

Black-hole binaries in scalar Gauss–Bonnet gravity

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HW, L. Gualtieri, P. Pani, T. P. Sotiriou [arXiv:1810.05177]

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Why scalar Gauss–Bonnet gravity?

action in quadratic gravity (e.g. Kanti et al '95, Alexander & Yunes '09, Yunes & Siemens '13, ...)

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left({}^{(4)}R + 2\alpha_{\text{GB}} f(\Phi) \mathcal{R}_{\text{GB}} + \alpha_{\text{CS}} h(\Psi) {}^*R R - \frac{1}{2}(\nabla\Phi)^2 \right)$$

with $\mathcal{R}_{\text{GB}} = R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$ and $f(\Phi) \sim e^\Phi$

High-energy physics

- higher curvature corrections relevant in strong-curvature regime
- low-energy limit of some string theories

(Gross & Sloan '87, Kanti et al '95, Moura & Schiappa 06)

- compactification of Lovelock gravity

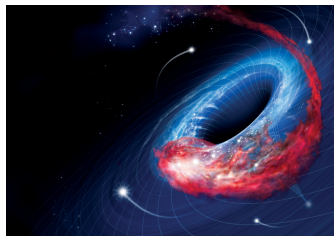
(Charmousis '14)

- representative for more involved theories

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¹see Okounkova et al '17 for parity violating (dynamical Chern-Simons) sector

²use geometric units $c = 1 = G$

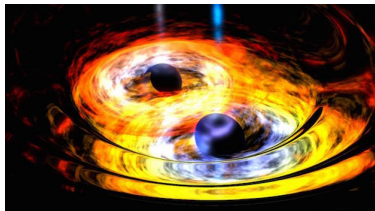


Black holes in scalar GB gravity

- black holes have scalar hair (of the second kind)!

(Kanti et al '95, Pani et al '09, '11, Stein et al '11, Sotiriou & Zhou '14, Ayzenberg & Yunes '14, Maselli et al '15, ...)

- black holes can exceed the Kerr bound (Kleihaus et al '11, '14)
- scalar hair forms dynamically (Benkel et al '16, Witek et al '18)



Black hole binaries:

- scalar dipole radiation
⇒ shift in binding energy
⇒ shift in orbital frequency
- ringdown signature?
- effects in nonlinear regime?

Observational bounds on scalar GB gravity

Observational (BH) constraints on coupling

- regular BH horizons & lightest observed BHs $M \sim 5M_{\odot}$: $\sqrt{|\alpha_{\text{GB}}|} \lesssim 7\text{km}$
- x-ray binary *A0620-00*: $\sqrt{|\alpha_{\text{GB}}|} \lesssim 10\text{km}$ (Yagi '12)
- inspiral of *GW151226*: $\sqrt{|\alpha_{\text{GB}}|} \lesssim 27\text{km}$ (Yagi, Yunes & Pretorius '16)
- here: inspiral + merger of *GW151226*: $\sqrt{|\alpha_{\text{GB}}|} \lesssim 3\text{km}$ (Witek, Gualtieri, Pani & Sotiriou '18)

scalar GB gravity as effective field theory

- Field equations

$$G_{ab} = \frac{1}{2} T_{ab}^{\Phi} - \alpha_{\text{GB}} \mathcal{G}_{ab}^{\text{GB}}, \quad \square \Phi = -2\alpha_{\text{GB}} f'(\Phi) \mathcal{R}_{\text{GB}}$$

with $\mathcal{R}_{\text{GB}} = R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$ and, typically, $f(\Phi) \sim e^{\Phi}$

- recall: well-posed initial value formulation necessary for *numerical stability*
- EFT-type expansion in coupling $\epsilon = \alpha_{\text{GB}}/\ell^2 \ll 1$

$$\epsilon^0: \quad G_{ab}^{(0)} = \frac{1}{2} T_{ab}^{(0)}, \quad \square^{(0)} \Phi^{(0)} = 0 \quad \Rightarrow \quad (g_{ab}^{(0)}, \Phi^{(0)}) = (g_{ab}^{\text{GR}}, 0)$$

$$\epsilon^1: \quad G_{ab}^{(1)} = 0, \quad \square^{(0)} \Phi^{(1)} = -f' \mathcal{R}_{\text{GB}}^{(0)} \quad \Rightarrow \quad (g_{ab}^{(1)}, \Phi^{(1)}) = (0, \Phi^{(1)})$$

$$\epsilon^2: \quad G_{ab}^{(2)} = \frac{1}{2} T_{\text{eff}}^{(0)}(g_{ab}^{(0)}, \Phi^{(1)}), \quad \square^{(0)} \Phi^{(2)} = -8M^2 f'_{(1)} \mathcal{R}_{\text{GB}}^{(0)}$$

- structure applicable to theories with EFT-type expansion (see, e.g., Okounkova et al '18)
- pathway to “parametrized NR”?

Numerical implementation

- EFT approach up to $\mathcal{O}(\epsilon)$
⇒ evolve scalar field & GR background simultaneously
- implemented in EINSTEIN TOOLKIT & CANUDA

(<https://bitbucket.org/canuda/>)



einsteintoolkit.org

GR code – ETK & Canuda

ADMBase
defines metric gfs

TwoPunctures
metric initial data

McLachlan or Canuda-Lean
metric evolution

AHFinderDirect,
WeylScal4 or Canuda-NPScalars

Multipole

sGB code – Canuda

EdGB_Base
defines scalar gfs

EdGB_Init
scalar field initial data

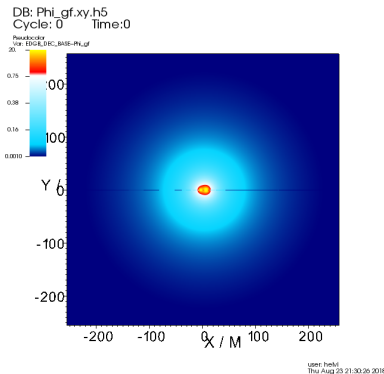
EdGB_Evol
scalar field evolution

Numerical simulations in sGB

Setup

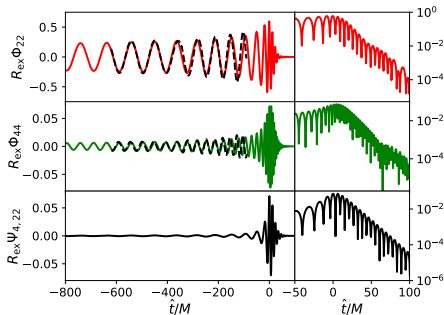
- $\epsilon^{(0)}$: non-spinning BH binary with $d/M = 10$ and mass-ratios $q = m_1/m_2 = 1, 1/2, 1/4$
- $\epsilon^{(1)}$: zero initial scalar field or superposition of solutions

Scalar field evolution

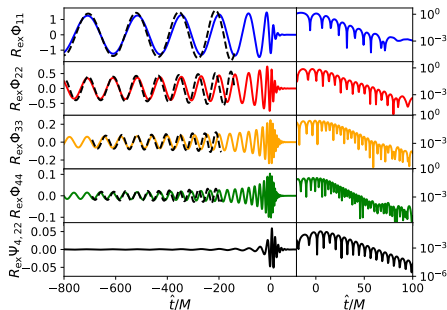


Scalar radiation

$$q = 1$$



$$q = 1/2$$



- early inspiral: agreement with PN prediction (Yagi et al '11)
- modulated ringdown (frequency domain so far only for Schwarzschild!)
 - superposition of scalar-led and gravitational-led modes
 - quality factors different for pure Kerr and Kerr + GWs

Validity of EFT-type approach

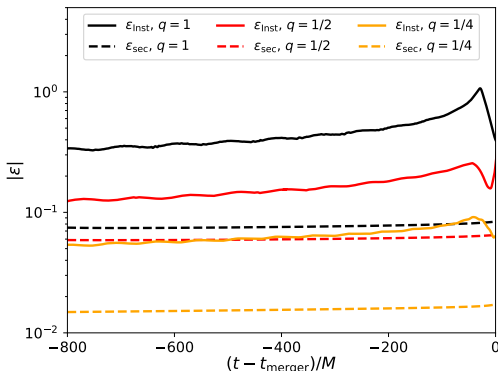
estimate second order effects: $G_{ab}^{(2)} = \frac{1}{2} T_{ab}^{\text{eff}} \left(g_{ab}^{(0)}, \Phi^{(1)} \right)$

Instantaneous validity

- compare energy fluxes
- $|\epsilon_{\text{Inst}}| \lesssim \sqrt{2 \frac{\dot{E}^{\text{GW}}}{\dot{E}^{(2)}}}$

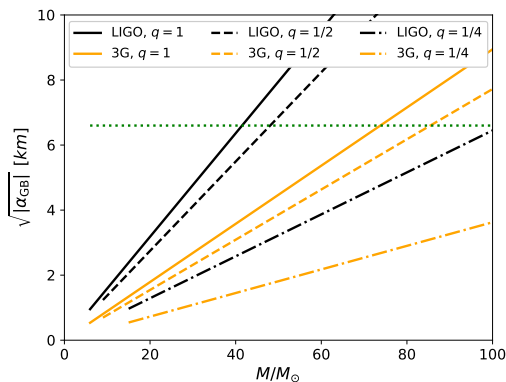
Secular effects

- compare phase evolution
- $|\epsilon_{\text{Sec}}| \lesssim \sqrt{2 \frac{\phi^{(0)}(t)}{\phi^{(2)}(t)}}$ with $\phi^{(k)} = \int dt \Omega^{(k)}$



Observational constraints

non-detection of dephasing $\Rightarrow$ bound on GB coupling: $|\epsilon| = \left| \frac{\alpha_{\text{GB}}}{4M^2} \right| \lesssim \sqrt{\frac{\Delta\phi_{\text{det}}}{\phi^{(2)}}}$



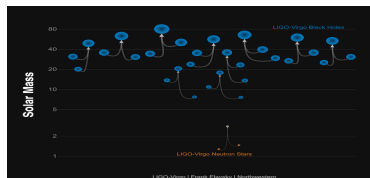
- e.g.: GW151226-type system: $\alpha_{\text{GB,LIGO}} \lesssim 2.7\text{km}$ $\alpha_{\text{GB,3G}} \lesssim 1.5\text{km}$
 $\Rightarrow$ 2 – 4 times better than existing constraints
- bounds improve for smaller-mass systems & smaller mass ratio

Summary and Outlook

Summary and Outlook I

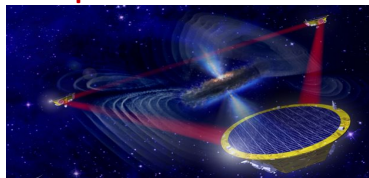
- GWs as new observational channel for beyond-standard model physics

Groundbased detectors



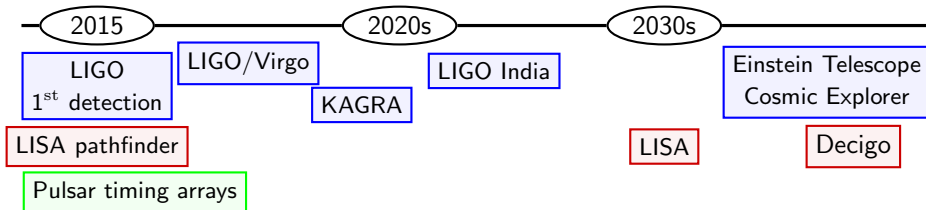
<https://dcc.ligo.org>

Spacebased detectors



Laser Interferometer Space Antenna – artistic impression

- new estimates:
 $10 - 100 \text{ events } \text{Gpc}^{-3} \text{y}^{-1}$
- consider joining Waveform WG
wav-wg@lisamission.org



Summary and Outlook II

- BUT: limited by our lack of knowledge of the merger phase in beyond-GR
⇒ need novel analytic & numerical methods to model waveforms
- here: first binary black hole evolutions in sGB
 - numerical infrastructure publicly available in CANUDA
 - most stringent observational bounds so far
 - improvement for 3G detections (smaller mass with higher SNR)
- next steps to connect theories with observations
 - ⇒ towards “parametrized” NR within perturbative expansion
 - ⇒ complete waveforms (PN+NR+perturbations)
 - ⇒ inform parametrized waveform model building
 - ⇒ more detailed analysis and comparison with observations

Thank you!

acknowledgements:



On hairy black holes in EdGB

Proving hairy-ness in shift-symmetric Horndeski gravity – an outline

(Hui & Nicolis '12; Sotiriou & Zhou '13, '14, Maselli et al '15)

- vacuum, static, spherically symmetric, asymptotically flat spacetimes

$$ds^2 = A(r)dt^2 + B(r)^{-1}dr^2 + r^2d\Omega^2$$

- shift-symmetry $\Phi \rightarrow \Phi + c \Rightarrow \exists$ conserved current $\nabla_a J^a = 0$

① assume $\Phi = \Phi(r) \rightarrow$ only $J^r \neq 0$

② regularity of norm $J^a J_a = \frac{(J^r)^2}{B}$ @ $r = r_h$ and $B|_{r_h} = 0$
 $\Rightarrow J^r|_{r_h} = 0$

③ conservation eq. $\nabla_a J^a = \partial_r J^r + 2\frac{J^r}{r} = 0 \Rightarrow J^r r^2 = c$
(ii) implies $c = 0 \Rightarrow J^r = 0 \quad \forall r$

④ schematically $J^r = B\Phi'F(g, g', g'', \Phi')$ (Hui & Nicolis '12)

- asymptotic flatness implies $\lim_{r \rightarrow \infty} B = 1$, $\lim_{r \rightarrow \infty} \Phi' = 0$, $F = k \neq 0$
- if $\Phi' \neq 0$ for r finite: contradiction to $J^r = 0 \Rightarrow \Phi' = 0 \quad \forall r$
 $\Rightarrow \Phi = \Phi_0 = 0$

⑤ **loophole in EdGB:** (Sotiriou & Zhou '13, '14)

- then $J^r = -B\Phi' - 4\alpha_{\text{GB}} \frac{A'}{A} \frac{B(B-1)}{r^2} = 0 \Rightarrow \Phi'$ can be non-trivial
- scalar charge P depends on BH mass $M \Rightarrow$ "hair of second kind"