Spontaneous scalarization and heavy neutron stars

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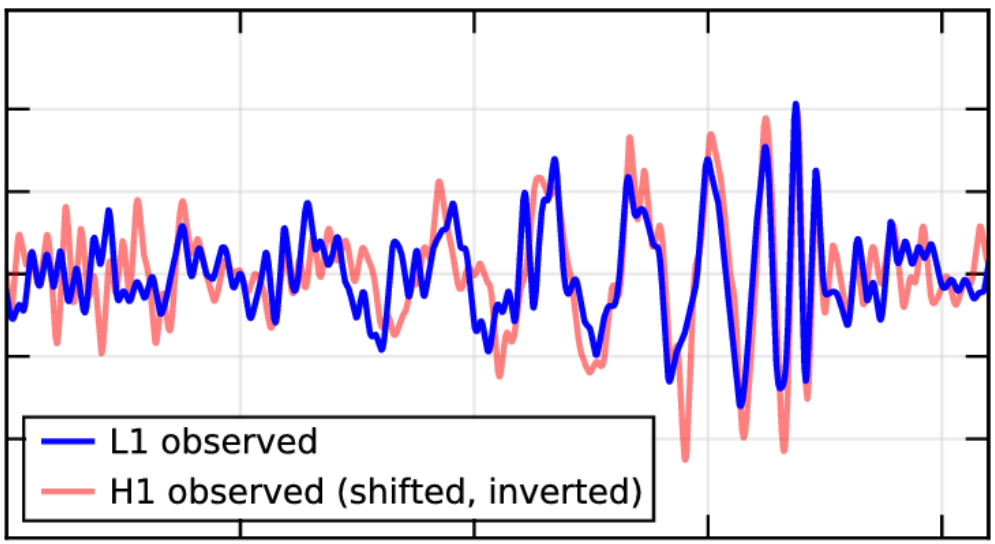
S.Morisaki and TS, PRD 96, 084026 (2017) [arXiv:1707.02809]

Introduction

Testing gravity at extreme density has become possible!

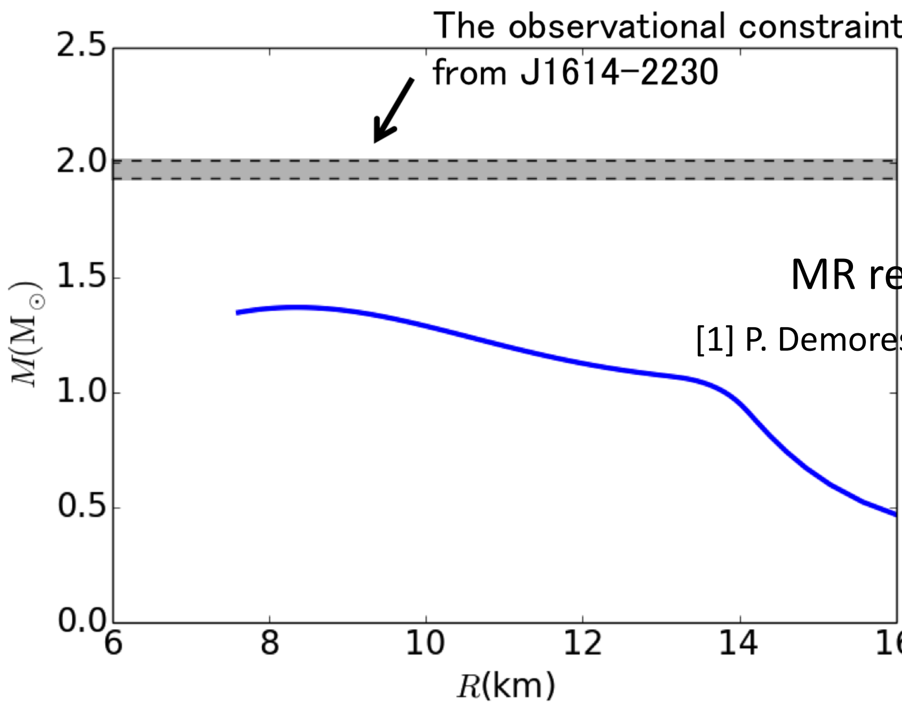
Livingston, Louisiana (L1)



Have we already found evidence for non-GR?

2M$_\odot$ Neutron Star

It is difficult to explain the existence of 2M$_\odot$ NS [1] if the effect of strange hadrons is taken into account.



MR relation with GS1 EOS

[1] P. Demorest *et al.*, Nature **467**, 1081(2010).

hyperon puzzle

Two possibilities

- Not complete understanding of nuclear matter

- GR is not correct

(Simplest) scalar-tensor theory

Physical metric

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

Including us

We feel $A^2(\phi)g_{\mu\nu}$ as our metric.

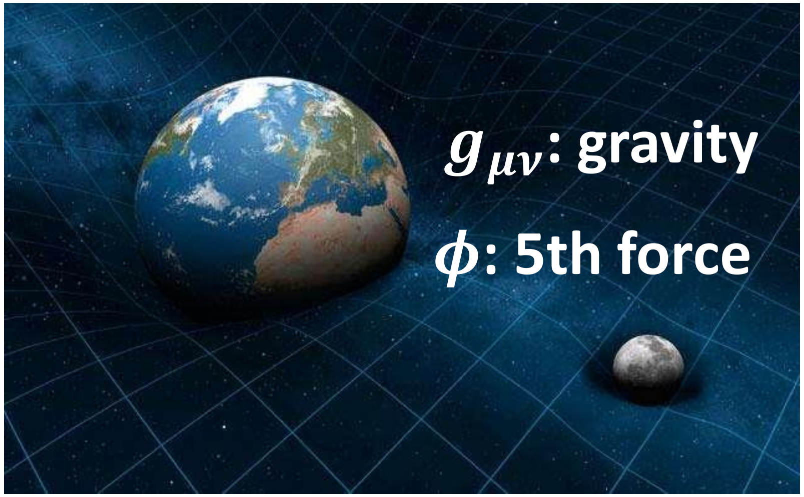
Universal coupling $A^2(\phi)$

may arise from non-minimal coupling between ϕ and $g_{\mu\nu}$.

$$S = \int d^4x \sqrt{-\tilde{g}} \left(\frac{\tilde{R}}{16\pi G} + f(\phi)\tilde{R} - \frac{1}{2} \tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi) \right) + S_m[\psi_m, \tilde{g}_{\mu\nu}]$$

I do not consider the origin of the universal coupling.

That we feel both $g_{\mu\nu}$ and ϕ means that we source $g_{\mu\nu}$ and ϕ.



Field equations

$$G_{\mu\nu} = 8\pi G \left[-\left(\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2} m_\phi^2 \phi^2 \right) g_{\mu\nu} + \partial_\mu \phi \partial_\nu \phi + \underline{A^2(\phi)} \tilde{T}_{\mu\nu} \right],$$

$$\Box_g \phi - \frac{dV_{\text{eff}}}{d\phi} = 0, \quad V_{\text{eff}} \equiv \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{4} \tilde{T} A^4(\phi).$$

The value ϕ depends on the environment(=$\tilde{T}$).

The effective gravitational constant ($GA^2(\phi)$) depends on the environment ($\phi = 0$ is GR).

Spontaneous scalarization

Damour&Esposite-Fareese 1993

$$\nabla^2\phi - \frac{d}{d\phi}V_{eff} = 0$$

from the conformal coupling

$$V_{eff} = \frac{m_\phi^2}{2}\phi^2 - \frac{T}{4}A^4(\phi) \approx \frac{m_\phi^2}{2}\phi^2 + \frac{\rho}{4}A^4(\phi)$$

ρ: energy density of matter

Around $\phi = 0$, approximating $A^2(\phi) \approx 1 + \frac{1}{2}A^{2''}(0)\phi^2$, we have

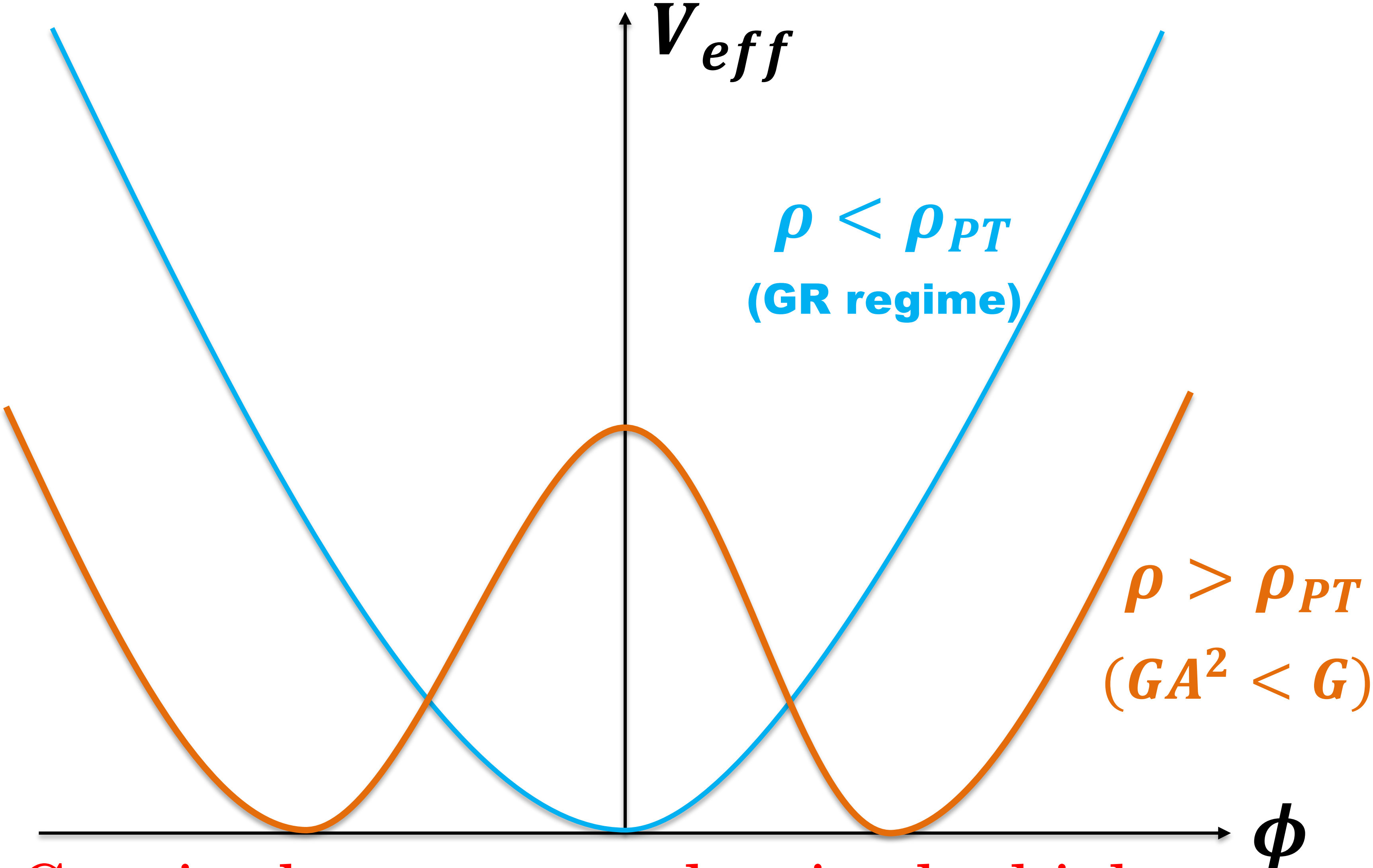
$$V_{eff} \approx \frac{\rho}{4} + \frac{1}{2}\left(m_\phi^2 + \frac{\rho}{2}A^{2''}(0)\right)\phi^2 + \ldots$$

If $A^{2''}(0) < 0$, then $\phi = 0$ becomes unstable for

$$\boldsymbol{\rho > \rho_{PT} = \frac{2m_\phi^2}{-A^{2''}(0)}}$$

and symmetry breaking occurs (**Spontaneous scalarization**).

Spontaneous scalarization



Gravity becomes weaker in the high density region.

Previous researches

☑ $m_\phi = 0$ [1]

△Stringent constraints from binary pulsar[2]

△GR is not cosmological attractor.

$m_\phi \neq 0$ [4]

◎ GR is cosmological attractor

◎ Oscillating ϕ behaves as dark matter

☑ $\lambda_\phi \equiv m_\phi^{-1} > 100\mathrm{km}$ [3]

☐ $\boldsymbol{\lambda_\phi \lesssim R_{NS} \sim 10\mathrm{km}}$

this talk

[1]:T. Damour and G. Esposito-Farese, Phys. Rev. Lett., **70**, 2220 (1993).
[2]:J. Antoniadis *et al*., Science **340**, 6131 (2013).
[3]:F. M. Ramazanoglu and F. Pretorius, Phys. Rev. D **93**, 064005 (2016).
[4]:P. Chen, TS, and J. Yokoyama, Phys. Rev. D **92**, 124016 (2015).

What we did in this study

S.Morisaki and TS 2017

We investigated the structure of non-spinning NSs in this model for $\lambda_\phi \lesssim 10$ km.

The parameters in this model are

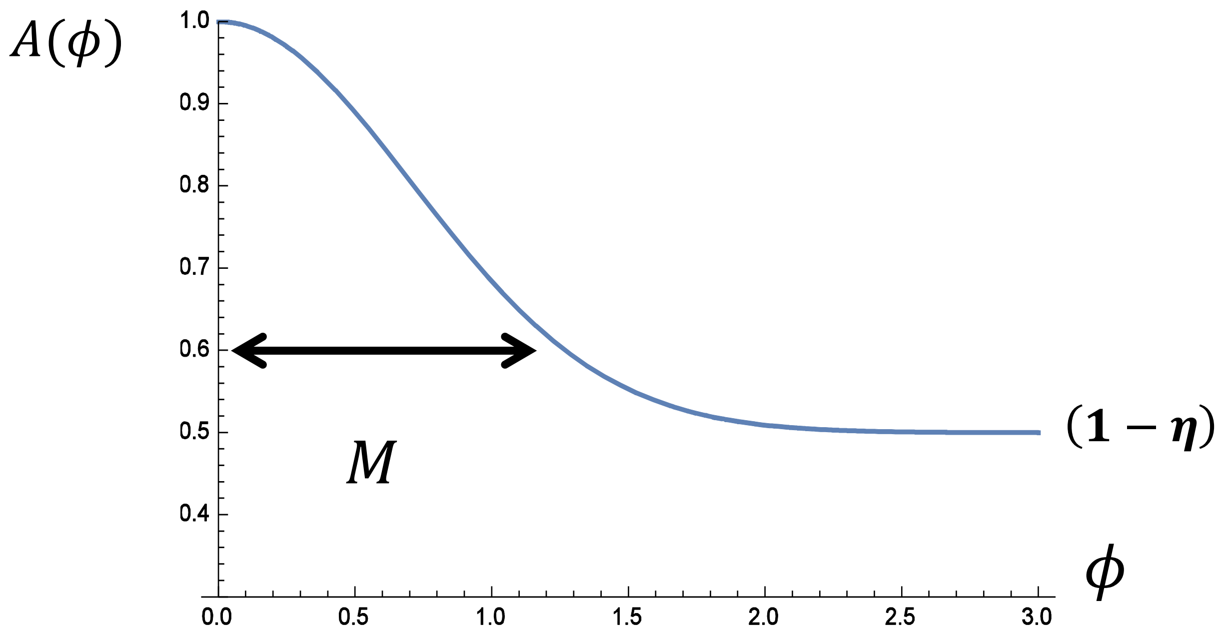
$\boldsymbol{\eta}$: How significantly gravity is weakened

$\boldsymbol{\rho_{PT}}$: Critical density for symmetry breaking

$\boldsymbol{\lambda_\phi}$: Compton wavelength

Functional form of $A^2(\phi)$ (phenomenological)

$$A^2(\phi) = 1 - \eta + \eta \exp\left[-\frac{\phi^2}{2M^2}\right], \; 0 < \eta < 1.$$

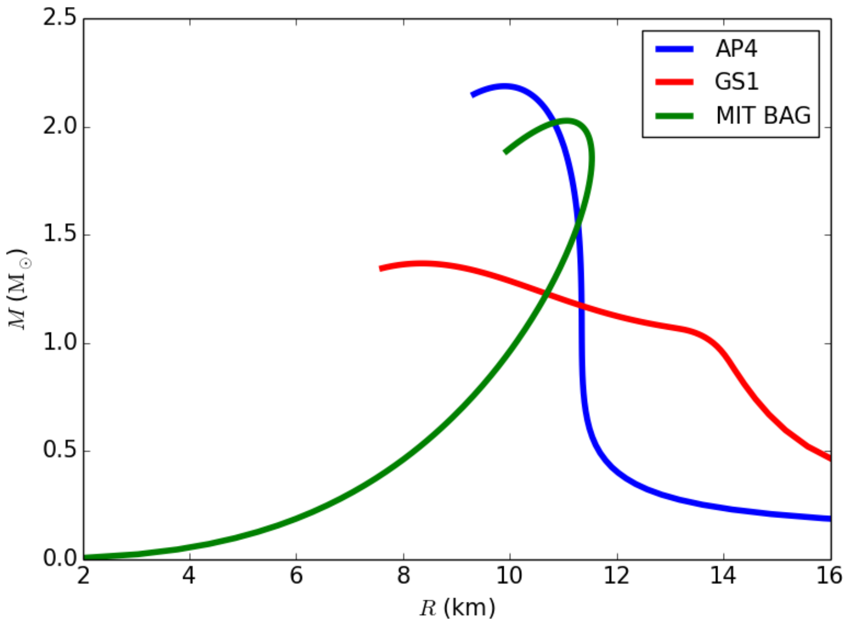


$G_{eff} = G$ for low density

$G_{eff} = (1-\eta)G$ for high density.

Equations of state (EOSs)

- npeμ → AP4 EOS [1]
- With strange hadrons → GS1 EOS [1]
  Our main target
- Strange quark matter → MIT BAG model [2]



Mass-Radius for various EoSs

[1]:J. S. Read et. al., Phys. Rev. D **79**, 124032 (2009). [2]A. Chodos et. al., Phys. Rev. D**9**, 3471 (1974).

Modified TOV equations

Static and spherically symmetric configuration

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -\mathrm{e}^{\nu(r)}dt^2 + \frac{dr^2}{1-\frac{2\mu(r)}{r}} + r^2 d\Omega^2,\ \phi = \phi(r),\ \tilde{p} = \tilde{p}(r),\ \tilde{\epsilon} = \tilde{\epsilon}(r).$$

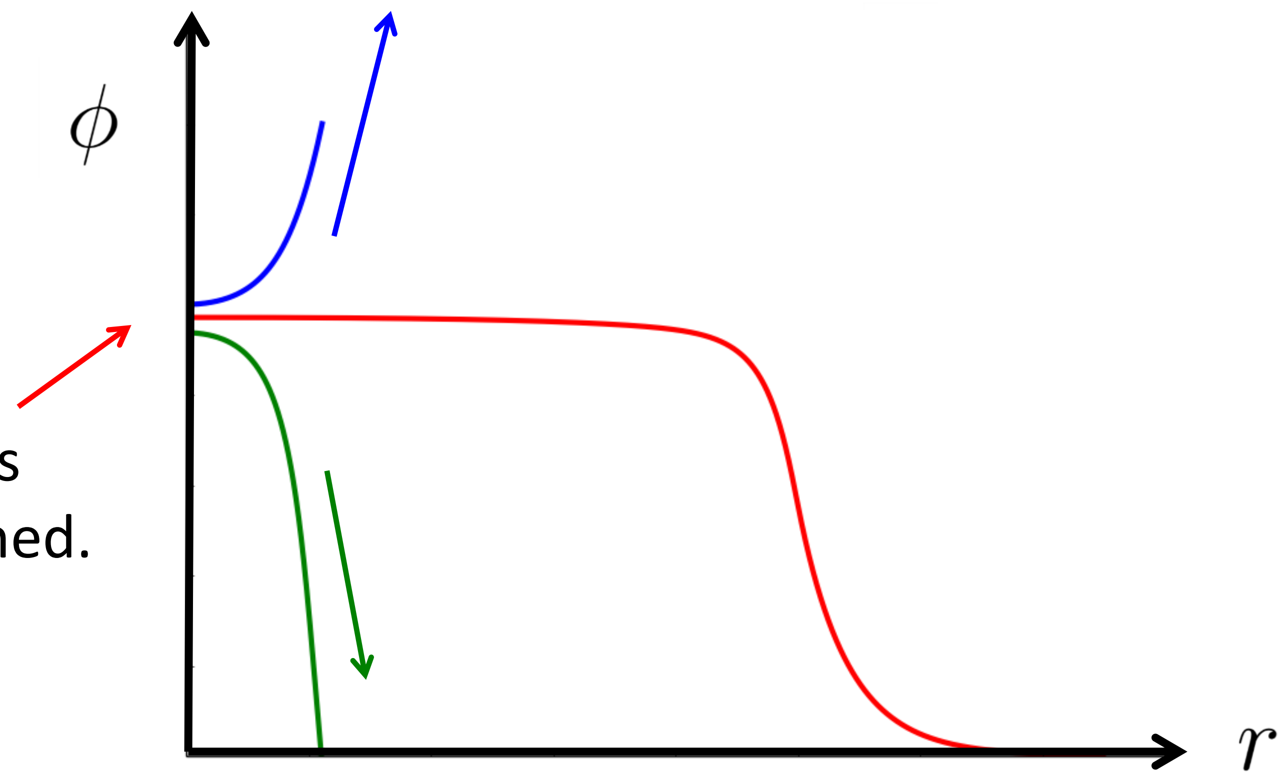
$$\rightarrow \left\{ \begin{aligned} \frac{d\mu}{dr} &= 2\pi G\left(r(r-2\mu)\left(\frac{d\phi}{dr}\right)^2 + r^2 m_\phi^2\phi^2\right) + 4\pi G A^4(\phi) r^2\tilde{\epsilon}, \\ \frac{d\nu}{dr} &= 4\pi G r\left(\frac{d\phi}{dr}\right)^2 + \frac{1}{r(r-2\mu)}\left(8\pi G r^3 A^4(\phi)\tilde{p} - 4\pi G r^3 m_\phi^2\phi^2 + 2\mu\right), \\ \frac{d\tilde{p}}{dr} &= -(\tilde{\epsilon}+\tilde{p})\left(\frac{1}{2}\frac{d\nu}{dr} + \underbrace{\frac{d\ln A(\phi)}{dr}}_{\text{Scalar force contribution}}\right), \\ (r-2\mu)\frac{d^2\phi}{dr^2} &= -2\left(1-\frac{\mu}{r}\right)\frac{d\phi}{dr} + m_\phi^2\left(4\pi G r^2\phi^2\frac{d\phi}{dr} + r\phi\right) \\ &\quad + rA^4(\phi)\left(4\pi G r(\tilde{\epsilon}-\tilde{p})\frac{d\phi}{dr} + \alpha(\tilde{\epsilon}-3\tilde{p})\right). \end{aligned} \right.$$

Boundary conditions

There is only one free parameter (neutron star mass)

$$\mu(0)=0,\ \nu(0)=0,\ \tilde{p}(0)=\tilde{p}_c,\ \phi'(0)=0,\ \lim_{r\to\infty}\phi(r)=0.$$

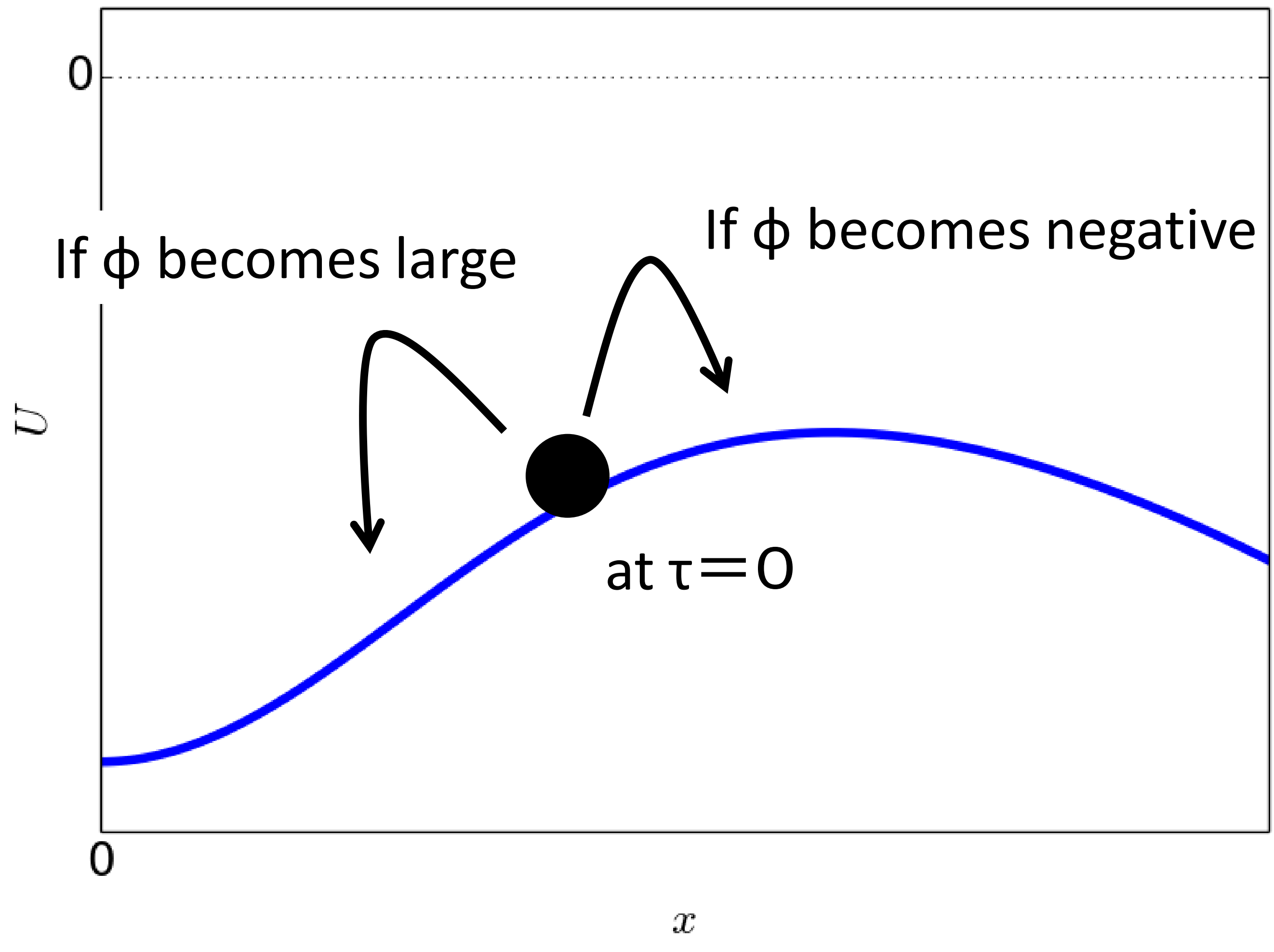
Non-singularity at r=0



Initial values must be tuned.

Mildly massive case($10\ \mathrm{km} \geq \lambda_\phi \gtrsim 1\ \mathrm{km}$)

We used the shooting method.



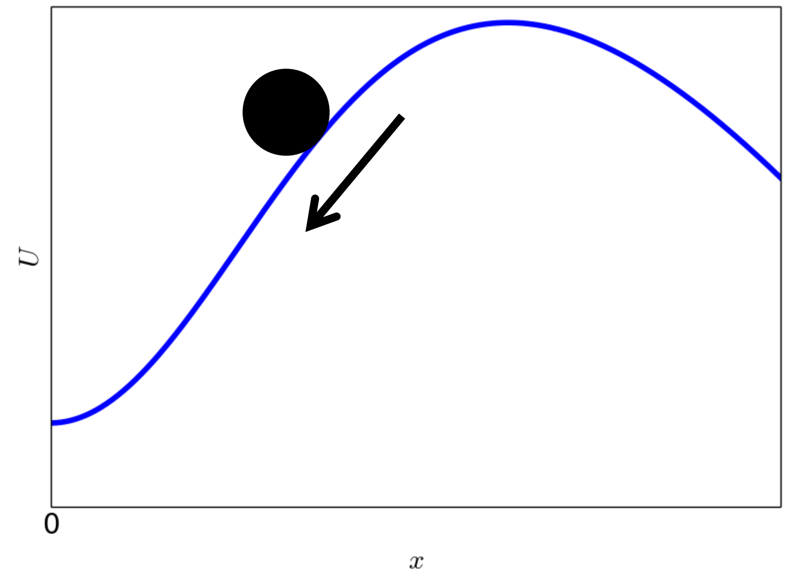
Very massive case ($\lambda_\phi \ll 1$km)

Numerical integration becomes difficult.

Numerical error grows exponentially.

$$\propto \exp\left[C\frac{r}{\lambda_\phi}\right]$$

with $C = \mathcal{O}(1)$.



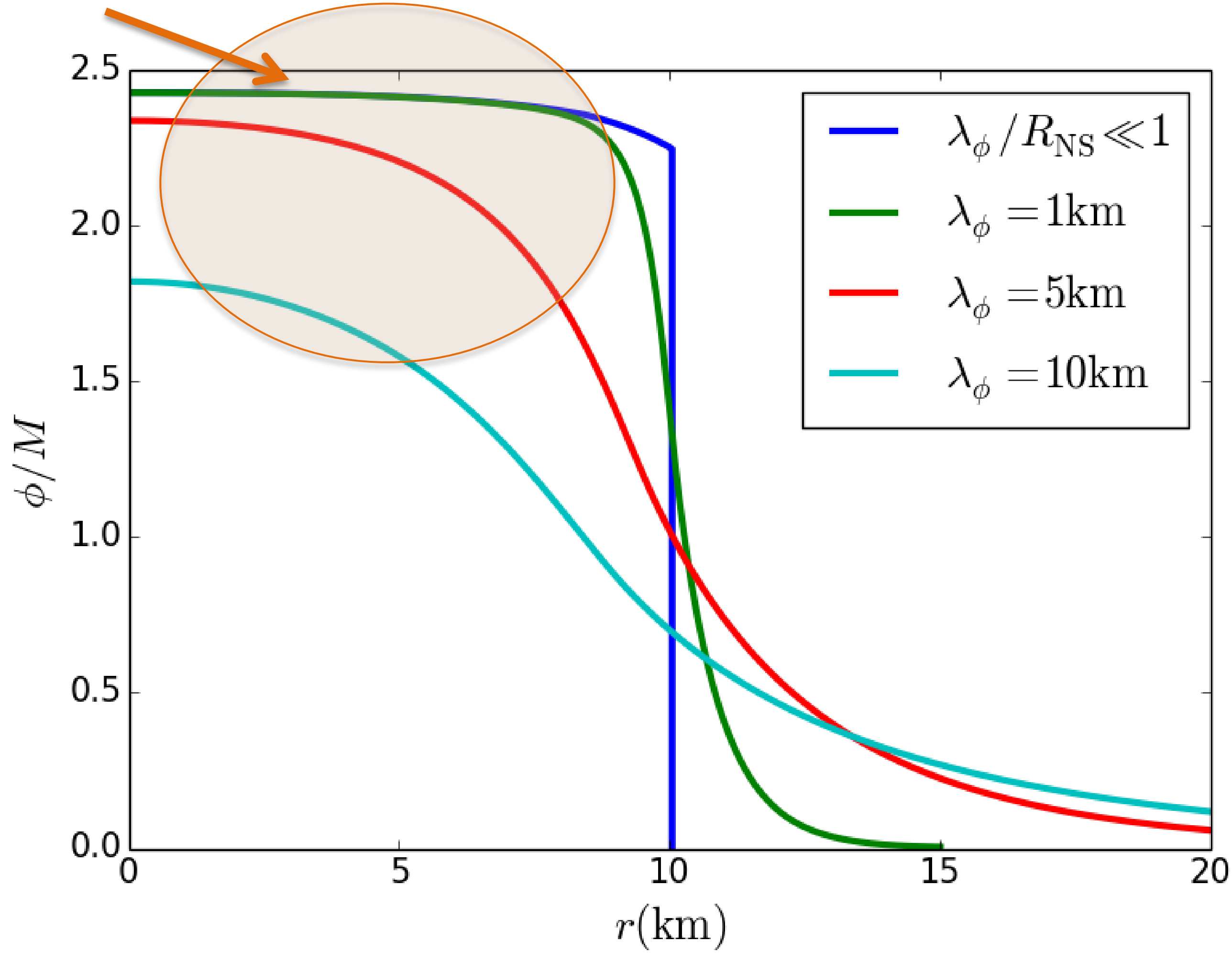
We have invented a semi-analytical method to solve this problem.

Results

Profile of ϕ

Scalarization phase

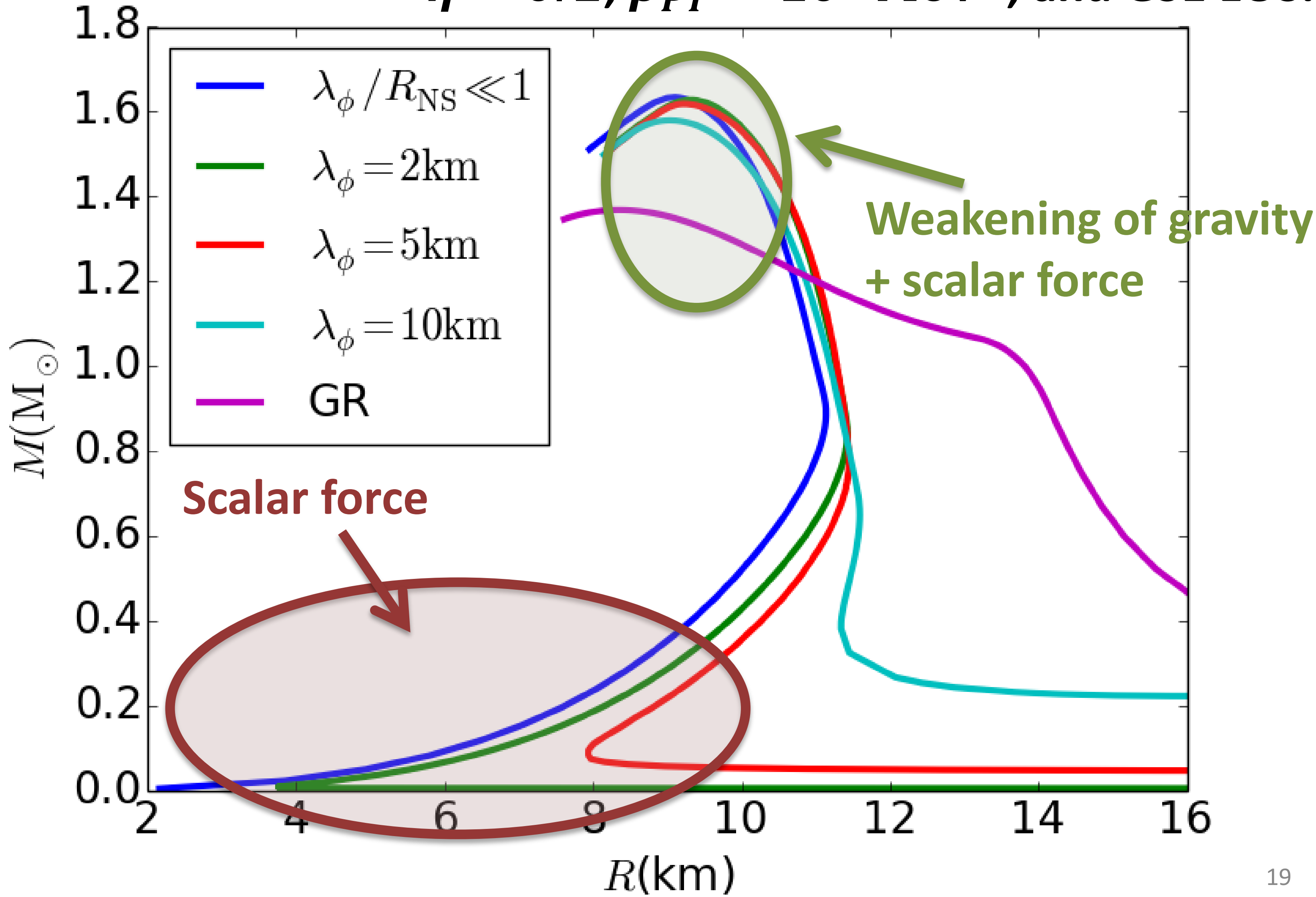
For $\eta = 0.2,\ \rho_{\rm PT} = 10^8\ {\rm MeV}^4,$ and AP4 EOS.



The semi-analytical result approximates the numerical results for short Compton wavelength.

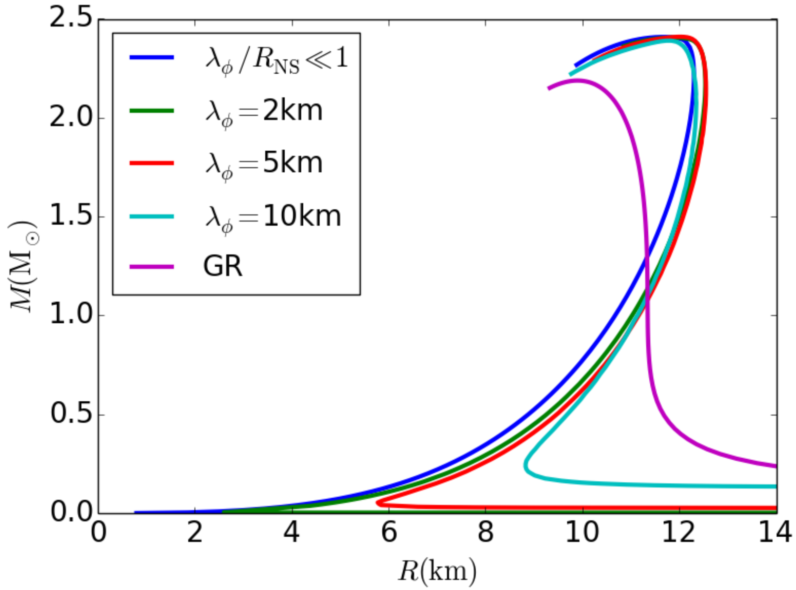
Mass-radius relation

$\eta = 0.2$, $\rho_{PT} = 10^8\ \mathrm{MeV}^4$, and GS1 EOS.

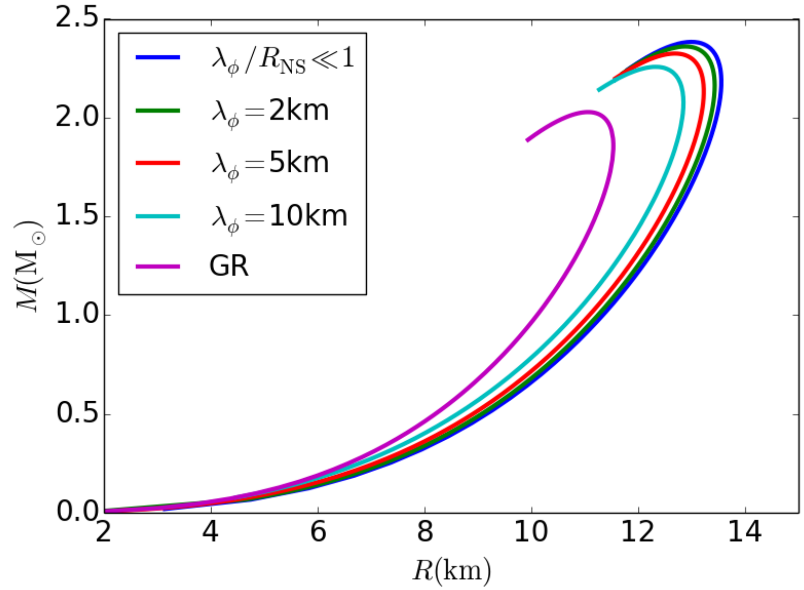


MR relation for other EOSs

The qualitative feature does not change for the other EOSs.



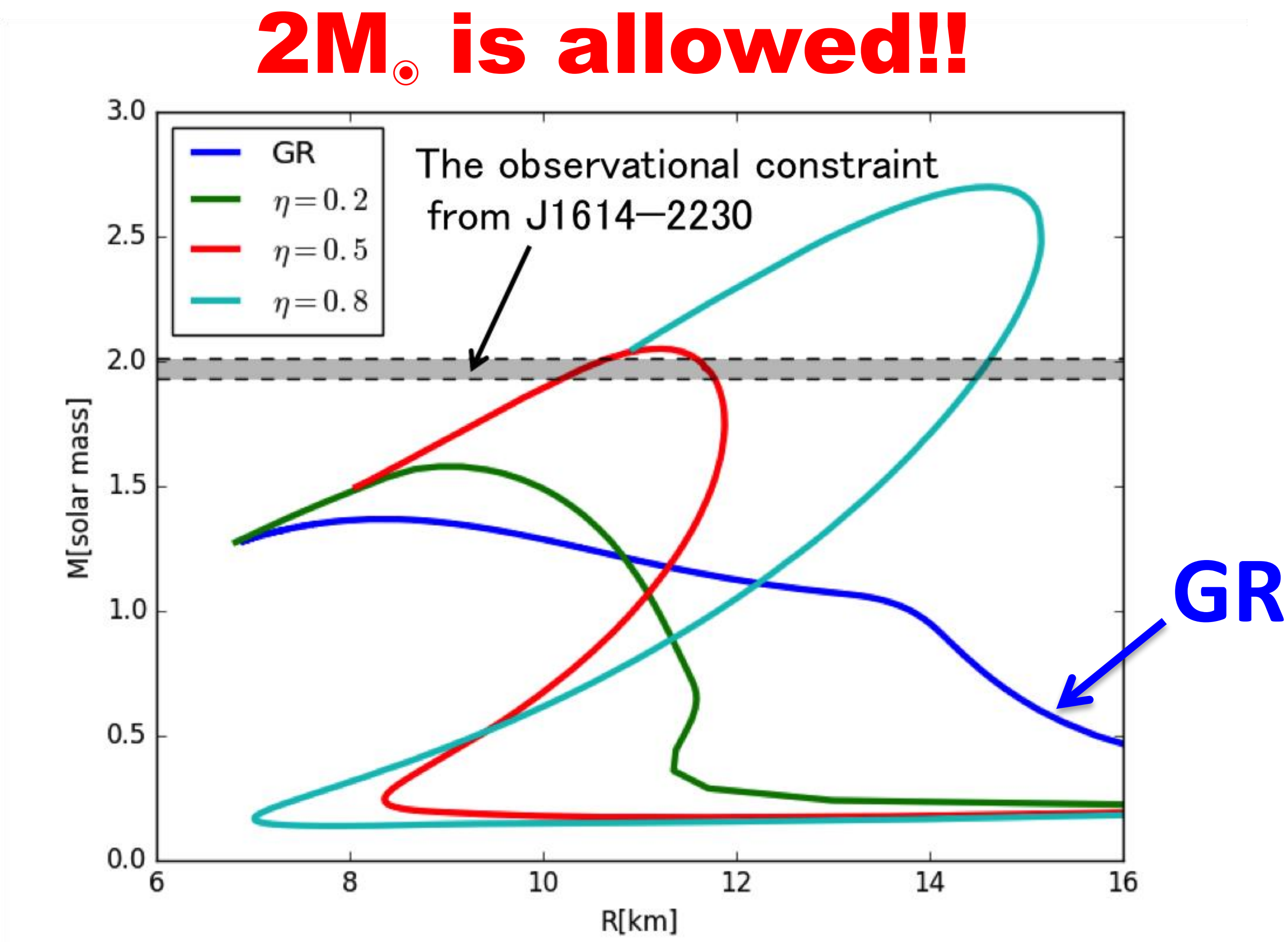
[a] AP4 EOS



[b] MIT BAG model

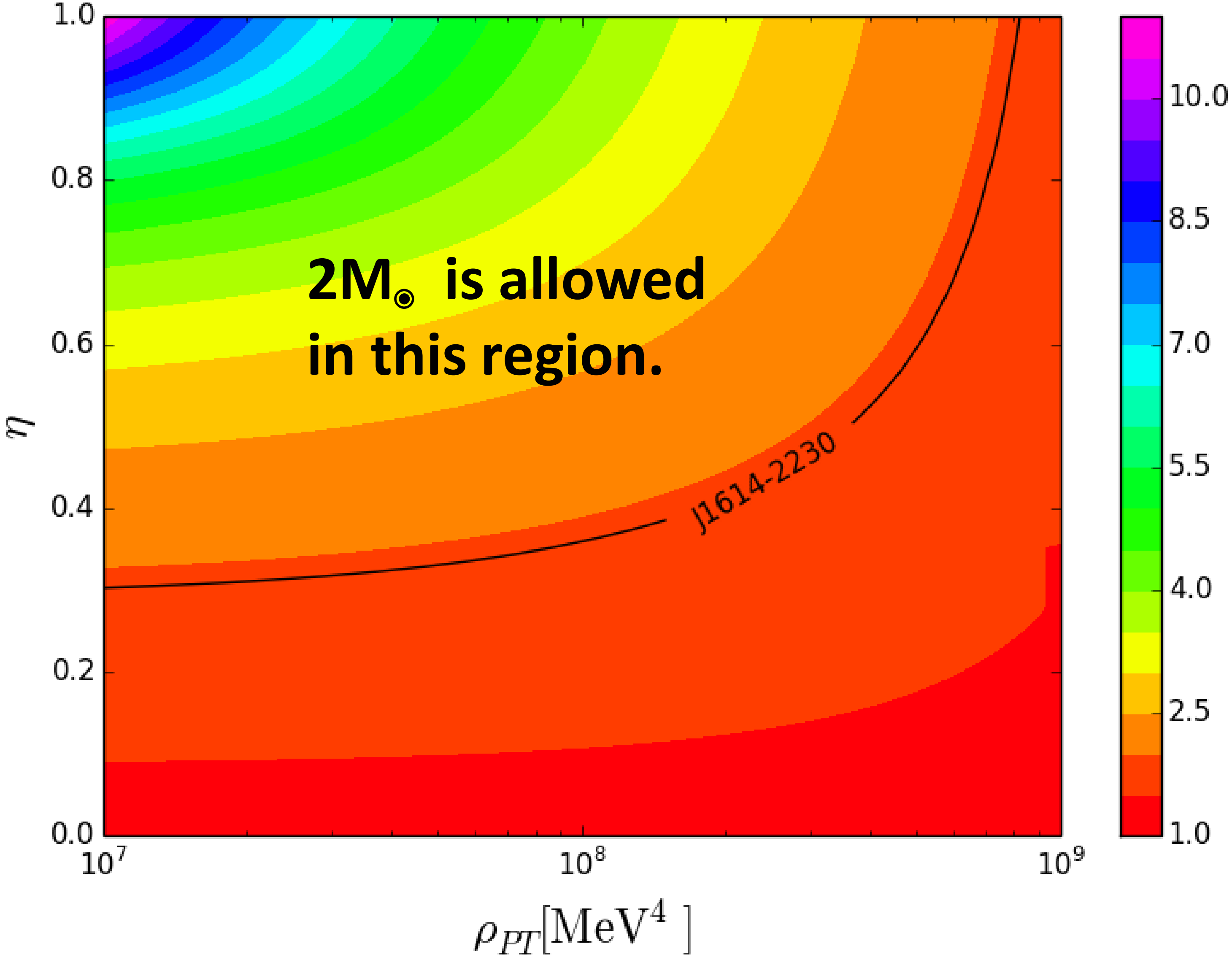
$$\text{For } \eta = 0.2, \ \ \rho_{\mathrm{PT}} = 10^8 \ \mathrm{MeV}^4.$$

Existence of $2M_\odot$ NS

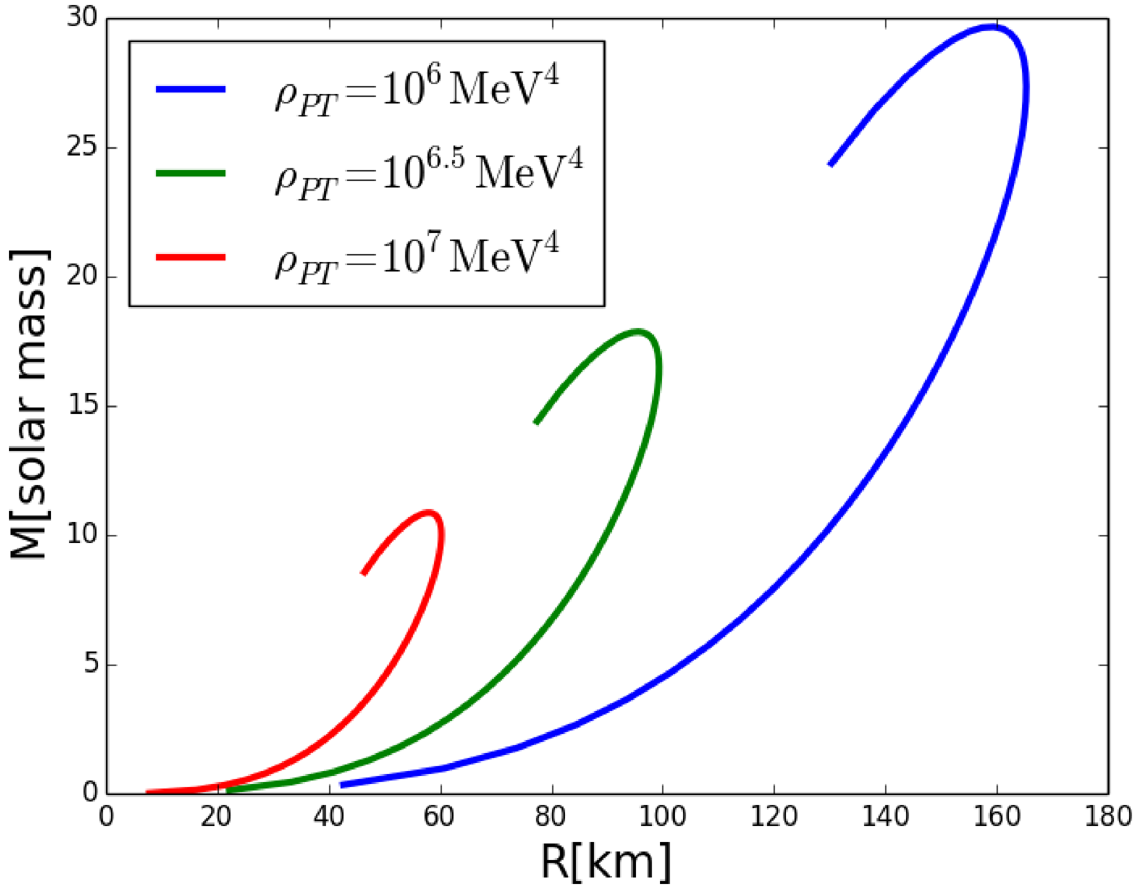


Mass-Radius for GS1 EOS, $\rho_{\rm PT} = 10^8\ \mathrm{MeV}^4,\ \lambda_\phi = 10\ \mathrm{km}$ and various values of η.

Maximum mass ($m_\phi \to \infty$ limit)

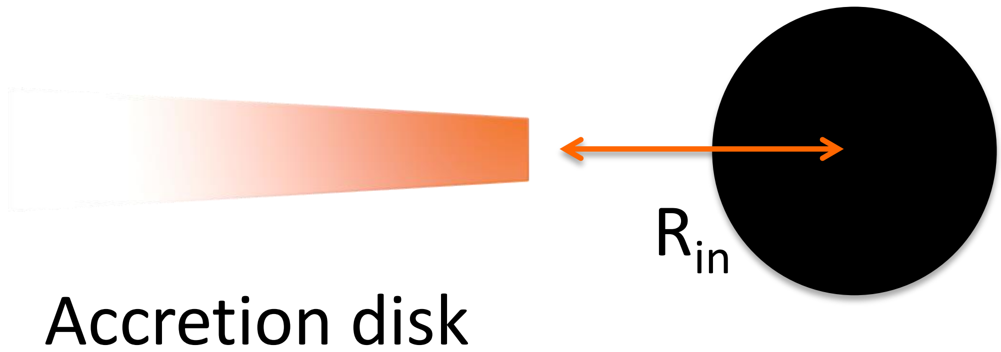


$30M_\odot$ neutron stars?



Mass-radius relation for GS1 EoS, $\eta = 1$, and $\lambda_\phi / R_{\mathrm{NS}} \ll 1$.

LMC X-3



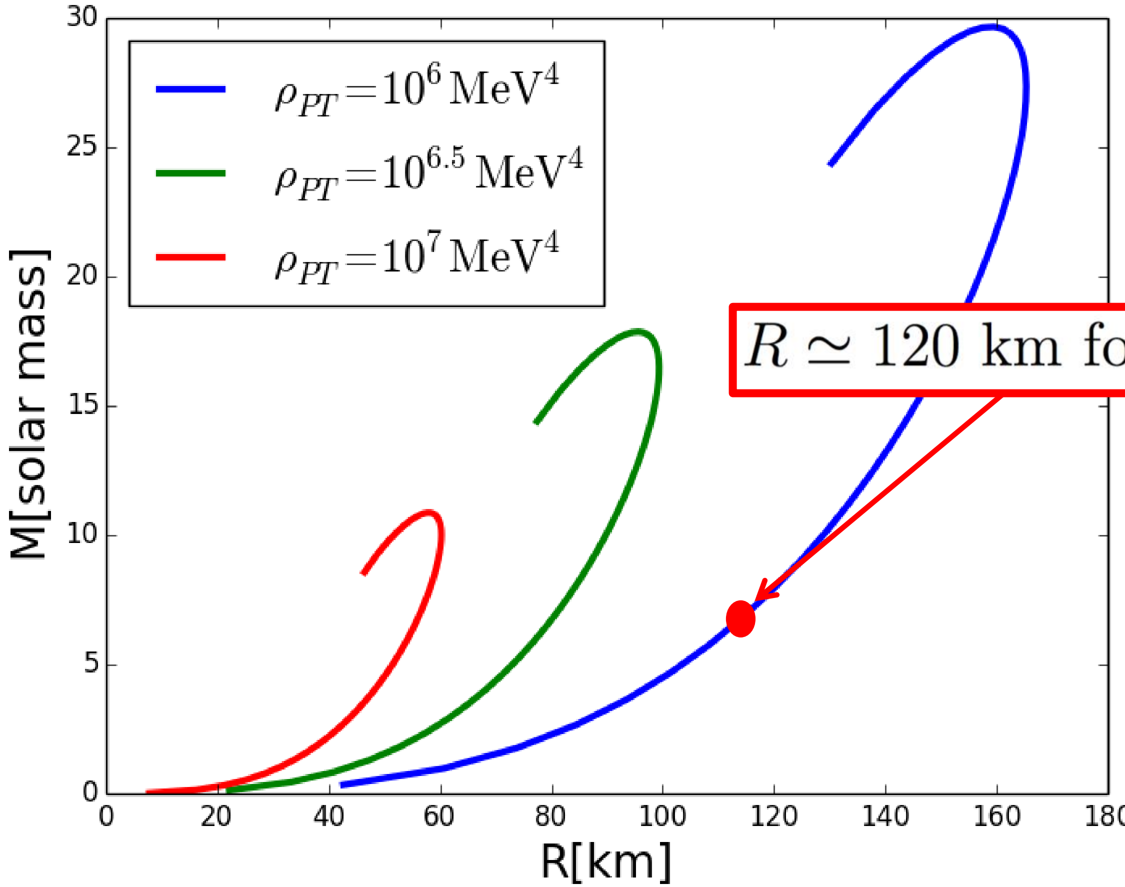
Spectral fit suggests $R_{\rm in} \simeq 50{\rm km}.$

$$R_{\rm in} = \frac{6GM}{c^2} \longrightarrow M \simeq 6M_\odot.$$

This massive star is a neutron star in our model.

Private communication with Kazuhiro Nakazawa and Shogo Kobayashi.

30M$_\odot$ neutron stars?



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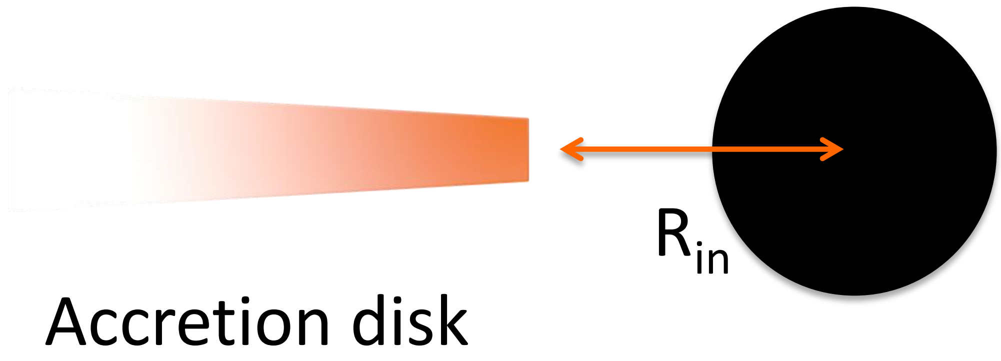

Spectral fit suggests $R_{\rm in} \simeq 50{\rm km}.$

$$R_{\rm in} = \frac{6GM}{c^2} \longrightarrow M \simeq 6M_\odot.$$

This massive star is a neutron star in our model.

30 $M_\odot$ NS is excluded.

Private communication with Kazuhiro Nakazawa and Shogo Kobayashi.

Conclusion

- The $2M_{\odot}$ neutron star is allowed in our model.
- Scalar force affects the internal structure significantly for massive scalar cases.

Future work

- Investigate stability
- How to test this scenario with astrophysical observations