The Observability of Gravitational Waves in Scalar-Tensor Theories

Kata Karácsonyi, Zoltán Keresztes
University of Szeged, Szeged, Hungary

The observation of gravitational waves has opened new possibilities for experimentally testing theories of gravity. In scalar–tensor theories beyond general relativity, additional breathing and longitudinal scalar polarizations are predicted alongside the plus and cross tensor modes. Scalar gravitational radiation appears one post-Newtonian order earlier than the quadrupolar tensor radiation, allowing the scalar polarization to be decomposed into quadrupolar and dipolar contributions.

The observability of polarization modes depends on the gravitational-wave detector network, the intrinsic parameters of the compact binary system, and the inclination of the source. By implementing the frequency-domain waveform model of Ref. [1] in a Python code, I investigate how the optimal signal-to-noise ratio of the purely tensor and scalar-tensor gravitational-wave signals varies with the inclination angle of the source. Furthermore, by extending the waveform model of Ref. [2] with scalar polarizations, we demonstrate through spectrogram and Q-transform representations that the dipolar scalar polarization evolves at half the frequency of the quadrupolar tensor and scalar polarizations. The dipolar scalar polarization becomes visibly distinguishable from the quadrupolar scalar contribution and the quadrupolar polarizations predicted by general relativity at sufficiently low frequencies.

My results indicate that the presence of scalar polarizations produces observable deviations in gravitational-wave signals in the low-frequency regime inaccessible to current LIGO–Virgo detectors, for suitable detector sensitivities and for sufficiently inclined systems ($\gtrsim 40^\circ$). Through detailed simulations of gravitational-wave signals, I prove that although the quadrupolar tensor radiation is always dominant across inclinations, the presence of scalar polarizations raises the optimal signal-to-noise ratio near edge-on inclinations, potentially bringing it above the minimum threshold for observability. By visualizations of simulated low frequency gravitational-wave signals, we show that the dipolar scalar polarization appears as a distinct feature separated from the quadrupolar polarizations on spectrogram and Q-transform representations. These results reveal a potential new method for testing general relativity with the third-generation Einstein Telescope gravitational-wave observatory currently under development in Europe.

[1] H. Imafuku, H. Takeda, A. Nishizawa, D. Watarai and K. Cannon, Statistical biases in parametrized searches for gravitational-wave polarizations, *Phys. Rev. D* **112** (2025), 024028.

[2] C. Cutler, É. E. Flanagan, Gravitational waves from merging compact binaries: How accurately can one extract the binary's parameters from the inspiral waveform?, *Phys. Rev. D* **49** (1994), 2658.