Title: Spontaneous scalarization in scalar-Gauss-Bonnet gravity and beyond

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Abstract:

In my talk I will discuss the black hole spontaneous scalarization in scalar-Gauss-Bonnet gravity. Some of the basic ideas, results and astrophysical consequences will be presented.
I will also discuss a new fully non-linear dynamical mechanism for the formation of scalarized black holes which is different from the spontaneous scalarization.

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Spontaneous scalarization in scalar-Gauss-Bonnet gravity and byond

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Scalar-Gauss-Bonnet gravity

- Scalar-Gauss-Bonnet theories are a particular sector of Horndeski theories.

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

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

- The field equations are of second order as in general relativity and the theory is free from ghosts.

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Scalar-Gauss-Bonnet gravity

Special class of sGB theories

- We focus on sGB theories with a coupling function satisfying

$$f(0) = 0, \qquad \frac{df}{d\varphi}(0) = 0\,, \qquad \frac{d^2 f}{d\varphi^2}(0) = \epsilon = \pm 1$$

- This special class is very interesting due to the following fact: All the stationary GR solutions are also solutions to the field equations of the sGB gravity

- This class of sGB theories is indistinguishable from GR in the weak field regime and can differ from GR in strong curvature regime only.

- This class of sGB theories exhibits the so-called spontaneous scalarization

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Spontaneous scalarization – basic ideas

- In a seminal paper T. Damour and G. Esposito-Farese (PRL (1993)) discovered the spontaneous scalarization of neutron stars in classical scalar-tensor theories.

Spontaneous scalarization in simple words

- Beyond certain threshold in the mass of objects (in the case of the classical scalar-tensor theories) or in the spacetime curvature (in the case of sGB), GR solutions become unstable within the bigger scalar-tensor theory. The instability leads to the development of a nontrivial scalar field and the compact objects acquire scalar hair - the compact objects get spontaneously scalarized.

- Why the spontaneous scalarization is so interesting and important? The spontaneous scalarization is almost the only known dynamical mechanism for endowing black holes (and other compact objects) with scalar hair without altering the predictions in the weak field limit.

Spontaneous scalarization – basic ideas

- In order to get insight into the theory of the spontaneous scalarization, we shall demonstrate the theoretical machinery of the black hole spontaneous scalarization on the case of static and spherically symmetric black holes in sGB gravity.
(D. Doneva and S. Y. , PRL 2018);

Spontaneous scalarization – basic ideas

- Recall that we consider sGB theories which are indistinguishable from GR in the weak field limit, i.e. $\frac{df}{d\varphi}(0) = 0$ (and with the normalization $\frac{d^2 f}{d\varphi^2}(0) = \epsilon = \pm 1$. We shall first focus on the case $\epsilon = 1$.

- We shall however show that the Schwarzschild solution within the certain range of the mass is unstable in the framework of our class of sGB theories.

- In the considered class of sGB theories the equations governing the perturbations of the metric are decoupled from the equation governing the perturbation of the scalar field. The equations for metric perturbations are in fact the same as those in the pure Einstein gravity and therefore we shall focus only on the scalar field perturbations.

Spontaneous scalarization – basic ideas

- The equation governing the scalar perturbations is

$$\Box_{(0)}\delta\varphi + \frac{1}{4}\lambda^2\mathcal{R}^2_{GB(0)}\delta\varphi = 0, \qquad => \qquad \Box_{(0)}\delta\varphi = \mu^2_{eff}\delta\varphi$$

Tachyonic instability $\mu^2_{eff} = -\frac{1}{4}\lambda^2 \mathrm{R}^2_{\{GB\}} < 0$

- The equation can be cast in Schrodinger form $\delta\varphi = \frac{u(r)}{r}e^{-i\omega t}Y_{lm}(\theta,\phi),$

$$\frac{d^2u}{dr_*^2} + [\omega^2 - U(r)]u = 0$$

with an effective potential

$$U(r) = \left(1 - \frac{2M}{r}\right)\left[\frac{2M}{r^3} + \frac{l(l+1)}{r^2} - \lambda^2\frac{12M^2}{r^6}\right]$$

Spontaneous scalarization – basic ideas

- A sufficient condition for the existence of a unstable mode is

$$\int_{-\infty}^{+\infty} U(r_*)dr_* = \int_{2M}^{\infty} \frac{U(r)}{1-\frac{2M}{r}}dr < 0.$$

- We can conclude that the Schwarzshild black holes with mass satisfying $\boldsymbol{M^2 < 0.3\,\lambda^2}$ are unstable within the framework of the sGB gravity. The Schwarzshild black holes become unstable when the curvature of the horizon exceeds a certain critical value $K_H > 8.3/\lambda^4$.

- This result naturally leads us to the conjecture that, in our class of GB theories and in the interval where the Schwarzschild is unstable, there exist black hole solutions with nontrivial scalar field.

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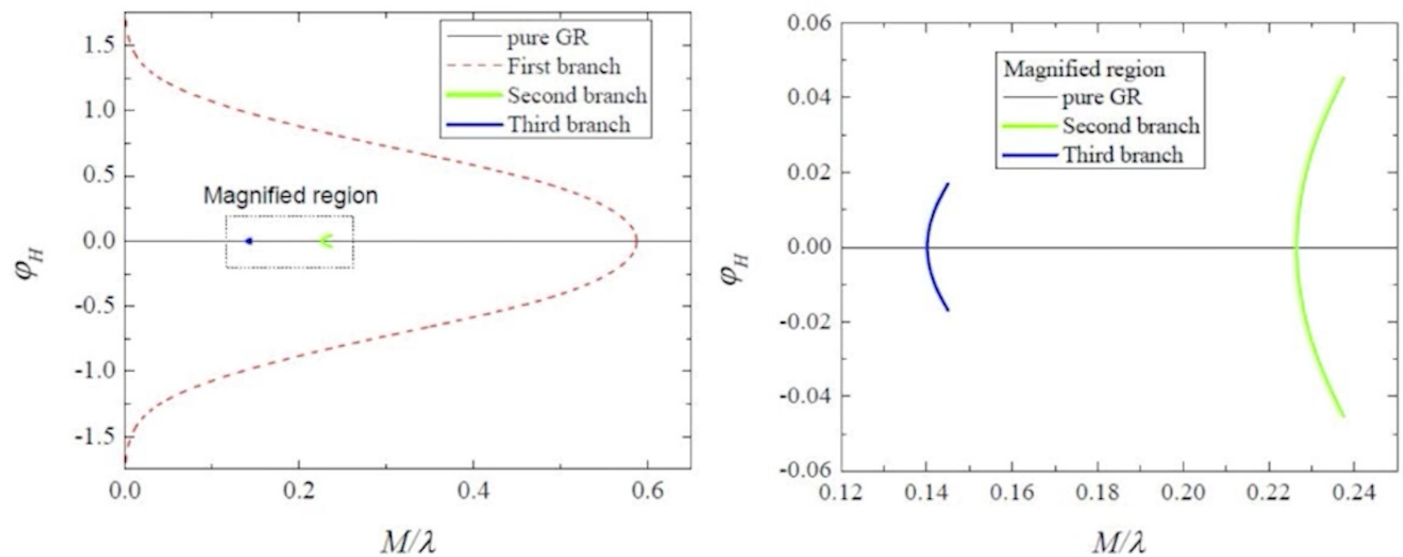
Scalarized Schwarzschild black hole

Results for coupling function $f(\varphi) = \frac{1}{12}\left[1 - \exp(-6\varphi^2)\right]$



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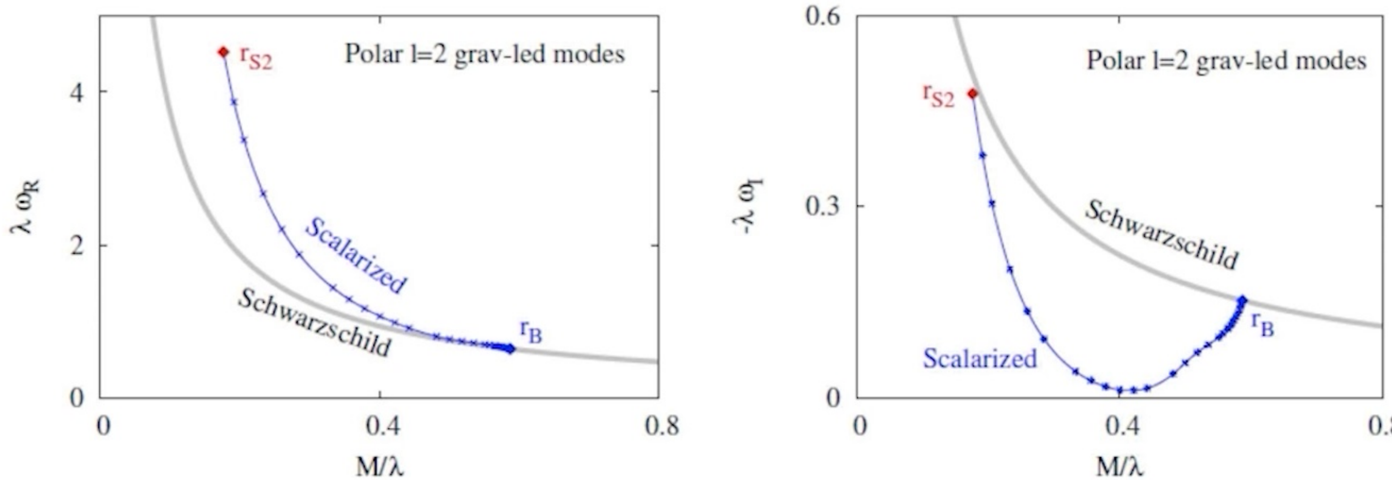
Scalarized Schwarzschild black hole

Stability of the scalarized solutions

- We investigated the axial and polar quasinormal modes of the scalarized solutions. On this base we showed that the fundamental branch of the scalarizied solutions is stable while the other branches are unstable. (Blazquez-Salcedo et. al.)



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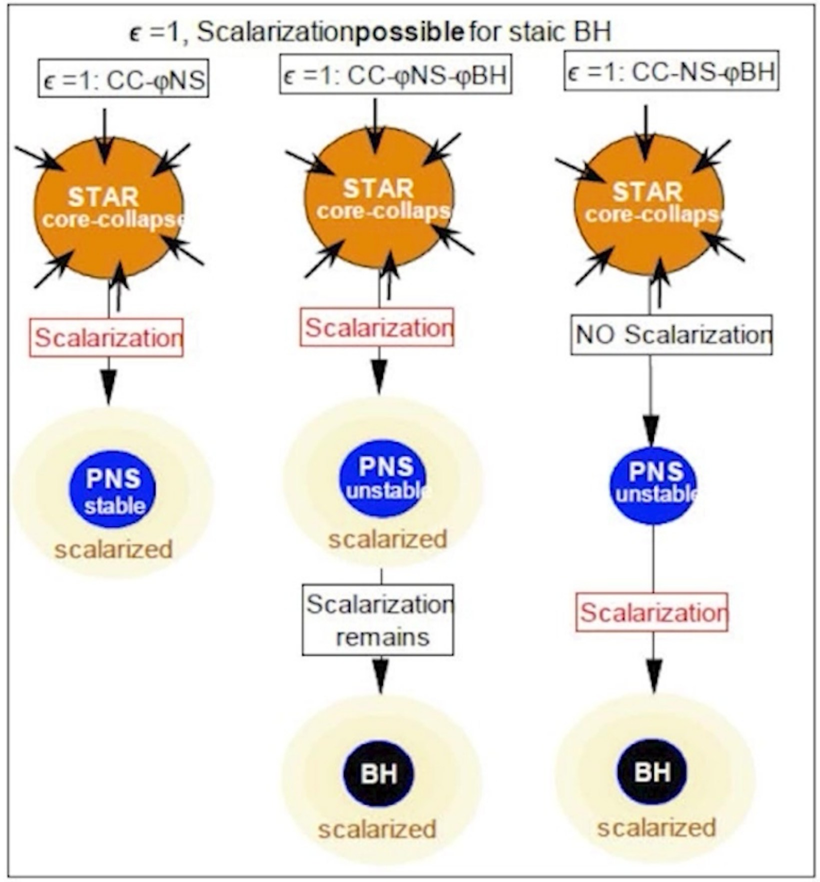
Realistic physical mechanism for the formation of isolated scalarized BHs and NSs

- The gravitational collapse can produce scalarized black holes and scalarized neutron stars starting with initial state with no scalar field present (H.-J. Kuan, D. Doneva and S. Y., PRL (2021))

- We have studied the fully nonlinear spherically-symmetric core-collapse in scalar-Gauss-Bonnet gravity. The qualitative picture is as follows.

Scalarization through core-collapse



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Beyond spontaneous scalarization

- Let us consider sGB theories that do not allow for spontaneous scalarization!

$$\frac{df}{d\varphi}(0) = 0 \ \ and \ \ \frac{d^2 f}{d\varphi^2}(0) = 0$$

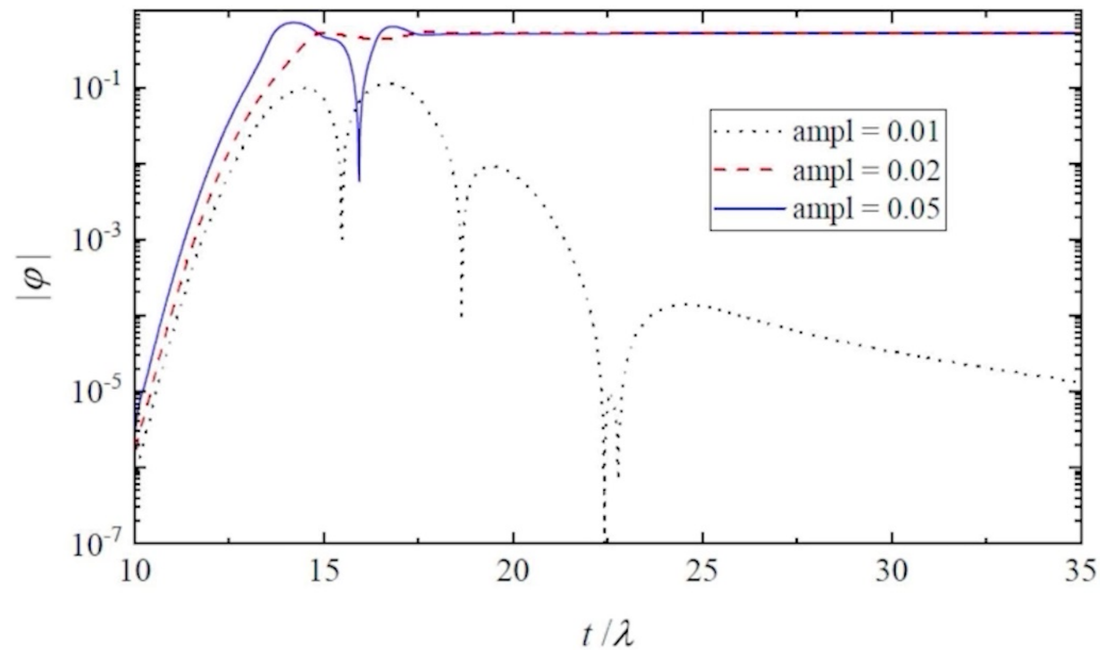
- With these conditions imposed on the coupling function, no tachyonic instability is possible, however, the sGB theories admit all the stationary solutions of GR!

- The Schwarzschild solution is linearly stable even within the sGB gravity!

- Now, we ask the following question: What happens to the Schwarzschild black hole within the sGB gravity if the black hole is acted by nonlinear perturbations?

Beyond spontaneous scalarization

$$f(\varphi) = \frac{1}{2\beta}\left(1 - e^{-\beta\varphi^4}\right) \quad \beta = 50, \quad \frac{M}{\lambda} = 0.1$$



Beyond spontaneous scalarization

- Up to now it was thought that the spontaneous scalarization is the only dynamical mechanism for endowing black holes (and other compact objects) with a scalar hair without altering the weak field limit of the theory. We have shown that there is another mechanisim, different from the spontaneous scalarization, which can generate scalar hair without altering the weak field limit.

- The new mechanism is fully nonlinear and the main ingredient of this mechanism is the nonlinear instability of the general relativistic solutions – contrary to the spontaneous scalarization which is characterized with a linear instability of the GR solutions. The new mechanism operates where the spontaneous scalarization (tachyonic instability) is impossible.

- The nonlinear mechanism works also for rotating black holes and neutron stars.

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Future perspectives

- Binary black hole and neutron star coalescences in sGB and dynamical scalarization and beyond spontaneous scalarization.

- This topic will be discussed in Daniela's talk.