Dark Energy or Modified Gravity?

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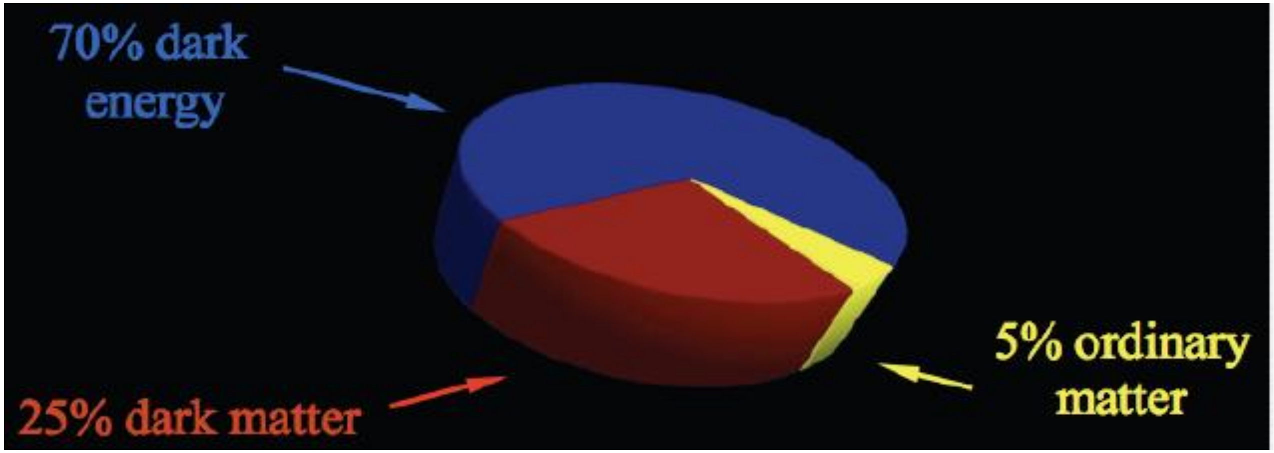
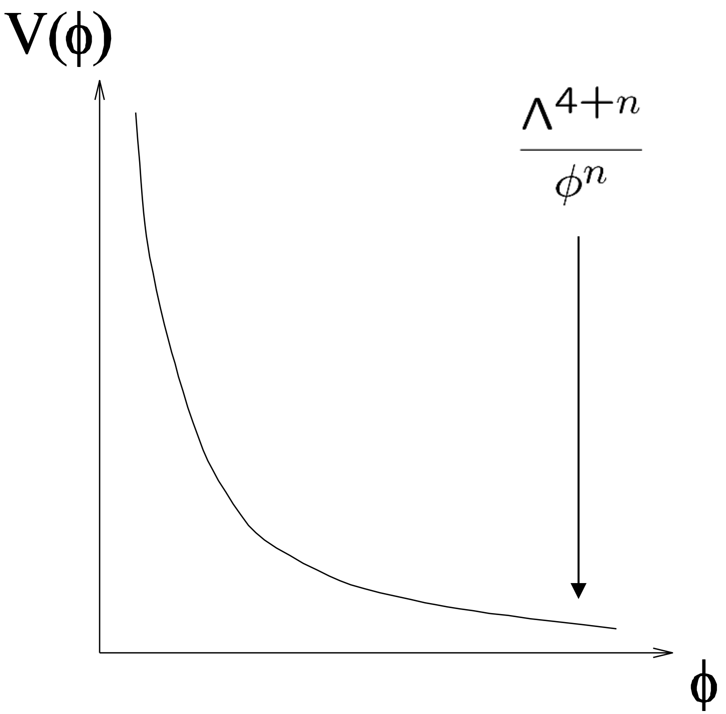
The Big Puzzle



Dark Energy ?

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

A scalar field is a good candidate as its energy density can be dominated by its potential implying that its pressure is almost opposite to ρ



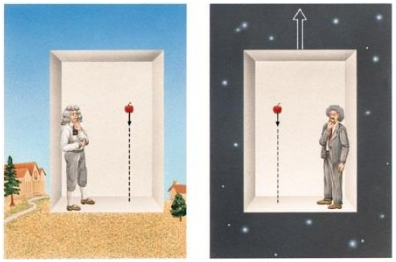
A field rolling down a runaway potential, reaching large values now?

It could also be that what we interpret as acceleration is in fact a manifestation of something more subtle:

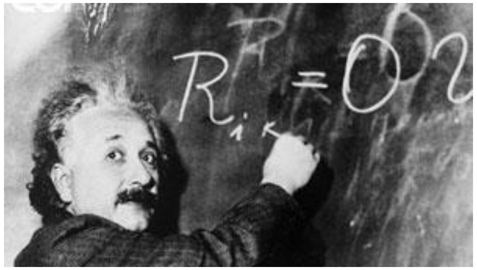
A modification of the laws of gravity on large scales

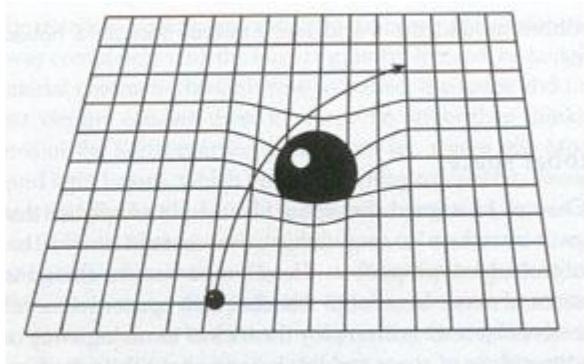
Gravity is described by the general theory of relativity (Einstein 1915) and encompasses several aspects which needs to be carefully understood when one tries to “modify gravity”.

The equivalence principle



The Einstein equation of General Relativity





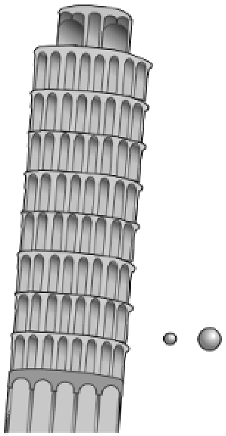
General relativity is a metric theory relating energy and geometry of the Universe:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

Energy momentum tensor

Ricci tensor

The equivalence principle is at the heart of general relativity. There are several versions which must be distinguished:



The weak equivalence principle (or universality of free fall) states that to massive tests bodies fall in the same way independently of their composition.

$$m_{\text{inert}}a = m_{\text{grav}}g$$

The equality of the inertial and gravitational masses for test bodies has been tested at the level of thirteen decimal places!

$$m_{\text{grav}} = m_{\text{inert}}$$

General relativity satisfies a stronger version of the equivalence principle.

The Einstein equivalence principle is at the heart of General Relativity

The weak equivalence principle is valid.

Result of any local non-gravitational experiment independent of the velocity of free falling frame (local Lorentz invariance)

Result of any non-gravitational experiment independent of where and when performed.

In the local free falling frame:

Violated if the fine structure constant or particle masses vary on cosmological scales.

the constants of nature are constant

the laws of physics are the ones of special relativity

the effect of the gravitational field can be effaced

test bodies follow straight lines (geodesics globally)

Not true in modified gravity: fifth force

The acceleration of the expansion of the Universe could have (at least) two dynamical explanations:

Dark Energy: a new form of matter

$$S=\frac{1}{16\pi G_N}\int d^4x\sqrt{-g}(R-\mathcal{L}_{DE})$$

Einstein-Hilbert action describing General Relativity. Einstein's equations are simply obtained using the least action principle

Lagrangian density of dark energy

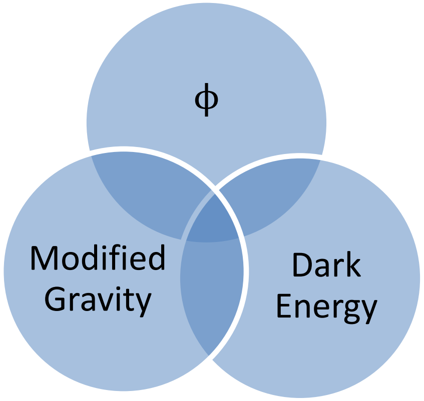
Modified law of gravity on large scales

$$S=\frac{1}{16\pi G_N}\int d^4x\sqrt{-g}h(R,R_{\mu\nu},R_{\mu\nu\rho\sigma})$$

Arbitrary corrections to the Einstein-Hilbert Lagrangian involving the Riemann and Ricci tensors.

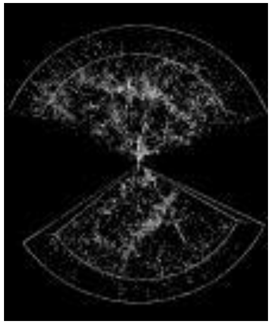
Surprisingly, both types of models involve scalar fields.

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.



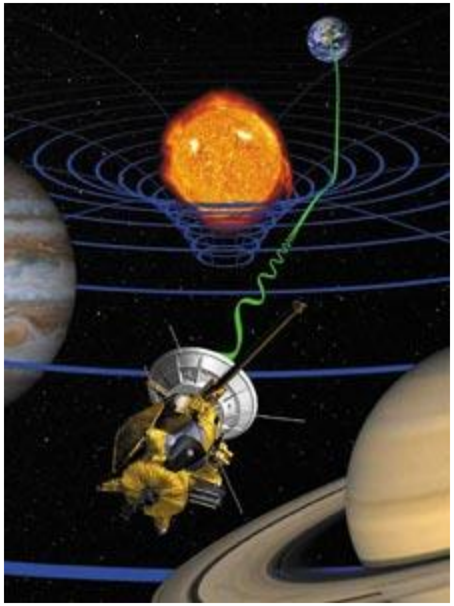
Deviations from Newton's law are parametrised by:

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

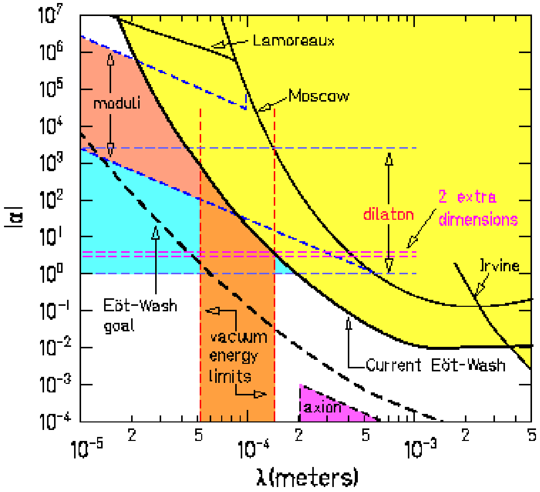
For large range forces with large λ, the tightest constraint on the coupling β comes from the Cassini probe measuring the Shapiro effect (time delay):

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

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



Bertotti et al. (2004)



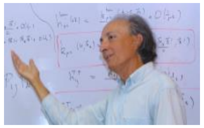
Around a background configuration and in the presence of matter, the Lagrangian can be linearised and the main screening mechanisms can be schematically distinguished :

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

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

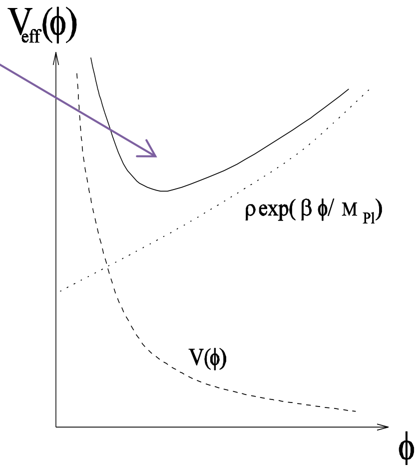


The effect of the environment (excluding Vainshtein)

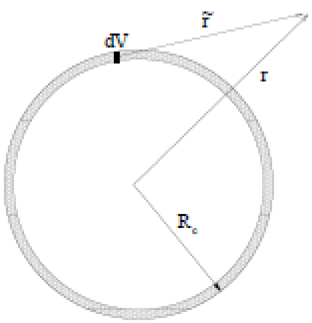
When coupled to matter, scalar fields have a matter dependent effective potential

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

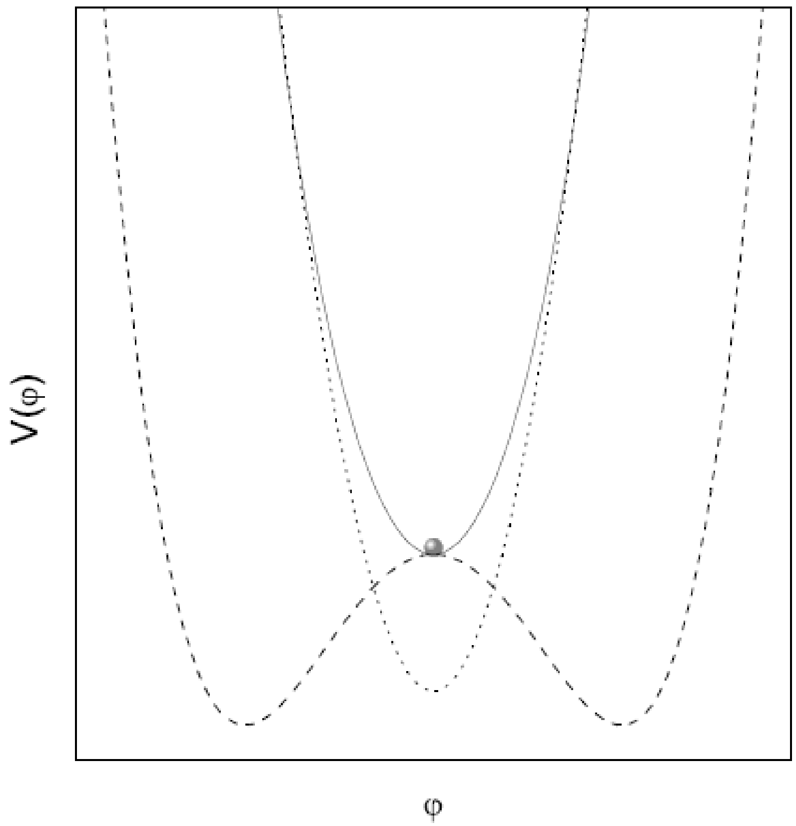
Environment dependent minimum

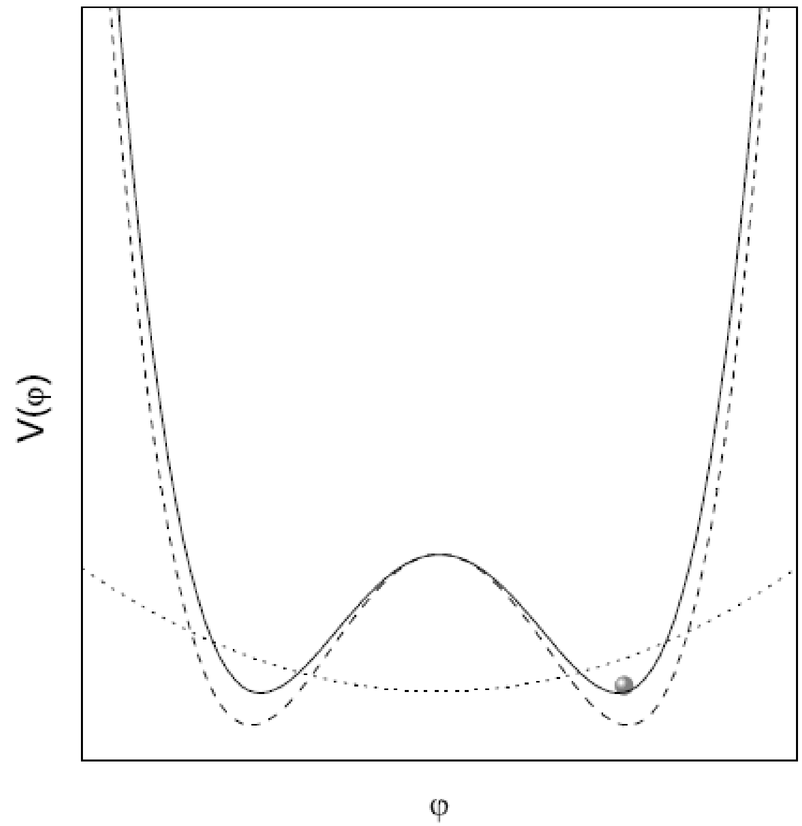


Chameleon



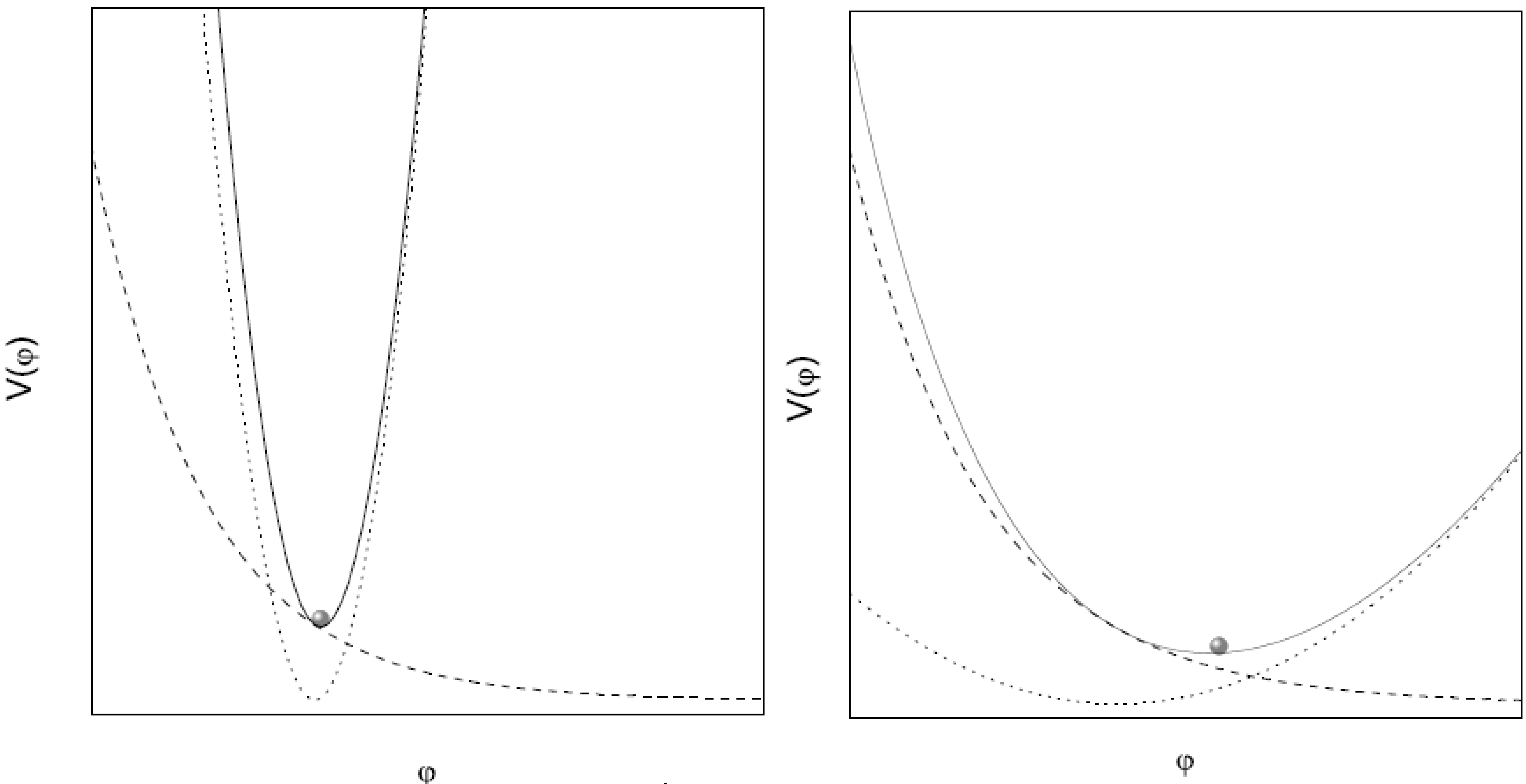
The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.





Symmetron

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



Dilaton

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

The cosmological background evolves like in the concordance model. The main difference coming from the modification of gravity arises at the perturbation level where the Cold Dark Matter density contrast evolves like:

$$\delta_c'' + \mathcal{H}\delta_c' - \frac{3}{2}\mathcal{H}^2 \frac{\rho_c}{\rho_c + \rho_b + \rho_\gamma + \rho_\phi}\left(1 + \frac{2\beta^2(a)}{1 + \frac{m^2 a^2}{k^2}}\right)\delta_c = 0$$

Modified gravity

The new factor in the bracket is due to a modification of gravity depending on the comoving scale k.

The growth of structures depends on the comoving Compton length:

$$\lambda_c = \frac{1}{ma}$$

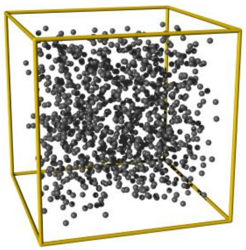
Gravity acts in an usual way for scales larger than the Compton length (matter era)

$$\delta \sim a$$

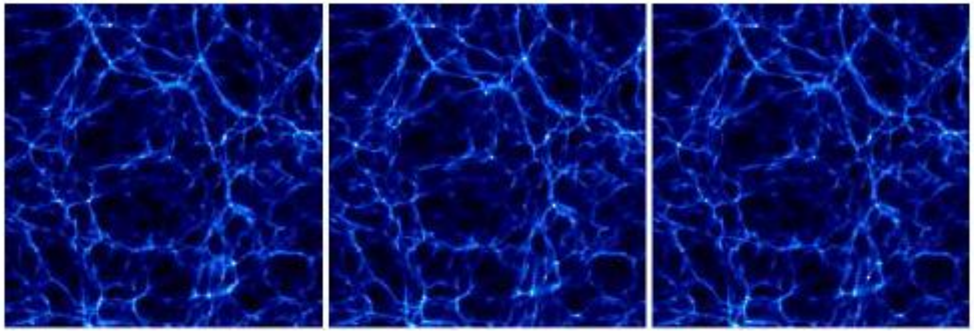
Gravity is modified inside the Compton length with MORE growth (matter era):

$$\boxed{\delta \sim a^{\frac{\nu}{2}}}, \quad \nu = \frac{-1 + \sqrt{1 + 24(1 + 2\beta_c^2)}}{2}$$

Properties around 1Mpc and below necessitates large scale N-body simulations



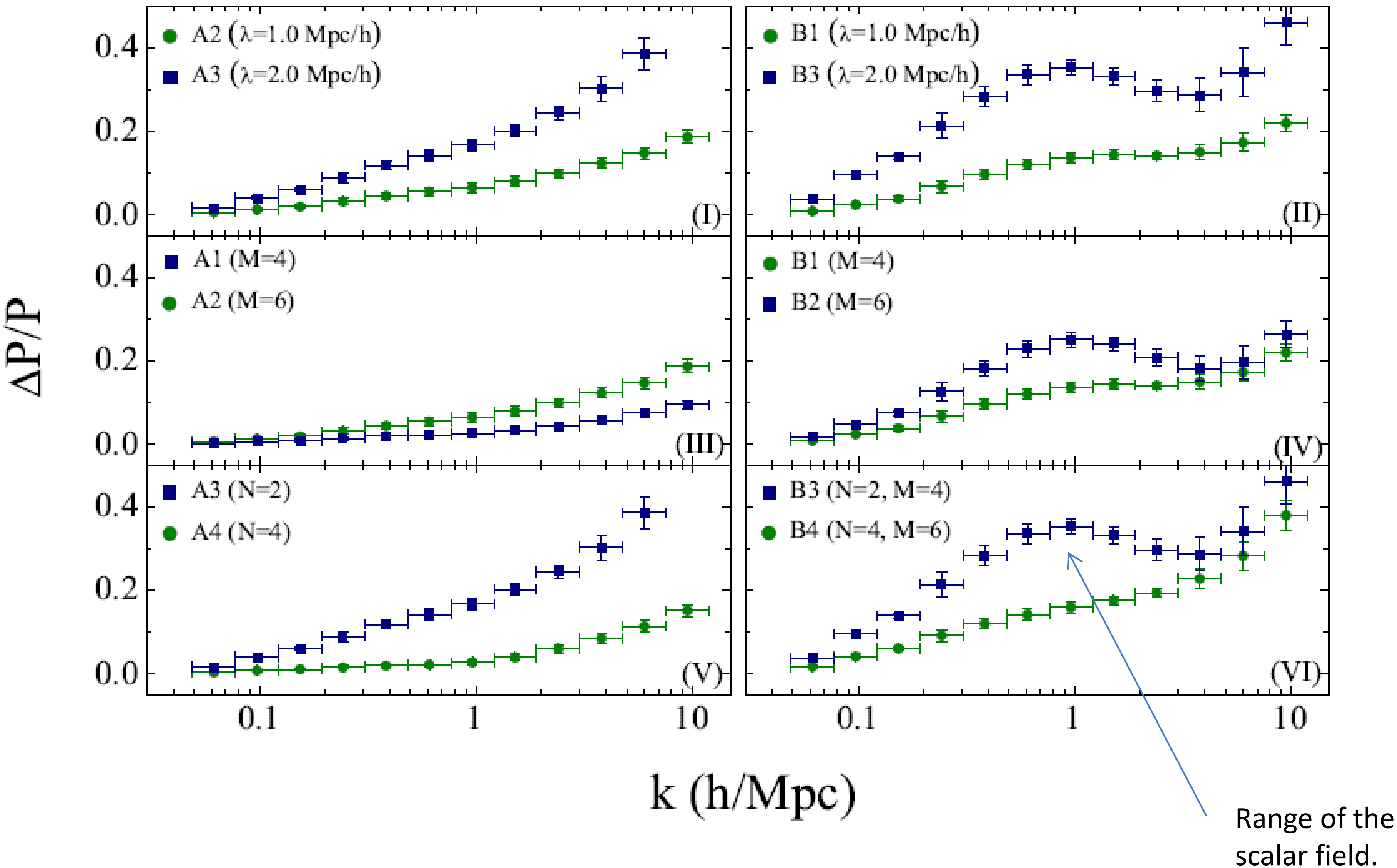
N-body simulations with around 10 million particles in a box up to 1 Gpc



Λ-CDM Linear Non-linear

Koyama, Li and Zhao (2013)

Large scale structures in the non-linear regime determined by m(a) and β(a). Non-linear effects simulated with ECOSMOG. Deviation of the power spectrum of the density spectrum from GR (Fourier space). Deviations in the quasi-linear and non-linear regimes.

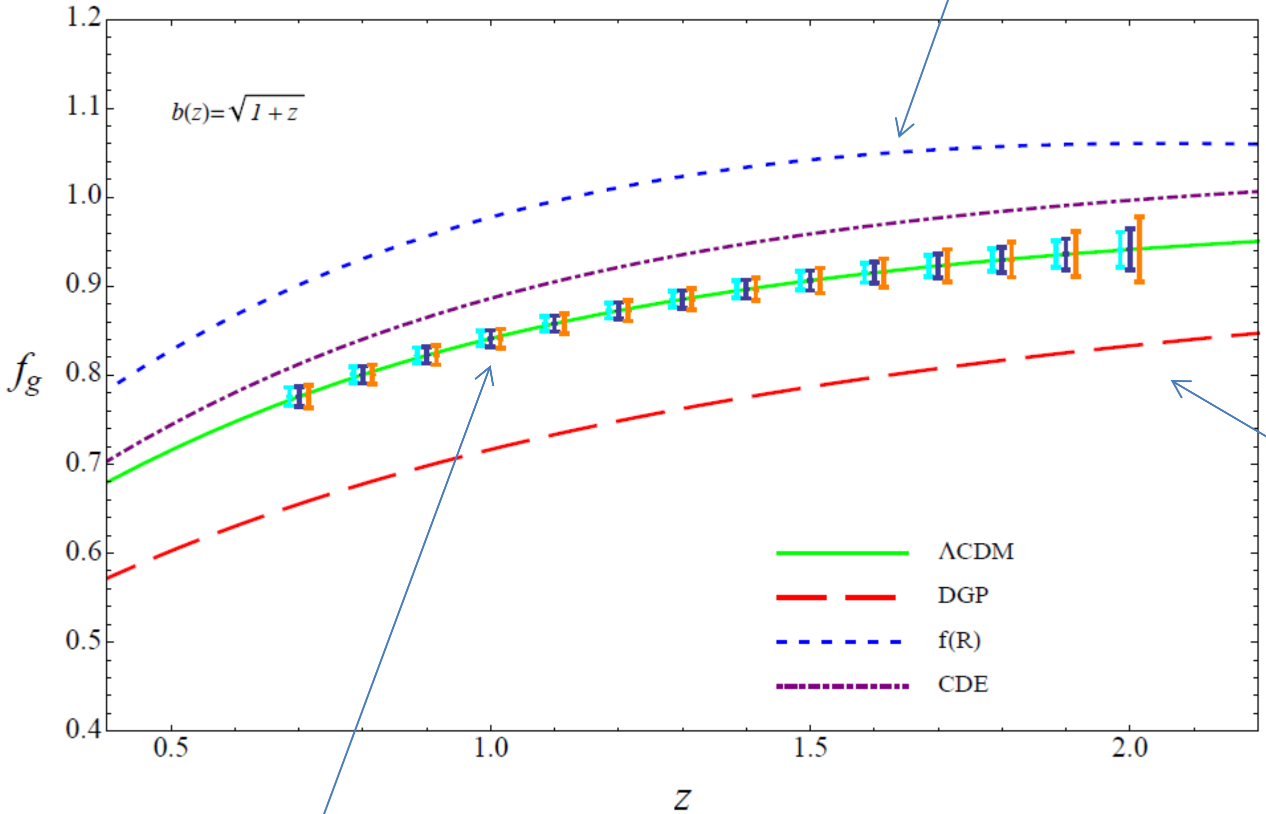


Power Spectrum deviation (symmetron)

EUCLID forecast: growth rate at the percent level

more growth

$$f_g(z) = \frac{d \ln \delta}{d \ln a}$$



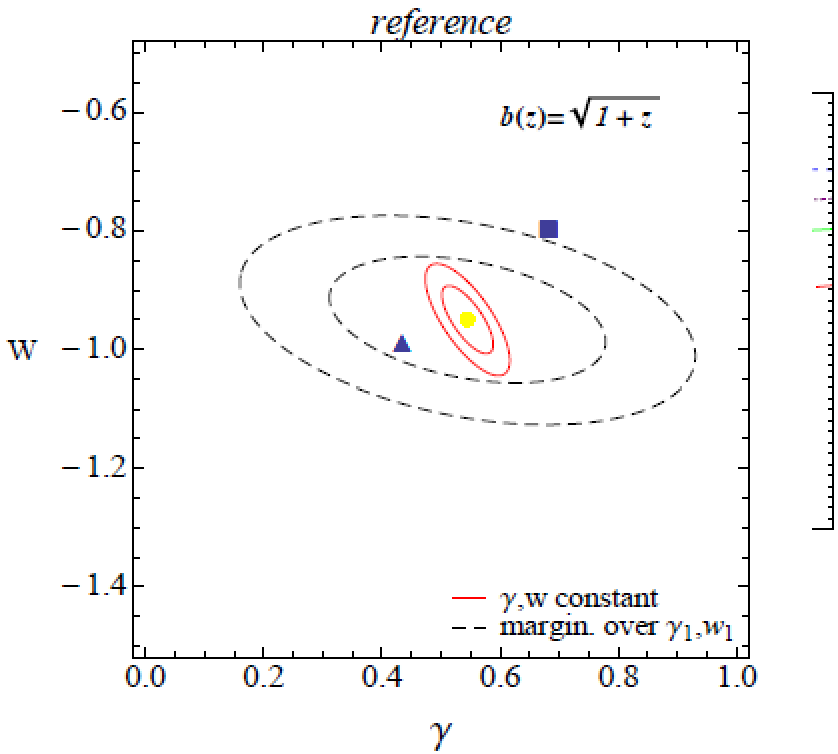
ΛCDM

Less growth

Forecast in the linear regime

EUCLID Forecast

Equation of state



Growth index

$$f_g(z) = \Omega_m^{\gamma}$$

Conclusions

Modified gravity on very large scales is constrained:

Astrophysical tests of the strong equivalence principle

Effects on the growth of structures in the quasi-linear regime

The different models are classified according to the mechanism preserving gravity in the solar system:

Chameleon/Damour-Polyakov

Vainshtein

These tests are complementary to lab/solar system experiments.