Nonlinear memory in binary black hole waveforms

[arXiv:1004.4209]

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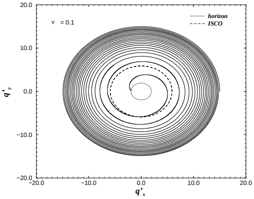
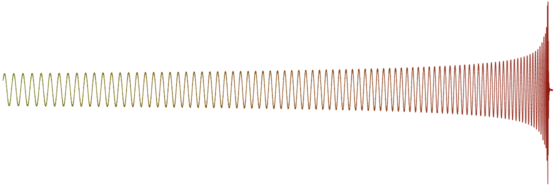
Introduction

- The gravitational wave signal from binary inspirals is principally oscillatory, due to the orbital motion of the sources
- Decomposed into spherical harmonic modes, the dominant term is the $(l, m) = (2, 2)$





- Sub-dominant wave modes contain important structure for both detection templates and source parameter estimation.

Gravitational "memory"

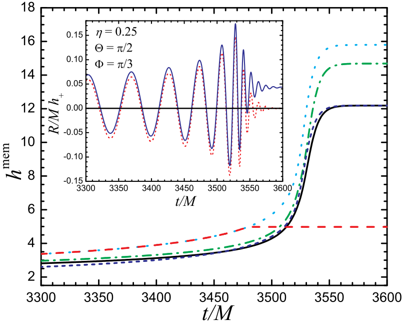
- A displacement of observers which persists after a GW has passed

$$\Delta h_{jk}^{TT} = \Delta \sum_{A=1}^{N} \frac{4M_A}{r\sqrt{1-v_A^2}} \left(\frac{v_A^j v_A^k}{1 - v_A \cos\theta_A} \right)^{TT}$$

[Thorne (1992)]

- Nonlinear memory: change in radiative multipole moments, sourced by radiated GWs
- Payne (1983), Christodoulou (1991), Blanchet & Damour (1992)*
- Non-oscillatory signal, grows monotonically over time, saturates at merger
- Depends on the entire past history of the signal
- Manifest in the $(\ell, 0)$ spherical harmonic wave modes
- Favata (2008–2010): Amplitude estimates via EOB

Gravitational "memory"



[Favata (2009)]

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Methods: Evolution code

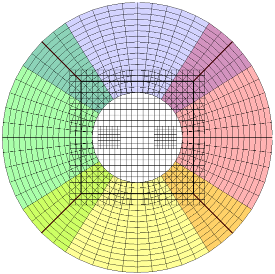
- Memory modes are challenging to evaluate numericially:
  - Correspond to a low-amplitude, non-oscillatory strain, h
  - Typically, numerical codes measure:

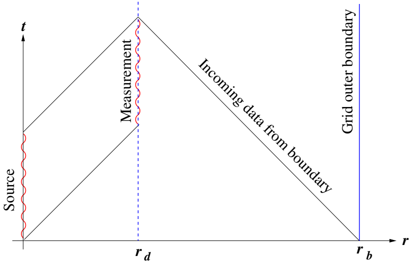
$$\psi_4 \simeq \ddot{h}$$

  - Confused by local gauge and finite-radius measurement effects
- Binary BH evolutions:
  - 3+1 evolution of spacelike slices
  - “BSSN” formulation of Einstein equation
  - “Moving puncture” gauges
  - Finite differences, Runge-Kutta evolution in time
- We incorporate some non-standard techniques:
  1. Adapted coordinates in the wave zone via multiblock grids
  2. Gauge invariant wave extraction at null infinity

Methods: Adapted coordinates in the wave zone

[arXiv:0910.3656 and 0910.3803]





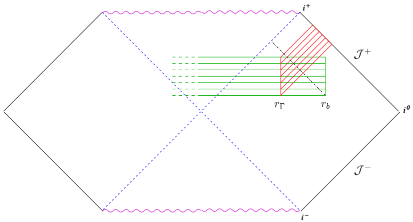
- Near-zone is covered by a cartesian patch
  - mesh refinement around BHs
- Wave-zone is covered by 6 radially oriented patches
  - Locally cartesian coordinates, regular everywhere
- Resulting efficiencies:
  - High radial resolution in the wave zone (out to $r > 1000M$)
  - Boundaries can be causally disconnected from measurements

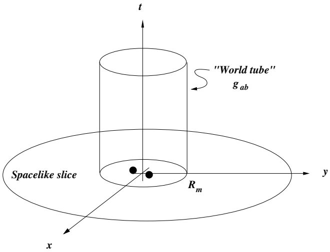
Methods: Characteristic GW extraction

[arXiv:0907.2637 and 0912.1285]

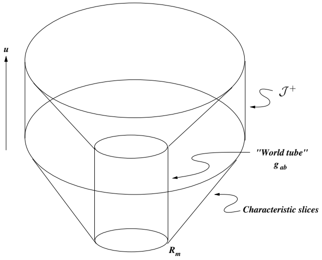
Measured observable:
Bondi news function, $\mathcal{N}$:

$$h = \int \mathcal{N} dt$$



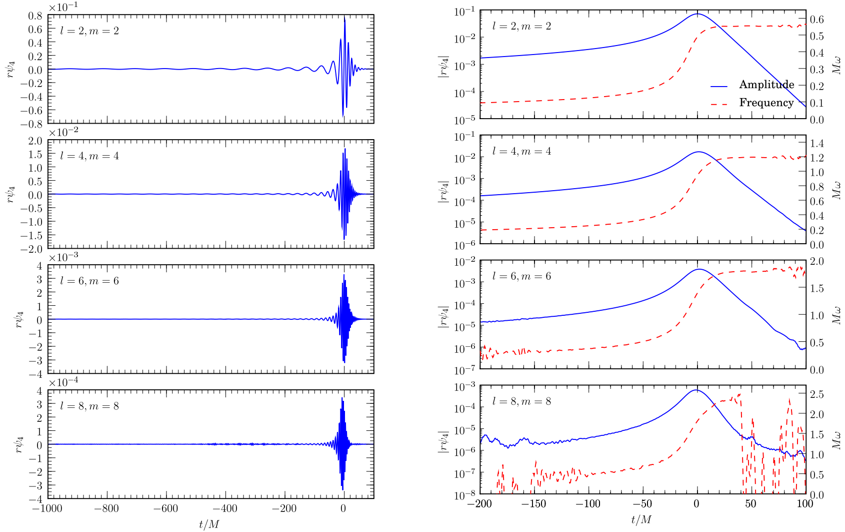


3+1 “Cauchy” evolution



Characteristic evolution

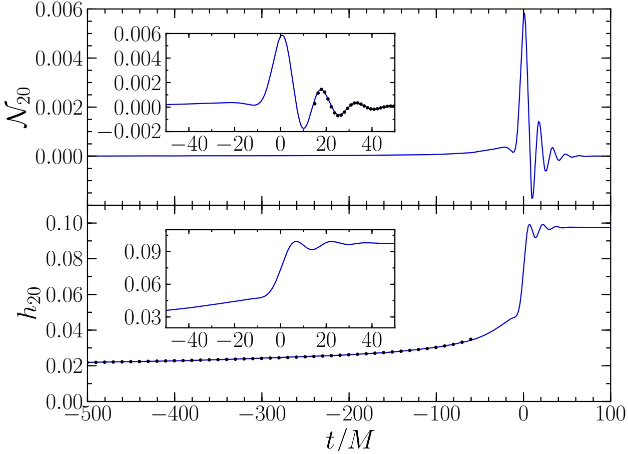
Gravitational waves (oscillatory modes):



- Measured ringdown frequencies agree to perturbative results to within $\Delta\omega/\omega = 1 \times 10^{-4}$

Gravitational memory $(\ell, m) = (2, 0)$ mode

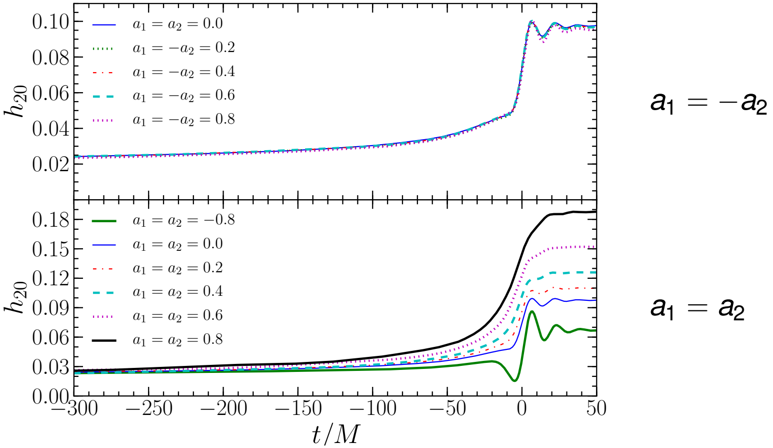
Non-spinning, equal-mass binary:



- Integration constant for *h* determined by fit to 3PN [Favata (2009)]

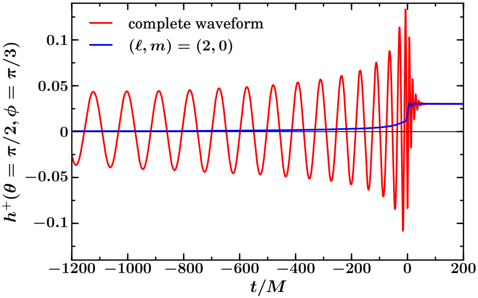
Memory vs. BH Spin

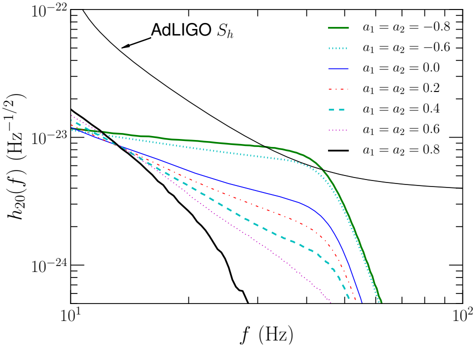
- Equal mass, spins aligned with orbital angular momentum



- Nearly identical results for $a_1 = -a_2$ (zero net spin)
- Prominent ringdown when spins are anti-aligned with orbit

Detectability (1): Interferometers





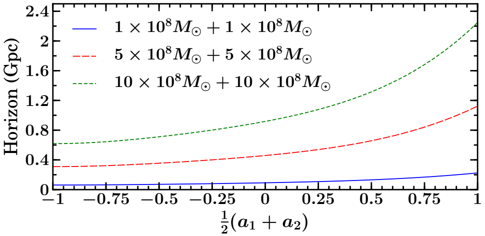
$145M_\odot + 145M_\odot$ binary,
$d = 300\mathrm{Mpc}$, $\theta = \pi/2$

- Including the memory induces a notable offset in the GW
- But for AdvLIGO/Virgo, mismatch is negligible ($\leq 10^{-5}$)

Detectability (2): Pulsar timing arrays

- Pulsars are precise clocks. Pulse time of arrival is sensitive to changes in the intervening spacetime:
  - GWs may be visible in correlated timing residuals from stable millisecond pulsars
- Current experiments: PPTA, EPTA, NANOGrav; Future: SKA
- Memory step-function leads to linear drift in timing residuals, may be visible over some years of observation.
- Pshirkov et al. (2010), van Haasteren et al. (2010), Seto (2010):

  $\Delta h \simeq 2 \times 10^{-15}$ for detection in PTA



Summary

- First measurements of the nonlinear GW memory modes via numrel, from late inspiral through merger.
- The $(\ell, 0)$ modes exhibit some interesting features:
  - Non-oscillatory during inspiral
  - Clear transition to ringdown
  - Stronger ringdown for low-spin merger remnant
- These modes don't contribute greatly to AdvLIGO/Virgo SNR, though ringdown can be prominent in some models.
- The memory offset during merger of supermassive BBHs provides a potential burst source for PTAs.
- There's plenty of interesting structure still to be found BBH waveforms.