

# INVESTIGATING QUANTUM SPACETIME THROUGH ICE CUBE ASTROPHYSICAL NEUTRINOS OBSERVATION\*

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The recent data on astrophysical neutrinos provided by the IceCube telescope offer a striking opportunity to test *in vacuo* dispersion of ultra-relativistic particles propagating in quantum spacetime scenarios inspired by phenomenological approaches to quantum gravity. We propose a novel method of investigation of these effects based on a statistical analysis of the correlation between neutrino energies, and the difference in detection times between neutrinos and candidate associated GRB trigger photons. The results we obtain show an amazingly high correlation of about 0.95, characterized by a false alarm probability of less than 0.1%.

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## 1. Introduction

The possibility of finding experimental evidence of quantum spacetime effects associated to models of quantum gravity would be of great importance for quantum gravity research, because it would allow us to test some of the assumptions at the basis of these models. In the past fifteen years, this perspective has led to the development of a “quantum gravity phenomenology” [1]. The main results have been obtained in frameworks where the tiny Planckian effects reach the sensitivity of presently available experiments due to some source of amplification.

*In vacuo* dispersion is a feature predicted by approaches in which quantum gravity effects manifest themselves at an effective level through a modification of relativistic symmetries characterizing the propagation of elemen-

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tary particles [1]. In these scenarios, ultra-relativistic particles propagate in vacuum with an energy-dependent speed<sup>1</sup>

$$v = c(1 + \eta E/E_P) , \quad (1)$$

where  $c$  is the speed of light,  $E_P \simeq 10^{-19}$  GeV is the Planck energy,  $E$  is the particle energy, and  $\eta$  a phenomenological parameter whose value (and sign) has to be determined by experiments. If one considers a distant event of simultaneous emission of two ultra-relativistic particles with different energy, a time delay between the two particles cumulates during their propagation. If the source distance is of cosmological scale, this time delay can be within the reach of the more advanced astrophysical particle telescopes.

The time delay at the detector can be described by the formula [2]

$$\Delta t = \eta \frac{\Delta E}{E_P} D(z) \pm \delta \frac{\Delta E}{E_P} D(z) , \quad (2)$$

where  $cD(z)$  is a distance factor encoding the interplay between spacetime curvature/expansion and Planck-scale effects, which takes this expression in terms of the redshift  $z$  of the source<sup>2</sup>

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

Here,  $H_0$ ,  $\Omega_\Lambda$  and  $\Omega_m$  are respectively the Hubble constant, the dark energy density and the matter density parameters, for which we take the values given in [5]. Formula (2), that describes a varied class of quantum space-time models, contains, besides  $\eta$ , a second parameter “ $\pm\delta$ ” to be determined experimentally, characterizing the quantum-uncertainty (fuzziness) effect. While for photons,  $\eta$  and  $\delta$  have been constrained up to Planck-scale sensitivity ( $|\eta| \lesssim 10$ ,  $\delta \lesssim 10$ ) through the analysis of the observation of GRB (Gamma Ray Bursts)-photons produced by a single source [6, 7] (GRB090510), the recently available data on astrophysical neutrinos provided by the IceCube observatory [8, 9], whose energy is up to PeV order high, offers a new striking opportunity to test *in vacuo* dispersion in the neutrino sector.

## 2. IceCube neutrinos and GRBs

The IceCube observatory, after a few years of operation, has detected, within a dataset from June 2010 to May 2014, 54 candidate astrophysical neutrinos [9]. It is expected that a significant number of them is produced at

<sup>1</sup> We here consider models where linear order corrections are present and neglect higher order corrections which would be suppressed by powers of  $(E/E_P)$ .

<sup>2</sup> This equation was first proposed in [3] in the context of LIV (Lorentz Invariance Violation) scenarios and recently derived (and generalized) in the context of DSR (Deformed Relativistic Symmetries) by the author in [4].

GRB sources through the interaction of high-energy protons with radiation, in association with ultra-high-energy cosmic rays [10, 11]. Still, IceCube has so far reported no detection of GRB-neutrinos [10, 11], assuming a neutrino to be considered associated to a GRB if it is detected in both angular and temporal coincidence with the GRB trigger photons. However, temporal coincidence applies only if the parameters  $\eta$  and  $\delta$  in formula (2) are set to zero. If one allows for the presence of quantum spacetime effects, testing the parameters close to the Planckian regime ( $|\eta| \sim |\delta| \lesssim O(10)$ ) imposes to enlarge the temporal window in which to look for GRB-neutrino candidates [2] up to 3 days of time mismatch between the neutrino and trigger GRB-photons detection.

In the analysis reported in [2], we tested Eq. (2) studying the (linear) correlation between  $\Delta t$  and the neutrino energies. We considered the 21 shower events<sup>3</sup> reported by IceCube with energies between 60 and 500 TeV. We selected neutrinos observed within 3 days of a GRB and in a 2-sigma angular coincidence with the relevant GRB. We are left with 9 GRB-neutrino candidates. Considering that some models suggest that particles of different species could have different values of  $\eta$ , and, in particular, that the sign of  $\eta$  could depend on the neutrinos helicity, we took  $|\Delta t|$  as our test variable, allowing for both cases of early and late neutrinos respect to GRB trigger photons. The data show an amazingly high correlation of 0.95, for which we estimated a “false alarm probability” (probability of finding such a high correlation if all neutrinos are background neutrinos that happened to fit by accident our GRB-neutrino selection criteria) of 0.03%. The details of the analysis are described in [2]. These results seem to indicate the presence

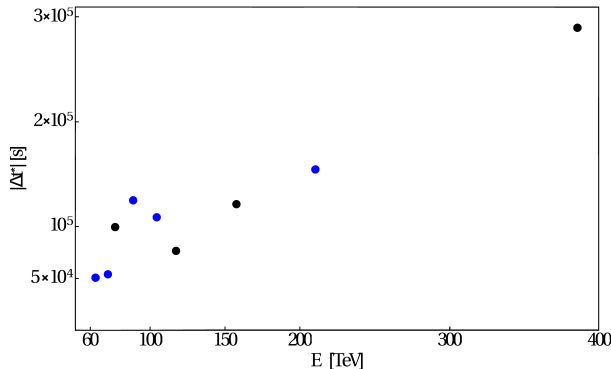


Fig. 1. The 9 neutrino points. Gray (blue)/black points are late/early neutrinos ( $\Delta t > 0/\Delta t < 0$ ). We rescale times as  $\Delta t^* = \Delta t D(1)/D(z)$  to avoid redshift dependence on the abscissa.

<sup>3</sup> Contrary to “track” events, for “shower” events we can reconstruct the neutrino energy.

of an effect of quantum-spacetime type, since a high correlation is possible only if the parameter  $\eta$  (and, to a lesser extent,  $\delta$ ) is different from zero. In particular, the case of neutrinos having the same absolute value of  $\eta$ , but some with positive and some with negative sign, seems to be favourite, as one can visually appreciate from Fig. 1. However, one has to be cautious, since the available data are still too few to jump to any conclusion. In particular, the role of background neutrinos in this kind of analysis needs to be further clarified [12]. As more data are going to be available soon, the statistical significance of the analysis will be improved and the survival of these effects will be put to the test.

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