Modifying Gravity II

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source of acceleration?

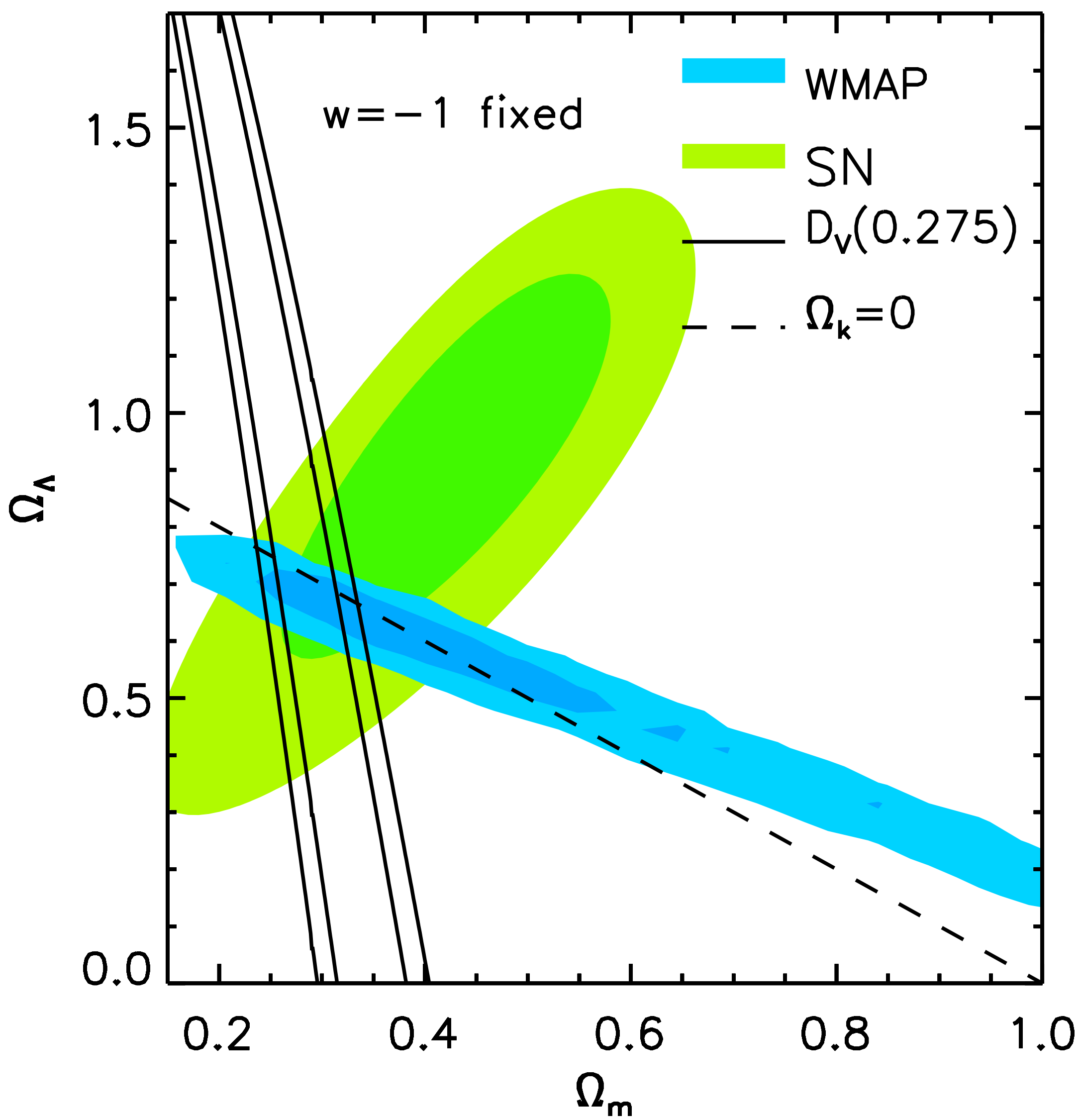
✦ Einstein equations

$$G_{\mu\nu} = 8\pi G\, T^{(m)}_{\mu\nu} - \Lambda g_{\mu\nu}$$

Geometry — Matter — Dark Energy

Modify gravity?

Add exotic matter?



Percival et al. '09

modifying gravity

Aim: to generalize Einstein equations to explain the acceleration of the Universe without explicit introduction of extra fields (Dark Energy)

Problem: we want to recover GR at short distances (inside the solar system) while modifying gravity at large distances

Normally, when modifying gravity,
additional degree(s) of freedom appear !

Mechanisms for recovering GR:

➡Chameleon mechanism

➡k-mouflage (Vainshtein) mechanism

chameleon effect

modifying the Einstein-Hilbert term

- A way to get acceleration of the Universe (Dark Energy):

$$S = \frac{M_P^2}{2}\int d^4x\sqrt{-g}\,R + S_m[\Phi_m; g_{\mu\nu}],$$

$$\Downarrow$$

$$S = \frac{M_P^2}{2}\int d^4x\sqrt{-g}\,f(R) + S_m[\Phi_m; g_{\mu\nu}],$$

so the dynamics is different compared to GR

scalar-tensor theories

Another way to modify gravity -- add nonminimally coupled scalar

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}\left(\nabla\phi\right)^2 - V(\phi)\right] + S_m[\Psi_m; \mathcal{A}^2(\phi)g_{\mu\nu}]$$

Fifth force due to the nonminimal coupling => modified dynamics!

f(R) by conformal transformation ->
particular form of the scalar-tensor theory

$$\mathcal{A}^2(\phi) = \exp(-\phi/\sqrt{6}M_P)$$

f(R) inflation

$$R \to R + \frac{R^2}{M^2}$$ inflation *Starobinsky'80*

modification of gravity in UV

by conformal transformation one can see there is
- helicity-0 graviton and
- a scalar field "scalaron" (driving inflation)

f(R) dark energy

$$R \to R - \frac{M^{2(n+1)}}{R^n}$$ Dark Energy *Carroll et.al.'03*

modification of gravity in IR

- Fast tachyonic instability, *Dolgov,Kawasaki'03*
- $\gamma = 1/2$ (need $\gamma = 1$)

- because of the fifth force!

- need a mechanism to screen locally the additional helicity-0 interaction

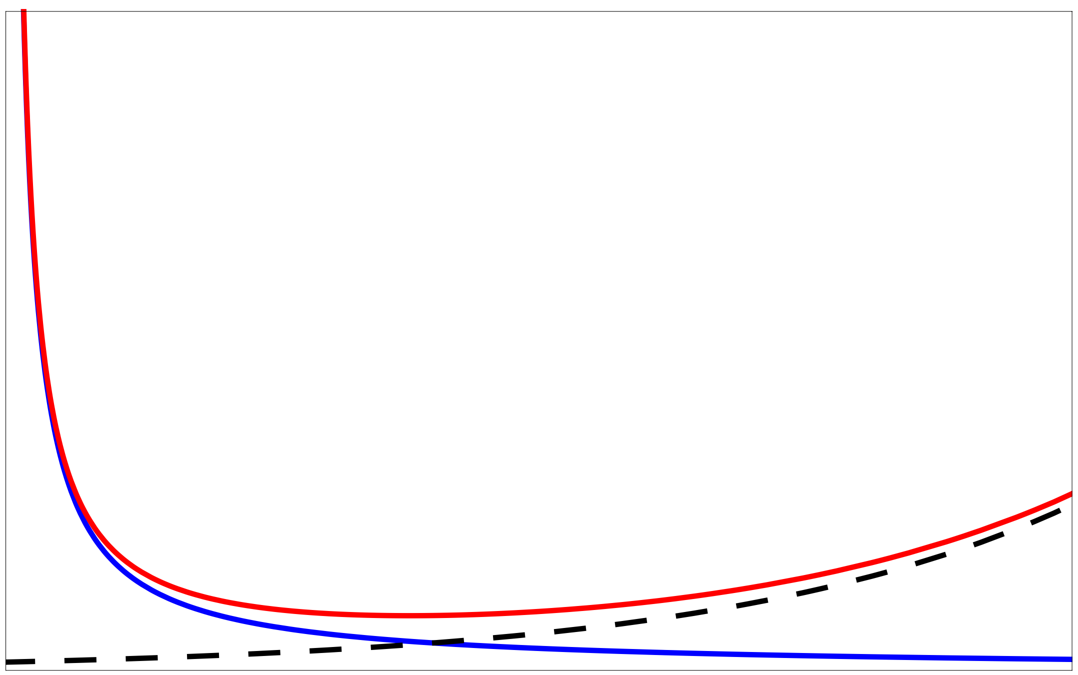
Chameleon effect in scalar-tensor theory

- Chameleon effect in scalar-tensor theory, Khoury,Weltman'03

$$S = \int d^4x \sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right] + S_m[\Psi_m; e^{\beta\phi/M_P} g_{\mu\nu}]$$

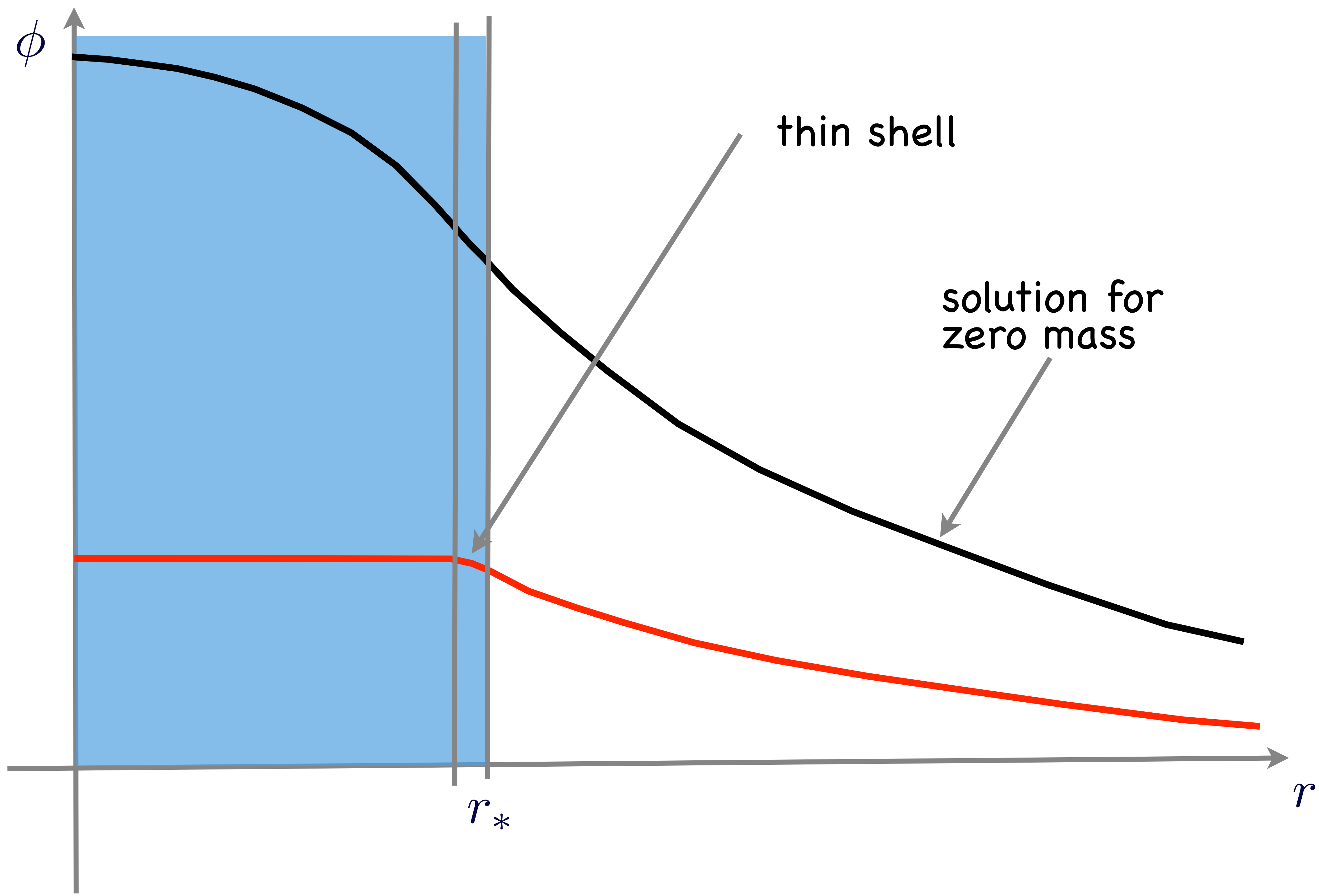
$$\Box\phi = -\frac{dV}{d\phi} - \frac{\beta}{M_P}T^{(m)}$$

scalar field moves
in the effective potential



$$V_{\rm eff} = V + \frac{1}{4}e^{4\beta\phi/M_P}(\tilde{\rho} - 3\tilde{P})$$

Why does the Chameleon work?



Vainshtein (k-mouflage) effect

k-mouflage

For the Vainshtein mechanism to work it is (generically) sufficient to have a non-linear kinetic term ("k-mouflage" gravity),

$$S = M_P^2 \int d^4x \sqrt{-g} \left[(1+\varphi)\frac{R}{2} + K(\varphi, \partial\varphi, \partial^2\varphi, \ldots) \right] + S_{\rm matter}$$

EB, Deffayet, Ziour et al'09

$$\partial^2 h + \partial^2 \varphi = M_{\rm P}^{-2} T$$

$$\partial^2 h + \mathcal{E}_\varphi = 0$$

$\Rightarrow$

$$\partial^2 \varphi + \mathcal{E}_\varphi = M_{\rm P}^{-2} T$$

$$\partial^2 \varphi = M_{\rm P}^{-2} T$$

$$h \neq h_{\rm GR}$$

$$\partial^2 \varphi \ll \mathcal{E}_\varphi = M_{\rm P}^{-2} T$$

$$h \approx h_{\rm GR}$$

k-mouflage

$$h_{\mu\nu} \sim \nu \sim \lambda \sim \frac{R_S}{R}$$ - metric functions in the linear regime

$$\phi \sim \frac{R_S}{m^2 R}$$ - scalar in the linear regime

$$K_{\rm dom}(\phi) \sim m^{2n-l}\partial^l \phi^n$$ - strongest scalar self-interaction

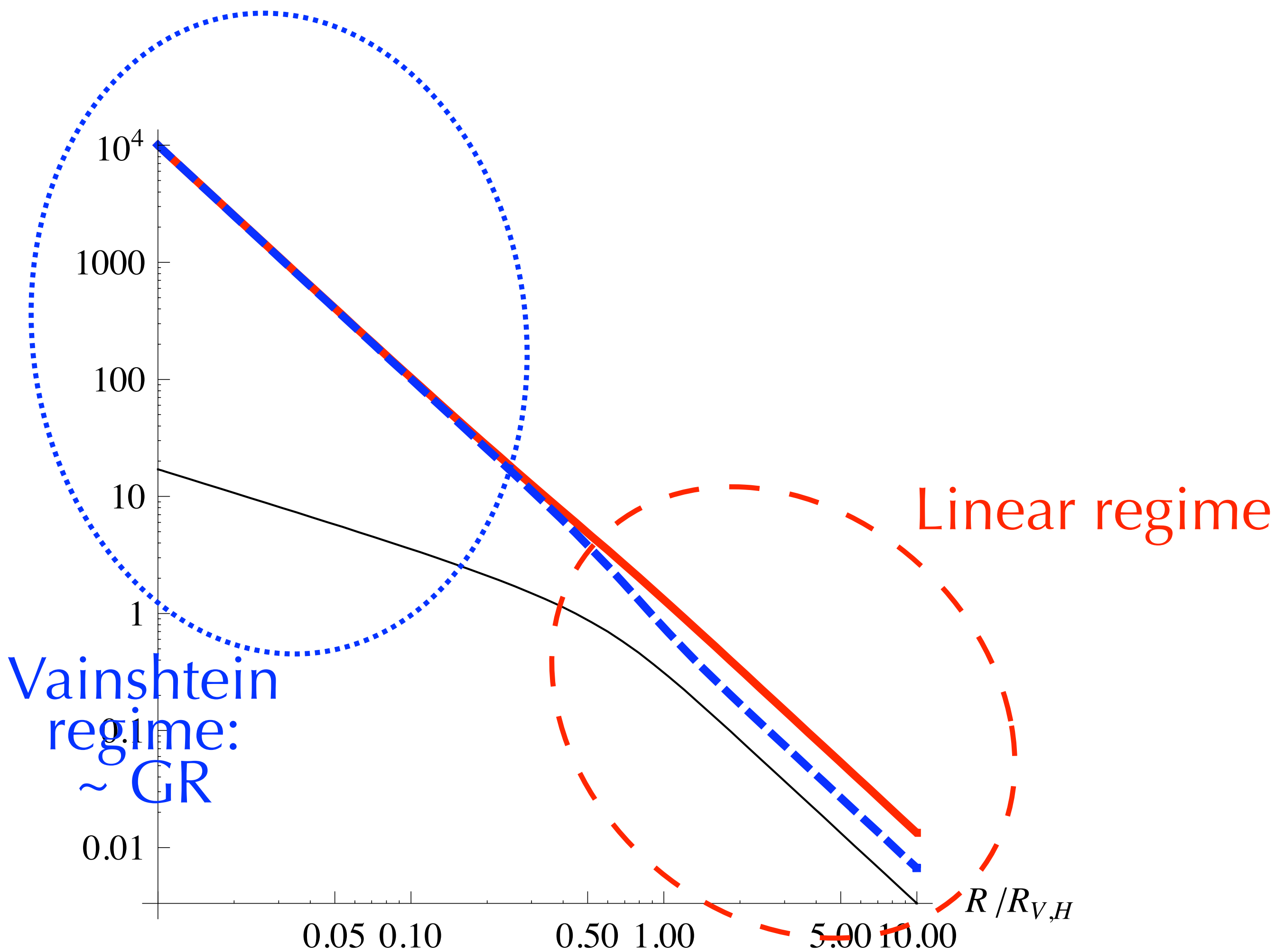
$$\frac{K(\phi)}{h\Box\phi} \sim \left(\frac{R_V}{R}\right)^{n+l-4}$$

$$R_V = \left(R_S^{n-2} m^{2-l}\right)^{1/(n+l-4)}$$

linear regime breaks down for $R < R_V$

k-mouflage

$$H(\phi)_{MG} = \frac{\alpha}{2}(\Box\phi)^3 + \frac{\beta}{2}(\Box\phi\,\phi_{;\mu\nu}\phi^{;\mu\nu}),$$
$$H(\phi)_{DGP} = m^2\Box\phi\,\phi_{;\mu}\phi^{;\mu},$$
$$H(\phi)_K = K(X), \quad \text{with} \quad X = m^2\phi_{;\mu}\phi^{;\mu}$$



The Vainshtein mechanism is valid for a broad class of models, including Horndeski theory

observational consequences

Fifth force on Earth

Khoury,Weltman'04

Parametrized fifth force: $V(r) = -\alpha \frac{M_1 M_2}{8\pi M_P^2} \frac{e^{-r/\lambda}}{r}$

For $\lambda \sim 10\text{cm}$ the tightest experimental constraint gives $\alpha < 10^{-3}$

Two bodies with no thin shell naturally $\alpha \sim 1$

Thus the test bodies should have thin shells

Atmosphere must have a thin shell
+
Fifth force experiments

→ $M \sim 10^{-3}\text{eV}$ for $V(\phi) = M^{4+n}\phi^{-n}$

Solar system tests

Khoury,Weltman'04

Lunar Laser Raging: $$\frac{|a_{Moon} - a_{Earth}|}{a_N} < 10^{-13}$$

Chameleon fifth force is suppressed due to the thin shell effect $$\frac{|a_{Moon} - a_{Earth}|}{a_N} < \beta^2 \times 10^{-14}$$

Post-Newtonian corrections: $$\beta_{eff} < 3\beta \times 10^{-7}$$

$$3 + 2\omega_{BD} = \frac{1}{2\beta_{eff}^2}$$

Cosmological tests

Brax,van de Bruck,Davis,Khoury,Weltman'04

Constraints from BBN, CMB.

Passed by choice of initial conditions for the value and velocity of the chameleon field

conclusions

- Modification of gravity on large scales requires restoring of General Relativity on small scales.
- There are basically 2 mechanisms to restore GR at small scales
- The Chameleon mechanism is based on non-linearity in the potential term and provides "thin-shell" effect
- Vainshtein (or k-mouflage) mechanism is based on non-linearity of a kinetic term.
- The theoretical models should pass local gravity tests.