Constraints on Black Hole Recoils with Gravitational Wave Detection

Objective: We aim to develop an analytic kicked gravitational waveform model that can be used to place projected constraints on measurements of kick velocities with future gravitational wave detections.

I. INTRODUCTION

When a pair of black holes emit gravitational waves during their evolution, the gravitational waves carry away energy from the binary, forcing the binary to coalesce. During this process, linear momentum is emitted from the binary in a generically anisotropic way that causes the center of momentum to oscillate during the inspiral of the evolution. As the binary merges, a recoil, or "kick", can be imparted to the remnant black hole as a result of the conservation of momentum, causing the remnant to move with some "kick velocity". This kick velocity can vary greatly depending on the intrinsic parameters of the binary system in consideration; for example, during the merger of supermassive black holes, this kick velocity can be up to thousands of kilometers per second, which can exceed the escape velocities of the galaxies from the which the black holes originated.

Throughout this LIGO REU, we will be working to determine if we can measure kick velocities with gravitational waves emitted from black hole binary inspirals. We will first develop a generic procedure by which we can add a kick, in the frequency-domain, to a gravitational waveform (namely the inspiral-merger-ringdown models PhenomD and PhenomP which model non-precessing and precessing binaries, respectively). We will then use this frequency-domain waveform to perform parameter estimation studies in which we determine bounds for the constraints that can be placed on kick velocities from a population of various sources that may differ in size or spin.

II. APPROACH

Analytic expressions for the velocity of a kicked black hole remnant exist in the time domain. Currently, black hole kicks are added to gravitational waveforms by taking the reverse Fourier transform of the waveform in the frequency domain, adding the kick velocity to the ringdown phase of the waveform, and then taking the Fourier transform of the waveform in the time domain to recover the "kicked waveform" in the frequency domain. This is all done numerically and thus does not allow for analytic manipulation of the frequency-domain waveform. To produce such an analytic frequency-domain waveform however, we must find time as a function of frequency so that we can obtain the velocity as a function of frequency. This velocity function can then be introduced to the ringdown phase of the PhenomD waveform model that we currently have. This will essentially introduce a redshift, that is a function of the velocity, in the ringdown gravitational waves that are emitted, which we can then test to make sure that the waveform recovers numerical relativity simulations. We are currently working to find time as a function of frequency for the PhenomD model. We expect this part of the process to take a few weeks but should near complete before the REU begins.

Once we have added this kick velocity to the PhenomD model, which we currently have codes for, we will modify our PhenomD waveform to include precession (PhenomP) and repeat the method to add the kick to this more advanced model. We expect that adding the kick to the PhenomP model will be relatively simple after having already done this for the PhenomD model. Upgrading the PhenomD model to the PhenomP model will be considerably more work than introducing the kick, but this has been done by collaborators and there is literature on how this upgrade is performed [1].

Using our kicked PhenomP model, we will perform a parameter estimation study in order to determine how well we could measure the kick velocity given various gravitational wave detections from different sources. We will conduct a Fisher Analysis parameter estimation study and assume that we make these gravitational wave detections with both ground- and space-based detectors. We can perform this study for hundreds of different binary systems by utilizing the computer clusters at either the Montana State University campus, or the Caltech campus. This process should only take a few days depending on the number of different sources that we want to consider.

III. PROJECT SCHEDULE

The first step, which is to find an expression for the velocity of a remnant black hole and incorporating it into gravitational waveforms, should be complete within the first couple weeks of the REU. We would like to produce a paper that explains in detail how these kicked waveforms are produced such that our results are reproducible. The second step, which is to upgrade our PhenomD code to PhenomP, and introducing the kick, should take between three and four weeks. The final step, which is to complete the parameter estimation study for the kick velocity for different black hole binary systems, should take between one and three weeks to complete. At this point, we'd like to produce a second paper that details the plausibility of measuring black hole kicks with gravitational wave detections. Thus, this project should result in two papers, the second of which would be completed in the fall.

This project will be carried out under the advisement of Dr. Davide Gerosa, and in collaboration with Dr. Nicolas Yunes at Montana State University and Dr. Christopher Moore at Cambridge University.

---

[1] M. Hannam, P. Schmidt, A. Bohé, L. Haegel, S. Husa, F. Ohme, G. Pratten, and M. Pürrer, Phys. Rev. Lett. **113**, 151101 (2014), arXiv:1308.3271 [gr-qc].
[2] N. Yunes, K. Yagi, and F. Pretorius, Phys. Rev. **D94**, 084002 (2016), arXiv:1603.08955 [gr-qc].
[3] D. Gerosa and C. J. Moore, Phys. Rev. Lett. **117**, 011101 (2016), arXiv:1606.04226 [gr-qc].
[4] S. Husa, S. Khan, M. Hannam, M. Pürrer, F. Ohme, X. Jiménez Forteza, and A. Bohé, Phys. Rev. **D93**, 044006 (2016), arXiv:1508.07250 [gr-qc].
[5] S. Khan, S. Husa, M. Hannam, F. Ohme, M. Pürrer, X. Jiménez Forteza, and A. Bohé, Phys. Rev. **D93**, 044007 (2016), arXiv:1508.07253 [gr-qc].
[6] D. Gerosa and A. Sesana, Mon. Not. Roy. Astron. Soc. **446**, 38 (2015), arXiv:1405.2072 [astro-ph.GA].