Modified gravity and compact objects

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Motivation

- Testable gravity modifications: neutron stars and black holes
- Tests of modified gravity
- Benchmarks for testing General Relativity

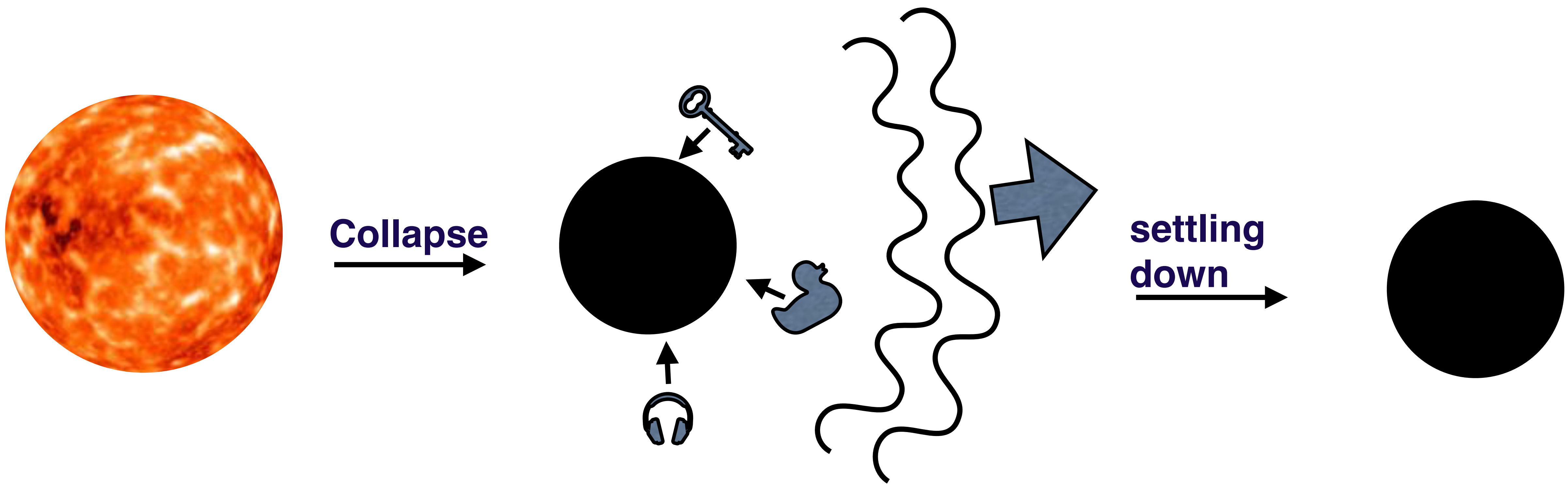
Outline

- Black holes in scalar-tensor theories
- Black holes in massive (bi)gravity
- Stars in modified gravity

Black holes

Black holes are bald (?)

- Gravitational collapse...
- Black holes eat or expel surrounding matter
- Their stationary phase is characterised by a limited number of charges
- No details about collapse
- Black holes are bald



M, J, Q

Black holes are bald (?)

No hair theorems/arguments dictate that adding degrees of freedom lead to trivial (General Relativity) or singular solutions.

E.g. in the standard scalar-tensor theories BH solutions are GR black holes with constant scalar.

Can we find non-GR black hole solutions:

✦ Circumvent no-hair black hole theorems ?

✦ “Hairs”, non-GR solutions : a way to test modified gravity

Horndeski theory

Generalized scalar-tensor theory

The most generic scalar-tensor theory in 4D, whose equations of motion contain no more than second derivatives

[Horndeski'1974]

$$S = \int d^4x \, \mathcal{L}_H \left[g, \partial g, \partial^2 g, \varphi, \partial \varphi, \partial^2 \varphi, \partial^3 \varphi, ... \right]$$

$\Downarrow$?

$$E[g, \partial g, \partial^2 g, \varphi, \partial \varphi, \partial^2 \varphi] = 0$$

No more than 2 derivatives in EOMs to avoid the Ostrogradsky ghost
(an extra d.o.f., because one need to specify additional Cauchy data: ghost-like d.o.f)

beyond Horndeski, DHOST

- No more than 2 derivatives in EOMs to avoid the Ostrogradski ghost
- When the equations of motion are of higher oder, in general it means a new degree of freedom which is a ghost
- Break assumption of the Ostrogradski theorem => a possibility to have higher order EOMs

+ beyond Horndeski + beyond^2 Horndeski (“DHOST”,“EST”)

[Zumalacárregui&García-Bellido’14
Gleyzes et al’15
Deffayet et al’15
Langlois and Noui’15
Crisostomi et al’16
Motohashi et al’16]

beyond Horndeski

Most general Horndeski shift-symmetric action:

$$\mathcal{L}_2 = K\left(X,\varphi\right)$$
$$\mathcal{L}_3 = G_3\left(X,\varphi\right)\Box\varphi$$
$$\mathcal{L}_4 = G_4(X,\varphi)\,R + G_{4,X}(X,\varphi)\left[\left(\Box\varphi\right)^2 - \left(\nabla\nabla\varphi\right)^2\right],$$
$$\mathcal{L}_5 = G_{5,X}\left(X,\varphi\right)\left[\left(\Box\varphi\right)^3 - 3\Box\varphi\left(\nabla\nabla\varphi\right)^2 + 2\left(\nabla\nabla\varphi\right)^3\right] - 6G_5\left(X,\varphi\right)\,G_{\mu\nu}\nabla^\mu\nabla^\nu\varphi$$

Beyond Horndeski:

$$\mathcal{L}_4^{bH} = F_4(X,\varphi)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\alpha\beta\gamma}{}_{\sigma}\varphi_\mu\varphi_\alpha\varphi_{\nu\beta}\varphi_{\rho\gamma}$$
$$\mathcal{L}_5^{bH} = F_5(X,\varphi)\epsilon^{\mu\nu\rho\sigma}\epsilon^{\alpha\beta\gamma\delta}\varphi_\mu\varphi_\alpha\varphi_{\nu\beta}\varphi_{\rho\gamma}\varphi_{\sigma\delta}$$

DHOST:

…

No hair for galileon

[Hui&Nicolis'12]

Shift-symmetric Horndeski Lagrangian

Assume that:

(i) spacetime and scalar field is static spherically symmetric,
(ii) spacetime is asymptotically flat, and
and the norm of the current is finite (at the horizon)
(iii) there is a canonical kinetic term in the action, analyticity of functions in the Lagrangian

A no-hair theorem then follows:
the metric is Schwarzschild and the scalar field is constant

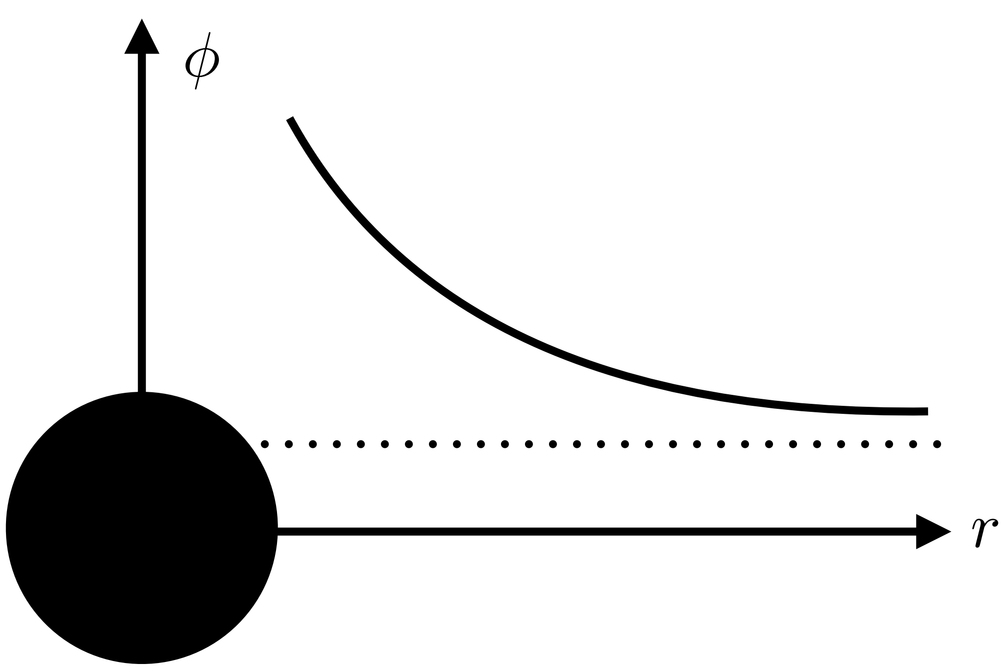
Avoiding no-hair theorem

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \lambda\phi\hat{G}\right]$$

Gauss-Bonnet invariant: $\hat{G} = R_{\mu\nu\sigma\alpha}R^{\mu\nu\sigma\alpha} - 4R_{\mu\nu}R^{\mu\nu} + R^2$

EoM for the scalar: $\Box\phi = -\lambda\hat{G}$

Source for the scalar: it cannot be trivial in BH background



[Campbell et al'92,
Kanti et al'96
Sotiriou and Zhou'13]

Constructing hairs

[Babichev, Charmousis'13]

$$\boxed{\mathcal{L}^{\Lambda\mathrm{CGJ}} = R - \eta(\partial\phi)^2 + \beta G^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - 2\Lambda.}$$

- Static spherically symmetric metric $\quad ds^2 = -h(r)dt^2 + \dfrac{dr^2}{f(r)} + r^2 d\Omega^2$
- Time-dependent scalar $\quad \phi = qt + \psi(r)$

<u>The general solution is given by cubic algebraic equation.</u>

Examples:

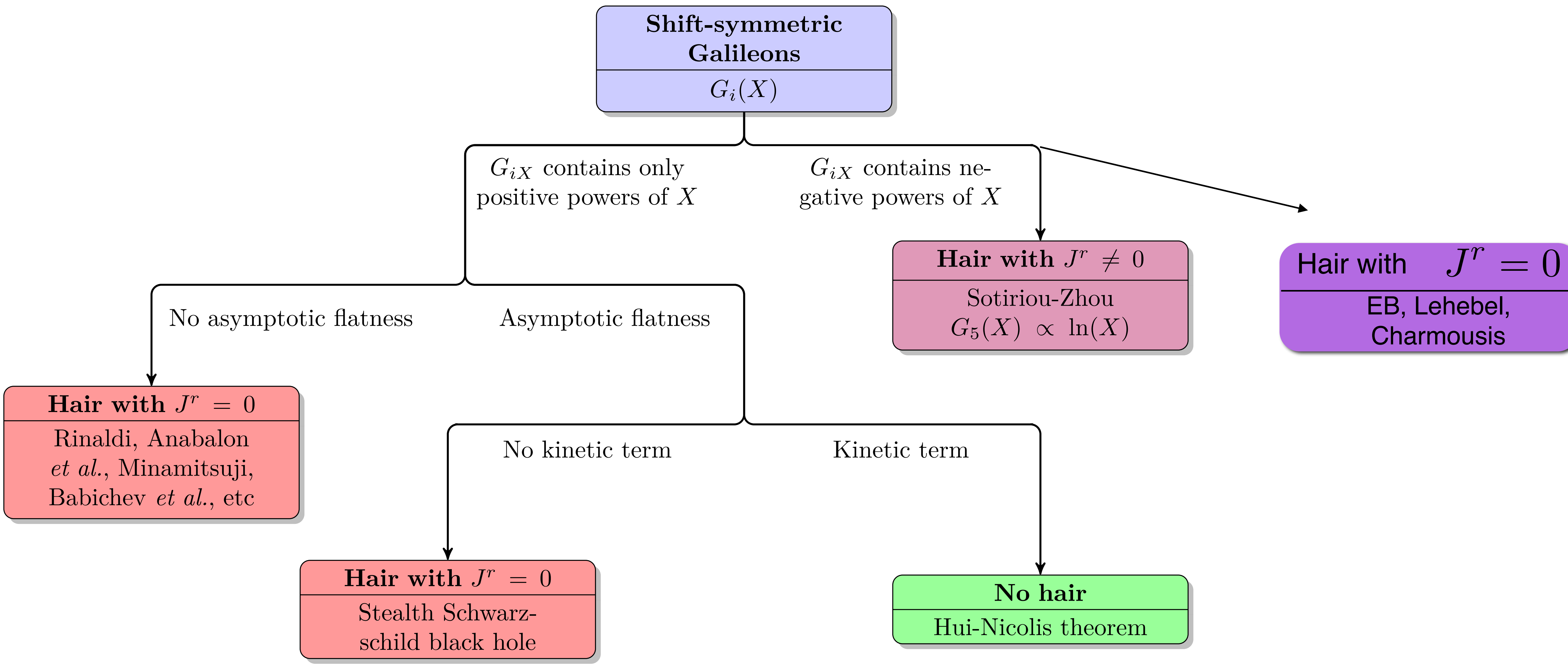
$$f = h = 1 - \frac{M}{r}, \quad \phi' = \pm q\frac{\sqrt{Mr}}{r-M}$$

Stealth Schwarzschild solution

$$f = h = 1 - \frac{M}{r} - \frac{\Lambda_{\mathrm{eff}}}{3}r^2, \quad \psi' = \pm\frac{q}{h}\sqrt{1-h}, \quad \Lambda_{\mathrm{eff}} = -\frac{1}{2\beta}$$

Asymptotically dS/AdS

Avoiding no-hair theorem



Plethora of solutions, including analytical ones

Rotating solutions

Looking for Kerr solution (but non-trivial scalar)

A class of Horndeski and beyond Horndeski theories allow for Kerr solution.

[EB,Charmousis, Lehebel'17]

$$\phi(r,\theta) = \sqrt{-2X_0}\left[a\sin\theta - \sqrt{a^2-2mr+r^2} - m\,\ln\left(\sqrt{a^2-2mr+r^2}-m+r\right)\right]$$

Kerr solutions in DHOST

[Charmousis et al'19]

Non-Kerr solution (numerics) in cubic Galileon

[Van Aelst et al'19]

Massive gravity

$$S_{PF} = M_P^2 \int d^4x \left[-\frac{1}{2} h^{\mu\nu} \mathcal{E}_{\mu\nu}^{\alpha\beta} h_{\alpha\beta} - \frac{1}{4} m^2 \left(h_{\mu\nu} h^{\mu\nu} - h^2 \right) \right]$$

[Fierz&Pauli'39]

Linearized Einstein-Hilbert term

mass term

avoiding Ostrogradsky ghost is difficult

Non-linear completion

[de Rham, Gabadadze, Tolley'10'11, Hassan & Rosen'12]

Two metrics:

- *physical metric*
- *extra metric (maybe non dynamical)*

$$S = M_P^2 \int d^3x \sqrt{-g} \left(\frac{R[g]}{2} + m^2 \mathcal{U}[g,f] \right) + \frac{\kappa M_P^2}{2} \int d^3x \sqrt{-f} \left(\mathcal{R}[f] \right)$$

Two types of solutions

- Bi-diagonal: When two metrics can be put in the diagonal form simultaneously.
- Non Bi-diagonal: When this is not the case

A “no-go theorem” for bi-diagonal black holes

[Deffayet, Jacobson’11]

Bi-diagonal

- Spherically symmetric BHs
  - Bi-diagonal solutions: the two metrics are GR-like and equal or proportional (horizons coincide). [...]
  - hairy BHs (numerics), non-GR [Volkov'12, Brito,Cardoso,Pani'13]
  - Charged GR BHs [EB& Fabbri'13]
- Rotating solutions

  Two GR-like equal metrics [EB& Fabbri'13]

Non Bi-diagonal

- Spherically symmetric BHs

  Non bi-diagonal solutions: the two metrics are GR-like and not proportional (horizons may not coinside). [Salam & Strathdee'77] [Isham & Storey'78]
- Rotating solutions

  Two GR-like non-equal metrics [EB& Fabbri'13]

BH perturbations in modified gravity

GR	scalar-tensor	bi-gravity
$\delta g_{\mu\nu}$	$\delta g_{\mu\nu}$ $\delta\phi$	$\delta g_{\mu\nu}$ $\delta f_{\mu\nu}$

Even for GR-like BHs in modified gravity perturbations are different from those of GR black holes.

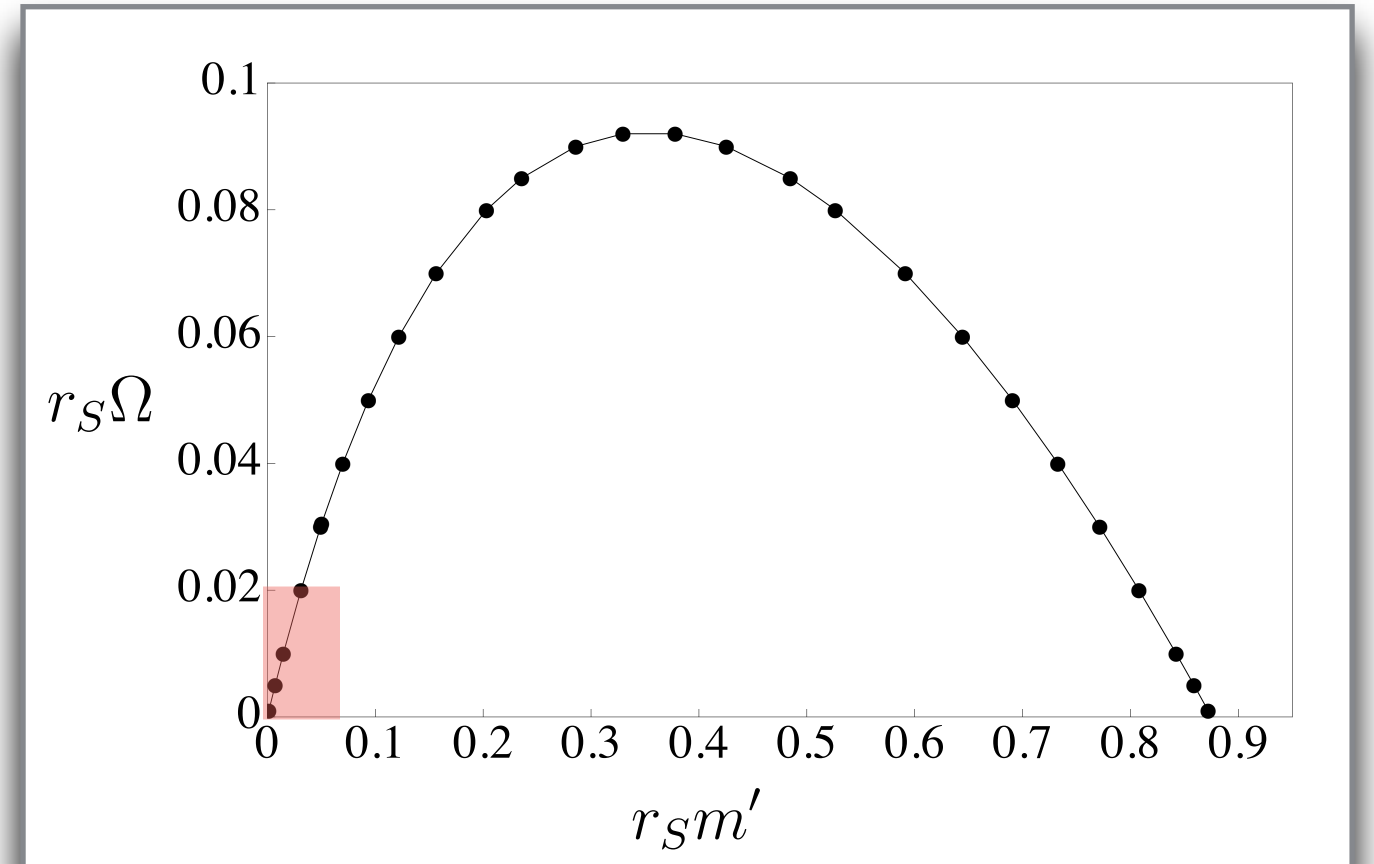
- ✦ Some solutions or/and parameters of the theory may be ruled out (instabilities!)
- ✦ Physical consequences?

BH perturbations in massive bi-gravity

Instability of bi-Schwarzschild BHs in massive (bi)gravity

[EB & Fabbri'13
Brito, Cardoso, Pani'13]

$$0 < m' < \frac{\mathcal{O}(1)}{r_S}$$



for $m' \sim H \rightarrow \boxed{\tau \sim H^{-1}}$

Very slow instability !

- ✦ Tachyonic instability
- ✦ Physically interesting

BH perturbations in massive bi-gravity

Almost GR perturbation for non-bi-diagonal solutions

[EB & Fabbri'14
EB,Brito,Pani'15]

- *Quasinormal spectrum of these solutions coincides with that of a Schwarzschild black hole in general relativity*
- *The full set of perturbation equations is generically richer than that of a Schwarzschild black hole in general relativity, and this affects the linear response of the black hole to external perturbations*
- *There appear modes, which do not feel any gravitational potential and therefore do not backscatter.*

Stars

Screening mechanism

We want to recover General Relativity at short distances

When modifying gravity, extra degrees of freedom appear, which alter gravitational interaction between bodies

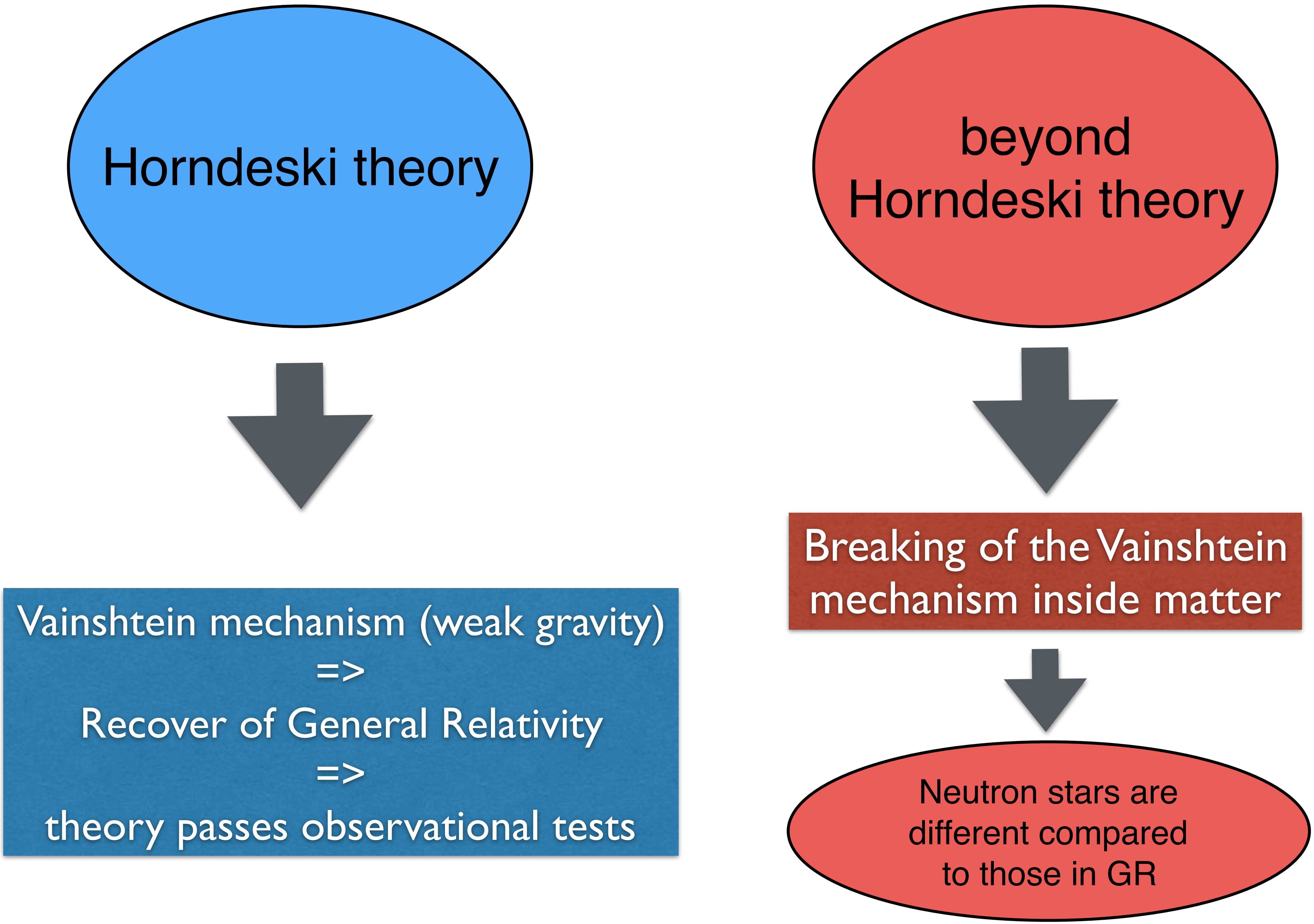
How to comply with both requirements ?

Consistent local physics?

Mechanisms to recover General Relativity:

- ➡ Chameleon (<u>non-linear potential</u> for a canonical extra propagating scalar) - scalar-tensor theories, f(R)
- ➡ Symmetron (<u>coupling to matter</u> depends of the environment)
- ➡ Vainshtein mechanism (<u>nonlinear kinetic term</u> effectively hides extra degree(s) of freedom) - k-essence, DGP, Galileon, Horndeski theory, massive gravity

Screening



Horndeski theory
Vainshtein mechanism (weak gravity)
=>
Recover of General Relativity
=>
theory passes observational tests
beyond
Horndeski theory
Breaking of the Vainshtein
mechanism inside matter
Neutron stars are
different compared
to those in GR

Newtonian order (Linearised gravity)

$$ds^2 = (-1 + 2\Phi)\, dt^2 + (1 + 2\Psi)\, \delta_{ij}\, dx^i\, dx^j$$

- For Horndeski theory GR is restored also inside matter
- For beyond Horndeski theory:

$$\frac{d\Phi}{dr} = \frac{G_N M(r)}{r^2} + \frac{\Upsilon_1 G_N}{4} \frac{d^2 M(r)}{dr^2}$$
$$\frac{d\Psi}{dr} = \frac{G_N M(r)}{r^2} - \frac{5\Upsilon_2 G_N}{4r} \frac{dM(r)}{dr}$$

(Breaking of GR)

[Kobayashi et al'15]

$$M(r) \equiv 4\pi \int_0^r s^2 \rho(s) ds$$

- Υ_1 and Υ_2 are only non-zero for beyond Horndeski theory

Constraints on beyond Horndeski parameters

- $\Upsilon_1 > -2/3$ for a sensible stellar profile
- $-0.22 < \Upsilon_1 < 0.027$

Chandrasekhar mass of dwarf stars

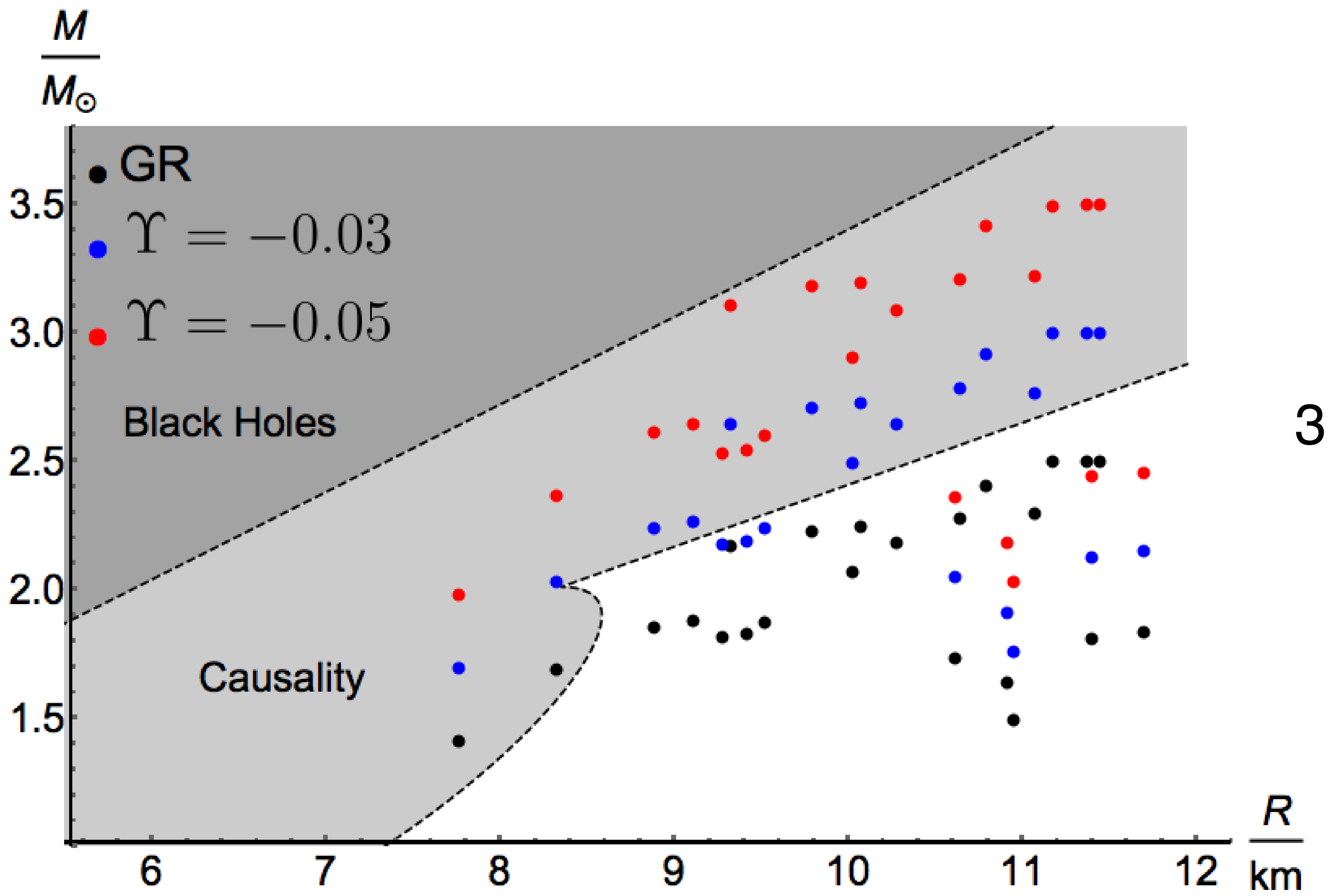
[Jain, Kouvaris, Nielsen'15]

Consistency of the minimum mass for hydrogen burning

[Sakstein'15]

- Sound speed of matter changes, $0 < \Upsilon_1 < 10^{-2}$ [EB,Lehebel'18]
- Helioseismology $-10^{-3} < \Upsilon_1 < 10^{-3}$ [Saltas,Lopes'19]

Neutron star maximum mass and radius

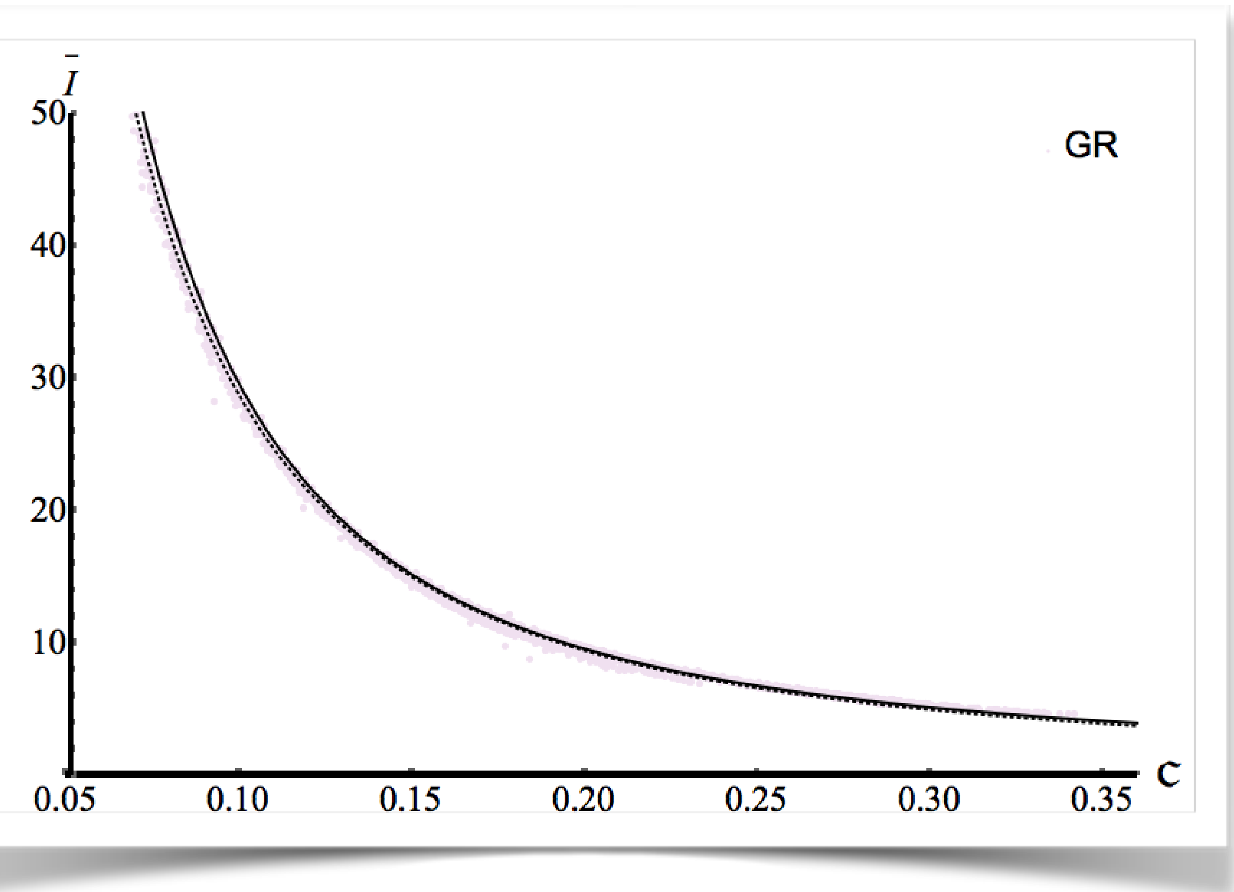


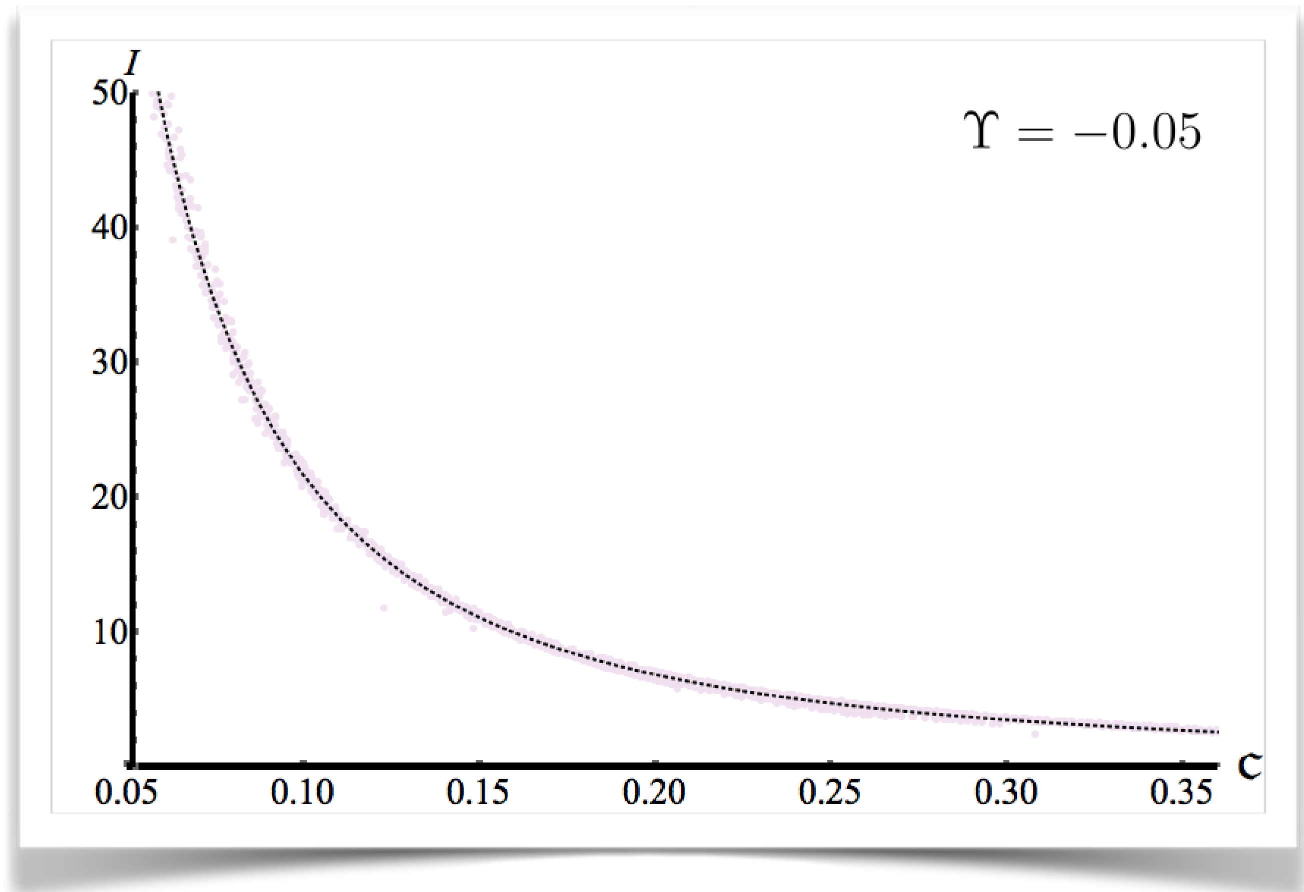
32 equations of state

[EB, Koyama, Langlois, Saito, Sakstein'16]

Slow rotating neutron stars

$\bar{I} - \mathcal{C}$ relation





Universal relation also holds in beyond Horndeski theory

[Sakstein, et al'17]

Conclusions

- In modified gravity theories properties of compact change.
- We can look for observational effects of modified gravity
- Constraints on modification of gravity
- Benchmarks for testing GR