Constraints on differential Shapiro delay between neutrinos and photons from IceCube-170922A

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On 22nd September 2017, the IceCube Collaboration detected a neutrino with energy of about 290 TeV from the direction of the gamma-ray blazar TXS 0506+056, located at a distance of about 1.75 Gpc. During the same time, enhanced gamma-ray flaring was also simultaneously observed from multiple telescopes, giving rise to only the second coincident astrophysical neutrino/photon observation after SN 1987A. We point out that for this event, both neutrinos and photons encountered a Shapiro delay of about 6300 days along the way from the source. From this delay and the relative time difference between the neutrino and photon arrival times, one can constrain violations of Einstein’s Weak Equivalence Principle (WEP) for TeV neutrinos. We constrain such violations of WEP using the Parameterized Post-Newtonian (PPN) parameter γ, and is given by |γν − γEM| < 4.8 × 10−3, for an arrival time difference of 15 days. This is the first direct proof that TeV neutrinos couple to gravity in the same way as photons.

PACS numbers: 97.60.Jd, 04.80.Cc, 95.30.Sf

I. INTRODUCTION

On 22nd September 2017, the IceCube experiment detected a neutrino-induced muon (called IceCube-170922A) having an energy of about 24 TeV, whose parent neutrino energy has been estimated to be about 290 TeV [1]. The location of the neutrino direction was found to be in positional coincidence with a TeV gamma-ray blazar. Following this detection, the Fermi-LAT and AGILE gamma-ray satellites reported enhanced flaring from this blazar during this time period from 0.1 to about 10 GeV. The MAGIC atmospheric Cherenkov telescope also reported a 6σ excess of 100 GeV gamma-rays compared to expected background around 28th September. The probability that the association of IceCube-170922A with the gamma-ray flare is a chance coincidence is disfavored at 3σ. More details on these observations can be found in Ref. [1]. This is the first direct evidence that blazars produce high-energy neutrinos and probably ultra-high-energy cosmic-rays.

These observations also enable a novel probe of General Relativity (GR) and the equivalence principle for TeV neutrinos. The total time it takes for neutrinos to reach the Earth from this blazar is equal to the sum of the distance divided by their (vacuum) speed and an additional delay due to the non-zero gravitational potential of the cumulative mass distribution along the line of sight.

The latter delay is known as Shapiro delay [2] and has been extensively used to test GR as well for astrophysical measurements for the past five decades [3–8]. The first ever calculation of this line-of-sight Shapiro delay was done in 1988, following the detection of neutrinos from SN 1987A at a distance of 50 kpc [9, 10] and optical light soon after the neutrino event. After this detection, two groups [11, 12] (see also Ref. [13]) pointed out that the neutrinos underwent a Shapiro delay of about 1-6 months due to the gravitational potential of the Milky Way (MW) galaxy. We note that until the current IceCube detection, this was the only direct and “smoking gun” evidence that neutrinos are affected by GR and obey WEP to a precision of 0.2-0.5%. Since IMB and Kamiokande detected both neutrinos and anti-neutrinos, these observations also showed that Shapiro delay for neutrinos is CP invariant [14]. Subsequently, two years ago, based on a 2σ putative association between a giant flare from the blazar PKS B1424-418 located at z = 1.522, and a 2 PeV IceCube neutrino, WEP was constrained to an accuracy of 10−5 [15].

Since 2016, there has been a proliferation of papers carrying out similar calculations of line-of-sight Shapiro delay for a large class of astrophysical objects [16–28] (and references therein). The main objective of these works was to constrain WEP using coincident electromagnetic (EM) wave or gravitational wave observations. The violation of WEP in these works has been parameterized in terms of the difference in PPN parameter ∆γ [6] between the astrophysical messengers.

Now that the first simultaneous detection of TeV neutrinos and high energy photons has happened, we carry out a similar test of WEP for neutrinos, by first calculating the line-of-sight Shapiro delay and then using the observed time difference between the neutrinos and gamma-rays to constrain the violation of WEP in terms of ∆γ. This bound will be the first ever limit for TeV neutrinos, since the bounds obtained in Refs. [11, 12] for in MeV energy range. We note that the non-zero mass of neutrino does not change the Shapiro delay as compared to a massless carrier [29].
II. SHAPIRO DELAY CALCULATION

The location of the neutrino direction was traced to RA = 77.43°, and δ = +5.69°. This was found to be in positional coincidence with a TeV gamma-ray blazar. Its redshift was estimated to be 0.3365 ± 0.001, from high resolution optical spectroscopy in the wavelength range from 4100-9000 Å, with the 10.4 m telescope in Canary Islands [30]. This redshift corresponds to approximately a luminosity distance of 1.75 Gpc, obtained using the online Cosmology calculator [31] (assuming the cosmological parameters as $H_0 = 69.6 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_m = 0.286$ and $\Omega_\Lambda = 0.714$).

To perform a ball-park estimate of the Shapiro delay calculation, we follow the same procedure as in Ref. [22], which was used to obtain the delay for GW150914. We first use the total estimated Shapiro delay for our Milky-Way (MW) galaxy by using the Navarro-Frenk-White (NFW) dark matter profile [32] from our previous works; this MW-induced delay is about 300 days at a distance of 400 kpc [33, 34]. Once we go beyond the galaxy virial radius, the delay follows a logarithmic trend as a function of distance for a point-like source and Schwarzschild metric:

$$
\Delta t_{\text{shapiro}} = (1 + \gamma) \frac{GM}{c^3} \ln \left( \frac{d}{b} \right),
$$

where $\gamma$ is the PPN parameter with value equal to unity in GR, $b$ is the impact parameter, and $d$ is the distance to the source. To calculate the total Shapiro delay due to our galaxy at a distance of 1.75 Gpc, we assume $b=8$ kpc and use the logarithmic enhancement factor from the above equation, which is equal to about a factor of three. Therefore, the Shapiro delay due to only our MW galaxy at a distance of 1.75 Gpc is equal to 900 days.

Next, we estimate the total number of MW equivalent galaxies by considering a cylindrical line-of-sight, whose surface area is determined by the galaxy virial radius and height by the distance to the source. The same procedure was used to estimate the extra-galactic Shapiro delay contribution to GW150914 [22]. This extra factor is given by $(r_{\text{vir}}/d)^2 \times N_{\text{tot}}$; where $r_{\text{vir}}$ is the virial radius, $d$ is the distance to the source and $N_{\text{tot}}$ is the total number of MW equivalent galaxies, $N_{\text{tot}}$ equal to $3.49 \times 10^8$ at a distance of 1.75 Gpc [35]. This estimate is comparable with that in Ref. [36], given by $N_{\text{tot}} = 3.1 \times 10^9$ at this redshift. Using the estimate of $N_{\text{tot}}$ from Ref. [35] and $r_{\text{vir}} = 250$ kpc, we get a total of 7 MW like galaxies in our cylindrical tube. Therefore, the total estimated Shapiro delay is equal to about 6300 days. We should point out that for our calculation, we have neglected the effects due to Hubble expansion, which would enhance the Shapiro delay estimates computed here [21].

III. CONSTRAINTS ON WEP

Once the Shapiro delay for a given mass distribution is known, if the neutrinos and gamma-rays arrive from the same source within a time interval equal to $\Delta t$, one can constrain the violations of WEP in terms of the PPN parameter $\Delta \gamma = |\gamma_\nu - \gamma_{\text{EM}}|$ and the calculated Shapiro delay $\Delta t_{\text{shapiro}}$ using [17]:

$$
\Delta \gamma \leq 2 \frac{\Delta t}{\Delta t_{\text{shapiro}}}. \quad (2)
$$

In Ref. [1], data for enhanced gamma-ray emission from the Fermi-LAT around the time of the IceCube neutrino event has been presented, after binning the data into seven-day intervals. The peak of the high energy gamma-ray emission happened 15 days prior to the IceCube signal. The probability that this is a chance coincidence has been rejected at $3\sigma$ [1]. Although, because of the coarse binning used by the gamma-ray telescopes, it is not possible to unambiguously determine the exact time difference between the detected neutrino and photons, for a conservative estimate we assume $|\Delta t| = 15$ days. We however note that the actual relative arrival time difference is probably less than a second. Assuming $|\Delta t| = 15$ days, we get $|\Delta \gamma| < 4.8 \times 10^{-3}$. We note however that for a second time lag, we would obtain $|\Delta \gamma| < O(10^{-9})$. This is the first test of WEP for TeV neutrinos over a distance of 1.75 Gpc, as the previous multi-messenger astrophysical neutrino detection occurred in the MeV energy range and at a distance of 50 kpc.

IV. CONCLUSIONS

After the announcement of the first concurrent detection of TeV neutrinos and gamma-ray photons by the IceCube and multiple gamma-ray collaborations [1], we calculated the line-of-sight Shapiro delay to this source (IceCube-170922A) following our previous works [22–24, 33, 34, 37, 38]. The total estimated Shapiro delay is about 3600 days. The coincident detection of gamma-rays allows us to test WEP for neutrinos. Assuming the neutrinos and photons arrived within an interval of 15 days, one can constrain WEP from the difference in PPN $\gamma$ parameters between the neutrinos and photons, and is given by $|\gamma_\nu - \gamma_{\text{EM}}| < 4.8 \times 10^{-3}$. This is the first such test for TeV neutrinos and is complementary to the limit obtained for MeV neutrinos from SN1987A [11, 12].

Note Added: After this work appeared on arXiv, we found two other works [39, 40], which have also independently set a limit on WEP for this event. Both of these used the gravitational potential of the Laniakea supercluster to estimate the Shapiro delay. Using $\Delta t = 7$ days [39] and $\Delta t = 15$ days [40], the inferred $\Delta \gamma$ values are given by $|\Delta \gamma| < 3.5 \times 10^{-7}$ and $|\Delta \gamma| < 7.3 \times 10^{-7}$, respectively.
Acknowledgments

E.O.K. acknowledges support from TUBA-GEBIP 2016, the Young Scientists Award Program. We are grateful to Richard Woodard for prior collaboration on these calculations and also acknowledge useful exchange with Ranjan Laha and Xiang-Yu Wang.

[1] M. Aartsen et al. (Liverpool Telescope, Swift/NuSTAR, MAGIC, H.E.S.S., AGILE, Kiso, VLA/17B-403, INTEGRAL, Kapteyn, Subaru, HAWC, Fermi-LAT, ASAS-SN, VERITAS, Kanata, IceCube), Science 361, eaat1378 (2018).
[2] I. I. Shapiro, Physical Review Letters 13, 789 (1964).
[3] I. I. Shapiro, M. E. Ash, and M. J. Tausner, Physical Review Letters 17, 933 (1966).
[4] B. Bertotti, L. Iess, and P. Tortora, Nature (London) 425, 374 (2003).
[5] E. B. Fomalont and S. M. Kopeikin, Astrophys. J. 598, 704 (2003), astro-ph/0302294.
[6] C. M. Will, Living Reviews in Relativity 17, 4 (2014), 1403.7377.
[7] J. H. Taylor, Jr., Reviews of Modern Physics 66, 711 (1994).
[8] P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts, and J. W. T. Hessels, Nature (London) 467, 1081 (2010), 1010.5788.
[9] R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, and A. Ciocio, Physical Review Letters 58, 1494 (1987).
[10] K. Hirata, T. Kajita, M. Koshiba, M. Nakahata, and Y. Oyama, Physical Review Letters 58, 1490 (1987).
[11] M. J. Longo, Physical Review Letters 60, 173 (1988).
[12] L. M. Krauss and S. Tremaine, Physical Review Letters 60, 176 (1988).
[13] J. D. Franson, New Journal of Physics 16, 065008 (2014), 1111.6986.
[14] J. M. Losecco, Phys. Rev. D 38, 3313 (1988).
[15] Z.-Y. Wang, R.-Y. Liu, and X.-Y. Wang, Physical Review Letters 116, 151101 (2016), 1602.06805.
[16] H. Gao, X.-F. Wu, and P. Mészáros, Astrophys. J. 810, 121 (2015), 1509.0150.
[17] J.-J. Wei, H. Gao, X.-F. Wu, and P. Mészáros, Physical Review Letters 115, 261101 (2015), 1512.07670.
[18] S. J. Tingay and D. L. Kaplan, Astrophys. J. Lett. 820, L31 (2016), 1602.07643.
[19] X.-F. Wu, J.-J. Wei, M.-X. Lan, H. Gao, Z.-G. Dai, and P. Mészáros, Phys. Rev. D 95, 103004 (2017), 1703.09935.
[20] J.-J. Wei, J.-S. Wang, H. Gao, and X.-F. Wu, Astrophys. J. Lett. 818, L2 (2016), 1601.04145.
[21] A. Nusser, Astrophys. J. Lett. 821, L2 (2016), 1601.03636.

[22] E. O. Kahya and S. Desai, Phys. Lett. B756, 265 (2016), 1602.04779.
[23] S. Desai and E. Kahya, European Physical Journal C 78, 86 (2018), 1612.02532.
[24] S. Boran, S. Desai, E. O. Kahya, and R. P. Woodard, Phys. Rev. D 97, 041501 (2018), 1710.06168.
[25] I. M. Shoemaker and K. Murase, Phys. Rev. D 97, 083013 (2018), 1710.06427.
[26] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, et al., Astrophys. J. Lett. 848, L13 (2017), 1710.05834.
[27] 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.
[28] 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. Lett. 851, L18 (2017), 1710.05805.
[29] S. K. Bose and W. D. McGinn, Phys. Rev. D 38, 2335 (1988).
[30] S. Paiano, R. Falomo, A. Treves, and R. Scarpa, The Astrophysical Journal Letters 854, L32 (2018).
[31] E. L. Wright, Pub. Astro. Soc. Pacific 118, 1711 (2006), astro-ph/0609593.
[32] J. F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. 462, 563 (1996), astro-ph/9508025.
[33] E. O. Kahya, Physics Letters B 701, 291 (2011), 1001.0725.
[34] S. Desai, E. O. Kahya, and R. P. Woodard, Phys. Rev. D 77, 124041 (2008), 0804.3804.
[35] P. Simon and S. Hilbert, Astron. & Astrophys. 613, A15 (2018), 1711.02677.
[36] C. J. Conselice, A. Wilkinson, K. Duncan, and A. Mortlock, Astrophys. J. 830, 83 (2016), 1607.03909.
[37] E. O. Kahya, Classical and Quantum Gravity 25, 184008 (2008), 0801.1984.
[38] S. Desai and E. O. Kahya, Modern Physics Letters A 31, 1650083 (2016), 1510.08228.
[39] R. Laha, ArXiv e-prints (2018), 1807.05621.
[40] J.-J. Wei, B.-B. Zhang, L. Shao, H. Gao, Y. Li, Q.-Q. Yin, X.-F. Wu, X.-Y. Wang, B. Zhang, and Z.-G. Dai (2018), 1807.06504.