Measuring Spin Precession in the Ringdown

Project Proposal, LIGO Student Undergraduate Research Fellowship, California Institute of Technology

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The effect of the progenitor masses and spins on the gravitational-wave signal from a binary black hole merger is relatively well understood, but less is known about how misaligned spins impact the ringdown signal. Therefore, it is an open question what we can infer about inspiral parameters from the ringdown alone. As several of the high-mass (most ringdown-dominated) binary black hole systems observed by LIGO have misaligned spins, the ability to predict inspiral properties from the ringdown would give us great insight into this portion of the population of black holes that are undergoing merger. In this project, we will extract quasi-normal modes from the ringdown signal in simulated gravitational-wave signals to determine if and how well those modes can accurately infer information about the inspiral. If what these modes predict is consistent with the properties of the simulation, this could be applied to real gravitational wave data to infer inspiral parameters.

I. INTRODUCTION

I will be working within the Laser Interferometer Gravitational-wave Observatory (LIGO) Collaboration exploring spin in binary black hole (BBH) mergers, and in particular how it impacts the ringdown. Most of the research done in this area has focused on the case where individual black holes (BHs) have aligned spins, in which it is clearer how mass and spin affect observed signals, e.g., [1–4]. Looking at the misaligned spin case–leading to spin-orbit precession–is particularly of interest because it gives information about how the system formed, e.g., [5, 6]. Since applying aligned-spin models to systems with precession may bias the recovery of system parameters (such as the masses and spins), it is important to understand how precession affects the ringdown. By studying if and how we can predict and infer properties of the individual progenitor BHs in precessing systems using just their post-merger data, we can better examine the population of BHs that undergo merger.

A BBH coalescence can be broken into three parts: the inspiral, the merger, and the ringdown. The inspiral period is when the two BHs are orbiting each other and emitting lower frequency gravitational waves (GWs) as they get closer together, and then eventually collide in the merger. For high-mass systems, the inspiral is difficult to observe with LIGO because the majority of GWs emitted before the merger are at a lower frequency than LIGO detects [7]. Because the inspiral period is difficult to probe in LIGO's frequency band for these systems, it is useful to be able to infer the properties of the inspiral period based on the frequencies observed in the more readily-visible ringdown. The ringdown is the period directly after the merger where the two BHs have now coalesced into a single remnant BH, and the remnant is rotating asymmetrically about its axis. This perturbed BH remnant is still emitting GWs as it equilibrates into its final stage, a Kerr BH [8]. These GWs consist of a sum of damped oscillations known as quasinormal modes (QNMs) [9–13].

QNMs are damped sinusoid frequencies emitted from the perturbed BH that include fundamental and overtone frequencies. They are called "quasi" because they decay over time, whereas normal modes do not. The longest lasting of these are referred to as the fundamentals, while any shorter lived modes are the overtones. The ringdown signal observed from an event is a sum of all the QNMs. It is known that the quadrupole mode is expected to be dominant in systems with equal masses and aligned spins, but higher harmonics are expected to be much more important in precessing systems [14]. For high-mass systems, these QNMs are the frequencies that can be observed more directly because they fall within LIGO's observable frequency band. In this project, we want to measure QNMs from numerical relativity (NR) simulations to see if our predictions are consistent with the true parameters in the simulation.

NR simulations are ideal for such studies because they are complete waveforms with all inspiral, merger, and ringdown times included, whereas the QNM model is only applicable during the ringdown. NR simulations are computationally expensive, so we will complement them with surrogate models [15] that are essentially interpolations of NR simulations. By looking at the NR surrogate model, we can observe what the signal in the ringdown looks like, and also what the inspiral parameters for the model are. Then, using the QNM model, we can dissect the waveform into its individual QNM components and use a least-squares fit to determine which combination of QNMs yields the observed waveform. Because all QNMs must agree on the same mass and spin for a BH remnant, there are a limited number of combinations of

QNMs that could produce an observed signal. The amplitudes of the QNMs carry information about the mass and spin of the inspiraling BHs. For the aligned-spin case, this information has been encoded in fitting formulas. See, for example, Refs. [1, 2, 16, 17]. In Fig. 1 we show fits from Ref. [16], where select fundamental QNM amplitudes have been fitted as a function of the symmetric mass ratio (for non-spinning BH binaries). However, the mapping from amplitudes to inspiral properties is less clear for precessing binaries, although a relationship is expected [8]. In addition, determining the final mass and spin of BHs in high-mass precessing systems is difficult, so it is less clear what values the QNMs should be agreeing on.

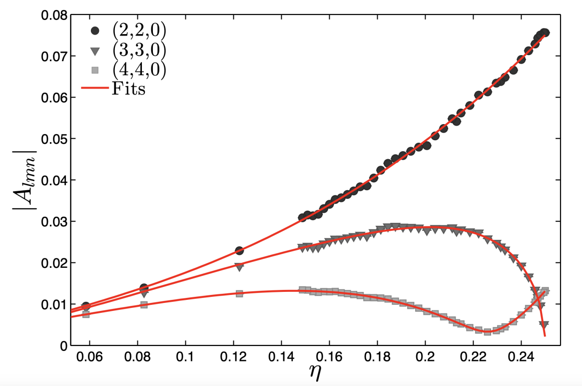

FIG. 1. Plot of amplitude vs. symmetric mass ratio shows how amplitudes vary according to mass of a system for different modes[16].

Understanding the relationship between the inspiral and ringdown properties for high-mass (e.g. ringdown-dominated) precessing systems is further motivated by the fact that several of the BBHs observed by LIGO are indeed high mass systems with intriguing spins. GW190521 is the highest mass BBH system observed by LIGO to date and is highly precessing [18]. It's precession measurement stems from the interplay between the quiet final inspiral cycle and the loud merger [19]. GW191109 and GW200129 are other high-mass systems with interesting spin configurations, but are plagued by data-quality issues: GW191109 has anti-aligned spins [20], while for GW200129 it is uncertain if the system is precessing or not [21]. For all of these events, the information about spins is coming primarily from their inspiral, which is either short/quiet and/or affected by data quality issues, so having ways to infer the inspiral properties *without* looking at this finicky inspiral serves as motivation for our study. If the QNM model is consistent with the NR surrogate model, this will help us understand if and how we can model inspiral parameters without being able to directly observe the inspiral period.

II. OBJECTIVES

The purpose of this project is to test how well examining the ringdown with a QNM model can be used to infer properties of the inspiral. We will start with the aligned-spin case, where the mapping from QNM amplitudes to inspiral properties is well understood [1, 2, 16, 17], and then move on to the precessing case. By analyzing simulated signals (for which we know the inspiral properties exactly), we can test how well the mappings work in practice for inferring inspiral properties. We can ask, for example, how many and which QNMs are needed to perform the mapping, and what signal-to-noise ratios (SNRs) are required. Our objectives are as follows:

1. Perform parameter estimation, and obtain posterior distributions, to determine if the QNM model and NR surrogate simulations agree on inspiral spin parameters for the aligned and precessing spin cases. Figure 2 shows a sketched example of what such posteriors may look like.

2. Examine how quality of the fits changes in different simulations, e.g., equal vs. unequal masses, large vs. small spins aligned vs. precessing spins.

3. How many modes do we need to make a good least squares fit?

Mappings for the QNM amplitudes in the precessing case are not well understood, although see Refs. [8, 22] for work in this direction. Consequently, a simpler question we could ask is when do the aligned-spin mappings break down (say, as a function of SNR and how much precession there is).

III. APPROACH

For performing simple least-squares fits to simulated data, we will make use of the `qnmfits` package [23]. More sophisticated Bayesian inference of simulated, and eventually real, LIGO data will make use of the `ringdown` package [24, 25]. The time-domain inference code of Miller *et al.* [19] may additionally be used for Bayesian parameter estimation with the NR surrogate waveform. For mapping between QNM amplitudes and progenitor BH properties, we can make use fitting formulas for the aligned-spin case available in Refs. [1, 2, 16, 17], or recently developed QNM amplitude surrogates [3, 4]. For the precessing case, we will base our work on the relationships between the so-called misalignment angle and QNM amplitudes found by Zhu *et al.* [8].

IV. PROJECT SCHEDULE

Before arrival: Become familiar with characteristics and data from QNM and NR surrogate models, and how mass and spin parameters imprint QNMs.

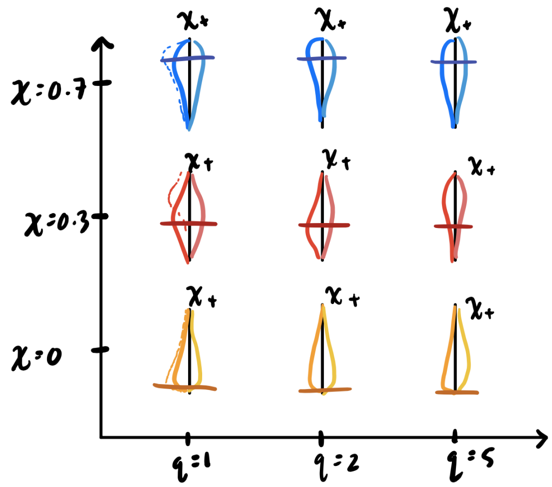

FIG. 2. Sketch of a violin plot showing posterior distributions on the inspiral spin parameter χ_+ (also known as $\chi_{\rm eff}$) [1]. In this sketch, the lighter color represents the *reconstructed* χ_+ parameter using the QNM fits; the darker color is χ_+ *directly inferred* with the NR surrogate when the full (dashed) or just ringdown (solid) data are analyzed. Each violin is from a simulated signal with a different primary spin $\chi_1 = \chi$ (vertical axis) and mass ratio q (horizontal axis). In practice, a version of this plot would be generated for each inspiral parameter we are measuring, for both the aligned and precessing cases.

Week 1-2: Become familiar with LIGO data analysis techniques and NR simulations, as well as relevant code.

Week 3-4: Aligned spin ringdown analysis and first interim report.

Week 5-8: Precessing spin ringdown analysis and second interim report.

Week 9-10: Wrapping up and final presentation.

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