# LIGO SURF 2015:
# Numerical Simulations of Black Hole Binaries

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## 1 Background

A binary black hole system loses energy in the form of gravitational waves. This causes the two black holes to inspiral towards each other, until finally, they coalesce into a single black hole. Little is known about the final stages of these black hole mergers from observation because black holes do not emit light. However, if we can analyze the emitted gravitational waves we will be able to build a picture of the inner workings of black holes.

Advanced LIGO will be operational soon and should regularly detect gravitational waves coming from some of the most fascinating events in the universe. By observing and analyzing gravitational waves, LIGO hopes to study events such as supernovae explosions and black hole mergers. However, in order to pull such a weak gravitational signals out of the noise in the data, LIGO needs expected waveform templates for possible events that it might observe. It is now possible to numerically solve Einstein's equations of general relativity for the merger of binary black holes and retrieve the resulting gravitational waves. For maximum efficiency in processing the data it collects, LIGO needs to only collect a database of waveforms that it could feasibly detect and tell the differences between.

If the merging black holes have opposing spin orientations, then upon merger, a significant amount of linear momentum is carried off by gravitational waves. Momentum must be conserved, so the resulting black hole will gain momentum that may be large enough for it to be kicked out of its host galaxy [1][2]. This strange phenomena is called a superkick. Extremely high spin superkick simulations have not been attempted yet, and we are interested in them because such high energy black hole mergers may behave differently than we expect.

Ultimately, we would like to know whether LIGO can detect the direction of the spins at merger. The magnitude and direction of a superkick are known to depend sensitively on how the spins are oriented at the moment of coalescence [3], yet it is unknown whether the gravitational waveforms produced by these mergers are affected by the spin orientation enough for LIGO to be able to detect. From previous work, we know that LIGO is not sensitive to the spin directions at the time of merger for low spins up to 0.5 relative to maximum. However, the superkick itself, and thus the effect on the waveform, should be much larger for higher spins. We want to know if LIGO could detect spin orientation for high spin cases.

Time limitations are a major challenge in numerical relativity: these simulations take weeks to months. Thus, it is necessary to make educated guesses for initial parameters of the black holes' orbit so that we can start the simulation at the more interesting orbits closer to merger. Eccentricity of orbit is one such parameter of interest. Isolated binary black hole systems radiate gravitational waves as they orbit, causing a reduction of eccentricity over time until the orbit is essentially circular [4][5]. Most of the black hole binaries that LIGO will observe will be of this type, so it is important in our simulations that the eccentricity produced by the initial conditions must be small enough before proceeding to completely evolve the merger[5]. There are currently algorithms for doing this, but improving them and making the process more efficient would greatly reduce the time each simulation takes.

Numerical simulations will help us learn about black hole superkicks. We hope to contribute to LIGO's efforts by determining whether spin orientation can be detected and improving eccentricity measurement and analysis.

## 2 Objectives

The main objective of this project is to simulate high spin black hole superkicks and determine if LIGO would be able to detect the direction of the spins at merger for high spin cases from the associated gravitational waveforms. The results will be informative to LIGO and reveal how dependent superkick waveforms are on the magnitude and orientation of the spins.

While the simulations are running, I will improve existing code to make the data analysis and future simulations faster, more efficient and more comprehensive. I will specifically focus on improving the measurement of the system's eccentricity. I will implement the ability to set constraints on parameters and calculate error bars to indicate the uncertainty in the eccentricity measurement. Ideally we would also like be able to calculate the eccentricity and its error bars while the simulations are running.

Successful completion of this project should result in a conclusion on whether LIGO can detect the difference between waveforms with distinctive spin orientations as well as an eccentricity measurement process with error bars that could ideally work while simulations are running, instead of post-processing.

## 3 Approach

This project is split into two distinct parts. The main, overall focus will be on conducting high-spin superkick simulations and analyzing their resulting gravitational waveforms. While the simulations are running, I will focus on improving the eccentricity reduction process.

I will run several high spin black hole superkick simulations for two different spin magnitudes. One simulation will have a relative spin of 0.91, where 1 is the maximum allowed by the theory of general relativity. This spin is quite high, but safely remains within the range that the supercomputer is capable of handling. Once this simulation has been eccentricity-reduced so that the eccentricity is very close to zero, we will start 3 more 0.91 spin superkick simulations identical to the first except with the spins oriented differently. After the simulations have been completely evolved, we will fit the strength of the superkick versus the orientation of the spins to determine the orientation that would give the maximum and minimum superkicks for this setup. Finally, simulations for these maximum and minimum configurations will be run and the waveforms will be analyzed to determine if LIGO can distinguish the difference.

We will also push the boundaries of high spin superkicks and concurrently attempt a 0.99 relative spin run. It will be informative if it the technology cannot yet handle such a high spin case, but even more so if this extremely high spin simulation is successful. The 0.99 spin case will be treated in the same fashion as described above for the 0.91 spin simulation. The resulting gravitational waveforms from these high spin configurations will then be analyzed and compared to those produced in a previous low, 0.50 spin simulation where it was determined that LIGO could not detect the difference between spin orientations.

The simulations will be run on the supercomputer Zwicky. As the simulations are running, I will improve the eccentricity measurement scripts. First, the existing code must be cleaned up and the eccentricity fit formulas must be completely converted to C++. Then I will analyze how the values from the eccentricity calculation change with respect to which window of time is considered. This will allow me to assign error bars to the eccentricity calculations for the simulation. I will add the ability to impose constraints on the simulation parameters and conduct more comprehensive and robust tests to determine how well the eccentricity reduction script works. Once these tools have been developed, I will incorporate them into a new, fully functional eccentricity-reduction script. Finally, we hope to implement this script into the main simulation code so that measurements of the eccentricity and associated uncertainties can be taken as the run progresses, rather than being computing after the run has completed. This will improve the efficiency of the simulation and help reduce how long each simulation takes.

When the superkick simulations have completed, I will analyze and visualize the resulting data and determine the significance of the results.

## 4 Work Plan

**Prior to summer**: I have begun academic term research with Mark Scheel. We have started the 0.91 spin simulation and I am becoming familiarized with the programs used and the work of the lab. We are also currently starting the 0.99 spin simulation.
**Weeks 1-3**: Improve eccentricity measurements: convert calculations to C++, construct error bars, allow for constraints on parameters, and conduct more robust tests.
**Week 4**: CGWAS 2015
**Weeks 5-6**: Figure out if there is anything going wrong with the superkick simulations, create a replacement eccentricity reduction script which implements the newly constructed tools.
**Weeks 7-8**: Analyze spin 0.91 superkick simulation data, implement eccentricity reduction into main simulation code for real-time eccentricity estimates.
**Weeks 9-10**: Analyze spin 0.99 superkick simulation data and determine the significance of the results.

# References

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