A Unified Description of Screened Modified Gravity

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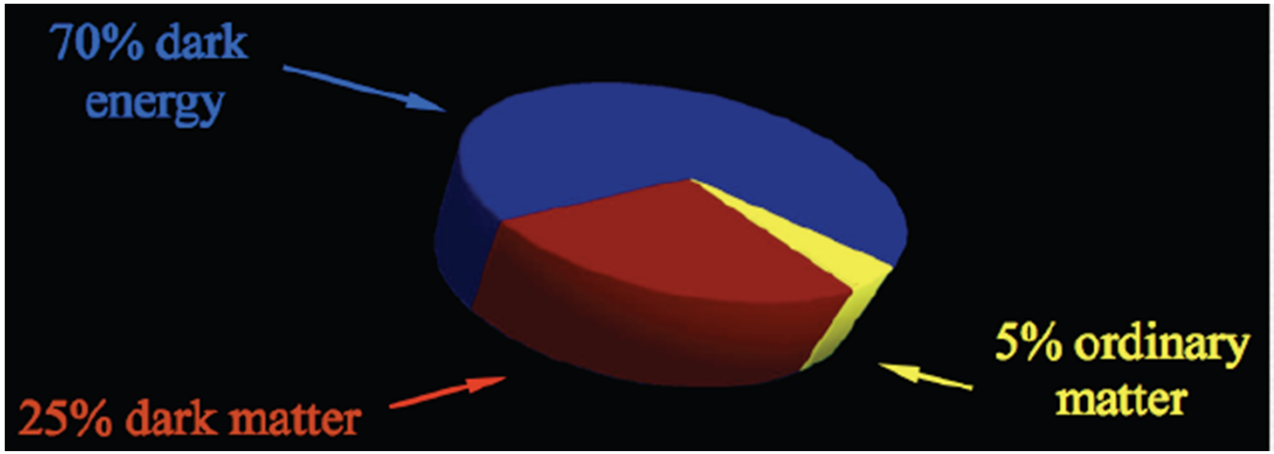
Outline

1) Dark energy or modified gravity: models and unified description

2) Screening or not screening: seeing modified gravity with microscope

3) Seeing modified gravity in the sky

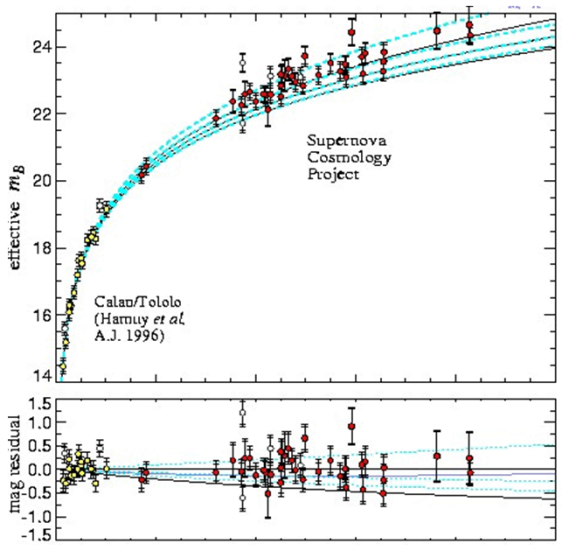
The Big Puzzle



Evidence: The Hubble Diagram

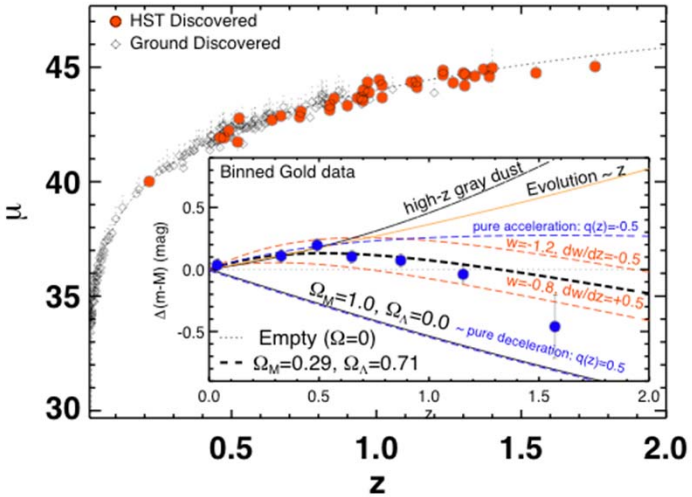
The explosion of high red-shift SN Ia (standard candles):

$$q_0 \equiv -\frac{a_0 \ddot{a}_0}{(\dot{a}_0)^2} \simeq -0.67 \pm 0.25$$



Within General Relativity, link to matter and dark energy

$$q_0 = -\Omega_\Lambda + \frac{1}{2}\Omega_m \sim -0.67$$



Dark Energy must exist!

The Cosmic Microwave Background

Fluctuations of the CMB temperature across the sky lead to acoustic peaks and troughs, snapshot of the plasma oscillations at the last scattering

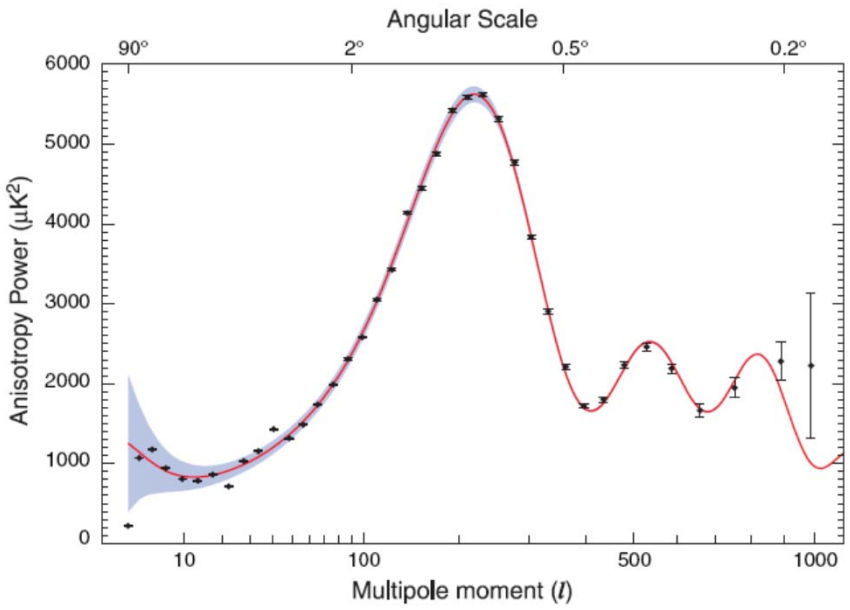
The position of the first peak:

$$l_1 \approx \frac{220}{\sqrt{\Omega_\Lambda + \Omega_m}}$$

The universe is spatially flat

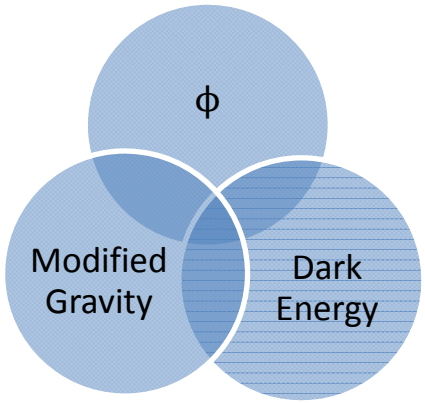
$$\Omega_\Lambda + \Omega_m = 1$$

$$\Omega_\Lambda = \frac{2}{3}\left(\frac{1}{2} - q_0\right) \sim 0.78$$



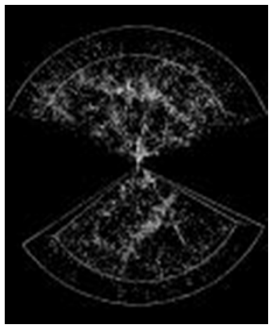
WMAP data

The acceleration of the Universe could be due to either:



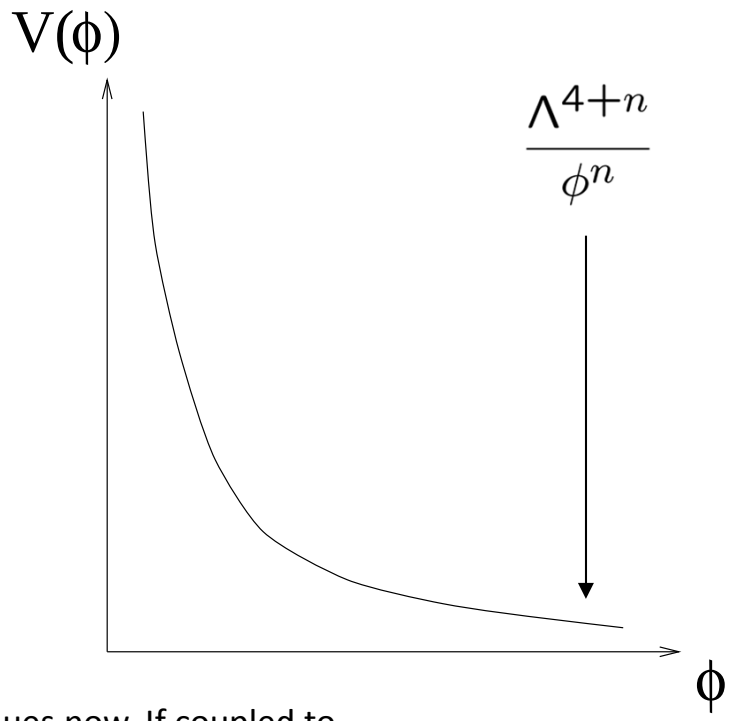
In both cases, current models use scalar fields. In modified gravity models, this is due to the scalar polarisation of a massive graviton (5=2+2+1). In dark energy, it is by analogy with inflation.

The fact that the scalar field acts on cosmological scales implies that its mass must be large compared to solar system scales.



Dark Energy or Modified Gravity?

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + V(\phi)$$



Field rolling down a runaway potential, reaching large values now. If coupled to CDM and/or baryons, this modifies gravity due to the existence of a long range fifth force whose range is of the size of the observable Universe.

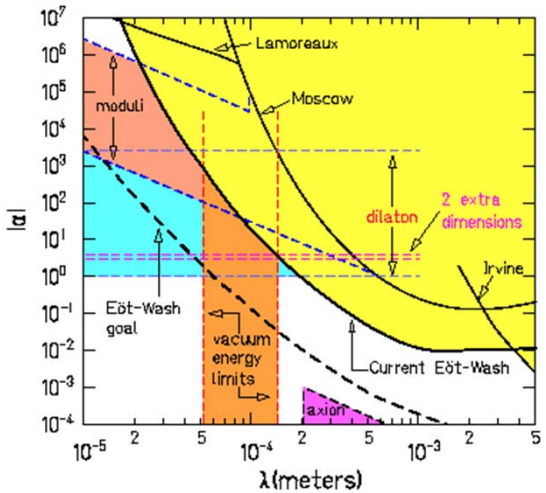
Deviations from Newton's law are parametrised by:

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

For fields of zero mass or of the order of the Hubble rate now, the tightest constraint on β comes from the Cassini probe measuring the Shapiro effect (time delay):

$$\beta^2 \leq 1.210^{-5}$$

The effect of a long range scalar field must be screened to comply with this bound and preserve effects on cosmological scales.



Around a background configuration and in the presence of matter, the Lagrangian can be linearised and the main screening mechanisms appear directly:

$$\mathcal{L} \supset -\frac{Z(\phi_0)}{2}(\partial\delta\phi)^2 - \frac{m^2(\phi_0)}{2}\delta\phi^2 + \frac{\beta(\phi_0)}{M_P}\delta\phi\delta T \ ,$$

The chameleon mechanism makes the range become smaller in a dense environment by increasing m

The Damour-Polyakov mechanism reduces β in a dense environment

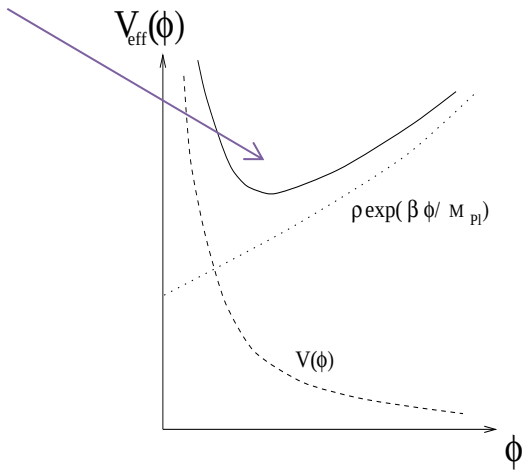
The Vainshtein mechanism reduces the coupling in a dense environment by increasing Z

The effect of the environment

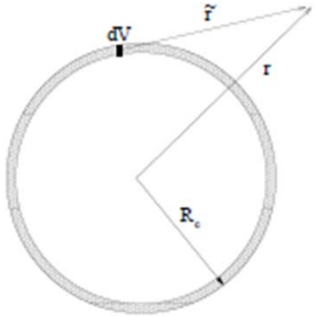
When coupled to matter, scalar fields have a matter dependent effective potential

$$V_{eff}(\phi) = V(\phi) + \rho_m(A(\phi) - 1)$$

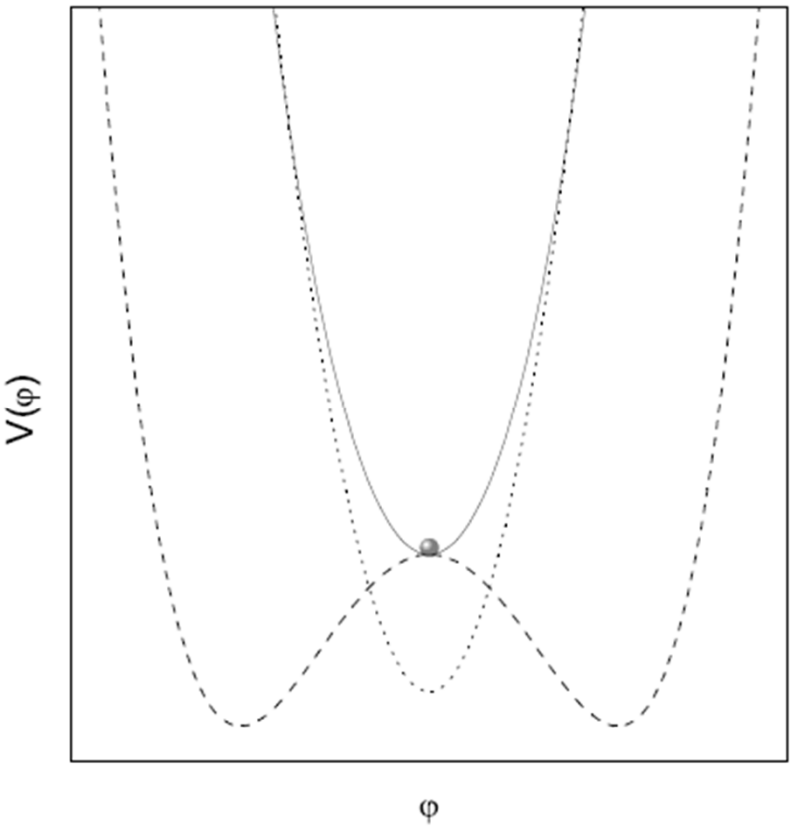
Environment dependent minimum

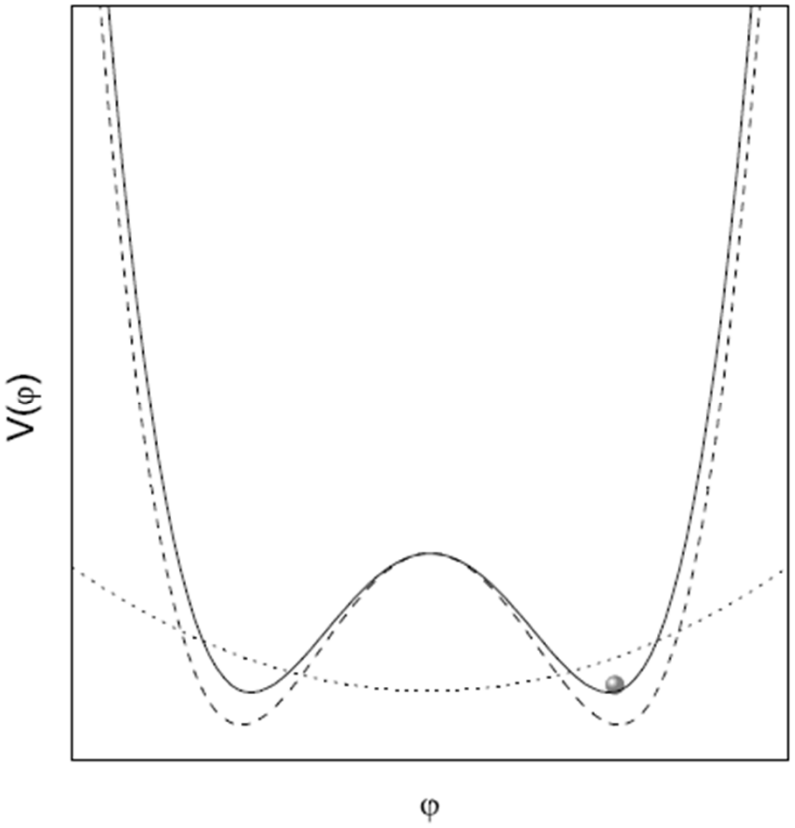


Chameleon=constant coupling



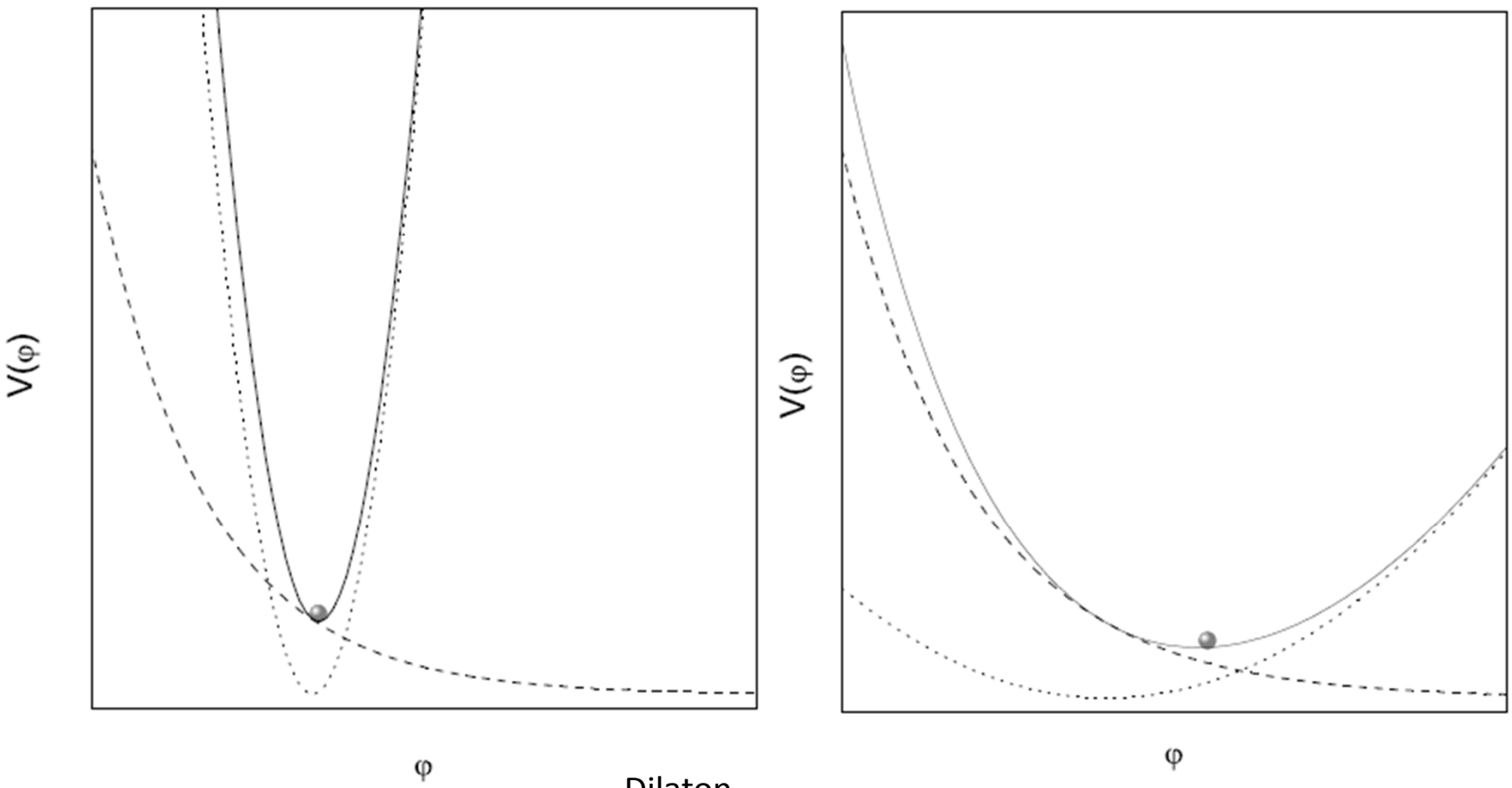
The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.





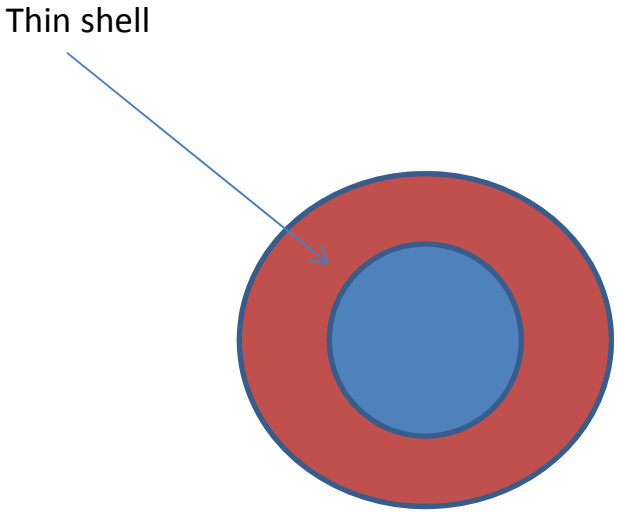
Symmetron

$$V(\phi) = V_0 - \frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^2, \;\; A(\phi) = 1 + \frac{A_2}{2m_{\rm Pl}^2}\phi^2$$

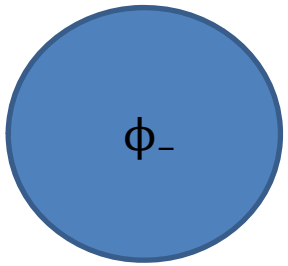


Dilaton

$$V(\phi) = V_0 e^{-\phi/m_{\mathrm{Pl}}}, \quad A(\phi) = 1 + \frac{A_2}{2m_{\mathrm{Pl}}^2}(\phi - \phi_\star)^2$$



For chameleons, when objects are big enough/dense enough, the field is screened outside. Inside it is nearly constant apart from inside thin shell whose size is inversely proportional to Newton's potential at the surface.



ϕ_+

For all chameleon, dilaton, symmetron models where either the potential and/or the coupling β is a non-linear function of ϕ, dense bodies are screened when their gravitational charge Q is small. So what is the gravitational charge in these models?

Brax-Davis-Li-Winther 2012

Value of the field far away

$$Q = \frac{\phi_\infty}{\Phi}$$

Newtonian potential at the surface of the body.

Lunar ranging test of the equivalence principle:

$$\eta \approx Q_E^2 \longrightarrow Q_E \leq 10^{-7}$$

For all screened models (excluding Vainshtein), satellites have a Newtonian potential

$$\Phi_{\text{sat}} \sim 10^{-24} \sim 10^{-15}\Phi_E$$

When the gravitational charge of the earth is not too small (model dependent):

$$10^{-15} \leq Q_E \leq 10^{-7}$$

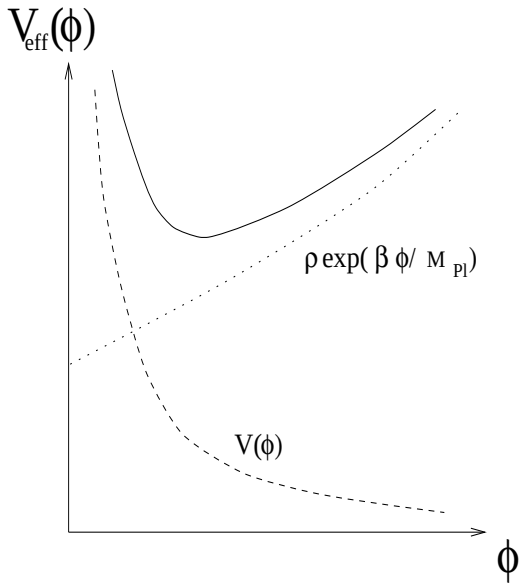
the field inside the satellite is the one in the galactic vacuum where the range of the scalar field is large (model dependent but larger than the solar system). In this case, test bodies feel a maximal violation of the equivalence principle:

$$10^{-19} \leq (\eta \approx 10^{-4} Q_E) \leq 10^{-11}$$

Composition dependent Nb and Be here (see Thibault Damour's talk).

Khoury-Weltman 2004

The family of screened modified gravity models (excluding Vainshtein) can be much more easily analysed using a reconstruction procedure.



The existence of a minimum for a medium of density ρ allows one to define a mapping between ρ and the value of the field and the value of the potential at the minimum. This implicit way of defining V(ϕ) is very useful as ρ itself can be parameterised by the expansion rate of the Universe

This implicit definition of the models depends only on the mass m(a) and the coupling β(a) at the minimum.

The non-linear potential of the model and the values of the field can be evaluated using:

$$\begin{aligned}\phi(a) &= \phi_i + \frac{3}{m_{\rm Pl}}\int_{a_i}^{a} da \frac{\beta(a)\rho(a)}{am^2(a)} \\ V(a) &= V_i - \frac{3}{m_{\rm Pl}}\int_{a_i}^{a} da \frac{\beta^2(a)\rho^2(a)}{am^2(a)}\end{aligned}$$

The full non-linear dynamics is reconstructed parametrically using the mass and the coupling function as a function of redshift! It works explicitly for chameleons, f(R), dilatons, symmetrons and one can invent new models!

As the Universe evolves from pre-BBN to now, the density of matter goes from the density of ordinary matter (10g/cm3) to cosmological densities. The minimum of the effective potential experiences all the possible minima from sparse densities (now) to high density (pre-BBN).

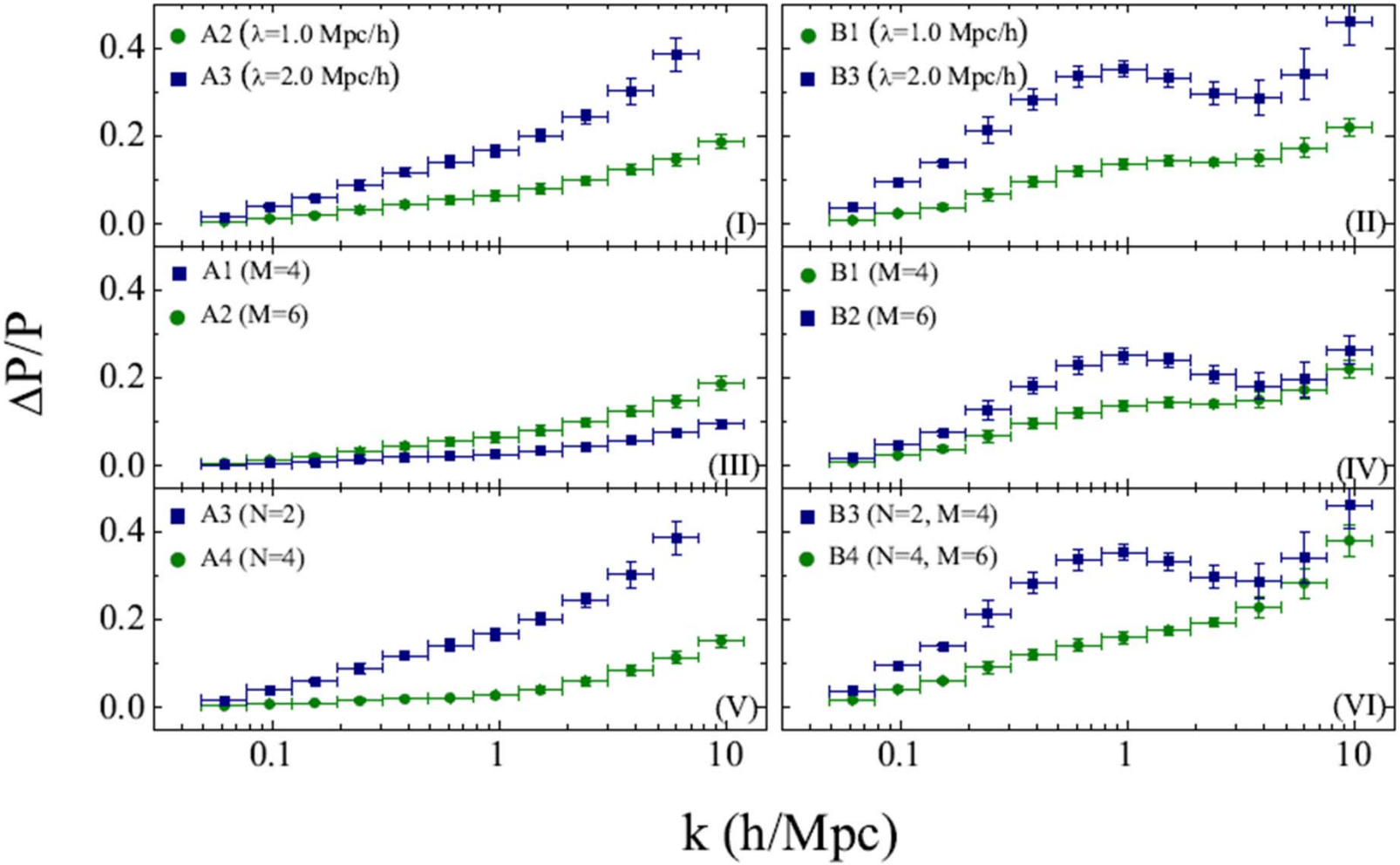
The loosest screening conditions requires that the Milky way is marginally screened, this corresponds to the absence of disruption of the galactic halo dynamics:

$$\frac{9\Omega_{m0}H_0^2}{m_0^2}\left(\int_{a_G}^{1}\frac{da}{a^4}\frac{\beta(a)}{\beta_0}\frac{m_0^2}{m^2(a)}\right) \leq 2\Phi_G$$

This implies the crucial bound:

$$\frac{m_0}{H_0} \geq 10^3$$

Effects of modified gravity can appear at most on the Mpc scale. Similar bound obtained from pulsar-white dwarf system (less loose and tied to the scalar emission of screened bodies).



Power Spectrum (symmetron models)

Summary

Screening is an essential property of dark energy/modified gravity models

Satellite tests of the equivalence principle are the best smoking gun for these models

Effects on structure formation (deviation from the concordance model) constrained by gravity bounds and only effective on Mpc scales.