Gravitational Radiation Characteristics of Nonspinning Black-Hole Binaries

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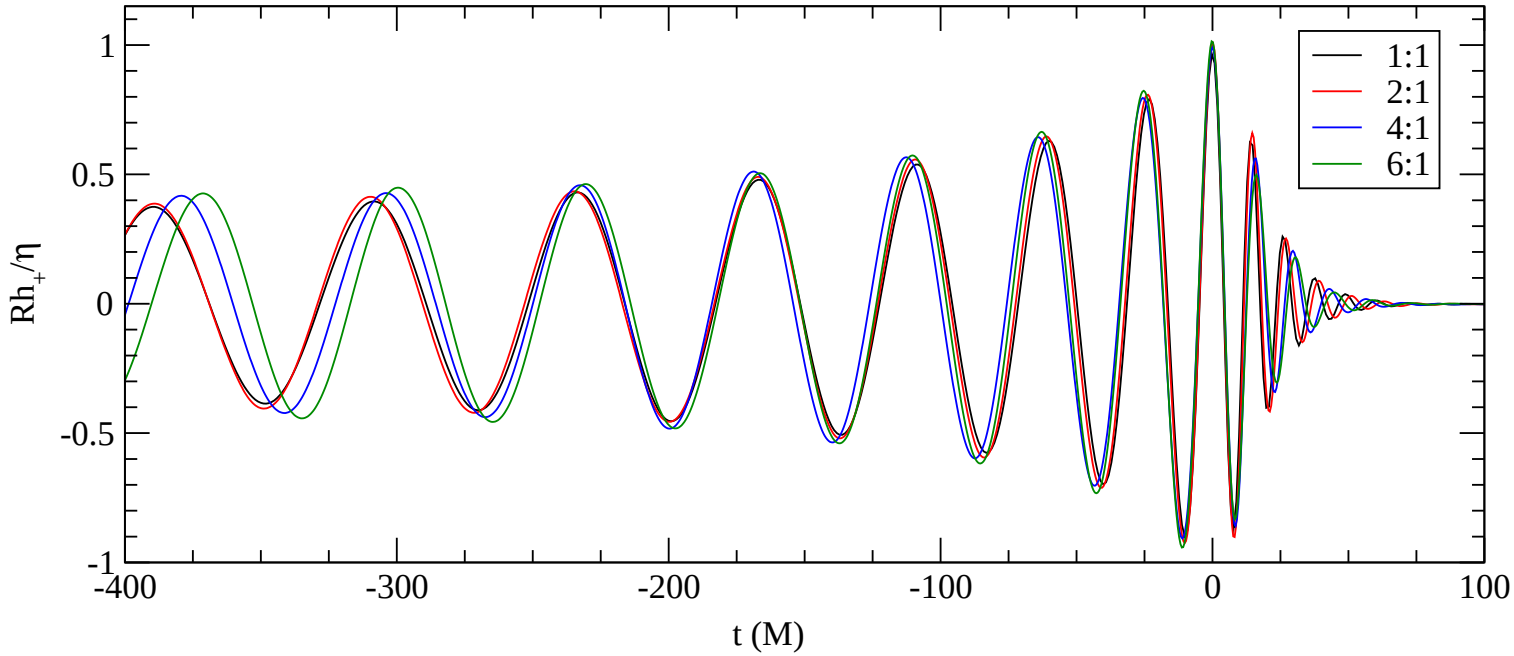
Outline

- Numerical Relativity waveforms for different mass ratios
- the Implicit Rotating Source picture
- modelling the full frequency evolution
- Full waveforms with pseudo-4PN EOB

NR Waveforms for Unequal-Mass BHBs

Numerical Relativity (NR) evolutions of merger of black-hole binaries (BHBs) with mass ratios 1:1, 2:1, 4:1, 6:1.



- BHBs give simple waveforms through merger
- . . . *if* we look at harmonic modes: $h \equiv \sum_{\ell m} h_{\ell m}\, {}_{-2}Y^{\ell,m}(\theta,\varphi)$.
- Strongest modes are circularly polarized: $h_{\ell m} = A_{\ell m} e^{im\phi}$.

The Implicit Rotating Source Picture

Looking at GW modes across harmonics, find that:

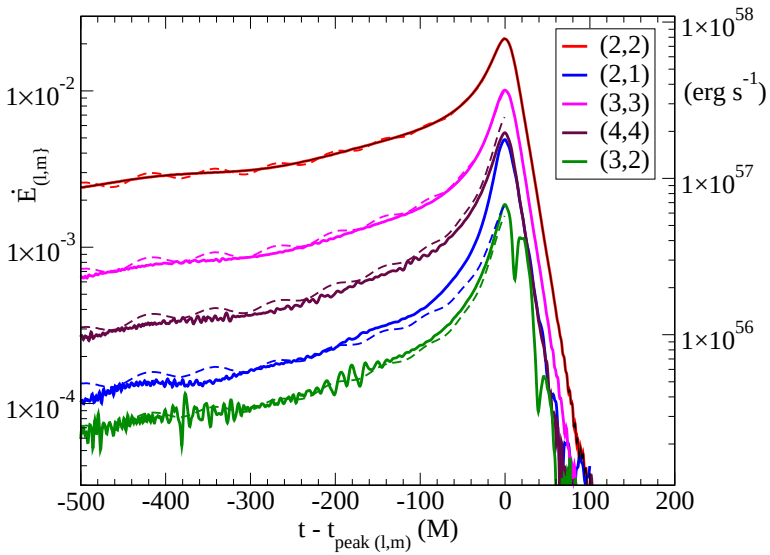


Figure: Power in each mode for 4:1 mass ratio.

- power partitioned into modes according to leading-PN-order predictions;
- phases of different modes simply related through merger;
- define "rotational phase" $\Phi_{\ell m} = \phi_{\ell m}/m +$ const

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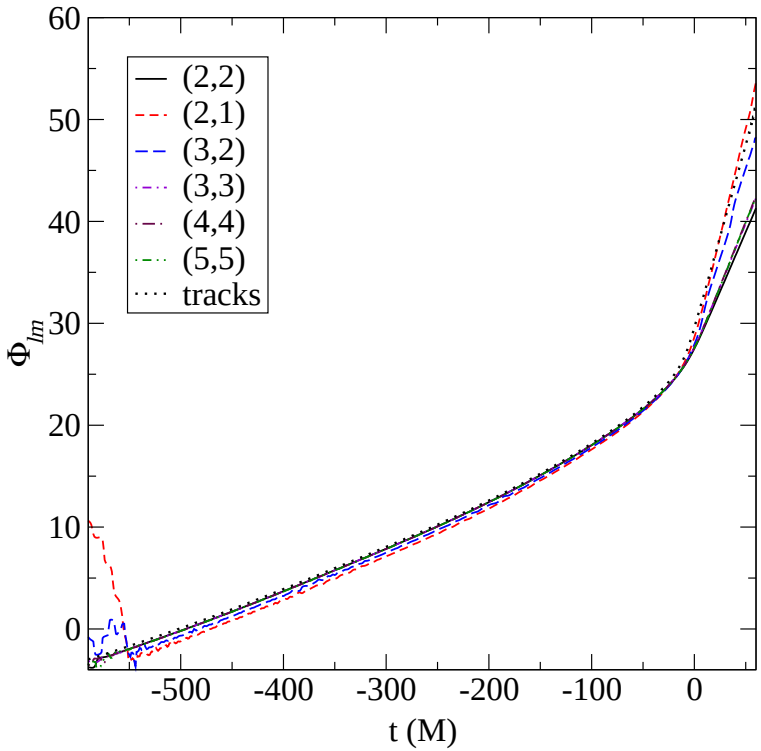

- power partitioned into modes according to leading-PN-order predictions;
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Figure: Rotational phase of each mode for 4:1 mass ratio.

The Implicit Rotating Source Picture

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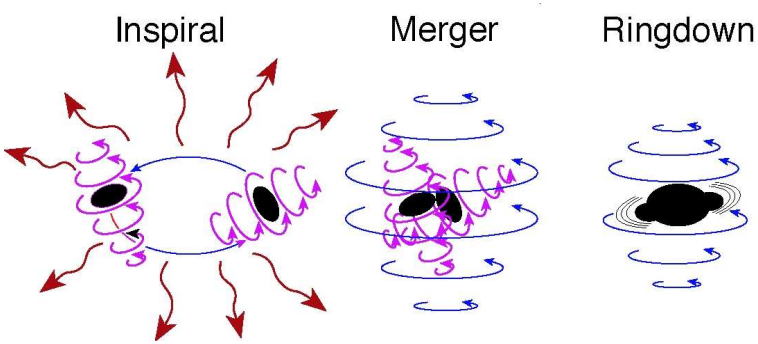

Figure: BHB Coalescence [Kip Thorne].

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. . . Get a picture of BHB as an "implicit rotating source" generating GWs all through inspiral, merger, & ringdown.

Full Late-Merger Frequency Model

Each (ℓ, m) mode's frequency ω settles down post-merger.

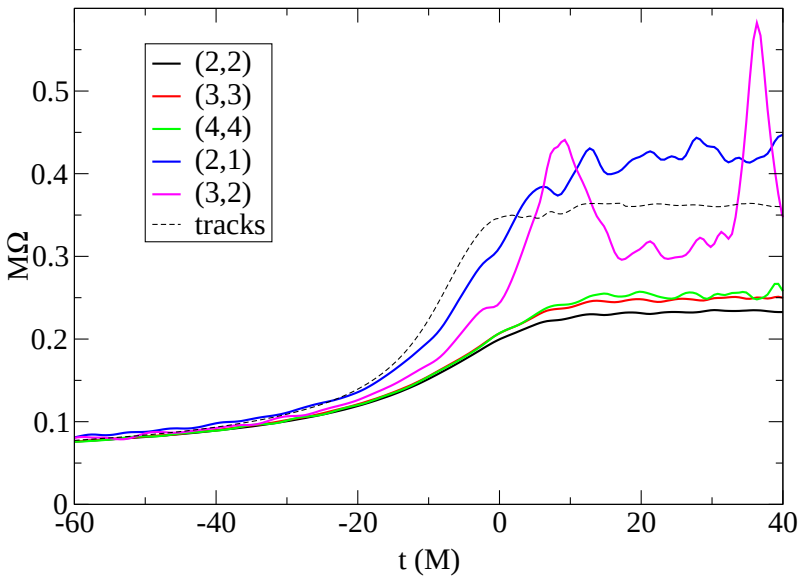

Figure: $\Omega_{\ell m}$ for 4:1 mass ratio.

- Rotational frequency $\Omega \equiv \omega/m$ has very similar shape for strongest modes.
- It can be well fit through merger by smooth step-like function.
- Works well for all mass ratios (100 : 1 from Damour & Nagar)

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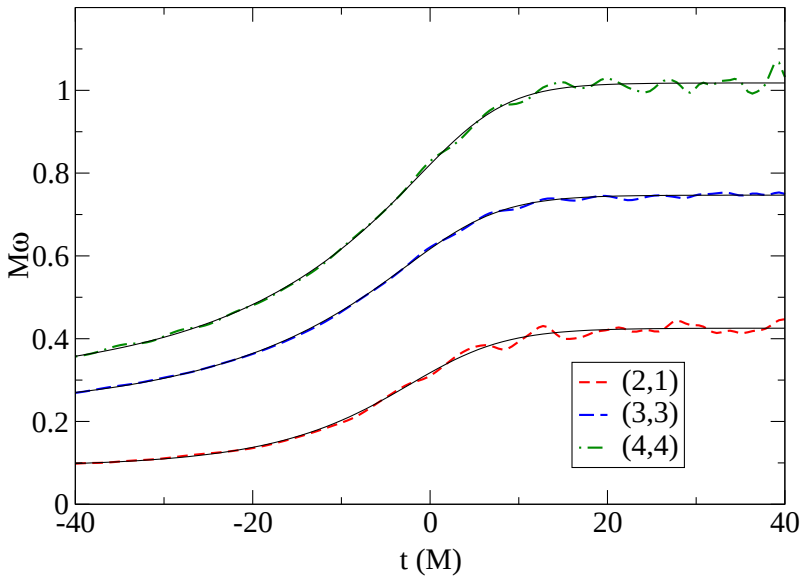

Figure: Fitting $\Omega_{\ell m}$ for 4:1 mass ratio.

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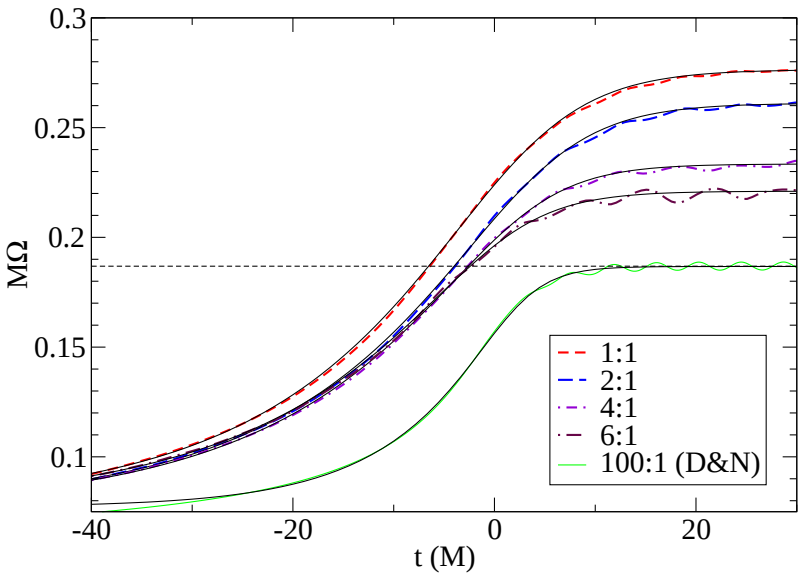

Figure: Fitting for Ω_{22} for all mass ratios.

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Late-Merger $E(\Omega)$ & $J(\Omega)$ Relations

IRS picture suggests a simple form for $E_{\ell m}(\Omega)$ and $J_{\ell m}(\Omega)$:

$$dE_{\ell m}/dt \propto \Omega d\Omega/dt, \quad dJ_{\ell m}/dt \propto d\Omega/dt.$$

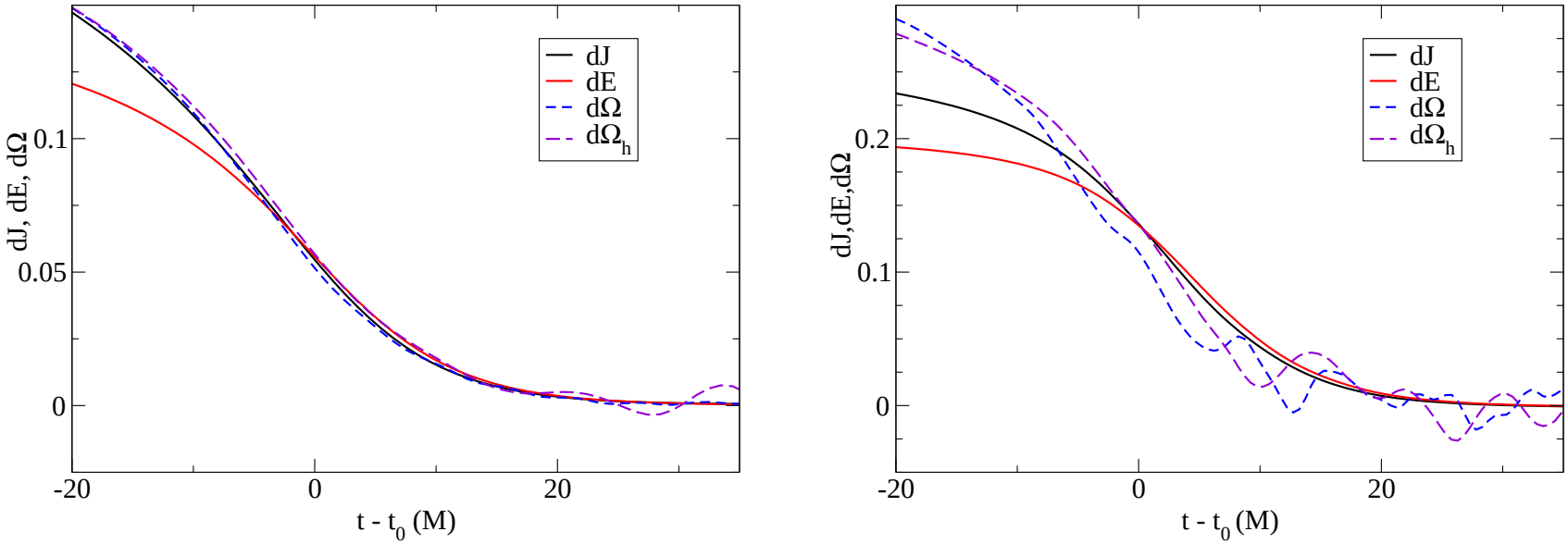
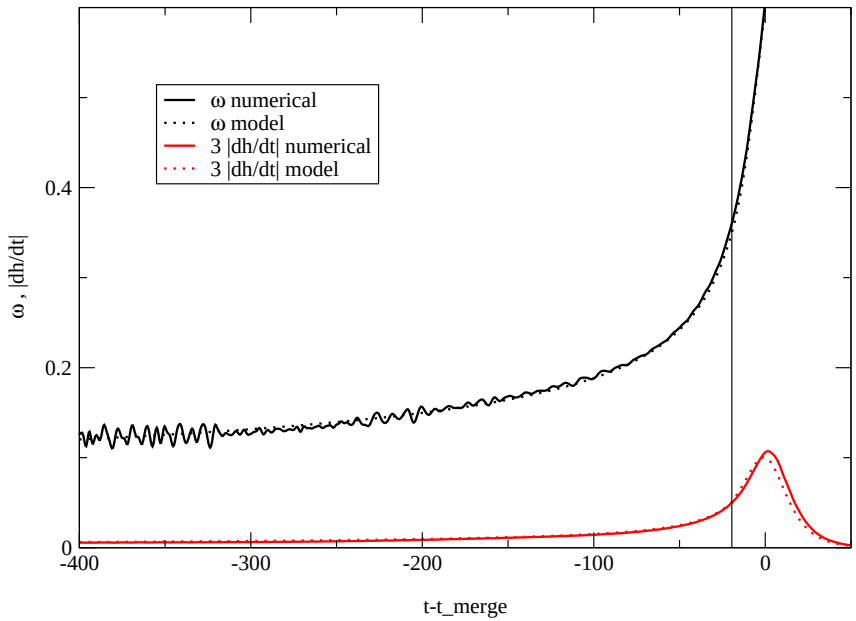


Figure: Decay of $E_{\ell m}$, $J_{\ell m}$, & $\Omega_{\ell m}$ for 1:1 (2,2) mode (left), 4:1 (2,1) mode (right).

Relevance to LISA: New BHB Waveform Templates

- Can merge Numerical Relativity (NR) results with post-Newtonian (PN) theory to get BHB waveform templates.
- Standard Effective One-Body (EOB) approach attaches PN inspiral to ringdown modes.
- Buonanno *et al.* (2008) used NR data to tune EOB with pseudo-4PN parameter.

- New frequency model replaces ringdown modes with Ω fit.
- Encodes both frequency (black) and amplitude (red) well.



Useful for LISA template construction. See Sean McWilliams' talk for s.

Summary

- NR simulations are expensive, & PN waveforms are cheap.
- “Implicit Rotating Source” picture captures essence of most important modes in full waveforms
- IRS can be combined with PN (EOB) analysis to give hybrid WFs that cover all non-spinning black-hole binary mergers.
- Extend to spinning mergers?
- Data Analysis implications: Sean McWilliams’s talk.