Le phénomène d'écrantage dans les scénarios de gravité modifiée

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Motivations

Accelerated expansion of the Universe ⟹

- dark energy
- modified gravity

Most of the models involve one or more scalar fields, which experience self-interactions and may also interact with matter.

⟹ "Fifth force" that has not been seen in local gravity experiments !

- the scalar field does not interact with baryonic matter components
- there is a mechanism to suppress the fifth force in local environments

⟹ "Screening" mechanisms associated with non-linearities of the system.

Khoury (1011.5909)

Two approaches:

- Focus on the cosmological behavior and on low-order (linear) perturbation theory.

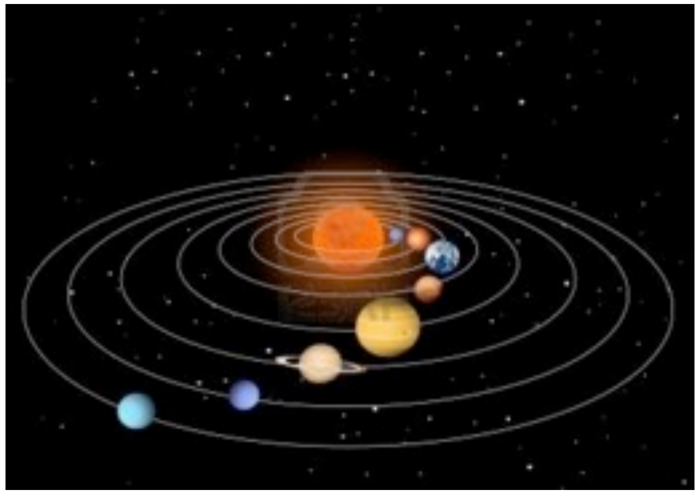
  One may study specific models or build general frameworks (EFT) that apply to a large class of theories. Gubitosi, Piazza & Vernizzi (JCAP 032, 2013)

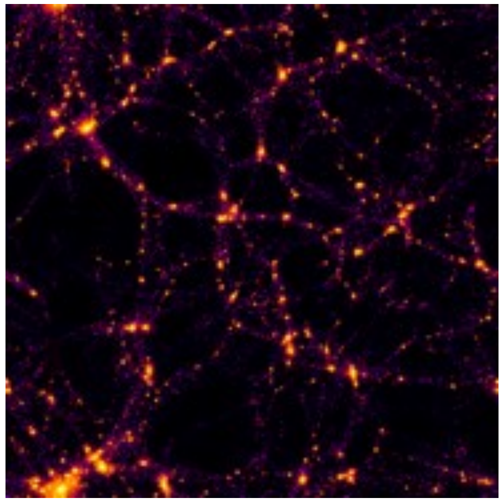
  The cosmological regime may be decoupled from the small-scale regime.

- Look for explicit models that make sense from local to cosmological scales.

  One needs to specify the model and its nonlinear screening mechanism. Combining Solar System and cosmological tests can provide strong constraints on the model.

  Gravity acts on all scales: it would be nice to have unified scenarios (or at least to see how one can build unified models).





Deviations from Newton's law are parametrized by

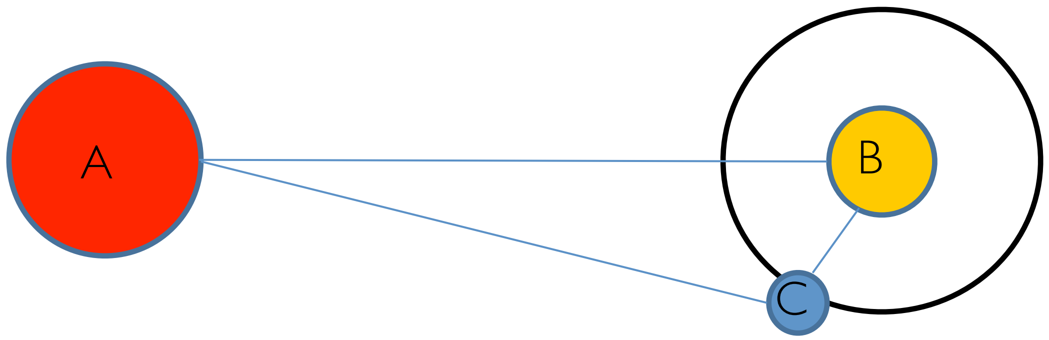
$$\Phi_N = -\frac{G_N M}{r}(1 + 2\beta^2 e^{-r/\lambda})$$

For long-range forces with large λ , the tightest constraint on the coupling β comes from the Cassini probe measuring the Shapiro effect (time delay):

Bertotti et al. (Nature 425, 374, 2003)

$$\boxed{\beta^2 \leq 4 \times 10^{-5}}$$

Violation of the equivalence principle



Lunar Laser Ranging experiment

$$\eta_{BC} \equiv \left| \frac{a_C - a_B}{a_C + a_B} \right|$$

$$\eta_{\mathrm{Moon-Earth}} \leq 10^{-13}$$

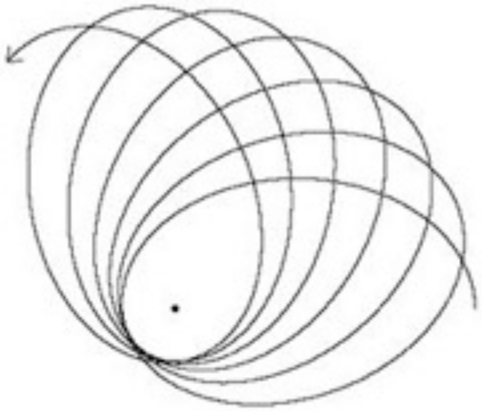
Will (Liv. Rev. Relat. 17, 4, 2014)

This experiment also constrains the time variation of the local Newton's constant:

$$\left| \frac{d \ln G_N}{dt} \right| < 10^{-12}\ \mathrm{yr}^{-1}$$

Williams et al. (PRL 93, 261101, 2004)

It also constrains the anomalous perihelion of the Moon:



$$|\delta\theta| < 2 \times 10^{-11}$$

Williams et al. (Class. Quant. Grav. 29, 184004, 2012)

Scalar-tensor theories

I- DEFINITIONS

A simple way to modify GR is to introduce 2 metrics:

- the first metric enters the Einstein-Hilbert action (gravitational part) $\tilde{g}_{\mu\nu}$
- the second metric enters the matter action (dynamical part) $g_{\mu\nu}$

$$S = \int d^4x \, \sqrt{-\tilde{g}} \frac{\tilde{M}_{\rm Pl}^2}{2} \tilde{R} + S_m(\psi_{\rm m}^{(i)}, g_{\mu\nu}) + \ldots$$

The relationship between these two metrics is set by additional degrees of freedom, such as a scalar field:

$$g_{\mu\nu} = C(\varphi, X)\tilde{g}_{\mu\nu} + D(\varphi, X)\partial_\mu\varphi\partial_\nu\varphi \qquad X = -\frac{1}{2}\,\partial^\mu\varphi\,\partial_\mu\varphi$$

Bekenstein (1993)

Simple case of a conformal coupling:

$$S = \int d^4x \, \sqrt{-\tilde{g}} \left[\frac{\tilde{M}_{\rm Pl}^2}{2} \tilde{R} + \tilde{\mathcal{L}}_\varphi(\varphi) \right] + S_m(\psi_{\rm m}^{(i)}, g_{\mu\nu}) \qquad g_{\mu\nu} = A^2(\varphi)\,\tilde{g}_{\mu\nu}$$

Coupling matter -- scalar field through the
Jordan-metric conformal rescaling

$$\beta \equiv \tilde{M}_{\rm Pl} \frac{d \ln A}{d\varphi}$$

II- GENERAL FEATURES

Newton's constant becomes time dependent: $\nabla^2 \tilde{\Psi}_{\rm N} = 4\pi A^2(\bar{\varphi}(t)) \tilde{\mathcal{G}}_{\rm N} \delta\rho_{\rm m}$

The gravitational potentials seen by matter receive an additional contribution:

$$ds^2 = -a^2(1+2\Phi)d\tau^2 + a^2(1-2\Psi)d\mathbf{x}^2 \qquad g_{\mu\nu} = A^2 \tilde{g}_{\mu\nu}$$

$$\boxed{\Phi = \tilde{\Psi}_{\rm N} + \frac{\delta A}{A}, \quad \Psi = \tilde{\Psi}_{\rm N} - \frac{\delta A}{A}} \Rightarrow \quad \Phi \neq \Psi \qquad \frac{\Phi + \Psi}{2} \neq \Phi$$

dynamical and lensing masses are different

- If A, hence $\mathcal{G}_{\rm N}$ change too much with time, this can modify BBN and orbits of planets and stars (binary pulsars and Lunar Ranging exp. testing Equiv. princ.)

$\left|\frac{\Delta A}{A}\right| \leq 0.1$ since BBN, therefore $A \simeq 1$ in these models.

- Screening: we wish to suppress the gradients of the scalar field

Screening mechanisms

Theories with a single nearly massless scalar field on large scales, with second-order equations of motion.

Khoury (1011.5909)

Brax & PV (PRD 90, 023507, 2014)

➡ Screening mechanisms may be classified in 3 categories:

Write the Lagrangian of the scalar fluctuations up to quadratic order as:

$$\mathcal{L} = -\frac{Z(\varphi_0)}{2}(\partial\delta\varphi)^2 - \frac{m^2(\varphi_0)}{2}(\delta\varphi)^2 - \beta(\varphi_0)\frac{\delta\varphi}{M_{\rm Pl}}\delta\rho_m$$

Vainshtein / K-mouflage

Chameleon

Damour-Polyakov

We can suppress the gradients of the scalar field (in dense environments) by:

- decreasing the coupling to matter ➡ no fifth force
- increasing the mass of the scalar field
- increasing the inertia of the scalar field (prefactor of the kinetic term) ➡ the field is frozen

These 3 mechanisms give rise to different behaviors.

$$\mathcal{L} = -\frac{Z(\varphi_0)}{2}(\partial\delta\varphi)^2 - \frac{m^2(\varphi_0)}{2}(\delta\varphi)^2 - \beta(\varphi_0)\frac{\delta\varphi}{M_{\rm Pl}}\delta\rho_m$$

Chameleon and Damour-Polyakov

$Z(\varphi) = 1$

linear order + quasi-static approximation

$$\frac{\delta\varphi}{M_{\rm Pl}} = -\frac{\beta(\varphi_0)\delta\rho_m}{M_{\rm Pl}^2\left(m^2(\varphi_0)+\frac{k^2}{a^2}\right)}$$

$$\Psi = \left[1 + \frac{2\beta^2(\varphi_0)}{1+m^2(\varphi_0)a^2/k^2}\right]\Psi_{\rm N}$$

GR is recovered on large (linear) scales, outside the Compton radius

Gravity is amplified on smaller scales by

$$1 + 2\beta^2$$

Vainshtein and K-mouflage mechanisms

$m = 0$

$$\frac{\delta\varphi}{M_{\rm Pl}} = -\frac{\beta(\varphi_0)a^2\delta\rho_m}{M_{\rm Pl}^2 Z(\varphi_0)k^2} = \frac{2\beta}{Z}\Psi_{\rm N}$$

$$\Psi = \left[1 + \frac{2\beta^2(\varphi_0)}{Z(\varphi_0)}\right]\Psi_{\rm N}$$

GR is not recovered on large linear scales

Gravity is amplified by

$$1 + 2\beta^2/Z$$

When the linear approximation breaks down: → screening

Small-scale linear regime: $\delta\varphi/M_{\rm Pl} \simeq 2\beta\Psi_{\rm N}$

the condition for screening, $|\delta\varphi| \sim |\varphi_0|$, reads as a condition on the value of Newton's potential

$$Z(\varphi) = 1 + a(\varphi)\frac{(\partial\varphi)^2}{\mathcal{M}^4} + b(\varphi)L^2\frac{\Box\varphi}{M_{\rm Pl}} + \ldots$$

K-mouflage

$$|\nabla\varphi| \gtrsim \mathcal{M}^2$$

gradient of Newton's potential

Vainshtein

$$\frac{|\nabla^2\varphi|}{M_{\rm Pl}} \gtrsim L^{-2}$$

curvature of Newton's potential

I- CHAMELEON SCENARIO

f(R) theories: $$S_{\mathrm{grav}} = \int d^4x\sqrt{-g}\frac{M_{\mathrm{Pl}}^2}{2}f(R)$$

GR: $$f(R) = R$$

This is equivalent to a scalar-tensor theory:

$$S = \int d^4x\sqrt{-\tilde{g}}\left[\frac{\tilde{M}_{\mathrm{Pl}}^2}{2}\tilde{R} - \frac{1}{2}(\partial\varphi)^2 - V(\varphi)\right] + S_m(\psi_m^{(i)}, g_{\mu\nu})$$

$$e^{-2\varphi/\sqrt{6}\tilde{M}_{\mathrm{Pl}}} = f', \quad V(\varphi) = \tilde{M}_{\mathrm{Pl}}^2\frac{Rf' - f}{2f'^2}$$

$$g_{\mu\nu} = e^{2\varphi/\sqrt{6}\tilde{M}_{\mathrm{Pl}}}\tilde{g}_{\mu\nu}$$

Hu & Sawicki (2007)

Because of the conformal coupling, there is an explicit coupling between matter and the scalar field. The KG eq. for the scalar field involves the effective potential:

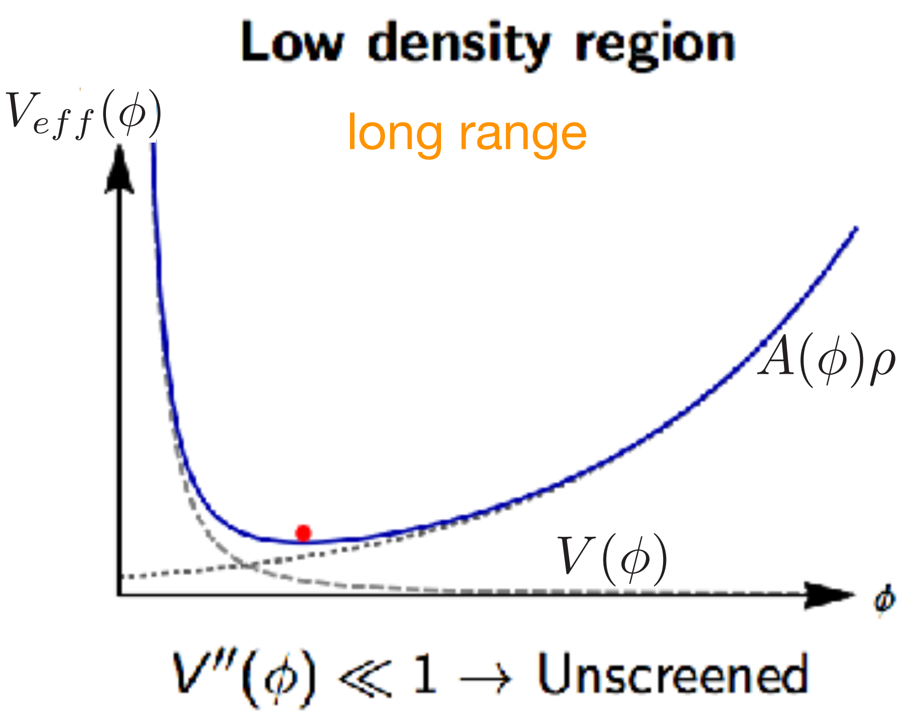
$$V_{\rm eff}(\varphi) = V(\varphi) + \rho[A(\varphi) - 1]$$

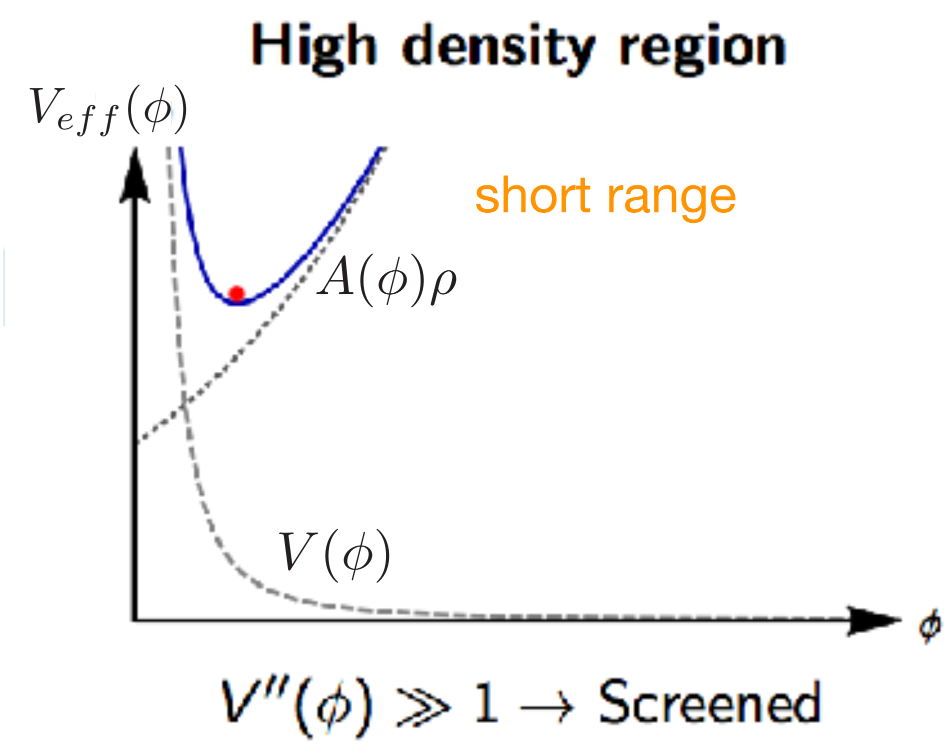
Khoury & Weltman (2004)

Brax et al. (2012)

Wang et al. (2012)

Typically: $V(\varphi) = \frac{M^{4+n}}{\varphi^n}$ $A(\varphi) = e^{\beta\varphi/\tilde{M}_{\rm Pl}}$

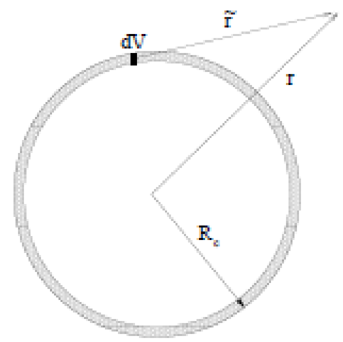




Mota (2016)

The minimum and curvature of the effective potential depend on the environment.

Thin-shell effect:



Khoury & Weltman (2004)

Brax (2016)

In a high-density object like a star, the scalar field becomes short-ranged. Only the surface of the object where the field has nonzero gradients contributes to the fifth force.

Screened and unscreened objects do not respond in the same fashion to a distant mass

→ violation of the strong equivalence principle

II- DAMOUR-POLYAKOV SCENARIO

Damour & Polyakov (1994)

A) Dilaton models

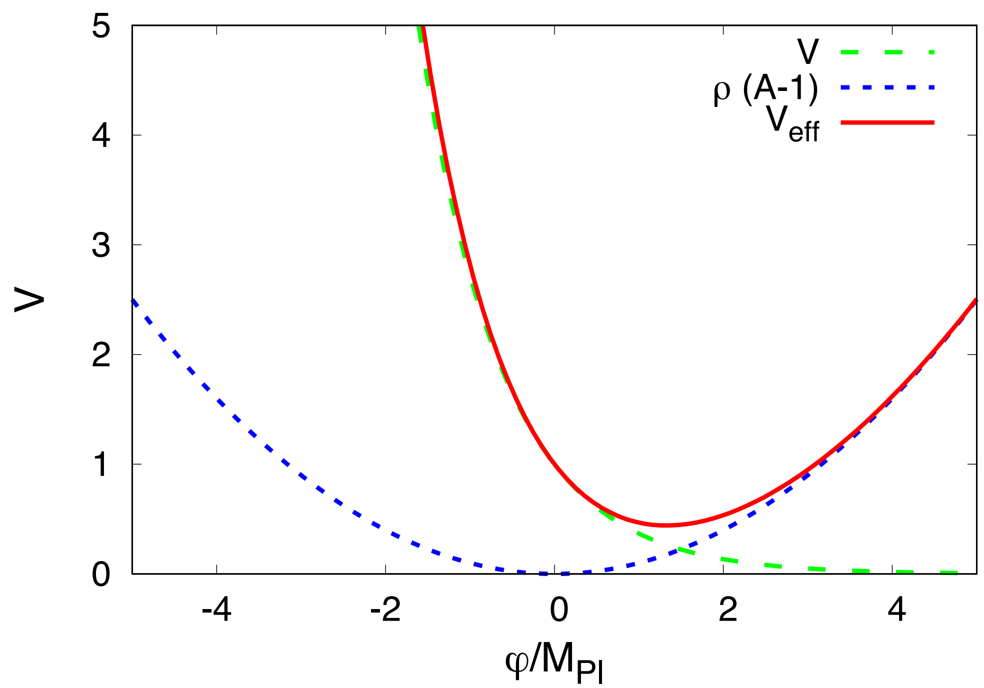
$$V_{\rm eff}(\varphi) = V(\varphi) + \rho[A(\varphi) - 1]$$

Typically: $V(\varphi) = V_0 e^{-\varphi/\tilde{M}_{\rm Pl}}$ $\quad A(\varphi) = 1 + \frac{A_2}{2\tilde{M}_{\rm Pl}^2}\varphi^2$

conformal function has a minimum

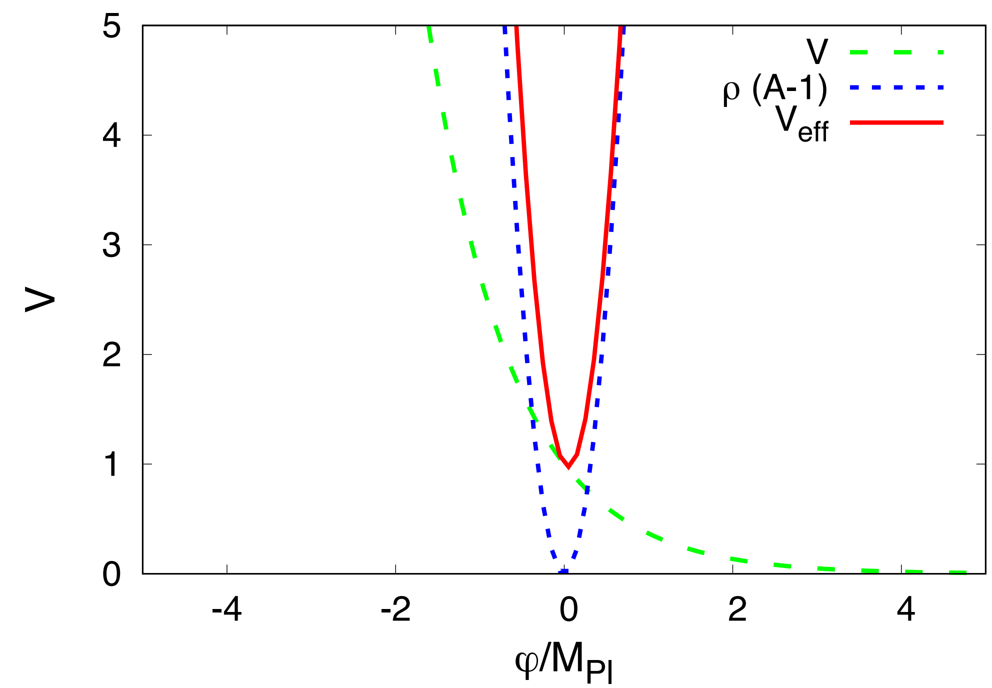
Low-density region

long range, large coupling



High-density region

short range, small coupling



$$\beta \equiv \tilde{M}_{\rm Pl} \frac{d \ln A}{d\varphi} \to 0$$

The coupling depends on the environment.

B) Symmetron models

$$V_{\rm eff}(\varphi) = V(\varphi) + \rho[A(\varphi) - 1]$$

Typically: $V(\varphi) = -\frac{\mu^2}{2}\varphi^2 + \frac{\lambda}{4}\varphi^4$

double well

$A(\varphi) = 1 + \frac{1}{2M^2}\varphi^2$

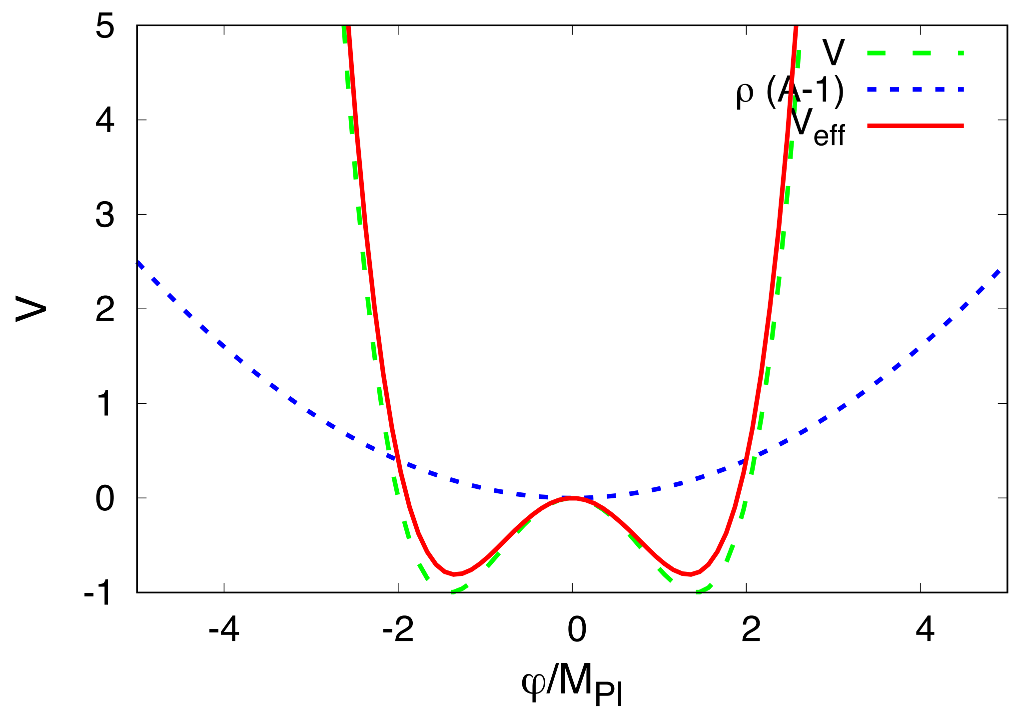
conformal function has a minimum

$$V_{\rm eff}(\varphi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\varphi^2 + \frac{\lambda}{4}\varphi^4$$

phase transition between low and high-density regions

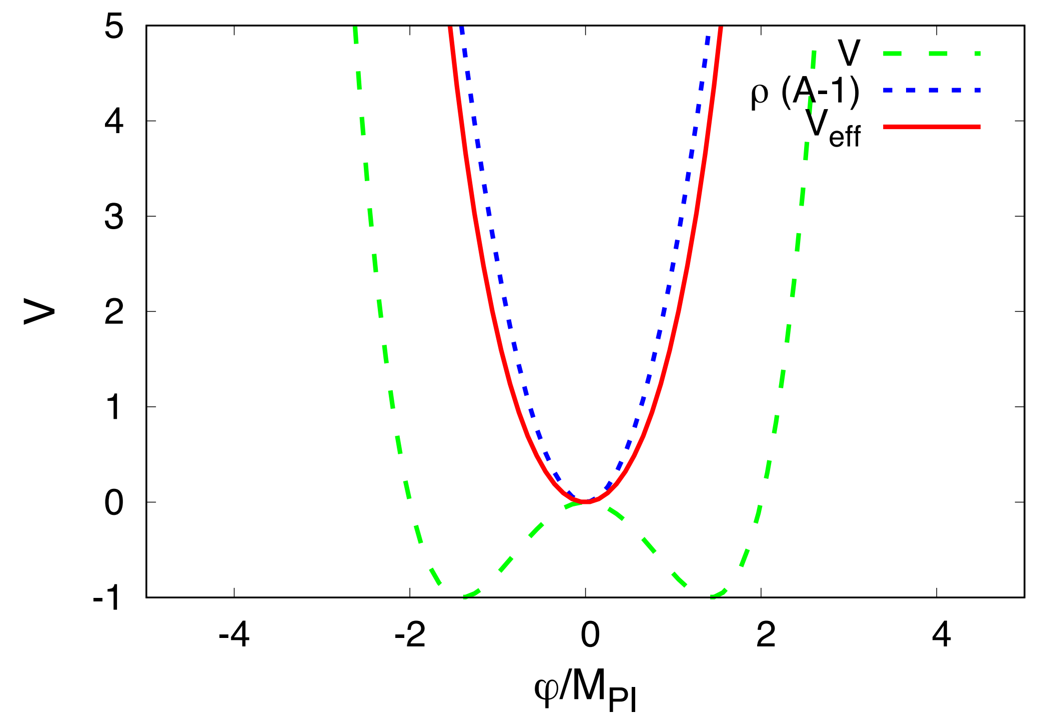
Low-density region

large coupling



High-density region

zero coupling



The coupling depends on the environment.

Hinterbichler & Khoury (2010)

Brax et al. (2012)

III- K-MOUFLAGE SCENARIO

Babichev et al. (2009)

Brax & V. (2014)

$$S = \int d^4x \sqrt{-\tilde{g}} \left[\frac{\tilde{M}_{\rm Pl}^2}{2} \tilde{R} + \mathcal{M}^4 K(\tilde{\chi}) \right] + S_m(\psi_{\rm m}^{(i)}, A^2(\varphi)\tilde{g}_{\mu\nu})$$

$$\tilde{\chi} = -\frac{1}{2\mathcal{M}^4} \partial^\mu \varphi \, \partial_\mu \varphi$$

In the linear regime the deviations from GR are set by: $\frac{2\beta^2}{\bar{K}'}$

Screening in the non-linear regime: $\bar{K}' \gg 1$

KG: $$\frac{d\varphi}{dr} K' \left(-\frac{1}{2\mathcal{M}^4} \left(\frac{d\varphi)}{dr} \right)^2 \right) = \frac{\beta M(<r)}{\tilde{M}_{\rm Pl} 4\pi r^2}$$

$$\frac{\beta}{\tilde{M}_{\rm Pl}} \frac{d\varphi}{dr} = \frac{2\beta^2}{K'} \frac{d\Psi_{\rm N}}{dr}$$

- far from the compact object:

$$\frac{d\Psi_{\rm N}}{dr} \to 0, \quad \frac{d\varphi}{dr} \to 0, \quad K' \to 1$$

gravity amplified by $1 + 2\beta^2$

- close to the compact object:

$$\frac{d\Psi_{\rm N}}{dr} \to \infty, \quad \frac{d\varphi}{dr} \to \infty, \quad K' \to \infty$$

5th force is negligible

Brax & V. (2014)

K-mouflage radius:

$$R_K = \left(\frac{\beta M}{4\pi \tilde{M}_{\rm Pl} \mathcal{M}^2} \right)^{1/2}$$

Inside R_K → we recover GR

Outside R_K → deviation from GR, gravity is amplified

No thin-shell effect !

$$\frac{d\varphi}{dr} K' \left(-\frac{1}{2\mathcal{M}^4} \left(\frac{d\varphi)}{dr} \right)^2 \right) = \frac{\beta M(< r)}{\tilde{M}_{\rm Pl} 4\pi r^2}$$

IV- VAINSHTEIN SCENARIO

The mechanism is similar to the K-mouflage case, except that it relies on the curvature rather than the gradient.

Cubic Galileon model: $$\mathcal{L}(\varphi) = -\frac{1}{2}(\partial\varphi)^2 - \frac{\partial^2\varphi}{2\Lambda^3}(\partial\varphi)^2 + \frac{\beta}{\tilde{M}_{\rm Pl}}\varphi T$$

We recover GR inside the Vainshtein radius: $$R_V = \left(\frac{3\beta M}{4\pi\tilde{M}_{\rm Pl}\Lambda^3}\right)^{1/3}$$

Vainshtein (1972)

Deffayet et al. (2011)

Nicolis, Rattazzi, Trincherini (2009)

V- COMPARISON

These 3 screening mechanisms appear at different scales and densities (different criteria).

Their effects are different:

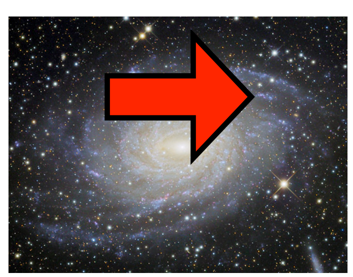
- recover GR at large scales (beyond Compton wavelenght) or not

- thin-shell effect or not

- time dependence of Newton's constant or not

short range

Chameleon:

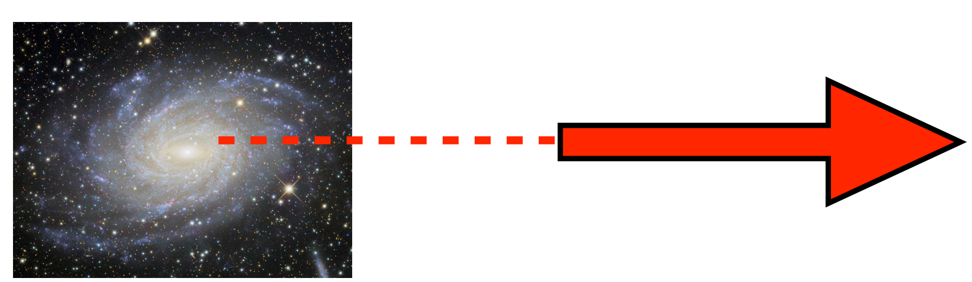


low amplitude

Damour-Polyakov (dilaton/symmetron):

damped within a characteristic radius

K-mouflage/ Vainshtein:



OBSERVATIONAL PROBES AND CONCLUSIONS

A) Deviations from LCDM on cosmological scales

Cosmological structures may probe the transition to the screening domain.

Deviation of the matter power spectrum on cosmological scales, for f(R) models.

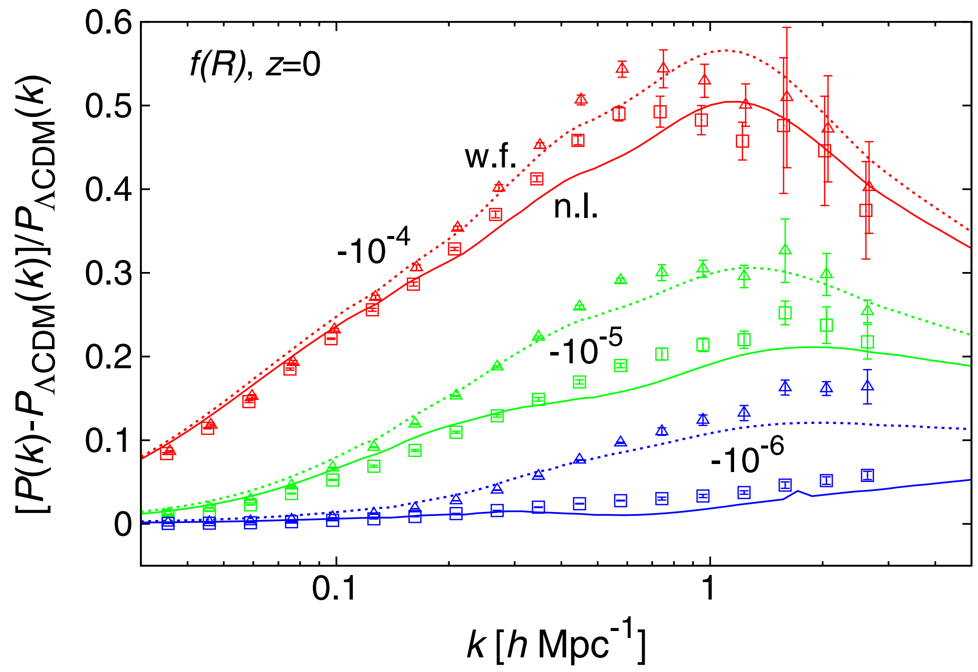
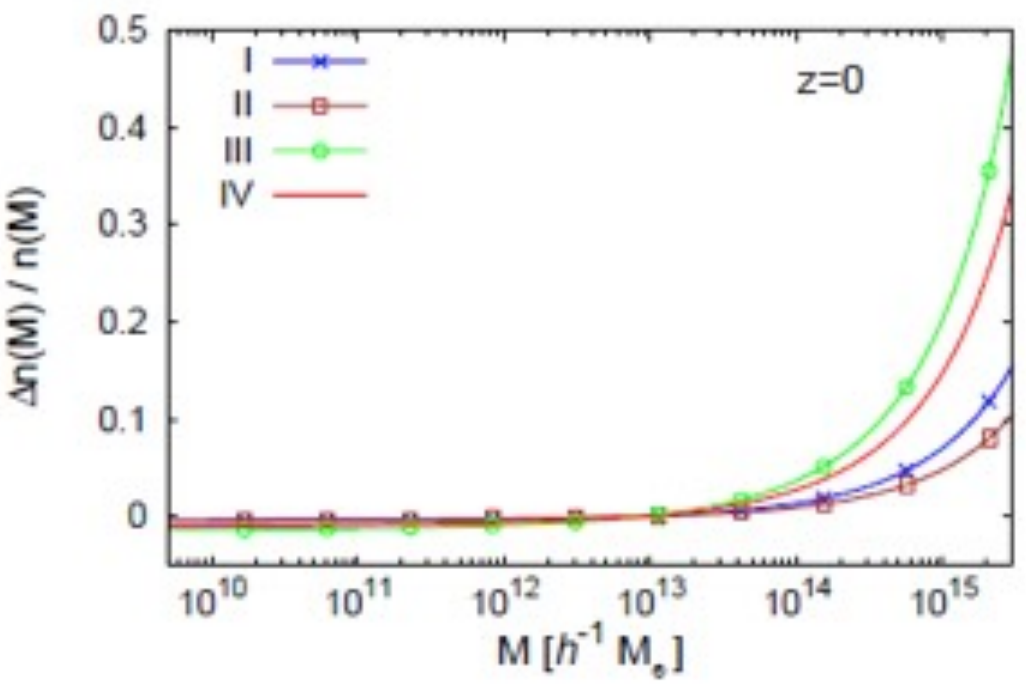


FIG. 13 (color online). Relative deviation from ΛCDM of the power spectrum in $f(R)$ theories, at redshift $z = 0$, for $n = 1$ and $f_{R_0} = -10^{-4}$, -10^{-5}, and -10^{-6}. In each case, the triangles and the squares are the results of the "no-chameleon" and "with-chameleon" simulations from Ref. [25], respectively. We plot the relative deviation of the nonlinear power spectrum without the chameleon effect (w.f., dotted lines) and with the chameleon effect (n.l., solid lines).

Deviation of the halo mass function, for K-mouflage models.



B) Deviations from GR on small scales

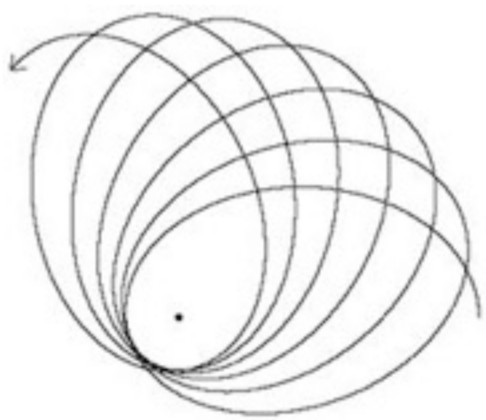
Screening ensures that the 5th force is much smaller than Newtonian gravity.

However, small deviations can still produce non-negligible effects,
for instance for the K-mouflage model:

anomalous perihelion of the Moon around the Earth:

$$\delta\theta = \pi r \frac{d}{dr}\left[r^2 \frac{d}{dr}\left(\frac{\epsilon}{r}\right)\right]$$

$$\epsilon = \frac{\delta \ln A}{\Psi_{\rm N}}$$



$$|\delta\theta| < 2 \times 10^{-11}$$

Williams et al. (Class. Quant. Grav. 29, 184004, 2012)

small force that does not behave as 1/r^2 → orbit does not close

One obtains: $\delta\theta = -8\pi \frac{\beta^2}{K'} \frac{\chi K''}{K' + 2\chi K''} \leq 2 \times 10^{-11}$ Brax & V. (2015)

→ The only way of satisfying the perihelion bound is to suppress K" in the Solar System.

C) Speed of gravitational waves

Many more complex models (e.g. galileons) give a speed c_T for gravitational waves that is different from the speed of light c.

If $c_T < c$ observed cosmic rays should have decayed away into gravitons by Cherenkov-like emission.

Detections of optical counterparts to gravitational waves sources would rule out models that give $c_T \neq c$

A multi-messenger event gives:

$$\boxed{\Delta t \sim \left(\frac{c_T}{c} - 1\right) \frac{d}{200\mathrm{Mpc}} 10^{17} \mathrm{seconds}}$$

Will (2014)

CONCLUSIONS

Light scalar fields involved in modified-gravity theories must be screened in the Solar System to satisfy very tight observational bounds.

There are 3 main mechanisms:

- chameleon
- Damour-Polyakov
- Kmouflage/Vainshtein

They operate in different manners, so that the screening transition appears at different scales and densities and behaves in different ways.

Observational probes can put constraints on these models and distinguish between the screening mechanisms.

- formation of cosmological structures (amplification/decrease of gravity)
- impact on velocity fields
- difference between dynamical and lensing mass (look for clusters of galaxies)
- violations of the equivalence principle
- non-universal coupling (baryons - dark matter)

Screening does not remove all modifications to gravity:

- speed of gravitational waves
- time dependence of Newton's constant (and of the Hubble expansion rate)
- scalar waves generated by catastrophic events (supernovae) could make screening unefficient and be detected ?