Black Holes and Neutron Stars Scalarization in generalised scalar-tensor theories

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N. Andreou, N. Franchini, GV and T. P. Sotiriou, PRD 99.124022, arXiv:1904.06365
GV, A. Lehébel and T. P. Sotiriou, PRD 102.024050, arXiv:2006.01153
G. Antoniou, A. Lehébel, GV and T. P. Sotiriou, PRD 104.044002, arXiv:2105.04479
GV, G. Antoniou, A. Lehébel and T. P. Sotiriou, PRD 104.124078, arXiv:2111.03644

Spontaneous scalarization

- Two branches of solutions: GR and scalarized
- Transition between the two when crossing a “threshold”

Compactness

Spin

Curvature

Tachyonic instability

Tachyon: wave degree of freedom with imaginary frequency due to negative mass square

$$\Box\phi - m^2\phi = 0 \xrightarrow{\phi \propto e^{-i\omega t + ik\cdot x}} \omega^2 = k^2 + m^2$$

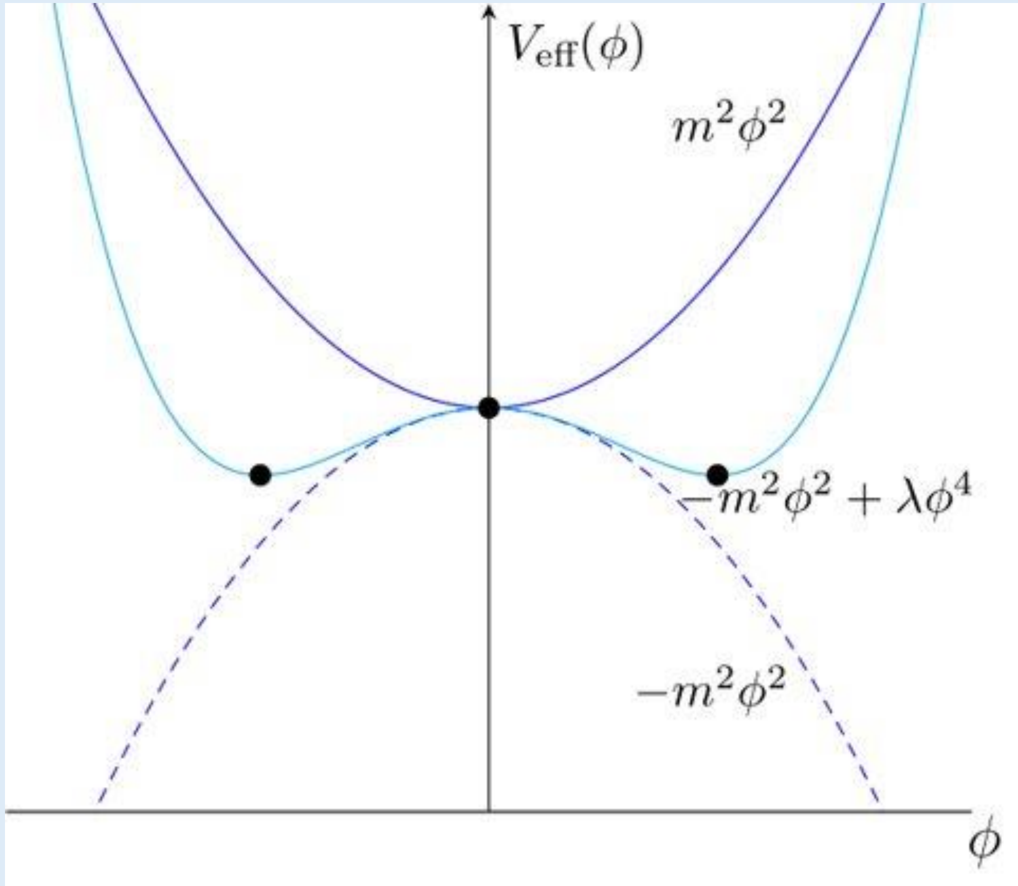
For low k and negative mass square,
the frequency becomes imaginary

→ Instability due to the exponential growth of the field

Suppressing the instability

- Process completed
  by considering nonlinearities of
  the system

- If they are strong enough,
  they can suppress the instability



Horndeski gravity

Most general action with a scalar field and second order field equations

$$S = \frac{1}{2\kappa} \sum_{i=2}^{5} \int \mathrm{d}^4 x \sqrt{-g} \mathcal{L}_i + S_{\mathrm{M}}$$

where

$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi, X) \\
\mathcal{L}_3 &= -G_3(\phi, X) \Box\phi \\
\mathcal{L}_4 &= G_4(\phi, X) R + G_{4X} [(\Box\phi)^2 - (\nabla_\mu \nabla_\nu \phi)^2] \\
\mathcal{L}_5 &= G_5(\phi, X) G_{\mu\nu} \nabla^\mu \nabla^\nu \phi \\
&\quad - \frac{G_{5X}}{6} \left[(\Box\phi)^3 - 3 \Box\phi (\nabla_\mu \nabla_\nu \phi)^2 + 2 (\nabla_\mu \nabla_\nu \phi)^3 \right]
\end{aligned}$$

with

$$X = -\nabla_\mu \phi \nabla^\mu \phi / 2$$

The minimal theory

$$\mathscr{G} \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

$$S = \frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\left\{R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + \gamma\, G^{\mu\nu}\nabla_\mu\phi\,\nabla_\nu\phi - \left(m_\phi^2 + \frac{\beta}{2}R - \alpha\mathscr{G}\right)\frac{\phi^2}{2}\right\} + S_{\mathrm{M}}$$

The scalar field equation:

$$\tilde{g}^{\mu\nu}\nabla_\mu\nabla_\nu\phi - m^2\phi = 0$$

with

$$\tilde{g}^{\mu\nu} = g^{\mu\nu} - \gamma\, G^{\mu\nu}$$

$$m^2 = m_\phi^2 + \frac{\beta}{2}R - \alpha\mathscr{G}$$

Black holes: the setup

$$S = \frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\left\{R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \left(\frac{\beta}{2}R - \alpha\mathscr{G}\right)\frac{\phi^2}{2}\right\} + S_{\mathrm{M}}$$

The line element: $ds^2 = -e^{\Gamma(r)} + e^{\Lambda(r)}dr^2 + r^2 d\Omega^2$

e^{Λ} can be solved algebraically. Two variables: Γ and ϕ.

Expansion near horizon: $\phi'_{r_{\mathrm{h}}} = \left(a + \sqrt{\Delta}\right)/b \longrightarrow \Delta \geq 0$

Defines existence region on $(r_{\mathrm{h}}, \phi_{\mathrm{h}})$ space for regular solution

Black holes: mass and scalar charge

Metric and scalar field at spatial infinity:

$$g_{rr} = e^{\Lambda} \simeq 1 - \frac{2M}{r}$$

$$\phi \simeq \frac{Q}{r}$$

We extract the value of the ADM mass and the scalar charge from:

$$M = -\left(\frac{1}{2} r^2 \Lambda' \, e^{-\Lambda}\right)\Bigg|_{r_{\max}} \qquad Q = -\left(r^2 \phi'\right)\Big|_{r_{\max}}$$

Black holes: properties of the solutions

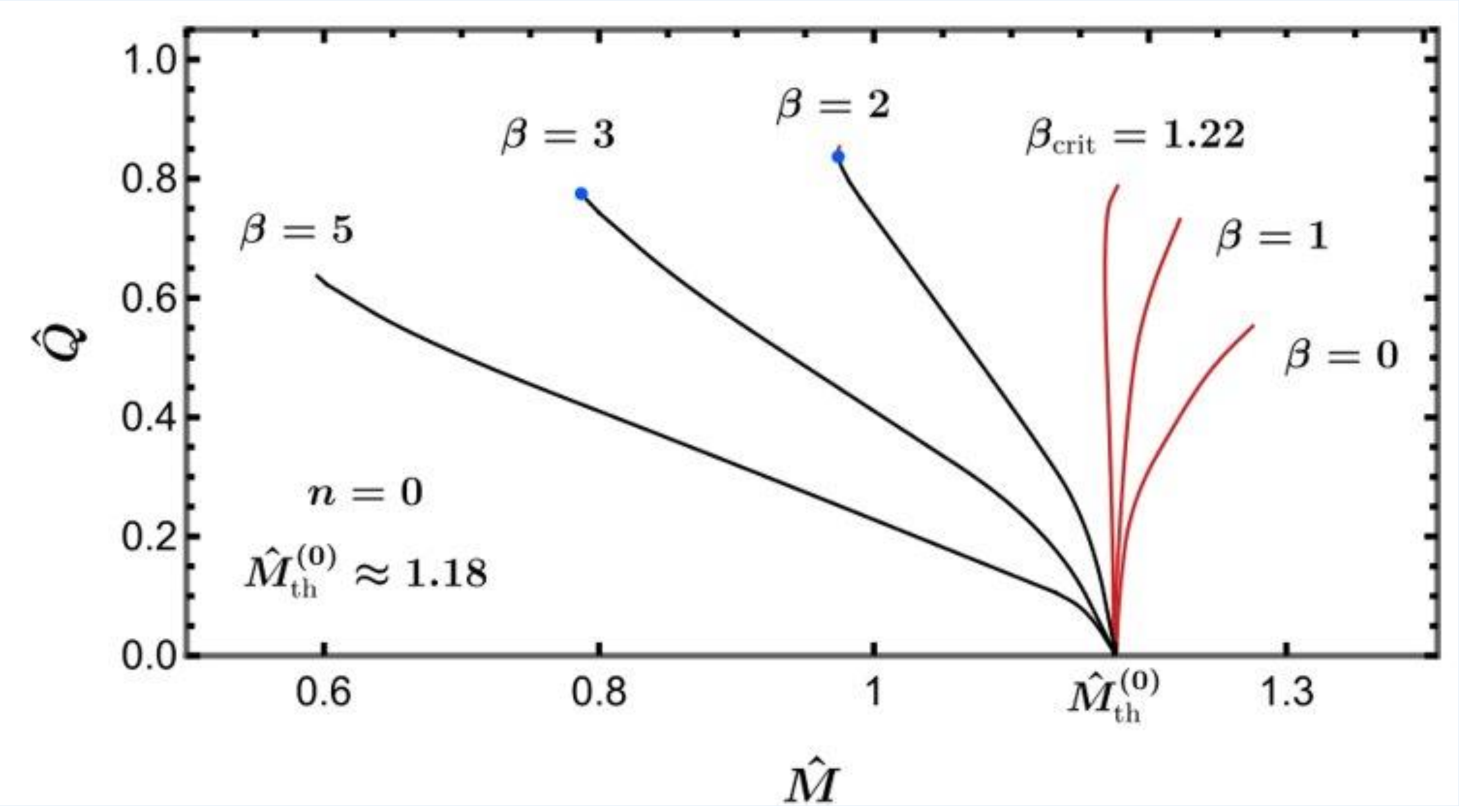
- Solutions with zero nodes

- Rescaled mass and scalar charge

$$\hat{M} = M/\sqrt{\alpha}$$

$$\hat{Q} = Q/\sqrt{\alpha}$$

$$\alpha > 0$$



Neutron stars: the setup

$$S = \frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\left\{R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi - \left(\frac{\beta}{2}R - \alpha\mathscr{G}\right)\frac{\phi^2}{2}\right\} + S_{\mathrm{M}}$$

Ansatz for the metric: $ds^2 = -e^{\Gamma(r)} + e^{\Lambda(r)}dr^2 + r^2 d\Omega^2$

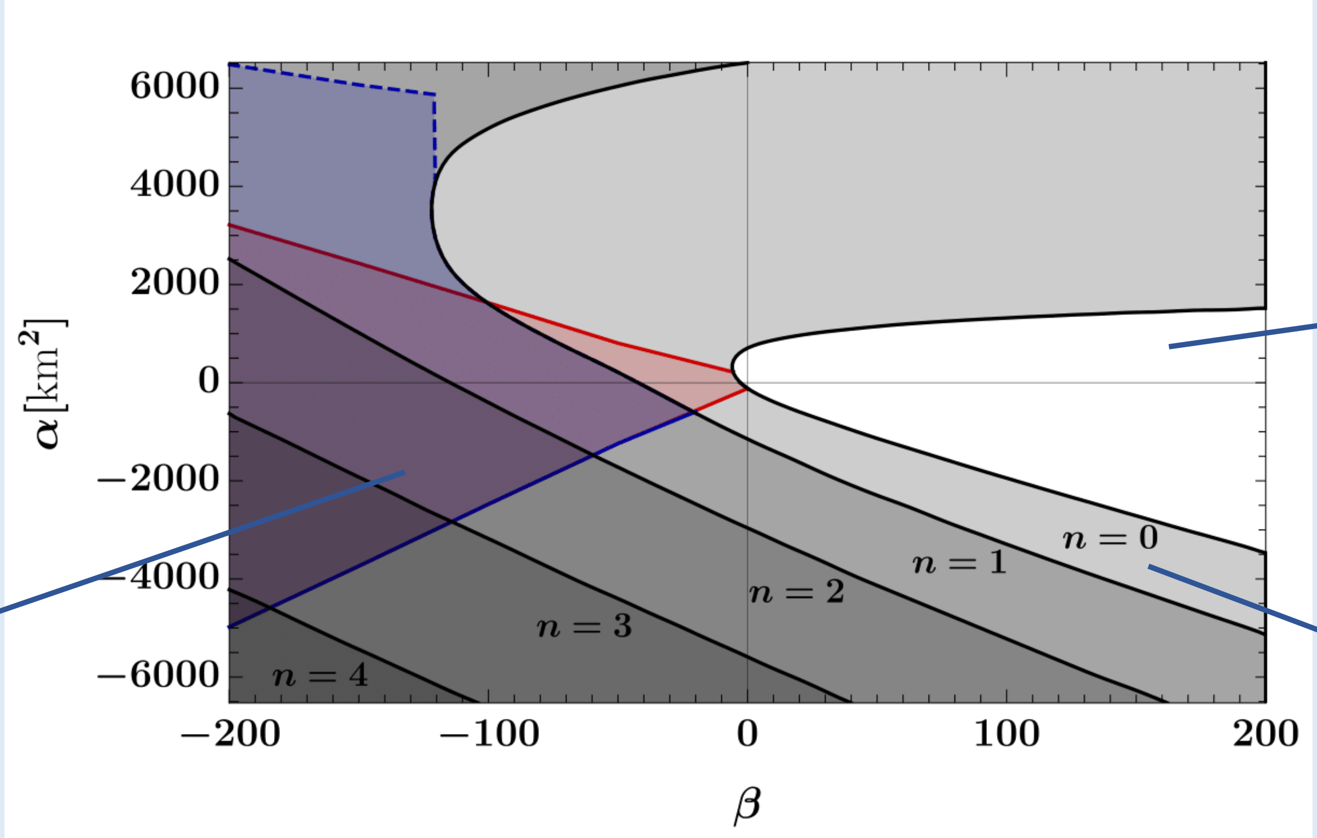
e^{Λ} can be solved algebraically. Three variables: Γ, ϕ and ϵ.

Expansion at $r \to 0$ of the form: $f(r) = \sum_{n=0}^{\infty} f_n r^n$

➡ Initial condition and existence equation for Λ_2

Neutron stars: existence regions

SLy EOS with central energy density s.t. $M_{GR} = 1.12\ M_{\odot}$



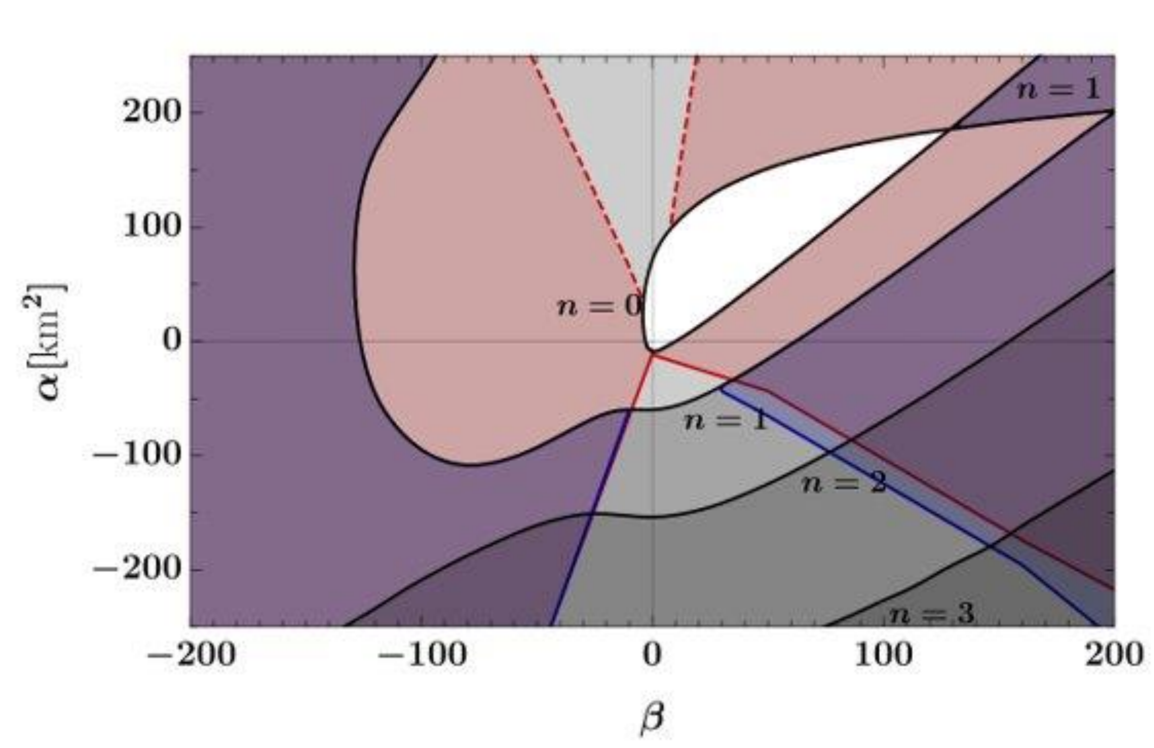
GR stable

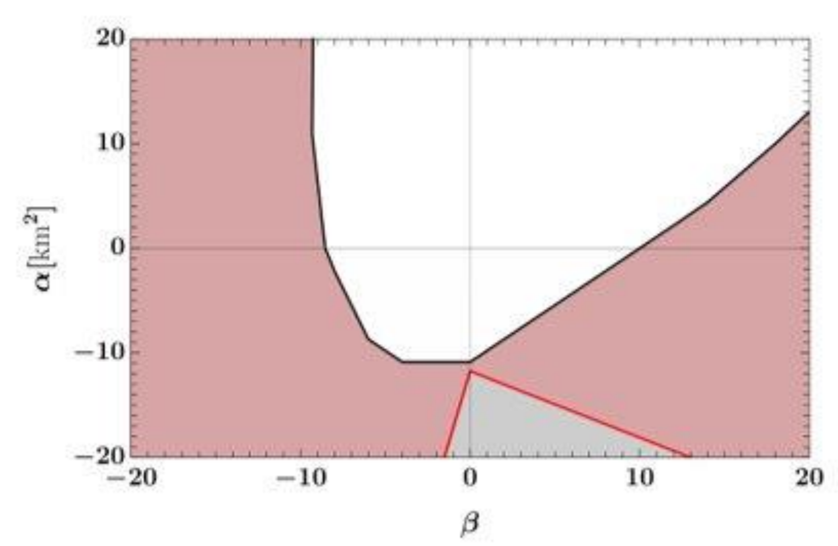
Scalarized solutions exist

GR unstable but no scalarized solutions exist

Neutron stars: existence regions

SLy EOS with central energy density s.t. $M_{GR} = 2.04\ M_{\odot}$





Neutron stars: binary pulsars constraints

"Sensitivity" of compact objects: $\alpha_I = 2\frac{\partial lnM_I}{\partial \phi_0}$

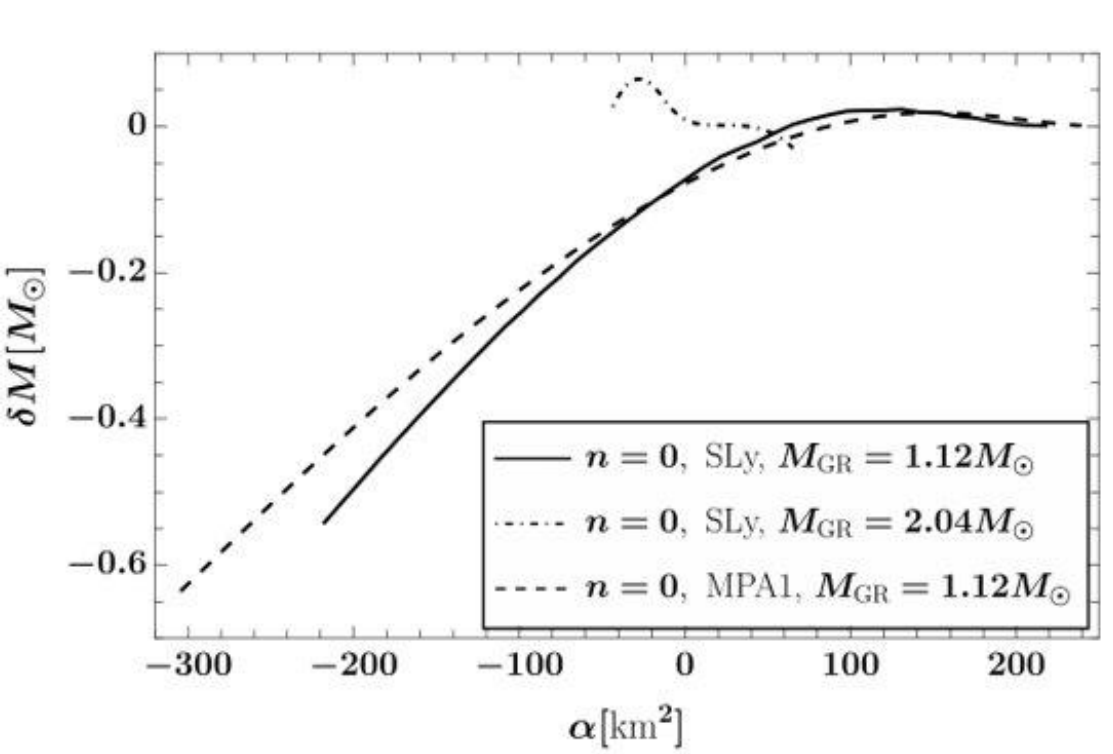
Constraint from binary pulsar, notably PSR J1738+0333 system:

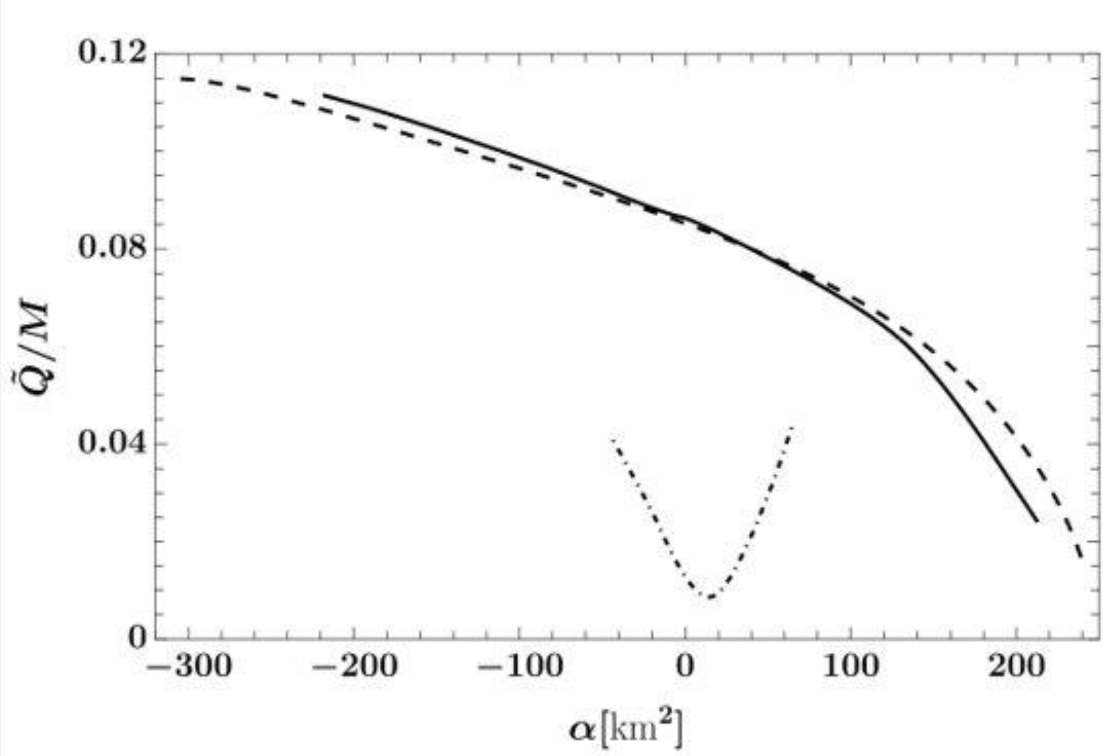
$$|\alpha_A - \alpha_B| \lesssim 2 \times 10^{-3}$$

$$\longrightarrow \boxed{\frac{\tilde{Q}}{M} \lesssim 6 \times 10^{-4}} \qquad \text{with} \quad \tilde{Q} = \frac{Q}{\sqrt{2\kappa}}$$

Neutron stars: properties of the star

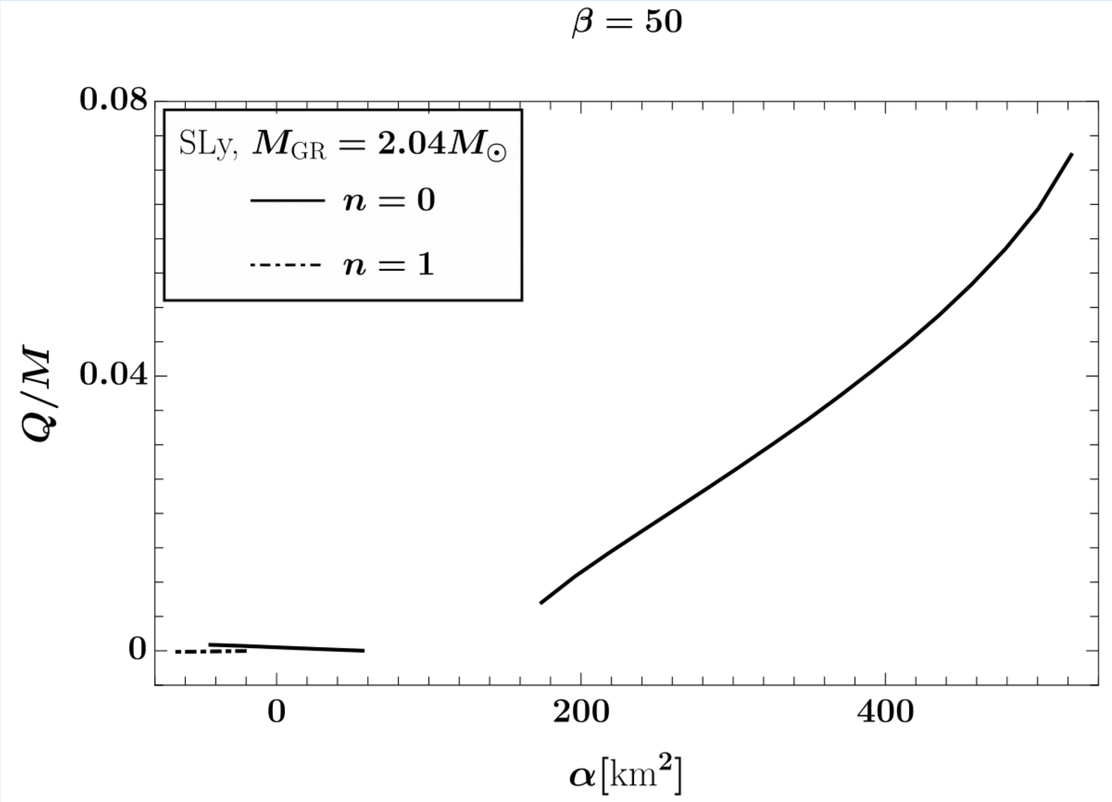
Small negative β coupling, e.g. $\beta = -10$





Neutron stars: properties of the star

Positive β coupling, e.g. $\beta = 50$



Small positive values of the Ricci scalar coupling

For small positive β:

- Neutron stars are either not or faintly scalarized
- Black holes scalarize and can introduce new interesting phenomenology
- Compatibility with attractor mechanism to GR on cosmological scales (G. Antoniou, L. Bordin and T. Sotiriou, arXiv:2004.14985)

Conclusions

- Study of spontaneous scalarization for Horndeski theory
- Identification of “minimal theory”
- Analysis of the threshold of spontaneous scalarization
- Study of black holes and neutron stars scalarization and their properties
- First preliminary constraints on coupling constant

Future perspectives

- Further connect results to observations (e.g. post-Newtonian analysis of inspiral phase of binaries)
- Study of scalarization induced by rotation for our model
- Study of well-posed initial value problem
- Stability analysis

Thank you!

Spontaneous scalarization for NSs

Damour and Esposito-Farese 1993

- First proposed by Damour and Esposito-Farese ’93
- Linear tachyonic instability around a GR neutron star configuration

$$S = \int d^4x\sqrt{-\tilde{g}}\left[\frac{\tilde{R}}{2\kappa} - \frac{1}{2}\partial_\lambda\tilde{\phi}\partial^\lambda\tilde{\phi}\right] + S_{\rm M}\left(\frac{\tilde{g}_{\mu\nu}}{\phi(\tilde{\phi})}, \psi_{\rm M}\right)$$

$$\phi = e^{-\frac{\beta\kappa}{2}\tilde{\phi}^2}$$

$$\tilde{\Box}\tilde{\phi} = \alpha(\tilde{\phi})T \quad \xrightarrow{\tilde{\phi} = \tilde{\phi}_0 + \delta\tilde{\phi}} \quad \tilde{\Box}\delta\tilde{\phi} = \underbrace{-\frac{1}{2}\beta\kappa\tilde{T}}_{\sim\, m_{\rm eff}^2}\delta\tilde{\phi}$$

with $\alpha(\tilde{\phi}) \equiv \frac{1}{2}\frac{\mathrm{d}\,\log\phi}{\mathrm{d}\tilde{\phi}}$

Spontaneous scalarization for BHs

Silva et al. 2018
Doneva et al. 2018
Antoniou et al. 2018

- Similar mechanism studied in scalar Gauss-Bonnet gravity
- Spontaneous scalarization for both neutron stars and black holes

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\left(R - \frac{1}{2}\nabla_\mu\phi\nabla^\mu\phi + f(\phi)\mathscr{G}\right) + S_{\rm M}[g_{\mu\nu},\psi_{\rm m}]$$

$$\Box\delta\phi + \underbrace{f_{,\phi\phi}\mathscr{G}}_{\wr \atop -m^2_{\rm eff}}\delta\phi = 0$$

$$\boxed{f_{,\phi\phi}\mathscr{G} > 0}$$

For tachyonic instability

Modified Einstein equations

$$G_{\mu\nu} = \kappa T^{\mathrm{PF}}_{\mu\nu} + T^{\phi}_{\mu\nu}$$

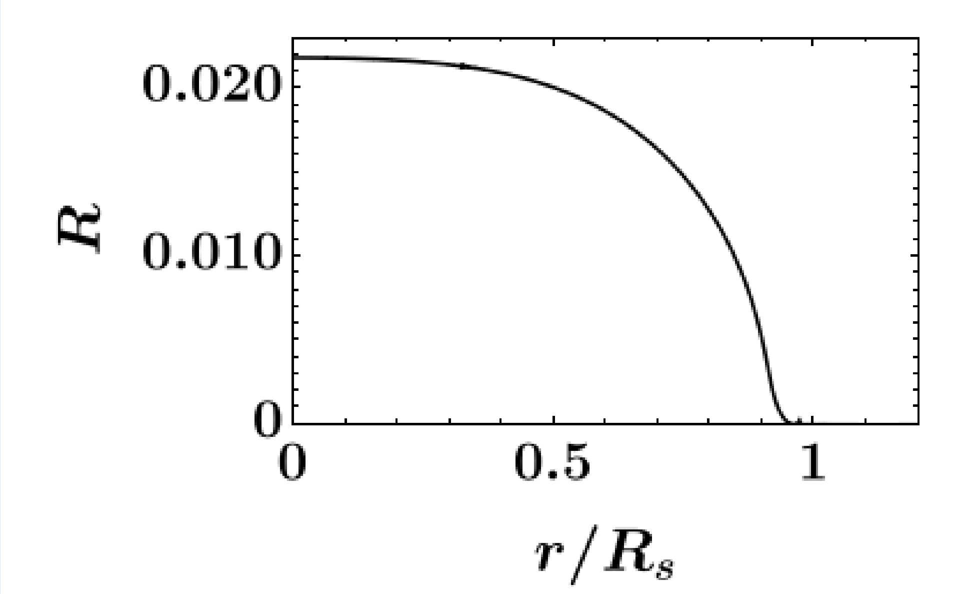
with

$$\begin{aligned} T^{\phi}_{\mu\nu} = & -\frac{1}{4} g_{\mu\nu} \nabla_\lambda \phi \nabla^\lambda \phi + \frac{1}{2} \nabla_\mu \phi \nabla_\nu \phi + \frac{\beta\phi^2}{4} G_{\mu\nu} \\ & + \frac{\beta}{4} \left(g_{\mu\nu} \nabla^2 - \nabla_\mu \nabla_\nu \right) \phi^2 \\ & - \frac{\alpha}{2g} g_{\mu(\rho} g_{\sigma)\nu} \epsilon^{\kappa\rho\alpha\beta} \epsilon^{\sigma\gamma\lambda\tau} R_{\lambda\tau\alpha\beta} \nabla_\gamma \nabla_\kappa \phi^2 \end{aligned}$$

Ricci scalar

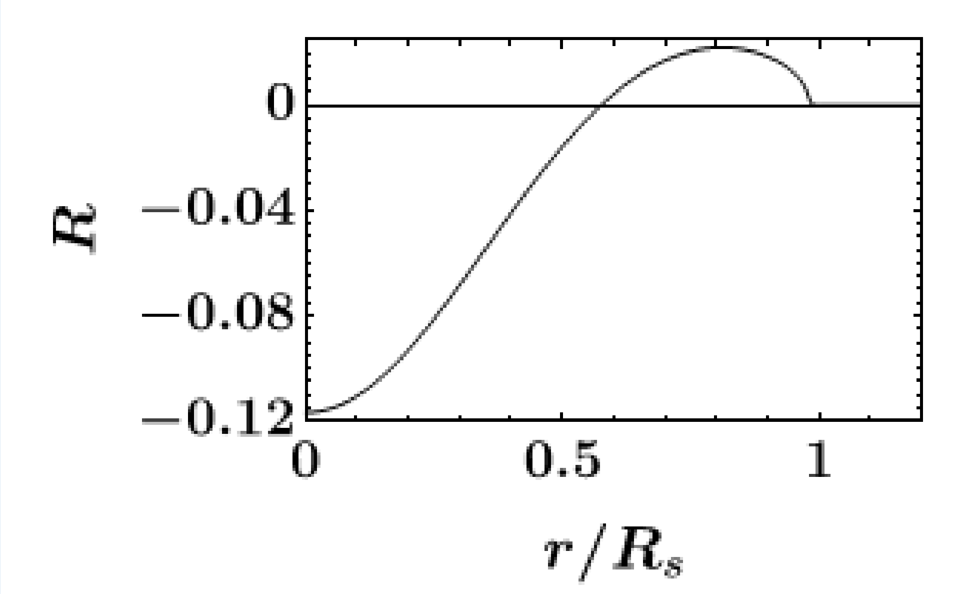
$$R = \kappa(\epsilon - 3P)$$

$M_{GR} = 1.12\ M_\odot$



$\epsilon >> P$

$M_{GR} = 2.04\ M_\odot$



$\epsilon << P$