DETECTION OF GRAVITATIONAL WAVE SOURCES IN DENSE STELLAR ENVIRONMENTS

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EXECUTIVE SUMMARY

The direct detection by the twin LIGO (Laser Interferometer Gravitational-Wave Observatory) detectors of gravitational waves from merging black holes has ushered in a revolution in astrophysics [1,2]. LIGO's detection campaigns are enabling the construction of catalogs of gravitational wave sources to enable accurate censuses of the mass and angular momentum distribution of black holes and neutron stars. These studies will provide new and detailed information about the formation, evolution, and environments in which compact objects reside. In particular, the detection of gravitational waves from eccentric compact binaries will provide the cleanest signature of compact object populations in dense stellar environments [3]. To detect these events, we introduce the first waveform model in the literature that reproduces the features of eccentric compact binary coalescence throughout merger. To validate this model, we used numerical relativity simulations performed with the Einstein Toolkit on the Blue Waters supercomputer.

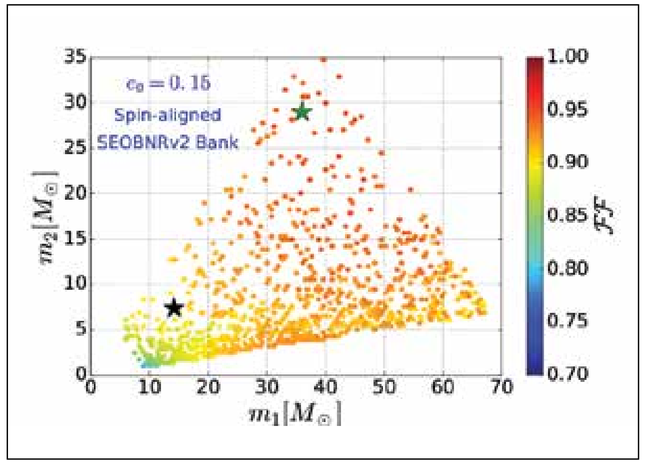

Figure 1: Recovery of eccentric, nonspinning signals (represented by points in the figure) using a template bank of 1.5 million quasi-circular, spin-aligned waveforms. The green and black stars represent GW150914 and GW151226. The Fitting Factor is computed by maximizing the overlap, or inner product, between every single eccentric signal and the 1.5M templates in the bank.

RESEARCH CHALLENGE

Gravitational wave (GW) observations provide insights into the astrophysical sources that generate them and can be used to map the structure of spacetime in the vicinity of compact binary sy holes (BHs) in the galactic cluster M22 led to the development of more accurate N-body algorithms to explore the formation and detectability of binary black holes (BBHs) formed in globular clusters [4]. These studies indicate that about 20% of BBH mergers in globular clusters will have eccentricities e_0~0.1 when they first enter the aLIGO band at 10Hz, and that ~10% may have eccentricities e_0~1 [5]. BBHs formed in the vicinity of supermassive BHs may also merge with significant residual eccentricities. aLIGO is uniquely positioned to enhance the reach of GW astronomy by targeting these events. At the time of the detection of the first GW transient, GW150914, there was no waveform model available to describe the evolution of eccentric compact binary coalescence (eCBC) from early inspiral through merger and ringdown [6]. Furthermore, we require new data analysis techniques to capture the imprint of eccentricity on GW signals [7].

In order to detect and characterize eCBC with aLIGO, we introduce an inspiral–merger–ringdown (IMR) waveform model that reproduces the dynamics of state-of-the-art, nonspinning, quasi-circular waveform models, and the dynamics of eccentric numerical relativity simulations.

METHODS & CODES

To construct our model, we derived higher-order post-Newtonian results for eCBC and then combined these results with state-of-the-art results from the self-force formalism and BHPT. This hybrid formalism is the first of its kind to reproduce CBC accurately for compact binaries with mass-ratios between 1 and 10.

To construct the merger phase of our model, we assume that the system circularizes prior to the merger event. We have found that this assumption covers the class of eCBC that aLIGO can detect using continuous waveform signals. Highly eccentric signals that do not fall into this category can be searched for in aLIGO data using burst search algorithms, which capture very well the burst-like nature of highly eccentric eCBC.

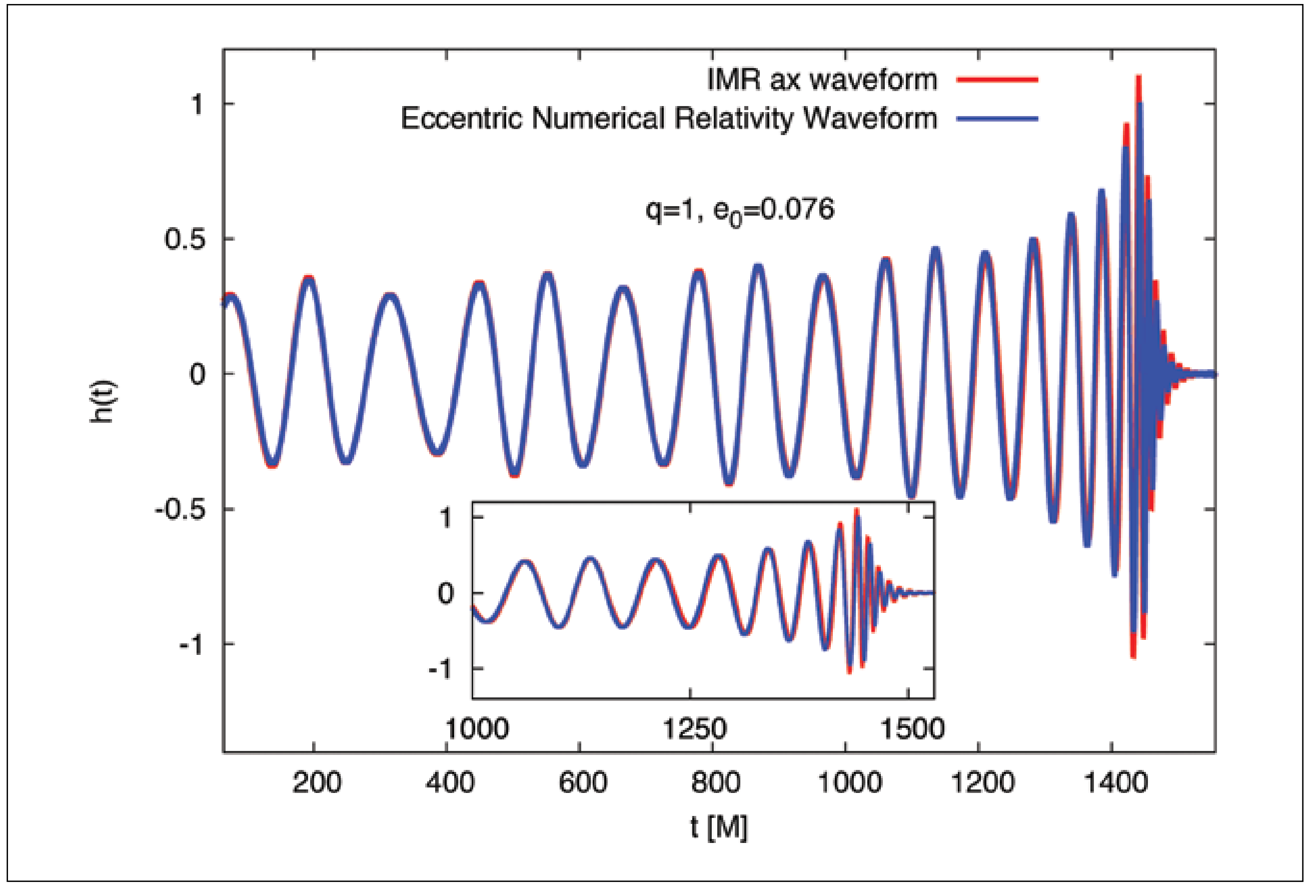

Figure 2: For an equal mass binary black hole system with initial eccentricity e_0=0.076 and mean anomaly l=3.09 at a gauge-invariant frequency value x=0.074, we present a direct comparison of the dynamics predicted by our model and an eccentric numerical relativity simulation.

RESULTS & IMPACT

We carried out the first systemic analysis of the effect of eccentricity on the first two GW transients detected by aLIGO. Fig. 1 indicates that the first two GW transients could have non-zero eccentricity at a GW frequency of 15Hz and still be misclassified as quasi-circular systems due to the restricted sensitivity of aLIGO below 25Hz. Thus, once aLIGO attains design sensitivity and is able to probe lower frequencies, we will be in a better position to accurately extract the signatures of eccentricity in GW transients.

This study is the first of its kind to show that the effect of eccentricity in waveform signals cannot be mimicked by spin corrections. Indeed, the signal manifold described by GWs with eccentricity e_0>0.1 at 15Hz is orthogonal to spin-aligned GW signal manifolds.

Another important result of this study is the validation of our waveform model using eccentric numerical relativity simulations. In Fig. 2 we show that our waveform model can accurately reproduce the true, accurate dynamics of these systems throughout the merger of the binary system. This is a noteworthy result because we did not use eccentric numerical simulations to calibrate our model. The exploitation of this model for upcoming GW detection campaigns with the aLIGO detectors will enable us to confirm or rule out the existence of compact binary populations that exist in dense stellar environments.

WHY BLUE WATERS

Blue Waters enabled us to create a large catalog of numerical relativity simulations, which required thousands of node hours that we ran in parallel to sample a deep region of parameter space. No other resource but Blue Waters can provide the required computational power to obtain a numerical relativity catalog of this nature in a timely manner. Furthermore, the Einstein Toolkit has been extensively used on Blue Waters since it began operations. NCSA Gravity Group members are key developers and maintainers of this software.

PUBLICATIONS AND DATA SETS

Huerta, E.A., et al., Complete waveform model for compact binaries on eccentric orbits. *Physical Review D*, 95 (2017), DOI: 10.1103/PhysRevD.95.024038.