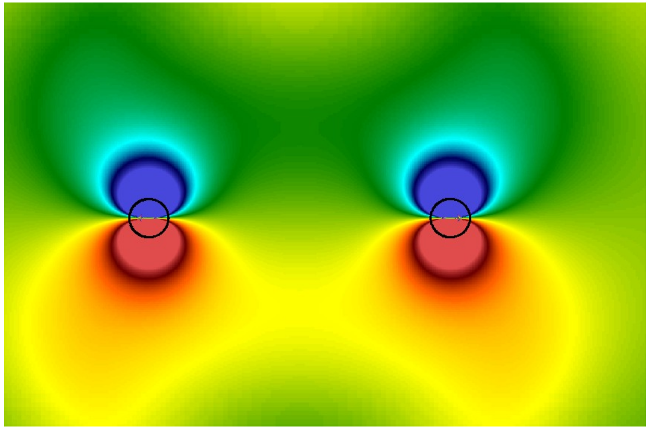
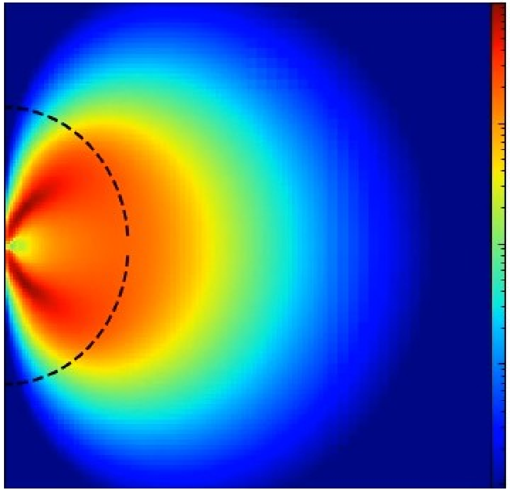
Numerical Relativity in effective field theories of gravity





Llibert Aresté Saló

PASCOS, Sheffield
25th June 2026

work with

Katy Clough, Maxence Corman, Daniela Doneva, Tamara Evstafyeva, Pau Figueras, Silvia Gasparotto, Harry Shum, Áron Kovács, Tamanna Jain, Harry Shum, Shaun Swain, Shunhui Yao, Jann Zosso et al

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GRCHOMBO

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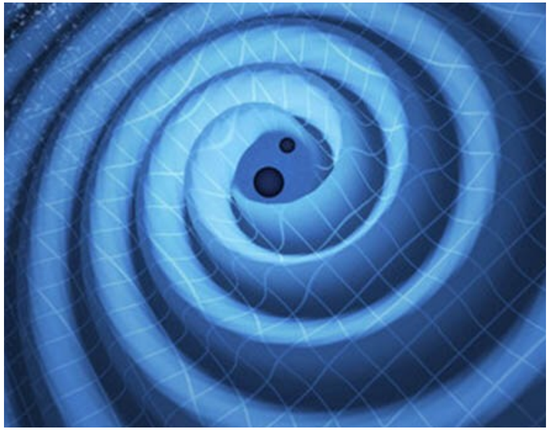
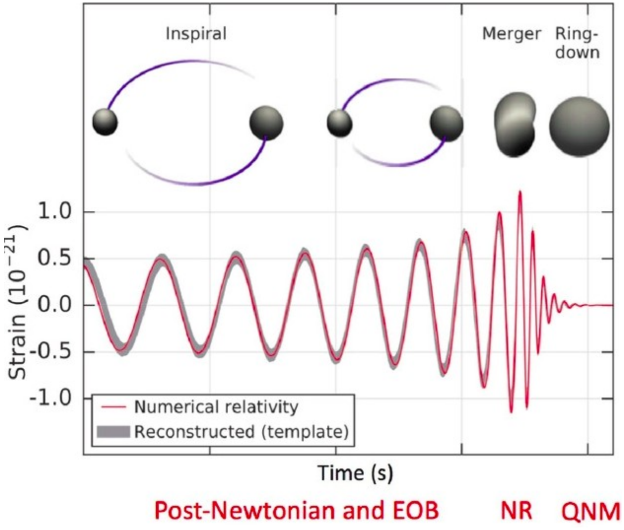
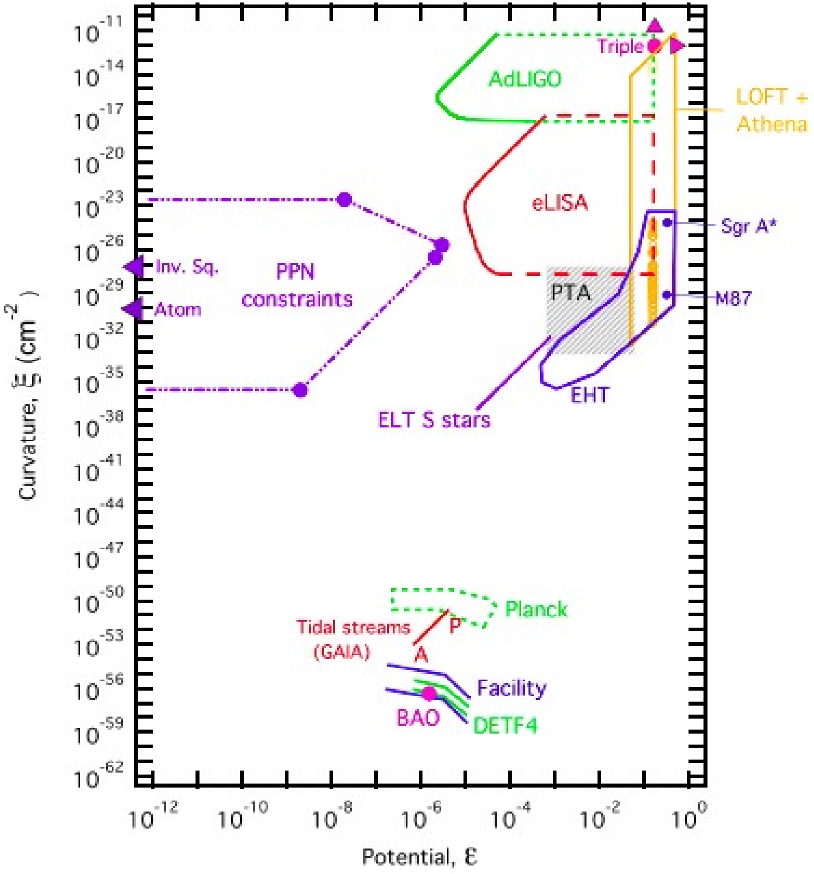


Motivation

[Baker et al ‘15]

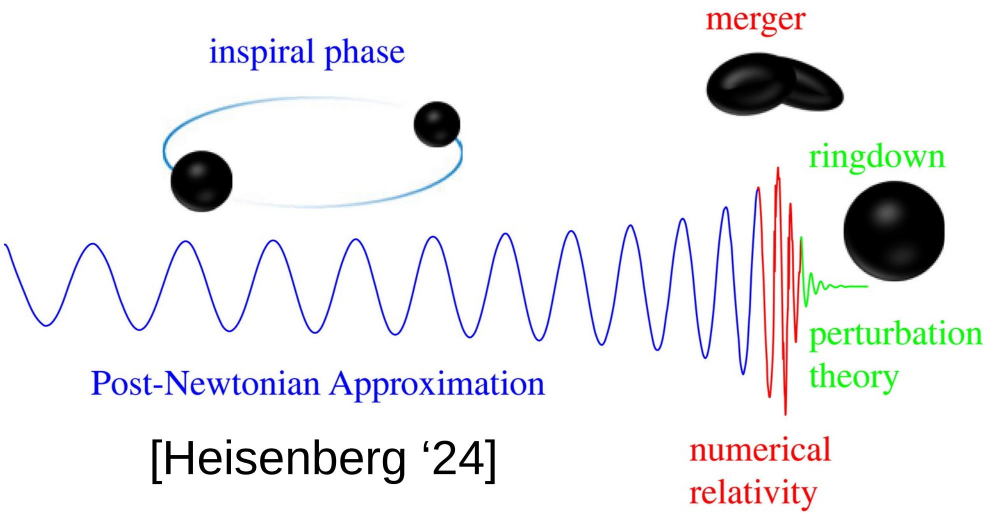
- Detection of gravitational waves ➡ Testing of the strong field regime.
- Numerical Relativity enables us to compute those waveforms.





Numerical Relativity

- Objective: evolve non-linear Einstein’s equations (+matter or modified gravity contributions) in a numerical grid.
- Especially important for studying the strong field regime of gravity.



[Heisenberg ‘24]

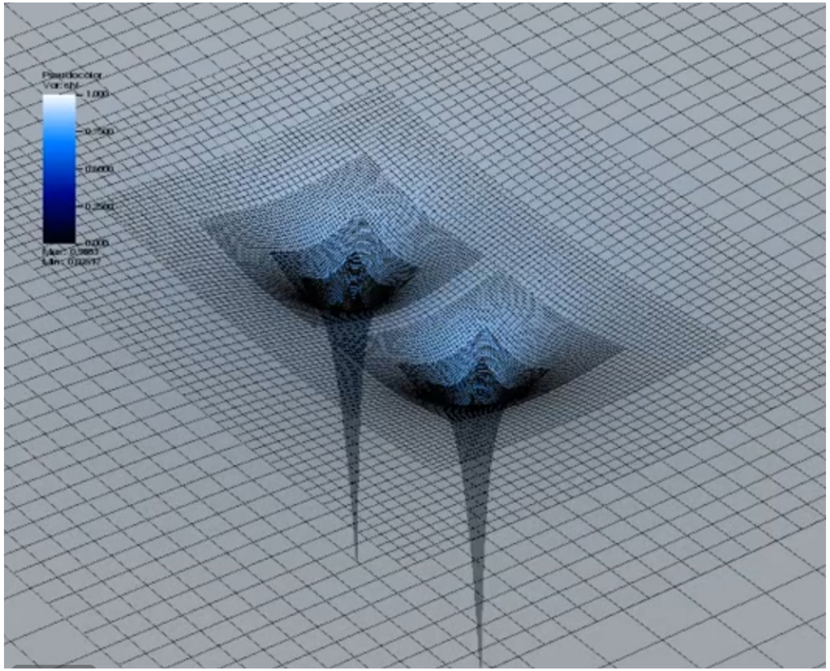
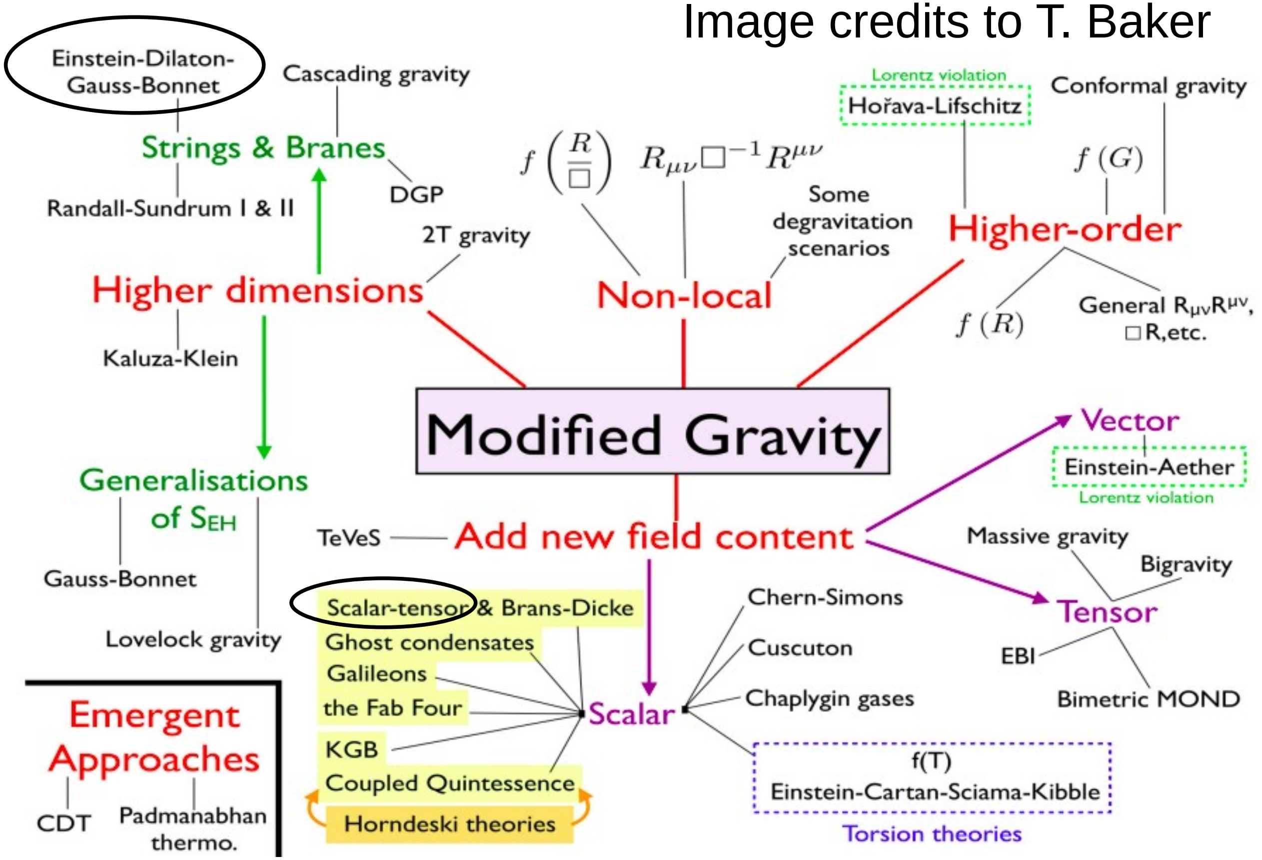


Image credits to K. Clough

Beyond GR

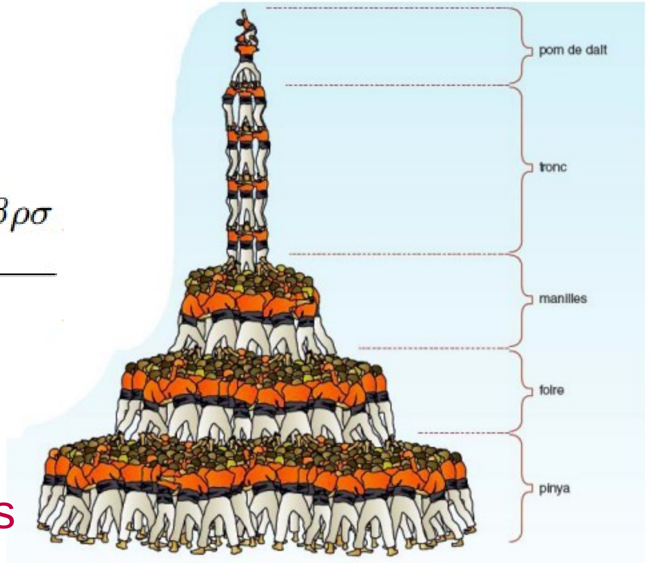
Image credits to T. Baker

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



Gravity as an EFT

	Parity-invariant	Non parity-invariant
8 deriv.	$-\frac{\mathcal{C}^2}{\Lambda^6}-\frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6}$	$-\frac{\mathcal{C}\tilde{\mathcal{C}}}{\Lambda_-^6}$
6 deriv.	$-c_3\frac{R_{\mu\nu\rho\sigma}R^{\mu\nu}{}_{\alpha\beta}R^{\alpha\beta\rho\sigma}}{\Lambda^4}$	$-\tilde{c}_3\frac{\tilde{R}_{\mu\nu\rho\sigma}R^{\mu\nu}{}_{\alpha\beta}R^{\alpha\beta\rho\sigma}}{\tilde{\Lambda}^4}$
4 deriv.	$+g_2(\phi)X^2+\lambda(\phi)\mathcal{L}^{GB}$	$+g(\phi)\,\tilde{\mathcal{C}}$
2 deriv.	$S=\frac{1}{2\kappa}\int d^4x\sqrt{-g}\,(R+X-V(\phi)$	Work in progress



$$X=-\frac{1}{2}(\partial\phi)^2 \quad \mathcal{L}^{\rm GB}=R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}-4R_{\mu\nu}R^{\mu\nu}+R^2 \quad \mathcal{C}=R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} \quad \tilde{\mathcal{C}}\equiv R_{\alpha\beta\gamma\delta}\tilde{R}^{\alpha\beta\gamma\delta}$$

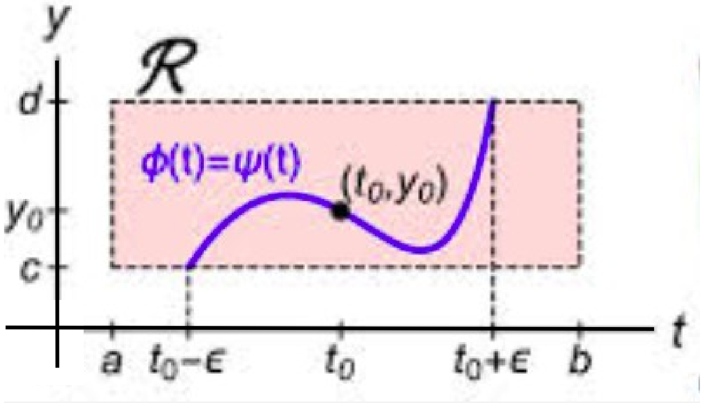
Four-Derivative parity-invariant Scalar-Tensor Theory of Gravity

Well-posedness

- An initial value (or Cauchy) problem

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

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

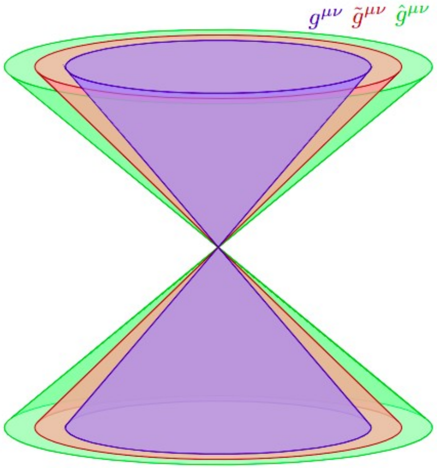


is (locally) **well-posed** if there exists a unique (local) solution for $t \in [0, T]$ for a given T>0 which depends smoothly on the initial data.

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

Well-posedness beyond GR

- Adding extra terms in Einstein's equations generally breaks well-posedness.
- Solution?
  - Modified Harmonic Gauge [Kovács and Reall '20] (modify the gauge) – adapted to the moving punctures [LAS, Clough and Figueras '22]



  - Fixing the equations [Cayuso, Ortiz and Lehner '17]

    (modify the evolution equations to control the high frequency modes)

  - Lagrangian regularisation [Figueras, Held and Kovács '24] (modify the lagrangian)

$$\mathscr{L}_{\mathrm{reg}} \equiv \sum_{k=0}^{n} \mathscr{L}_{\mathrm{reg},k} = \sum_{k=0}^{n} \ell^{2k+2} \left(\alpha_k R^{ab} \Box^k R_{ab} - \beta_k R \Box^k R \right)$$

Einstein-scalar-Gauss-Bonnet

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

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

- Well-posed in the modified puncture formulation in the weakly coupled regime [LAS, Clough and Figueras ‘22].
- Implemented in **GRFolres** (https://github.com/GRTLCollaboration/GRFolres) [LAS et al ‘23] and in **MHDuet** [LAS et al ‘26].
- Soon ready for GPUs (~10 times faster) -- new code **GRTeclyn** coming.

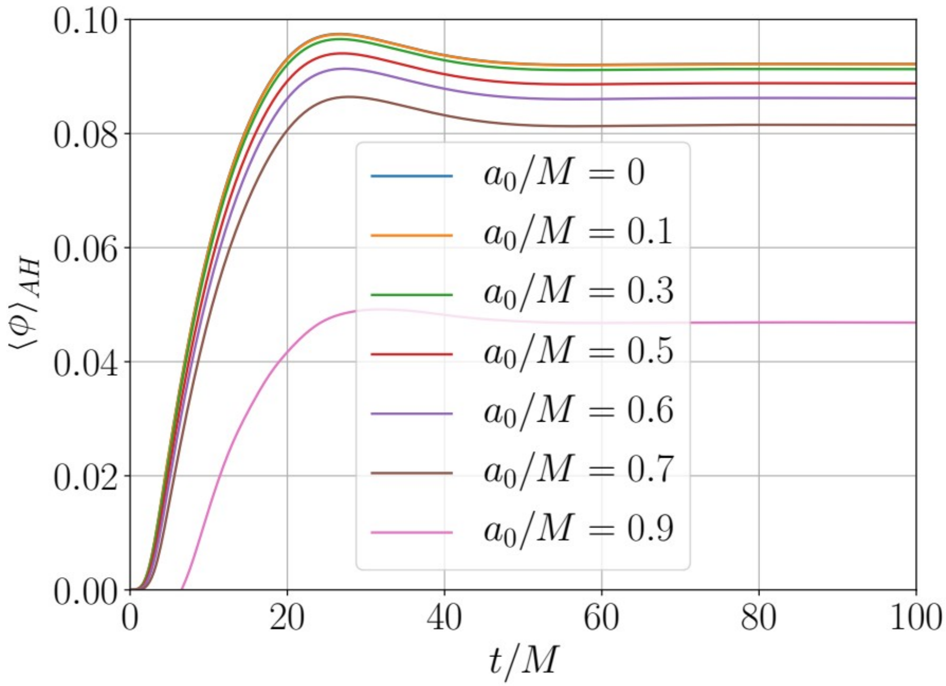
Types of coupling

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

- We consider here $g_2(\phi) = V(\phi) = 0$, which reduces to massless Einstein-scalar-Gauss-Bonnet (EsGB).
- Types of coupling for $\lambda(\phi)$:
  - Type I ($\lambda(\phi) \sim \phi + O(\phi^2)$) : only hairy compact object solutions exist.
  - Type II ($\lambda(\phi) \sim \phi^2 + O(\phi^3)$): both GR and hairy compact object solutions exist.

Type I: Isolated Black Holes

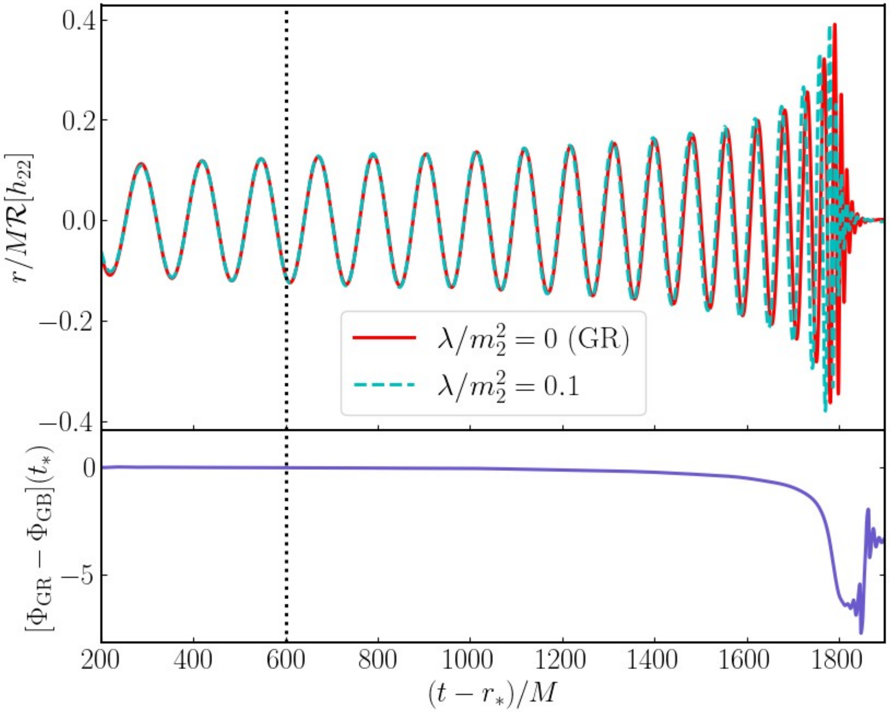
- Coupling function: $\lambda(\phi) = \lambda\phi$.
- Scalar hair develops dynamically in isolated spinning black holes and is stable.



[LAS, Clough and Figueras ‘25]

Type I: Binary Black Holes (quasi-circular)

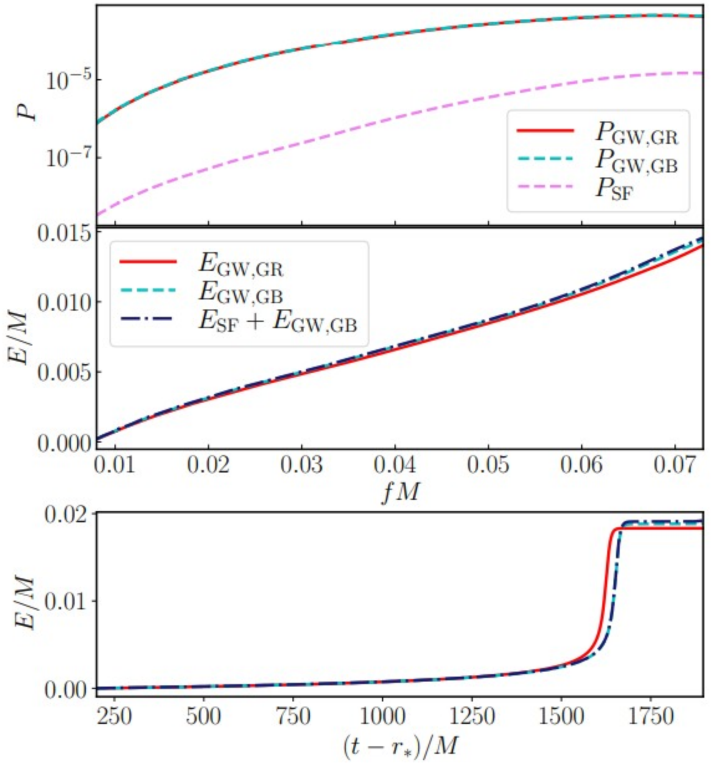
- Study of near equal mass binaries.
- Total dephasing comes from conservative (positive) and radiative dynamics (negative), which compete with each other.
- Analytical results so far seem to underestimate the conservative effects, which are important in the strong field regime.



Work in progress with Maxence Corman and Katy Clough

Type I: Binary Black Holes (quasi-circular)

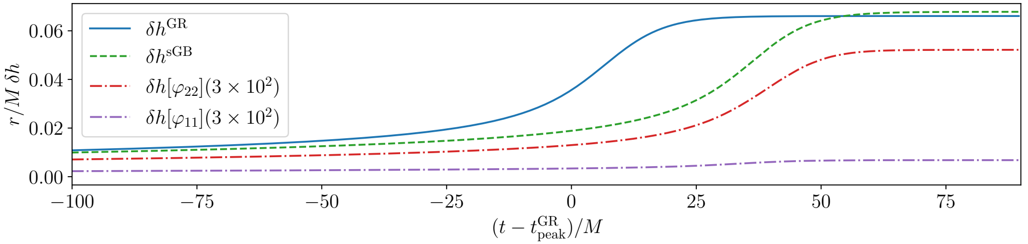
- Higher binding energy at the same frequency (which induces a release of more mass during the merger in EsGB).
- Study in progress about its degeneracy (or not) with GR parameters (ongoing work with Maxence Corman, Tamara Evstafyeva, Katy Clough and Nico Yunes).



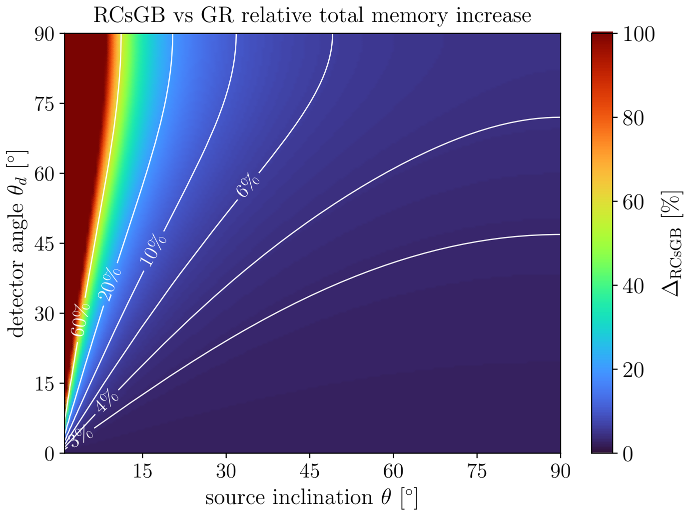
[Corman, LAS, and Clough '25]

Type I: Binary Black Holes (quasi-circular)

- GW memory provides an additional channel to break degeneracies.
- Final value in EsGB systems can be up to ~2% higher than in GR



[Gasparotto, Zosso, LAS, Doneva and Yazadjiev '26]

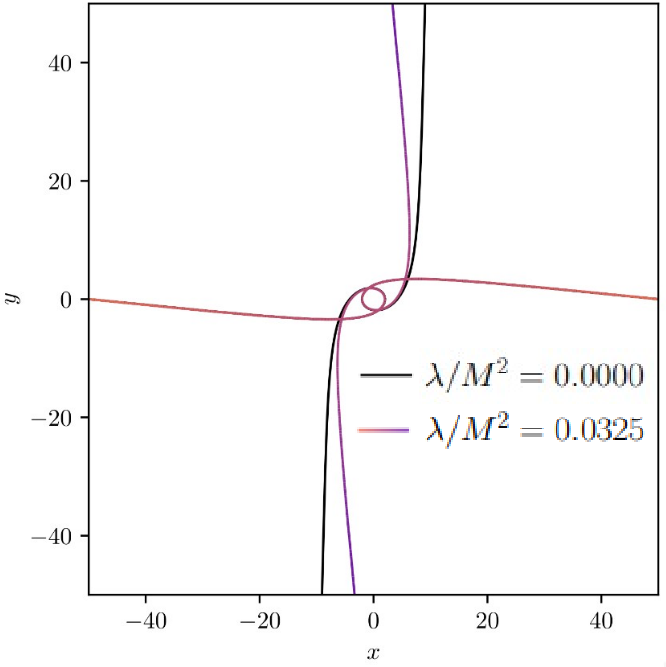


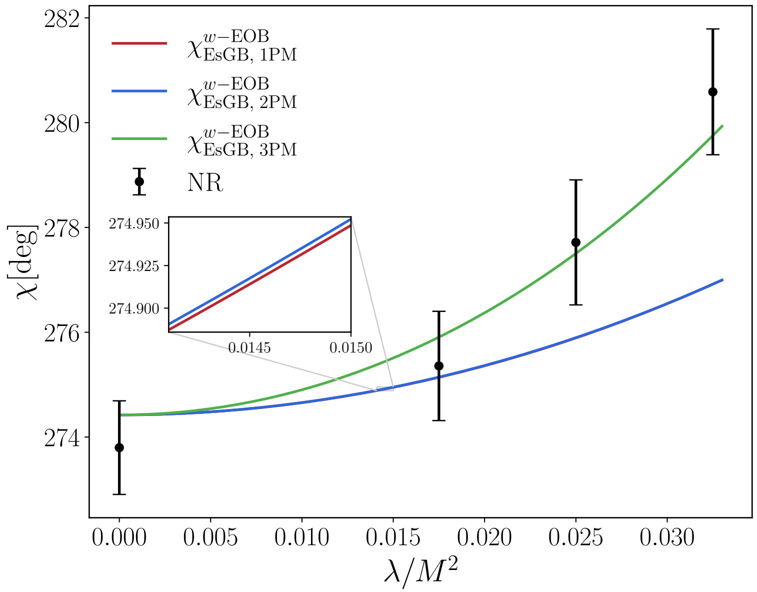
- This deviation can increase significantly when adding a non-minimal Ricci coupling at the level of the physical detector response, which admits a breathing polarisation.

[Zosso, Gasparotto, LAS, Doneva and Yazadjiev '26]

Type I: Binary Black Holes (scattering)

- Hyperbolic encounters in EsGB.
- Scattering angle increases with the coupling.





[Swain, Jain and LAS '26]

Excellent agreement with EoB analytics

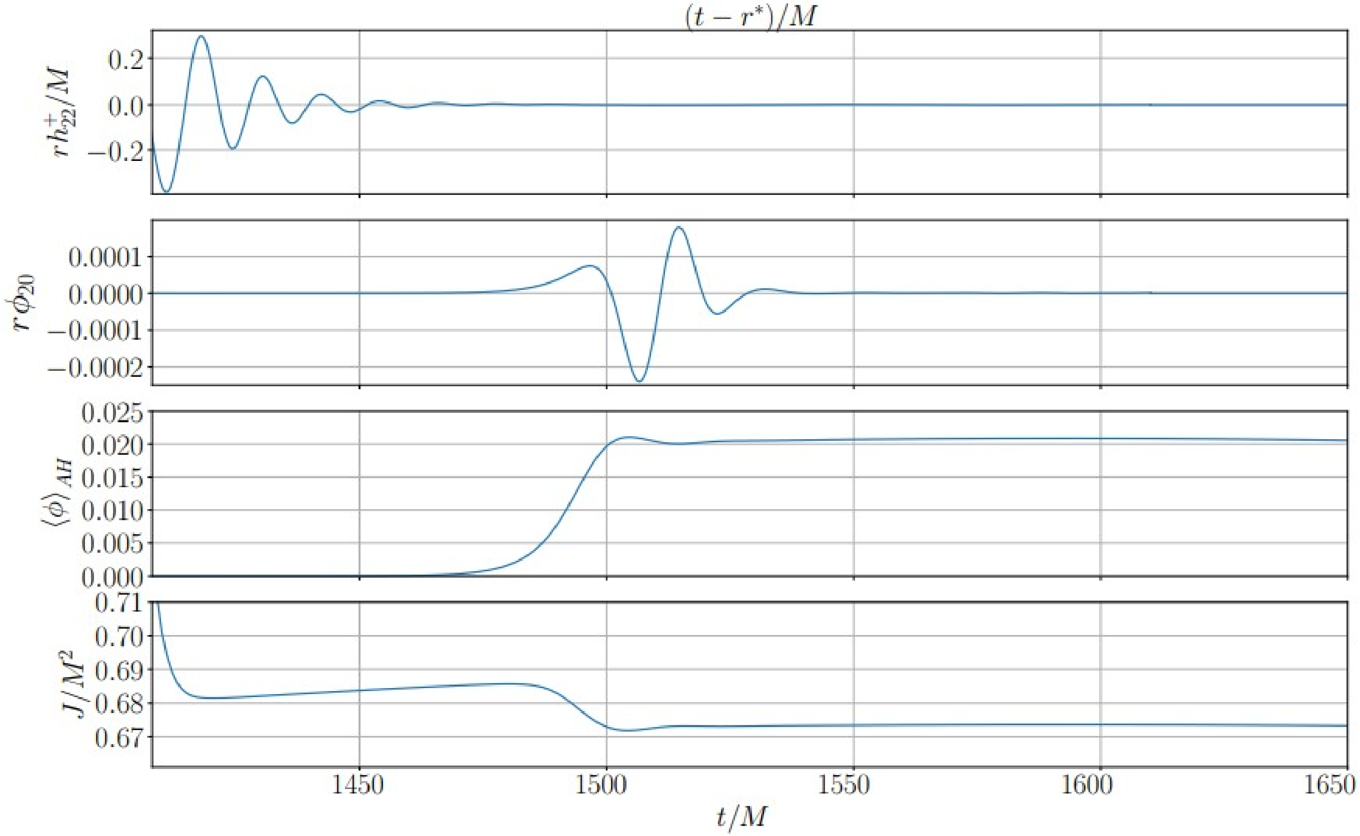
Type II: Spontaneous scalarisation

- Coupling function:

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

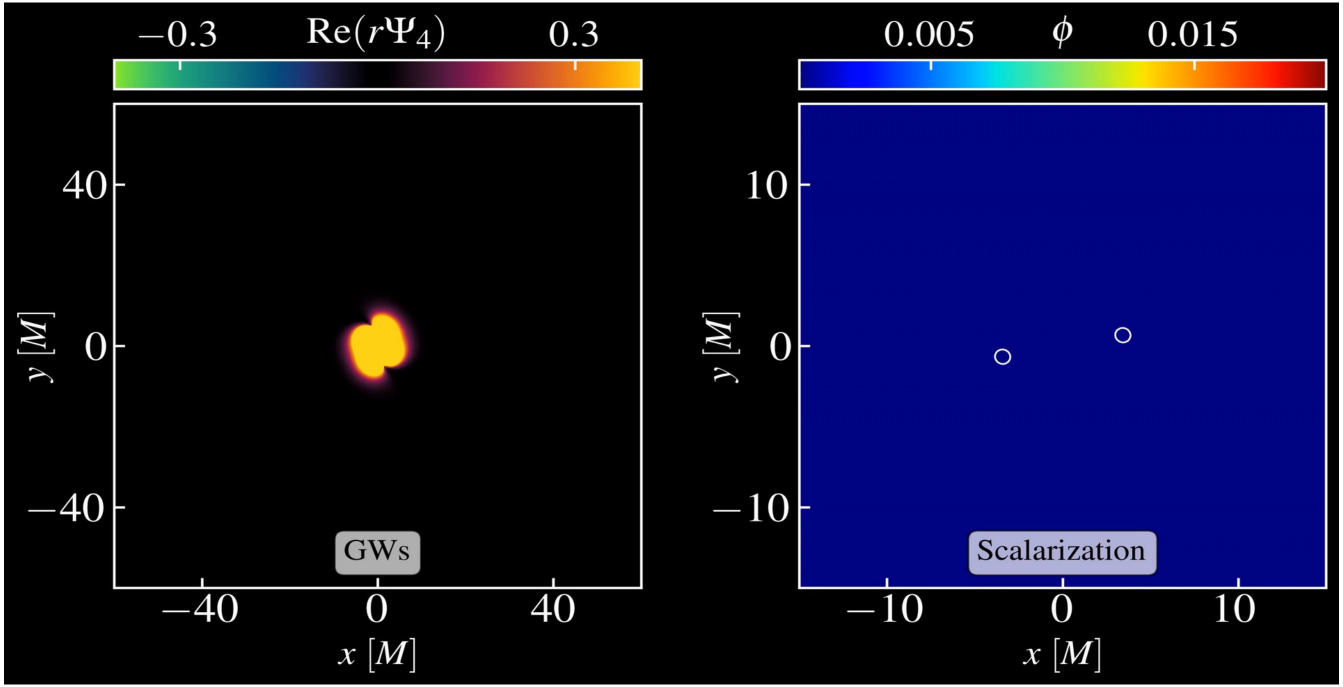
[Doneva et al ‘22].

- Spin-induced scalarisation.
- Stable hairy Black Hole Merger.



[LAS, Clough and Figueras ‘23]

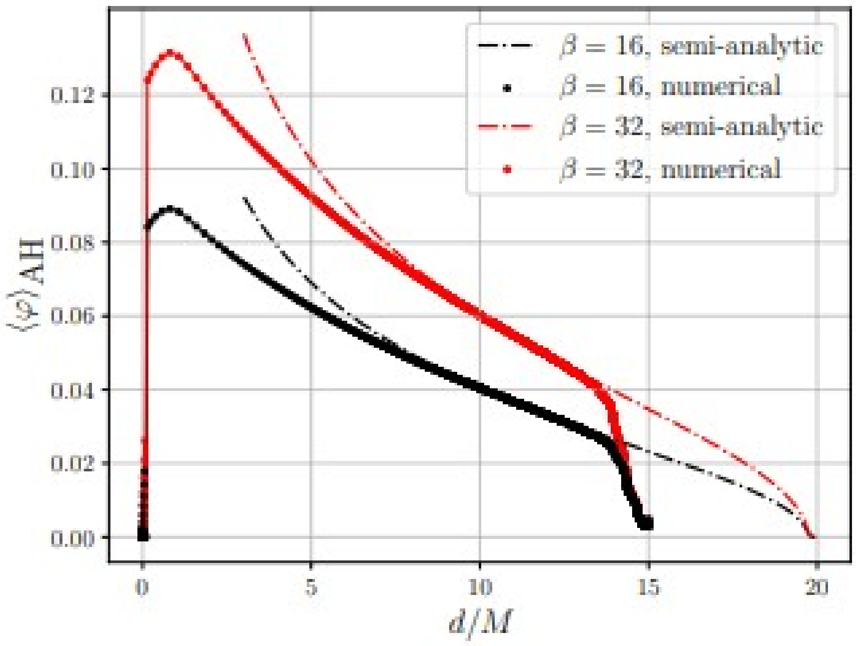
Type II: Spontaneous scalarisation (BBH)



Credits to J. Aurrekoetxea

Type II: Dynamical scalarisation

- First developed for neutron stars in scalar-tensor theories [Barausse et al ‘13, Shibata et al ‘14, Palenzuela et al ‘14] .
- Scalar field develops dynamically during inspiral and it descalarises during the merger.

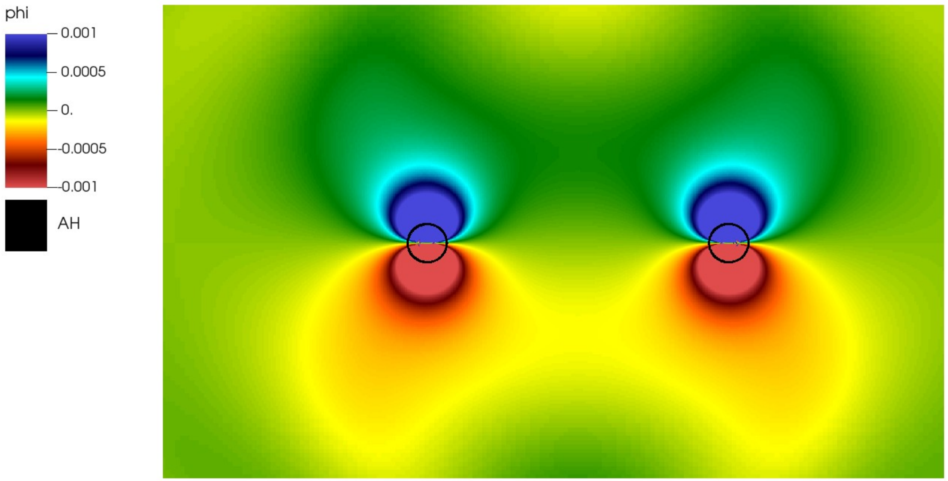


[Capuano, LAS, Doneva, Barausse and Yazadjev ‘26]

Dynamical Chern-Simons

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\,\left(R - \frac{1}{2}(\partial\phi)^2 + \lambda(\phi)R_{\mu\nu\rho\sigma}\widetilde{R}^{\mu\nu\rho\sigma}\right) \qquad \tilde{R}_{abcd} = \frac{1}{2}\epsilon_{ab}{}^{ef}R_{efcd}$$

- Non parity-invariant sector of the most general 4-derivative scalar tensor theory of gravity.
- Well-posed in the FHK (Figueras-Held-Kovács) formulation by performing the following redefinitions corresponding to fiducial massive modes:



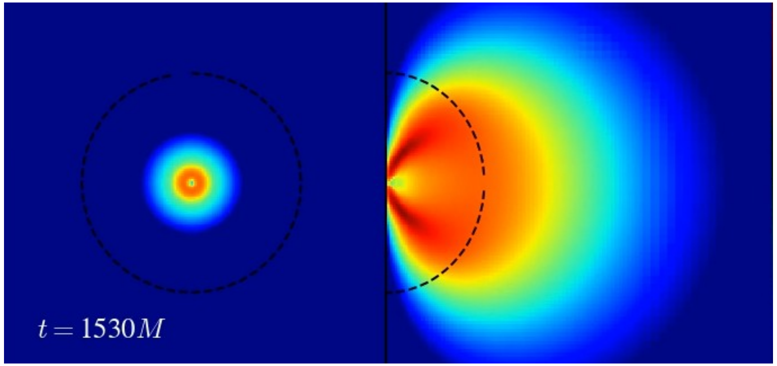
$$g_{ab} \to g_{ab} + \alpha\left[R_{ab} - \tfrac{1}{2}\left((\nabla_a\phi)(\nabla_b\phi) + g_{ab}V(\phi)\right)\right]$$

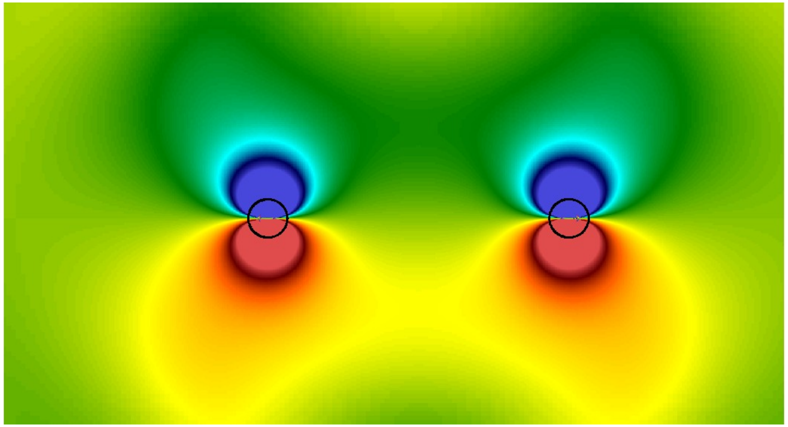
$$\phi \to \phi + \gamma\left(\Box\phi - V'(\phi)\right)$$

Work in progress with Maxence Corman, Pau Figueras, Aron Kovács and Shunhui Yao

Summary

- We show consistent results from BBH simulations in EsGB in the full non-linear regime and have seen some novel signatures.
- Promising progress towards dCS.





FURTHER WORK

- Understand the degeneracy of beyond-GR effects with GR parameters.
- Study higher derivative theories of gravity.

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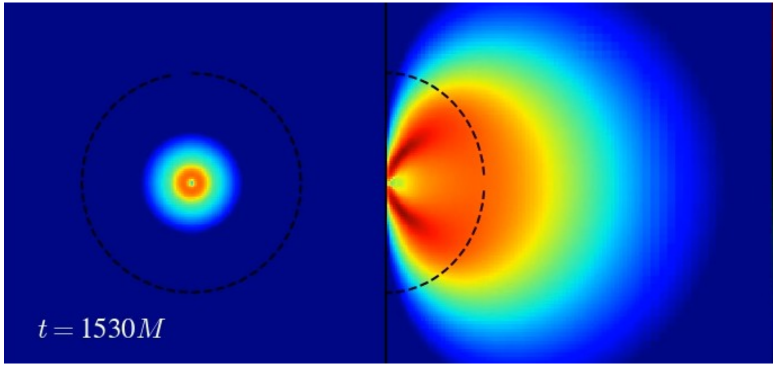

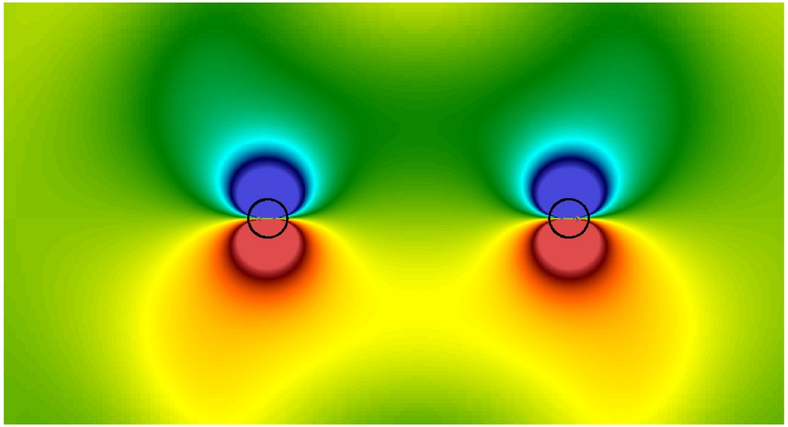

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THANK YOU FOR YOUR ATTENTION!