Data driven modeling of peak frequency and luminosity of black hole mergers

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May 2019

1 Introduction

In 1916, Albert Einstein predicted the existence of gravitational waves in his general theory of relativity. These waves are ripples in the fabric of space-time that carry information about changes in the gravitational field. However, due to the weak nature of their interaction with matter, the only gravitational waves detectable on Earth come from the most violent processes in the Universe, one example being black hole mergers. Almost a century after Einstein's prediction, on September 14th, 2015, LIGO (Laser Interferometer Gravitational Wave Observatory) achieved the first direct detection of gravitational waves [1], from two black holes merging, heralding a new era of astronomy that not only uses light but also gravitational waves as a source of information about the Universe.

Once gravitational waves reach Earth, their amplitude is extremely small, a thousand times smaller than the nucleus of the hydrogen atom. Despite this, these slight ripples allow scientists to infer the properties of the source of the waves, as well as test general relativity in the highly dynamical strong field regime. In particular, the gravitational fields are strongest just as the two black holes are about to merge, and this is typically associated with the peak amplitude of the gravitational wave. Therefore, several tests have been devised which make use of the properties of the gravitational wave at the peak, particularly the luminosity and frequency [2, 3]. Further, knowing the peak luminosity of black hole merger can provide information on the amount of power radiated in the merger process. For instance, in the first detection [4], the power radiated was larger than the power radiated in light from the entire observable Universe combined!

However, the peak corresponds to the time at which the the gravitational fields are extreme and the black holes are moving at about half the speed of light. All analytic methods break down at this stage, and full numerical simulations of Einstein's equations are necessary. Unfortunately, these simulations are very expensive, with a single simulation taking a month on a supercomputer. Therefore, several approximate models for the peak luminosity and frequency have been developed over the years (see e.g. Refs. [5, 2]). These models make some assumptions about the phenomenology of the fits based on physical motivation and intuition, and calibrate any free parameters to numerical simulations. While these models are very fast, the are typically less accurate than the simulations themselves.

To combine the accuracy of numerical simulations and the speed of approximate models, surrogate modeling provides an alternative where one directly interpolates between existing numerical simulations. These models have been shown to be comparable in accuracy to numerical simulations, while taking only a fraction of a second to evaluate [6, 7]. In this SURF project, we will create a surrogate model for the peak luminosity and frequency of binary black hole mergers. Using techniques akin to machine-learning, specifically Gaussian process regression, we will train our model directly against the data from numerical simulations, creating a purely data-driven model that does not need to make any additional assumptions about the underlying phenomenology.

2 Objectives

We will develop a surrogate model that predicts the peak luminosity and frequency of binary black hole mergers by directly interpolating between numerical simulations, without adding additional assumptions. We will use Gaussian process regression to construct our model.

3 Approach

Gaussian process regression (GPR) has been successfully applied in surrogate modeling applications for the predicting the gravitational waveform [8] and the properties of the final black hole left after the merger [6]. In this project we will apply similar methods to model the peak luminosity and frequency. GPR does not need to make assumptions about the underlying phenomenology of the data. Instead, GPR implicitly reconstructs the phenomenology when it is trained against the data. In addition, GPR naturally provides an error estimate along with the fit evaluation. As was the case for the previous GPR based surrogate models, we expect our final fits to be able to reproduce the numerical simulations at an accuracy comparable to the simulations themselves.

4 Work Plan

For the first two weeks of my SURF project, I will familiarize myself with surrogate modeling, black hole mergers, formulae for peak luminosity and frequency, and earlier models that fit for these quantities. This period of familiarization will allow me to get accustomed to techniques that I will use later in my project. The next three weeks, I will develop the first draft of my surrogate model for peak luminosity and frequency, using the GPR method. Over the next three weeks, I will evaluate the accuracy of my model by comparing to numerical simulations. Similarly I will compare existing models, and quantify the improvements achieved by my model. If necessary I will make modifications to my model to improve its accuracy. The final two weeks I will wrap up my project and prepare my final write up and my presentation.

References

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