Facing Dark Energy in SUGRA

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Outline

1-Acceleration of the Universe: SUGRA approach (three sectors)

2-Dark Energy and Gravitational Issues (constraints from the non-existence of fifth forces)

3-Shift Symmetry (dark energy relation to the superpotential)

4-Shift Symmetry Breaking (models with a minimum)

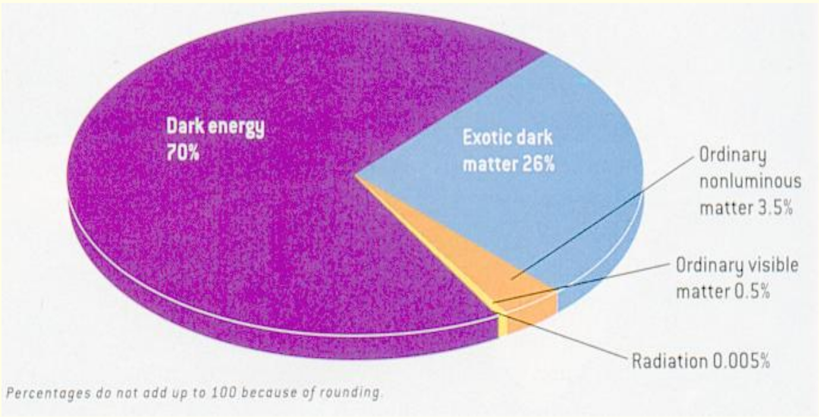
Acceleration of the Universe

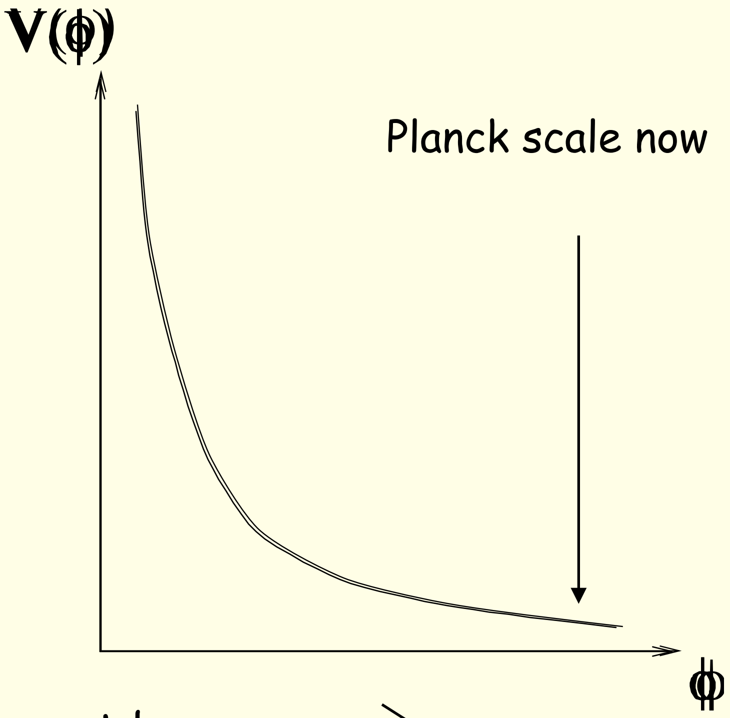
SN Ia supernovae data , Large Scale Structures and the Cosmic Microwave Background give strong indication that our universe behaves very differently from a matter dominated universe

This can be interpreted in four distinct ways:

- General Relativity must be complemented with a pure cosmological constant (the most economical interpretation)
- General Relativity must be modified on large scales (existence of ghosts)
- There exists a new matter component called dark energy (quantum problems, coincidence problem)
- The cosmological principle (Copernic) must be questioned (we could live in a local void and misinterpret data)

Dark Energy



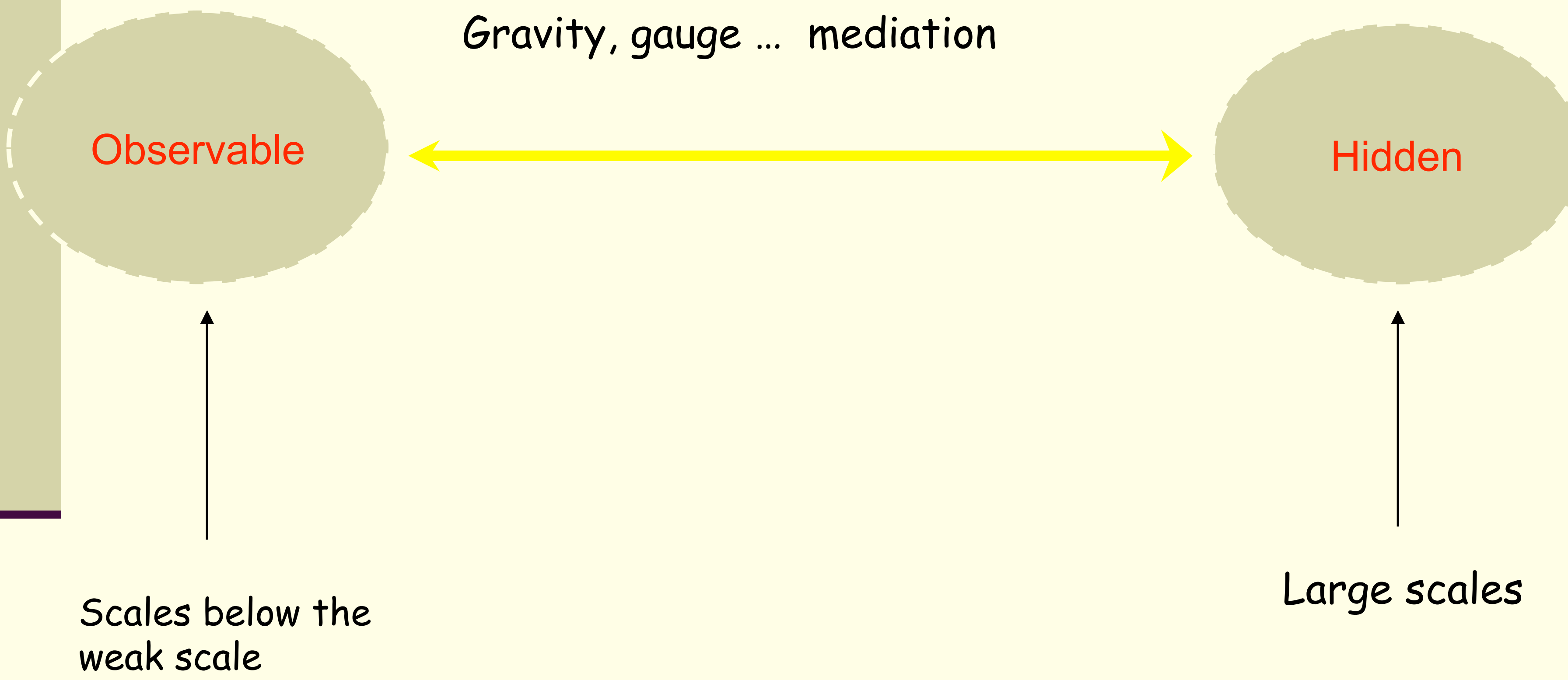


Field rolling down a runaway potential, must be related to the rest of particle physics!

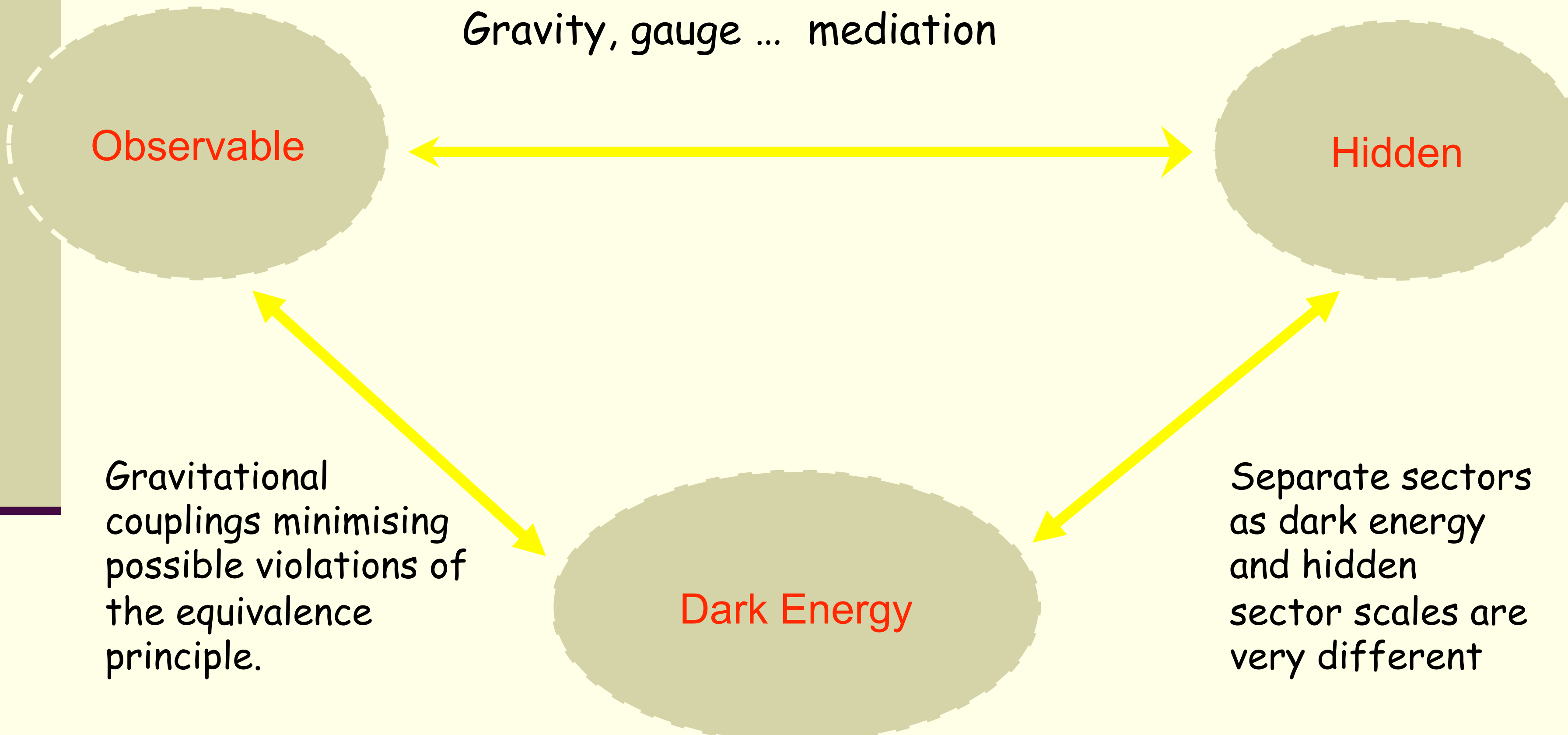
Supergravity

Quantum fluctuations affect the shape of the potential.

Supergravity Framework



Supergravity Framework



Three sectors

- The Kahler potential and the superpotential are assumed to be separated:

$$K = K_{\mathrm{DE}}(Q,\bar{Q}) + K_h(z,\bar{z}) + K_{\mathrm{MSSM}}(\phi^a,\bar{\phi}^{\bar{a}})$$

$$W = w(Q) + W_h(z) + W_{\mathrm{MSSM}}(\phi^a)$$

- Dark energy perturbs the hidden sector dynamics:

$$< z >= z_0(Q,\bar{Q})$$

- The fermion masses become dark energy dependent

$$m_{\mathrm{u,d}} = \lambda e^{\kappa_4^2 K(Q,\bar{Q})} v_{\mathrm{u,d}}(Q,\bar{Q})$$

Scalar-tensor theory

Gravitational Tests

Scalar-tensor theories suffer from the potential presence of a fifth force mediated by the scalar field.

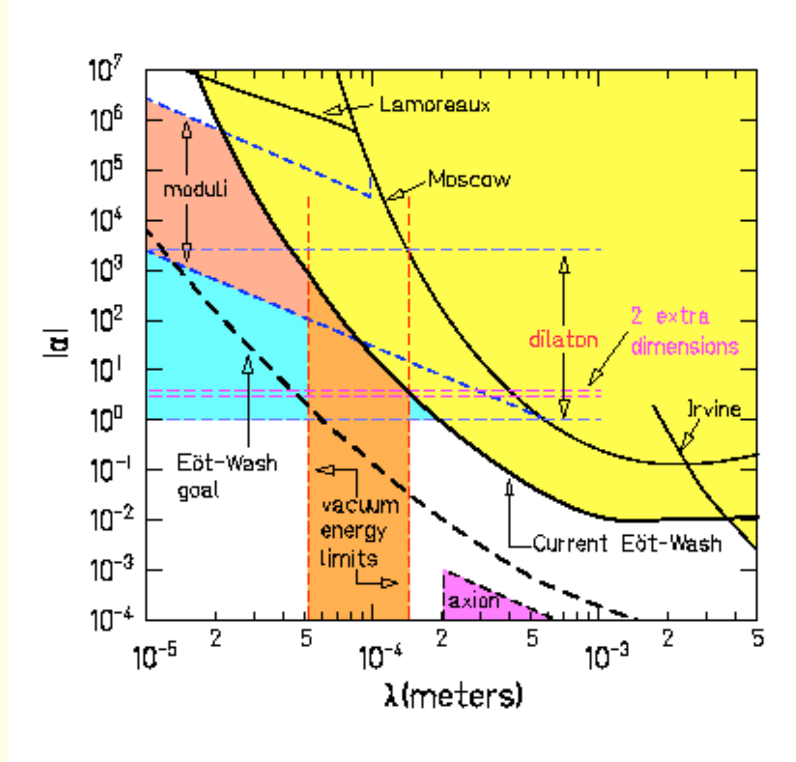
Alternatives:

Non-existent if the scalar field has a mass greater than :

$$m \geq 10^{-3}\ \mathrm{eV}$$

If not, strong bound from Cassini experiments on the gravitational coupling:

$$\alpha^2 \leq 10^{-5}$$



Gravitational Problems

- Deviations from Newton's law are tested on macroscopic objects. The gravitational coupling is:

$$\kappa_4 \alpha = \frac{\mathrm{d} \ln m_{\mathrm{atom}}}{\mathrm{d} Q_n}$$

- The deviation is essentially given by:

$$\alpha \approx [\frac{3}{2}\frac{m_u + m_d}{\Lambda_{QCD}} - \frac{1}{8}\frac{N-Z}{N+Z}\frac{m_u - m_d}{\Lambda_{QCD}}]\kappa_4 \partial_{Q_n} K_{\mathrm{DE}}$$

- For runaway models reaching the Planck scale now:

$$\partial_{Q_n} K_{\mathrm{DE}} = \frac{Q_n}{2} \longleftarrow \text{O(1) now}$$

Too Large !

- For moduli fields:

$$K_{\mathrm{DE}} = -n \ln(\kappa_4 (Q + \bar{Q})) \rightarrow \partial_{Q_n} K_{\mathrm{DE}} = \sqrt{2n}$$

Shift Symmetry

- A shift symmetry $Q \longrightarrow Q+c$ prevents the existence of the gravitational problems (analogy with the η problem in supergravity inflation)

$$K_{\mathrm{DE}}(Q,\bar{Q}) = K_{\mathrm{DE}}(Q-\bar{Q})$$

- This also suppresses the dangerous supersymmetry breaking contribution to the dark energy potential (mass term for canonical fields)

$$\delta V_{\mathrm{DE}} = m_{3/2}^2 K_{\mathrm{DE}}^{Q\bar{Q}} K_Q K_{\bar{Q}}$$

Polonyi Coupled to Dark Energy

- Explicit calculations can be performed in simple susy breaking models such as Polonyi's. Results should be generic though:

$$K_h(z,\bar{z}) = |z|^2,\ W(z) = m^2(z+\beta)$$

$$\kappa_4\beta = 2-\sqrt{3}$$

- The dark energy sector:

$$K_{DE}(Q,\bar{Q}) = -\frac{1}{2}(Q-\bar{Q})^2$$

- In the absence of dark energy the hidden sector is stabilised:

$$\kappa_4 z_0 = \sqrt{3}-1$$

- Dark energy shifts the minimum:

$$\delta z(Q) = (\sqrt{3}-1)\frac{w}{m^2}$$

Small expansion parameter

Dark Energy Dynamics

- The dark enenrgy potential is proportional to the dark energy superpotential:

$$V_{\mathrm{DE}}(Q) = -2\sqrt{3}e^{\kappa_4^2|z_0|^2}\kappa_4 m^2 w(Q)$$

- Typical examples can be provided by non-perturbative phenomena along the meson branch of susy QCD:

$$w(Q) = (N_f - N_c)\frac{\Lambda^{(3N_c-N_f)/(N_c-N_f)}}{Q^{2N_f/(N_c-N_f)}}$$

- The order of magnitude of the superpotential now must be dictated by the value of the vacuum energy now:

$$\kappa_4 \frac{w}{m^2} \approx 10^{-88}\left(\frac{100\mathrm{GeV}}{m_{3/2}}\right)^2$$

Electro-weak Breaking

- Of course, the fact that the hidden sector minimum becomes dark energy dependent implies that all the soft terms become dark energy dependent too.
- After the renormalisation group evolution, the Higgs fields pick up dark energy dependent vevs.
- All in all, the smallness of the dark energy perturbation implies that:

O(1)

$$v_{u,d}(Q) = v^0_{u,d} + C_{u,d}\frac{w}{m^2}$$

- As a result, the atomic masses behave also in a simple way:

$$m_{\mathrm{atom}}(Q) = m^0_{\mathrm{atom}} + C_{\mathrm{atom}}\frac{w}{m^2}$$

- The expected result is that dark energy (almost) decouples from matter:

$$\alpha \approx 10^{-70}\left(\frac{m_{3/2}}{100\mathrm{GeV}}\right)^{-2}\left(\frac{m^0_{\mathrm{atom}}}{1\mathrm{GeV}}\right)^{-1}$$

Shift Symmetry Breaking I

- Unless the shift symmetry is exact, one can expect higher order corrections in the kahler potential to modify the previous results and possibly jeopardise the existence of a runaway potential.
- As a simple example consider the effect of:

$$\delta K_{\mathrm{DE}}(Q,\bar{Q}) = c_p \frac{(Q+\bar{Q})^p}{m_{\mathrm{Pl}}^{p-2}}$$

- The minimum in the hidden sector is shifted:

$$\delta z \approx (\sqrt{3}-1)\frac{w}{m^2} - \frac{\kappa_4}{2}(\partial_Q \delta K_{\mathrm{DE}}(Q))^2$$

- The dark energy potential has a new contribution:

$$V_{\mathrm{DE}}(Q) \approx -2\sqrt{3}m^4 e^{\kappa_4^2 z_0^2}(\frac{\kappa_4 w}{m^2}) + m_{3/2}^2(\partial_Q \delta K_{\mathrm{DE}})^2$$

Shift Symmetry Breaking II

- The resulting potential is not runaway anymore!
- It develops a very shallow minimum:

$$\frac{Q_{min}}{m_{\rm Pl}} \sim \left(\frac{H_0}{m_{3/2}}\right)^{1/(p-1)}$$

- The mass at the minimum is small:

$$m_Q^2 \sim m_{3/2}^{2/(p-1)} H_0^{2(p-2)/(p-1)}$$

- Fortunately, the "dark energy" fields decouples from matter:

$$\alpha \approx 10^{-44} c_p \left(\frac{m_{3/2}}{100\text{GeV}}\right)^{-1}$$

- Unfortunately, the cosmological dynamics of this model is well known to be equivalent to Lambda-CDM since before BBN!

Loop Corrections I

Quantum fluctuations destabilise all the previous results

$$\delta V = \frac{\Lambda^4}{16\pi^2}\mathrm{Str}M^0 + \frac{1}{32\pi^2}\mathrm{Str}M^2\Lambda^2 + \ldots$$

Cosmological constant problem

Hierarchy problem (Higgs mass)

Large contributions due to scalars

Loop Corrections II

All the masses are corrected by the dark energy contributions:

$$m_i = m_i^0 + C_i \frac{w}{m^2}$$

The leading correction to the dark energy potential:

$$\delta V_{\mathrm{DE}} = \frac{1}{16\pi^2} \mathrm{Str}(m_i^0 C_i) \frac{\Lambda_c^2}{m^2} w$$

This can be reabsorbed by redefining the overall scale of the superpotential

$$w = M_0^3 f(\kappa_4 Q), \quad M_0^3 \to \left(1 - \frac{1}{32\sqrt{3}\pi^2} e^{-\kappa_4 |z_0|^2} \mathrm{Str}(m_i^0 C_i) \frac{\Lambda_c^2}{\kappa_4 m^4}\right) M_0^3$$

The dark energy potential shape is stable at one loop.

Conclusions

- Dark energy can be embedded in particle physics models based on supergravity provided the dark energy sector has a shift symmetry.
- If the shift symmetry is not exact, the models become essentially equivalent to a Lambda-CDM model.
- Of course, these results could be invalidated in very particular settings where the hidden, observable and dark energy sectors could couple in such a way as to avoid gravitational problems.