Limits on Neutrino Lorentz Violation from Multimessenger Observations of TXS 0506+056

John Ellis\textsuperscript{a,b,c}, Nikolaos E. Mavromatos\textsuperscript{a,d}, Alexander S. Sakharov\textsuperscript{e,f}, Edward K. Sarkisyan-Grinbaum\textsuperscript{f,g},

\textsuperscript{a}Theoretical Particle Physics and Cosmology Group, Physics Department
King’s College London, Strand, London WC2R 2LS, United Kingdom
\textsuperscript{b}Theoretical Physics Department, CERN, CH-1211 Genève 23, Switzerland
\textsuperscript{c}NICPB, Rėvala pst. 10, 10143 Tallinn, Estonia
\textsuperscript{d}Currently also at: Department of Theoretical Physics and IFIC, University of Valencia - CSIC, Valencia, E-46100, Spain
\textsuperscript{e}Physics Department, Manhattan College
4513 Manhattan College Parkway, Riverdale, NY 10471, United States of America
\textsuperscript{f}Experimental Physics Department, CERN, CH-1211 Genève 23, Switzerland
\textsuperscript{g}Department of Physics, The University of Texas at Arlington
502 Yates Street, Box 19059, Arlington, TX 76019, United States of America

Abstract

The observation by the IceCube Collaboration of a high-energy ($E \gtrsim 200$ TeV) neutrino from the direction of the blazar TXS 0506+056 and the coincident observations of enhanced γ-ray emissions from the same object by MAGIC and other experiments can be used to set stringent constraints on Lorentz violation in the propagation of neutrinos that is linear in the neutrino energy: $\Delta v = -E/M_1$, where $\Delta v$ is the deviation from the velocity of light, and $M_1$ is an unknown high energy scale to be constrained by experiment. Allowing for a difference in neutrino and photon propagation times of $\sim 10$ days, we find that $M_1 \gtrsim 3 \times 10^{16}$ GeV. This improves on previous limits on linear Lorentz violation in neutrino propagation by many orders of magnitude, and the same is true for quadratic Lorentz violation.
It is desirable to probe fundamental physical principles as sensitively as possible, and Lorentz invariance is no exception. Specifically, one may ask how accurately we know that different species of massless particles travel at the speed of light, and how accurately we know that massive particles travel at the same speed in the high-energy limit. Over the past two decades, since the publication of [1], considerable effort has been put into constraining different forms of Lorentz violation, and specifically a linear coefficient $M_1$ in the velocity $v$ of energetic photons: $\Delta v = -E/M_1$, using distant time-dependent astrophysical sources of energetic photons such as pulsars, gamma-ray bursts (GRBs) and active galactic nuclei (AGNs). However, analyses of possible Lorentz violation in photon propagation have been beset by difficulties in disentangling intrinsic time delays in the sources from time delays accumulated during propagation, and we consider that the strongest robust limit on $M_1$ for photons is between $10^{17}$ and $10^{18}$ GeV [2]. There have also been analyses of possible Lorentz violation in neutrino propagation from Supernova 1987A and in a terrestrial neutrino beam, but these are sensitive only to $M_1 \sim 2 \times 10^{11}$ GeV and potentially $\sim 4 \times 10^8$ GeV, respectively [3]. More recently, data on the first observed black-hole binary merger [4] were used to set the much weaker limit $M_1 \gtrsim 100$ keV for graviton propagation [5], and the near-coincidence of gravitational waves and $\gamma$-rays from a neutron-star binary merger has been used to establish that their velocities are the same to within $\sim 10^{-17}$ [6].

Very recently, the IceCube Collaboration has reported the observation of an ultra-high-energy neutrino from the direction of the blazar TXS 0506+056, and together with a number of other groups, most notably the MAGIC Collaboration, have reported [7] an enhanced level of activity in $\gamma$-ray and photon emission from this source, which is located at a distance $\sim 4 \times 10^9$ ly. As we discuss in this paper, the great distance of TXS 0506+056 and the high energy $\gtrsim 200$ TeV of the observed high-energy neutrino, in conjunction with the $\gamma$-ray observations, provides unique sensitivity to Lorentz violation in neutrino propagation, which almost rivals that to linear Lorentz violation in photon propagation. The sensitivity to linear Lorentz violation in neutrino propagation is to $M_1 \gtrsim 3 \times 10^{16}$ GeV, approaching the Planck energy scale that might be characteristic of the possible quantum-gravity effects that were the original motivation for [1].

We first review the observations of TXS 0506+056 reported by the IceCube Collaboration and the teams studying its electromagnetic emissions [7]. The primary observation by IceCube was that of a single neutrino with energy $\sim 290$ TeV (90% CL lower limit 183 TeV) on 22 September 2017, dubbed IceCube-170922A, coming from a direction within $0.1^\circ$ of the catalogued $\gamma$-ray source TXS 0506+056, whose redshift $z = 0.3365 \pm 0.0010$. Several $\gamma$-ray experiments, notably MAGIC, VERITAS, HESS,
Fermi-LAT, AGILE and Swift made observations showing that TXS 0506+056 was in a flaring state over a period within about 10 days of IceCube-170922A [7]. The IceCube Collaboration has also reported an excess of neutrinos observed earlier from the direction of TXS 0506+056, confirming this as the source of IceCube-170922A [8], and analyses have supported the hypothesis that a single astrophysical mechanism is responsible for emitting both the neutrino and the $\gamma$-rays [9].

The similarity in arrival times of IceCube-170922A and the electromagnetic emissions can be used immediately to estimate the corresponding sensitivity to a difference $\Delta v_{\nu\gamma}$ in the propagation speeds in vacuo of the neutrino and photons, assuming that both speeds are independent of energy. We assume a distance of $4 \times 10^9$ ly and an illustrative time difference of 10 days [1] so that $\Delta v_{\nu\gamma}/c \sim 10 \text{ days}/4 \times 10^9 \text{ years} \sim 10^{-11}$ [2]. This is six orders of magnitude worse than the corresponding constraint on the difference in propagation speeds of gravitational waves and photons derived from the near-simultaneous observations of the binary neutron-star merger: $\Delta v_{\text{GW}\gamma} \lesssim 10^{-17}$ [6]. However, it is much better than the corresponding sensitivity to an energy-independent $\Delta v_{\nu\gamma}$ from the observations of neutrinos emitted during the collapse of supernova 1987A: $\Delta v_{\nu\gamma} \lesssim 4 \text{ hours}/1.5 \times 10^5 \text{ years} \sim 3 \times 10^{-9}$.

An energy-independent difference between the velocities of neutrinos (or gravitational waves) and photons would require the extremely radical step of abandoning the framework of special relativity. A less radical hypothesis would be that Lorentz invariance is an emergent symmetry in the low-energy limit, but is subject to modification that increases with energy. This is indeed the suggestion that has been made in a number of different theoretical frameworks, including the ‘space-time foam’ expected in models of quantum gravity [10], phenomenological models suggested by features of cosmic-ray physics [11] and other considerations [12], the suggestion that Lorentz invariance may be broken spontaneously [13, 14], models of loop quantum gravity [15], doubly-special relativity theories [16] and quantum field theories of the Lifshitz type [17]. In such frameworks, Lorentz invariance is a good symmetry in the low-energy limit, but is violated increasingly at high energies.

The first such possibility that we consider is that $\Delta v_{\nu\gamma}$ increases linearly with energy:

$$\Delta v_{\nu\gamma} = -E/M_1.$$  

The possibility of such a linear violation of Lorentz invariance was raised in [1] on the basis of intuition about the properties of space-time foam suggested

---

1Since the redshift of TXS 0506+056 is not very large, and the estimates of $\Delta t$ and the energy of are not very accurate, we do not include effects associated with the expansion of the Universe during propagation.

2Henceforth, we use natural units in which the conventional velocity of light $c = 1$.

3Constraints on Čerenkov radiation in vacuo require $\Delta v < 0$, as expected in the model of [18].
by a heuristic string-inspired model of quantum-gravitational fluctuations in space-time. In such a case, one’s first guess could be that \( M_1 \) would be comparable to the Planck mass: \( M_1 \sim M_P \simeq 10^{19} \) GeV. However, the value of \( M_1 \) would depend in a string-inspired model on unknown quantities such as the string coupling, the density of defects in space-time, and the strength of particle interactions with such defects, which may not be universal between different particle species \cite{19}, so we maintain phenomenological open minds about the possible magnitude of \( M_1 \). The model of space-time foam proposed in \cite{18} would suggest that the velocities of neutrinos would deviate from the low-energy velocity of light less than photons, so that (in an obvious notation) \( M_{1,\nu} \gg M_{1,\gamma} \), because the photon would have stronger interactions with the space-time defects. This is because, in such a stringy model of space-time foam, only species that carry no non-trivial quantum numbers under the standard model group have unsuppressed interactions with the foam, in which case the fact that neutrinos are fermions with non-trivial SU(2)\( _L \) properties renders space-time foamy effects invisible to them. However, initially we will be agnostic whether the photon velocity or the neutrino velocity deviates more from the low-energy velocity of light. When they are comparable, \( M_1 = (M_{1,\gamma} \times M_{1,\nu})/(M_{1,\gamma} - M_{1,\nu}) \), but when there is a hierarchy between them, \( M_1 \rightarrow \) the smaller of \( M_{1,\gamma} \) and \( M_{1,\nu} \).

We recall that a difference in velocity \( \Delta v = -E/M_1 \) induces a difference in arrival time \( \Delta t = \Delta v \times D = (E \times D)/M_1 \), where \( D \) is the propagation distance. For our numerical purposes, we assume the value \( E_\nu = 200 \) TeV for the energy of the event IceCube-170922A \cite{7}, and note that the energies of the \( \gamma \)-rays measured by MAGIC and other experiments are negligible in comparison. A simple order-of-magnitude estimate then yields a sensitivity to

\[
M_1 \gtrsim \frac{H_0^{-1} E}{\Delta t} \int_0^{z_{src}} \frac{(1 + z)}{\sqrt{\Omega_\Lambda + \Omega_M (1 + z)^3}} dz \approx 3 \times 10^{16} \text{ GeV},
\]

which is over 6 orders of magnitude stronger than the limit obtained previously \cite{3} from an analysis of the neutrino signal from supernova 1987A\footnote{In calculating \( \text{(1)} \) we used the standard cosmological \( \Lambda \)CDM model with dark energy and dark matter contributions \( \Omega_\Lambda = 0.7 \) and \( \Omega_M = 0.3 \), respectively, and Hubble expansion rate \( H_0 = 68 \text{ km/s/Mpc} \). See \cite{2} for detailed derivation of \( \text{(1)} \).} The sensitivity \( \text{(1)} \) is, nevertheless, an order of magnitude weaker than the robust limit on photon Lorentz violation \cite{2}, so refers directly to the neutrino.

It is instructive also to compare the sensitivity \( \text{(1)} \) to the possible improvement in the supernova limit, should another core-collapse supernova be observed in our galaxy. Multi-dimensional simulations of such events suggest that their neutrino emissions might
exhibit time variations in the millisecond range, in which case measurements might attain a sensitivity to \( M_1 \sim 2 \times 10^{13} \) GeV \(^2\) [20], still 3 orders of magnitude less than the IceCube-170922A/MAGIC sensitivity [1]. This sensitivity is also far beyond that we can envisage using a terrestrial neutrino beam. It was estimated using the timing capabilities of the OPERA detector and assuming that timing information could be available for neutrino events upstream in rock that a sensitivity to \( M_1 \sim 4 \times 10^8 \) GeV could be attained [3]. Thus the IceCube-170922A/MAGIC sensitivity seems to outclass the capabilities of terrestrial experiments as well as possible future supernova observations.

One can also consider a possible quadratic violation of Lorentz invariance: \( \Delta v = -E^2/M_2^2 \), which would be an option in some of the alternative models of Lorentz violation mentioned above [11–15,17]. In this case, the IceCube-170922A/MAGIC sensitivity would be to

\[
M_2 \gtrsim \left[ \frac{3H_0^{-1}}{2\Delta t} E^2 \int_0^{z_{\text{src}}} \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \right]^{1/2} \approx 10^{11} \text{ GeV} \tag{2}
\]

which is over 5 orders of magnitude stronger than the corresponding limit from supernova 1987A [3]. In the case of quadratic Lorentz violation, the supernova 1987A limit was estimated to be to \( M_2 \sim 4 \times 10^4 \) GeV, the possible sensitivity of a future galactic supernova event was estimated to be to \( M_2 \sim 10^6 \), and the potential sensitivity of a terrestrial experiment was estimated to be to \( M_2 \sim 7 \times 10^5 \) GeV. Again, the large distance of TXS 0506+056 and the high energy of the IceCube-170922A event enable it to outclass the competition.

We conclude that the advent of multimessenger neutrino/photon astronomy [7,8] has not only launched a new era in the study of the origins of high-energy cosmic rays, but also made possible a breakthrough in the exploration of Lorentz symmetry using neutrinos. We may anticipate that more coincidences between high-energy neutrino events and electromagnetic emissions will be observed, enabling the rough estimates made here to be refined and improved. Such coincidences would contribute to fundamental physics as well as resolving important issues in astrophysics.

\[\text{In fact, we are unaware of neutrino experiments that have sought to test Lorentz invariance in the way proposed here. For alternative searches for Lorentz violation using neutrinos, see [21,22]. We are grateful to Francesca Di Lodovico for drawing our attention to these references.}\]
Acknowledgements

The research of J.E. and N.E.M. was supported partly by the STFC Grant ST/L000258/1. N.E.M. also acknowledges the hospitality of IFIC Valencia through a Scientific Associate-ship (Doctor Vingulado). The work of A.S.S. was supported partly by the US National Science Foundation under Grants PHY-1505463 and PHY-1402964.

References

[1] G. Amelino-Camelia, J. R. Ellis, N. E. Mavromatos, D. V. Nanopoulos and S. Sarkar, Tests of quantum gravity from observations of gamma-ray bursts, Nature 393, 763 (1998), doi:10.1038/31647, [arXiv:astro-ph/9712103], see also J. R. Ellis, K. Farakos, N. E. Mavromatos, V. A. Mitsou and D. V. Nanopoulos, Astrophysical probes of the constancy of the velocity of light, Astrophys. J. 535, 139 (2000) doi:10.1086/308825 [astro-ph/9907340].

[2] J. Ellis, R. Konoplich, N. E. Mavromatos, L. Nguyen, A. S. Sakharov and E. K. Sarkisyan-Grinbaum, Robust Constraint on Lorentz Violation Using Fermi-LAT Gamma-Ray Burst Data, [arXiv:1807.00189] [astro-ph.HE].

[3] J. R. Ellis, N. Harries, A. Meregaglia, A. Rubbia and A. Sakharov, Probes of Lorentz Violation in Neutrino Propagation, Phys. Rev. D 78, 033013 (2008) doi:10.1103/PhysRevD.78.033013 [arXiv:0805.0253] [hep-ph]].

[4] B. P. Abbott et al. [LIGO Scientific and Virgo Collaborations], Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116 (2016) no.6, 061102 doi:10.1103/PhysRevLett.116.061102 [arXiv:1602.03837] [gr-qc]].

[5] J. Ellis, N. E. Mavromatos and D. V. Nanopoulos, Comments on Graviton Propagation in Light of GW150914, Mod. Phys. Lett. A 31 (2016) no.26, 1675001 doi:10.1142/S0217732316750018 [arXiv:1602.04764] [gr-qc]].

[6] B. P. Abbott et al. [LIGO Scientific and Virgo and Fermi GBM and INTEGRAL and IceCube and IPN and Insight-Hxmt and ANTARES and Swift and Dark Energy Camera GW-EM and Dark Energy Survey and DLT40 and GRAWITA and Fermi-LAT and ATCA and ASKAP and OzGrav and DWF (Deeper Wider Faster Program) and AST3 and CAASTRO and VINROUGE and MASTER and J-GEM and GROWTH and JAGWAR and CaltechNRAO and TTU-NRAO and NuSTAR and Pan-STARRS and KU and Nordic Optical Telescope and ePESSTO and GROND
and Texas Tech University and TOROS and BOOTES and MWA and CALET and
IKI-GW Follow-up and H.E.S.S. and LOFAR and LWA and HAWC and Pierre Auger
and ALMA and Pi of Sky and DFN and ATLAS Telescopes and High Time Reso-
lution Universe Survey and RIMAS and RATIR and SKA South Africa/MeerKAT
Collaborations and AstroSat Cadmium Zinc Telluride Imager Team and AGILE
Team and 1M2H Team and Las Cumbres Observatory Group and MAXI Team and
TZAC Consortium and SALT Group and Euro VLBI Team and Chandra Team at
McGill University], *Multi-messenger Observations of a Binary Neutron Star Merger*,
Astrophys. J. **848** (2017) no.2, L12 doi:10.3847/2041-8213/aa91c9 [arXiv:1710.05833
[astro-ph.HE]].

[7] IceCube Collaboration *et al.*, *Multimessenger observations of a flaring blazar coinci-
dent with high-energy neutrino IceCube-170922A*, Science **361** (2018) eaat1378 doi:
0.1126/science.aat1378.

[8] IceCube Collaboration, *Neutrino emission from the direction of the blazar TXS
0506+056 prior to the IceCube-170922A alert*, Science **361** (2018) no.6398, 147
doi:10.1126/science.aat2890.

[9] S. Gao, A. Fedynitch, W. Winter and M. Pohl, *Interpretation of the coincident
observation of a high energy neutrino and a bright flare*, [arXiv:1807.04275
[astro-ph.HE]]; M. L. Ahnen *et al.* [Finnish Centre of Astronomy with ESO Collabora-
tion and Finnish MAGIC Consortium: Tuorla Observatory], *The blazar TXS
0506+056 associated with a high-energy neutrino: insights into extragalactic jets
and cosmic ray acceleration*, doi:10.3847/2041-8213/aad083 [arXiv:1807.04300
[astro-ph.HE]]; P. Padovani, P. Giommi, E. Resconi, T. Glauch, B. Arsioli, N. Sahakyan and
M. Huber, *Dissecting the region around IceCube-170922A: the blazar TXS 0506+056 as
the first cosmic neutrino source*, doi:10.1093/mnras/sty1852 [arXiv:1807.04461
[astro-ph.HE]]; A. Keivani *et al.*, *A Multimessenger Picture of the Flaring Blazar
TXS 0506+056: implications for High-Energy Neutrino Emission and Cosmic
Ray Acceleration*, [arXiv:1807.04537 [astro-ph.HE]]; K. Murase, F. Oikonomou and
M. Petropoulou, *Blazar Flares as an Origin of High-Energy Cosmic Neutrinos?*,
[arXiv:1807.04748 [astro-ph.HE]].

[10] See, for example, J. A. Wheeler and K. W. Ford, *Geons, black holes, and quantum
foam: a life in physics*, (Norton, New York, 1998) ISBN 0-393-04642-7.
[11] L. Gonzalez-Mestres, *Lorentz symmetry violation and high-energy cosmic rays*, arXiv:physics/9712005 and *Lorentz symmetry violation and superluminal particles at future colliders*, arXiv:physics/9708028.

[12] S. R. Coleman, S. L. Glashow, *High-energy tests of Lorentz invariance*, Phys. Rev. D59 (1999) 116008 [hep-ph/9812418]; T. Jacobson, S. Liberati, D. Mattingly, *A Strong astrophysical constraint on the violation of special relativity by quantum gravity*, Nature 424 (2003) 1019-1021 [astro-ph/0212190]; *Lorentz violation at high energy: Concepts, phenomena and astrophysical constraints*, Annals Phys. 321 (2006) 150-196 [astro-ph/0505267]; N. E. Mavromatos, *String Quantum Gravity, Lorentz-Invariance Violation and Gamma-Ray Astronomy*, Int. J. Mod. Phys. A 25 (2010) 5409 [arXiv:1010.5354 [hep-th]]; S. Liberati, L. Maccione, *Quantum Gravity phenomenology: achievements and challenges*, J. Phys. Conf. Ser. 314 (2011) 012007 [arXiv:1105.6234 [astro-ph.HE]] and references therein.

[13] V. A. Kostelecky, *Lorentz violating and CPT violating extension of the standard model*, arXiv:hep-ph/9912528.

[14] R. C. Myers, M. Pospelov, *Ultraviolet modifications of dispersion relations in effective field theory*, Phys. Rev. Lett. 90 (2003) 211601 [hep-ph/0301124]; J. Alfaro, L. F. Urrutia, *Gauge invariant non-linear electrodynamics motivated by a spontaneous breaking of the Lorentz symmetry*, Phys. Rev. D81 (2010) 025007 [arXiv:0912.3053 [hep-ph]].

[15] R. Gambini, J. Pullin, *Nonstandard optics from quantum space-time*, Phys. Rev. D59 (1999) 124021 [gr-qc/9809038].

[16] G. Amelino-Camelia, *Relativity in space-times with short distance structure governed by an observer independent (Planckian) length scale*, Int. J. Mod. Phys. D 11, 35 (2002) doi:10.1142/S0218271802001330 [gr-qc/0012051]; J. Magueijo and L. Smolin, *Lorentz invariance with an invariant energy scale*, Phys. Rev. Lett. 88, 190403 (2002) doi:10.1103/PhysRevLett.88.190403 [hep-th/0112090].

[17] E. M. Lifshitz, *On the theory of second-order phase transitions I*, Zh. Eksp. Teor. Fiz. 11 (1941) 255; E. M. Lifshitz, *On the theory of second-order phase transitions II*, Zh. Eksp. Teor. Fiz. 11 (1941) 269; P. Horava, *Quantum Gravity at a Lifshitz Point*, Phys. Rev. D79 (2009) 084008 [arXiv:0901.3775 [hep-th]]; M. Visser, *Lorentz symmetry breaking as a quantum field theory regulator*, Phys. Rev. D80, 025011 (2009)
for a comprehensive review in our context, see: J. Alexandre, *Lifshitz-type Quantum Field Theories in Particle Physics*, arXiv:1109.5629 [hep-ph] and references therein.

[18] J. R. Ellis, N. E. Mavromatos and D. V. Nanopoulos, *Derivation of a Vacuum Refractive Index in a Stringy Space-Time Foam Model*, Phys. Lett. B 665, 412 (2008) doi:10.1016/j.physletb.2008.06.029 [arXiv:0804.3566 [hep-th]]. T. Li, N. E. Mavromatos, D. V. Nanopoulos and D. Xie, *Time Delays of Strings in D-particle Backgrounds and Vacuum Refractive Indices*, Phys. Lett. B 679, 407 (2009) doi:10.1016/j.physletb.2009.07.062 [arXiv:0903.1303 [hep-th]].

[19] J. R. Ellis, N. E. Mavromatos and A. S. Sakharov, *Synchrotron radiation from the Crab Nebula discriminates between models of space-time foam*, Astropart. Phys. 20, 669 (2004) doi:10.1016/j.astropartphys.2003.12.001 [astro-ph/0308403].

[20] J. Ellis, H. T. Janka, N. E. Mavromatos, A. S. Sakharov and E. K. G. Sarkisyan, *Probing Lorentz Violation in Neutrino Propagation from a Core-Collapse Supernova*, Phys. Rev. D 85 (2012) 045032 doi:10.1103/PhysRevD.85.045032 [arXiv:1110.4848 [hep-ph]].

[21] K. Abe et al. [Super-Kamiokande Collaboration], *Test of Lorentz invariance with atmospheric neutrinos*, Phys. Rev. D 91 (2015) no.5, 052003 doi:10.1103/PhysRevD.91.052003 [arXiv:1410.4267 [hep-ex]].

[22] K. Abe et al., *Search for Lorentz and CPT violation using sidereal time dependence of neutrino flavor transitions over a short baseline*, Phys. Rev. D 95 (2017) no.11, 111101 doi:10.1103/PhysRevD.95.111101 [arXiv:1703.01361 [hep-ex]].