Title: Spontaneous black hole scalarization

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Series: Strong Gravity

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Abstract: General Relativity remains to this day our best description of gravitational phenomena. Nonetheless, issues such its quantization and cosmological constant problem suggest Einsteinâ€™s theory might not be final theory of the gravitational interaction. Motivated by these questions, theorists have proposed a myriad of extensions to General Relativity over the decades. In this seminar, I will focus on theories with extra scalar fields. In particular, I will describe how some of these theories can evade Solar System constraints and yet yield to new effects in the strong-gravity regime of compact objects, i.e. neutron stars and black holes. This is achieved through a process known as spontaneous scalarization, in which a compact object growths 'scalar hair' once certain conditions are met and remains 'bald' otherwise. I will review the basics of this effect and then focus on recent efforts in understanding it for black holes both in isolation and in binaries.

Spontaneous black hole scalarization

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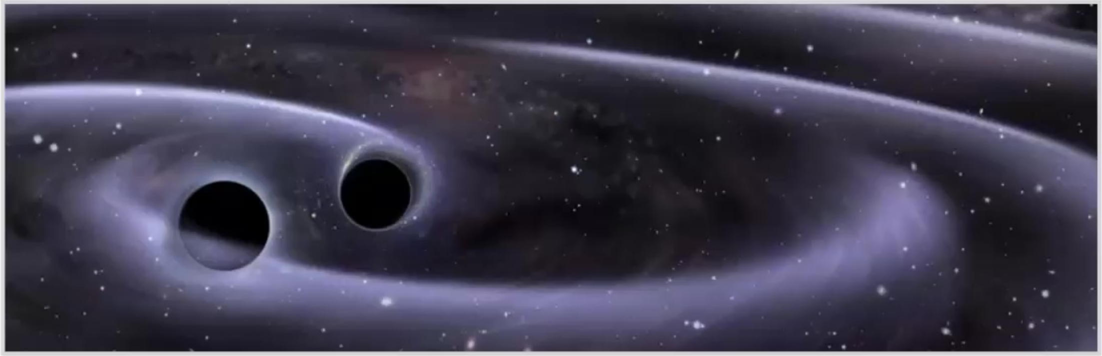
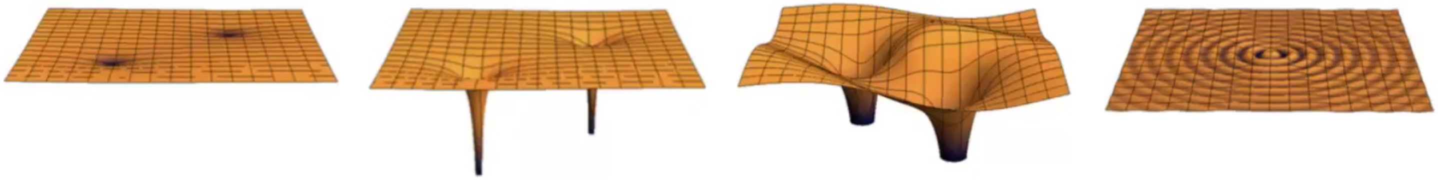
MAX-PLANCK-GESELLSCHAFT

Perimeter Institute for Theoretical Physics
Strong gravity seminar
Waterloo, Canada - 11 Feb. 2021

Experimental relativity

«[…] It does not make any difference how smart you are, who made the guess, or what his name is – if it disagrees with experiment it is wrong. That is all there is to it.»



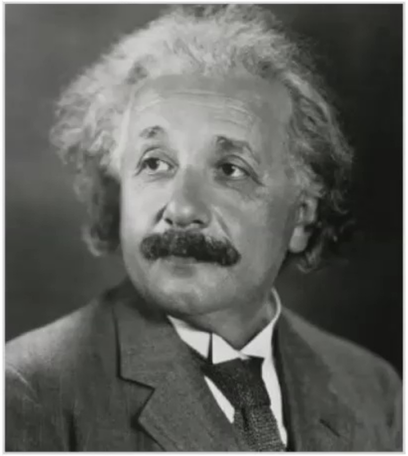


Small velocities, *weak* fields | *Mild* velocities, *strong* fields | *High* velocities, *strong* fields | Spacetime *ripples*

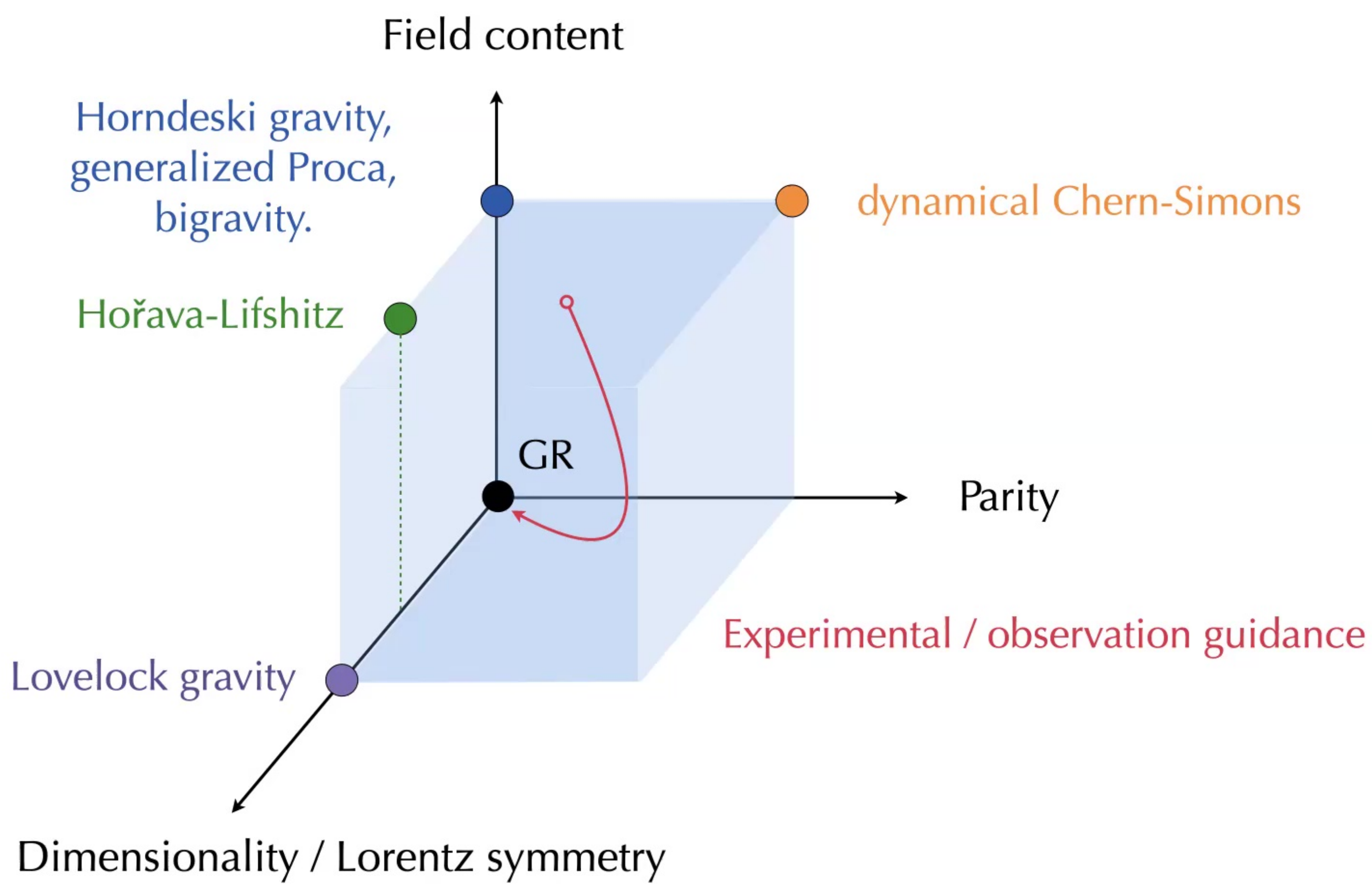
Why continue testing general relativity?

- Cornerstone of modern physics;
- Quantisation of gravity;
- Cosmology (dark energy?);
- Unbiased tests of gravity;
- Theoretical interest («but what if…?»).

«Don't you believe me?»



The «hypercube» of gravity theories



Example: neutron stars in scalar-tensor theories

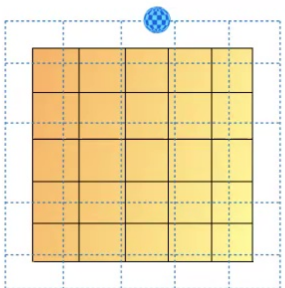
$$A(\varphi) = \exp(\beta\phi^2) \qquad \Box\varphi = -4\pi\beta\varphi T$$

scalar field $\approx q/r$

$g_{\mu\nu}$

φ

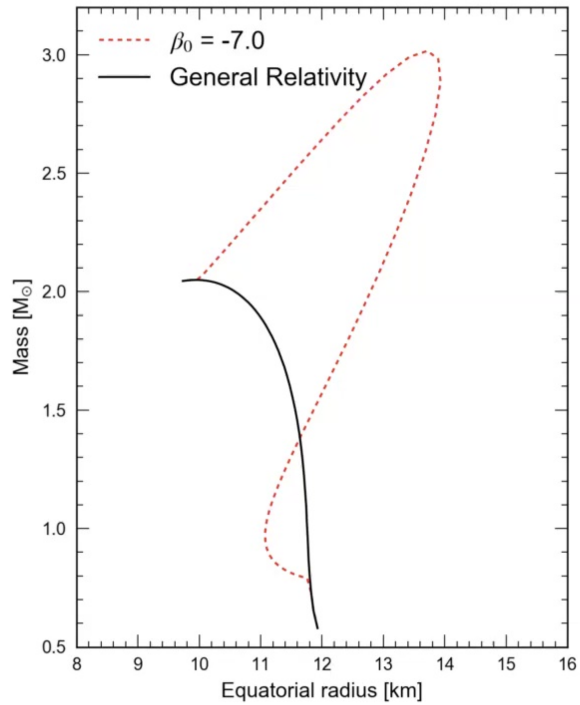
$A^2(\varphi)g_{\mu\nu}$

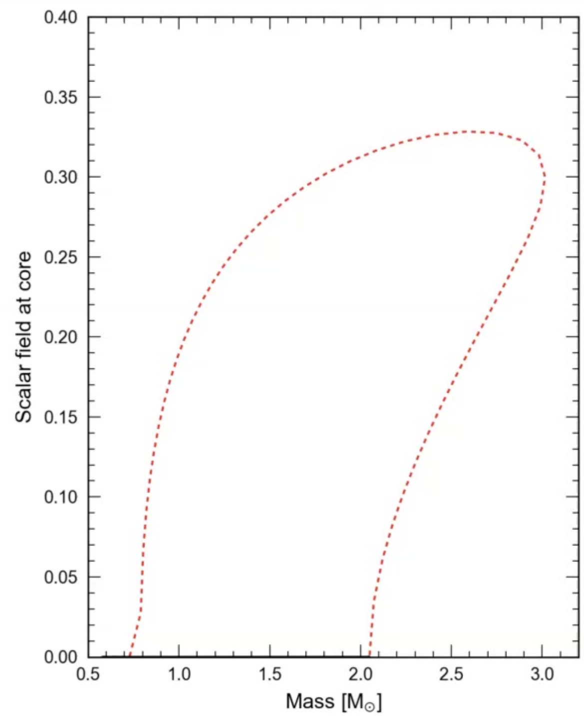


$A^2(\varphi)g_{\mu\nu}$ → matter

matter → $\{g_{\mu\nu}, \varphi\}$

$\{g_{\mu\nu}, \varphi\}$ → $A^2(\varphi)g_{\mu\nu}$





Damour & Esposito-Farèse (1993, 1996), Harada (1997)
Barausse, Lehner, Palenzuela, Ponce+ (2013, 2014, 2015), Shibata+ (2014, 2015), …

but what about black holes?

Towards spontaneous black hole scalarization

Towards spontaneous black hole scalarization

«The black holes of nature […] the only elements
in their construction are our concepts of space and time.»

$$\Box\varphi = -f(\varphi)_{,\varphi}\,\mathscr{C}$$

Gauss-Bonnet?
{Pontryagin?} ← Curvature

Spontaneous scalarization induced by curvature?

A concrete model

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\,[R + \partial^\mu\varphi\partial_\mu\varphi + f(\varphi)\mathscr{G}]$$

$$\Box\varphi = -f(\varphi)_{,\varphi}\cdot\mathscr{G}$$

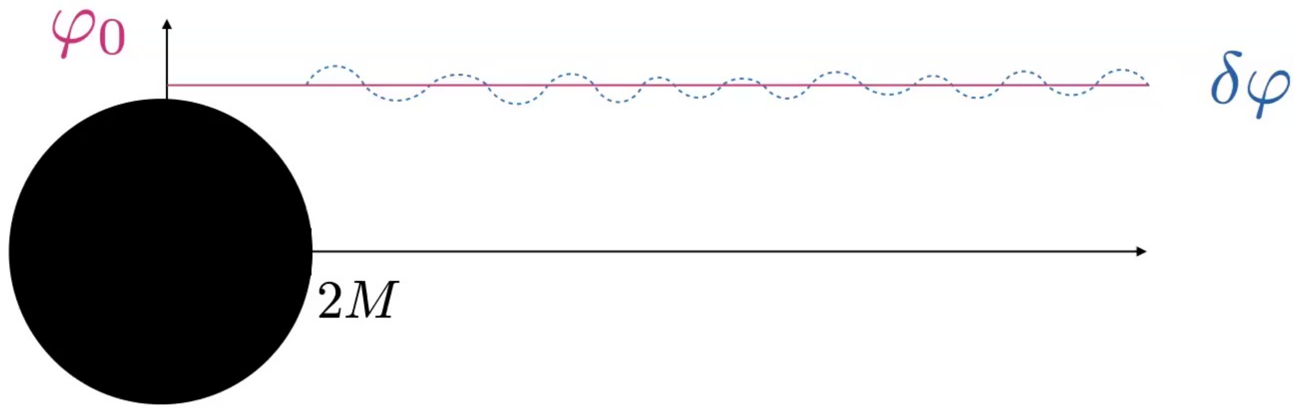
Existence for GR solutions: $f(\varphi_0)_{,\varphi} = 0$

Kerr family is a solution iff: $f(\varphi)_{,\varphi\varphi}\,\mathscr{G} < 0$

What does this mean?

(Silva, Sakstein, Gualtieri, Sotiriou & Berti '18)
See EFT in Macedo et al. (2019)

Effective mass



$$\left[\Box \qquad - m_{\rm eff}^2 \qquad \right] \delta\varphi = 0$$

tachyonic instability?

Obs.: the *same* reasoning applies for stars which we discussed earlier.
cf. Harada (1997)

A concrete model

$$f(\varphi) \equiv \frac{1}{8}\eta\varphi^2 \qquad m_{\text{eff}}^2 = -\frac{1}{4}\eta\mathscr{G}$$

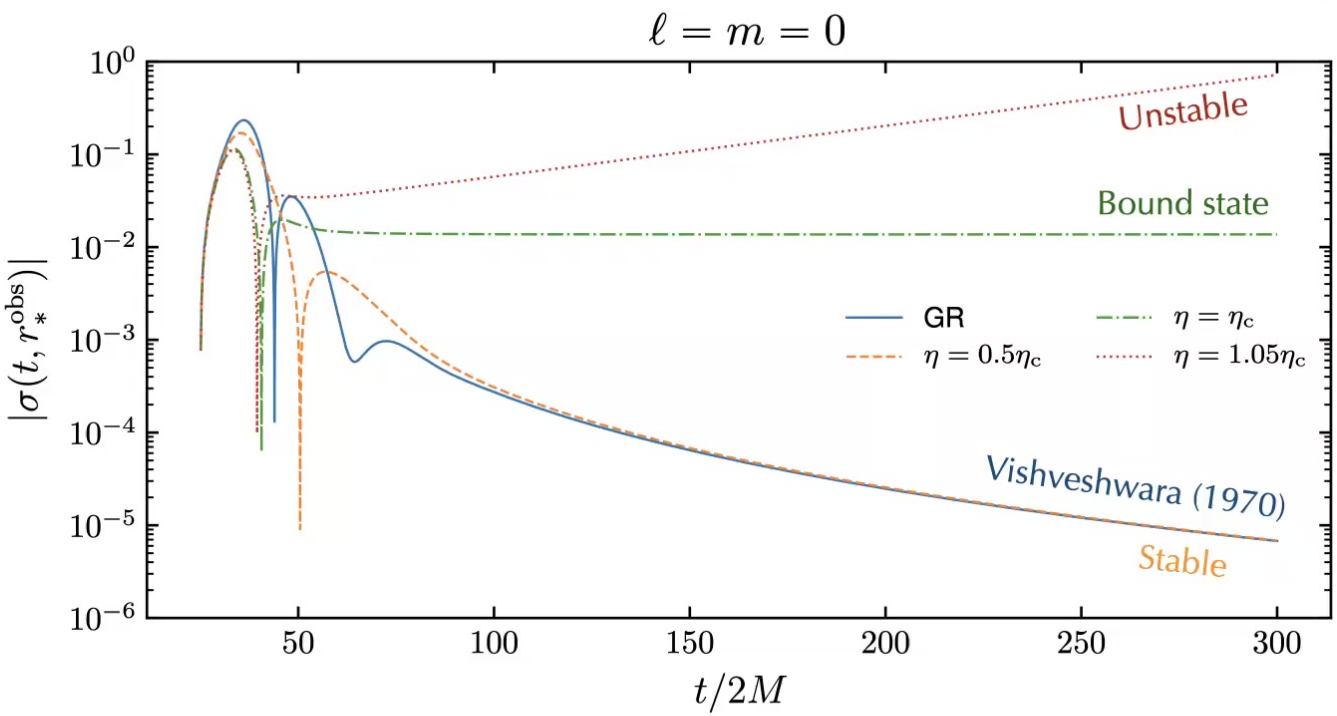
Instability of the Schwarzschild solution

$$\mathscr{G} = \frac{48M^2}{r^6} \qquad m_{\text{eff}}^2 < 0 \quad \text{if} \quad \eta \quad \text{positive}$$

Silva, Sakstein, Gualtieri, Sotiriou & Berti (2017)
Doneva & Yazadjiev (2017)

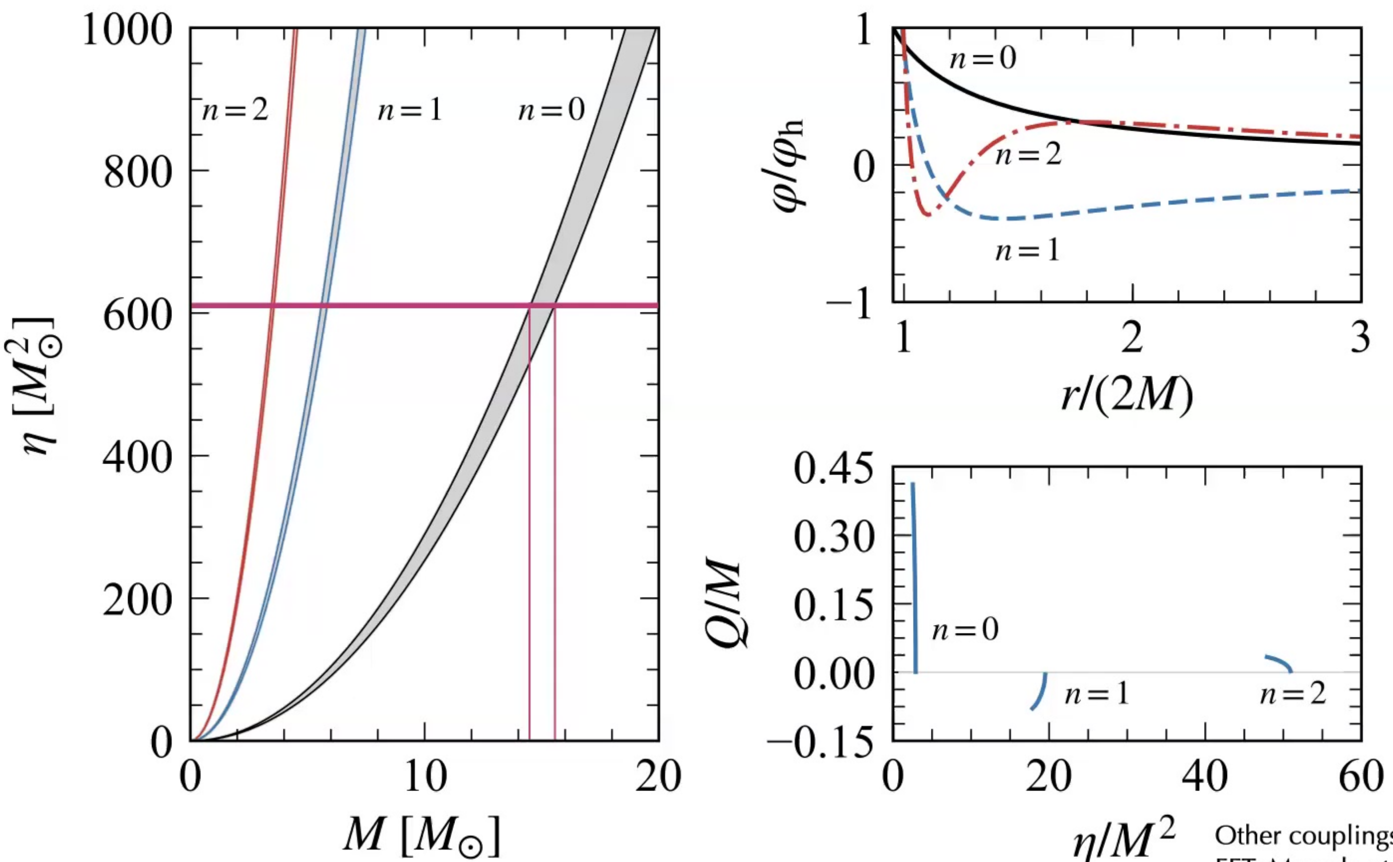
Visualising the instability

Time-domain numerical integration $(\Box - m_{\text{eff}}^2)\,\delta\varphi = 0$ $\quad m_{\text{eff}}^2 \sim -\eta \cdot \mathscr{G}$ $\quad \delta\varphi = \sum_{\ell m} \sigma_{\ell m}(t,r) Y_{\ell m}(\theta,\phi)/r$



$\eta_c/(2M)^2 = 0.726$

Nonrotating spontaneous scalarized BHs



Striking contrast with

$f(\varphi) \propto \exp(\varphi)$

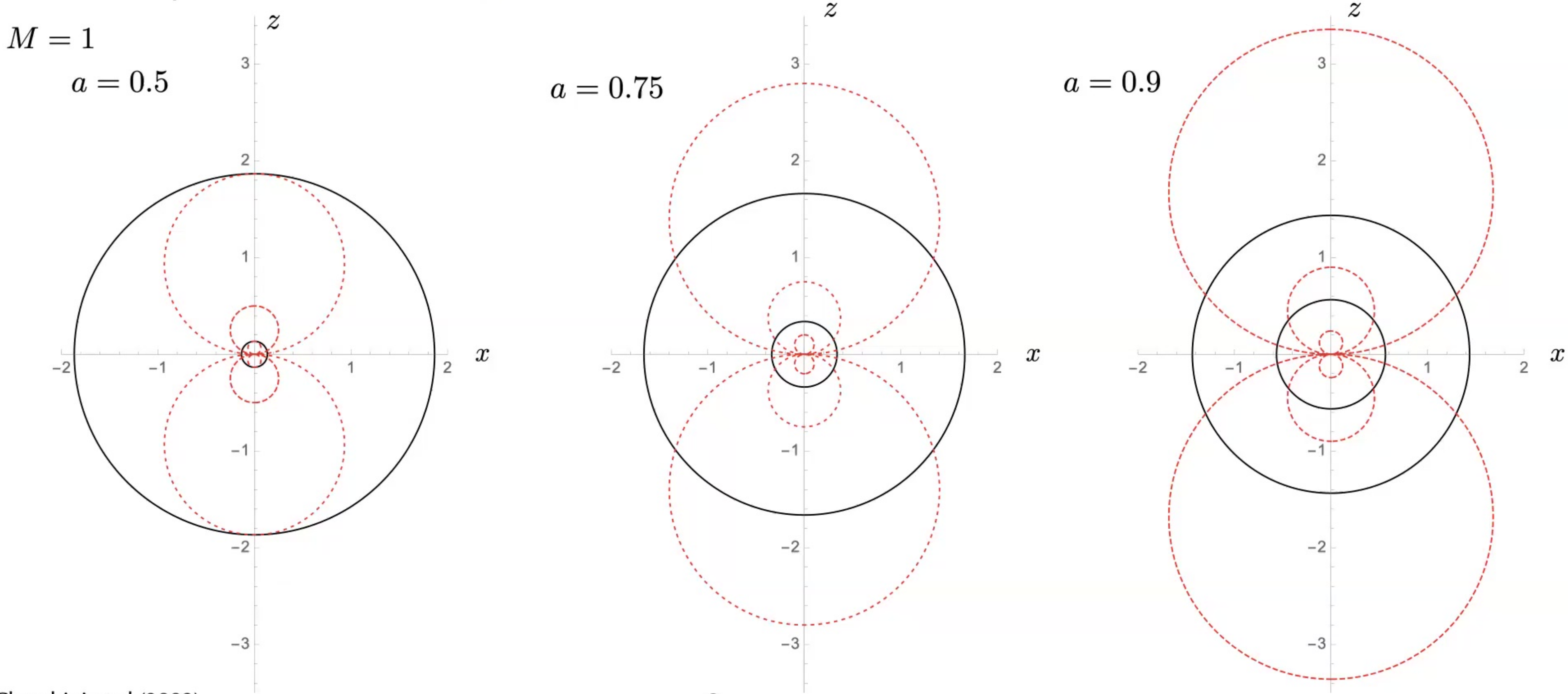
$f(\varphi) \propto \varphi$

where black holes *always* have hair

Other couplings: Doneva & Yazadjiev (2017), Antoniou+ (2017)
EFT: Macedo et al. (2019)
Stability: Silva et al. (2019), Blazquez-Salcedo+ (2018, 2020)

What about rotation?

Linear analysis, but now around Kerr…



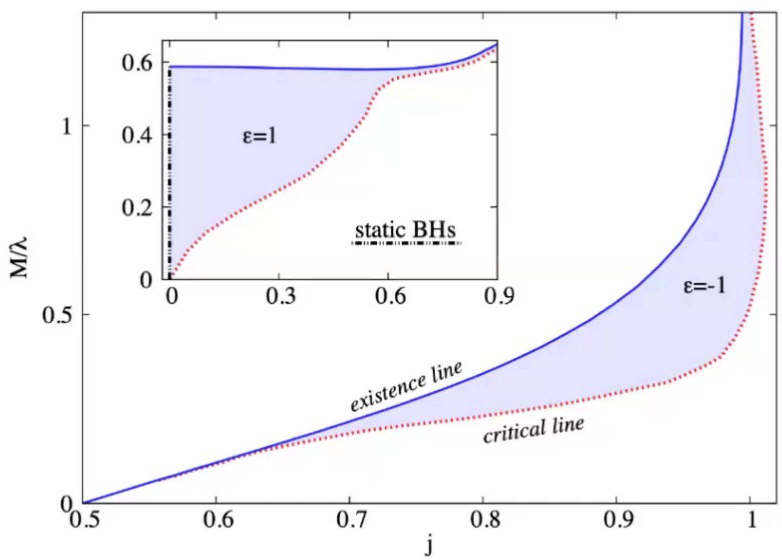
Cherubini et al (2002)
Dima et al. (2020) {also Hod (2020), Doneva et al. (2020), …}

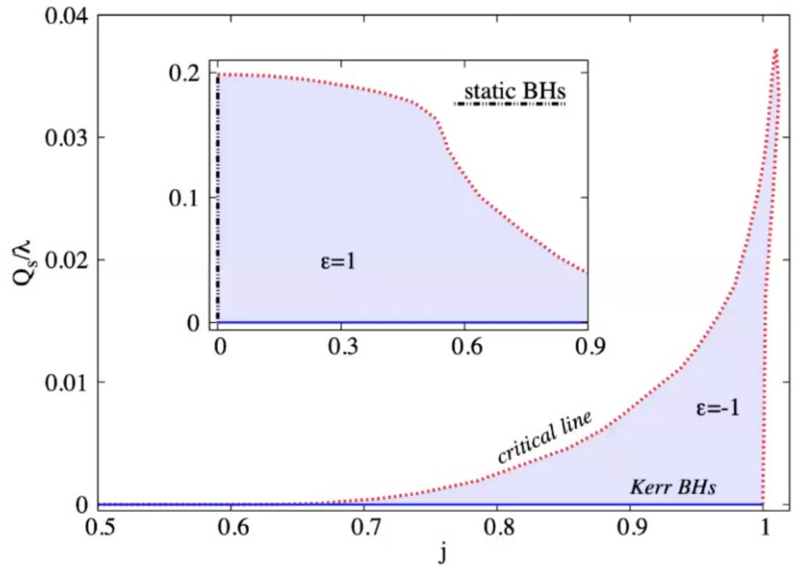
$$m_{\text{eff}}^2 \sim -\eta \cdot \mathscr{G}$$

… spin-induced instability?

Spin-induced scalarized black holes

$$f(\varphi) = (\lambda^2\epsilon/12)[1 - \exp(-6\varphi^2)]$$





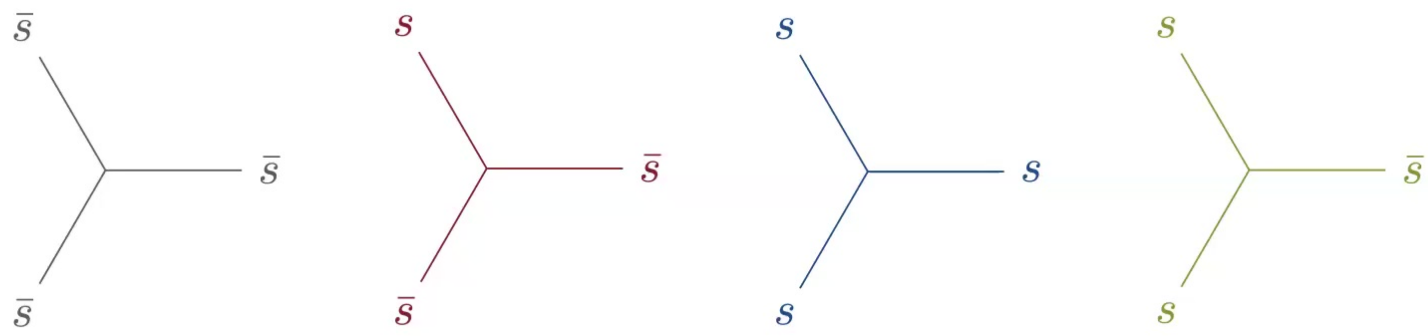
Herdeiro, Radu, Silva, Sotiriou and Yunes (2020)
Cunha, Herdeiro and Radu (2019)
[see also Collodel et al. (2019) & Berti et al. (2020)]

Spontaneous scalarization in binaries

What happens BH binaries?
First study at the decoupling limit

$s :=$  $\bar{s} :=$ 

Einstein Toolkit + Canuda

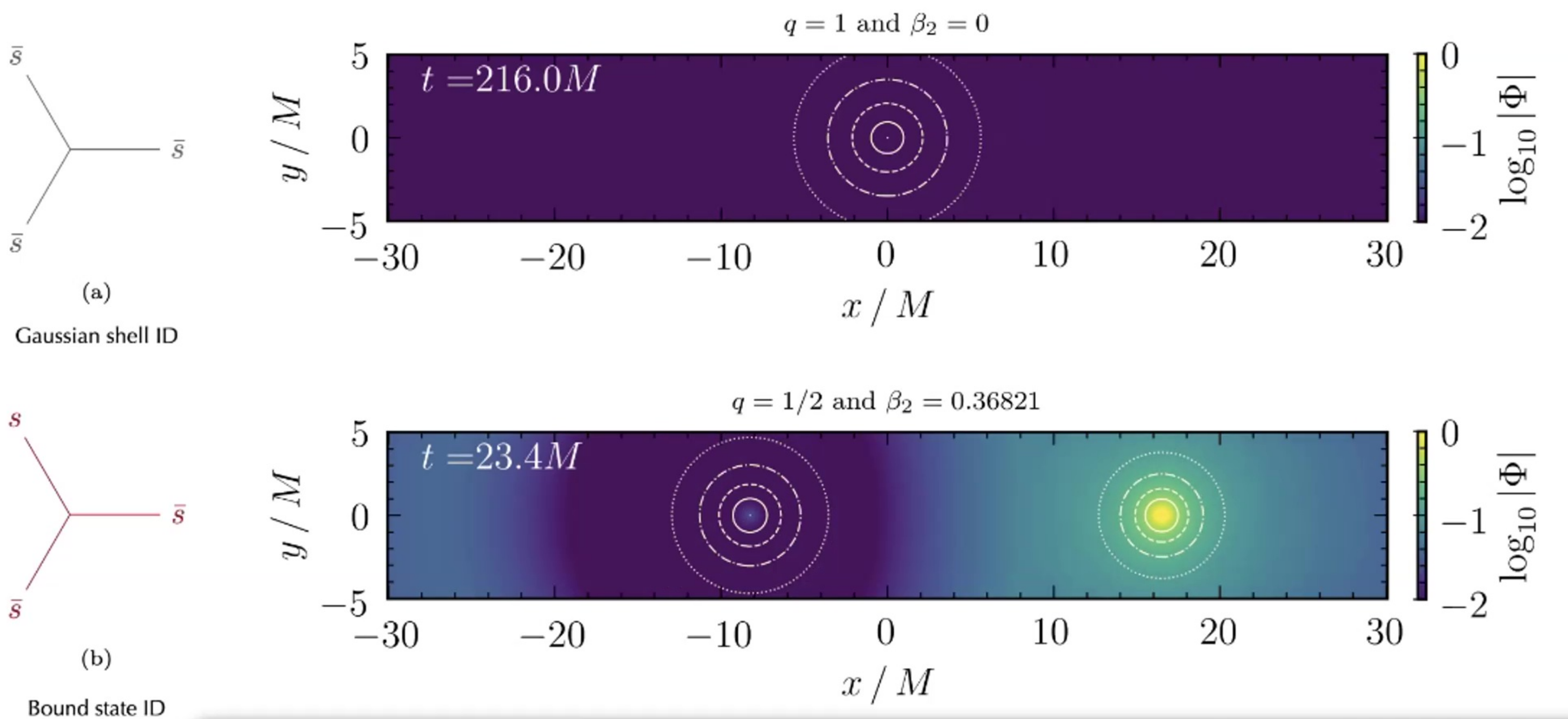


(a) (b) (c) (d)

Witek, Gualtieri, Pani and Sotiriou (2018) $[\sim \phi \cdot \mathscr{G}]$
Witek, Zilhão, Ficarra, Elley (2020) [Canuda]
Silva, Witek, Yunes and Elley (2020)

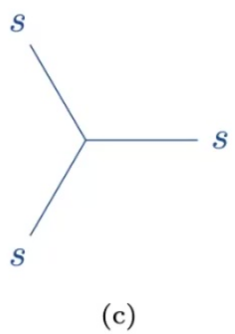
`https://bhscalarization.bitbucket.io`
`Canuda Numerical Relativity`

Spontaneous (de)scalarization in binaries: head-on collision

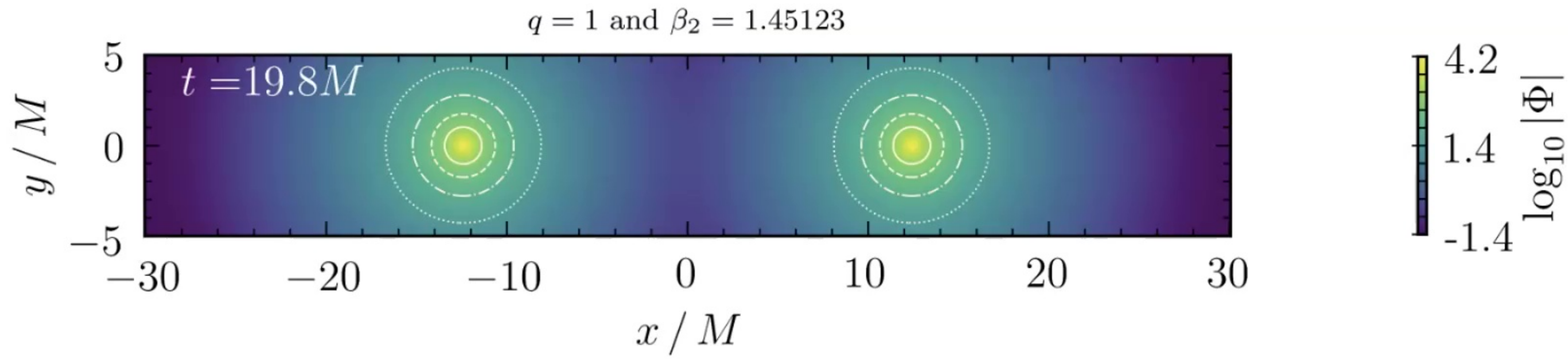


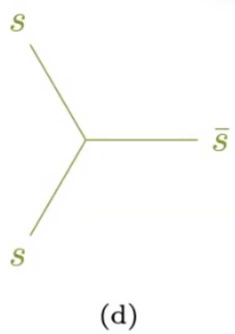
Movie time

Spontaneous (de)scalarization in binaries: head-on collision

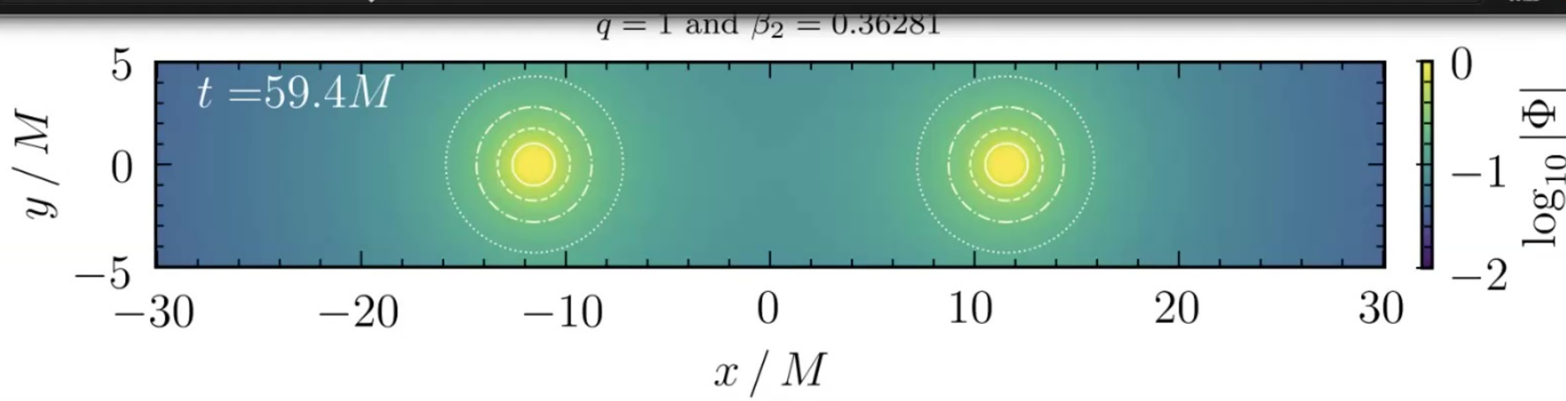


Bound state ID





Bound state ID

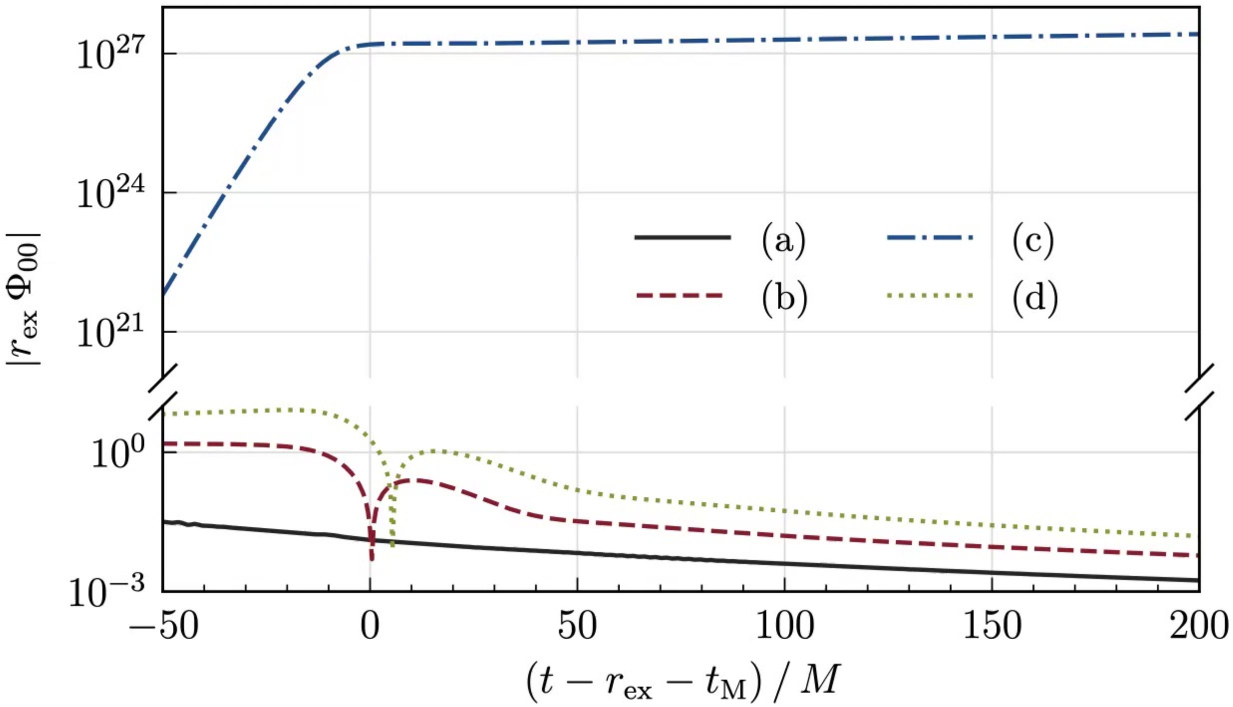


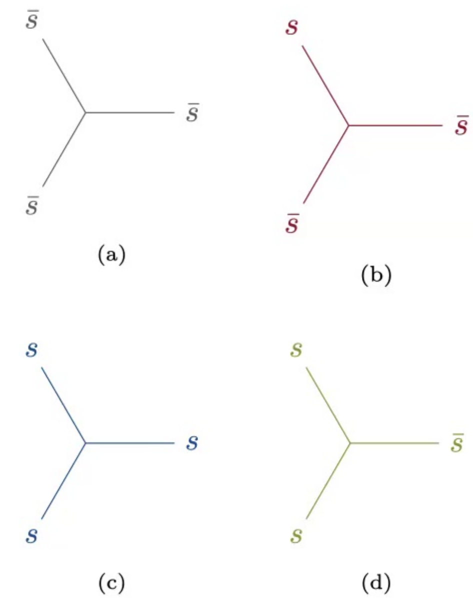
Movie time

Spontaneous (de)scalarization in binaries: head-on collision

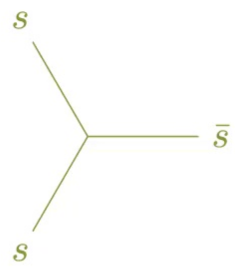
Monopole scalar field at fixed extraction radii
{remember the “Vishveshwara”-like experiments?}
$r_{\rm ex} = 50M$

Silva, Witek, Yunes and Elley (2020)



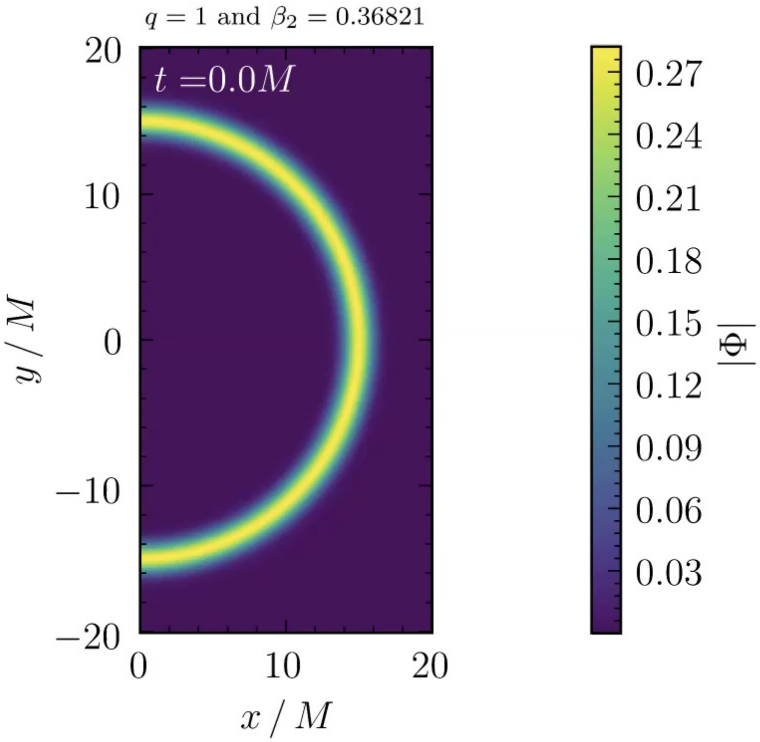


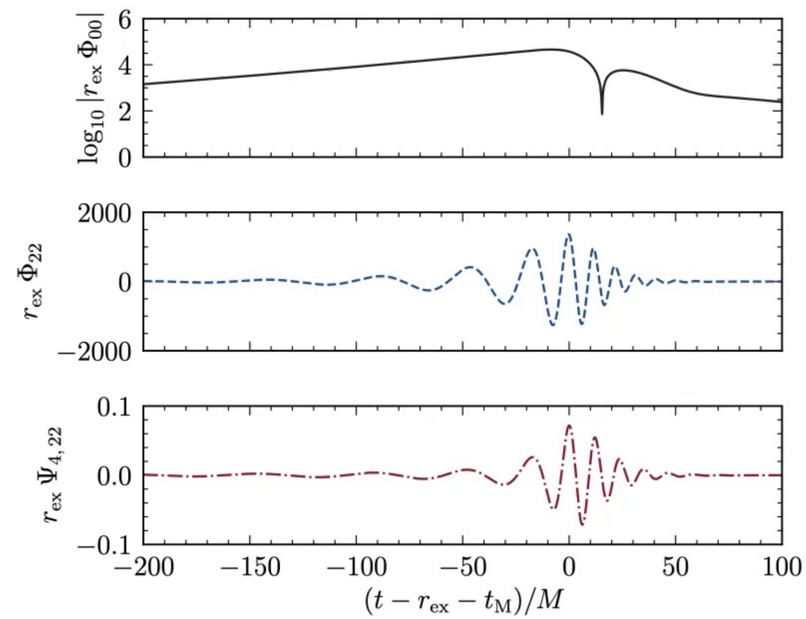
Spontaneous (de)scalarization in binaries: quasi-circular inspiral



(d)

Gaussian shell ID



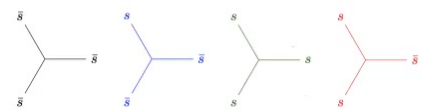


Conclusions and directions for future work

Scalar fields coupled to curvature invariants, can result in spontaneous hair growth of black holes.

Solutions of isolated black holes are well-understood, but more work is needed to understand formation and stability.

The next frontier lies in the binary dynamics. Firsts results in the decoupling limit. Needs in both theoretical and computational fronts.



With gravitational waveforms; confront theory against observations.

Spontaneous black hole «vectorisation» / «tensorisation»?

Thank you!

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