D

Symmetrons + Dilatons

Brax, van de Bruck, ACD + Shaw 1005.3735

Both models ~~have~~ screen via the coupling to matter 'switching off' as a function of density.

Dilatons — are less well known, but more motivated.
The potential:

$$V(\phi) = V_0 \, e^{-\phi/m_{pl}} + \mathcal{O}(e^{-2\phi})$$

comes from string theory in the strong coupling limit. In strong coupling limit we do not know dilaton coupling to matter! (only weak coupling).

In Einstein frame $\tilde{g}_{\mu\nu} = A^2(\phi)\, g_{\mu\nu}$

+ we can define $A(\phi_0) = 1$ when $\phi = \phi_0$ today. Then

$$S = \int \sqrt{-g}\, d^4x \; \frac{R}{16\pi G} - \frac{k^2(\phi)}{8\pi G} (\nabla\phi)^2 - V(\phi)$$

$$+ S_m\left(\psi, A^2(\phi)\, g_{\mu\nu}\right).$$

~~where~~ & if $e^{-\phi_0} \ll 1$ then

$k(\phi)$ is $\mathcal{O}(1)$ [it comes from string theory]

D2

$A(\phi)$ is unknown. Keeping the string coupling in the strong coupling regime $g < 1/\phi$. ie ϕ small. we choose.

$$A(\phi) = A_0\left[1 + \frac{A_2}{2}(\phi - \phi_0)^2\right].$$

we set $A_0 = 1$

$$\therefore \quad \beta(\phi) = A_2(\phi - \phi_0).$$

$$V_{eff} = \kappa_4^2\left(V(\phi) + \rho_m A(\phi)/n\right)$$

$$\Box\phi = \frac{\kappa_4^2}{2}\frac{\partial V_{eff}}{\partial\phi},$$

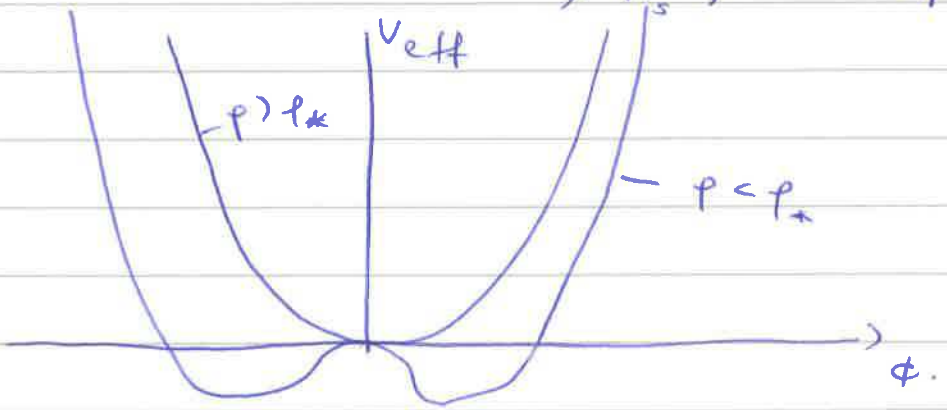
So has a minimum. At high density $\phi \to \phi_0$, so coupling to matter 'switches off', but not in low density regime.
This is environmentally dependent Damour–Polyakov mechanism. '94.

Note: $A(\phi) = e^{\beta\phi}$ doesn't give a thin shell - no chameleon mechanism and solar system unscreened.

Symmetrons, – Hinterbichler + Khoury 1001.4525

$$V(\phi) = -\frac{1}{2}\mu^2\phi^2 + \frac{\lambda}{4}\phi^4 \qquad A(\phi) = 1 + \frac{\phi^2}{2M_s^2}$$

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



where $\rho_* = \mu^2 M_s^2$ ~ critical density

$$\phi^*_{min} = \frac{\pm}{\sqrt{\lambda}}\sqrt{1 - \rho/_{\mu^2 M_s^2}}$$

$$\sim \pm \mu/\sqrt{\lambda} \qquad \rho \ll \rho_*.$$

Z_2 sym. spontaneously broken +

$$\beta(\phi_0) \approx \frac{\mu M_{pl}}{\lambda M_s^2}.$$

Generalised Moduli – see Brax, ACD, Li + Winter, 1203.4812.

(uses a tomographic method & simple parametrisation)

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Solar System Constraints.

We ~~know~~ need to recover GR in the solar system, which constrains our theories. For example ~~there is no~~ we know GR works on earth + in the Earth–moon system. Hence, the fifth force must be screened on the moon + on earth.

On Earth. — $R_\oplus = 6\times10^{8}\,cm$

treat earth as solid body of. $\rho_\oplus = 10\,g/cm^3$

$\rho_{atmos} = 10^{-3}\,g/cm^3$

for our $\rho_G = 10^{-24}\,g/cm^3$

so $\rho(r)$ $\begin{cases} \rho_\oplus & 0<r<R_\oplus \\ \rho_{atmos} & R_\oplus<r<R_{atmos} \\ \rho_G & r > r_{atmos} \end{cases}$

$R_{atmos} = R_\oplus + 10\,km.$

The tightest constraint comes from.

$$\boxed{\frac{\Delta R_\oplus}{R_\oplus} = \frac{\Phi_G - \Phi_{atmos}}{6\beta\, M_{pl}\, \Phi_\oplus} < 10^{-7}.}$$

since $\frac{\Delta R_{atmos}}{R_{at}} \lesssim 10^{-3}$ when calculated

$+ \Phi_{atmos} \sim 10^{-4}\,\Phi_\oplus$

& exterior sol^n

$$\phi(r) = \frac{\beta}{4\pi M_{pl}} \frac{3\Delta R_\oplus}{R_\oplus} M_\oplus \frac{e^{-m_\infty(r-R_{atm})}}{r} + \phi_\infty \qquad (*)$$

$\therefore$ $\phi(r) \sim \phi_\oplus \qquad 0 < r < R_\oplus$

$= \phi_{atm} \qquad R_\oplus < r < R_{atm}$

$= (*) \qquad r > R_{atm}$

This gives us

$$|\vec{F}_\phi| = 3\beta^2 \left(\frac{3\Delta R_\oplus}{R_\oplus}\right) \frac{M_\oplus M}{8\pi M_{pl}^2 r^2}$$

on a body of mass M.

e.g. free fall of two different bodies in

$$\eta = 2\frac{|a_1 - a_2|}{a_1 + a_2} \sim 10^{-4} \beta^2 \frac{\Delta R_\oplus}{R_\oplus}$$

Eötvös parameter.

$\Rightarrow$ for this shell thin is small. $\eta \lesssim 10^{-13}$

A rough rule of thumb:

Require
$$\boxed{\frac{\Delta R}{R} < \Phi_N.}$$

If this is violated $\Longrightarrow$ back to the blackboard.

<u>Moon</u> – lunar laser ranging gives precise measurement of the lunar orbit & constrains free-fall acceleration of moon + earth toward sun to be less than $O(10^{-13})$

$$\therefore \quad \frac{|a_{moon} - a_{\oplus}|}{a_N} \lesssim 10^{-13}$$

$\hookrightarrow$ Newtonian acceleration

$$\text{now} \quad \frac{\Delta R_{moon}}{R_{moon}} \sim \frac{\Delta R_{\oplus}}{R_{\oplus}} \frac{\overbrace{\Phi_{\oplus}}^{10^{-9}}}{\underbrace{\Phi_{moon}}_{10^{-11}}} < 10^{-5}$$

Compute a_{moon} & $a_{\oplus}$

$$\Rightarrow \quad \frac{|a_{moon} - a_{\oplus}|}{a_N} \approx \beta^2 \left(\frac{\Delta R_{\oplus}}{R_{\oplus}}\right)^2 < \beta^2 \underline{\underline{10^{-14}}}$$

Similarly we can test with the orbit of Mercury.

We can continue require the galaxy to be screened.

$$\therefore \quad \frac{\Delta R}{R} < 10\,\Phi_N^G \lesssim 10^{-6}$$

Time delay.

Now consider the Shapiro time delay. This is usually calculated in a PPN expansion.

- light bending around a heavy source (e.g. sun)

let
$$\Phi(r) = \Phi_N(r) + \frac{\beta\,\phi_0(r)}{M_{pl}}.$$

so
$$\Phi(r) = -G_{eff}\,\frac{M_A}{r}$$

$\uparrow$ effective Newton constant.

Consider a photon trajectory between two points, with impact parameter b

$$r = b/\cos\theta$$

The Jordan frame metric is

$$ds_J^2 = -(1+2\Phi)\,dt^2 + (1-2(1+\gamma)\Phi)\,dx^2$$

$$dx^2 = dr^2 + r^2\,d\theta^2 - b/\cos^2\theta\,d\theta$$

The modification in the time delay due to modified gravity is

$$\frac{d}{dx}\delta t = -2\gamma\Phi$$

$$= 2\gamma \frac{G_{eff}\, m_A}{r\cos\theta}.$$

what is γ? This can be computed from the Jordan frame metric

$$|1-\gamma| = \frac{2\beta^2}{1+\beta^2} \sim 2\beta^2$$

measurement of time delay constrains β.
For screened objects $\beta \to \beta_{eff} \equiv \beta \frac{\Delta R}{R}$

Cassini – constrains $\underline{\beta^2 \lesssim 4.10^{-5}.}$

Vainshtein Screening (taken from 1408.4759)

- including shape dependence.

Galileon

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{k_3}{\Lambda^3}(\partial \phi)^2 \Box \phi$$

$$\mathcal{L}_m = \mathcal{L}(\tilde{g}_{\mu\nu}, \psi)$$

$$\frac{e^{\beta\phi}}{M_{pl}} T^\mu_\nu$$

Field eqn

$$\frac{\beta \rho}{M_{pl}} = \Box \phi + \frac{1}{\Lambda^3}\left[(\Box \phi)^2 - (\nabla_\mu \nabla_\nu \phi)(\nabla^\mu \nabla^\nu \phi)\right]$$

$$+ O(1/\Lambda^6)$$

$$\therefore \frac{\beta}{M_{pl}} r^2 \rho(r) = (r^2 \phi')' + \frac{2(r\phi'^2)'}{\Lambda^3}$$

$r < r_0 \quad \rho = \rho_0$

$$\phi' = \frac{\Lambda^3}{4} r \left(\sqrt{1 + \frac{r_V^3}{r_0^3}} - 1\right) \quad r < r_0$$

$$= \frac{\Lambda^3 r}{4} \left(\qquad \right) \quad r > r_0$$

$$M = \frac{4\pi}{3} r_0^3 \rho_0 \qquad r_V = \left(\frac{2\beta M}{\pi M_{pl} \Lambda^3}\right)^{1/3}.$$

PTO

$r < r_V$

$$\boxed{\left|\frac{F_\phi}{F_N}\right| = 4\beta^2 \left(\frac{r}{r_V}\right)^{3/2}}$$

put in values for M $\Rightarrow$ r_V - large.

$\Lambda^3 \sim M_{pl} H_0^2$.