Testing General Relativity with Binary Black Hole Mergers

LIGO SURF 2017 Project Proposal

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Introduction/Background: Gravitational Waves and LIGO

In 1915, Einstein revolutionized the field of physics by introducing his theory of general relativity to the world. This theory passed every test that Newton's gravity had failed, from gravitational lensing to the precession of Mercury to the calibration of GPS satellites. However, for almost a century, scientists could only hope to test general relativity in the weak field gravity limit. It was only after the completion of Advanced LIGO that researchers had access to data from black hole mergers, astrophysical objects that provided examples of gravitational fields stronger than had ever been measured before.

In September 2015, just days after the start of its first observing run, Advanced LIGO had identified and analyzed a candidate binary black hole (BBH) merger event [1]; within months, they had two more. To carry out their analyses, LIGO researchers first used numerical general relativity to generate template waveforms modeling BBH inspiral, merger, and ringdown phases, parameterizing these templates by several factors (such as the masses and three-dimensional spin vectors of the both black holes). Interpolating between a relatively small number of template waveforms allowed researchers to efficiently creates thousands of templates. Researchers could then fit these template waveforms to probable BBH signals to determine the parameter values for a given signal. They then computed the post-newtonian coefficients (higher order modifications to general relativity) and found general relativity to be consistent with the observed signals [1],[2]. This provided strong evidence that these signals were indeed from BBH mergers.

However, post-newtonian coefficients are valid only for the early inspiral phase of a merge. As the black holes in a binary system spiral closer together, v/c approaches 1, leading to a probable breakdown of the post-newtonian expansion. The post-newtonian coefficients become invalid as the BBH system pushes even further into the strong-field gravity limit. It is during the merger and ringdown phase that these BBH systems become perfect candidates for

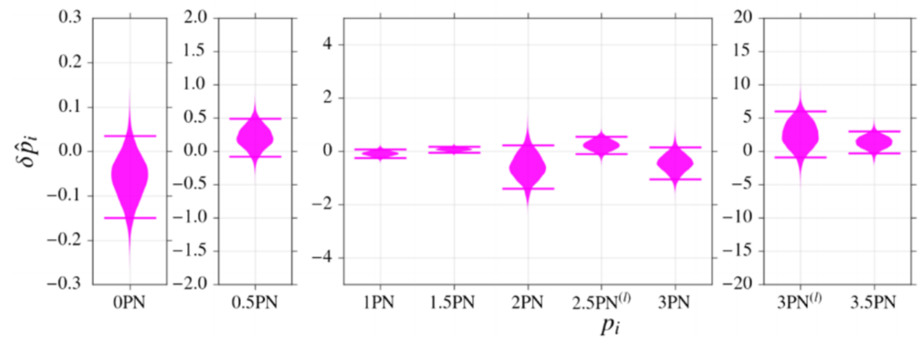

Figure 1: Deviations of some post-newtonian coefficients from their nominal values from GW150914 and GW151226 inspirals. These show general relativity is valid at least for the early inspiral phase of a merger. [2]

testing for deviations from general relativity.

Objectives: General Relativity and BBH Mergers

Overall, my goal is to determine the extent to which deviations from general relativity can account for the BBH signals LIGO has detected. Any deviations from general relativity will be most evident when gravity approaches the strong field limit, or when $\frac{GM_{tot}}{rc^2}$ = (using Kepler's 3rd law) $\frac{4\pi^2 r^2}{P^2 c^2} = \frac{v^2}{c^2}$ approaches 1 (particularly in the merger and ringdown phases). For my analyses, I will assume that any such deviations will take the functional form $e^{\frac{\lambda GM}{rc^2}}$, and I will investigate what happens as the parameter λ deviates from 0 (the general relativity limit).

I anticipate my analyses being broken up into three stages:

Stage 1: for each BBH signal that LIGO has detected and characterized, I will modify the template waveform that was the best fit for that signal by $e^{\frac{\lambda GM}{rc^2}}$, taking care to vary λ from 0 in a controlled fashion. For different values of λ, I will check to what degree the modified waveform template proves a better fit to the BBH signal than the original waveforms, taking care to ensure my methods and findings are statistically meaningful. The result (for each BBH signal) will be a graph modeling the signal-to- noise ratio for a range of λs. Anticipated time: 2-3 weeks.

Stage 2: I will analyze the findings of stage 1 and calculate a probability distribution function for each BBH event, measuring the likelihood that a given value of λ correctly accounts for that BBH event. I will then compile all the analyzed BBH events into a single distribution function with the goal of finding

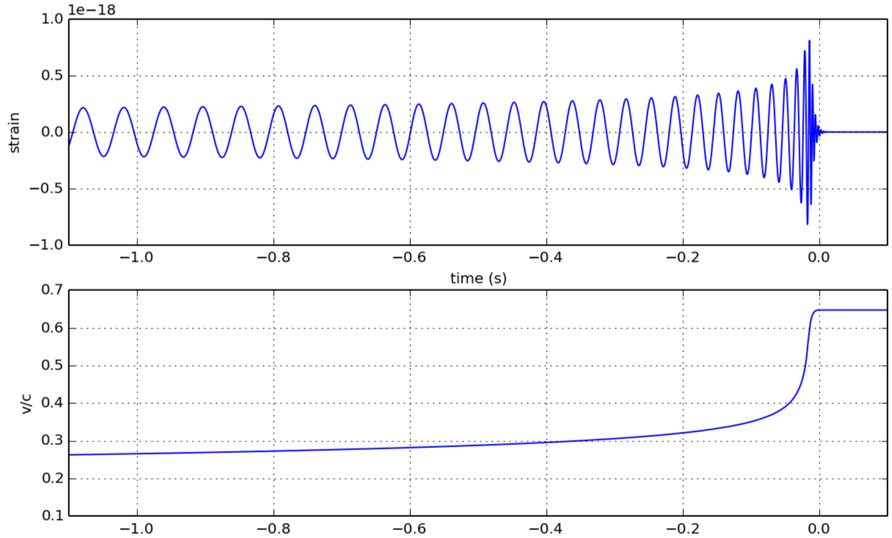

Figure 2: From the GW150914 event. Note that during the merger and ringdown phases, v/c becomes an appreciable fraction of 1. [3]

the value of λ that best models general relativity deviations for all the BBH events. This graph will mark the completion of stage 2. Anticipated time: 3-4 weeks.

Stage 3: I will calculate the number of BBH detections needed to corroborate (or rule out) a deviation from general relativity at any given value of λ. Creating this graph will mark the successful completion of my analyses. Anticipated time: 3-4 weeks.

Detailed Time Frame

- Week 1: Finalization of project and familiarization with LIGO's software.
- Weeks 2-4: Work on stages 1 and 2. Learn computer modeling and simulation and Bayesian inference. Research literature on deviations from general relativity and BBH waveform modeling.
- Week 4: Write status report 1. Visit LLO.
- Weeks 5-8: Work on stages 2 and 3. Write status report 2.
- Weeks 9-10: Compile final results. Write and present talk on project and results.
- September: Complete final paper.

Approach: Quantifying Deviations from General Relativity

The largest barriers I anticipate for this project will be both familiarizing myself with LIGO's code and methods of analysis and learning how to recreate the elements relevant to my own project from scratch. In order to perform my own analyses, I will need to understand, at the very least, how LIGO sifts through all of its data to search for candidate BBHs and how it combines different waveform templates together to find a the best-fit match for a given BBH signal, so that I can create code that does this myself. Gaining familiarity with LIGO's code may take up to two weeks, although I expect to gain proficiency simultaneously with conducting the first stage of my analyses. I will also be working under researchers who wrote this code, so I will be able to ask questions about any elements of LIGO's code that I cannot understand even after careful scrutiny.

The equipment over the course of this project I will need is limited: just a working computer (which I will provide) and whatever software LIGO uses in its analyses. In addition to using LIGO's code to analyze the BBH signals, I will be writing my own code to conduct all the statistical analyses described above and also to modify LIGO's template waveforms by the parameter λ. I will also need to familiarize myself with Monte Carlo simulations and statistical analysis, which I can do throughout the month of June, before I even begin my analyses.

Since this project is largely an independent one, I do not expect completion of my project to be dependent on results from others. However, completing a given stage of analysis is crucial to moving onto later stages, so I will need to work efficiently to complete each step in my analyses in a timely manner and be sure to ask my adviser for aid when I become unreasonably stuck on a specific issue.

I will be working most closely with my SURF mentor, Alan Weinstein. However, I will also be in touch with his groups's graduate students and postdocs, as well as my SURF LIGO peers.

References

[1] B. P. Abbott et al., *GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence.* PHYSICAL REVIEW LETTERS. PRL 116, 241103 (2016).

[2] B. P. Abbott et al., *Binary Black Hole Mergers in the First Advanced LIGO Observing Run.* PHYS. REV. X 6, 041015 (2016)

[3] "BINARY BLACK HOLE SIGNALS IN LIGO OPEN DATA." LIGO Open Science Center. 18 July 2016. Web.