Title: Nonlinear memory in numerical waveforms

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Abstract: In addition to the dominant oscillatory modes gravitational waves contain non-oscillatory components which arise as drifts or offsets in the signals. Nonlinear gravitational memory arises from a change in mass multipole moments of a boundsystem due to contributions from the emitted gravitationalwaves. In practice it appears as a slowly monotonically growingsignal during the inspiral which sees a rapid rise at thetime of merger. The low amplitude and non-oscillatory natureof these signals present unique challenges for modeling.I discuss recent efforts to evaluate these signals in numericalsimulations using characteristic extraction as well as theirpotential relevance to detection.

Nonlinear memory in binary black hole waveforms

[arXiv:1004.4209]

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Gravitational "memory"

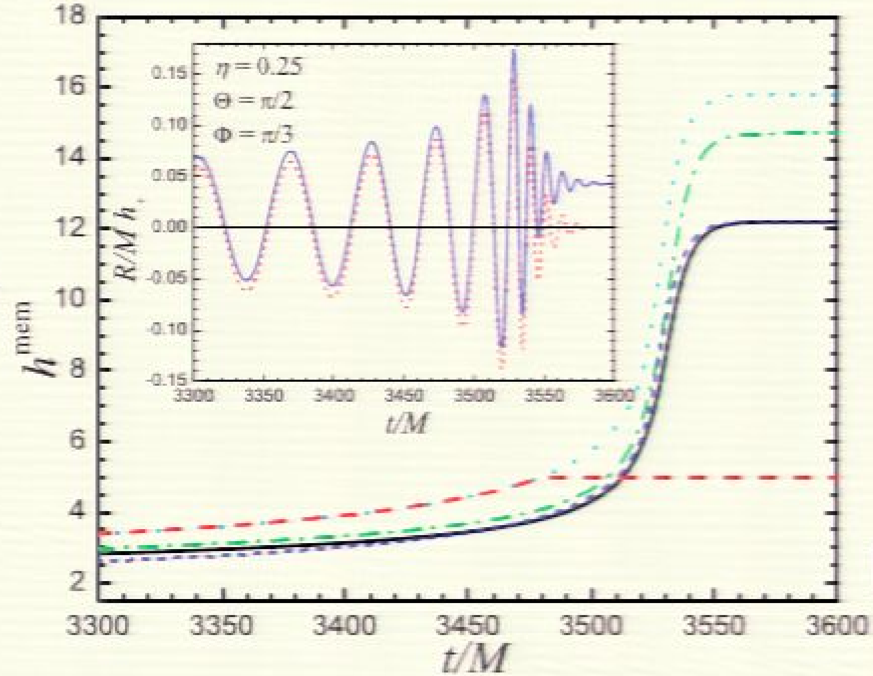
- A displacement of observers which persists after a GW has passed

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

[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
- Manifests in the $(\ell, 0)$ spherical harmonic wave modes

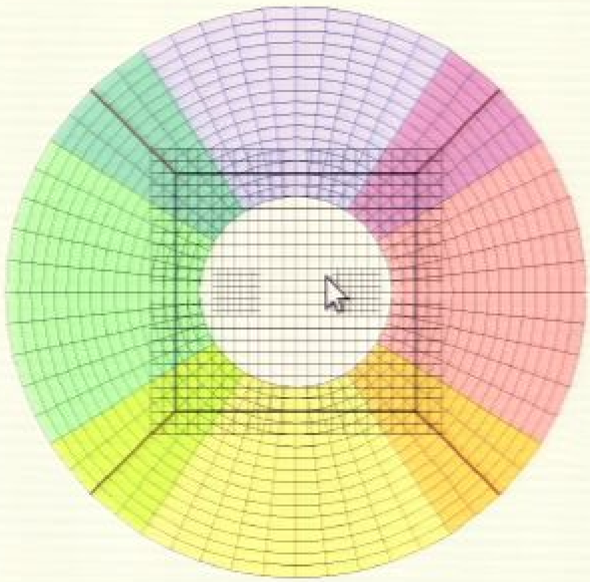
Gravitational “memory”

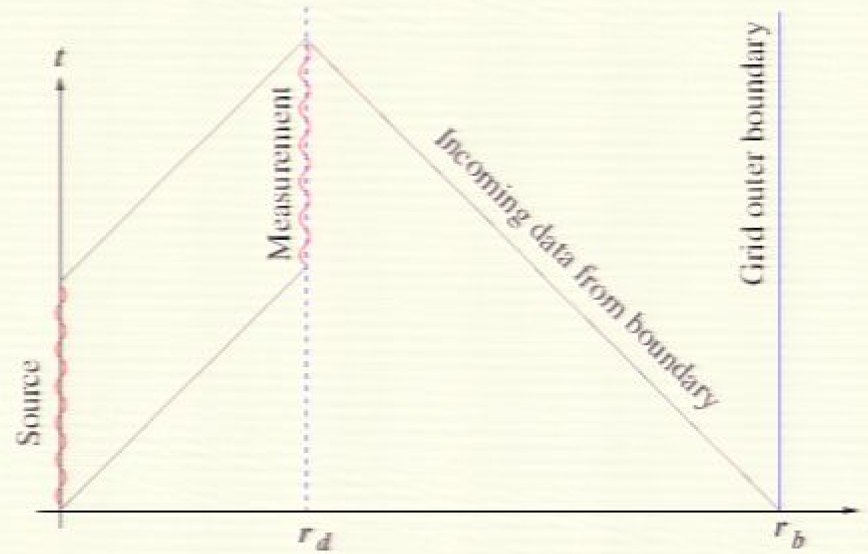


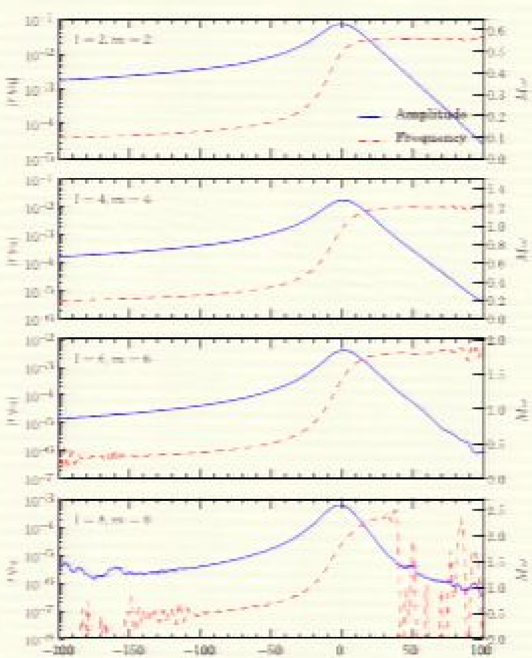
[Favata (2009)]

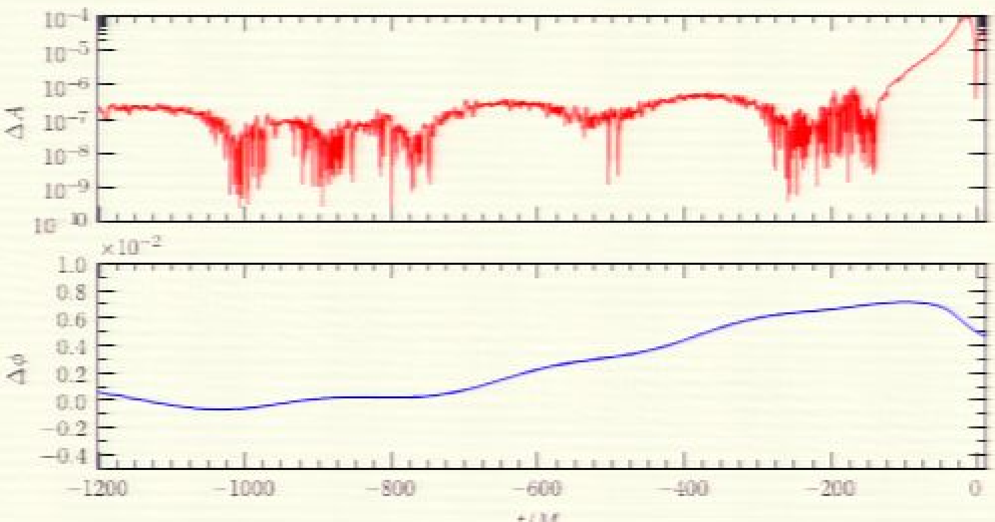
- Revisited by Favata (2008, 2009, 2010)
  - Extended PN estimate to 3PN
  - EOB estimate including merger
- Memory modes are challenging to evaluate numerically:
  - Low amplitude, non-oscillatory strain, h
  - ψ_4 corresponds to two time derivatives of h
  - Confused by gauge effects from local wave extraction

Methods: Evolution code









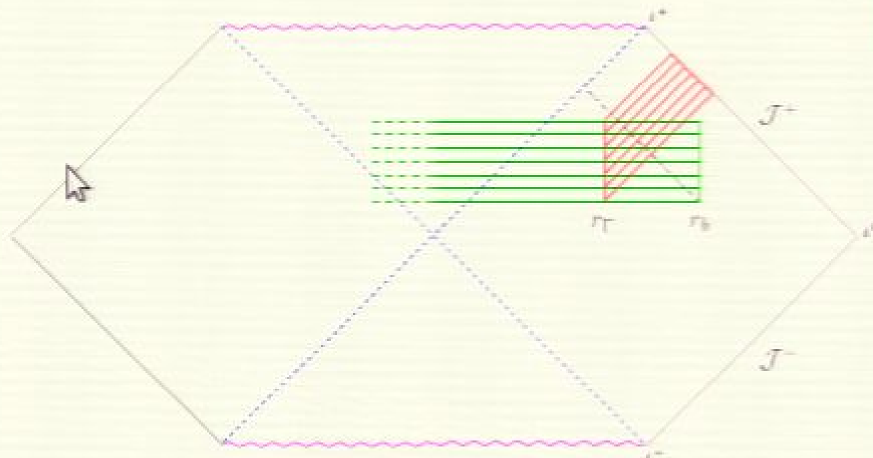
[arXiv:0910.3656 and 0910.3803]

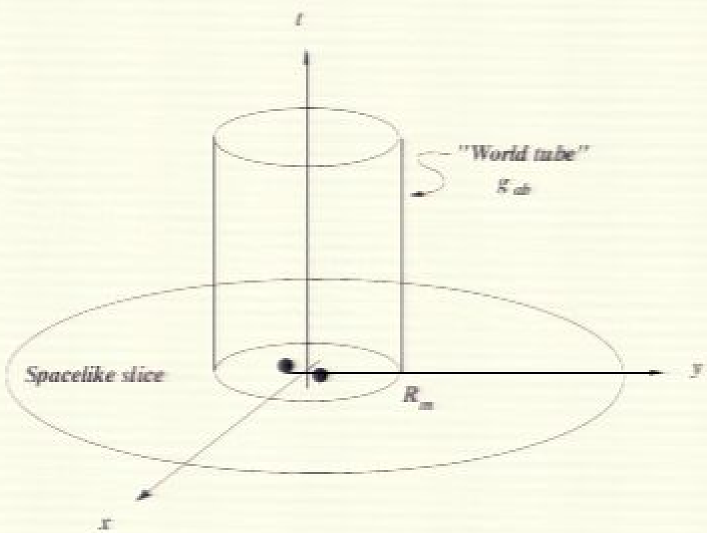
Methods: Characteristic GW extraction

[arXiv:0907.2637 and 0912.1285]

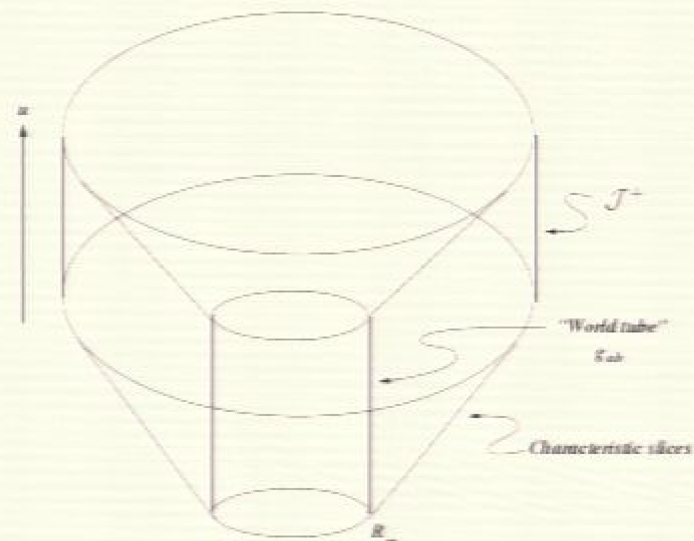
Measured observable:
Bondi news function, $\mathcal{N}$:

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





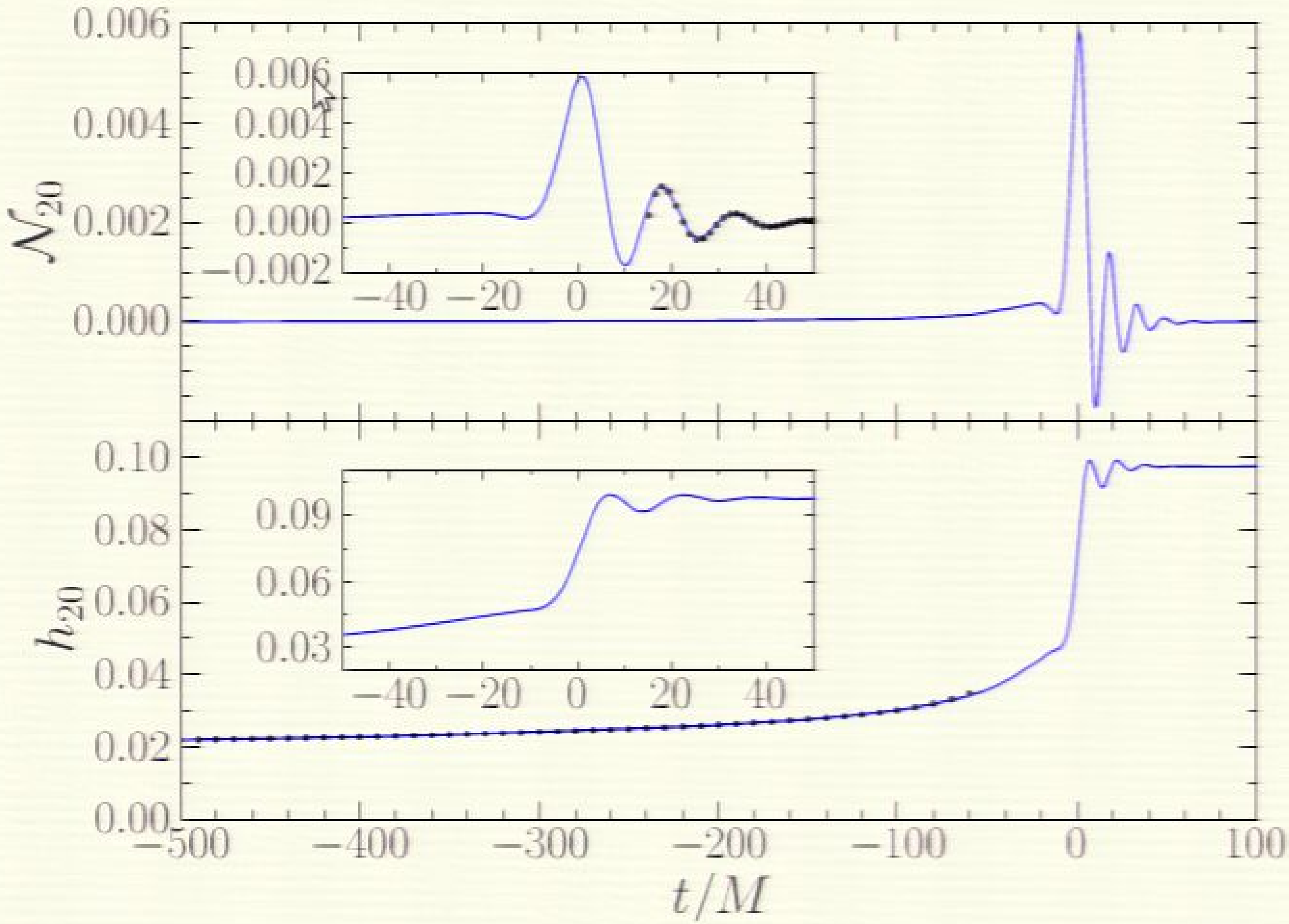
3+1 "Cauchy" evolution



Characteristic evolution

Matching to PN and ringdown

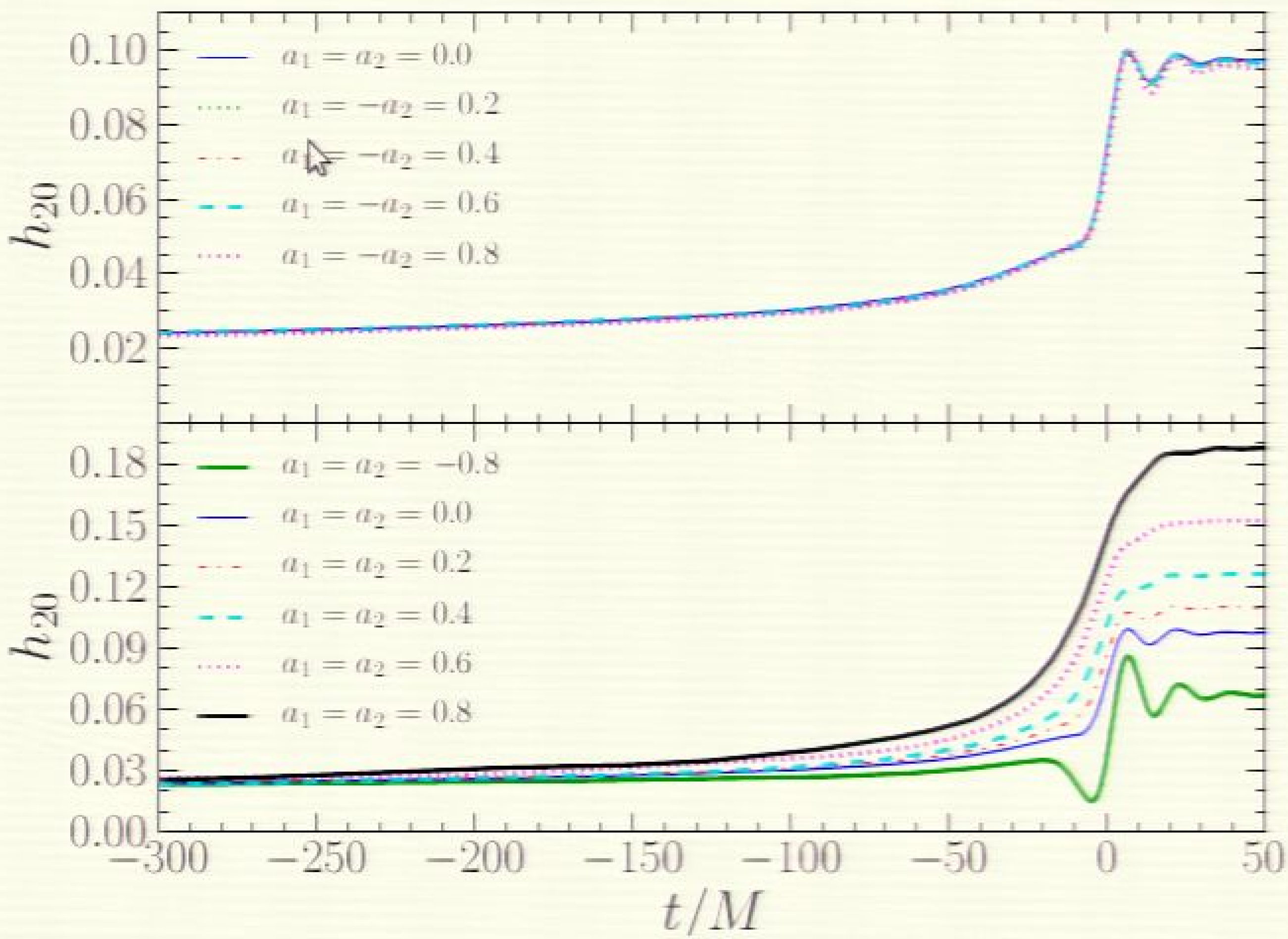
Non-spinning, equal-mass binary:



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

Memory vs. BH Spin

- Equal mass, spins aligned with orbital angular momentum

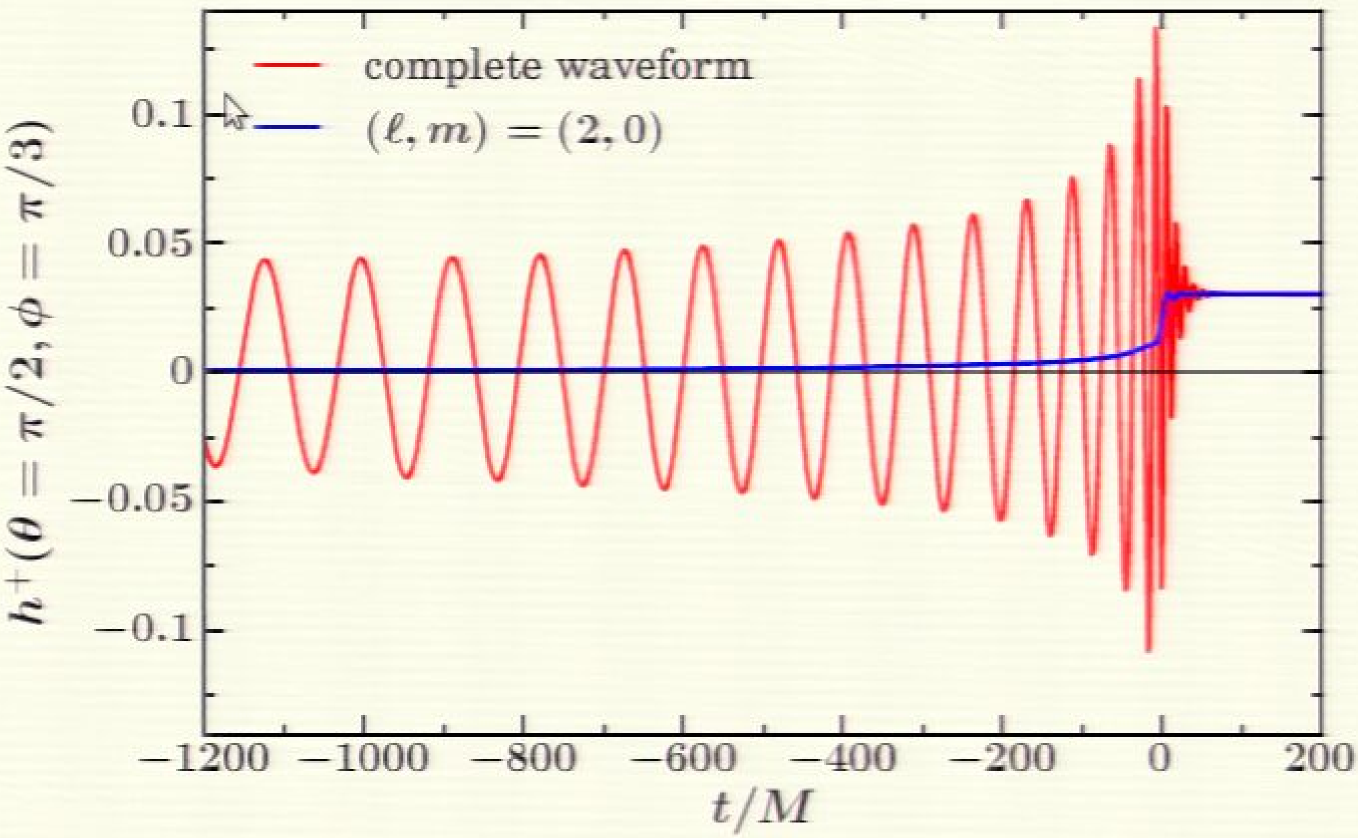


$a_1 = -a_2$

$a_1 = a_2$

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

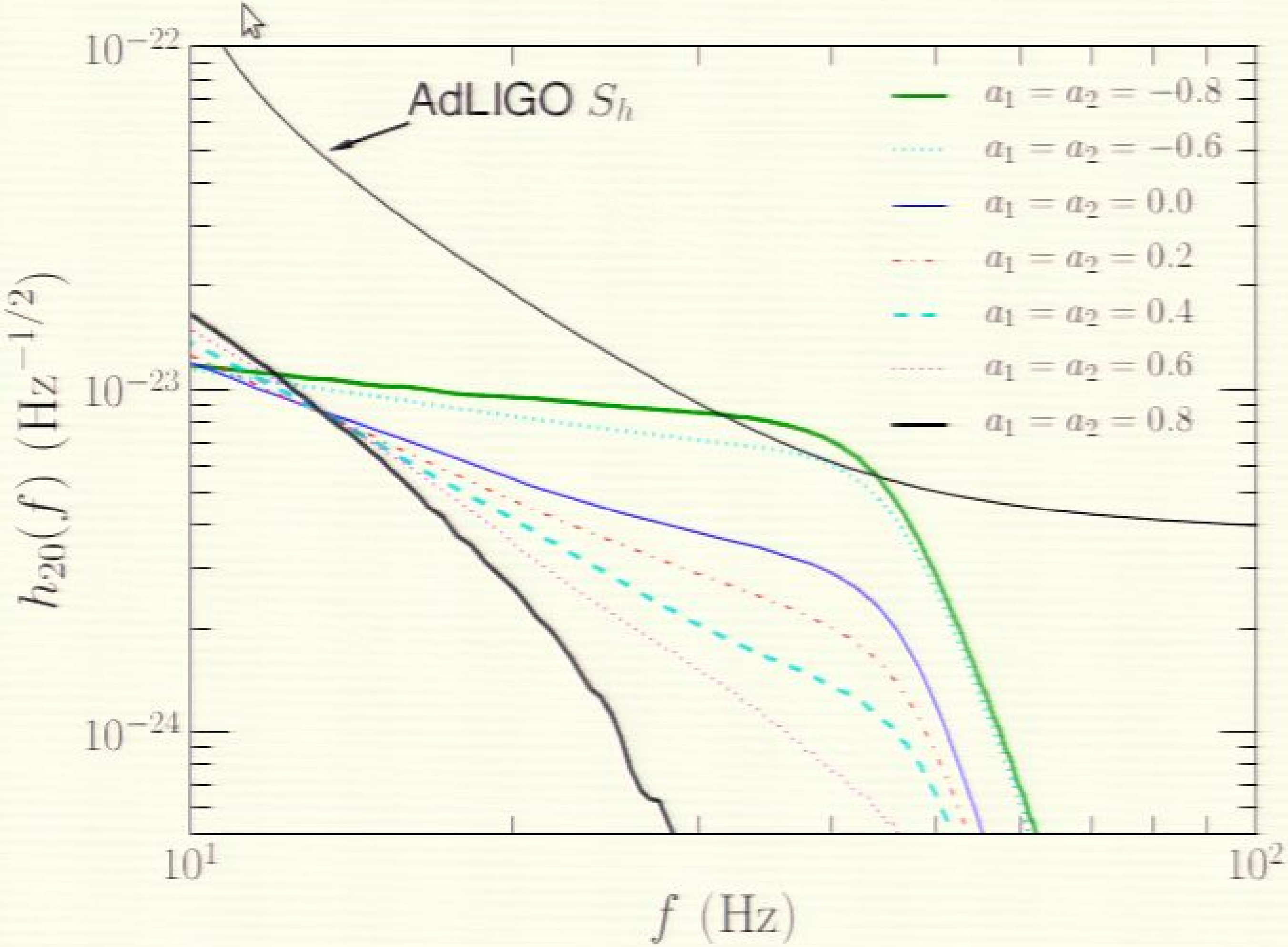
Detectability: Interferometers



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

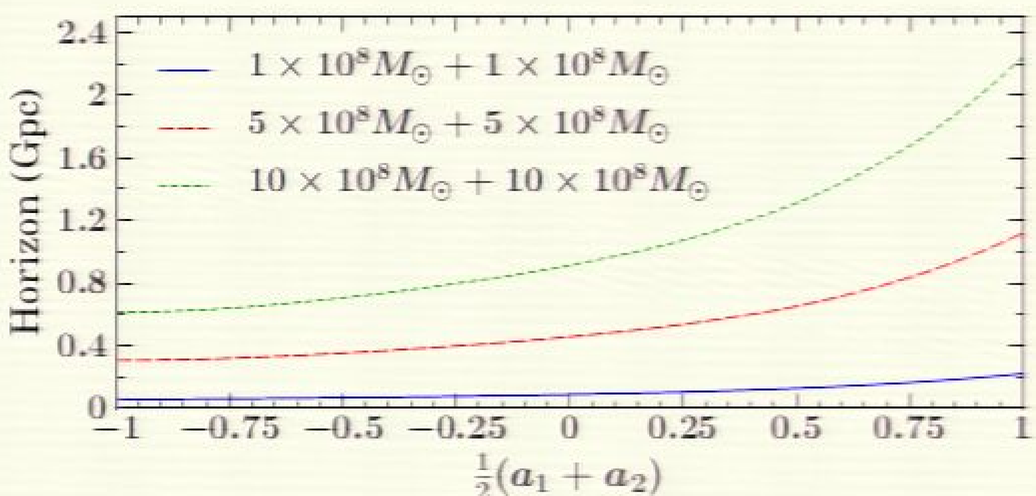
Detectability: Interferometers

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



Detectability: Pulsar timing

- 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.

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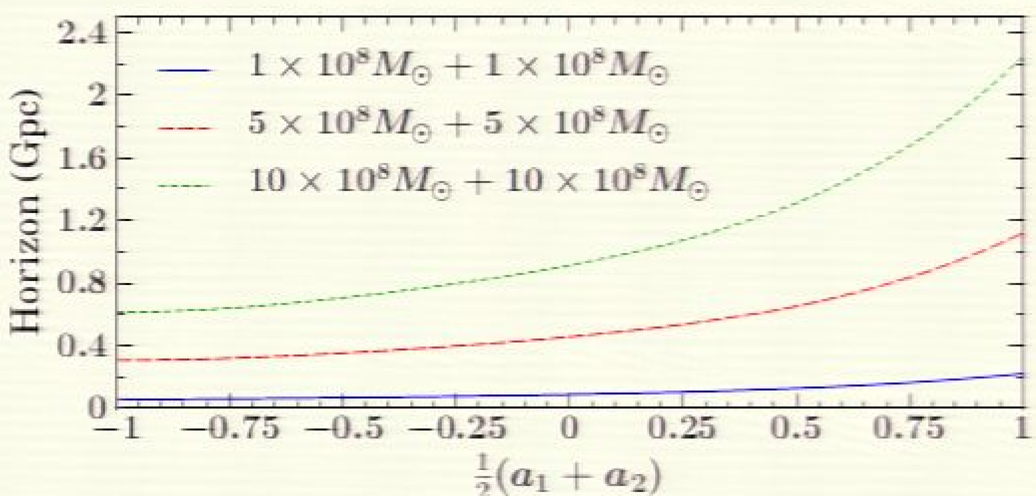

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