Multimessenger Tests of Einstein’s Weak Equivalence Principle and Lorentz Invariance with a High-energy Neutrino from a Flaring Blazar

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The detection of the high-energy (≈ 290 TeV) neutrino coincident with the flaring blazar TXS 0506+056, the first and only 3σ neutrino-source association to date, provides new, multimessenger tests of the weak equivalence principle (WEP) and Lorentz invariance. Assuming that the flight time difference between the TeV neutrino and gamma-ray photons from the blazar flare is mainly caused by the gravitational potential of the Laniakea supercluster of galaxies, we show that the deviation from the WEP for neutrinos and photons is conservatively constrained to be an accuracy of $10^{-6} - 10^{-7}$, which is 3–4 orders of magnitude better than previous results placed by MeV neutrinos from supernova 1987A. In addition, we demonstrate that the association of the TeV neutrino with the blazar flare sets limits on the energy scale of quantum gravity for both linear and quadratic violations of Lorentz invariance (LIV) to $E_{QG,1} > 3.2 \times 10^{15} - 3.7 \times 10^{16}$ GeV and $E_{QG,2} > 4.0 \times 10^{10} - 1.4 \times 10^{11}$ GeV. These improve previous limits on both linear and quadratic LIV in neutrino propagation by 5–7 orders of magnitude.

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I. INTRODUCTION

On 22 September 2017, the IceCube Collaboration detected a high-energy neutrino, IceCube-170922A, with an energy of ≈ 290 TeV [1]. The best-fit reconstructed location is right ascension R.A. = 77.43+0.95−0.65 and declination Dec. = +5.72+0.50−0.30 (degrees, J2000, 90% containment region). It was soon determined that the arrival direction of IceCube-170922A was consistent with the location of the blazar TXS 0506+056 and coincident with a flaring state observed since April 2017 by the Fermi-LAT [2]. The AGILE gamma-ray telescope confirmed the enhanced gamma-ray activity at energies above 0.1 GeV from TXS 0506+056 in 10 to 23 September 2017. Follow-up observations of the blazar led to the detection of a significant gamma-ray signal with energies up to 400 GeV around 28 September to 4 October 2017 by the MAGIC telescope. The significance of the temporal and spatial coincidence of the neutrino event and the blazar flare is estimated to be at the 3σ level [1], which is the highest level of confidence for cosmic neutrinos to date. TXS 0506+056 is a blazar of BL Lacertae type and its redshift has been recently measured to be $z = 0.3365$ [3].

With the physical association between the flare of TXS 0506+056 and the high-energy neutrino, the flight time difference between the TeV neutrino and the blazar photons can in principle be used to constrain violations of Einstein’s weak equivalence principle (WEP) and Lorentz invariance, since both their violations can lead to arrival time differences for neutral particles of different-species or with different energies arising from the same astrophysical object. TXS 0506+056 showed the elevated level of gamma-ray emission in the GeV band starting in April 2017, which is prior to the IceCube-170922A alert [2]. The maximum possible arrival-time delay between the beginning of the flare and the arrival of the neutrino is about 175 days. On the other hand, the Fermi-LAT and AGILE observations showed that the peak of the high-energy gamma-ray flare occurs ~ 15 days earlier than the neutrino event. If we assume that the neutrino event was emitted around the same time of the peak, the time delay between the TeV neutrino and gamma-ray photons turns out to be about 15 days.

Einstein’s WEP is a fundamental postulate of general relativity and other metric theories of gravity. It states that any two different species of massless (or negligible rest mass) messenger particles (photons, neutrinos, and gravitational waves), or any two particles of the same species but with varying energies, if emitted simultaneously from the same astronomical source and traveling through the same gravitational field, should reach our
Earth at the same time [4, 5]. In the neutrino sector, the arrival time delays of MeV neutrinos and photons from supernova SN 1987A have been used to test the WEP accuracy [6, 7] through the Shapiro (gravitational) time delay effect [8]. They proved that the Shapiro delay for neutrinos is equal to that for photons at an accuracy of 0.2-0.5%. Assuming that the flight time difference between a PeV neutrino and gamma-ray photons from a flare of the blazar PKS B1424-418 is mainly attributed to the gravitational potential of supercluster, Ref. [9] showed that the WEP constraint can be further improved by two orders of magnitude. Based on the associations between five TeV neutrinos and gamma-ray photons from gamma-ray bursts (GRBs), Ref. [10] tightened the constraint on the deviation from WEP to an accuracy of $10^{-11} - 10^{-13}$ when adopting the gravitational potential of the Laniakea supercluster of galaxies. Besides the neutrino-photon delays, such a test has been also applied to the delays of photons with different energies (e.g., GRBs [11, 12, 13], fast radio bursts [14, 15], TeV blazars [16], and the Crab pulsar [17, 18, 19, 20]), and the delays between photons and gravitational waves [21, 22, 23, 24, 25, 26, 27, 28].

Lorentz invariance is a fundamental symmetry of Einstein’s relativity. However, violations of Lorentz invariance (LIV) at the Planck energy scale $E_{\text{Pl}} = \sqrt{\hbar c^3/G} \approx 1.22 \times 10^{19}$ GeV are predicted in many quantum gravity (QG) theories attempting to unify general relativity and quantum mechanics (see Refs. [29, 30], and references therein). As a consequence of LIV effects, the velocity of massless particles (photons or neutrinos) in a vacuum would have an energy dependence, also known as vacuum dispersion [31, 32, 33]. The QG energy scale ($E_{\text{QG}}$) used for representing LIV could therefore be constrained by comparing the flight time differences of particles with different energies originating from the same source [34, 35]. The current best limits on $E_{\text{QG}}$ have been obtained from the highest energy (31 GeV) photon of GRB 090510. The limits set are $E_{\text{QG,1}} > 9.1 \times 10^{19}$ GeV $> (1 - 10) E_{\text{Pl}}$ and $E_{\text{QG,2}} > 1.3 \times 10^{11}$ GeV $> 10^{-8} E_{\text{Pl}}$ for linear and quadratic leading order LIV-induced vacuum dispersion, respectively [36, 37] (see also Refs. [38, 39] and summary constraints for LIV therein). In the neutrino sector, Ref. [40] used the SN1987A MeV neutrinos to constrain the linear and quadratic LIV energy scales, and obtained the limits of $E_{\text{QG,1}} > 2.7 \times 10^{10}$ GeV and $E_{\text{QG,2}} > 4.6 \times 10^{8}$ GeV. Ref. [9] analyzed possible LIV effects in neutrino propagation from an association between a PeV neutrino and the outburst activity of blazar PKS B1424-418, and set the limits of $E_{\text{QG,1}} > 1.1 \times 10^{17}$ GeV and $E_{\text{QG,2}} > 7.3 \times 10^{11}$ GeV. Based on the associations between five TeV neutrinos and GRBs, Ref. [10] set the most strictest limits up to now on neutrino LIV, implying $E_{\text{QG,1}} > 6.3 \times 10^{8} - 1.5 \times 10^{21}$ GeV and $E_{\text{QG,2}} > 2.0 \times 10^{11} - 4.2 \times 10^{12}$ GeV.

Although the tests on both the WEP and LIV have reached high precision in the neutrino sector, most of the tests rely on the use of low-significance neutrinos correlated with photons, which are not very reliable. Specifically, except for the MeV neutrinos from SN 1987A, the significance of the PeV neutrino (or five TeV neutrinos) being associated with the flare of PKS B1424-418 (or GRBs) is relatively low. The coincidences between five TeV neutrinos and GRBs only yielded a combined p-value of 0.32 [41], and a 5% probability for a chance coincidence between the PeV neutrino and the PKS B1424-418 flare remains [42]. New high-energy neutrinos with confirmed astrophysical sources and with higher significance (e.g., this IceCube-170922A event) are essential for further testing the WEP and LIV to a higher accuracy level.

II. TESTS OF THE WEP

The motion of test particles in a gravitational field can be described by the parametrized post-Newtonian (PPN) formalism. All metric theories of gravity satisfying the WEP predict that $\gamma_1 = \gamma_2 = \gamma$, where the PPN parameter $\gamma$ reflects the level of space curvature by unit rest mass and the subscripts denote two different particles [4, 5]. The WEP accuracy can therefore be characterized by constraining the differences of the $\gamma$ values for different particles. On the basis of the Shapiro time delay effect [8], the time interval required for particles to pass through a given distance is longer by

$$t_{\text{gra}} = -\frac{1 + \gamma}{c^2} \int_{r_a}^{r_o} U(r) dr$$

in the presence of a gravitational potential $U(r)$, where the integration is along the propagation path from the source $r_a$ to the observer $r_o$. Once the WEP fails, the $\gamma$ values for different particles will no longer be the same, resulting in the arrival-time delay of two different particles arising from the same source. The relative Shapiro time delay is given by

$$\Delta t_{\text{gra}} = \frac{\gamma_1 - \gamma_2}{c^2} \int_{r_a}^{r_o} U(r) dr,$$

where the difference of the $\gamma$ values $\Delta \gamma = \gamma_1 - \gamma_2$ is deemed as a measure of a possible deviation from the WEP.

To estimate the relative Shapiro delay with Eq. (2), one needs to figure out the gravitational potential $U(r)$. Generally speaking, $U(r)$ consists of three parts: the gravitational potentials of our Milky Way, the intergalactic space, and the source host galaxy. For the cosmological sources, the Shapiro delay caused by the gravitational potential of the large scale structure (e.g., nearby clusters and/or superclusters) has been proved to be more important than the Milky Way’s and the host galaxy’s gravity [43, 44, 45]. Thus, we here consider the gravitational potential of the Laniakea supercluster of galaxies.

Laniakea is a newly discovered supercluster of galaxies, in which our Milky Way reside [46]. The gravitational...
The LIV effect predicts an energy-dependent speed of propagation in a vacuum for neutrinos and photons. The leading term in the modified dispersion relation for particles (with energy $E \ll E_{\text{QG}}$) is

$$E^2 \simeq p^2c^2 + m^2c^4 \pm E^2\left(\frac{E}{E_{\text{QG,n}}}\right)^n,$$

where $m$ is the rest mass of the particle, the $n$-th order expansion of leading term stands for linear ($n=1$) or quadratic ($n=2$) LIV model, and $+1$ ($-1$) corresponds to the “subluminal” and (“superluminal”) case. The term $m^2c^4$ among in Eq. (4) is negligible when the test particles are massless or nearly massless. Note that the superluminal neutrinos would lose their energy rapidly due to both vacuum pair emission and neutrino splitting [49, 50], and excellent bounds on LIV have been made for superluminal neutrinos [51, 52, 53]. Here we set the limits on subluminal neutrino LIV. Because of the speed of particles have an energy dependence, two particles with different energies originating from the same source would arrive on Earth at different times. The arrival-time difference due to the LIV effect is expressed as [32]

$$\Delta t = \frac{1 + n}{2H_0} \frac{E_h^n - E_i^n}{E_{\text{QG,n}}^n} \int_0^z \frac{(1 + z')^n dz'}{\Omega_m(1 + z')^3 + \Omega_\Lambda};$$

where $E_h$ and $E_i$ ($E_h > E_i$) are the energies of different particles. Here we use the cosmological parameters obtained by the Planck observations: $\Omega_m = 0.315$, $\Omega_\Lambda = 0.685$, and $H_0 = 67.3$ km s$^{-1}$ Mpc$^{-1}$ [54].

Similarly, the maximum possible arrival-time delay between the beginning of the gamma-ray flare and the arrival of the neutrino ($\sim 175$ days) is firstly adopted as the upper limit of the delay between the TeV neutrino and photons. For linear and quadratic LIV, we obtain the limits of $E_{\text{QG,1}} > 3.2 \times 10^{15}$ GeV and $E_{\text{QG,2}} > 4.0 \times 10^{10}$ GeV. With the assumption that the TeV neutrino was emitted around the same time of the flare peak, the time delay between the neutrino and gamma-ray photons would be shorter ($\sim 15$ days), leading to much stricter limits on LIV, i.e., $E_{\text{QG,1}} > 3.7 \times 10^{16}$ GeV and $E_{\text{QG,2}} > 1.4 \times 10^{11}$ GeV. The resulting constraints for these two assumed delays are summarized in Table I. Compared with the corresponding limits from MeV neutrinos of SN 1987A, our limits on $E_{\text{QG,1}}$ and $E_{\text{QG,2}}$ represent an improvement of at least 5–7 orders of magnitude. We also note that one independent work [55] constrained linear and quadratic LIV by assuming a difference in neutrino and photon propagation times of $\sim 10$ days.

### IV. CONCLUSIONS

Very recently, a high-energy ($\sim 290$ TeV) neutrino, IceCube-170922A, was detected in coincidence with the

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**TABLE I:** Limits on the WEP and LIV with two assumed time delays between the TeV neutrino and the blazar photons.

| $\Delta t_{\text{obs}}$ (days) | $|\gamma_\nu - \gamma_\gamma|$ | $E_{\text{QG,1}}$ (GeV) | $E_{\text{QG,2}}$ (GeV) |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 175                         | $8.5 \times 10^{-6}$        | $3.2 \times 10^{15}$        | $4.0 \times 10^{10}$        |
| 15                          | $7.3 \times 10^{-7}$        | $3.7 \times 10^{16}$        | $1.4 \times 10^{11}$        |
gamma-ray emitting blazar TXS 0506+056 during an active phase, with chance coincidence being rejected at 3σ level [1]. This is the first time in history that confirming blazars may be a source of cosmic neutrinos with the highest confidence level. Based on this association between the TeV neutrino and the blazar flare, we demonstrate that multimessenger WEP tests and neutrino LIV constraints can be carried out by using the arrival time delay between the neutrino and the photons. Adopting the maximum possible arrive-time difference between the neutrino and photons (∼175 days), we show that the conservative limit on the difference of the PPN γ parameter for neutrinos and photons is as low as |γν − γγ| < 8.5 × 10^{-6}, improving the previous WEP tests from Mev neutrinos of SN 1987A by 3 orders of magnitude. On the other hand, we place stringent limits on linear and quadratic LIV, namely E_{QG1} > 3.2 × 10^{15} GeV and E_{QG2} > 4.0 × 10^{10} GeV, which are an improvement of 5–6 orders of magnitude over the previous results obtained from SN neutrinos. If the TeV neutrino was emitted around the same time of the flare peak, the arrival-time difference between the neutrino and photons is about 15 days. With this shorter time delay, the tests of the WEP and Lorentz invariance can be further improved by 1 order of magnitude.

Acknowledgments

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[1] IceCube Collaboration and et al., Science 361, 146 (2018).
[2] A. J. Tetarenko, G. R. Sivakoff, A. E. Kimball, and J. C. A. Miller-Jones, The Astronomer’s Telegram 10861 (2017).
[3] S. Paiano, R. Falomo, A. Treves, and R. Scarpa, Astrophys. J. 854, L32 (2018), 1802.01939.
[4] C. M. Will, Living Rev. Rel. 9, 3 (2006), gr-qc/0510072.
[5] C. M. Will, Living Rev. Rel. 17, 4 (2014), 1403.7377.
[6] M. J. Longo, Phys. Rev. Lett. 60, 173 (1988).
[7] L. M. Krauss and S. Tremaine, Phys. Rev. Lett. 60, 176 (1988).
[8] I. I. Shapiro, Phys. Rev. Lett. 13, 789 (1964).
[9] Z.-Y. Wang, R.-Y. Liu, and X.-Y. Wang, Phys. Rev. Lett. 116, 151101 (2016), 1602.06805.
[10] J.-J. Wei, X.-F. Wu, H. Gao, and P. Mészáros, JCAP 8, 031 (2016), 1603.07568.
[11] H. Gao, X.-F. Wu, and P. Mészáros, Astrophys. J. 810, 121 (2015), 1509.01150.
[12] Y. Sang, H.-N. Lin, and Z. Chang, Mon. Not. R. Astron. Soc. 460, 2282 (2016), 1605.02834.
[13] H. Yu, S.-Q. Xi, and F.-Y. Wang, Astrophys. J. 860, 173 (2018), 1708.02396.
[14] J.-J. Wei, H. Gao, X.-F. Wu, and P. Mészáros, Phys. Rev. Lett. 115, 261101 (2015), 1512.07670.
[15] S. J. Tingay and D. L. Kaplan, Astrophys. J. 820, L31 (2016), 1602.07643.
[16] J.-J. Wei, J.-S. Wang, H. Gao, and X.-F. Wu, Astrophys. J. 818, L2 (2016), 1604.04145.
[17] Y.-P. Yang and B. Zhang, Phys. Rev. D 94, 101501 (2016), 1608.07657.
[18] Y. Zhang and B. Gong, Astrophys. J. 837, 134 (2017), 1612.00717.
[19] S. Desai and E. Kahya, European Physical Journal C 78, 86 (2018), 1612.02532.
[20] C. Leung, B. Hu, S. Harris, A. Brown, J. Gallicchio, and H. Nguyen, Astrophys. J. 861, 66 (2018), 1804.04722.
[21] X.-F. Wu, H. Gao, J.-J. Wei, P. Mészáros, B. Zhang, Z.-G. Dai, S.-N. Zhang, and Z.-H. Zhu, Phys. Rev. D 94, 024061 (2016), 1602.01566.
[22] E. O. Kahya and S. Desai, Phys. Lett. B 756, 265 (2016), 1602.04779.
[23] X. Li, Y.-M. Hu, Y.-Z. Fan, and D.-M. Wei, Astrophys. J. 827, 75 (2016), 1601.00180.
[24] M. Liu, Z. Zhao, X. You, J. Lu, and L. Xu, Phys. Lett. B 770, 8 (2017), 1604.06668.
[25] J.-J. Wei, B.-B. Zhang, X.-F. Wu, H. Gao, P. Mészáros, B. Zhang, Z.-G. Dai, S.-N. Zhang, and Z.-H. Zhu, JCAP 11, 035 (2017), 1710.05860.
[26] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acerne, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, et al., Astrophys. J. 848, L13 (2017), 1710.05834.
[27] H. Wang, F.-W. Zhang, Y.-Z. Wang, Z.-Q. Shen, Y.-F. Liang, X. Li, N.-H. Liao, Z.-P. Jin, Q. Yuan, Y.-C. Zou, et al., Astrophys. J. 851, L18 (2017), 1710.05805.
[28] I. M. Shoemaker and K. Murase, Phys. Rev. D 97, 083013 (2018), 1710.06427.
[29] D. Mattingly, Living Reviews in Relativity 8, 5 (2005), gr-qc/0502097.
[30] G. Amelino-Camelia, Living Reviews in Relativity 16, 5 (2013), 0806.0339.
[31] G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, and D. V. Nanopoulos, International Journal of Modern Physics A 12, 607 (1997), hep-th/9605211.
[32] U. Jacob and T. Piran, Nature Physics 3, 87 (2007), hep-ph/0607145.
[33] V. A. Kostelecký and M. Meweś, Astrophys. J. 689, L1 (2008), 0809.2846.
[34] G. Amelino-Camelia, J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, and S. Sarkar, Nature 393, 763 (1998), astro-ph/9712103.
[35] J. Ellis and N. E. Mavromatos, Astroparticle Physics 43, 50 (2013), 1111.1178.
[36] A. A. Abdo, M. Ackermann, M. Ajello, K. Asano, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet, G. Barbiellini, M. G. Baring, et al., Nature 462, 331 (2009), 0908.1832.

[37] V. Vasileiou, A. Jacholkowska, F. Piron, J. Bolmont, C. Couturier, J. Granot, F. W. Stecker, J. Cohen-Tanugi, and F. Longo, Phys. Rev. D 87, 122001 (2013), 1305.3463.

[38] V. A. Kostelecky and N. Russell, Reviews of Modern Physics 83, 11 (2011), 0801.0287.

[39] S. Liberati, Classical and Quantum Gravity 30, 133001 (2013), 1304.5795.

[40] J. Ellis, N. Harries, A. Meregaglia, A. Rubbia, and A. S. Sakharov, Phys. Rev. D 78, 033013 (2008), 0805.0253.

[41] M. G. Aartsen, K. Abraham, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, D. Altmann, T. Anderson, I. Ansseau, et al., Astrophys. J. 824, 115 (2016), 1601.06484.

[42] M. Kadler, F. Krauß, K. Mannheim, R. Ojha, C. Müller, R. Schulz, G. Anton, W. Baumgartner, T. Beuchert, S. Buson, et al., Nature Phys. 12, 807 (2016), 1602.02012.

[43] A. Nusser, Astrophys. J. 821, L2 (2016), 1601.03636.

[44] S.-N. Zhang, ArXiv e-prints (2016), 1601.04558.

[45] Z.-X. Luo, B. Zhang, J.-J. Wei, and X.-F. Wu, JHEAp 9, 35 (2016), 1604.02566.

[46] R. B. Tully, H. Courtois, Y. Hoffman, and D. Pomarède, Nature 513, 71 (2014), 1409.0880.

[47] D. Lynden-Bell, S. M. Faber, D. Burstein, R. L. Davies, A. Dressler, R. J. Terlevich, and G. Wegner, Astrophys. J. 326, 19 (1988).

[48] S. Boran, S. Desai, and E. O. Kahya, ArXiv e-prints (2018), 1807.05201.

[49] L. Maccione, S. Liberati, and D. M. Mattingly, JCAP 3, 039 (2013).

[50] F. W. Stecker, S. T. Scully, S. Liberati, and D. Mattingly, Phys. Rev. D 91, 045009 (2015), 1411.5889.

[51] E. Borriello, S. Chakraborty, A. Mirizzi, and P. D. Serpico, Phys. Rev. D 87, 116009 (2013), 1303.5843.

[52] J. S. Díaz, V. A. Kostelecký, and M. Mewes, Phys. Rev. D 89, 043005 (2014), 1308.6344.

[53] F. W. Stecker, Astroparticle Physics 56, 16 (2014), 1306.6095.

[54] Planck Collaboration, P. A. R. Ade, N. Aghanim, C. Armitage-Caplan, M. Arnaud, M. Ashdown, F. Atrio-Barandela, J. Aumont, C. Baccigalupi, A. J. Banday, et al., Astron. Astrophys. 571, A16 (2014), 1303.5076.

[55] J. Ellis, N. E. Mavromatos, A. S. Sakharov, and E. K. Sarkisyan-Grinbaum, ArXiv e-prints (2018), 1807.05155.