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Compact stars in massive scalar-tensor theories – models and gravitational wave emission

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Scalar-tensor theories

- **Essence:** one or several scalar fields that can be viewed as mediators of the gravitational interaction in addition to the spacetime metric

- **Action:**

Jordan frame
Physical one

$$S = \frac{1}{16\pi G_*}\int d^4x\sqrt{-\tilde{g}}\left[F(\Phi)\tilde{R} - Z(\Phi)\tilde{g}^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 2U(\Phi)\right] + S_m\left[\Psi_m;\tilde{g}_{\mu\nu}\right]$$

✓ Conformal transformation of the metric
✓ Redefinition of the scalar field

Einstein frame
Much simpler!

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

The price we pay for simplicity: Explicit coupling between the matter and the scalar field

Field equations in STT (Einstein frame)

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G_* T_{\mu\nu} + 2\partial_\mu\varphi\partial_\nu\varphi - g_{\mu\nu}g^{\alpha\beta}\partial_\alpha\varphi\partial_\beta\varphi - 2V(\varphi)g_{\mu\nu}$$

$$\nabla^\mu\nabla_\mu\varphi = -4\pi G_* k(\varphi)T + \frac{dV(\varphi)}{d\varphi}.$$

These equations have to be supplemented with:

- Equation for hydrostatic equilibrium
- Equation of state of the nuclear matter

Scalar-tensor theories with a massive scalar field

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

Coupling function $\alpha(\varphi) = \frac{d\, lnA(\varphi)}{d\, \varphi}$

- The coupling function can be expanded as $\boldsymbol{\alpha(\varphi) = \alpha_0 + \beta\varphi +}$ **higher order terms**

$$\boldsymbol{\alpha(\varphi) = \beta\varphi}$$

  - Equivalent to GR in the weak field regime.
  - Can differ significantly when strong fields are considered.
  - Nonuniqueness of the neutron star solutions can exist – one solution with trivial scalar field and one or several others with nontrivial scalar field.

- **Observational constraints in the massless case:** $\alpha_0 < 0.004$ and $\beta > -4.5$ (Damour & Esposito-Farese (1996,1998), Will (2006), Freire et al (2012), Antoniadis et al (2013))

- **The mass** of the scalar field – accomplished via **a nonzero potential** of the scalar field $V(\varphi) = \frac{1}{2}m_\varphi^2\varphi^2$

Scalar-tensor theories with a massive scalar field

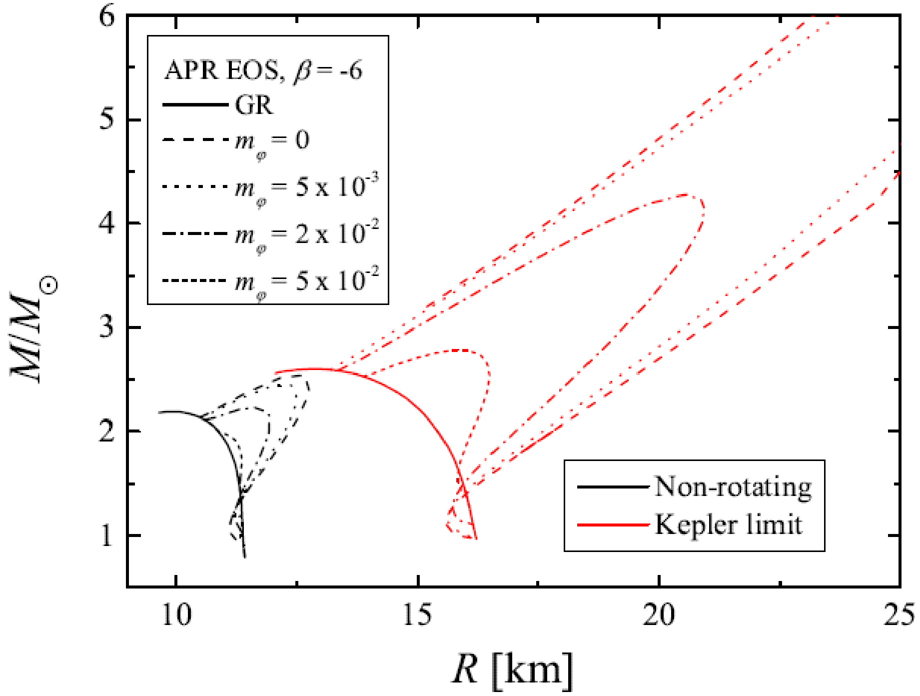
- **The scalar field mass m_φ leads to a finite range of the scalar field of the order of its Compton wavelength $\lambda_\varphi = 2\pi/m_\varphi$.**
  - The presence of the scalar field will be suppressed outside the compact objects at distances $D > \lambda_\varphi$.
  - This means in turn that all observations of compact objects involving distances greater than λ_φ cannot put constraints, or at least stringent constraints, on the scalar tensor theories.
- A new and promising line of research (Popchev Master Thesis (2015); F. Ramazanoğlu, F. Pretorius (2016), Yazadjiev, Doneva & Popchev (2016), Doneva &Yazadjiev (2016), Yazadjiev, Doneva & Kokkotas (2017), Morisaki & Suyama (2017)).
- If the Compton wave-length of the scalar field λ_φ is much smaller than the separation of the two stars in the binary system the emitted scalar gravitational radiation will be negligible $\mathbf{10^{-16}eV} < \boldsymbol{m_\varphi}$.

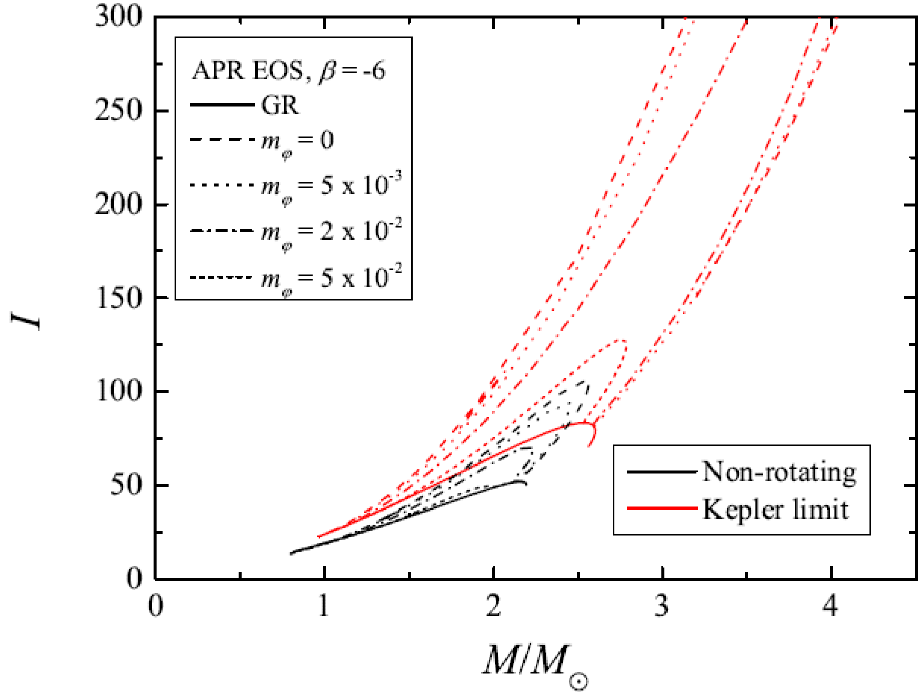
  F. Ramazanoğlu, F. Pretorius (2016); Yazadjiev, DD & Popchev (2016)

Neutron star models in massive STT

Theory with **spontaneous scalarization:**

$$\alpha(\varphi) = \beta\varphi \;\Leftrightarrow\; A(\varphi) = \exp\left(\frac{\beta}{2}\varphi^2\right), \beta < 0$$

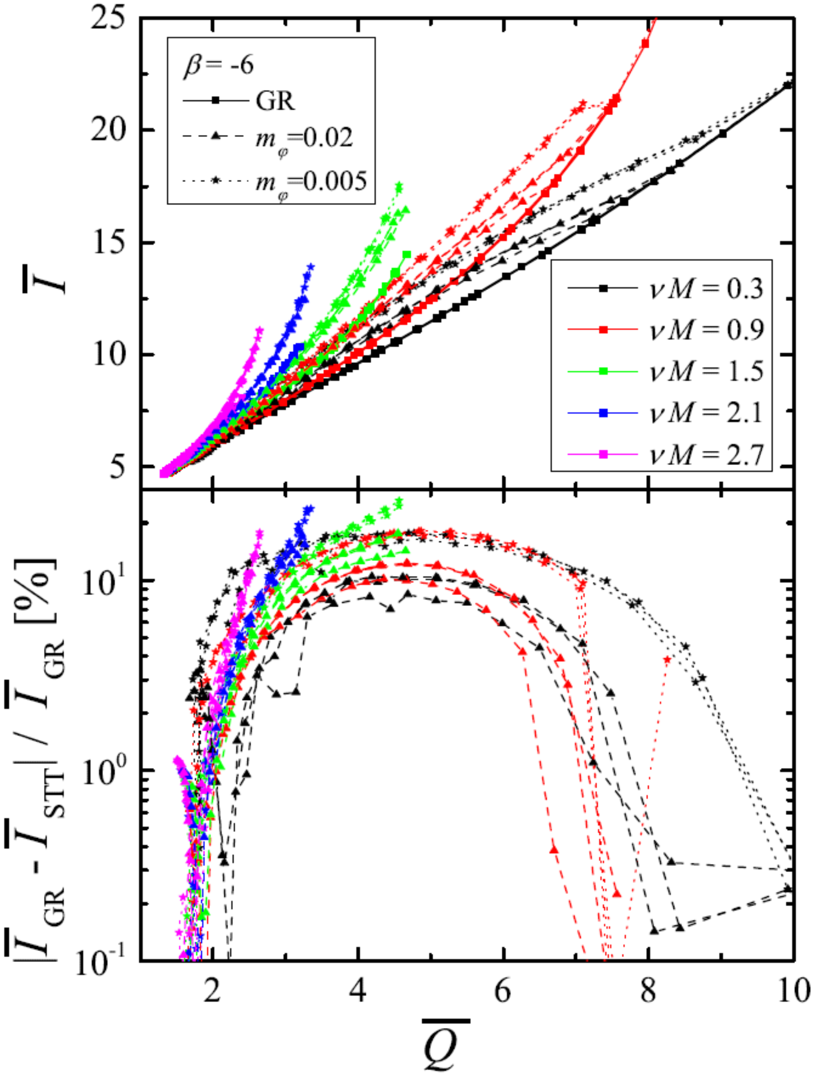




Yazadjiev, DD & Popchev (2016); DD & Yazadjiev (2016)

Neutron stars – universal relations

Massive STT



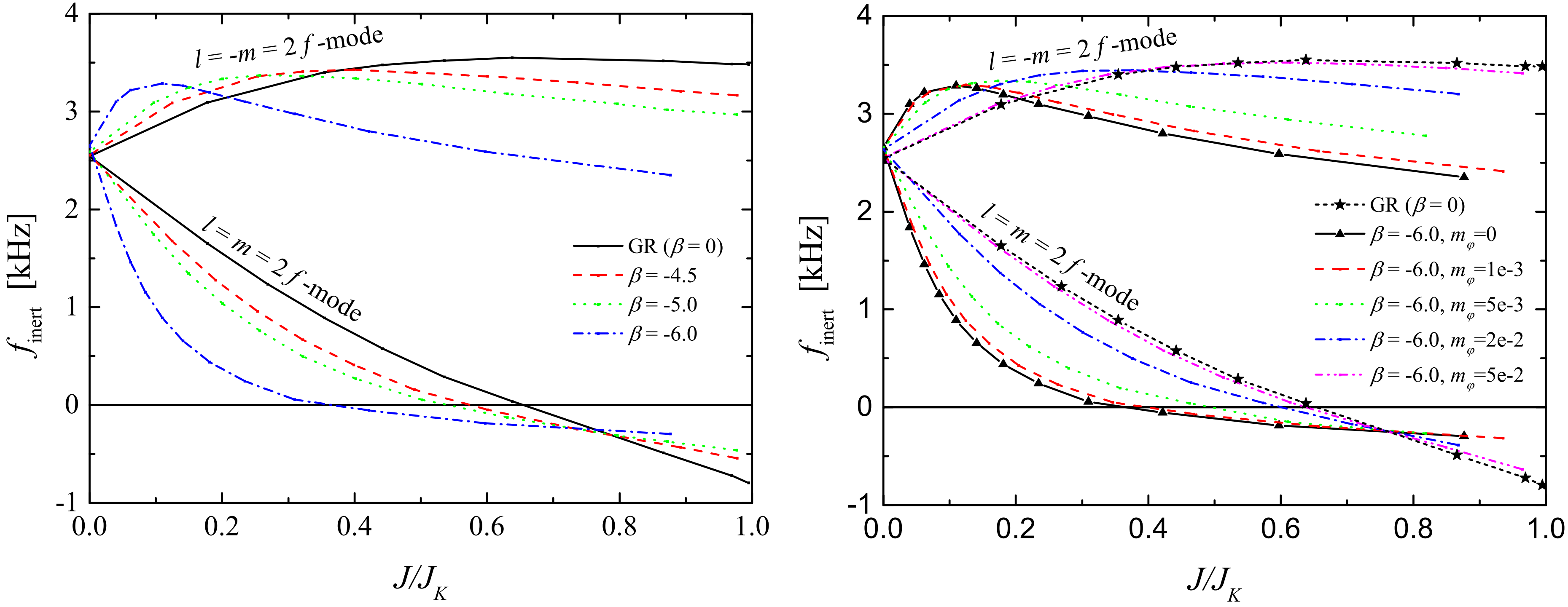
- Most of the studied alternative theories of gravity give only marginal deviations from GR (eg. Sham, Lin, Leung(2014); Kleinhaus, Kunz, Mojica (2014), Pani, Berti (2014), Doneva, Yazadjiev, Staykov, Kokkotas (2014)).

- I-Love-Q relations: appreciable deviations from GR for some alternative theories of gravity (**dynamical Chern-Simons gravity** Yagi&Yunes(2013), $f(R)$ gravity DD, Yazadjiev, Kokkotas (2015), **massive STT** Yazadjie,DD (2016))

- **Unnormalized relations** STILL differ significantly from GR. Solution:
  - ➢ Different normalization
  - ➢ Different universal relation

Oscillation modes of rapidly rotating neutron stars

- ***f*-mode** oscillation frequencies, $l = |m| = 2$ case (prone to the CFS instability)



Yazadjiev, DD, Kokkotas (2017)

For NS mergers see L. Sagunski et al (2017)

Conclusions

- The mass of the scalar field can **reconcile the theory with the observations** for a much larger range of parameters compared to the massless case.

- The neutron stars in massive scalar-tensor theories can **differ significantly from the pure general relativistic case**.

- **Astrophysical implications** should be examined in order to set constraints on the theory.