CENTER FOR COMPUTATIONAL RELATIVITY AND GRAVITATION

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Exploring the small mass ratio binary black hole merger with Numerical Relativity

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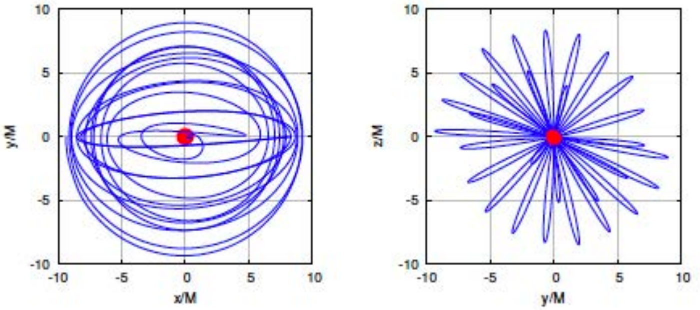
Introduction

- In Capra 14 (2011) We presented first full numerical simulation 100:1 for two orbits before merger:

  C. O. Lousto and Y. Zlochower, Phys. Rev. Lett. **106**, 041101 (2011), arXiv:1009.0292 [gr-qc].

- More recently, we studied the GW beaconing with precessing q=1/7, q=1/15 binaries and found excellent results with updated techniques and AMR grid:

  C. O. Lousto and J. Healy, Phys. Rev. **D99**, 064023 (2019), arXiv:1805.08127 [gr-qc].



- We will revisit the scenario of the nonspinning small mass ratio binaries as we did for up to q=1/10 in:

  J. Healy, C. O. Lousto, and Y. Zlochower, Phys. Rev. **D96**, 024031 (2017), arXiv:1705.07034 [gr-qc].

  [Presented in Capra 20 (2017)]

-> But we now push it to q=1/15, 1/32, 1/64, and 1/128

Numerical Simulations

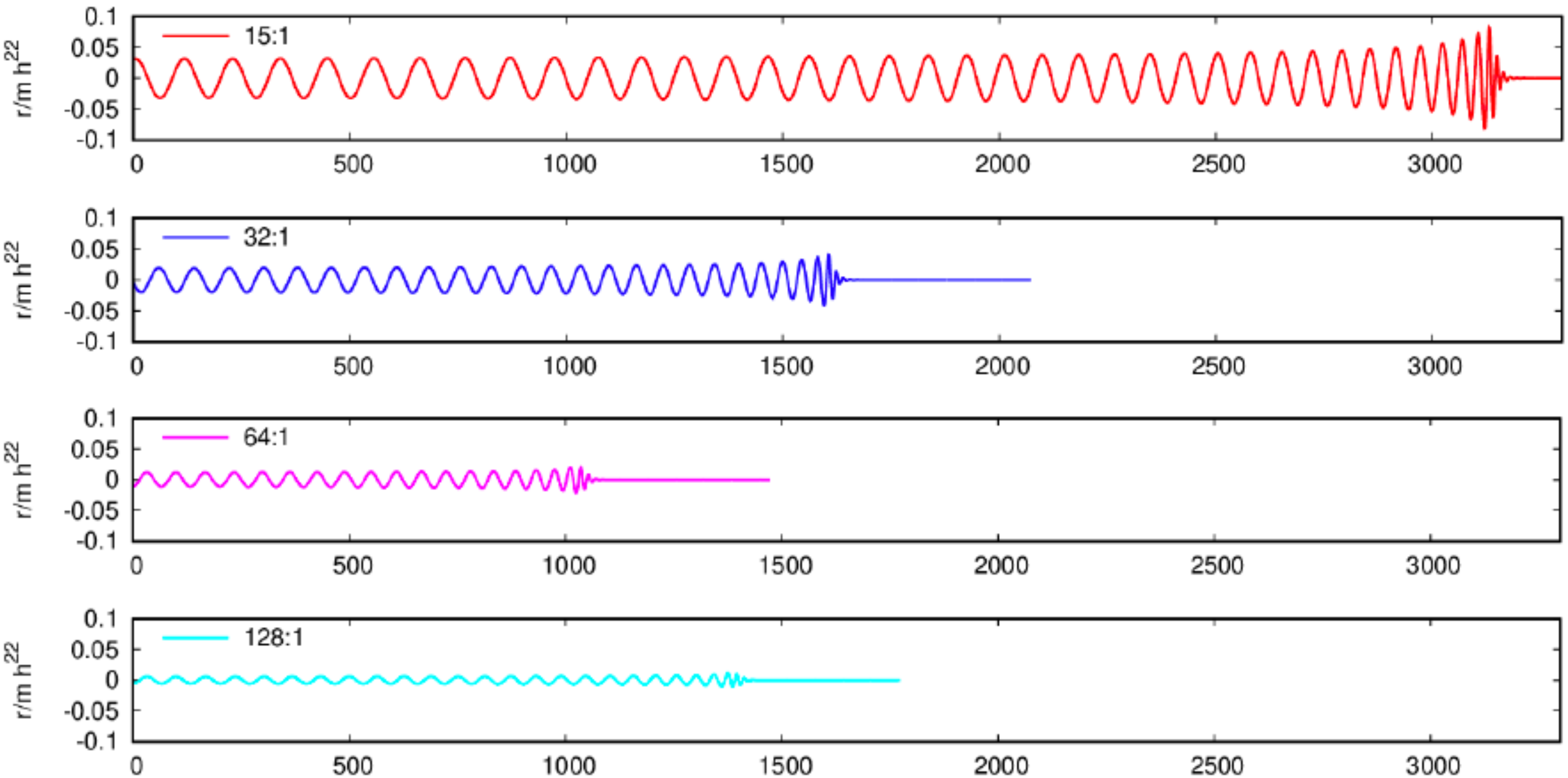
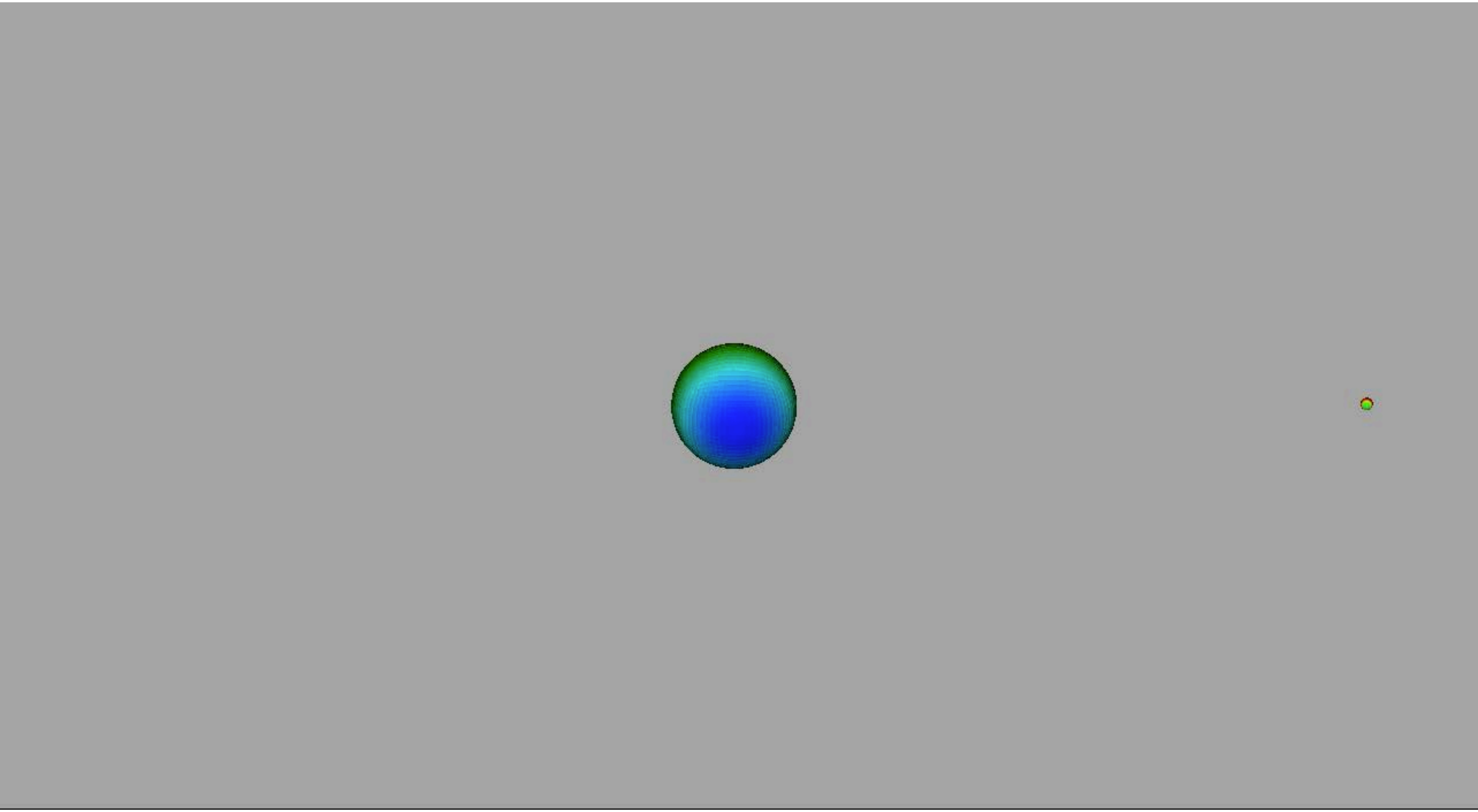


FIG. 1. (2,2) modes (real part) of the strain waveforms versus time (t/m), for the $q = 1/15, 1/32, 1/64, 1/128$ simulations.

Numerical Simulations



128:1 merger orbit and horizons
Viz: Nicole Rosato.

Numerical Simulations

Convergence:

TABLE I. The final black hole mass $M_{\rm rem}/m$, spin $\alpha_{\rm rem}$, and its recoil velocity v_m, and the Luminosity $\mathcal{L}$, waveform frequency ω_{22} at the maximum amplitude $h_{\rm peak}$, for each resolution of the $q = 1/15$ simulations. Extrapolation to infinite resolution and order of convergence is derived.

resolution	$M_{\rm rem}/m$	$\alpha_{\rm rem}$	v_m[km/s]	$\mathcal{L}_{\rm peak}$[ergs/s]	$m\omega_{22}^{\rm peak}$	$h_{\rm peak}$
n100	0.994837	0.188442	33.45	1.659e+55	0.2902	0.08526
n120	0.994876	0.188874	34.67	1.678e+55	0.2860	0.08473
n140	0.994891	0.188987	35.24	1.683e+55	0.2866	0.08466
$n \to \infty$	0.994905	0.189047	36.07	1.687e+55	0.2868	0.08464
order	4.63	6.87	3.40	6.01	10.33	10.82

TABLE II. The final black hole mass $M_{\rm rem}/m$, spin $\alpha_{\rm rem}$, and its recoil velocity v_m, and the Luminosity $\mathcal{L}$, waveform frequency ω_{22} at the maximum amplitude $h_{\rm peak}$, for the sequence of the $q = 1/32, 1/64, 1/128$ simulations. Also given are the initial simple proper distance, SPD, and number of orbits to merger N for these simulations.

q	$M_{\rm rem}/m$	$\alpha_{\rm rem}$	v_m[km/s]	$\mathcal{L}_{\rm peak}[ergs/s]$	$m\omega_{22}^{\rm peak}$	$h_{\rm peak}$	SPD	N
1/32	0.9979	0.1006	9.14	4.260e+54	0.2820	0.0424	9.51	13.02
1/64	0.9990	0.0520	2.34	1.113e+54	0.2812	0.0220	8.22	9.98
1/128	0.9996	0.0239	0.96	3.313e+53	0.2746	0.0116	8.19	12.90

Speeds: 2.7M/h (q=1/15 with 6th order) on 8 nodes (448 cores) in Frontera. CFL=1/4.
1.1 M/h (q=1/32 with 8th order), 0.6M/h (q=1/64), 0.32M/h (q=1/128)

Results

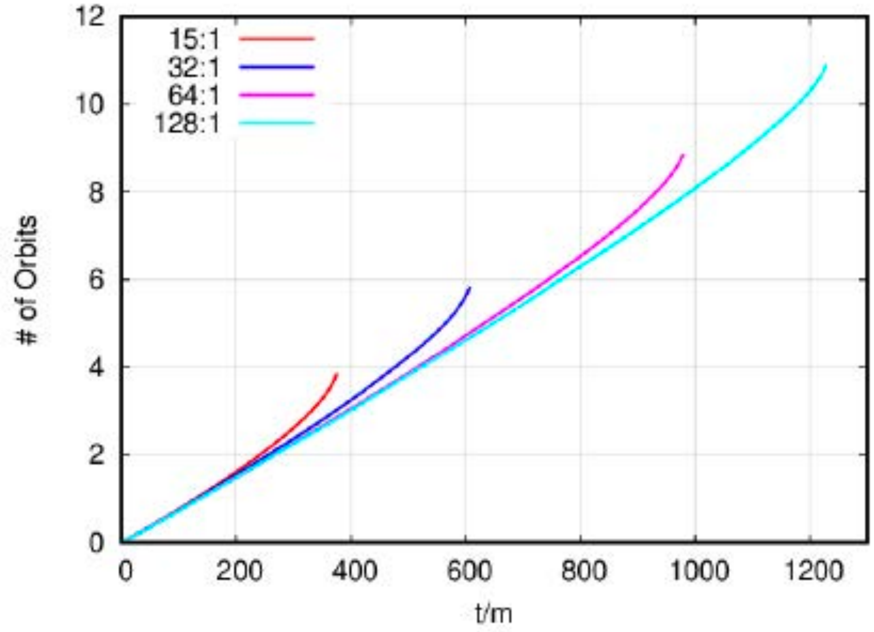
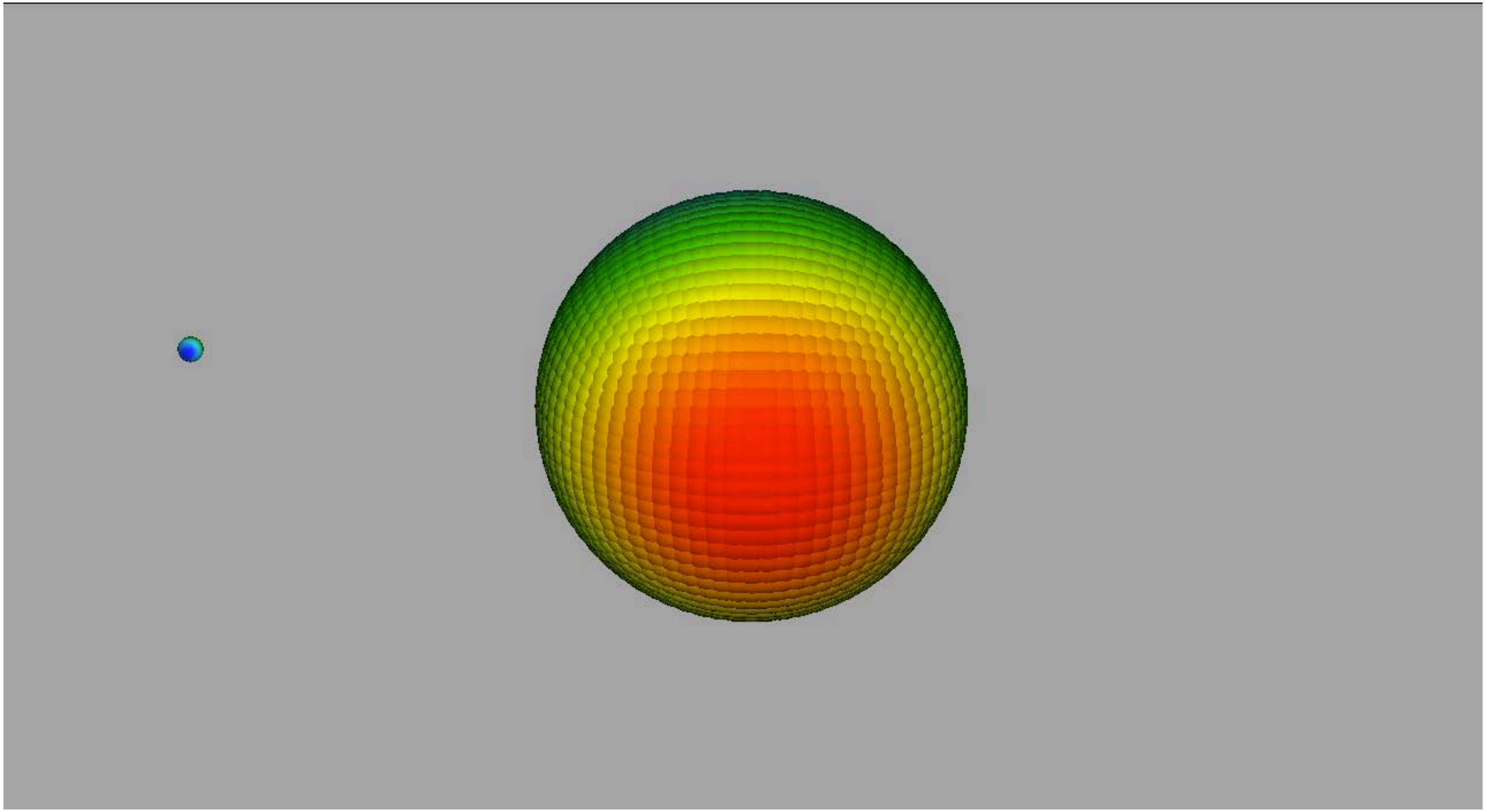


FIG. 2. Comparative number of orbits and time to merger, from a fiducial orbital frequency $m\Omega_i = 0.0465$ for the $q = 1/15, 1/32, 1/64, 1/128$ simulations.

$T_{merger} \sim (83.2M)\ eta^{-0.56}$, $eta=m_1m_2/m^2$

Results



128:1 merger horizons (rescaled) Curvature K
Viz: Nicole Rosato.

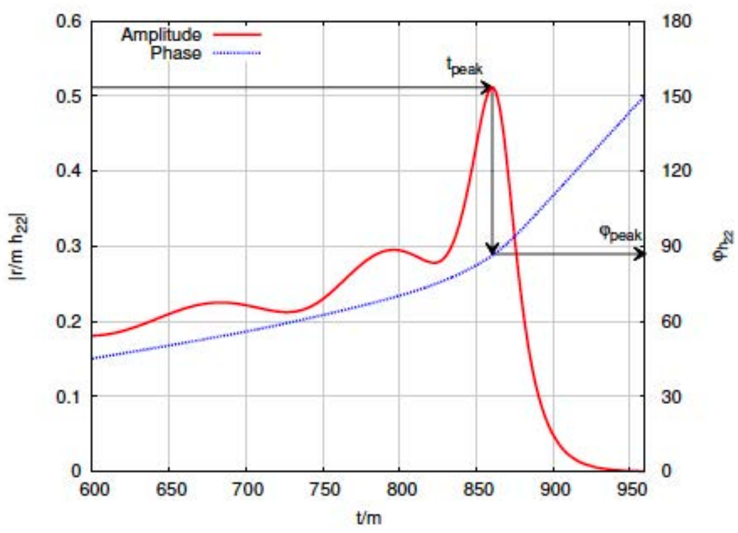
Analysis

$$\frac{M_{\rm rem}}{m} = (4\eta)^2 \left\{M_0 + K_{2d}\,\delta m^2 + K_{4f}\,\delta m^4\right\} + \left[1 + \eta(\tilde{E}_{\rm ISCO} + 11)\right]\delta m^6, \tag{1}$$

where $\delta m = (m_1 - m_2)/m$ and $m = (m_1 + m_2)$ and $4\eta = 1 - \delta m^2$.

$$\alpha_{\rm rem} = \frac{S_{\rm rem}}{M_{\rm rem}^2} = (4\eta)^2\left\{L_0 + L_{2d}\,\delta m^2 + L_{4f}\,\delta m^4\right\} + \eta \tilde{J}_{\rm ISCO}\delta m^6. \tag{2}$$

$$v_m = \eta^2 \delta m\left(A + B\,\delta m^2 + C\,\delta m^4\right). \tag{3}$$



$$h_{\rm peak} = (4\eta)^2\left\{H_0 + H_{2d}\,\delta m^2 + H_{4f}\,\delta m^4\right\} + \eta\,\tilde{H}_p\,\delta m^6, \tag{4}$$

where $\tilde{H}_p(\alpha_{\rm rem})$ is the particle limit, taking the value $H_p(0) = 1.4552857$ in the nonspinning limit [18].

$$\mathcal{L}_{\rm peak} = (4\eta)^2\left\{N_0 + N_{2d}\,\delta m^2 + N_{4f}\,\delta m^4\right\}. \tag{5}$$

$$m\omega_{22}^{\rm peak} = (4\eta)\left\{W_0 + W_{2d}\,\delta m^2 + W_{4f}\,\delta m^4\right\} + \tilde{\Omega}_p\,\delta m^6, \tag{6}$$

where $\tilde{\Omega}_p(\alpha_{\rm rem})$ is the particle limit, taking the value $\tilde{\Omega}_p(0) = 0.279525$ in the nonspinning limit [18].

[18] A. Bohé *et al.*, Phys. Rev. **D95**, 044028 (2017), arXiv:1611.03703 [gr-qc].

Analysis

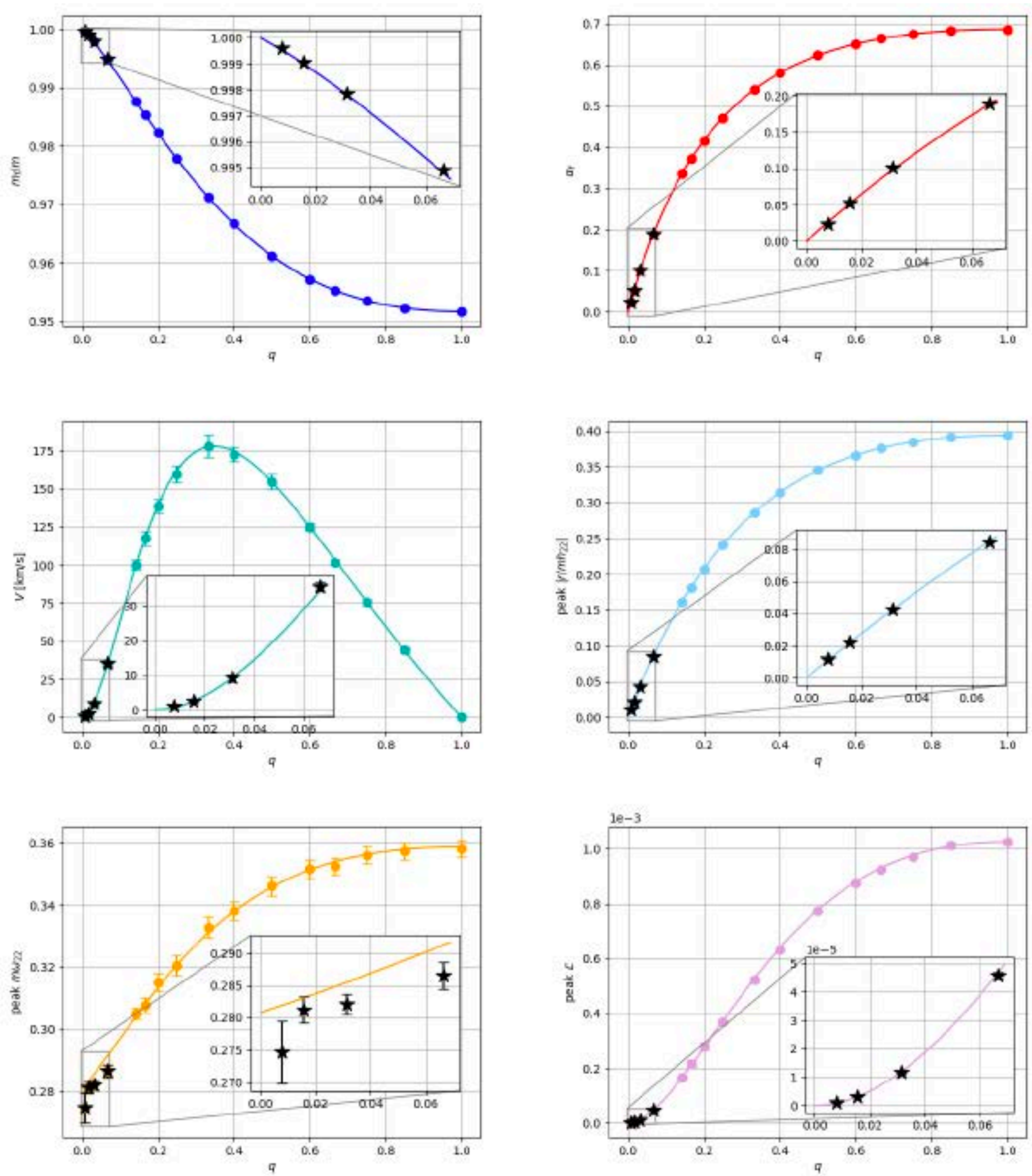


FIG. 3. Final mass, spin, recoil velocity, peak amplitude, frequency, and luminosity. Predicted vs. current results for the $q = 1/15, 1/32, 1/64, 1/128$ simulations. Each panel contains the prediction from the original fits in Ref. [13] (solid line), data used to determine the original fits (filled circles), and the data for the current results (stars). An inset in each panel zooms in on the new simulations. Again, we stress no fitting to the new data is performed in this plot.

[13] J. Healy, C. O. Lousto, and Y. Zlochower, Phys. Rev. **D96**, 024031 (2017), arXiv:1705.07034 [gr-qc].

Conclusions

- We have passed all first accuracy tests up to q=1/128
- Assessed errors ~2%
- Adding spin to large black hole with same grid is straightforward
- Can still use speed ups for massive productions for applications to
  - 3G GW detectors
  - LISA for calibration of perturbative techniques

Appendix: Refitted coefficients

TABLE III. Fitting coefficients of the phenomenological formulas (1)-(6)

M_0	K_{2d}	K_{4f}
0.95165 ± 0.00002	1.99604 ± 0.00029	2.97993 ± 0.00066
L_0	L_{2d}	L_{4f}
0.68692 ± 0.00065	0.79638 ± 0.01086	0.96823 ± 0.02473
A	B	C
-8803.17 ± 104.60	-5045.58 ± 816.10	1752.17 ± 1329.00
$N_0 \times 10^3$	$N_{2d} \times 10^4$	$N_{4f} \times 10^4$
(1.0213 ± 0.0004)	(-4.1368 ± 0.0652)	(2.46408 ± 0.1485)
W_0	W_{2d}	W_{4f}
0.35737 ± 0.00097	0.26529 ± 0.01096	0.22752 ± 0.01914
H_0	H_{2d}	H_{4f}
0.39357 ± 0.00015	0.34439 ± 0.00256	0.33782 ± 0.00584