Searching for Lorentz Violation with Multi-messenger Gravitational Astronomy

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Abstract

Violations of relativity (Lorentz violation), if detected, could provide experimental evidence of the long-sought unified theory of physics that combines quantum physics and General Relativity. Gravitational waves, ripples in spacetime that travel to us from distance collisions of star-like objects, provide a new tool in the ongoing search for Lorentz violation. Recently Earth-based gravitational-wave detectors observed gravitational waves and light from the same astrophysical event, making a sensitive comparison of the speeds of these waves possible. The speed comparison and the sky position of the event can be used to significantly extend the depth of the Lorentz-violation search, because a difference in the speeds of the signals implies a Lorentz violation. A linear programming optimization approach can refine the search further once a sufficient number of multi-messenger events have been observed. We have assembled a codebase to automate these calculations.

Background

General Relativity predicts that shaking masses create ripples in space-time called gravitational waves that propagate through space. Gravitational waves are extremely faint: they would cause a 1 km-long object to shift in length by less than a hundredth of the width of a proton. Consequently, detecting these signals is a major challenge. The first gravitational waves were detected by the Laser Interfereometer Gravitational Observatory (LIGO) in 2015, using two pairs of perpendicular 4 km-long tunnels (as shown in Fig. 1) that use laser light to very accurately measure fluctuations in distance [1].

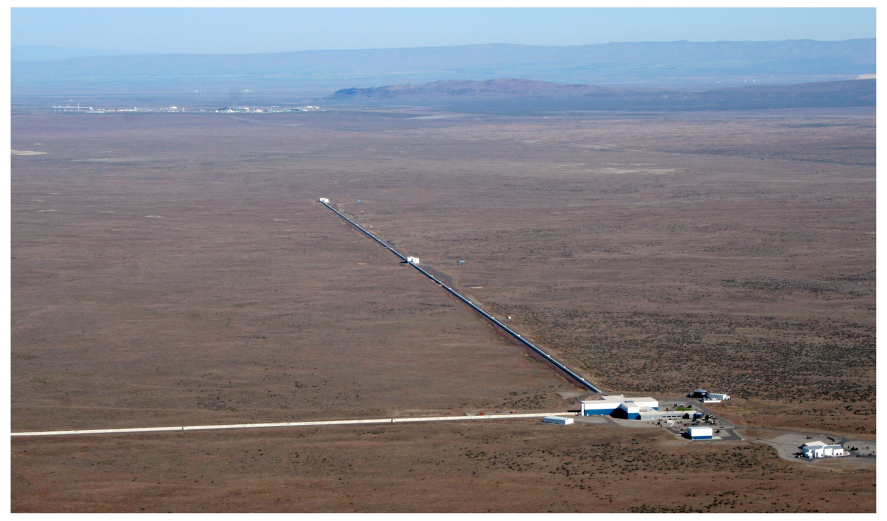

Figure 1: An aerial view of the LIGO Hanford Observatory in Washington, USA. (https://www.ligo.org/multimedia/gallery/lho.php)

Another gravitational wave detection was the merging of a binary neutron star system, which is the only astronomical event from which both gravitational and electromagnetic waves have been detected. Approximately 2 seconds after the gravitational signal, a gamma ray burst from the same event was recorded by an earth-orbiting detector. This seconds-long delay occurred over a travel time of approximately 130 million years [2]. General Relativity predicts that gravitational waves propagate at the speed of light, so the difference in arrival times between these two signals poses an interesting problem. Though the delay is likely due to emission time differences, the two signals traveling at different speeds would indicate Lorentz violation.

The Standard-Model Extension

The Standard-Model Extension (SME) is a theoretical framework to catalog the search for Lorentz violation, a dependence of results on the velocity or orientation of the experiment. Should these violations be detected, they would provide valuable experimental evidence and analytic insight for a unified theory of quantum physics and General Relativity. [3] Lorentz violations in the SME are quantified by coefficients, whose values can be sought in experiments. This can be thought of as a series expansion where the first term contains all of known physics and each addition accounts for some violation thereof.

Multi-messenger Astronomy

The difference in velocity of gravitational and electromagnetic waves in the SME is given by

$$\Delta v = -\sum_{\substack{\ell m \\ \ell \leq 2}} Y_{\ell m}(\hat{n}) \left(\frac{1}{2}(-1)^{1+\ell} \bar{s}_{\ell m} - \bar{c}_{\ell m} \right), \qquad (1)$$

Where $Y_{\ell m}$ is a spherical harmonic (visualized in Fig. 2), $\hat{n}$ is the position of the event in the sky, and $\bar{s}$ and $\bar{c}$ are coefficients for Lorentz violation in the gravitational and electromagnetic sectors, respectively. Note that direction-dependent speed differences would be expected.

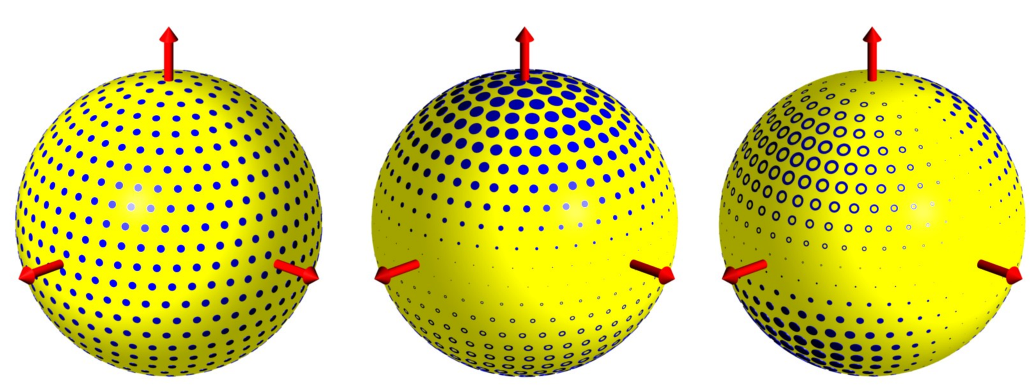

Figure 2: An illustration of the spherical harmonics (from left to right) Y_{00}, Y_{10}, and Y_{21}. The circles' radii represent the magnitude of the spherical harmonic at that location. Filled circles indicate positive values, while empty circles indicate negative values. (https://web.calpoly.edu/~mmewes/)

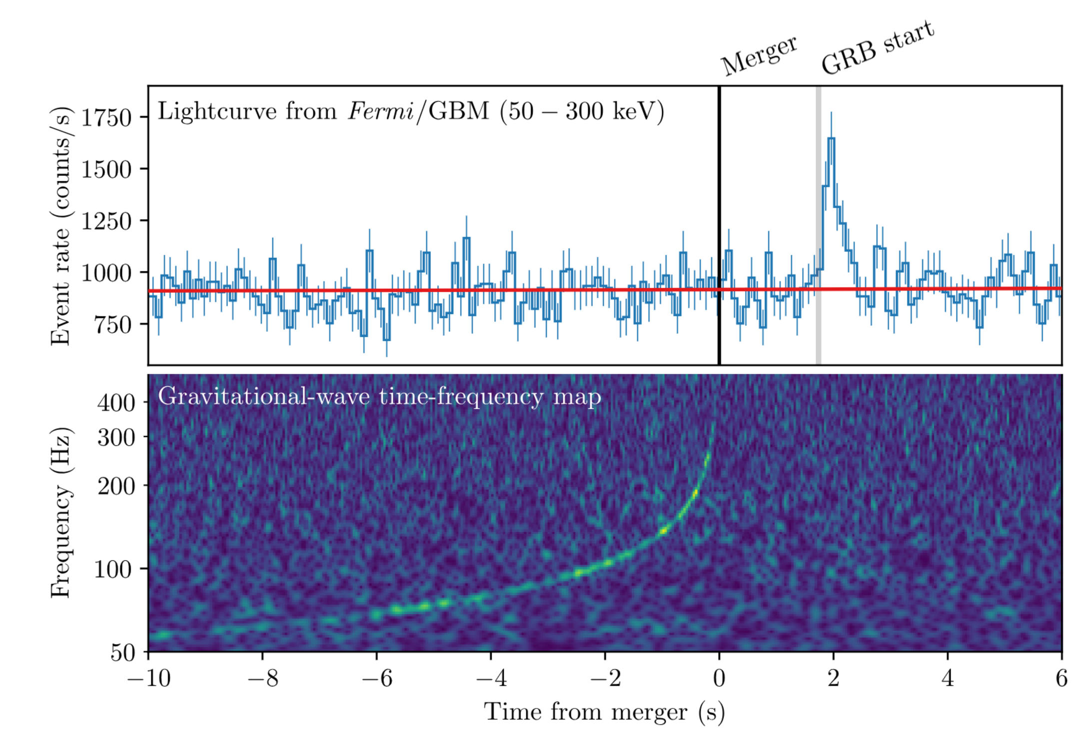

Figure 3: The coincidence of the LIGO gravitational wave (bottom) and Fermi gamma ray burst (top) signals from the binary neutron star merger. [2]

Single Event

For a single multi-messenger event, we can constrain each coefficient for Lorentz violation individually. By setting all electromagnetic sector coefficients and all but one gravitational sector coefficient to zero, we obtain from Eqn. 1 the expression

$$\Delta v = -Y_{\ell m}(\hat{n}) \left(\frac{1}{2}(-1)^{1+\ell} \bar{s}_{\ell m} \right) \qquad (2)$$

from which we can calculate upper and lower bounds for $\bar{s}_{lm}$ using $\Delta v_{\min}$ and $\Delta v_{\max}$. This method is viable because there is no theoretical reason to expect multiple different violations of Lorentz symmetry in opposition to each other; in addition, this method is for temporary use until a sufficient number of events have been observed to make use of the linear programming constraint method. This method was used to constrain coefficients for gravitational Lorentz violation following the first detection of a multi-messenger gravitational event, and improved the previous constraints by several orders of magnitude [2].

Linear Programming Constraint

An example constraining two values rather than nine as in Fig. 4 is useful to understanding the linear programming constraint method. Consider the generic coefficients s_1 and s_2, bounded by two linear combination constraints similar to Eqn. 3. The two constraints taken individually are unbounded, but the region that satisfies both constraints has distinct minima and maxima for s_1 and s_2—in this case, the four vertices of the quadrilateral shape created.

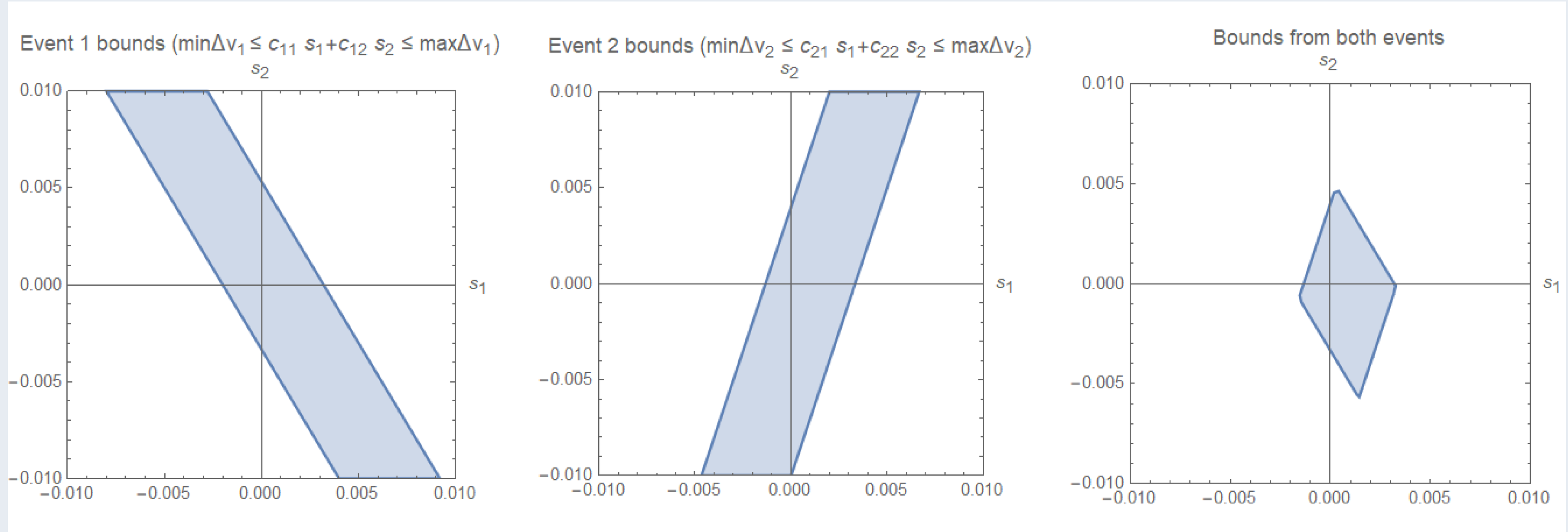

Figure 4: An example of a linear programming constraint in two dimensions.

Multiple Events

There are nine leading-order terms in the series expansion describing gravitational Lorentz violation. As such, nine multi-messenger events are necessary for a linear programming constraint on these coefficients. Using the bounds on Δv from each event, Eqn. 1 yields two inequalities that can be combined into

$$\Delta v_{\min} \leq -\sum_{\substack{\ell m \\ \ell \leq 2}} Y_{\ell m}(\hat{n}) \left(\frac{1}{2}(-1)^{1+\ell} \bar{s}_{\ell m} \right) \leq \Delta v_{\max}. \qquad (3)$$

Since the sky position of each event is known and we are assuming the electromagnetic sector coefficients to be zero, the center term of Eqn. 3 becomes a linear combination of the nine gravitational coefficients. These coefficients will be unbounded until there are at least nine sets of bounds, at which point all coefficients will have some minimum and maximum on the bounded region.

Moving Forward

The single and multiple event methods described here have been implemented in Python 2.7, and are ready to be used with any multi-messenger events that may be detected starting with LIGO's third observational run in 2019. However, more improvements can be added to this system before then. One is using luminosity distance and arrival time difference to automate the calculation of Δv_{min} and Δv_{max}, as well as adjust these values for a variety of confidence intervals and assumptions regarding emission time. In addition, with the detection of more events, we should be able to determine how much of the differences in arrival time come from differences in emission time. This is because a time delay due to difference in propagation velocity between the two signals should increase with respect to the distance traveled by the signals, whereas a difference in emission time would not.

References

[1] B. P. Abbott et al.
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[2] B. P. Abbott et al.
Gravitational waves and gamma-rays from a binary neutron star merger: GW170817 and GRB 170817A.
ApJ, 848(2):L13, 2017.

[3] For a review, see: Jay D. Tasson.
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