Black Holes & Neutron Stars in Tensor-Vector-Scalar Theory

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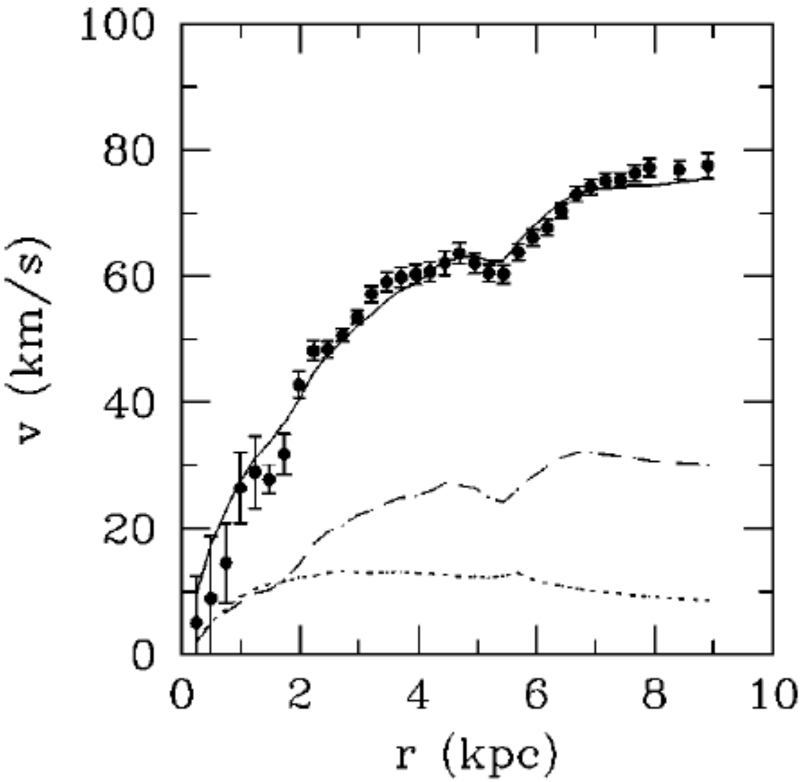
Modified Newtonian Dynamics (MoND)

Milgrom (1983); Bekenstein & Milgrom (1984)

Phenomenologically based on observations of spiral galaxies:

1) Asymptotically flat rotation curves

2) Tully-Fisher law (relationship between rotation velocity & luminosity in spiral galaxies)



$$\mu\left(|\mathbf{a}|/a_0\right)\mathbf{a} = -\nabla\Phi_N$$

$$\mu(x) = \begin{cases} x & \text{for} \quad x \ll 1 \\ 1 & \text{for} \quad x \gg 1 \end{cases}$$

has been argued to be "better" than CDM

1) more predictive than CDM

2) more easily falsifiable (only one parameter)

Modified Newtonian Dynamics (MoND)

Milgrom (1983); Bekenstein & Milgrom (1984)

Not a covariant theory;

Good as a toy-model... need relativistic theory

Bekenstein (2004)
"Relativistic gravitation theory for the modified Newtonian dynamics paradigm"

Tensor-Vector-Scalar theory
(TeVeS)

Bekenstein's TeVeS Theory

Bekenstein (2004) - Relativistic version of MoND

Weak Acceleration Limit

TeVeS = MoND

Cosmological Scales

Strong Lensing
LSS, CMB

Newtonian Limit

Parametrized Post-Newtonian (PPN) coefficients agree with all solar system tests.

What can we learn about TeVeS in strong gravitational fields?

But first, we need to understand more about the theory

A TeVeS Primer

TeVeS = Tensor - Vector - Scalar

$$S_{\rm tot} = S_g + \mathcal{K} S_v + k S_s + S_{\rm mat}$$

Vector-field Coupling Constant (i.e. strength of the vector field)

Scalar-field Coupling Constant (i.e. strength of the scalar field)

Scalar field ==> extra potential to gravitational field

Vector field ==> required light bending properties

Reduces to GR when

$$\mathcal{K} = k = 0$$

A TeVeS Primer

Tensor, vector and scalar fields combine to give physical metric...

Clocks & Rulers measured by physical metric

$$\tilde{g}_{\mu\nu} = \mathrm{e}^{-2\varphi}\left(g_{\mu\nu} + \mathcal{U}_\mu \mathcal{U}_\nu\right) - \mathrm{e}^{2\varphi}\mathcal{U}_\mu \mathcal{U}_\nu$$

Stretch / **Shrink** Einstein metric in directions **orthogonal** / **parallel** to $\mathcal{U}^\mu$ by $\mathrm{e}^{-2\varphi}$

put in "by hand" to make sure extra lensing is required in accordance with observations

Solving TeVeS field equations in Strong-Field regime

Giannios (2005) :- **"Schwarzschild" solution**

Sagi & Bekenstein (2008) :- **"Reisner-Nordstrom"**

PL, Sotani & Giannios (2008) :- **"TOV" solution for perfect fluid i.e. neutron star models**

Using observations of neutron star masses, we put constraints on $\mathcal{K}$ and φ_c.

And THEN.......

Seifert (2007):- Schwarzschild-TeVeS unstable

Contaldi et al. (2008):- Evolving vector field causes caustics

Sagi (2009):- Superluminal propagation of scalar waves

Conclusion: original TeVeS theory does not work!!

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Conclusion: original TeVeS theory does not work!!

Skordis (2008), Contaldi et al. (2008) & Sagi (2009)

"Generalized-TeVeS"

Fixes aforementioned problems by allowing for more general dynamics of the vector field

A Generalized TeVeS Primer

TeVeS = Tensor - Vector - Scalar

$$S_{\rm tot} = S_g + K S_K + K_+ S_{K_+} + K_2 S_{K_2} + K_4 S_{K_4} + k S_s + S_{\rm mat}$$

"... most general kinetic term for A, which is diffeomorphism invariant, quadratic in derivatives and ... consistent with $A^2 = -1$ constraint"*

Reduces to original TeVeS when

$$K_+ = K_2 = K_4 = 0$$

* Contaldi et al. (2008)

Solving Generalized-TeVeS field equations

PL (2009) :- Schwarzschild solution
:- Reisner-Nordstrom solution
:- TOV (i.e. neutron stars)

1) Can only measure one certain combination of vector-field coupling constants using static, spherically symmetric spacetimes.

2) BHs and NSs look **EXACTLY** the same in TeVeS and Gen-TeVeS (providing only using EM radiation);

$$K_2 = 0 \quad \& \quad K + K_+ - K_4 = \mathcal{K}$$

Solving Generalized-TeVeS field equations

PL (2009) :- Schwarzschild solution
:- Reisner-Nordstrom solution
:- TOV (i.e. neutron stars)

3) All results of Giannios (2005), Sagi & Bekenstein (2008), PL, Sotani & Giannios (2008) and Sotani (2009) for TeVeS also hold for Gen-TeVeS.

4) Result is **NOT** generalizable. Easy to prove that rotating or time dependent spacetimes will look different in two theories $(K_2 \neq 0)$

What do **black holes** look like in Generalized TeVeS?

Assumptions:

- ✓ Static and spherically symmetric
- ✓ Only non-zero term of vector field is time component
  - ✓ Only subset of possible solutions
  - ✓ Effect of radial component has not been studied

 Paul D. Lasky

Vacuum Spacetimes:

black holes and naked singularities

Giannios (2005), Sagi & Bekenstein (2008), PL (in prep.)

$$d\tilde{s}^2 = \left(\frac{1 - r_c/r}{1 + r_c/r}\right)^a dt^2 + \left(1 + \frac{r_c}{r}\right)^{2+a}\left(1 - \frac{r_c}{r}\right)^{2-a}\left(dr^2 + r^2 d\Omega^2\right)$$

- ✓ **'a'** is extra free parameter relating to "scalar mass" of the black hole.
- ✓ Solution is actually **identical** to a subset of the **Brans-Dicke type I solutions**
  - ✓ **a** = **2** is only black hole solution - **identical to GR-Schwarzschild solution**!
  - ✓ **0** < **a** < **2** and **2** < **a** < **4** are naked singularities
  - ✓ **a** > **4** have non-essential singularity, but divergent surface area.

Vacuum Spacetimes:
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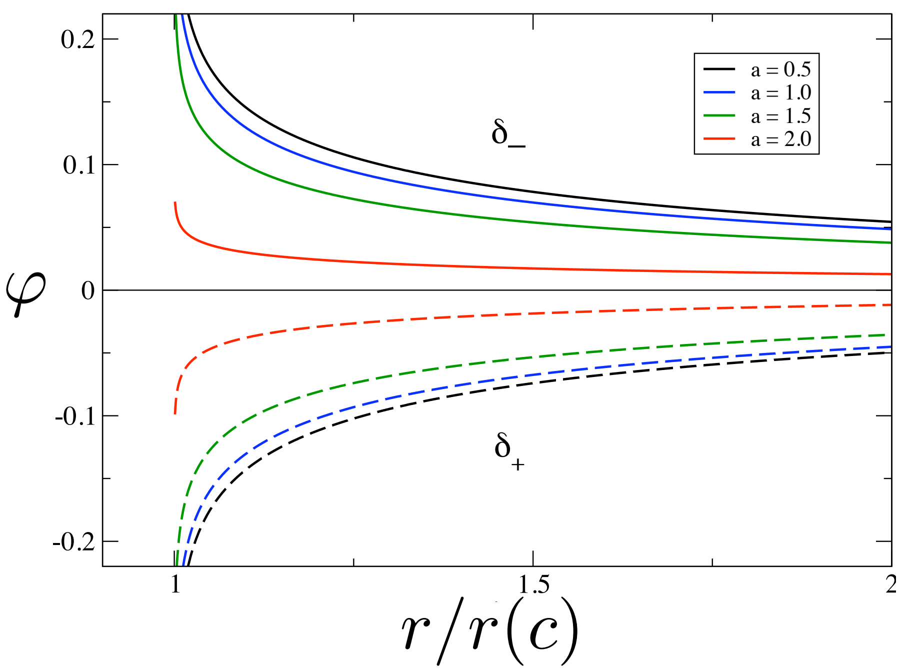
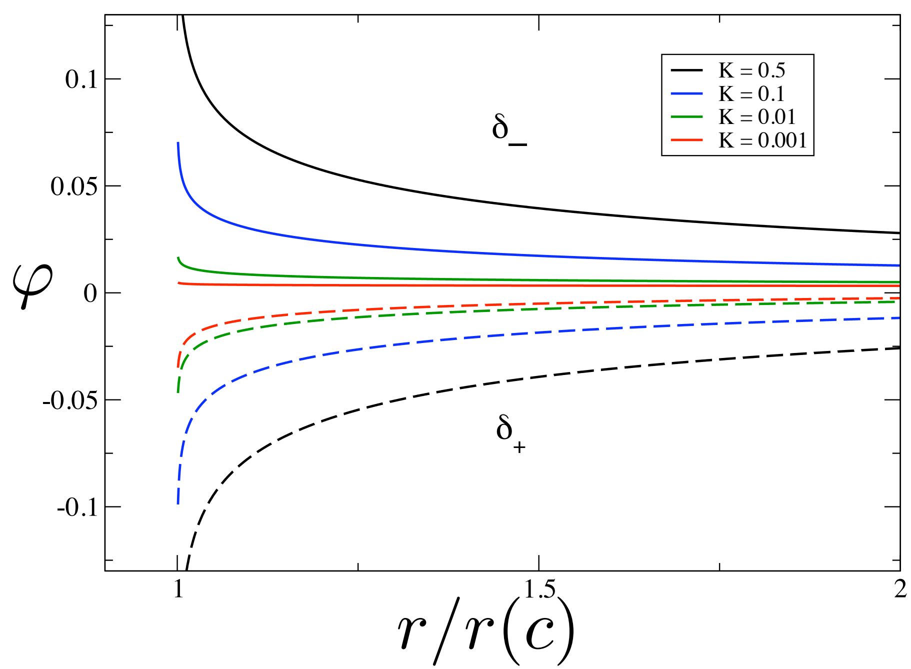
✓ Actually 2 “background” solutions which give same physical metric. These will give different perturbations, etc.





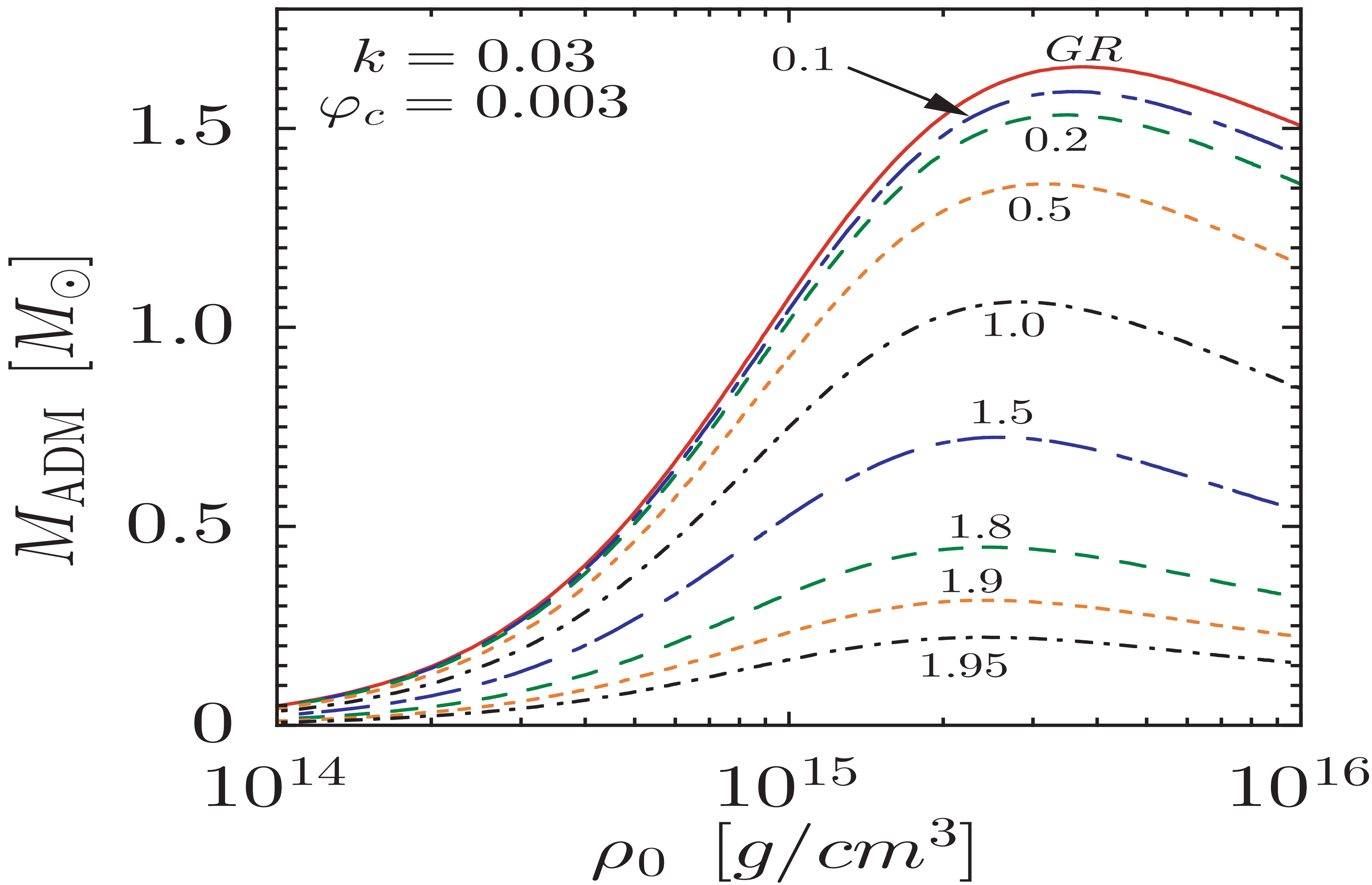
What do neutron stars look like in Generalized TeVeS?

Assumptions:

- ✓ Static and spherically symmetric
- ✓ Only non-zero term of vector field is time component
  - ✓ Only subset of possible solutions
  - ✓ Effect of radial component has not been studied
- ✓ For Neutron star assumed perfect fluid

Neutron Stars in Generalized TeVeS

PL, Sotani & Giannios (2008), PL (2009)



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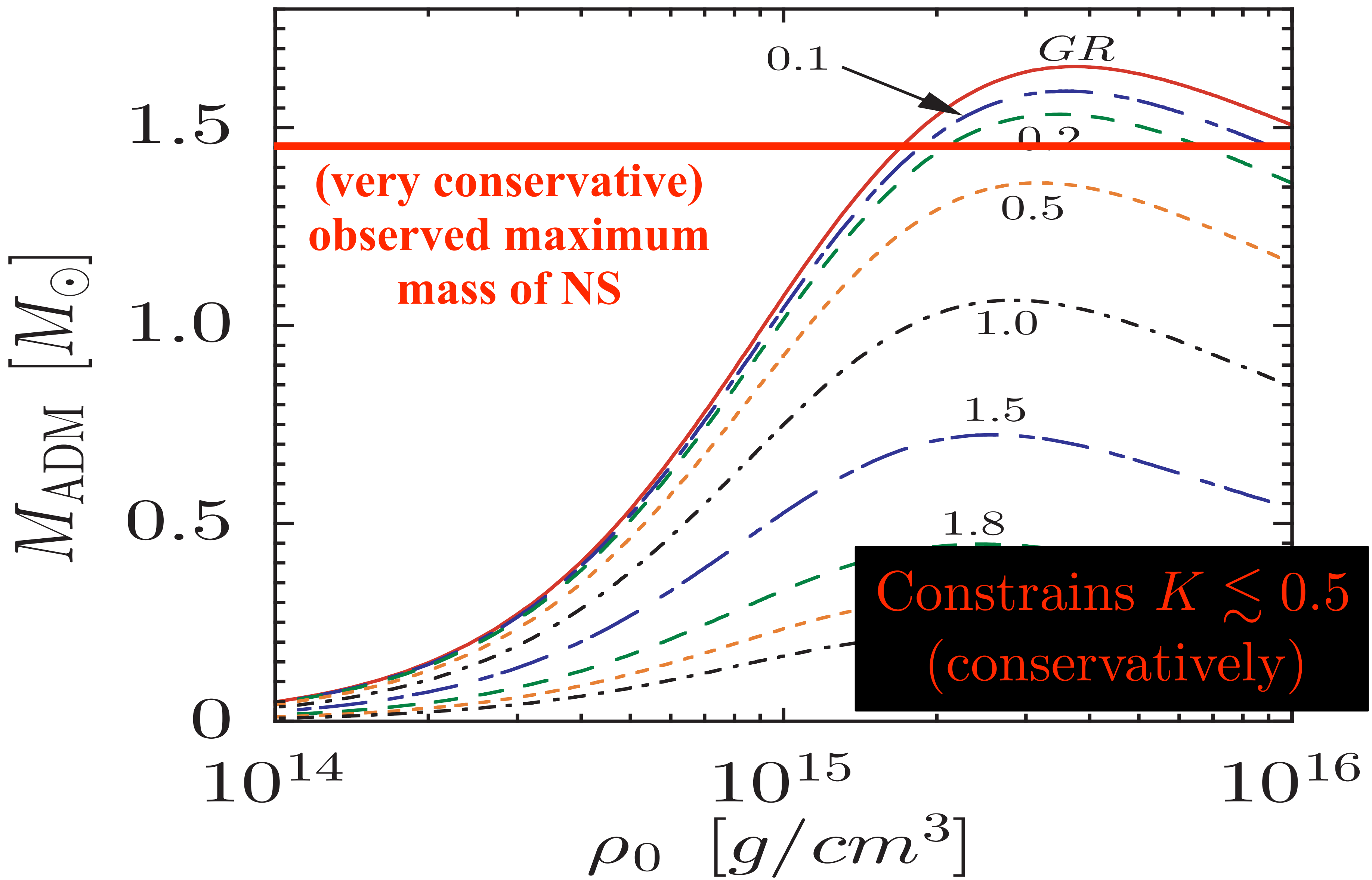

Neutron Stars in Generalized TeVeS

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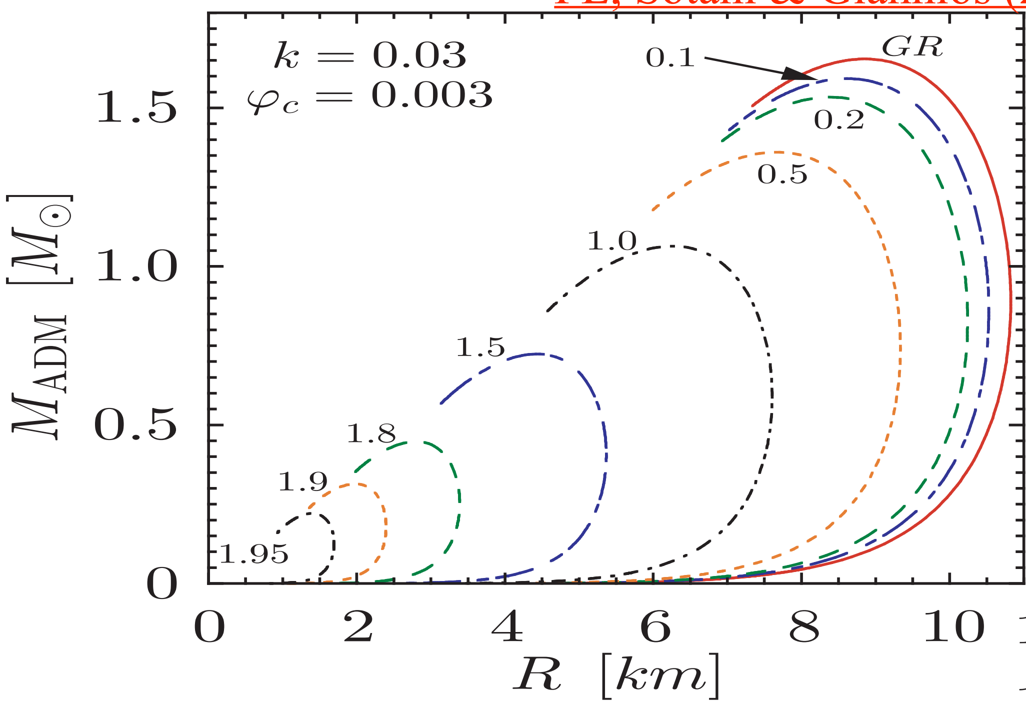

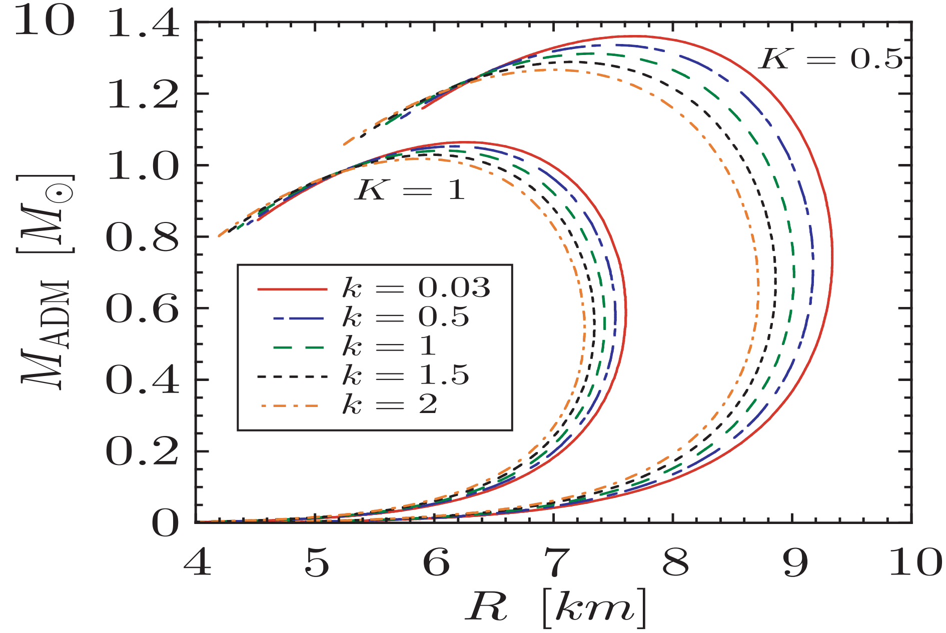

Conclusions

- ✓ Generalized TeVeS still a viable theory in the strong-field regime
- ✓ Can utilise NS observations to restrict parameter space of theory
- ✓ Vacuum spacetimes can have different structure to GR, but also admit Schwarzschild as a solution.
- ✓ Many open questions for vacuum spacetimes;
  - ✓ **Does gravitational collapse lead to naked singularities or black holes?**
  - ✓ **Are such objects stable?**
  - ✓ **What is the structure of rotating BHs?**
  - ✓ **Many questions to do with gravitational wave emission**
  - ✓ **etc.**

THANK YOU!