Scalar-Tensor theories of gravity after GW170817

Gianmassimo Tasinato

Modified gravity

Why modify gravity?

`attempt to shed light on DE and DM by changing the gravitational sector`

$$\boxed{G_{\mu\nu}} = T_{\mu\nu}$$

Simplest possibility

`add` **single scalar field** `that participates to gravitational interactions and also affects cosmological dynamics`

Modified gravity

Simplest possibility

add **single scalar field** that participates to gravitational interactions and also affects cosmological dynamics

- Brans-Dicke, quintessence
- $K(X)$ theories
- Galileons/Horndeski
- Beyond Horndeski, EST/DHOST
- ????

Derivative self-interactions and couplings with scalar-gravity
no Ostrogradsky instabilities

(Beyond) Horndeski

$$L_2 \equiv G_2(\phi, X)\ , \qquad L_3 \equiv G_3(\phi, X)\,\Box\phi\ ,$$

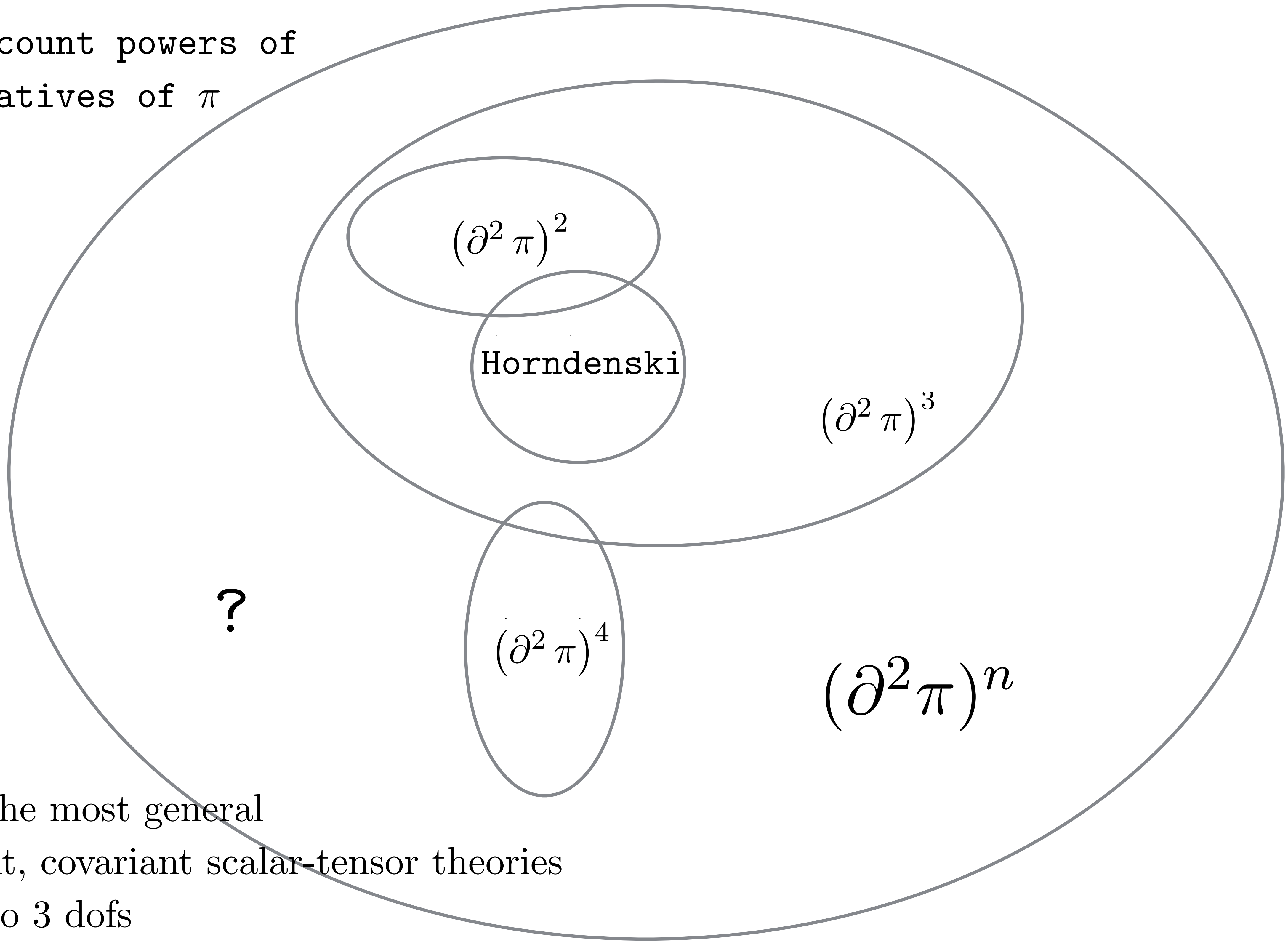
$$L_4 \equiv G_4(\phi, X)\,{}^{(4)}R - 2G_{4,X}(\phi, X)(\Box\phi^2 - \phi^{\mu\nu}\phi_{\mu\nu})$$
$$+ F_4(\phi, X)\varepsilon^{\mu\nu\rho}{}_{\sigma}\,\varepsilon^{\mu'\nu'\rho'\sigma}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\ ,$$

$$L_5 \equiv G_5(\phi, X)\,{}^{(4)}G_{\mu\nu}\phi^{\mu\nu}$$
$$+ \frac{1}{3}G_{5,X}(\phi, X)(\Box\phi^3 - 3\,\Box\phi\,\phi_{\mu\nu}\phi^{\mu\nu} + 2\,\phi_{\mu\nu}\phi^{\mu\sigma}\phi^{\nu}{}_{\sigma})$$
$$+ F_5(\phi, X)\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}\ ,$$

$$\boxed{X \equiv g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi}$$

Most general scalar-tensor theory?

Criterion: count powers of
second derivatives of π



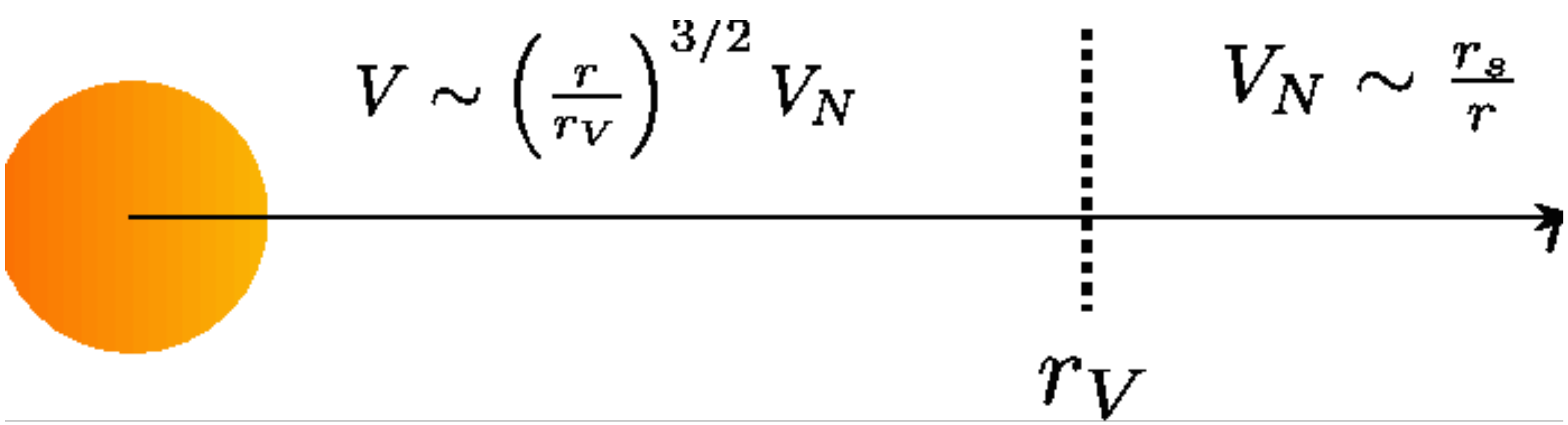
We don't know the most general
form of consistent, covariant scalar-tensor theories
propagating up to 3 dofs

Why should we care ?

- Cosmological solutions that **self-accelerate** with no need of a cosmological constant

  $\rightarrow$ Distinctive dynamics of cosmological fluctuations (growth of structure), testable with future surveys

- Automatic implementation of Vainshtein screening mechanism, to evade solar system constraints on deviations from GR



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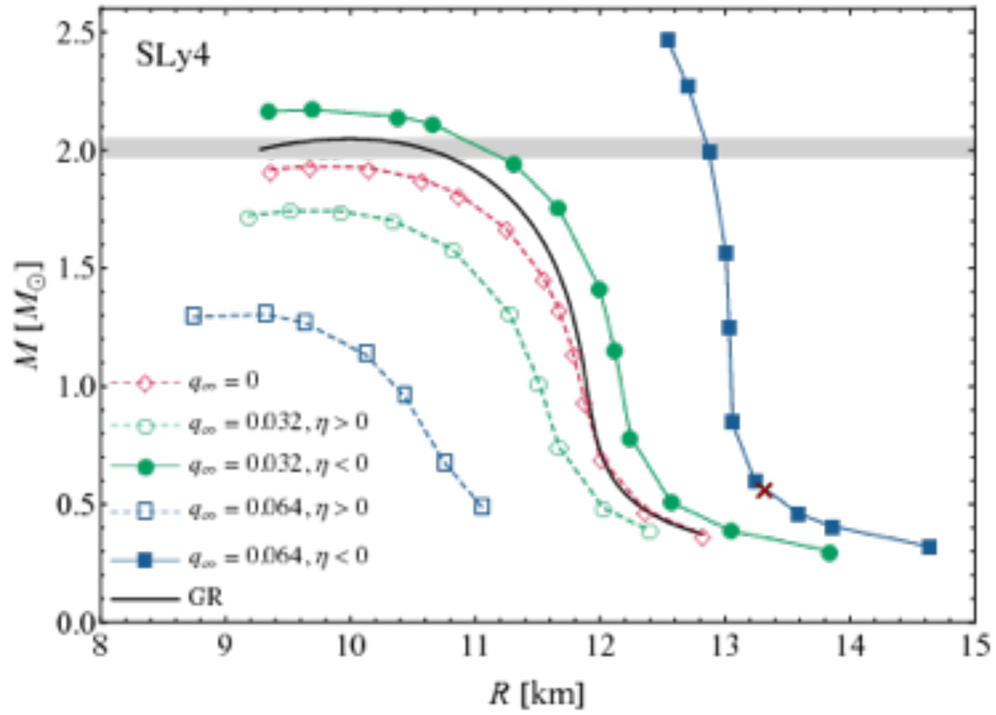
- Rich phenomenology for compact objects

  – Black holes with scalar hairs, and distinctive features

  – Neutron stars more compact and/or more massive than in GR



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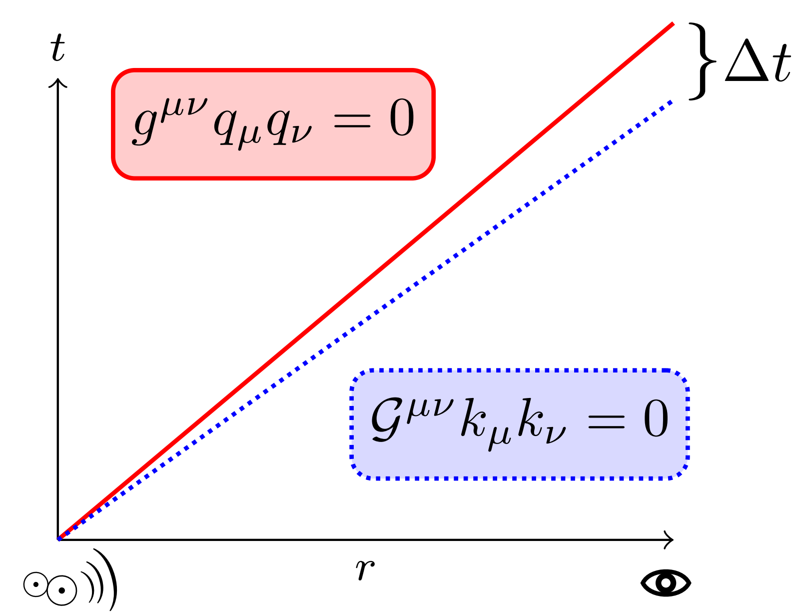
- **Generically,** $c_T < 1$



Implications of the Neutron Star Merger GW170817 for Cosmological Scalar-Tensor Theories

Jeremy Sakstein[1,*] and Bhuvnesh Jain[1,†]

Dark Energy after GW170817

Paolo Creminelli[1] and Filippo Vernizzi[2]

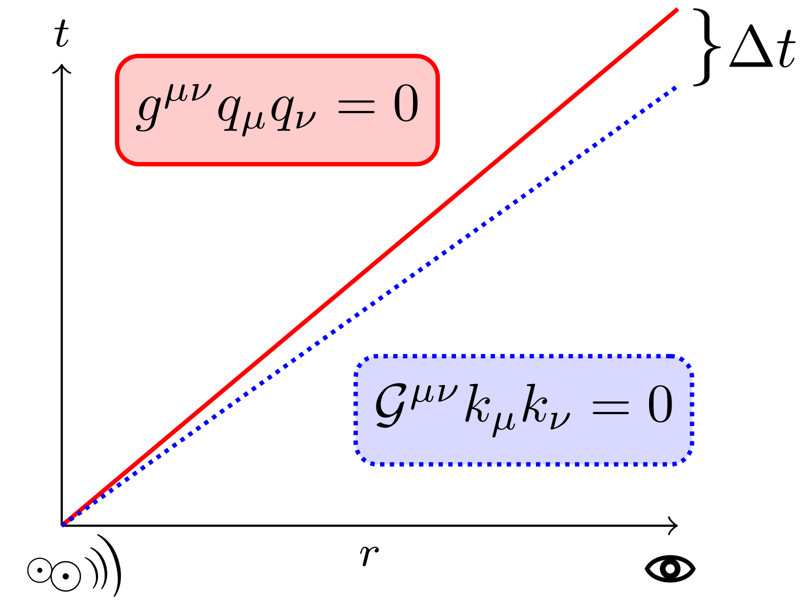
Dark Energy after GW170817

Jose María Ezquiaga[1,2,*] and Miguel Zumalacárregui[2,3,†]

Strong constraints on cosmological gravity from GW170817 and GRB 170817A.

T. Baker,[1] E. Bellini,[1] P. G. Ferreira,[1] M. Lagos,[2] J. Noller,[3] and I. Sawicki[4]

Kinetic mixing scalar-gravity



$$L_2 \equiv G_2(\phi, X)\,, \qquad L_3 \equiv G_3(\phi, X)\,\Box\phi\,,$$

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$\Downarrow$

Derivative couplings graviton to scalar

change c_T

Who survives to $(c^2 - c_T^2)/c^2 < 10^{-15}$??

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Very good! Finally a criterium to greatly reduce the size of parameter space

Who survives to $(c^2 - c_T^2)/c^2 < 10^{-15}$??

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&\quad + F_5(\phi, X)\varepsilon^{\mu\nu\rho\sigma}\varepsilon^{\mu'\nu'\rho'\sigma'}\phi_\mu\phi_{\mu'}\phi_{\nu\nu'}\phi_{\rho\rho'}\phi_{\sigma\sigma'}\,,
\end{aligned}}$$

$$\blacktriangleright \quad G_{5,X} = 0\,, \qquad F_5 = 0\,,$$

$$2G_{4,X} - XF_4 + G_{5,\phi} = 0$$

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

Bad for compact objects

Who survives to $(c^2 - c_T^2)/c^2 < 10^{-15}$??

$$\left.\begin{array}{ll} G_{5,X} = 0\,, & F_5 = 0\,, \\ & \\ 2G_{4,X} - XF_4 + G_{5,\phi} = 0 & \end{array}\right\}$$

no (symmetry)
reason to select
this combination

▼

$$\boxed{\begin{aligned} L_{c_T=1} &= G_2(\phi,X) + G_3(\phi,X)\Box\phi + B_4(\phi,X)\,{}^{(4)}R \\ &- \frac{4}{X}B_{4,X}(\phi,X)(\phi^\mu\phi^\nu\phi_{\mu\nu}\Box\phi - \phi^\mu\phi_{\mu\nu}\phi_\lambda\phi^{\lambda\nu})\,, \end{aligned}}$$

What to do?

Options:

1

$$\cancel{2G_{4,X} - XF_4 + G_{5,\phi} = 0}$$

$$L_{c_T=1} = G_2(\phi, X) + \boxed{G_3(\phi, X)\Box\phi}$$

Full study of consequences of this reduced action, not excluded by GW081708

- Screening mechanisms still apply (cubic Galileon)
- Consequences for BHs and neutron stars
  (still not clear if any difference from BransDicke in this respect)

2 . . . or find good reasons to continue to work on more complicated theories

What about massive gravity?

dRGT is consistent covariant theory of massive gravity; Hassan-Rosen extended to bigravity

$$S=\int \mathrm{d}^4x\left[M_P^2\sqrt{-g}\,R[g]+\sqrt{-g}\,P_g(X,\varphi)+2\sqrt{-g}\,m^2M^2V+M_f^2\sqrt{-f}\,R[f]\right]$$

$$V=\sum_{n=0}^{4}\beta_n\,\mathcal{E}_n(\sqrt{g^{-1}f})$$

$$\mathcal{E}_0(\mathbb{X})=1,\quad \mathcal{E}_1(\mathbb{X})=\mathrm{Tr}(\mathbb{X})\equiv[\mathbb{X}],\quad \mathcal{E}_2(\mathbb{X})=\frac{1}{2}\left([\mathbb{X}]^2-[\mathbb{X}^2]\right),$$

$$\mathcal{E}_3(\mathbb{X})=\frac{1}{3!}\left([\mathbb{X}]^3-3[\mathbb{X}^2][\mathbb{X}]+2[\mathbb{X}^3]\right),$$

$$\mathcal{E}_4(\mathbb{X})=\frac{1}{4!}\left([\mathbb{X}]^4-6[\mathbb{X}^2][\mathbb{X}]^2+8[\mathbb{X}^3][\mathbb{X}]+3[\mathbb{X}^2]^2-6[\mathbb{X}^4]\right).$$

What about massive gravity?

dRGT is consistent covariant theory of massive gravity;
Hassan-Rosen extended to bigravity

$$\boxed{E^2 = k^2 + m^2}$$ **modified dispersion relation**

$$or\ v^2 = 1 - \frac{m^2}{E^2}$$

Bounds:

$m < 10^{-22} eV$ from GW150914 — Phase difference in waveforms.

$m < 10^{-22} eV$ — from time-delay of GW081708

(not competitive with solar system constrains $m < 10^{-33} eV$)

Survived to GW081708! (But many other problems to address)