Neutron stars in $f(\mathcal{R},\mathcal{T})$ gravity with realistic equations of state in the light of massive pulsars and GW170817[1]

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[1] R. Lobato et al. In: *JCAP* 12 (2020), p. 039. arXiv: 2009.04696 [astro-ph.HE].

Outline

Stellar structure

- For many studies of compact star properties, it is sufficient to treat the matter that constitues these objects as a prefect fluid

$$T^{\mu\nu} = \mathrm{diag}[\rho, -\mathrm{p}, -\mathrm{p}, -\mathrm{p}], \quad (1)$$

- To construct non-rotating stars we use a spherical symmetry

$$ds^2 = e^{\phi} dt^2 - e^{\lambda} dr^2 - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2, \quad (2)$$

to obtain the stellar structure equations known as Tolman-Oppenheimer-Volkoff[2] (TOV)

$$\frac{dm}{dr} = 4\pi r^2 \epsilon, \quad (3)$$

$$\frac{dp}{dr} = -\frac{m\epsilon}{r^2}\left[1 + \frac{p}{\epsilon}\right]\left[1 + \frac{4\pi r^3 p}{m}\right]\left[1 - \frac{2m}{r}\right]^{-1}. \quad (4)$$

[2] J. R. Oppenheimer et al. In: *Physical Review* 55.4 (Feb. 1939), pp. 374–381, Richard C. Tolman. In: *Physical Review* 55.4 (Feb. 1939), pp. 364–373.

Mass-radius for different EOS with constrains of GW170817[3] and two massive pulsars[4] within of GR

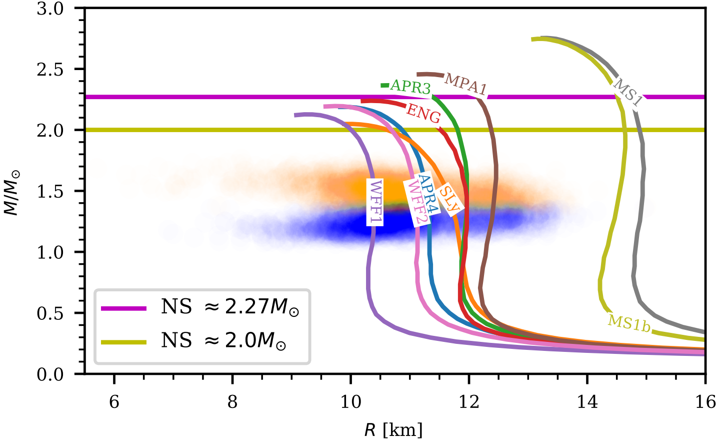


Figure: Mass vs radius. Hadronic EOS.

[3] The LIGO Scientific Collaboration and the Virgo Collaboration et al. In: *Physical Review Letters* 121.16 (Oct. 2018), p. 161101.

[4] John Antoniadis et al. en. In: *Science* 340.6131 (Apr. 2013), p. 1233232.

Hydrostatic equilibrium equations in $f(R, T)$ gravity

- Proposed by Harko[5], the theory assumes the gravitational part of the action depends on a generic function of R and T. The total action reads

$$S = \frac{1}{16\pi}\int d^4x f(R, T)\sqrt{-g} + \int d^4x \mathcal{L}_m \sqrt{-g}. \tag{5}$$

- The hydrostatic equilibrium equations for a spherical object assuming in the $f(R, T) = R + 2\lambda T$ are[6]

$$\frac{dm}{dr} = 4\pi\rho r^2 + \frac{\lambda}{2}(3\rho - p)r^2, \tag{6}$$

$$\frac{dp}{dr} = -(\rho + p)\frac{4\pi p r + \frac{m}{r^2} - \frac{\lambda(\rho - 3p)r}{2}}{\left(1 - \frac{2m}{r}\right)\left[1 + \frac{\lambda}{8\pi + 2\lambda}\left(1 - \frac{d\rho}{dp}\right)\right]}, \tag{7}$$

[5] Tiberiu Harko et al. en. In: *Physical Review D* 84.2 (July 2011).

[6] P. H. R. S. Moraes et al. en. In: *Journal of Cosmology and Astroparticle Physics* 2016.06 (2016), p. 005, G. A. Carvalho et al. en. In: *The European Physical Journal C* 77.12 (Dec. 2017).

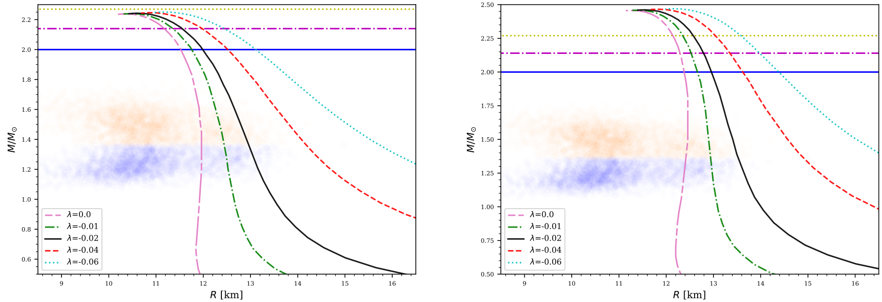
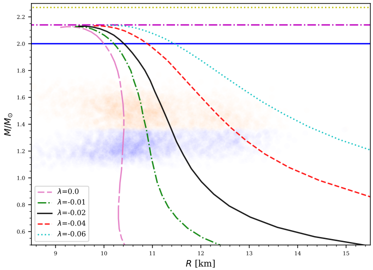
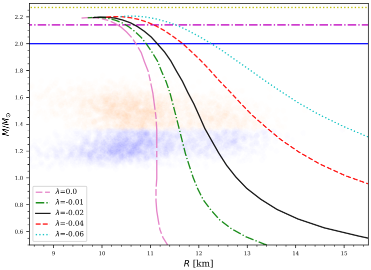


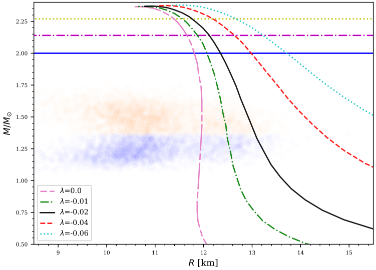
Figure: On the left side, the mass-radius relation for the ENG equation of state. On the right side, the mass-radius relation for the MPA1 equation of state. It was considered five values of λ in the mass-radius for each EoS, going from $\lambda = -0.06$ to 0.0, for $\lambda = 0$, the theory retrieves general relativity. The blue and orange cloud region is the constraints for mass-radius from the GW170817 event, which was a merger of two neutron stars with an observation in the electromagnetic and gravitational spectrum. The blue continuous line at 2.0 $M\odot$, the magenta dot-dashed line at 2.14 $M\odot$ and the yellow dot line at 2.27 $M\odot$ represent the most massive pulsars observed up to now. The pulsar with 2.14 $M\odot$ has a 95.4% credibility level.



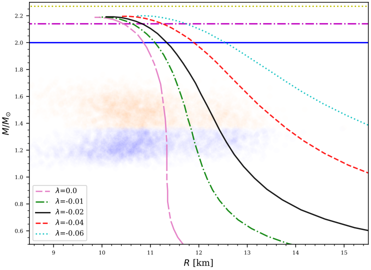
(a) WFF1 equation of state.



(b) WFF2 equation of state.



(c) APR3 equation of state.



(d) APR4 equation of state.

- **We also study neutron stars in $f(\mathcal{R},\mathcal{T})$ gravity through RFMs models[7],**

$$\begin{aligned}\mathcal{L} \quad &= \overline{\psi}(i\gamma^\mu\partial_\mu - M)\psi + g_\sigma\sigma\overline{\psi}\psi - g_\omega\overline{\psi}\gamma^\mu\omega_\mu\psi - \frac{g_\rho}{2}\overline{\psi}\gamma^\mu\vec{\rho}_\mu\vec{\tau}\psi + \frac{1}{2}(\partial^\mu\sigma\partial_\mu\sigma - m_\sigma^2\sigma^2)\\ &-\frac{A}{3}\sigma^3 - \frac{B}{4}\sigma^4 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{C}{4}(g_\omega^2\omega_\mu\omega^\mu)^2 - \frac{1}{4}\vec{B}^{\mu\nu}\vec{B}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu\\ &+g_\sigma g_\omega^2\sigma\omega_\mu\omega^\mu\left(\alpha_1 + \frac{1}{2}\alpha_1' g_\sigma\sigma\right) + g_\sigma g_\rho^2\sigma\vec{\rho}_\mu\vec{\rho}^\mu\left(\alpha_2 + \frac{1}{2}\alpha_2' g_\sigma\sigma\right) + \frac{1}{2}\alpha_3' g_\omega^2 g_\rho^2\omega_\mu\omega^\mu\vec{\rho}_\mu\vec{\rho}^\mu.\end{aligned}$$

[7] Bao-An Li et al. en. In: *Physics Reports* 464.4 (Aug. 2008), pp. 113–281, M. Dutra et al. In: *Physical Review C* 90.5 (Nov. 2014), p. 055203.

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- **We choose BKA20, BSR8, IU-FSU, and Z271s4 as representative parametrizations of the "families" BKA, BSR, FSU, and Z271.**

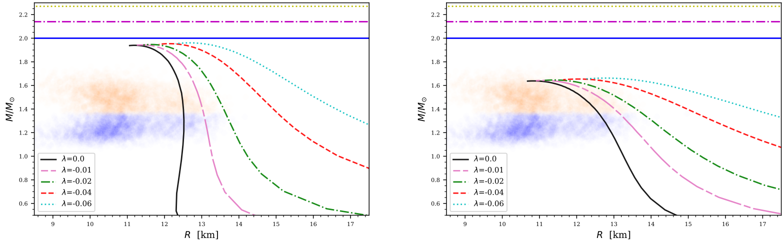

Figure: On the left side, the mass-radius relation for the IU-FSU equation of state. On the right side, the mass-radius relation for the Z271s4 equation of state.

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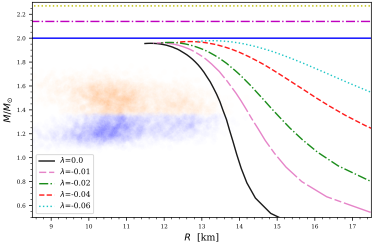
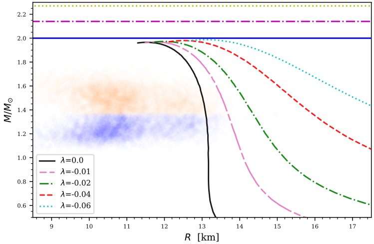
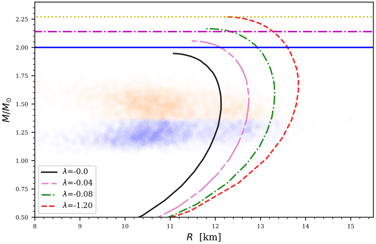
Effect of the crust



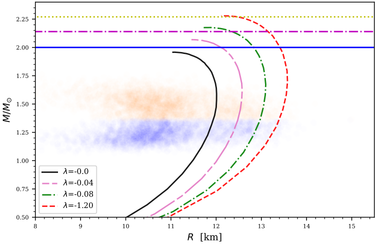
(a) BKA20 equation of state.



(b) BSR8 equation of state.



(c) BKA20 equation of state without crust.



(d) BSR8 equation of state without crust.

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3. **The pressure in theory of gravity depends on the inverse of the sound velocity v_s. Since, v_s is low in the crust, $|\lambda|$ need to be very small. We found that the increment in the star mass is less than 1%, much smaller than previous ones obtained not considering the realistic stellar structure, and the star radius cannot become larger, its changes compared to GR is less than 3.6% in all cases.**

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6. **Finally, we highlight that our results indicate that conclusions obtained from NS studies done in modified theories of gravity without using realistic EsoS that describe correctly the NS interior can be unreliable.**

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- FAPESP Thematic Project 2013/26258-4
- Committee of PANIC Lisbon Portugal - Particles and Nuclei International Conference

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[1] John Antoniadis et al. en. In: *Science* 340.6131 (Apr. 2013), p. 1233232.

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