Physics Letters B 761 (2016) 318–325

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

IceCube and GRB neutrinos propagating in quantum spacetime

Giovanni Amelino-Camelia [a,b,*], Leonardo Barcaroli [a], Giacomo D'Amico [a,b], Niccoló Loret [c], Giacomo Rosati [d]

[a] Dipartimento di Fisica, Università di Roma "La Sapienza", P.le A. Moro 2, 00185 Roma, Italy
[b] INFN, Sez. Roma1, P.le A. Moro 2, 00185 Roma, Italy
[c] Institut Ruđer Bošković, Division of Theoretical Physics, Bijenička cesta 54, 10000 Zagreb, Croatia
[d] Institute for Theoretical Physics, University of Wrocław, Pl. Maksa Borna 9, Pl–50-204 Wrocław, Poland

ARTICLE INFO

Article history:
Received 8 June 2016
Received in revised form 16 July 2016
Accepted 28 July 2016
Available online 10 August 2016
Editor: M. Cvetič

Keywords:
IceCube
Planck scale
Neutrino phenomenology
Gamma ray burst

ABSTRACT

Two recent publications have reported intriguing analyses, tentatively suggesting that some aspects of IceCube data might be manifestations of quantum-gravity-modified laws of propagation for neutrinos. We here propose a strategy of data analysis which has the advantage of being applicable to several alternative possibilities for the laws of propagation of neutrinos in a quantum spacetime. In all scenarios here of interest one should find a correlation between the energy of an observed neutrino and the difference between the time of observation of that neutrino and the trigger time of a GRB. We select accordingly some GRB-neutrino candidates among IceCube events, and our data analysis finds a rather strong such correlation. This sort of study naturally lends itself to the introduction of a "false alarm probability", which for our analysis we estimate conservatively to be of 1%. We therefore argue that our findings should motivate a vigorous program of investigation following the strategy here advocated.

1. Introduction

The prediction of a neutrino emission associated with gamma ray bursts (GRBs) is generic within the most widely accepted astrophysical models [1]. After a few years of operation IceCube still reports [2] no conclusive detection of GRB neutrinos, contradicting some influential predictions [3–6] of the GRB-neutrino observation rate by IceCube. Of course, it may well be the case that the efficiency of neutrino production at GRBs is much lower than had been previously estimated [7–9]. However, from the viewpoint of quantum-gravity/quantum-spacetime research it is interesting to speculate that the IceCube results for GRB neutrinos might be misleading because of the assumption that GRB neutrinos should be detected in very close temporal coincidence with the associated γ-rays: a sizeable mismatch between GRB-neutrino detection time and trigger time for the GRB is expected in several much-studied models of neutrino propagation in a quantum spacetime (see Refs. [10–19] and references therein).

This possibility was preliminarily explored in Ref. [18] using only IceCube data from April 2008 to May 2010, and focusing on 3 weak but intriguing candidate GRB neutrinos (see Refs. [20,21]): a 1.3 TeV neutrino 1.95° off GRB090417B with detection time 2249 seconds before the trigger of GRB090417B, a 3.3 TeV neutrino 6.11° off GRB 090219 and detection time 3594 seconds before the GRB 090219 trigger, and a 109 TeV neutrino 0.2° off GRB091230A and detection time some 14 hours before the GRB091230A trigger. The analysis reported in Ref. [18] would have been more intriguing if the 109 TeV event could be viewed as a promising cosmological-neutrino candidate, but for that event there was a IceTop-tank trigger coincidence. A single IceTop-tank trigger is not enough to firmly conclude that the event was part of a cosmic-ray air shower, but of course that casts a shadow on the interpretation of the 109-TeV event as a GRB neutrino.

Unaware of the observations reported in Ref. [18], recently Stecker et al. reported in Ref. [19] an observation which also might encourage speculations about neutrino propagation in quantum spacetime. Ref. [19] noticed that IceCube data are presently consistent with a ~ 2 PeV cutoff for the cosmological-neutrino spectrum, and that this could be due to novel processes (like "neutrino splitting" [10,19]) that become kinematically allowed in the same class of quantum-spacetime models considered in Ref. [18].

The study we are here reporting was motivated by these previous observations of Refs. [18] and [19]. Like Ref. [18] our focus is on the hypothesis of GRB neutrinos with quantum-spacetime properties, also exploiting the fact that, while Ref. [18] was limited to IceCube data up to May 2010, the amount of data now available

* Corresponding author.
E-mail address: amelino@roma1.infn.it (G. Amelino-Camelia).

http://dx.doi.org/10.1016/j.physletb.2016.07.075

from IceCube [22] is significantly larger. Conceptually the main issue we wanted to face is indeed related to the amount of IceCube data: as studies like these start to contemplate larger and larger groups of "GRB-neutrino candidates" some suitable techniques of statistical analysis must be adopted, and (unlike Refs. [18] and [19]) we wanted to devise a strategy of analysis applicable not only to one "preferred model", but to a rather wide class of scenarios for the properties of the laws of propagation of neutrinos in a quantum spacetime.

As discussed more quantitatively below, the effects on propagation due to spacetime quantization can be systematic or of "fuzzy" type. Combinations of systematic effects and fuzziness are also possible, and this is the hypothesis most challenging from the viewpoint of data analysis. We came to notice that in all these scenarios one should anyway find a correlation between the energy of the observed GRB neutrino and the difference between the time of observation of that neutrino and the trigger time of the relevant GRB. Intriguingly our data analysis finds a rather strong such correlation, and we therefore argue that our findings should motivate a vigorous program of investigation following the strategy here advocated.

2. Quantum-spacetime-propagation models and strategy of analysis

The class of scenarios we intend to contemplate finds motivation in some much-studied models of spacetime quantization (see, *e.g.*, [10–17] and references therein) and, for the type of data analyses we are interested in, has the implication that the time needed for a ultrarelativistic particle[1] to travel from a given source to a given detector receives a quantum-spacetime correction, here denoted with Δt. We focus on the class of scenarios whose predictions for energy (E) dependence of Δt can all be described in terms of the formula (working in units with the speed-of-light scale "c" set to 1)

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

Here the redshift- (z-)dependent $D(z)$ carries the 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 literature [10–12] we take for $D(z)$ the following form[2]:

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

where Ω_Λ, H_0 and Ω_0 denote, as usual, respectively the cosmological constant, the Hubble parameter and the matter fraction, for which we take the values given in Ref. [24]. With M_P we denote the Planck scale ($\simeq 1.2 \cdot 10^{28}$ eV) while the values of the parameters η_X and δ_X in (1) characterize the specific scenario one intends to study. In particular, in (1) we used the notation "$\pm\delta_X$" to reflect the fact that δ_X parametrizes the size of quantum-uncertainty (fuzziness) effects. Instead the parameter η_X characterizes systematic effects: for example in our conventions for positive η_X and $\delta_X = 0$ a high-energy neutrino is detected systematically after a low-energy neutrino (if the two neutrinos are emitted simultaneously).

The dimensionless parameters η_X and δ_X can take different values for different particles [10,17,25,26], and it is of particular interest for our study that in particular for neutrinos some arguments have led to the expectation of an helicity dependence of the effects (see, *e.g.*, Refs. [10,25] and references therein). Therefore even when focusing only on neutrinos one should contemplate four parameters, η_+, δ_+, η_-, δ_- (with the indices $+$ and $-$ referring of course to the helicity). The parameters η_X, δ_X are to be determined experimentally. When non-vanishing, they are expected to take values somewhere in a neighborhood of 1, but values as large as 10^3 are plausible if the solution to the quantum-gravity problem is somehow connected with the unification of non-gravitational forces [10,27,28] while values smaller than 1 find support in some renormalization-group arguments (see, *e.g.*, Ref. [29]).

Presently for photons the limits on η_γ and δ_γ are at the level of $|\eta_\gamma| \lesssim 1$ and $\delta_\gamma \lesssim 1$ [30,31], but for neutrinos we are still several orders of magnitude below 1 [10,19]. This is mainly due to the fact that the observation of cosmological neutrinos is rather recent, still without any firm identification of a source of cosmological neutrinos, and therefore the limits are obtained from terrestrial experiments[3] (where the distances traveled are of course much smaller than the ones relevant in astrophysics).

For reasons that shall soon be clear we find convenient to introduce a "distance-rescaled time delay" Δt^* defined as

$$\Delta t^* \equiv \Delta t \frac{D(1)}{D(z)} \qquad (3)$$

so that (1) can be rewritten as

$$\Delta t^* = \eta_X \frac{E}{M_P} D(1) \pm \delta_X \frac{E}{M_P} D(1) \,. \qquad (4)$$

This reformulation of (1) allows to describe the relevant quantum-spacetime effects, which in general depend both on redshift and energy, as effects that depend exclusively on energy, through the simple expedient of focusing on the relationship between Δt and energy when the redshift has a certain chosen value, which in particular we chose to be $z = 1$. If one measures a certain Δt for a candidate GRB neutrino and the redshift z of the relevant GRB is well known, then one gets a firm determination of Δt^* by simply rescaling the measured Δt by the factor $D(1)/D(z)$. And even when the redshift of the relevant GRB is not known accurately one will be able to convert a measured Δt into a determined Δt^* with accuracy governed by how much one is able to still assume about the redshift of the relevant GRB. In particular, even just the information on whether a GRB is long or short can be converted into at least a very rough estimate of redshift.

Of course a crucial role is played in analyses such as ours by the criteria for selecting GRB-neutrino candidates. We need a temporal window (how large can the Δt be in order for us to consider a IceCube event as a potential GRB-neutrino candidate) and we need criteria of directional selection (how well the directions estimated for the IceCube event and for the GRB should agree in order for us to consider that IceCube event as a potential GRB-neutrino candidate). While our analysis shall not include the above-mentioned 109-TeV neutrino (from Ref. [18]), we do use it to inspire a choice

[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 tens or hundreds of TeVs) the mass is completely negligible.

[2] The interplay between quantum-spacetime effects and curvature of spacetime is still a lively subject of investigation, and, while (2) is by far the most studied scenario, some alternatives to (2) are also under consideration [23].

[3] Supernova 1987a was rather close by astrophysics standards and the signal detected in neutrinos was of relatively low energy.