Title: Non-linear dynamics in modified gravity

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Series: Strong Gravity

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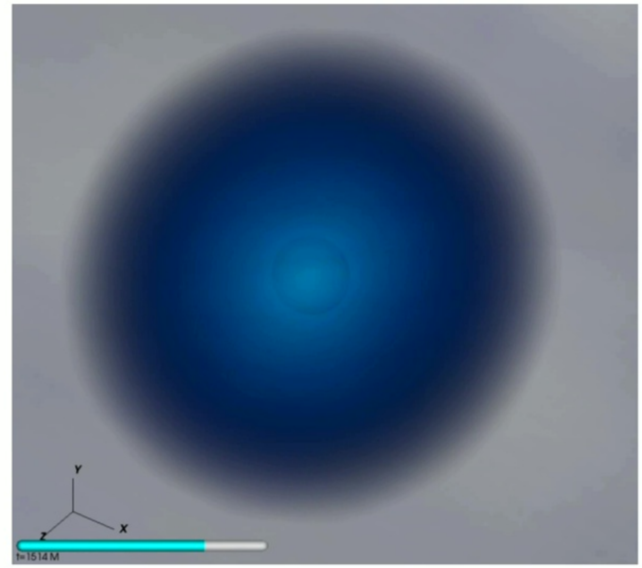
Abstract: In this talk I will present our 3+1 formulation of the Four-Derivative scalar-tensor theory of gravity with a modified puncture gauge that proves to be well-posed. Then I will show the results from Binary Black Hole evolutions that we have obtained from the implementation of these equations with GRFolres, the extension for modified gravity of our numerical relativity code GRChombo.

Zoom link https://pitp.zoom.us/j/96339156414?pwd=ajhWb1hQNFRYalRpUEd3ajhYdTFldz09

Non-linear dynamics in modified gravity



Llibert Aresté Saló

Joint work with
Katy Clough and Pau Figueras

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PRD **108**, 084018 (2023)

Perimeter Institute, 21st December 2023

Queen Mary
University of London

GR CHOMBO

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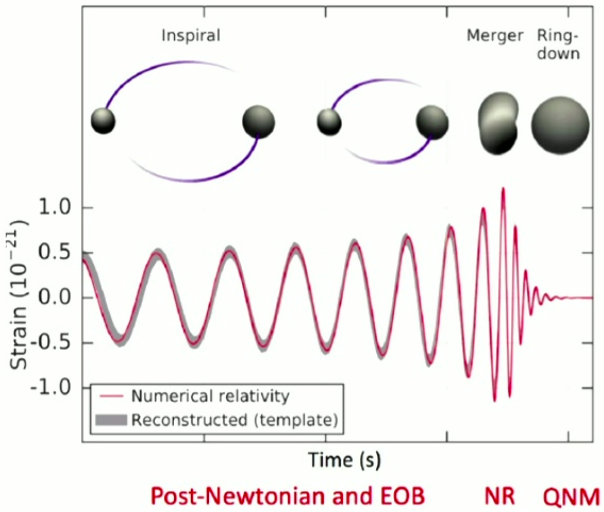
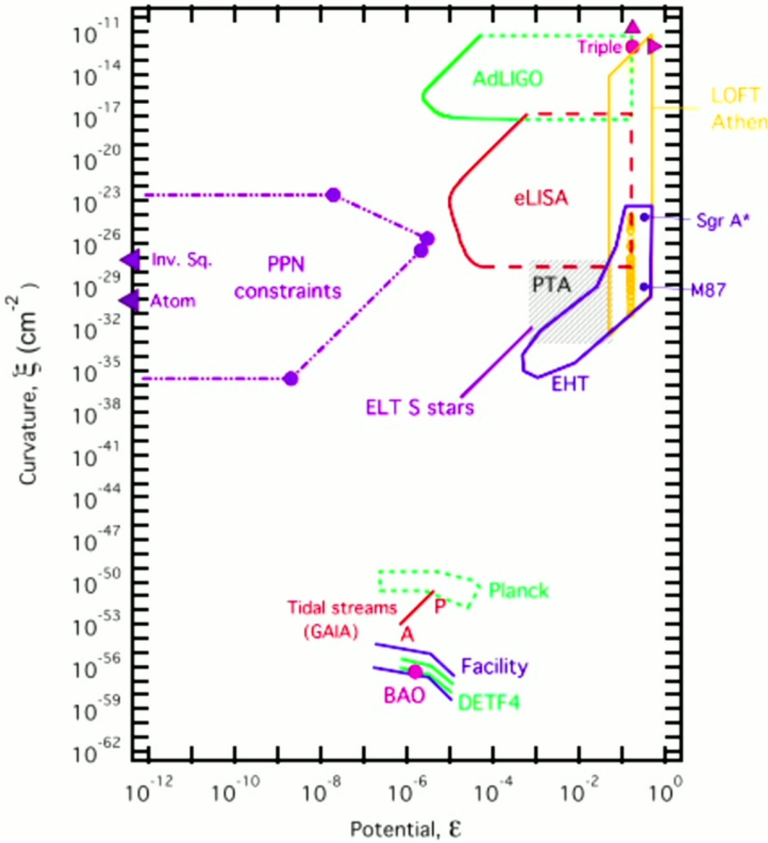
Motivation

- Detection of gravitational waves ➡ Testing of the strong field regime.
- Numerical Relativity enables us to compute those waveforms.



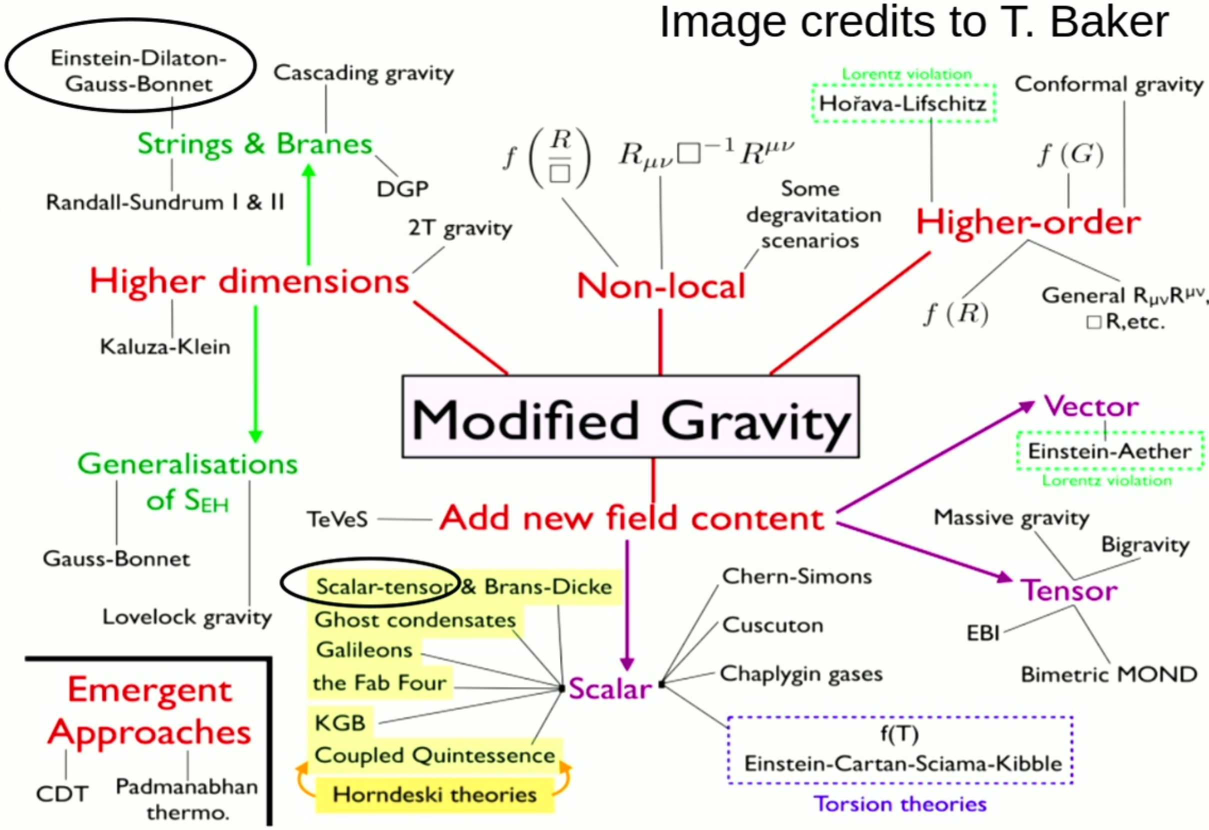
[Baker et al ‘15]



Modified gravity

Image credits to T. Baker

- Multiple possibilities for modifying gravity.
- Effective field theory.

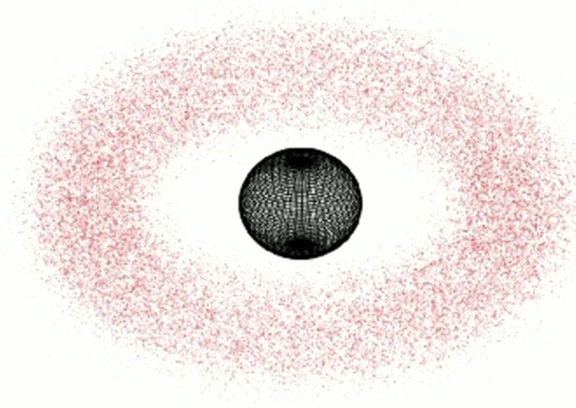


The theory

- We consider the Four-Derivative Scalar Tensor Theory of Gravity:

$$S=\int d^4 x\sqrt{-g}\left(R+X-V(\phi)+g_2(\phi)X^2+\lambda(\phi)\mathcal{L}^{GB}\right),$$
$$X=-\frac{1}{2}(\partial_\mu\phi)^2,\ \mathcal{L}^{GB}=R^2-4R_{\mu\nu}R^{\mu\nu}+R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

- It violates the No-Hair Theorem.

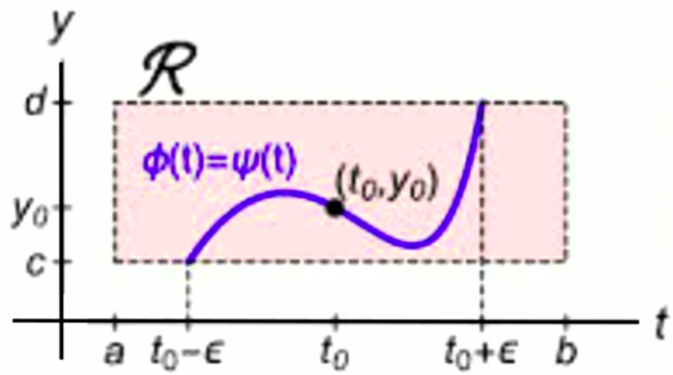


Well-posedness

- An initial value (or Cauchy) problem

$$\partial_t u = F(x^i, u, \partial_i u, \dots, \partial_{i_1} \dots \partial_{i_m} u, \dots)$$

$$u|_{t=0} = f(x^i)$$



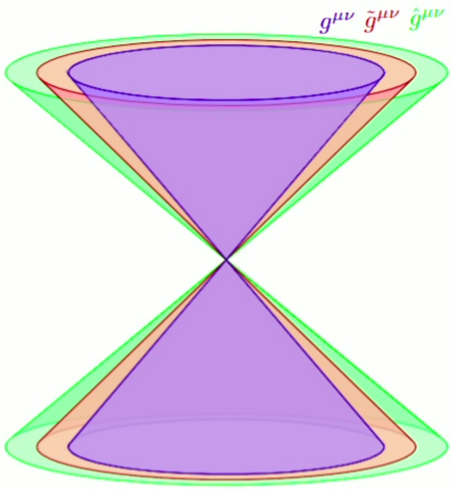
is (locally) well-posed if there exists a unique (local) solution for $t \in [0, T]$ for a given T>0 which depends smoothly on the initial data.

- Only well-posed initial value problems can lead to stable Numerical Relativity simulations.

Modified Harmonic Gauge

- Proposed in [Kovács and Reall '20].
- Well-posed formulation of weakly coupled Lovelock and Horndeski theories of gravity.
- Different propagation speeds for the unphysical modes.
- Implemented in EsGB [East and Ripley '21, Corman, Ripley and East '23].

[Kovács and Reall '20]

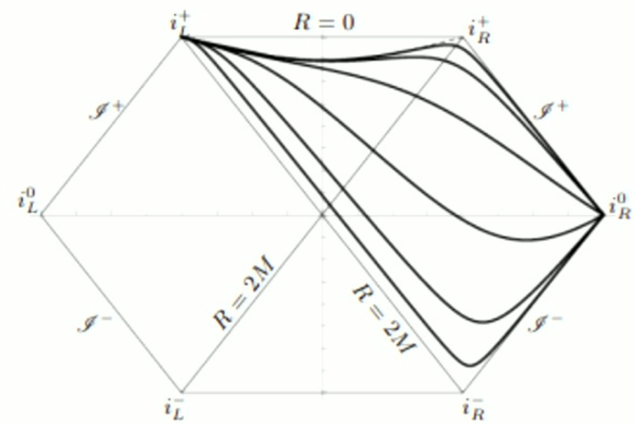


$$\tilde{g}^{\mu\nu} = g^{\mu\nu} - a(x) n^\mu n^\nu$$
$$\hat{g}^{\mu\nu} = g^{\mu\nu} - b(x) n^\mu n^\nu$$
$$0 < a(x) < b(x)$$

Our formulation

- Moving puncture gauge (singularity-avoiding coordinates).
- 1+log slicing for the lapse and Gamma driver for the shift:

$$\partial_t\alpha \;=\; \beta^i\partial_i\alpha - 2\alpha(K-2\Theta),$$
$$\partial_t\beta^i \;=\; \beta^j\partial_j\beta^i + \tfrac{d}{2(d-1)}\hat{\Gamma}^i\,,$$



[Hannam et al ‘08]

which yield in the modified approach as

$$\partial_t\alpha = \beta^i\partial_i\alpha - \tfrac{2\alpha}{1+a(x)}(K-2\Theta),$$
$$\partial_t\beta^i = \beta^j\partial_j\beta^i + \tfrac{d}{2(d-1)}\,\tfrac{\hat{\Gamma}^i}{1+a(x)} - \tfrac{a(x)\alpha D^i\alpha}{1+a(x)}.$$

Modified Harmonic Gauge

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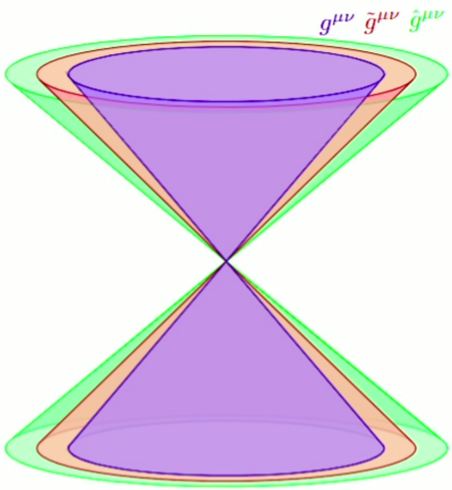


$$\tilde{g}^{\mu\nu} = g^{\mu\nu} - a(x) n^{\mu} n^{\nu}$$
$$\hat{g}^{\mu\nu} = g^{\mu\nu} - b(x) n^{\mu} n^{\nu}$$
$$0 < a(x) < b(x)$$

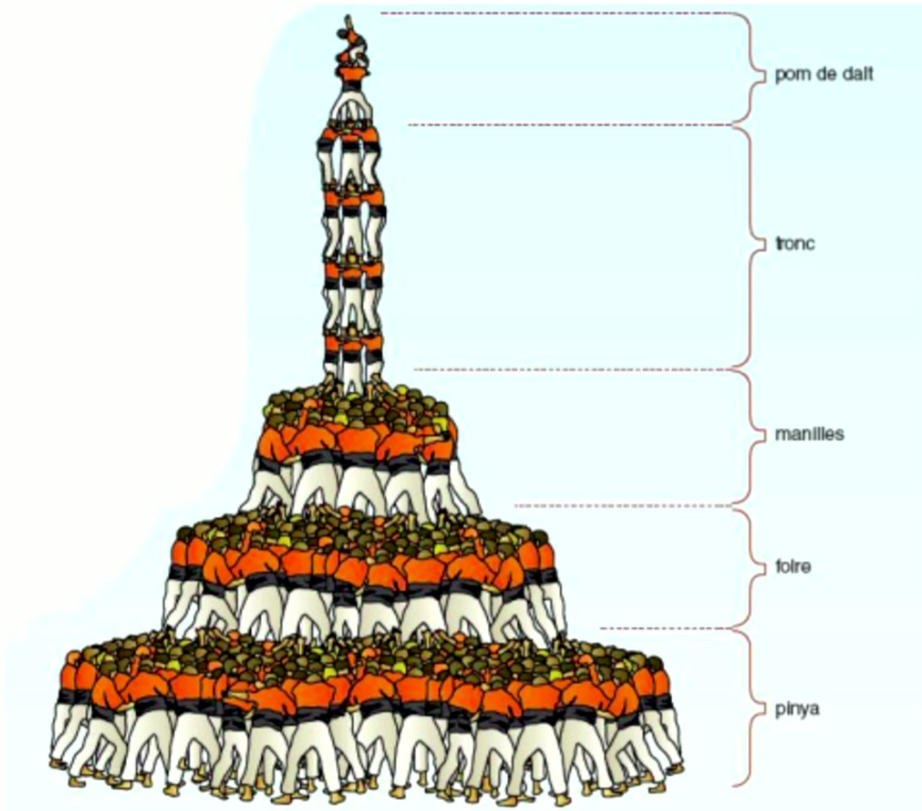
Results

$$S=\int d^4x\sqrt{-g}\left(R+X+g_2(\phi)X^2+\lambda(\phi)\mathcal{L}^{GB}\right)$$

$$X=-\frac{1}{2}(\partial_\mu\phi)^2,\ \mathcal{L}^{GB}=R^2-4R_{\mu\nu}R^{\mu\nu}+R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

- Well-posed in our modified CCZ4 formulation in the weakly coupled regime.
- Implemented in its full non-linear form in **GRFolres** [LAS et al '23], an extension of **GRChombo,** https://github.com/GRTLCollaboration/GRFolres**.**

GRFolres



GRAVITY

...

Higher derivatives (GRManilles??)

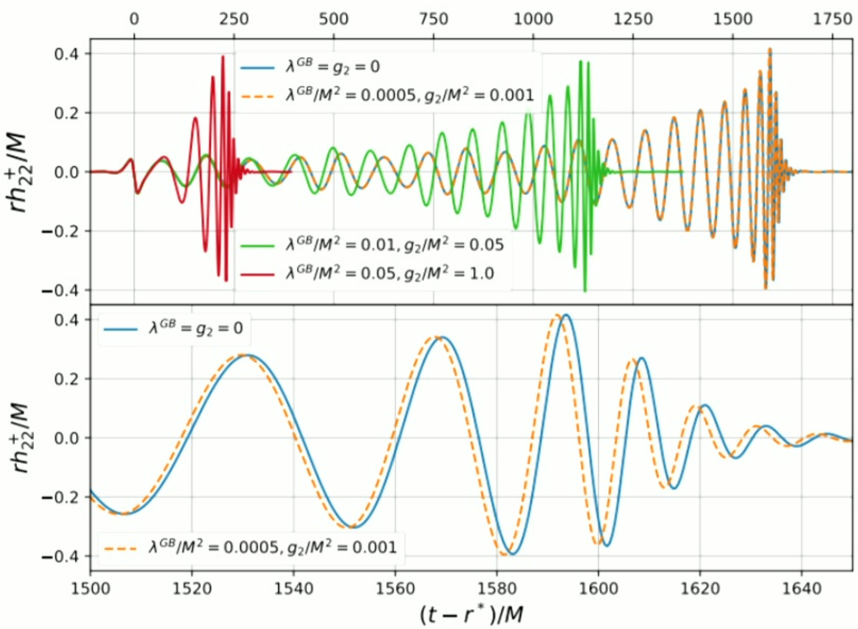
4∂ST (GRFolres)

GR (GRChombo / GRTeclyn)

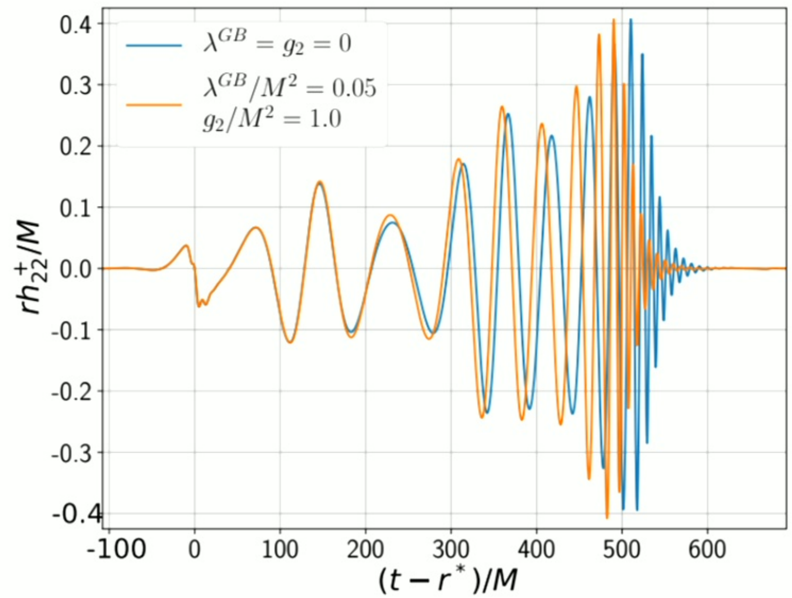
Shift-symmetric 4∂ST theory

- All Black Hole solutions are hairy.

$$\lambda(\phi)=\frac{1}{4}\lambda^{GB}\phi \qquad g_2(\phi)=g_2$$



Non-spinning Black Hole binaries
[LAS, Clough and Figueras '22]

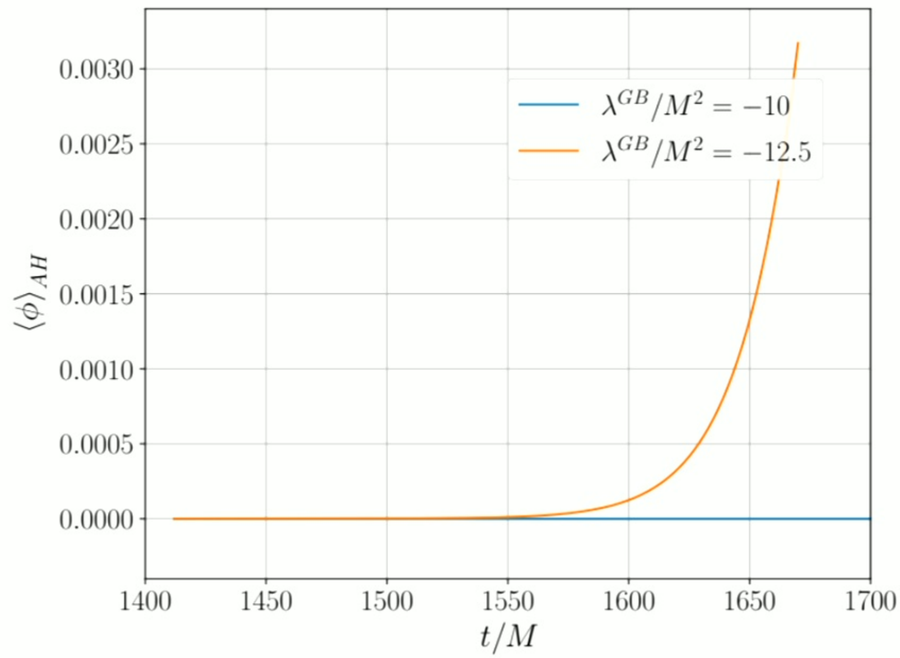


Initially spinning Black Hole binaries
[LAS, Clough and Figueras '23]

Quadratic EsGB

$$\lambda(\phi)=\frac{1}{4}\lambda^{GB}\phi^2$$

- Studied in [Silva et al '21, Elley et al '22] without backreaction.
- Hairy and non-hairy Black Holes.
- Spin-induced tachyonic instability that triggers spontaneous scalarisation [Silva, Sakstein, Gualtieri, Sotiriou and Berti '18].



[LAS, Clough and Figueras '23]

Exponential quadratic EsGB

$$\lambda(\phi) = \frac{1}{4\sigma}\lambda^{GB}\left(1 - e^{-\sigma\phi^2}\right)$$

- Proposed in [Doneva et al '22].
- Spin-induced scalarisation.
- Stable hairy Black Hole Merger.

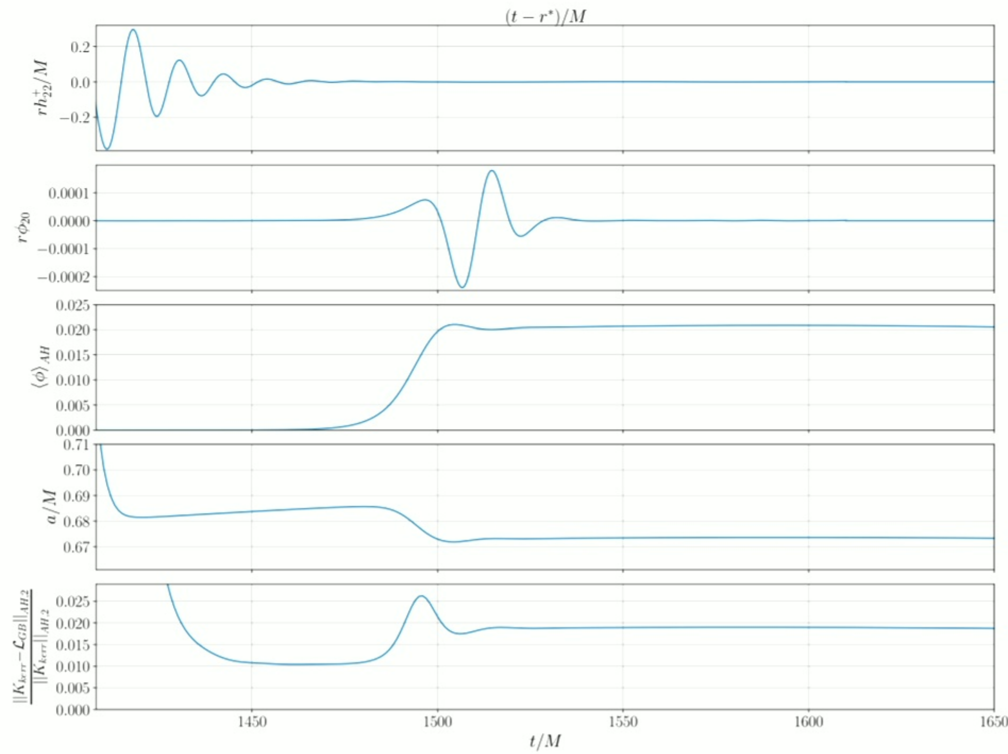
Grav. strain

Scalar radiation

Exp. value of ϕ at the Merger's AH

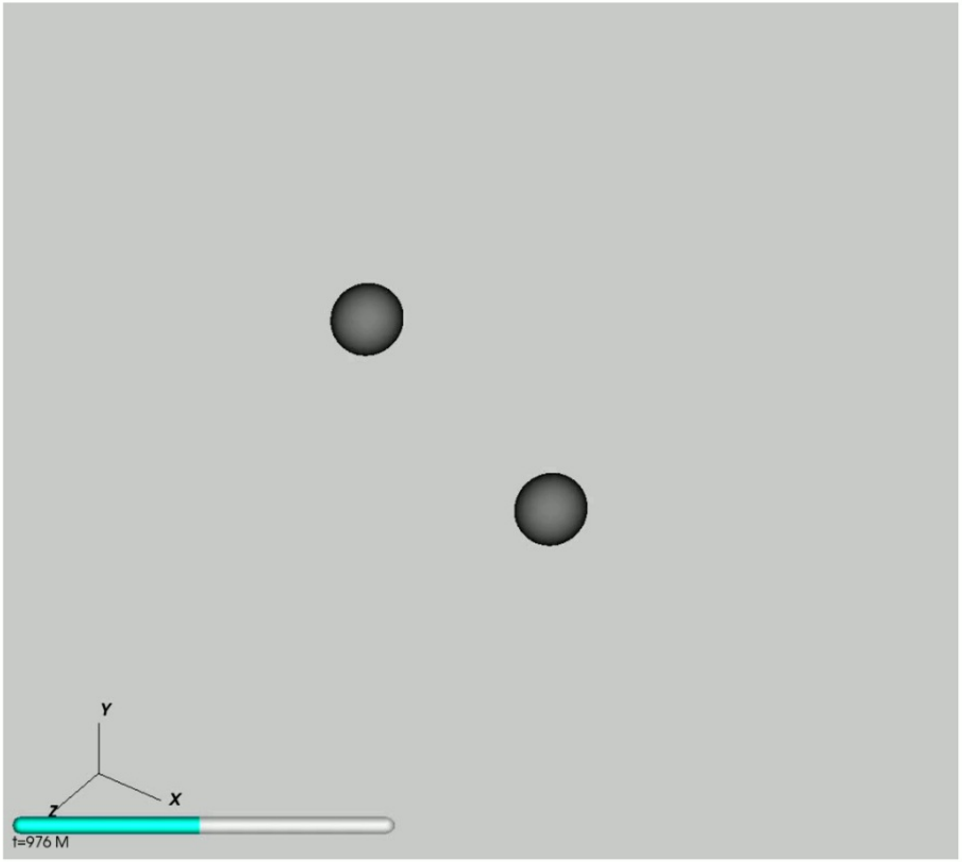
Spin

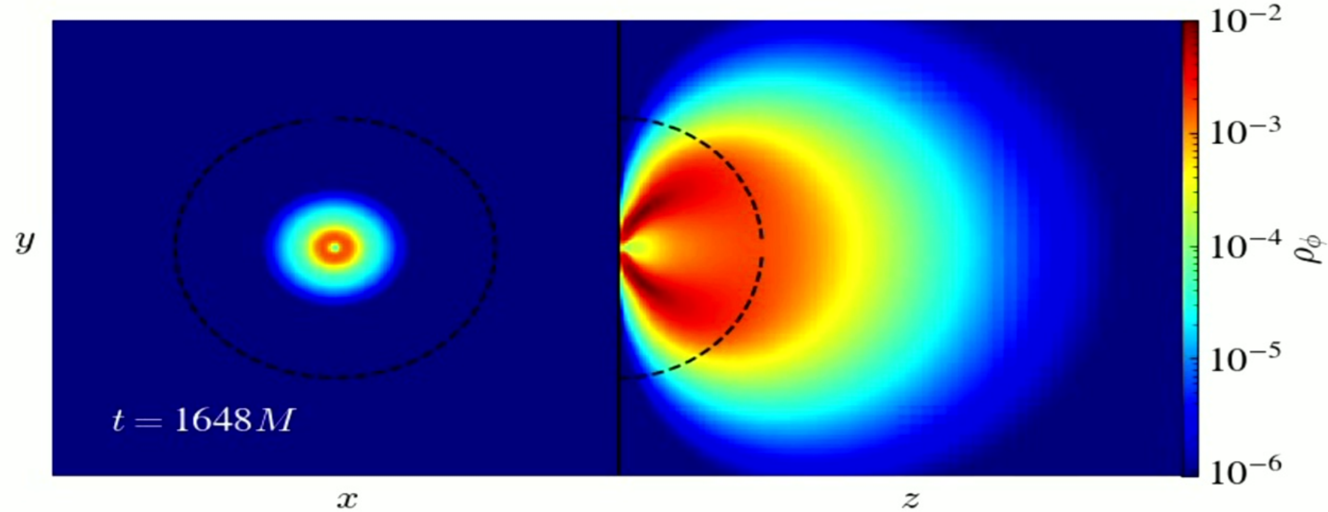
Deviation from Kerr's Kretschmann



[LAS, Clough and Figueras '23]

Exponential quadratic EsGB

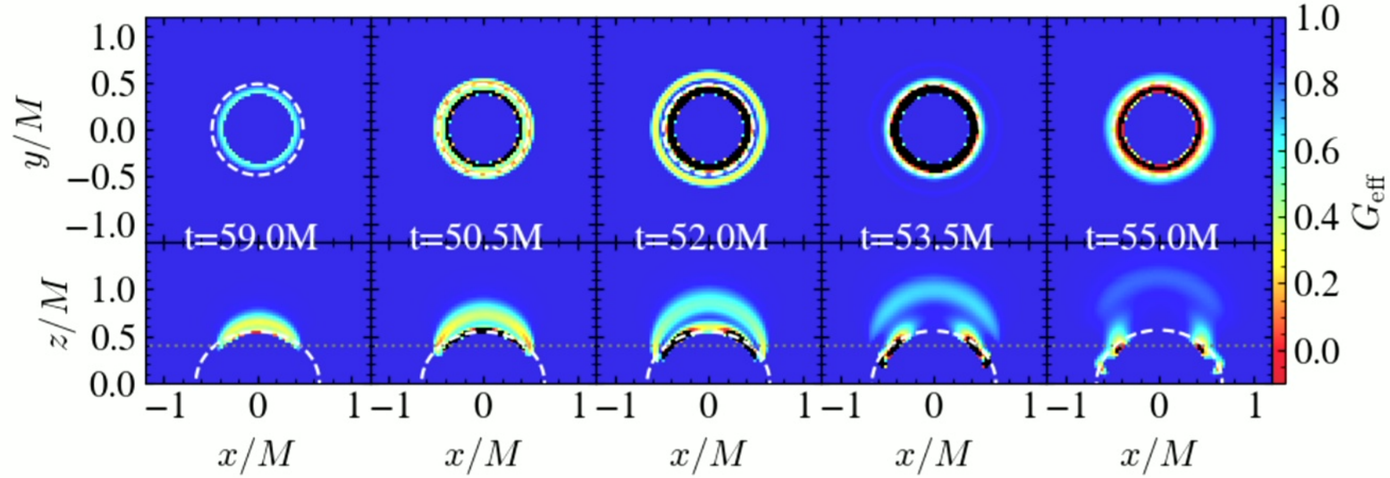




10^{-2}
10^{-3}
10^{-4}
ρ_ϕ
10^{-5}
10^{-6}
y
$t = 1648M$
x
z

Hyperbolicity loss

- Some of the physical modes lie on the null cone of an effective metric.
- The change of sign of its determinant determines the transition from a hyperbolic system to an elliptic system.

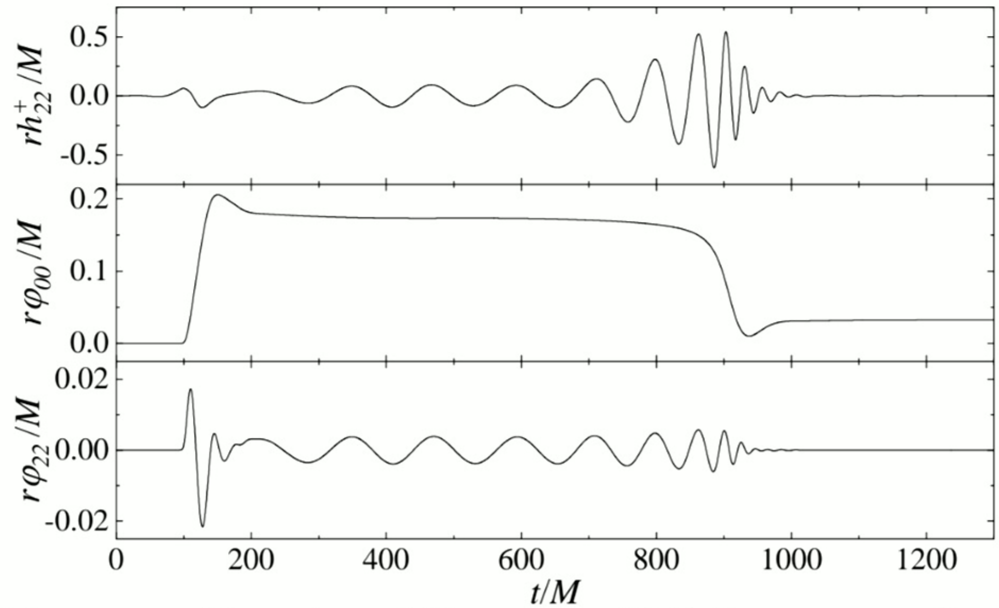


[Doneva, LAS, Clough, Figueras and Yazadjev ‘23]

See also [Ripley and Pretorius ‘19]

Non-equal mass binaries

- We have been able to evolve non-equal mass binaries with mass ratios 1:2 and 1:3

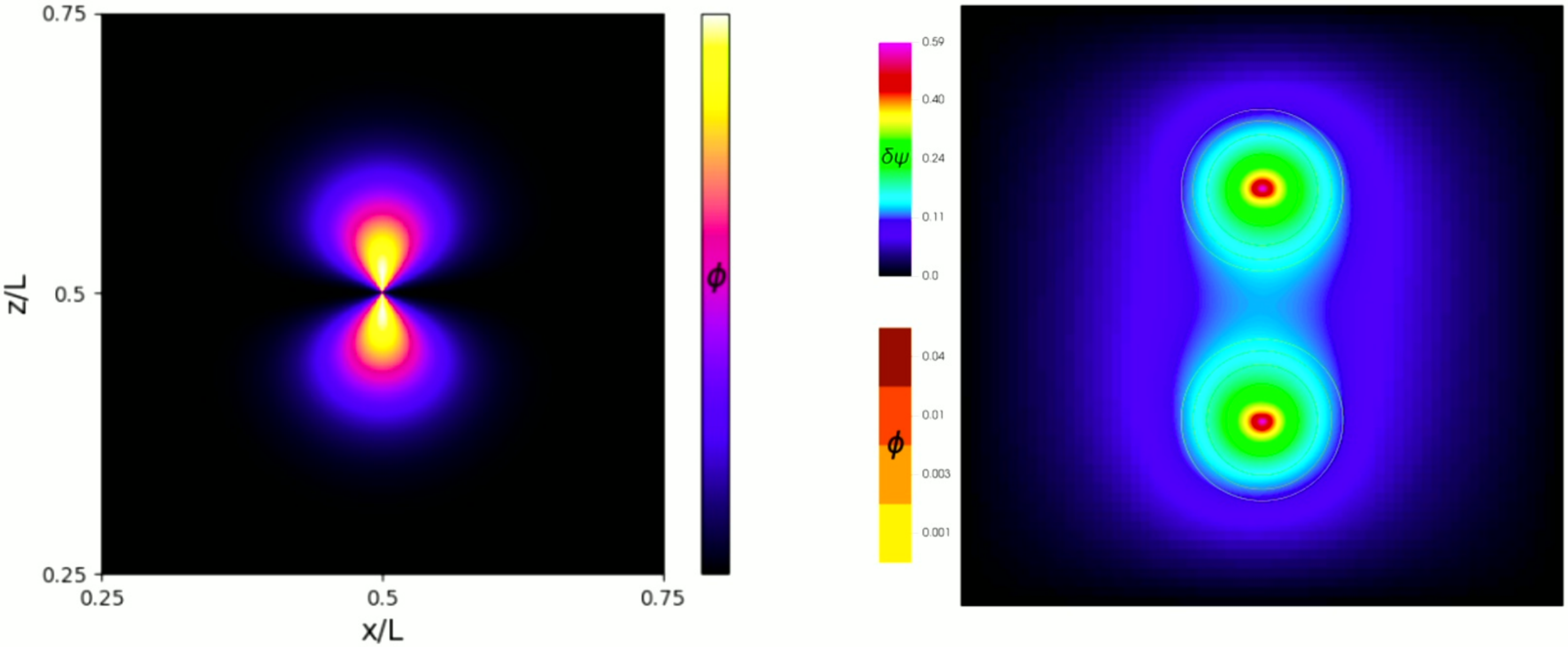


[LAS, Doneva, Clough, Figueras, Rossi and Yazadjev '24] (in preparation)

See also [Corman, Ripley and East '23]

Initial conditions

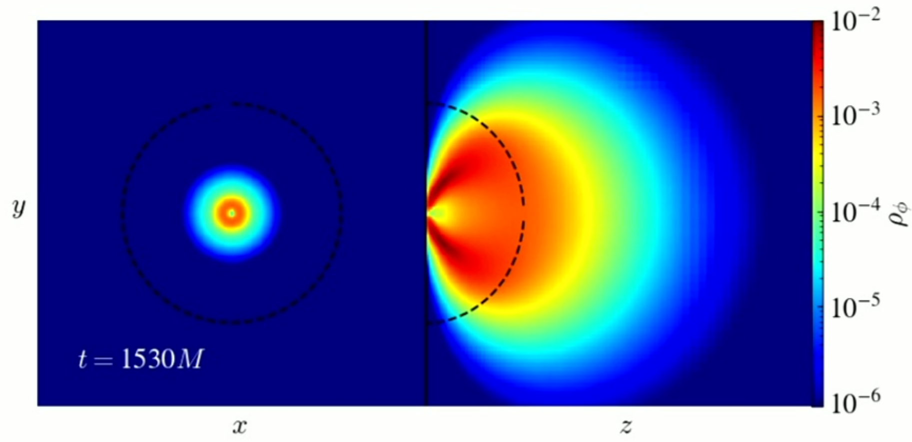
- CTTK method [Aurrekoetxea, Clough and Lim ‘22]



[Brady, LAS, Clough, Figueras and P.S. ‘23]

Summary

- Well-posed formulation in singularity-avoiding coordinates of the 4∂ST theory.
- Equal and non-equal mass binaries simulations in the full non-linear theory.
- Non-trivial dynamics for the scalar field.



Further directions

- Introduce hydrodynamics - Neutron Stars.
- Cosmological spacetimes – inflation.
- Black strings in 5-dimensional Lovelock theories.