In vacuo dispersion features for gamma-ray-burst neutrinos and photons

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Over the past 15 years there has been considerable interest in the possibility of quantum-gravity-induced in vacuo dispersion, the possibility that spacetime itself might behave essentially like a dispersive medium for particle propagation. Two recent studies have exposed what might be in vacuo dispersion features for gamma-ray-burst (GRB) neutrinos of energy in the range of 100 TeV and for GRB photons with energy in the range of 10 GeV. We here show that these two features are roughly compatible with a description such that the same effects apply over four orders of magnitude in energy. We also show that it should not happen so frequently that such pronounced features arise accidentally, as a result of (still unknown) aspects of the mechanisms producing photons at GRBs or as a result of background neutrinos accidentally fitting the profile of a GRB neutrino affected by in vacuo dispersion.

The possibility of quantum-gravity-induced in vacuo dispersion, an energy dependence of the travel times of ultrarelativistic (that is, of negligible mass) particles from a given source to a given detector, has been suggested in several studies5–10. Part of the interest in this possibility comes from the fact that it is a rare example of a candidate quantum-gravity effect that could lead to observably large manifestations—even if, as it appears to be safe to assume, its characteristic length scale is of the order of the minute Planck length (inverse of the Planck energy scale $M_p \approx 10^{19}$ eV) or, at the most, not much larger than that.

The best opportunity for such experimental tests has so far been provided by observations of gamma-ray bursts (GRBs)11–19, which set up a sort of race among photons of different energies and (probably) neutrinos11–19, all emitted within a relatively small time window. The fact that our understanding of the mechanisms producing GRBs remains primitive is the main challenge, since any given time-of-arrival difference between two particles can, in principle, always be attributed to the emission mechanism.

For more than a decade, the analyses of GRB data from the perspective of in vacuo dispersion were done considering only photons and focusing mostly on what could be tentatively inferred from each single GRB. Recently, thanks mainly to the IceCube telescope, it became possible to contemplate the possibility that we might also be observing some GRB neutrinos affected by in vacuo dispersion; moreover, for GRB photons the abundance of observations cumulatively obtained by the Fermi telescope reached a level sufficient for statistical analyses over the whole collection of Fermi-observed GRBs.

Some of the authors of the current work were involved in the studies20–22 of IceCube neutrino data that exposed a feature interpretable as a manifestation of in vacuo dispersion. Intriguing statistical analyses of in vacuo dispersion over the whole collection of Fermi-observed GRBs were performed23–25; those investigations also led to exposing an in vacuo-dispersion-like feature. Here we quantify the statistical significance of these two features, and show that they are consistent with each other.

Model

The class of scenarios we intend to contemplate here is grounded in some much-studied models of spacetime quantization1–4 and, for the type of data analyses we are interested in, has the implication that the time needed for a ultrarelativistic particle to travel from a given source to a given detector receives a quantum spacetime correction, here denoted as $\Delta t$. We focus on the class of scenarios whose predictions for energy ($E$) dependence of $\Delta t$ can all be described in terms of the following equation (working in units with the speed-of-light scale $c$ set to 1):

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

(1)

Here the redshift ($z$) dependent $D(z)$ carries information on the distance between source and detector, and it factors in the interplay between quantum spacetime effects and the curvature of spacetime. As usually done in the relevant literature1–3 (keeping in mind that the possibility of alternative descriptions, so far unexplored, is of course open26), we take for $D(z)$ the following form:

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

(2)

where $\Omega_m$, $H_0$ and $\Omega_\Lambda$ denote, as usual, the cosmological constant, the Hubble parameter and the matter fraction, respectively (values taken from ref. 27).

The values of the parameters $\eta_X$ and $\delta_X$ in equation (1) characterize the specific scenario that is intended to be studied. In particular, in (1) we used the notation $\pm \delta_X$ to reflect 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 dimensionless parameters $\eta_2$ and $\delta_2$ can take different values for different types of particles$^{1,12,21,22}$, and it is of interest to this study that (particularly for neutrinos) some arguments have led to the expectation of a helicity dependence of the effects (see, for example, refs$^{1,2,23}$ and references therein). Therefore, even when focusing only on neutrinos, four parameters should be contemplated: $\eta_2$, $\delta_2$, $\eta_3$, and $\delta_3$ (the indices + and − refer to the helicity). Analogous considerations apply to photons and their polarization$^{15,24}$. The parameters $\eta_3$ and $\delta_3$ are expected to take values somewhere in a neighbourhood of 1, but values as large as 10$^6$ are plausible if the solution to the quantum gravity problem is somehow connected to the unification of non-gravitational forces, as some arguments suggest$^{14,24,25}$.

Following refs$^{17–19}$, we introduce a ‘distance-rescaled energy’, $E^*$, defined as:

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

so that equation (1) can be rewritten as:

$$\Delta t = \eta_3 D(1) \frac{E^*}{M_p} \pm \delta_3 D(1) \frac{E^*}{M_p}$$

This reformulation of equation (1) allows the description of relevant quantum spacetime effects (which generally depend on both redshift and energy) as effects that depend exclusively on energy, through the simple expedient of focusing on the relationship between $\Delta t$ and energy when the redshift has a certain chosen value (which we chose to be $z = 1$). When energy $E$ is measured for a certain GRB particle then $E^*$ is obtained by simply rescaling $E$ by the factor $D(z)/D(1)$, with $z$ being the redshift of the relevant GRB.

Equation (4) is ideally structured to handle the possibility that there is an offset between the time of emission of the low-energy particles used as reference (following ref.$^{19}$, we take as reference the time of observation of the first peak of the low-energy component of a GRB) and the time of emission of the higher-energy particle of interest. This is consistent with the results of dedicated data analyses of such time offsets$^{26}$. $\Delta t$ would receive both a contribution from the quantum spacetime effects given by the right-hand side of equation (4) and a contribution due to the time offset at the source, described as $(1 + z)\Delta t_0$ (the factor $(1 + z)$ taking into account time dilatation). These observations can be used to replace equation (4) with

$$\Delta t = \eta_3 D(1) \frac{E^*}{M_p} \pm \delta_3 D(1) \frac{E^*}{M_p} + (1 + z) \Delta t_0$$

Figure 1 | $\Delta t$ versus $E^*$ for our maximum-correlation GRB neutrino candidates. The points correspond to the nine GRB neutrino candidates marked with a $\checkmark$ [Table 1]. Filled points correspond to ‘late’ neutrinos ($\Delta t > 0$), while open points are ‘early’ neutrinos ($\Delta t < 0$).

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Previous analysis of GRB neutrino candidates

We first revisit, from the perspective of equation (5), our neutrino analysis of ref.$^{15}$. A key point is that, at the scales of interest for this study, for neutrinos with energy $\geq 100$ TeV, in vacuum dispersion could produce $\Delta t$ values of anything between a few hours and a couple of days. A balanced$^{15}$ criterion for our GRB neutrino candidates requires that the observation of the neutrino is within 3 days of the observation of the GRB, focusing on IceCube events with energy between 60 TeV and 500 TeV. Since accurate energy determination is so crucial for this purpose, we also restrict our focus to ‘shower events’$^{27–30}$. As directional criteria for the selection of GRB neutrino candidates, we consider the signal direction PDF depending on the space angle difference between GRB and neutrino$^{31}$, requiring the pair composed by the neutrino and the GRB to be at an angular distance within a 2-standard-deviation region.

There are 21 events suitable for our analysis from the publicly available IceCube data$^{35–37}$, and we find that 9 of these 21 events fit our requirements for candidate GRB neutrinos. The main properties of these 9 candidates are summarized in Table 1 and Fig. 1.

As shown in Table 1, for some IceCube events our selection criteria produce multiple GRB neutrino candidates. If we pick as reference the cases that give the highest value of correlation, a correlation of 0.866 is found — and even taking instead as reference the cases that give the lowest correlation, we are still left with the rather high value of correlation of 0.526. Figure 1 is obtained if the scenario with highest correlation is picked as reference (for the cases with multiple candidates).

Even taking into account this multiple-candidate issue, we find, as discussed in the Methods, that the level of correlation that characterizes our GRB neutrino candidates would be very untypical for background neutrinos that accidentally happened to fit our GRB neutrino selection criteria: such a level of correlation would be produced accidentally in only 1% of cases.

The very high correlation found in the data is particularly surprising given that probably not all but at least some of the GRB
neutrinos are expected to be background neutrinos. This is mainly due to the wide temporal window we adopt and the limited directional accuracy of IceCube neutrino events. As detailed in the Methods, we also estimate the possible implications of this observation for the statistical significance of our results for neutrinos, and find that the implications do not significantly affect our overall result.

Analysis of Fermi telescope photons

Having revisited briefly the case for in vacuo dispersion for neutrinos, we now proceed with our analysis of the case for in vacuo dispersion for photons, emerging from previous investigations\(^1\text{7–19}\).

These analyses\(^1\text{7–19}\) focus on the highest-energy photons among those observed for GRBs by the Fermi telescope, and implement some time-window selection criteria. We here propose some criteria of our own, alternative to the energy-window and time-window criteria adopted by those previous studies\(^1\text{7–19}\)—as might be considered a natural option as new data are accumulated. However, in Supplementary Table 1 and Supplementary Fig. 1, we show using presently available data that the two sets of criteria produce very close results.

In fixing the time window, we require that, at the source, the time of emission of our selected photons is consistent with an offset with respect to the time of emission of the first low-energy peak of the GRB of up to 20s—but of course also allowing for a sizeable range of effects due to the wide temporal window we adopt and the limited directional accuracy of IceCube neutrino events. As detailed in the Methods, we also estimate the possible implications of this observation for the statistical significance of our results for neutrinos, and find that the implications do not significantly affect our overall result.

Table 2 | Properties of our 11 GRB photons.

| \(E_{\text{obs}}\) (GeV) | \(E_{\text{em}}\) (GeV) | \(E^*\) (GeV) | \(\Delta t\) (s) | \(z\) | GRB |
|-----------------|-----------------|-------------|--------------|-----|-----|
| 1 | 40.1 | 14.2 | 25.4 | 4.40 | 1.82 | 090902B |
| 2 | 43.5 | 15.4 | 27.6 | 35.84 | 1.82 | 090902B |
| 3 | 51.1 | 18.1 | 32.4 | 16.40 | 1.82 | 090902B |
| 4 | 56.9 | 29.9 | 26.9 | 0.86 | 0.90 | 090510 |
| 5 | 60.5 | 19.5 | 40.0 | 20.51 | 2.11 | 090926A |
| 6 | 66.5 | 12.4 | 47.1 | 10.56 | 4.35 | 080916C |
| 7 | 70.6 | 29.8 | 40.7 | 33.08 | 1.37 | 100414A |
| 8 | 103.3 | 77.1 | 25.2 | 18.10 | 0.34 | 130427A |
| 9 | 112.5 | 39.9 | 71.5 | 71.98 | 1.82 | 090902B |
| 10 | 112.6 | 51.9 | 60.7 | 62.59 | 1.17 | 160509A |
| 11 | 146.7 | 27.4 | 104.1 | 34.53 | 4.35 | 080916C |

Table 2 lists some properties of the 11 photons picked up by our selection criteria. \(E_{\text{obs}}\) is energy at observation; \(E_{\text{em}}\) is energy at emission; \(E^*\) is the energy in the rest frame of the GRB, within the estimate of \(\Delta t\) (the difference between the time of observation of the relevant photon and the time of observation of the first low-energy peak), our time selection criterion takes the form

\[
|\Delta t| \leq 10^{-16}D(z) + (1 + z)20s
\]  

(6)

Here 20 s is our mentioned window of \(\tau_{\text{off}}\), while the parameter we fix at 10\(^{-16}\) allows for in vacuo dispersion effects in amounts roughly comparable to the corresponding range of effects explored by the previous studies\(^1\text{7–19}\).

For what concerns our window on photon energies, consistent with our focus on properties at the source (rather than observed properties), we require that our selected photons be emitted at the source with energy greater than 40 GeV.

We show in Table 2 and Fig. 2 the 11 Fermi telescope photons, from GRBs of well-known redshift, selected by the time window of equation (6) and our requirement of an energy of at least 40 GeV at emission.

The content of Fig. 2 is rather striking. In particular, 8 of our 11 photons are all compatible with the same value of \(\eta\) and \(\tau_{\text{off}}\), with an impressive correlation of 0.9959. This sets up a rather easy question that can be investigated statistically: if there is no in vacuo dispersion, and therefore the correlation shown by the data is just accidental, how likely would it be for such 11 photons to include 8 that line up so nicely? As discussed in the Methods, we find that this would happen accidentally in only 0.0013\% of cases.

Overall consistency

For both the neutrino feature and the photon feature, there is a rather low probability of accidental occurrence. Perhaps most notably, the two features are to a good extent compatible with each other. If the 8 photons on the ‘main line’\(^1\text{9}\) of Fig. 2 are focused on, a noteworthy characterization is obtained by assuming \(\delta_\eta = 0\), so that the whole feature is due to a non-zero value for \(\eta\); within that simplified characterization, \(\eta = 34 \pm 1\). This should be compared with the estimate of \(\eta\) that can be obtained from the neutrino data. This comparison should be handled with some care, since, as mentioned, some quantum spacetime models predict independent in vacuo dispersion parameters for different particles, and also a possible dependence of the effects on polarization for photons and/or on helicity for neutrinos. Still, a comparable magnitude of the effects for different particles would be tentatively expected. A first important observation is that Fig. 1 includes\(^1\text{4}\) five neutrinos whose interpretation in terms of in vacuo dispersion would require positive \(\eta\), and four that would require negative \(\eta\). Another complication for our purposes originates in the fact that we expect that 3 or 4 of those 9 GRB neutrino candidates are actually background neutrinos that happened to accidentally fit our profile of a GRB neutrino candidate (see Methods). Indicatively, we can perform an estimate of the absolute value \(|\eta|\), assuming that 3 of the 9 GRB neutrino candidates are background: essentially we estimate \(|\eta|\) for each possible group of 6 neutrinos among our 9 GRB neutrino candidates, and we combine these estimates into a single overall estimate. This leads to the estimate \(|\eta| = 19 \pm 4\).

So we have an estimate of \(\eta = 34 \pm 1\) and an estimate of \(|\eta| = 19 \pm 4\), which are closely comparable, as theoretical
Challenges for a quantum gravity interpretation

Our quantification of statistical significance gave impressive results for both the neutrino and photon features, as well as for the consistency between them. We still feel that the overall situation should be assessed in depth, since the class of effects we explored here would imply, if truly discovered, that fundamental physics goes beyond its current horizons. Steps like these, rare as they are in fundamental physics, must require extremely high statistical evidence — and so more data is required. Nonetheless it is inevitable to assess and find possible interpretations for the present situation.

What would be required if the data situation described here did persist as more data is accrued, but one wanted to explore a possible astrophysical origin, rather than in vacuo dispersion? We believe that it would be very unlikely to find an astrophysical origin for the neutrino feature: the relevant effects are on the order of a couple of days, and neutrinos observed two days before or after a GRB could not possibly be GRB neutrinos (unless in vacuo dispersion takes place).

If the neutrino feature fades away but the photon feature persists, then an astrophysical origin could be realistically sought for, since the size of the effects for photons is between a few and ~100 seconds, which may well be the time scale of some mechanisms intrinsic to GRBs. Still, such astrophysical interpretations would (awkwardly) assume that the observed redshift dependence matched the data well only accidentally: the data points in Fig. 2 (those on the main line) line up only because the $D(z)$ has been factored into the analysis, and the $D(z)$ is a form of dependence on redshift that reflects propagation.

In terms of a quantum gravity interpretation, it should be noted that, for photons, all our values of $\Delta t$ are positive. Unless the (unknown) polarization of the signal is misleading, it should be concluded that the effect is not polarization dependent. This would encourage scenarios with quantum spacetimes whose low-energy limit is not amenable to standard effective-field-theory techniques: within a standard effective-field-theory setup, the sort of effects we explored would be polarization dependent.

The main challenges for the interpretation of the photon feature in terms of the model (5) come from previous data analyses based on equation (5), which had given negative results. Most of these previous analyses focused mainly on single photons associated to a GRB, and produced results that appear to be incompatible with values of $\eta$ of about 30 (as considered in the present study). This might suggest that the correct (‘fundamental’) description of the effects considered here is of a statistical nature, such that it might be unnoticeable in certain analyses focused on a single particle. Still, we feel that the 30 GeV photon observed from the short GRB090510 deserves special consideration, even if the fundamental description of the effects is statistical in nature. That 30 GeV photon was observed within the half-second time window where most GRB090510 photons with energy between 1 and 10 GeV were also observed. In light of this, it is natural to assume that the 30 GeV photon could not have accrued an in vacuo dispersion effect of more than a second, travelling from a redshift of 0.9 (the redshift of GRB090510), which implies $|\eta| < 1$. It might be significant that the 30 GeV photon from GRB090510 is the only photon in our sample coming from a short GRB: if the effect is present for long GRBs and absent for short GRBs, then the interpretation should be astrophysical. Alternatively, it could be noted that GRB090510, with its redshift of 0.9, is one of the closest GRBs relevant for our photon analysis. A scenario in which the effect is pronounced only at large redshifts could be of quantum spacetime origin, but of course would require a quantum spacetime picture in which the dependence on the redshift of the effects is not exactly governed by the function $D(z)$, such as those in ref. 32.

The statistical analysis should also be taken into account, involving several photons from a few GRBs. Any attempt of quantum gravity interpretation of the feature discussed here should explain why the previous analysis obtains negative results. Postponing a more detailed and technical comparison, we note that here we used selection criteria very different from those of the previous study, for each of the GRBs considered, that study focused on a tight temporal window, much tighter than the one that would be achieved for those same GRBs our criterion (see equation (6)). The end result is that the previous analysis does not include 9 of our 11 photons (Fig. 2). Also potentially noteworthy is the fact that we only consider photons with energy at emission greater than 40 GeV, while the previous analysis obtained statistical results involving all photons with observed energy greater than 30 MeV: only two of our photons with energy greater than 40 GeV are included in that analysis, and it can be assumed that those two photons do not carry much weight in that analysis, since the statistical study is dominated by the more abundant photons of energy between 30 MeV and 40 GeV.

Evidently there are several technical and conceptual issues that our results bring to light. Of course, the situation will become clearer as more data is accrued, but meanwhile we believe the statistical significance found in this study should stimulate more in-depth studies of quantum spacetime models. The results obtained so far on in vacuo dispersion are only preliminary, as a result of the complexity of the relevant formalisms, and it is plausible that equation (1) provides only a rough approximation of the correct picture.

Methods

Statistical analysis for neutrinos. The correlation between $|\Delta t|/(1+z)$ and $E^{*}/(1+z)$ that can be easily inferred from Table 1 and Fig. 1 is evidently high, but in itself does not provide the most interesting quantity here, which must be some sort of false-alarm probability: if there were all background neutrinos, how likely would it be to accidentally have data in such good agreement with the expectation of the quantum spacetime models contemplated here? It needs to be estimated how often a sample composed exclusively of background neutrinos would accidentally produce 9 or more GRB neutrino candidates with correlation comparable to (or greater than) the correlation we found in the data. As standard for this sort of analyses, we estimate this false-alarm probability by performing simulations that randomize the times of detection of the 21 IceCube neutrinos relevant for our analysis, with the randomization confined to the time interval

**Figure 3** $|\Delta t|/(1+z)$ versus $E^{*}/(1+z)$ for our GRB photons and GRB neutrino candidates. Here the content of Figs 1 and 2 has been combined to allow an overview of the correlation between $|\Delta t|/(1+z)$ and $E^{*}/(1+z)$. 

Prejudice would lead us to expect. Perhaps more importantly, the hypothesis that both features are accidental should also face the challenge introduced by this correspondence of values.

The level of consistency between the neutrino feature and the photon feature is visually illustrated in Fig. 3.
where those neutrinos ever were sought. Our focus is on a correlation between observation time and energy (and redshift), which should be washed away in such randomizations. Such randomizations produce ‘fake’ data samples with the properties expected for background neutrinos, for which the correlation can arise only accidentally.

In performing this sort of statistical analysis, it must be accepted that the redshift is known for only a few of the GRBs involved in the study. Only one short GRB of unknown redshift is used, and we assume a redshift of 0.6 for it, which is a reasonable rough estimate for a short GRB. For some of our long GRBs we do have a redshift determination and, consistently with the hypothesis being tested here, those known values of redshift should be used\(^1\) to obtain at least a rough estimate of the redshift of long GRBs for which the redshift is unknown. This is illustrated by the fact that the set of neutrinos marked by a dagger symbol in Table 1; those 9 candidates include 8 long GRBs, 2 of which have known redshift, and we assign to the other 6 long GRBs the average \(7\) of those two values of redshift (\(z = 1.497\)). As we have previously shown\(^1\), the outcome of our neutrino analysis does not depend strongly on these assumptions on redshifts, but some (however rough) estimates are needed as input.

Another issue that must be addressed concerns the fact that, as shown in Table 1, for some of our neutrinos there are multiple GRB candidate partners. It is important that this multiple-partner issue is handled in ways that do not introduce bias. A safe option\(^2\) is to pick up the combination that produce the highest correlation. Of course, if we use this criterion both for our true data and for the ‘fake’ simulated data obtained by time randomizations, no systematic bias can be introduced.

We performed 10\(^5\) randomizations of the times of detection of the 21 IceCube neutrinos relevant for our analysis. The correlation between \(\Delta t\) and \(\Delta E\) for the 9 GRB neutrino candidates shown in Fig. 1 (solving the multiple-partner problem by maximizing correlation) is 0.886. Our time-randomized analysis (again, handling the multiple-partner issue by maximizing correlation) produces cases with correlation greater or equal to 0.866 with only a probability of 0.11%.

To ensure that nothing much depends on the maximum-correlation criterion adopted for handling the multiple-partner issue, we redid the entire analysis replacing the maximum-correlation criterion with a minimum-correlation criterion: in the presence of neutrino events with multiple GRB candidate partners, the combination with the lowest correlation is picked, both for the true data and for the ‘fake’ simulated data obtained by time randomizations. For our data, this minimum value of correlation (found by handling accordingly the cases of multiple candidate GRB partners) is 0.526, and the corresponding false-alarm probability turns out to be 0.36%.

The maximum-correlation criterion is evidently more meaningful, since it is consistent with the hypothesis we are testing (that is, if \(\Delta t\) and \(\Delta E\) dispersion is at work, then among multiple candidate GRB partners the right one would be the one that maximizes correlation). However, the false-alarm probability obtained with the minimum-correlation criterion could be adopted as a very conservative estimate.

On the role of background neutrinos. Due to the nature of our study, we were obliged to adopt large temporal and directional windows for selecting GRB neutrino candidates. An effect of this is that some of our 9 GRB neutrino candidates are background neutrinos that accidentally fit our criteria (and this conclusion must be reached even when assuming the presence of \(\Delta t\) and \(\Delta E\) dispersion). This can be deduced by observing that out of the 21 neutrinos in our sample there are at least 12 neutrinos that are background (since only 9 turned out to fit our requirements for GRB neutrino candidates). We can therefore ask how likely it would have been for one or more of those 12 neutrinos to accidentally appear to be GRB neutrinos of the type we are looking for. This can be estimated by randomizing the times and directions of those 12 neutrinos. Of course, if, say, it is likely that 2 of those 12 neutrinos could appear as GRB neutrinos, we will assume that a proportionate number of our 9 GRB neutrino candidates are background.

The analysis must be done self-consistently: one assumes that 12 neutrinos relevant for our analysis. The correlation between \(|\Delta t|\) and \(|\Delta E|\) for the 5-set with maximum correlation has found by taking in all possible ways 8 out of the 11 neutrinos (1 of the 21 GRB neutrino candidates are background neutrinos. The 5-set with maximum correlation has correlation \(r = 0.9992\). The false-alarm probability turns out to be 0.48%, if we require that simulated data (obtained by time randomization) include at least 9 candidates, among which there is at least a 5-set of candidates with correlation greater or equal to 0.9992.

In summary, we start from an estimate of the false-alarm probability of 0.11%, which is obtained by background GRB neutrinos could take us from 0.11% to 0.57%. These findings lead us to quote conservatively in the main text an overall estimate of the false-alarm probability of 1% (however, we do not feel that at the present time it would make much of a difference if this estimate had been 2% or even 3%).

Statistical analysis for photons. Assessing the statistical significance of the data situation for photons, summarized in Fig. 2, presents us with challenges similar to that of the neutrino case. The most striking aspect of Fig. 2 is that among our 11 photons line up very nicely. The value of correlation for those 8 photons is 0.9959. We estimate an associated false-alarm probability by performing simulations in which (while keeping their energy fixed at the observed value) we randomize, within the time window specified by our time-selection criterion, the time delay of each of our 11 high-energy photons with respect to the GBM peak of the relevant GRB, and we assign to each of these randomizations a value of correlation given by the maximum value of correlation found by taking in all possible ways 8 out of the 11 photons. We find that these simulated values of correlation are \(\geq 0.9959\) only in 0.0013% of cases.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

G.A.-C. was in charge of project planning, led most of the interpretation, and assisted in data analysis. G.D’A. and G.R. had the leading role in the data analysis and assisted in the interpretation. N.L. assisted in the data analysis and assisted in the interpretation.

Additional information

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Competing interests

The authors declare no competing financial interests.