21st International Conference on General Relativity and Gravitation
Columbia University, New York

UNIVERSITY of GUELPH

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

TESTING SCALAR-TENSOR THEORIES OF GRAVITY WITH HIGHLY COMPACT NEUTRON STARS

RAISSA F. P. MENDES

Based on:
- R. F. P. Mendes, Phys. Rev. D 91, 064024 (2015), arXiv:1412.6789.
- R. F. P. Mendes and N. Ortiz, Phys. Rev. D 93, 124035 (2016), arXiv:1604.04175. (see also N. Ortiz's talk!)

A WORD ON NEUTRON STARS

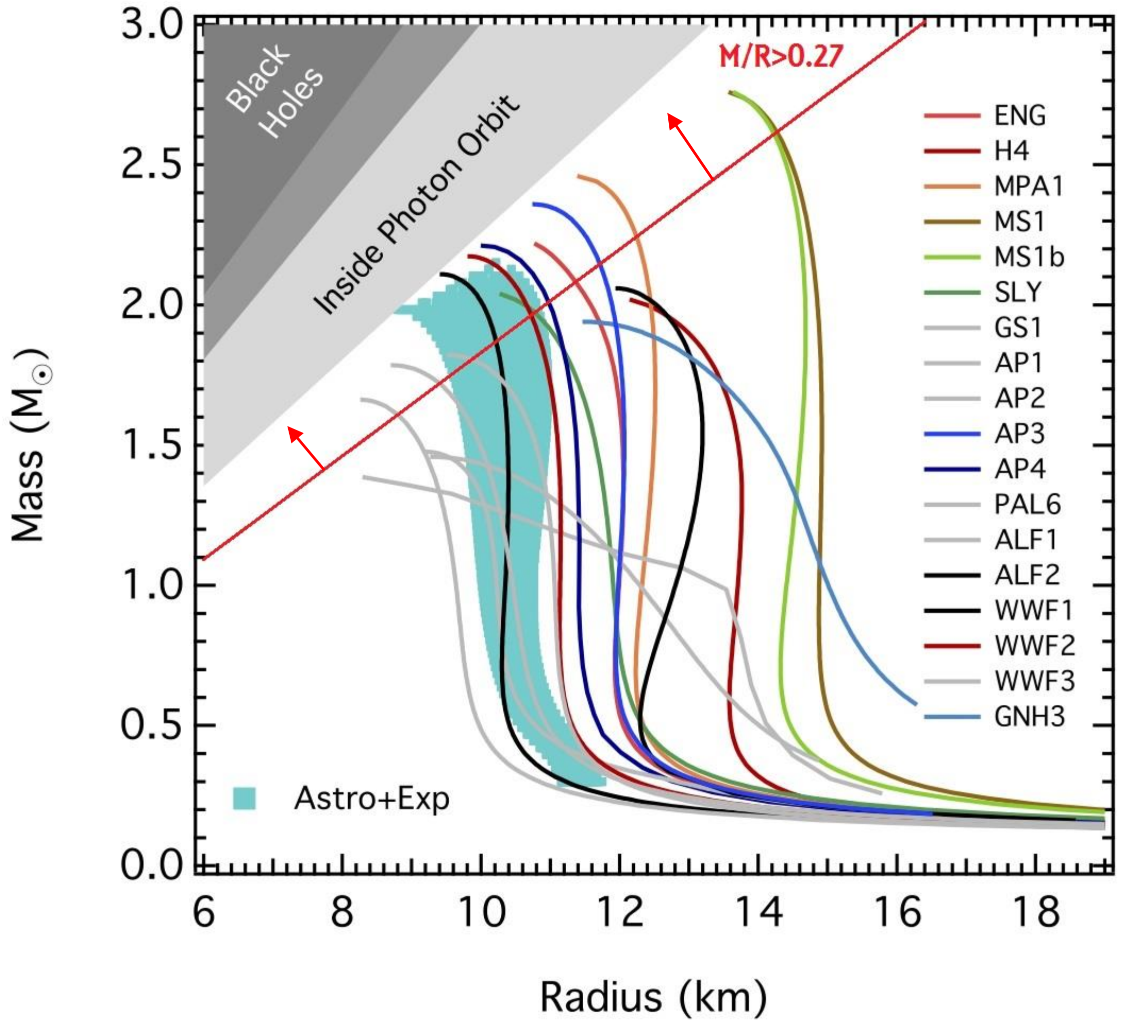
- + 2500 pulsars in the Galaxy; 90% isolated.
- Precise masses for ~35 NS, from 1.17 to $2M_\odot$.
- Radius measurements for a dozen NS pinned down to the 9.9 - 11.2 km range.

- Well described by perfect fluid with cold equation of state, $p = p(\rho)$.
- One-to-one relation: EoS ↔ M/R diagram.

- Particularly relevant for us: "<u>highly compact</u>" neutron stars, satisfying

$$\boxed{p_c > \frac{1}{3}\epsilon_c}$$

which is achieved if $M/R \gtrsim 0.27$.



http://xtreme.as.arizona.edu/NeutronStars/

SCALAR-TENSOR THEORIES OF GRAVITY

- Natural, mathematically consistent and simple alternative to GR.
- Tractable: full nonlinear numerics (Barausse et al. 2013, Palenzuela et al. 2014, Shibata et al. 2014)
- Jordan frame:

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

$$g_{\mu\nu} = F(\Phi)\,\tilde{g}_{\mu\nu} = a(\phi)^{-2}\tilde{g}_{\mu\nu}$$

$$\phi = \int d\Phi\left[\frac{3}{4}\frac{F'^2(\Phi)}{F^2(\Phi)} + \frac{1}{2}\frac{Z(\Phi)}{F(\Phi)}\right]^{1/2}$$

- Einstein frame:

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

- Examples:
  - Fierz-Jordan-Brans-Dicke theory: $F(\Phi) = \Phi$, $Z(\Phi) = \omega_{BD}/\Phi$.
  - (massless) NMC scalar field: $F(\Phi) = 1 - \xi\Phi^2$, $Z(\Phi) = 1$.

SCALAR-TENSOR THEORIES OF GRAVITY

$$S = \frac{1}{16\pi}\int d^4x\,\sqrt{-g}\left[R - 2g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right] + S_m\left[\Psi_m; a(\phi)^2 g_{\mu\nu}\right]$$

- Field equations:

$$G_{\mu\nu} - 2\nabla_\mu\phi\nabla_\nu\phi + g_{\mu\nu}\nabla_\rho\phi\nabla^\rho\phi = 8\pi T_{\mu\nu}$$
$$\nabla_\mu\nabla^\mu\phi = -4\pi\,\alpha(\phi)T$$
$$\nabla_\mu T^{\mu\nu} = \alpha(\phi)T\nabla^\nu\phi$$

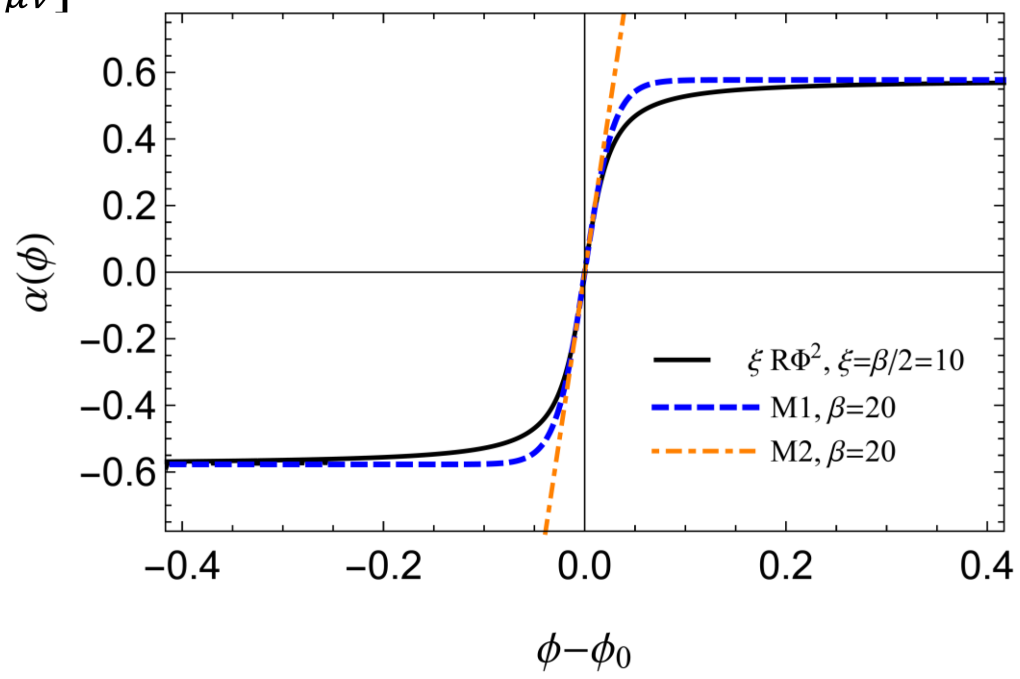
with $\alpha(\phi) \coloneqq d\ln a(\phi)/d\phi$.

- Expand:

$$\boxed{\alpha(\phi) = \alpha_0 + \beta_0(\phi-\phi_0) + O[(\phi-\phi_0)^2]}$$

$\alpha_0 \sim \frac{1}{\sqrt{\omega_{BD}}} \sim 0$
(Solar System)

Responsible for the most interesting effects!

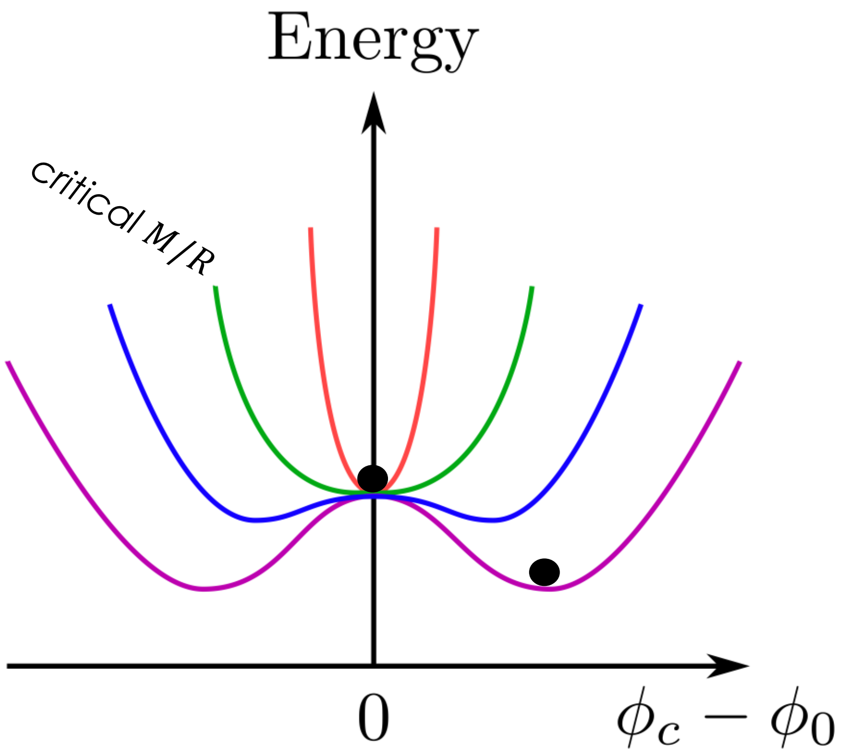


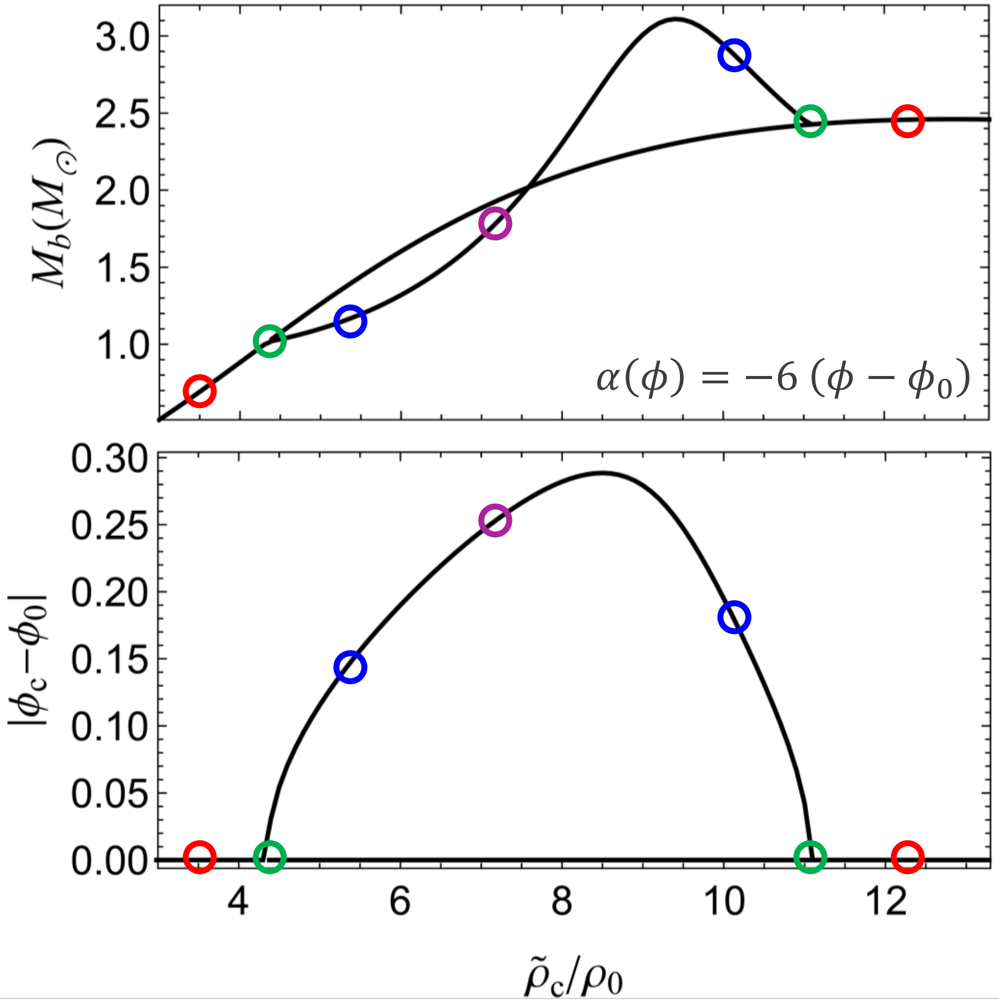
Model 1 (**M1**): $\alpha(\phi) = \frac{1}{\sqrt{3}}\tanh[\sqrt{3}\,\beta\,(\phi-\phi_0)]$
Model 2 (**M2**): $\alpha(\phi) = \beta\,(\phi-\phi_0)$

Differ only in $O[(\phi-\phi_0)^2]$ terms.

SPONTANEOUS SCALARIZATION OF NEUTRON STARS

- Nonperturbative strong-field effect (Damour & Esposito-Farèse, 1993)
- Phase transition ~ spontaneous magnetization

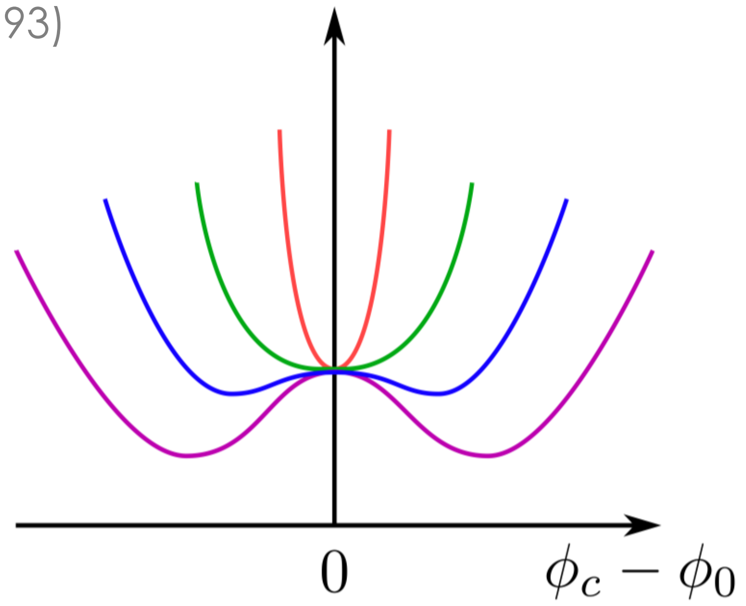




SPONTANEOUS SCALARIZATION OF NEUTRON STARS

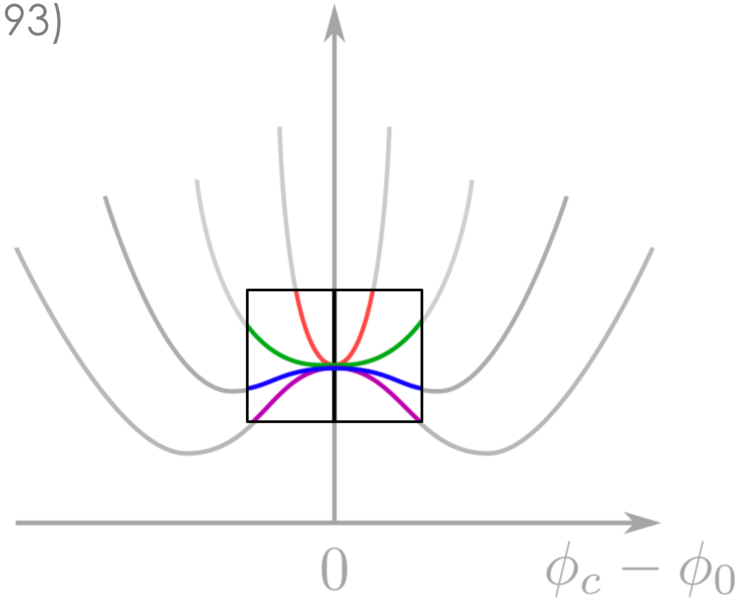
- Nonperturbative strong-field effect (Damour & Esposito-Farèse, 1993)
- Strong field effects can be very important!

- Scalarization depends crucially on $\beta_0 = \alpha'(\phi_0)$.
  - Known to happen when $\beta_0 \lesssim -4.35$.
  - Dipolar radiation: PT rules out $\beta_0 \lesssim -4.5$ (Freire et al. 2012)
  - $\beta_0 > 0$ largely unexplored (and unconstrained)!



SPONTANEOUS SCALARIZATION OF NEUTRON STARS

- Nonperturbative strong-field effect (Damour & Esposito-Farèse, 1993)
- Strong field effects can be very important!
- Scalarization depends crucially on $\beta_0 = \alpha'(\phi_0)$.
  - Known to happen when $\beta_0 \lesssim -4.35$.
  - Dipolar radiation: PT rules out $\beta_0 \lesssim -4.5$ (Freire et al. 2012)
  - $\beta_0 > 0$ largely unexplored (and unconstrained)!

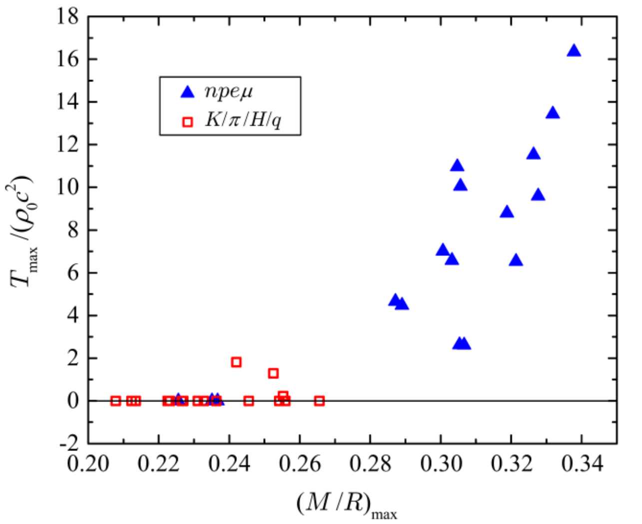


- Insight from linear stability analysis (Harada 1997)

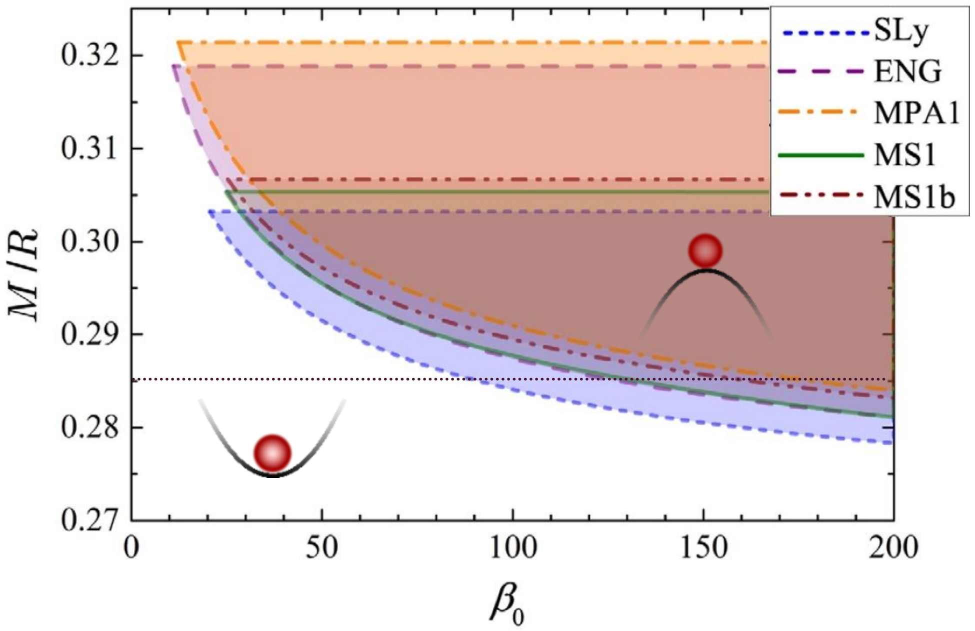
Equil. solution $g_{\mu\nu} = g^E_{\mu\nu}$ $\phi = \phi_0$ → Linear scalar perturbation $\phi = \phi_0 + \delta\phi$ → $\nabla_\mu \nabla^\mu \delta\phi = -4\pi\beta_0 T \delta\phi$ → Unstable modes if $\mathrm{m}^2_{\mathrm{eff}} = -4\pi\beta_0 T$ sufficiently negative

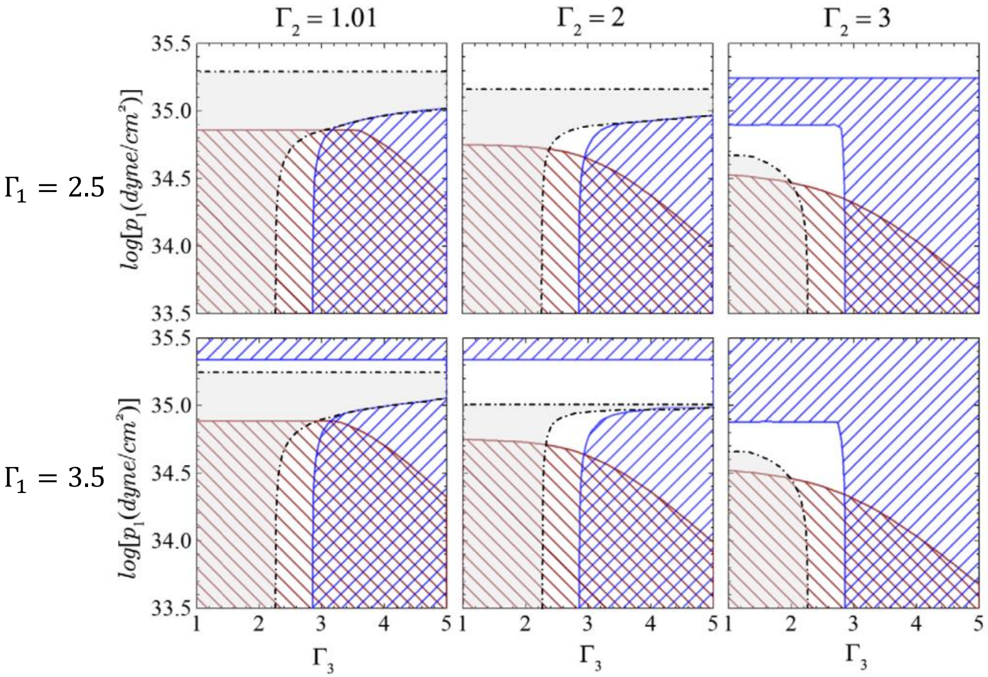
- $T > 0$ ($\Rightarrow p > \epsilon/3$) necessary for instability if $\beta_0 > 0$: ***How "exotic" is this condition?***

$T > 0$ INSIDE "REALISTIC" NEUTRON STARS?



- Analysis of EOS in *parametrized* form & of *theoretical* models [Mendes, PRD91, 064024 (2015)]
- $T > 0$ inside hydrodynamically stable stars?
  - Yes! According to many (but not all!) viable EOS.
  - Usually EOS allowing *more compact stars* ($npe\mu$ models).

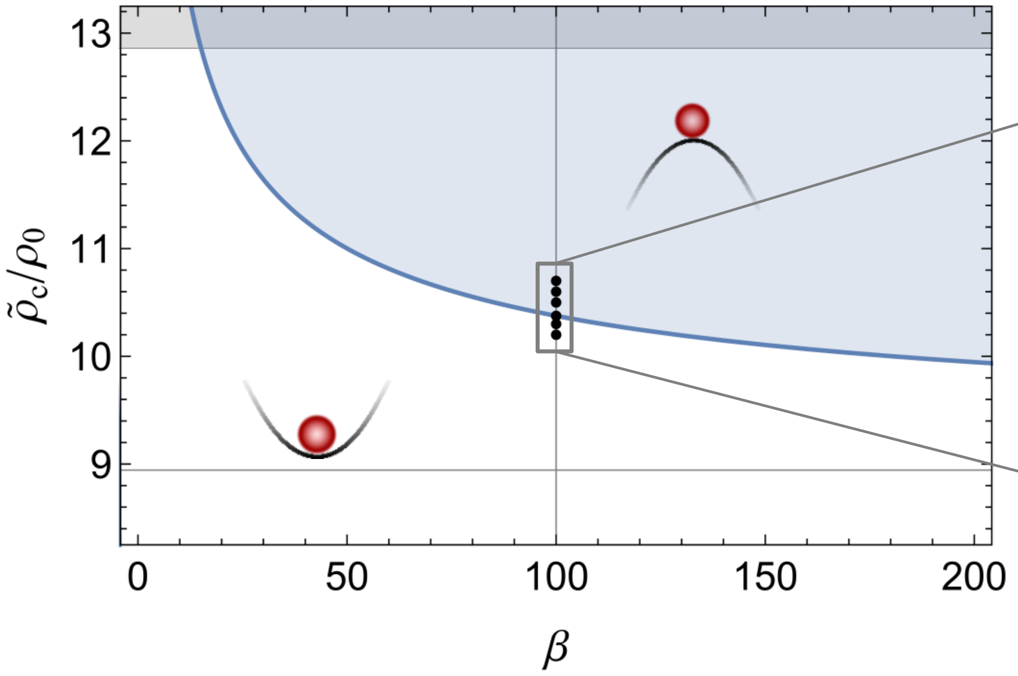




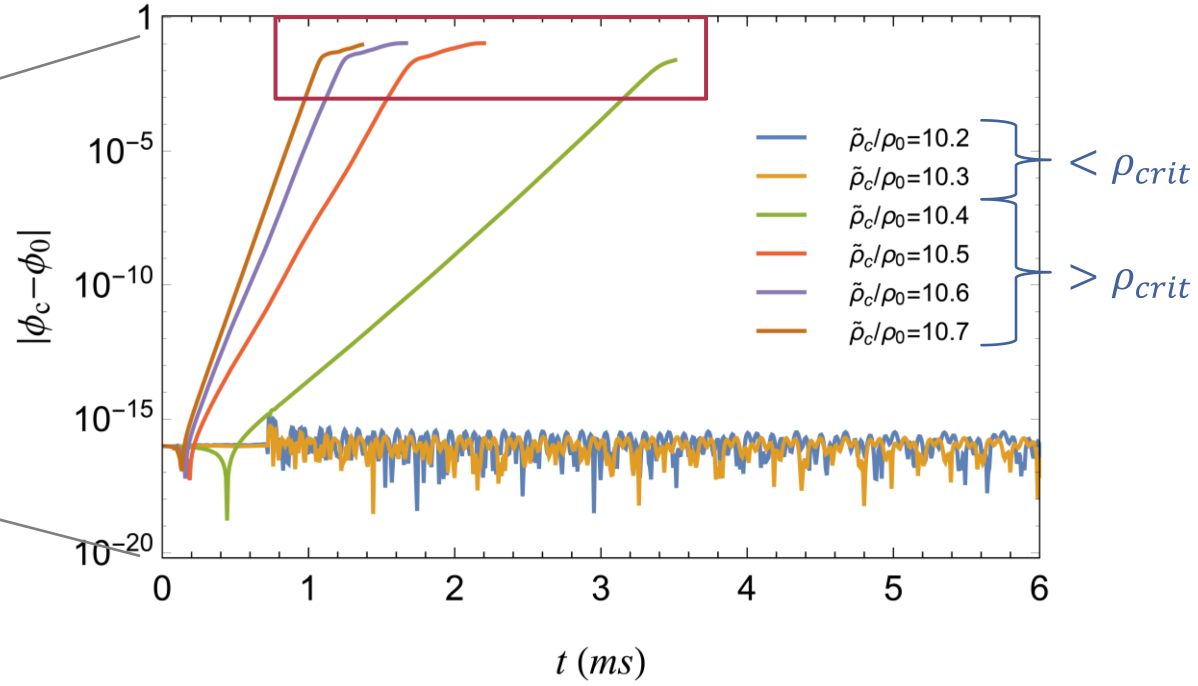
Excluded:
- red: $M_{max} < 2M_{\odot}$
- blue: $c_s > 1$

Viable:
- Gray: $T < 0$
- White: $T > 0$

LINEAR STABILITY OF GR SOLUTIONS



What is the **nonlinear development** of the instability in this case?



Equil. solution $g_{\mu\nu} = g^E_{\mu\nu}$ $\phi = \phi_0$ → Linear scalar perturbation $\phi = \phi_0 + \delta\phi$ → $\nabla_\mu \nabla^\mu \delta\phi = -4\pi\beta T \delta\phi$ → Unstable modes if $\mathrm{m}^2_{\mathrm{eff}} = -4\pi\beta T$ sufficiently negative

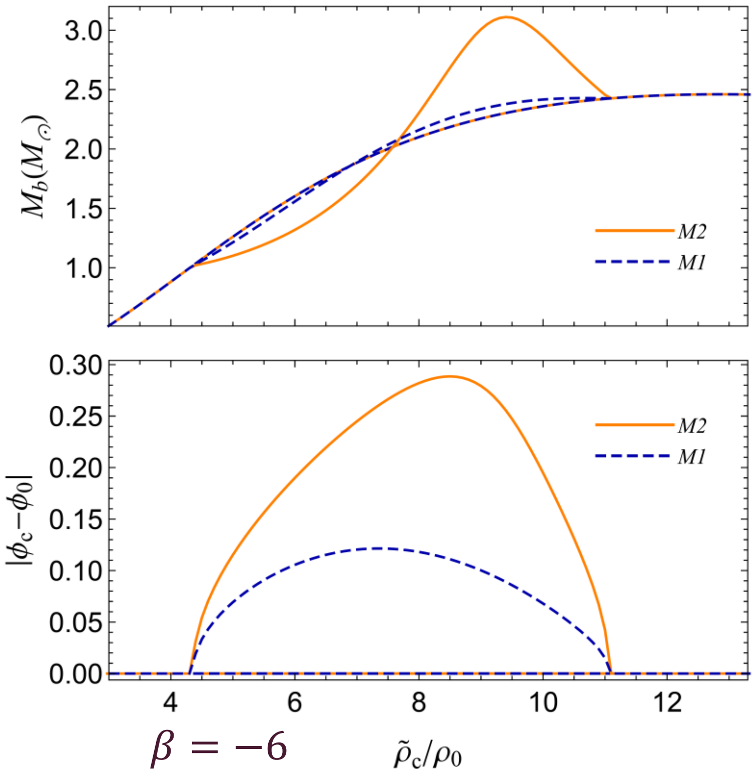
NONLINEAR DEVELOPMENT

M1: $\alpha(\phi) = \frac{1}{\sqrt{3}} \tanh[\sqrt{3}\, \beta\, (\phi - \phi_0)]$

M2: $\alpha(\phi) = \beta\, (\phi - \phi_0)$

$$\boxed{\beta < 0}$$

- GR solution unstable $\Longrightarrow$ Scalarization
  - Scalarization depends only on β
  - Details of solutions depend on $\alpha(\phi)$



$\beta = -6$

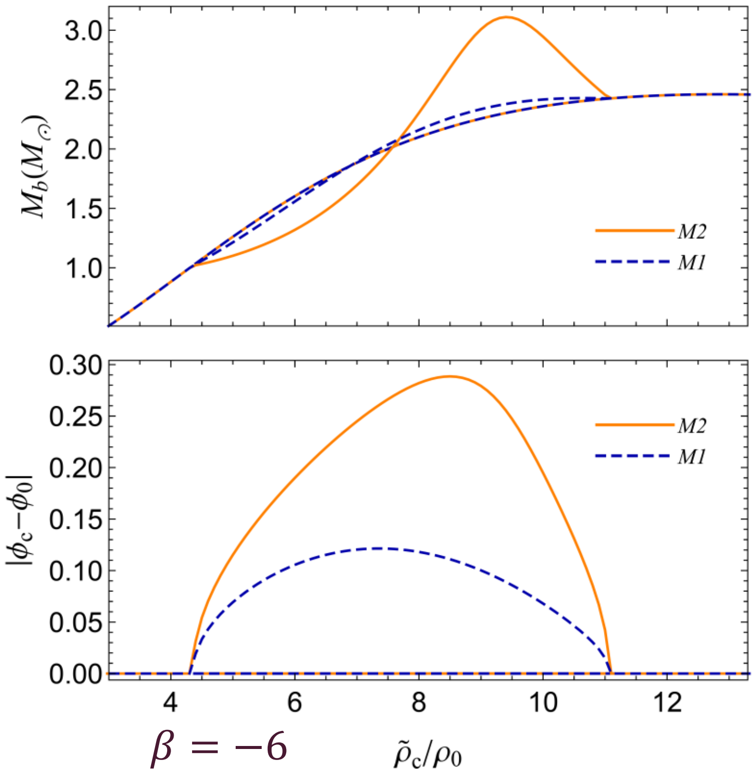
NONLINEAR DEVELOPMENT

M1: $\alpha(\phi) = \frac{1}{\sqrt{3}}\tanh[\sqrt{3}\,\beta\,(\phi - \phi_0)]$

M2: $\alpha(\phi) = \beta\,(\phi - \phi_0)$

$\beta < 0$

- GR solution unstable $\Longrightarrow$ Scalarization
  - Scalarization depends only on β
  - Details of solutions depend on $\alpha(\phi)$

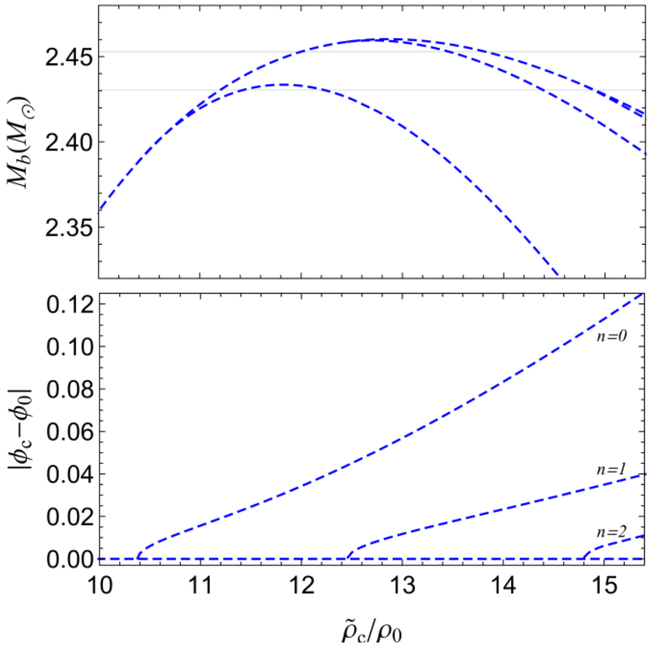


$\beta = -6$

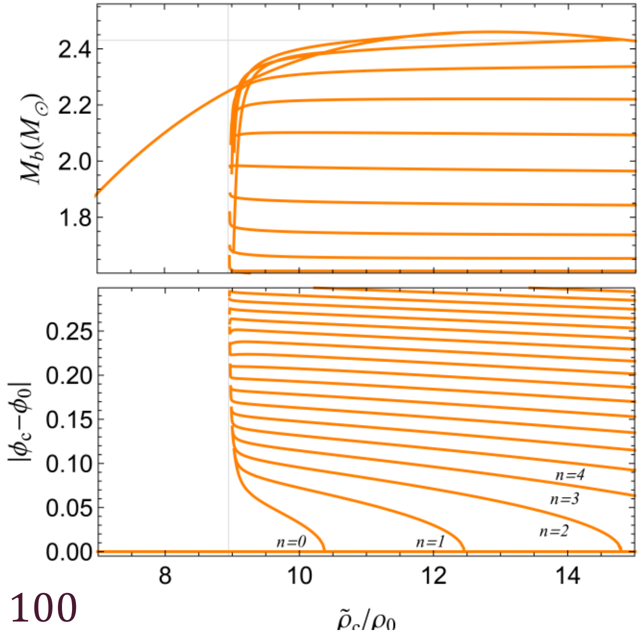
$\beta > 0$

More in N. Ortiz talk!

- GR solution unstable $\Longrightarrow$ Model-dependent outcomes!
  - **M1**: Spontaneous scalarization OR gravitational collapse (Mendes & Ortiz 2016)
  - **M2**: gravitational collapse (Palenzuela & Liebling 2016; Mendes & Ortiz 2016)

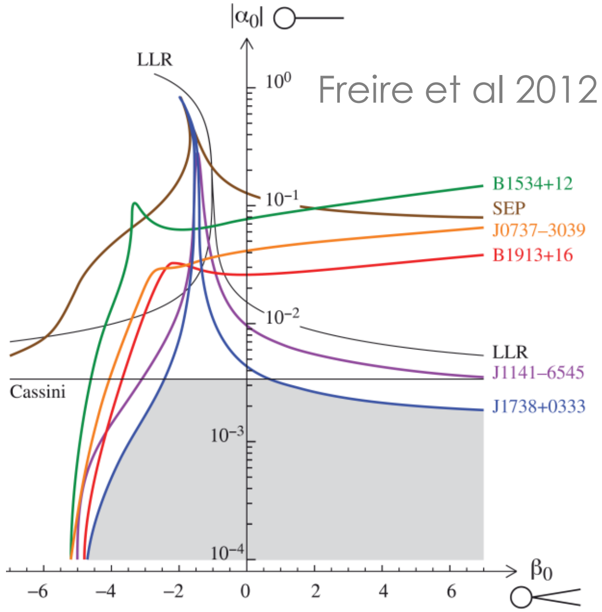


$\beta = 100$



DISCUSSION: OBSERVATIONAL CONSTRAINTS

- Current constraints on STTs with coupling function
$$\alpha(\phi) = \alpha_0 + \beta_0(\phi - \phi_0) + O[(\phi - \phi_0)^2]$$
  - Solar system: $|\alpha_0| < 3.5 \times 10^{-3}$
  - Pulsar timing: $\beta_0 > -4.5$
  - Cosmology: potentially constrains full form of $\alpha(\phi)$. (Boisseau et al. 2000)
    - Model $\alpha(\phi) = \beta\phi$ yields bad cosmology for $\beta < 0$! (Damour & Nordtvedt 1993)
- First constraints on $\beta_0 > 0$ if NS with $M/R \gtrsim 0.27$ are confirmed.
- Observational signatures:
  - Scalarization: changes in orbital dynamics, redshift of surface atomic lines, gravitational wave emission.
  - Premature gravitational collapse: mere observation of star beyond threshold compactness!
  - Dynamical scalarization (in progress)?
- Results are sensitive to the details of the coupling function!



Freire et al 2012