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Quantum-Spacetime Perspective on the KM3-230213A Neutrino

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Abstract

The announcement of the KM3-230213A neutrino is generating a flood of astrophysics studies, mostly investigating its origin. We here focus on aspects of this observation that could be relevant for research programs on quantum gravity and spacetime quantization. It is at least amusing that KM3-230213A most likely traveled billions of light-years, but its rest-frame existence only lasted less than 0.1 seconds and ended with it being hit by a nucleon of Planckian energy. In addition, and perhaps more significantly, KM3-230213A is a remarkable probe of the types of microscopic structure of spacetime conjectured in some quantum-spacetime scenarios, and according to one of these scenarios, there is a candidate source: the gamma-ray burst GRB090401B observed 14 years earlier.

Keywords: quantum gravity; quantum spacetime; relativity

1. Introduction

The recently announced neutrino 230213A (KM3-230213A [1]) is perceived as an observation of rare significance for astrophysics, also because of the insight that could be gained if we managed to establish its origin. In this paper, we focus on other potential implications of 230213A in connection with results obtained in several proposed models (see, e.g., refs. [2–4]) of the gravity-induced quantum properties of spacetime. In particular, the quantum properties of spacetime could affect the laws of particle propagation by introducing corrections governed by the energy of the particle and by a characteristic scale M_{QG} expected to be within 1 or 2 orders of magnitude [5] of the Planck scale $M_P \equiv \sqrt{\hbar c^5/G} \sim 10^{16}$ TeV. We argue that the 230213A neutrino could play an important role in these quantum-spacetime studies, since its energy, estimated at $2.2 \cdot 10^5$ TeV (between 1.1×10^5 and 7.9×10^5 TeV at 68% confidence [1]), is about 100 times bigger than the previous neutrino-energy record.

In order to illustrate the significance of the 230213A neutrino for quantum-spacetime research, we focus on "in-vacuo dispersion", which is the most studied candidate quantum-gravity modification of particle propagation. As shown, e.g., in refs. [2,5–10] and references

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therein, several descriptions of spacetime quantization lead to in-vacuo dispersion (an alternative candidate origin of in-vacuo dispersion is provided by some dark-matter scenarios [11]). For what concerns its effects on particles observed from distant astrophysical sources, in-vacuo dispersion can be simply characterized as an excess contribution Δt to the travel time of the particles. At leading order in E/M_{QG}, it is given by [5,6,9,10,12,13]:

$$\Delta t = D(z)\frac{E}{M_{QG}}\,, \tag{1}$$

where E is the particle's energy and $D(z)$ is a function of the redshift z of the source emitting the particle:

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

(H_0 is the Hubble constant; Ω_Λ and Ω_m are the cosmological constant and matter densities [14]). If indeed M_{QG} is not much smaller than the Planck scale, the effects of (1) are essentially negligible on terrestrial scales but can produce tangible delays [5,6,10] for high-energy particles we observe from cosmologically distant astrophysical sources.

The paper is structured as follows. In Section 2, we briefly describe the observation of 230213A in its rest frame, pointing out how its peculiar properties might help address a difficult open problem in quantum-spacetime research. In Section 3, we relate the failure of previous searches for a transient source of the 230213A neutrino to a long-standing GRB-neutrino puzzle, discussing the potential relevance of the in vacuo dispersion hypothesis for both issues. In Section 4, we show that, assuming in vacuo dispersion, one indeed finds a candidate source for 230213A and discuss the implications of this surprising result for in vacuo dispersion studies. Finally, in Section 5, we offer some closing remarks.

2. Rest-Frame Description of the 230213A Observation

The neutrino-rest-frame description of the observation of 230213A is rather striking because of how its ultra-high energy $E \sim 2.2 \times 10^5$ TeV combines with the smallness of neutrino masses.

Assuming that 230213A had mass $m \sim 0.02$ eV, which is rather conservative in light of current upper bounds on neutrino masses [15], and that its journey was very long when measured in terms of the cosmic time t, say $\bar{t} \sim 10^{10}$ years (corresponding to a redshift $\bar{z} \sim 1.7$), one finds that 230213A's existence in its rest frame lasted no more than the following:

$$\bar{\tau} = \int_{-\bar{t}}^{0} \frac{d\tau}{dt}\,dt = \int_{\bar{a}}^{1} \frac{m}{p^0(a)}\frac{da}{aH(a)} = \frac{m}{E}\int_0^{\bar{z}} \frac{dz}{(1+z)^2 H_0\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}} \simeq 0.02\,\mathrm{s}\,.$$

The Hubble time H_0^{-1}, which sets the scale of the propagation time in an earthbound frame, gets completely suppressed by the huge factor $E/m \sim 1.1 \times 10^{19}$, which is by far the largest boost with respect to earthbound frames ever observed. Such a large boost has another consequence on the rest-frame description, which is rather fascinating from the point of view of quantum gravity. The 230213A neutrino was observed through its interaction with a nucleon in the Malta Escarpment, not far from the KM3NeT telescope (the muon produced in that collision was subsequently detected in the KM3NeT underwater facility [1]), and the energy of that nucleon, in the 230213A rest frame, is Planckian. In fact, a particle of energy 10^{-3} TeV in an earthbound reference frame has energy 1.1×10^{16} TeV ($\sim M_P$) in the 230213A rest frame.

The above observations could encourage future studies of propagation in quantum spacetime adopting the neutrino-rest-frame perspective, in which case it is the Planckian nucleon that propagates for about 0.02 seconds before hitting 230213A. This change of perspective is potentially very interesting because, while the propagation of a 100-PeV neutrino in an earthbound frame is expected to be only slightly affected by the quantum properties of spacetime, the propagation of a Planckian nucleon in the 230213A rest frame probes the full-quantum-gravity regime of the theory and requires going well beyond the leading-order corrections in E/M_{QG} provided so far by theoretical investigations set in earthbound frames [5,6,10]. In general, modeling exactly (to all orders in E/M_{QG}) particle propagation in a quantum spacetime is a daunting theoretical challenge, and very little progress has been made in this direction so far. In the particular 230213A scenario we are contemplating here, however, the availability of a robust leading-order description of the process in an earthbound frame, based on in vacuo dispersion as described by Equation (1), might provide some guidance and help shed light on Planckian propagation in the 230213A rest frame.

3. The Origin of 230213A, the GRB-Neutrino Puzzle, and In Vacuo Dispersion

The origin of 230213A is currently a complete mystery for astrophysicists and has attracted a lot of attention in recent studies. A priori, 230213A could either belong to the persistent isotropic astrophysical neutrino flux observed over the past 15 years by the IceCube observatory (made up of genuinely cosmogenic neutrinos as well as neutrinos coming from too distant and/or too faint sources to be individually resolved) or have been produced by some exceptional astrophysical transient. The first scenario, however, is considered very unlikely [1,16] in light of the bounds on the isotropic neutrino flux previously established by IceCube. As for transient sources, the natural candidates are blazars and GRBs (gamma-ray bursts), which are widely expected to have a sizable neutrino emission. However, blazars do not seem to have enough firepower to produce a neutrino with such a high energy [16,17]. A GRB origin, instead, would make perfect sense (see, e.g., ref. [18]), but no GRBs with direction compatible with that of 230213A were observed in good temporal coincidence with 230213A.

From the point of view of quantum-spacetime phenomenology, the absence of a GRB source candidate for 230213A can be related to a wider puzzle concerning GRB neutrinos of lower energies. Neutrinos in the range 50–2000 TeV have been observed by IceCube for more than a decade [19], and it is established that some of them were produced by blazars [20], but so far IceCube has not reported any neutrino in good directional and temporal coincidence with a GRB. This is puzzling since GRB models reliably predict a neutrino emission sufficient for IceCube to detect at least a few GRB neutrinos per year (see, e.g., ref. [21]). Of course, GRB models may need to be revised in such a way as to have a lower level of neutrino emission. However, it is also possible that IceCube is actually observing some GRB neutrinos but is currently unable to identify them as such. The existence of 230213A, which looks very much like a GRB neutrino but cannot be traced back to any GRB source, makes such an association-failure scenario more compelling. And in vacuo dispersion could easily explain the lack of GRB-neutrino associations so far. In fact, current searches of GRB neutrinos assume that the high-energy neutrinos should be observed in close temporal coincidence with the much-lower-energy gamma-ray transient, as required by standard propagation physics (at TeV energies and above, neutrinos should travel at nearly exactly the same speed as photons). For cosmological sources like GRBs ($z \gtrsim 1$) and typical astrophysical neutrino energies ($E \gtrsim 50$ TeV), though, Δt in Equation (1) would vary from several days to a few weeks even for a value of M_{QG} just below the Planck scale M_P, meaning that GRB neutrinos would be detected much later than the associated gamma rays.

Indeed, we tested GRB and IceCube data for in vacuo dispersion in a series of previous studies (see refs. [22,23], and references therein), obtaining preliminary but encouraging results summarized in Figure 1.

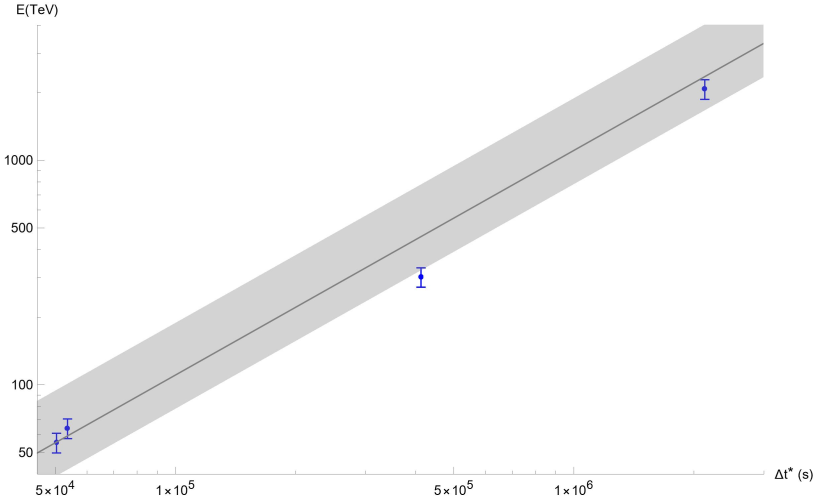

Figure 1. Here Δt^* is $\Delta t D(1)/D(z)$ (the factor $D(1)$ being introduced only to give Δt^* dimensions of time). Equation (1) predicts a linear relationship between Δt^* (computed using the redshift of the GRB and the Δt between neutrino and GRB) and E. The data points give Δt^* and E for four GRB-neutrino candidates found in IceCube data, while the gray band and the gray line reflect the properties of the search window motivated in ref. [22].

In all these studies, we analyzed IceCube neutrinos with energy between 50 and 2000 TeV classified as shower events. The restriction to shower events is motivated by the fact that the statistical approach we had been developing to establish the significance of GRB-neutrino associations is strongly based on consistency with the energy dependence predicted by Equation (1), and therefore requires the rather sharp (about 10% relative uncertainty) energy determination available for shower events (muon-mediated events, classified as track events, have substantially larger energy uncertainties). The gray band in Figure 1 reflects the search window motivated in ref. [22] and then used for the investigation reported in ref. [23], corresponding to values M_{QG} of order $0.1 M_P$ in Equation (1). The four points in Figure 1 represent the four GRB-neutrino candidates found by the analysis reported in ref. [23], i.e., four IceCube neutrinos in good directional agreement with a candidate GRB source whose time-of-observation offset is consistent with the time–energy search window given by the gray band in Figure 1. Δt^* is the time-of-observation difference between the neutrino and the associated GRB rescaled by $D(z)$, where z is the GRB redshift, while E is the neutrino energy; therefore, Equation (1) predicts a linear relationship between Δt^* and E, in good agreement with the content of Figure 1.

Of course, all four GRB-neutrino candidates of Figure 1 could be accidental: it might have happened that four IceCube neutrinos unrelated to GRBs accidentally had direction consistent with a GRB and also fell by chance within the time–energy search window highlighted in Figure 1. But, through dedicated simulations (see ref. [23] for details), we found that this occurs with rather small probability: the level of consistency between the four GRB-neutrino candidates and the in vacuo dispersion expectations encoded in Equation (1) is such that the overall significance of Figure 1 is 0.6% [23], still not good enough for any excitement, but evidently encouraging for the in vacuo dispersion hypothesis. Since with just four GRB-neutrino candidates we find significance at the 0.6% level, a large improvement in significance could be achieved by finding a few more such GRB-neutrino candidates.

4. In Vacuo Dispersion at the Highest Energies: A GRB Source for 230213A

From our previous discussion, it should be clear that extremely-high-energy neutrinos like 230213A may play a crucial role in validating the above in vacuo dispersion scenario, since there is reason to believe that they do actually come from GRB sources. If this is the case, the level of in vacuo dispersion favored by the four data points in Figure 1 would imply a delay of several years for a neutrino with energy 2.2×10^5 TeV. Accordingly, assuming in vacuo dispersion, one should expect to find a GRB source in good directional agreement with 230213A observed several years earlier than 230213A. This consideration motivated us, in a recent study reported in ref. [24], to search a list of all known-redshift GRBs observed over the last 30 years for GRBs in good directional agreement with the 230213A neutrino. The restriction to known-redshift events was dictated by the need to check the consistency of any candidate GRB source for 230213A with Equation (1), as directional compatibility, by itself, cannot provide evidence for in vacuo dispersion.

Much to our surprise, given the relatively small number of GRBs whose redshift has been measured (our list [23], to date the most comprehensive of its kind, contains 652 GRBs out of more than 3800 well-localized GRBs observed in the same timeframe [25,26]), we indeed found a candidate source: GRB090401B [27,28], whose remarkable directional agreement with 230213A is characterized visually in Figure 2. GRB090401B was produced by the collapse of a massive star at redshift 3.1 [27,28] and was observed about 4.38×10^8 s (about 14 years) earlier than the 230213A neutrino. The significance of this finding can be quantified by computing the associated probability of chance alignment, i.e., the probability that 230213A and an unrelated known-redshift GRB happen to be observed in such a directional agreement as shown in Figure 2. By appropriately simulating the GRB background, one finds [24] that the probability of chance alignment is 5.5%, corresponding to a 1.9σ significance in Gaussian statistics.

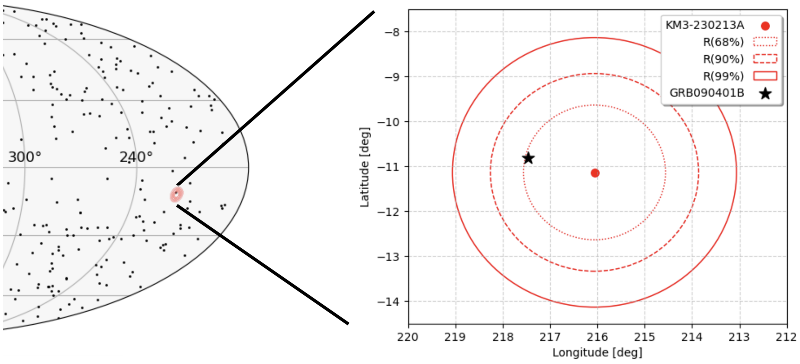

Figure 2. An assessment in galactic coordinates of the directional compatibility between GRB090401B and 230213A. On the left, the dots represent GRBs of known redshift and the red circle reflects the experimental information on the direction of 230213A [1] (the dot inside the red circle is for GRB090401B). The right side quantifies visually the directional compatibility between GRB090401B and 230213A.

Having found a candidate GRB source with the expected properties, we took the next natural step of checking how well the GRB090401B-230213A pair fits in the specific in vacuo dispersion scenario emerging from our previous analysis of lower-energy IceCube neutrinos, summarized in Figure 1. Our findings on this aspect are visualized in Figure 3, which clearly shows that a GRB090401B origin for the 230213A neutrino is definitely a possibility if the in vacuo dispersion scale M_{QG} is of order $0.1 M_P$. To substantiate this visual intuition, we quantified the agreement of the GRB090401B-230213A pair with our previous time–energy search window (see ref. [24] for details) and recomputed the probability of chance alignment with the additional requirement that the GRB-230213A pair is found in a comparable agreement with the gray band. The resulting value of 1.5% (2.4σ in Gaussian statistics) [24] considerably improves on the purely directional significance found above, meaning that, despite the large energy uncertainty associated with the 230213A neutrino (well visible in Figure 3), its level of consistency with our previous analysis is not typical.

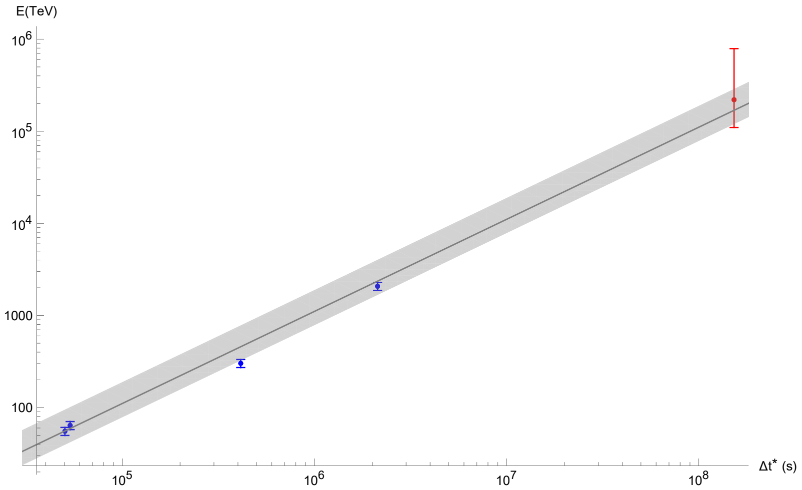

Figure 3. Here Δt^* and the gray band are defined as in Figure 1. The four lower-energy (blue) data points, already shown in Figure 1, represent the GRB-neutrino candidates highlighted in ref. [23]. The (red) data point with the highest energy represents the pair composed of GRB090401B and the 230213A neutrino.

As hinted at at the end of Section 3, it would be desirable to include the GRB090401B-230213A pair as a fifth GRB-neutrino candidate in the analysis reported in ref. [23], so as to strengthen our preliminary evidence of in vacuo dispersion. Unfortunately, we are presently unable to attribute an overall significance to the five data points in Figure 3, because, as already stressed above, the statistical approach we introduced in ref. [23] is only applicable to data points with a small energy uncertainty, i.e., to shower-event neutrinos, whereas 230213A is a track-event neutrino with a very large energy uncertainty.

Work aimed at consistently estimating the statistical significance of a sample comprising both shower-event and track-event GRB-neutrino candidates should evidently be a priority for this research program. That new methodology will be a crucial step for empowering in vacuo dispersion studies, especially when a few other ultra-high-energy track-event neutrinos like 230213A are observed. In this respect, there is a particularly amusing hypothetical scenario that can be contemplated, which would provide very strong evidence of in vacuo dispersion: the observation within a few years of a neutrino with energy 20% or 30% higher than 230213A and direction once again compatible with the direction of GRB090401B.

5. Conclusions

Only time will tell if additional neutrino observations can transform the very preliminary evidence here reported into a groundbreaking discovery. Even setting aside that most optimistic scenario, it is clear that the observation of the 230213A neutrino, since it marks the onset of a much higher energy window for neutrino astrophysics, will completely reshape the horizon of investigations of quantum-gravity-induced in vacuo dispersion for neutrinos. This is not a new research area, but it had been dormant for a long time: the current bound on in vacuo dispersion for neutrinos is still based on the historic observation of neutrinos from the SN1987a supernova and only amounts to $M_{QG} > 2.7 \times 10^7$ TeV [29].

Instead, limits on in vacuo dispersion for photons have been progressing at a steady pace, especially over the last 15 years (see, e.g., ref. [5] and references therein). The mismatch between the in vacuo dispersion sensitivities achieved so far for photons and neutrinos is particularly significant in light of the fact that there are quantum-spacetime models predicting very different in vacuo dispersion properties for photons and neutrinos [2,3,8,30]. The advent of the astrophysics of ultra-high-energy neutrinos, like 230213A, will surely have a very positive impact on this issue: if no discovery is made, the bound on in vacuo dispersion for neutrinos could be improved by more than 12 orders of magnitude, since, for example, for a neutrino of energy 10^5 TeV from a GRB at a typical redshift of 2, one could probe up to $M_{QG} \sim 10^{20}$ TeV.

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