The adventures of black holes: The case of quadratic gravity

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H.O. Silva, **HW** , M. Elley, N. Yunes [arXiv:2012.10436]
B. Shiralilou, T. Hinderer, S. Nissanke, N. Ortiz, **HW** [arXiv:2012.09162]

Gravitational scattering, inspiral, and radiation, GGI Florence, 30 April 2021

Nature's mysteries

High-energy physics
Quantum gravity

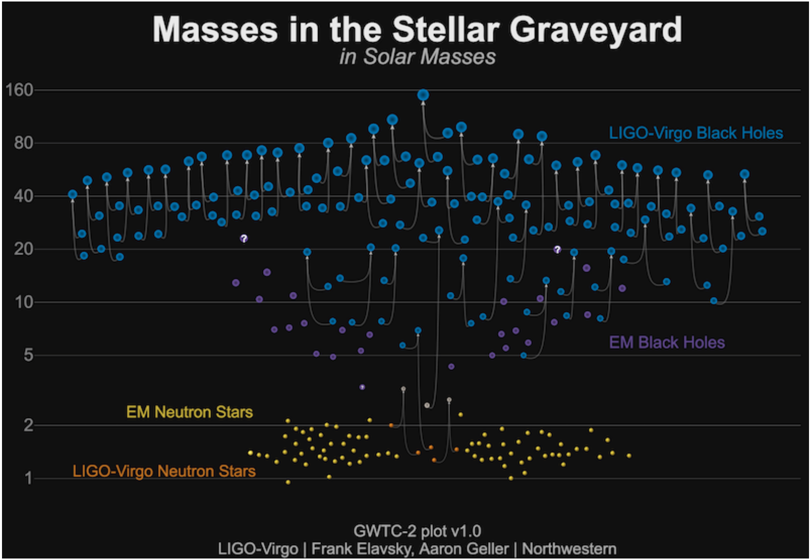
- Beyond-standard model particle physics
- Extensions of general relativity
- Test general relativity in new regimes

Cosmology
Dark energy

Particle physics
Dark matter

Black holes and gravitational waves as "gravity detectives" for new physics

We have data!



(LVC '20)

Do we have theories?

Yes, plenty . . .

But:
Lack concrete obversable predictions

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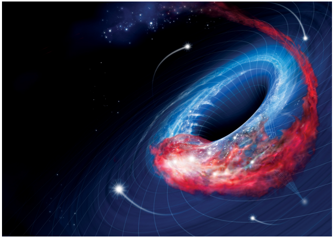
A concrete class of theories:

Scalar Gauss–Bonnet gravity (aka "curvature^2")

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)



Scalar Gauss–Bonnet gravity in a nutshell

Action

$$S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left(R + \frac{\alpha_{\rm GB}}{4} f(\Phi) \mathscr{G} - \frac{1}{2} (\nabla\Phi)^2 \right)$$

- Gauss–Bonnet invariant: $\mathscr{G} = R_{abcd} R^{abcd} - 4 R_{ab} R^{ab} + R^2$
- Coupling function $f(\Phi)$ selects subclass (Antoniou et al'17)

Type I:

- $f'(\Phi_0) \neq 0$
- E.g.: $f \sim \Phi$, $f \sim \exp(\Phi)$
- hairy black holes

Type II:

- $f'(\Phi_0) = 0$
- E.g.: $f \sim \Phi^2$, $f \sim \exp(\Phi^2)$
- spontaneous scalarization

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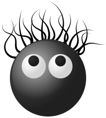
Type I: Hairy black holes

- Coupling function $f'(\Phi_0) \neq 0$
- Examples: shift-symmetric $f \sim \Phi$, dilatonic $f \sim \exp(\Phi)$
- Scalar field equation for shift-symmetric coupling

$$\Box\Phi = -\frac{\alpha_{\rm GB}}{4} f'(\Phi)\mathscr{G} = -\frac{\alpha_{\rm GB}}{4}\mathscr{G}$$

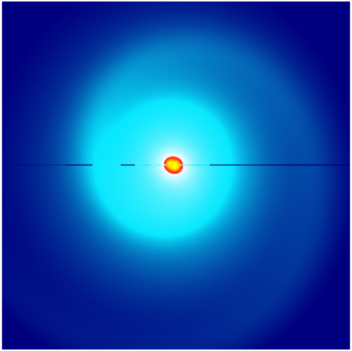
- Black holes always have scalar hair
(Kanti et al '95, Torii et al '96, Pani et al '09, '11, Yunes & Stein '11, Sotiriou & Zhou '14, Ayzenberg & Yunes '14, Maselli et al '15, ...)
- Black holes can exceed the Kerr bound (Kleihaus et al '11, '14)
- Scalar hair forms dynamically (Benkel et al '16, Witek et al '18, Ripley & Pretorius '19)



Type I: Black hole binary dynamics

- Evolution of hairy black holes ⇒ scalar dipole radiation
- implemented in EINSTEIN TOOLKIT & CANUDA
  https://bitbucket.org/canuda/ (Witek, Zilhão, Elley, Ficarra, Silva '20)

einsteintoolkit.org
CANUDA

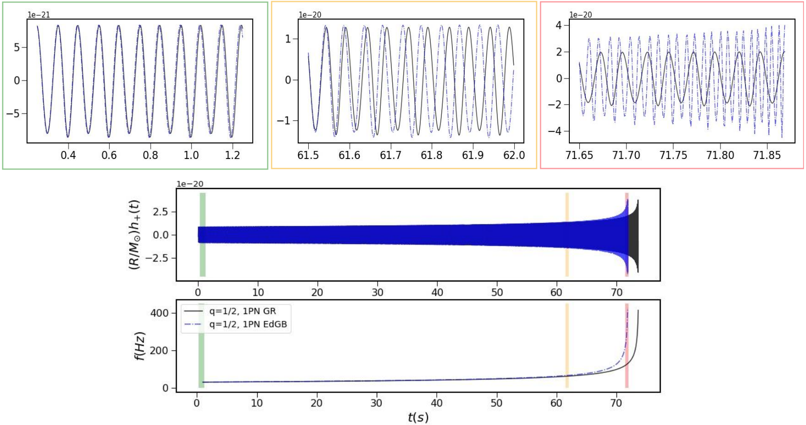


(Binary with $q = 1/2$, $M = 1$, decoupling) (**HW**, Gualtieri, Pani, Sotiriou '19)

(Recent progress of NR in quadratic gravity: sGB: Witek et al '18, '20; Okounkova '20; East & Ripley '20; dCS: Okounkova et al '17 - '19)

Type I: Black hole binary dynamics – inspiral

- Energy fluxes from post-Newtonian approach for small $\alpha_{\rm GB}/M^2 \ll 1$ (Yagi et al '11)
- Two-body Lagrangian and sensitivities up to $\mathcal{O}((\alpha_{\rm GB}/M^2)^4)$ (Julié & Berti '19)
- Gravitational waveforms for general coupling (Shiralilou et al '20)



(Binary with $q = 1/2$, $M = 15M_\odot$, $\alpha_{\rm GB}/M^2 = 0.03$) (Shiralilou, Hinderer, Nissanke, Ortiz, **HW** '20)

Type II: Spontaneous black hole scalarization

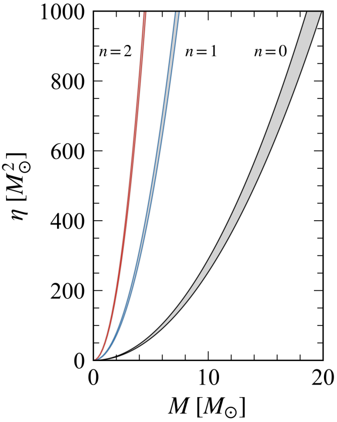
- Coupling function $f'(\Phi_0) \sim \Phi^2$
- Scalar field equation

$$0 = \Box\Phi + \frac{\eta}{4} f'(\Phi_0)\mathscr{G} = \left(\Box - m_{\rm eff}^2\right)\Phi$$

- GR solutions exist if $f'(\Phi_0) = 0$
- Kerr solution is unique iff $m_{\rm eff}^2 \sim -f''(\Phi)\mathscr{G} > 0$
- tachyonic instability if $m_{\rm eff}^2 \sim -f''\mathscr{G} < 0$

  $\Rightarrow$ spontaneous scalarization of black holes

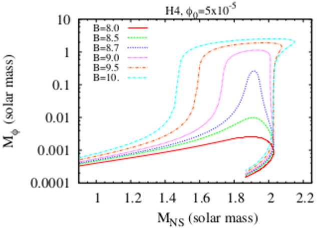
Phase-space of nonlinear solutions



(Silva et al '17)

(Silva et al '17, Doneva et al '17, Antoniou et al '17, Macedo et al '19, Ripley & Pretorius '20)
(Stability of scalarized black holes: Silva et al '19, Blazquez-Salcedo et al '18, '20)
(Spin-induced scalarization: Dima et al '20, Hod '20, Doneva et al '20, Herdeiro et al '20, Berti et al '20)

Interludium: neutron stars in scalar-tensor theories



(Shibata et al '13)

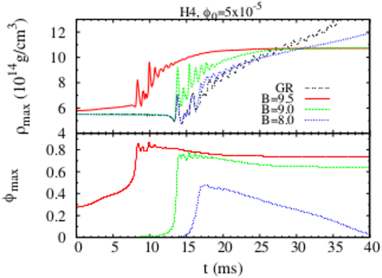
- in scalar-tensor theories

$$\Box\Phi \sim -B\Phi T$$

- isolated neutron stars spontaneously scalarize

Sufficiently compact binary neutron stars:

- dynamical scalarization ($\bar{s} + \bar{s} \to s$)
- induced scalarization ($\bar{s} + s \to s$)



(Shibata et al '13)

(Damour & Esposito-Farése '93, '96; Shibata et al '13; Barausse, Palenzuela, Lehner et al '12, '13; ...
In general EFTs: Khalil et al '19)

Type II: Black hole head-on collisions

- first study in decoupling limit (Silva, Witek, Elley, Yunes '20)
- background: head-on collisions and inspiralling black holes
- remain scalarized or **dynamical descalarization**

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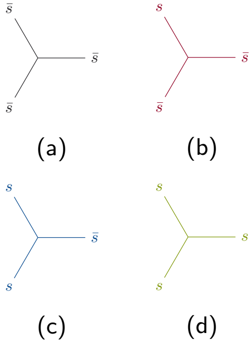
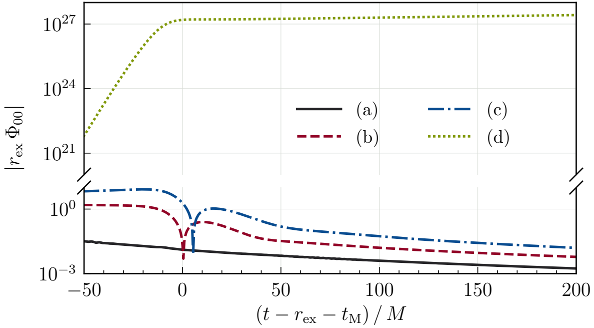


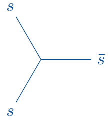


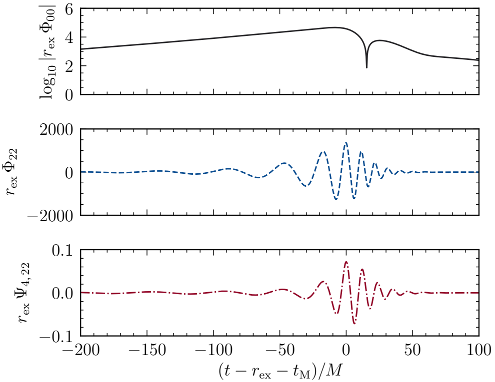
Website: `https://bhscalarization.bitbucket.io/`

Youtube channel: `https://www.youtube.com/channel/UC_417F40VkEyQd48VHkZeDA`

Type II: black hole head-on inspiral

- inspiral with $q = 1$, $M = 2m = 1$, $D = 10M$, $r_{\rm ex} = 50M$
- **dynamical descalarization**





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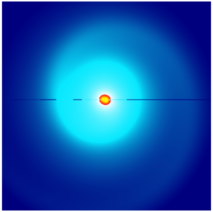
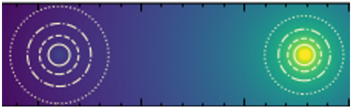
Observational implications

Type I:

- pre-merger: scalar radiation
  $\Rightarrow$ dephasing of gravitational wave
- merger+postmerger: hairy BH $\Rightarrow$ modify ringdown
- observational bound $\sqrt{\alpha_{\rm GB}} \lesssim 1.7$km
  (Yagi '12, Nair et al '19, Wang et al '21, Perkins et al '21)



(**HW**, Gualtieri, Pani, Sotiriou '19)



(Silva, **HW**, Elley, Yunes '20)

Type II:

- unconstrained!
- pre-merger: scalar radiation
  $\Rightarrow$ dephasing of gravitational wave
- merger + postmerger: complete discharging
  - $\Rightarrow$ final object = GR black holes
  - $\Rightarrow$ impact on ringdown?
  - $\Rightarrow$ impact on merger?

Summary and Outlook

Summary

- coupling to higher curvature $\Rightarrow$ hairy or scalarized black holes (similar for dCS gravity)
- pre-merger: scalar radiation and gravitational wave phase shift
- post-merger:
  - Type I: hairy black hole
  - Type II: dynamical **de**scalarization

Outlook

- nonlinear evolution $\Rightarrow$ dynamical scalarization? merger & endstate?
- inspiral $\rightarrow$ rotating black hole $\Rightarrow$ spin-induced scalarization?
- Observational implications
  - quantify phase-shift
  - understand ringdown

Thank you!

On hairy black holes in scalar GB gravity

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

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

- consider vacuum, static, spherically symmetric, asymptotically flat spacetimes

$$\mathrm{d}s^2 = A(r)\mathrm{d}t^2 + B(r)^{-1}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$

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

1. assume $\Phi = \Phi(r) \to$ 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 $\lim_{r\to\infty} B = 1$, $\lim_{r\to\infty} \Phi' = 0$, $F = k \neq 0$
   - 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 sGB: (Sotiriou & Zhou '13,'14)
   - then $J^r = -B\Phi' - 4\alpha_{\mathrm{GB}}\frac{A'}{A}\frac{B(B-1)}{r^2} = 0 \Rightarrow \Phi'$ can be non-trivial
   - scalar charge P depends on BH mass $M \Rightarrow$ "hair of second kind"

back