Could quantum gravity slow down neutrinos?

Giovanni Amelino-Camelia, Maria Grazia Di Luca, Giulia Gubitosi, Giacomo Rosati & Giacomo D'Amico

In addition to its implications for astrophysics, the hunt for neutrinos originating from gamma-ray bursts could also be significant in quantum-gravity research, as they are excellent probes of the microscopic fabric of spacetime. Some previous studies based on neutrinos observed by the IceCube observatory found intriguing preliminary evidence that some of them might be gamma-ray burst neutrinos whose travel times are affected by quantum properties of spacetime that would slow down some of the neutrinos while speeding up others. The IceCube collaboration recently significantly revised the estimates of the direction of observation of their neutrinos, and we here investigate how the corrected directional information affects the results of the previous quantum-spacetime-inspired analyses. We find that there is now little evidence for neutrinos being sped up by quantum spacetime properties, whereas the evidence for neutrinos being slowed down by quantum spacetime is even stronger than previously determined. Our most conservative estimates find a false-alarm probability of less than 1% for these ‘slow neutrinos’, providing motivation for future studies on larger data samples.

Over the last few years one of the most studied candidate effects of quantum gravity has been in vacuo dispersion, an energy dependence of the speed of ultra-relativistic particles (see for example refs. 1–10 and references therein). This effect could also lead to observably large manifestations, even if, as it seems safe to assume1–7, its characteristic length scale turns out to be of the order of the minute Planck length, or not much larger than that. Observations of gamma-ray bursts (GRBs)1–4, which (nearly) simultaneously emit photons of different energies and (probably11–14) neutrinos, could be well suited to finding a manifestation of the energy dependence of the speed.

Some of us (G. A.-C., G.D. and G.R.) were involved in some studies9,15–19 of IceCube neutrino data that produced intriguing results: these studies compared observation times and directions of GRBs with those of IceCube neutrinos, finding preliminary statistical evidence that some of those neutrinos could be GRB neutrinos receiving a contribution to their travel times from quantum-gravity-induced in vacuo dispersion. A potential weak point of those analyses was that they found comparable statistical significance for neutrinos being slowed down and neutrinos being sped up by in vacuo dispersion: the most popular quantum-gravity intuition is that all particles with half-integer spin should be affected by the same effect, although a specific model with breakdown of relativistic invariance can accommodate10 an effect that has opposite sign for the two helicities of the neutrino (a scenario that might be relevant here given that we have no helicity information for IceCube neutrinos).

The IceCube collaboration recently significantly revised20 their estimates of the direction of observation of their neutrinos, and here we investigate how the corrected directional information affects the results of the previous quantum-gravity-inspired analyses. We start by quickly reviewing the formalization and parameterization of the model already used in the previous studies of refs. 15–19:

\[ \Delta t = \frac{\eta D(z)}{M_P} \frac{x(E, z)}{M_P} \]  

(1)

where \( \Delta t \) is the contribution to the travel time of the neutrino from quantum-gravity-induced in vacuo dispersion, \( \eta \) is a dimensionless parameter to be determined experimentally, \( M_P \) denotes the Planck
scale ($-10^{28}$ eV, inverse of the Planck length) and $D(1)$ is the value that the function:

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

takes when the redshift $z$ of the GRB associated with the neutrino is 1, and $\zeta$ is a function of $D(z)$ and of the energy $E$ of the neutrino: $\zeta(E, z) = ED(z)/D(1)$. Here we use $\Omega_\Lambda$, $H_0$, and $\Omega_m$, as usual, for the cosmological constant, the Hubble parameter and the matter fraction (for which we take the values given in ref. 21).

In the data analysis $\Delta t$ was estimated in terms of the difference in the times of observation between a GRB and a neutrino that could tentatively be described as produced in coincidence with that GRB. If there were no quantum-gravity effects, a GRB neutrino would be observed (nearly) simultaneously with the GRB that produced it, and we attribute the whole of the time-of-arrival difference to the quantum-gravity-induced $\Delta t$ of the neutrino, as the photons composing the GRB signal are of much lower energies than our neutrinos and the effect we are studying depends linearly on energy (so any $\Delta t$ of the photons would be negligible with respect to the $\Delta t$ of the neutrino). Our first task was to find these ‘GRB-neutrino candidates’; neutrinos whose direction is compatible with a GRB direction and whose energy and time of observation render them compatible, according to equation (1), with the time of observation of the GRB. As was clarified in detail in refs. 15–19 (and will be clear from the analysis reported here below), we could not be certain that any of our GRB-neutrino candidates were a GRB neutrino: the correspondence between direction and time of observation can of course also occur accidentally and for the single association between GRB and neutrino our strategy of analysis will inevitably be inconclusive. However, if such associations are numerous enough (and ‘significant enough’, see below) we could end up in the position of being certain that our data sample contained some GRB neutrinos whose propagation was affected by quantum gravity, despite not being able to establish which of our GRB-neutrino candidates actually are GRB neutrinos.

Given that one of our main goals was to weigh the impact of the revised estimates on this sort of quantum-gravity-motivated analysis of the direction of observation of IceCube neutrinos, for this study we used the same data sample and the same criteria for the selection of GRB-neutrino candidates already used in the previous studies in which they are described in detail. We stress here that the analyses were confined to neutrinos with energies between 60 and 500 TeV and were considered GRB-neutrino candidates if the GRB and the neutrino were observed at times that differed by no more than 3 days and the angular distance between the direction of the neutrino and the direction of the GRB was within a 3σ region, where $\sigma = \sqrt{\sigma_{GRB}^2 + \sigma_{\nu}^2}$ ($\sigma_{GRB}$ and $\sigma_{\nu}$ denote the directional uncertainties for the GRB and for the neutrino, respectively).

Taking into account the recently revised estimates of the direction of observation of IceCube neutrinos we had only three GRB-neutrino candidates that appear to be ‘early’ (that is, neutrinos that could have been sped up by quantum-gravity effects). The details of these three GRB-neutrino candidates are shown in Table 1 and we found that the probability of accidentally finding at least three such early neutrinos in our data sample is 81% (Methods). While of course we cannot exclude that this might have to be reassessed as more data accrue, it is evident that at present the corrected IceCube data provide no encouragement for the hypothesis of quantum-gravity effects speeding up neutrinos. Moreover, the study recently reported in ref. 22 further disfavours this hypothesis: the relatively robust evidence that a neutrino with energy of at least 183 TeV was observed from the blazar TXS 0506+056 strongly constrains ‘superluminal’ neutrinos (the early neutrinos of our analysis) as such superluminal neutrinos should quickly lose energy via electron–positron pair production.

Next we looked at the hypothesis of ‘late’ GRB neutrinos, where our findings are even more intriguing than those previously reported (using erroneous neutrino directions) in refs. 15–19. We identified seven GRB-neutrino candidates that appear to be late (that is, neutrinos that could have been slowed down by quantum-gravity effects) and we found that the probability of accidentally finding at least seven late neutrinos in our data sample is only 5% (Methods). Late neutrinos therefore deserve further investigation.

Our seven late GRB-neutrino candidates are shown in Table 2 and Fig. 1 and they have a correlation of 0.56. Table 2 also reflects the fact that among the three possible GRB partners for the neutrino with energy of 86.1 TeV, for Fig. 1 we selected the one that produced the highest overall correlation.

Going back to the background issues that our selection criteria confront us with, it is important to note that it is actually likely, with probability of 83%, that at least one of our seven late GRB-neutrino candidates is accidental, and the probability of at least two accidental candidates is still relatively high at 39% (while the probability of at least three accidental candidates goes down to 18%; Methods). This suggests that, even if the quantum-gravity model is tentatively assumed to be correct, among the data points in Fig. 1 it is likely that there are one or two that represent noise.

We must also stress that to produce Fig. 1 one must assign a redshift to the GRBs, but $z$ is known only for a minority of GRBs, and in fact the redshift was measured for only one of the data points in Fig. 1. As emphasized in refs. 15–19, this issue of estimating the redshift for GRBs whose redshift was not measured is challenging, because we anticipate that the redshift distribution of GRBs that produce neutrinos will be significantly different from the redshift distribution of generic GRBs. We follow refs. 15–19 by estimating the redshift of all long GRBs relevant for Fig. 1 on the basis of the single case in which the redshift is known. Only one short GRB is relevant for Fig. 1 and it is of unknown redshift, so (following again refs. 15–19) we assigned it a redshift of 0.6 (definitions of short and long GRBs follow those in ref. 24.)
The fact that there are no vertical error bars in Fig. 1 reflects the accuracy of the relevant time measurements (the corresponding vertical error bars would not be visible on the scales of Fig. 1). The lack of horizontal error bars in Fig. 1 does not imply that $\kappa$ is determined very accurately, but instead reflects the fact that we were unable to estimate the uncertainty on $\kappa$: the publicly available IceCube neutrino data report an estimated value of the neutrino energy, but do not report the uncertainty (however, at the energies relevant for our analysis, this should be less than 10%; ref. 23); moreover, for most of our neutrinos the estimate of $\kappa$ was also affected by the unknown uncertainty of our crude estimate of the GRB redshift. When more data are available the redshift distribution of GRBs that produce neutrinos can be estimated reliably from the analysis itself: one would use the distribution of the GRB-neutrino candidates with known redshift to estimate the redshift distribution of those whose redshift is unknown. This would improve our redshift estimate and also provide an uncertainty for it. With the few data points presently available the best course of action was to render the analysis as insensitive as possible to this lack of knowledge of the redshift distribution (in the analysis of the statistical significance of our findings we focused on the values of correlation, which do not depend explicitly on uncertainties), and to check a posteriori that the results did not depend strongly on the assumptions made for redshift (in Methods we show that our findings on the significance of the feature exposed in Fig. 1 depend only weakly on the assumptions made for redshift).

Also relevant for understanding Fig. 1 is the fact that there are three GRBs compatible with one of our neutrinos within our temporal and directional window. The same issue was faced in refs. 15–17, and we followed again those previous studies by selecting the GRB that paired with that neutrino in the way that led to the highest overall correlation for the analysis. While the impact of this highest-correlation criterion might have to be scrutinized more carefully if, when more suitable neutrinos are observed, one found several neutrinos pairing with more than one GRB, as our analysis involves only one such neutrino, we find (as shown in Methods) that our estimates of the significance of the feature exposed in Fig. 1 depended only weakly on the adoption of this highest-correlation criterion.

The line in Fig. 1 was obtained by the best fit to the data points, which provided $\eta = 21.7$ with $6\eta = 4.5$. Within the model that we used as a working assumption, the spread of data points around that best-fit line should be interpreted by considering that one or two of the points are likely to be just noise, and we relied on a rough estimate of redshift for nearly all the points. In relation to our best-fit line we should also comment on similar approaches that were applied to photons, rather than neutrinos, and allowed an average time offset that was fitted to the data between the high-energy particle (for us a neutrino, a photon in ref. 26) and the low-energy gamma-ray signal to be determined. We did not attempt this because for photons these time offsets are typically estimated to be on the order of a few seconds, which would be a negligible period in our neutrino analysis. It can be seen that if there was a much larger offset applicable to neutrinos, our best-fit line would have to be adjusted to it, but our calculations of correlations would remain unaffected (the correlation is insensitive to a time shift applied identically to all data points), and all our assessments of the statistical significance of the feature exposed here rely exclusively on the correlation.

Our next task was to estimate a false-alarm probability, that is, an estimate of how likely it would be for our data sample to accidentally produce (without any intervening quantum-gravity effects) at least seven late GRB-neutrino candidates with a correlation of at least 0.56. Following again what was done in refs. 15–17, we did this by performing $10^5$ randomizations of the times of detection of the neutrinos relevant for our analysis, keeping their energies and directions fixed. Applications of this method of statistical analysis to cases that do not involve the study of neutrinos can be found in refs. 27–31. The key merit of this approach is that one obtains fully realistic simulated data by just randomly ‘reshuffling’ the real data in a way that only affects the correlation being studied, without modifying other properties of the data. For each of these randomizations we redid the analysis just as if they were real data, including selecting the highest-correlation cases when multiple GRB partners were found for a neutrino. We found that this false-alarm probability was only 0.7%, which we feel is our key result motivating further studies.

Our primary objective was reached: we established that the revised estimates of the direction of observation of IceCube neutrinos strongly affect the quantum-gravity-motivated analysis. There is now no encouragement for the hypothesis of early neutrinos, while for late neutrinos the preliminary evidence is significantly stronger than found with the previous incorrect estimates of the directions.

In closing, we focus on one additional task: extending the energy range of the analysis above 500 TeV. As stressed in refs. 15–19, going below 60 TeV should be a useless exercise since most of the additional GRB-neutrino candidates would be background, atmospheric neutrinos. Going above 500 TeV would not pose background problems but it was not done here because of the size of the time window required: the effect grows linearly with energy and therefore, given that a 3 d window was needed for neutrinos of up to 500 TeV, for a neutrino of 2 PeV (for example) one might have to adopt a 12 d window, in which case the challenge of handling multiple GRB ‘partners’ would grow significantly. We propose a way to include neutrinos with energies greater than 500 TeV that does not require such wide temporal windows: one would still only use the neutrinos with energy between 60 and 500 TeV to estimate a value $\eta$ of equation (1) and then look for candidate GRB neutrinos with energies higher than 500 TeV that are compatible with that estimate of $\eta$.

We found two late GRB-neutrino candidates with energies greater than 500 TeV (Table 3) that are compatible with $\eta = 21.7 \pm 9.0$ (we allowed for a $2\eta$ interval). We encountered the multiple-GRB-partner issue here again, which we handled in the same way by resorting to

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**Table 3 | Petaelectronvolt GRB-neutrino candidates**

| $E_\nu$ (TeV) | $\Delta t$ (s) | $z$ | GRB length |
|---|---|---|---|
| 110801B* | 1,035.5 | 706,895 | S |
| 110730A | 1,035.5 | 907,892 | L |
| 110725A | 1,035.5 | 1,320,217 | L |
| 120909A | 1,800 | 7,435,884 | 3.93 | L |

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**Fig. 1 | Late GRB-neutrino candidates.** The seven late GRB-neutrino candidates with energies between 60 and 500 TeV are shown. The blue line is the best fit to the seven points with the linear relationship between $\Delta t$ and $\kappa$ given by equation (1).
the highest-correlation criterion. The two resulting GRB-neutrino candidates are shown in red triangles in Fig. 2, together with the seven candidates already shown in Fig. 1. The overall correlation for the nine points in Fig. 2 is 0.9997.

This very high correlation does not in itself characterize the significance of our findings: we would also need a false-alarm probability that quantifies how likely it would be for the available neutrinos with energies greater than 500 TeV to accidentally produce late GRB-neutrino candidates leading to this high value of correlation, when combined with our late GRB-neutrino candidates with energies between 60 and 500 TeV. We performed $10^5$ randomizations of the times of detection of the available neutrinos with energies greater than 500 TeV, keeping their energies and directions fixed, and computed the probability of having at least two late GRB-neutrino candidates with energies greater than 500 TeV that are compatible with $\eta = 21.7 \pm 9.0$ and produce an overall correlation of at least 0.9997. For our simulated data we also handled the multiple-GRB-partner issue by selecting the case with the highest correlation. We found that the false-alarm probability was only 0.005%.

We do not dwell on the potential significance of this relatively low false-alarm probability: our investigations started with the goal of studying the impact of ref. 20 on analyses focusing on the range of 60–500 TeV, and the inclusion of events with energies greater than 500 TeV was an afterthought that, while evidently leading to an intriguing result, should not divert attention from the main part of our analysis. Still, combining our findings in the range of 60–500 TeV and our findings for energies greater than 500 TeV, there seems to be plenty of motivation for monitoring the evolution of this type of analysis as more high-energy-neutrino data are accrued.

**Methods**

**Early neutrinos with energies between 60 and 500 TeV**

For the GRBs we used the catalogue that can be found at icecube.wisc.edu/~grbweb_public/Summary_table.html. For the neutrinos we used the same data sample of refs. 15–19 and we also followed refs. 15–19 in focusing on ‘shower events’ with energies between 60 and 500 TeV. Using the selection criteria of refs. 15–19 (but now relying on the corrected directional data of the more recent ref. 20) we found three early GRB-neutrino candidates, which are reported in Table 1.

We estimated the probability of three early GRB-neutrino candidates being found accidentally in our dataset (without any intervening quantum-gravity effect) by generating $10^5$ simulated datasets, each obtained by randomizing the time of observation of the neutrinos, while keeping their energy and direction fixed, and counting how many times there were at least three neutrinos that found an early GRB-association in these simulated datasets. We found that this happened in 81% of the cases, and we therefore conclude that our three early GRB-neutrino candidates are most likely to be pure background.

**Late neutrinos with energies between 60 and 500 TeV**

We found seven late GRB-neutrino candidates with energies between 60 and 500 TeV, which we report in Table 2.

By generating $10^5$ simulated datasets, each obtained by randomizing the time of observation of the neutrinos while keeping their energy and direction fixed, we found that the probability of accidentally obtaining, without any intervening quantum-gravity effect, at least seven late GRB-neutrino candidates with energies between 60 and 500 TeV was only 5%.

However, even assuming that some of our seven late GRB-neutrino candidates were ‘signal’ (that is, their propagation times were affected by quantum gravity) it is likely that some of them are ‘background’ (that is, they were picked up in the analysis accidentally). To address this we performed an analysis that sets aside our seven selected neutrinos: we randomized the times of observation of the neutrinos that were not selected by our criteria (and therefore should be assumed to be unrelated to any of the GRBs, with or without quantum-gravity effects) and computed how frequently in such randomizations one found the accidental appearance of late GRB-neutrino candidates. Essentially, through these randomizations we estimated the fraction $\zeta$ of an ensemble of neutrinos that did not include GRB neutrinos that would accidentally be picked up as GRB-neutrino candidates. In general, if such an analysis considers $N$ neutrinos and there are $M$ true GRB neutrinos, the number $L$ of GRB-neutrino candidates found clearly will be such that $N \geq L \geq M$, and one can then estimate $M$ through the relationship $M + \zeta (N - M) = L$, in which $N$ and $L$ are known, whereas $\zeta$ is estimated using the randomizations. Following this procedure, we found a probability of 83% that at least one of our seven late GRB-neutrino candidates was a background neutrino, a probability of 39% that at least two neutrinos were background and a probability of 18% that at least three neutrinos are background.

**On combining early neutrinos with late neutrinos**

Taking into account the recently revised estimates20 of the direction of observation of IceCube neutrinos, we found no encouragement for the early-neutrino hypothesis and a noteworthy false-alarm probability for late neutrinos. With the previous (erroneous) version of the IceCube data there was a statistically significant case separately for early neutrinos and for late neutrinos, and the highest statistical significance was actually found when combining early and late neutrinos in a single analysis. The most popular quantum-gravity intuition is that all particles with half-integer spin should be affected by the same effect, but there is a model with breakdown of relativistic invariance that can accommodate an effect that has opposite sign for the two helicities of the neutrino (a scenario that might be relevant here given that we have no helicity information for IceCube neutrinos), and therefore it is legitimate to also contemplate the possibility of combining early and late neutrinos in a single analysis.

The fact that (with the corrected IceCube data) we found only three early-neutrino candidates, and that we estimated that all three are likely to be background, already suggests that with the corrected IceCube data we should also find no support for this hypothesis combining early and late neutrinos, but it is still interesting to obtain a quantitative assessment of this point.

We did this by applying the same statistical tools that we applied separately to early and late neutrinos to the combination of all our GRB-neutrino candidates (both early and late). We found that for this case the false-alarm probability was 4.6%. In itself a false-alarm probability of 4.6% would not be discouraging, but the key observation here is that for the late neutrinos on their own we found a false-alarm probability of 0.005%, and this was a much lower number compared to the case of combining early and late neutrinos.
Late neutrinos with energies above 500 TeV
We selected shower neutrinos with energies greater than 500 TeV as late GRB-neutrino candidates if they satisfied the same angular criterion used for the lower-energy neutrinos, and if the difference between their time of arrival and that of the GRB was positive and lay within the range $\Delta t - \Delta \eta \cdot X(E, z)$ $\leq 25\eta \cdot X(E, z)$. We found two such late GRB-neutrino candidates, and their properties are given in Table 3. For one of these neutrinos we found three possible GRB partners and we handled this again by selecting the case that led to the highest overall correlation.

Weakness of the dependence on the highest-correlation criterion
As stressed above, one of the neutrinos that played a role in our analysis, a neutrino with energy 86.1 TeV, is compatible with three GRBs within our temporal and directional window. This was handled by focusing on the GRB neutrino pair for our 86.1 TeV neutrino that produced the highest overall correlation. We used the same highest-correlation criterion as when our simulated data presented more than one GRB paired with the same neutrino. Adopting the same criterion for both real and simulated data ensured that our estimates of false-alarm probabilities were not biased, but one might still wonder whether our highest-correlation criterion was inadvertently largely responsible for our low false-alarm probabilities.

To probe this issue, we paired our 86.1 TeV neutrino with GRB120121B, which among the three possible GRB partners produced the lowest correlation ($0.53$) (as shown in Table 2, for our main analysis we paired the 86.1 TeV neutrino with GRB120121A, producing the highest correlation of $0.56$). In our simulations we then compared this lowest value of correlation of our true data with the highest value of correlation for the simulated data, thereby giving an ‘unfair advantage’ to the simulated data. This of course produced an increase in the false-alarm probability, but a relatively moderate one: from the $0.7\%$ found in our main analysis, the false-alarm probability was increased to $0.9\%$.

Weakness of the dependence on the assumptions about redshift
As stressed above, for GRBs whose redshift is unknown analyses such as ours can estimate that unknown redshift by inferring a redshift distribution for GRBs observed in neutrinos from the data themselves. While this approach should be very powerful when a large data sample becomes available, at present we are forced to make these estimations on the few data available and must therefore expect that the inferred distribution is very uncertain. However, as we shall show here, our key results (which take the form of false-alarm probabilities) do not seem to depend strongly on the uncertainties in the redshift distribution.

We propose that at present (as few data are available) one should only use the average redshift value of GRBs observed in neutrinos for the analysis, so a single redshift value is estimated and attributed to all GRBs of unknown redshift. We used the same criterion for unknown redshifts for our simulated data as well, and our estimates of false-alarm probabilities are therefore not biased, but one might still wonder whether our criterion for handling unknown redshifts was inadvertently largely responsible for our low false-alarm probabilities.

To probe this issue, we still used our redshift criterion on true data, but for simulated data we estimated the redshift of GRBs whose redshift was unknown by choosing the value that produced the highest correlation. We still adjusted only a single parameter (the same redshift value was given to all GRBs in the simulated data whose redshift was unknown), but we adjusted that parameter in a way that maximized the correlation. We were once again giving an ‘unfair advantage’ to the simulated data, and of course this produced only a relatively moderate increase in the false-alarm probability: from the $0.7\%$ found in our main analysis, the false-alarm probability was increased to $1.2\%$.

Data availability
For the GRBs we used the catalogue that can be found at icecube.wisc.edu/~grbweb_public/Summary_table.html. For neutrinos we used the data reported in ref. 20.

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Author contributions

G.A.-C. proposed the project. All authors contributed to all aspects of the analysis, with G.A.-C., G.G. and G.R. leading the work on pure theory, G.A.-C., G.D. and G.G. leading the work on statistical methods and M.G.D.L., G.G. and G.R. leading the numerical work.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Giovanni Amelino-Camelia.

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