Black-hole binaries in Einstein-dilaton Gauss–Bonnet gravity

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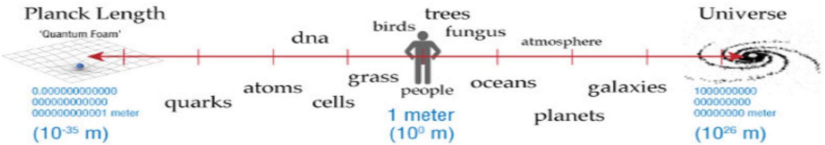
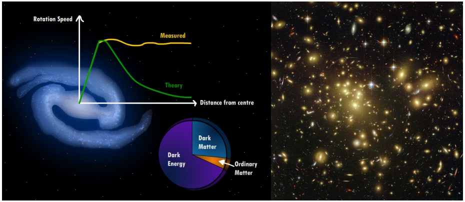
Why challenging general relativity?





Cosmology

- observational evidence for dark matter/energy
- cosmological constant problem
- evolution of the universe

High-energy physics

- general relativity is non-renormalizable
- UV completion and quantum gravity?
- curvature singularities

A need for theoretical predictions. . .

GR very well tested, e.g. on solar system scales, with binary pulsars, with gravitational waves from black holes and neutron stars

BUT: in merger regime only null tests!!!

- very few theoretical predictions in extensions of GR (scalar-tensor theory [Healy et al '11, Berti '13, Barausse et al '12, Shibata et al '13], dynamical Chern-Simons [Okounkova et al '17])
- needed to calibrate parametrized models, e.g., extensions of EoB, ppN, ppE, . . .
- no parametrized numerical models → choose most promising candidates

(credit: LIGO / Virgo Scientific Collaborations)

Here:

Einstein-dilaton Gauss-Bonnet gravity

action of EdGB gravity (e.g. Kanti et al '95)

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

$$G_{ab} = 8\pi T^{\Phi}_{ab} - 16\pi \alpha_{\mathrm{GB}} \mathcal{G}^{\mathrm{GB}}_{ab} \,,$$
$$\Box\Phi = -\alpha_{\mathrm{GB}} f'(\Phi) \mathcal{R}_{\mathrm{GB}}$$

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

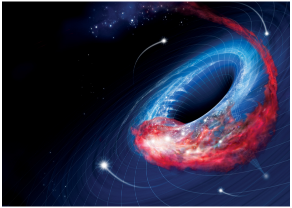
[1]

[1] use geometric units $c = 1 = G$

Why EdGB gravity?

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)



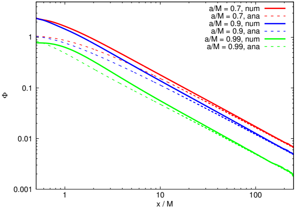
Why EdGB gravity? – musings on compact objects

- in standard scalar-tensor theory:
  - no-hair theorems for BHs
    (Bekenstein '95, Heusler '96, Sotiriou & Faraoni '11)
  - neutron stars can have scalar hair
    (Damour & Esposito-Farese '93, '96, . . .)

- BUT: reverse in quadratic gravity!
  - BHs can have hair!
    (Hui & Nicolis '12, Sotiriou & Zhou '14)
  - monopole scalar charge for neutron star vanishes (Yagi et al '15)

- rotating black holes with $\chi = \frac{J}{M^2}$ in small coupling approximation
  (Kanti et al '95, Pani et '09, '11, Stein & Yunes '11, Sotiriou & Zhou '14, Ayzenberg & Yunes '14, Maselli et al '15, Kleihaus et al '11, '14, . . .)

- $\alpha^0_{\rm GB}$: no modification to GR solution, i.e.,
  $\mathrm{d}s^2 = \mathrm{d}s^2_{\rm Kerr}\,, \quad \Phi = const = 0$
- $\alpha^1_{\rm GB}$: no modification to metric, but scalar hair
  (courtesy of Kent Yagi)



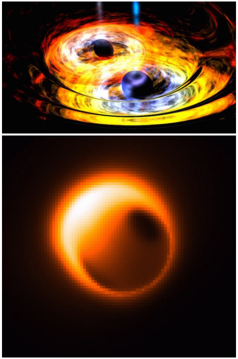
$$\Phi = \sum_{l\geq 0,\text{even}} \mathcal{P}_l \frac{M^{l+1}}{r^{l+1}} P_l(\cos\theta) \left[1 + \mathcal{O}\left(\frac{M}{r}\right)\right]$$

$$\mathcal{P}_0 = 4\frac{\alpha\mathrm{GB}}{M^2}\frac{\sqrt{1-\chi^2} - 1 + \chi^2}{\chi^2} \qquad \mathcal{P}_2 \sim -\frac{28}{15}\frac{\alpha_{\rm GB}}{M^2}\chi^2\left(1 - \frac{5\chi^2}{98}\right) + \mathcal{O}(\chi^6)$$

Why EdGB gravity? – musings on compact binaries

⇒ modified dynamics and extra polarizations, e.g,

- induced scalar dipole & quadrupolar radiation
  ⇒ increased inspiral rate
- shift in binding energy
  ⇒ correction to orbital phase
- change in ISCO: $r_{\rm ISCO}/M \sim 6 - \frac{16297}{9720}\alpha_{\rm GB}^2$
- spin can exceed Kerr bound (Kleihaus et al '11)
- ...



(www.eventhorizontelescope.org)

Setting the stage for numerical evolutions

Mathematical considerations:

- field equations are second order $\Rightarrow$ potential for well-posed PDE system?
  - in generalized harmonic gauge only weakly hyperbolic (Papallo & Reall '17, Papallo '17)
  - extension to Baumgarte-Shapiro-Shibata-Nakamura-type formulation + puncture-type gauge underway (work in progress with L. Gualtieri and P. Pani)
  - good chances as effective field theory (Choquet-Bruhat '88, Delsate et al '14)

- $g_{\mu\nu} = g^{(0)}_{\mu\nu} + \epsilon g^{(1)}_{\mu\nu} + \mathcal{O}(\epsilon^2)$, $\Phi = \epsilon\Phi^{(1)} + \mathcal{O}(\epsilon^2)$ and take $\epsilon \sim \alpha_{\rm GB}$

$$\alpha^0_{\rm GB}: \quad G^{(0)}_{ab} = 0\,,$$

$$\alpha^1_{\rm GB}: \quad \Box\Phi^{(1)} = -\mathcal{R}^{(0)}_{\rm GB}\,, \quad \mathcal{R}^{(0)}_{\rm GB} = R^2 - 4R_{ab}R^{ab} + R_{abcd}R^{abcd}$$

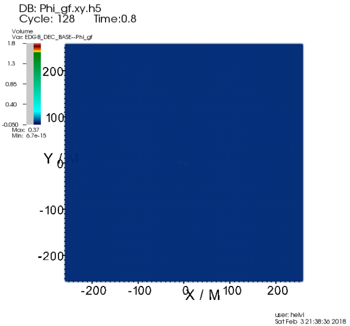
$\Rightarrow$ in practise for up to $\alpha^1_{\rm GB}$: evolve scalar in a GR background

BH binaries in EdGB – setting the stage

Time evolution in 3+1 dimensions, code based on EINSTEIN TOOLKIT
Initial data:

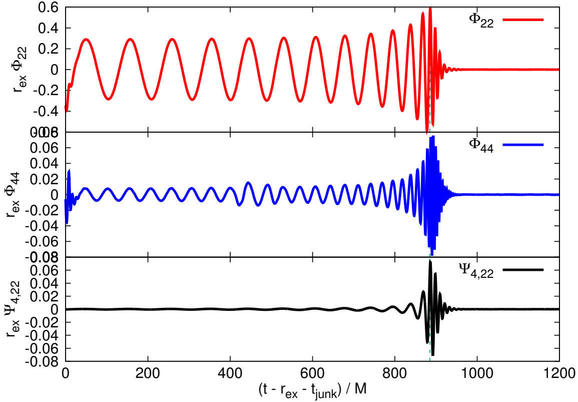
- $\alpha^0_{\rm GB}$: non-spinning BH binary with $x_\pm = \pm 5$ ($\sim 8 - 10$ orbits before merger), mass-ratios $q = m_1/m_2 = 1, 1/2, 1/4$
- $\alpha^1_{\rm GB}$: zero initial scalar field or superposition of solutions
- HERE: $q = 1$ and $\Phi_{t=0} = 0, \Pi_{t=0} = -\mathcal{L}_n \Phi = 0$

Scalar field evolution – equatorial plane



Results

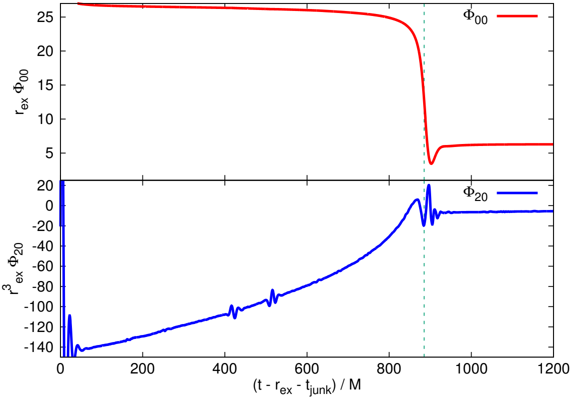
Scalar radiation measured at $r_{\rm ex}/M = 40$



- excitation of scalar radiation in $l = m = 2$ and $l = m = 4$ sourced by curvature / orbital dynamics
- post-merger ringdown

Results

Scalar field waveforms with $m = 0$, measured at $r_{\rm ex}/M = 40$



- non-trivial scalar excitation
- post merger: approach to analytic solution

$$\Phi \sim \mathcal{P}_0 \frac{M}{r} + \mathcal{P}_2 \frac{M^3}{r^3} Y_{20} \quad \mathcal{P}_0 \sim \frac{2\alpha_{\rm GB}}{M^2} \quad \mathcal{P}_2 \sim -\frac{\alpha_{\rm GB}}{M^2}\chi^2$$

Summary and Outlook

Take home message:

- study black holes in Einstein-dilaton Gauss-Bonnet theory
  - motivated from "stringy" models
  - black holes have hair – fundamentally different from GR
  - first nonlinear study of BH binaries (up to $\mathcal{O}(\alpha_{\rm GB}^{(1)})$)
    $\rightarrow$ burst of scalar radiation excited in late inspiral & merger
    $\rightarrow$ settling down to hairy, rotating solution at late times

Outlook

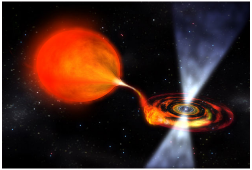
- extension to $\mathcal{O}(\alpha_{\rm GB}^{2})$ within EFT approach
  $\rightarrow$ include deformation of metric and GW signal
- modelling as full theory? PDE structure within BSSN+puncture gauge approach
- construct inspiral-merger-ringdown signal for GW searches

Thank you!

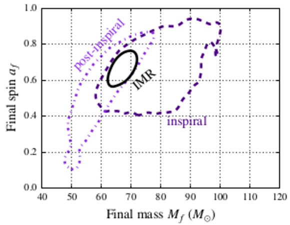
acknowledgements:

Constraints on EdGB

- theoretical constraint:
  - static BHs only exist for $\left|\frac{\alpha_{\rm GB}}{M^2}\right| \lesssim \frac{1}{2\sqrt{3}}$
    (Kanti et al '95, Sotiriou & Zhou '14)
- strongest observational constraint:
  - orbital decay of x-ray binaries
    $\frac{\dot{P}}{P} \sim \frac{\dot{L}}{L}$ with $\dot{L} \sim \dot{L}_{\rm GR}\left(1 + \frac{5}{96}\bar{\alpha}^2_{\rm GB} v^{-2}\right)$
    $\Rightarrow \sqrt{|\alpha_{\rm GB}|} \lesssim 2km$ (Yagi '12)
- What can GWs do for us? Not much, actually
  - due to degeneracies between spin magnitudes, component masses & coupling
  - modification of GW phase & amplitude not present in noise $\Rightarrow \sqrt{|\alpha_{\rm GB}|} \lesssim \delta^{1/4}\left(r_{12}/m\right)^{-1/4}$
  - with $\delta \sim 4\%$, $r_{12} = 2m$, $m \sim 30 M_{\odot}$, $\chi \sim 0$:
    $\sqrt{|\alpha_{\rm GB}|} \lesssim 23km$



Testing strong field gravity (LSC/LVC '16, '17)

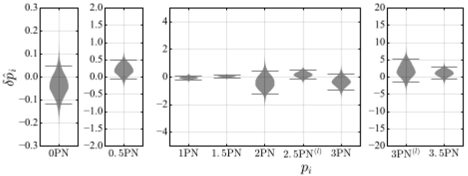


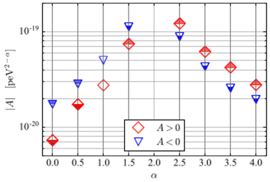
Consistency tests

- consistent parameter estimation from inspiral & inspiral-merger-ringdown
- post-peak data consistent with QNM

Null tests

- substract best GR fit from data: remainder consistent with noise
- constraints on parametrized post-Newtonian



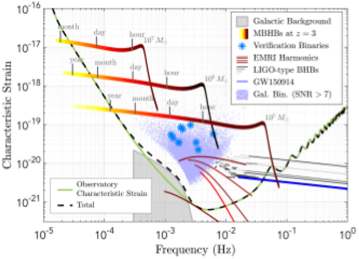


Modified dispersion relations $E^2 = p^2c^2 + Ap^\alpha c^\alpha$

- constraint on graviton Compton wavelength: $\lambda_G \geq 1.6 \cdot 10^{13} km$ $(m_G \lesssim 7.7 \cdot 10^{-23} eV/c^2)$

back

Future prospects – multiband GW astronomy

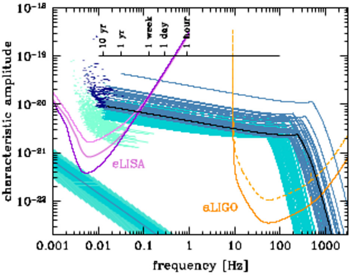


(LISA consortium '17)

- extreme mass ratio inspirals
  - multipolar structure
  - Kerr nature
- post-merger of massive binaries
  - ringdown modes
  - tests of "no-hair" theorems

testing for

- additional radiation channels
- propagation properties
- presence of light fundamental fields



(Sesana '16; see also Vitale '16)