Modeling the source of GW150914 with targeted numerical-relativity simulations

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Abstract

In fall of 2015, the two LIGO detectors measured the gravitational wave signal GW150914, which originated from a pair of merging black holes (Abbott \textit{et al} Virgo, LIGO Scientific 2016 \textit{Phys. Rev. Lett.} 116 061102). In the final 0.2 s (about 8 gravitational-wave cycles) before the amplitude reached its maximum, the observed signal swept up in amplitude and frequency, from 35 Hz to 150 Hz. The theoretical gravitational-wave signal for merging black holes, as predicted by general relativity, can be computed only by full numerical relativity, because analytic approximations fail near the time of merger. Moreover, the nearly-equal masses, moderate spins, and small number of orbits of GW150914 are especially straightforward and efficient to simulate with modern numerical-relativity codes. In this paper, we report the modeling of GW150914 with numerical-relativity simulations, using black-hole masses and spins consistent with those inferred from LIGO’s measurement (Abbott \textit{et al} LIGO Scientific Collaboration, Virgo...
Collaboration 2016 *Phys. Rev. Lett.* **116** 241102. In particular, we employ two independent numerical-relativity codes that use completely different analytical and numerical methods to model the same merging black holes and to compute the emitted gravitational waveform; we find excellent agreement between the waveforms produced by the two independent codes. These results demonstrate the validity, impact, and potential of current and future studies using rapid-response, targeted numerical-relativity simulations for better understanding gravitational-wave observations.

**Keywords:** numerical relativity, black-hole binaries, gravitational waves

(Some figures may appear in colour only in the online journal)

### 1. Introduction

On September 14, 2015, the Advanced Laser Interferometer Gravitational-Wave Observatory (Advanced LIGO) directly measured gravitational waves for the first time [1], giving birth to a new era of astronomy. The waves were emitted by a pair of black holes with masses $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$ [1, 2] that orbited each other, collided, and merged about 1.3 billion years ago.

The gravitational wave signal from this event, named GW150914, is consistent with general relativity. The inspiral and post-inspiral portions of the signal imply a consistent mass and spin for the final, remnant black hole, the data following the peak amplitude are consistent with the least-damped quasinormal mode for that remnant, and the waveform shows no evidence of dispersion, which would imply a massive graviton [3]. Moreover, a number of gravitational waveforms produced by different numerical-relativity codes are consistent with GW150914 [1, 4].

LIGO has already observed a second gravitational-wave signal from merging black holes (called GW151226) [5] and a third possible signal (called LVT151012) [6]; many more such observations are expected soon. Extrapolating from the observations of GW150914 and GW151226 and including LVT151012, Advanced LIGO is expected to observe between roughly five to tens of gravitational-wave signals from merging black holes during its next six-month observing run (O2) starting in 2016 [6].

The GW150914 observation included eight gravitational-wave cycles, covering the late inspiral, merger, and ringdown phases of the binary (see figure 2 of [1]); this late phase of a binary-black-hole (BBH) merger can be described accurately only by directly solving the full equations of general relativity. To extract and validate robust conclusions about the astrophysical and fundamental significance of these events [1–3, 7], correct and complete solutions to Einstein’s equations will be critical, and near the time of merger, such solutions can be obtained only through direct correct and complete solutions to Einstein’s equations will be critical, and can be obtained only through direct numerical simulation.

The first attempts to solve the general relativity field equations numerically date to the 1960s, when Hahn and Lindquist [8] performed the first studies. Smarr followed these early efforts with some success in the 1970s [9, 10]. The field matured in the 1990s, when a large collaboration of research groups worked together toward solving the ‘Grand Challenge’ of evolving BBHs [11]. The crucial final breakthrough came in 2005, when three groups [12–14] devised two completely independent techniques to numerically solve the BBH problem. The first solution [12] handled the spacetime singularity by excising the regions interior to the black hole horizons, while the second technique [13, 14], dubbed the ‘moving punctures approach’, used singularity avoiding slices of the black hole spacetimes.
Since then, through considerable effort by many research groups (reviewed, e.g. in [15–19]), each of these techniques have matured, yielding two distinct, independent approaches to modeling BBHs with numerical relativity. Important analytic and numerical developments [20–22] have improved the accuracy and efficiency of the codes implementing each technique. Each technique has enabled numerical relativists to begin constructing catalogs of BBHs and associated gravitational waveforms [21, 23–28]. Excluding the total mass of the system (because of the scale invariance of general relativity) and assuming a negligible eccentricity (the most likely astrophysical scenario), a BBH can be characterized by seven intrinsic parameters: the ratio $q$ of the holes’ masses and the initial spin-angular-momentum vectors $S_i^1$ and $S_i^2$ of each hole; as a result, these catalogs must include many BBH simulations to span the parameter space of BBH events that LIGO could observe. Note that early work has already used numerical-relativity waveforms for detection and parameter estimation (including extrinsic parameters) in LIGO, for the injection of waveforms [23, 29–31], into LIGO noise, and for establishing common error measures to establish standard of required waveform accuracy [24].

In this paper, we present a detailed comparison of the targeted numerical BBH simulations that modeled GW150914 in figures 1 and 2 of [1], provided by two codes: the spectral Einstein code (SpEC) [32] and LazEv [33]. We chose the parameters (masses and spins) of these simulations to be consistent with estimates of the parameters for GW150914 [1, 2]. Note that we are not presenting any additional information on parameter estimates in this paper. The parameters we chose are consistent with LIGO’s observation of GW150914, but we could have chosen different parameters that are also consistent with the observation. As discussed in [1, 2], there is considerable uncertainty in parameter estimates for GW150914, particularly for the black-hole spins.

By comparing the results from these two codes, our study extends the statement made in the caption of figure 1 of [1]: that the numerical relativity calculations shown there are ‘confirmed to 99.9%’. Our investigation extends previous validation studies of each code internally [34, 35], and against one another [36], using common standards for waveform accuracy [24], to current versions of both numerical-relativity codes for the important case of modeling GW150914.

SpEC and LazEv are completely independent. They use different formulations of Einstein’s equations for the decompositions of $G_{\mu\nu} = 8\pi T_{\mu\nu}$ into evolution equations and constraints, solving for different dynamical variables. They use different methods to choose coordinates and to handle the spacetime singularities inside the black holes. They use different analytic and numerical methods for generating constraint-satisfying initial data, for the geometries for the numerical grid, for the spacetime evolution, for refining the numerical grid, and for extracting the gravitational waveforms from the evolved variables. They share no subroutines in common. But despite these vast differences, we show in this paper that the two codes produce the same physics. This is a very strong test of both codes and of the analytical and numerical methods underlying them.

Moreover, our comparison itself began independently, after one subset of the authors of this paper had initiated a SpEC simulation and another subset had initiated a LazEv simulation. While we based both simulations on the same mass and spin parameter estimates for GW150914, we began discussing the comparison only when lower resolutions had finished and higher resolutions were already under way. We made no special effort to tune the codes or the simulations to agree with each other. In this way, we have demonstrated the agreement of our codes under realistic working conditions, where multiple groups independently perform rapid follow up to a LIGO observation.
These results build confidence that both numerical methods produce consistent physics by correctly solving Einstein’s equations of general relativity, which in turn builds confidence in studies making use of numerical-relativity simulations to follow up LIGO observations, even for events with much smaller experimental uncertainty than GW150914. Besides the comparison in [1] between GW150914 and the targeted numerical-relativity simulations that are of focus of this paper, a recent study directly estimates the source properties of GW150914 by comparing the observation to catalogs of numerical-relativity simulations [4] (including the simulations we consider in this paper). Recent studies also injected numerical-relativity waveforms into LIGO data for GW150914, to help assess systematic errors in approximate waveform models [2, 3, 37], and a recent study [38] compared numerical-relativity waveforms and fits for the remnant masses and spins to approximate waveforms with properties consistent with GW150914.

This paper is organized as follows. In section 2 we briefly describe the formalism and implementation of SpEC, used by the Simulating eXtreme Spacetimes (SXS) collaboration to numerically evolve BBHs. In section 3 we describe the different formalism and code implementation of LazEv, used by the Rochester Institute of Technology (RIT) group. Table 1 summarizes the independent methods these two codes employ to construct and evolve initial data for black holes. In section 4, we directly compare the waveforms produced by each approach to one another. In section 5 we conclude with a discussion of the significance of those comparisons and implications for future comparisons of observations with numerical-relativity calculations.

2. Simulations using pseudospectral, excision methods

Simulations labeled SXS are carried out using the spectral Einstein code (SpEC) [32]. Given initial BBH parameters, a corresponding weighted superposition of two boosted, spinning Kerr–Schild black holes [66] is constructed, and then the constraints are solved [42, 48, 67] by a pseudospectral method to yield quasi-equilibrium [44, 66] initial data. Small adjustments in the initial orbital trajectory are made iteratively to produce initial data with low eccentricity [50, 51, 68].

The initial data are evolved using a first-order representation [55] of a generalized harmonic formulation [56, 57, 69] of Einstein’s equations, and using damped harmonic gauge [61, 70, 71]. The equations are solved pseudospectrally on an adaptively-refined [72, 73] spatial grid that extends from pure-outflow excision boundaries just inside apparent horizons [61, 74–77] to an artificial outer boundary. Adaptive time-stepping automatically achieves time steps of approximately the Courant limit. On the Cal State Fullerton cluster, ORCA, the simulation achieved a typical evolution speed of $O(100) \frac{M}{\text{d}^{-1}}$ for the highest resolution (here we measure simulation time in units of $M$, the total mass of the binary). After the holes merge, all variables are automatically interpolated onto a new grid with a single excision boundary inside the common apparent horizon [74, 75], and the evolution is continued. Constraint-preserving boundary conditions [55, 63, 78] are imposed on the outer boundary, and no boundary conditions are required or imposed on the excision boundaries.

We use a pseudospectral fast-flow algorithm [79] to find apparent horizons, and we compute spins on these apparent horizons using the approximate Killing vector formalism of Cook, Whiting, and Owen [80, 81].

Gravitational wave extraction is done by three independent methods: direct extraction of the Newman–Penrose quantity $\Psi_4$ at finite radius [50, 74, 82], extraction of the strain $h$ by matching to solutions of the Regge–Wheeler–Zerilli–Moncrief equations at finite radius [83, 84].
and Cauchy-characteristic extraction [85–89]. The latter method directly provides gravitational waveforms at future null infinity, while for the former two methods the waveforms are computed at a series of finite radii and then extrapolated to infinity [90]. Differences between the different methods, and differences in extrapolation algorithms, can be used to as error estimates on waveform extraction. These waveform extraction errors are important for the overall error budget of the simulations, and are typically on the order of, or slightly larger than, the numerical truncation error [91, 92]. In this paper, the waveforms we compare use Regge–Wheeler–Zerilli–Moncrief extraction and extrapolation to infinity. We have verified that our choice of extrapolation order does not significantly affect our results. We have also checked that corrections to the wave modes [93] to account for a small drift in the coordinates of the center of mass have a negligible effect on our results.

### 3. Simulations using finite-difference, moving-puncture methods

RIT simulations evolve BBH data sets using the LazEv [33] implementation of the moving puncture approach [13, 14] with the conformal function $W = \sqrt{\chi} = \exp(-2\phi)$ suggested by [94]. For the simulation presented here, we use centered, sixth-order finite differencing in space [95], a fourth-order Runge-Kutta time integrator and a 7th-order Kreiss–Oliger dissipation operator. This sixth-order spatial finite difference scheme allows us to gain a factor $\sim 4/3$ in efficiency with the respect to the eighth-order implementation, because it reduces the number of ghost zones from 4 to 3. We also allowed for a Courant factor $CFL = 1/3$ instead of the previous $CFL = 0.25$ [96] gaining another speedup factor of 4/3. We verified that for this relaxing of the time integration step we still conserve the horizon masses and spins
of the individual black holes during evolution and the phase of the gravitational waveforms to acceptable levels. This plus the use of the new XSEDE supercomputer *Comet* at SDSC\(^9\) lead to typical evolution speeds of 250 M \(d^{-1}\) on 16 nodes for \(N100\) and similar for the higher resolution runs given the good weak scaling of LazEv. Note that our previous [97, 98] comparable simulations averaged \(\sim 100\) M \(d^{-1}\).

*RIT*’s code uses the *EinsteinToolkit* [20, 99]/*CACTUS* [100]/*Carpet* [65] infrastructure. The *Carpet* mesh refinement driver provides a ‘moving boxes’ style of mesh refinement. In this approach, refined grids of fixed size are arranged about the coordinate centers of both holes. The *Carpet* code then moves these fine grids about the computational domain by following the trajectories of the two black holes.

We use *AHFinderDirect* [101] to locate apparent horizons. We measure the magnitude of the horizon spin using the *isolated horizon* (IH) algorithm detailed in [102] and as implemented in [103]. Note that once we have the horizon spin, we can calculate the horizon mass via the Christodoulou formula

\[
m = \sqrt{m_{\text{tot}}^2 + S^2/4m_{\text{tot}}^2},
\]

where \(m_{\text{tot}} = \sqrt{A/(16\pi)}\), \(A\) is the surface area of the apparent horizon, and \(S\) is the spin angular momentum of the black hole (in units of \(M^2\)). In the tables below, we use the variation in the measured horizon irreducible mass and spin during the simulation as an estimate of the error in computing these quantities. We measure radiated energy, linear momentum, and angular momentum, in terms of the radiative Weyl Scalar \(\Psi_4\), using the formulas provided in [104, 105]. However, rather than using the full \(\Psi_4\), we decompose it into \(\ell\) and \(m\) modes and solve for the radiated linear momentum, dropping terms with \(\ell > 6\). The formulas in [104, 105] are valid at \(r = \infty\). We extract the radiated energy-momentum at finite radius and extrapolate to \(r = \infty\). We find that the new perturbative extrapolation described in [106] provides the most accurate waveforms. The difference between linear and quadratic extrapolations provides an independent measure of the error.

### 4. Results

To model GW150914, we used each of the two codes to simulate a nonprecessing, unequal mass binary with the spin of the larger black hole aligned with the orbital angular momentum, and the spin of the smaller black hole antialigned. This choice of parameters is within the 90% confidence curves of GW150914 [2], but it is only one of many possible choices consistent with the observation. The initial data parameters for both codes are given in tables 2 and 3\(^10\).

These tables show that the parameters of the two simulations are not exactly identical, primarily because we constructed and evolved the initial data independently but also because making the parameters exactly the same is challenging, given how different the methods for specifying initial data are in the two approaches. The largest difference is that the SXS simulation starts earlier in the inspiral than the RIT case, but also the two simulations have different orbital eccentricities and very small differences in the initial masses.

Both simulations start with a relatively small binary separation, so the entire evolution through coalescence requires a time of roughly a few thousand \(M\), where \(M\) is the sum of the Christodoulou masses of both black holes. Because the mass ratio is near unity and the spins are small, this simulation is not difficult to perform for modern numerical relativity codes; for

\(^9\) [https://portal.xsede.org/sdsc-comet](https://portal.xsede.org/sdsc-comet)

\(^10\) Note that data from the SXS configuration, including the gravitational waveform and the masses and spins as functions of time, are publicly available as simulation SXS:BBH:0305 at [www.black-holes.org/waveforms](http://www.black-holes.org/waveforms)
both codes considered here, this simulation required about 1–2 weeks to complete for LazEv (running with 384 cores using the Intel Xeon E5-2680v3 processors of Comet at SDSC\textsuperscript{11}) and for SpEC (running with 36–48 cores using Intel Xeon E5-2630 and E5-2630v2 processors of ORCA at California State University, Fullerton). For each code, both simulations were repeated several times using different values of a parameter controlling the numerical resolution. Increasing the resolution results in higher accuracy, but requires more computation time and resources. Running multiple resolutions provides checks that the results converge with increasing resolution, and also provides an error estimate. The LazEv simulation was performed at three resolutions labeled N100, N110, and N120, where N110 and N120 represent a global increase of the finite difference resolution by factors of 1.1 and 1.2, respectively, compared to the N100 case. The SpEC simulation was performed at multiple resolutions labeled L0 through L6 in order of increasing resolution; L6 represents a spectral adaptive-mesh-refinement error tolerance that is a factor of \(e\) smaller than that of L5.

The top panel of figure 1 displays the \((\ell, m) = (2, 2)\) spin-weighted spherical harmonic mode of the gravitational waveform extracted from the two simulations, at the lowest resolution. The differences between these two simulations are not visible at this scale. Because of the finite signal-to-noise ratio of GW150914, the statistical error in the waveform reconstruction reported in figures 1 and 2 of [1] is far larger than the differences seen here. Note that we take a deliberately conservative approach to alignment here: we only apply a constant time shift (setting the peaks of the \((2, 2)\) modes to \(t = 0\)) and a constant phase shift (setting the phase to zero radians at \(t = -0.6\) s. Later (figure 3 and table 4), we will compare the mismatch of the waveforms, which (consistently for each mode) applies constant time and phase offsets that optimize the match of the \((2, 2)\) mode and which weights the difference inversely to LIGO’s noise (equation (3)).

To better see the differences between the waveforms, the lower panel of figure 1 zooms in on the difference between the \((\ell, m) = (2, 2)\) modes, and figure 2 plots fractional amplitude differences and phase differences, including not only the \((\ell, m) = (2, 2)\) mode but several of the most significant higher modes. In figure 2, as in figure 1, we apply a constant time shift so that the peak \((\ell, m) = (2, 2)\) occurs at time \(t = 0\) and a constant phase shift so each wave has a phase of zero radians at time \(t = -0.6\) s. Differences between resolutions of each simulation estimate the numerical error. The differences between the SXS and RIT simulations’ highest resolutions is far too small to be visible in a plot like the top panel of figure 1 or in figure 1 of [1], which compares the waveforms to LIGO’s measured gravitational-wave strain for GW150914. Nevertheless, the differences are larger than our estimates of the numerical errors.

We suspect that the level of disagreement is determined in part by effects from small differences in the initial configurations (mass, spin, eccentricity, etc). Another potential source of systematic error is the method used for wave extraction: LazEv computes \(\Psi_4\) and then integrates to find the gravitational-wave strain \(h\), while SpEC computed the waves shown in figure 2 by matching to Regge–Wheeler–Zerilli–Moncrief solutions. Differences between SpEC and LazEv also become large at late times in the ringdown, when the wave amplitude becomes smaller than the numerical error in the simulations.

To quantify the magnitude of the differences between these waveforms, we use the match,

\[
\mathcal{M} = \frac{\langle h_1 | h_2 \rangle}{\sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}},
\]

as implemented via a complex overlap as described in equation (2) in [107]:

\[\text{https://portal.xsede.org/sdsc-comet}\]
The Fourier transform of $f$ is denoted by $\hat{f}(f)$. In both cases, the apparent horizons $\mathcal{H}$ are the union of the ${\cal H}_i$ and $\mathcal{H}_r$.

For the RIT configuration, the punctures begin with centers, in the asymptotically inertial coordinate frame, at coordinates $(x_i, y_i, 0)$ and $(x_0, y_0, 0)$, where $y_i = y_0 = -0.0335 M$. In both cases, $M = m_1 + m_2$ is the sum of the Christodoulou masses of the two black holes. The two codes specify initial data differently, so not all parameters are relevant for both codes.

| Configure | $x_i/M$ | $y_i/M$ | $P_i/M$ | $P_f/M$ | $m_1/M$ | $m_2/M$ | $S_1/M^2$ | $S_2/M^2$ | $m_1/M$ | $m_2/M$ | $M_{ADM}/M$ |
|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|-----------|
| RIT       | $-6.7308$ | $5.5192$ | $0.083116$ | $-0.00440$ | $0.40207$ | $0.51363$ | $-0.08932$ | $0.09963$ | $0.45055$ | $0.54945$ | $0.99141$ |
| SXS       | $-7.8597$ | $6.4004$ | $-0.00332$ | $0.00332$ | $-0.00332$ | $0.00332$ | $-0.00332$ | $0.00332$ | $0.45026$ | $0.54980$ | $0.99235$ |

Table 3. Physical properties of the initial black holes at time $t = 0$. The table shows the mass ratio $q = m_2/m_1$ and dimensionless spins $\chi_1 = S_1/m_1^2$ and $\chi_2 = S_2/m_2^2$. The table also shows the initial orbital properties of both configurations. The holes begin at coordinate separation $d_0$ with initial orbital angular frequency $\Omega_0$ and initial radial expansion $\tilde{a}_0$. Each hole’s initial coordinate radial velocity $v_r$ and coordinate distance from the center of mass $r_0$ are related to the expansion by $\tilde{a}_0 = v_r/r_0$. These initial data result in an initial orbital eccentricity $e$. Here $M = m_1 + m_2$ is the sum of the Christodoulou masses of the two black holes.

| Configure | $q$ | $\chi_1$ | $\chi_2$ | $M\Omega_0$ | $M\tilde{a}_0 \times 10^4$ | $d_0/M$ | $e$ |
|-----------|-----|---------|---------|-------------|-----------------|-------|-----|
| RIT       | $1.220$ | $-0.4400$ | $0.3300$ | $0.02118$ | $-1.1712$ | $12.2500$ | $0.0012$ |
| SXS       | $1.221$ | $-0.4400$ | $0.3300$ | $0.01696$ | $-0.5306$ | $14.2601$ | $0.0008$ |

$$\langle h_1 | h_2 \rangle = 2 \int_{-\infty}^{\infty} \frac{df}{S_0(f)} [\hat{h}_1(f)\hat{h}_2(f)^*],$$  (3)

where $\hat{h}(f)$ is the Fourier transform of $h(t)$ and $S_0(f)$ is the power spectral density of the detector noise (here, taken to be the advanced LIGO design power spectrum [108]). When we compute the match using equation (3), we apply to each mode an overall constant time shift and an overall constant phase shift chosen to optimize the match of the $(2, 2)$ mode.

For our match calculations, we conservatively adopt the design-sensitivity noise power spectrum of advanced LIGO [109]; if we instead would compute matches using the observed O1 sensitivity, the matches would be larger. For instance, the $(\ell, m) = (2, 2)$ mode would have a match of 99.9% (the basis of the ‘confirmed to 99.9%’ statement in [1]), instead of 99.8%, as shown here. Table 4 shows the match between the $(\ell, m)$ spin-weighted spherical harmonic gravitational waveform modes of different RIT resolutions versus the SXS L6 resolution, for a total mass of $70 M_\odot$. To account for finite simulation duration, we set the lower frequency of our match calculation to $m \times 11$ Hz. Note that for the $m = 4$ and $m = 5$ modes, which are much less significant than the dominant $(\ell, m) = (2, 2)$ mode, this is above the frequency of 35 Hz where the GW150914 signal first entered the LIGO band. For each mode, the beginning of each waveform (a duration of several $M$ in time) is tapered, to reduce transient effects in their Fourier transforms. For the dominant $(2, 2)$ mode, the match is close to unity for all RIT resolutions. Most other significant modes also display a high degree of agreement, particularly for $\ell \leq 3$. The table also shows the overlap of L6 with itself (with minimum frequency 22 Hz in
all cases, to indicate the relative importance of each mode. Some modes that are much less significant than the $l=2,m=2$ mode have low matches but are (except for some of the least significant modes) convergent, suggesting that higher numerical resolution is necessary to accurately compute these high order modes.

To provide a sense of scale for this comparison, we also evaluate the match between the two simulations’ $\ell,m = (2,2)$ modes and the same modes of a template waveform with the same parameters (i.e. the same mass ratio and spins) generated by SEOBNRv2 [110], one of the approximate, analytic waveform models used to infer GW150914’s properties in [2]. Figure 3 shows the mismatch (1 minus the match), for successively higher starting cutoff frequencies, $f_{\text{min}}$, above 20 Hz. At high frequencies, the two simulations are much more consistent with one another than with the semianalytic SEOBNR model. Below about 20 Hz, the two simulations disagree with each other and with SEOBNRv2, but this is because the RIT simulation starts at 19.5 Hz and the SXS simulation starts at 15.7 Hz, and because the waveforms from both simulations are tapered. Note that in order to respond quickly to GW150914, to reduce computation time both of these simulations were chosen to start at higher frequencies than typical for full numerical simulations. Therefore, the low-frequency mismatch shown in figure 3 overstates the differences between the two codes for longer, more typical simulations.

The evolution of the aligned spinning binary leads to remnant masses, spins and recoil velocities as shown in table 5. They display an excellent agreement between the two codes, to at least three significant figures, and they appear convergent with increasing resolution. The fraction $E_{\text{rad}}/M$ of the initial mass $M$ radiated as gravitational waves can be inferred (via energy conservation) to be

$$
\frac{E_{\text{rad}}}{M} = 1 - \frac{m_{\text{rem}}}{M}.
$$

Figure 1. A comparison of the $(\ell,m) = (2,2)$ mode extracted from the two fiducial simulations from SpEC and LazEv. Time is shown in seconds for a total mass of $70M_\odot$. The bottom panel zooms in to show the difference between the SpEC and LazEv $(2,2)$ modes, using resolutions are $N=120$ (LazEv) and $L=6$ (SpEC). Here, we take a conservative approach to assessing differences in the waveforms: we apply a constant time shift to each waveform, so that the peak $(2,2)$ amplitude is at $t=0$, and a constant phase offset to each waveform, so that the phase is zero radians at $t=-0.6$ s. Table 4 and figure 2, in contrast, assess differences by computing the match, a comparison weighted by LIGO’s noise. Note that lower resolution versions of these waveforms were used in the comparison in the caption of figure 1 of [1], which reported the agreement (match) of these waveforms as 99.9%, using LIGO’s noise curves for GW150914 [1].
The SXS and RIT simulations agree that 1 − \(m_{\text{rem}}/M = 4.80\%\) of the initial mass is radiated as gravitational waves. For GW150914, whose initial mass in the source frame is \(M = 65.4_{-5.9}^{+6.9} \odot\) [2], the radiated energy predicted by the SXS and RIT simulations, \(3.1 \odot\), is consistent with the estimate of \(3.0 \pm 0.5 \odot\) given in [1].

### 5. Discussion

We have demonstrated that two completely independent codes to evolve binary black holes (SpEC and LazEv) produce very similar results. As shown in figure 1 and table 4, we find good agreement even with moderately low resolution simulations (i.e. \(N100\) and \(L5\)). The convergence of each code to the results of the other, as summarized in table 4, suggests that both the generalized harmonic [12] and moving puncture [13, 14] approaches lead to accurate solutions of the general relativity field equations. Given that the initial configurations are not exactly the same (different eccentricities, slightly different masses and spins), we consider this general agreement an excellent verification of the analytic formulations, numerical methods, and code implementations used in both SpEC and LazEv.

The next steps in further verifying the results of numerical relativity codes will be to consider binary systems with precession and to consider simulations that follow a larger number of binary orbits. For these more demanding tests, it will be more important to start different codes with closely coordinated initial parameters. This study will be the subject of a future publication.
Future work also includes considering cases with more extreme parameters. Here, the simulations’ very good agreement with the SEOB waveform is not surprising, since the moderate spins and almost equal masses make this an especially easy region of the parameter space to model. But for higher mass ratios and more extreme spins, numerical relativity might disagree more strongly with semianalytic, approximate waveforms, especially in regions where the semianalytic models have not been tuned to numerical relativity. Recent studies have begun exploring the agreement of numerical relativity and approximate, analytic waveforms in different regions of the BBH parameter space [22, 28, 38, 111, 112].

However, from the results of figure 3 we can already conclude that even if analytic waveform models provide a very good approximation to the true prediction of general relativity,
full numerical solutions of Einstein’s equations can be more accurate than analytic models. Targeted followup with numerical relativity can therefore be an important tool for comparing gravitational-wave observation and theory and for reliably measuring potential deviations from Einstein’s theory of gravitation [3].

Our study suggests that both groups’ standard production simulations are sufficiently accurate and efficient to respond rapidly and comprehensively to further events like GW150914, informing the analysis and interpretation of LIGO data. Followup simulations of events like GW150914 can be performed on a timescale of days to weeks (depending on resolution) and at low computational cost, with confidence that both methods produce consistent physics. This is important for the construction of numerically generated waveform data banks with simulations from heterogeneous codes and formalisms.

However, numerical-relativity simulations can be considerably more costly and challenging elsewhere in the BBH parameter space, particularly if they remain in LIGO’s band for more orbits, such as GW151226, or if they have more extreme parameters. For instance, the
SpEC simulation modeling GW151226 that appears in figure 5 of [5] (SXS:BBH:0317 at http://black-holes.org/waveforms) required approximately 2 months to complete, and a recent simulation similar to those used here to model GW150914 but with spins $\chi = +0.96$ for the larger black hole and $\chi = -0.9$ for the smaller black hole (SXS:BBH:0306 at http://black-holes.org/waveforms) required approximately two months to complete. Future work includes enabling more rapid, targeted follow up numerical-relativity simulations for these more challenging cases.

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