The adventures of black holes: The case of fundamental physics

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11^{th} Iberian Gravitational Wave meeting, 9 June 2021

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Nature's mysteries

High-energy physics
Quantum gravity

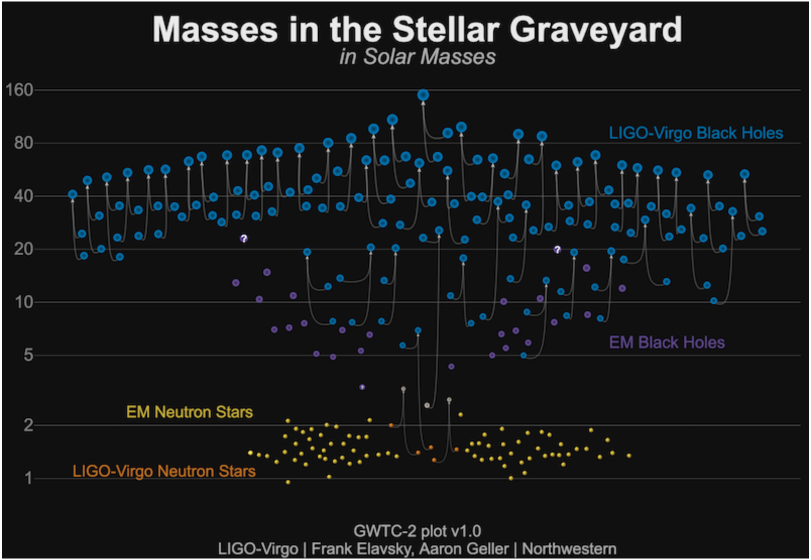
- Probe nuclear matter in neutron star mergers
- Beyond-standard model particle physics
- Strong field tests of gravity

Nuclear theory
Equations of state

Particle physics
Dark matter

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

We have (gravitational wave) data!



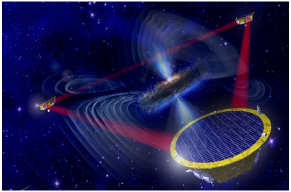
(LVC '15-'20; +KAGRA since 2020)

Present and future of gravitational wave astronomy

Groundbased detectors

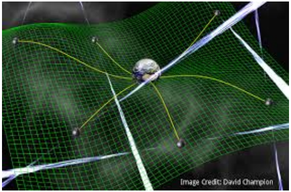
Laser Interferometer Gravitational wave Observatory – Livingston

Spacebased detectors

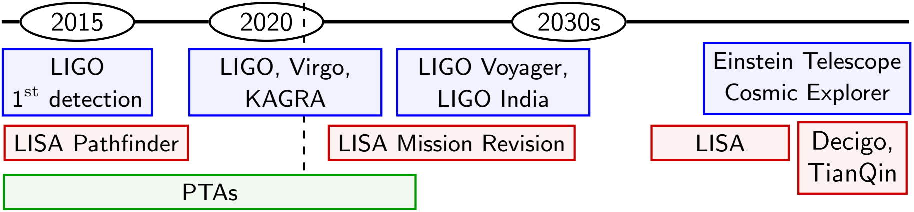


Laser Interferometer Space Antenna

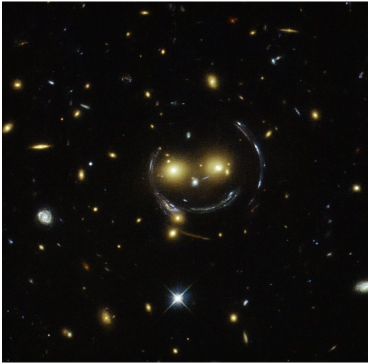
Pulsar-timing arrays



artistic impression



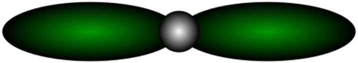
Dark matter?



(credit: Hubble-Space-Telescope)

Example: Black holes as cosmic particle detectors

- superradiant instability
  → formation of bosonic condensates around black holes



Detectors:	PTAs	LISA	Decigo	LIGO/Virgo/KAGRA/3G	
Frequencies:	nHz	mHz	dHz	10Hz - kHz	
M ($M_\odot$):	10^{10}	10^{6}	10^{3}	50	5
μ_S (eV):	10^{-21}	10^{-17}	10^{-14}	10^{-12}	10^{-11}

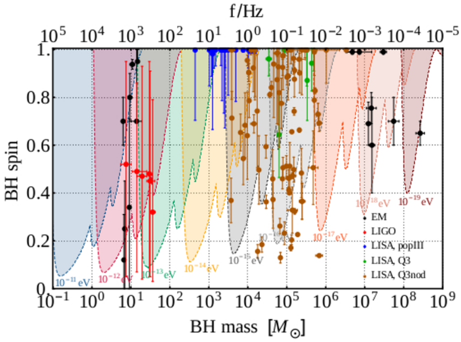
- QCD axion, axion-like particles as dark matter candidates, string axiverse
  (Peccei & Quinn '77, Arvanitaki & Dubovsky '10, '11, Kodama & Yoshino '11, Hui et al '16, Baumann et al '18, '19, . . .)
- Any ultra-light bosonic field coupled to gravity
  ⇒ black holes as probe for BSM particles complementary to traditional colliders

(Press & Teukolsky '72; Damour et al '76; Detweiler '80; Zouros & Eardley '79; Cardoso et al '05; Dolan '07; Rosa & Dolan '11; Pani et al '12; **HW** et al '12; Dolan '12; Shlapentokh-Rothman '14; Okawa, **HW** et al '14; Brito et al '15; Zilhao, **HW** et al '15; Moschidis '16; East '17, '18; Frolov et al '18; Dolan '18; Ficarra, Pani, **HW** '19, Baumann et al '18, '19, Herdeiro et al '19, Siemonsen & East '19, Ghosh et al '19, Clough et al '19, Hui et al '19, Creci, Vandoren, **HW** '20, Bamber et al '20, '21, Chia '20, Baryakhtar et al '21, . . .)

Example: Black holes as cosmic particle detectors

Observable signatures:

- gaps in spin–mass phase space of black hole population
  (Arvanitaki et al '09, '10; Pani et al '12; Brito et al '15-'20; Ficarra et al '18; ...)
- gravitational waves with $f_{22} \sim 20 \left[\frac{M}{M_\odot}\right]^{-1}$ kHz
  (Arvanitaki et al '14; Yoshino et al '13; Okawa, **HW**, Cardoso '14; Zilhão, **HW** '15, East et al '17-'20)
- black hole shadow (Herdeiro et al '19; Creci, Vandoren, **HW** '20,...)



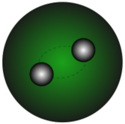
(Brito, Ghosh et al '17)

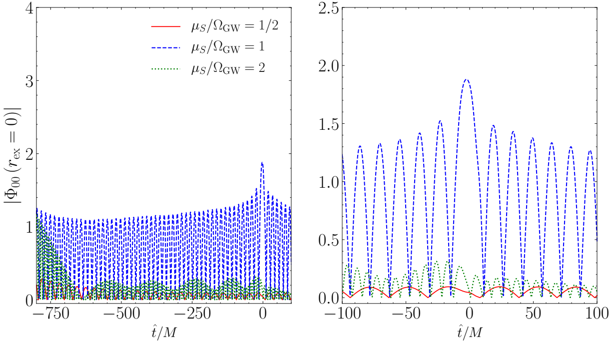
(For binaries: Baumann et al '18 – '20, Wong et al '19, '20, Hang & Zhang '19, Berti et al '19, Annulli et al '20, Ikeda et al '20, Choudhary et al '20, ...)

Example: Black hole binaries in dark matter cloud

[G. Ficarra, R. Luna, R. Emparan, **HW**, in prep.]

- implemented in Einstein Toolkit & Canuda
  (Witek, Zilhão, Elley, Ficarra, Silva '20)
- vary ratio $\mu_{\rm S}/\Omega_{\rm GW}$ and BH mass ratio
- resonance at merger if $\mu_{\rm S}/\Omega_{\rm GW} = 1$





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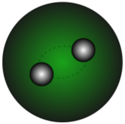
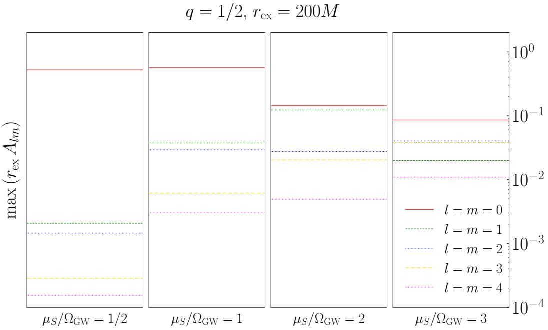


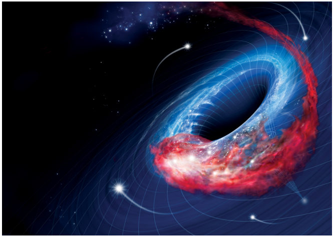


- "stirring" by BH binary $\Rightarrow$ excite higher multipoles
- impact of gravitational radiation? Work in progress, so stay tuned!

Signatures of beyond-GR theories?

Example: quadratic gravity

- 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)



Example: Scalar Gauss–Bonnet gravity

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

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

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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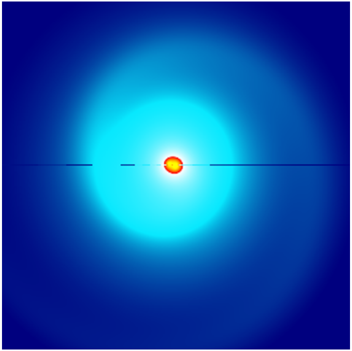
Example: Scalar Gauss–Bonnet gravity – Type I

- 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, Blázquez-Salcedo et al '16, '17, Pierini & Gualtieri '21, Owen et al '21, Kleihaus et al '11, '15, Benkel et al '16, Witek et al '18, Ripley & Pretorius '19, . . .)
- Binaries of hairy black hole ⇒ scalar dipole radiation
- Implemented in Einstein Toolkit & Canuda
  https://bitbucket.org/canuda/ (Witek, Zilhão, Elley, Ficarra, Silva '20)

einsteintoolkit.org
Canuda

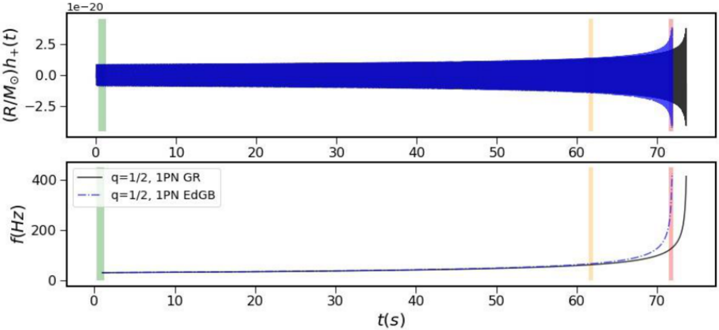


(Binary with $q = 1/2$, $M = 1$, decoupling) (**HW**, Gualtieri, Pani, Sotiriou '19)

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

Example: Scalar Gauss–Bonnet gravity – Type I

- 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)



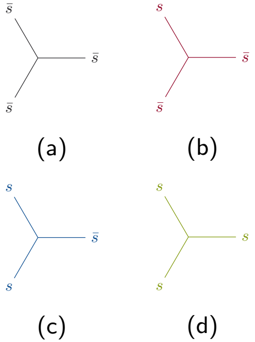
(Binary with $q = 1/2$, $M = 15M_\odot$, $\alpha_{\rm GB}/M^2 = 0.03$)

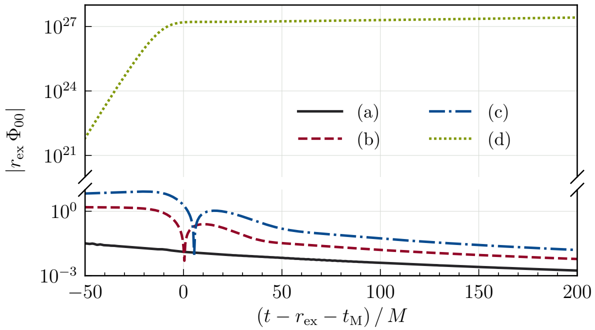
[Shiralilou, Hinderer, Nissanke, Ortiz, **HW** [arXiv:2012.09162]]

Example: Scalar Gauss–Bonnet gravity – Type II

- spontaneously scalarized black holes (Silva et al '17, Doneva et al '17,...)
- Evolution of scalarized BH binaries @ decoupling
  (Silva et al '20; see also: Annulli '21, East & Ripley '21)
- remain scalarized or **dynamical descalarization**

einsteintoolkit.org
CANUDA

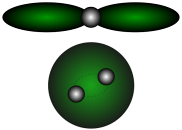




[Silva, **HW** , Elley, Yunes [arXiv:2012.10436]]
Website: `https://bhscalarization.bitbucket.io/`

Summary and Outlook

Black holes, neutron stars and gravitational waves as “gravity detectives”

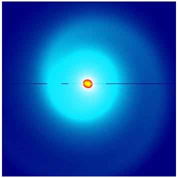


Part 1: Black hole (binaries) as cosmic particle detectors

- resonances during (early) inspiral
  (Baumann et al ’18-’20, Berti et al ’19; Yang & Zhang ’19)
- @ merger: resonance if $\mu_{\rm S}\Omega_{\rm GW} \sim 1$,
  excitation of higher (scalar) multipoles (Ficarra et al, in prep.)
- Ongoing: nonlinear evolution: expect GW phase-shift

Part 2: Scalar Gauss–Bonnet (quadratic) gravity

- pre-merger: gravitational wave phase shift
- observational bound $\sqrt{\alpha_{\rm GB}} \lesssim 1.7$km
  (Yagi ’12, Nair et al ’19, Wang et al ’21, Perkins et al ’21)
- New phenomenon: *dynamical descalarization*
  (unconstrained!)



Thank you!

Example: Scalar Gauss–Bonnet gravity – Type II

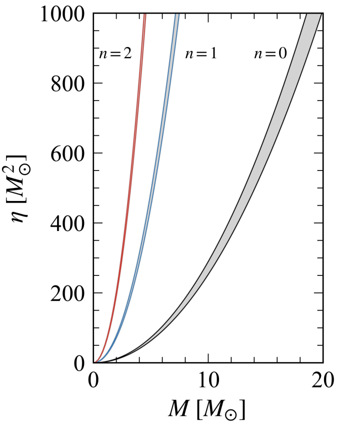
- Coupling function $f'(\Phi) \sim \Phi^2$
- Scalar field equation

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

- 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, Collodel et al '19, Ripley & Pretorius '20, Doneva & Yazadjiev '21)
(Stability of scalarized black holes: Silva et al '19, Blázquez-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)
(Spontaneous vectorization: Barton et al '21) (Scalarization in dCS: Doneva et al '20-'21)

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

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

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

back