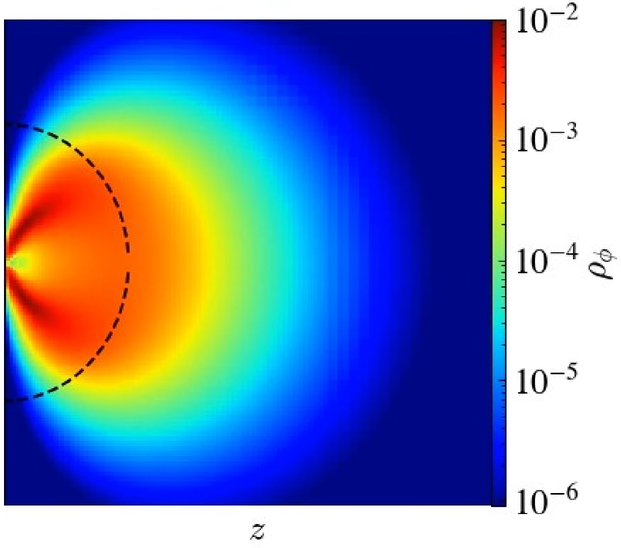
Non-linear dynamics in modified gravity



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Pollica, 19th September 2024

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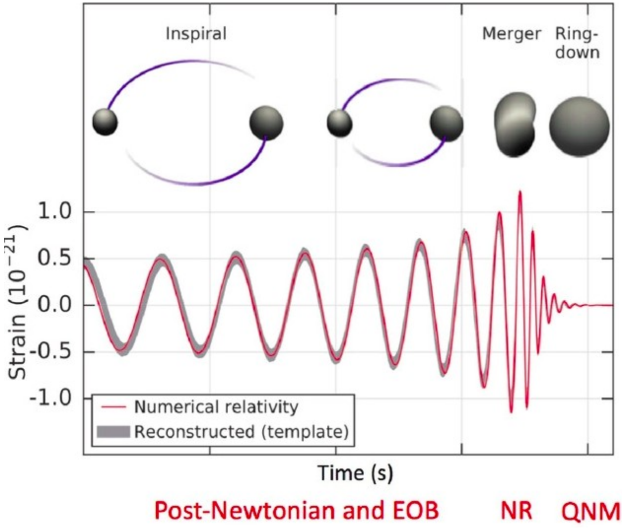
GRChombo

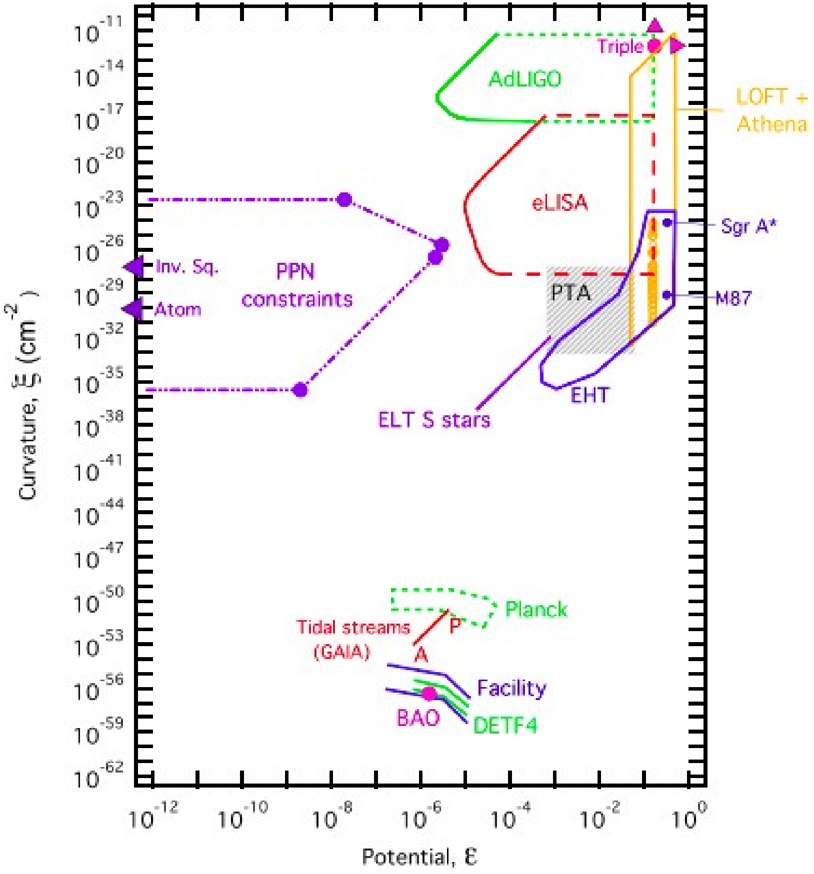
Contents

Motivation

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



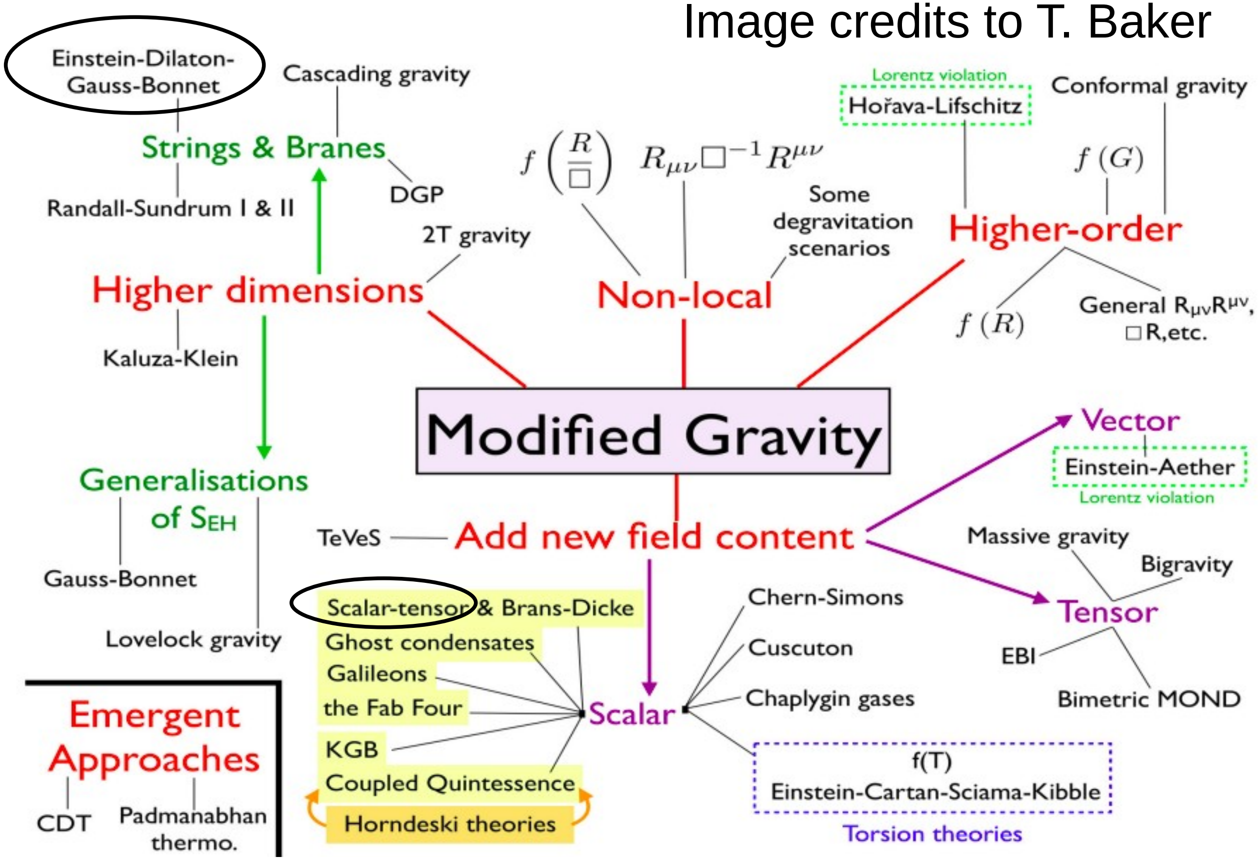
[Baker et al ‘15]



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:

$$S=\int d^4x\sqrt{-g}\Big(\underbrace{R+X-V(\phi)}_{2^{nd}\text{ deriv.}}+\underbrace{g_2(\phi)X^2+\lambda(\phi)\mathcal{L}^{GB}}_{4^{th}\text{ deriv.}}\Big),$$

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

which yields Einstein-scalar-Gauss-Bonnet (EsGB) when $V(\phi)=g_2=0$.

- It violates the No-Hair Theorem.
- It is an EFT of gravity in the weak coupling regime:

$$\lambda(\phi),g_2(\phi)\ll L^2,$$

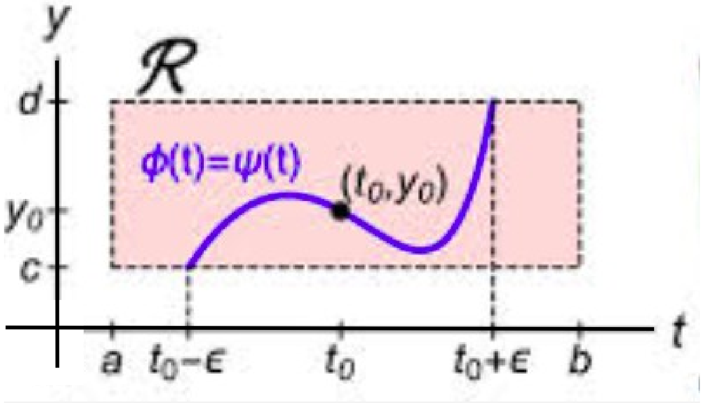
where L is the characteristic length of the system.

Well-posedness

- An initial value (or Cauchy) problem

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

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



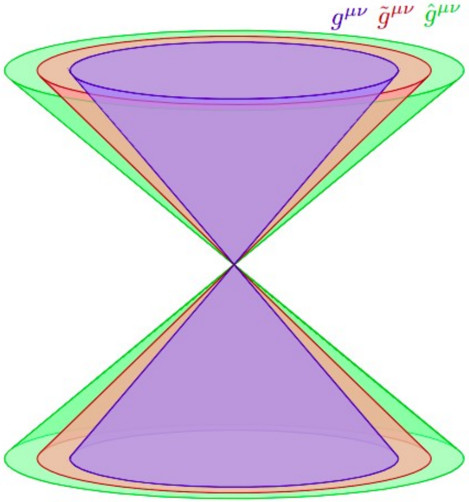
is (locally) well-posed if there exists a unique (local) solution for $t \in [0, T]$ for a given T>0 which depends smoothly on the initial data.

- 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 in GHC coordinates [East and Ripley ‘21, Corman, Ripley and East ‘23, Corman and East ‘24].

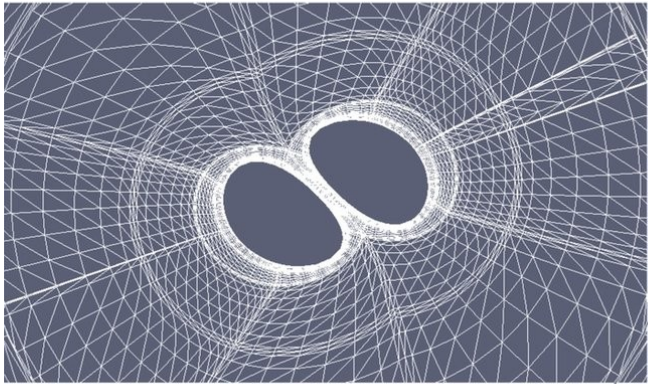
[Kovács and Reall ‘20]

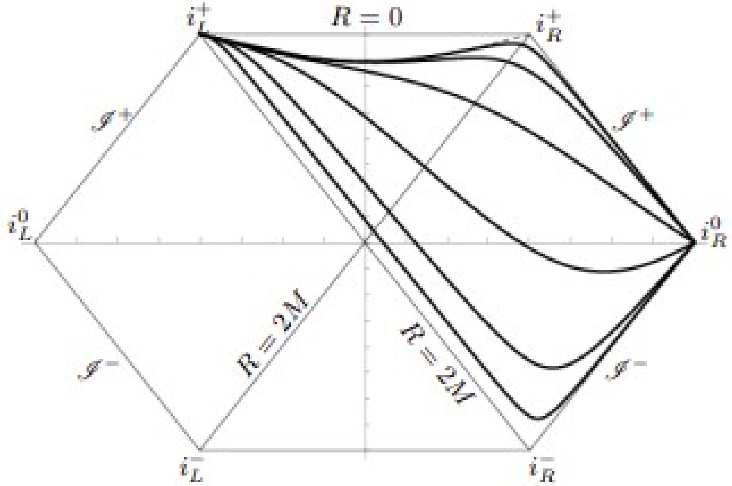


$$\tilde{g}^{\mu\nu} = g^{\mu\nu} - a(x)n^\mu n^\nu$$
$$\hat{g}^{\mu\nu} = g^{\mu\nu} - b(x)n^\mu n^\nu$$
$$0 < a(x) < b(x)$$

Our formulation

- Moving puncture gauge (singularity-avoiding coordinates).
- It does not need excision of the inner horizon





[Hannam et al ‘08]

Results

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

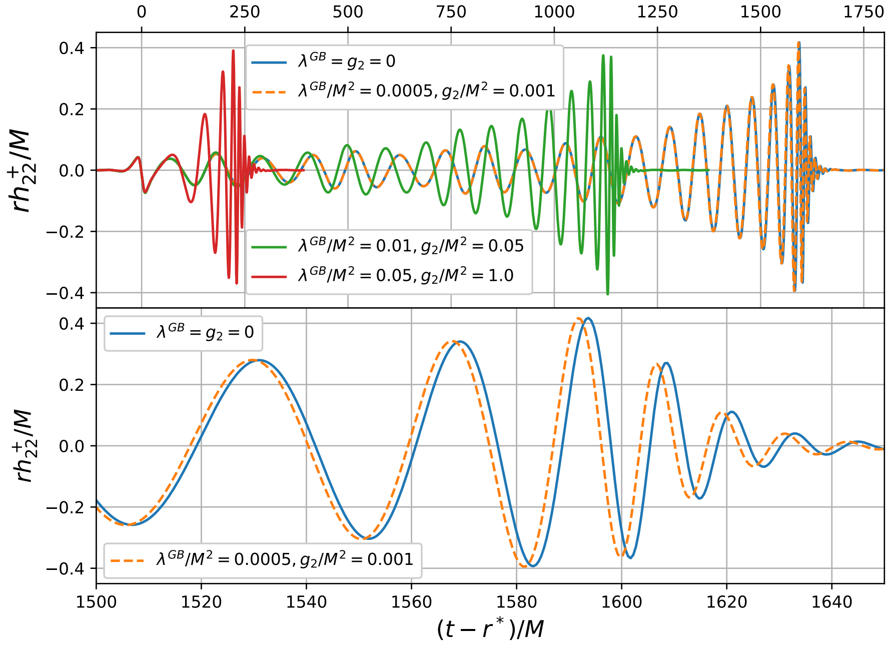
$$X = -\frac{1}{2} (\partial_\mu \phi)^2 , \mathcal{L}^{GB} = R^2 - 4 R_{\mu\nu} R^{\mu\nu} + R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}$$

- 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**.**

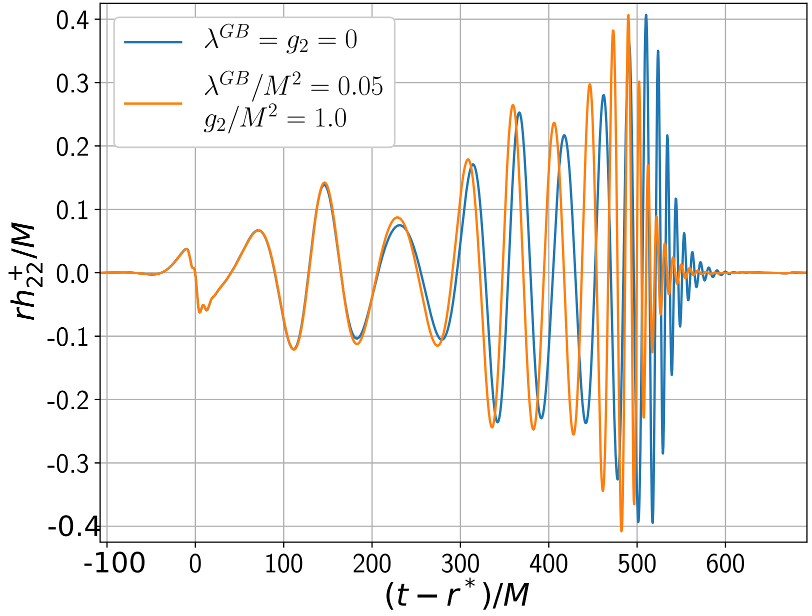
Shift-symmetric 4∂ST theory

- 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]

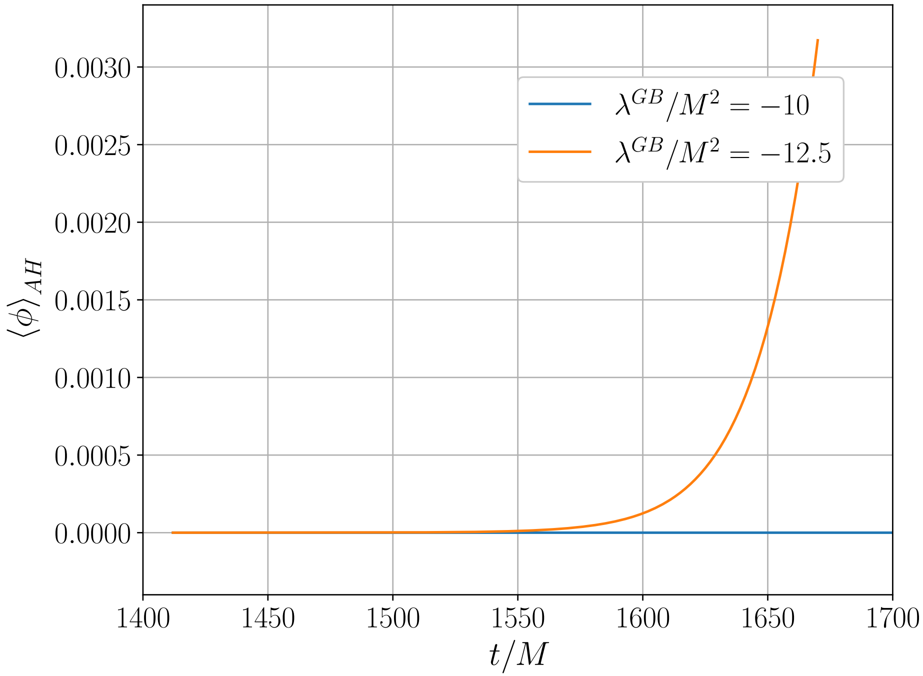


Initially spinning Black Hole binaries
[LAS, Clough and Figueras '23]

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 scala-risation [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.

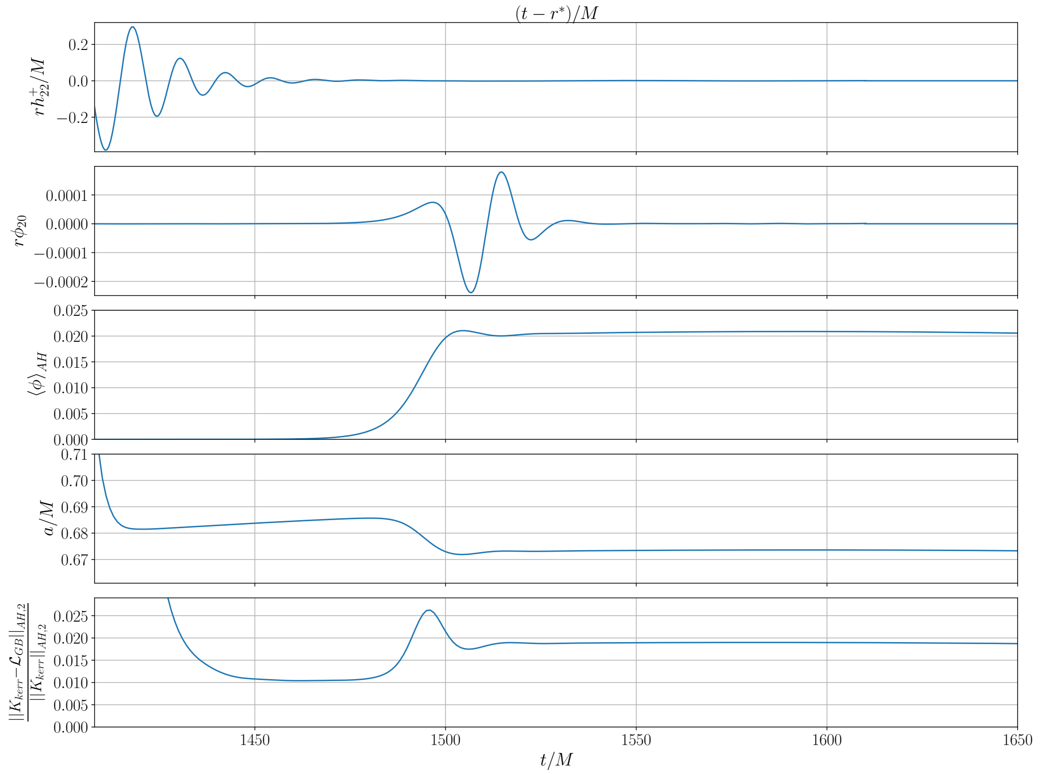
Grav. strain

Scalar radiation

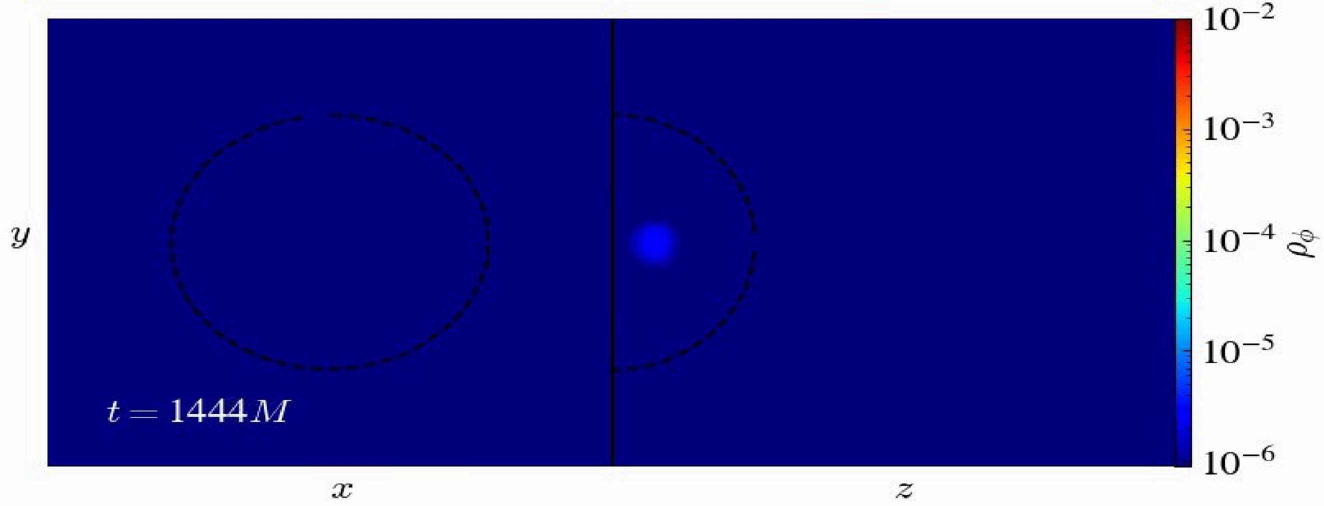
Exp. value of ϕ at the Merger’s AH

Spin

Deviation from Kerr’s Kretschmann



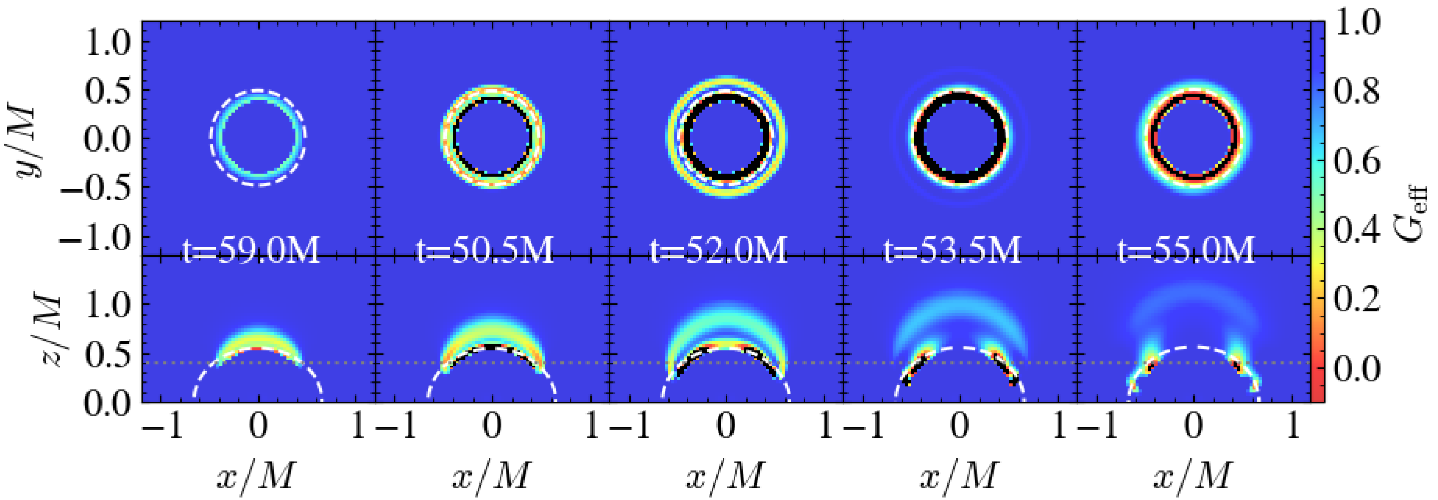
[LAS, Clough and Figueras ‘23]



$t = 1444M$
y
x
z
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ρ_ϕ

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.

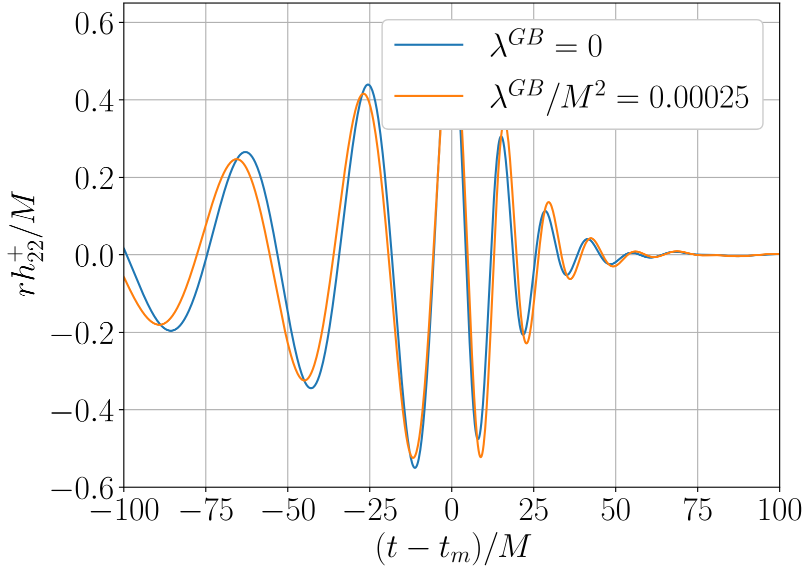


[Doneva, LAS, Clough, Figueras and Yazadjev ‘23]

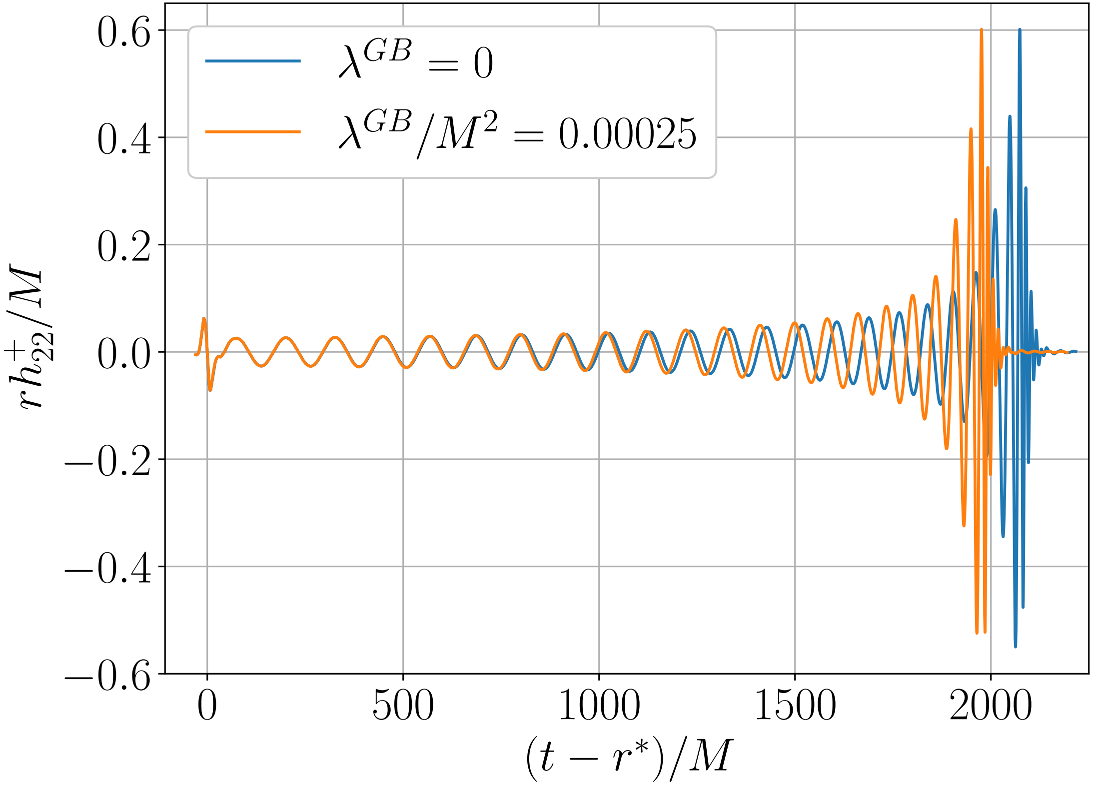
See also [Ripley and Pretorius ‘19]

Non-equal mass binaries

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



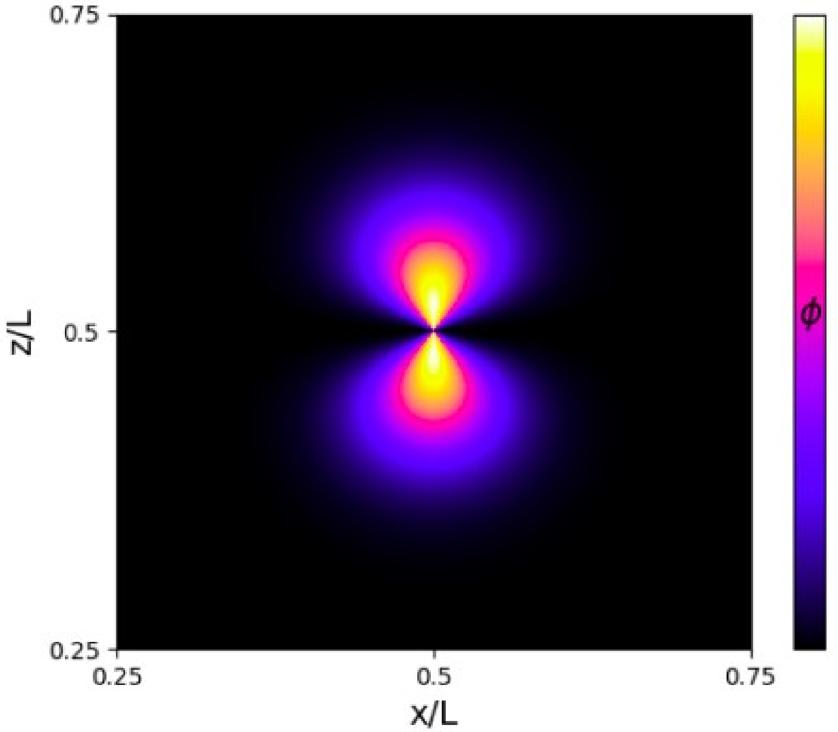
See also [Corman, Ripley and East '23]

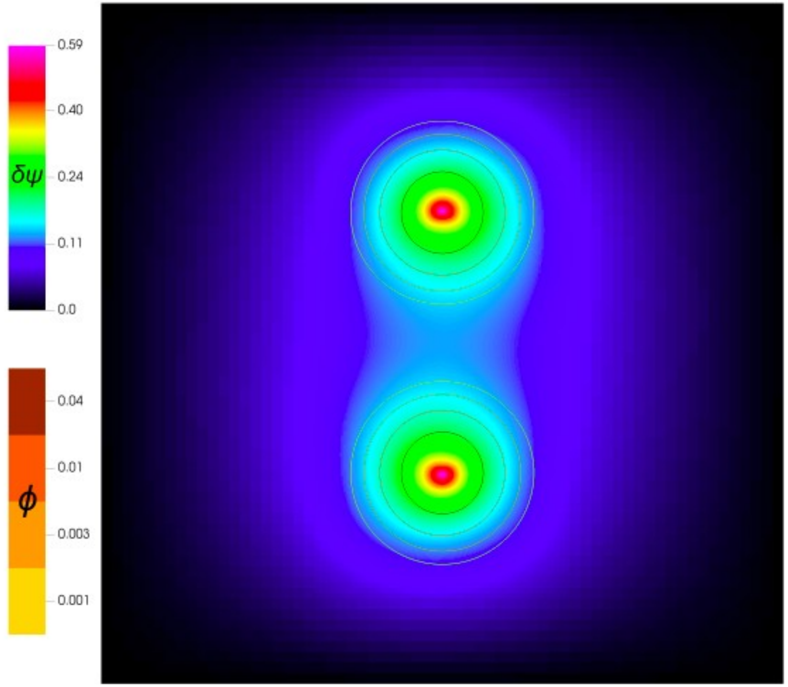


[Doneva, LAS, Clough, Figueras and Yazadjev '24] (in preparation)

Initial conditions

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

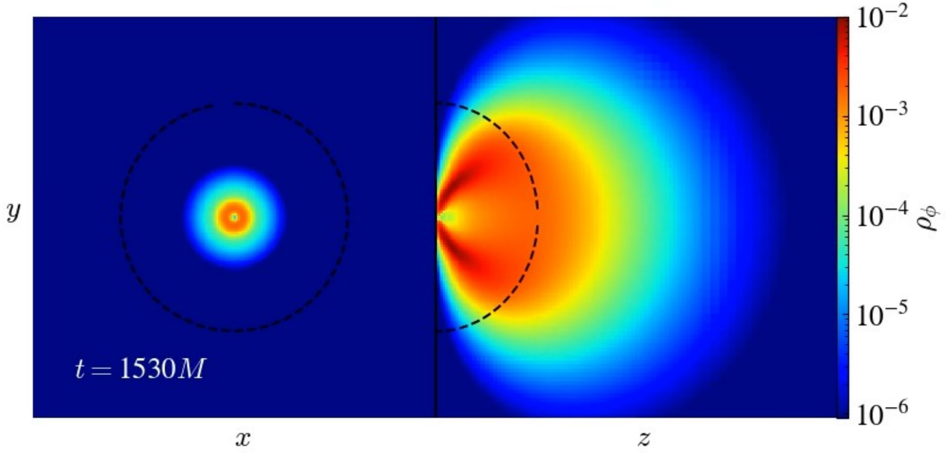




[Brady, LAS, Clough, Figueras and P.S. '23]

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 work

- Make our modified gravity waveforms available to the community.
- Understand whether modified gravity effects are degenerate with environmental effects, a shift in GR parameters...
- Explore other high derivative theories (see [Held, Figueras, Kovács ‘24])

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THANK YOU FOR YOUR ATTENTION!