Scalarization of compact objects

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Plan of the talk:

- Scalarization – general idea
- Neutron star scalarization in scalar tensor theories
- Black hole scalarization in extended scalar-tensor theories
- Conclusions

There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.
- *Hamlet* (1.5.167-8), Hamlet to Horatio

Observations

- Strong field regime not well constrained
- Dark Energy
- Dark Matter (?)

Theory

- Theories trying to unify all the interactions
- Attempts to quantize gravity
- Examining GR from a broader perspective help us understand it better

- General idea:
  - ✓ **Modified theory** of gravity **possessing** an additional mediator of the gravitational interaction – a **scalar field** φ
  - ✓ **Perturbative equivalent to GR in the weak field**
  - ✓ Nonlinear effects for strong fields – **scalarization**
  - ✓ **Not possible** to be modelled directly by **approximate metrics or perturbative techniques.**

- Conditions for scalarization
  - ✓ A **gravitational theory** were $\varphi = 0$ **is always a solution** of the field equations
  - ✓ A **source of the scalar field** should be present leading to **negative values** of the **square of the effective mass**, i.e. tachyonic instability

Scalarization – general idea

- **Einstein frame action (Scalar-tensor theories)**

$$S = \frac{1}{16\pi G_*}\int d^4x\,\sqrt{g}\,[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\varphi\varphi - 4V(\varphi)] + S_m[\psi_m, A^2(\varphi)g_{\mu\nu}]$$

- **Field equations**

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G_* T_{\mu\nu} + 2\partial_\mu\varphi\,\partial_\nu\varphi\, - g_{\mu\nu}g^{\alpha\beta}\partial_\alpha\varphi\partial_\beta\varphi - 2V(\varphi)g_{\mu\nu}$$

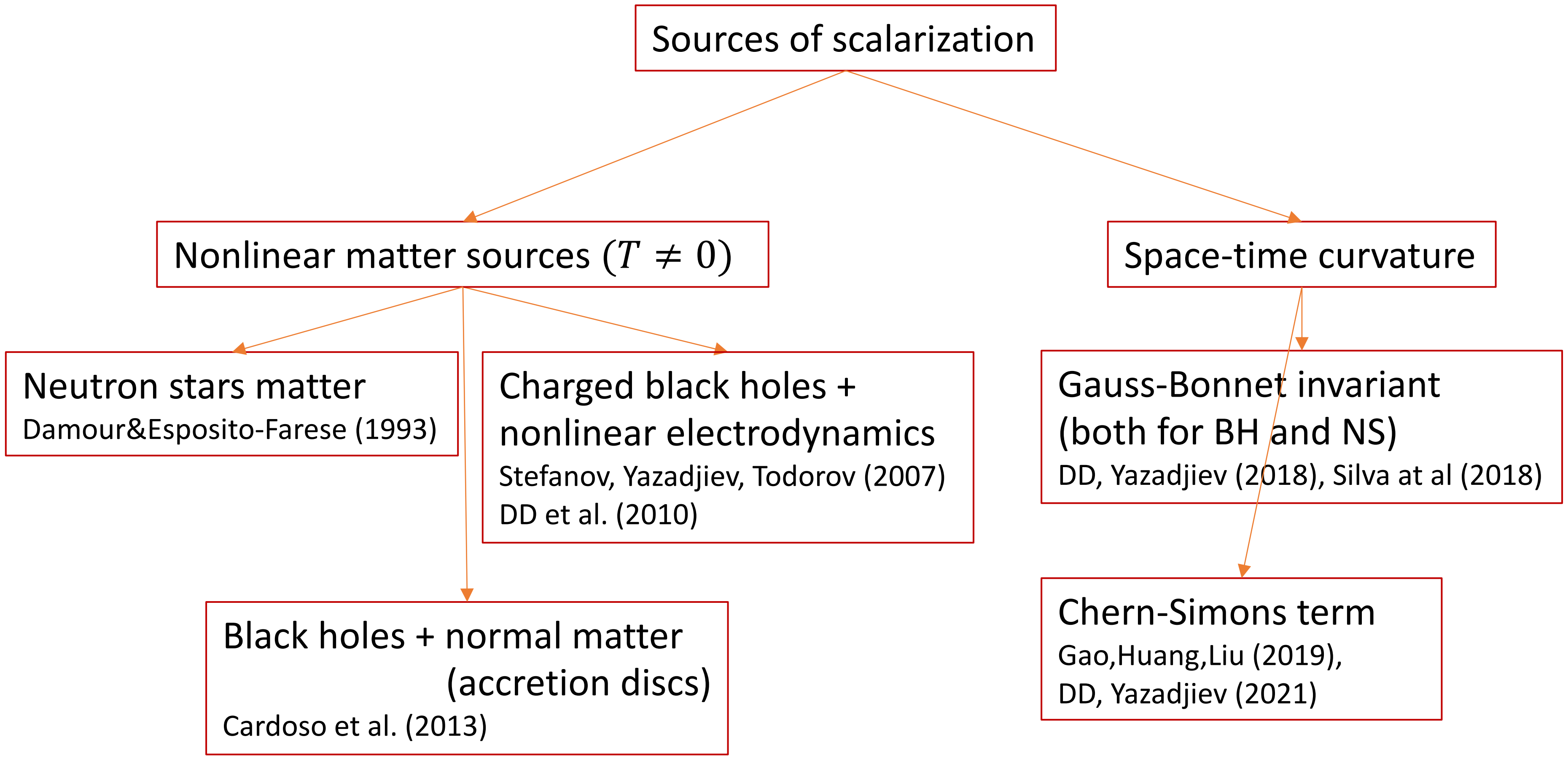
$$\Box\varphi = -4\pi G_*\alpha(\varphi)T + \frac{dV(\varphi)}{d\varphi}$$

- **Spontaneous scalarization** occurs if the pure **GR** solution is **unstable against scalar perturbations** $\delta\varphi$

$$(\Box - \mu^2_{\rm eff})\delta\varphi = 0, \text{ where } \mu^2_{\rm eff} = \frac{d\alpha}{d\varphi}|_{\varphi=0} 4\pi G_\star T$$

- If $\boldsymbol{\mu^2_{\rm eff} < 0}$ a **tachyonic instability** is present leading to a development of the scalar field
- If φ grows the **nonlinear terms** start operating and instability **settles to a stable scalarized compact object**

Scalarization – general idea



Neutron star scalarization

Scalarized neutron stars – DEF model

- **Scalarization of neutron stars** Damour&Esposito-Farese (1993) due to a **nonzero trace** of the energy momentum tensor. **Energetically more favorable** over the GR solutions.

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- Assume the following form of the **coupling function**:

$$\alpha(\varphi) = \frac{d\ln\big(A(\varphi)\big)}{d\varphi} = \alpha_0 + \beta_0\varphi$$

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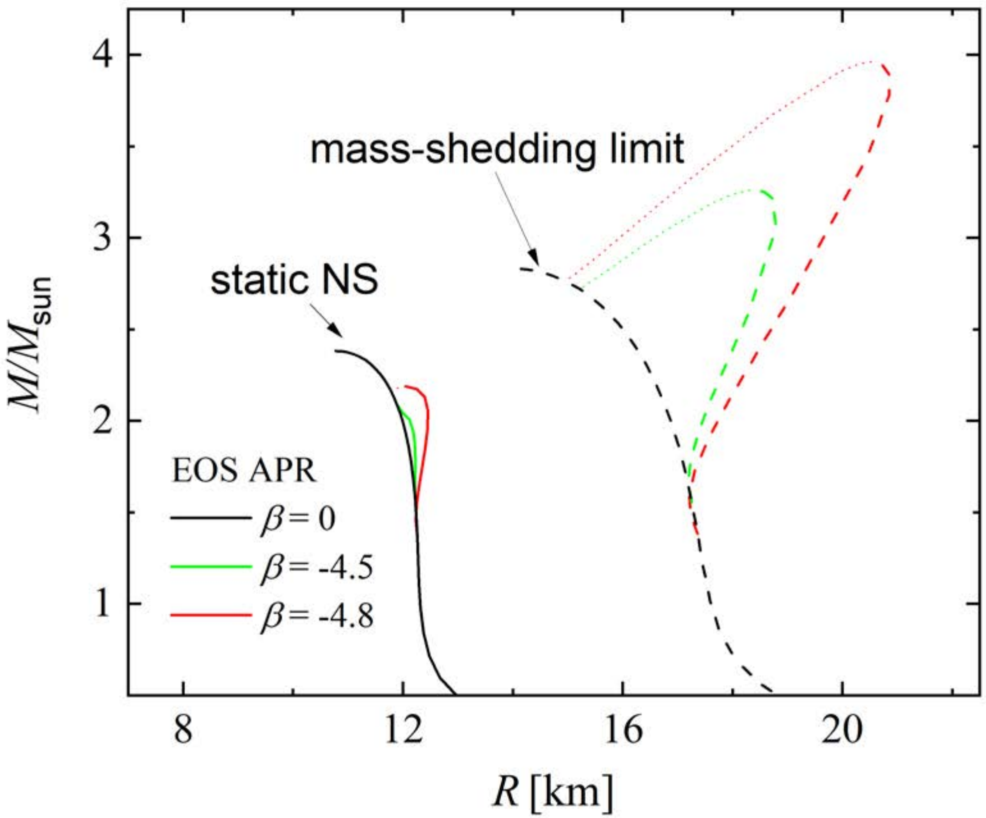

Scalarized neutron stars – DEF model

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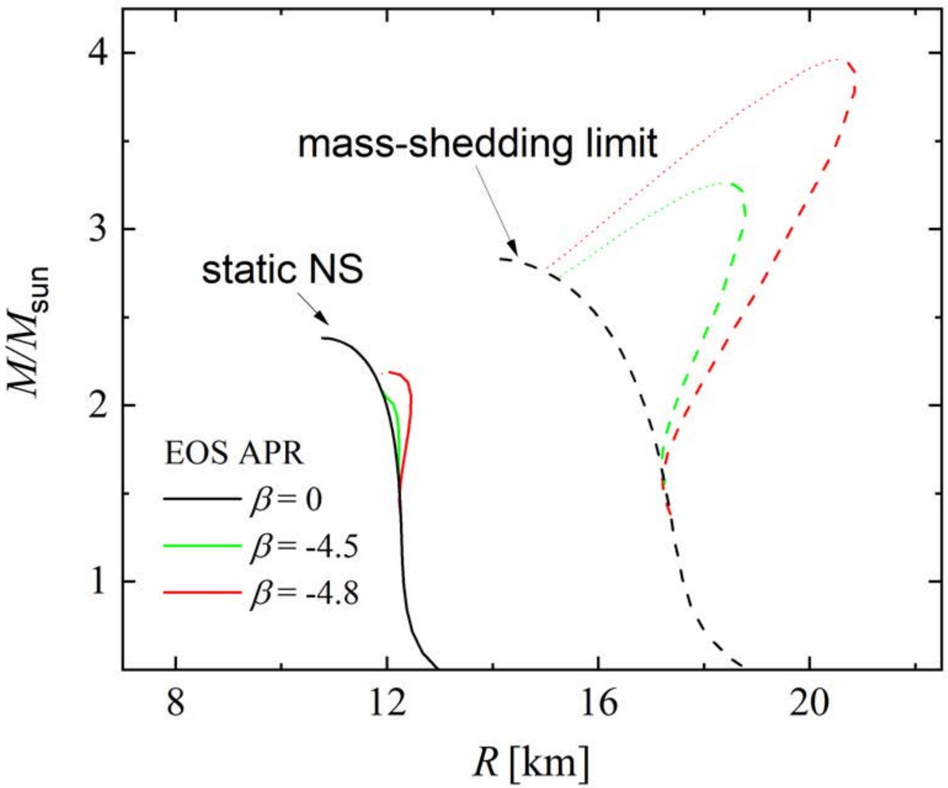
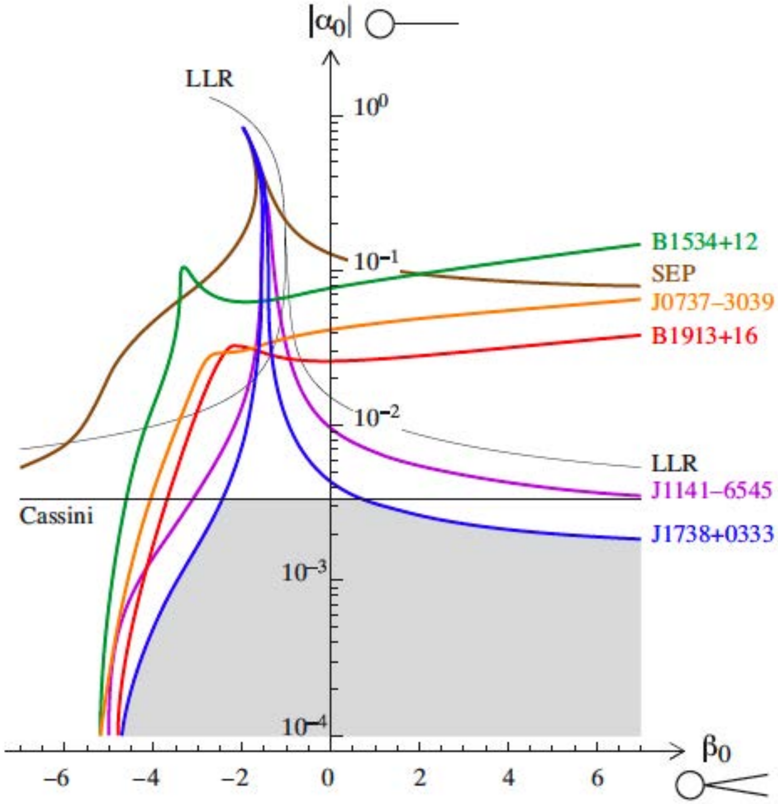
- For $\mathrm{r} \to \infty, \varphi \sim \frac{D}{r}$, where D is the scalar charge. If $|D| > 0$ – **scalar dipole radiation**



DD, Yazadjiev, Stergioulas, Kokkotas (2013,2014)



Freire at al (2012)

Scalar field potential

$$\Box\varphi = -4\pi G_* \alpha(\varphi) T + \frac{dV(\varphi)}{d\varphi}$$

$$V(\varphi) = \frac{1}{2} m_\varphi^2 \varphi^2 + \lambda \varphi^4$$

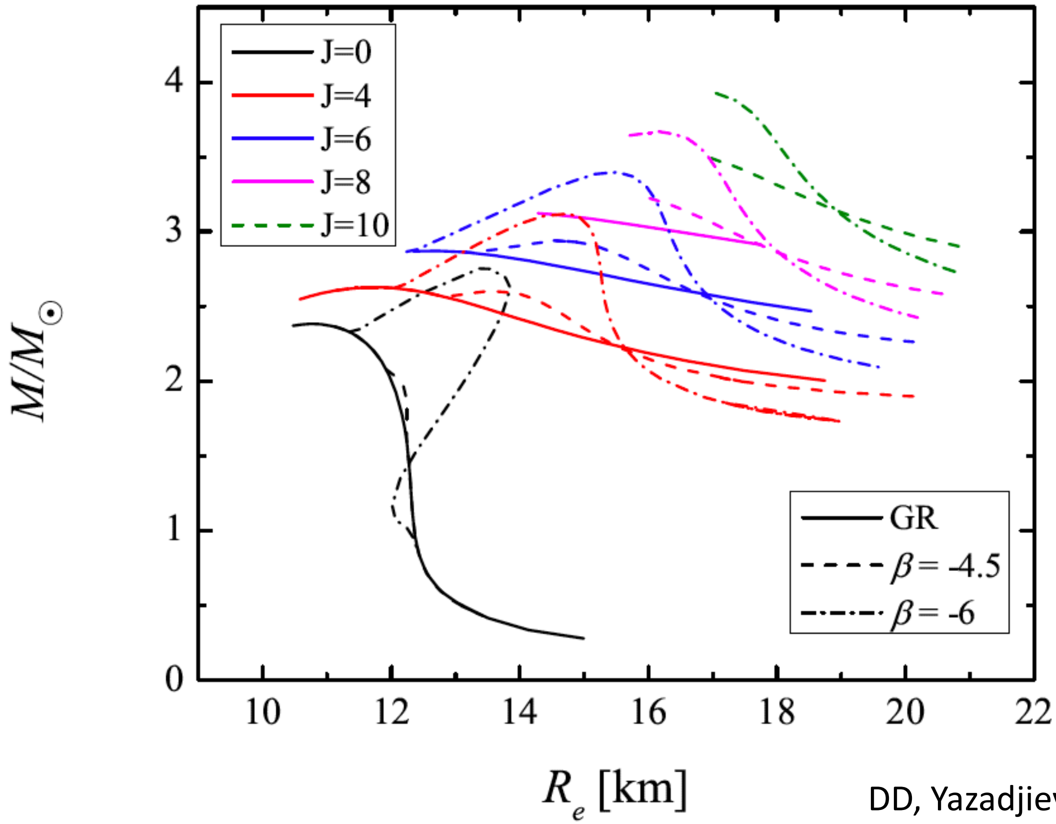
Scalar field mass

Self-interaction term

- Introduces an **effective range of the scalar field** connected to its **Compton wavelength** $\lambda_\varphi = \frac{2\pi}{m_\varphi}$. For $\boldsymbol{r} \gg \boldsymbol{\lambda_\varphi}$ the scalar field drops exponentially.
- For $\boldsymbol{m_\varphi} \gg \mathbf{10^{-16}}$**eV** practically **not constraints on** $\boldsymbol{\beta_0}$ can be imposed on the basis of the binary pulsar observations Ramazanoglu,Pretorius(2016), Yazadjiev,DD(2016), Rosca-Mead et al. (2020)
- The scalar field mass suppressed the scalar field, but larger β_0 are allowed. Thus, very large devations from GR can be achieved Yazadjiev,DD(2016), Rosca-Mead et al. (2020)

Differential rotation

- ***j*-constant differential rotation** law $u_t u^\phi = F(\Omega) = A_{\rm diff}^2\,(\Omega_c - \Omega)$ with $A_{\rm diff} = 1.225$
- **Higher *J*** reached for the scalarized NS
- The **maximum mass** of the possible supremassive configurations **increases** significantly.



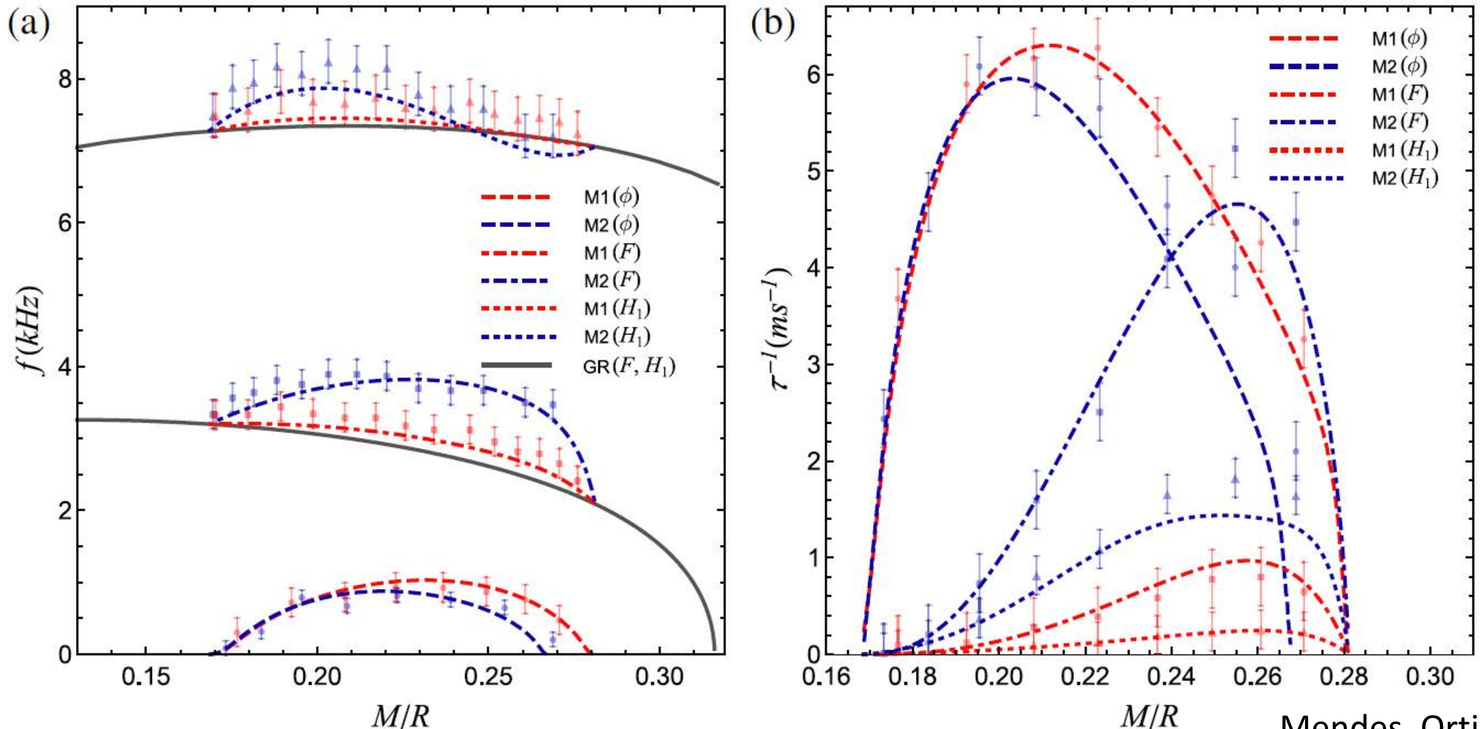
DD, Yazadjiev, Stergioulas, Kokkotas (2018)

Radial perturbations

- The scalar field **radiates energy** and thus the **oscillations are damped**
- A **new class** of scalar **modes** appear Mendes, Ortiz (2018)

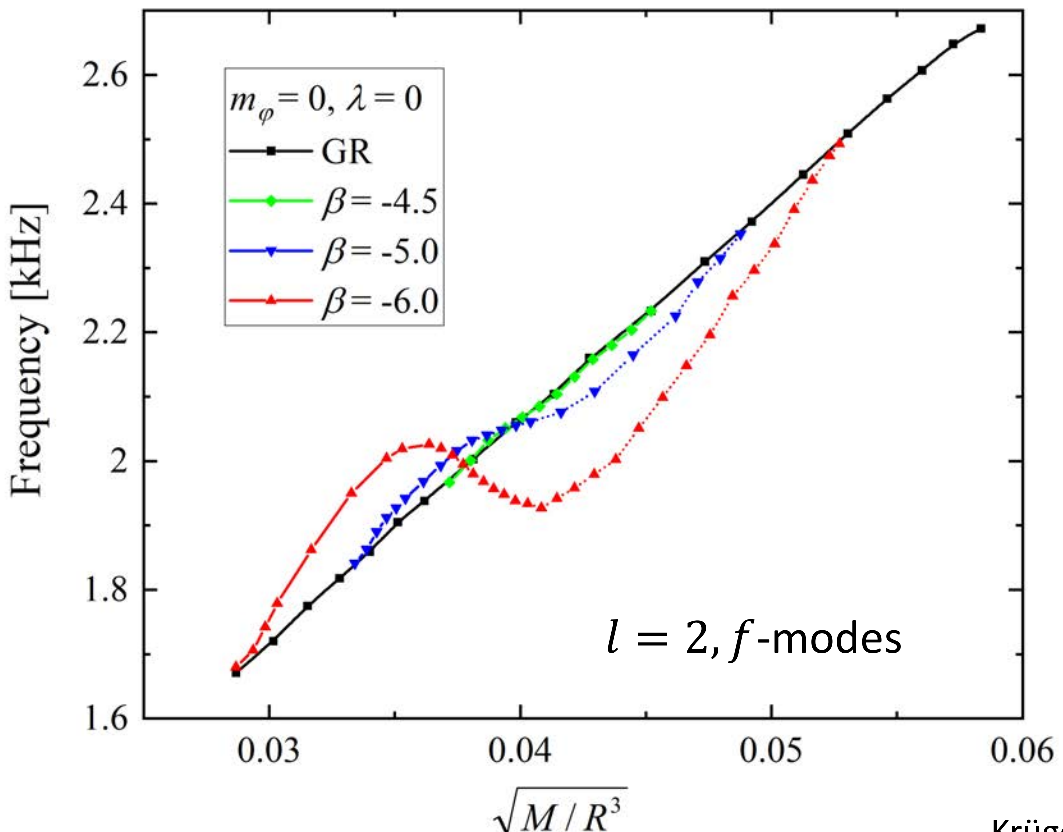
$$e^{3\lambda_{(0)}}(\tilde{\epsilon}_{(0)}+\tilde{p}_{(0)})\ddot{\xi}-\left(\frac{\Gamma_1\tilde{p}_{(0)}}{a^4_{(0)}r^2}e^{\lambda_{(0)}+3\nu_{(0)}}(e^{-\nu_{(0)}}a^4_{(0)}r^2\xi)'\right)'+A_\xi\xi+A_{\delta\phi}\delta\phi+A_{\delta\phi'}\delta\phi'=0,$$

$$e^{2\lambda_{(0)}-2\nu_{(0)}}\delta\ddot{\phi}-\delta\phi''+B_{\delta\phi'}\delta\phi'+B_{\delta\phi}\delta\phi+B_{\xi'}\xi'+B_\xi\xi=0$$



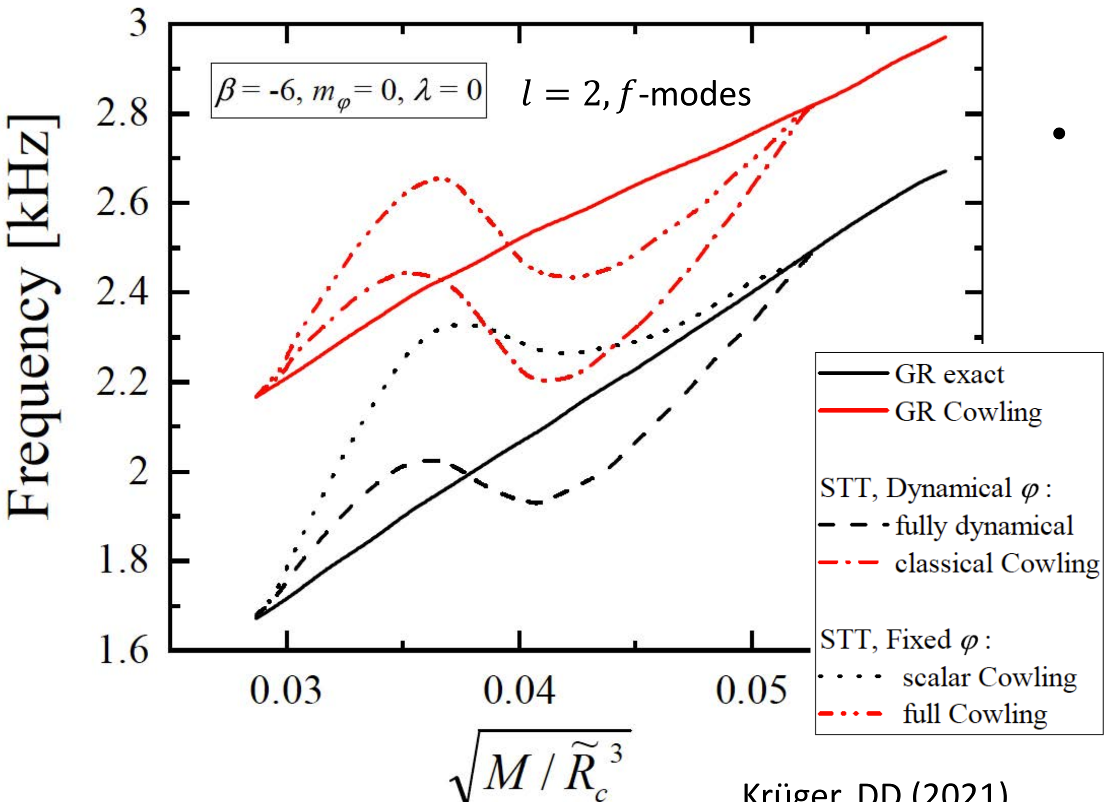
Mendes, Ortiz (2018)

- **Nonradial** stellar **oscillations** ($l = 2$, f-modes) Krüger, DD (2021).
- Time evolution of the coupled system of equations for the metric, fluid and the scalar field perturbations – allows to handle the boundary conditions easier.



Krüger, DD (2021)

- **Accuracy** of the **Cowling approximation** for scalarized neutron stars (Sotani, Kokkotas (2004), Sotani (2014))
  - ✓ **full** Cowling – fixed **spacetime & scalar field**
  - ✓ **classical** Cowling – fixed **spacetime**
  - ✓ **scalar** Cowling – fixed **scalar field**



Krüger, DD (2021)

- **Hypothesis –** the Cowling approximation will give **good results** also in other **more complicated alternative theories** of gravity

Neutron star scalarization possible also in **other alternative theories** of gravity:

- **Gauss-Bonnet** gravity DD,Yazadjiev (2018)
- **Chern-Simons** gravity (not yet constructed)
- Other types of **Horndeski** theories Andreou et al. (2019)
- Tensor-**multi-scalar** theories DD,Yazadjiev (2020)

Scalarized black holes

Gauss-Bonnet theory - basics

- **Quadratic gravity –** the action is supplemented with all possible curvature invariants of second order. Motivated by the **attempts to quantize gravity**.

$$S = \frac{1}{16\pi}\int \sqrt{-g}d^4x\Big[R - 2\nabla_\mu\varphi\nabla^\mu\varphi - V(\varphi)$$
$$+ f_1(\varphi)R^2 + f_2(\varphi)R_{\mu\nu}R^{\mu\nu} + f_3(\varphi)R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} + f_4(\varphi)^{*}RR\Big] + S_{\rm matter}\left[\chi, \gamma(\varphi)g_{\mu\nu}\right]$$

- **Drawback** – in its general form it leads to field equations that are of order higher than two and ghosts can appear.

- **Quadratic gravity –** the action is supplemented with all possible curvature invariants of second order. Motivated by the **attempts to quantize gravity**.

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- **Gauss-Bonnet gravity –** the equations are of second order

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

Gauss-Bonnet invariant:

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

Quadratic theory

- **Quadratic gravity –** the action is supplemented with all possible curvature invariants of second order. Motivated by the **attempts to quantize gravity**.

$$S = \frac{1}{16\pi}\int \sqrt{-g}\, d^4x \Big[R - 2\nabla_\mu \varphi \nabla^\mu \varphi - V(\varphi)$$
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- **Gauss-Bonnet gravity –** the equations are of second order

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

- **(dynamical) Chern-Simons gravity –** deviated from GR only in the presence of a parity-odd source such as rotation

$$S = \frac{1}{16\pi}\int d^4x \sqrt{-g}\Big[R - 2\nabla_\mu \varphi \nabla^\mu \varphi + 8\lambda^2 f(\varphi) {}^*\mathcal{R}\mathcal{R} \Big]$$

Pontryagin invariant.

- **Field equations –** Gauss-Bonnet gravity**:**

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Gamma_{\mu\nu} = 2\nabla_\mu\varphi\nabla_\nu\varphi - g_{\mu\nu}\nabla_\alpha\varphi\nabla^\alpha\varphi - \frac{1}{2}g_{\mu\nu}V(\varphi),$$
$$\nabla_\alpha\nabla^\alpha\varphi = \frac{1}{4}\frac{dV(\varphi)}{d\varphi} - \frac{\lambda^2}{4}\frac{df(\varphi)}{d\varphi}\mathcal{R}^2_{GB},$$

- **Conditions for the existence** of scalarized solutions

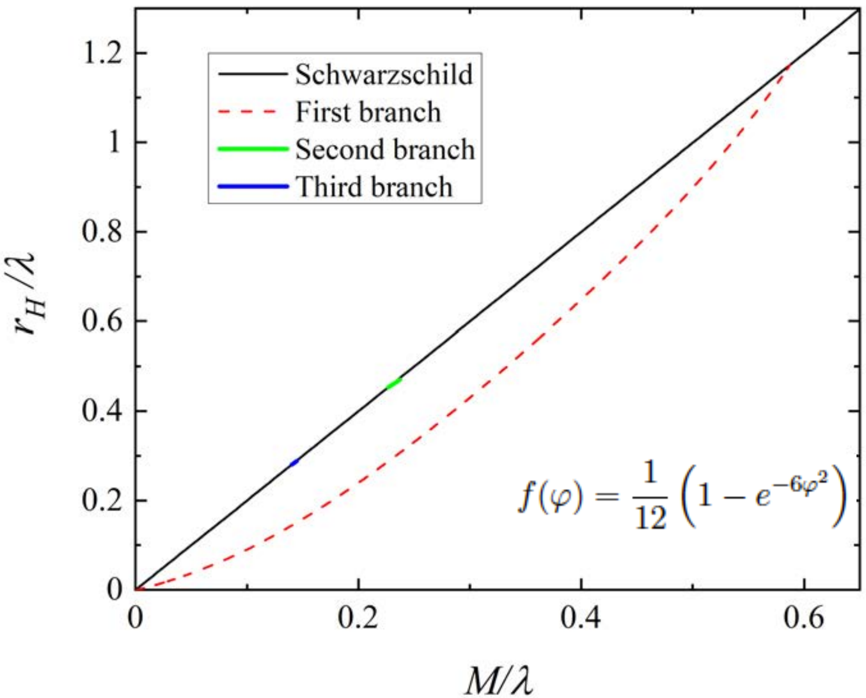
$$(\Box - \mu^2_{\mathrm{eff}})\delta\varphi = 0 \text{ with } \mu^2_{\mathrm{eff}} = -\frac{\lambda^2}{4}\frac{d^2f}{d\varphi^2}(0)R^2_{GB} < 0$$

Scalarization possible for: $\frac{df}{d\varphi}(0) = 0,\ \frac{d^2f}{d\varphi^2}(0) > 0$

- **Scalarization** in a similar way possible also in **Chern-Simons gravity**.

Black hole scalarization in Gauss-Bonnet gravity

- **Scalarized solutions** with different number of nodes exist that **bifurcate from the Schwarzschild solution** DD, Yazadjiev (2018), Silva et al. (2018), Antoniou, Bakopoulos, Kanti (2018) and the first $n = 0$ branch can be stable Blazquez-Salcedo, DD, Kunz, Yazadjiev (2018), Blazquez-Salcedo, DD, Kahlen, Kunz, Yazadjiev (2019,2020)
- **Energetically more favorable** over the Schwarzschild black hole.
- For low black hole masses - **loss of hyperbolicity.**



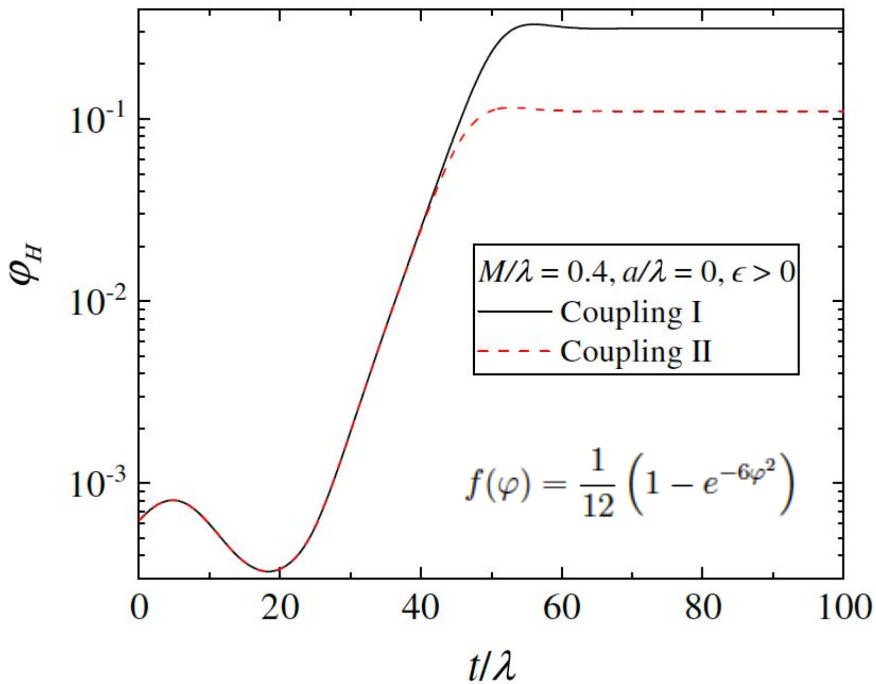
DD, Yazadjiev (2018)

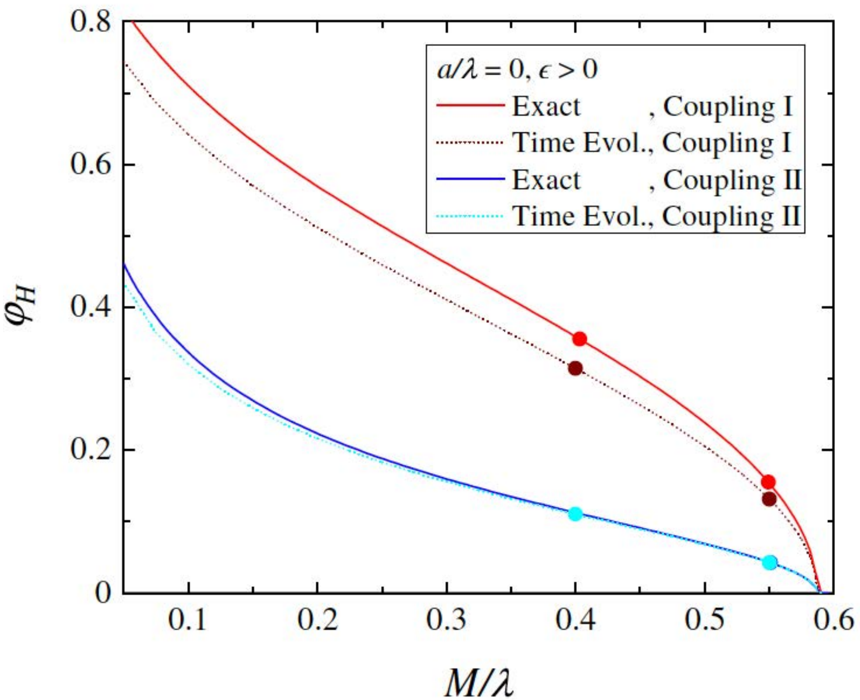
- The stability is dependent on the exact form of the **coupling function** and possibly the scalar field **potential**. Minamitsuji, Ikeda (2019), Silva et al. (2019),Macedo et al. (2019), DD, Staykov, Yazadjiev (2019)
- **Rotation downsizes the phenomenological effects of scalarization** Cunha, Herdeiro, Radu (2019), Collodel at al (2019).
- **Non-GR effects** are only **significant for low spin** (BH shadow, QPO oscillations)

Decoupling limit

- Study only the **scalar field evolution** on a **fixed spacetime background**

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





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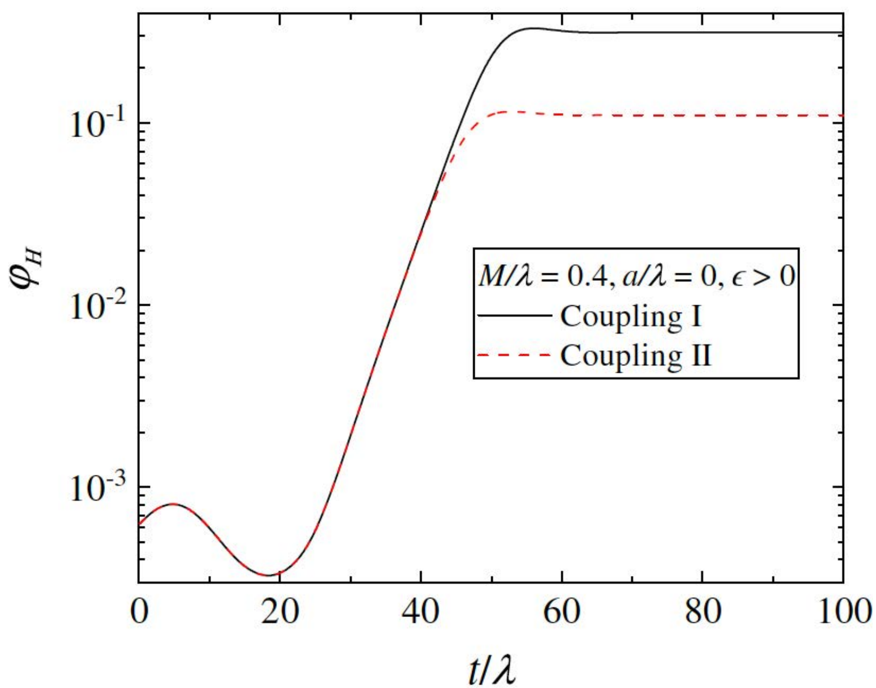
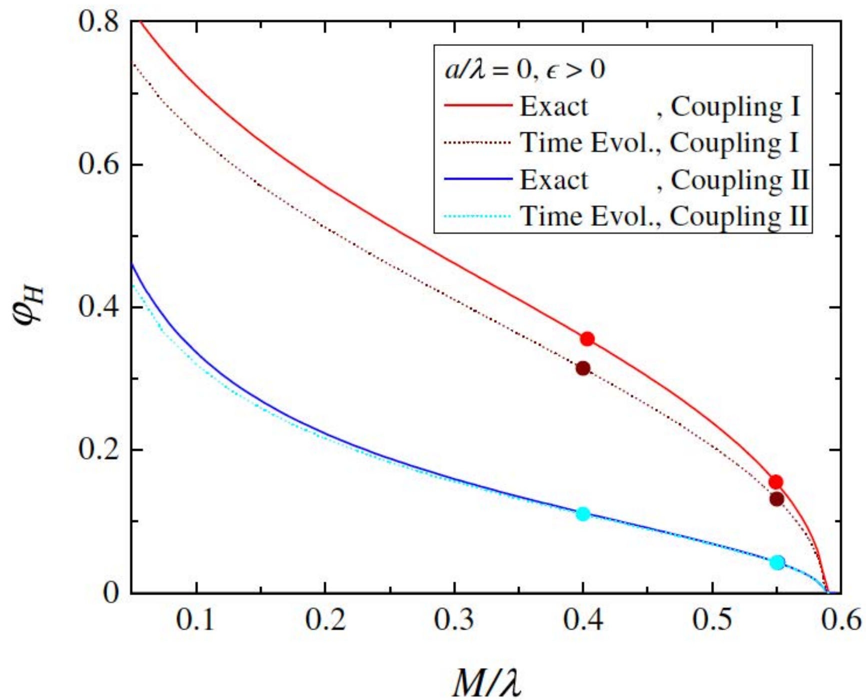




DD, Yazadjiev (2021)

Decoupling limit – Rotating solutions

- Study only the **scalar field evolution** on a **fixed spacetime background**

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

- Scalar fied equation on a Kerr brackground

$$ds^2 = -\frac{\Delta - a^2 \sin^2\theta}{\Sigma} dt^2 - 2a \sin^2\theta \frac{r^2 + a^2 - \Delta}{\Sigma} dt d\phi + \frac{(r^2+a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma} \sin^2\theta d\phi^2 + \frac{\Sigma}{\Delta} dr^2 + \Sigma d\theta^2$$

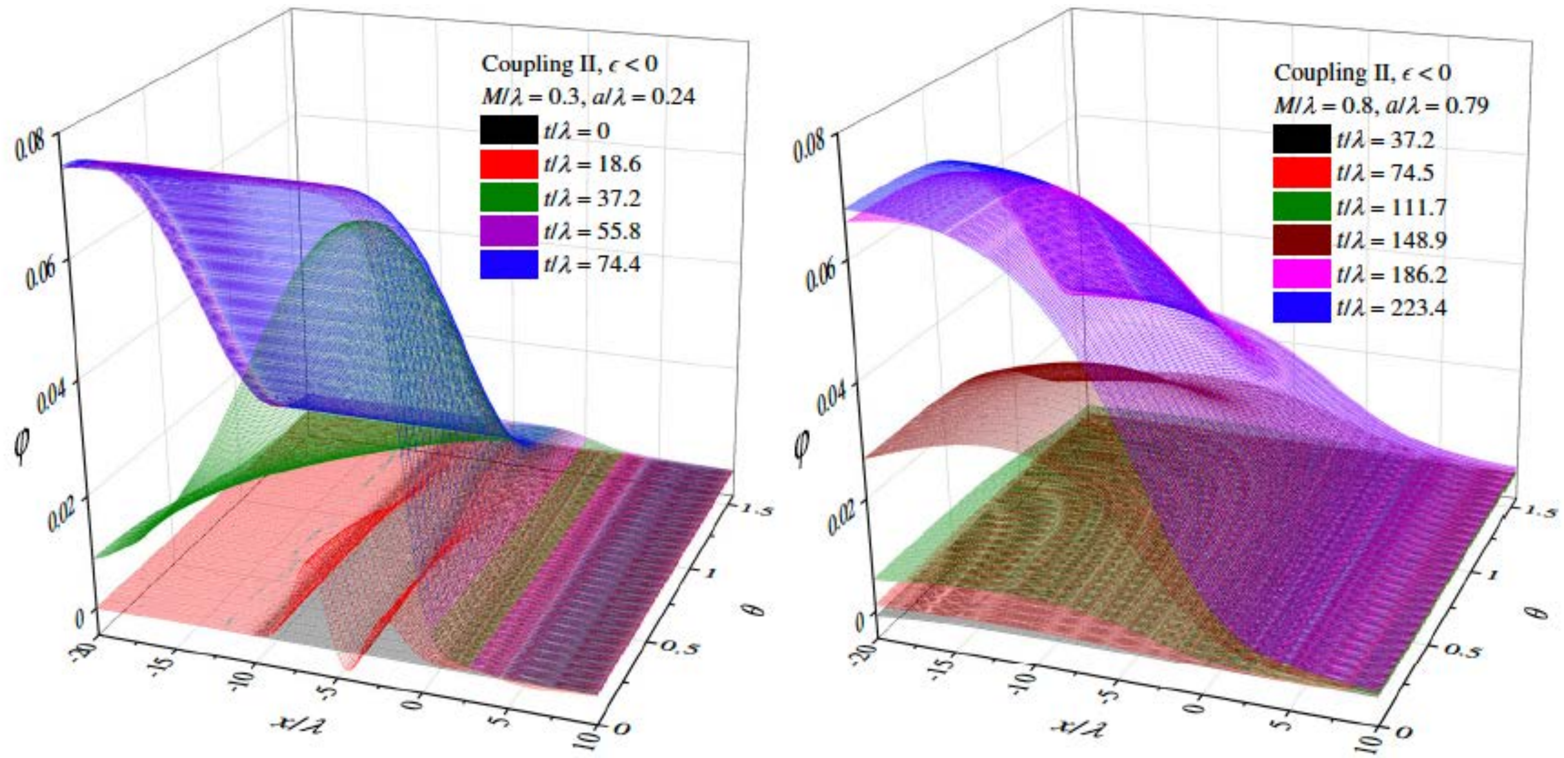
$$- \left[(r^2+a^2)^2 - \Delta a^2 \sin^2\theta \right] \partial_t^2 \varphi + (r^2+a^2)^2 \partial_x^2 \varphi + 2r\Delta \partial_x \delta\varphi - 4Mar \partial_t \partial_{\phi_*} \varphi$$
$$+ 2a(r^2+a^2)\partial_x \partial_{\phi_*} \varphi + \Delta \left[\frac{1}{\sin\theta} \partial_\theta (\sin\theta \partial_\theta \varphi) + \frac{1}{\sin^2\theta} \partial^2_{\phi_*} \varphi \right]$$
$$= -\lambda^2 \frac{12 M^2 \Delta}{\Sigma^5} (r^2 - a^2\cos^2\theta)(r^4 - 14a^2 r^2 \cos^2\theta + a^4 \cos^4\theta) \frac{df(\varphi)}{d\varphi}.$$

$\frac{1}{4} R^2_{GB}$

Decoupling limit – Rotating solutions

- Study only the **scalar field evolution** on a **fixed spacetime background**

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



DD, Yazadjiev (2021)

Dynamical Chern-Simons gravity (decoupling limit)

- Only the rotating black holes differ from the Kerr solutions

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - 2\nabla_\mu\varphi\nabla^\mu\varphi + 8\lambda^2 f(\varphi)^\star\mathcal{R}\mathcal{R}\right]$$

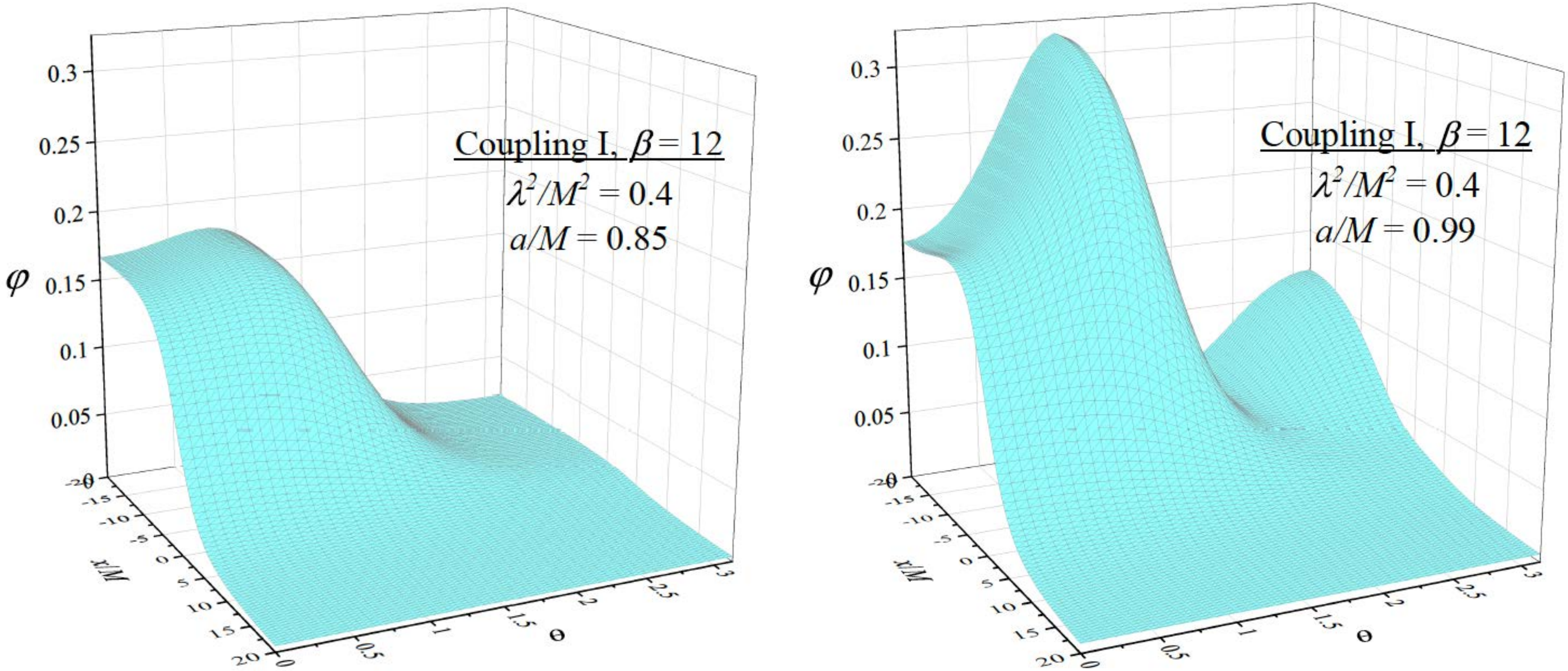
$$\nabla_\alpha\nabla^\alpha\varphi = -2\lambda^2\frac{df(\varphi)}{d\varphi}\;{}^*RR$$

$$\begin{aligned}&-\left[(r^2+a^2)^2-\Delta a^2\sin^2\theta\right]\partial_t^2\varphi+(r^2+a^2)^2\partial_x^2\varphi+2r\Delta\partial_x\varphi-4Mar\partial_t\partial_{\phi_*}\varphi\\&+2a(r^2+a^2)\partial_x\partial_{\phi_*}\varphi+\Delta\left[\frac{1}{\sin\theta}\partial_\theta(\sin\theta\partial_\theta\varphi)+\frac{1}{\sin^2\theta}\partial^2_{\phi_*}\varphi\right]\\&=-\lambda^2\frac{192aM^2\Delta}{\Sigma^5}r\cos\theta(3r^2-a^2\cos^2\theta)(r^2-3a^2\cos^2\theta)\frac{df(\varphi)}{d\varphi}.\end{aligned}$$

$2\,{}^*RR$ Pontryagin invariant.

Dynamical Chern-Simons gravity (decoupling limit)

- Scalar field profiles of the scalarized black holes.



DD, Yazadjiev (2021)

Conclusions and future perspectives

- Scalarization is a very interesting nonlinear effect allowing for large deviations from GR while keeping the weak field regime unaltered.
- Can be sourced by the curvature of the spacetime itself, matter, exotic fields, nonlinear electrodynamics, etc.
- Interesting observational signatures are expected that can help us further constrain the strong field regime of gravity.

Future perspectives:

❖ Dynamics of scalarized BH and NS should be further studied.

❖ Construction of scalarized BH and NS in other classes of alternative theories

❖ Spontaneous vectorization and tensorization

❖ Further understanding of the problems appearing for certain theories allowing scalarization and determining whether they are viable and how to overcome the problems.

THANK YOU!