Gravitational memory in binary black hole mergers

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Summary

Gravitational waves are a fundamental prediction of Einstein's relativity, and a promising source of astrophysical information as a number of international projects to measure them (LIGO, Virgo, LISA) improve in sensitivity over the next decade.

Interferometric detectors are sensitive to oscillations in the local spacetime metric. **Gravitational wave "memory"** is a non-oscillatory signal, arising from *nonlinear* interactions of the waves with themselves [1]. It is a result of graviton-graviton interactions, sourced by the changing multipole moments of an isolated system, and results in a change in the local spacetime metric caused by the passage of the wave:

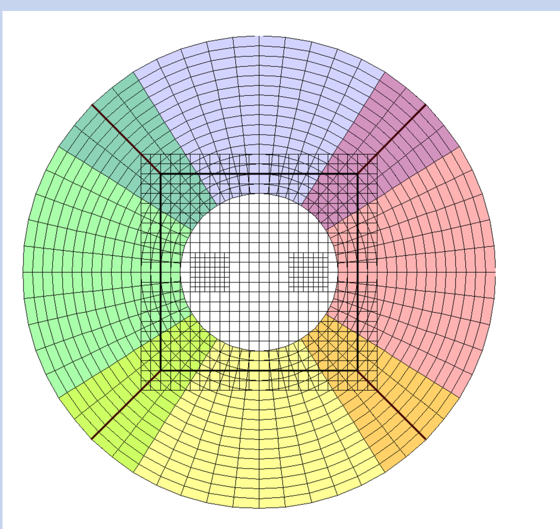
$$\Delta h_{jk}^{TT} = \Delta \sum_{A=1}^{N} \frac{4M_A}{r\sqrt{1-v_A^2}} \left(\frac{v_A^j v_A^k}{1 - v_A \cos\theta_A} \right)^{TT}$$

During a binary black hole merger, the memory signal may be prominent. Its profile gradually grows as the bodies spiral together, followed by a steep rise during the late orbits and merger. The amplitude of the rise can only be predicted by accurate numerical simulations of the merger process.

We use numerical evolutions of binary black holes to evaluate the nonlinear memory during late-inspiral, merger and ringdown. We identify two main components of the signal: the monotonically growing portion corresponding to the memory, and an oscillatory part which sets in roughly at the time of merger and is due to the black hole ringdown. Counter-intuitively, the ringdown is most prominent for models with the lowest total spin. Thus, the case of maximally spinning black holes *anti-aligned* to the orbital angular momentum exhibits the highest signal-to-noise (SNR) for interferometric detectors. The largest memory offset, however, occurs for highly spinning black holes, with an estimated value of $h_{20}^{\rm tot} \simeq 0.24$ in the maximally spinning case. These results are central to determining the detectability of nonlinear memory through gravitational wave interferometers and pulsar timing array measurements.

Methods

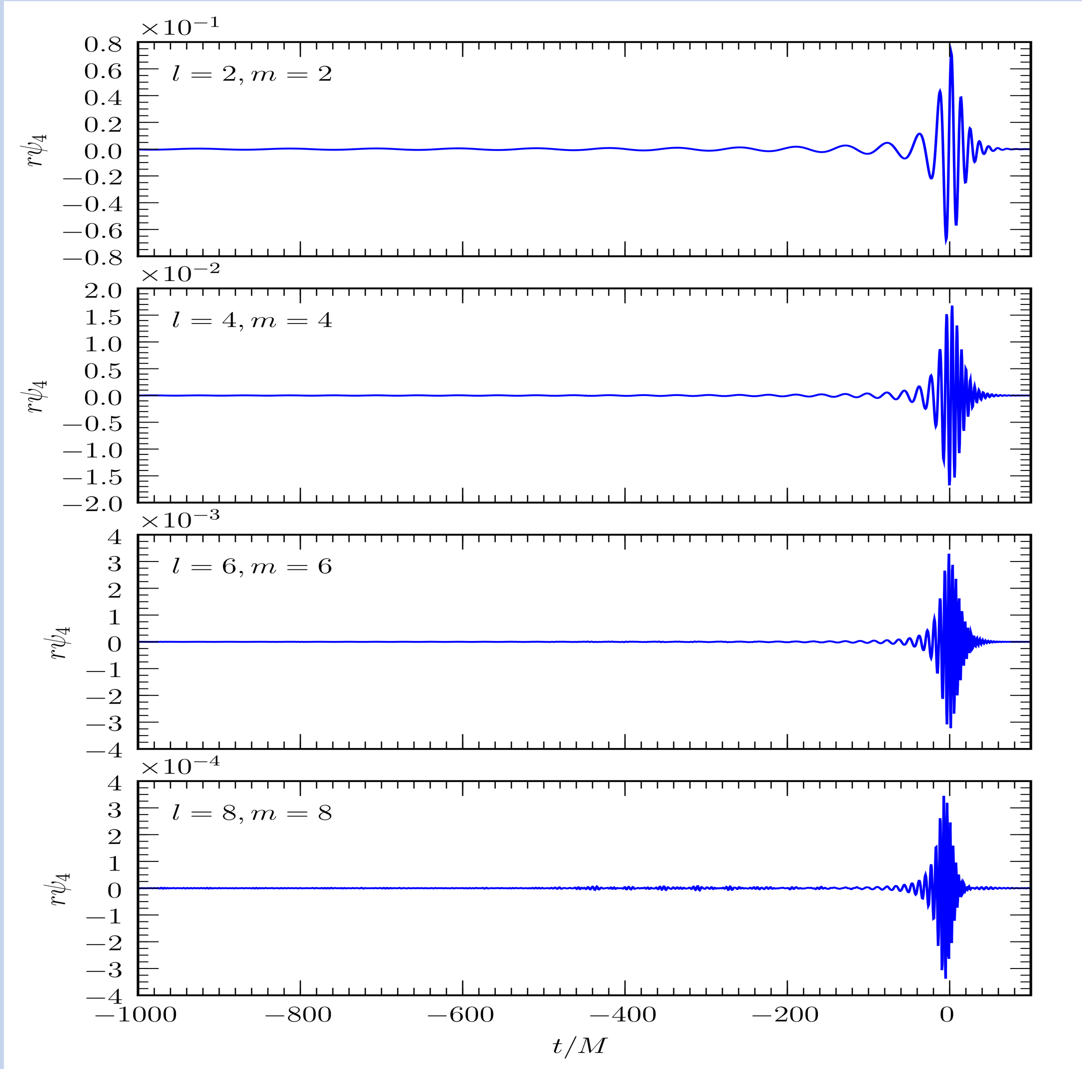
The vacuum Einstein equations are evolved as a set of hyperbolic PDEs. We use finite differences to discretize the spacetime, with adaptive mesh refinement and curvilinear coordinates (see figure) [3, 4, 5].



A Runge-Kutta method evolves the variables which define the local geometry of the dynamical spacetime. Binary black holes (BHs) are specified as "punctures" surrounded by event horizons []. Post-Newtonian models provide initial parameters for BHs in quasi-circular orbits. Fully relativistic spacetime evolutions follow the last several orbits and merger. These calculations are expensive in 3D, requiring supercomputers such as the BSC's *Mare Nostrum* cluster.

Oscillatory modes

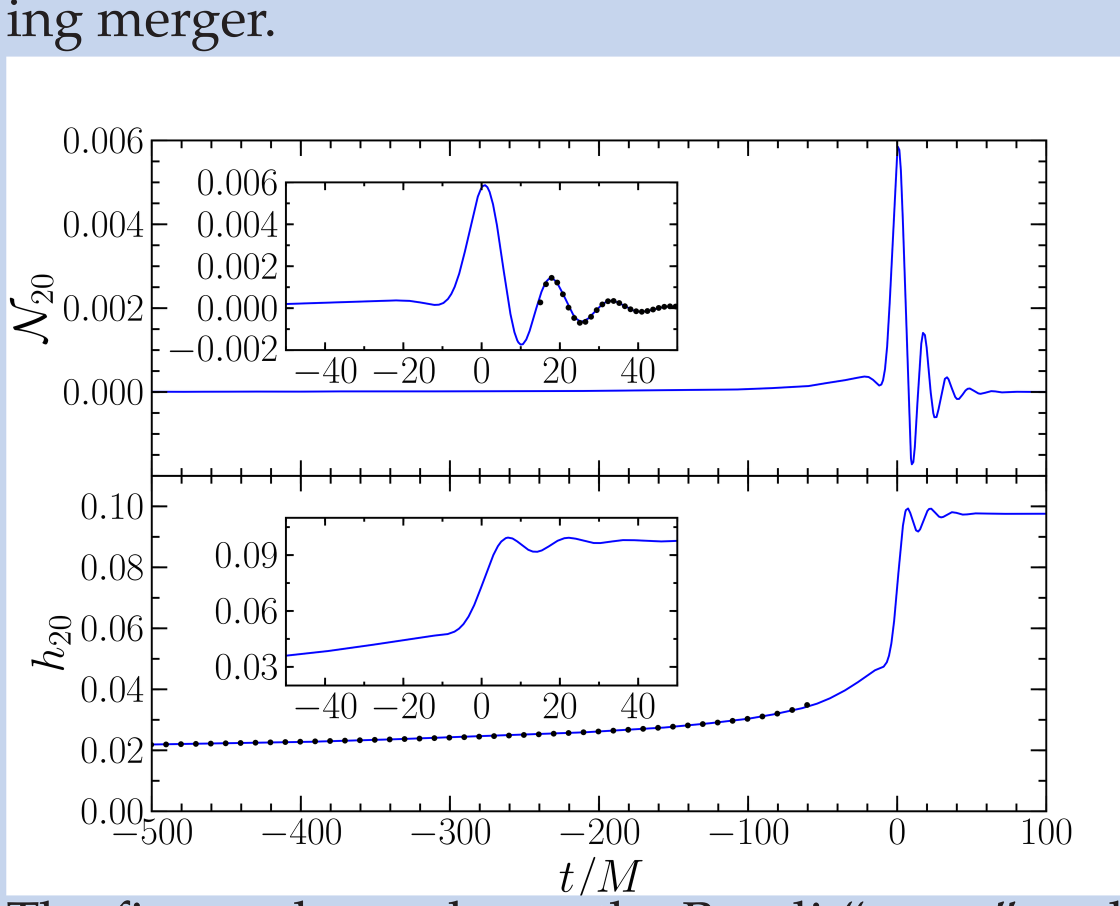
The oscillatory modes of the gravitational waves are measured to high precision up to the $(\ell, m) = (8, 8)$ spherical harmonic mode. We observe up to 8th order convergence in the numerical truncation error.



These modes are determined by the orbital motion of the bodies and are the dominant signal expected to be measured by interferometric detectors.

Calibration

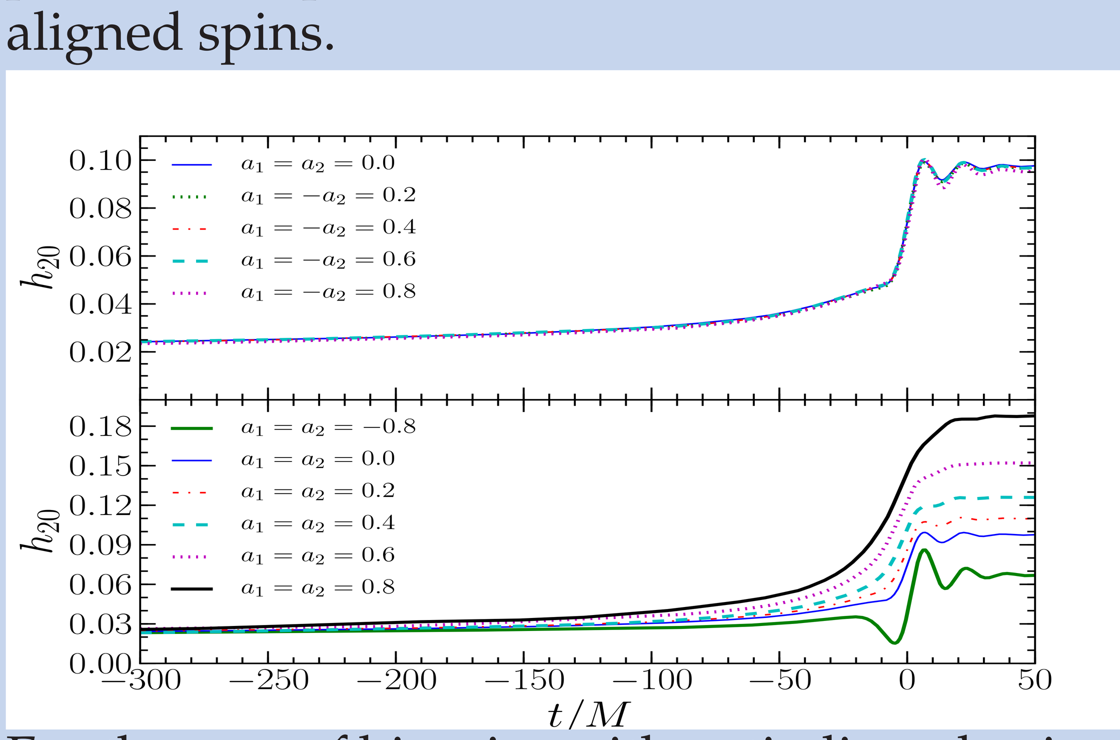
The memory signal is non-oscillatory during inspiral, though it picks up a ringing tone during merger.



The figure above shows the Bondi "news" and its first time integral, the gravitational strain which is actually measured. The numerically determined signal (blue) can be matched with post-Newtonian estimates during the inspiral (dotted, lower plot) and perturbative estimates of the ringdown (dotted, upper plot).

Memory vs. BH Spin

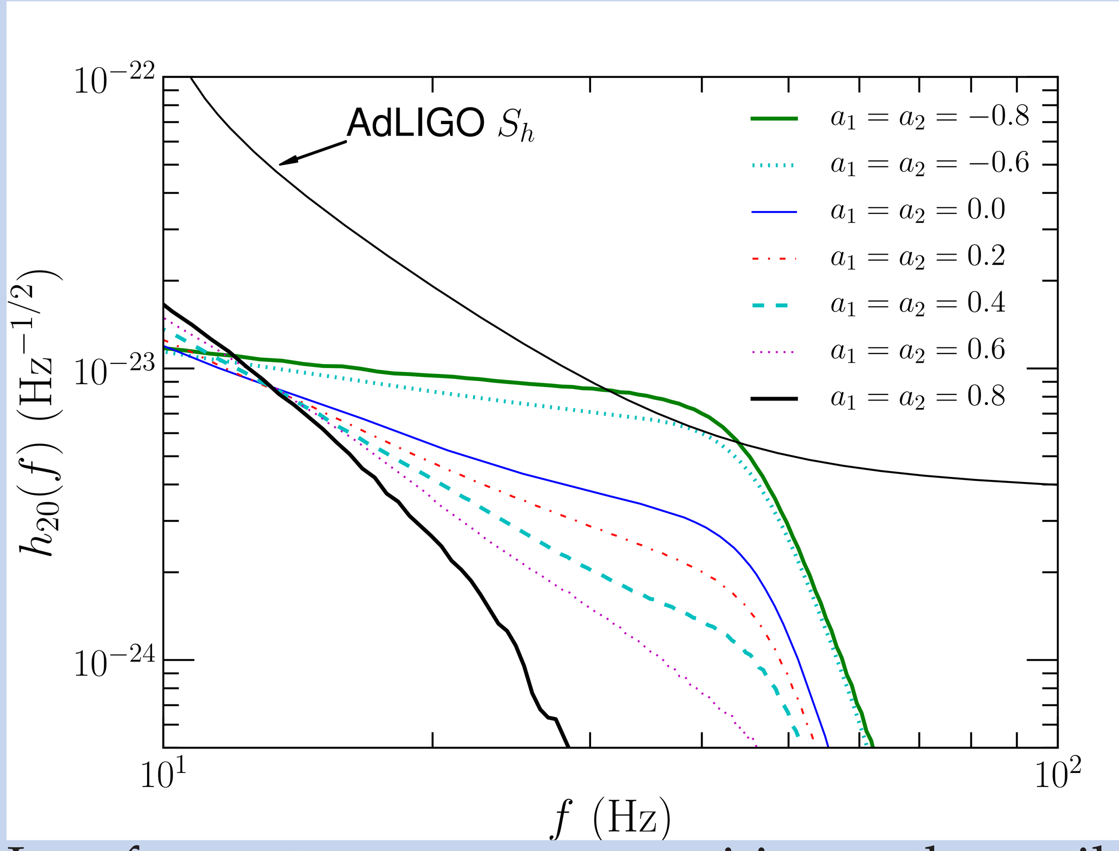
We have determined the merger signal for a parameter space of black hole binaries with aligned spins.



For the case of binaries with anti-aligned spins, $a_1 = -a_2$ (upper), the signals are essentially identical. For equal aligned spins, $a_1 = a_2$ (lower), the memory signal increases dramatically with increased spin.

Detection: Interferometers

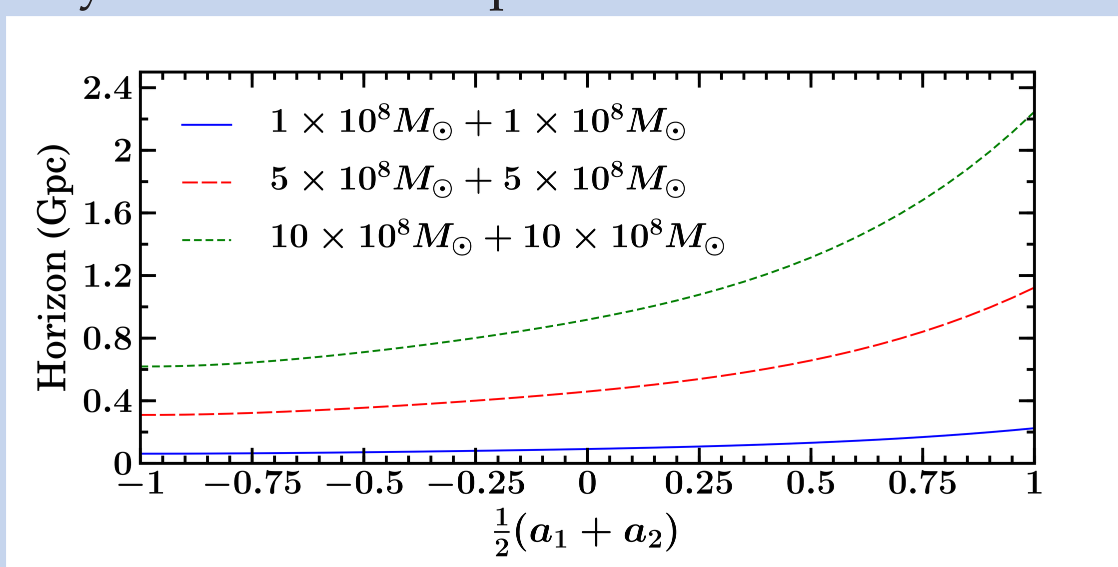
The amplitude of the gravitational memory for astrophysically relevant models can be compared with the noise curves of the upcoming generation of interferometric detectors.



Interferometers are most sensitive to the oscillatory ringdown signal. As such the highly spinning but anti-aligned models are most visible. Displayed are the Fourier domain representations for different equal and aligned spin models at the optimal total mass $M = 290 M_\odot$ ($145 M_\odot + 145 M_\odot$ binary) at a distance $d = 300$Mpc and at an angle $\theta = \pi/2$. Only the $a_1 = -a_2 = 0.8$ model is barely visible above the advanced-LIGO noise.

Detection: Pulsar timing arrays

An alternative approach to measuring GWs is to use pulsars as high precision clocks, and look for systematic residuals in pulse arrival times. PTA measurements are particularly sensitive to the step-function nature of the memory signal. Recent calculations [6] suggest a strain amplitude $\Delta h \simeq 2 \times 10^{-15}$ will be measurable over a 10-year observation period.



Our numerical models suggest that for binaries with realistic spins $a_1 = a_2 = 0.7$ [7], galactic binaries will be observable to several Gpc.

Assuming conservative estimates of SMBH merger event rates [8], we would have a merger rate of $0.1 \mathrm{yr}^{-1}$ at redshifts $z \lesssim 1$ for $\sim 10^8 M_\odot$ binary sources. Hence, we can expect to detect approximately one such event over a period of ten years.

References

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