Scalar field coupling with matter inside scalarized neutron stars

Nicola Franchini - University of Nottingham

Gravity@Malta 2018 - University of Malta

24-01-2018

Modifications to General Relativity, why?

In the briefest way possible:

- Experimental problems: dark matter and dark energy.
- Theoretical problem: quantization of gravity.

Possible solution: modify GR. New degrees of freedom.

Scalar-tensor theories

Let me add a scalar field to Einstein-Hilbert action

- Jordan frame

$$S_J = \int \mathrm{d}^4x \frac{\sqrt{-\tilde{g}}}{4} \left(\Phi \tilde{R} - \frac{\omega(\Phi)}{\Phi} \tilde{\nabla}^\mu \Phi \partial_\mu \Phi \right) + S_m[\Psi^A, \tilde{g}_{\mu\nu}].$$

Scalar-tensor theories

Let me add a scalar field to Einstein-Hilbert action

- Jordan frame

$$S_J = \int \mathrm{d}^4x \frac{\sqrt{-\tilde{g}}}{4} \left(\Phi \tilde{R} - \frac{\omega(\Phi)}{\Phi} \tilde{\nabla}^{\mu}\Phi \partial_{\mu}\Phi \right) + S_m[\Psi^A, \tilde{g}_{\mu\nu}].$$

  Conformal transformation $\tilde{g}_{\mu\nu} = A^2(\varphi) g_{\mu\nu}$, and mapping $\Phi = A^{-2}(\varphi)$

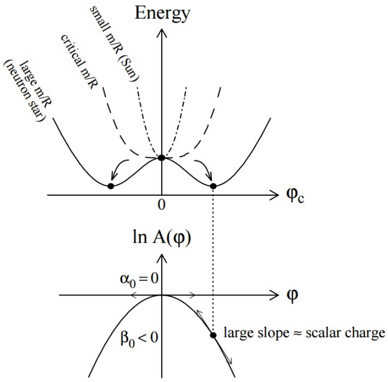
- Einstein frame

$$S_E = \int \mathrm{d}^4x \frac{\sqrt{-g}}{4} \left(R - 2\nabla^{\mu}\varphi \partial_{\mu}\varphi \right) + S_m[\Psi^A, A^2(\varphi) g_{\mu\nu}].$$

Where is the scalar field?

$$\log A(\varphi) \simeq \alpha_0 + \beta_0(\varphi - \varphi_0)^2 \longrightarrow \Box\varphi = -T\beta_0(\varphi - \varphi_0).$$

Phase transition for high compactness and $\beta \lesssim -4$: spontaneous scalarization



[Damour, Esposito-Farése - 1993], [Esposito-Farése - 2004]

Coupling φ with matter: why not?

Nothing wrong in principle, but

- Nobody has seen it.

Coupling φ with matter: why not?

Nothing wrong in principle, but

- Nobody has seen it.
- A coupling with the whole standard model is hard to describe.

Coupling φ with matter: why not?

Nothing wrong in principle, but

- Nobody has seen it.
- A coupling with the whole standard model is hard to describe.
- Drastic changes to star properties.

Coupling φ with matter: why not?

Nothing wrong in principle, but

- Nobody has seen it.
- A coupling with the whole standard model is hard to describe.
- Drastic changes to star properties.
- Scalarization is still working?

Coupling φ with matter: EM toy model

$$S_E = \int \mathrm{d}^4x \frac{\sqrt{-g}}{4}\left(R - 2\overline{D^\mu\varphi}D_\mu\varphi - F_{\mu\nu}F^{\mu\nu}\right) + S_m[\Psi^A, A^2(\varphi)g_{\mu\nu}, \mathcal{A}_\mu],$$

where

$$D_\mu = \partial_\mu - \mathrm{i}e\mathcal{A}_\mu, \qquad F_{\mu\nu} = \partial_\mu\mathcal{A}_\nu - \partial_\nu\mathcal{A}_\mu.$$

First non-trivial modification: mass to the photon

$$m_\gamma^2 = \frac{e^2}{4\pi}\bar{\varphi}\varphi.$$

[Coates, Horbatsch, Sotiriou - 2016].

Coupling φ with matter: equations of motion

The system is invariant under $U(1)$ transformation:

$$\varphi \to \varphi e^{ie\lambda}, \qquad \mathcal{A}_\mu \to \mathcal{A}_\mu + \partial_\mu \lambda.$$

In the gauge where φ is real, the equations of motion read:

$$G_{\mu\nu} = 2(T_{\mu\nu} + T^{(\mathcal{A})}_{\mu\nu}),$$
$$\nabla^\mu F_{\mu\nu} = m_\gamma^2 \mathcal{A}_\nu,$$
$$(\Box - e^2 \mathcal{A}^\mu \mathcal{A}_\mu)\varphi = -T\beta\varphi.$$

Ok, but does the star remain neutral and scalarized?

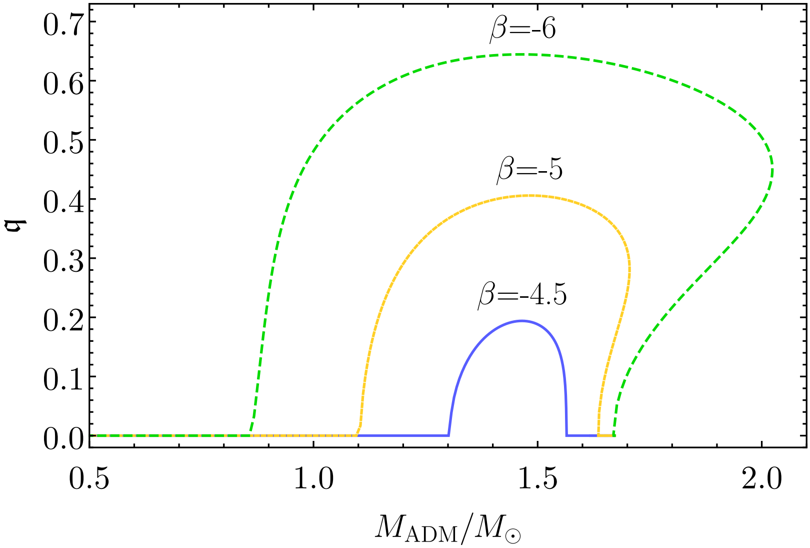
Coupling φ with matter: star properties

In spherical symmetry, and assuming neutral matter:

- "No EM hair" theorem: $\mathcal{A}_\mu = 0$ and the star remains neutral.
- Scalarization goes through in the standard fashion.
- Presence of a massive photon not really cumbersome.

[NF, Coates, Sotiriou - 2017]

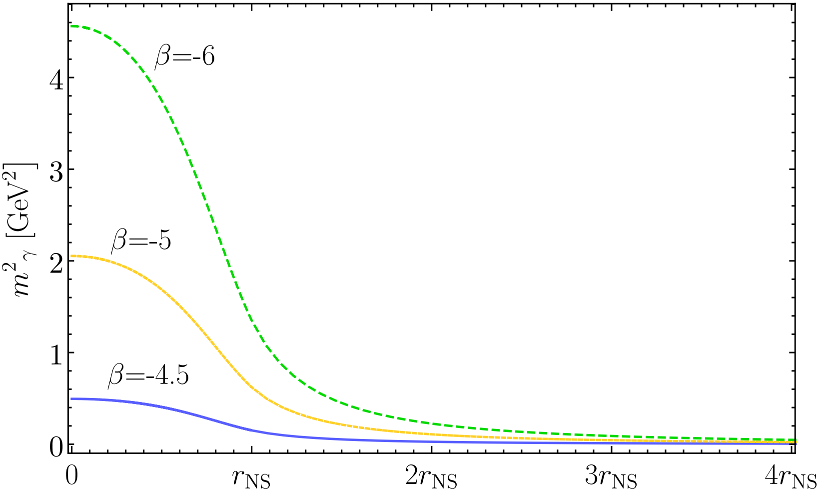
Scalarization with massive photon



[NF, Coates, Sotiriou - 2017] compare with **[Damour, Esposito-Farése - 1993]**

Scalarization with massive photon

For $e = 10^{-36}$ C: tiny coupling charge yields a huge photon mass!



[NF, Coates, Sotiriou - 2017]

Conclusions

The model is clearly unphysical, yet interesting:

- Scalarization still works and can hide the new coupling;
- No drastic modifications to the star structure;
- New effects (such photon mass) that can be measured and constrained.

Conclusions

The model is clearly unphysical, yet interesting:

- Scalarization still works and can hide the new coupling;
- No drastic modifications to the star structure;
- New effects (such photon mass) that can be measured and constrained.

Knowing this, it will be interesting to study:

- Scalar field coupling with more reasonable matter;
- Generalize the non-minimal coupling between scalar field and matter as an effective description with a φ-dependent fluid.