Testing Specific Theories Beyond General Relativity with LIGO

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1 Abstract

Gravitational-waves observed by LIGO have allowed us to study populations of compact binaries and test general relativity in the strong-field regime. However, there has yet been evidence of disagreements with predictions of Einstein's general theory of relativity with the current population of binary merger events. We intend to apply Bayesian inference to the inspiral phase of gravitational-wave signals in binary black hole merger events, in order to obtain posterior distributions for the 15 source parameters and 10 post-Newtonian deviation parameters. This parameter estimation involves using the hybrid sampling method, first presented in [22]. Hierarchical inference will then be applied to ensembles of events to test specific theories beyond general relativity, such as the dynamical Chern Simons (dCS) and Einstein-dilaton Gauss-Bonnet (EdGB) theories. This will result in attempting to accurately constrain the bounds on the coupling coefficients that characterize these specific theories.

2 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) [18]. LIGO utilizes dual recycled, Fabry-Pérot-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 remnant black hole becomes stable in the ringdown stage and its gravitational-wave radiation 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 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 disagreement with predictions of general relativity [22]. By assuming general relativity is accurate, we are able to place constraints on alternative theories [19]. Einstein's general theory of relativity has been tested extensively in the weak-field regime, yet theoretical expectations suggest 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 [23]. The inspiral phase can be accurately modeled with a post-Newtonian formalism [7]. The 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 [21]. 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 [15]. By focusing on the inspiral phase, we aim to look for potential deviations from general relativity by e.

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 [15, 22].

3 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. [22], in order to infer every deviation parameter at the same time. The parameter estimations results will then be used to inform a hierarchical inference approach [9]. The subsequent results will 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.

4 Methods

4.1 Hybrid Sampling

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 10 post-Newtonian deviation parameters [5]. The hybrid sampling method is computationally efficient and recovers posterior distributions [22]. 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 [16]. These nested samples initialize the walkers of a parallel tempered Markov Chain Monte Carlo (MCMC) with the implementation of the package ptemcee in order to obtain generic, multi-dimensional samples [8, 20].

4.2 Hierarchical Inference

After generating posterior distributions for all the astrophysical and deviation parameters, we will apply a hierarchical approach to test specific theories using all the possible deviations from general relativity for each gravitational-wave event. This hierarchical procedure involves combining multiple gravitational wave events and marginalizing over individual event parameters [9]. In sampling the parameters of these events, we are able to understand the underlying population parameters. These population parameters can describe the coupling coefficients of specific theories beyond general relativity. The hierarchical inference method further entails using a Gaussian Mixture Model (GMM), which is a computationally inexpensive density estimation procedure [17]. The GMM estimates the posterior probability densities of each individual event. This is accomplished by efficiently evaluating the likelihood functions for each event [9].

5 Progress

For our source model, the post-Newtonian parameterization of the phase evolution during the inspiral phase of the general relativistic waveform in the frequency domain is

$$\Phi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128} \times \sum_{k=0}^{7} \frac{1}{\eta^{k/5}} \Big(\varphi_k + \varphi_{k,l} \ln \tilde{f}\Big) \tilde{f}^{(k-5)/3} \,, \tag{1}$$

where t_c is the time and ϕ_c is the phase when the binary black holes coalesce, $\eta \equiv \frac{m_1 m_2}{M^2}$ is the symmetric mass ratio of the system, and $\tilde{f}$ is the frequency [14].

We have started running the hybrid sampling method, focusing on the inspiral phase of a simulated binary black hole signal. This injection only has a modification of 20% to the φ_2 parameter, first order post-Newtonian term, in order to test if deviations could be recovered from this method. In this hybrid sampling step, the initial deviation parameter walkers are Gaussian distributed. In addition, there is a greater than 0.9 match cut to the general relativity waveform. In this assumption, we restrict the deviation to be within 10% of the waveform which is indicative that the waveform appears to be similar to the general relativity waveform.

We have completed two parameter estimation runs on the injected signal with the hybrid sampling method. In this first run, all the deviation parameters were modified separately, similar to [22]. The posterior distributions from a few of the parameters are shown in Figure 1. Meanwhile, on the second run, we have changed all the deviation parameters simultaneously. By changing each of the deviation parameters, they are then able to be generalized in order to extend them to specific theories. Figure 2 shows the posterior distributions for a few deviation parameters. In directly plotting the two-dimensional representation of parameters, we can search for correlations between them through visual inspection. In particular, correlations between deviation parameters can reflect how near-identical waveforms can be generated using different parameters.

The corner plots in Figures 1 and 2 denote the marginal posterior distributions and their two-dimensional posterior distributions. Given that the posterior distributions are roughly smooth, this indicates that the parameters successfully converged using the hybrid sampling method, even when the deviation parameters are jointly inferred. Based on Figure 1, there is a positive correlation between the chirp mass, $\mathcal{M}$, and the deviation parameter, $\delta\varphi_1$. This can be indicative of the relationship between the two parameters in Eq. 1. In Figure 2, there appears to be a correlation between $\delta\varphi_2$ and $\delta\varphi_3$. It can be reasonably inferred that this is due to these parameters describing the early inspiral regime.

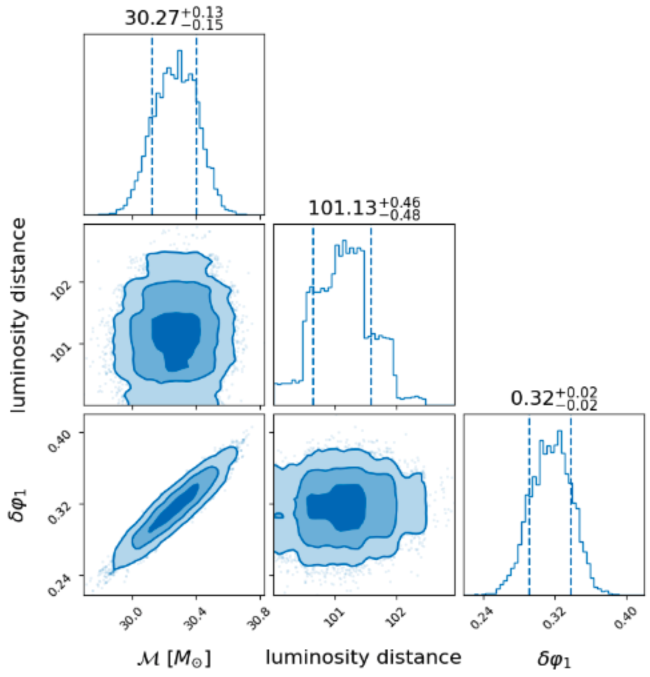

Figure 1: Marginal posterior distributions from two source parameters, $\mathcal{M}$ and the luminosity distance, and the first order post-Newtonian deviation parameter.

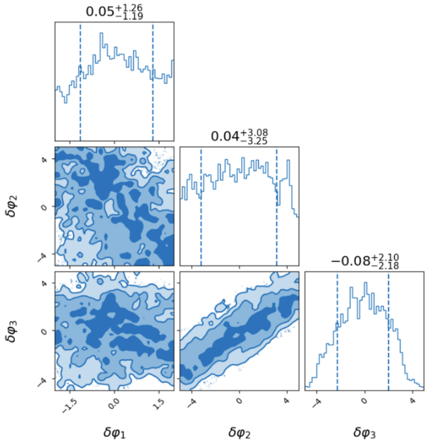

Figure 2: Marginal posterior distributions of three deviation parameters resulting from jointly inferring each deviation parameter.

6 Challenges

A main challenge so far has stemmed from trying to understand the HTCondor software commands that enable High Throughput Computing (HTC). HTCondor is used to submit tasks, such as running the hybrid sampling method, to the computing cluster. I have learned how to submit a job to the cluster and understand the format of the different files involved, such as the queue and configuration files. I also learned how to initialize the injections and set the priors for the deviation parameters in a joint inference of all the deviations rather than separately. Furthermore, in the process of trying to successfully run the hybrid sampling method, I learned how the log files can be the first point of reference in trying to debug when errors occur.

Another challenge includes understanding the science from current results, such as Figures 1 and 2. I'm currently learning how to interpret these posterior distributions and building the intuition for assumptions that can be made with correlations amongst the source and deviation parameters. I have also learned how deviation parameters parameterize waveforms in tests of general relativity.

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