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KM3NeT constraint on Lorentz-violating superluminal neutrino velocity

The KM3NeT Collaboration[1]*

Lorentz invariance is a fundamental symmetry of spacetime and foundational to modern physics. One of its most important consequences is the constancy of the speed of light. This invariance, together with the geometry of spacetime, implies that no particle can move faster than the speed of light. In this article, we present the most stringent neutrino-based test of this prediction, using the highest-energy neutrino ever detected to date, KM3-230213A. If we assume an extragalactic source as the origin, the arrival of this event, with an energy of 220^{+570}_{-110} PeV, sets a constraint on $\delta \equiv c_\nu^2 - 1 < 4.2^{+9.2}_{-3.7} \times 10^{-22}$.

Lorentz invariance, which states that physical phenomena look the same for all inertial observers, is a key component underlying the Standard Model of particle physics. Lorentz invariance *violation* (LIV), while so far unobserved, is predicted by models of quantum gravity[1–3] which are parametrized by effective field theories such as the Standard Model Extension (SME)[4–7].

Since an observation of LIV would provide compelling evidence of such new physics, it has experimentally been tested in various ways: for example, using electronic transitions[8], gamma-ray bursts[9], high-energy neutrino oscillations[10], and top quark production at colliders[11].

Lorentz invariance also predicts the constancy of the speed of light and, therefore, that the speed of light in vacuum is the upper bound on the speed of any massive particle; if one is found to be superluminal, that would unambiguously indicate LIV. As such, superluminality has been probed with particles such as electrons and cosmic rays[12–15]. Neutrinos, as the lightest known massive particles, can provide another probe of LIV as they propagate. Several experimental searches for superluminal neutrino propagation have been performed, for instance, at OPERA[16] and MINOS[17,18]; while conclusive evidences of superluminal propagation, and therefore LIV, has not been observed, limits have been set.

We characterize superluminal propagation[19,20] by a parameter

$$\delta \equiv c_\nu^2 - 1,$$

where c_ν is the neutrino speed in units of the speed of light. Note that in our definition, δ is consistent with the definition in refs. 15,19 but twice that of the definition used in ref. 21. A superluminal neutrino rapidly loses energy primarily via the process of pair emission of electrons $\nu \to \nu + e^+ + e^-$[19,20,22]. In this work, we assume that the electron is not also superluminal, which has been independently constrained in, for instance, ref. 14. The calculation of the decay width $\Gamma = \Gamma(E, \delta)$, where E is the neutrino energy, is presented in refs. 19,20 and used, for instance, in ref. 21 to set a limit on δ. It is generally possible to set a limit on δ using any neutrino if we know its energy and propagated distance. Astrophysical neutrinos, which are neutrinos originating from outside the Solar System, are uniquely useful for this purpose because they arrive at high energies and from long distances, both of which serve to competitively constrain the size of the LIV effect, via the δ parameter. Indeed, there have been many previous efforts using astrophysical neutrinos to constrain LIV; see, for example, refs. 22–32.

KM3NeT[33] is a research infrastructure comprising two detector arrays in the Mediterranean Sea which, among other scientific aims, is being built to detect such astrophysical neutrinos. The larger detector array is known as Astroparticle Research with Cosmics in the Abyss (ARCA). Using photodetectors, ARCA is able to detect the Cherenkov light induced by the passage of relativistic charged particles produced in neutrino interactions; based on the timing, sensor position, and amount of light collected, ARCA can reconstruct its energy and direction. Moreover, ARCA can reconstruct different event morphologies, discriminating primarily between muons and particle showers. It offers the ability to measure the particle types and flavours of neutrino interactions. Recently, ARCA observed a muon indicative of an ultra-high-energy (UHE) neutrino event, termed KM3-230213A[34], with an estimated neutrino energy

$$E_{\mathrm{UHE}} = 220^{+570}_{-110}\ \mathrm{PeV}\,,$$

which is the highest-energy neutrino ever observed to date. In particular, for KM3-230213A, a median muon energy of 120 PeV is reconstructed by observing the number of triggered photodetectors, and comparing the observation to Monte Carlo simulations of similar high-energy muons. To translate this muon energy to a neutrino energy, Monte Carlo simulations of neutrinos with an E^{-2} energy spectrum producing a muon of 120 PeV, are generated; E_{UHE} is the median energy of these simulated neutrinos. For details, see ref. 34. The minimum neutrino energy is the reconstructed muon energy of 120 PeV; this conservative bound still leads to limits with the same order of magnitude as those assuming the median neutrino energy E_{UHE}. While the source of KM3-230213A is not yet known, its high energy and

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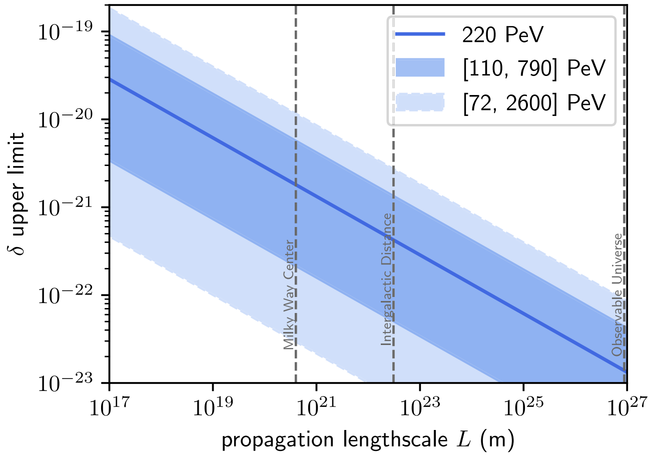

Fig. 1 | Upper limits. We plot the value of δ scanning over a wide range of L assuming we hold the energy constant at E_{UHE}. The bands correspond to the 68% and 90% confidence intervals in the energy estimation of KM3-230213A[34]. We also indicate in the vertical dashed lines some length scales of interest: the size of the Milky Way, intergalactic distances (1 Mpc), and the size of the observable Universe.

likely extragalactic[34,35] ($L \geq$ 1Mpc) nature, assuming an astrophysical source as the origin, already allows us to set a strong constraint on δ. In this work, we find that in a likely scenario, $\delta < 4.2^{+9.2}_{-3.7} \times 10^{-22}$, further reducing the parameter space in which LIV can exist.

Results and discussion

We evaluate the limit on δ using the procedure described in ref. 20. First, we calculate the decay width Γ as given in ref. 19 and determine a decay length c_ν/Γ. The width has a strong energy dependence, $\Gamma(E, \delta) \propto E^5\delta^3$, which can be estimated from dimensional analysis as done in ref. 19 or obtained via a full matrix element calculation as done in ref. 20. Secondly, we consider the propagated distance L as ten times the decay length, $L = 10c_\nu/\Gamma$. The choice of ten decay lengths is purely conventional, as done in ref. 20, but also conservative - assuming fewer decay lengths travelled for the same L will yield more stringent limits on δ. Finally, we compute the δ which is required to produce this L value at a fixed energy E_{UHE}. The result of this calculation, scanning over a wide range of L, is shown in Fig. 1.

Conservatively taking the minimum distance travelled to be of Galactic scale, which means $L \approx 4 \times 10^{20}$ m, around the radius of the Milky Way, we can set the limit

$$\delta < 1.8^{+3.9}_{-1.7} \times 10^{-21},$$

where the range stems from the 68% confidence interval in the energy measurement[34].

Given the event direction[35], a more likely scenario would be an intergalactic lengthscale, $L \approx$ 1Mpc, which results in the limit

$$\delta < 4.2^{+9.2}_{-3.7} \times 10^{-22}.$$

To place this into context, we can cast a limit on δ in terms of a minimal $d = 4$ SME parameter $\mathring{c}^{(4)}$[7,36] if we assume the isotropic limit and the rest frame of the cosmic microwave background (CMB), as discussed in ref. 36. The relation is straightforward, $\delta/2 = -\mathring{c}^{(4)}$, yielding the limit

$$\mathring{c}^{(4)} > -2.1^{+1.9}_{-4.6} \times 10^{-22}$$

which can be compared to other limits, for instance, in table D34 of ref. 7. We emphasize that the assumption of an isotropic frame here is a simplifying assumption; in general, LIV will be anisotropic in most inertial reference frames. For details, see ref. 36.

Table 1 | A comparison of various limits on δ set with the same method of using 10 decay lengths

Method	Energy scale	Limit on δ
IceCube TXS 0506+056	~290 TeV	2.4×10^{-18}
Stecker et al. (ref. 21)	60TeV-2 PeV	$2 \times 5.2 \times 10^{-21}$
KM3-230213A (conservative)	~220 PeV	1.8×10^{-21}
KM3-230213A (extragalactic)	~220 PeV	4.2×10^{-22}

The exception is the limit set by ref. 21, which is detailed in that respective work; the factor of 2 accounts for the difference in the definitions of δ. Limits here are obtained assuming that the electron is not superluminal. For context, we have also included the energy scale used to set these limits.

In Table 1 we show the upper limits on δ, calculated using the same method described above, for other high-energy events and baselines of note. In particular, we consider the best values obtained using IceCube observations of TXS 0506+056[37,38].

Competitive limits of around $10^{-18}-10^{-20}$ have also been obtained with more sophisticated methods such as in refs. 14,21,29. For comparison in Table 1, we also show the most competitive limit, from ref. 21, for which a Monte Carlo approach is used to model spectral distortions in neutrino observations. This approach is more dependent on the astrophysical flux modelling compared to our method.

As done in ref. 19, there is also the possibility of setting a limit using a defined terminal energy, which is the energy scale after which significant losses do not occur. We have confirmed that this method yields a similar limit to within one order of magnitude: $\delta < 2.6 \times 10^{-22}$ at E_{UHE} for the likely extragalactic scenario.

The effect of cosmological redshift can also be considered, which manifests as an effective energy loss that contributes in addition to the pair emission. If we assume that the neutrino source distribution follows the star formation rate, which peaks at redshift of a few z[39], this represents a $\mathcal{O}(1)$ factor of energy loss and will not have a significant effect that competes with the electron pair emission on intergalactic distances. If we assume larger redshifts from even more distant sources, ignoring this additional energy loss effect in the calculation of our δ limit renders it more conservative.

Finally, the criteria for the primary energy loss mechanism, electron pair emission, is energy-dependent. A superluminal neutrino behaves as a particle with an effective mass $E\sqrt{\delta}$; therefore, the energy E of the neutrino must satisfy $E > 2m_e/\sqrt{\delta}$ for pair emission to be possible, where m_e is the electron mass. Therefore, as δ is constrained to be successively smaller, we approach the regime where pair emission may require arbitrarily high neutrino energies, and this mechanism cannot be used to further constrain δ. For instance, already at $\delta = 10^{-22}$ we require $E > 100$ PeV, where E is the energy at which the neutrino decays, necessarily higher than the energy E_{UHE} at detection (which is assumed in Fig. 1). Despite this limitation, observable effects, such as distortions in cosmogenic neutrino energy spectra, may still be expected and used to set even tighter limits at ultra-high energies[40].

Conclusion

We report on a limit on the LIV parameter δ (and SME parameter $\mathring{c}^{(4)}$) using KM3-230213A, the most energetic neutrino ever detected to date. Our result, to our knowledge, improves upon the current best limits by one order of magnitude, while making minimal and conservative assumptions about the origin of the neutrino.

Repeated searches for LIV, and corresponding limits set, serve as a critical, ongoing, test of one of the cornerstones of modern physics. At the fundamental level, an observation of LIV would change our understanding of causality and spacetime structure, and permit models of quantum gravity that predict LIV[1,4–7]. At the more phenomenological level, LIV could affect well-known phenomena like the GZK cutoff[41], and the neutrino dispersion relation. These possibilities clearly warrant a comprehensive search for LIV;

to this end, our limit shows that Lorentz invariance is, so far, on solid ground – and that avenues for LIV to occur are shrinking.

Given electron pair emission in vacuum as the primary energy loss mechanism, our constraints cannot be significantly improved upon using this method without detecting a neutrino of significantly higher energy, or relieving some of our conservative assumptions. The competitiveness of our limit highlights the growing role that UHE neutrinos, and neutrino telescopes, can play in testing fundamental symmetries.

Data availability

The data required to reproduce the results in this work consists of the energy of KM3-230213A, which is detailed in ref. 34.

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References

1. Li, C. & Ma, B.-Q. Lorentz and CPT breaking in gamma-ray burst neutrinos from string theory. *JHEP* **03**, 230 (2023).
2. Jacob, U. & Piran, T. Neutrinos from gamma-ray bursts as a tool to explore quantum-gravity-induced Lorentz violation. *Nat. Phys.* **3**, 87–90 (2007).
3. Amelino-Camelia, G. & Smolin, L. Prospects for constraining quantum gravity dispersion with near-term observations. *Phys. Rev. D.* **80**, 084017 (2009).
4. Colladay, D. & Kostelecky, V. A. CPT violation and the standard model. *Phys. Rev. D.* **55**, 6760–6774 (1997).
5. Kostelecky, V. A. Gravity, Lorentz violation, and the standard model. *Phys. Rev. D.* **69**, 105009 (2004).
6. Colladay, D. & Kostelecky, V. A. Lorentz violating extension of the standard model. *Phys. Rev. D.* **58**, 116002 (1998).
7. Kostelecky, V. A. & Russell, N. Data tables for Lorentz and CPT Violation. *Rev. Mod. Phys.* **83**, 11–31 (2011).
8. Hohensee, M. A. et al. Limits on violations of Lorentz Symmetry and the Einstein equivalence principle using radio-frequency Spectroscopy of Atomic Dysprosium. *Phys. Rev. Lett.* **111**, 050401 (2013).
9. Chen, M., Pan, Y., Liu, T. & Cao, S. New Constraints on Lorentz Invariance Violation at High Redshifts from Multiband of GRBs (2024). 2412.07625.
10. Aartsen, M. G. et al. Neutrino interferometry for high-precision tests of Lorentz symmetry with IceCube. *Nat. Phys.* **14**, 961–966 (2018).
11. Hayrapetyan, A. et al. Searches for violation of Lorentz invariance in top quark pair production using dilepton events in 13 TeV proton-proton collisions. *Phys. Lett. B* **857**, 138979 (2024).
12. Jacobson, T., Liberati, S. & Mattingly, D. A Strong astrophysical constraint on the violation of special relativity by quantum gravity. *Nature* **424**, 1019–1021 (2003).
13. Coleman, S. R. & Glashow, S. L. Cosmic ray and neutrino tests of special relativity. *Phys. Lett. B* **405**, 249–252 (1997).
14. Stecker, F. W. Limiting superluminal electron and neutrino velocities using the 2010 Crab Nebula flare and the IceCube PeV neutrino events. *Astropart. Phys.* **56**, 16–18 (2014).
15. Coleman, S. R. & Glashow, S. L. High-energy tests of Lorentz invariance. *Phys. Rev. D.* **59**, 116008 (1999).
16. Adam, T. et al. Measurement of the neutrino velocity with the OPERA detector in the CNGS beam using the 2012 dedicated data. *JHEP* **01**, 153 (2013).
17. Adamson, P. et al. Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam. *Phys. Rev. D.* **76**, 072005 (2007).
18. Adamson, P. et al. Precision measurement of the speed of propagation of neutrinos using the MINOS detectors. *Phys. Rev. D.* **92**, 052005 (2015).
19. Cohen, A. G. & Glashow, S. L. Pair creation constrains superluminal neutrino propagation. *Phys. Rev. Lett.* **107**, 181803 (2011).
20. Huo, Y., Li, T., Liao, Y., Nanopoulos, D. V. & Qi, Y. Constraints on Neutrino velocities revisited. *Phys. Rev. D.* **85**, 034022 (2012).
21. Stecker, F. W. & Scully, S. T. Propagation of Superluminal PeV IceCube Neutrinos: A high energy spectral cutoff or new constraints on lorentz invariance violation. *Phys. Rev. D.* **90**, 043012 (2014).
22. Stecker, F. W., Scully, S. T., Liberati, S. & Mattingly, D. Searching for traces of Planck-Scale Physics with high energy neutrinos. *Phys. Rev. D.* **91**, 045009 (2015).
23. Laha, R. Constraints on neutrino speed, weak equivalence principle violation, Lorentz invariance violation, and dual lensing from the first high-energy astrophysical neutrino source TXS 0506+056. *Phys. Rev. D.* **100**, 103002 (2019).
24. Boran, S., Desai, S. & Kahya, E. O. Constraints on differential Shapiro delay between neutrinos and photons from IceCube-170922A. *Eur. Phys. J. C.* **79**, 185 (2019).
25. Ellis, J., Mavromatos, N. E., Sakharov, A. S. & Sarkisyan-Grinbaum, E. K. Limits on Neutrino Lorentz violation from multimessenger observations of TXS 0506+056. *Phys. Lett. B* **789**, 352–355 (2019).
26. Wei, J.-J. et al. Multimessenger tests of Einstein's weak equivalence principle and Lorentz invariance with a high-energy neutrino from a flaring blazar. *JHEAp* **22**, 1–4 (2019).
27. Argüelles, C. A., Katori, T. & Salvado, J. New physics in astrophysical neutrino flavor. *Phys. Rev. Lett.* **115**, 161303 (2015).
28. Abbasi, R. et al. Search for quantum gravity using astrophysical neutrino flavour with IceCube. *Nat. Phys.* **18**, 1287–1292 (2022).
29. Borriello, E., Chakraborty, S., Mirizzi, A. & Serpico, P. D. Stringent constraint on neutrino Lorentz-invariance violation from the two IceCube PeV neutrinos. *Phys. Rev. D.* **87**, 116009 (2013).
30. Zhang, X. & Ma, B.-Q. Testing Lorentz invariance and CPT symmetry using gamma-ray burst neutrinos. *Phys. Rev. D.* **99**, 043013 (2019).
31. Huang, Y. & Ma, B.-Q. Lorentz violation from gamma-ray burst neutrinos. *Commun. Phys.* **1**, 62 (2018).
32. Amelino-Camelia, G., Guetta, D. & Piran, T. Icecube Neutrinos and Lorentz invariance violation. *Astrophys. J.* **806**, 269 (2015).
33. Adrian-Martinez, S. et al. Letter of intent for KM3NeT 2.0. *J. Phys. G* **43**, 084001 (2016).
34. Aiello, S. et al. Observation of an ultra-high-energy cosmic neutrino with KM3NeT. *Nature* **638**, 376–382 (2025).
35. Adriani, O. et al. On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A (2025). 2502.08387.
36. Diaz, J. S., Kostelecky, A. & Mewes, M. Testing relativity with high-energy astrophysical neutrinos. *Phys. Rev. D.* **89**, 043005 (2014).
37. Wang, K. et al. Limiting superluminal neutrino velocity and lorentz invariance violation by neutrino emission from the Blazar TXS 0506+056. *Phys. Rev. D.* **102**, 063027 (2020).
38. Aartsen, M. G. et al. Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert. *Science* **361**, 147–151 (2018).
39. Behroozi, P. S., Wechsler, R. H. & Conroy, C. The average star formation histories of galaxies in dark matter Halos from z=0–8. *Astrophys. J.* **770**, 57 (2013).
40. Gorham, P. W. et al. Implications of ultra-high energy neutrino flux constraints for Lorentz-invariance violating cosmogenic neutrinos. *Phys. Rev. D.* **86**, 103006 (2012).
41. Gonzalez-Mestres, L. Lorentz symmetry violation, vacuum and superluminal particles (1997). physics/9709006.

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Author contributions

This work is the result of all the institutes and authors of the KM3NeT Collaboration. Their contributions include designing, constructing, and operating the detector, collecting the data, performing simulations, conducting data analysis, and discussing the results. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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