Title: Scalarized black holes - from equilibrium models to nonlinear dynamics

Speakers: Daniela Doneva

Collection/Series: 50 Years of Horndeski Gravity: Exploring Modified Gravity

Subject: Cosmology, Strong Gravity, Mathematical physics

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Abstract:

Black holes in Horndeski theories of gravity are a perfect playground for exploring possible deviations from General Relativity in a theory-specific manner and studying their astrophysical manifestation. I will review the recent advances in constructing stationary hairy black hole models in Gauss-Bonnet theories. Special attention will be paid to their nonlinear dynamics when isolated or put in a binary, and the resulting astrophysical implications. The potential loss of hyperbolicity will also be discussed.

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Scalarized black holes

from equilibrium models to nonlinear dynamics

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In collaboration with:

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Black holes with scalar hair in Gauss-Bonnet gravity

scalar-Gauss-Bonnet gravity

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - 2\nabla_\mu\varphi\nabla^\mu\varphi - V(\varphi) + \lambda^2 f(\varphi)\mathcal{R}^2_{GB}\right].$$

Gauss-Bonnet invariant:

$$\mathcal{R}^2_{GB} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\alpha\beta}R^{\mu\nu\alpha\beta}$$

- Schwarzschild $R^2_{GB} = \frac{48M^2}{r^6}$: relevant only **very close to the compact object** (for relation with cosmology see **Anson et al (2019), Babichev et al (2024)**)
- Field equations :

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Gamma_{\mu\nu} = 2\nabla_\mu\varphi\nabla_\nu\varphi - g_{\mu\nu}\nabla_\alpha\varphi\nabla^\alpha\varphi - \frac{1}{2}g_{\mu\nu}V(\varphi),$$

$$\nabla_\alpha\nabla^\alpha\varphi = \frac{1}{4}\frac{dV(\varphi)}{d\varphi} - \frac{\lambda^2}{4}\frac{df(\varphi)}{d\varphi}\mathcal{R}^2_{GB},$$

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Scalar field coupling $f(\varphi)$ $\nabla_\alpha \nabla^\alpha \varphi = -\frac{\lambda^2}{4}\frac{df(\varphi)}{d\varphi} R^2_{GB}$

Expand $f(\varphi)$ in series around $\varphi = 0$:

$$f(\varphi) = f_0 + f_1\varphi + f_2\varphi^2 + f_3\varphi^3 + f_4\varphi^4 + O(\varphi^5)$$

Type I:

- $f_1 \neq 0$: **shift-symmetric** theory, Schwarzschild is not a solution, $|\varphi| > 0$ always
  Kanti et al PRD(1996), Torii et al (1996), Pani&Cardoso PRD (2009)

Type II:

- $f_1 = 0$, $f_2 > 0$, $R^2_{GB} > 0$: **spontaneous** scalarization, Kerr unstable for **small masses** DD, Yazadjiev PRL (2018), Silva et al PRL (2018), Antoniou et al (2018)
- $f_1 = 0$, $f_2 < 0$, $R^2_{GB} < 0$: **spin-induced** scalarization, Kerr unstable for **large spins**
  Dima et al PRL (2020), DD et al RPD(2020), Berti at al PRL (2021), Herdeiro et al PRL (2021)

Beyond Type II:

- $f_1 = 0$, $f_2 = 0$: $\mu^2_{\text{eff}} = 0$, **nonlinear** scalarization, Kerr **linearly stable always, nonlinear scalarized phases can co-exist** DD, Yazadjiev, PRD Lett. (2021)

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Scalar field coupling $f(\varphi)$

- Better numerically – consider an **exponential function**
  - ✓ Stable beyond-GR black holes
  - ✓ Additional parameter in the exponent controls the deviation from GR

$$f(\varphi) = \frac{1}{2\beta} e^{-\beta(\varphi^2 + \kappa\varphi^4)} \; \left(\text{leading order} \sim \boldsymbol{\varphi^2 + \kappa\varphi^4}\right)$$

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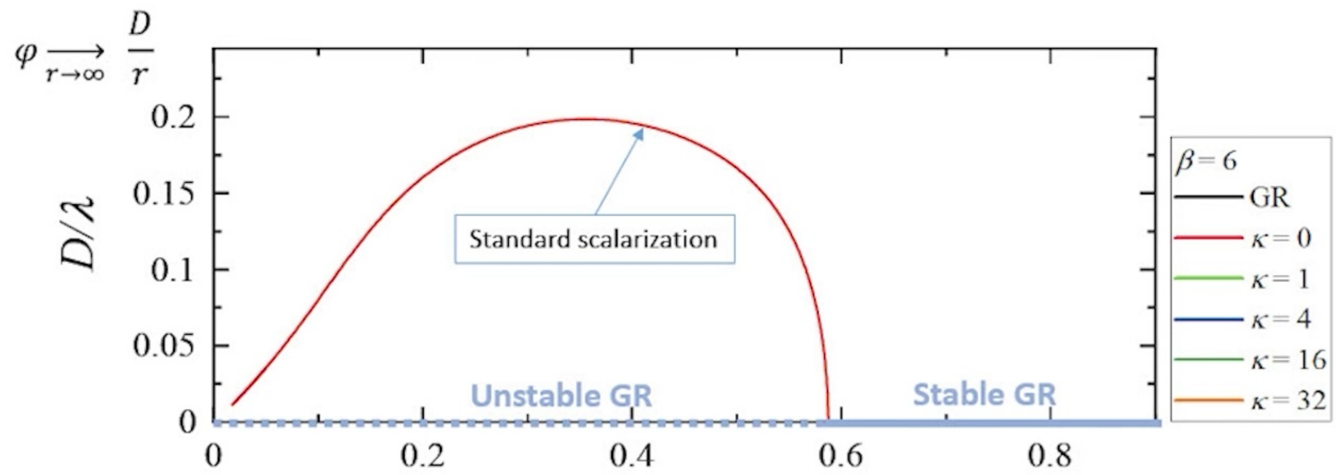
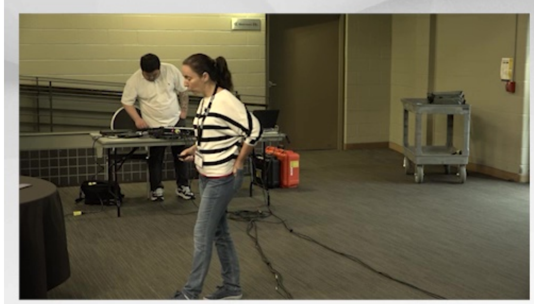
Standard scalarization with φ^2

$$f(\varphi) = \frac{1}{2\beta} e^{-\beta(\varphi^2 + \kappa\varphi^4)} \; (\text{leading order} \sim \boldsymbol{\varphi^2 + \kappa\varphi^4})$$



DD, Yazadjiev, PRD Lett. (2021)



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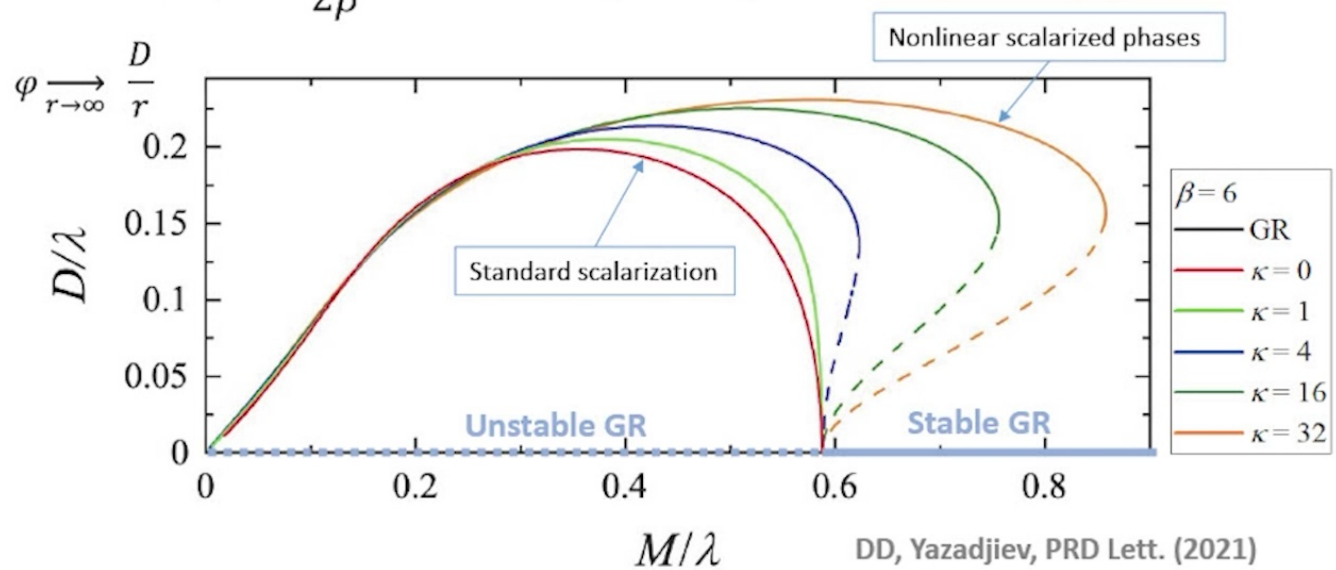
Standard + nonlinear scalarization

$$f(\varphi) = \frac{1}{2\beta} e^{-\beta(\varphi^2+\kappa\varphi^4)} \ (\text{leading order} \sim \boldsymbol{\varphi^2 + \kappa\varphi^4})$$



DD, Yazadjiev, PRD Lett. (2021)

- Transition from **stable scalarized to GR** happens with a **jump**
- For a similar effect for charged BH see **Blázquez-Salcedo et al. PLB (2020)**

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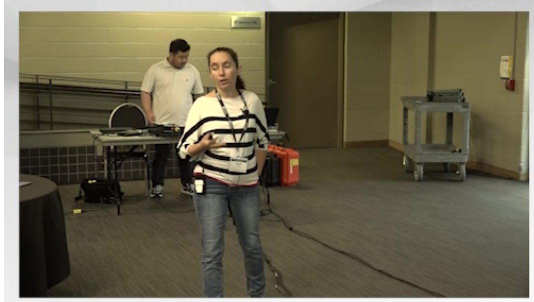

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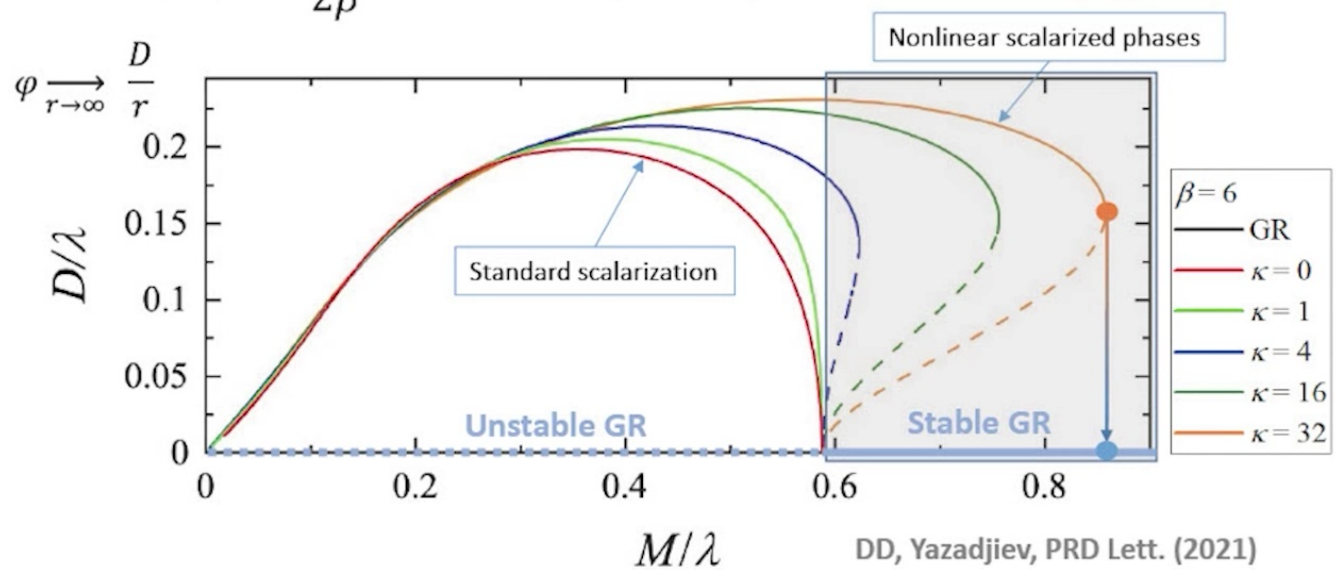

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Well-posedness

- A solution exists;
- The solution is unique;
- It changes continuously with changes in the data.

Gauss-Bonnet equations – significatly more complicated

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Gamma_{\mu\nu} = \frac{1}{2}\nabla_\mu\varphi\nabla_\nu\varphi - \frac{1}{4}g_{\mu\nu}\nabla_\alpha\varphi\nabla^\alpha\varphi - \frac{1}{2}g_{\mu\nu}V(\varphi)$$

$$\nabla_\alpha\nabla^\alpha\varphi = \frac{dV(\varphi)}{d\varphi} - \frac{\lambda}{4}\frac{df(\varphi)}{d\varphi}\mathcal{R}^2_{GB},$$

$$\Gamma_{\mu\nu} = -\frac{1}{2}R\Omega_{\mu\nu} - \Omega^\alpha_\alpha\left(R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}\right) + 2R_{\alpha(\mu}\Omega^\alpha_{\nu)} - g_{\mu\nu}R^{\alpha\beta}\Omega_{\alpha\beta} + R^\beta{}_{\mu\alpha\nu}\Omega^\alpha_\beta$$

$$\Omega_{\mu\nu} = \lambda\nabla_\mu\nabla_\nu f(\varphi)$$

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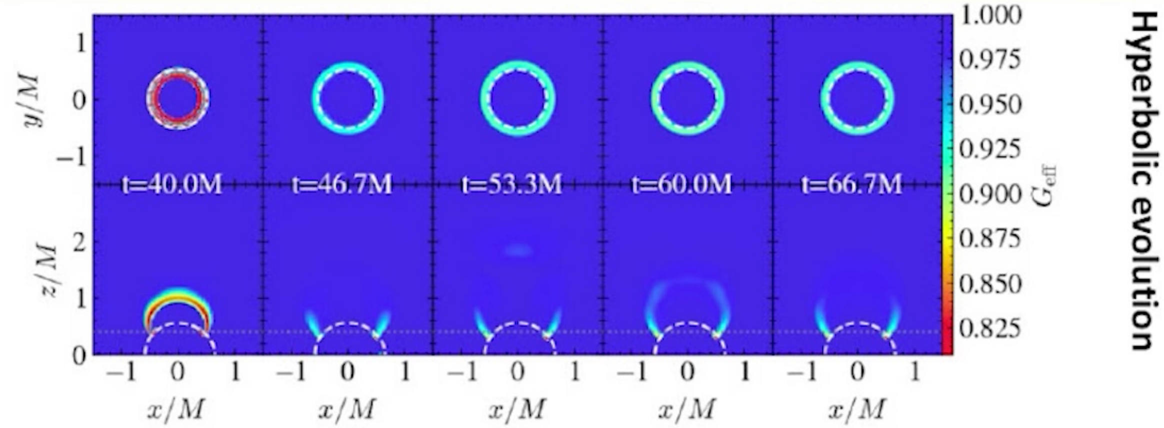
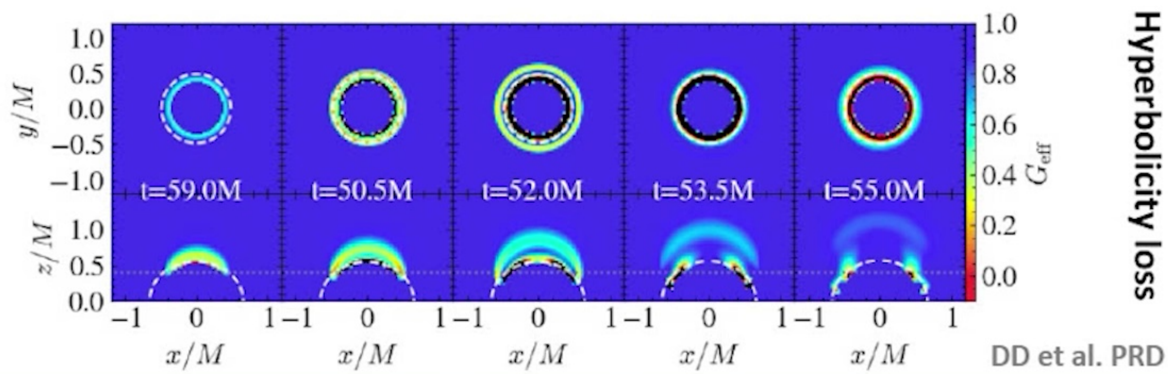
Normalized determinant – spin-induced black hole



VS.



DD et al. PRD (2023)

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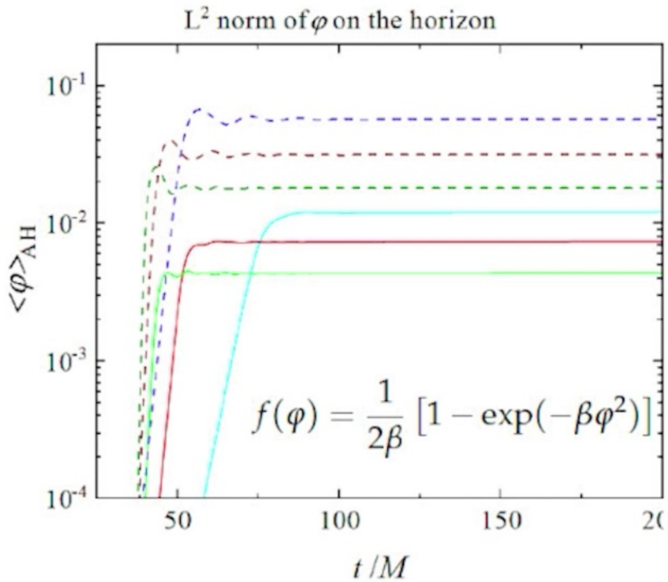
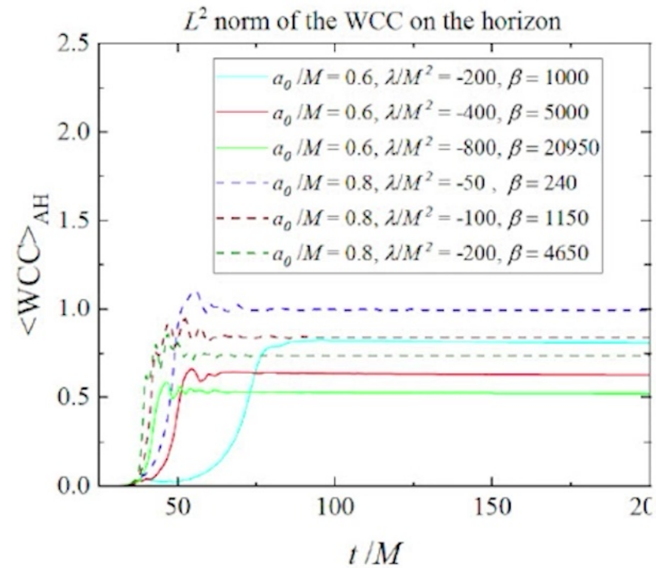
Limitting models and weak coupling condition

- **Weak coupling condition**

$$\sqrt{|\lambda f'(\varphi)|}/L \ll 1$$

$$L^{-1} = \max\{|R_{ij}|^{1/2}, |\nabla_\mu \varphi|, |\nabla_\mu \nabla_\nu \varphi|^{1/2}, |\mathcal{R}^2_{GB}|^{1/4}\}$$





DD et al. PRD (2023)

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Resolving the problem

- **Gauge change** – not very likely to help, hyperbolicity loss due to eigenvalues of physical modes becoming imaginary Areste-Salo et al PRL (2022), PRD (2022), DD et al. PRD (2023)

- **Fixing approach** Franchini et al PRD (2022), Cayuso at al PRL (2023)
  - ✓ A prescription to control the high frequency behaviour of an EFT
  - ✓ Modify in an *ad hoc* way the higher-order contributions to the field equations
  - ✓ Add a driver equation to let the solution relax to its correct value

- **Additional interactions** in the action can mitigate the hyperbolicity loss

$$S = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\,\left[R - \frac{1}{2}\nabla_\mu\varphi\nabla^\mu\varphi + \frac{1}{4}\lambda^{GB} f(\varphi)R^{GB} - \beta(\varphi)R\right]$$

Ricci scalar coupling

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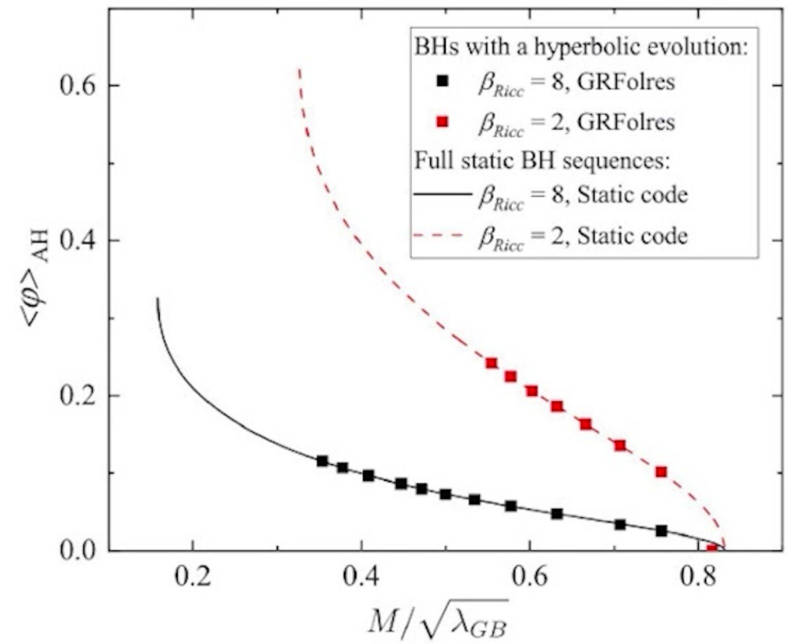
Ricci scalar coupling $\lambda(\varphi) = \lambda_{\rm GB}\,\varphi^2 \quad \beta(\varphi) = \beta_{\rm Ricc}\,\varphi^2$

- Effective metric: $g^{\mu\nu}_{\rm eff} = g^{\mu\nu}(1-\beta(\varphi)) - \Omega^{\mu\nu}$
- **3+1 simulations** – hyperbolicity maintained only for "weak" scalar field



DD, Areste-Salo, Yazadjiev PRD (2024)

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Ricci scalar coupling

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Binary mergers

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Standard + nonlinear scalarization

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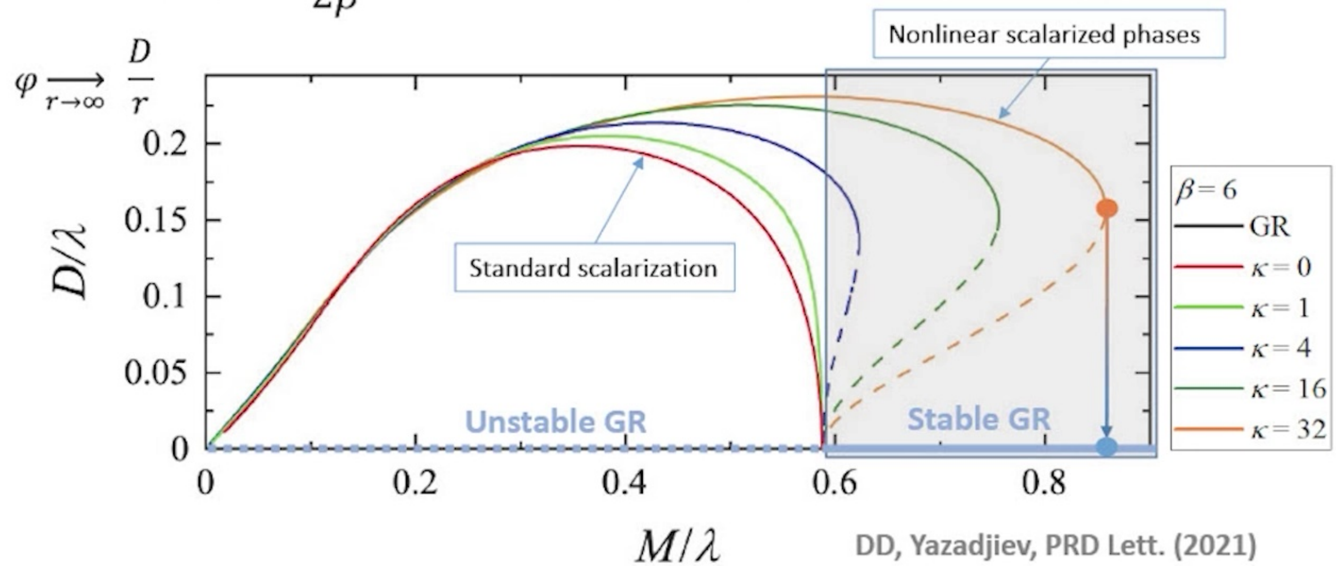

DD, Yazadjiev, PRD Lett. (2021)

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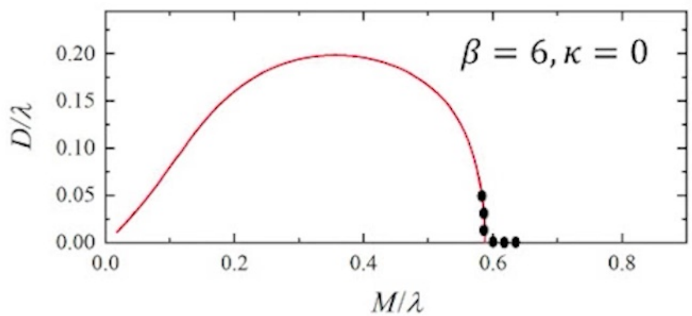
Decoupling limit – jump in the solutions

$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta\left(\varphi^2 + \kappa\varphi^4\right)}\right)$$



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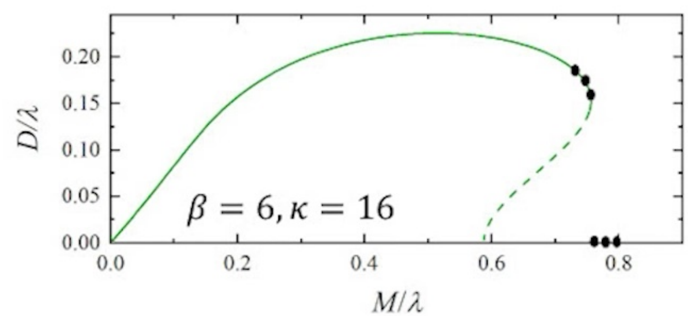

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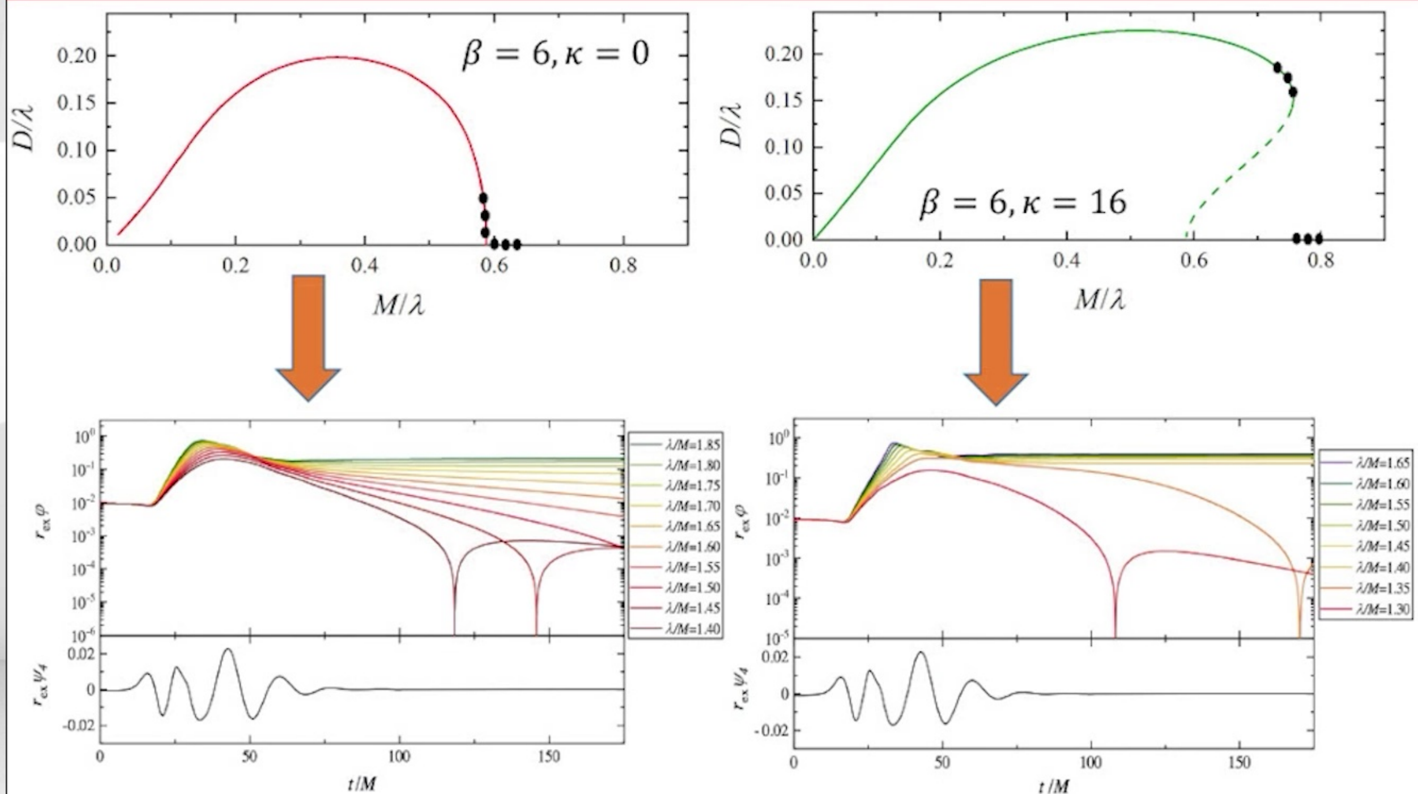
Head on collision: Jump vs. No Jump



DD, Vano-Vinuales, Yazadjiev (2022)

- IMR (in)consistency in modified gravity?

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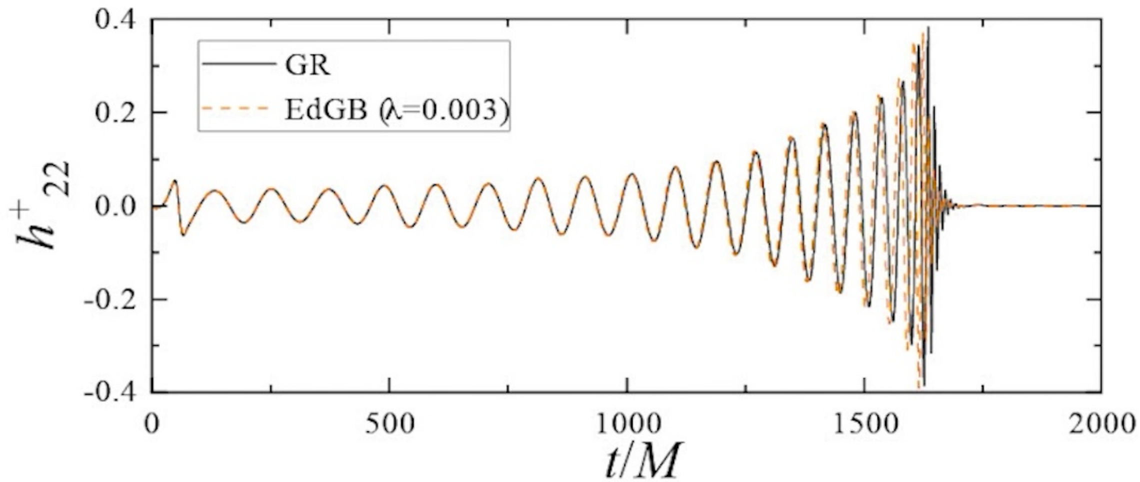
Full problem – inspiral of two equal mass BHs

- Solving the full problem with **GRFolres + GRChombo** in a **modified puncture gauge** Kovacs&Real PRL (2021), Areste-Salo et al PRL (2023) (for other codes *see Max's talk* East&Ripley PRL (2021), Corman at al. PRD (2023), and *Felix's talk* for EOB approach)
- **EdGB gravity** (no scalarization)
- **Scalar dipole radiation** – **zero** for equal mass binary



DD, Aresté Saló, Clough, Figueras, Yazadjiev, in preparation

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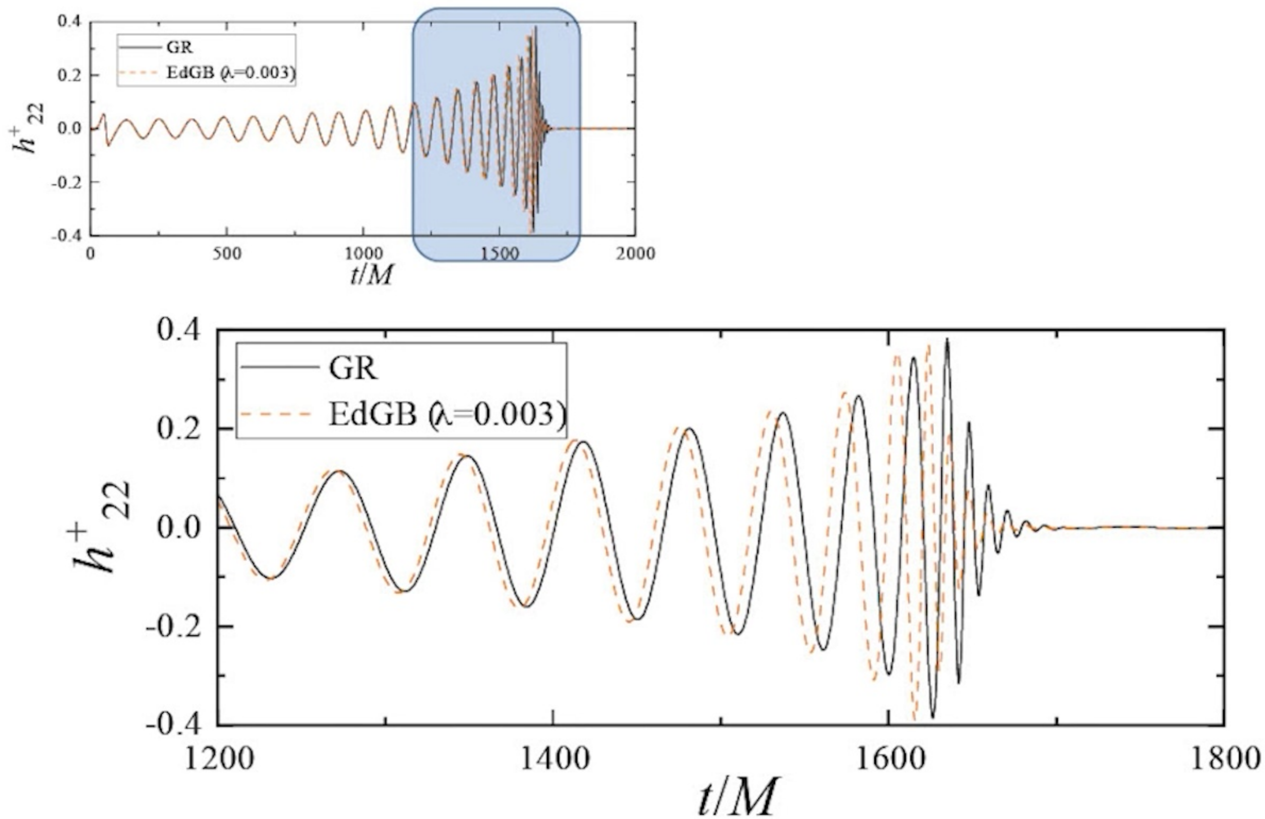
Inspiral of two equal mass BHs – zoom of the merger



DD, Aresté Saló, Clough, Figueras, Yazadjiev, in preparation

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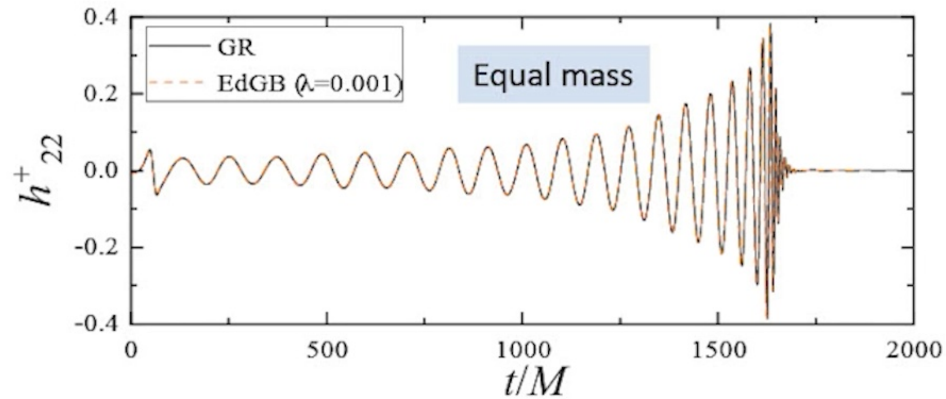
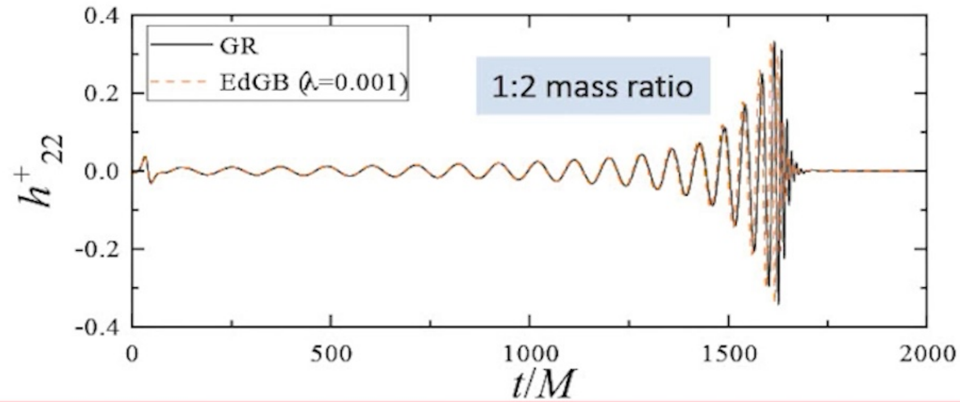
Equal vs unequal mass

- Smaller coupling – no difference in the equal case





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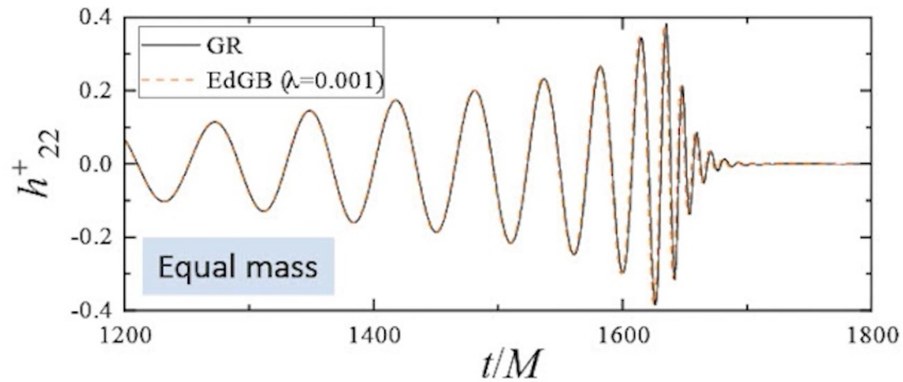
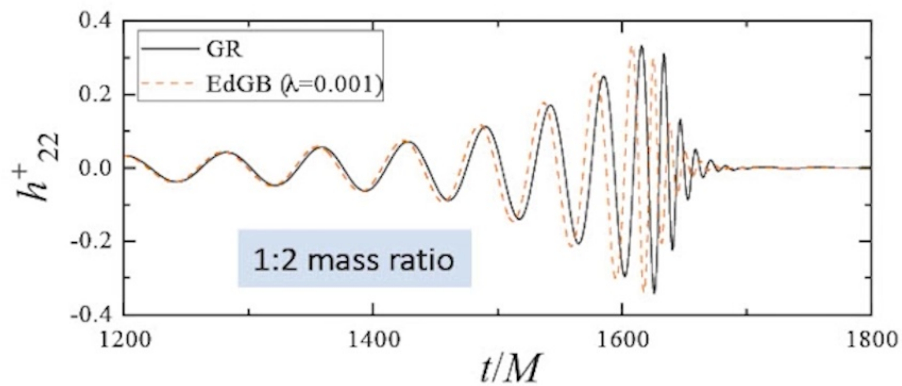
Equal vs unequal mass - zoomed

- Smaller coupling – no difference in the equal case





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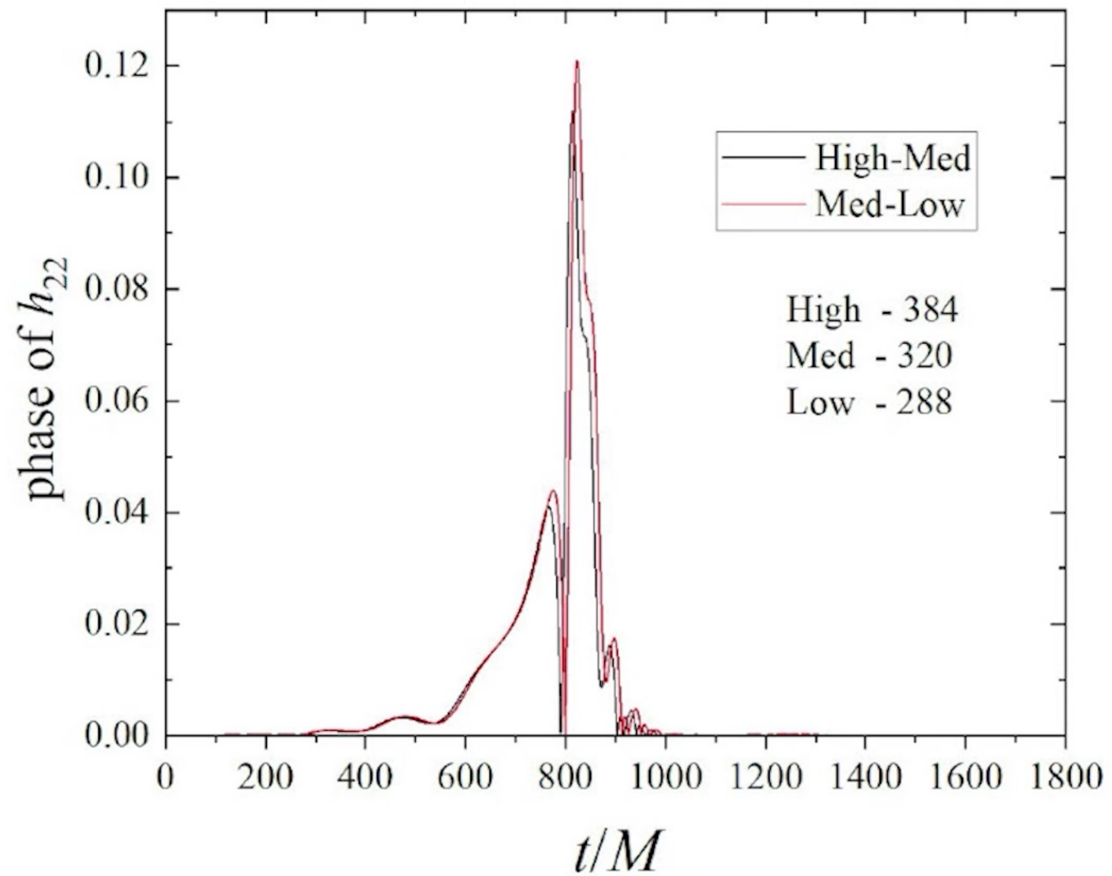
Unequal mass 1/3 – convergence



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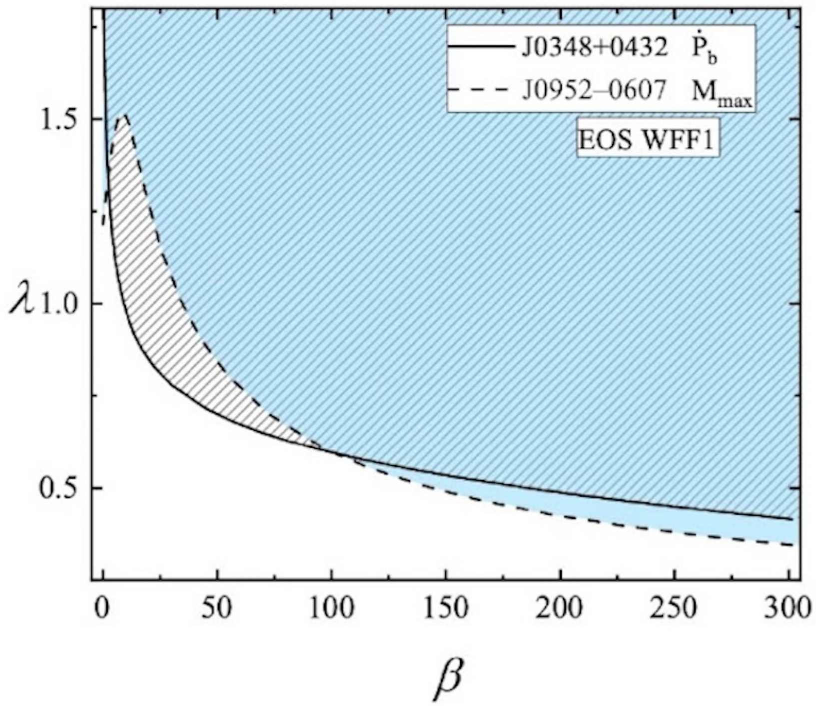
Binary pusars – Einstein-dilaton-Gauss-Bonnet theory

- Constraints from J0348 + 0432 and the maximum mass of J0952 – 0607



Yordanov, Staykov, DD, Yazadjiev (2024)

- EdGB gravity with coupling

$$f(\varphi) = \frac{\lambda^2}{2\beta} e^{2\beta\varphi}$$

(leading order $\sim \lambda^2 \varphi$)

- Constrains from **binary black hole mergers**

$$\lambda < 3.01$$

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Conclusions

- Black holes in Horndeski theories offer a **very interesting venue of exploration**.
- Binary mergers can posses a **qualitatively new phenomenology**
- **Well-posedness** more subtle than in GR
- **Weak coupling condition** should always be obeyed

Outlook

- A deeper investigation **of binary mergers** and their **astrophysics signatures**

Final goal: understand which exotics are physically motivated and constrain them via GWs.

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THANK YOU!

Studying hyperbolicity

- **Principle symbol** – a matrix assembled by the coefficients in front of the leading (2nd) order derivative in the differential equation
- The contribution from **the Gauss-Bonnet sector to the principal part** of the evolution equations **only affects the physical modes** (purely gravitational modes and mixed scalar-gravitational ones).
- The eigenvalues from the purely gravitational sector lie on **the null cone of the effective metric** Real PRD (2021), Areste-Salo et al PRL (2022), PRD (2022)

$$g^{\mu\nu}_{\text{eff}} = g^{\mu\nu} - \Omega^{\mu\nu}$$
$$\Omega_{\mu\nu} = \lambda\, \nabla_\mu \nabla_\nu f(\varphi)$$

- **Hyperbolicity loss:** the normalized determinant of the effective metric (with respect to GR) < 0 (East&Ripley PRL (2021), Areste-Salo et al PRL (2022), Hegade et al PRD (2023)))

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