Possible relevance of quantum spacetime for neutrino-telescope data analyses

Giovanni Amelino-Camelia\textsuperscript{a}, Dafne Guetta\textsuperscript{b,c} and Tsvi Piran\textsuperscript{d}
\textsuperscript{a}Dipartimento di Fisica, Sapienza Università di Roma and INFN, Sez. Roma1, P.le A. Moro 2, 00185 Roma, EU
\textsuperscript{b}Department of Physics, ORT Braude, Sifunit 51 St. P.O.Box 78, Karmiel 21982, Israel
\textsuperscript{c}Osservatorio Astronomico di Roma, via Frascati 33, 00040 Monteporzio Catone, Italy
\textsuperscript{d}The Racah Institute for Physics, The Hebrew University of Jerusalem, Jerusalem, 91904, Israel

One of the primary goals of neutrino telescopes, such as IceCube, is the discovery of neutrinos emitted by gamma-ray bursts (GRBs). Another source of interest in the results obtained by these telescopes is their possible use for tests of the applicability of Einstein’s Special Relativity to neutrinos, particularly with respect to modifications that lead to Lorentz invariance violation that have been conjectured by some models of quantum space-time. We examine here the fascinating scenario in which these two aspects of neutrino-telescope physics require a combined analysis. We discuss how neutrinos that one would not associate to a GRB, when assuming a classical spacetime picture, may well be GRB neutrinos if the possibility that Lorentz invariance is broken at very high energies is taken into account. As an illustrative example we examine three IceCube high energy neutrinos that arrived hours before GRBs (but from the same direction) and we find that the available, IceCube data, while inconclusive, is compatible with a scenario in which one or two of these neutrinos were GRB neutrinos and their earlier arrival reflects Lorentz invariance violation. We outline how future analyses of neutrino data should be done in order to systematically test this possibility.

Prominent on the agenda of the current generation of neutrino telescopes is the search for neutrinos emitted in the same gigantic explosion responsible for Gamma ray bursts (GRBs). Another source of interest in the results obtained by these telescopes is their possible use for tests of the applicability of Einstein’s Special Relativity to neutrinos, particularly with respect to modifications that lead to Lorentz invariance violation that have been conjectured by some models of quantum space-time. We examine here the fascinating scenario in which these two aspects of neutrino-telescope physics require a combined analysis. We discuss how neutrinos that one would not associate to a GRB, when assuming a classical spacetime picture, may well be GRB neutrinos if the possibility that Lorentz invariance is broken at very high energies is taken into account. As an illustrative example we examine three IceCube high energy neutrinos that arrived hours before GRBs (but from the same direction) and we find that the available, IceCube data, while inconclusive, is compatible with a scenario in which one or two of these neutrinos were GRB neutrinos and their earlier arrival reflects Lorentz invariance violation. We outline how future analyses of neutrino data should be done in order to systematically test this possibility.

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the 35 TeV event was very clearly a cosmic ray since it triggered the IceTop surface array, whereas for the 109 TeV event there was only one IceTop-tank trigger in time coincidence. This single IceTop-tank trigger may suggest it was part of a cosmic-ray air shower but could also be a background in the tank’s photomultiplier. Indeed the 109 TeV event has been described as the most significant GRB-neutrino candidate so far reported by IceCube, even combining both the IC40 and the IC59 data sets. Following these remarks we exclude the 35 TeV event but we include the 109 TeV event in our analysis.

The fact that all 3 GRB-neutrino candidates were detected sizably in advance of the triggers of the GRBs they could be associated with is not particularly significant from the standard perspective of this sort of analysis, and actually obstructs any such attempt to view them as GRB neutrinos: no current GRB model suggests that neutrinos could be emitted thousands of seconds before a GRB. But a collection of GRB-neutrino candidates all sizably in advance of (or all with a sizable delay with respect to) corresponding GRB triggers is just what one was expecting on the basis of the quantum-spacetime-inspired Lorentz invariance violation scenario [13, 14], and this may invite further analysis.

This scenario for the discovery of GRB neutrinos [13, 14] was based on results for models of spacetime quantization suggesting that (see, e.g., [18–22]) it is possible for the quantum properties of spacetime to introduce small violations of the special relativistic properties of classical spacetime. A key consequence of this picture would be that the time needed for a ultrarelativistic particle to travel from a given source to a given detector is \( t = t_0 + t_{LIV} \). Here \( t_0 \) is the time that would be predicted in classical space-time, while \( t_{LIV} \) is the contribution to the travel time due to quantum properties of spacetime. For energies much smaller than, \( M_{LIV} \), the scale of onset of these quantum-spacetime effects, one expects that at lowest order \( t_{LIV} \) is given by [23]:

\[
t_{LIV} = -s_\pm \frac{E}{M_{LIV}} \frac{D(z)}{c},
\]

where

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

Here the information cosmology gives us on spacetime curvature is coded in the denominator for the integrand in \( D(z) \), with \( \zeta \) being the redshift and \( \Omega_\Lambda \), \( H_0 \) and \( \Omega_0 \) denoting, as usual, respectively the cosmological constant, the Hubble parameter and the matter fraction. The “sign parameter” \( s_\pm \), with allowed values of 1 or \(-1\), as well as the scale \( M_{LIV} \) would have to be determined experimentally. The label “LIV” stands for Lorentz-invariance Violation, since the aspects of special relativity here at stake are indeed those connected to Lorentz invariance [18–22] and there is interest in this class of effects from the intrinsic Lorentz-invariance test theory perspective [25], with or without spacetime quantization. We must stress however that most theorists favor naturalness arguments suggesting that \( M_{LIV} \) should take a value that is rather close to the “Planck scale” \( M_P = \sqrt{\hbar c^5/G_N} \approx 1.22 \cdot 10^{19} \text{TeV} \).

The picture of quantum-spacetime effects summarized in [1] does not apply to all quantum-spacetime models. One can envisage quantum-spacetime pictures that do not violate Lorentz symmetry at all, and even among the most studied quantum-spacetime pictures that do violate Lorentz symmetry one also finds variants producing (see, e.g., [14, 18, 25]) features analogous to [1] but with the ratio \( E/M_{LIV} \) replaced by its square, \( (E/M_{LIV})^2 \), in which case the effects would be much weaker and practically undetectable at present. We focus here on the most studied Lorentz-invariance-violating scenario, the one centered on [1].

It is important that some quantum-spacetime models allow for laws roughly of the type [1] to apply differently to photons and neutrinos. An attractive hypothesis [22, 23] is that the quantum-spacetime effects should still be accommodated within the formalism of effective quantum field theory, where effects of the type shown in [1] would take the shape of dimension-5 operators added to the Lagrangian density and contributing to the particle’s propagator. Within that effective-field-theory setup one can formulate exactly [1] for neutrinos, but not for photons (though a variant of [1] with an added polarization dependence is allowed for photons). And even among quantum-spacetime models that do not fully comply with the demands of a description within the effective-field-theory framework neutrinos deserve dedicated interest. In particular, for the most studied such quantum spacetime, the so-called “Moyal non-commutative spacetime”, it is remarkably found [26] that the implications of spacetime quantization for particle propagation end up depending on the standard-model charges carried by the particle and its associated coupling to other particles. Accurate studies of [1] for neutrinos would be our first opportunity to tangibly constrain such possibilities for a particle carrying weak-interaction charge.

Testing the applicability of [1] to GRB neutrinos is in principle simple. GRBs last anywhere between a few and ~1000 seconds and if \( t_{LIV} = 0 \) the associated neutrinos are, of course, expected to be detected within approximately the same time window. Such a coincidence in arrival time of GeV photons and sub-Mev photons in some GRBs enabled the Fermi satellite to set limits for \( M_{LIV} / \text{photons} \gtrsim M_P \) for photon propagation using just this idea [27]. If instead \( t_{LIV} \) is described by [1], for sufficiently high energies and sufficiently high redshifts, \( t_{LIV} \) would be large, and the neutrinos would be detected either significantly before or significantly after the time interval when the low-energy photons of the same GRB are observed. But here resides the challenge that most significantly affects the interpretation of the observations. If the neutrinos are detected much before or much after the time interval when.

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1. Of course the only regime of particle propagation that is relevant for this manuscript is the ultrarelativistic regime, since photons have no mass and for the neutrinos we are contemplating (energy of a few TeVs and above) the mass is completely negligible.

2. A somewhat similar description of the challenges for testing [1] at IceCube was given by Gonzalez-Garcia and Halzen a few years ago [28]. Consistently with what we are here arguing, they concluded that these challenges would have to be reassessed once the first data from IceCube could be analyzed.
the GRB is observed how would we know that they are GRB neutrinos? There is, as mentioned, a background of other neutrinos (in particular atmospheric neutrinos) that the telescopes detect. The key discriminator being used in searching for candidate GRB neutrinos exploits the fact that the expected rate of background neutrinos is sufficiently low that the chances of accidentally catching a background neutrino are negligibly small when restricting the search to neutrinos from (roughly) the same direction of the GRB photons and in a narrow time window around the time of arrival of the signal in photons. If however $t_{\text{GRB}}$ is described by (1), also considering that $M_{\text{GRB}}$ has, as mentioned, a rather sizable “theoretical uncertainty” and $E$ has a significant observational error, the temporal window should be made considerably larger and contending with background neutrinos may be a severe challenge. Jacob and Piran [13] have addressed this issue for GRB neutrinos of energies higher than those here of interest. In that case, they argue, the background noise is sufficiently low that a detection of a neutrino from the direction of a GRB can be significant even when there is a sizable mismatch of detection times.

However, even at lower energies one can efficaciously test (1) upon adopting a change of approach such that the selection of GRB-neutrino candidates is based on rather tight directional criteria (the direction of the neutrinos should be determined to be rather accurately consistent within the point spread function of the detector with the direction of the GRB potentially associated to it) while the time-window criteria for the selection of GRB neutrinos should be relaxed but in a systematic way allowing for (1). If this strategy is adopted we would gain the ability to test both the $t_{\text{GRB}} = 0$ hypothesis and the hypothesis that $t_{\text{GRB}}$ be described by (1). It should be appreciated that these two hypotheses would affect the data analyses not only quantitatively but also qualitatively. If indeed GRBs are sources of TeV neutrinos and $t_{\text{GRB}} = 0$ then at some point we will have quite a few such directionally-selected GRB-neutrino candidates, and some of them will be established to be definitely GRB neutrinos because of a level of time coincidence with the associated GRBs that would allow us to exclude confidently the possibility of having caught a background neutrino. On the other hand, if $t_{\text{GRB}}$ is described by (1) one should expect that we might never have a specific neutrino that can be conclusively associated to a GRB and yet we could deduce that some of the neutrinos (without knowing which ones) did come from GRBs, just because the distribution of times of detection of directionally-selected neutrinos would not be just random (as in the case of a sample of pure background neutrinos): the sample would manifest a higher probability of detecting neutrinos in a certain energy-dependent and redshift dependent time window, governed by (1), systematically advanced or delayed with respect to the gamma-ray trigger of the GRB.

Of course, the accumulation of candidate GRB neutrinos will provide more or less insight depending on how sharply the energy of the neutrino candidates is determined experimentally, on the availability of accurate position and redshift of the GRB and on the robustness of the inferred value of $t_{\text{GRB}}$. Neutrino energies are determined by IceCube with a 30% uncertainty [16]. GRB positions are determined very accurately if X-ray of optical afterglow is observed and redshift determination can be achieved if a strong optical afterglow with suitable absorption lines is detected or if a host galaxy is identified. Concerning the robustness of the inferred value of $t_{\text{GRB}}$ one should notice that, according to current models, the emission of neutrinos should coincide with the GRB trigger in gamma rays up to a possible advanced emission of a few tens of seconds or a possible delay of emission which could go as far as about 100 seconds after the duration of the burst. It is of course still appropriate to describe $t_{\text{GRB}}$ as the difference between the time of detection of the neutrino and the trigger time of the GRB tentatively associated to it, but in testing the hypothesis characterized by $t_{\text{GRB}}$ one should take into account the uncertainty in the emission time of neutrinos within the GRB event that current models allow for. So to each candidate GRB neutrino we should assign a time offset $t_{\text{GRB}} - t_{\text{GRB}}$ where $\Delta t_{\text{GRB}}$ reflects the uncertainty GRB modeling attributes to the delay of emission of neutrinos with respect to the GRB trigger. In this respect we should stress that in all 3 events that we examine here the inferred value of $t_{\text{GRB}}$ is significantly larger than 1000 seconds, so the possibility that the neutrino might have been emitted a few tens of seconds before the GRB trigger can be neglected. Instead, the possibility that neutrinos be emitted at any time during the GRB phenomenon and up to 100 seconds after the GRB ends can occasionally matter, but only for bursts of unusually long duration, long enough to make this $\Delta t_{\text{GRB}}$ non-negligible with respect to $t_{\text{GRB}}$. Amusingly one of the three GRBs relevant for our analysis is just in this situation: GRB090417B had an unusually long duration of some 2300 seconds, so for the $t_{\text{GRB}}$ of the neutrino tentatively associated to GRB904017B we shall allow for a $\Delta t_{\text{GRB}}$ of 2400 seconds. While such long GRBs are rare, similar cases may present themselves again as more GRB-neutrino candidates are accumulated.

Once data are collected following these criteria a first level of assessment in relation to the content of Eq.(1) can be given in the spirit illustrated in Fig. 1. With a large number of directionally-selected GRB-neutrino candidates one could conclusively test (1), even without any redshift information about the relevant GRBs and even if each individual event had a nonnegligible chance of being a background event. Fig.1 conveys this message by taking as illustrative example the case $x = 1$ and $M_{\text{GRB}} = 0.1 M_P$. The shaded area of Fig. 1 shows how these illustrative hypotheses would affect the prediction from (1) of the correlation between values of the energy of the candidate GRB neutrinos and of the inferred value of $t_{\text{GRB}}$, given in terms of the time-of-detection difference with respect to the trigger of the lower-energy photon signal of the relevant GRB. The thickness of the shaded area in Fig. 1 reflects the simplifying assumption that the redshifts of the candidate GRB sources of the neutrinos all take value between 0.2 and 8. (This broad redshift range encompasses more than 95% of the long GRBs with known redshifts; the darker part of the shaded region of Fig. 1 would apply to GRBs in the narrower redshift range from 0.9 to 3, which contains about 50% of values found for long GRBs with known redshifts).
While at first glance in Fig. 1, all the 3 GRB-neutrino candidates fit within the shaded region, this figure essentially factors out all information on redshifts of the candidate sources. The assessment of these 3 candidate GRB neutrinos can be made more precise by imposing the consistency condition that a group of genuine GRB-neutrino events governed by (1) should all be consistent with the same value of $M_{\text{LIV}}$ when taking into account the (however partial) information available on their redshift.

As an illustration of a Lorentz invariance violation inspired analysis of the data we examine here the scenario in which the three IceCube events are GRB neutrinos and the arrival times are determined by (1). Fig. 2a depicts the allowed range of redshifts and $M_{\text{LIV}}$ for each of the neutrino events, assuming $t_{\text{LIV}}$ given by (1). Fig. 2b (respectively 2c) describes the probability that an observed long (respectively short) burst is at a certain redshift $z$ on the basis of the observed redshift distribution for the long GRBs (29) and for the short GRBs (30).

A horizontal line in Fig. 2a corresponds to a given value of $M_{\text{LIV}}$ and for illustrative purposes two such lines are shown. Each line implies a range of redshift values (corresponding to the one-standard-deviation energy range of each one of the neutrinos) for each one of the bursts. These ranges should be compared with the expected probabilities that the bursts have a given redshift as seen by Figs. 2b and 2c. Here one should distinguish between GRB090417B and GRB091230A that are long GRBs with an observed redshift distribution extending from 0.1 to 9.4 and peaking in the region $0.5 < z < 3$, and GRB090219, a short GRB whose expected redshift is between 0.1 and 1.

It is remarkable that even with the limited data available concerning these three events some conclusions can be drawn from this analysis. One sees from Fig. 2 that the hypothesis that all 3 neutrinos are GRB neutrinos is consistent with a combination of values of redshift and $M_{\text{LIV}}$. This is shown with the continuous lines in panel (a): blue is for 109 TeV and $t_{\text{LIV}}$ of 14 hours, red is for 3.3 TeV and $t_{\text{LIV}} = 3594s$, and gray is for 1.3 TeV and $t_{\text{LIV}} = 2249s$. Dashed lines delimit the range of uncertainty due to the uncertainty in the energy determinations and $M_{\text{GRB}}$ (which is appreciable only for the lowest dotted gray line). Panel (b) (respectively (c)) describes the probability that an observed long (respectively short) burst has a certain redshift. For $M_{\text{LIV}} < 0.05 M_P$, it is plausible to interpret both the 109 TeV and the 3.3 TeV events as GRB neutrinos governed by (1). For higher values of $M_{\text{LIV}}$ taking the 3.3 TeV event as a GRB neutrino requires a redshift for short burst GRB090219 that is unlikely on the basis of panel (c). Interpreting the 1.3 TeV event as a GRB neutrino requires values of $M_{\text{LIV}}$ no greater than $\sim 0.01 M_P$, since in panel (a) this allows the 1.3 TeV event to be associated to a source at redshift of 0.35 (as established for GRB090417B). For $M_{\text{LIV}} < 0.01 M_P$ one can also interpret the 3.3 TeV event as a GRB neutrino governed by (1), since then the inferred value of redshift for short burst GRB090219 is consistent with panel (c). However, at values of $M_{\text{LIV}}$ as low as $\sim 0.01 M_P$ the interpretation of the 109 TeV in association to the long burst GRB091230A is disfavored by the probability distribution shown in panel (b).

4 A more precise estimate can be obtained using additional information concerning a burst, such as its fluence.
the events) to be attributed very unlikely redshift values. This hypothesis would lead to the assumption that GRB091230A was closer than both GRB090417B and GRB090219, the farthest being GRB090417B. However, GRB090417B was a very long optically-dense with a rather robust association with a SDSS galaxy at redshift $z \approx 0.35$ [31]. It would seem rather implausible that for GRB091230A, a long GRB whose redshift was not determined, had a redshift smaller than 0.35 (less than 2% of the observed long GRBs have $z < 0.35$). Therefore the possibility that all three events are associated with GRBs is unlikely. On the other hand for GRB090219, which was a short burst, it is rather plausible to assume that $z < 0.35$ (about 30% of short GRBs have $z < 0.35$). It is therefore reasonable to contemplate the hypothesis that both the 1.3TeV event and the 3.3TeV event are GRB neutrinos. This would require $M_{LIV} \lesssim 0.01 M_P$. Another reasonable possibility is that the 1.3TeV event was background, but both the 109 TeV event and the 3.3TeV event were GRB neutrinos. Making the reasonable assumption that the long burst GRB091230A was at redshift $0.4 < z < 5.5$ (see Fig. 2b) one gets a range of compatible values of $M_{LIV}: 0.02 M_P < M_{LIV} < 0.5 M_P$. While the 3.3TeV candidate from the short burst GRB090219 implies $M_{LIV} \lesssim 0.05 M_P$. Combined together we find that for $0.02 M_P \lesssim M_{LIV} \lesssim 0.05 M_P$ both the 109 TeV event and the 3.3TeV event could be tentatively considered as GRB neutrinos.

In summary we conclude that at most 2 of the 3 GRB-neutrino candidates could possibly be GRB neutrinos governed by $M_{LIV}$ for neutrinos. We stress that the hypothesis that one or two of the candidate events might be GRB neutrinos governed by $M_{LIV}$ should only be viewed within the realm of plausibility, the most likely interpretation of the data being of course that all 3 candidates are insignificant background events. Nonetheless, going back to a key point we made earlier, it is interesting that we have here a quantum-spacetime model with independent reasons of interest within which one gets a rather plausible interpretation of presently available IceCube data as including perhaps as many as 2 GRB neutrinos.

While unlocking the secrets of the mechanisms producing neutrinos at GRB sources is of very high intrinsic interest, in assessing the motivation for future efforts along this line of analysis one should also take into account that the possible confirmation of the Lorentz invariance violation contemplated here would have a gigantic impact on fundamental physics. One would not only have the first much-sought evidence of a quantum property of spacetime (and evidence imposing at least an adaptation of Einstein’s special relativity to that quantum spacetime context), but one would also have a very intelligible hint concerning the correct description of quantum spacetime. This is particularly true since tests of the applicability of Eq. (1) to photons from GRB090510 observed by the Fermi gamma-ray telescope lead to a bound for photons of $M_{LIV}$ ($\text{photons} > 1.2 M_P$ [27]). If indeed for neutrinos future data ended up providing evidence for $0.01 M_P \lesssim M_{LIV} \lesssim 0.1 M_P$ this would immediately direct us toward the few models, mentioned earlier, in which the laws of particle propagation in quantum spacetime depends on either the spin of the particle or its standard-model charges.

We stress that to further investigate this scenario some measures should be adopted at neutrino telescopes such as IceCube. Specifically one should consider a joint analysis of candidate events that are localized within the direction of GRBs but shifted in time, searching for a possible common interpretation with a single $M_{LIV}$ value, in the way presented here. One can view this new suggested analysis in Bayesian like approach. Lacking an exact model for GRB neutrino emission and given that the prompt emission could produce high energy GRB neutrinos, standard analyses assume a prior according to which GRB neutrinos should emerge more or less uniformly within about a 100 sec after the trigger. Inclusion of possible neutrino emission during the jet propagation within a Collapsar should shift this prior back by $\sim 20 - 30$ seconds prior to the trigger. The new analysis that considers $L_{IV}(E, z, M_{LIV})$ should adopt a new prior in which this original duration is modified according to $[1]$. For a given data set that will include neutrino candidates from GRBs with and without redshift one should then estimate the probability of association of neutrinos to GRBs according to the standard old prior but also using this new one. In principle a significant fit with this new prior could point towards Lorentz invariance violation and enable us to estimate $M_{LIV}$.

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