Title: Embedding Quintessence in Spontaneously Broken N=1 Supergravity

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Abstract: I will present the embedding of runaway quintessence models in supergravity coupled to observable matter and hidden supersymmetry breaking. Serious obstructions appear either in the gravitational sector of the theory or cosmologically. Alternatives will be discussed.


Supergravity and Dark Energy
Ph.Brax and J. Martin
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perimeter Institute
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astro-ph/0605228
astro-ph/0606306

Motivation

- ★ Is Dark Energy a scalar field theory? If yes:
- ★ Embed dark energy into high energy physics with a status similar to inflation or even better dark matter.
- ★ Answer some very pressing questions:
  - Who is driving dark energy?
  - How does it couple to matter?
  - How does it couple to dark matter?
  - How many fundamental parameters?
- ★ Model building issues:
  - Is it connected to Supersymmetry?
  - Is it connected to extra dimensions?
  - Is it connected to String theory?
- ★ Falsify dark energy models

Dark Energy in Broken Supergravity

★ General Framework :

- Coupling the Observable, Hidden and Dark Energy sectors
- Breaking susy and soft Terms
- Electroweak symmetry breaking
- Gravity tests

★ Models?

- Models with an early minimum
- No-scale models
- Warping

Large Field Attractor

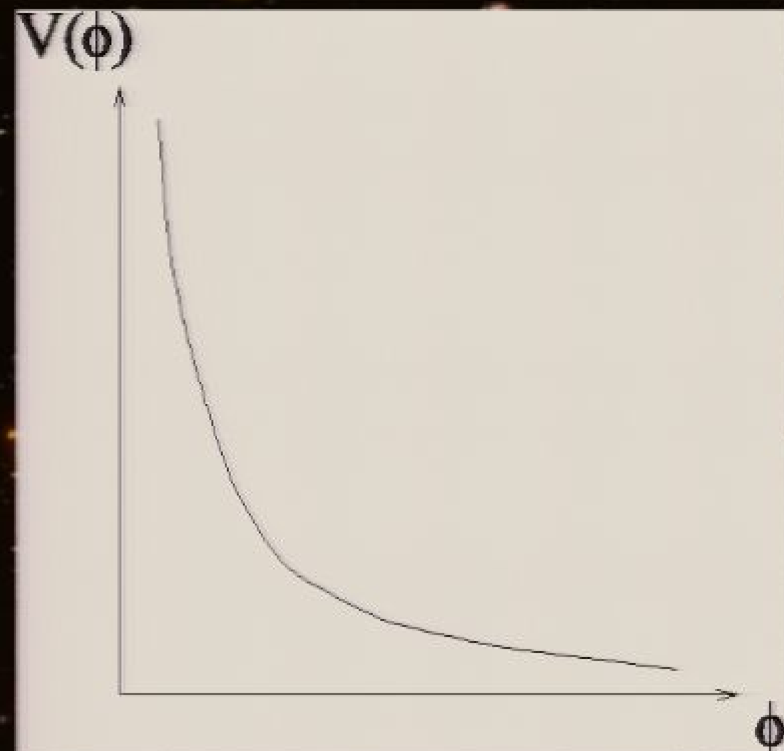
★ Quintessence and Attractors:

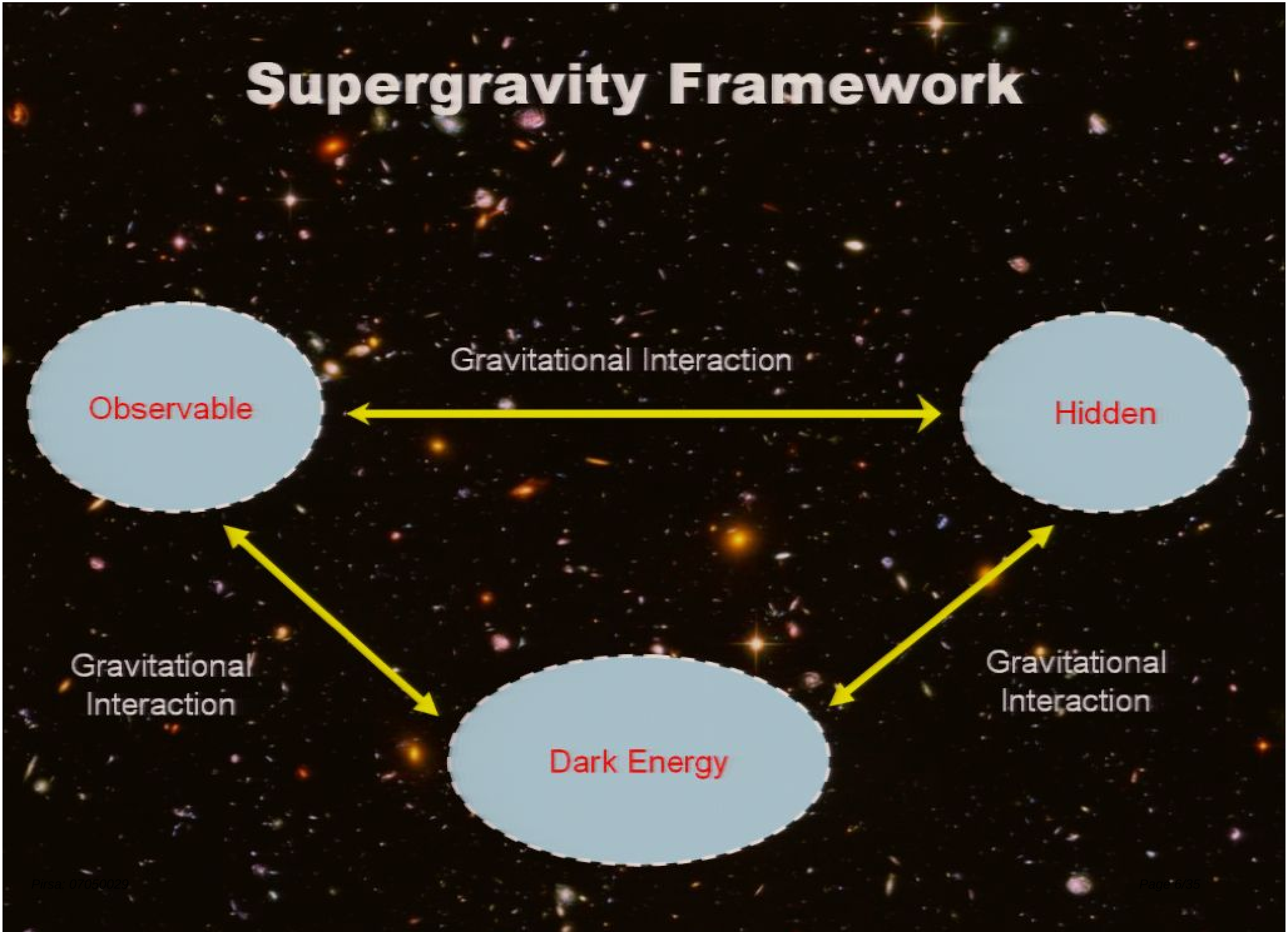
most quintessence models with insensitivity to initial conditions require an attractor mechanism

e.g. inverse power law potentials, exponential potentials ……

★ Large values of $Q_{\rm now} \approx m_{\rm Pl}$

Supergravity can handle large field values and connects gravity with high energy physics




Supergravity Framework
Observable
Gravitational Interaction
Hidden
Gravitational
Interaction
Dark Energy
Gravitational
Interaction

Three Sectors

★ Hidden sector

Kahler potential $K_{\text{hid}} = \sum_i z_i \bar{z}_i + \dots$

Superpotential $W_{\text{hid}}(z_i)$

★ Observable Sector

Kahler potential $K_{\text{obs}} = \sum_a \phi_a \bar{\phi}_a + \dots$

Superpotential

$$W_{\text{obs}} = \frac{1}{3}\sum_{abc} \lambda_{abc}\phi_a\phi_b\phi_c + \frac{1}{2}\sum_{ab}\mu_{ab}\phi_a\phi_b + \dots$$

★ Dark Energy sector

Kahler potential K_{quint}

Superpotential W_{quint}

Fields $\{\text{d}_\alpha\} \equiv \{\text{Q}, \text{X}_\alpha, \text{Y}_\alpha\}$

Quintessence field Q

Spontaneous Susy Breaking

★ Susy broken in the Hidden sector

$$\frac{\partial V}{\partial z_i} = 0$$

★ Parameterised by the vev's

$$\kappa^{1/2} < z_i >\sim a_i(Q), \quad \kappa < W_{\text{hid}} >\sim M_s(Q), \quad \kappa^{1/2} < \partial_i W_{\text{hid}} >\sim c_i(Q) M_s(Q)$$

★ Susy broken by the F-term vev's

$$F_{z_i} = e^{\kappa K_{\text{quint}} + \sum_i |a_i|^2} \frac{1}{\kappa^{1/2}} \left[(M_s + \kappa < W_{\text{quint}} >) a_i + M_s c_i \right]$$

★ The gravitino mass

$$m_{3/2} = e^{\kappa K_{\text{quint}} + \sum_i |a_i|^2} (M_s + \kappa < W_{\text{quint}} >) \equiv e^{\kappa K_{\text{quint}}} m^0_{3/2}$$

The Effective Theory

- After susy breaking, effective theory for Observable sector coupled to Dark Energy

$$m_{\mathrm{Pl}} \to \infty, \quad m_{3/2} \quad \text{fixed}$$

- The Dark Energy potential

$$\begin{aligned} V_{\mathrm{DE}} &= \mathrm{e}^{\sum_i |a_i|^2} V_{\mathrm{quint}} + M_{\mathrm{S}}^2 \mathrm{e}^{\kappa K_{\mathrm{quint}} + \sum_i |a_i|^2} [\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \frac{\partial K_{\mathrm{quint}}}{\partial d_\beta} \frac{\partial K_{\mathrm{quint}}}{\partial d_\alpha^\dagger} - \frac{3}{\kappa}] \\ &+ M_{\mathrm{S}} \mathrm{e}^{\kappa K_{\mathrm{quint}} + \sum_i |a_i|^2} \Big\{ [\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \frac{\partial K_{\mathrm{quint}}}{\partial d_\beta} \frac{\partial K_{\mathrm{quint}}}{\partial d_\alpha^\dagger} - \frac{3}{\kappa}] (\kappa W_{\mathrm{quint}} + \kappa W_{\mathrm{quint}}^\dagger) \\ &+ \left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \left(\frac{\partial K_{\mathrm{quint}}}{\partial d_\beta} \frac{\partial W_{\mathrm{quint}}^\dagger}{\partial d_\alpha^\dagger} + \frac{\partial K_{\mathrm{quint}}}{\partial d_\alpha^\dagger} \frac{\partial W_{\mathrm{quint}}}{\partial d_\beta} \right) \Big\} + \sum_i |F_{z_i}|^2 , \end{aligned}$$

with

$$\begin{aligned} V_{\mathrm{quint}}(Q) &= \mathrm{e}^{\kappa K_{\mathrm{quint}}} \Big[\left(K_{\mathrm{quint}}^{-1}\right)^{d_\alpha^\dagger d_\beta} \left(\kappa W_{\mathrm{quint}} \frac{\partial K_{\mathrm{quint}}}{\partial d_\beta} + \frac{\partial W_{\mathrm{quint}}}{\partial d_\beta} \right) \left(\kappa W_{\mathrm{quint}}^\dagger \frac{\partial K_{\mathrm{quint}}}{\partial d_\alpha^\dagger} \right. \\ &\left. + \frac{\partial W_{\mathrm{quint}}^\dagger}{\partial d_\alpha^\dagger} \right) - 3\kappa W_{\mathrm{quint}} W_{\mathrm{quint}}^\dagger \Big] . \end{aligned}$$

highly dependent on the susy breaking sector

The Soft Breaking Terms

★ Susy , spontaneously broken, leads to soft terms

$$V_{\mathrm{mSUGRA}} = \cdots + \mathrm{e}^{\kappa K} V_{\mathrm{susy}} + A_{abc}\left(\phi_a\phi_b\phi_c + \phi_a^\dagger\phi_a^\dagger\phi_c^\dagger\right) + B_{ab}\left(\phi_a\phi_b + \phi_a^\dagger\phi_b^\dagger\right) + m^2_{a\bar{b}}\phi_a\phi_b^\dagger .$$

★ Soft terms depend on the dark energy sector

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&+ \frac{1}{3}M_{\mathrm{S}}\sum_i a_i c_i\Big\}, \\
B_{ab} &= \mu_{ab}\mathrm{e}^{\kappa K_{\mathrm{quint}} + \sum_i |a_i|^2}\Big\{(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}}) + \frac{1}{2}(M_{\mathrm{S}} + \kappa W^\dagger_{\mathrm{quint}})[\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \\
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&+ \frac{1}{2}M_{\mathrm{S}}\sum_i a_i c_i\Big\}, \\
m^2_{a\bar{b}} &= \mathrm{e}^{\kappa K_{\mathrm{quint}} + \sum_i |a_i|^2}\left[M_{\mathrm{S}}^2 + M_{\mathrm{S}}\left(\kappa W_{\mathrm{quint}} + \kappa W^\dagger_{\mathrm{quint}}\right) + \kappa^2 W_{\mathrm{quint}} W^\dagger_{\mathrm{quint}}\right]\delta_{a\bar{b}}
\end{aligned}$$

Gaugino Masses

★ Gauginos acquire a mass depending on the gauge coupling function

$$\Re\left[f_G(d_\alpha, z_i)\right] = \frac{1}{g_G^2}$$

★ The mass depends on the F-terms breaking supersymmetry

$$\left(m_{1/2}\right)_G = \frac{1}{f_G + f_G^\dagger}\left(\sum_\alpha F^{d_\alpha}\frac{\partial f_G}{\partial d_\alpha} + \sum_i F^{z_i}\frac{\partial f_G}{\partial z_i}\right) \equiv \mathrm{e}^{\kappa K_{\mathrm{quint}}/2}\left(m_{1/2}^0\right)_G \quad (1)$$

★ The gauge coupling dependence on the dark energy sector leads to variations of constants

Variation of Constants

★ The gauge coupling constants at the weak scale

$$\frac{1}{\alpha_i(m)} = 4\pi f_i - \frac{b_i}{2\pi} \ln\left(\frac{m_{\mathrm{GUT}}}{m}\right),$$

★ The fine structure constant at the weak scale

$$\alpha_{\mathrm{QED}}(Q) = \frac{\alpha_2^2}{\alpha_1 + \alpha_2},$$

★ The proton to electron mass ratio varies

$$\frac{\Delta r}{r} \sim -\frac{8\pi^2}{b_3}\Delta f_3 + b_{\mathrm{u}}\frac{m_{\mathrm{u}}}{m_{\mathrm{p}}}\Delta\alpha_{\mathrm{u}} + \left(b_{\mathrm{d}}\frac{m_{\mathrm{d}}}{m_{\mathrm{p}}} - 1\right)\Delta\alpha_{\mathrm{d}} + \frac{C_{\mathrm{p}}\alpha_{\mathrm{QED}}}{m_{\mathrm{p}}}\frac{\Delta\alpha_{\mathrm{QED}}}{\alpha_{\mathrm{QED}}}. \quad (1)$$

Electro-weak Symmetry Breaking

★ The Higgs potential depends on the dark energy sector via the soft terms evaluated at the electro-weak scale

$$V^{\text{Higgs}} = e^{\kappa K_{\text{quint}}}[\left(|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_u}\right)\left|H^0_u\right|^2 + \left(|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_d}\right)\left|H^0_d\right|^2 - 2\mu B(Q)\left|H^0_u\right|\left|H^0_d\right|] + \frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H^0_u\right|^2 - \left|H^0_d\right|^2\right)^2 .$$

★ The two Higgs vev's depend on quintessence too

$$< H^0_u > \equiv v_u = v \sin\beta, \quad < H^0_d > \equiv v_d = v \cos\beta$$

★ The angle β depends on quintessence

$$\tan\beta(Q) = \frac{2|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_u}(Q) + m^2_{H_d}(Q)}{2\mu B(Q)} \times \left(1 \pm \sqrt{1 - 4\mu^2 B^2(Q)\left[2|\mu|^2 e^{\sum_i |a_i|^2} + m^2_{H_u}(Q) + m^2_{H_d}(Q)\right]^{-2}}\right).$$

Boson and Fermion Masses

★ The Higgs scale becomes (large $\tan\beta \gg 1$ regime)

$$v(Q) = \frac{2\mathrm{e}^{\kappa K_{\mathrm{quint}}/2}}{\sqrt{g^2+g'^2}} \sqrt{\left| |\mu|^2 \, \mathrm{e}^{\sum_i |a_i|^2} + m_{H_\mathrm{u}}^2 \right|} + \mathcal{O}\left(\frac{1}{\tan\beta}\right).$$

★ The gauge boson masses depend on quintessence

$$m_{W^\pm}^2 = \frac{g^2}{2}\left(v_\mathrm{u}^2 + v_\mathrm{d}^2\right) \equiv \frac{g^2}{2} v^2 , \quad m_{Z^0}^2 = \frac{1}{2}\left(g^2 + g'^2\right)\left(v_\mathrm{u}^2 + v_\mathrm{d}^2\right).$$

★ The matter Fermion masses depend on quintessence

$$m_{\mathrm{u},a}^{\mathrm{F}}(Q) = \lambda_{\mathrm{u},a}^{\mathrm{F}} \mathrm{e}^{\kappa K_{\mathrm{quint}}/2 + \sum_i |a_i|^2/2} v_\mathrm{u}(Q) , \quad m_{\mathrm{d},a}^{\mathrm{F}}(Q) = \lambda_{\mathrm{d},a}^{\mathrm{F}} \mathrm{e}^{\kappa K_{\mathrm{quint}}/2 + \sum_i |a_i|^2/2} v_\mathrm{d}(Q) ,$$

Violation of the Weak Equivalence Principle

- At the microscopic level, particles of types u or d do not have the same mass dependence on quintessence ⟶ WEP violation

- Coupling to matter

$$A_{\mathrm{u,d}}(Q) \equiv \mathrm{e}^{\kappa K_{\mathrm{quint}}/2+\sum_i |a_i|^2/2} \frac{v_{\mathrm{u,d}}(Q)}{v_{\mathrm{u,d}}(0)} .$$

- Scalar-tensor effective action

$$\begin{aligned} S \;=\; & -\frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\left[R+\frac{1}{2}g^{\mu\nu}\partial_\mu Q\partial_\nu Q+V_{\mathrm{DE}}(Q)\right]+S_{\mathrm{mat}}\left[\phi_{\mathrm{u},a}, A_{\mathrm{u}}^2(Q)g_{\mu\nu}\right] \\ & +S_{\mathrm{mat}}\left[\phi_{\mathrm{d},a}, A_{\mathrm{d}}^2(Q)g_{\mu\nu}\right] . \end{aligned}$$

- Need to analyse the WEP violation for macroscopic bodies

Fifth Force

- ★ Gravity tests are only relevant for nearly massless quintessence, Newton's law becoming

$$F_N = G_N(1 + 2\alpha_{\mathrm{A}}\alpha_{\mathrm{B}})m_{\mathrm{A}}m_{\mathrm{B}}/r^2_{\mathrm{AB}}$$

- ★ Cassini experiments constraint

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

- ★ The gravitational coupling constant

$$\alpha_{\mathrm{A}} = \kappa^{-1/2}\mathrm{d}\ln m_{\mathrm{A}}/\mathrm{d}Q$$

Coupling to matter

$$\alpha_{\rm u} \;=\; \frac{\kappa^{1/2}}{2}\partial_Q K_{\rm quint} + \frac{\kappa^{-1/2}}{2}\sum_i \partial_Q |a_i|^2 + \frac{\kappa^{-1/2}}{v}\frac{{\rm d}v}{{\rm d}Q} + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right) ,$$

$$\begin{aligned}\alpha_{\rm d} \;=\; & \frac{\kappa^{1/2}}{2}\partial_Q K_{\rm quint} + \frac{\kappa^{-1/2}}{2}\sum_i \partial_Q |a_i|^2 - \kappa^{-1/2}\left(\frac{{\rm d}m^2_{\rm H_u}}{{\rm d}Q} + \frac{{\rm d}m^2_{\rm H_d}}{{\rm d}Q}\right) \\ & \times \left(2|\mu|^2 {\rm e}^{\sum_i |a_i|^2} + m^2_{\rm H_u} + m^2_{\rm H_d}\right)^{-1} + \kappa^{-1/2}\frac{{\rm d}\ln B(Q)}{{\rm d}Q} + \frac{\kappa^{-1/2}}{v}\frac{{\rm d}v}{{\rm d}Q} \\ & + \mathcal{O}\left(\frac{1}{\tan^2\beta}\right) .\end{aligned}$$

Scalar Potential and Gravitino Mass

- The scalar potential has the structure:

$$V(Q) = \kappa_4^2 M^6 v_1(\kappa_4 Q) + M_s M^3 v_2(\kappa_4 Q) + \frac{M_s^2}{\kappa_4^2} e^{\kappa_4^2 K} (\kappa_4^2 K^{Q\bar{Q}} K_Q K_{\bar{Q}} - 3) + \sum_i |F_{z_i}|^2$$

for the superpotentials

$$W_{\text{quint}} = M^3 \mathcal{W}(\kappa_4 Q), \quad W_{\text{hid}} = M_s^3 \mathcal{W}_{\text{hid}}(z_i)$$

- For regular Kahler potentials:

$$K_{\text{quint}} = Q\bar{Q} + \dots$$

- The scalar potential becomes

$$V(Q) = M_s M^3 v_2(\kappa_4 Q) + m_{3/2}^2 |Q|^2$$

- There is a minimum, typically very small compared to the Planck scale

- The mass of the quintessence field is very large

$$m_Q \simeq m_{3/2}$$

Cosmological Evolution

- ★ Quintessence field stabilised at small value
- ★ Quintessence field convergence to minimum before BBN
- ★ Cosmological evolution equivalent to a pure cosmological constant both at the background and perturbative levels

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No-scale

- ★ No gravitino mass for the quintessence field:

$$K = -\frac{n}{\kappa_4^2} \ln[\kappa_4(Q+\bar{Q})]$$

- ★ The scalar potential becomes runaway

$$V(Q) = M_s M^3 v_2(\kappa_4 Q)$$

- ★ Large coupling to gravity

$$\alpha_Q = \sqrt{2n} + \ldots$$

- ★ No chameleon effect despite coupling to matter

Axions

★ In the no-scale case, the imaginary part of the complex scalar field is an axion.

$$Q = \rho + ia$$

★ The presence of a shift symmetry of the Kahler potential implies no coupling to matter (up to effect due to the hidden sector)

$$a \to a + c$$

★ Necessitates to stabilise the real part.

$$m_\rho \geq 10^{-3}\text{eV}$$

★ How to reconcile a large mass for the real part with a small mass for the imaginary part?

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★ Explicit example:

$$K = -\frac{3}{\kappa_4^2} \ln(\kappa_4(Q+\bar{Q}) - \frac{\kappa_4^2}{3}(k_{\rm obs} + k_{\rm hid}))$$

★ Matter and hidden sectors on D3 branes, quintessence=moduli.

★ No gravitino mass but large gravitational coupling....

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Warping

★ Preserve no-scale property and suppress coupling to gravity:

$$K = -\frac{3}{\kappa_4^2} \ln(1 - z\bar{z} + \Omega_{UV} + z\bar{z}\Omega_{IR})$$

★ Typical of Supersymmetric Randall-Sundrum models:

$$z = e^{-kT}$$

★ Easier to use the canonically normalised field

$$q = \frac{1}{2} \ln \frac{1+z}{1-z}$$

★ The coupling to matter behaves like:

$$A(q) = \cosh^3(\sqrt{\frac{2}{3}}q) + \dots$$

Small Field Dark Energy

★ The gravitational coupling is large at short distance:

$$\alpha_q = \sqrt{6}, \;\; z = O(1)$$

★ The gravitational coupling is small at large distance:

$$\alpha_q = 2q = 2z, \;\; z \ll 1$$

★ This leads to the possibility of studying small field dark energy models akin to small field inflation models (hybrid etc…)

Conclusion

- ★ Coupling quintessence to particle physics in supergravity would lead to very interesting phenomenology
- ★ Obstruction to quintessence models
- ★ Warped models?