Astrophysical tests of Lorentz invariance: Towards multi-gamma-ray bursts analyses

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Lorentz symmetries represent one of the cornerstones of modern physics, and yet independent approaches aiming at combining general relativistic with quantum effects often imply some form of departures from them. According to the simplest models, particles having different energies emitted at the same time from a given source should be detected at different times from a far-away detector, thereby producing a phenomenon of in-vacuo dispersion with a linear correlation between the time of observation and particles' energy. Given that, the search for energy-dependent time lags in gamma-ray bursts (GRB) has gradually become a standard way to make tests of fundamental physics and also look for the first signatures of the sought-after quantum theory of gravity. Most of the current studies, considering a single GRB or just the most energetic photon for each GRB analysed, allowed to set very tight constraints on the relevant scale, usually believed to be close to the Planck mass. However, due to the rather poor understanding of the spectral evolution of GRBs, statistical analyses over collections of GRBs would provide more reliable outcomes. Here we test in-vacuo dispersion by analysing all the photons with energy at the emission greater than 5 GeV emitted from 7 GRBs observed by Fermi-LAT. Remarkably, we find preliminary evidence of in-vacuo-dispersion-like spectral lags consistently with what has been noticed by some recent studies which, though, had focused only on the energy range above 40 GeV.

Keywords: Gamma-ray bursts.

1. Introduction

Over the last 15 years there has been considerable interest (see *e.g.* Refs. 1–9 and references therein) in quantum-gravity (QG) induced in-vacuo dispersion, the possibility that spacetime itself might behave essentially like a dispersive medium for particle propagation: there might be an energy dependence of the travel times of ultrarelativistic particles from a given source to a given detector.

The most studied[1–9] modelization of quantum-gravity-induced in-vacuo dispersion is

$$\Delta t = \eta_X \frac{E}{M_P} D(z) \pm \delta_X \frac{E}{M_P} D(z)\,, \tag{1}$$

where z is the redshift of the relevant GRB and

$$D(z) = \int_0^z d\zeta \frac{(1+\zeta)}{H_0\sqrt{\Omega_\Lambda + (1+\zeta)^3\Omega_m}}\,. \tag{2}$$

Ω_Λ, H_0 and Ω_m denote, as usual, respectively the cosmological constant, the Hubble parameter and the matter fraction[16]. M_P denotes the Planck scale ($\simeq 1.2 \cdot 10^{28} eV$) and the values of the parameters η_X and δ_X in (1) are to be determined experimentally. Here "$\pm\delta_X$" accounts for quantum-uncertainty (fuzziness) effects, while η_X characterizes systematic effects. Finally, the label X intends to allow for a possible dependence[1,9] on the type of particles and/or on their spin/helicity. We shall not consider either fuzziness or particle/spin dependent effects.

Eq. (1) tells us that, if we wish to test the in-vacuo-dispersion hypothesis, then we need far away transient sources emitting very-high energy particles. Given that, gamma-ray bursts (GRBs) perhaps represent the most suitable sources[1–4]. Many studies have been able to set very tight constraints on the QG scale (i.e. $E_{QG} \equiv M_P/\eta_X$ if $\delta_X = 0$) close to or, in some analyses, even beyond the Planck scale (see, e.g., Ref. 17 and references therein). However, the main challenge for this type of analyses consists in the difficulty to disentangle the QG effect from the intrinsic spectral lags. In absence of a satisfactory astrophysical mechanism to take into account source effects, there are two natural ways to face this problem: use multiple kind of sources and/or messengers, and increase the size of the data.

Some of us were involved in the first studies using IceCube data for searching for GRB-neutrino in-vacuo-dispersion candidates[8,10–12]. Analogous investigations were performed in a series of studies[13–15] focusing on the highest-energy GRB photons observed by the Fermi telescope. As summarized in Fig. 1 these studies provided rather strong statistical evidence of in-vacuo-dispersion-like spectral lags. For each point in Fig. 1 (black points are "GRB-neutrino candidates"[10], while the blue points are GRB photons with energy at emission greater than 40 GeV) we denote by Δt the difference between the time of observation of the relevant particle and the time of observation of the first low-energy peak in the GRB, while E^* is the redshift-rescaled energy of the relevant particle defined as $E^* \equiv (E \times D(z))/D(1)$. The linear correlation between Δt and E^* visible in Fig. 1 is just of the type expected for quantum-gravity-induced in-vacuo dispersion, and it has been estimated[10] that such a high level of correlation would occur accidentally (in absence of in-vacuo dispersion) only in less than 1% of cases, while GRB photons could produce such high correlation only in less than 0.1% of cases[12].

This "statistical evidence" motivated us to explore whether or not the in-vacuo-dispersion-like spectral lags persist at lower energies. Thus, we here contribute to the attempt to reduce the impact of intrinsic delays by extending the window of the statistical analysis down to 5 GeV. This increases the number of photons analyzed by more than an order of magnitude (only 11 photons are considered in Fig. 1, whereas the analysis we here report involves 148 photons). Indeed, given the poor

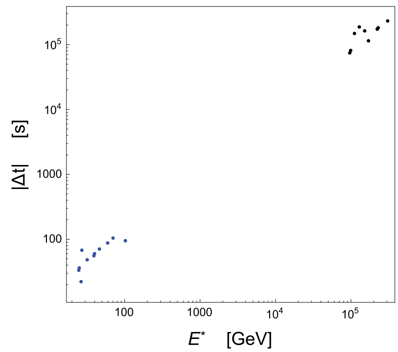

Fig. 1. Values of $|\Delta t|$ versus E^* for the IceCube GRB-neutrino candidates discussed in Refs. 10, 12 (black points) and for the GRB photons discussed in Refs. 12, 15 (blue points). The photon points in figure also factor in the result of a one-parameter fit estimating the average magnitude of intrinsic time lags (details in Refs. 12, 15).

understanding of the GRB time spectra, analyses based on the time of observation of a single photon[18] may not uncover a feature, which though could be revealed by statistical analyses.

2. Data analysis: Widening the energy window

Our analysis focuses on the same GRBs whose photons took part in the analyses which led to the picture here summarized in Fig. 1, i.e. GRB080916C, GRB090510, GRB090902B, GRB090926A, GRB100414A, GRB130427A, GRB160509A, but includes all the photons with energy at the source greater than 5 GeV. Since we cannot assume all the GRB photons were emitted in coincidence with the first GRB peak as in Fig. 1, we consider a Δt_{pair}, which gives for each pair of photons in our sample their difference of time of observation. Thus, each pair of photons (from the same GRB) gives us an an estimated value of η_γ

$$\eta_\gamma^{[pair]} \equiv \frac{M_P \Delta t_{pair}}{D(1) E^*_{pair}}\,, \tag{3}$$

where E^*_{pair} is the difference in values of E^* for the two photons in the pair. Of course the Δt_{pair} for many pairs of photons in our sample could not possibly have anything to do with in-vacuo dispersion: if the two photons were produced from different phases of the GRB (different peaks) their Δt_{pair} will be dominated by the intrinsic time-of-emission difference. Those values of $\eta_\gamma^{[pair]}$ will be spurious, they will be "noise" for our analysis. However we also of course expect that some pairs of photons in our sample were emitted nearly simultaneously, and for those pairs the Δt_{pair} could truly estimate η_γ. Form Fig. 1 one gets $\eta_\gamma = 30 \pm 6$, then we would expect that values of $\eta_\gamma^{[pair]}$ of about 30 are more frequent than expected without a relationship between arrival times and energy of the type produced by in-vacuo dispersion.

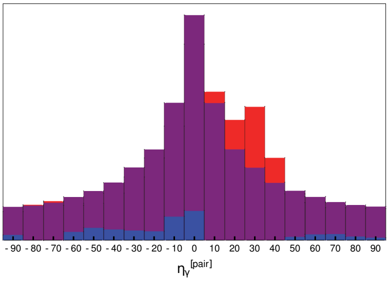

Fig. 2. Normalized distribution of $\eta_\gamma^{[pair]}$ for all pairs of photons (from the same GRB) within our data set. For bins where the observed population is higher than expected we color the bar in purple up to the level expected, showing then the excess in red. For bins where the observed population is lower than expected the bar height gives the expected population, while the blue portion of the bar quantifies the amount by which the observed population is lower than expected.

This is just what we find, as shown perhaps most vividly by the content of Fig. 2. The main point to be noticed in Fig. 2 is that we find in our sample a frequency of occurrence of values of $\eta_\gamma^{[pair]}$ between 25 and 35 which is tangibly higher than one would have expected in absence of a correlation between Δt_{pair} and E^*_{pair}. Following a standard strategy of analysis (see, *e.g.*, Ref. 17) we estimate how frequently $25 \leq \eta_\gamma^{[pair]} \leq 35$ should occur in absence of correlation between Δt_{pair} and E^*_{pair} by producing 10^5 sets of simulated data, each obtained by reshuffling randomly the times of observation of the photons in our sample. We also performed some variants of our analysis, first by dividing our data sample in three different energy ranges and considering only those pairs made of photons belonging to different groups (or excluding the photons with energy at the emission greater then 40 GeV, i.e. the only ones contributing to Fig. 1). Following a different procedure, we also estimated η_γ with a best-fit technique performed for every triplet of photons from the same GRB. Remarkably, the excess of results for $\eta_\gamma^{[pair]}$ between 25 and 35 shows up in all these analyses with an overall significance of about 0.5%.

3. Discussion and Outlook

In summary we found rather striking indications in favor of values of η_γ of about 30 in GRB data for all photons with energy at emission greater than 5 GeV. On the basis of our exploration, on future similar-size GRB data samples one should find again at least some partial manifestation of the same feature. We are of course much further from establishing whether this feature truly is connected with QG-induced in-vacuo dispersion, rather than being some intrinsic property of GRB signals. The imprint of in-vacuo dispersion is coded in the $D(z)$ for the distance dependence and, while that does give a good match to the data, one should keep in mind that only a few redshifts (a few GRBs) were relevant for our analysis. Moreover, given the very tight constraints on systematic QG delays[18], in-vacuo dispersion should most likely be of statistical ("fuzzy") nature.

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