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Distinguishing scalar gravitational-wave polarizations with next-generation detectors

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ABSTRACT

We describe a fortunate coincidence between the breakdown of the long-wavelength approximation for the response of long XG interferometers and the possible appearance of alternative polarizations for systems with high intrinsic curvature with highly dynamical gravitational fields. This would allow an XG interferometer with arms $O(40)$ km long to distinguish between scalar modes of gravitational radiation, which are otherwise indistinguishable with current gravitational-wave detectors (4 km) and shorter XG designs (≤ 20 km).

1. INTRODUCTION

The polarization content of gravitational waves (GWs) is a fundamental observable that reflects some of the most basic symmetries of spacetime. General metric theories of gravity allow for up to six independent GW polarizations (Eardley et al. 1973b,a), of which General Relativity (GR) permits only two. The two modes permitted by GR are referred to as tensor modes because of their quadrupolar symmetry under rotations around the direction of propagation (spin ± 2). However, extensions of GR may, and generally do, allow for vector (dipolar, spin ± 1) and/or scalar modes (monopolar, spin 0). That is, we can always find a synchronous gauge in which we can decompose the spatial components of the strain h_{ij} as a sum of the tensor (h_+, $h_\times$), vector (h_x, h_y), and scalar (h_b, h_l) polarizations as[1]

$$h_{ij} = \begin{bmatrix} h_b + h_+ & h_\times & h_x \\ h_\times & h_b - h_+ & h_y \\ h_x & h_y & h_l \end{bmatrix} . \quad (1)$$

Different theories may allow for different combinations of these modes to propagate, but observing any amount of scalar or vector modes, regardless of their amplitude, would immediately point to physics beyond GR. **Obsevationally ascertaining that only tensor polarizations exist is a primary scientific target for tests of gravity**.

Of the six possible polarization modes, current detectors (Aasi et al. 2015; Acernese et al. 2015; Aso et al. 2013) can only identify five, since they cannot distinguish between the two scalar modes: breathing (h_b) and longitudinal (h_l). This is true of any small differential-arm antenna, for which the two scalar modes are indistinguishable (without source and theory specific models) even with perfect knowledge of the source sky location. More specifically, in the long-wavelength (small antenna) limit, differential arm detectors are only sensitive to the traceless linear combination of the two scalar modes. This is because, if the round-trip light-travel time set by the length of the detector arms is short compared to the frequency of the GW signal ($f \ll 2L/c$), then the detector response is given by the geometrical projection of the strain onto the detector arms. That is, the strain is measured by light traversing the length of the detector arms essentially instantaneously compared to the rate at which the strain changes. Such detectors cannot distinguish between isotropic expansions or contractions of the metric (the trace of the metric) as their read-out is inextricably tied to directional differences in expansion/contraction.

2. INTERFEROMETRIC RESPONSE BEYOND THE LONG-WAVELENGTH APPROXIMATION

However, this is not true for large instruments. For detectors with long arms, for which the long-wavelength approximation does not apply, the light-travel time can become comparable to the GW frequency. The response of such instruments then depends in a more complicated way on how the phase of the strain evolves over the time it takes for light to propagate up and down the detector arm. *De facto*, the detector is less sensitive to higher frequencies because the strain oscillates and "averages out" over the time required to make the measurement (see, e.g., Essick et al. 2017). Similar effects are expected for any detector sensitive to frequencies comparable to the

[1] Although widespread, the decomposition into this specific *linear* polarization basis is not unique.

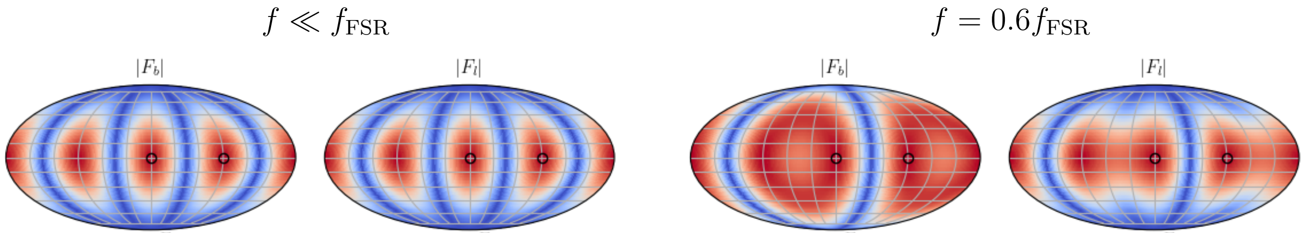

Figure 1. Mollweide projections of the magnitude of the detector response to the breathing mode and longitudinal mode as a function of the direction to the source at (*left*) $f \ll f_{\rm FSR}$ and (*right*) $f = 0.6 f_{\rm FSR}$, approximately ISCO for a 1+1 $M_\odot$ binary at $z \ll 1$ in a 40 km Cosmic Explorer.

light-travel-time along its arms, such as the Laser Interferometer Space Antenna (LISA) and Pulsar Timing Arrays (PTAs).

Resonating cavities in current detectors have free-spectral ranges ($f_{\rm FSR} = c/2L$) of 37.5 kHz and 50.0 kHz, for LIGO and Virgo/KAGRA respectively, much larger than any expected astrophysical signal. Longer arms in XG detectors will correspond to smalller $f_{\rm FSR}$, though, at 15.0 kHz for Einstein Telescope's 10 km arms, 7.5 kHz for a 20 km Cosmic Explorer, and 3.7 kHz for a 40 km Cosmic Explorer. For comparison, the observed GW frequency of a compact binary near the inner-most stable circular orbit (ISCO) is approximately

$$f_{\rm det,ISCO} \approx (2.2\,{\rm kHz}) \left(\frac{2\,M_\odot}{M_{\rm src,tot}}\right) \frac{1}{1+z} \qquad (2)$$

for a system with total source-frame mass $M_{\rm src,tot}$ at redshift z.

Although they complicate the detector response, **high-frequency interferometric effects allow us to probe physics inaccessible within the the long-wavelength approximation**. Specifically, the detector response no longer only depends on the geometric projection of the strain onto the detector arms but also on its frequency and the direction in which the GW is traveling. This means that the GW's propagation breaks the degeneracy mentioned above and allows us to distinguish between the breathing and longitudinal modes. Figure 1 compares the amplitude of the detector response in the Fourier domain to h_b and h_l at low frequencies ($f \ll f_{\rm FSR}$) and at ISCO for a 1+1 $M_\odot$ binary in a 40 km Cosmic Explorer. This is 60% of $f_{\rm FSR}$ for a 40 km Cosmic Explorer, but it would be only 30% and 15% for a 20 km Cosmic explorer or Einstein Telescope, respectively. As Fig. 3 of Essick et al. (2017) shows, the long-wavelength approximation only begins to break down significantly for frequencies $f \gtrsim f_{\rm FSR}/2$. Therefore, of the proposed arm lengths, we would only expect such effects to matter for a 40 km Cosmic Explorer. By this metric, then, **only detectors with arms longer than $\approx 34\,$km would be able to distinguish between scalar polarizations near ISCO with low-mass (solar-mass) mergers**.

Finally, we remark on a convenient coincidence. If we consider GR to be the small-curvature limit of a more general theory, then we might expect to first observe non-tensor polarizations from binaries that reach the largest intrinsic-curvatures. Low-mass binaries reach higher curvatures before merging compared to high-mass binaries, and they reach their highest curvatures just before merging. This is also when the gravitational field is the most dynamic. Therefore, we may naturally expect alternate polarizations to first appear near merger within low-mass binaries, which is exactly where a 40 km Cosmic Explorer would be able to break the degeneracy between scalar modes. **These considerations suggest that at least one 40 km detector be included in any XG network**, and detectors with longer arms would be able to break this degeneracy at even lower frequencies.

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