Snowmass2021 - Letter of Interest

Gravitational Wave Propagation as a Probe of Fundamental Physics

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

Contact Information:
Jay D. Tasson (Carleton College) [jay.tasson@ligo.org],
Leïla Haegel (Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France) [leila.haegel@ligo.org],
Kellie Ault-O'Neal (Embry-Riddle Aeronautical University)[aultk@my.erau.edu],

Abstract:

Gravitational wave (GW) observation provides a vast array of new and unique opportunities to test fundamental physics. One such opportunity is to probe the speed of GWs and the related propagation properties of dispersion and birefringence. These tests utilize a variety of GW data-analysis methods and many either require or benefit from electromagnetic-counterpart observations from various parts of the electromagnetic spectrum. Among other things, these tests provide novel, high-sensitivity tests of Lorentz invariance. These tests have been and will continue to be inspired by a variety of theoretical ideas and interpreted in a variety of ways, notably as establishing aspects of the structure of spacetime. They have been used to constrain specific models, like massive gravity, and the results have been reported in the context of phenomenological models, as well as in the context of the effective field-theory based framework of the gravitational Standard-Model Extension (SME). In the coming years, new GW observations and new types of analysis are expected to provide additional probes of fundamental physics that significantly increase both the breadth and depth of these searches.

Introduction. The speed of gravitational waves and whether or not they exhibit dispersion and/or birefringence are foundational questions about gravity that must be addressed by experiment. Apart from their intrinsic merits as fundamental measurements, searches for a GW speed that differs from light, vacuum dispersion, and vacuum birefringence provide opportunities to detect clear evidence for new physics. Lorentz invariance is a foundational principle of spatial symmetry, and is therefore an assumption of both General Relativity through the Einstein equivalence principle and the Standard Model of particle physics. Consequently, violations of Lorentz invariance, such as those that could be signaled by the properties above, are of intense interest because they can arise in a variety of models and frameworks [1–4] and have been identified as a means of probing Planck-scale physics with feasible technology [5]. In the remainder of this letter we address planned and ongoing work to probe each of these properties.

Speed of gravity. As we experimentally interrogate the properties of GWs, their speed is arguably among the most fundamental measurements to be made. General Relativity predicts that GWs propagate at the speed of light, but experimental verification of this was surprisingly limited prior to 2017, consisting of indirectly inferred limits (see discussion in Ref. [6]) and a weak direct test [7] from the GWs emitted by binary systems of black holes and detected by advanced LIGO (aLIGO) [8] and Advanced Virgo (AdVirgo) [9]. The initial observation of GWs and gamma-rays from a single event, the merging of a binary system of neutron stars in aLIGO and AdVirgo, improved this result by a stunning 10 orders of magnitude within some conservative assumptions about the relative time of emission of the messengers. This was further interpreted as correspondingly improved limits on certain Lorentz-violating terms in the SME [6].

Though the initial multimessenger event provided a leap forward in our experimental knowledge of the speed of GWs, it remains one measurement. Additional measurements from future observations promise additional science via a variety of avenues. The relative emission time of the messengers is an additional unknown in speed of gravity measurements that introduced additional assumptions in the initial measurement. As additional events are observed at a variety of distances, the effects of emission time and speed will be disentangled providing more sensitive and more robust measurements. Sensitivity in these measurements increases with distance, another feature that suggests additional improvements will result from the study of additional likely events, particularly as instruments gain the ability to detect more distant sources. Future instruments under study make these possibilities truly impressive. For example, a Voyager-Einstein Telescope network can be expected to make thousands of binary neutron star detections per year at distances of more than 100 times that of the existing binary neutron star detection [10]. Though not all will have electromagnetic counterparts, deticated efforts with electromagnetic observers such as the Fermi Gamma-ray Burst Monitor [11, 12] and the Swift observatory [13] aim to maximize the possibility.

There are also opportunities for additional breadth in these kinds of studies. General Lorentz-violating theories involve anisotropic effects [1]. In the context of speed tests, this involves a relative speed for GWs and photons that is direction dependent. Additional multimessenger events distributed across the sky will permit exploration of this possibility with high sensitivity. Since GW observations that come with photon observations are rare relative to the number of GW observations overall, lower sensitivity techniques based on GW observations alone are also being used to probe this possibility [14]. Finally, comparing speeds with a third messenger, neutrinos, provides another copy of many of these questions.

Dispersion. The notion that gravitational waves have the same speed independent of their frequency or polarization underlies the discussion above which focuses on comparing the speed of GWs to the speed of other particles. Here we effectively consider comparing the speeds of the multiple frequencies of GWs, which would manifest itself in GW observations as a frequency-dependent dephasing of the signal. To date, the LIGO and Virgo Collaborations have explored this possibility [15–17] in terms of the popular phenomenological dispersion relation $E^2 = p^2 + A_\alpha p^\alpha$, where E is energy, p is momentum, and A_α, α are phenomenological parameters [2]. Values of α from 0 to 4 in half-integer steps (excluding $\alpha = 2$) have been constrained from the propagation of GWs emitted by coalescing binary systems of black holes and neutron stars [15–17]. The $\alpha = 0$ case corresponds to a massive graviton and the $\alpha = 2$ case, which is not constrained by GW observations alone, is captured by the speed comparisons considered in the prior section. The power of dispersive searches for Lorentz violation is highlighted by comparison with the photon sector, where Lorentz symmetry has been tested effectively by seeking vacuum dispersion of photons from astrophysical sources [18–20]. The current constraints from GW measurements are improving with the new detections occurring in each aLIGO and AdVirgo run, and will improve further as advanced ground- and space- based interfermometers are developed [21]. The considerably increased sensitivity of the future space-based interferometer LISA, that will detect GWs from several binary systems of black holes per day originating from a considerably increased volume of the Universe, will extend the reach of these tests by orders of magnitude [22].

Beyond the promise of improved sensitivities in the future, the current phenomenological model has only a partial overlap with the possibilities that arise in a complete field-theory-based analysis of linearized gravity [1, 23]. Here, anisotropy is explicit and remains to be probed. The search for anisotropic dispersion may also be facilitated by electromagnetic observations since precise sky localization significantly improves the analysis. In addition to highlighting the possibility of anisotropy, the field-theoretic analysis shows that a different set of powers of the momentum are of interest. Lorentz violation has been probed with a wide range of techniques [24], and the field theoretic framework of the SME provides opportunities to compare GW-related tests with other methods.

Birefringence. In addition to offering additional insights into the search for dispersion, the complete field-theory-based analysis of linearized gravity provided by the SME highlights the possibility of birefringence [1, 23]. Constraints on anisotropic birefringence have been performed with the events detected during the first two observational runs of aLIGO and AdVirgo [1, 25]. Improved analysis methods are currently being developed for application to future events that will make more direct use of GW data. Birefringence offers the final notion of a ‘speed test’ as it can be understood as comparing the speed of different polarizations of GWs. The effect leads to frequency-dependent changes in the polarization, thus a polarization that changes with frequency is the key signal [23]. In extreme cases, these sorts of Lorentz violation can even generate pulse separation [1, 25].

Within a field-theoretic description, dispersion comes with birefringence at odd powers of the momentum making birefringence a part of a consistent search in this context. Like the other signals discussed in this letter, birefringence may also be anisotropic. Hence, exploring multiple events distributed across the sky is of interest. Searching for birefringence probes a qualitatively new property of GWs and tests additional types of Lorentz-invariance violation. Like vacuum dispersion, searches for vacuum birefringence of photons from astrophysical sources have also been used very effectively already in the search for new physics [18, 26, 27] and are likely to continue to do so [28].

Summary. In addition to being necessary measurements in placing the basic wave properties of GWs on an experimental footing, tests of the propagation properties of GWs will provide a powerful tool in the search for new physics over the next decade.

References

[1] V.A. Kostelecký and M. Mewes. Testing local Lorentz invariance with gravitational waves. *Phys. Lett. B*, 757:510–514, Jun 2016.

[2] S. Mirshekari, N. Yunes, and C.M. Will. Constraining Lorentz-violating, modified dispersion relations with gravitational waves. *Phys. Rev. D*, 85:024041, Jan 2012.

[3] G. Calcagni. Fractal universe and quantum gravity. *Phys. Rev. Lett.*, 104:251301, Jun 2010.

[4] P. Hořava. Quantum gravity at a lifshitz point. *Phys. Rev. D*, 79:084008, Apr 2009.

[5] V.A. Kostelecký and S. Samuel. Spontaneous breaking of Lorentz symmetry in string theory. *Phys. Rev. D*, 39:683–685, Jan 1989.

[6] B.P. Abbott et al. Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A. *Astrophys. J.*, 848:L13, Oct 2017.

[7] N. Cornish, D. Blas, and G. Nardini. Bounding the speed of gravity with gravitational wave observations. *Phys. Rev. Lett.*, 119:161102, Oct 2017.

[8] J. Aasi et al. Advanced LIGO. *Class. Quant. Grav.*, 32:074001, 2015.

[9] F. Acernese et al. Advanced Virgo: a second-generation interferometric gravitational wave detector. *Class. Quant. Grav.*, 32(2):024001, 2015.

[10] C. Mills, V. Tiwari, and S. Fairhurst. Localization of binary neutron star mergers with second and third generation gravitational-wave detectors. *Phys. Rev. D*, 97:104064, May 2018.

[11] The Fermi Gamma-ray Burst Monitor Team, the LIGO Scientific Collaboration, the Virgo Collaboration, :, R. Hamburg, et al. A joint Fermi-GBM and LIGO/Virgo analysis of compact binary mergers from the first and second gravitational-wave observing runs. *arXiv:2001.00923*, 2020.

[12] E. Burns et al. A Fermi gamma-ray burst monitor search for electromagnetic signals coincident with gravitational-wave candidates in advanced LIGO's first observing run. *The Astrophysical Journal*, 871(1):90, jan 2019.

[13] A. Tohuvavohu et al. Gamma-ray urgent archiver for novel opportunities (GUANO): Swift/bat event data dumps on demand to enable sensitive sub-threshold GRB searches. *arXiv:2005.01751*, 2020.

[14] X. Liu et al. Measuring the speed of gravitational waves from the first and second observing run of advanced LIGO and advanced Virgo. *Phys. Rev. D*, 102:024028, Jul 2020.

[15] B. P. Abbott et al. Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1. *Phys. Rev. D*, 100:104036, Nov 2019.

[16] B. P. Abbott et al. GW170104: Observation of a 50-solar-mass binary black hole coalescence at redshift 0.2. *Phys. Rev. Lett.*, 118:221101, Jun 2017.

[17] B.P. Abbott et al. Tests of general relativity with GW170817. *Phys. Rev. Lett.*, 123:011102, Jul 2019.

[18] A.S. Friedman et al. Constraints on Lorentz invariance and *cpt* violation using optical photometry and polarimetry of active galaxies bl lacertae and s5 $\mathrm{B0716}+714$. *Phys. Rev. D*, 99:035045, Feb 2019.

[19] F. Kislat and H. Krawczynski. Search for anisotropic Lorentz invariance violation with γ-rays. *Phys. Rev. D*, 92:045016, Aug 2015.

[20] V. Vasileiou et al. Constraints on Lorentz invariance violation from Fermi-Large Area Telescope observations of gamma-ray bursts. *Phys. Rev. D*, 87:122001, Jun 2013.

[21] A. Samajdar and K. G. Arun. Projected constraints on the dispersion of gravitational waves using advanced ground- and space-based interferometers. *Phys. Rev. D*, 96:104027, Nov 2017.

[22] E. Barausse et al. Prospects for fundamental physics with LISA. *arXiv:2001.09793*, 1 2020.

[23] M. Mewes. Signals for Lorentz violation in gravitational waves. *Phys. Rev. D*, 99:104062, May 2019.

[24] V.A. Kostelecký and N. Russell. Data tables for Lorentz and CPT violation, 2020 Edition,. *arXiv:0801.0287v13*, 2020.

[25] L. Shao. Combined search for anisotropic birefringence in the gravitational-wave transient catalog GWTC-1. *Phys. Rev. D*, 101(10):104019, 2020.

[26] F. Kislat and H. Krawczynski. Planck-scale constraints on anisotropic Lorentz and CPT invariance violations from optical polarization measurements. *Phys. Rev. D*, 95:083013, Apr 2017.

[27] E. Komatsu et al. Seven-year wilkinson microwave anisotropy probe (WMAP) observations: Cosmological interpretation. *The Astrophysical Journal Supplement Series*, 192(2):18, Jan 2011.

[28] L. Pogosian, M. Shimon, M. Mewes, and B. Keating. Future cmb constraints on cosmic birefringence and implications for fundamental physics. *Phys. Rev. D*, 100:023507, Jul 2019.

Additional Authors:

Michalis Agathos (University of Cambridge) [magathos@damtp.cam.ac.uk]
Ofek Birnholtz (Bar-Ilan University) [ofek.birnholtz@biu.ac.il]
Michael S. Briggs (University of Alabama in Huntsville) (michael.briggs@uah.edu)
Eric Burns (Louisiana State University) [ericburns@lsu.edu]
Marco Cavaglia (Missouri University of Science and Technology) [cavagliam@mst.edu]
Sylvain Chaty (Université de Paris, France) [sylvain.chaty@u-paris.fr]
Nelson Christensen (Observatoire de la Côte d'Azur) [nelson.christensen@oca.eu]
Sebastien Clesse (University of Louvain) [sebastien.clesse@uclouvain.be]
Michael Coughlin (University of Minnesota) [cough052@umn.edu]
Raymond Frey (University of Oregon) [rayfrey@uoregon.edu]
Archisman Ghosh (Ghent University) [archisman.ghosh@ugent.be]
Adam Goldstein (Universities Space Research Association) [agoldstein@usra.edu]
Maximiliano Isi (Massachusetts Institute of Technology) [maxisi@mit.edu]
Rico K. L. Lo (California Institute of Technology) [kllo@caltech.edu],
Bagrat Mailyan (Center for Underground Physics, Institute for Basic Science, South Korea) [mbagrat@gmail.com]
Suvodip Mukherjee (University of Amsterdam)[s.mukherjee@uva.nl]
Francesco Pannarale (Sapienza University of Rome) [francesco.pannarale@uniroma1.it]
Brandon Piotrzkowski (University of Wisconsin-Milwaukee) [piotrzk3@uwm.edu]
Geraint Pratten (University of Birmingham) [g.pratten@bham.ac.uk]

Mairi Sakellariadou (King's College London) [mairi.sakellariadou@kcl.ac.uk]
Danièle Steer (APC, University of Paris, France) [steer@apc.univ-paris7.fr]
Nicola Tamanini (Max Planck Institute for Gravitational Physics) [nicola.tamanini@aei.mpg.de]
Aaron Tohuvavohu (University of Toronto) [tohuvavohu@astro.utoronto.ca]
Rhondale Tso (California Institute of Technology) [rtso@caltech.edu]
Péter Veres (University of Alabama in Huntsville) [peter.veres@uah.edu]