EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Black holes in effective field theories: Dynamics and new observational signatures

Daniela Doneva

University of Tübingen

In collaboration with:
Stoytcho Yazadjiev, Llibert Aresté Saló, Katy Clough, Pau Figueras, Alex Vañó-Viñuales

Beyond-GR black holes in EFT

Effective field theories

- Einstein’s theory is **not renormalizable**
- A solution: supplement Einstein-Hilbert action with **higher-order curvature invariants**.
- EFT – keep **only the low energy c**orrections to the action, assuming that they are dominant on astrophysical scales.
- Desire: field equations of **second order** and **well posed**
- Best candidate: **scalar-Gauss-Bonnet** theory

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: $R^2_{GB} = \frac{48M^2}{r^6}$
- Field equations :

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

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

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:

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

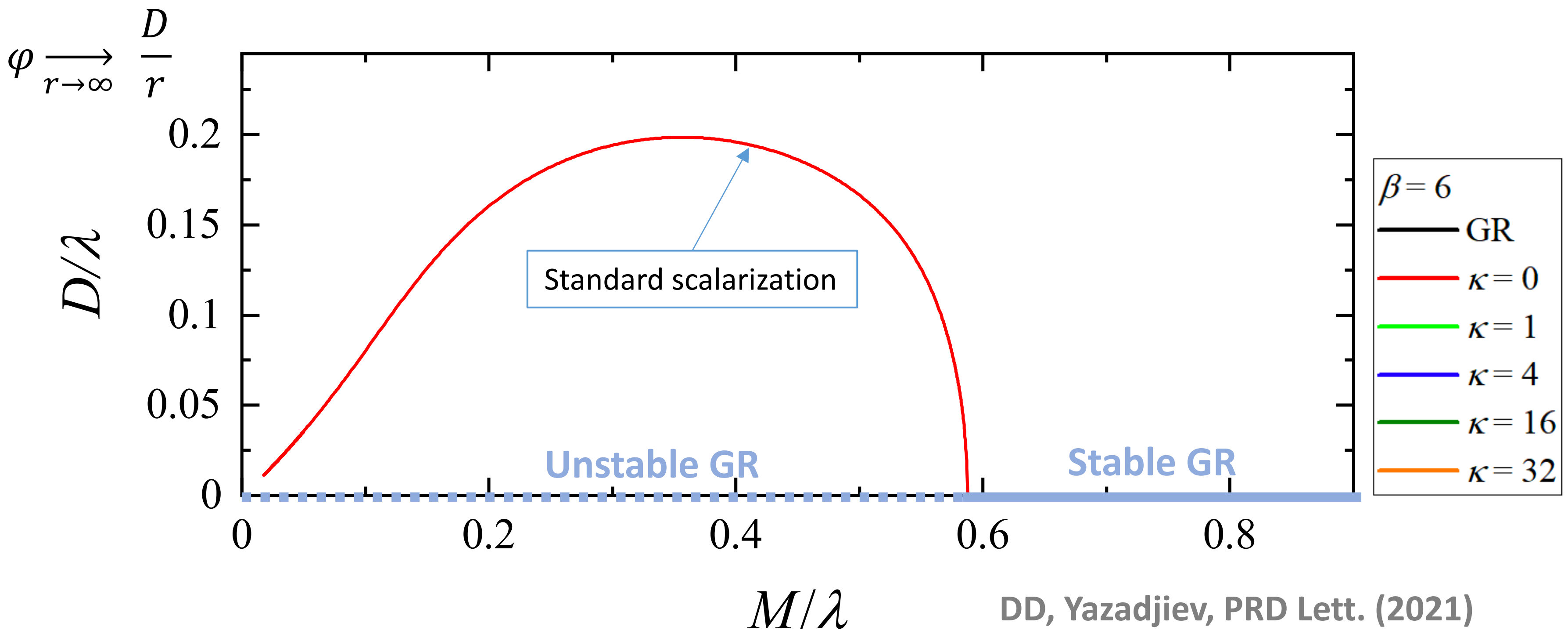
Scalar field coupling $f(\varphi)$

- Better numerically – consider an **exponential function**

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

Standard scalarization with φ^2

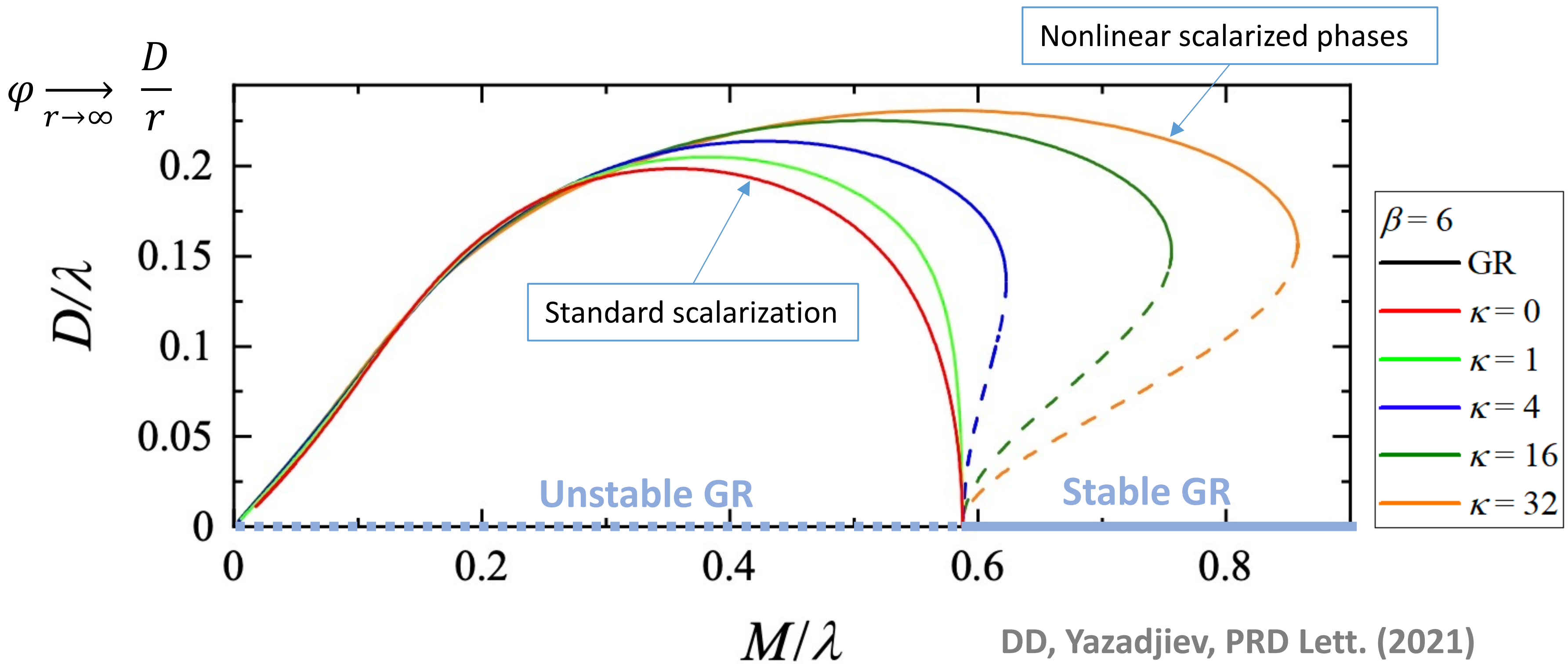
$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta(\varphi^2 + \kappa\varphi^4)}\right)$$



DD, Yazadjiev, PRD Lett. (2021)

Standard + nonlinear scalarization

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

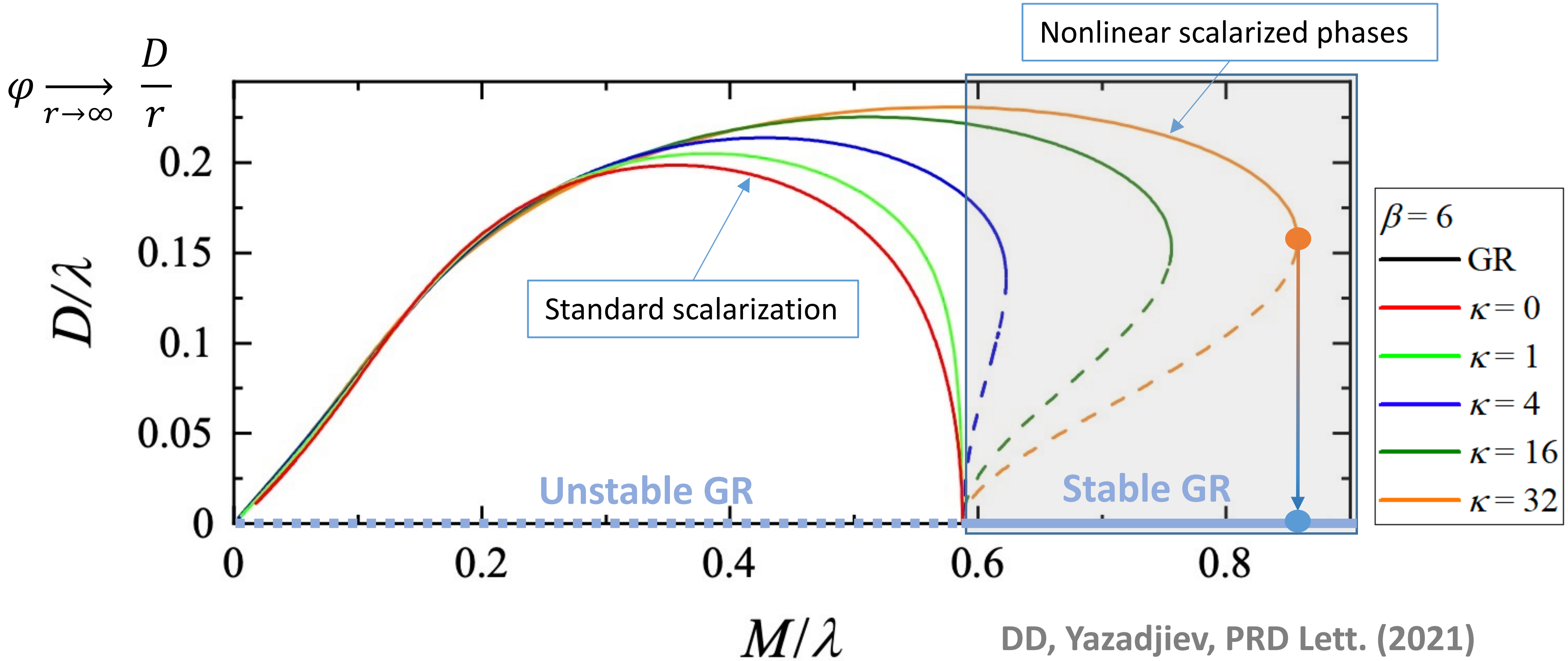


DD, Yazadjiev, PRD Lett. (2021)

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

Standard + nonlinear scalarization

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



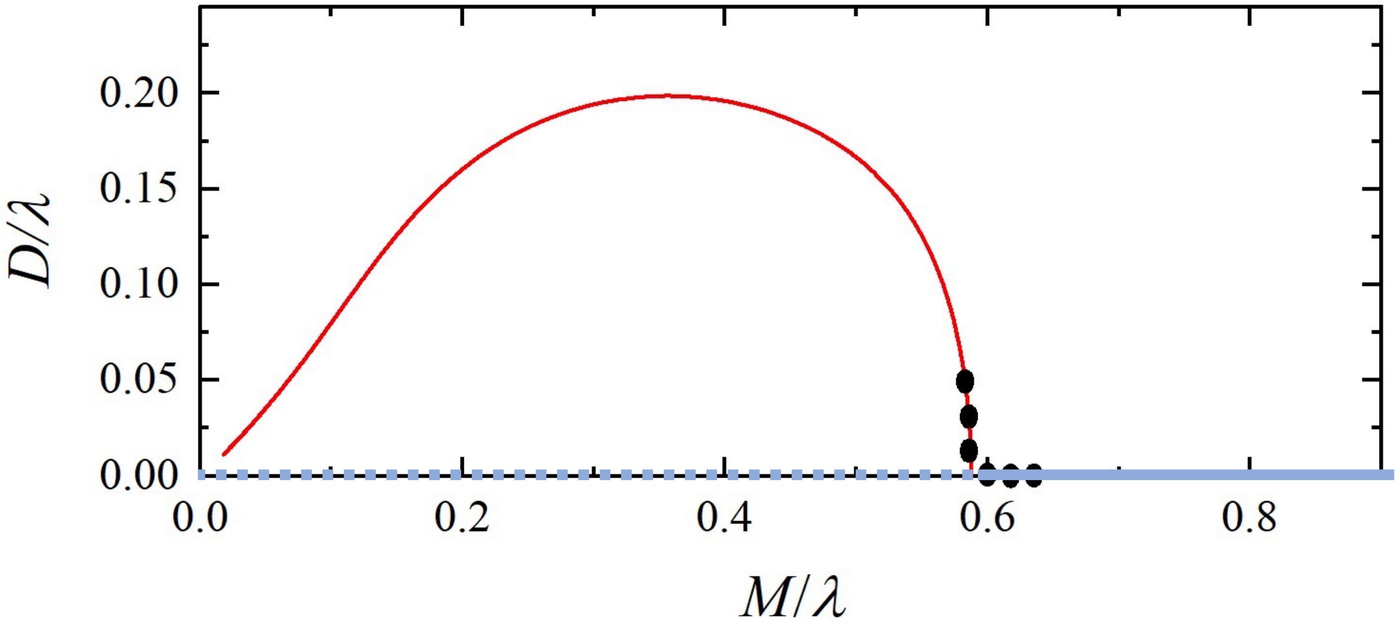
DD, Yazadjiev, PRD Lett. (2021)

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

Binary mergers

Dynamical descalarization

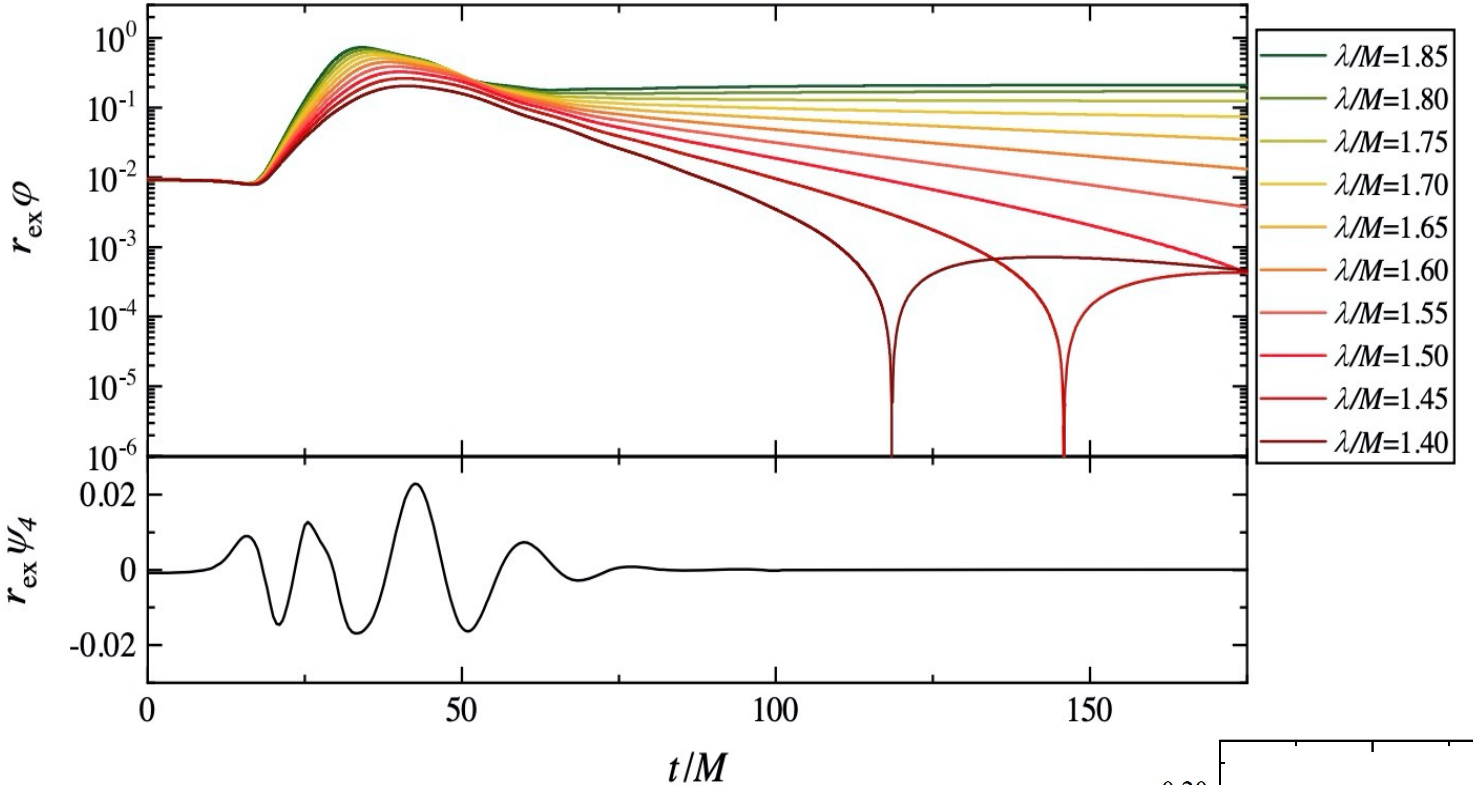
$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta(\varphi^2 + \cancel{\kappa\varphi^4})}\right) \; (\beta = 6, \kappa = 0)$$



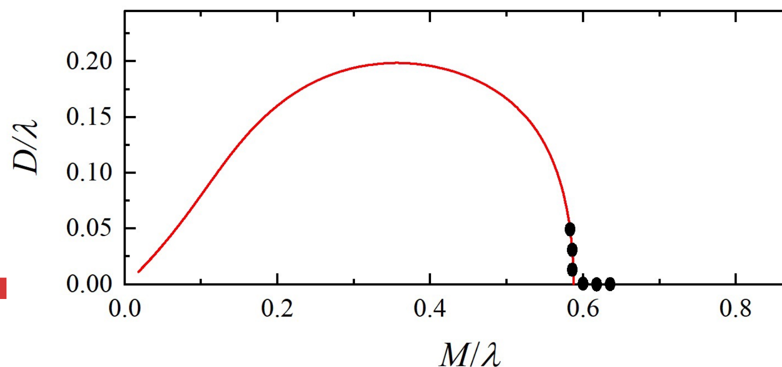
- Decoupling limit Silva et al. RPL (2021), Elley et al. PRD (2022)
- Full problem East&Ripley PRL (2021), Areste-Salo et al PRL (2022), Corman at al. (2023)

Dynamical descalarization

$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta(\varphi^2 + \kappa\varphi^4)}\right)\ (\beta = 6, \kappa = 0)$$

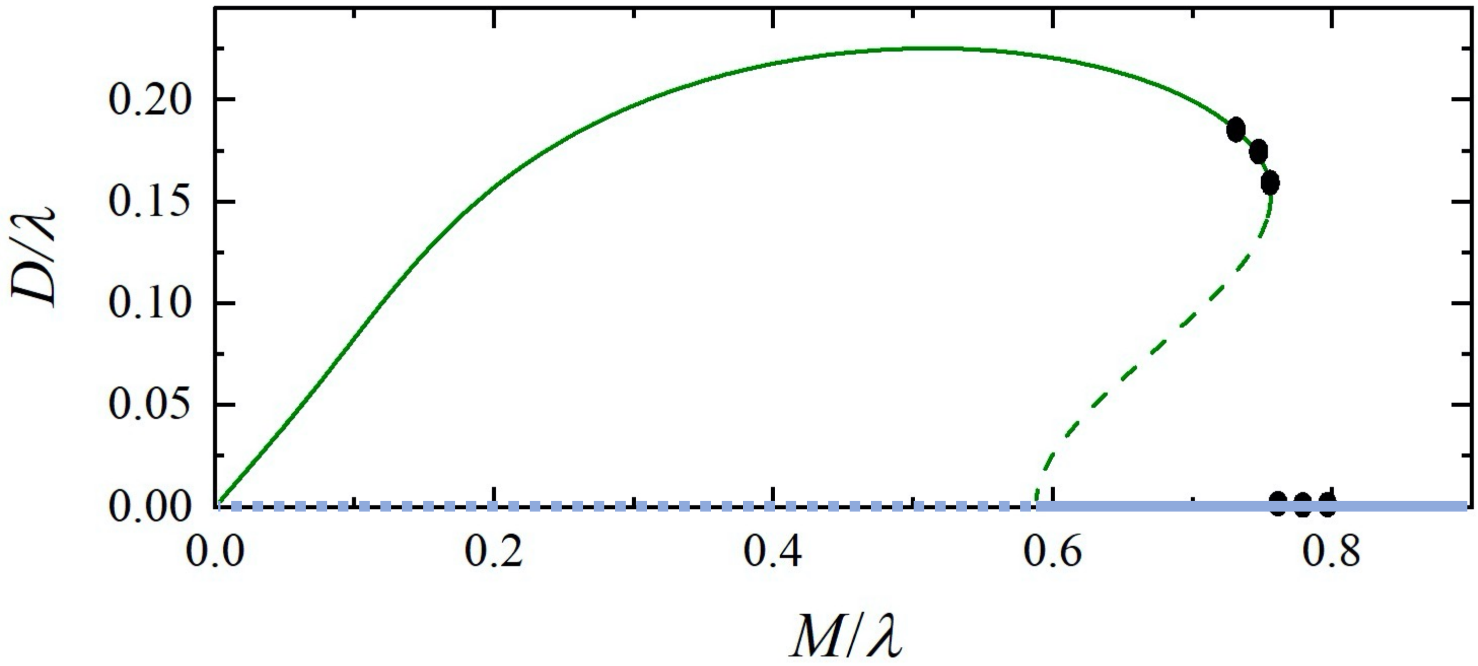


DD, Vano-Vinuales, Yazadjiev PRDLett. (2022)



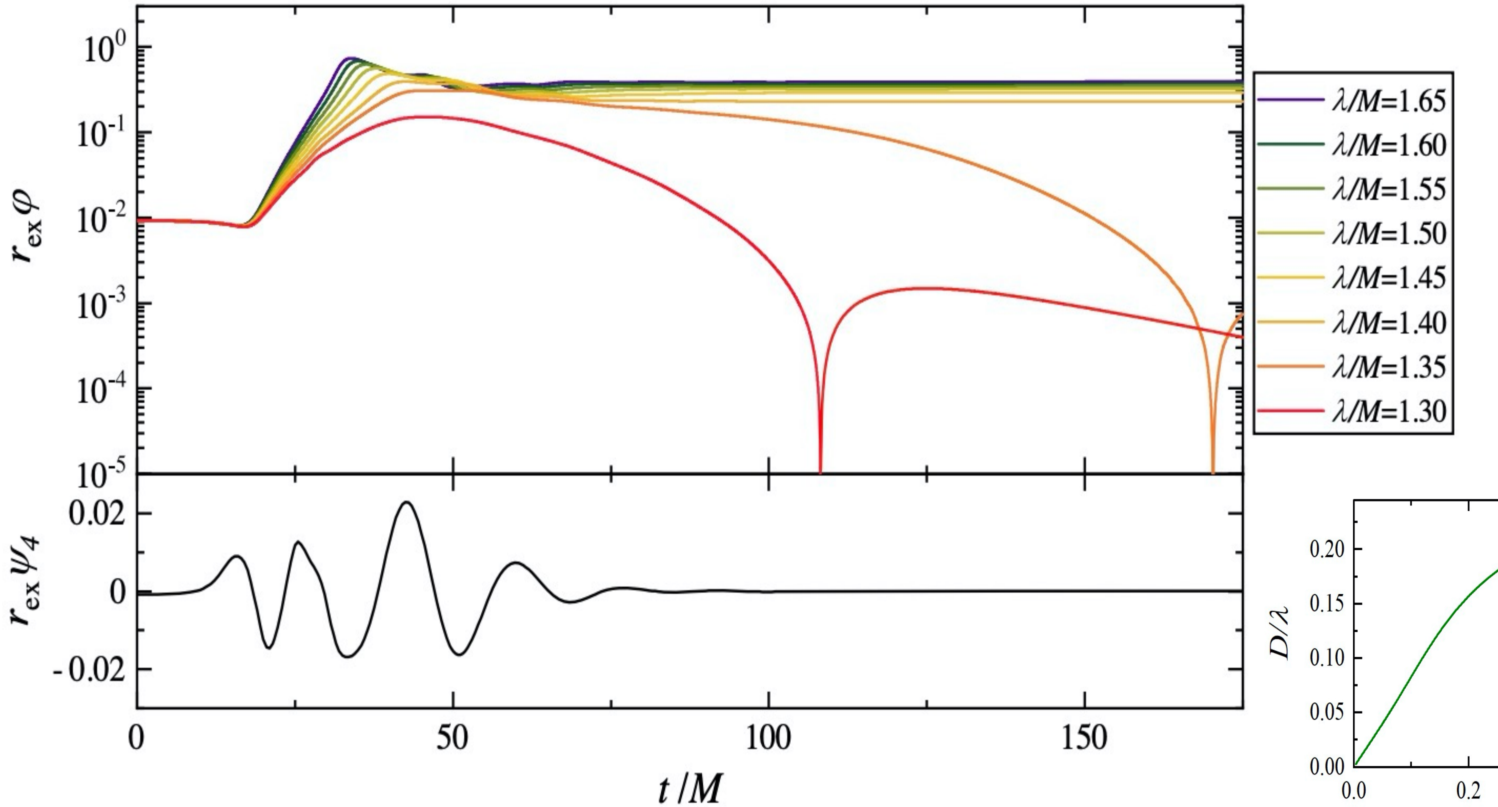
Dynamical descalarization WITH a jump

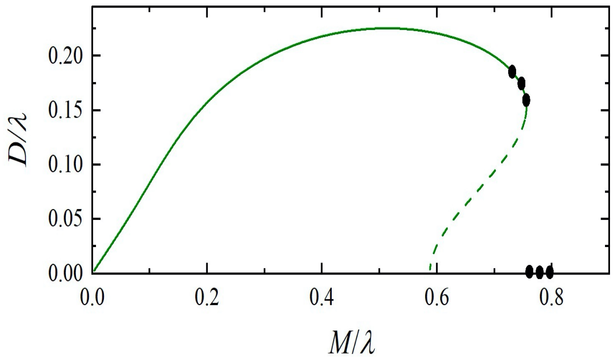
$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta\left(\varphi^2 + \kappa\varphi^4\right)}\right)\ (\beta = 6, \kappa = 16)$$



Dynamical descalarization WITH a jump

$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta(\varphi^2 + \kappa\varphi^4)}\right)\ (\beta = 6, \kappa = 16)$$





DD, Vano-Vinuales, Yazadjiev PRD Lett (2022)

- **Similarities** with the **matter phase transitions** during neutron star binary mergers **Most et al. PRL (2019), Bauswein et al. PRL (2019), Weih et al. (2020).**

Well-posedness

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

Studying hyperbolicity

- **Principle symbol** – a matrix assembled by the coefficients in front of the leading (2nd) order derivative in the differential equation

- Scalar-Gauss-Bonnet gravity: Can be written in terms of an **effective metric**
  Real PRD (2021), Areste-Salo et al PRL (2022), PRD (2022)

$$g^{\mu\nu}_{\rm eff} = g^{\mu\nu} - \Omega^{\mu\nu}$$

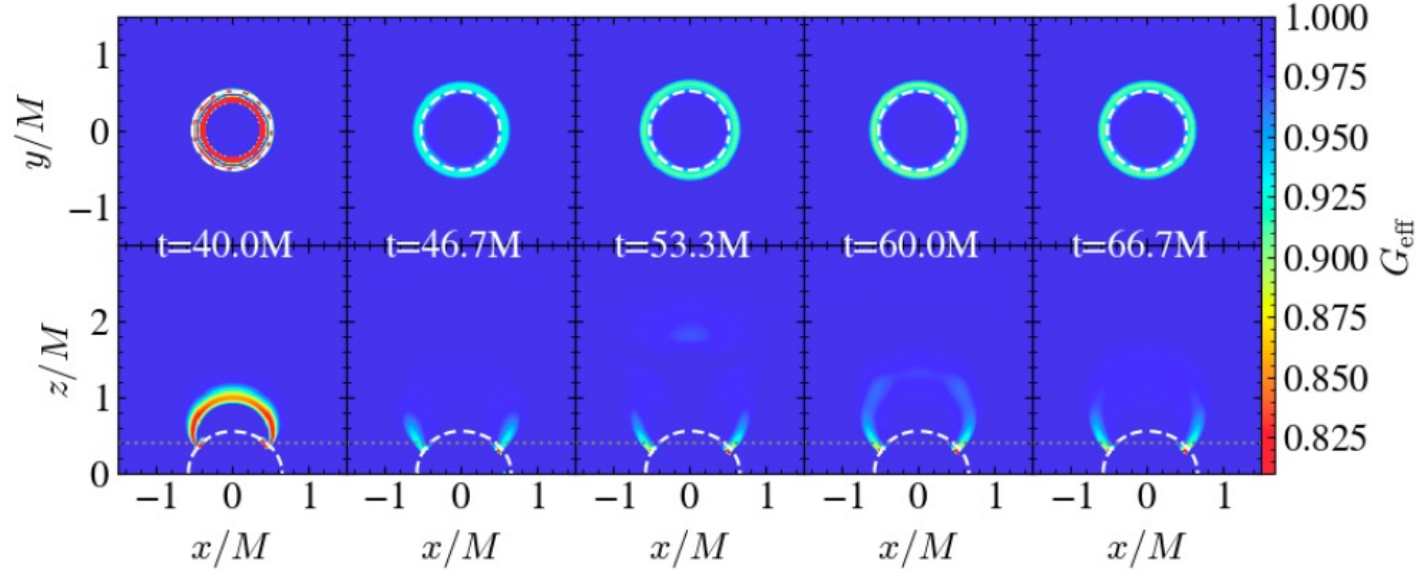
$$\Omega_{\mu\nu} = \lambda \nabla_\mu \nabla_\nu f(\varphi)$$

- **Hyperbolicity loss** when the determinant of the effective metric < 0

East&Ripley PRL (2021), Areste-Salo et al PRL (2022), Hegade et al PRD (2023), Corman at al. PRD (2023)

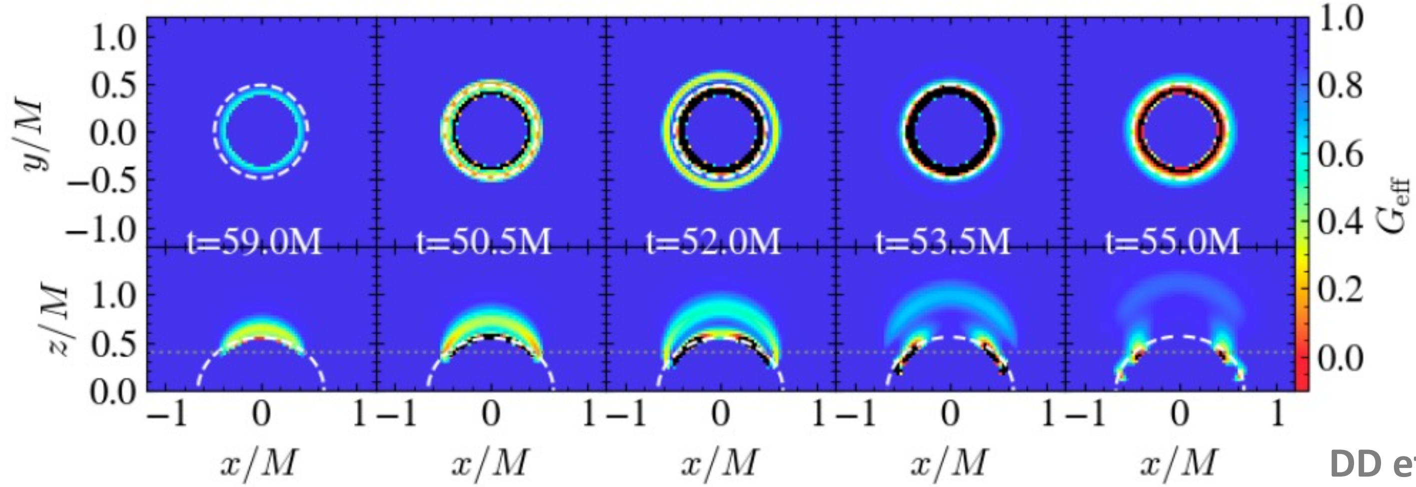
- **Modified harmonic gauge** in Gauss-Bonnet theory – the system remains **hyperbolic in weak coupling** limit Kovacs&Real PRL (2021)

Normalized determinant – spin-induced black hole



Hyperbolic evolution

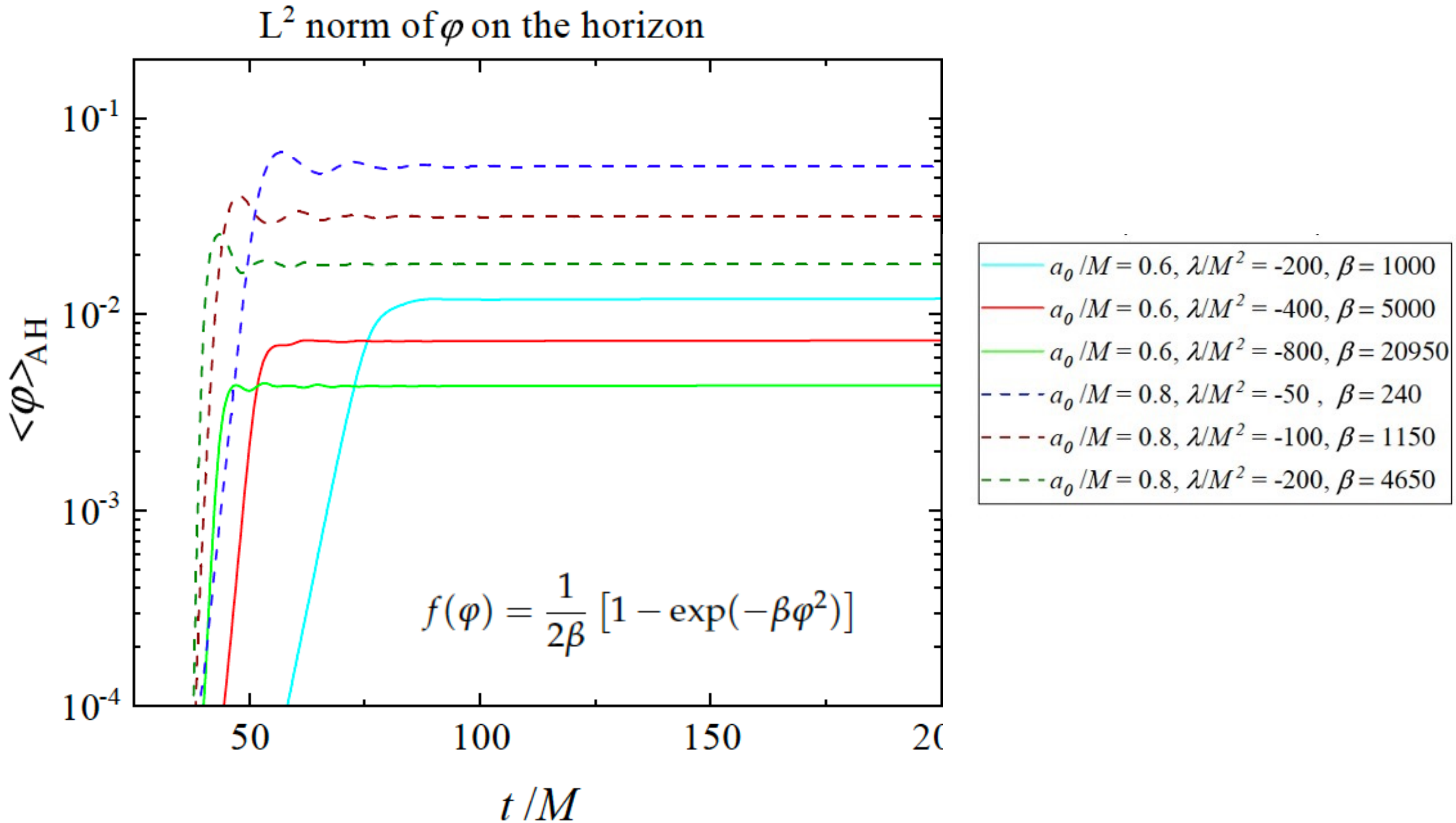
vs.



Hyperbolicity loss

DD et al. PRD (2023)

Limitting models for hyperbolicity loss



DD et al. PRD (2023)

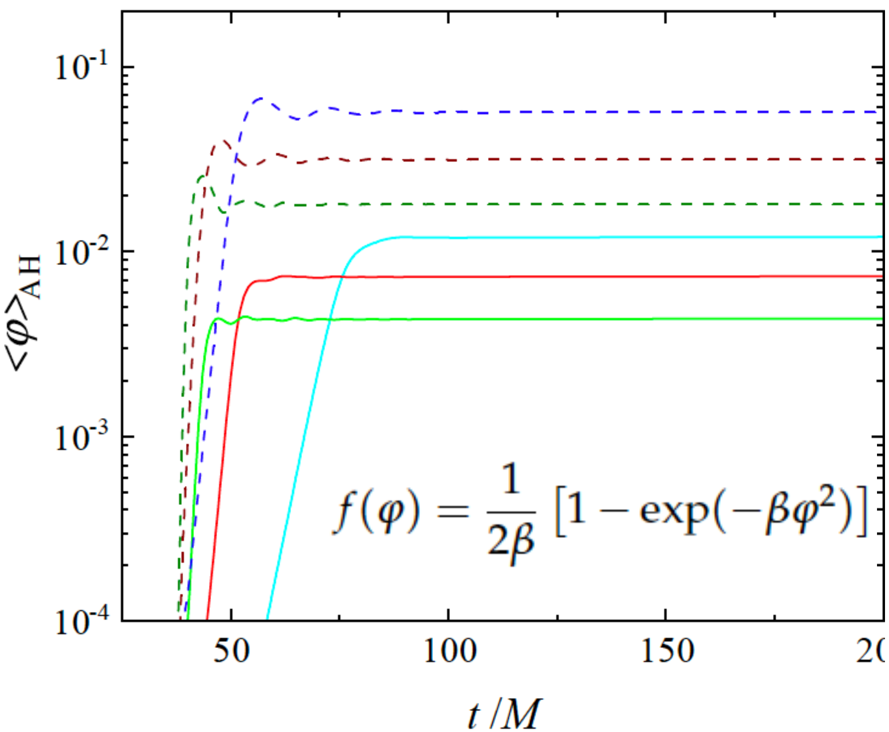
Limitting models and weak coupling condition

- **Weak coupling condition**

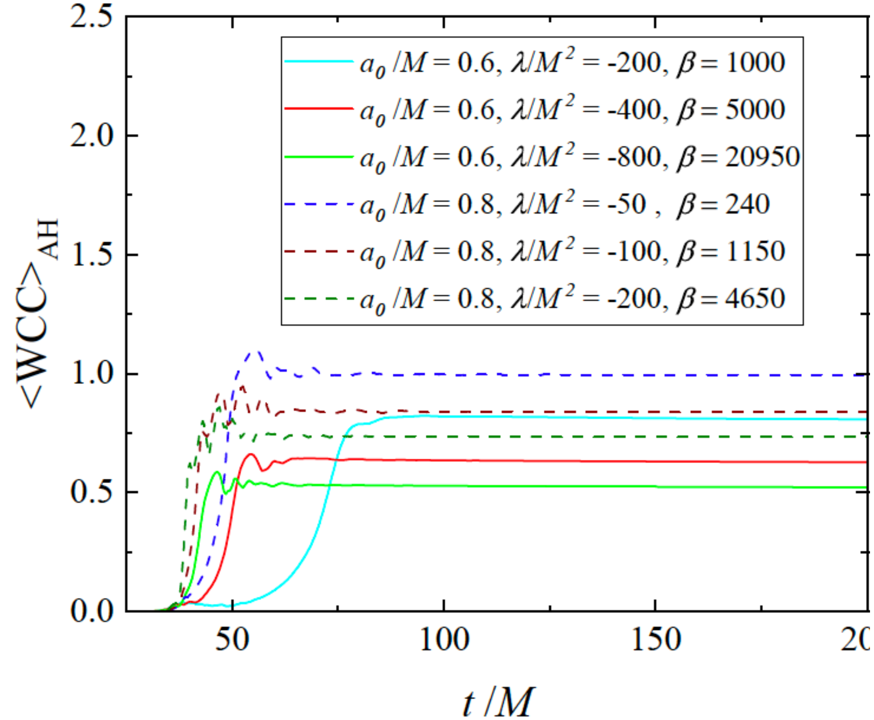
$$\sqrt{|\lambda f'(\varphi)|}/L \ll 1$$

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

L^2 norm of φ on the horizon



L^2 norm of the WCC on the horizon



DD et al. PRD (2023)

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

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

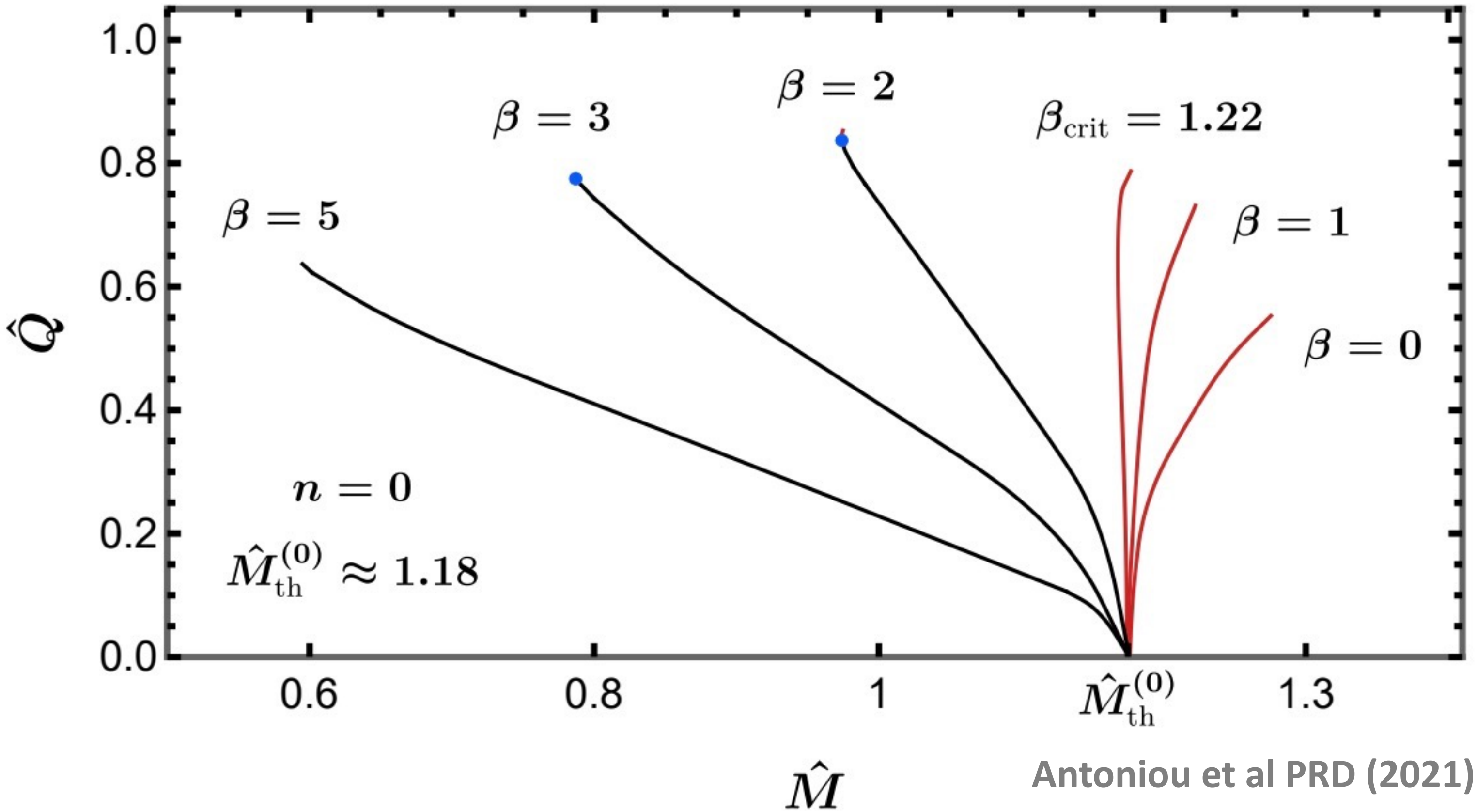
$$S = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\,\left[R - \frac{1}{2}\nabla_\mu\varphi\nabla^\mu\varphi + \frac{1}{4}\lambda^{GB} f(\varphi) R^{GB} - \beta(\varphi) R\right]$$

Ricci scalar coupling

Ricci scalar coupling

$$f(\varphi) \sim \varphi^2, \qquad \beta(\varphi) \sim \beta\varphi^2$$

- Previously unstable solution **turn stable** Antoniou et al PRD (2021)
- Loss of hyperbolicity is **mitigated** in 1D simulation Thaalba et al (2023)



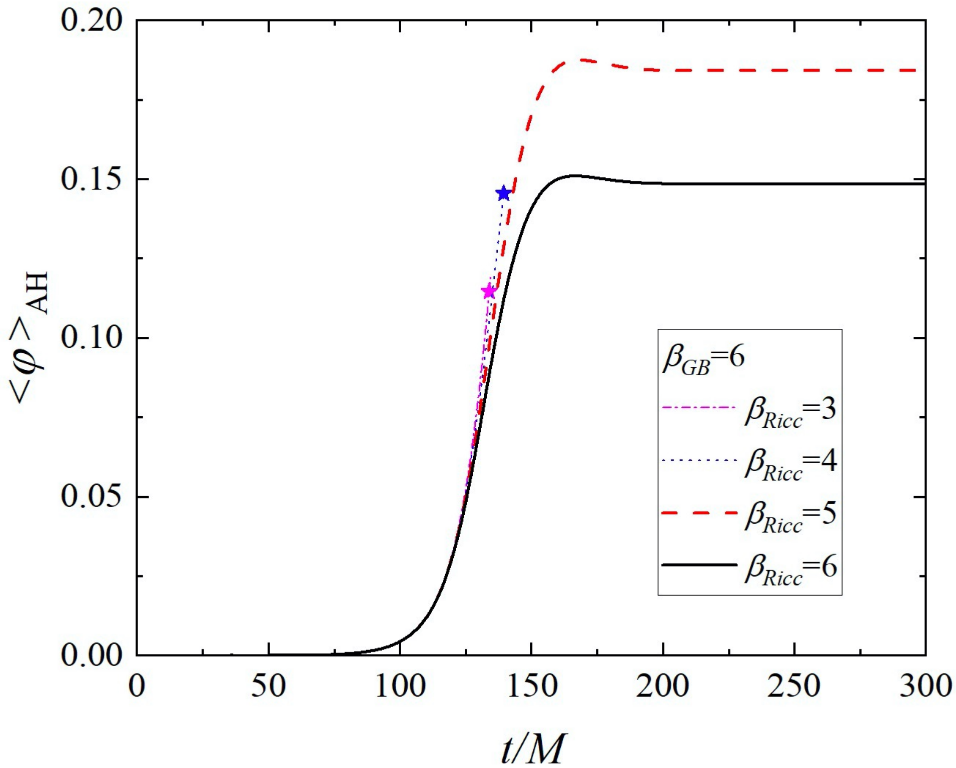
Antoniou et al PRD (2021)

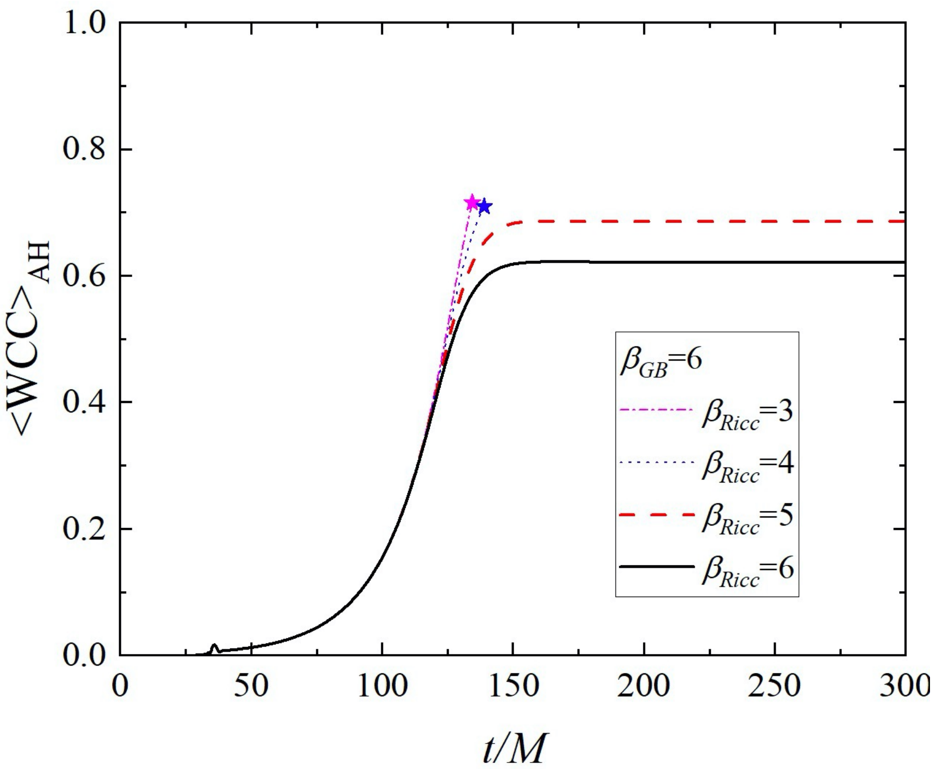
Ricci scalar coupling – 3D simulations

$$f(\varphi) \sim e^{-\beta_{GB}\varphi^2}, \qquad \beta(\varphi) \sim e^{-\beta_{Ricc}\varphi^2}$$

- Evolution of a single nonrotating black hole

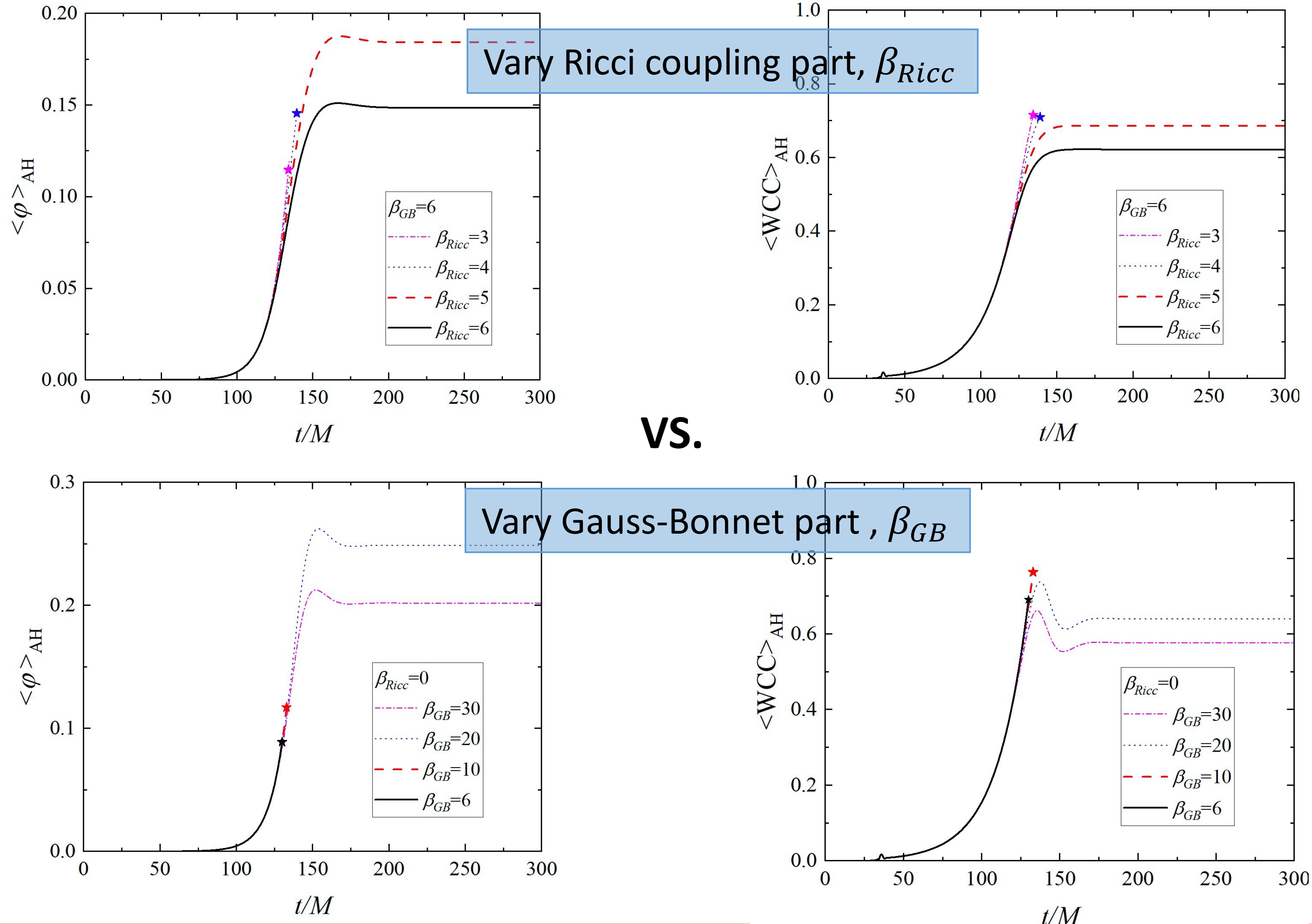
DD, Areste-Salo, Cough, Figueras, Yazadjiev, in prep.





Ricci coupling vs. GB coupling variation

$$f(\varphi) \sim e^{-\beta_{GB}\varphi^2}, \qquad \beta(\varphi) \sim e^{-\beta_{Ricc}\varphi^2}$$



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)

Conclusions

- Black holes in EFT 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

- Exploring further the **fixing equation approach**
- A deeper investigation **of binary mergers** and their **astrophysics signatures**

THANK YOU!