Modified Gravity 2

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Summary

- Modification of gravity is welcome at large scales but not at small scales
- Many interesting aspects of modified gravity can be captured by a scalar field
- This scalar field is usually coupled to matter
- We will consider the simplest coupling which comes from the most popular models (such as DGP, f(R), ...)
- The coupling to matter produces a fifth force

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If matter is coupled to the following metric $\bar{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$, the geodesic equation becomes

$$\frac{d^2 x^\mu}{d\tau^2} + \bar{\Gamma}^\mu_{\rho\sigma} \frac{dx^\rho}{d\tau} \frac{dx^\sigma}{d\tau} = 0$$

$$\frac{d^2 x^\mu}{d\tau^2} + \Gamma^\mu_{\rho\sigma} \frac{dx^\rho}{d\tau} \frac{dx^\sigma}{d\tau} + \left[\delta^\mu_\rho \frac{A_{,\sigma}}{A} + \delta^\mu_\sigma \frac{A_{,\rho}}{A} - g_{\rho\sigma} \frac{A^{,\mu}}{A} \right] \frac{dx^\rho}{d\tau} \frac{dx^\sigma}{d\tau} = 0$$

$$\frac{d^2 x^i}{dt^2} = -\partial^i \Phi - \partial^i \ln\, A(\phi)$$

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$$F = -Q\nabla\phi$$

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- Example 1
  - f(R) gravity is equivalent to

$$S = \int \sqrt{-g} d^4x \Big[R - (\partial\phi)^2 - V(\phi) \Big] + S_m[e^{2\phi/\sqrt{6}} g_{\mu\nu}, \Psi_m]$$

  - So $Q = \dfrac{1}{\sqrt{6}} \simeq 1$
  - We will have huge constraints from fifth force experiments

- Example 2 (Brans-Dicke theory)

$$
\begin{aligned}
S &= \int \sqrt{-g} d^4x \left[\phi R - \frac{\omega}{\phi} (\partial\phi)^2 \right] + S_m[g_{\mu\nu}, \Psi_m] \\
&= \int \sqrt{-g} d^4x \left[R - \frac{\omega + 3/2}{\phi^2} (\partial\phi)^2 \right] + S_m[\frac{1}{\phi} g_{\mu\nu}, \Psi_m] \\
&= \int \sqrt{-g} d^4x \left[R - (\partial\Phi)^2 \right] + S_m[e^{2Q\Phi} g_{\mu\nu}, \Psi_m]
\end{aligned}
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$$Q = \frac{1}{\sqrt{2\omega + 6}}$$

Because we don't measure any fifth force so $Q \ll 1 \Rightarrow \omega \gg 1$

Unnatural fine-tuning of the parameter of the model, we want a theory where $Q \simeq 1$

3 ways to hide

$$S = \int \sqrt{-g} d^4x \left[R - Z^{\mu\nu}(\phi, \partial\phi, \cdots)\partial_\mu\phi\partial_\nu\phi - V(\phi) \right] + S_m[e^{2Q\phi} g_{\mu\nu}, \Psi_m]$$

- $Q \ll 1$
  Unnatural like Brans-Dicke theories
- We use the potential $V(\phi)$ (Chameleon mechanism)
  Like $f(R)$-gravity, chamelon gravity, Brans-Dicke with a potential ...
- We use the non-linearities $Z^{\mu\nu}$ (Vainshtein mechanism)
  Brane models (DGP), massive gravity ...

Chameleon (*J. Khoury, A. Weltman 2004*)

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

- Equation of motion
- Dynamics governed by effective potential:

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Dynamics governed by effective potential

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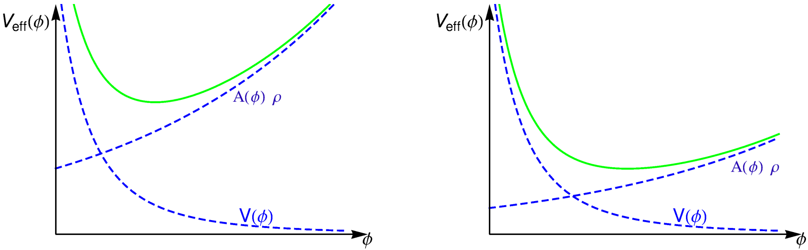

Large ρ Small ρ

$$m_{eff}^2 = \frac{d^2 V_{eff}}{d\phi^2}$$

Simple example

- Ratra-Peebles potential $V(\phi) = \dfrac{M^5}{\phi}$
  - For simplicity we will consider $A(\phi) = e^{Q\phi} \simeq 1 + Q\phi$

$$ \tag{1} $$

  - The scalar field sits at the minimum of the potential $V_{eff,\phi} = 0$ which gives $\phi_{min} = \left(\dfrac{M^5}{Q\rho}\right)^{1/2}$
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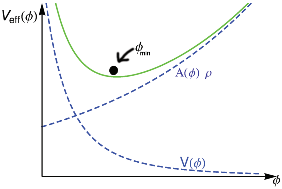

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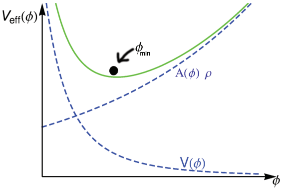

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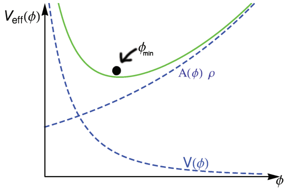

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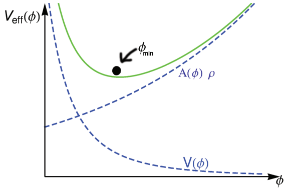
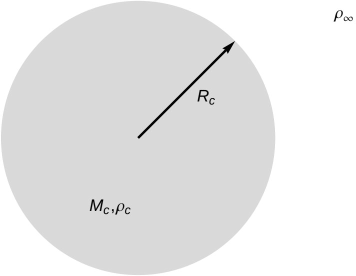


$$M < 10^{-3}\text{eV}$$

This is the dark energy scale !!!

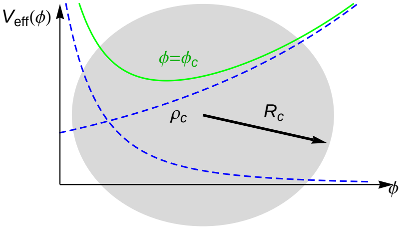
Solution for a compact object

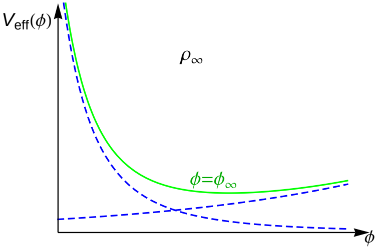


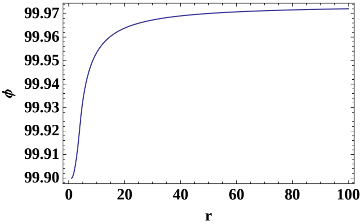
$$\Box\phi = V_{,\phi} + A_{,\phi}\rho$$

$$\frac{\mathrm{d}^2\phi}{\mathrm{d}r^2} + \frac{2}{r}\frac{\mathrm{d}\phi}{\mathrm{d}r} = V_{,\phi} + A(\phi)\rho(r)$$

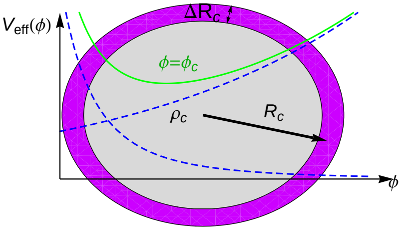
The boundary conditions specify that the solution be nonsingular at the origin: $\frac{\mathrm{d}\phi}{\mathrm{d}r} = 0$ at $r = 0$
And that the force on a test particle vanishes at infinity: $\phi \to \phi_\infty$ as $r \to \infty$

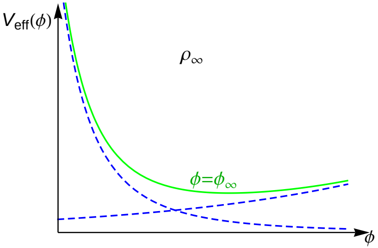


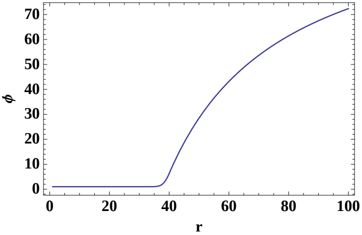




$$\phi(r) \approx -\left(\frac{Q}{4\pi}\right)\frac{M_c e^{-m_\infty (r-R_c)}}{r} + \phi_\infty$$







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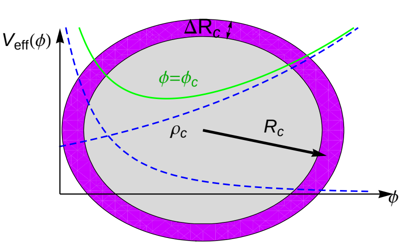

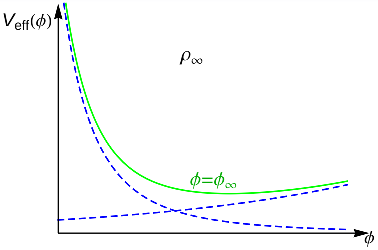

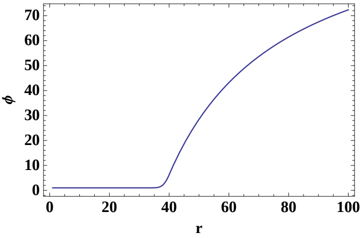

- Field reaches effective minimum almost everywhere in the body
- All field variations confined to small region near body surface
- This region is called a thin-shell
  $$\frac{\Delta R_c}{R_c} \ll 1$$

$$\frac{\Delta R_c}{R_c} \approx \frac{\phi_\infty - \phi_c}{6Q\Phi_c}, \quad \text{with} \quad \Phi_c = \frac{GM_c}{R_c}$$

Fifth Force on Body with Thin-Shell

A test mass M_1 in a static chameleon field ϕ experiences a force $\overrightarrow{F}_\phi$

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- Example (Earth)
  Modeled as a sphere of radius $R_c = 6000\ Km$ and density $\rho_c = 10g/cm^3$.
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$$\epsilon = \frac{\Delta R_c}{R_c} \approx 10^{-8} \ll 1$$

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Using the thin-shell parameter $\epsilon_\oplus = \dfrac{\Delta R_\oplus}{R_\oplus}$ for the Earth:

$$a_\oplus \approx \frac{GM_\odot}{r^2}\left[1 + 18Q^2\epsilon_\oplus^2\frac{\Phi_\oplus}{\Phi_\odot}\right]$$
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$$\epsilon_{\oplus} < \frac{8.8\times10^{-7}}{|Q|}$$

Chameleon in the lab

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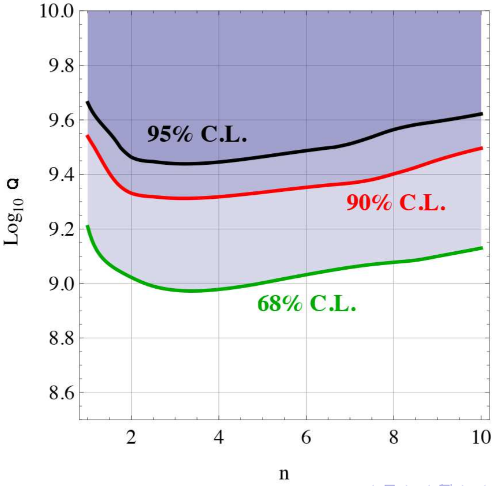

Physical effects

- Small galaxies should move faster than large ones in general
- Stars within unscreened galaxies may show the effects of modified gravity
  - Enhanced gravitational force makes stars of a given mass brighter and hotter than in GR
  - More ephemeral since they consume their fuel at a faster rate
- Internal motions of objects inside an unscreened galaxy
  - majority of stars inside an unscreened galaxy are themselves screened
  - diffuse gas inside the same galaxy likely remains unscreened because the gravitational potential at a gas cloud should be dominated by the potential of the galaxy rather than that of the gas cloud itself
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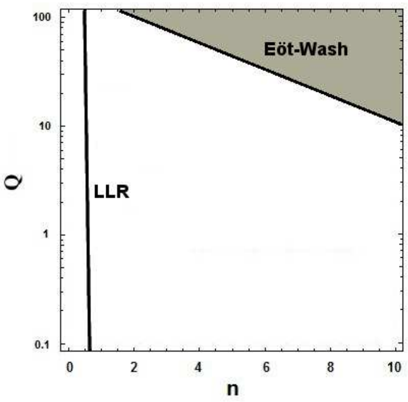

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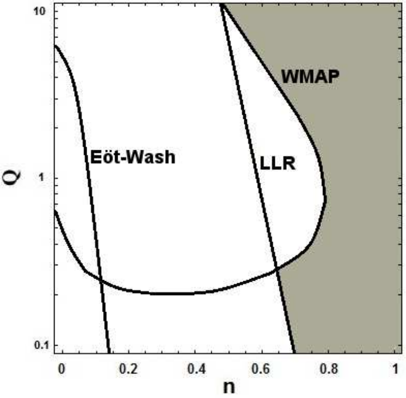
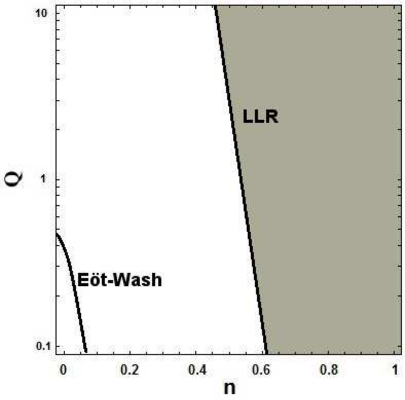


Some results

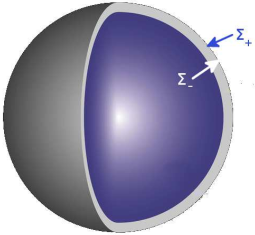
- $V(\phi) = M^4 + \dfrac{M^{4+n}}{\phi^n}$ (D. F. Mota, D. J. Shaw 2007)

They found that Eöt-Wash experiments rules out the model except if $n \gg 1$

- $V(\phi) = M^4 e^{M^n/\phi^n}$ (R.G., B. Moraes, D. Mota, D. Polarski, S. Tsujikawa, H. Winther)
- $V(\phi) = M^4(1 - \mu(1 - e^{-\phi})^n)$ for $\mu = 0.05$



Application to neutron stars



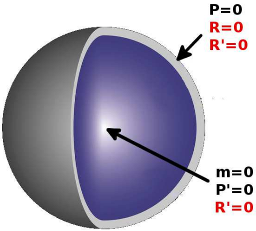
Generalized Israel Junction conditions

(Deruelle, Sasaki, Sendouda, 2007)

- $[h_{\mu\nu}]_\Sigma = 0$
- $[K_{\mu\nu}]_\Sigma = 0$
- $[R]_\Sigma = 0$
- $[\nabla_\mu R]_\Sigma = 0$

- Exterior solution
  - No Jebsen-Birkhoff theorem
  - Realistic astrophysical compact objects $\Rightarrow$ consistent with solar system
  - Should define a well defined black hole with regular horizon
  - BH no-scalar-hair theorems (Bekenstein 1995, Sudarsky 1995)

$\Rightarrow$ Schwarzschild

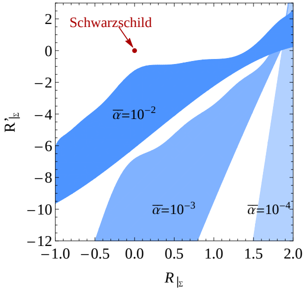


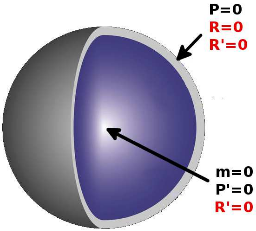
$$S = \int d^4x\sqrt{-g}\,\left(R + \alpha R^2\right)$$

- $\alpha \ll 1 \Rightarrow$ Singular problem, boundary layer problem
- WKB approximation $\Rightarrow R = f(r) + A\,exp\left(-\frac{r_S - r}{\sqrt{\alpha}}\right) + O(\sqrt{\alpha})$
- Difficult to satisfy all the conditions
  - Constant equation of state $\rho = C^{st}$
  - Polytropic equation $\rho = AP^{\gamma}$
  - All boundary conditions cannot be satisfied for generic EoS

$\Downarrow$

2 fine-tuning: EoS and initial conditions





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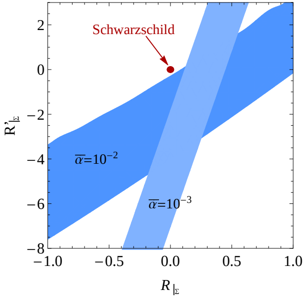

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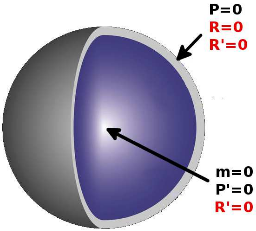

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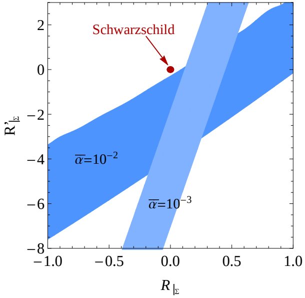
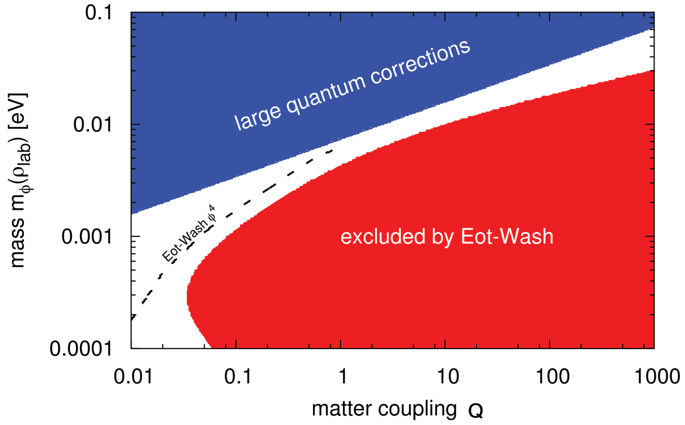
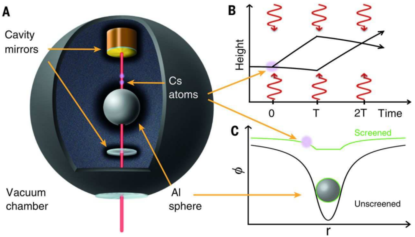


Quantum corrections

- Quantum corrections to the potential can be large if the effective mass is large (1-loop Coleman-Weinberg) (A. Upadhye, W. Hu, J. Khoury 2012)



- Atomic particles in a ultra-high vacuum chamber can mimic cosmos conditions
- The experiment is realized inside a vacuum chamber in order to reduce the screening effect
- An atom beam is split in two, one half of it is subjected to some field, and then the beams are combined again
- From the resulting interference pattern one can extract the force that acted on the beams



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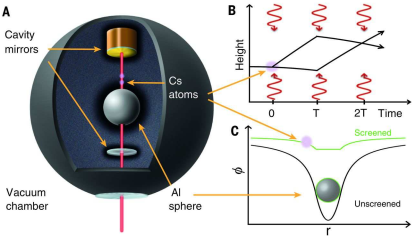

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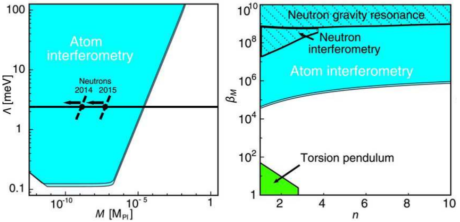

$$V(\phi) = \Lambda^4 + \frac{\Lambda^{4+n}}{\phi^n}$$

$$\text{coupling} = \frac{\phi\rho}{M}$$

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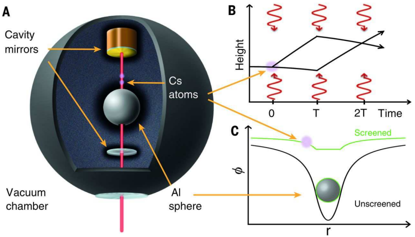

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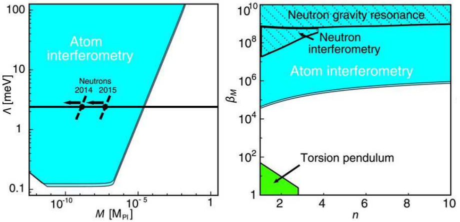

"Our experiments excluded chameleons at the scale of the cosmological constant $\Lambda = 2.4$ meV for $M < 2.3 \times 10^{-5} M_{Pl}$"

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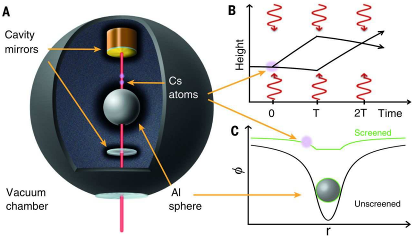

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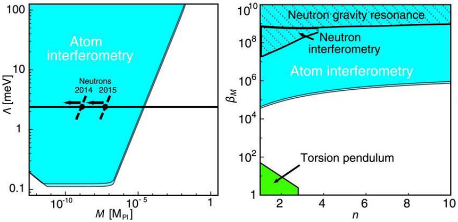

"This result rules out chameleons that would reproduce the observed acceleration of the cosmos"

Symmetron mechanism *(K. Hinterbichler, J. Khoury 2010)*

Same action with $V(\phi) = -\frac{\mu^2}{2}\phi^2 + \frac{\lambda}{4}\phi^4, \quad A(\phi) = 1 + \frac{\phi^2}{2M^2}$

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

Dilaton mechanism *(T. Damour, A. Polyakov 1994)*

Same action with $V(\phi) = V_0\, e^{-\phi/M_{Pl}}$, $\quad A(\phi) = 1 + \frac{(\phi - \phi_\star)^2}{2M^2}$

$$V_{eff} = V_0\, e^{-\phi/M_{Pl}} + \frac{(\phi - \phi_\star)^2}{2M^2}\rho$$