Screening the Dilaton?

Philippe Brax

Institut de Physique Théorique

Université Paris-Saclay

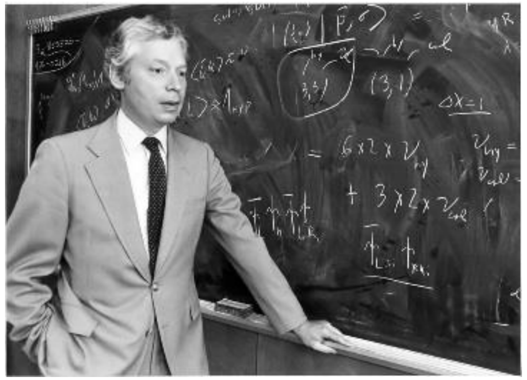
Collaboration with C. Burgess and F. Quevedo.

2310.02092
230812004
2307.06781

The dark energy scale is in the ***pico-eV range***: apparent fine-tuning compared to standard model scales.

$$\delta\rho_\Lambda = M^4, \quad M \sim 100\mathrm{GeV}$$

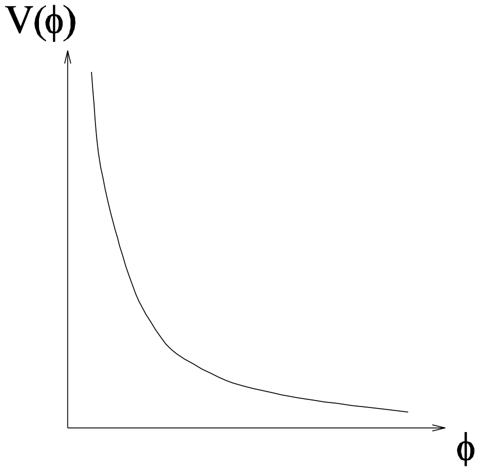
Weinberg's theorem states that there is no non-fined tuned vacuum with a vanishing cosmological constant in a 4d quantum field theory respecting **Poincare invariance**.



Dynamical configurations

↓

Dark energy



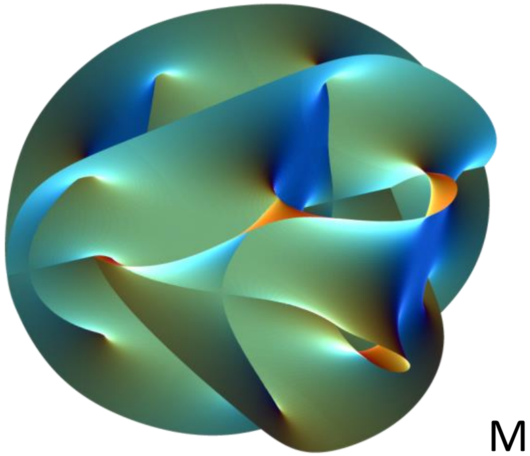
Scalar field rolling down its potential

The most important stringy -cum-quantum gravity conjectures for dark energy are:

See **David Andriot's** talk

✓ ***The de Sitter conjecture***: a pure vacuum energy with no dynamics is not compatible with string theory.

✓ ***The vacuum conjecture:*** Empty space-time is described by the dynamics of at least one scalar field with a potential such that



$$|\frac{dV}{d\phi}| \geq c\frac{V}{m_{\rm Pl}}$$

$$c = \mathcal{O}(1)$$

This forbids very flat potentials. This favours runaway potentials where the field is a "moduli".

Moduli could be "sizes" of extra-dimensions

Runaway dilaton model:

Focus on simplest potential with runaway behaviour:

$$V(\phi) = V_0 e^{-\lambda\phi/m_{\rm Pl}}$$

Klein-Gordon equation

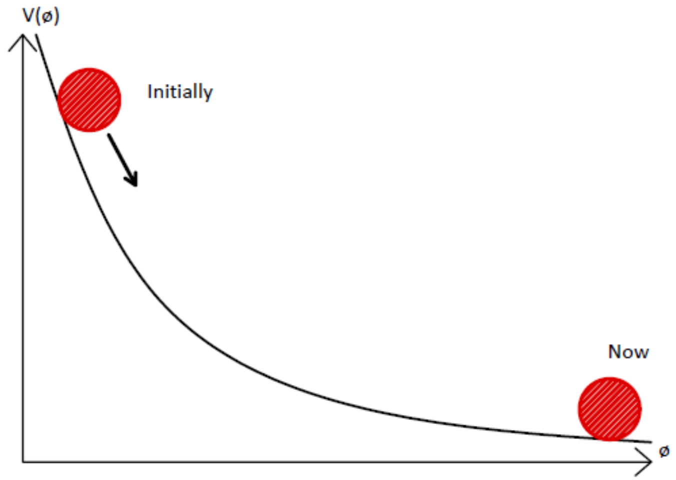
$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

$$\gamma = \frac{2}{\lambda}, \quad \alpha = \frac{2}{\lambda^2}$$

Friedmann:

$$H^2 = \frac{\frac{1}{2}\dot{\phi}^2 + V(\phi) + \rho}{3m_{\rm Pl}^2}$$

matter



Initially dark energy is subdominant and then starts dominating when matter becomes very small.

$$\phi = \phi_\star + \gamma m_{\rm Pl} \ln \frac{t}{t_\star}$$

$$a = a_\star \left(\frac{t}{t_\star}\right)^\alpha$$

Some features:

- The field evolution is an attractor. The same long time behaviour will always happen even if one changes the initial conditions.

- Dark energy is determined by the position of the field now:

$$3\Omega_\Lambda H_0^2 m_{\rm Pl}^2 = V_0 e^{-\lambda\phi_{\rm now}/m_{\rm Pl}}$$

- The field is ***extremely light***:

$$m_\phi^2 = \frac{d^2V}{d\phi^2}|_{\rm now} = \lambda^2 \frac{V_{\rm now}}{m_{\rm Pl}^2} = 3\lambda^2\Omega_\Lambda H_0^2$$

Mass of the order of the Hubble rate

$$H_0 \sim 10^{-42}\ {\rm GeV}$$

Acceleration takes place with:

$$\omega_\phi = \frac{p_\phi}{\rho_\phi}$$

$$\omega_\phi = -1 + \frac{\lambda^2}{3}$$

$$\lambda \leq \sqrt{2}$$

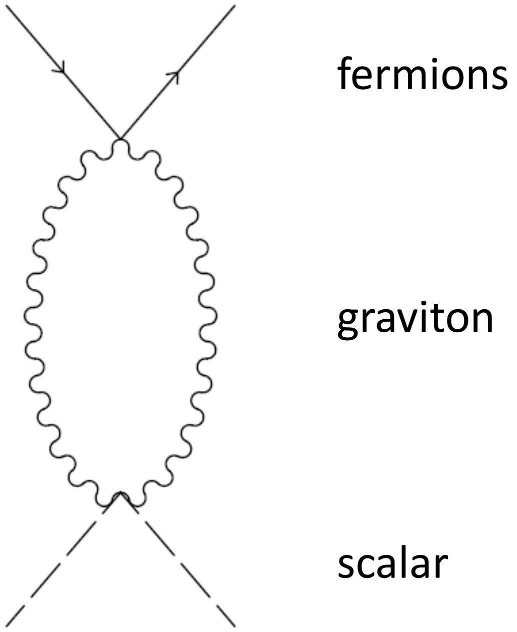
Notice that this is just about what is required by the de Sitter and vacuum conjectures…

Problem: assumption that scalar decoupled from matter!

Effective coupling:

$$\mathcal{L} \supset -\frac{\beta}{m_{\rm Pl}} m_\psi \phi \bar{\psi}\psi$$

No ***reason*** to assume $\beta = 0$



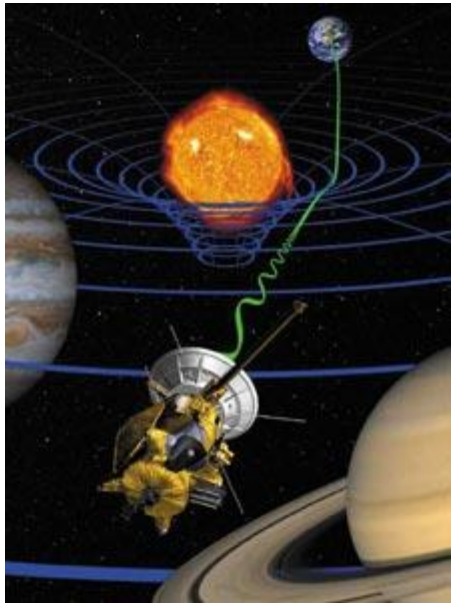
Coupling to matter induced by quantum corrections

$$\beta \sim \frac{H^2}{m^2} \int \frac{d^4 p}{p^4}$$

divergent

Deviations from Newton's law are parametrised by:

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



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. (2004)

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

Coupled scalar field models play a role in the dynamics of the Universe.

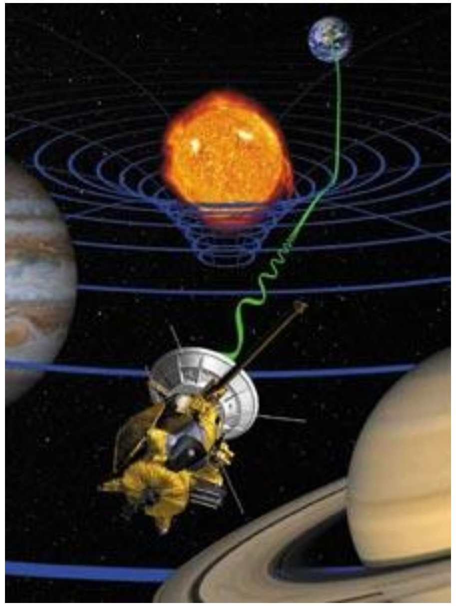
Problem: long range interactions on cosmological scales

↓

Strong deviations from GR in the solar system?

↓

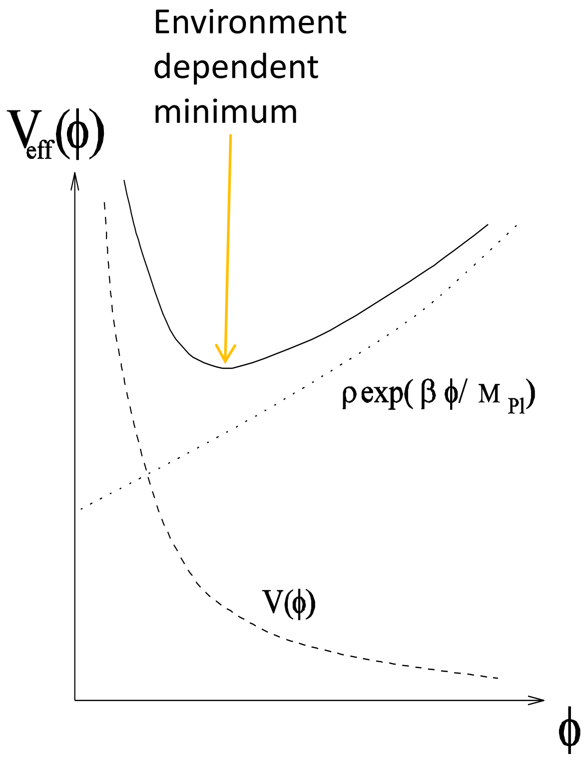
SCREENING

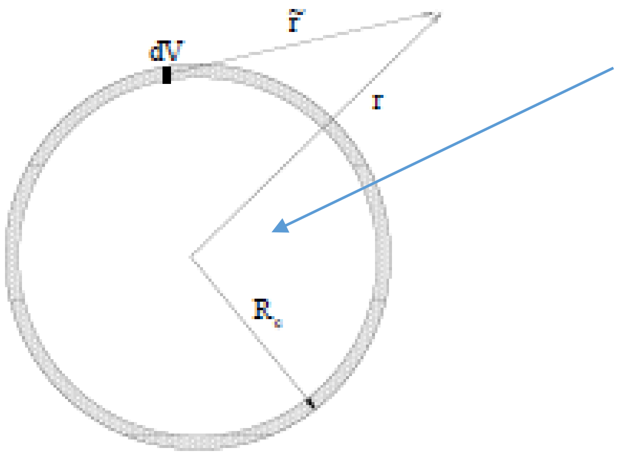


Chameleon Screening

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

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





Large mass inside object

$$m_{\rm in} R \gg 1$$

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.

Contrary to what is usually assumed in cosmology, the scalar models arising from more fundamental (?) theories such as string theory always arise in pairs, and both could play a role:

Supersymmetry → **Superfields=complex fields**

$$\mathcal{L} = K_{a\bar{a}} \partial_\mu z^a \partial^\mu \bar{z}^{\bar{a}}$$

These fields in general have no potential as they arise as moduli in compactifications and one can deform the compactification manifold with no cost (unless there are fluxes…) or non-perturbative phenomena occur (like in QCD).

In general they couple to matter with a conformal coupling

$$g^J_{\mu\nu} = e^{K/3m^2_{\rm Pl}} g_{\mu\nu}$$

Jordan

Einstein

Explicit couplings could also appear for instance the Yukawa couplings could be moduli-dependent

Coupled massless moduli →  **Screening** 

??

The axion profile: *clues from the QCD axion*.

Screening will be triggered when the axion potential and its coupling function to matter have two distinct minima

How could this work?

Moduli space metric with one shift symmetry singling out the axion:

$$a \to a + C$$

$$ds^2 = (m_{\rm Pl}^2 d\phi^2 + f^2 W^2(\phi) da^2)$$

Axion decay constant normalising the axion field

The **function *W*** *will act as potential* for the dilaton once the axion has acquired a non-trivial profile.

The Klein-Gordon equation for the axion is simply:

$$\nabla_\mu(W^2(\phi)\partial^\mu a) = \frac{1}{f^2}\partial_a V_{eff}$$

$$V_{\rm eff}(a) = V(a) + n(x)U(a)$$

Matter density

The effective potential depends on two functions whose shapes are determined in the QCD example.

$$V_{\rm QCD}(a) = -\Lambda^4_{\rm QCD}(1 - \frac{4m_u m_d}{(m_u+m_d)^2}\sin^2(\frac{a}{2}))^{1/2}$$

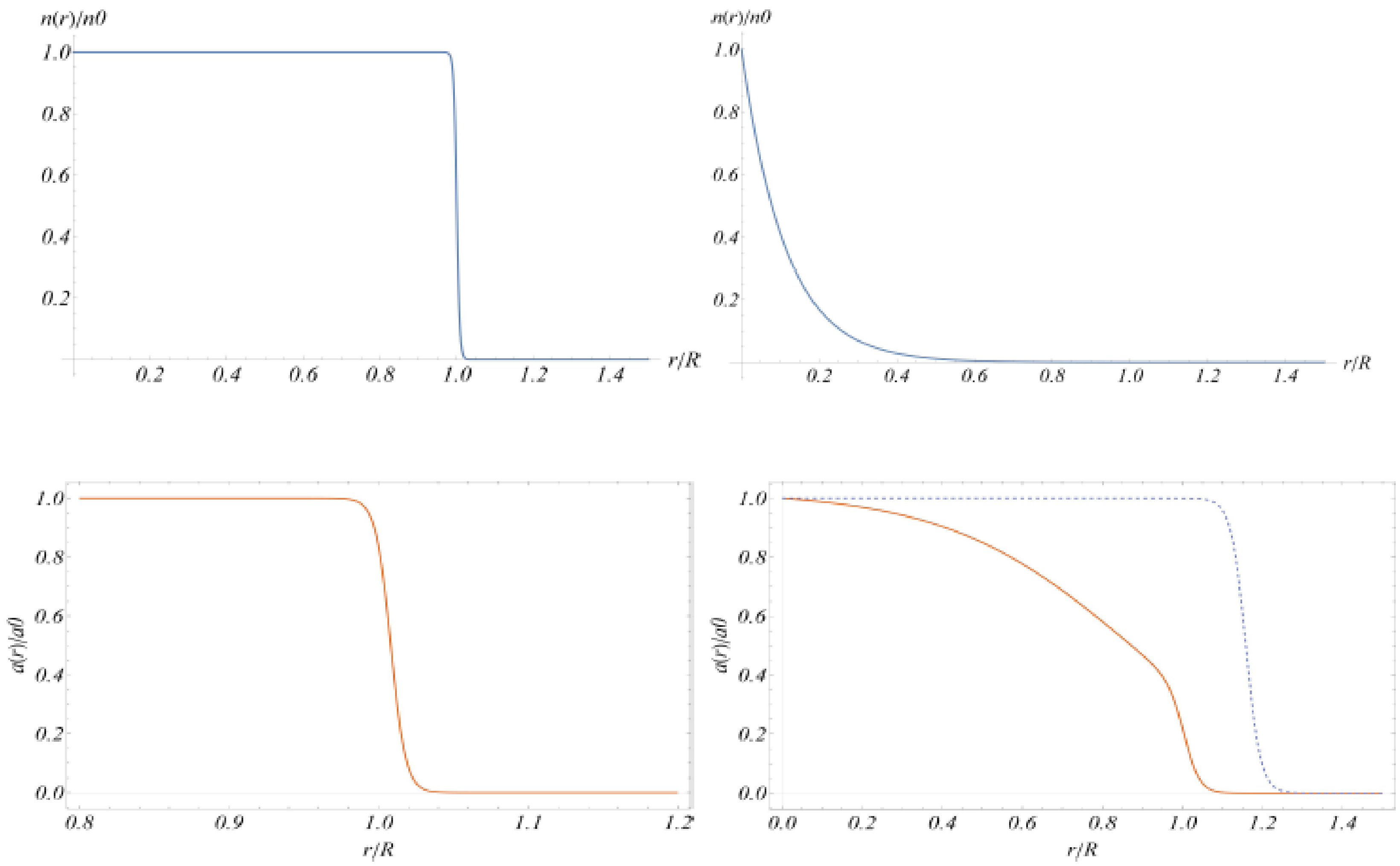
$$U(a) = \sigma_B \cos\frac{a}{2}$$

Minimised at a=0 in vacuum to solve the QCD CP problem.

Of order of the QCD scale

Minimised at a=π

The axion profile depends on the mass of the axion inside and outside matter.



$$m_{\rm in} R \gg 1$$

Size of the object.

The Klein-Gordon for the dilaton is:

Coupling constant to matter.

$$\Box\phi = \frac{f^2}{m_{\rm Pl}^2} W W' (\partial a)^2 + \frac{\mathcal{G}}{m_{\rm Pl}^2}\rho$$

Axion driven "potential"

Far away from the body we expect:

$$\phi = \phi_\infty - \frac{L}{r}$$

$$L = 2\mathcal{G} G_N M$$

In the absence of screening.

Usually determined by the cosmological dynamics at infinity

When the *mass of the axion is very large* compared to the inverse size of the object, we can apply the

Narrow Width Approximation

The axion field jumps over a size:

$$\ell \simeq m_a^{-1}$$

$$a = a_+\Theta(r-R) + a_-\Theta(R-r)$$

$$a' = (a_+ - a_-)\delta(r-R)$$

We will need the expression for the square of a' :

$$(a')^2 = \frac{\delta(r-R)}{2\ell}$$

Same trick as when calculating cross section from the square of the matrix elements .

The delta function as a source term implies a jump of the derivative of the dilaton:

$$\phi'_{\rm out}(R) - \phi'_{\rm in}(R) = \frac{f^2}{m_{\rm Pl}^2}\left(\frac{WW'}{2\ell}\right)_{r=R}(a_+ - a_-)^2$$

$$L = R^2 \phi'_{\rm ext}(R)$$

Needs to be negative to reduce the scalar charge of the object

The scalar charge L is determined by the competition between the different energy sources for the scalar field profile. This completion will select the asymptotic value of the field at infinity and determine the scalar charge.

In the axio-dilaton case, the energetics works completely differently as there mass of the dilaton is taken to be negligible and the kinetic energy depends on the asymptotic value.

$$E_{\rm kin} = 2\pi \int_0^\infty dr\ r^2 (f^2 W^2 (a')^2 + m_{\rm Pl}^2 (\phi')^2)$$

Gives a surface contribution

Same as before but dependent on the asymptotic value

$$E_{\rm kin,a} = \frac{\pi f^2}{\ell} R^2 W^2 (r=R)(a_+^2 - a_-^2)$$

$$E_{\rm kin} = E_0 + \frac{L^2}{4 G_N R}$$

$$L = 2\mathcal{G}M + \frac{f^2}{m_{\rm Pl}^2} R^2 (\frac{WW'}{2\ell})_{r=R} (a_+ - a_-)^2$$

Minimising the energy with respect to the asymptotic value would determine:

$$W'(r = R) = 0$$

If it were not the contribution from the axion surface term in W.

Screening takes place when the scalar is attracted dynamically close to **W'=0**

$$W^2(\phi) = W_\star^2 + \frac{W_1^2}{2}(\phi - \phi_\star)^2 + \dots$$

Having expanded W close to a minimum, the effective coupling to matter L can be obtained by minimising the energy with respect to the boundary value at infinity:

$$\mathcal{G}_{\text{eff}} \equiv \frac{L}{2G_N M} = \frac{\mathcal{G}}{1 + \frac{R}{\ell}\hat{W}_1^2(a_+ - a_-)^2}$$

$$\hat{W}_1^2 = \frac{f^2}{m_{\text{Pl}}^2} W_1^2 = \mathcal{O}(1)$$

Screening takes place as:

$$\frac{\ell}{R} \ll 1 \Rightarrow \frac{\mathcal{G}_{\text{eff}}}{\mathcal{G}} = \mathcal{O}(\frac{\ell}{R}) \ll 1$$

The dilaton is screened thanks to the large mass of the axion.

In the presence of many bodies, close enough to each of them we expect the biggest one to determine the value of the field outside and the screening of all the smaller objects:

$$\phi_{\rm min} - \phi_\star \simeq -\frac{8\mathcal{G}\ell m_{\rm Pl}^2}{f^2 W_1^2 (a_+ - a_-)^2}\left(\frac{G_N M}{R^2}\right)$$

The object's surface gravity

The object will the largest surface gravity wins.

Prospects and open questions

- Cosmology

The cosmology of this new screening mechanism is terra incognita.

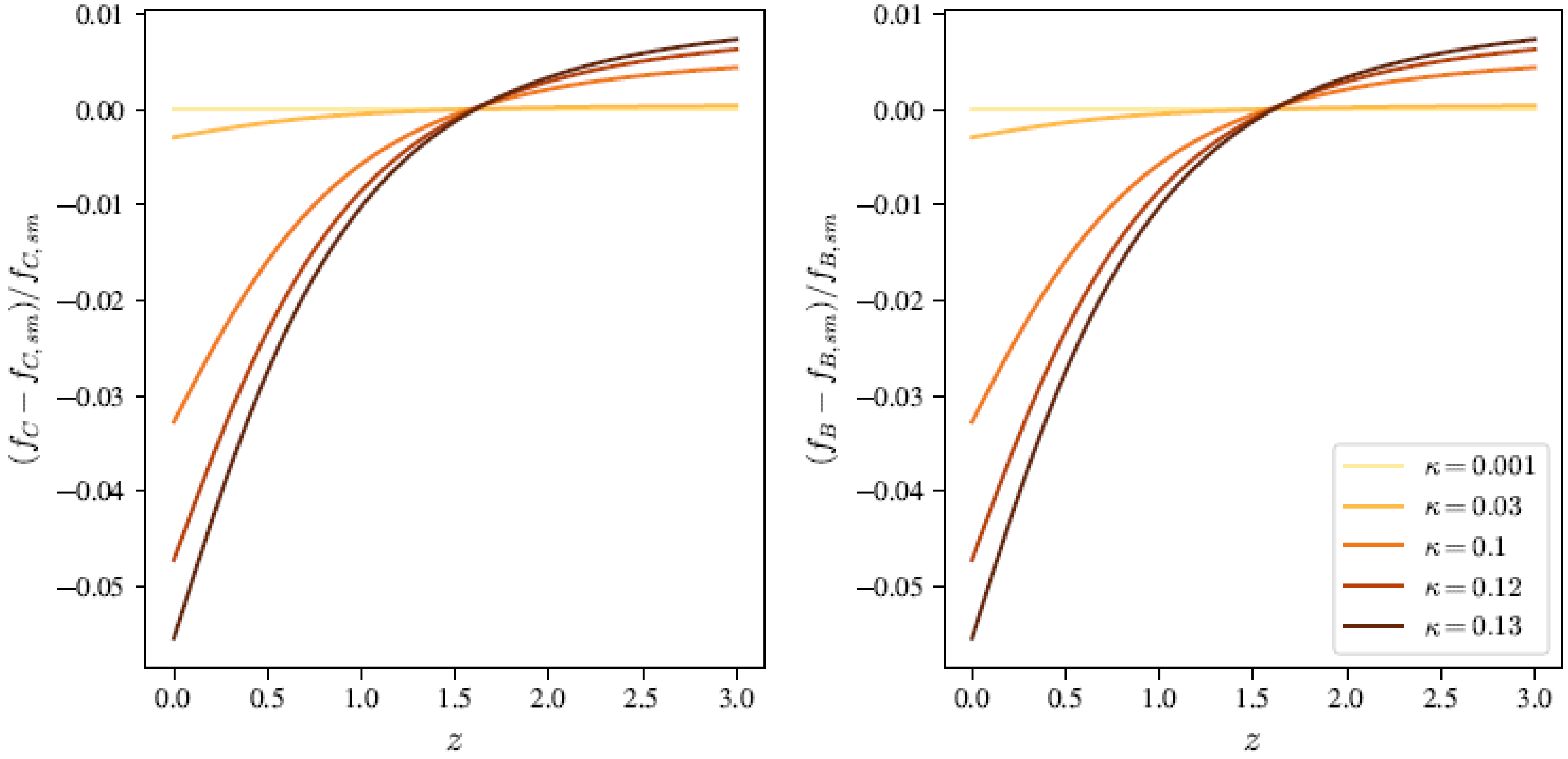
- Numerics

Screening in the presence of many bodies must be checked numerically. In particular the issue of frustration must be addressed. This could have important consequences for the violation of the equivalence principle by small objects aboard satellites.

- Model Building

How do you construct a model with a minimum for W? Usual axio-dilaton systems have exponential tails.

Reduction of growth in the linear regime.



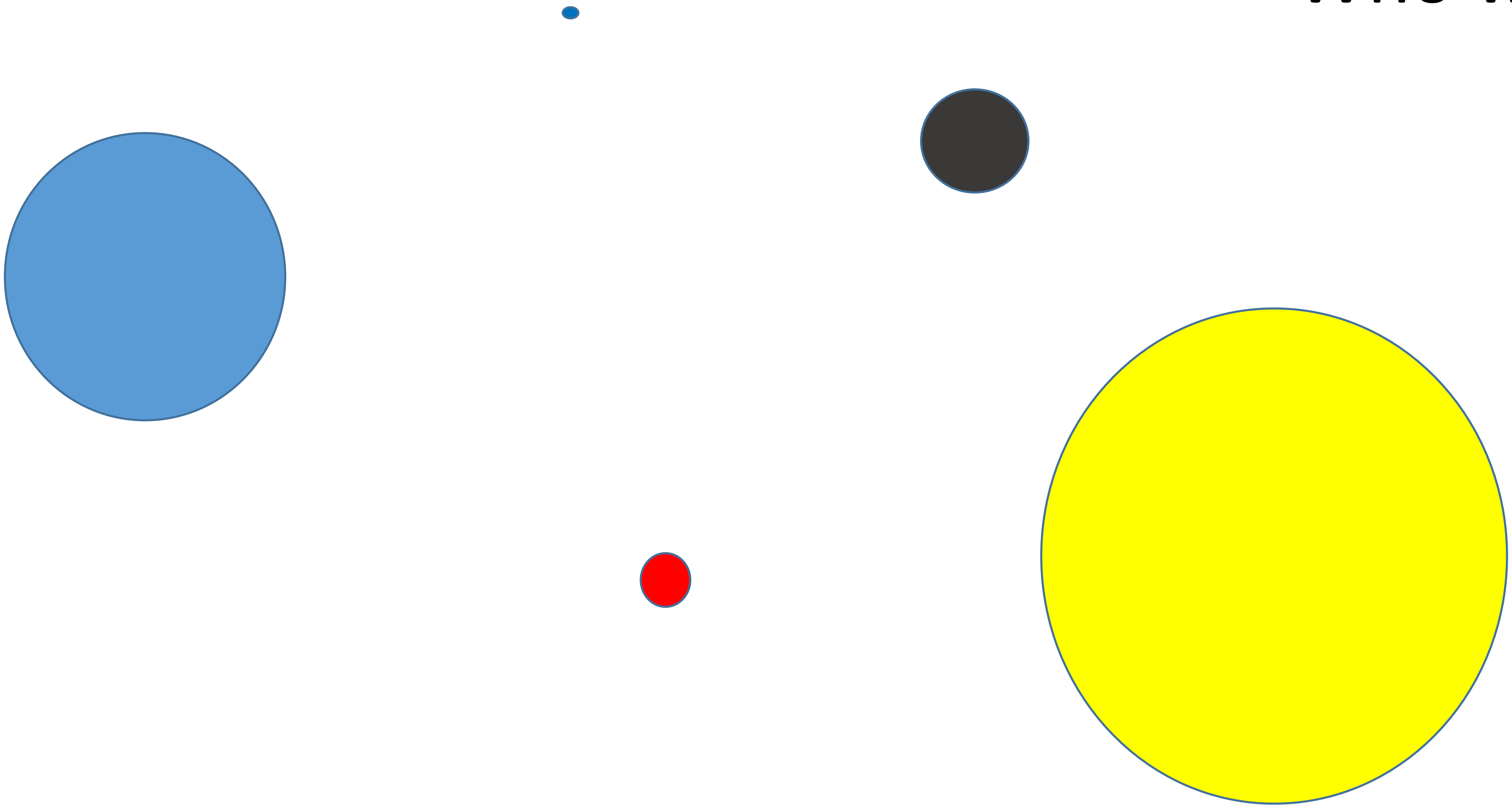
$$f = \frac{\partial \ln \delta}{\partial \ln a}$$

Unscreened case, volume modulus

SUPPLEMENTS

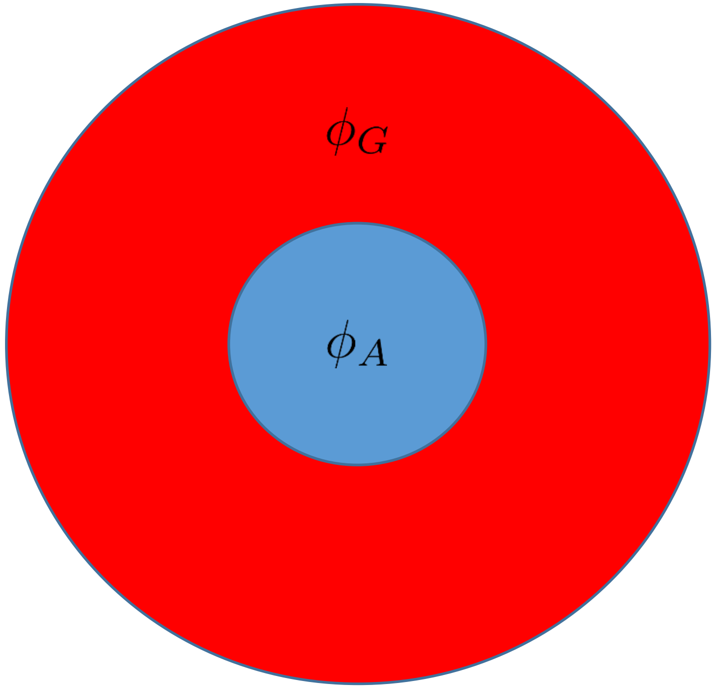
Frustration

Who wins?



Chameleons:

The screening criterion for an object BLUE embedded in a larger region RED expresses the fact that the Newtonian potential of an object must be larger than the variation of the field:



Scalar charge: $$Q_A = \frac{|\phi_G - \phi_A|}{2m_{\rm Pl}\Phi_A}$$

$$Q_A \leq \beta_G$$

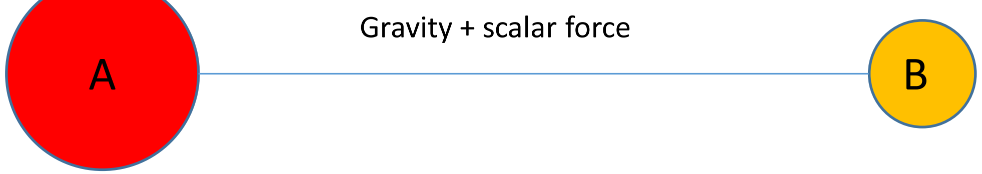
Screening criterion

Φ_A Newton's potential at the surface

Due to the scalar interaction, within the Compton wavelength of the scalar field, the inertial and gravitational masses differ for screened objects:

$$G_{A,B} = G_N(1 + 2Q_A Q_B)$$

Interaction rate depending on the objects



Value of the field far away

$$Q_A = \frac{\phi_\infty}{2m_{\rm Pl}\Phi_A}$$

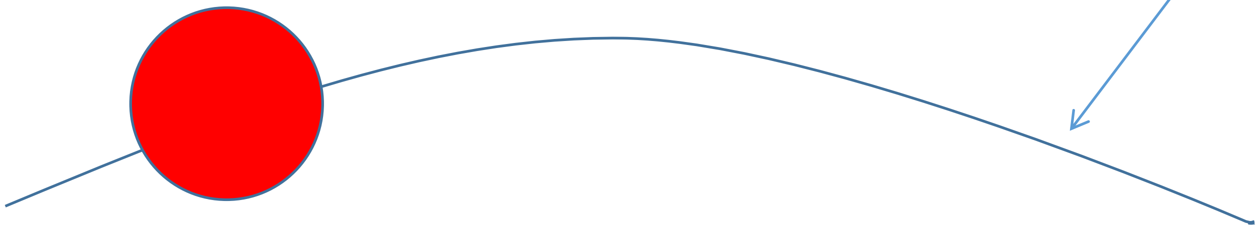
Newtonian potential at the surface of the body.

$$Q_A \leq \beta_\infty$$

Screening criterion for compact objects

Massive bodies with differ scalar charges fall differently. Hence a violation of the strong equivalence principle.

The motion of astrophysical objects in Vainshtein and K-mouflage theories does not violate the **strong equivalence principle:**

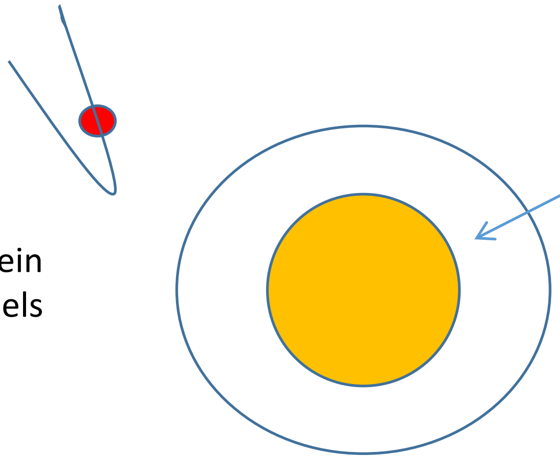


Trajectories due to gravity + scalar in an external gradient of the scalar field, for instance due to another object nearby.

$$\ddot{X} = -\nabla\Phi_N - Q\nabla\phi_{\rm ext}$$

Universal scalar charge, no violation of the strong equivalence principle.

Unlike chameleons, Vainshtein and K-mouflage do not affect the charge Q: $Q = \beta$



Outside the Vainshtein radius, the object feels the scalar force

$\nabla\phi_{\rm ext} \ll 2\beta\nabla\Phi_N$

The scalar force is screened because the gradient of the external scalar field is suppressed.

$\nabla\phi_{\rm ext} = 2\beta\nabla\Phi_N$ outside the Vainshtein radius

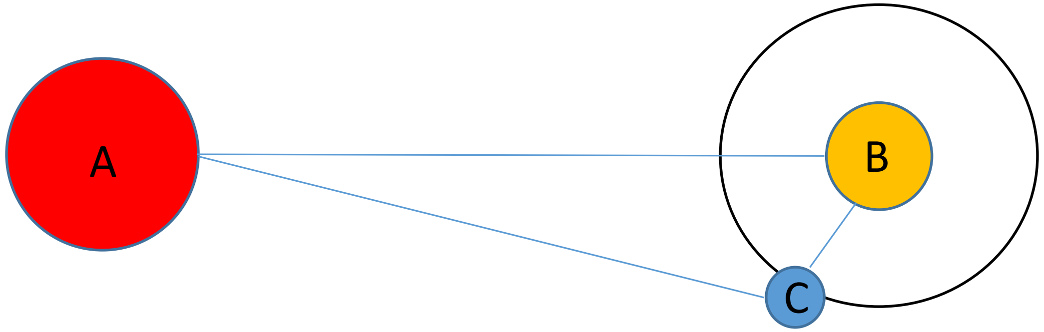
Due to the scalar interaction, within the Compton wavelength of the scalar field, the inertial and gravitational masses differ for screened objects:

VIOLATION OF THE STRONG EQUIVALENCE PRINCIPLE

$$\Phi_\oplus \sim 10^{-9}$$

$$\Phi_\odot \sim 10^{-6}$$

$$\Phi_{\rm moon} \sim 10^{-11}$$



The tightest constraint on planetary motion is obtained by the Lunar Laser Ranging experiment measuring the distance between the Earth and the Moon. The bound is on the Eotvos parameter A=Sun B= Earth C=Moon

$$\eta_{\rm moon-earth} \le 10^{-13}$$

For this system, this is related to the scalar charge of the Earth:

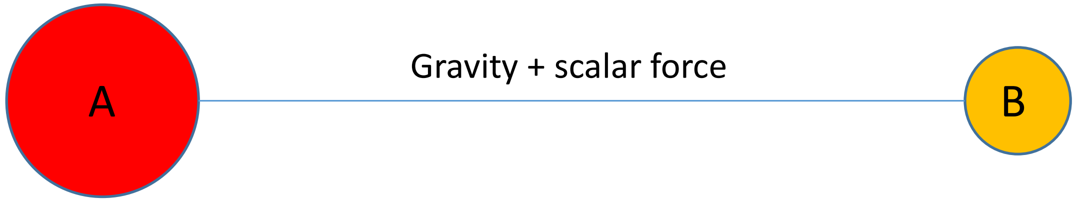
$$\eta_{BC} \equiv \left|\frac{a_C - a_B}{a_C + a_B}\right| = Q_A |Q_C - Q_B|$$

$$\eta_{\rm moon-earth} \approx 10^{-1} Q_\oplus^2 \longrightarrow Q_\oplus \le 10^{-6}$$

Due to the scalar interaction, within the Compton wavelength of the scalar field, the inertial and gravitational masses differ for unscreened objects:

$$G_{A,B} = G_N(1 + 2\beta_\infty^2)$$

Coupling between objects



If only unscreened objects existed, one could rescale Newton's constant and recover the equality between the gravitational and inertial masses.

This cannot be done as light rays deviate in the presence of matter according to the un-rescaled Newton constant! This corresponds to the fact that matter particles do not follow geodesics of the geometrical metric g (one of the consequence of Einstein's equivalence principle).

Burgess and Quevedo concentrated on the axio-dilaton case corresponding to the volume modulus of compactifications from 10d to 4d:

$$K = -3m_{\mathrm{Pl}}^2 \ln(T + \bar{T})$$

The volume modulus can be decomposed in:

$$T = e^{\phi} + ia \longrightarrow e^{K/6m_{\mathrm{Pl}}^2} = e^{-\phi/2}$$

dilaton

axion

Dilaton coupling to matter of order one!

They also assume that the matter action depends on the axion:

$$\mathcal{A} = -\frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta a}$$

There are two coupled Klein-Gordon equations:

Fiducial coupling κ=1 in supergravity

$$\Box\phi + (\partial a)^2 e^{-2\phi} = \frac{\kappa}{2}\frac{T}{m_{\rm Pl}^2}$$

$$\Box a - 2\partial_\mu\phi\partial^\mu a = \frac{e^{2\phi}}{3m_{\rm Pl}^2}\mathcal{A}$$

In the absence of matter, the solutions are **“surfing fields**” on the moduli space :

$$a = \alpha - \beta\tanh X,\ \ \phi = \ln\frac{\beta}{\cosh X}$$

$$X = \frac{\gamma\beta}{r} + \delta$$

The constants of integration are determined by the source and the field values of infinity:

$$\gamma = -\frac{1}{3m_{\rm Pl}^2}\int_0^R r^2 dr\mathcal{A}$$

$$\alpha = -\frac{1}{3\gamma m_{\rm Pl}^2}\int_0^R r^2 dr(\kappa\rho + a\mathcal{A})$$

Surfing fields:

The solutions of the Klein-Gordon for a sigma model:

$$S = -\frac{1}{2}\int d^4x\sqrt{-g}\;\mathcal{G}_{ab}\partial_\mu\phi^a\partial^\mu\phi^b$$

are explicitly given by:

$$\phi^a = \Phi^a(\sigma)$$

Geodesics on the moduli space defining by the metric:

$$\mathcal{G}_{ab}$$

Solution of the wave equation:

$$\Box\sigma = 0$$

Can be generalised to curved backgrounds and generate wormhole solutions.

$$a_\infty = \alpha - \beta \tanh\delta, \quad \beta = \sqrt{e^{2\phi_\infty} + (\alpha - a_\infty)^2}$$

A point particle evolving in the background of this scalar configuration feels a fifth force "naively" determined by the conformal factor A and the coupling to the dilaton. The PPN parameter is

$$g^J_{\mu\nu} = (-1 + \frac{2G_N M}{r})dt^2 + (1 + 2\gamma_{\rm PPN}\frac{G_N M}{r})(dr^2 + r^2 d\Omega^2)$$

We are interested in the case where the axion couples linearly with a tiny coupling:

$$\mathcal{A} = -\epsilon T, \quad \epsilon \ll 1$$

In this case the PPN parameter is:

$$\gamma_{\rm PPN} = \frac{3 - \epsilon\kappa\alpha\tanh\delta}{3 + \epsilon\kappa\alpha\tanh\delta}$$

$$\gamma_{\rm PPN} \to 1 \text{ for } \epsilon \ll 1$$

Screening!!

This is the essence of the proposed Burgess-Quevedo screening. Is it too good to be true?? Where does screening come from???

Let us now use the equations inside the source and match with the surfing moduli outside the source. This leads to:

$$\begin{cases} \beta = \sqrt{e^{2\phi_\infty} + (\frac{\kappa}{\epsilon} + a_0 - a_\infty)^2} \\ \tanh\delta = 1 - \frac{\epsilon^2}{\kappa}\frac{e^{2\phi_0}}{2} \end{cases} \longrightarrow \begin{cases} \beta \simeq \frac{\kappa}{\epsilon} + a_0 - a_\infty \\ \gamma_{\text{PPN}} = \frac{3-\kappa^2}{3+\kappa^2} \end{cases}$$

This corresponds to **NO SCREENING** and a linear coupling to gravity

$$\text{coupling} = \frac{\kappa}{\sqrt{6}}$$

For axio-dilaton in sugra, same coupling as f(R) and massive gravity

Screening only takes place when the field at infinity is tuned:

$$a_\infty - a_0 = \frac{\kappa}{\epsilon}$$

In the absence of potentials, the fields at infinity should be determined by the cosmological evolution.
Generically no screening as nothing tunes the fields at infinity to the right values.

Way outs?

The axion profile can trigger the screening of the dilaton

Acts as a catalyst for the dilaton behaviour in the presence of matter.

Energetics

Traditionally for a nearly massless and unscreened field we have two sources of energy:

$$E_{\rm kin} = 4\pi m_{\rm Pl}^2 \int_0^\infty dr r^2 \frac{\phi'^2}{2} = E_0 + \frac{L^2}{4G_N R}$$

Kinetic energy inside independent of the asymptotic value of the field

Kinetic energy outside the body also independent of the asymptotic value of the field.

$$E_{\rm pot} = 4\pi \int_0^\infty rd\ r^2 V(\phi) \simeq 2\pi m_\phi^2 R_{out}^2 (\phi_\infty - \phi_{\rm min})^2$$

IR cutoff

Minimised

$$\phi_\infty = \phi_{\rm min}$$