In-vacuo-dispersion-like spectral lags in gamma-ray bursts

Giovanni Amelino-Camelia,1,2 Giacomo D’Amico,1,2 Fabrizio Fiore,3 Simonetta Puccetti,4 and Michele Ronco1,2

1Dipartimento di Fisica, Università di Roma “La Sapienza”, P.le A. Moro 2, 00185 Roma, Italy
2INFN, Sez. Roma1, P.le A. Moro 2, 00185 Roma, Italy
3Osservatorio Astronomico di Roma, Via Frascati 33, Monte Porzio Catone, I00078, Italy
4Agenzia Spaziale Italiana, Unità di Ricerca Scientifica, Via del Politecnico, 00133 Roma, Italy

Some recent studies exposed rather strong statistical evidence of in-vacuo-dispersion-like spectral lags for gamma-ray bursts (GRBs), a linear correlation between time of observation and energy of GRB particles. Those results focused on testing in-vacuo dispersion for the most energetic GRB particles, and in particular only included photons with energy at emission greater than 40 GeV. We here extend the window of the statistical analysis down to 5 GeV and find results that are consistent with what had been previously noticed at higher energies.

Over the last 15 years there has been considerable interest (see e.g. Refs.1-10 and references therein) in quantum-gravity-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.

It is well established [1–4] that the analysis of GRBs could allow us to test this in-vacuo-dispersion hypothesis. Some of us were involved in the first studies using IceCube data for searching for GRB-neutrino in-vacuo-dispersion candidates [9,11,13]. Analogous investigations were performed in a series of studies [14–16] (also see [17]) 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 we denote by $\Delta t$ 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:

$$E^* \equiv E \frac{D(z)}{D(1)}$$

where $z$ is the redshift of the relevant GRB and

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

$\Omega_\Lambda$, $H_0$ and $\Omega_m$ denote, as usual, respectively the cosmological constant, the Hubble parameter and the matter fraction, for which we take the values given in Ref.15.

The most studied [1–10] modelization of quantum-gravity-induced in-vacuo dispersion is

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

which in terms of $E^*$ takes the form

$$\Delta t = \eta_X D(1) \frac{E^*}{M_P} \pm \delta_X D(1) \frac{E^*}{M_P}.$$  

$M_P$ denotes the Planck scale ($\approx 1.2 \cdot 10^{28}$eV) and the values of the parameters $\eta_X$ and $\delta_X$ in [3] are to be determined experimentally. In [3] the notation “$\pm \delta_X$” reflects the fact that $\delta_X$ parametrizes the size of quantum-uncertainty (fuzziness) effects. Instead the parameter $\eta_X$ characterizes systematic effects: for example in our conventions for positive $\eta_X$ and $\delta_X = 0$ a high-energy particle is detected systematically after a low-energy particle (if the two particles are emitted simultaneously). The label $X$ for $\delta_X$ and $\eta_X$ intends to allow for a possible dependence [1–10] of these parameters on the type of particles (so that for example for neutrinos and photons one would have $\eta_{\nu_+, \delta_{\nu_+}, \eta_{\nu_+}, \delta_{\nu_+}}$ and in principle also on spin/helicity (so that for example for neutrinos one would have $\eta_{\nu_-, \delta_{\nu_-}, \eta_{\nu_-}, \delta_{\nu_-}}$).

The black points in Fig.1 are “GRB-neutrino candidates” in the sense of Ref.11, while the blue points correspond to GRB photons with energy at emission greater than 40 GeV. The linear correlation between $\Delta t$ and $E^*$

![Figure 1](image-url)

**FIG. 1.** Values of $|\Delta t|$ versus $E^*$ for the IceCube GRB-neutrino candidates discussed in Refs. 11,13 (black points) and for the GRB photons discussed in Refs. 13,16 (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. 13,16).
visible in Fig.1 is just of the type expected for quantum-gravity-induced in-vacuo dispersion. It might of course be accidental, but it has been estimated [11] that for the relevant GRB-neutrino candidates such a high level of correlation would occur accidentally only in less than 1% of cases, while GRB photons could produce such high correlation (in absence of in-vacuo dispersion) only in less than 0.1% of cases [13]. The “statistical evidence” summarized in Fig.1 is evidently intriguing enough to motivate us to explore whether or not the in-vacuo-dispersion-like spectral lags persist at lower energies.

One challenge for this is that evidently we cannot simply apply to lower-energy photons the reasoning which led to Fig.1: as stressed above the $\Delta t$ in Fig.1 is 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, so it is a $\Delta t$ which makes sense for in-vacuo-dispersion studies only for photons which one might think were emitted in (near) coincidence with the first peak of the GRB. This assumption is (challengeable [11] but) plausible [16] for the few highest-energy GRB photons relevant for Fig.1, with energy at emission greater than 40 GeV, but of course it cannot apply to all photons in a GRB. Conceptually the main aspect of novelty of our analysis concerns a strategy for handling this challenge.

We consider the same GRBs relevant for the analysis summarized in Fig.1, but now including all photons from those GRBs with energy at the source greater than 5 GeV, thereby lowering the cutoff by nearly an order of magnitude. Only 11 photons took part in the previous analyses whose findings were summarized in our Fig.1, whereas the analysis we are here reporting involves a total of 148 photons. For the reasons discussed above, we do not consider the $\Delta t$ (with reference to the first peak of the GRB), but rather we consider a $\Delta t_{\text{pair}}$, which gives for each pair of photons in our sample their difference of time of observation. Essentially each pair of photons (from the same GRB) in our sample is taken to give us an estimated value of $\eta_\gamma$, by simply computing

$$\eta_{\gamma}^{\text{[pair]}} = \frac{M_P \Delta t_{\text{pair}}}{D(1) E_{\gamma}^{*}},$$

where $E_{\gamma}^{*}$ is the difference in values of $E_\gamma$ for the two photons in the pair. Of course the $\Delta t_{\text{pair}}$ 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 $\Delta t_{\text{pair}}$ will be dominated by the intrinsic time-of-emission difference. Those values of $\eta_{\gamma}^{\text{[pair]}}$ 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 $\Delta t_{\text{pair}}$ could truly estimate $\eta_\gamma$. Since estimating $\eta_\gamma$ from the photons in Fig.1 one gets $\eta_\gamma = 30 \pm 6$, the preliminary evidence here summarized in Fig.1 would find additional support if this sort of analysis showed that values of $\eta_{\gamma}^{\text{[pair]}}$ of about 30 are surprisingly frequent, more frequent than expected without a relationship between arrival times and energy of the type produced by in-vacuo dispersion.

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 $\eta_{\gamma}^{\text{[pair]}}$ between 25 and 35 which is tangibly higher than one would have expected in absence of a correlation between $\Delta t_{\text{pair}}$ and $E_{\gamma}^{*}$. Following a standard strategy of analysis (see, e.g., Refs. [17] [20]) we estimate how frequently $25 \leq \eta_{\gamma}^{\text{[pair]}} \leq 35$ should occur in absence of correlation between $\Delta t_{\text{pair}}$ and $E_{\gamma}^{*}$ by producing $10^5$ sets of simulated data, each obtained by reshuffling randomly the times of observation of the photons in our sample. More details on this and other aspects of our analysis are given in Appendix A. Also in Appendix A we show that our findings are strikingly robust with respect to restricting the analysis to only part of our data set: values of $\eta_{\gamma}^{\text{[pair]}}$ between 25 and 35 occur at a rate higher than expected for all meaningful portions of our data set. Most notably, values of $\eta_{\gamma}^{\text{[pair]}}$ between 25 and 35 occur at a rate higher than expected even if we exclude from the analysis the photons whose energy at emission is greater than 40 GeV (the photons that were taken into account in the analyses leading to the content of our Fig.1).

It is also noteworthy that we find (see Appendix A) that an excess of results for $\eta_{\gamma}^{\text{[pair]}}$ between 25 and 35 as big as shown by our data should occur accidentally (in absence of in-vacuo dispersion) in less than 0.5% of cases.

Also intriguing is the content of our Fig.3, which of-
the associated value of both photons have energy at emission lower than 40 GeV and for our pairs of GRB photons, including only cases in which the energy at emission greater than 40 GeV, and what we now find for GRB signals. Within our analysis 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. If we are actually seeing some form of in-vacuo dispersion it would most likely be of statistical (“fuzzy”) nature since other studies have provided evidence strongly disfavoring the possibility that this type of in-vacuo-dispersion effects would affect systematically all photons [21].

As a further test of robustness of our findings we performed a variant of our analysis focused on triplets of photons rather than pairs. For any 3 photons (from the same GRB, of course) in our data sample we obtain an estimated value of $\gamma$ by a best-fit technique described in detail in Appendix A. Evidently also for these triplets we expect a combination of spurious results for $\gamma$ (photons in the triplets being emitted at the times of two or three different peaks of the GRB) and of meaningful results for $\gamma$ (cases of three photons emitted nearly simultaneously). As one can easily infer from Fig.4 our statistics for such triplets is rather low and as a result our estimate of the expected distribution is not fully robust, but still the excess of results for $\gamma$ between 25 and 35 is so large that we can confidently assume it is meaningful.

In summary we found rather striking indications in favor of values of $\gamma$ of about 30 in GRB data for all photons with energy at emission greater than 5 GeV. We used data that were already available at the time of the studies that led to Fig.1 (which in particular focused on photons with energy at emission greater than 40 GeV) but nobody had looked before at those data for photons with energy at emission between 5 and 40 GeV, from the perspective of Fig.1. We therefore feel that it might be legitimate to characterize what we here reported as a successful prediction originating from the analyses on which Fig.1 was based. Combining the statistical significance here exposed with the already noteworthy statistical significance of the independent analyses [11, 13, 16] whose findings were here summarized in Fig.1, we are starting to lean toward expecting that not all of this is accidental, in the sense that 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 quantum-gravity-induced in-vacuo dispersion, rather than being some intrinsic property of GRB signals. Within our analysis 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. If we are actually seeing some form of in-vacuo dispersion it would most likely be of statistical (“fuzzy”) nature since other studies have provided evidence strongly disfavoring the possibility that this type of in-vacuo-dispersion effects would affect systematically all photons [21].

[1] G. Amelino-Camelia, Living Rev. Rel. 16, 5 (2013).

[2] U. Jacob and T. Piran, arXiv:hep-ph/0607145 Nature
emission, which we denote by $E$.

Characterized by different ranges of values for the energy at emission, we divide our data sample in different subgroups, characterized by different ranges of values for the energy at emission, which we denote by $E_0$. We label as “high” the photons in our sample with $E_0 > 40\text{GeV}$, with “medium” those with $15\text{GeV} \leq E_0 \leq 40\text{GeV}$, and with “low” those with $5\text{GeV} \leq E_0 \leq 15\text{GeV}$. Our “high” photons were already taken into account in the previous studies which led to Fig.1, so it is particularly valuable to keep them distinct from the other photons in our sample (the ones we label as “medium” and “low”).

Let us start with the content of Fig.2, which takes into account all pairs of photons (of course from the same GRB) within our data set. Each such pair typically contributes to more than one of our bins, considering that the energies of the photons are not known very precisely. The contribution of a given pair to each bin is computed generating a gaussian distribution with mean value $\eta$ (calculated with Eq. (5)) and standard deviation $\sigma_\eta$ obtained by error propagation of the energy uncertainty, which we assume to be of 10%. Then, we compute the area of this distribution, which we limit in the interval $[\eta - \sigma_\eta, \eta + \sigma_\eta]$, falling within each bin, in order to evaluate the value to assign to a given bin. Thus, each pair in general contributes to more than one bin and does that with a gaussian weight. The expected frequency of occurrence of values of $\eta_\text{[pair]}$ corresponding to a given bin was estimated by producing $10^5$ sets of simulated data, each obtained by reshuffling randomly the times of observation of the photons (of each GRB) in our sample. Of particular significance for our objective is the higher than expected observed frequency of values of $\eta_\text{[pair]}$ between 25 and 35. Interestingly we find, using our simulated data obtained by time reshuffling, that the excess in bin $25 \leq \eta_\text{[pair]} \leq 35$ visible in Fig.2 is expected to occur accidentally only in 1.2% of cases.

In Fig.5 we report the results of an analysis that is just like the analysis that produced Fig.2 but now excluding the contributions from the “high” photons (with energy at emission greater than 40 GeV). It is noteworthy that one still has a higher than expected observed frequency

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{Results of a study of the type already described in the previous Fig.2, but now taking into account only pairs of photons that do not involve a “high” photon. Color coding of the bars is the same as for Fig.2.}
\end{figure}
find a higher than expected observed frequency of values of $\eta_{[pair]}$ between 25 and 35, and for this case we estimate, using our simulated data obtained by time reshuffling, that the excess of occupancy of the bin $25 \leq \eta_{[pair]} \leq 35$ visible in Fig.5 should occur accidentally only in 0.6% of cases.

It is noteworthy that a higher than expected observed frequency of values of $\eta_{[pair]}$ between 25 and 35 is present also if we constrain the two photons in a pair to be of different type, for what concerns our categories of “high”, “medium” and “low”. In Fig.6 we show the results we obtain for pairs composed of a “medium” ($15 GeV \leq E_0 \leq 40 GeV$) and a “low” ($5 GeV \leq E_0 \leq 15 GeV$) photon. For this case we estimate, using our simulated data obtained by time reshuffling, that the excess of occupancy of the bin $25 \leq \eta_{[pair]} \leq 35$ visible in Fig.6 should occur accidentally only in 0.2% of cases.

In Fig.7 we show the results we obtain for pairs composed of a “high” ($E_0 > 40 GeV$) and a “low” ($5 GeV \leq E_0 \leq 15 GeV$) photon. As visible in Fig.7, once again we find a higher than expected observed frequency of values of $\eta_{[pair]}$ between 25 and 35, even though in this case the statistical significance is less striking: using our simulated data obtained by time reshuffling, we find that the excess of occupancy of the bin $25 \leq \eta_{[pair]} \leq 35$ visible in Fig.7 should occur accidentally in about 14% of cases (though this result reflects in part also the fact that we do not have high statistics of high-low pairs).

In closing this appendix we go back to the content of our Fig.4, concerning triplets of photons. We considered all triplets of photons (of course from the same GRB) in our data set and we assigned to each of these triplets a value of $\eta_{[pair]}$ obtained by performing the best linear fit with entries the observation times and the $E^*$ of the 3 photons, using equation (4) (so the slope of the best-fit line going through the three points is $D(1)\eta_{[pair]}$). For this triplet analysis the role of “spurious results” (see the main text) can be stronger, and we tame it by taking into account only values of $\eta_{[pair]}$ obtained by our best-linear-fit procedure with $\chi^2$ smaller than 5. The uncertainties in the energies are taken into account as done for the analyses based on pairs, so here too a given triplet can contribute to more than one bin in our histogram. Using our simulated data obtained by time reshuffling, we estimate that the excess of occupancy of the bin $25 \leq \eta_{[pair]} \leq 35$ visible in Fig.4 should occur accidentally only in 0.3% of cases.

Between the main text and this appendix we discussed a total of 5 analyses which are to a large extent independent, though not totally independent. Each analysis uses different pairs, and in one case triplets, but for example the results reported in Fig.6 and Fig.7 could be used to anticipate to some extent the results of Fig.2 and Fig.4. Considering the (rather high) level of independence of the different analyses it is striking that in all cases we found an excess of results with $\eta_{[pair]}$ between 25 and 35. We found that 4 of our analyses have significance between 0.2% and 1.2%, while the fifth analysis has significance of about 14%. The present data situation is surely intriguing, but dwelling on percentages is in our opinion premature. We therefore prudently quote in the main text an overall significance of about 0.5%, but surely more refined techniques of analysis of the overall statistical significance would produce an even more striking estimate.