Can LIGO Detect Signals with Large Violations of General Relativity?

Claire Williams[1], Salvatore Vitale[2], Maximiliano Isi[2], Sylvia Biscoveanu[2]

[1]Carleton College Department of Physics and Astronomy [2]MIT Kavli Institute for Astrophysics and Space Research

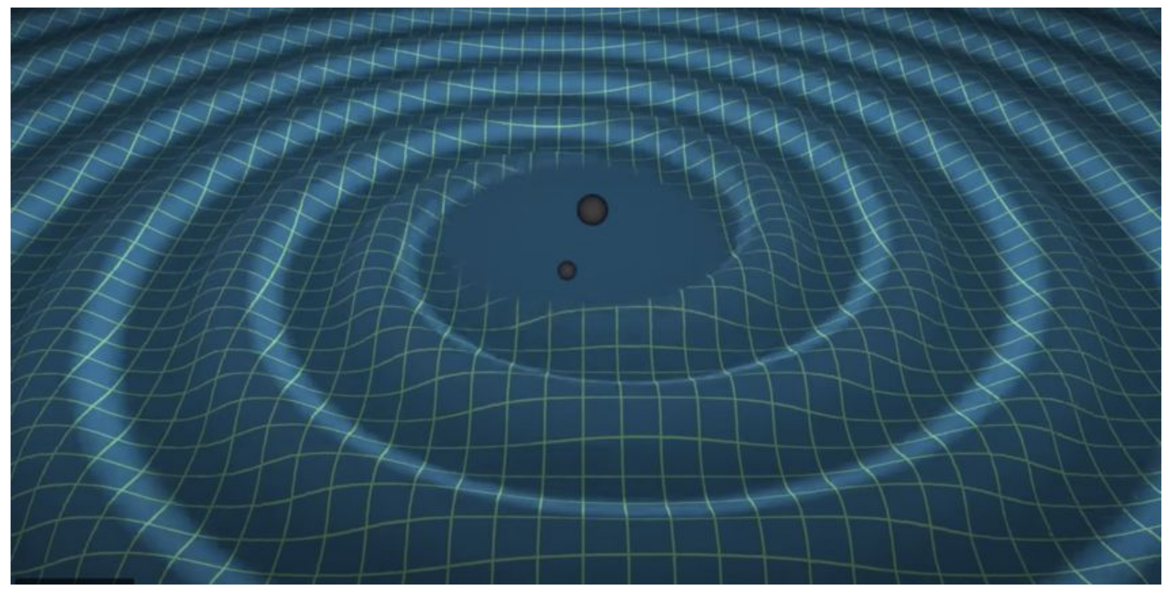

Figure 1: The merger of two black holes generates gravitational waves. (Source: LIGO/Caltech[1])

Testing the theory of general relativity (GR) is a central science objective of the Laser Interferometer Gravitational-Wave Observatory (LIGO). This work is motivated by concerns that LIGO's search algorithms would be unable to detect GR-violating signals because they compare observational data to theoretical waveforms that assume GR. We test the ability of one of these algorithms to identify simulated binary black hole merger waveforms containing various deviations away from GR. Outside of a small range where deviations are small, signals with a variety of deviations over a range of masses are found to have a significant drop in fit with the search's set of GR waveforms. The results suggest that LIGO's constraints on these deviations may apply to a smaller region of parameter space than previously believed, and that a significantly GR-violating event may be undetectable to this search.

Testing General Relativity with LIGO

According to the theory of general relativity (GR), collisions of black holes and other compact objects warp the fabric of spacetime, emitting gravitational waves (GWs) (See Fig. 1). The Laser Interferometer Gravitational-Wave Observatory (LIGO) directly measures these waves. One way to test GR is to check the observed signals against theoretical waveforms from black-hole mergers, putting constraints on how much each signal allows for deviation from the GR prediction. In this work, we look at a set of deviation parameters labeled $\delta\chi_i$. If there is no deviation we expect $\delta\chi_i = 0$. Figure 2 shows LIGO's current best constraints on these parameters. All include the zero case and several have been constrained significantly below 1.

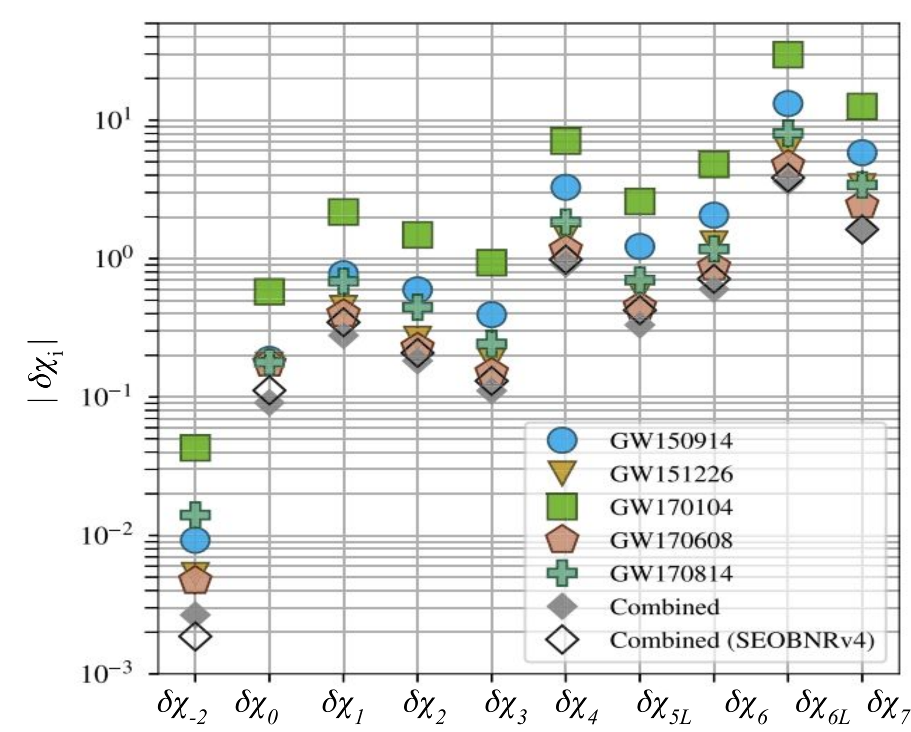

Figure 2 : Current constraints on the $\delta\chi_i$ parameters. This plot shows LIGO's 90% confidence upper bounds on the magnitude of the GR-violating parameters from measurements of the black hole binaries detected in its first and second observing runs. (Source: LIGO[2])

Potential Bias in Matched-Filter Searches for GW events

LIGO's detectors, which measure motion 10,000 times smaller than an atomic nucleus,[3] pick up noise from many sources, requiring statistical searches of the data to find real astrophysical events. One search algorithm is PyCBC, which uses a matched filter method to distinguish between signal and noise. This involves comparing the data to a bank of "template" waveforms, which are predicted waveforms for a variety of mergers. Figure 3 shows how strain data (in blue) is compared to the best fitting template in the bank (in orange).

The template waveforms used in this search are currently generated under the assumption that GR is the correct theory of gravity, so they all follow its predictions exactly. This has led to concerns that the search might not be able to pick up a signal which deviates significantly away from this theory. As an example, see Fig. 4, which shows a GR waveform from a black hole merger compared to the waveform you would measure from the same merger if $\delta\chi_0 = -1$. If this bias exists, it would mean that the current tight constraints on deviation parameters like the $\delta\chi_i$ (Fig. 2) might not be taking into account a population of GR-violating mergers.

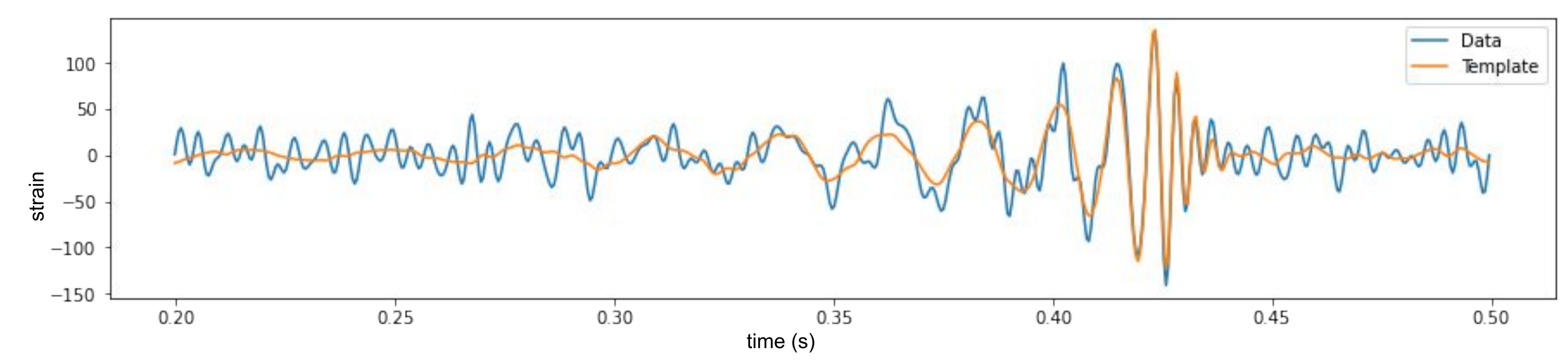

Figure 3: Matched filtering in action. The blue line shows the strain data from one of the detectors, and the orange line shows the template waveform selected as the best fit for this signal. A matched-filter algorithm compares all points in the strain to template waveforms with a variety of parameters to find the one with the best fit. (Source: GW Open Data Workshop on GitHub[4])

Searching for GR-Violating Signals

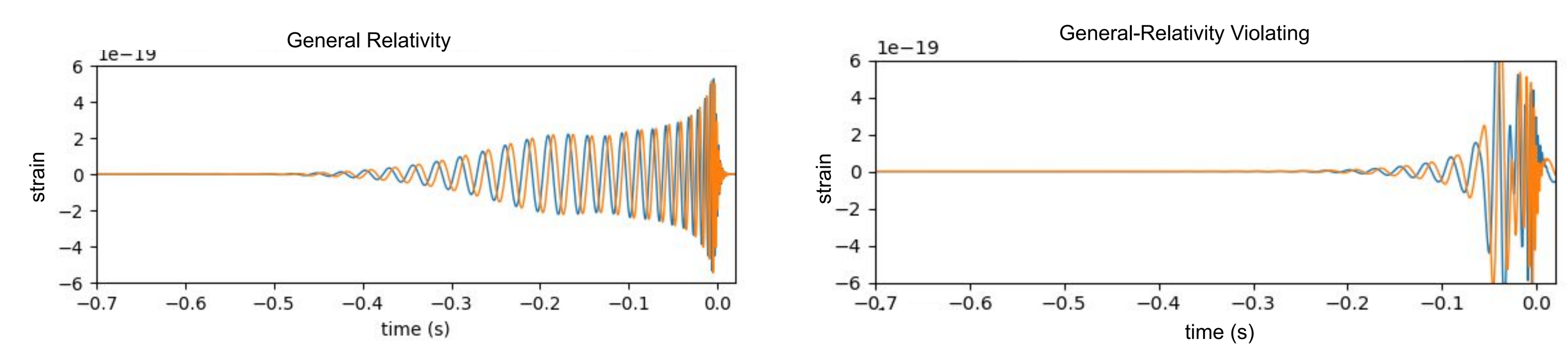

Figure 4: Violations of relativity parameterized by $\delta\chi_0$. The waveform on the left is an example of a simulated black hole binary merger waveform generated using the predictions of GR. On the right is the waveform for the same black hole merger if the $\delta\chi_0$ deviation parameter is set to -1.

Here we will assign the best-fitting waveform in the template bank a "match" value between zero and one which quantifies how well it fits the signal waveform (higher is better). The threshold match for inclusion in the template bank is 0.97, so this is the range we hope to see for the non-GR waveforms. We generate 45 different waveforms for black hole binary mergers with a range of violations ($-10 \le \delta\chi_i \le 10$) and search for them using the template bank from LIGO's second observing run. We repeat this for a range of masses, and for various $\delta\chi_i$ orders.

Signs of GR Bias

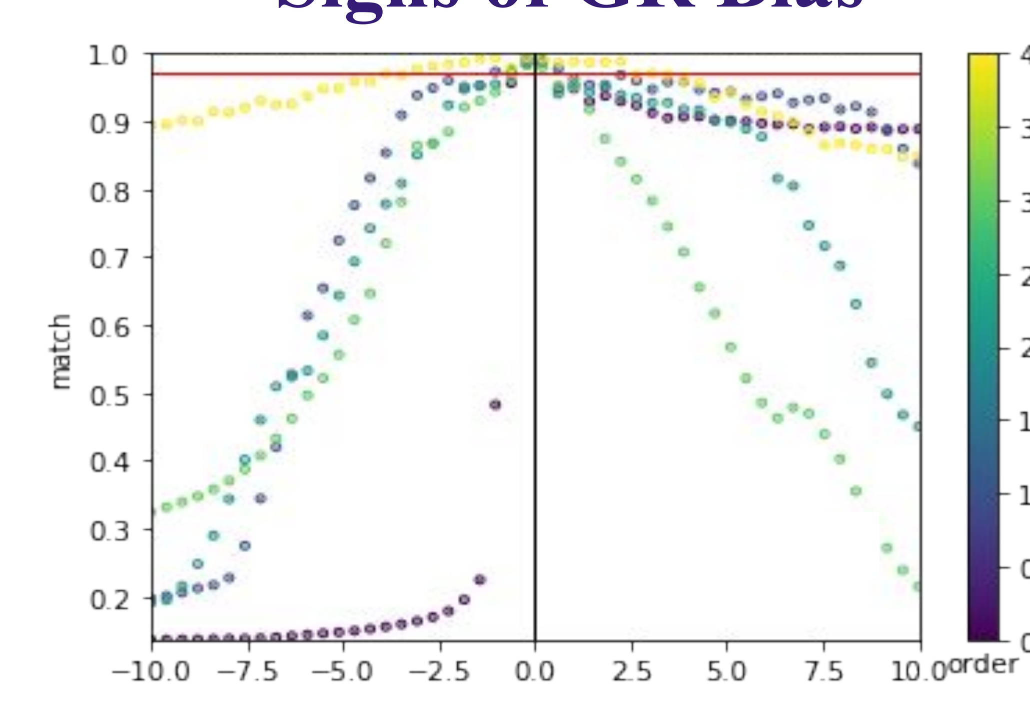

Figure 5: Match for $\delta\chi_i$ between -10 and 10 for the first 5 $\delta\chi_i$ orders for simulated black hole binary mergers with equal component masses of 10 solar masses. Color corresponds to the dchi order. The black line denotes $\delta\chi_i = 0$, which is the GR case that the search is designed to detect. As expected, the highest matches at every order occur at this 0 value. The horizontal red line denotes the threshold match of 0.97, which is the minimum value for inclusion in the template bank.

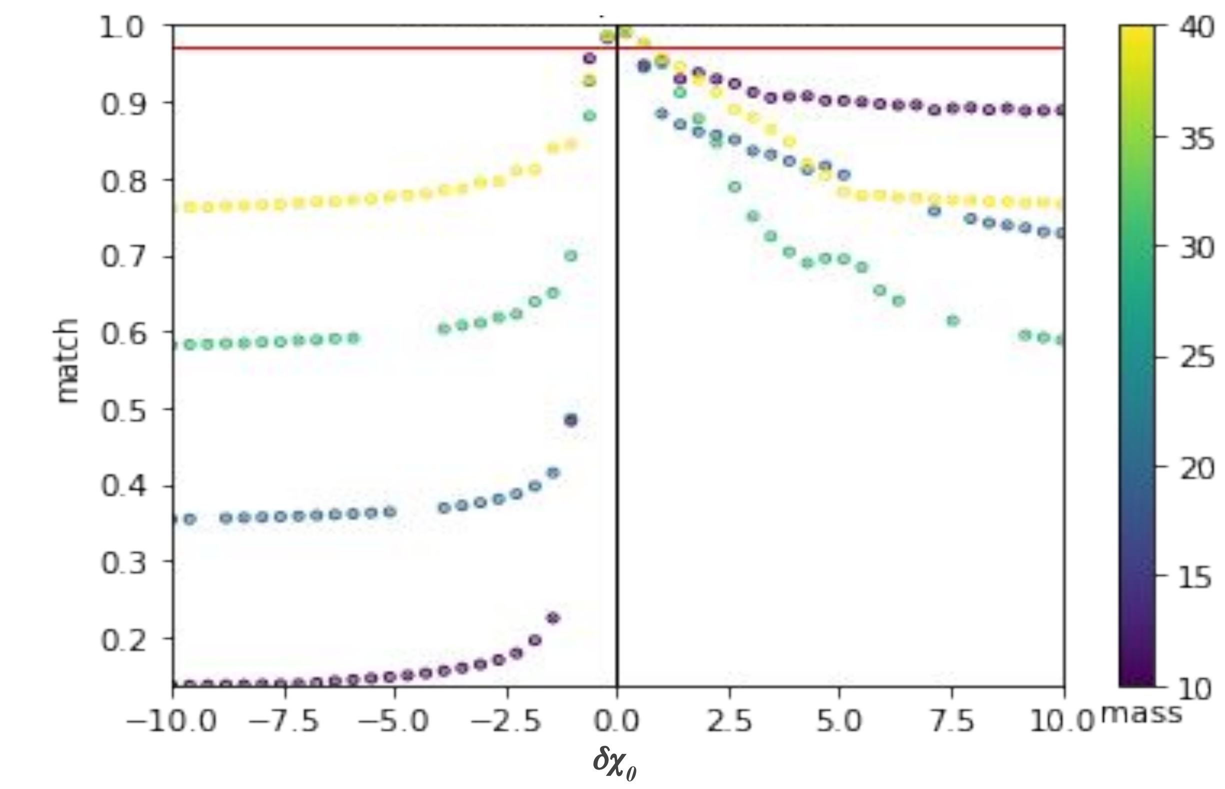

Figure 6: Match for $\delta\chi_0$ between -10 and 10 for simulated black hole binary mergers with equal component masses. Color corresponds to component mass in solar masses. The black line denotes $\delta\chi_0 = 0$, which is the GR case that the search is designed to detect. As expected, the highest matches at every mass occur at this value. The horizontal red line denotes the threshold match of 0.97, which is the minimum value for inclusion in the template bank.

Figures 5-6 show the results of some of these tests. Figure 5 shows the match values for a system with 10 solar-mass black holes for various $\delta\chi_i$. The vertical black line is placed at $\delta\chi_i = 0$, the GR case. The horizontal red line shows the threshold match value of 0.97 for inclusion in the template bank. Figure 6 shows this same plot for $\delta\chi_0$ for a variety of equal mass black hole binary mergers between 10 and 40 solar masses.

The results show that the best matches occur for systems with $\delta\chi_i$ close to zero, which is expected given that this is the GR case which the search was designed to detect. Concerningly, the match drops off quickly beyond this small range around $\delta\chi_i = 0$, for many $\delta\chi_i$ orders and masses (again, anything below the red line is outside the threshold). This suggests that these signals may not be detectable to this search.

Next Steps

This work suggests that non-GR signals may not be detectable to LIGO's matched filter search algorithms, and thus LIGO's tests of GR may not be constraining as broad a region of parameter space as previously believed. To pursue the question of how detectable these non-GR signals are, the next steps for this project are to find how the match parameter used here relates to the signal-to-noise ratio (SNR) of a signal in actual data. This involves taking one of the GR violating waveforms, such as the right side of Fig. 4, and inserting it into a piece of actual detector noise, and calculating the significance of this signal.

References

1) "Ripples in the Spacetime Pond" https://www.ligo.caltech.edu/video/ligo20160615v1
2) "Tests of General Relativity with the Binary Black Hole Signals from the LIGO-Virgo Catalog GWTC-1" Phys. Rev. D 100, 104036 (2019)
3) "About LIGO" https://www.ligo.caltech.edu/page/about
4) GW Open Data Workshop #3 (2020) https://github.com/gw-odw/odw-2020

Acknowledgements

This work was funded by the Kolenkow-Reitz Fellowship. Computing resources were provided by the LIGO cluster. Special thanks to Jay Tasson and to the MIT LIGO Lab Data Analysis Working Group for their support and feedback.

Carleton

LIGO Scientific Collaboration