Cosmology and scalarized compact objects

black holes and neutron stars

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Table of contents

The talk is based on

- Phys. Rev. D **103** (2021) No. 2, 024012, arXiv:2004.14985 [gr-qc], in collaboration with L. Bordin and T. Sotiriou.
- Phys. Rev. D (accepted) arXiv:2204.01684 [gr-qc] in collaboration with C.F.B. Macedo, R. McManus and T. Sotiriou.
- Phys. Rev. D **104** (2021) 4, 044002, arXiv:2105.04479 [gr-qc], in collaboration with A. Lehébel, G. Ventagli and T. Sotiriou.

Origins and motivation

Gravity = GR ?

$\rightarrow$ Gravity is perhaps the least understood of the physical interactions and as of now it is best described using the theory of **General Relativity (GR)**.

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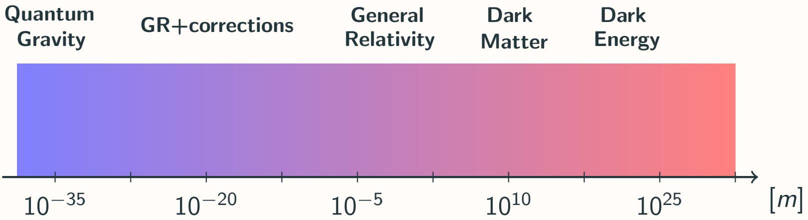
$\rightarrow$ Despite its numerous successes, GR faces limitations and challenges and allows for generalizations:

- Not properly quantized
- Issues with singularities (and infinities)
- Not very constrained in the strong-field regime
- Dark energy and dark matter are not well described, within the standard GR framework

Gravity = GR ?

To tackle these issues new terms are introduced

- scalar or vector fields (ϕ, $\vec{A}$...)
- curvature corrections (R^2, $R^{ab}R_{ab}$, $R^{abcd}R_{abcd}$, ${}^*R\,R$...)



Scalarization and cosmology

Scalarization in Neutron Stars

$$S = \frac{c^3}{16\pi G} \int d^4x \sqrt{-g} \left(R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\right) + S_m\left[\psi_m, e^{2a(\varphi)}g_{\mu\nu}\right]. \quad (2)$$

- Scalar eq. yields $\Box\phi \propto \ldots a'(\varphi)T$.
- If, for some $\phi = \phi_0$, $a'(\phi_0) = 0 \Rightarrow$ GR.
- Take $a(\varphi) = \beta_0\varphi^2/2$.
- Estimating the energy

$$\text{Energy} \approx mc^2\left(\frac{\varphi_c^2/2}{Gm/Rc^2} + e^{\beta_0\varphi_c^2/2}\right)$$

For large M/R minima start forming.

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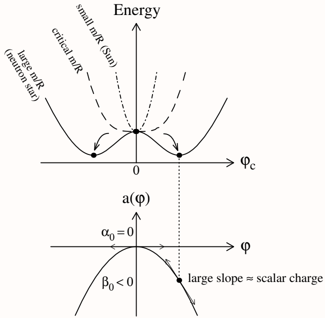

Fig. taken from arXiv:gr-qc/0402007

Scalarization in Black Holes

One class of theories within the Horndeski framework that evades no-hair theorems contains the Gauss-Bonnet term coupled with the scalar field.

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\left[R - \frac{1}{2}(\partial\phi)^2 + f(\phi)\mathcal{G}\right]. \qquad (3)$$

$\rightarrow$ The scalar eq. $\quad \Box\phi = -f'(\phi)\,\mathcal{G} \Rightarrow \big[\Box + \overbrace{f''(\phi_0)\mathcal{G}}^{-m^2_{\text{eff}}}\big]\delta\phi = 0.$

$\rightarrow$ We are interested in theories that are connected to GR and therefore accept GR as a solution $\rightarrow f'(\phi_0) = 0,\ -f''(\phi_0)\,\mathcal{G} > 0$ [1,2,3] .

[1] Antoniou et al. Phys. Rev. Lett. 120 (2018) 13, 131102
[2] Silva et al. Phys. Rev. Lett. 120 (2018) 13, 131104
[3] Doneva et al. Phys. Rev. Lett. 120 (2018) 13, 131103

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If $m_{\text{eff}}^2 < 0 \longrightarrow$ non-trivial scalarized solutions

Scalarization in Black Holes

$$\mathcal{G}_{\mathrm{Kerr}} = \frac{48M^2}{(r^2+\chi^2)^6}\left(r^6 - 15r^4\chi^2 + 15r^2\chi^4 - \chi^6\right)$$

- For $\chi = 0 \Rightarrow \mathcal{G} > 0$ scalarization requires $f''(\phi_0) > 0$.
- For $\chi \neq 0 \rightarrow \mathcal{G} \lesseqgtr 0$ *spin-induced* scalarization for $f''(\phi_0) < 0$.

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$\to$ In the **minimal model** satisfying the conditions above

$$\mathcal{L} = \left(1 + \frac{\beta\phi^2}{4}\right) R + X + \gamma\, G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi - \frac{\alpha\phi^2}{2}\mathcal{G} - \frac{1}{2}m_\phi^2\phi^2, \qquad (4)$$

where $X = -(\nabla\phi)^2/2$ is the scalar kinetic term.

Issues of scalarization models

Models of scalarization usually face a number of problems:

1. Neutron-star constraints
2. Stability (the exponential coupling yields stable solutions but does not satisfy our conditions)
3. Well posedness
4. Cosmological consistency

Cosmology

Is scalarization consistent with cosmology however?

$\rightarrow$ To answer this we need to study the theory in cosmological scales. We assume an FLRW metric and a barotropic cosmic fluid, $p_a = w_a \rho_a$, with the index $a = r, m, de$ and $w_a = 1/3, -1, 0$ for radiation domination (RD), matter domination (MD) and dark energy domination (DED) respectively.

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To avoid inconsistencies with cosmology, we assume a **sub-dominant scalar field**:

$$|\rho_\phi(z_i)| \ll |\rho_a(z_i)|$$

Cosmological attractor

Evolution of scalars in a cosmological background[1]:

- $\mathcal{L} = R + X - m_{\text{eff}}^2\phi^2/2 \implies \mathcal{E}_\phi \propto e^{-t(3H-2\omega)}$
- $\mathcal{L} = R + X + f(\phi)\mathcal{G} \implies \mathcal{E}_\phi \propto e^{-\frac{3Ht}{2}}(C_1 e^{-\omega t} + C_2 e^{\omega t})$ for $f \sim \phi^2$

[1] Franchini et al. Phys. Rev. D **101** (2020) 6, 064068

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- $\mathcal{L} = R + h(\phi)R + X + f(\phi)\mathcal{G}$, let's see what happens for $f, h \sim \phi^2$

The scalar equation reads[2]

$$\ddot{\phi} + 3H\dot{\phi} + m_{\text{eff}}^2(t)\phi = 0\,, \tag{5}$$

friction term **mass term**

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[2]Antoniou et al. Phys. Rev. D **103** (2021) No. 2, 024012

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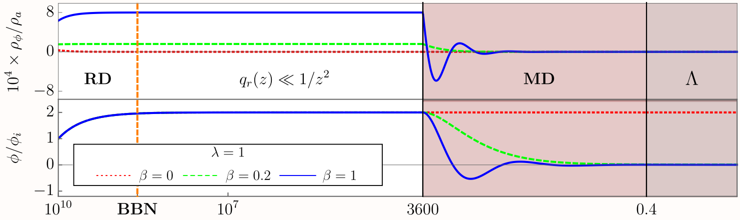
$\rightarrow$ We need to keep an eye on the sign of $m_{\text{eff}}^2 = \beta R/2 - \alpha \mathcal{G}$:

	Radiation	**Matter**	**Dark Energy**
$\mathcal{G}$	< 0	< 0	> 0
R	0	> 0	> 0

Cosmological attractor

We do the analysis in terms of the redshift. We consider $\alpha = 1 > 0$ (initially) and $\phi_i \sim 1$ (not fine tuning) just before BBN.

$$\phi_a'' + f_a(z)\phi_a' + q_a(z)\phi_a = 0, \tag{7}$$



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$\underline{\alpha > 0}$:

- For $\beta \leq 0$ no attractor behavior at late times
- For $0 < \beta < \beta_{crit}$ the oscillator is underdamped $\rightarrow$ no attractor
- For $\beta \geq \beta_{crit}$ critically or overdamped $\rightarrow$ attractor! ✓

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$\alpha < 0$:

- Spontaneous scalarization in the interior of neutron stars- makes no difference during BBN and at later times.

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$\rightarrow$ For scalarized neutron stars we showed a significant suppression which is consistent with observations. ✓

$\rightarrow$ They hyperbolicity of the problem is improved. ✓

Perspectives

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What did we see so far?

- Consistency with cosmology
- Avoidance of binary pulsar constraints
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- Probe earlier cosmological times
- QNM modes need further exploration
- Deeper look into well-posedness

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Thank you!

Questions?