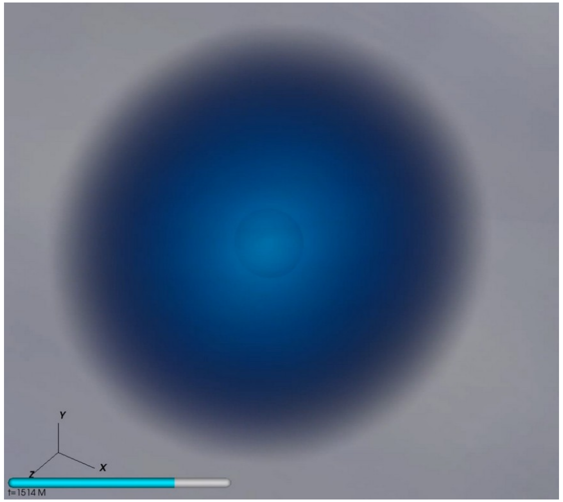
Non-linear dynamics in modified gravity



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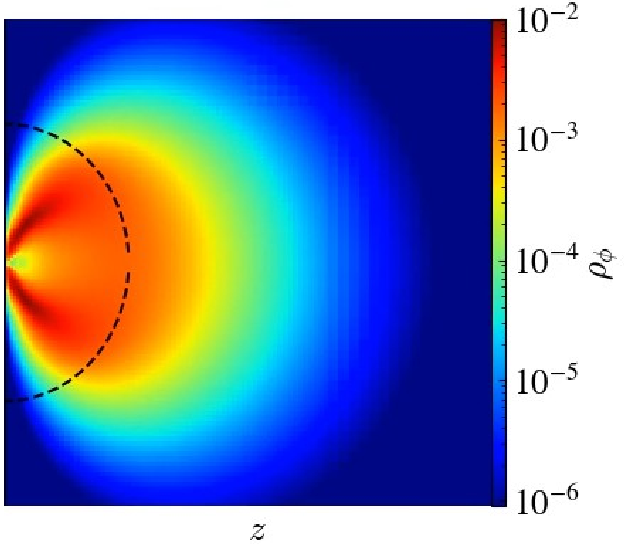

AEI, Potsdam, 3rd September 2024

Queen Mary University of London
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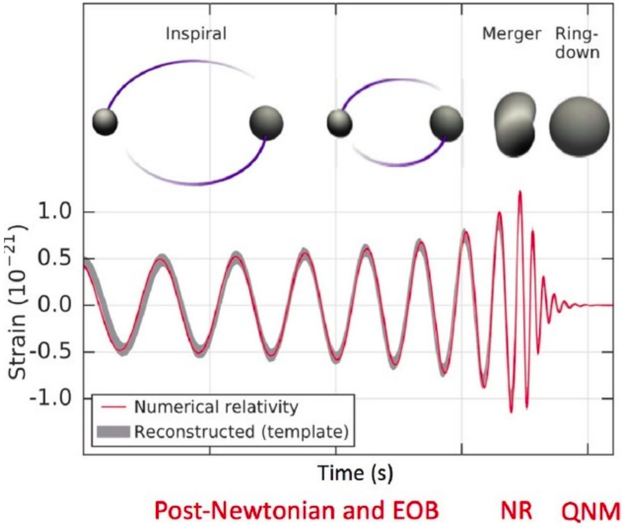
GRCHOMBO

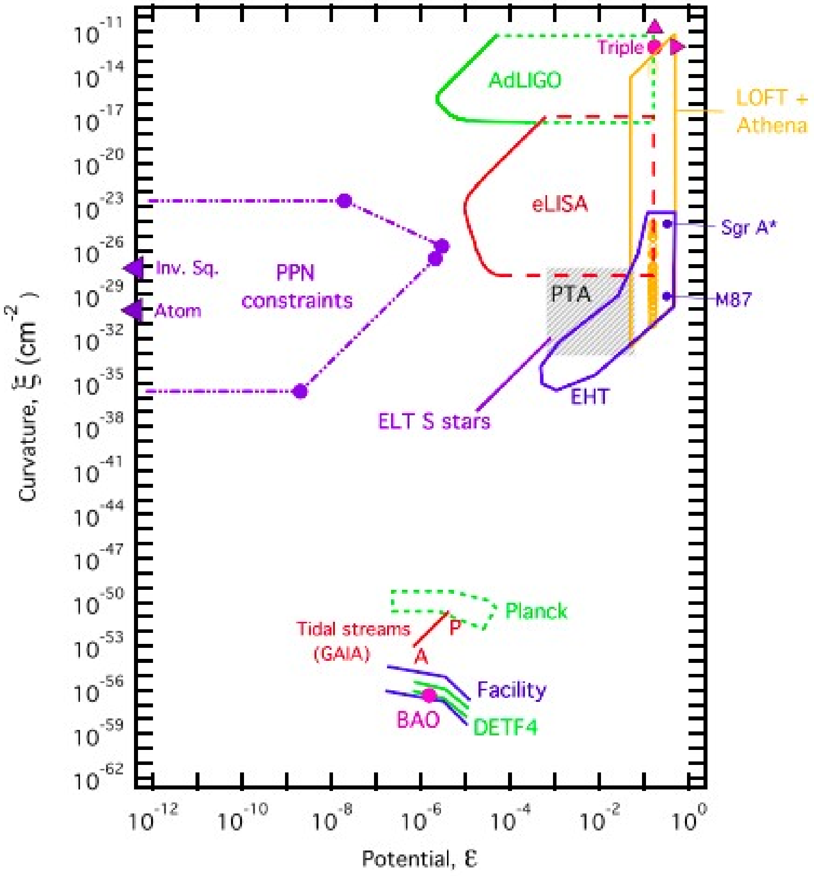
Contents

Motivation

[Baker et al '15]

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

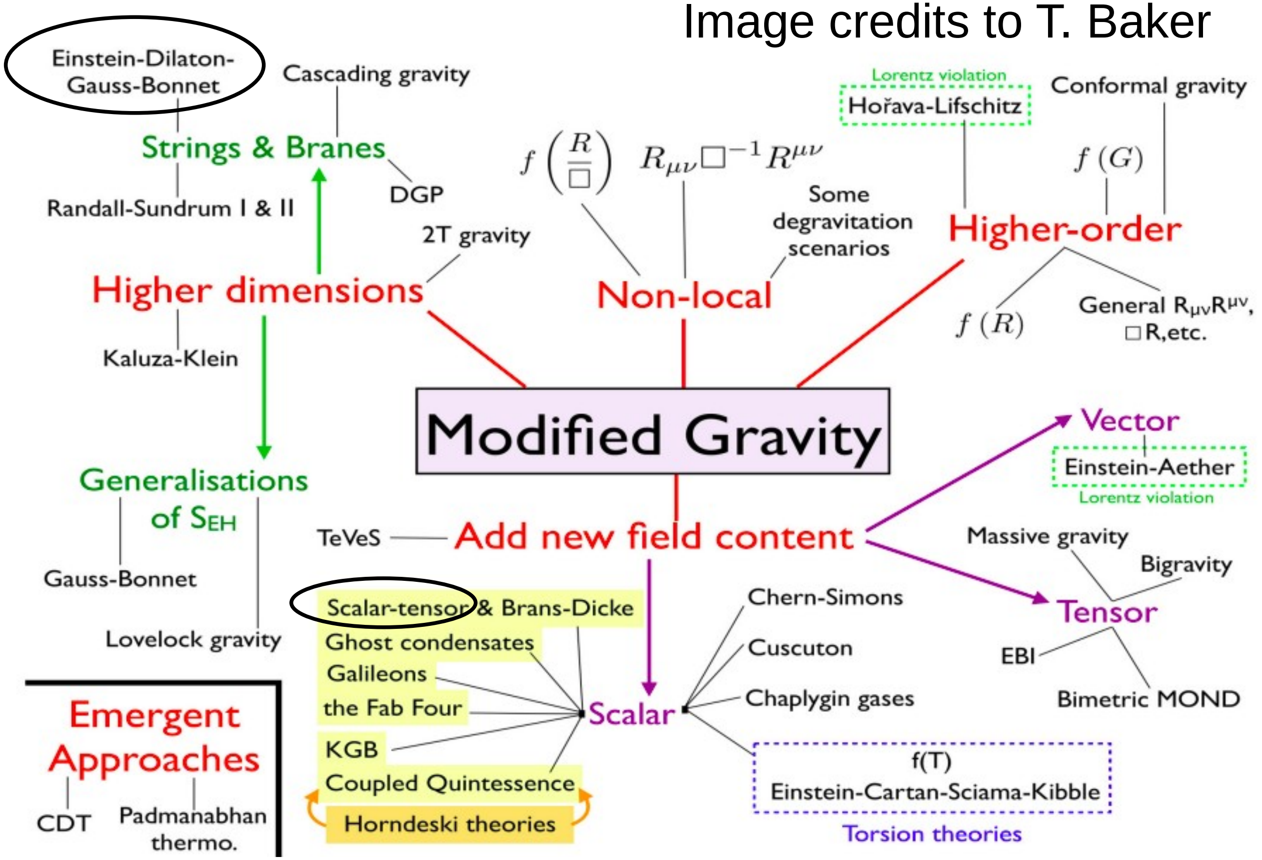




Modified gravity

Image credits to T. Baker

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



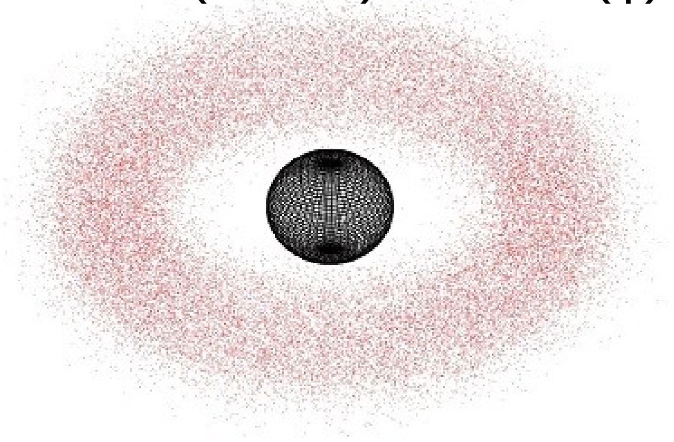
The theory

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

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

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

- It violates the No-Hair Theorem.

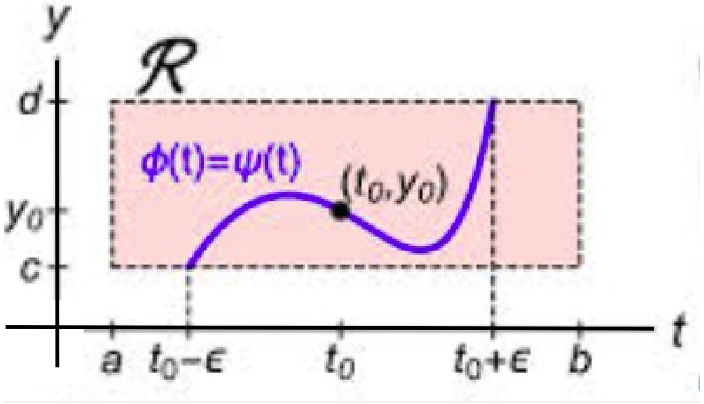


Well-posedness

- An initial value (or Cauchy) problem

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

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

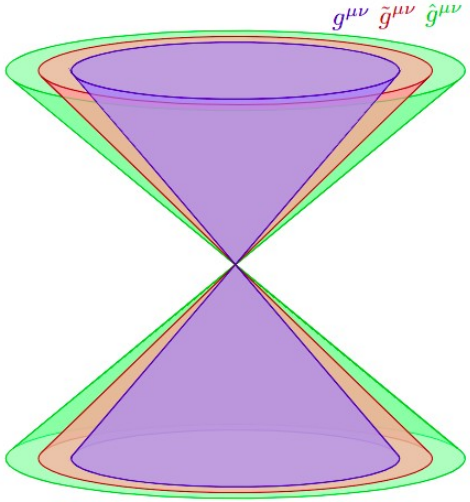


is (locally) well-posed if there exists a unique (local) solution for $t \in [0, T]$ for a given T>0 which depends smoothly on the initial data.

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

Modified Harmonic Gauge

[Kovács and Reall ‘20]



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

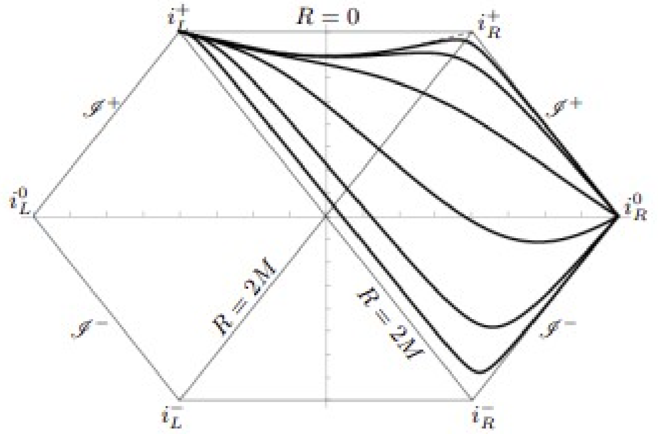
- Proposed in [Kovács and Reall ‘20].
- Well-posed formulation of weakly coupled Lovelock and Horndeski theories of gravity.
- Different propagation speeds for the unphysical modes.
- Implemented in EsGB [East and Ripley ‘21, Corman, Ripley and East ‘23, Corman and East ‘24].

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

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

Results

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

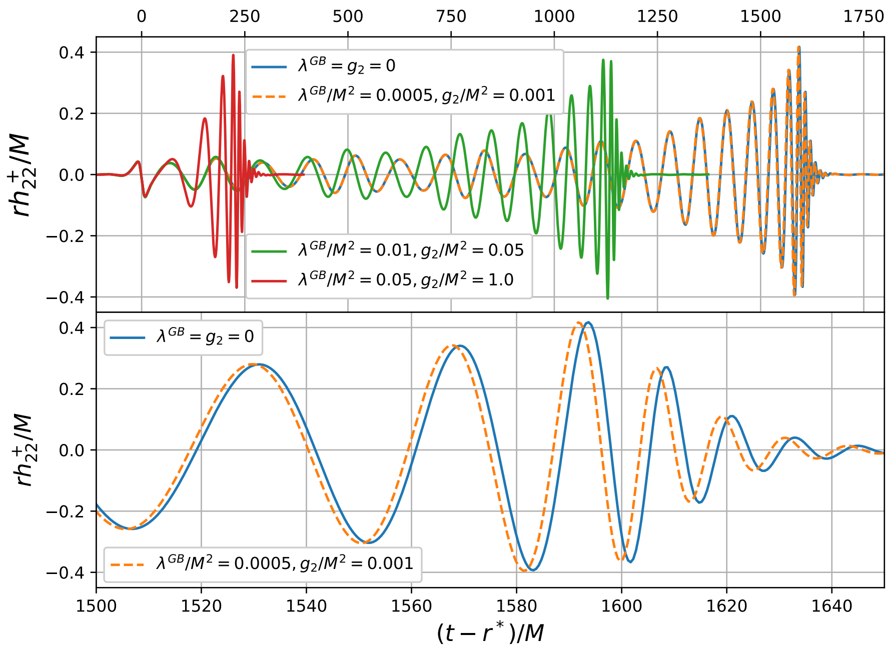
$$X=-\frac{1}{2}(\partial_\mu\phi)^2,\ \mathcal{L}^{GB}=R^2-4R_{\mu\nu}R^{\mu\nu}+R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

- 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**.**

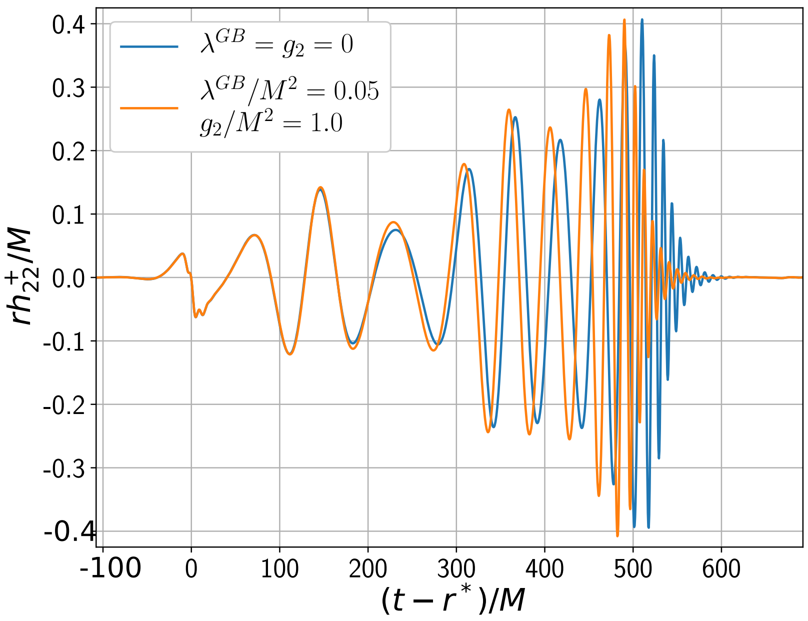
Shift-symmetric 4∂ST theory

- 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]

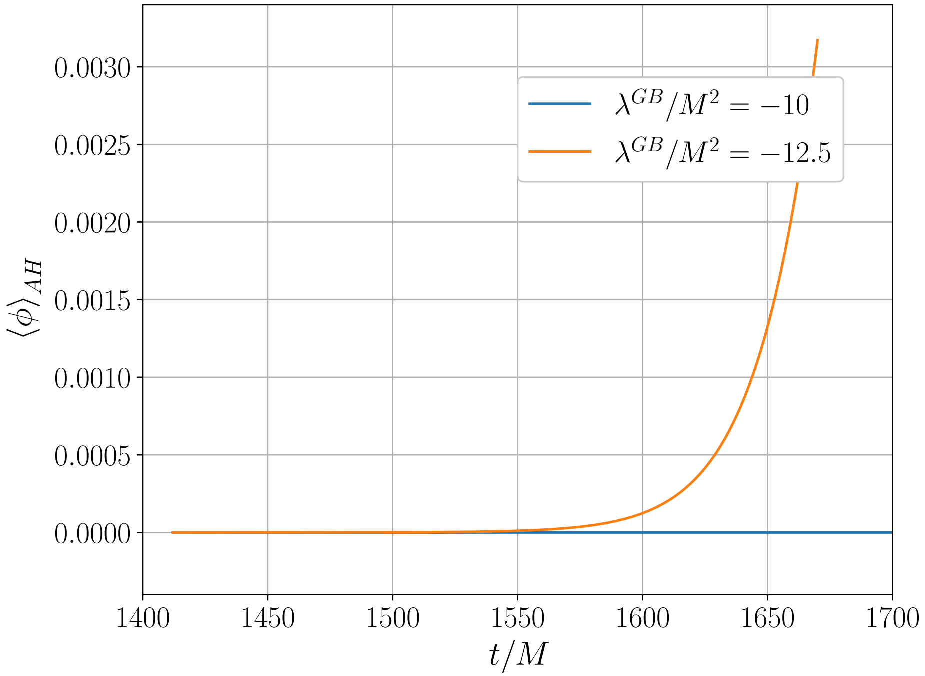


Initially spinning Black Hole binaries
[LAS, Clough and Figueras '23]

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.

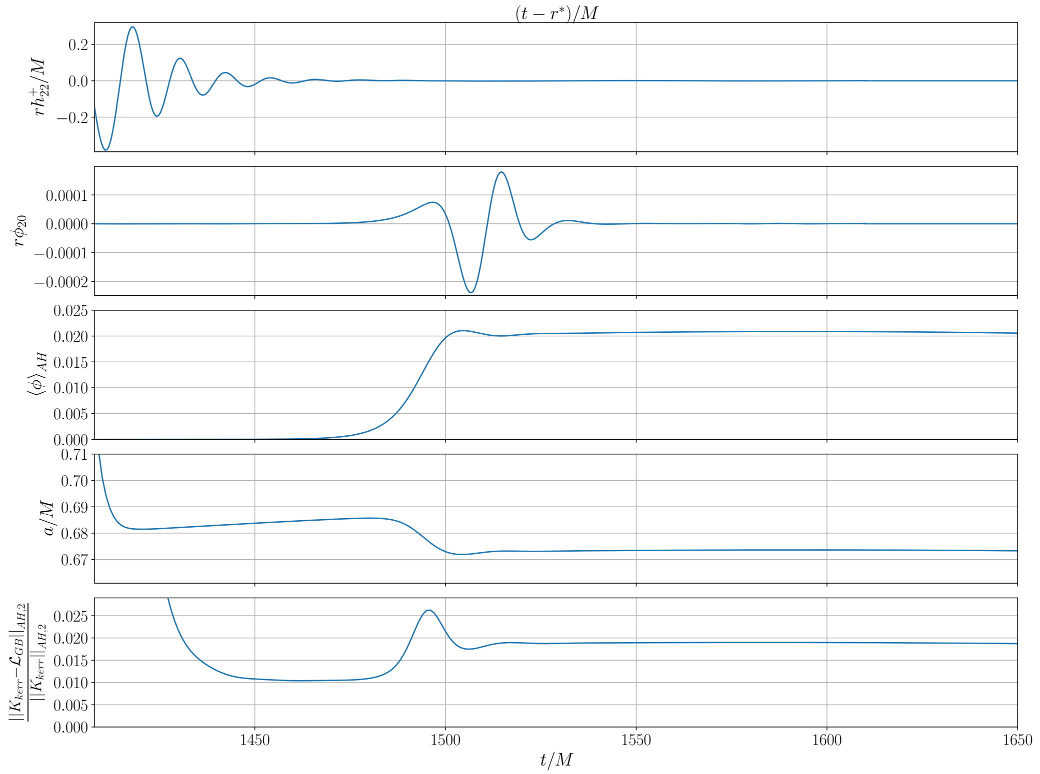
Grav. strain

Scalar radiation

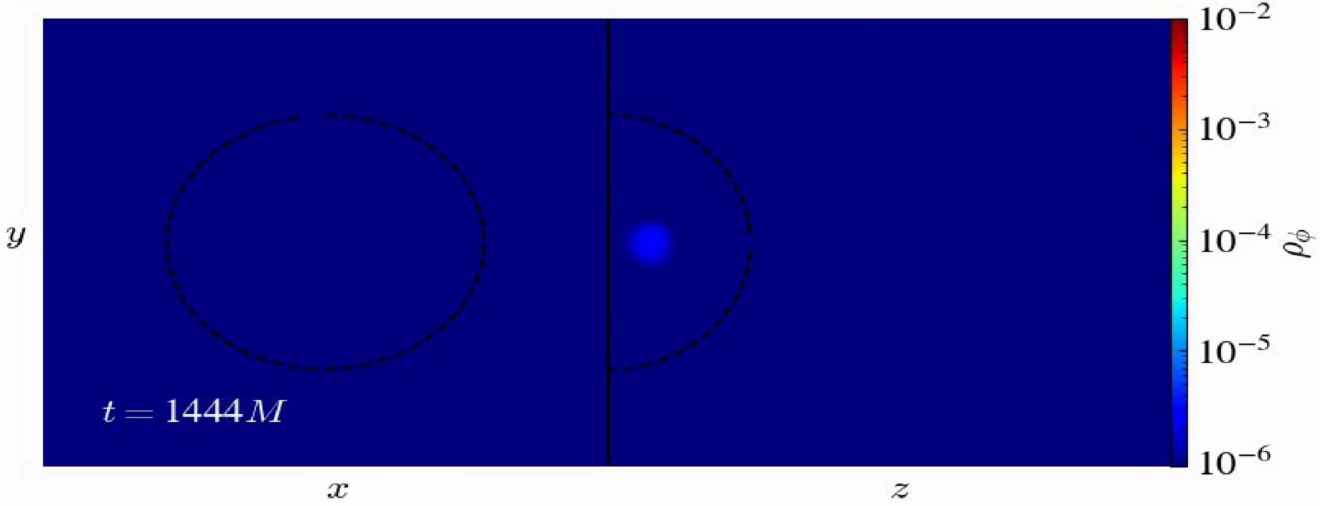
Exp. value of ϕ at the Merger's AH

Spin

Deviation from Kerr's Kretschmann



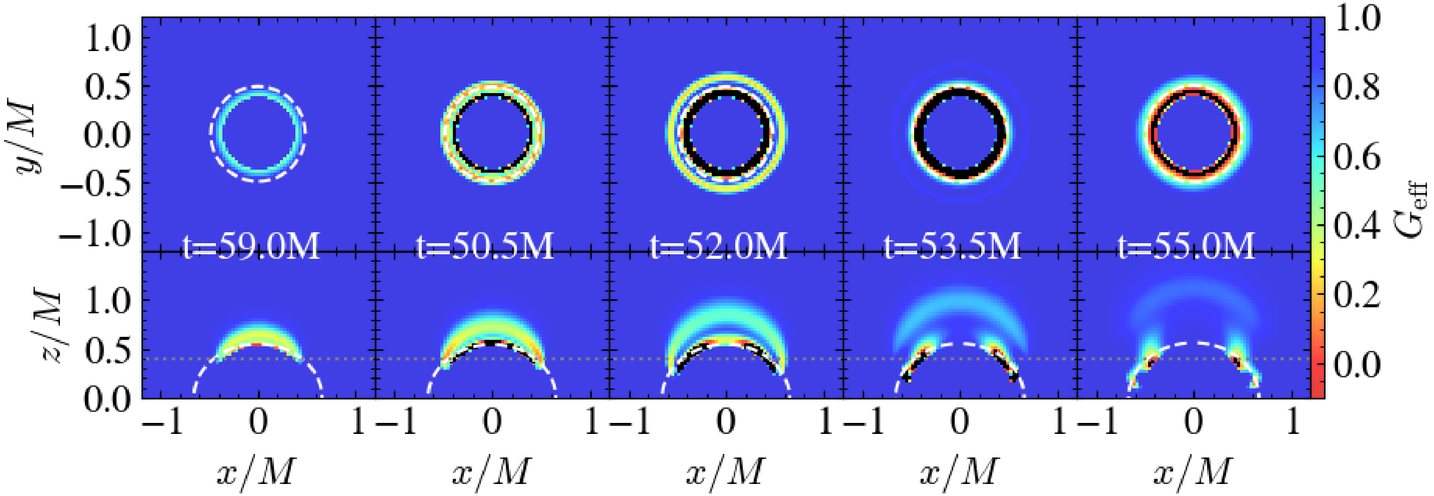
[LAS, Clough and Figueras '23]



y
$t = 1444M$
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.

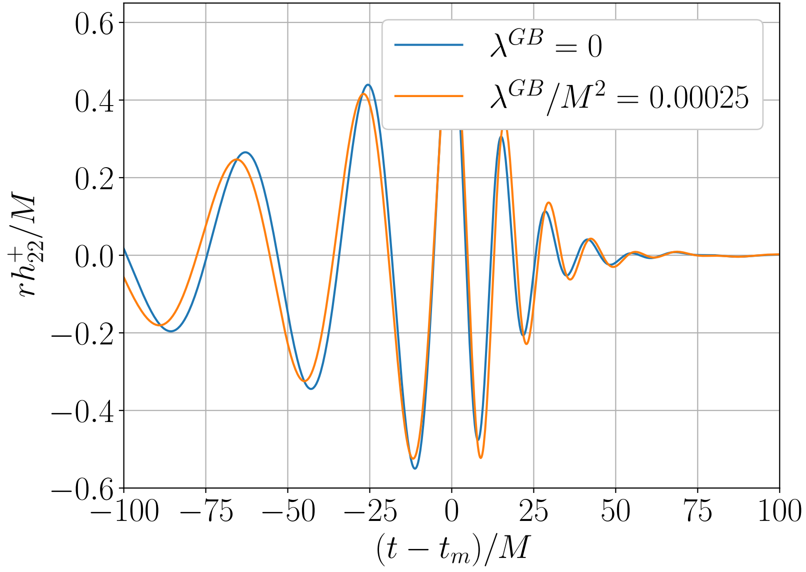


[Doneva, LAS, Clough, Figueras and Yazadjev ‘23]

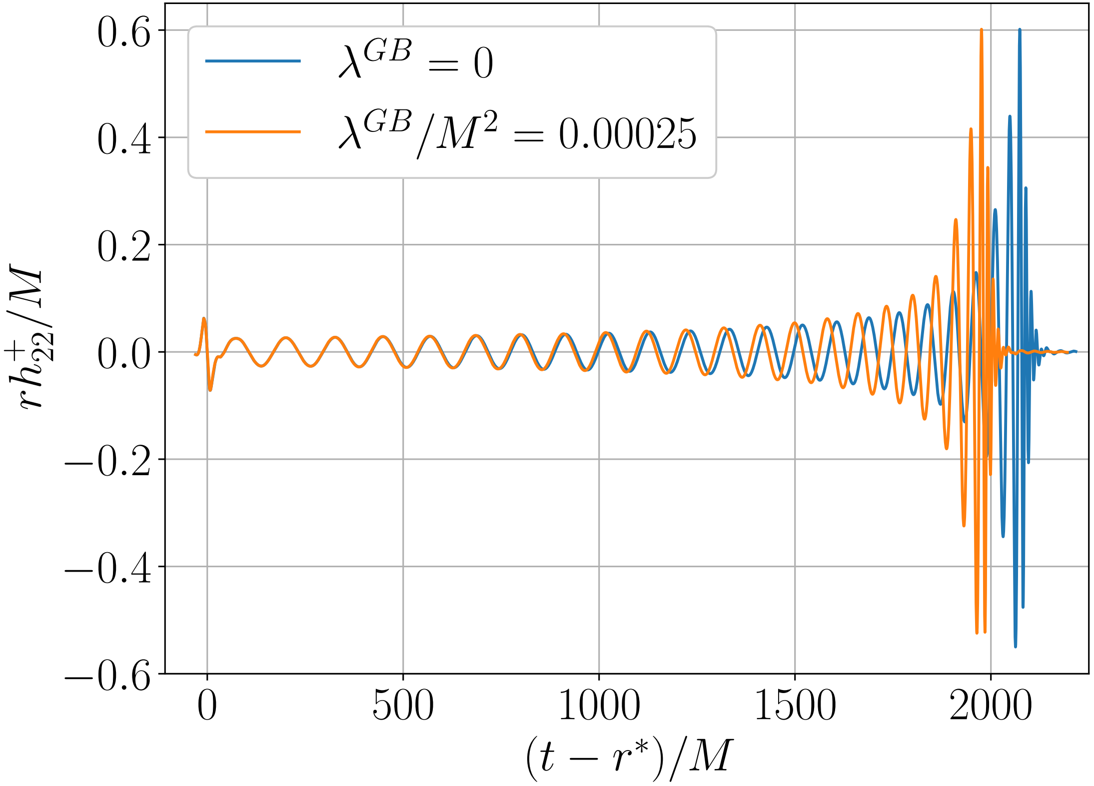
See also [Ripley and Pretorius ‘19]

Non-equal mass binaries

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



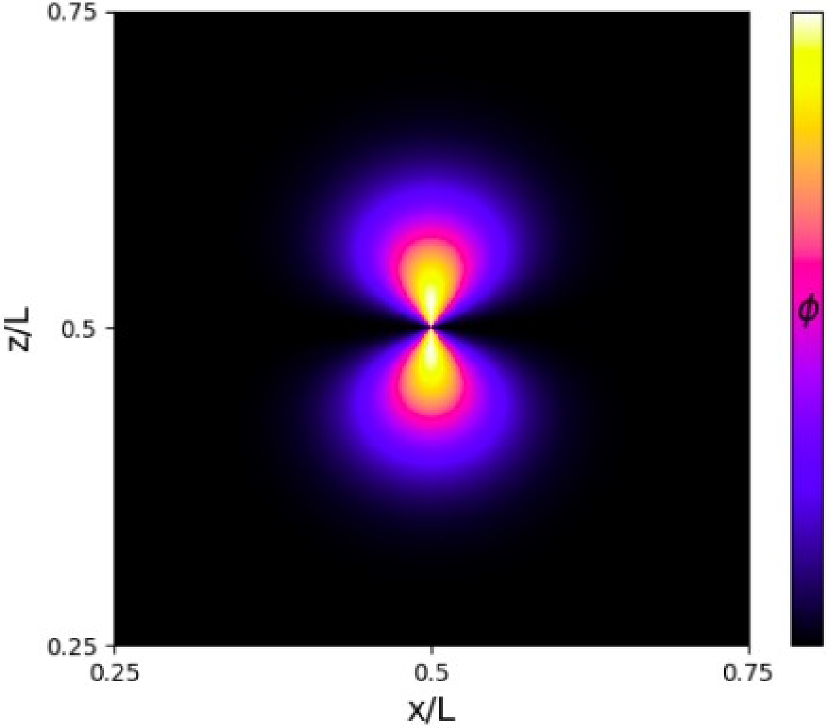
See also [Corman, Ripley and East '23]

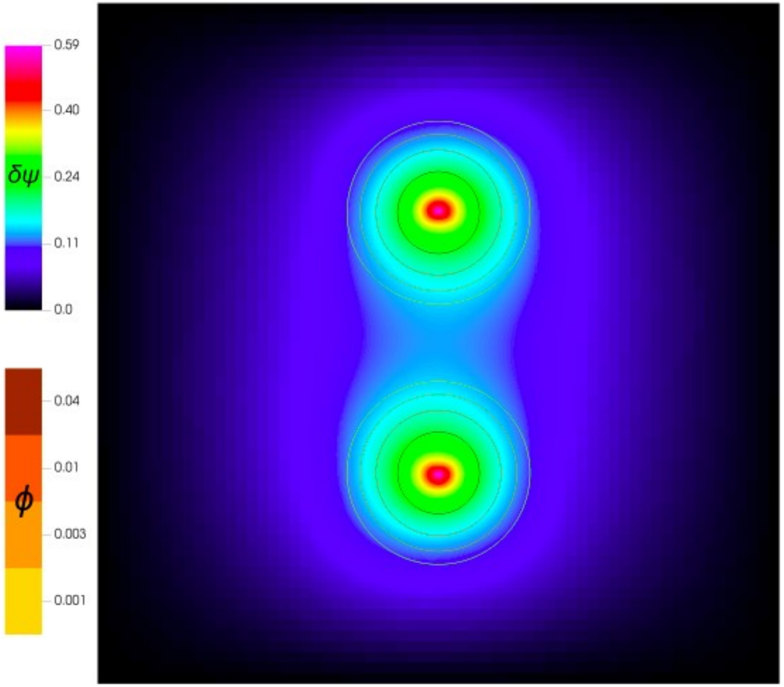


[Doneva, LAS, Clough, Figueras and Yazadjev '24] (in preparation)

Initial conditions

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

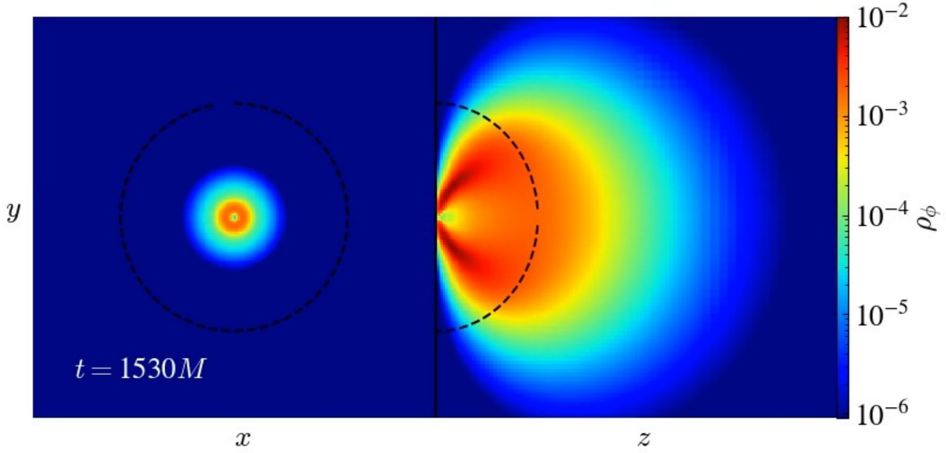




[Brady, LAS, Clough, Figueras and P.S. '23]

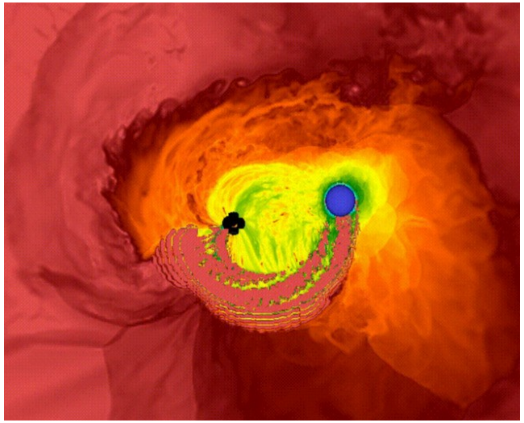
Summary

- 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 directions

- MHD EsGB in MHDuet (in collaboration with Miguel Bezares).
- Hydrodynamics in GRChombo (in collaboration with Dina Traykova and Josu Aurrekoetxea).



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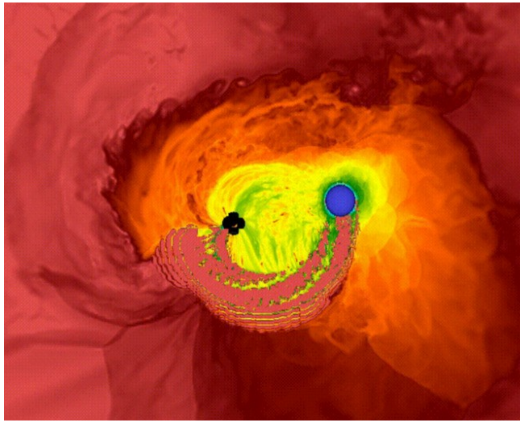

THANK YOU FOR YOUR ATTENTION!