Gravitational-Wave Memory Effects in XG Observatories

SUMMARY

The observation of gravitational-wave memory effects will be a crucial and fundamental test of the (non)linear nature of general relativity (GR). Memory effects correspond to the permanent displacement that observers experience due to the passage of gravitational waves. They are closely connected to asymptotic symmetries and the infrared properties of gravity. Low-frequency ($\lesssim 50$ Hz) sensitivity is necessary for the observation of memory effects. Planned XG observatories will see memory from individual stellar-mass binary mergers, provided that they achieve a low-frequency noise characteristic strain sensitivity on the order of 10^{-24}. Memory can also aid in the astrophysical interpretation of hyperbolic encounters, primordial black hole mergers, supernovae events, and neutron-star mergers.

Key questions and scientific context in brief

Gravitational-wave memory effects (Zel'dovich and Polnarev 1974; Christodoulou 1991) are intimately connected to the infrared properties of gravitational radiation and scattering (Strominger 2017). Detectable in ground-based interferometers (Lasky et al. 2016), they are an observational probe of various (non)linear gravitational phenomena and can be used to study new classes of astrophysical sources.

The main scientific questions that can be addressed by studying memory are:

1. Do the memory effects produced by binary black hole mergers match the predictions of (non)linear GR? If not, what is the source of the discrepancy? If so, how can this inform the effort to understand the infrared properties of gravitational radiation and scattering?
2. Can we use XG observations of memory effects to place more stringent bounds on the population rates and/or physics of:
   (a). hyperbolic black hole encounters, whose signals are dominated by their memory component (see Zel'dovich and Polnarev 1974; Kovacs and Thorne 1978; Rüter et al. In prep.);
   (b). primordial binary black hole mergers, which for sub-solar mass black holes produce signals whose only observable component in XG detectors is the memory component (see McNeill, Thrane, and Lasky 2017; Ebersold and Tiwari 2020);
   (c). supernovae, for which the memory is sourced not only by anisotropic gravitational-wave emission, but also neutrinos, implying a potentially detectable signal with XG detectors below ≈ 50 Hz (see Richardson et al. 2022; Vartanyan et al. 2023);
   (d). neutron stars, for which memory is known to drastically improve the measurement of matter effects—especially in black hole-neutron star mergers—for XG detectors (see Tiwari, Ebersold, and Hamilton 2021; Yang and Martynov 2018).

Potential scientific impact of XG detectors on the key questions

Because memory dominates at low frequencies, XG detectors are ideal for measuring this currently unobserved prediction of GR from stellar mass black hole mergers. Cosmic Explorer is expected to see memory in a single event once every two years with a signal-to-noise ratio (SNR) larger than 5 (Grant and Nichols 2023). Combining multiple events leads to a significantly faster detection (Lasky et al. 2016). With an XG detector

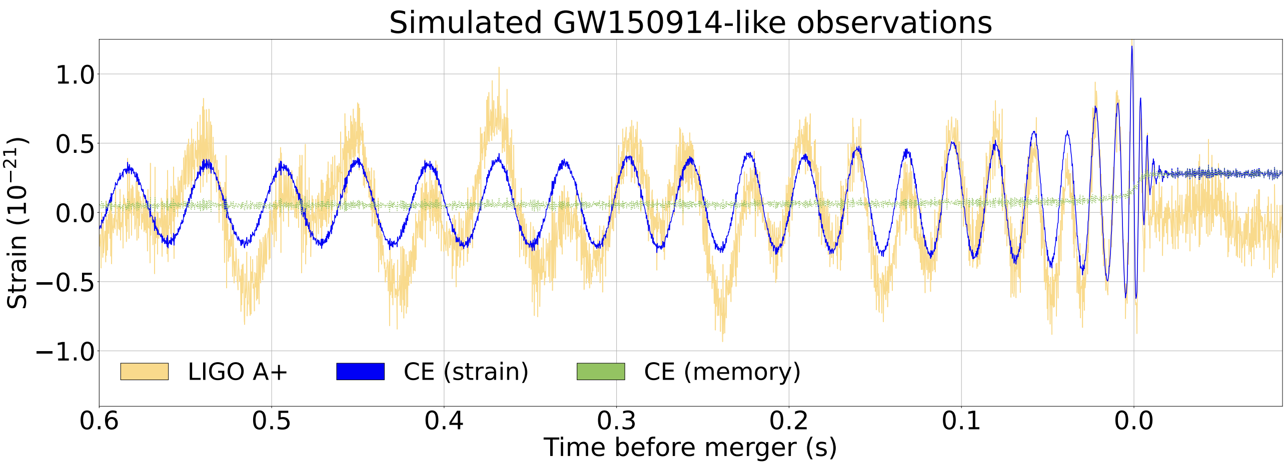

Figure 1: Simulated gravitational-wave detector strain and memory measurements for a GW150914-like signal from two merging black holes. The strain is shown as a function of time for the signal superimposed on both simulated LIGO A+ noise (yellow) and simulated Cosmic Explorer noise (strain in blue, memory in green). Note that here the noise is introduced in the time-domain and there is no frequency-domain filtering.

capable of observing memory, we can expect to place bounds on the population rates of hyperbolic encounters, whose signal is dominated by ordinary memory (see, e.g., Zel'dovich and Polnarev 1974), and sub-solar mass primordial black hole mergers, whose signal is too high of a frequency to be observable, except for the part of the signal that is sourced by the memory (see Ebersold and Tiwari 2020).

Benchmarks for XG detectors to enable the scientific impact

As a rough order-of-magnitude estimate for the benchmarks needed to observe memory effects, we model the memory as a step function in time and assume that only the dominant, $(2, 0)$ spin-weighted spherical harmonic mode is observed. For a GW150914-like system, the magnitude of the memory is $h^{\text{disp}} \simeq 3 \times 10^{-22}$ (see Mitman et al. 2020). With this in mind, the benchmark of interest is then the noise characteristic strain h_n between 10 and 100 Hz that is required to yield an observation of the memory at an SNR of 5 in a single event. A short calculation shows this should be below

$$h_n \equiv \sqrt{f S_n(f)} \lesssim 3 \times 10^{-24} \times \frac{h^{\text{disp}}}{3 \times 10^{-22}} \times \frac{5}{\text{threshold SNR}} \times \left(\frac{\text{\# of detectors}}{2}\right)^{1/2} . \tag{1}$$

Note though that the memory SNR will also depend on the shape of the noise characteristics at low frequencies. This illustrates that memory will certainly be observable by an XG detector such as Cosmic Explorer and perhaps even a detector like Voyager, provided that an event with a high SNR is observed.

SCIENTIFIC IMPACT OF XG DETECTORS

1. Detection of memory effects.
2. Observational verification of the infrared properties of gravity and its symmetries.
3. Perform tests of GR by comparing observed memory signals to numerical relativity.
4. Place bounds on the population rates of hyperbolic encounters and primordial black hole mergers.

XG DETECTOR AND NETWORK REQUIREMENTS

1. Characteristic strain with sufficient low-frequency sensitivity $\lesssim$ 50 Hz.

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