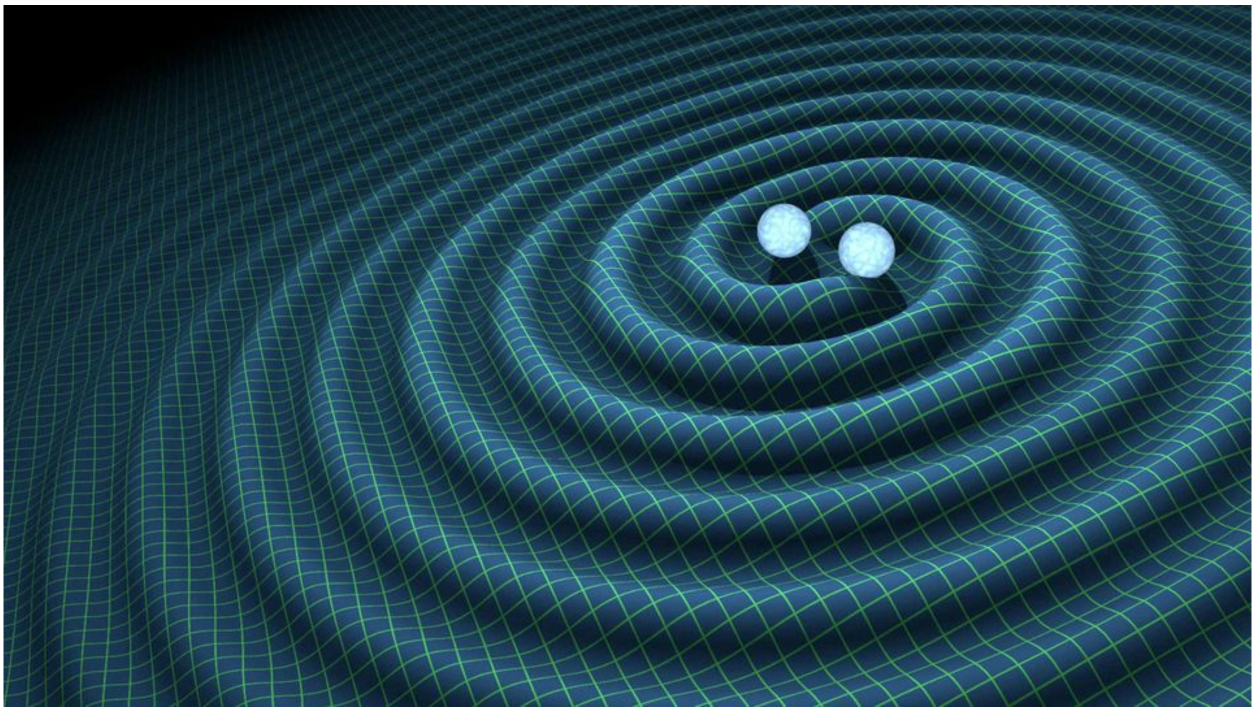
Course Project for ASTR 510 - Computational Astrophysics

Simulations of Binary Black Hole Mergers
With the Einstein Toolkit



(Image source: MIT https://www.youtube.com/watch?v=B4XzLDM3Py8)

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Introduction

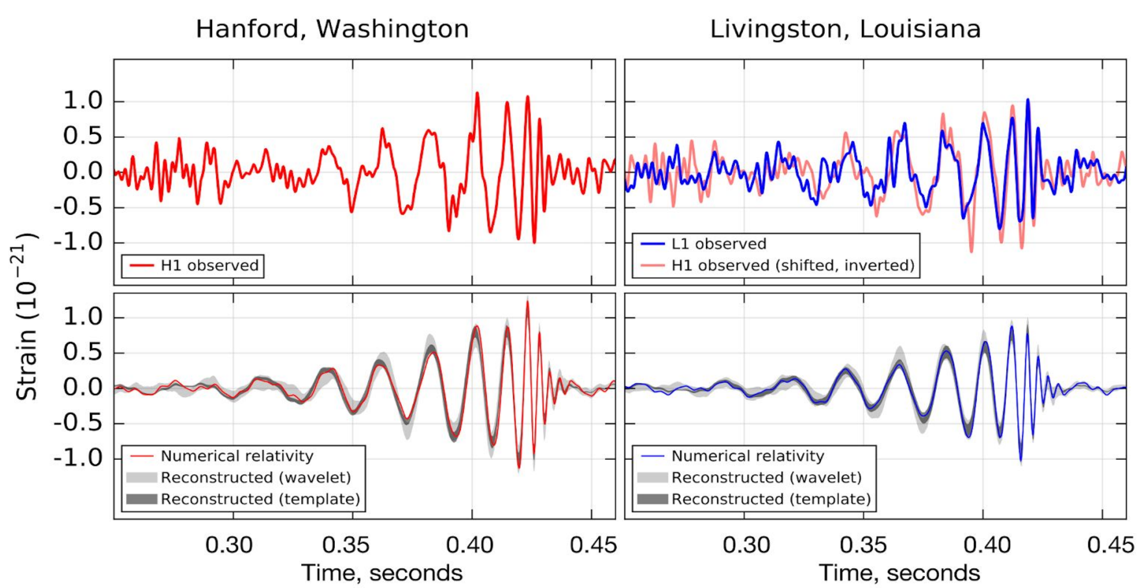
With the first gravitational waves having been detected recently by LIGO [1], we can expect a huge influx of gravitational wave data in the immediate future. Numerical relativity simulations are crucial for determining the origin of the detected gravitational waveforms.

For this project, I will be performing numerical relativity simulations of the merger of a binary system of black holes having perfectly circular orbits, using the Einstein toolkit [2], in order to measure the emitted gravitational waves.

Write in the style you would use for an ApJ or PRL paper. This reads more like a magazine article.

Importance of Gravitational Waves

After exactly a century since the theoretical prediction of gravitational waves by Albert Einstein, the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration, in what was the most precise measurement ever made by mankind, finally announced the first direct detection of gravitational waves on 11 February 2016, thus paving the way for a new era of gravitational wave astronomy [1].



Number figures & refer to them in text.

(Figure shows the first detection of gravitational waves [1])

Gravitational waves, unlike electromagnetic radiation, have the unique property that they cannot be shielded. This allows us to see events occurring in locations such as the galactic center that would otherwise be obscured by intervening matter.

Moreover, we can probe extremely energetic events in regions of strong gravitational fields which were inaccessible to us up to now. For example, the merger of the two black holes which led to the detection released more energy in the form of gravitational radiation at that instant than the total energy output of all the stars in the universe put together. This will allow us to test Einstein's theory of General Relativity more rigorously than ever before and possibly discover new laws of physics in case those tests fail. Can you give numbers here?

Role of Numerical Relativity and High-Performance Computation

The equations of General Relativity are highly nonlinear and impossible to solve analytically (with the exception of a few simple cases). Although linearized weak field approximations to these equations were used by Einstein to predict the existence of gravitational waves, this method can only be used to study gravitational waves far away from their source of origin.

Due to the extremely weak amplitudes of gravitational waves, our detectors are capable of detecting only the brightest of the gravitational waves that reach us. Such strong waves are only created by the interactions between the densest compact objects such as neutron stars and black holes. Due to the high gravitational fields involved in the process, we cannot use weak field approximations to solve the equations of general relativity. All attempts at tackling these situations using purely analytical techniques have failed.

The only methods at our disposal to solve the full set of equations are numerical simulations with the aid of computers. Due to the complex nature of the equations of General Relativity, these simulations require extreme amounts of computational resources, often requiring the most powerful supercomputers of our time. Thus, unsurprisingly, numerical relativists were among ~~one of~~ the first people to adopt the use of supercomputers for academic research.

Improvements in theoretical techniques and computing capabilities over the last decade ha~~s~~ve made simulations of the merger of binary black holes possible. These simulations have shown that the gravitational waves emitted during inspiral, merger and ringdown stages have a unique shape and signature which only depends on certain properties of the binary system such as the masses, spins, etc. It was by comparing the signal detected by LIGO with these results from numerical relativity that we concluded that a merger of two black holes was the source of these gravitational waves. Furthermore, we were able to estimate the masses and spins of these black holes with some degree of uncertainty.

Again, giving some numbers here would be useful.

The analysis of the big data reaching the LIGO detectors in order to filter noise and extract multiple gravitational waveforms and then estimate various astrophysical parameters also requires a lot of high-performance data-intensive computing.

Need for this Project

rephrase to avoid long sequence of modifiers

Currently, ~~there are~~ only closed source state-of-the-art numerical relativity simulation codes, such as the Spectral Einstein Code developed by the sXs collaboration [4], ~~which~~ can be used to predict the gravitational waves emitted by binary black hole mergers. The waveforms generated by this group were the ones that were used to classify the recent detection by LIGO as a merger of black holes and to estimate their masses, spins, and other properties.

Thus there is a need to create open-source simulation~~s~~ codes, that can be used by anyone and can be scaled to run on HPC clusters as well as more powerful supercomputers such as Blue Waters, to corroborate the waveforms generated by these other codes as well as to promote the spirit of the scientific method by completely revealing all steps involved in the process.

With the ever increasing computational power of supercomputers (soon to enter the exascale regime) we now have the ability to do extremely precise simulations of almost every kind of scenario we can imagine. However, these simulations are still very expensive and time-consuming. Therefore, the publicly available catalogues of gravitational waveforms are very sparse, covering only a small subset of the total parameter space [3].

LIGO relies on various semi-analytic models as well as statistical fits in order to fully cover the remaining region. Various free parameters in these semi-analytic models are details?

obtained through fitting with numerical relativity simulations. Therefore increasing the size of the publicly available catalogues by adding more waveforms generated by numerical relativity simulations covering a wide range of astrophysical systems would allow us to create and calibrate better semi-analytical and statistical models that can quickly generate reasonably accurate waveforms that cover the entire spectrum of possible parameter values falling within the detection thresholds of LIGO as well as other upcoming gravitational wave detectors such as NANOGrav [5] and LISA.

Scope for Possible Extensions in the Future

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My current research at NCSA involves studying binary systems of compact objects having significant orbital eccentricity prior to the merger event. Although most binary black hole systems quickly lose eccentricity due to gravitational wave emission during the early inspiral stage, external perturbations, caused by interactions with the environment or by the presence of a third compact object in the vicinity, can produce noticeable eccentricities in the orbits close to the merger. Having an effective model covering eccentric orbits can help as determine more astrophysical properties about the binary systems and their environments.

With Dr. Eliu Huerta at NCSA, I have previously developed a semi-analytic model that predicts the gravitational waves emitted by these systems. This model has the advantage of generating the waveforms for a wide range of parameters extremely ~~fast~~ quickly while requiring minimal computational resources. Therefore, our code can be used to populate the entire parameter space with template waveforms for all orbital eccentricities which will be matched against detected signals in order to determine various properties.

However, there are no numerical relativity simulations of systems with highly eccentric orbits (>0.1) as of today [3,4]. Therefore, I plan to extend this project in the future to perform numerical relativity simulations of systems with eccentric orbits thus allowing us to validate our semi-analytic model and possibly improve its accuracy.

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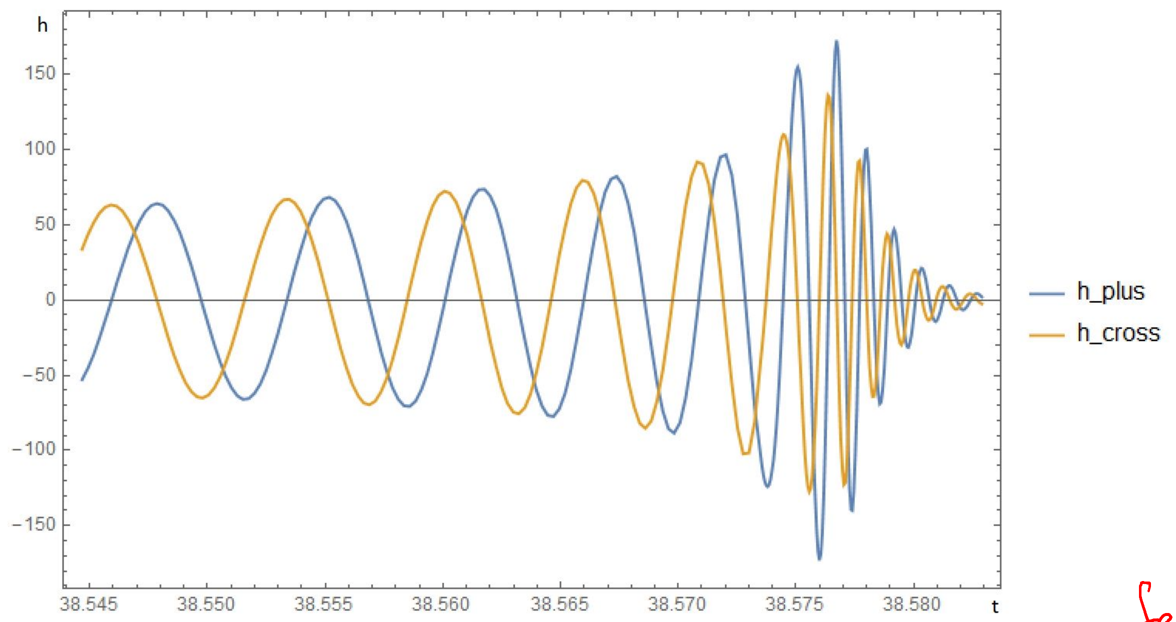

(Figure showing one of the waveforms generated by my semi-analytic model) ~ Figure #, reference in text

Furthermore, this simulation code can also be extended to cover mergers involving combinations of supermassive black holes, neutron stars, white dwarfs and possibly other exotic compact objects. This will be useful when more gravitational wave detectors such as NANOGrav, LISA, etc. come online which will dramatically increase the spectrum of gravitational wave generating events that can be detected.

Use ApJ or PRL reference format

References

[1] Observation of Gravitational Waves from a Binary Black Hole Merger - B. P. Abbott et al.

[2] The Einstein Toolkit: A Community Computational Infrastructure for Relativistic Astrophysics - F. Löffler et al.

[3] The NINJA-2 catalog of hybrid post-Newtonian/numerical-relativity waveforms for non-precessing black-hole binaries - P. Ajith et al.

[4] Spectral Einstein Code - sXs collaboration

[5] The North American Nanohertz Observatory for Gravitational Waves - F. Jenet et al.