Remarks on Graviton Propagation in Light of GW150914

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Abstract

The observation of gravitational waves from the Laser Interferometer Gravitational-Wave Observatory (LIGO) event GW150914 may be used to constrain the possibility of Lorentz violation in graviton propagation, and the observation by the Fermi Gamma-Ray Burst Monitor of a transient source in apparent coincidence may be used to constrain the difference between the velocities of light and gravitational waves: $c_g - c_\gamma < 10^{-17}$.

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The discovery of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) in event GW150914 [1] opens a new era in astronomy, making possible the measurement of astrophysical processes that have been inaccessible to observations with electromagnetic waves. The question then arises what fundamental physics we can learn from gravitational wave observations in general and LIGO event GW150914 in particular. As examples, the LIGO Collaboration itself [2] has reported an upper limit on the graviton mass $m_g < 10^{-22}$ eV, and it has been suggested that observations of binary black-hole mergers could constrain models of quantum physics near black-hole event horizons [3].

In this comment we derive two additional constraints on graviton propagation, assuming that it is massless. First, the LIGO data on GW150914 can be used to constrain the possibility of Lorentz violation [4] in gravitational wave propagation, assuming that low-frequency gravitational waves (low-energy gravitons) travel at the conventional speed of light in vacuo $c$ (that we set to unity from now on), whereas higher-frequency waves (higher-energy gravitons) may travel at frequency- (energy-)dependent velocities. Secondly, assuming instead that the velocities of gravitational and electromagnetic waves $c_g$ and $c_\gamma$ are frequency- (energy-)independent, we use the apparent coincidence of a transient source with photon energies $> 50$ keV observed by the Fermi Gamma-Ray Burst Monitor (GBM) [5] to constrain the difference between the velocities of light and gravitational waves in vacuo: $c_\gamma - c_g < 10^{-17} c$.

The LIGO constraint on the graviton mass was obtained from a detailed numerical comparison of the measured GW150914 wave-form with that calculated for a black-hole merger [2]. We recall that the GW150914 signal consisted of a ‘chirp’ of increasing frequencies $\omega \sim 100$ Hz, with a range of frequencies $\Delta \omega = O(100)$ Hz. The presence of a gravitino mass would induce an energy- (frequency-)dependent deviation of the velocities of the waves emitted during the ‘chirp’ from that of light: $\Delta v|_{m_g} \sim -m_g^2/2\omega^2$. Such a deviation $\Delta v$ would cause a dispersion in their arrival times [6], which is constrained by concordance of the observed signal with numerical relativity calculations.

It was suggested in [7] that quantum-gravitational effects might induce an energy- (frequency-)dependent velocity of propagation in vacuo for both electromagnetic and gravitational waves $\Delta v|_{LV n} \simeq -\xi(\omega/M_n)^n : n = 1$ or 2 where $M_n$ is some large mass scale, where $\xi = +1(−1)$ for subluminal (superluminal) propagation and low-energy (-frequency) waves would travel at the conventional velocity of light. Such a Lorentz-violating effect would give rise to an energy-dependent dispersion in the arrival times of gravitational waves, though with a different energy dependence from a graviton mass. Such Lorentz violation might be induced by the effects of space-time foam on wave prop-
agation, in which case one might expect that \( M_n = \mathcal{O}(M_P) \sim 10^{19} \text{ GeV} \). We recall that subluminal propagation is implied by concrete models of space-time foam within brane theory \[8\].

It was suggested \[9\] that the existence of such Lorentz violation \[4\] could best be probed by studying energetic photon emissions from distant transient astrophysical sources such as gamma-ray bursters (GRBs) or active galactic nuclei (AGNs). The most sensitive limits on such an effect have been placed by MAGIC \[10\] and HESS \[11\] observations of AGNs and Fermi observations of GRBs \[12\]. No analogous constraint has previously been established on the possibility of such Lorentz violation in the propagation of gravitational waves (gravitons), but this is now possible with the LIGO discovery of the gravitational waves produced in event GW150914, as we now discuss.

In order to obtain a first order-of-magnitude constraint on Lorentz violation in gravitational wave propagation, we assume that a detailed numerical analysis could establish a limit on \( \Delta v_{LVn} \) as the LIGO Collaboration established on \( \Delta v_{mg} \), considering as an illustration the linear subluminal LV case \( n = 1 \).

\[
\Delta v_{LV1} = -\left( \frac{\omega}{M_1} \right) \approx \Delta v_{mg} = -\left( \frac{m_g^2}{2\omega^2} \right).
\]

Accordingly, we estimate \( M_1 \gtrsim 2\omega^3/m_g^2 \), where we estimate \( \omega \simeq 100 \text{ Hz} \) and use the LIGO limit \( m_g \lesssim 10^{-22} \text{ eV} \) to obtain \( M_1 \gtrsim 100 \text{ keV} \).

Clearly, this is many orders of magnitude less than the limit \( M_1 \gtrsim 10^{19} \text{ GeV} \) obtained for photons (electromagnetic waves) \[10\][12], and also many orders of magnitude less than the naive expectation based on ideas of space-time foam, but it is a start \[7\].

The limit \[2\] corresponds to a variation in in the velocities of the \( \mathcal{O}(100) \text{ Hz} \) gravitational waves emitted by GW150914 at the level of \( \mathcal{O}(10^{-17}) \). As such, it would have a negligible effect on the physical scale of the merger event, and hence on the waveform of the gravitational waves (\( 10^{-12} \text{ m on a scale of 100 km} \)). Certainly, no such effect would be expected in the framework \[7,8\] that motivated this study. The sensitivity to Lorentz violation should be evaluated using a full numerical simulation of the black-hole

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1Since the source of event GW150914 is estimated to have a redshift \( z \lesssim 0.1 \), effects due to cosmological expansion and uncertainties in the cosmological model do not affect significantly our estimate. We expect a similar limit in the superluminal case where the LV effect would have the opposite sign from a graviton mass.

2We note that substituting the lower limit \[2\] back into the expression \[1\] for gravitational wave with \( \omega \sim 100Hz \) yields (in our subluminal example): \( \Delta v_{LV1} = c_g - 1 \sim 4 \times 10^{-18} \), which corresponds also to the deviation of the propagation speed of massive gravitons from the massless case in a Lorentz-invariant vacuum.
merger, and one might expect the sensitivity to increase by an order of magnitude with the observation of a neutron-star merger with characteristic frequency $\omega \sim 1000$ Hz. Looking to the future, observations of the mergers of more massive black holes would not give an increase in sensitivity, but a new frontier would be opened if/when tensor CMB perturbations are observed [13].

We now discard the possibility of energy (frequency) dependence in the velocities of gravitational and electromagnetic wave propagation, and ask instead how similar these velocities must be. For this analysis [3] we use the arrival times of the GW150914 signal and the apparently coincident flash of photons with energies $> 50$ keV observed $\sim 0.4$ s later by the Fermi GBM [5]. The plausibility of the Fermi GBM signal has been questioned [16], but also a number of models have been proposed to explain it [17], which predict that any such photons would have been emitted in the aftermath of the merger. Using the distance estimate of $\sim 10^9$ light-years to the source of GW150914, the following upper bound on the difference between the velocities of light and gravitational waves, $c_g - c_\gamma$:

$$c_g - c_\gamma \lesssim 10^{-17}.$$  

We note that the possibility $c_g < c_\gamma$ cannot be excluded if the photons were emitted more than 0.4 s after the gravitational waves.

Another constraint on the velocity of gravitation waves from GW150914 was given in [18], but this is much more stringent [5]. For completeness, we recall that an indirect lower bound on $c_g$ was set in [19], derived from the non-observation of gravitational Cherenkov radiation from high-energy cosmic rays. If the origin of the latter is assumed to be extragalactic then $c_\gamma - c_g < 2 \times 10^{-19} c_\gamma$, otherwise the bound is weaker: $c_\gamma - c_g < 2 \times 10^{-15} c_\gamma$. On the other hand, we emphasise that our constraint $c_g - c_\gamma \lesssim 10^{-17}$ cannot be regarded as definitive, since the Fermi GBM report [3] cannot be regarded as a definitive observation of a photon flash in coincidence with GW150914. We await with interest possible future observations of light flashes coincident with gravitational wave events.

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3 For previous discussions of the possibility of such an analysis and the assumptions involved, see [14].

4 We note, however, that the significance of this apparent coincidence is not high, and that the INTEGRAL experiment did not see a signal of similar strength at similar energies [15].

5 Previous upper limits on Lorentz violation in photon propagation [10,12] ensure that the $c_\gamma$ inferred from the putative Fermi GBM observation of GW150914 can be identified with the standard velocity of light with an accuracy much greater than this constraint.
Note Added

The LIGO Collaboration has recently reported \cite{20} the observation of a second gravitational wave event, GW151226, interpreted as the merger of two black holes with masses \( \sim 14.2 \) and 7.5 solar masses at a distance \( d \sim 440 \) Mpc. The peak amplitude of the gravitational wave train is at \( \sim 450 \) Hz. We make a rough estimate of the sensitivity to \( M_1 \), as follows. In view of the consistency of the gravitational wave train with calculations in general relativity, we assume that

\[
\Delta v \cdot d \lesssim \frac{1}{\omega},
\]

where \( \Delta v \) is the fractional deviation of the wave propagation velocity from that of light, and we take (conservatively) \( \omega \sim 200 \) Hz, leading to

\[
M_1 = \frac{\omega}{\Delta v} \gtrsim 400 \text{ keV}.
\]

This very crude estimate would need to be refined by a detailed numerical analysis, but it reinforces the point that mergers of smaller objects can give more stringent constraints on Lorentz violation.

To date, there have been only negative results from searches \cite{21} for a possible electromagnetic counterpart to GW151226, so it provides no further constraint on any possible difference between the velocities of gravitational and electromagnetic waves.

We note finally that the LIGO Collaboration describe also \cite{22} a possible signal (LVT151012) for a merger of a pair of black holes with masses \( \sim 28, 16 \) solar masses at a distance \( \sim 1000 \) Mpc. If real, this merger would have a sensitivity to \( M_1 \) intermediate between those of GW150914 \cite{2} and GW151226 \cite{4}.

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References

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

[2] B. P. Abbott et al. [LIGO Scientific Collaboration and Virgo Collaboration], “Tests of general relativity with GW150914,” arXiv:1602.03841 [gr-qc].

[3] S. B. Giddings, “Gravitational wave tests of quantum modifications to black hole structure,” arXiv:1602.03622 [gr-qc].

[4] For reviews on models and constraints see: S. Liberati, “Lorentz symmetry breaking: phenomenology and constraints,” J. Phys. Conf. Ser. 631, no. 1, 012011 (2015). doi:10.1088/1742-6596/631/1/012011 “Tests of Lorentz invariance: a 2013 update,” Class. Quant. Grav. 30, 133001 (2013) doi:10.1088/0264-9381/30/13/133001 [arXiv:1304.5795 [gr-qc]]; G. Amelino-Camelia, “Quantum-Spacetime Phenomenology,” Living Rev. Rel. 16, 5 (2013) doi:10.12942/lrr-2013-5 [arXiv:0806.0339 [gr-qc]]; J. Ellis and N. E. Mavromatos, “Probes of Lorentz Violation,” Astropart. Phys. 43, 50 (2013) doi:10.1016/j.astropartphys.2012.05.004 [arXiv:1111.1178 [astro-ph.HE]]; N. E. Mavromatos, “String Quantum Gravity, Lorentz-Invariance Violation and Gamma-Ray Astronomy,” Int. J. Mod. Phys. A 25, 5409 (2010) doi:10.1142/S0217751X10050792 [arXiv:1010.5354 [hep-th]], and references therein.

[5] V. Connaughton et al., “Fermi GBM Observations of LIGO Gravitational Wave event GW150914.” arXiv:1602.03920 [astro-ph.HE].

[6] C. M. Will, “Bounding the mass of the graviton using gravitational wave observations of inspiralling compact binaries,” Phys. Rev. D 57, 2061 (1998) doi:10.1103/PhysRevD.57.2061 [gr-qc/9709011].

[7] G. Amelino-Camelia, J. R. Ellis, N. E. Mavromatos and D. V. Nanopoulos, “Distance measurement and wave dispersion in a Liouville string approach to quantum gravity,” Int. J. Mod. Phys. A 12, 607 (1997) doi:10.1142/S0217751X97000566 [hep-th/9605211].

[8] 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]];
[9] 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 [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].

[10] J. Albert et al. [MAGIC Collaboration], J. Ellis, N. E. Mavromatos, D. V. Nanopoulos, A. S. Sakharov, and E. K. G. Sarkisyan, “Probing Quantum Gravity using Photons from a flare of the active galactic nucleus Markarian 501 Observed by the MAGIC telescope,” Phys. Lett. B 668, 253 (2008) doi:10.1016/j.physletb.2008.08.053 [arXiv:0708.2889 [astro-ph]].

[11] A. Abramowski et al. [HESS Collaboration], “Search for Lorentz Invariance breaking with a likelihood fit of the PKS 2155-304 Flare Data Taken on MJD 53944,” Astropart. Phys. 34, 738 (2011) doi:10.1016/j.astropartphys.2011.01.007 [arXiv:1101.3650 [astro-ph.HE]].

[12] M. Ackermann et al. [Fermi GBM/LAT Collaboration], “A limit on the variation of the speed of light arising from quantum gravity effects,” Nature 462, 331 (2009) doi:10.1038/nature08574 [arXiv:0908.1832 [astro-ph.HE]].

[13] L. Amendola, G. Ballesteros and V. Pettorino, “Effects of modified gravity on B-mode polarization,” Phys. Rev. D 90 (2014) 043009 doi:10.1103/PhysRevD.90.043009 [arXiv:1405.7004 [astro-ph.CO]]; M. Raveri, C. Baccigalupi, A. Silvestri and S. Y. Zhou, “Measuring the speed of cosmological gravitational waves,” Phys. Rev. D 91 (2015) no.6, 061501 doi:10.1103/PhysRevD.91.061501 [arXiv:1405.7974 [astro-ph.CO]].

[14] A. Nishizawa and T. Nakamura, “Measuring Speed of Gravitational Waves by Observations of Photons and Neutrinos from Compact Binary Mergers and Supernovae,” Phys. Rev. D 90 (2014) 4, 044048 doi:10.1103/PhysRevD.90.044048 [arXiv:1406.5544 [gr-qc]]; A. Nishizawa, “Constraining the propagation speed of gravitational waves with compact binaries at cosmological distances,” arXiv:1601.01072 [gr-qc].

[15] V. Savchenko et al., “INTEGRAL upper limits on gamma-ray emission associated with the gravitational wave event GW150914,” [arXiv:1602.04180 [astro-ph.HE]]. Observations at other wavelengths were also negative: B. P. Abbott et al. [LIGO Scientific and Virgo and Australian Square Kilometer Array Pathfinder (ASKAP) and
BOOTES and Dark Energy Survey and Dark Energy Camera and Fermi GBM and Fermi-LAT and GRAvitational Wave Inaf TeAm (GRAWITA) and INTEGRAL and Intermediate Palomar Transient Factory (iPTF) and InterPlanetary Network and J-GEM and La Silla-QUEST Survey and Liverpool Telescope and LOFAR and MASTER and MAXI and MWA and Pan-STARRS and PESSTO and Pi of the Sky and SkyMapper and Swift and C2PU and TOROS and VISTA Collaborations, “Localization and broadband follow-up of the gravitational-wave transient GW150914,” arXiv:1602.08492 [astro-ph.HE], but not directly in contradiction with [5].

[16] M. Lyutikov, “Fermi GBM signal contemporaneous with GW150914 - an unlikely association,” arXiv:1602.07352 [astro-ph.HE].

[17] See, for example, X. Li, F. W. Zhang, Q. Yuan, Z. P. Jin, Y. Z. Fan, S. M. Liu and D. M. Wei, “Implication of the association between GBM transient 150914 and LIGO Gravitational Wave event GW150914,” arXiv:1602.04460 [astro-ph.HE]; B. Zhang, “Mergers of Charged Black Holes: Gravitational Wave Events, Short Gamma-Ray Bursts, and Fast Radio Bursts,” arXiv:1602.04542 [astro-ph.HE]; A. Loeb, “Electromagnetic Counterparts to Black Hole Mergers Detected by LIGO,” Astrophys. J. 819 (2016) no.2, L21 doi:10.3847/2041-8205/819/2/L21 [arXiv:1602.04735 [astro-ph.HE]]; R. Yamazaki, K. Asano and Y. Ohira, “Electromagnetic Afterglows Associated with Gamma-Ray Emission Coincident with Binary Black Hole Merger Event GW150914,” arXiv:1602.05050 [astro-ph.HE]; R. Perna, D. Lazzati and B. Giacomazzo, “Short Gamma-Ray Bursts from the Merger of Two Black Holes,” arXiv:1602.05140 [astro-ph.HE]; B. J. Morsony, J. C. Workman and D. M. Ryan, “Modeling the Afterglow of GW150914-GBM,” arXiv:1602.05529 [astro-ph.HE]; K. Murase, K. Kashiyama, P. Meszaros, I. Shoemaker and N. Senno, “Ultra-fast Outflows from Black Hole Mergers with a Mini-Disk,” arXiv:1602.06938 [astro-ph.HE]; H. Tagawa, M. Umemura and N. Gouda, “Mergers of accreting stellar-mass black holes,” arXiv:1602.08767 [astro-ph.GA]; L. Lehner, S. L. Liebling, C. Palenzuela, O. L. Caballero, E. O’Connor, M. Anderson and D. Neilsen, “Unequal mass binary neutron star mergers and multimessenger signals,” arXiv:1603.00501 [gr-qc]; S. E. Woosley, “The Progenitor of GW 150914,” arXiv:1603.00511 [astro-ph.HE]; D. Malafarina and P. S. Joshi, “Electromagnetic counterparts to gravitational waves from black hole mergers and naked singularities,” arXiv:1603.02848 [gr-qc].

[18] D. Blas, M. M. Ivanov, I. Sawicki and S. Sibiryakov, “On constraining the speed of gravitational waves following GW150914,” arXiv:1602.04188 [gr-qc].
[19] G. D. Moore and A. E. Nelson, “Lower bound on the propagation speed of gravity from gravitational Cherenkov radiation,” JHEP **0109**, 023 (2001) doi:10.1088/1126-6708/2001/09/023 [hep-ph/0106220].

[20] B. Abbott et al., [LIGO Scientific Collaboration and Virgo Collaboration], “GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence” Phys. Rev. Lett. **116** (2016), no. 24, 241103 doi:10.1103/PhysRevLett.116.241103 [arXiv:1606.04855 [gr-qc]].

[21] P. S. Cowperthwaite et al., “A DECam Search for an Optical Counterpart to the LIGO Gravitational Wave Event GW151226,” [arXiv:1606.04538] [astro-ph.HE]; S. J. Smartt et al., “A search for an optical counterpart to the gravitational wave event GW151226,” [arXiv:1606.04795] [astro-ph.HE]; J. L. Racusin et al., “Searching the Gamma-ray Sky for Counterparts to Gravitational Wave Sources: Fermi GBM and LAT Observations of LVT151012 and GW151226,” [arXiv:1606.04901] [astro-ph.HE].

[22] B. Abbott et al., [LIGO Scientific Collaboration and Virgo Collaboration], “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, [arXiv:1606.04856] [gr-qc].