FINAL SURF REPORT

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0.1 PROJECT BACKGROUND

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.

0.2 PROJECT OBJECTIVES

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.

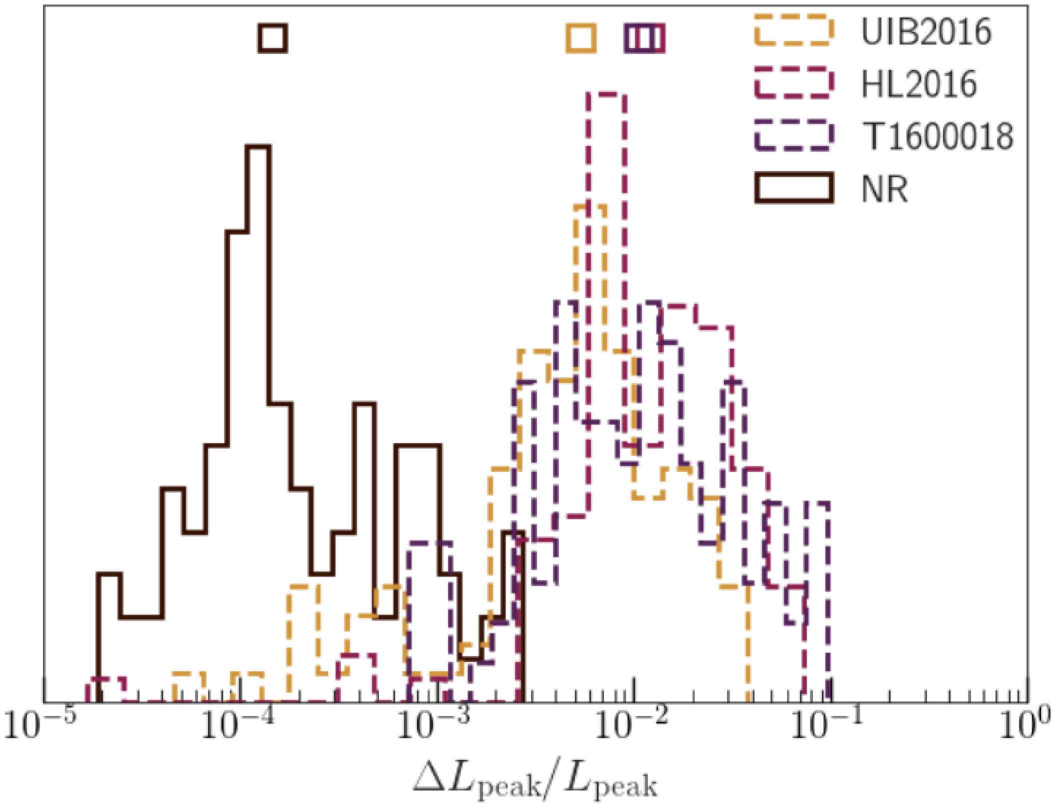
Initially, we will begin with comparing the results of Numerical Relativity (NR) calculated luminosity to Phenomenological Estimated luminosity. If this difference is larger than the model error, we will proceed to make the GPR model for peak luminosity. Then we will calculate the error of this fit by calculating the difference between the model's prediction of luminosity values and the NR calculated luminosity.

We will use the same method for creating the GPR model of peak frequency.

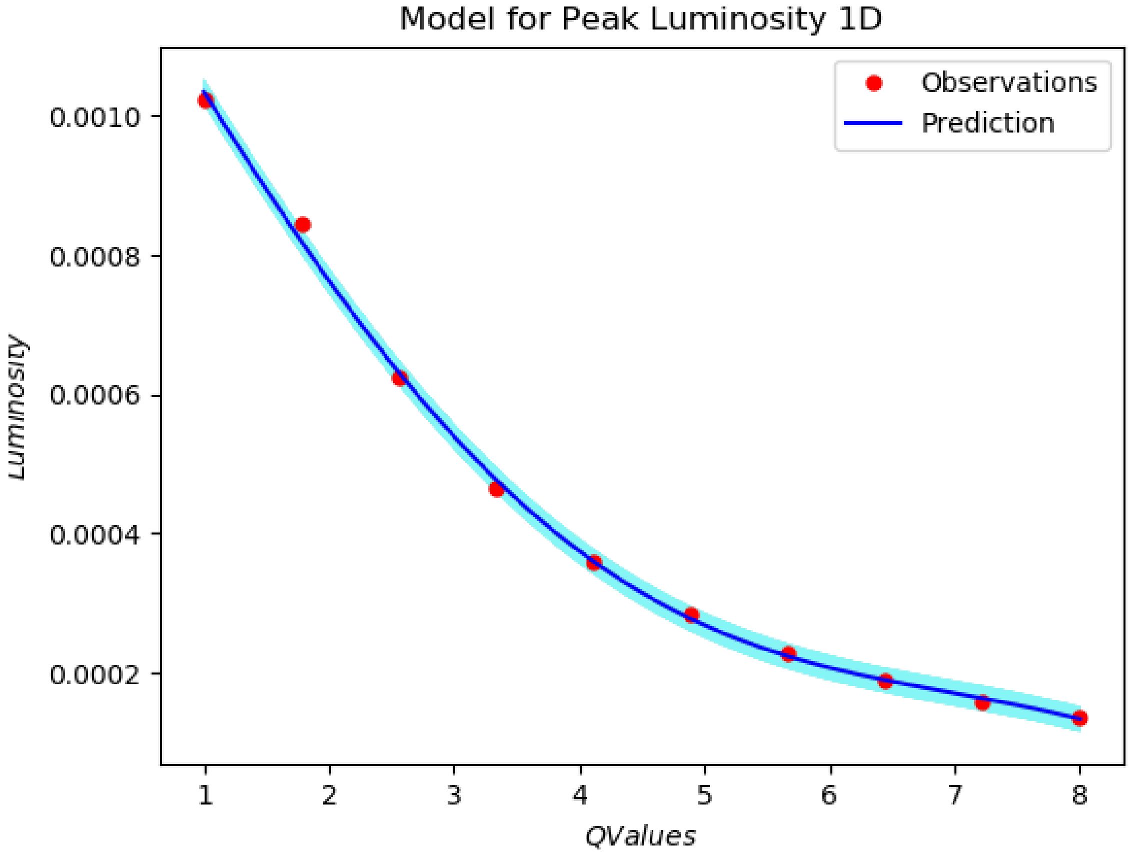
0.3 PROJECT UPDATES

I spent the first week getting settled and access to necessary materials. The LIGO SURF also had a series of talks that introduced us to the basics of the LIGO detector and the data analysis process.

The second week, I began my project by creating histograms comparing the peak luminosity values derived by calculations from the NR simulations and the peak luminosity values derived by the phenomenological estimations. Then, I found the errors associated with the NR calculated luminosity and the model estimated luminosity.

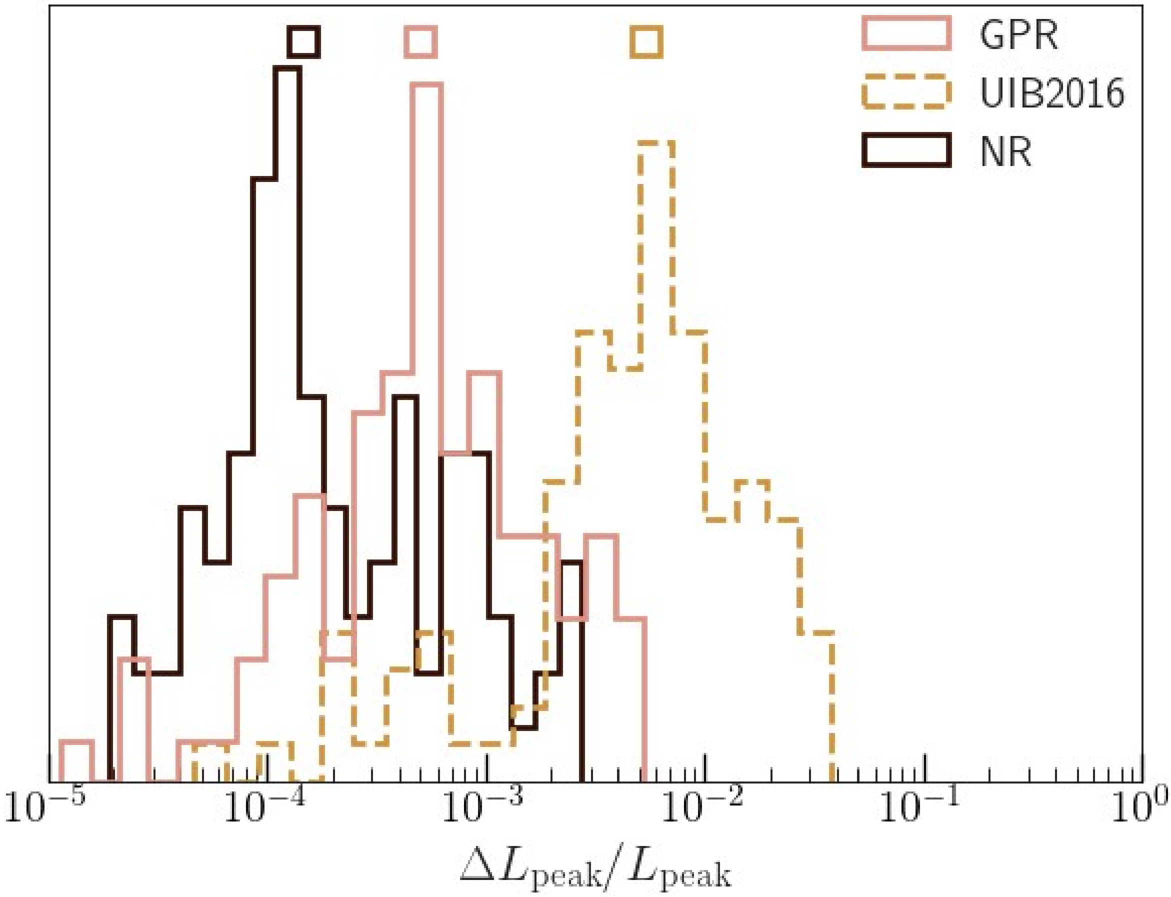


The third week, I began creating a GPR script for a 1D case of luminosity, with the only parameter being the mass ratio of the two binary black holes (BBH), q.



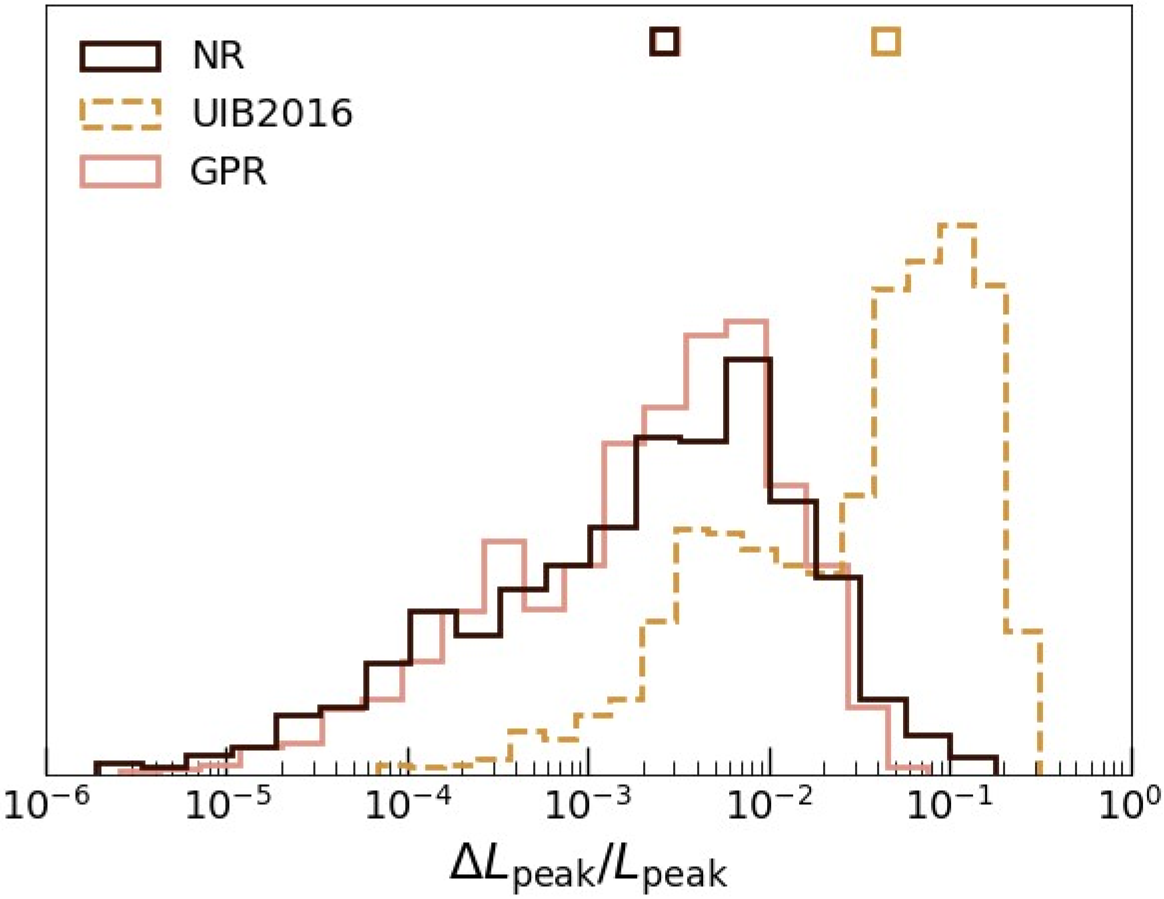
Once I was done with the 1D case, I began working on the 3D GPR script for peak luminosity. The parameters for this problem are the mass ratio of the BBH, and the z component of the spin vector of the two black holes. I was able to create a model for the peak luminosity using GPR for the 3D case.

After I created the initial GPR script, I began working on optimizing the script to create errors similar to NR errors. I first began by looking at my mentor's, Vijay Varma, earlier scripts which utilized the same fitting paramters. After I fixed my parameters to smooth the parameter space, I was able to utilize the GPR method to create errors that were similar to the NR errors that were computed. In this initial model, there was a clear decrease of errors by two orders of magnitude.



The fifth week, I began working with the earlier code Dr. Varma created to model final mass spin and other parameters of black hole mergers. I aimed to alter the code to utilize GPR to create a model for peak luminosity. After successfully altering Dr. Varma's code, I was able to create a GPR model for peak luminosity that replicated errors similar to NR resolution errors with training data, meaning the tested data was used to create the model.

I then expanded the surrogate model to 7 dimensions, removing the assumption that the spins of the black holes are aligned with the systems angular momentum. The resultant peak luminosity model for precessing systems, the 7 dimensional case, yielded GPR modeled errors that essentially saturated the NR resolution error.



0.4 CONCLUSIONS

Implementing Gaussian Process Regression on Numerical Relativity data to create a model for peak luminosity created models that had an order of magnitude increase in accuracy. Further work involves creating finer resolution numerical relativity simulations. This will hopefully lead to more accurate GPR models for peak relativity, given that the model's error saturates the NR Resolution error.

0.5 ACKNOWLEDGEMENTS

I would like to thank everyone who helped me complete my summer project. A special thanks to Vijay Varma, my mentor who was such a help the entire summer, Alan Weinstein, Masha Okounkova, and the SURF program.

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