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Neutron stars in modified gravity

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Motivations

* General relativity is well tested in weak field regime, while the strong field regime is essentially unconstrained.

* The quantum corrections in the strong field regime give rise to a modification of Einstein gravity.

* The attempts to construct a unified theory of the interactions, naturally lead to scalar-tensor type generalizations of General Relativity and theories of gravity with Lagrangians containing various kind of curvature corrections to the usual Einstein-Hilbert Lagrangian.

* Besides the theoretical reasons, there are well-known observational facts that force us to go beyond the original Einstein theory – the accelerated expansion of the Universe.

Scalar-tensor and f(R) gravity

Einstein frame action

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

Coupling function $\alpha(\varphi) = \dfrac{d\ln(\mathcal{A}(\varphi))}{d\varphi}$

$$G^*_{\mu\nu} = 8\pi G T^*_{\mu\nu} + 2\partial_\mu\varphi\partial_\nu\varphi - g^*_{\mu\nu}g^{*\alpha\beta}\partial_\alpha\varphi\partial_\beta\varphi - \frac{1}{2}V(\varphi)g^*_{\mu\nu},$$

$$\nabla^*_\mu\nabla^{*\mu}\varphi - \frac{1}{4}\frac{dV(\varphi)}{d\varphi} = -4\pi G\alpha(\varphi)T^*,$$

R-squared gravity

f(R) gravity: $$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}f(R) + S_{\rm matter}(g_{\mu\nu},\chi)$$

R-squared gravity: $f(R) = R + aR^2$

Einstein frame:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g^*}\left[R^* - 2g^{*\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right] + S_{\rm matter}(e^{-\frac{2}{\sqrt{3}}\varphi}g^*_{\mu\nu},\chi)$$

$$m_\Phi = \frac{1}{\sqrt{6a}}, \qquad V(\varphi) = \frac{1}{4a}\left(1 - e^{-\frac{2\varphi}{\sqrt{3}}}\right)^2$$

Coupling function $\alpha(\varphi) = -1/\sqrt{3}$

Reduced field equations

$$ds_*^2 = -e^{2\phi(r)}dt^2 + e^{2\Lambda(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\vartheta^2)$$

$$\frac{1}{r^2}\frac{d}{dr}\left[r(1-e^{-2\Lambda})\right] = 8\pi G A^4(\varphi)\rho + e^{-2\Lambda}\left(\frac{d\varphi}{dr}\right)^2 + \frac{1}{2}V(\varphi),$$

$$\frac{2}{r}e^{-2\Lambda}\frac{d\phi}{dr} - \frac{1}{r^2}(1-e^{-2\Lambda}) = 8\pi G A^4(\varphi)p + e^{-2\Lambda}\left(\frac{d\varphi}{dr}\right)^2 - \frac{1}{2}V(\varphi),$$

$$\frac{d^2\varphi}{dr^2} + \left(\frac{d\phi}{dr} - \frac{d\Lambda}{dr} + \frac{2}{r}\right)\frac{d\varphi}{dr} = 4\pi G\alpha(\varphi)A^4(\varphi)(\rho - 3p)e^{2\Lambda} + \frac{1}{4}\frac{dV(\varphi)}{d\varphi}e^{2\Lambda},$$

$$\frac{dp}{dr} = -(\rho + p)\left(\frac{d\phi}{dr} + \alpha(\varphi)\frac{d\varphi}{dr}\right),$$

Boundary conditions: $\rho(0) = \rho_c, \quad \Lambda(0) = 0, \quad \frac{d\varphi}{dr}(0) = 0,$

$$\lim_{r\to\infty}\phi(r) = 0, \quad \lim_{r\to\infty}\varphi(r) = 0$$

$$p(r_S) = 0$$

Nonrotating stars in R-squared gravity

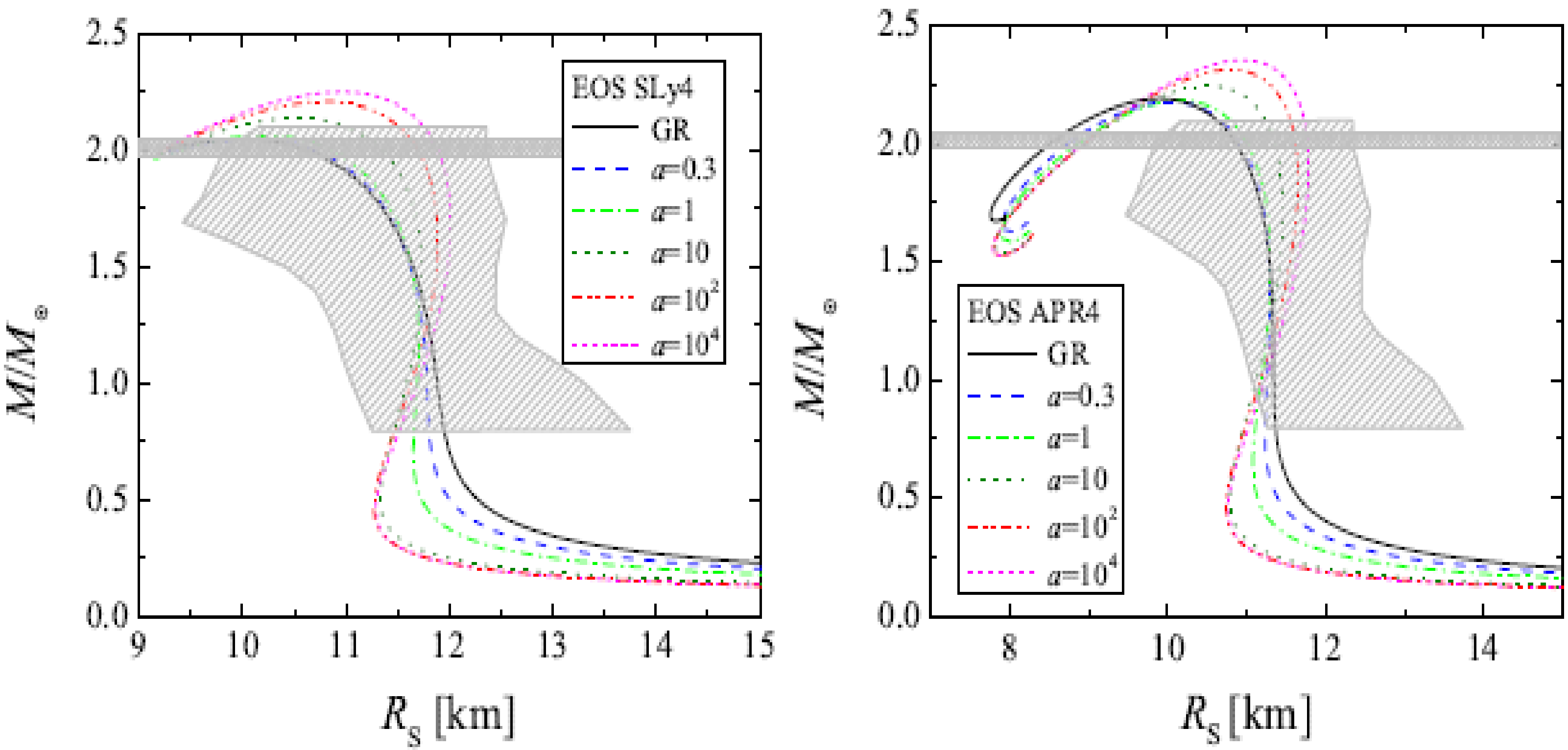
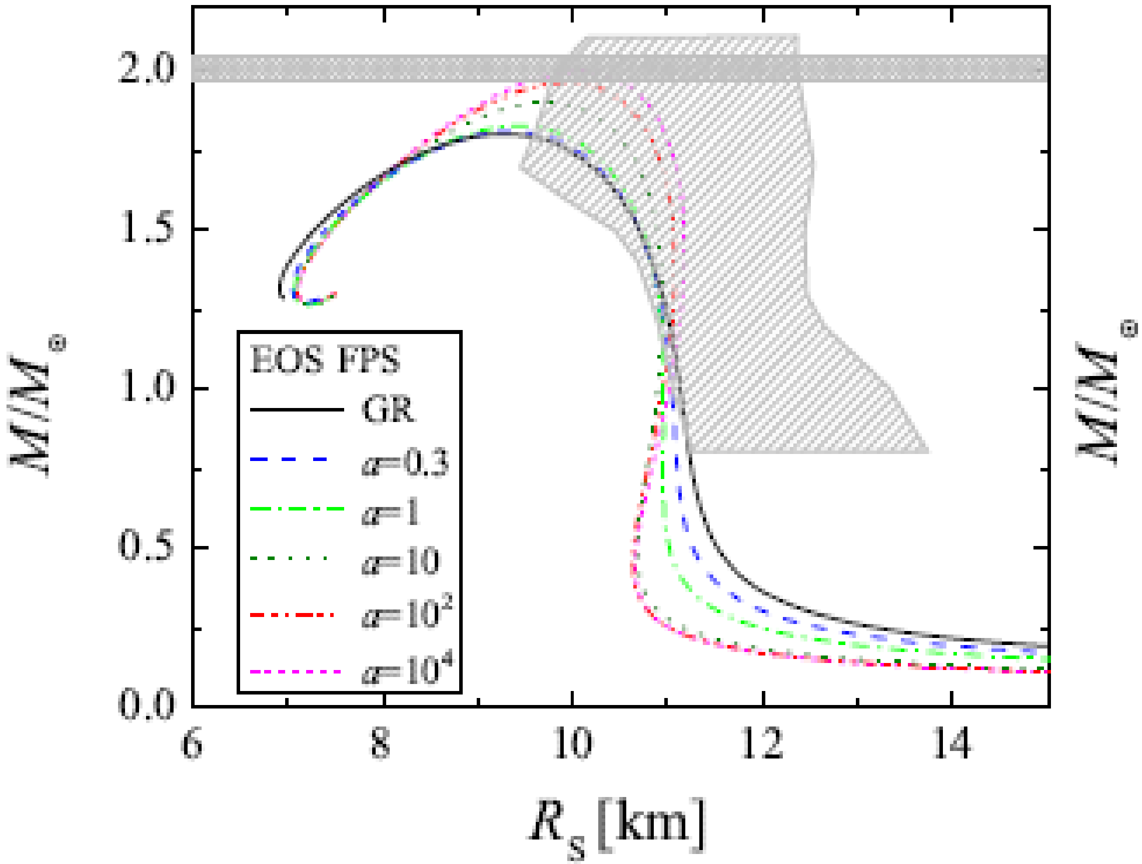


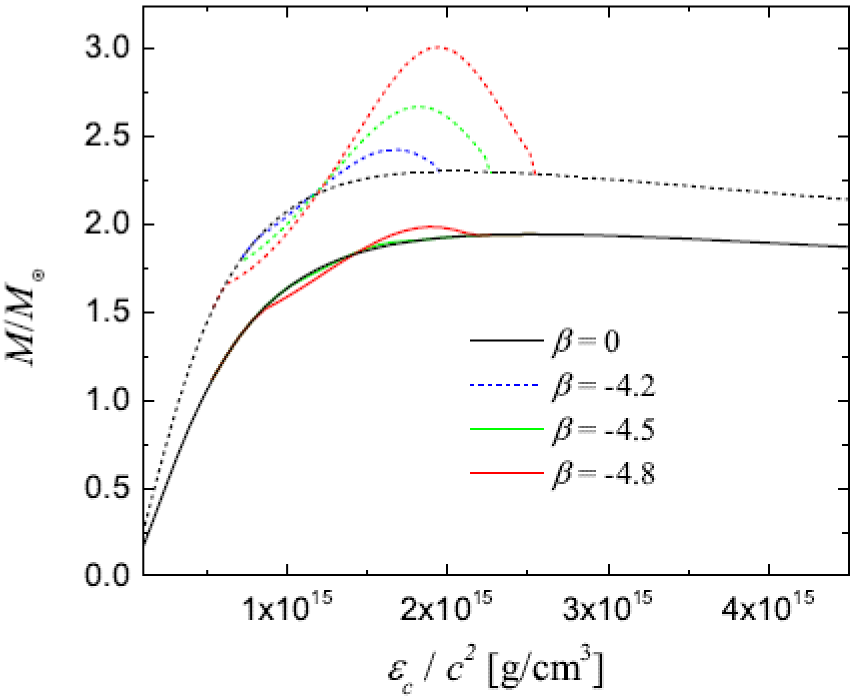
Figure 1. The mass of radius relation for EOS SLy4 (left panel) and APR4 (right panel). Different styles and colors of the curves correspond to different values of the parameter a. The current observational constrains are shown as shaded regions.

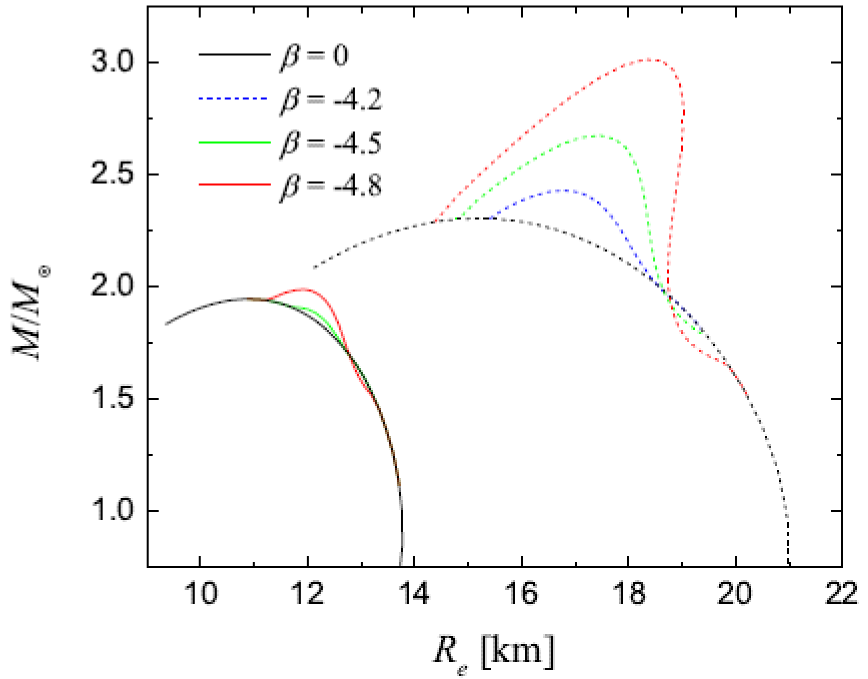
Nonrotating stars in R-squared gravity



Spontaneously scalarized neutron stars

Coupling function $\alpha(\varphi) = \beta\varphi$ – spontaneous scalarization, nonuniqueness of the solutions



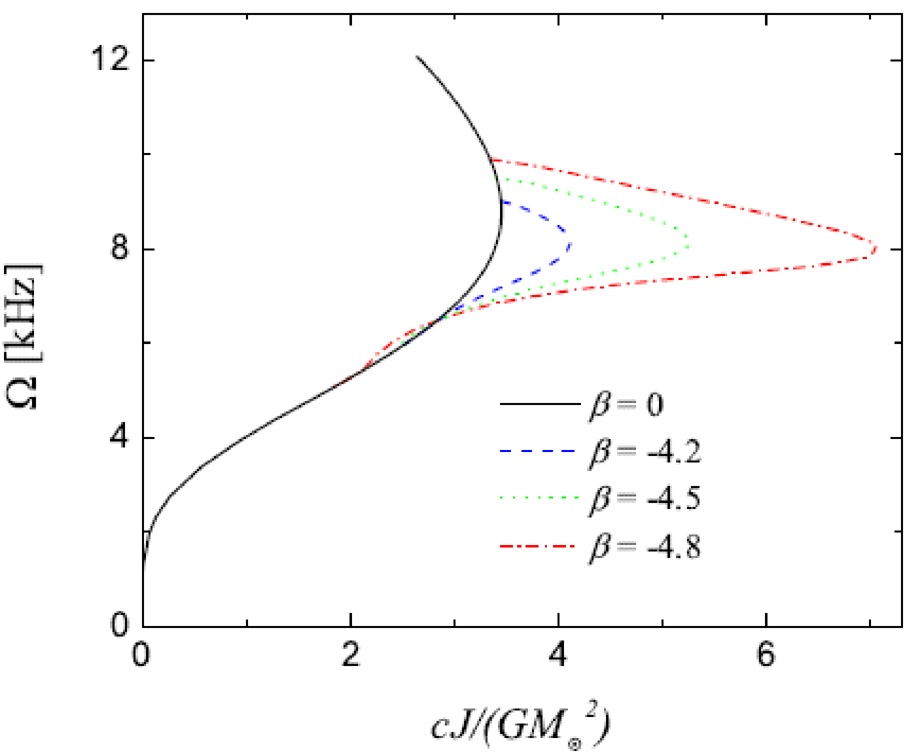


- The effect of scalarization is *much stronger* for fast rotation.
- Scalarized solutions exist for a *much larger range of parameters* than in the static case.

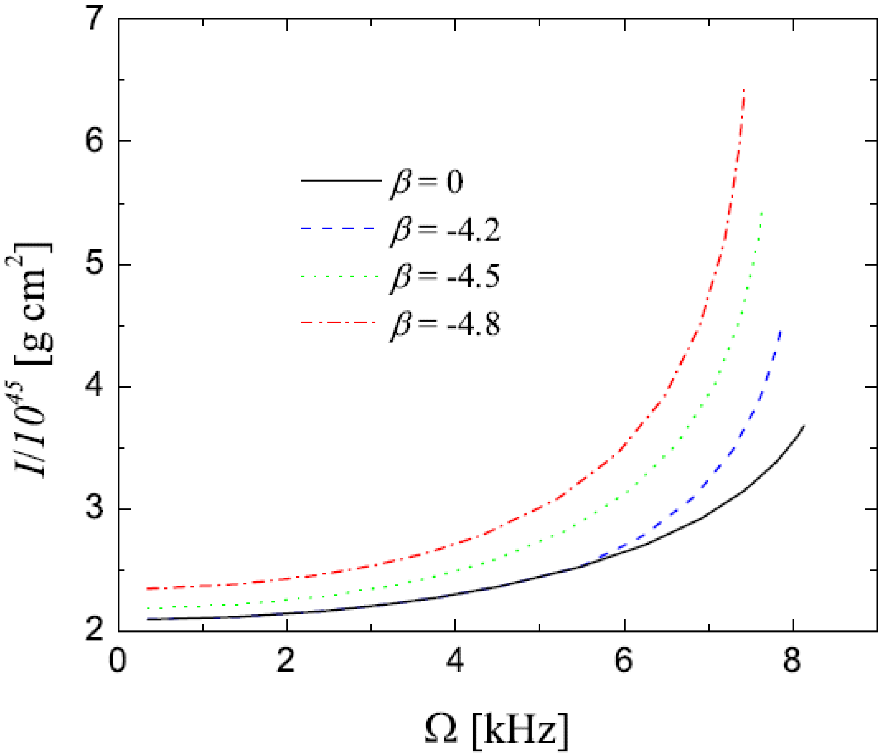
Spontaneously scalarized neutron stars

Angular momentum and moment of inertial – could *differ twice* for scalarized solutions

Sequences of models rotating at the Kepler limit

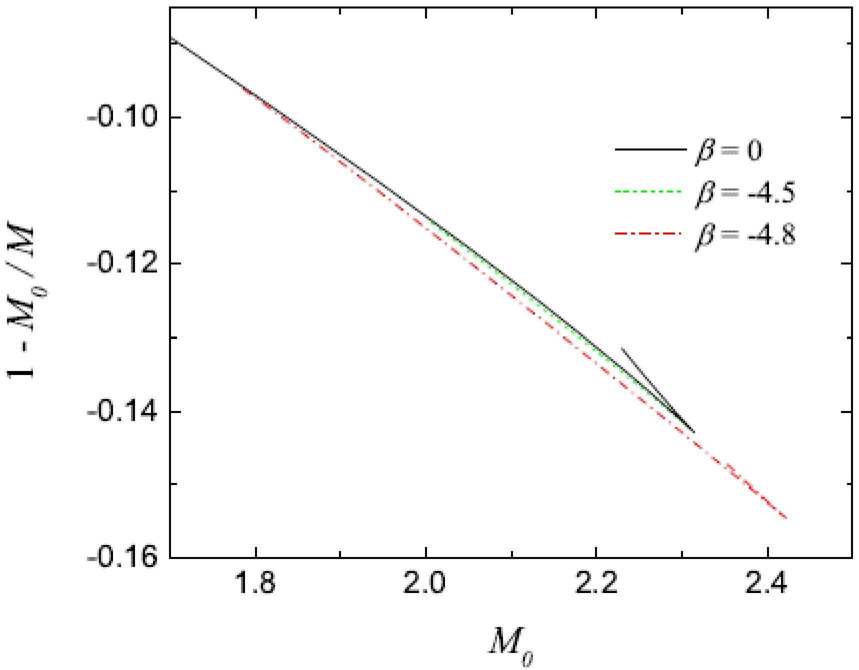


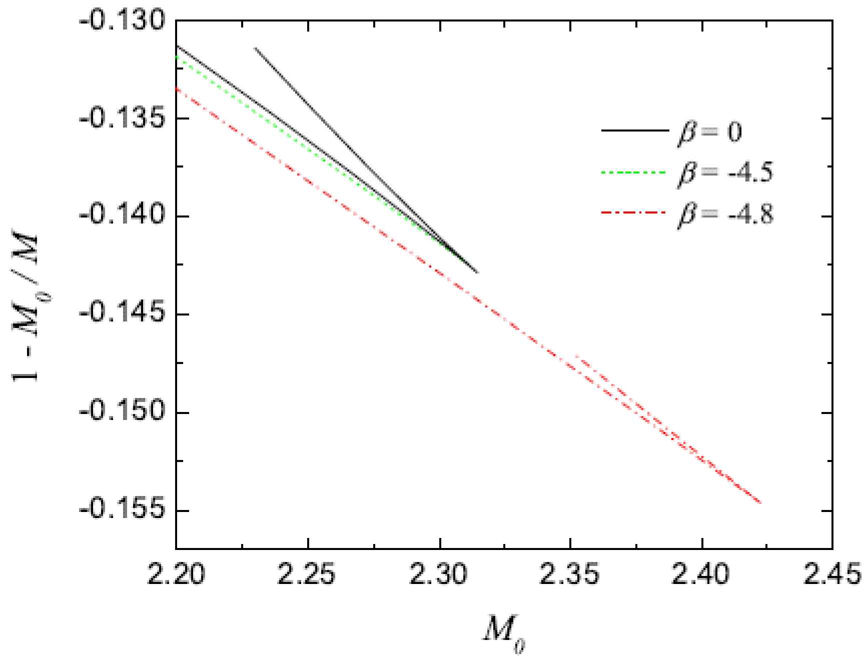
Models with constant central energy density



Spontaneously scalarized neutron stars

Stability of the solutions : The scalarized neutron stars are *energetically more favorable*!





Sequences of fixed angular momentum J are plotted.

Thank you !