The adventures of black holes: The case of quadratic gravity

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H.O. Silva, **HW** , M. Elley, N. Yunes [PRL 127 (2021); 2012.10436]
B. Shiralilou, T. Hinderer, S. Nissanke, N. Ortiz, **HW** [PRD 103 (2021); 2012.09162]
B. Shiralilou, T. Hinderer, S. Nissanke, N. Ortiz, **HW** [arXiv:2105.13972]

Workshop I: Computational Challenges in Multi-Messenger Astrophysics,
IPAM / UCLA, 7 October 2021

Nature's mysteries

High-energy physics
Quantum gravity

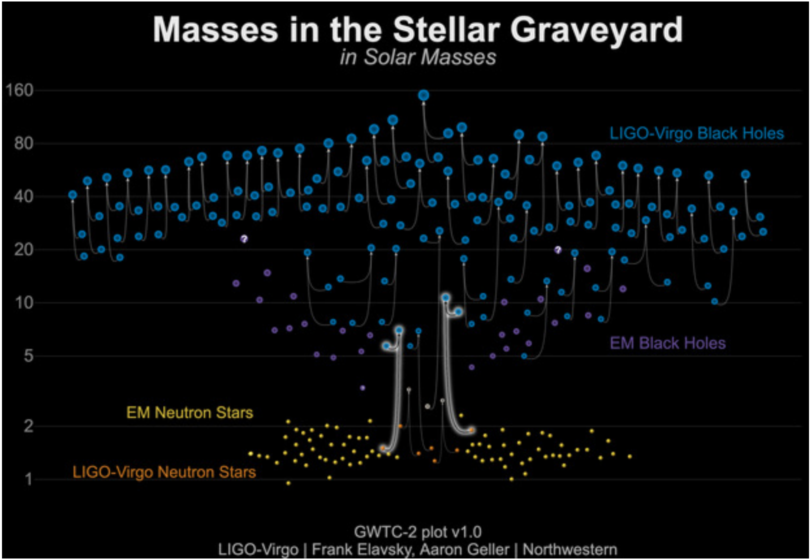
- Beyond-standard model particle physics
- Extensions of general relativity
- Test general relativity in new regimes

Cosmology
Dark energy

Particle physics
Dark matter

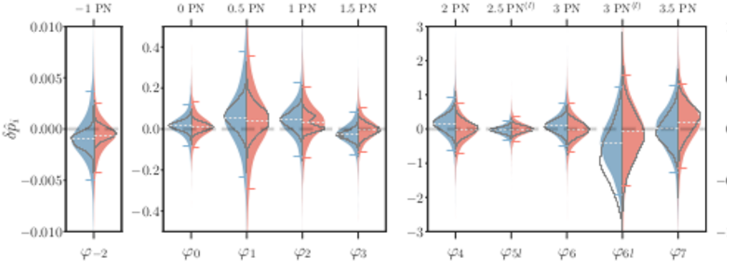
Black holes and gravitational waves as "gravity detectives" for new physics

We have data!



(LVC '21)

Strong field tests of gravity



(LVC Tests of gravity with O1-O3 '20)

Caveats:

- testing null hypothesis "GR"
- vary 1 ppN parameter at a time – consistent?
- match theory-agnostic tests to specific gravity theories?

⇒ need theory-specific modelling *including the merger*

Do we have theories?

Yes, plenty . . .

But:
Concrete obversable predictions?

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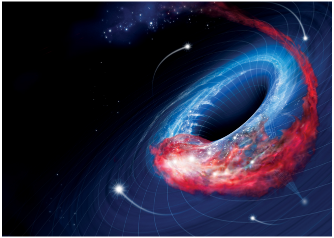
A concrete class of theories:

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)
- representative for theory-class w/ quadratic curvature terms



Scalar Gauss–Bonnet gravity in a nutshell

Action

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

- 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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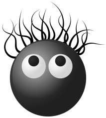
Type I: Hairy black holes

- 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

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

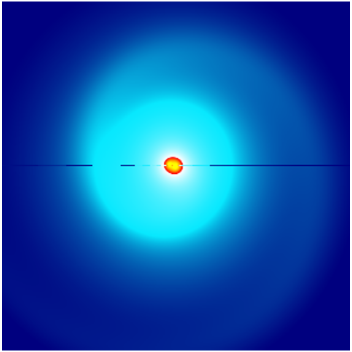
- Black holes always have scalar hair
(Kanti et al '95, Torii et al '96, Pani et al '09, '11, Yunes & Stein '11, Sotiriou & Zhou '14, Ayzenberg & Yunes '14, Maselli et al '15, . . .)
- Black holes can exceed the Kerr bound (Kleihaus et al '11, '14)
- Scalar hair forms dynamically (Benkel et al '16, Witek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



Type I: Black hole binary dynamics – merger

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

einsteintoolkit.org
CANUDA

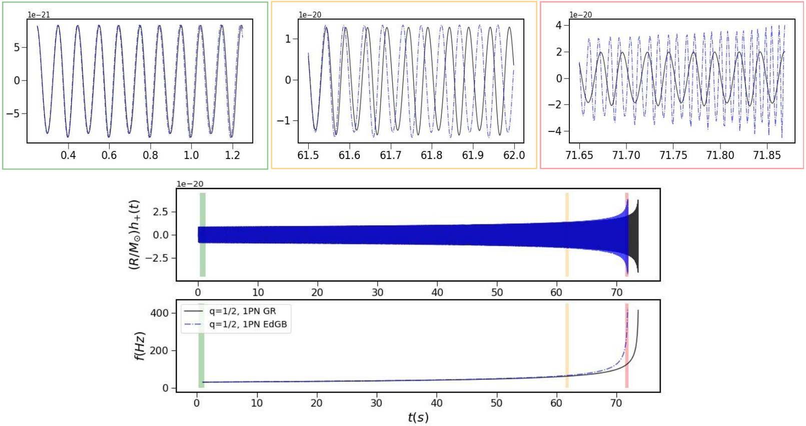


(Binary with $q = 1/2$, $M = 1$, decoupling) (**HW**, Gualtieri, Pani, Sotiriou '19)

(Recent NR in quadratic gravity: sGB: Witek et al '18, '20; Okounkova '20; East & Ripley '20, '21; dCS: Okounkova et al '17 - '19, Rab^2: Held et '21)

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, '21)



(Binary with $q = 1/2$, $M = 15M_\odot$, $\alpha_{\rm GB}/M^2 = 0.03$) (Shiralilou, Hinderer, Nissanke, Ortiz, **HW** '20, '21)

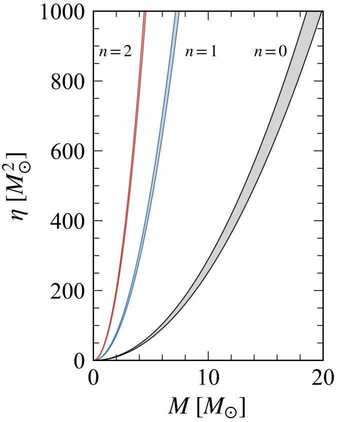
Type II: Spontaneous black hole scalarization

- 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
- rotating black holes: $\mathscr{G} < 0$
  $\Rightarrow$ spin-induced scalarization if $f'' < 0$

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)
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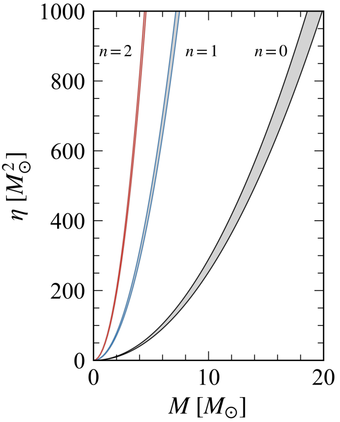

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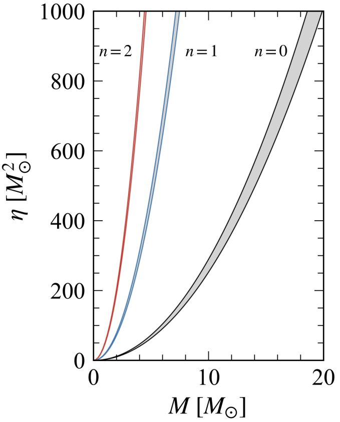

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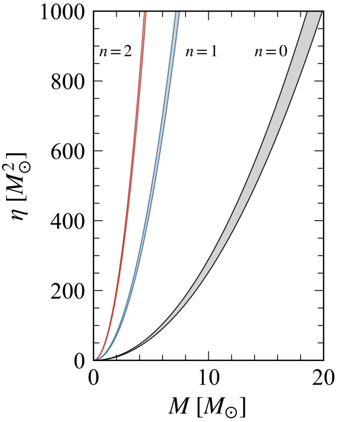

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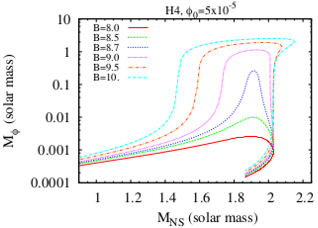
Interludium: neutron stars in scalar-tensor theories



(Shibata et al '13)

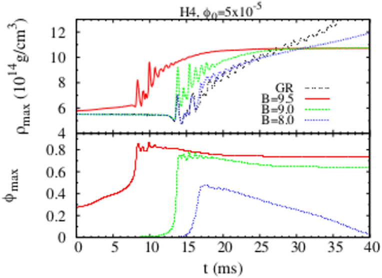
- in scalar-tensor theories

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

- 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, Palenzuela et al '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; also East & Ripley '21)
- background: head-on collisions and inspiralling black holes
- remain scalarized or **dynamical descalarization**

einsteintoolkit.org
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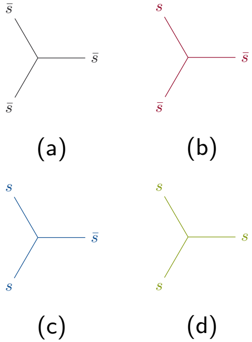
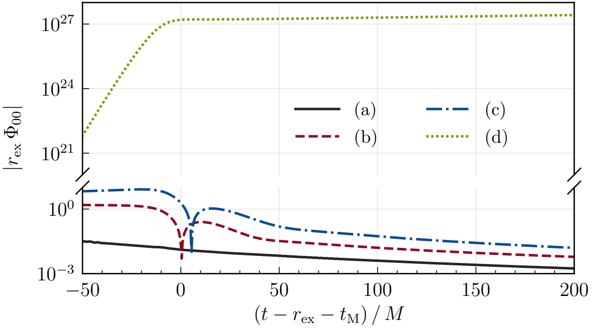




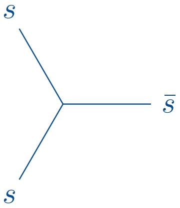
Website: https://bhscalarization.bitbucket.io/

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

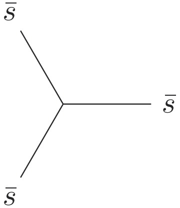
Type II: black hole inspiral (in prep. with M. Elley, H.O. Silva and N. Yunes)

- inspiral with $q = 1$, $M = 2m = 1$, $D = 10M$, vary spin, $r_{\rm ex} = 50M$
- choose negative coupling → spin-induced (de)scalarization

Dynamical desclarization



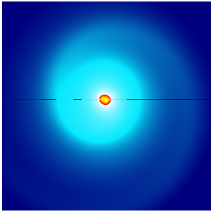
Spin-induced scalarization



Observational implications

Type I: s + s → s

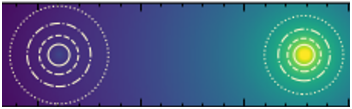
- pre-merger: scalar radiation
  ⇒ dephasing of gravitational wave
- merger+postmerger: hairy BH ⇒ modify ringdown
- observational bound $\sqrt{\alpha_{\rm GB}} \lesssim 1.7$km
  (Yagi '12, Nair et al '19, Wang et al '21, Perkins et al '21)



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

Type II: unconstrained

- s + s → $\bar{s}$ or s + $\bar{s}$ → $\bar{s}$
  - pre-merger: scalar radiation
    ⇒ dephasing of gravitational wave
  - merger + postmerger: discharging
    ⇒ final object = GR black holes
- $\bar{s} + \bar{s} \to s$
  - pre-merger: identical to GR evolution
  - post-merger: spin-induced scalar
  - "hidden" beyond-GR effects



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

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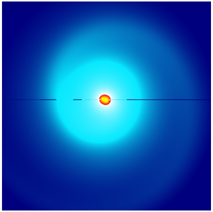

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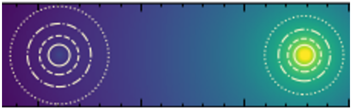

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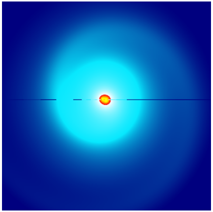

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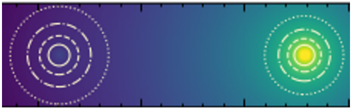

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Summary and Outlook

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
    spin-induced dynamical scalarization
- beyond-GR effects may remain "hidden"

Outlook

- nonlinear evolution $\Rightarrow$ dynamical scalarization? merger & endstate?
- extension to other quadratic theories, e.g., dynamical Chern-Simons
  (in progress with A.Dima and C. Richards)
- Observational constraints

Thank you!

Some advertisement for NR enthusiasts

- NR community calls (initiated by Nils Fischer):
  - every first Monday of the month @ 9am PT / 11am CDT / 6pm CEST
  - `https://github.com/sxs-collaboration/nr-community-call/wiki`

- Workshop: "New frontiers in strong gravity"
  - 3 - 16 July 2022 @ Benasque Science Center (Spain)
- Workshop: "NR-community meetup 2022"
  - mid-August 2022 @ ICERM (Brown University)

Thank you!

ILLINOIS

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