Testing Specific Theories Beyond General Relativity with LIGO

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1 Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has opened up a new era of physics with its first observation of a binary black hole merger [1]. Approximately 90 compact binary merger events have been observed thus far with the latest gravitational-wave transient catalog (GWTC-3) [17]. LIGO utilizes sensitive Michelson interferometers to measure gravitational-wave emissions from distant astrophysical sources [2]. Binary black hole mergers are characterized by two orbiting black holes that undergo distinct phases: an inspiral, merger, and ringdown phase that results in the formation of a single massive black hole [10]. Once the black holes form a binary system, through the emission of gravitational-waves, the binary black holes lose orbital angular momentum and eccentricity which leads the black holes to inspiral in a quasi-circular orbit. As the orbiting black holes approach the merger, numerical relativity methods characterize this stage because the post-Newtonian expansion that describes the inspiral, loses accuracy [7]. At the start of the merger, there is a plunge where the black hole horizons merge and their orbits become unstable. The resulting combined black hole becomes stable in the ringdown stage and is characterized by quasi-normal modes [4]. The gravitational-wave radiation provides the opportunity to test fundamental physics in the strong-field, highly dynamical regime of gravity which has been previously inaccessible in experimental tests of general relativity [11].

Gravitational-waves detected by LIGO have allowed us to study populations of binaries and test general relativity in the strong-field regime with ensembles of events [3, 9]. With the current population of binary merger events, there has yet been evidence of disagreement with predictions of general relativity [21]. By assuming general relativity is accurate, we are able to place constraints on alternative theories [18]. Einstein's general theory of relativity has been tested extensively in the weak-field regime, yet theoretical evidence has shown that at high energies general relativity breaks down [6]. This motivates testing theories around compact sources such as binary black hole mergers which involve stronger curvatures and shorter dynamical time scales [2, 6].

During the inspiral phase, gravitational-wave signals transition from weak fields to moderately strong fields, and spacetime is violently curved when binaries merge [22]. This phase can be accurately modeled with a post-Newtonian formalism [7]. Post-Newtonian formalism is a method for solving Einstein's field equations in the weak-field regime and it has been proven to be effective in describing fast, strong-field systems [20]. This method perturbatively expands the binary's evolution in powers of orbital frequency. Post-Newtonian phasing coefficients describe the physical effects in the relativistic dynamics of binaries, such as spin-spin interactions [14]. By focusing on the inspiral phase, we aim to look for potential deviations from general relativity.

As LIGO becomes more sensitive, the number of binary mergers will grow which will allow for deviations to be more accurately constrained. By analyzing inspiral phase post-Newtonian coefficients for many gravitational-wave events, we are able to understand alternate theories whose coefficients vary in their post-Newtonian expression. The consistency of these coefficients with predictions of general relativity serve as a precise, independent test of the theory [14, 21].

2 Objectives

We intend to apply Bayesian inference to the inspiral phase of gravitational-wave sources to obtain posterior distributions for 15 source parameters and 10 post-Newtonian deviation parameters. These posterior probabilities are sampled using the hybrid sampling method, first presented in Ref. [21]. In order to infer every deviation parameter at the same time, a hierarchical inference approach will be applied [9]. The parameter estimations resulting from the previous analysis will then be used to demonstrate theories beyond general relativity, such as the dynamical Chern Simons (dCS) and Einstein-dilaton Gauss-Bonnet (EdGB) theory [12, 13]. This will result in attempting to improve the bounds on the coupling coefficients characterizing these specific theories beyond general relativity.

3 Methods

The first objective involves applying hybrid sampling via Bilby to jointly infer the 15 source, general relativity, parameters of the binary black hole merger events in GWTC-3 and the 10 post-Newtonian deviation parameters [5]. The hybrid sampling method is computationally efficient and recovers posterior distributions [21]. This method treats general relativity as the initial prediction in order to initialize the deviation parameter estimation. For each gravitational-wave signal, the data is sampled first using nested sampling via dynesty and then sampled with the implementation of ptemcee in order to obtain generic, multi-dimensional samples [8, 15, 19].

After generating posterior distributions for all the astrophysical and deviation parameters, we will apply a hierarchical approach. By applying hierarchical inference, we aim to test specific theories using all the possible deviations from general relativity, for each gravitational-wave event generated from the previous analysis. This hierarchical procedure involves combining multiple gravitational wave events, marginalizing over individual event parameters, and sampling their hyperparameters [9]. In sampling the hyperparameters of these events, we are able to understand the underlying population parameters. These population parameters describe the source signals which includes orientation, phase, component masses, and component spins. The hierarchical inference method further entails using a Gaussian Mixture Model (GMM), which is a computationally inexpensive density estimation procedure [16]. The GMM estimates the posterior probability densities of each individual event and speeds up the hierarchical inference analysis. This is accomplished by efficiently evaluating the likelihood functions for each event [9].

4 Timeline

- 1st-2nd week: Getting acquainted with gravitational-wave data analysis and performing parameter inference with Bilby.
- 3rd week: Understanding and running the hybrid sampling code.
- 4th week: Apply the hybrid sampling method to an individual event and infer a subset of the post-Newtonian deviation parameters.
- 5th week: Run the hybrid sampling analysis on the full set of general relativity and deviation parameters.
- 6th week: Understand and run the GMM code for hierarchical inference and obtain GMM representations of the likelihoods for each event.
- 7th week: Continue to run the previous analysis and apply the results to the specific theories beyond general relativity, dCS and EdGB.
- 8th week: Finish runs and verify results.
- 9th-10th week: Work on writing final report and presentation.

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