FUSING NUMERICAL RELATIVITY AND DEEP LEARNING TO DETECT ECCENTRIC BINARY BLACK HOLE MERGERS USING HIGHER-ORDER WAVEFORM MULTIPOLES

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EXECUTIVE SUMMARY

An ever-increasing number of gravitational wave detections with the LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo observatories has firmly established the existence of binary black hole mergers. Using a catalog of numerical relativity simulations that describes eccentric black holes mergers with mass-ratios $1 \leq q \leq 10$, and eccentricities $e_0 \lesssim 0.18$ ten gravitational wave cycles before the merger event, the research team determined the mass-ratio, eccentricity, and binary inclination angle combinations that maximize the contribution of the higher-order waveform multipoles $(l, |m|)$ for gravitational wave detection. The researchers then explored the implications of these results in the context of stellar-mass black holes that are detectable by LIGO detectors and showed that compared to models that only include the $(l, |m|) = (2, 2)$ mode, the inclusion of higher-order waveform multipoles can increase the signal-to-noise ratio of eccentric binary black hole mergers by up to approximately 45% for mass-ratio binaries $q \leq 10$.

RESEARCH CHALLENGE

Motivated by recent electromagnetic observations that suggest the existence of compact binary populations in galactic cluster M22 [1] and in the galactic center [2], and considering that eccentricity provides one of the cleanest signatures to identify these compact binary populations, the research team studied the detectability of these signals in LIGO. LIGO relies on waveform models to detect gravitational waves in its data stream. While numerical relativity simulations are free from approximation errors and represent the actual gravitational waves produced by colliding black holes, these simulations are too expensive to use directly. Approximate models, on the other hand, will often ignore all subdominant modes in the gravitational waves, potentially resulting in a reduced detection accuracy in LIGO. Assessing the impact of these approximations is only possible using high-fidelity numerical simulations covering a sizable region of the black hole parameter space accessible to LIGO. Computing this many numerical relativity waveforms with sufficient accuracy is a formidable challenge since Einstein's equations of general relativity are among the most complex partial differential equations encountered in modern physics.

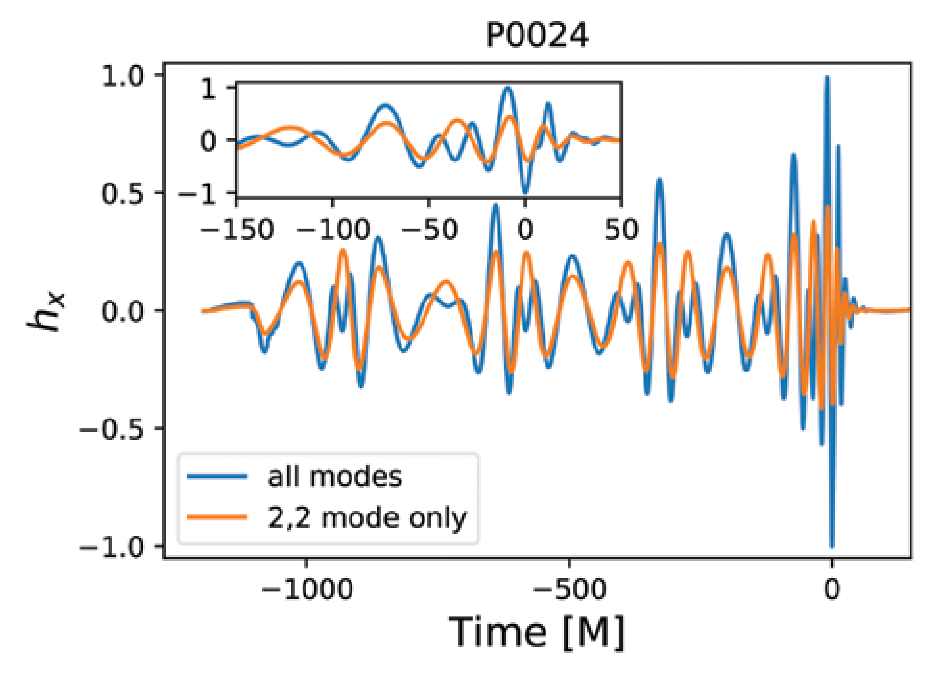

Figure 1

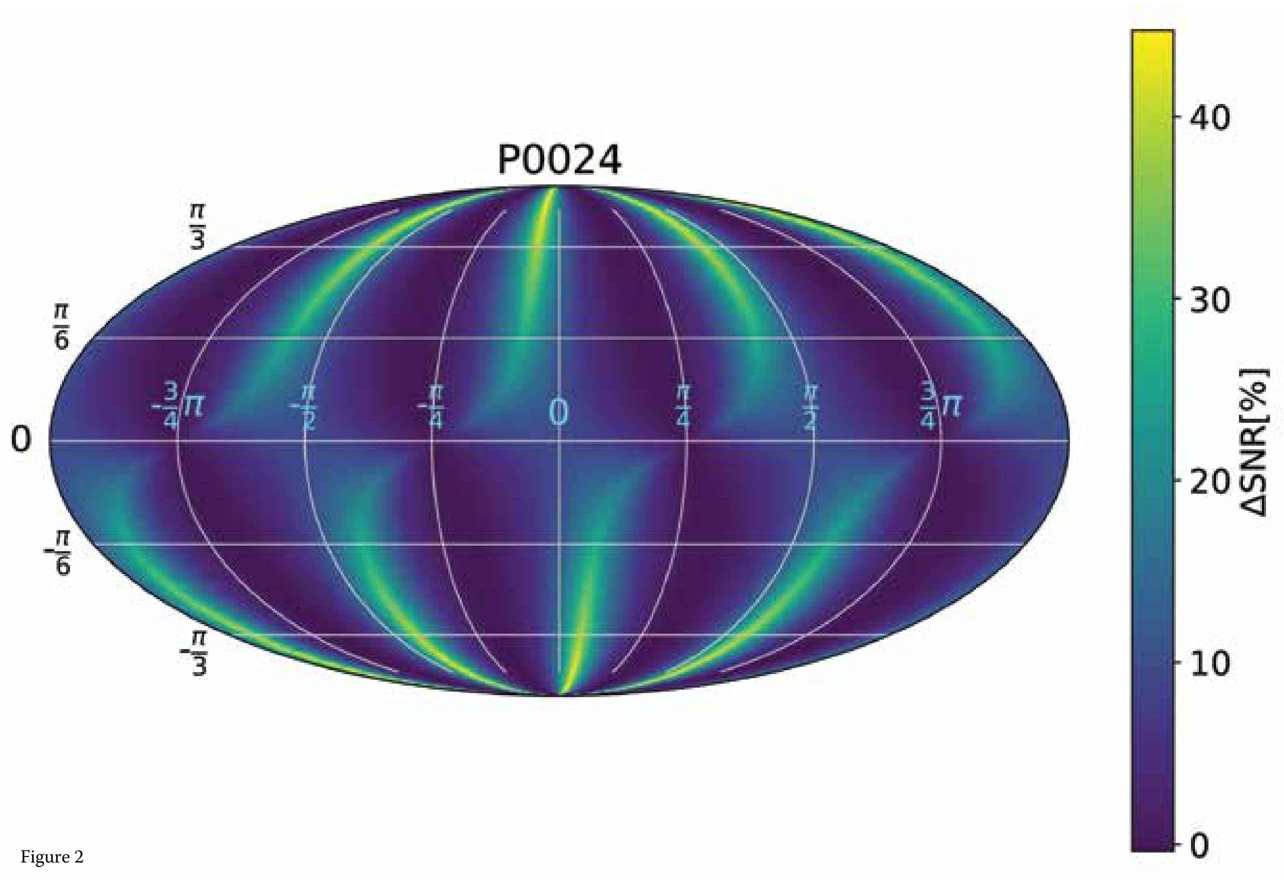

Figure 2

METHODS & CODES

The researchers used the Einstein Toolkit, a community-driven, open source astrophysics framework. The toolkit is OpenMP+MPI hybrid parallelized and uses automatic code generation to create compute kernels for general relativity. It employs eighth-order finite-differencing stencils in space and fourth-order accurate time integration. Adaptive mesh refinement including subcycling in time is used to resolve both the centers of the black holes as well as the gravitational waves far away from the black holes where they are detectable by LIGO.

RESULTS & IMPACT

The research team showed that the inclusion of higher-order waveform multipoles can increase the signal-to-noise ratio of eccentric binary black hole mergers by up to approximately 45% for mass-ratio binaries $q \leq 10$. Fig. 1 shows a representative waveform prediction with or without including higher-order modes. Generally speaking, higher-order modes add extra structure to the waveform, with more complex structure being present in eccentric black hole collisions than in purely circular inspirals and collisions. Fig. 2 shows the relative increase in signal-to-noise ratio depending on the sky-location of the source. The improvement obtained by including higher-order modes is most prominent in regions of the sky where the $(l, |m|) = (2, 2)$ mode is strongly suppressed. Including these modes will thus be critical to search for and find astrophysically motivated eccentric black hole collisions. Furthermore, the team showed that machine learning can accurately reconstruct higher-order waveform multipole signals embedded in real LIGO data.

WHY BLUE WATERS

Only Blue Waters provides the compute capabilities to simulate the hundreds of binary black hole collisions required to construct a waveform catalog suitable to explore the effect of higher-order multipoles on detectability by LIGO.

PUBLICATIONS & DATA SETS

A. Rebei *et al.*, "Fusing numerical relativity and deep learning to detect higher-order multipole waveforms from eccentric binary black hole mergers," *Phys. Rev. D*, vol. 100, no. 4, pp. 044025–044040, Aug. 2019.