

# Spontaneous scalarization with an extremely massive field and heavy neutron stars

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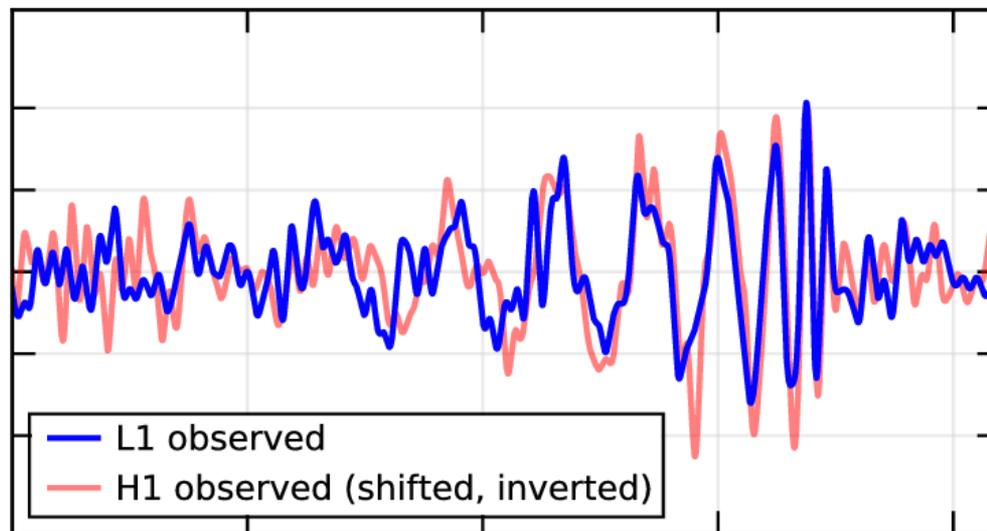
S.Morisaki and TS, PRD 96, 084026 (2017) [arXiv:1707.02809]

*WG3: Strong-field dynamics in alternative theories*

# Introduction

Era of testing gravity at extreme density has arrived!

Livingston, Louisiana (L1)



**What are the interesting models?**

# Simple scalar-tensor theory

(that deviates from GR only at high density)

## GR + scalar field with conformal coupling

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

**Physical metric**  
↓

↑  
**Including us**

$\phi$  could be dark matter.

P. Chen, TS and J. Yokoyama 2015

## Universal coupling $A^2(\phi)$

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

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

# Spontaneous scalarization

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

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

from the conformal coupling

$\rho$ : energy density of matter

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

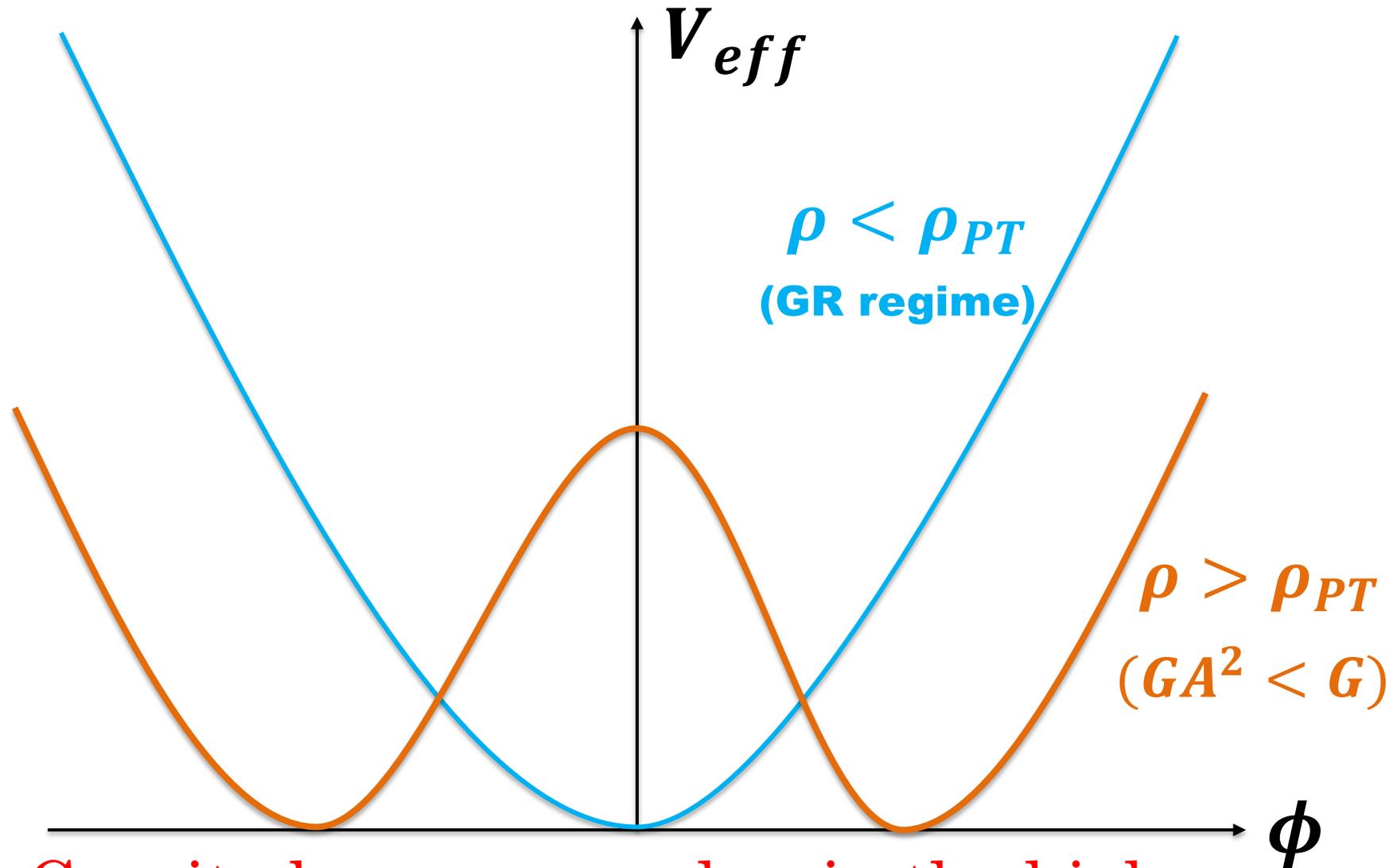
$$V_{eff} \approx \frac{\rho}{4} + \frac{1}{2} \left( m_\phi^2 + \frac{\rho}{2} A^{2''}(0) \right) \phi^2 + \dots$$

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

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

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

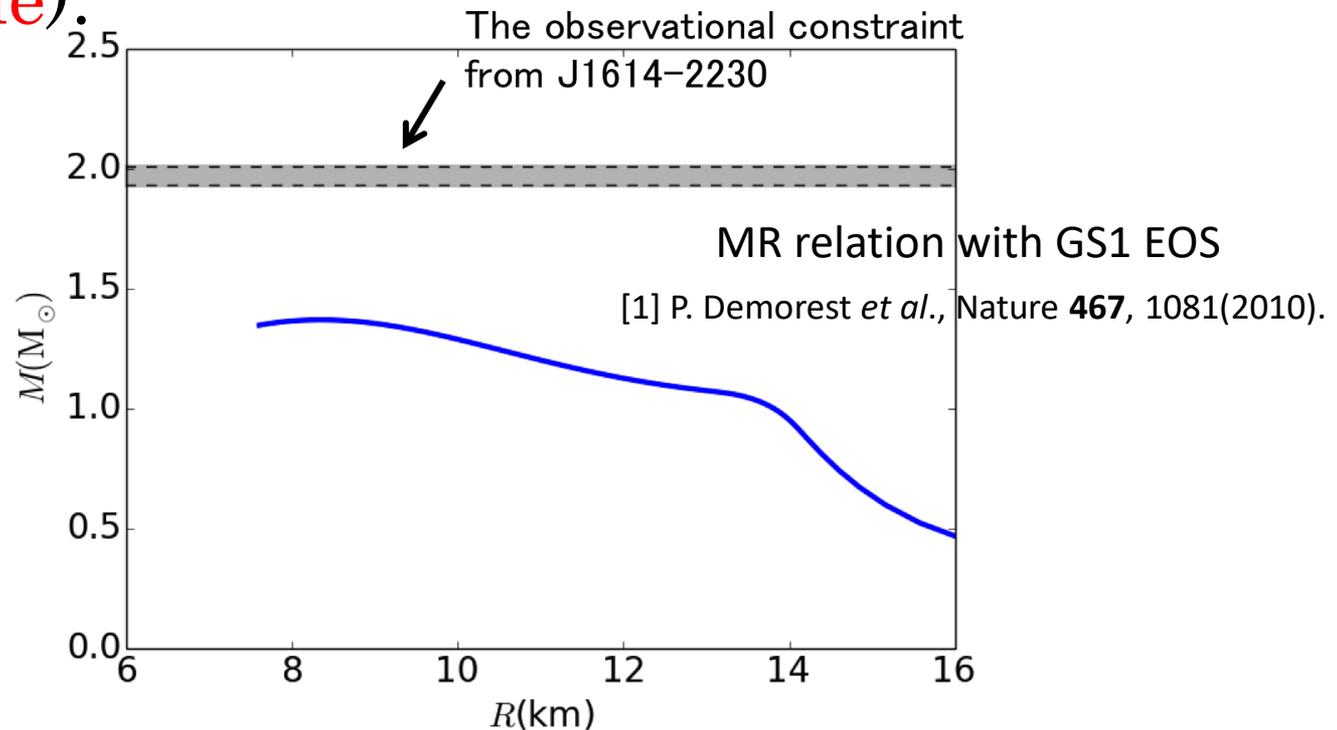
# Spontaneous scalarization



Gravity becomes weaker in the high density region.

# 2M<sub>⊙</sub> Neutron Star

It is difficult to explain the existence of **2M<sub>⊙</sub> NS** [1] if the effect of strange hadrons is taken into account (**hyperon puzzle**).



**Does SS allow more massive NSs?**

# 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  $\phi$  behaves as dark matter

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

□  $\lambda_\phi \lesssim R_{NS} \sim 10\text{km}$

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

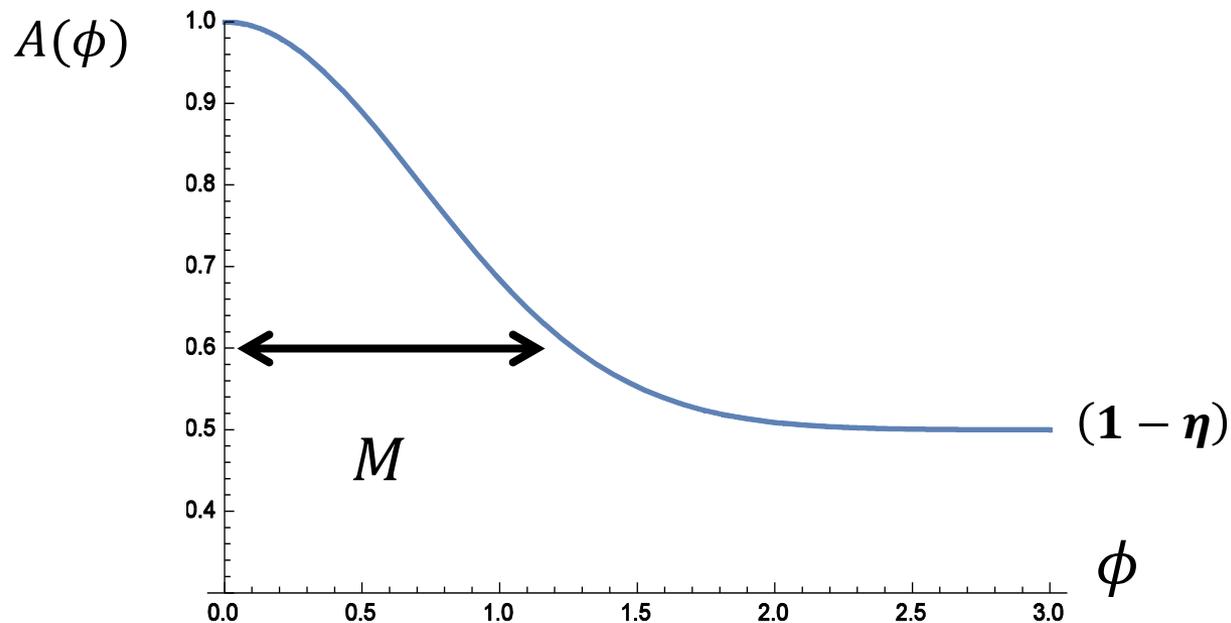
$\eta$ : How significantly gravity is weakened

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

$\lambda_\phi$ : Compton wavelength

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

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

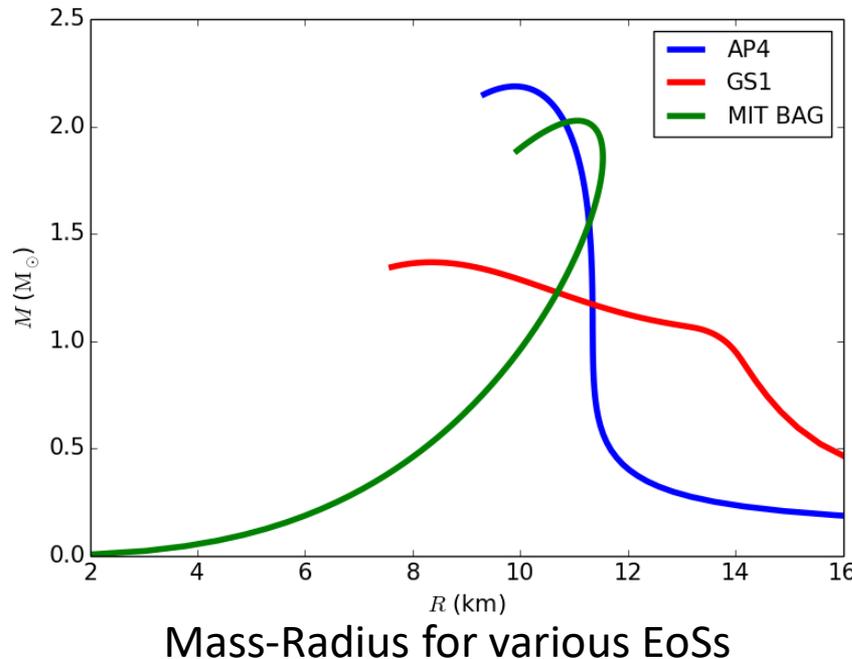


$G_{eff} = G$  for low density

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

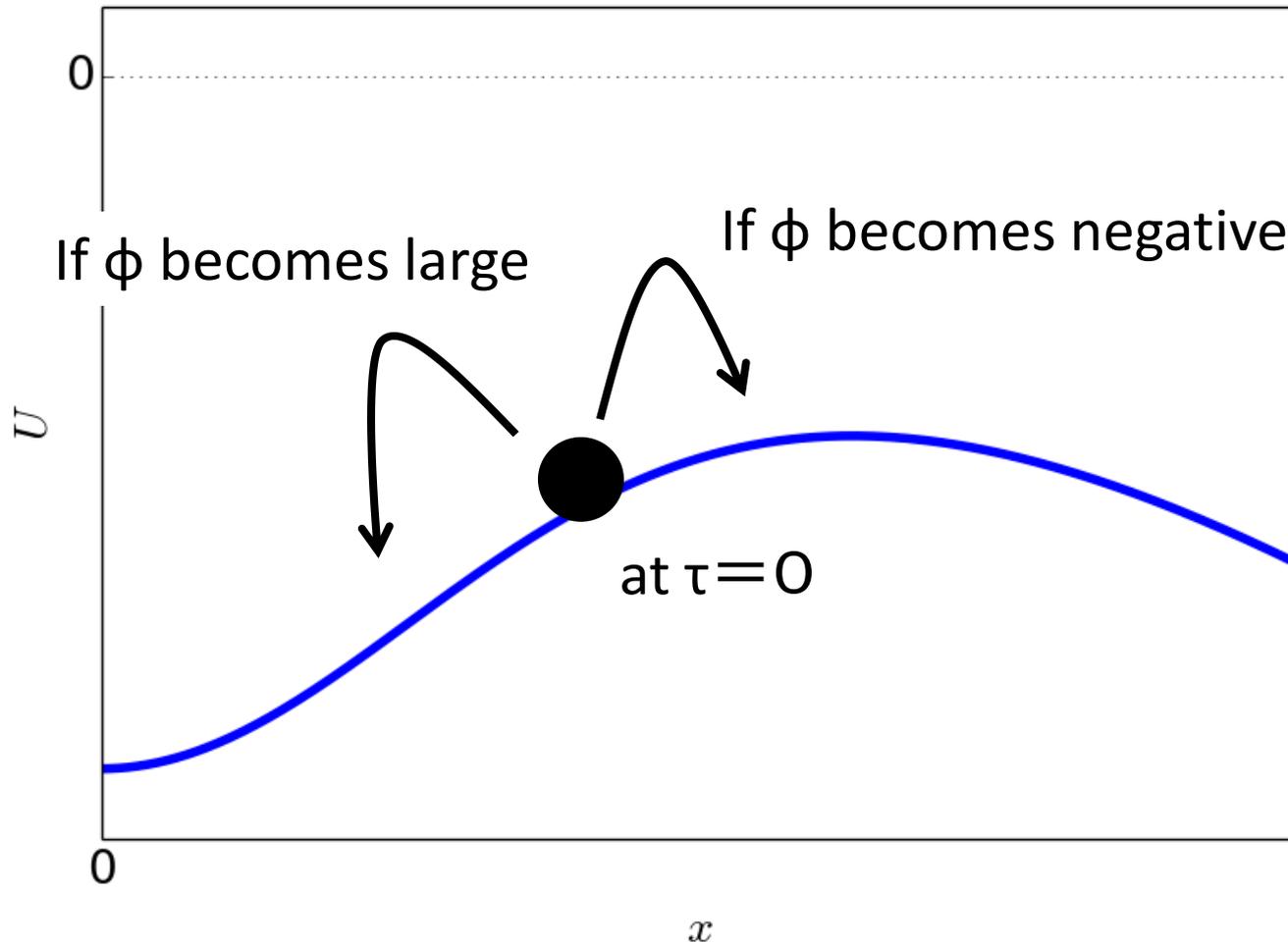
# Equations of state (EoSs)

- $npe\mu$   $\longrightarrow$  AP4 EOS [1]
- With strange hadrons  $\longrightarrow$  GS1 EOS [1]  
Our main target
- Strange quark matter  $\longrightarrow$  MIT BAG model [2]



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

We used the **shooting method**.



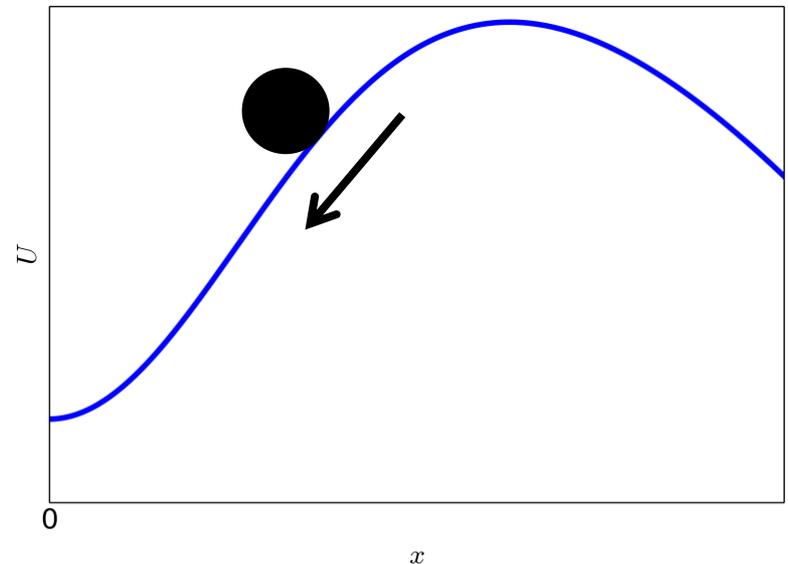
# Very massive case ( $\lambda_\phi \ll 1\text{km}$ )

Numerical integration becomes difficult.

Numerical error grows exponentially.

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

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



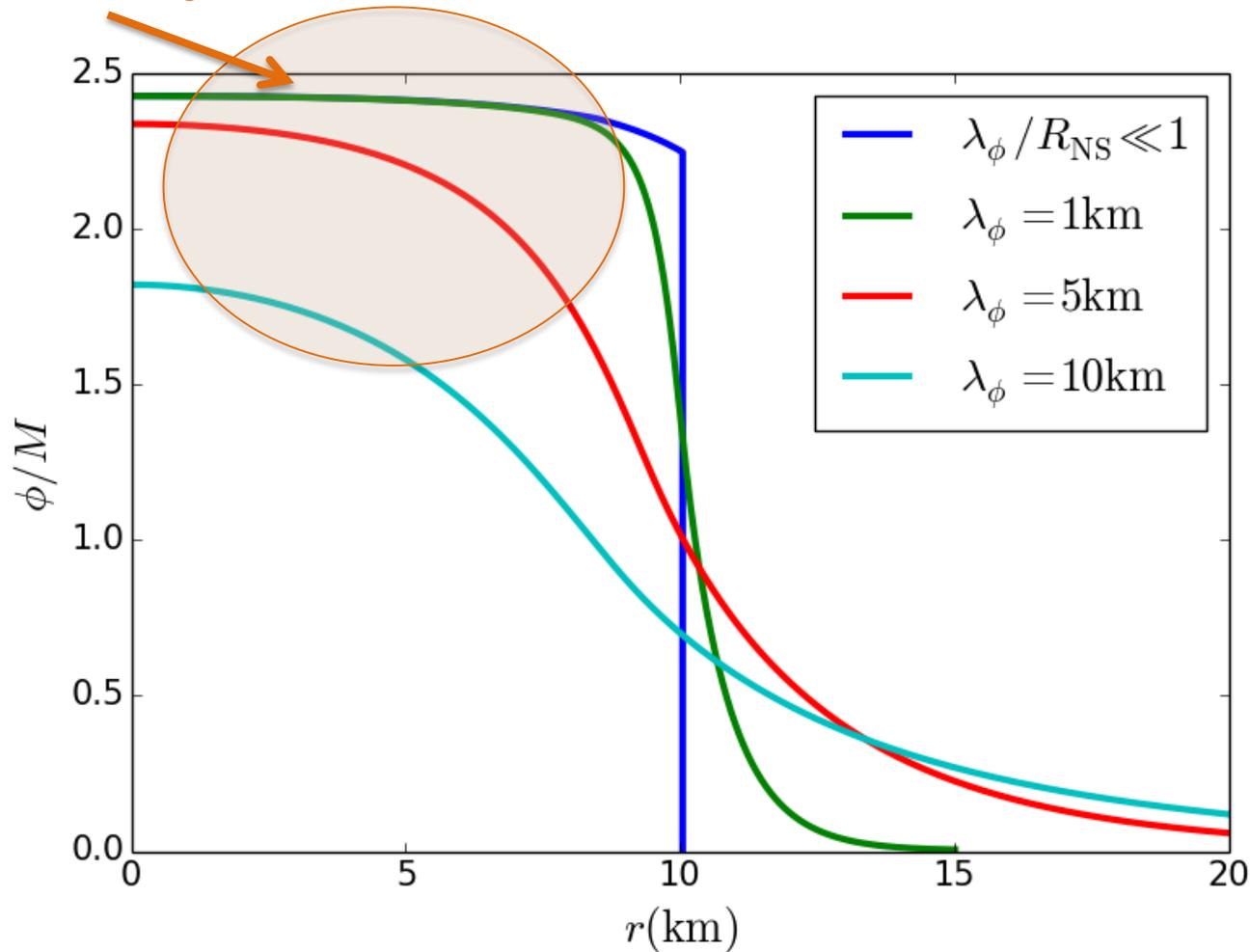
We have invented a semi-analytical method to solve this problem.

# Results

# Profile of $\phi$

Scalarization phase

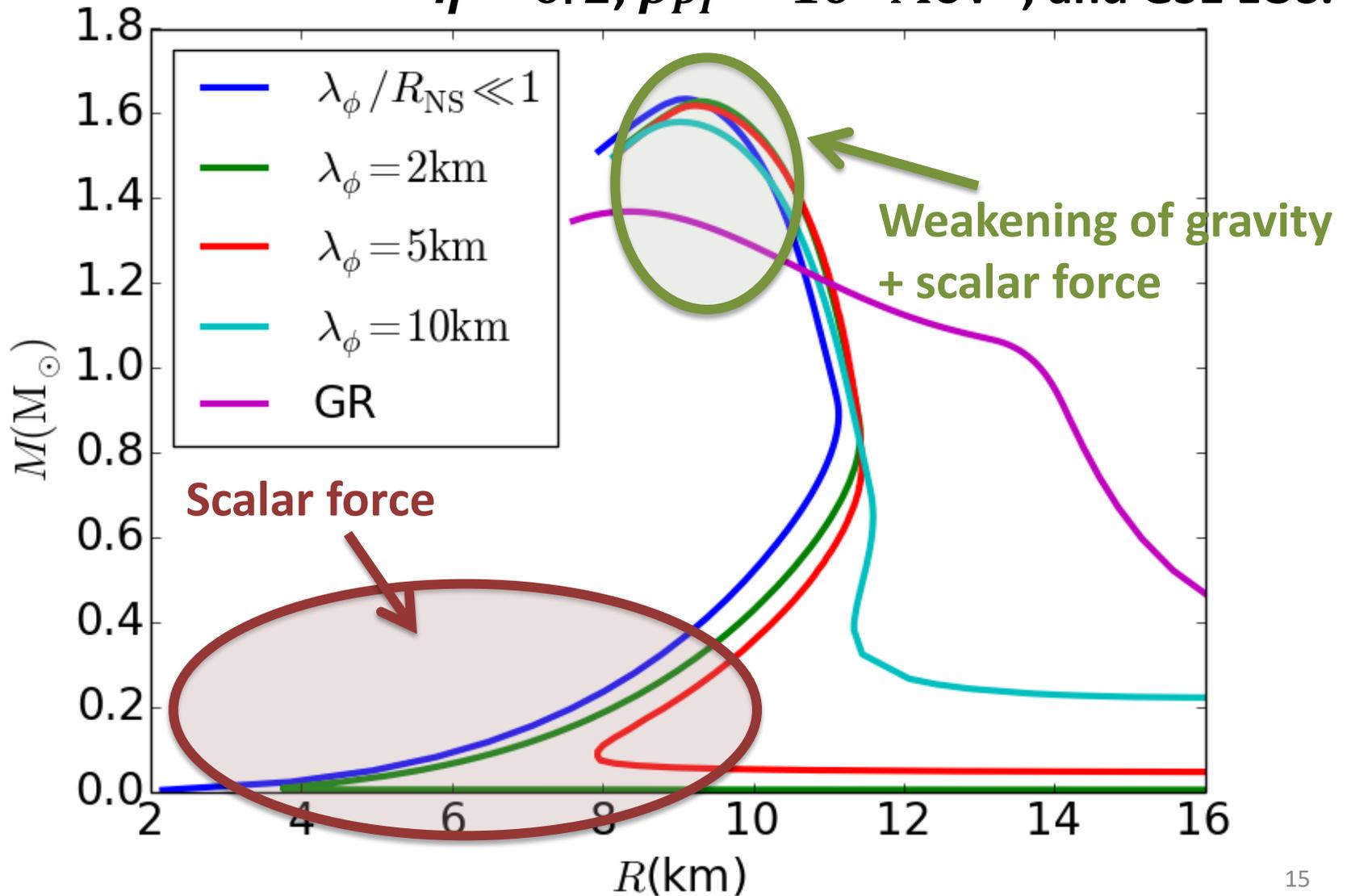
For  $\eta = 0.2$ ,  $\rho_{\text{PT}} = 10^8 \text{ MeV}^4$ , and AP4 EOS.



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

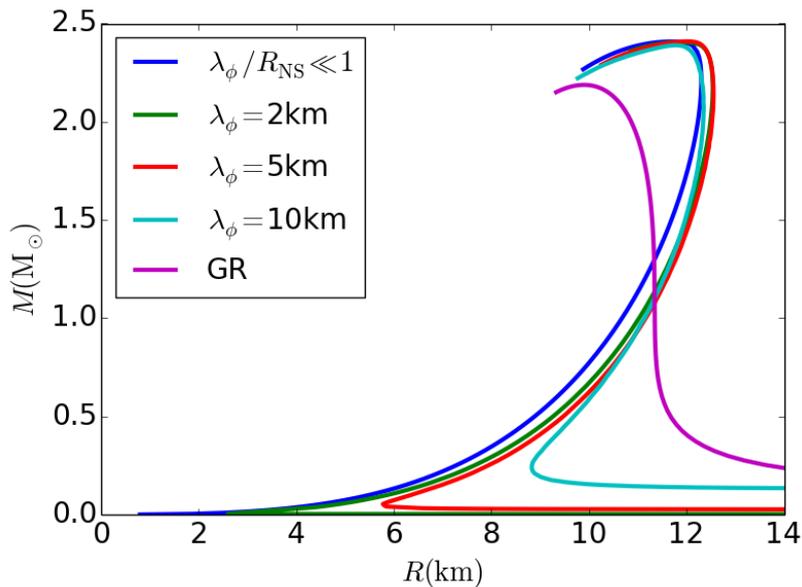
# Mass-radius relation

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

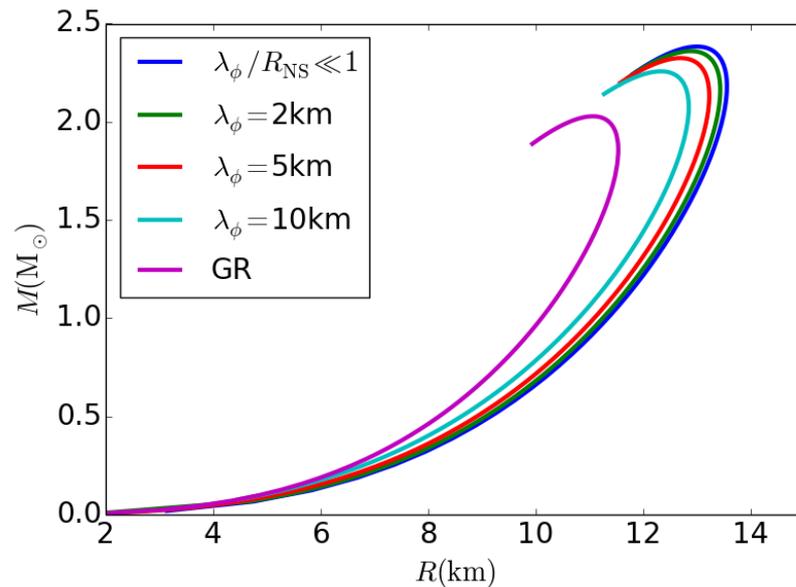


# MR relation for other EOSs

The qualitative feature does not change for the other EOSs.



[a] AP4 EOS

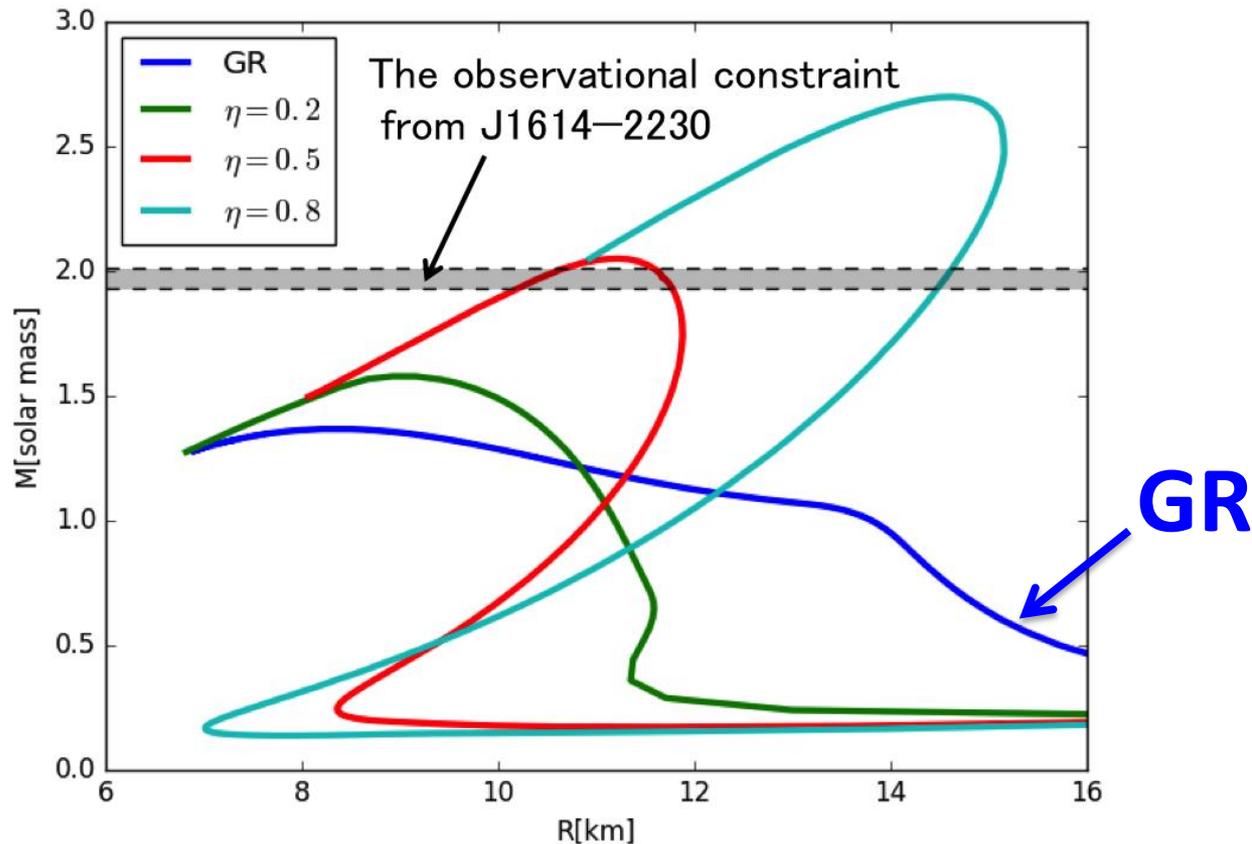


[b] MIT BAG model

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

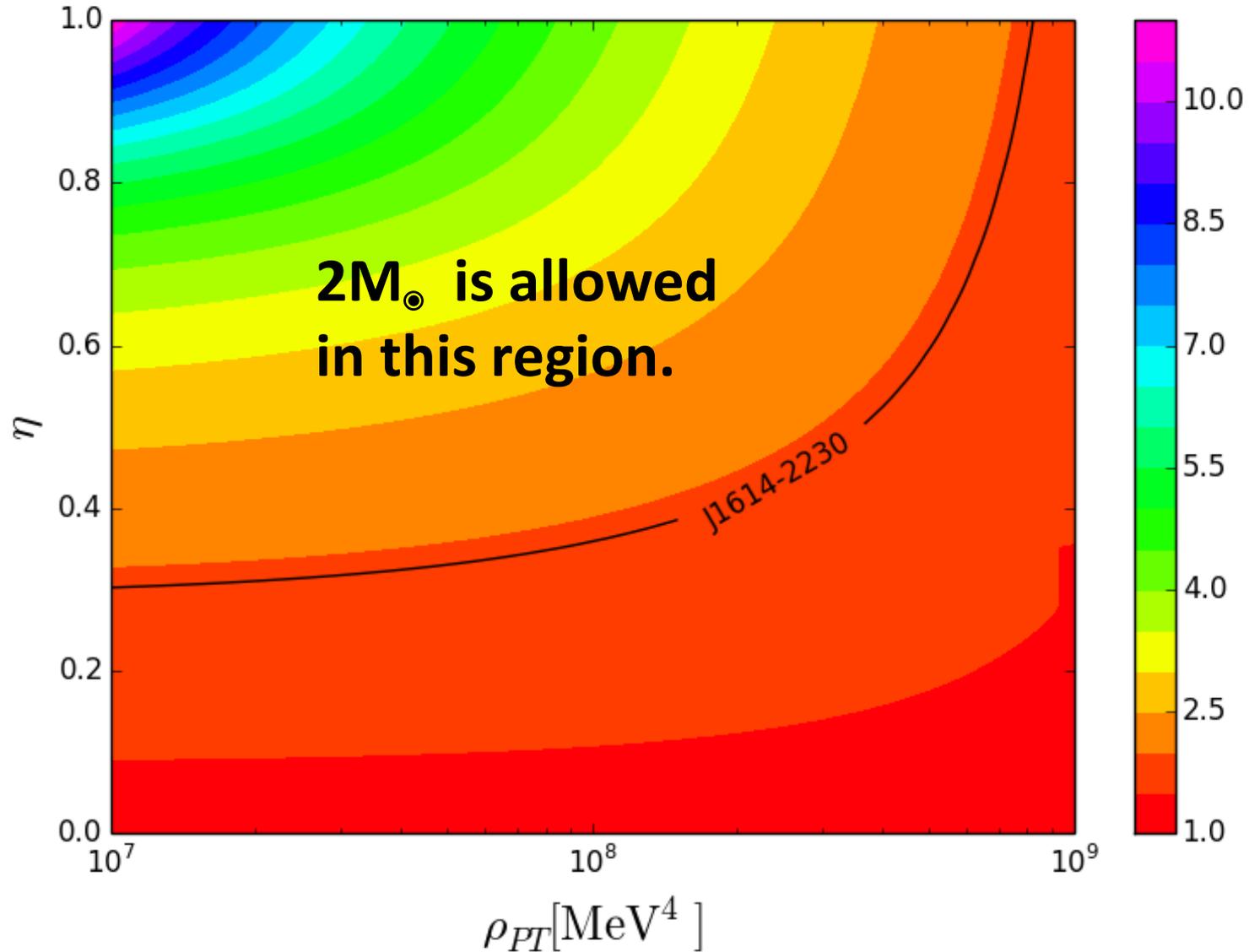
# Existence of $2M_{\odot}$ NS

**$2M_{\odot}$  is allowed!!**

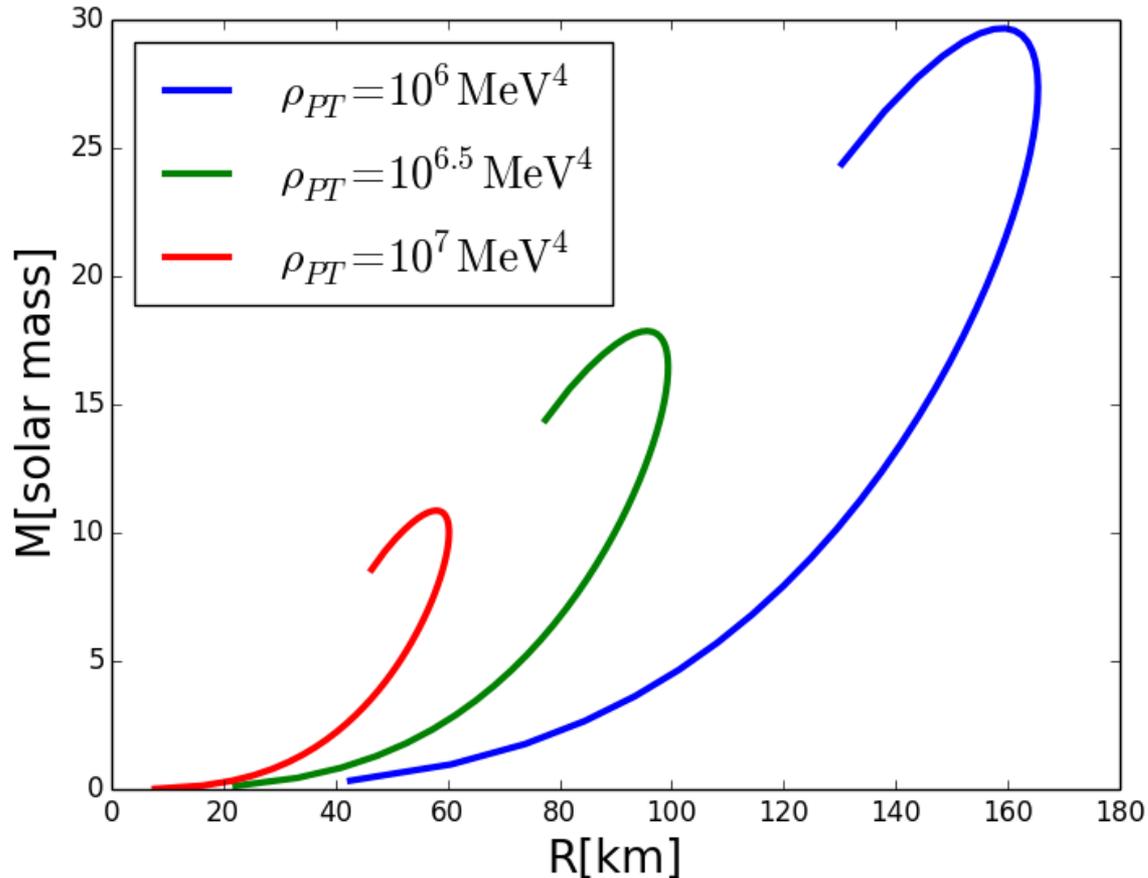


Mass-Radius for GS1 EOS,  $\rho_{\text{PT}} = 10^8 \text{ MeV}^4$ ,  $\lambda_{\phi} = 10 \text{ km}$  and various values of  $\eta$ .

# Maximum mass ( $m_\phi \rightarrow \infty$ limit)

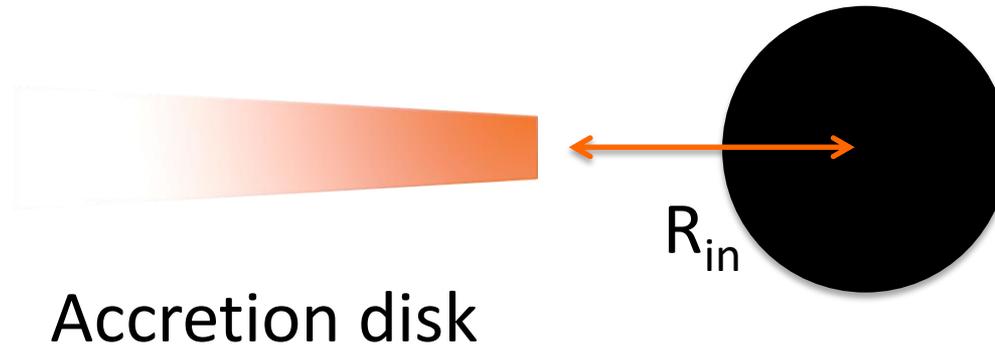


# 30M<sub>⊙</sub> neutron stars?



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

# LMC X-3

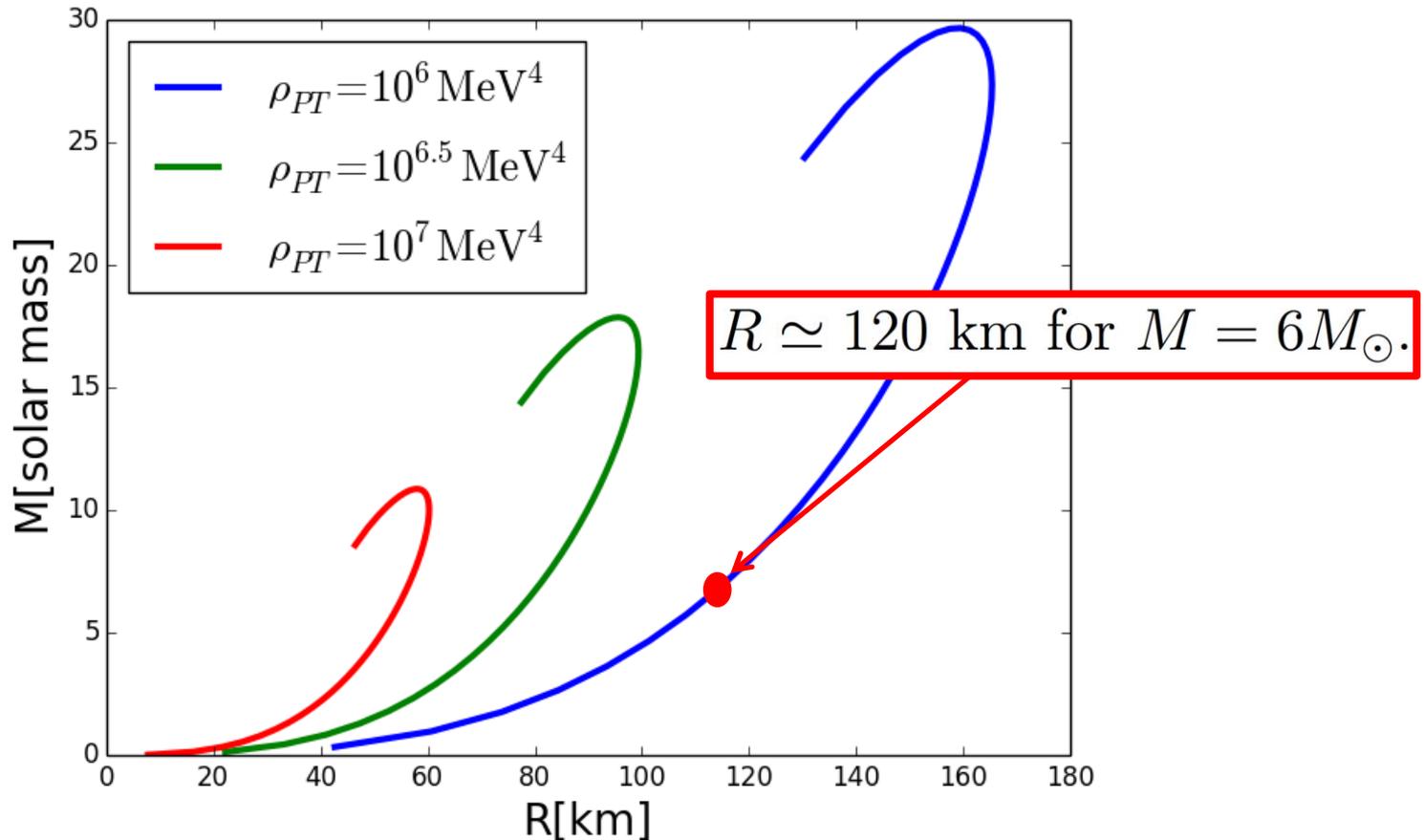


Spectral fit suggests  $R_{\text{in}} \simeq 50\text{km}$ .

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

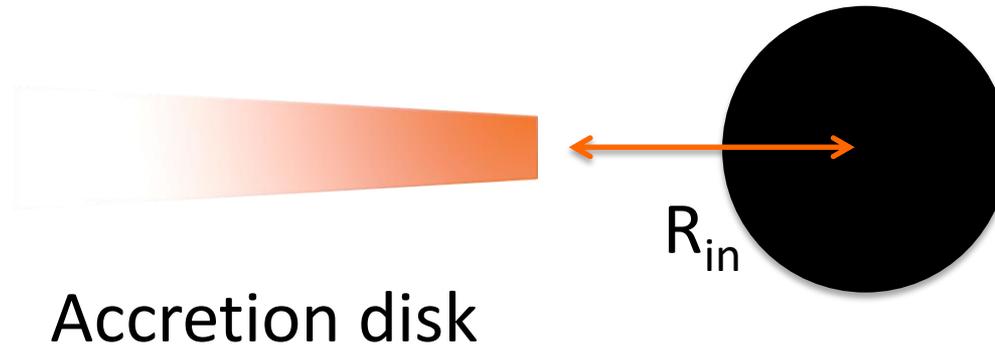
**This massive star is a neutron star in our model.**

# $30M_{\odot}$ neutron stars?



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

# LMC X-3



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

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

This massive star is a neutron star in our model.

**30  $M_{\odot}$  NS is excluded.**

# 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