Strong-field gravity may hide new physics

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Gravitational Waves, Black Holes and Fundamental Physics

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Based on the work made in collaboration with Andrew Coates and Thomas Sotiriou.

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Modifications to General Relativity

General Relativity: best theory for gravity, but…

- Mostly unknown in the strong-field regime
- Quantization? Renormalization? QG theory?
- Dark energy, dark matter

Low energy theory: modified GR ⇨ New degrees of freedom

Scalar-Tensor theories

- Jordan frame

$$S_J = \frac{1}{16\pi}\int \mathrm{d}^4x\sqrt{-\tilde{g}}\left(\Phi\tilde{R} - \frac{\omega(\Phi)}{\Phi}\tilde{\nabla}^\mu\Phi\tilde{\nabla}_\mu\Phi\right) + S_m[\Psi^A, \tilde{g}_{\mu\nu}]$$

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Conformal transformation: $\tilde{g}_{\mu\nu} = B^2(\phi)g_{\mu\nu}$

Field redefinition: $\Phi = \left(G_N B^2(\phi)\right)^{-1}$

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- Einstein frame

$$S_E = \frac{1}{16\pi G_N}\int \mathrm{d}^4x\sqrt{-g}\left(R - 2\nabla^\mu\phi\partial_\mu\phi\right) + S_m[\Psi^A, B^2(\phi)g_{\mu\nu}]$$

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- Jordan frame

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Modification w.r.t. GR

- Einstein frame

$$S_E = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g} \left(R - 2\nabla^{\mu}\phi \partial_{\mu}\phi \right) + S_m[\Psi^A, B^2(\phi) g_{\mu\nu}]$$

Scalar field equation

Equation of motion of the scalar field

$$\Box\phi = -4\pi G_N T \alpha(\phi)$$

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Trace of stress-energy tensor

$$\alpha(\phi) = \frac{\mathrm{d}\log B(\phi)}{\mathrm{d}\phi}$$

Scalar field equation

Equation of motion of the scalar field

$$\Box\phi = -4\pi G_N T\alpha(\phi)$$

Expanding $\alpha(\phi)$ around ϕ_0, a constant solution of the equation

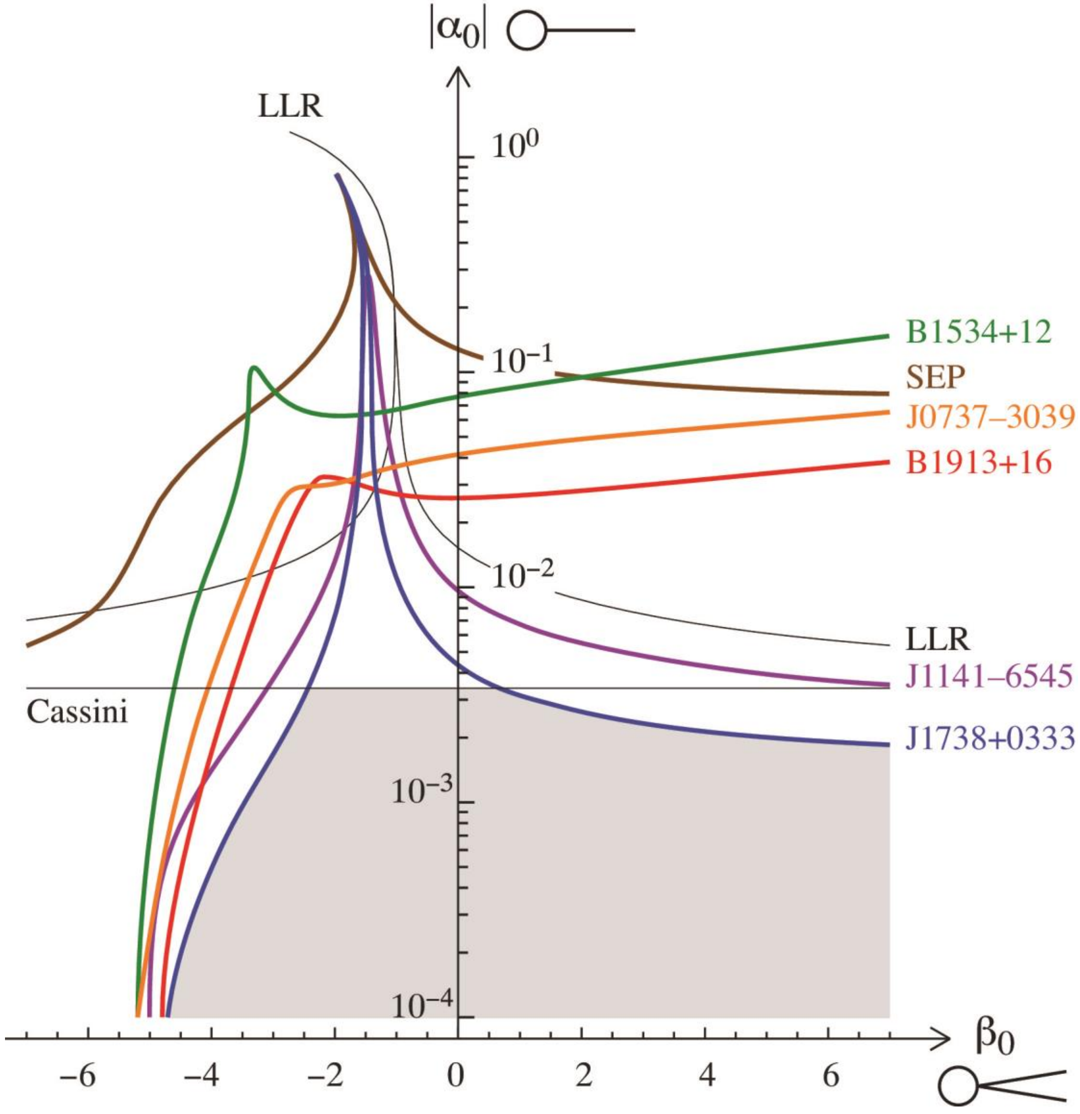
$$\alpha(\phi) = \alpha_0 + \beta(\phi - \phi_0) + \ldots$$

Scalar field constraints

Parameter constraints

$$\alpha(\phi) = \alpha_0 + \beta(\phi - \phi_0) + \ldots$$

For the purposes of calculations
we can set $\alpha_0 = 0$



[Freire, et al., 2012]

Spontaneous scalarization

$$\Box\phi = m_{\rm eff}^2\,\phi$$

$$m_{\rm eff}^2 = -4\pi G_N T\beta < 0 \qquad \text{if} \qquad \beta < 0$$

Spontaneous scalarization

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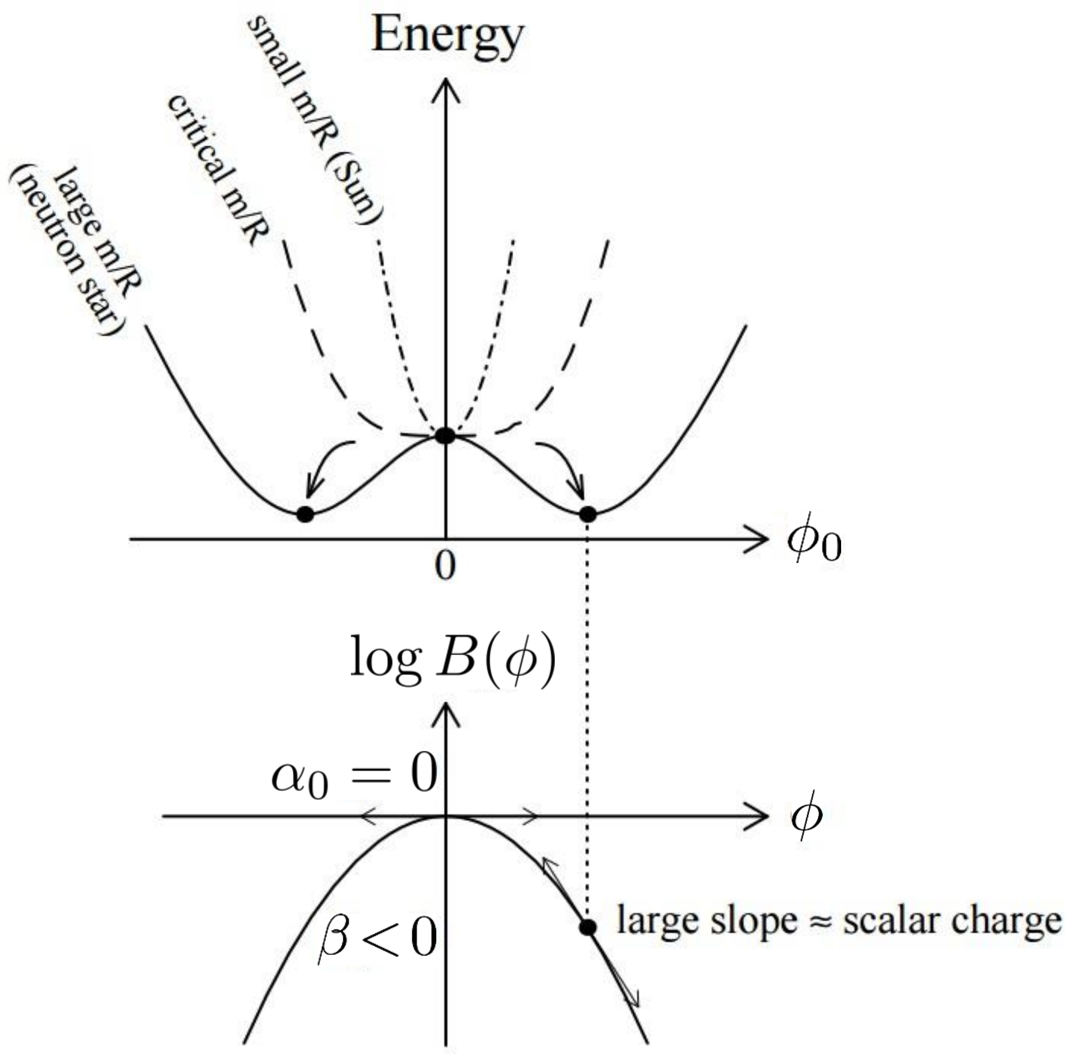
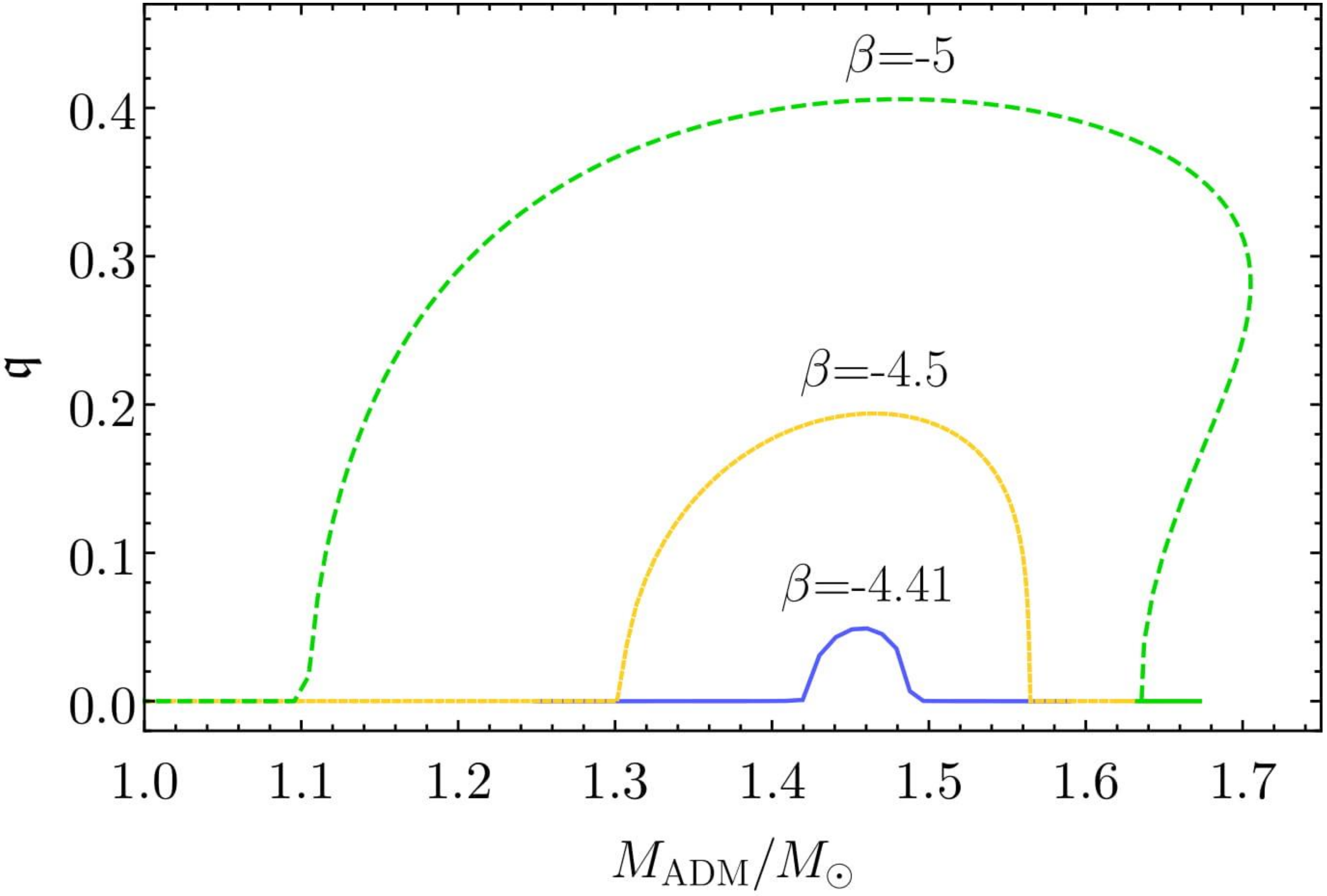
Spontaneous scalarization:

- Instability suppressed
- High density
- Phase transition
- $\beta \lesssim -4$



[Esposito-Farese, 2004]

Spontaneous scalarization



Normalized scalar field charge

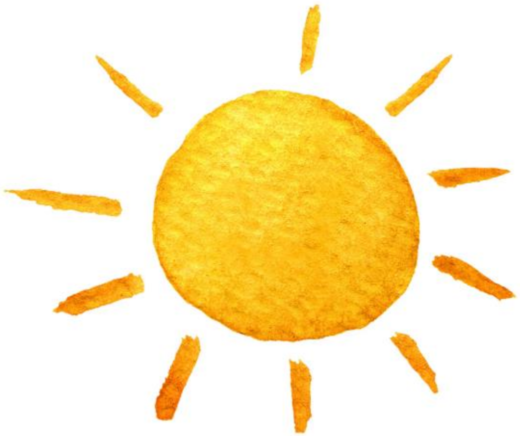
Spontaneous scalarization

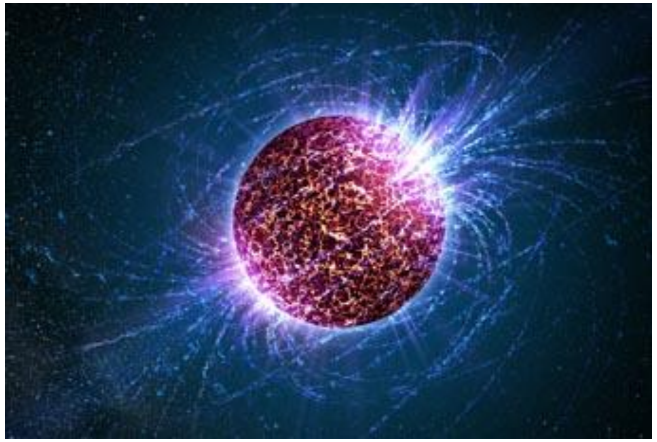
Solar mass star
No scalarization

Phase transition

Avoid constraints

Dense neutron star
Scalarization



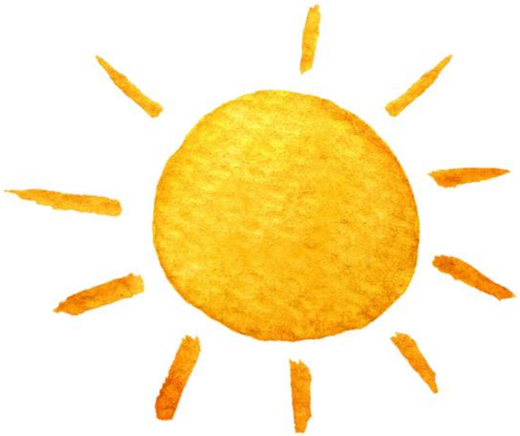


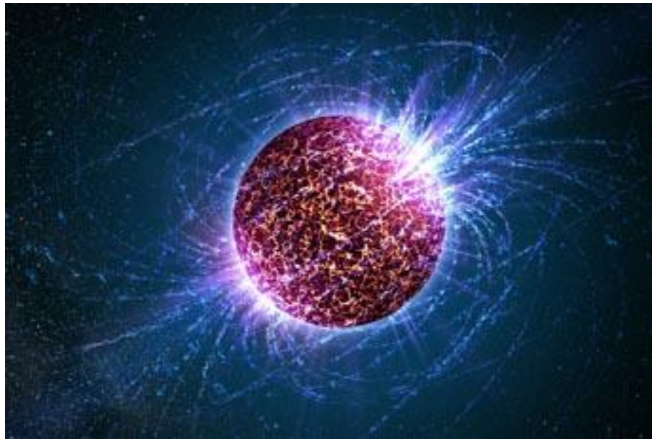
Spontaneous scalarization

Solar mass star
No scalarization

Phase transition
←
Screening new physics

Dense neutron star
Scalarization
New interactions?





New physics in scalarized neutron stars

We notice that:

- Screening of new gravity effects
- Screening of new interactions

Are not in contrast if:

- Scalarization goes through
- New interaction suppressed away from scalarized star

New physics in scalarized neutron stars

Toy model: scalar field + EM

$$S_E = \int \mathrm{d}^4x\sqrt{-g}\left(\frac{R}{4} - \frac{1}{2}g^{\mu\nu}\overline{D_\mu\phi}D_\nu\phi\right) +$$

$$-\frac{1}{4}\int \mathrm{d}^4x\sqrt{-g}F_{\mu\nu}F^{\mu\nu} + S_m[\Psi^A; B^2(\bar{\phi}\phi)g_{\mu\nu}; A_\mu]$$

New physics in scalarized neutron stars

Toy model: scalar field + EM

$$D_\mu = \partial_\mu - \mathrm{i}eA_\mu$$

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$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

Properties of the model

- U(1) gauge invariance $\phi \to \phi\, \mathrm{e}^{\mathrm{i}e\lambda}, \quad A_\mu \to A_\mu + \partial_\mu \lambda$
  - Gauge with $\phi = \bar{\phi}$

- Photon mass $m_\gamma^2 = \dfrac{e^2}{4\pi}\phi^2$ ⟶ Gravitational Higgs

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Build a neutron star:

- Spherical symmetry
- Neutral matter
- Spontaneous scalarization required

$$(\Box - e^2 A^\mu A_\mu)\phi = -4\pi G_N T \beta \phi$$

Terms which can spoil scalarization

Neutron star solution

- $A_\mu = 0$ everywhere
- Neutron star neutral
- Scalarization goes through

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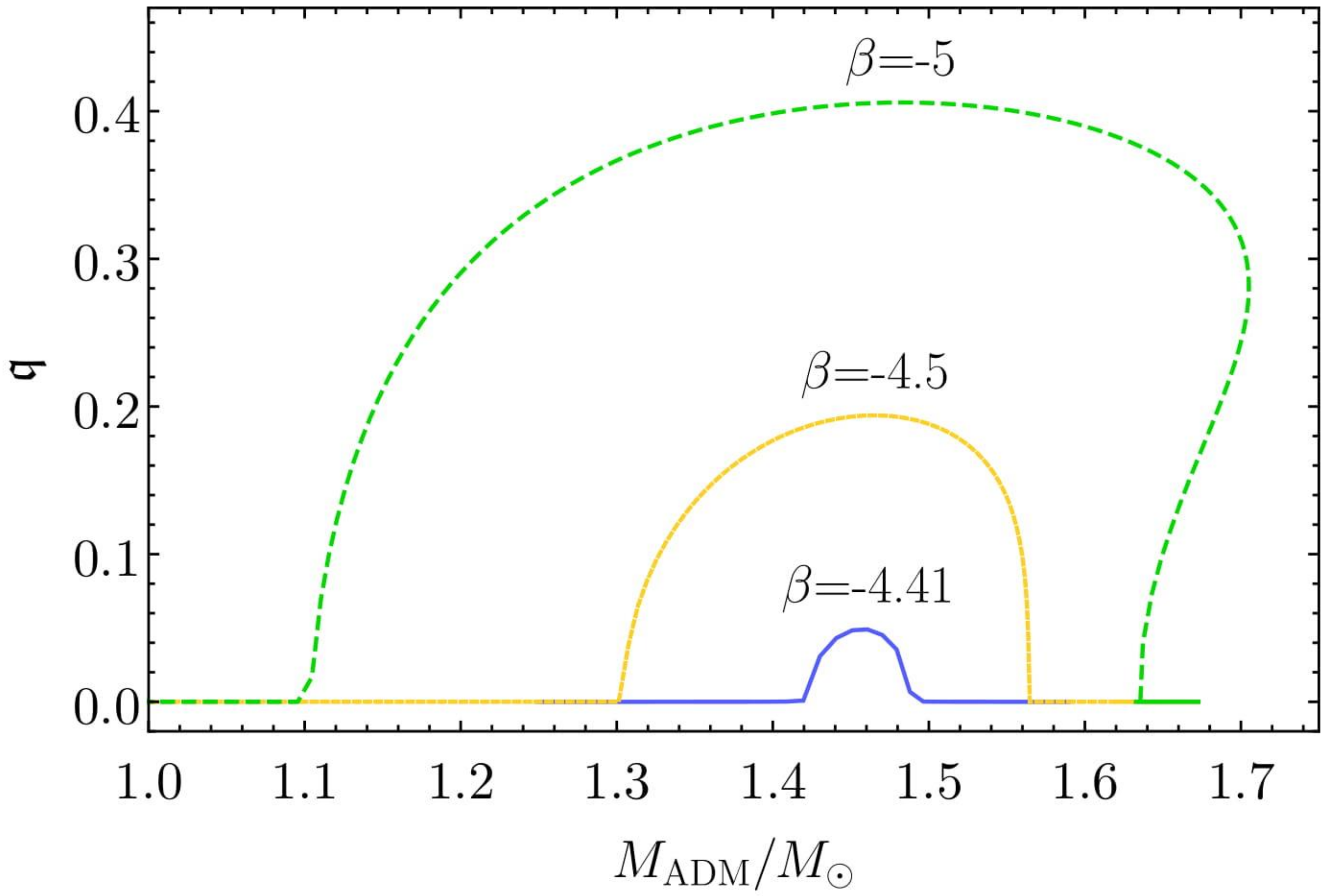
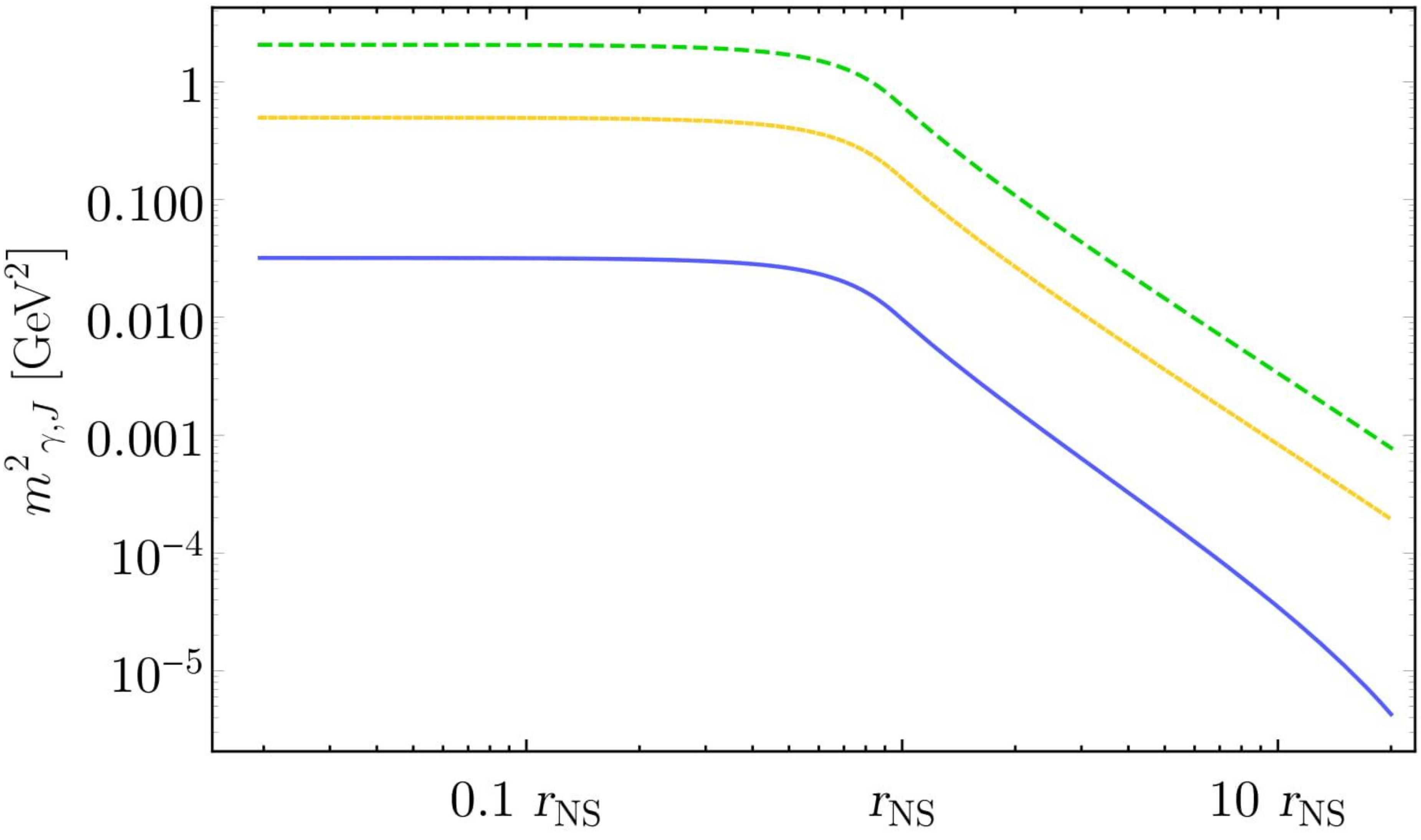


[NF, Coates, Sotiriou, 2017]

Neutron star solution

Coupling charge $e = 10^{-36}\,\mathrm{C}$



[NF, Coates, Sotiriou, 2017]

Conclusions

Main results from the toy model:

- Scalarization occurs
- Extremely powerful effect

For the future:

- Model with more realistic matter
- Generalise with a ϕ-dependent Equation of State
- Smoking gun: stars with different density have different EOS

Thanks for the attention =D

Back-up slides - No EM hair

Spherically symmetric EM field

$$A_\mu = (A_0(r), A_1(r), 0, 0)$$

Maxwell equations

$$\nabla^\mu F_{\mu\nu} = m_\gamma^2 A_\nu \quad \Rightarrow \quad A_1(r) = 0$$

Contracting and integrating

$$\int_{\mathcal{V}} \mathrm{d}^4x \sqrt{-g} \left(A^\nu \nabla^\mu F_{\mu\nu} - m_\gamma^2 A^\nu A_\nu \right) = 0$$

Back-up slides - No EM hair

Integrating by parts

$$\int_{\mathcal{V}} \mathrm{d}^4x \sqrt{-g} \left(\frac{F^{\mu\nu} F_{\mu\nu}}{2} + m_\gamma^2 A^\nu A_\nu \right) = \int_{\partial\mathcal{V}} \mathrm{d}^3\sigma \, n^\mu A^\nu F_{\mu\nu}$$

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In our gauge

$$g^{tt}A_0\partial_r A_0$$

Vanishes on the boundary

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