developed LV model able to explain the observed time delays has a string theory origin and does not admit an EFT formulation [8-12]. In particular, in [12] it is not only suggested that the considered QG model could possibly account for all the observed time delays, but it is shown that it might also explain consistently the dark energy content of the Universe. Therefore, if observed time delays were due to such QG effects, the propagation of GeV photons over cosmological distances could not be described within EFT. Given that EFT is accurately verified with terrestrial accelerators up to $\sim 100\,\mathrm{GeV}$, this would be a very striking and revolutionary conclusion.

Here we show that experimental data on the photon content of Ultra-High-Energy Cosmic Rays (UHECR) lead 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 [13].

2. – Time delays

Effects suppressed by the Planck scale $M_{\mathrm{Pl}} \simeq 1.22 \cdot 10^{19}\,\mathrm{GeV}$ are in principle hard to detect. Yet in some peculiar situations these tiny effects can be possibly magnified and become sizable. In order to identify these situations, it is required to work in a well-defined theoretical framework to describe particle dynamics.

In the model [8-12] only purely neutral particles, such as photons or Majorana neutrinos, possess LV-modified dispersion relations. For photons this has the form $E_\gamma^2 = p^2 - \xi \cdot p^\alpha / M^{\alpha-2}$, with the free parameter $\xi > 0$. Hence only subluminal photons are present in the theory, and photon propagation in vacuum is not birefringent. In particular, the model outlined in [8-12] predicts $\alpha = 3$, hence we will fix $\alpha = 3$ in the following. Due to stochastic losses in interactions with the D-brane foam, exact energy-momentum conservation during interactions does not hold. This last phenomenon is controlled by the free parameter ξ_I [8, 13]. Because both ξ and ξ_I are dimensionless, their natural values are $\mathcal{O}(1)$, and constraints stronger than $\mathcal{O}(1)$ mean that extra suppression of the LV effects has to be invoked.

This model evades most of the present constraints. The electron and birefringence constraints discussed in [7] 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 [11]. UHECR constraints do not apply as well [13]. However, photons with different energy travel at different speeds. Then, if a source at redshift $\bar{z}$ simultaneously emitted two photons at energy $E'_1 \neq E'_2$, their time delay at Earth will be $\Delta t \simeq \xi \Delta E / M \cdot H_0^{-1} \int_0^{\bar{z}} \mathrm{d}z (1+z) / \sqrt{\Omega_\Lambda + (1+z)^3 \Omega_{\mathrm{M}}}$, where ΔE is the observed energy difference and the integral on redshift accounts also for redshift of the energy [14-16]. 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 [2] and GRB 090510 [3] (see however [15] 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 conservative constraint of order $\xi \lesssim 0.8$ [3] on LV effects expressed by the modified dispersion relation under consideration. 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 $\xi \simeq 0.4$ and a possible evolution of the D-particle density with redshift [12].

3. – Photon absorption in D-brane models

In order to constrain the D-brane model, we exploit the process of pair production, $\gamma\gamma \to e^+e^-$, which is in particular responsible for the absorption of UHE photons produced in GZK interactions [17, 18]. 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 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 [19, 20]. It was 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 [21], 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 the constraint $|\xi| < \mathcal{O}(10^{-14})$ in the EFT framework [22, 23].

We address here the problem whether the same argument can be applied in the space-time foam model with energy non-conservation. The threshold equations read [8]

$$E_1 + \omega = E_2 + E_3 + \delta E_D, \qquad p_1 - \omega = p_2 + p_3, \tag{1}$$

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. Equation (1) leads to the following threshold equation ($x \equiv E_{\mathrm{th}}/M$) [13]:

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

Equation (2) has in general a lower and an upper threshold (E_{low} and E_{up}, respectively). From the observational requirement that $E_{\mathrm{up}} > 10^{19}$ eV, with ξ_I and ξ varying independently (and setting $M = M_{\mathrm{Pl}}$, $\omega = 6 \times 10^{-4}$ eV and $m_e = 0.511$ MeV, and neglecting all the terms more than linear in either ξ or ω/M [8]), values of ξ_I, $\xi > 10^{-12}$ are excluded [13] by the *non*-observation of a significant photon fraction in the UHECR spectrum by the Auger experiment [24]. This result also holds if we allow the UHECR source distribution to evolve with redshift (see fig. 1) [13].

The interactions between photons and D-particles might be suppressed if 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 [11]. In the standard string framework M_D is expected to be at least of order M_{Pl} [12], therefore this would not be an issue for our constraint. However, in some compactification schemes, lower values of M_D cannot be excluded [11]. If $\Delta p \gg M_D$, g_s is replaced by an effective coupling $g_s^{\mathrm{eff}} = g_s/\Gamma$, 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

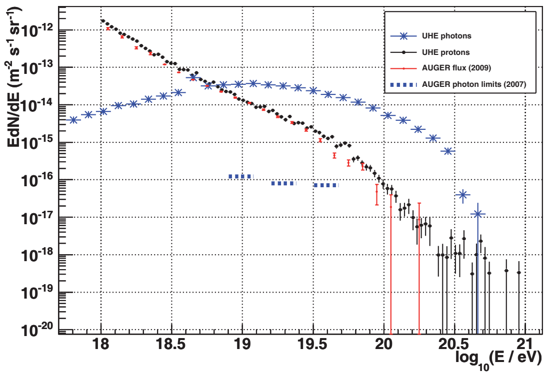

Fig. 1. – (Colour on-line) UHE proton and photon simulated spectra assuming that pair production is inhibited for $z < 0.2$ and $z > 1$ for a proton injection spectrum $\propto E^{-2.5}$ up to 10^{21} eV and source density redshift evolution as in [25]. Error bars on the simulated proton flux correspond to the statistical error of the simulation. Measured UHECR flux (in red) is from [26], while upper limits on the integral photon flux (dashed, in blue) are from [24].

suppression $1/\Gamma^2$. In order to explain the observed time delays in the GeV–TeV energy range within the model [11], M_D has to be substantially larger than the TeV scale. However, on the basis of kinematics the maximum suppression factor can be estimated as being $\mathcal{O}(10^{10})$, thereby weakening our constraint to $\xi_I, \xi \lesssim 10^{-2}$(1).

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(1) Some possible implementations of the model [9] were recently proposed [27] which would naturally evade the constraints here presented.

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