Inspiral-merger-ringdown waveforms in Einstein-scalar-Gauss-Bonnet gravity within the effective-one-body formalism

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Motivation: tests of GR with gravitational waves

Gravitational waves (GWs) from coalescing binary systems allow us to test Einstein's theory of general relativity (GR) in the strong-field regime.

Theory-independent tests: modify GR waveform models by introducing generic, parameterized deviations or look for consistency between the signal and the data.

- ✓ Can, in principle, constrain a wide range of alternative theories.
- ✗ No guarantee that parameterized deviations represent waveforms in actual beyond-GR theories.
- ✗ Degeneracies complicate constraining several deviation parameters simultaneously.

Theory-specific tests: predict waveforms in a particular alternative theory of gravity and estimate the underlying physical parameters of the theory from GW data.

Abbott+, 2112.06861 (2021)

Motivation: Einstein-scalar-Gauss-Bonnet gravity

In this work, we provide the first example of an inspiral-merger-ringdown waveform model in a beyond-GR theory, focusing on Einstein-scalar-Gauss-Bonnet (EsGB) gravity.

$$\mathrm{S}_{\mathrm{EsGB}} = \int d^4x\sqrt{-g}\left(\frac{1}{16\pi}R - \frac{1}{2}(\nabla\varphi)^2 + \alpha_{\mathrm{GB}}f(\varphi)R^2_{\mathrm{GB}}\right)$$

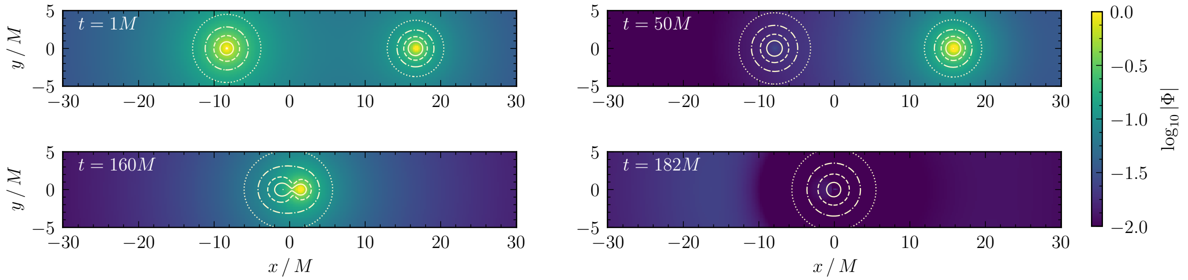
- Massless scalar field φ
- Gauss-Bonnet scalar $R^2_{\mathrm{GB}} = R^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} - 4R^{\mu\nu}R_{\mu\nu} + R^2$
- Fundamental length $\sqrt{\alpha_{\mathrm{GB}}}$ and dimensionless function $f(\varphi)$ that define the theory

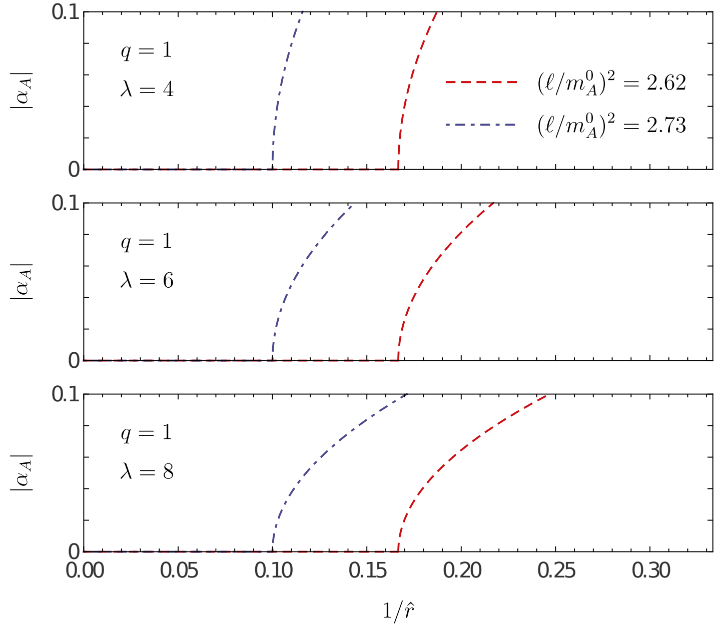
Among the simplest modifications of GR, arising from an effective field theory perspective and in the low-energy limit of string theory, subclass of Horndeski theory.

Gross and Sloan, Nucl. Phys. B 291, 41-89 (1987); Kobayashi, Rept. Prog. Phys. 82, 8, 086901 (2019)

Motivation: Einstein-scalar-Gauss-Bonnet gravity

Black-hole (BH) solutions with scalar "hair" and a rich phenomenology (e.g. "spontaneous" or "dynamical" "(de)scalarization" of BH systems).





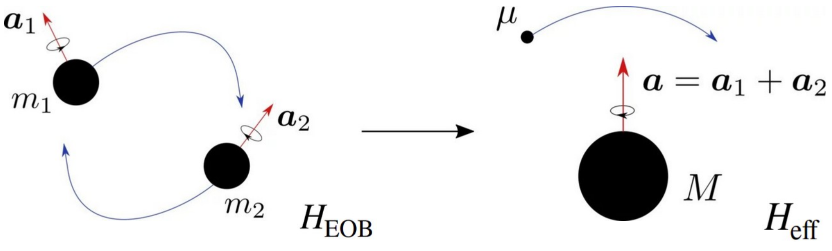
Credit: Silva+, PRL 127, 031101 (2021); Julié, arXiv:2312.16764 (2023)

Doneva and Yazadjiev, PRL 120, 131103 (2019); Silva+, PRL 120, 131104 (2018); Silva+, PRL 127, 031101 (2021); Julié, 2312.16764 (2023)

Effective-one-body waveforms in GR

The effective-one-body (EOB) formalism maps the dynamics of a compact binary to that of a test particle in a deformed BH background, with the deformation parameter being the symmetric mass ratio ν.

We extend the EOB waveform model for BBHs SEOBNRv5PHM.



- Inspiral-plunge: combine and resum information from analytical approximation methods.

$$H^{\rm EOB} = M\sqrt{1 + 2\nu\left(\frac{H_{\rm eff}}{\mu} - 1\right)}$$

$$\mathcal{F} = \frac{\Omega^2}{8\pi}\sum_{\ell,m} m^2 \left|h_{\ell m}\right|^2$$

$$\dot{\vec{r}} = \frac{\partial H^{\rm EOB}}{\partial \vec{p}}$$

$$\dot{\vec{p}} = -\frac{\partial H^{\rm EOB}}{\partial \vec{r}} + \vec{\mathcal{F}}$$

$$h_{\ell m}^{\text{insp-plunge}} = h_{\ell m}^{\rm Newt}\, S_{\ell m} T_{\ell m} e^{i\delta_{\ell m}} \left(\rho_{\ell m}\right)^{\ell}$$

Notation

$M = m_A + m_B$

$q = m_A/m_B \geq 1$

$\mu = m_A m_B/M$

$\nu = \mu/M$

- Merger-ringdown: physically motivated ansatz calibrated to numerical-relativity (NR) simulations and BH perturbation theory.

Buonanno and Damour, PRD 59, 084006 (1999), PRD 62, 064015 (2000); Pompili+, PRD 108, 124035 (2023); Ramos-Buades+, PRD 108, 124037 (2023)

EsGB corrections: inspiral-plunge

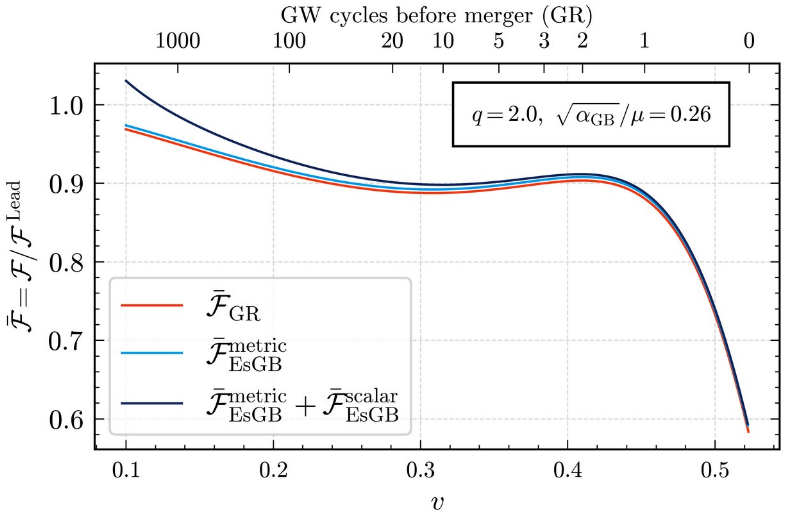
- EOB Hamiltonian: non-spinning corrections up to 3PN in EsGB and scalar-tensor (ST) theories.
- Inspiral waveform modes: non-spinning corrections up to 2PN to $\rho_{\ell m}, \delta_{\ell m}$, recast in the EOB factorization.
- Effective gravitational constant ($\alpha_i = -Q_i/m_i$, where Q_i are the BHs' scalar charges):

$$\frac{GM}{r} \to \frac{G_{AB}M}{r}, \quad v = (GM\Omega)^{1/3} \to (G_{AB}M\Omega)^{1/3} \quad \text{where} \quad G_{AB} = G\,(1 + \alpha_A \alpha_B)$$

- Scalar flux up to 1.5PN:

$$\mathcal{F} \to \mathcal{F} + \mathcal{F}_{\rm scalar}$$

  - Dipolar radiation (-1PN) dominant at low frequencies: larger effect for long inspirals.
  - Proportional to $(\alpha_A - \alpha_B)^2$: larger effect for asymmetric binaries and NSBHs ($\alpha_i = 0$ for NSs).

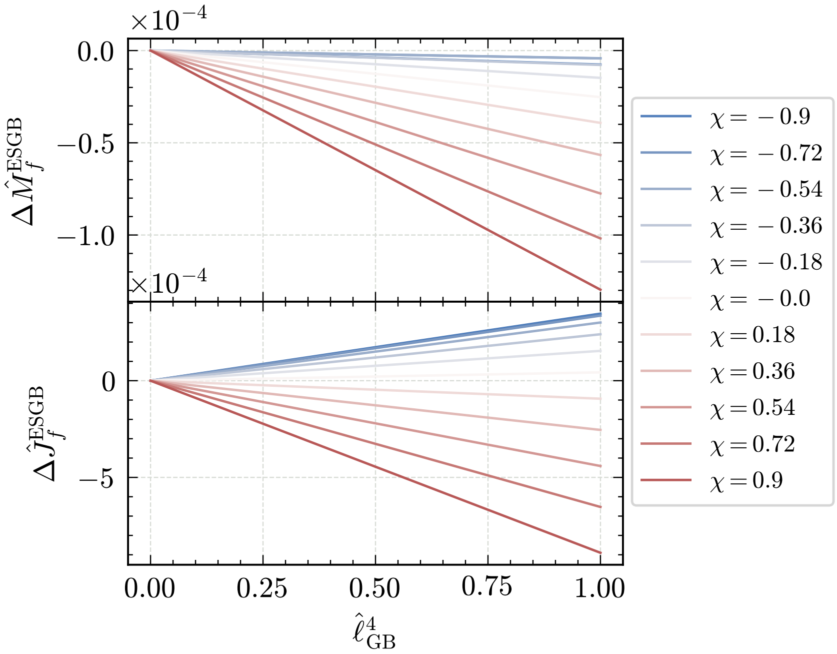


Julié+, PRD 107, 104044 (2023); Jain+ PRD 107, 084017 (2023); Sennett+, PRD 94, 084003 (2016); Bernard+, JCAP 08 008 (2022); Julié+, PRD 105, 124031 (2022)

EsGB corrections: merger-ringdown

- Quasi-normal-mode frequencies $\sigma_{\ell m0}$: corrections accurate up to $\chi_f \simeq 0.8$.
- Final mass and spin: corrections from EOB Hamiltonian and angular momentum at merger.
- Waveform amplitude and frequency at merger: small corrections to be calibrated to NR simulations in EsGB, not yet available in sufficient number.
  - Account for uncertainty in the merger morphology with parameterized deviations, to be marginalized over in parameter estimation.

$$|h_{\ell m}^{\rm NR,GR}| \to |h_{\ell m}^{\rm NR,GR}| \left(1 + \hat{\ell}_{\rm GB}^4 \delta A_{\ell m}\right)$$
$$\omega_{\ell m}^{\rm NR,GR} \to \omega_{\ell m}^{\rm NR,GR} \left(1 + \hat{\ell}_{\rm GB}^4 \delta \omega_{\ell m}\right)$$



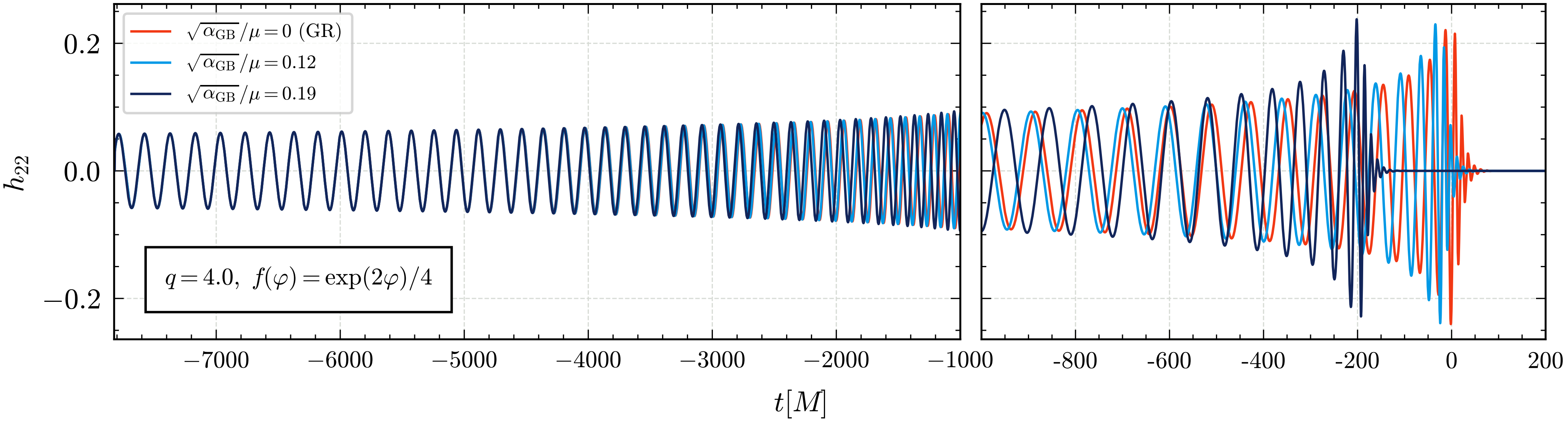
Notation

$$\hat{\ell}_{\rm GB} = 4\pi^{1/4} \frac{\sqrt{\alpha_{\rm GB}}}{\mu}$$

Chung+, 2405.12280 (2024); Maggio+ PRD 108, 024043 (2023)

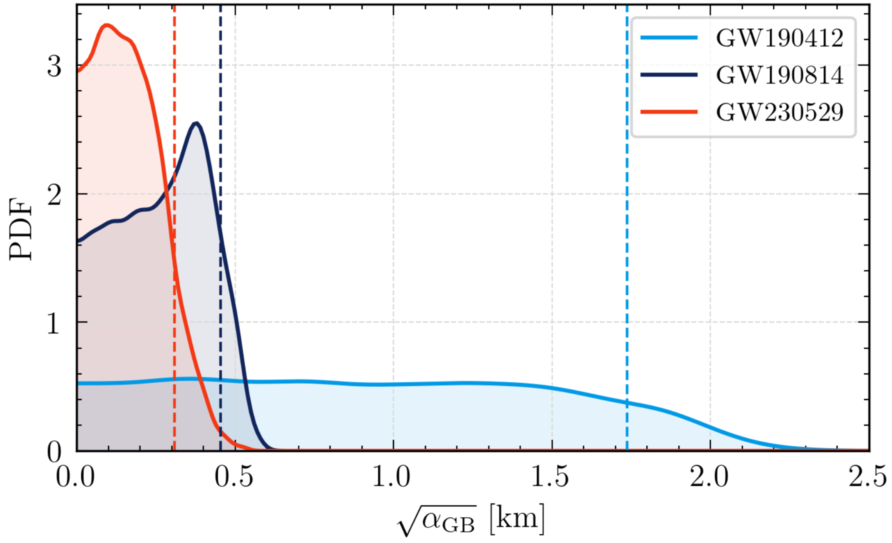
Waveform morphology

- EsGB corrections accelerate the inspiral, mostly due to the additional energy dissipation via the scalar field, and the binary merges earlier in time.
- Corrections to the conservative dynamics are smaller, but not negligible ($\Delta\,\Omega_{\rm ISCO}\,/\,\Omega_{\rm ISCO} \sim 10^{-2}$).
- The effect of QNM corrections is very small ($\Delta\sigma_{\ell m0}/\sigma_{\ell m0} \sim 10^{-4}$).
- Systems with $\sqrt{\alpha_{\rm GB}}/\mu \sim 0.1$ (depending on q and on the SNR) could be distinguished from GR waveforms with LIGO.



Parameter estimation

- We perform parameter estimation on the events GW190412, GW190814 and GW230529 with `parallel bilby`, including in the analysis the EsGB coupling $\sqrt{\alpha_{\rm GB}}$ with uniform priors.
- We can place constraints on the coupling of the theory $\sqrt{\alpha_{\rm GB}}$ and perform Bayesian model selection by computing the natural log Bayes factor between the EsGB and GR hypotheses.
- GW230529 poses the current best constraint on EsGB gravity with $\sqrt{\alpha_{\rm GB}} \leq 0.31$ km (90% CI).



Event	$\sqrt{\alpha_{\rm GB}}$ (90% CI)	$\ln BF^{\rm EsGB}_{\rm GR}$
GW190412	1.77 km	-0.52
GW190814	0.48 km	-0.02
GW230529	0.31 km	-0.94

Ashton+, AJSS 241, 27 (2019); Smith+, MNRAS 498, 4492 (2020); Lyu+, PRD 105, 064001 (2022); Perkins+, PRD 104, 024060 (2021); Sänger+, 2406.03568 (2024)

Conclusions

- We present the first example of an IMR waveform model in a beyond-GR theory, focusing on EsGB gravity.
- We used our model to place constraints on the coupling of the theory and to perform Bayesian model selection between EsGB and GR. GW230529 currently poses the best constraint with $\sqrt{\alpha_{\rm GB}} \leq 0.31 \text{ km}$ (90% CI).

Future work

- Validation/calibration against NR simulations in EsGB, inclusion of EsGB corrections in the spin sector, effective modeling of dynamical scalarization.
- Forecasts for next-generation GW detectors.

Corman+, PRD 107, 024014 (2023); Aresté Saló+, PRD 108, 084018 (2023); Khalil+, PRD 106, 104016 (2022)