Nonlinear Curvature Effects in GWs from Inspiralling Black Holes

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Take Home Point

For a generic class of beyond GR theories, we now have the forward modelling of GWs which allows us to test, for the first time, the effect of possible curvature nonlinearities: a step beyond theory-agnostic tests of gravity

Why Scalar Gauss-Bonnet (sGB) theories?

Effective Action with Quadratic Curvature Terms

$$I = \int \frac{d^4x\sqrt{-g}}{16\pi}\left(R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + \alpha f(\varphi)\mathcal{R}^2_{\rm GB}\right)$$

$$\mathcal{R}^2_{\rm GB} = R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$$

Simplest, well-behaved extension to strong-field effective action of gravity

(Stelle ’77, Gross & Sloan ‘87 , Kovacs 2021)

Violation of the No-hair Theorem, dynamical and spontaneous scalarization of black holes

…testable features with gravitational waves

Limitations of current tests

- **Current tests of gravity:** Theory-agnostic, parametrized tests against GR
- **Specific mapping to sGB** theory parameters (Carson & Yagi '20) :

Limited to the Newtonian-order modelling of inspiral waveform

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Sensitive only to the effect of the scalar field on the dynamics (e.g. scalar dipole radiation)

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Need to go beyond Newtonian-order to constrain the non-linear curvature corrections

GW Event	Coupling constant $\sqrt{\alpha}$ [km]
GW170608	2.29
GW151226	2.76
GW150914	17.16
GW170729	28.71

Forward Modelling: computing new ready to implement gravitational waveforms

- **Inspiral waveform and phasing:** : post-Newtonian approach (Will & Wiseman '96)

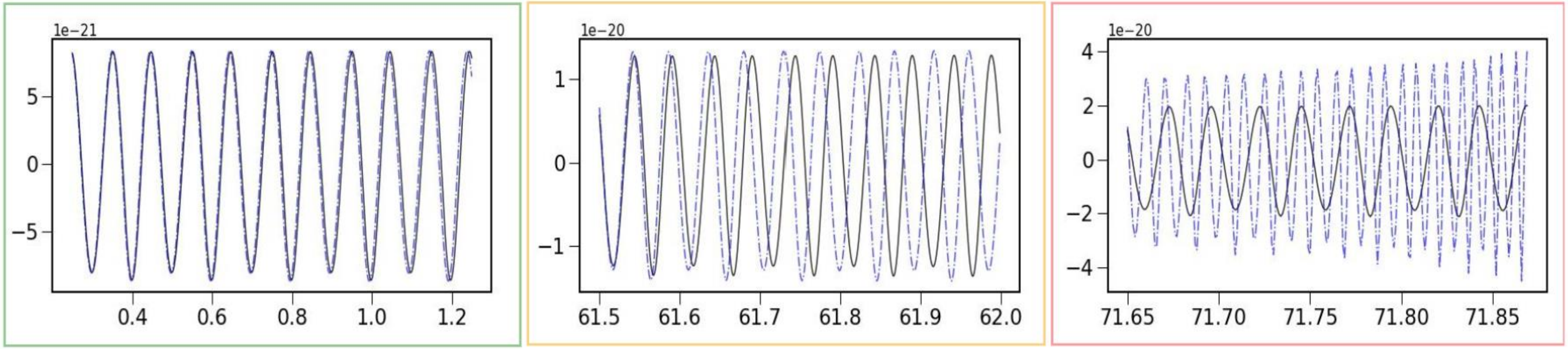
$$\psi = \phi - \phi_0 \qquad h^{\mu\nu} \equiv \mathfrak{g}^{\mu\nu} - \eta^{\mu\nu}$$

$$\Box_\eta \psi = -\frac{8\pi G}{c^4}\tau_s \qquad \Box_\eta h^{\mu\nu} = \frac{16\pi G}{c^4}\tau^{\mu\nu}$$

$$f'(\phi_0)\nabla_{ad}\delta\phi\Big(-4\eta^{\alpha e}\eta^{df}\partial_f\partial_e h^{a\beta} + 4\eta^{\alpha d}\eta^{ef}\partial_f\partial_e h^{a\beta} + 4\eta^{\alpha e}\eta^{\beta f}\partial_f\partial_e h^{ad} - 2\eta^{a\beta}\eta^{\alpha d}\eta^{ef}\eta_{gh}\partial_f\partial_e h^{gh} + ...\Big) + \mathcal{O}(h^2\delta\phi^2)$$

Higher-curvature terms start at 1 post-Newtonian order, and are now computed for the ready-to-implement gravitational waveforms

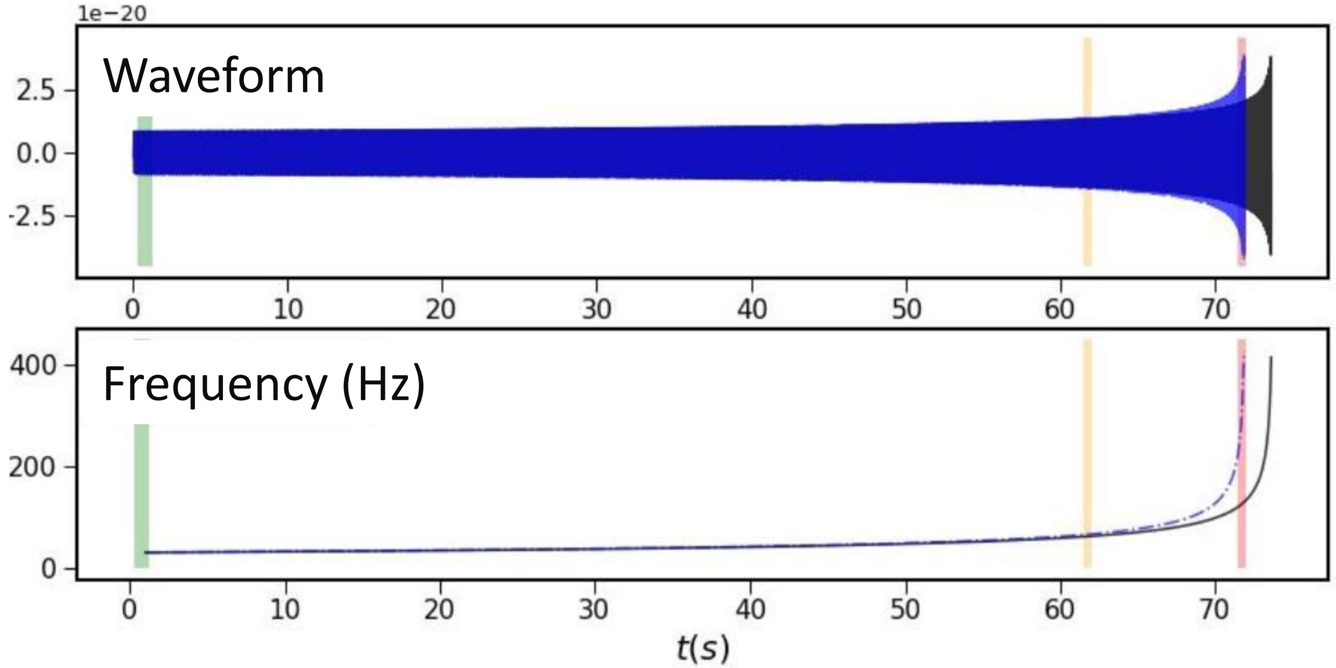
Results: testable deviations from GR



(within current bounds)

$\alpha = 6.75\ (km)^2$

Total mass: 15 M_{sun}
mass ratio: 1/2



Blue: This work
Black: GR

arXiv: 2012.09162

Conclusions and Prospectives

For a generic class of beyond GR theories, we now have the forward modelling of GWs which allows us to test, for the first time, the effect of possible curvature nonlinearities: a step beyond theory-agnostic tests of gravity

Next step to connect with GW observations:

- Testing waveforms against current GW data
- Complete analytical + numerical relativity waveform templates