Particle Physics Models of Quintessence

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Talk based on the two following papers:

"Dark Energy and the MSSM", P. Brax & J. Martin, hep-th/0605228

"The SUGRA Quintessence Model Coupled to the MSSM", P. Brax & J. Martin, JCAP 11, 008 (2006), astro-ph/0606306

Outline:

1- Quintessence in brief (assuming High-Energy inputs)

2- Quintessence and the rest of the world: how the observable sector of particle physics is affected by the presence of dark energy? In SUGRA, the coupling can be entirely computed.

3- Consequences (two main effects studied so far). "No-go theorem" : difficult to reconcile cosmology with local (eg solar system) tests.

4- Conclusions.

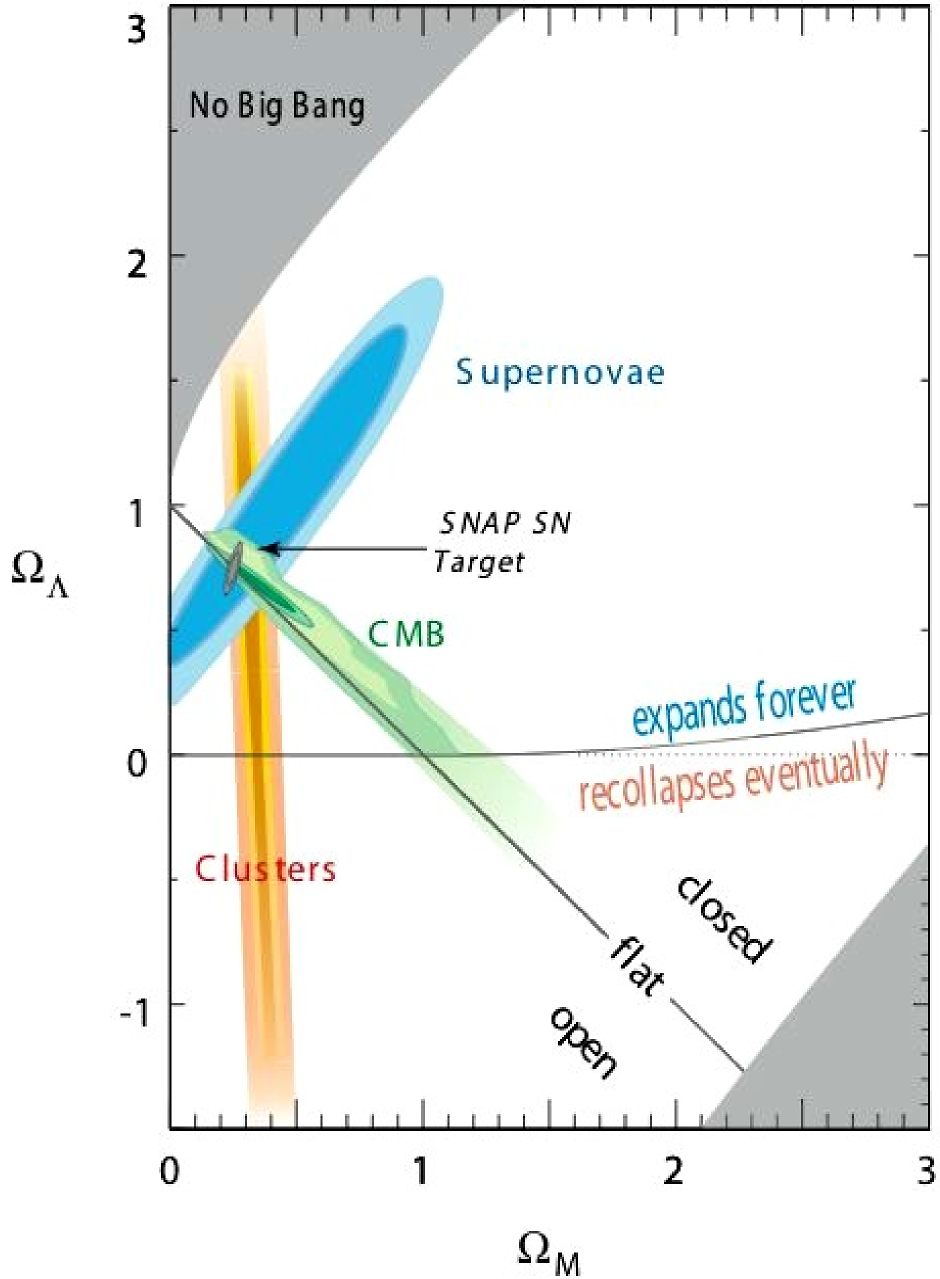
Observational Status

- The Universe is accelerating:

$$q_0 \equiv -\frac{a_0 \ddot{a}_0}{(\dot{a}_0)^2} \simeq -0.67 \pm 0.25$$

- If the acceleration is caused by some dark energy then, today, it represents about 70% of the critical energy density

- Assuming that dark energy is the cosmological constant, one faces serious problems in explaining its magnitude. Hence, it is interesting to seek for alternatives



The prototype of alternatives to the CC is a scalar field (quintessence)

$$\rho_Q = \frac{\dot{Q}^2}{2} + V(Q)$$

$$p_Q = \frac{\dot{Q}^2}{2} - V(Q)$$

If the potential energy dominates, one can have negative pressure (as for inflation)

1- This allows us to study dark energy with time-dependent equation of state

2- This is not a "reverse-engineering" problem, ie give me the equation of state and I will give you the potential because we require additional properties, to be discussed in the following.

3- Since we have a microscopic model, we can consistently computed the cosmological perturbations

4- This allows us to discuss the link with high-energy physics and to play the game of model building. As we will see this is at this point that we have serious difficulties …

5- This does not solve the CC problem. Instead of explaining Ω_Λ =0.7 of the critical energy density we are just back to Λ =0

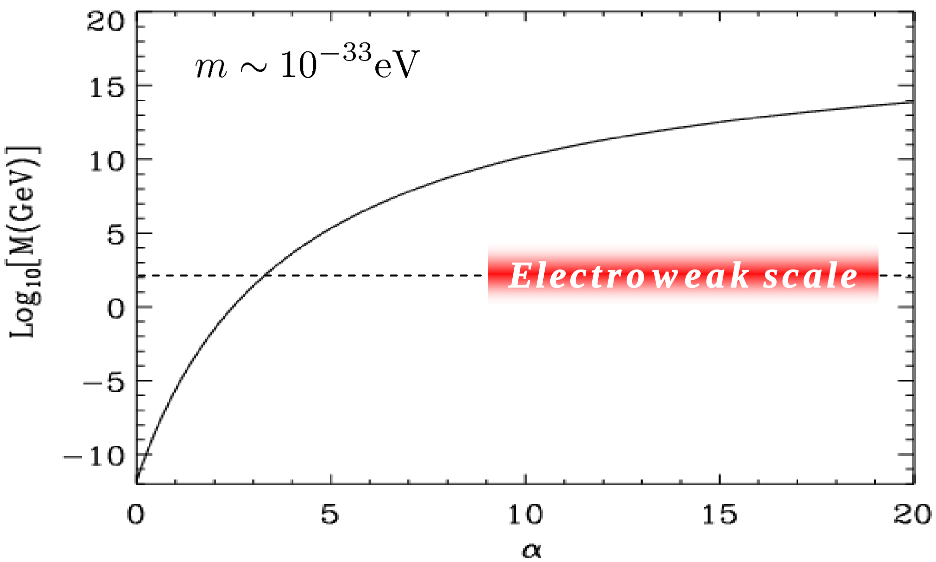
Quintessence: scalar field dominating the today's energy density budget of the Universe and such that its potential allows insensitivity to the initial conditions and reasonable model building.

Tracking behavior → $V(Q) = M^{4+\alpha}Q^{-\alpha}$ → $\langle Q \rangle_{\rm today} \sim m_{\rm Pl}$ → SUGRA

SUGRA potential: $V(Q) = {\rm e}^{4\pi Q^2/m_{\rm Pl}^2} M^{4+\alpha}Q^{-\alpha}$

$\Omega_{\rm Dark\ energy} \simeq 0.7$

P. Brax & J. Martin, PLB 468, 40 (1999), astro-ph/9905040



What are the effects of the SUGRA corrections?

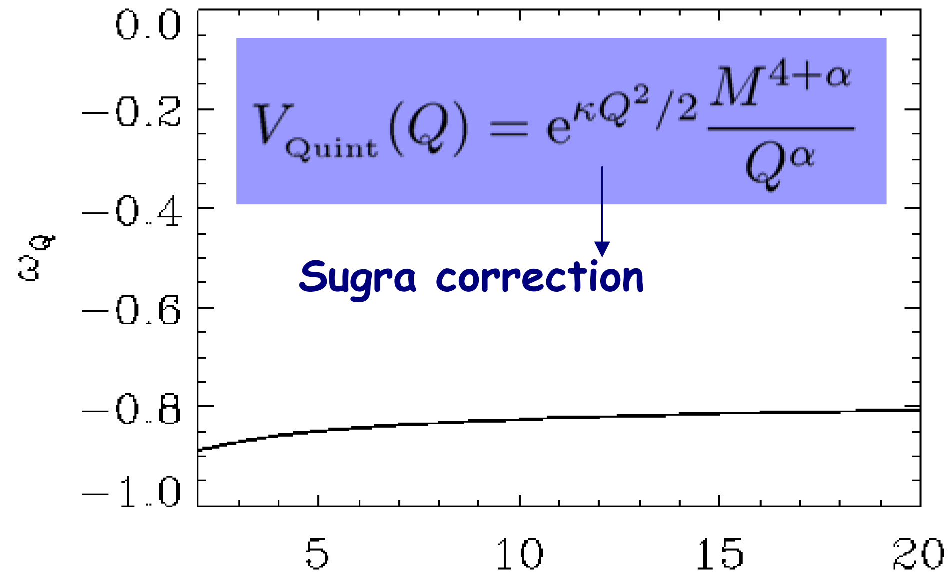
1- The attractor solution still exists since, for large redshifts, the vev of Q is small in comparison with the Planck mass

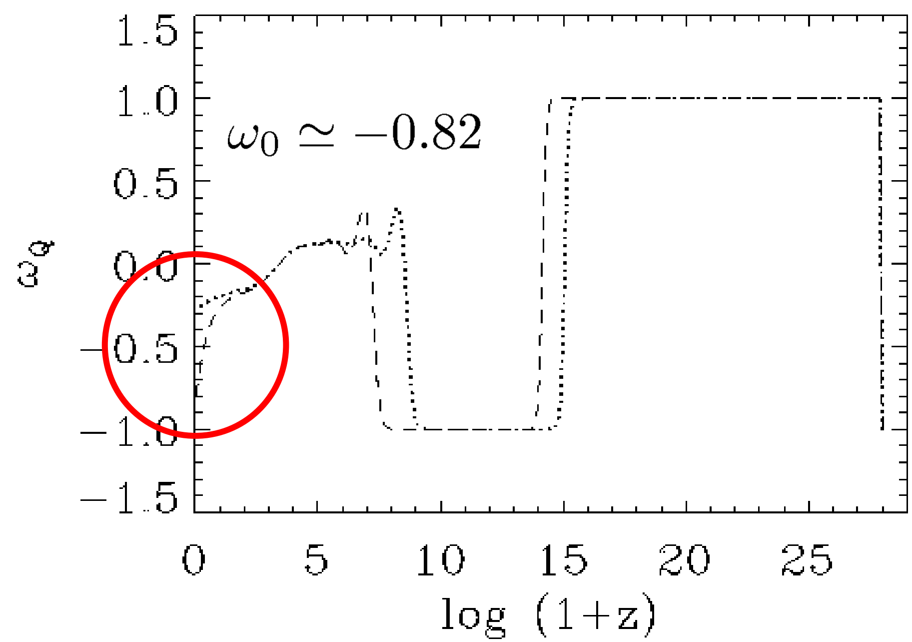
2- The exponential corrections pushes the equation of state towards -1 at small redshifts

$$\omega_{Q} = \frac{\dot{Q}^2/2 - V(Q)}{\dot{Q}^2/2 + V(Q)} = \omega_0 + \omega_1 z + \cdots$$

3- The present value of the equation of state becomes "universal", i.e. does not depend on α

For Quintessence, the η -problem becomes the η -opportunity





Remarks

1- So far, we have treated quintessence as if it were isolated from the rest of the world.

2- Certainly, the quintessence field has to be embedded into particle physics.

3- Clearly, this cannot be done into the standard model of particle physics. We have just seen that SUGRA plays a key role. It is therefore natural to consider the Minimal Standard SUGRA model as the relevant extension of the standard model.

4- Since SUGRA is universal, this will uniquely determine the couplings between quintessence and the rest of the world.

Quintessence and the rest of the world

$$K_{\mathrm{obs}} = \sum_a \phi_a \phi_a^\dagger + \cdots$$

$$\begin{aligned} W_{\mathrm{obs}} &= \frac{1}{3}\sum_{abc} \lambda_{abc}\phi_a\phi_b\phi_c \\ &+ \frac{1}{2}\sum_{ab} \mu_{ab}\phi_a\phi_b \end{aligned}$$

$$K_{\mathrm{hid}} = \sum_i z_i z_i^\dagger + \cdots$$

$$W_{\mathrm{hid}} = W(z_i)$$

where the standard fields live: electrons, quarks, dark matter etc …

where susy is broken: Poloyni field, etc …

Usual structure of the standard model: two sectors

Gravity mediated

Observable sector

mSUGRA

Hidden sector

SUSY

$$K_{\text{obs}} = \sum_a \phi_a \phi_a^\dagger + \cdots$$

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

Modification of the Quintessence potential

$$K_{\text{hid}} = \sum_i z_i z_i^\dagger + \cdots$$

$$W_{\text{hid}} = W(z_i)$$

Quintessence dependence of couplings & masses

Quintessence sector

$$Q \in \{d_\alpha\}$$

$$K_{\text{quint}} = K_{\text{quint}}(d_\alpha)\,,$$

$$W_{\text{quint}} = W_{\text{quint}}(d_\alpha)$$

$$K = K_{\text{quint}} + K_{\text{hid}} + K_{\text{obs}}\,, \qquad W = W_{\text{quint}} + W_{\text{hid}} + W_{\text{obs}}$$

Remarks

The hidden sector is not known but, as in the standard case, can be parameterized

<u>At high energies (typically GUT scale)</u>

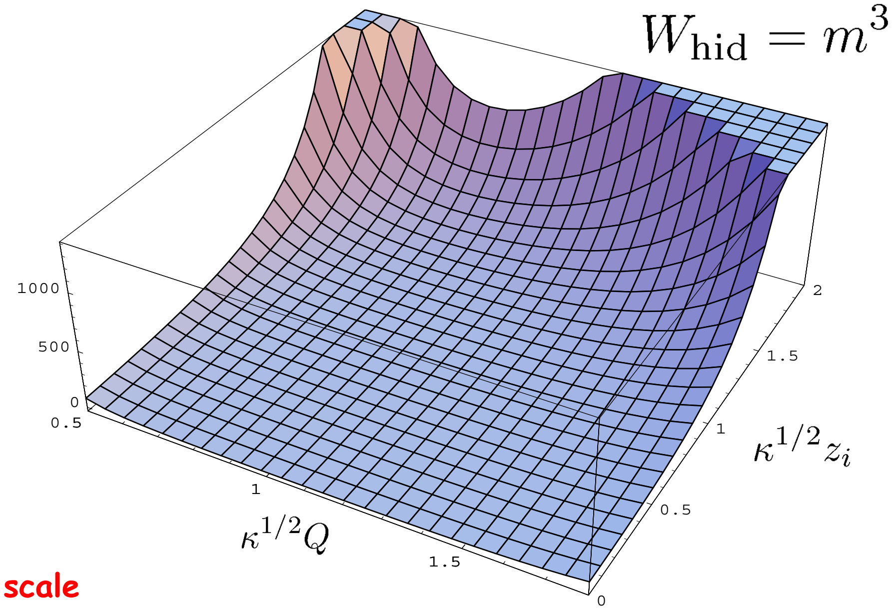
$$\partial_{z_i} V(z_j, Q, \langle \phi_a \rangle = 0) = 0$$

$$\downarrow$$

$$\kappa^{1/2} \langle z_i \rangle_{\rm min} \simeq a_i(Q)$$

$$\kappa \, \langle W_{\rm hid} \rangle_{\rm min} \simeq M_{\rm S}(Q)$$

Susy breaking scale



$$\kappa^{1/2} \left\langle \frac{\partial W_{\rm hid}}{\partial z_i} \right\rangle_{\rm min} \simeq c_i(Q) M_{\rm S}(Q)$$

$$F_{z_i} = e^{\kappa K_{\rm quint}/2 + \sum_i |a_i|^2/2} \frac{1}{\kappa^{1/2}} \times \left[\left(M_{\rm S} + \kappa \, \langle W_{\rm quint} \rangle \right) a_i + M_{\rm S} c_i \right]$$

<u>Note:</u> One can also discuss and question the assumption of separate sectors although this is the standard one. It can easily be modified and the corresponding consequences are under investigation.

The presence of the dark sector has <u>two main effects</u>

1- The soft terms in the observable sector become Q-dependent. As a consequence, the electroweak transition is affected.

2- The shape of the quintessence potential is also modified by the "soft terms" in the dark sector. Depending on the hidden sector, the runaway shape of the quintessence potential can be lost.

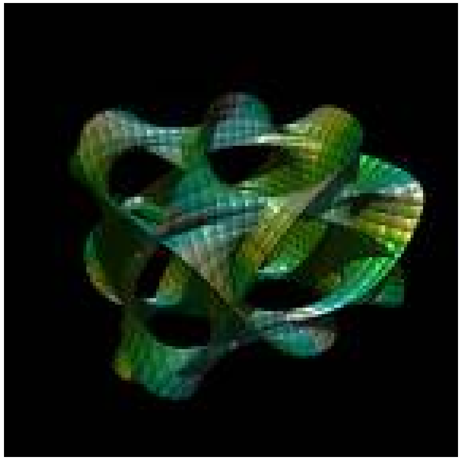
The big uncertainty comes from the dark sector: what are the Kahler and super potentials in this sector? It is necessary to know them in order to compute the physical effects in detail. We will discuss <u>two main possibilities</u>.

<u>Polynomial (regular at origin):</u>

$$K_{\rm quint} = QQ^\dagger + XX^\dagger + YY^\dagger \frac{(QQ^\dagger)^p}{m_{\rm C}^{2p}} + \cdots$$

$$W_{\rm quint} = \lambda X^2 Y + \cdots$$

<u>No scale:moduli quintessence</u>



$$K_{\rm quint} = -\frac{3}{\kappa}\ln\left[\kappa^{1/2}\left(Q+Q^\dagger\right)\right]$$

$$W_{\rm quint} = W_{\rm quint}(Q)$$

Effect 1: The soft terms in the observable sector becomes Q-dependent

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

Standard potential of the MSSM

$$A_{abc} = \lambda_{abc}{\rm e}^{\kappa K_{\rm quint}+\sum_i |a_i|^2}\Biggl\{\left(M_{\rm s}+\kappa W_{\rm quint}^\dagger\right)+\frac{1}{3}\left(M_{\rm s}+\kappa W_{\rm quint}^\dagger\right)\Biggl[\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \times\frac{\partial K_{\rm quint}}{\partial d_\beta}\frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger}+\sum|a_i|^2-3\Biggr]+\frac{1}{3}\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta}\frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger}\frac{W_{\rm quint}}{\partial d_\beta} +\frac{1}{3}M_{\rm s}\sum a_i c_i\Biggr\}$$

$$B_{ab} = \mu_{ab}{\rm e}^{\kappa K_{\rm quint}+\sum_i |a_i|^2}\Biggl\{\left(M_{\rm s}+\kappa W_{\rm quint}^\dagger\right)+\frac{1}{3}\left(M_{\rm s}+\kappa W_{\rm quint}^\dagger\right)\Biggl[\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta} \times\frac{\partial K_{\rm quint}}{\partial d_\beta}\frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger}+\sum|a_i|^2-3\Biggr]+\frac{1}{2}\kappa\left(K^{-1}\right)^{d_\alpha^\dagger d_\beta}\frac{\partial K_{\rm quint}}{\partial d_\alpha^\dagger}\frac{W_{\rm quint}}{\partial d_\beta} +\frac{1}{2}M_{\rm s}\sum a_i c_i\Biggr\}$$

$$m_{a\bar{b}}^2 = {\rm e}^{\kappa K_{\rm quint}+\sum_i |a_i|^2}\left[M_{\rm s}^2+M_{\rm s}\left(\kappa W_{\rm quint}+\kappa W_{\rm quint}^\dagger\right)+\kappa^2 W_{\rm quint}W_{\rm quint}^\dagger\right]\delta_{a\bar{b}}$$

The soft terms are now quintessence dependent

Application to the Electro-weak transition in the MSSM

- There are two Higgs instead of one
- The EW transition is intimately linked to the breaking of SUSY

$$W_{\rm obs} = \mu(H_{\rm u}^{+} H_{\rm d}^{-} - H_{\rm u}^{0} H_{\rm d}^{0}) + \cdots$$

$$M_{\rm SB} \geq 1{\rm TeV}$$

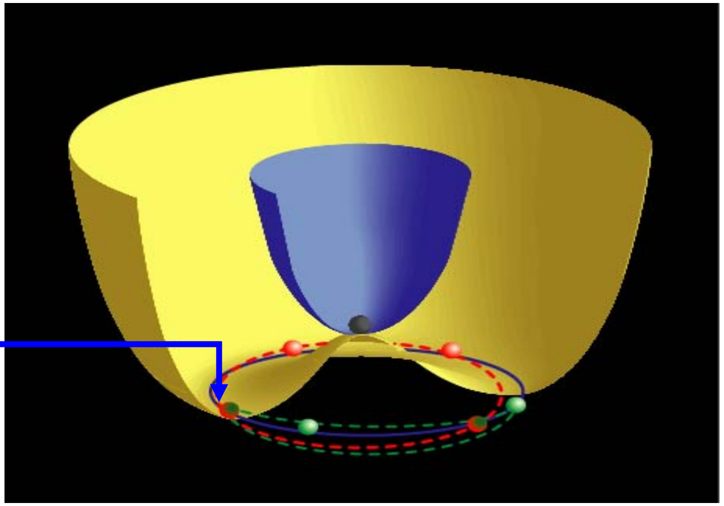
Without the breaking of SUSY, the Higgs potential only has a global minimum. The breaking of SUSY modifies the shape of the potential through the soft terms

$$V_{\rm mSUGRA} = \cdots + e^{\kappa K} V_{\rm SUSY} + A_{abc}\left(\phi_a\phi_b\phi_c + \phi_a^{\dagger}\phi_b^{\dagger}\phi_c^{\dagger}\right) + B_{ab}\left(\phi_a\phi_b + \phi_a^{\dagger}\phi_b^{\dagger}\right) + m_{a\bar{b}}^2 \phi_a \phi_b^{\dagger}$$

Then, the particles acquire mass when the Higgs acquire a non-vanishing vev

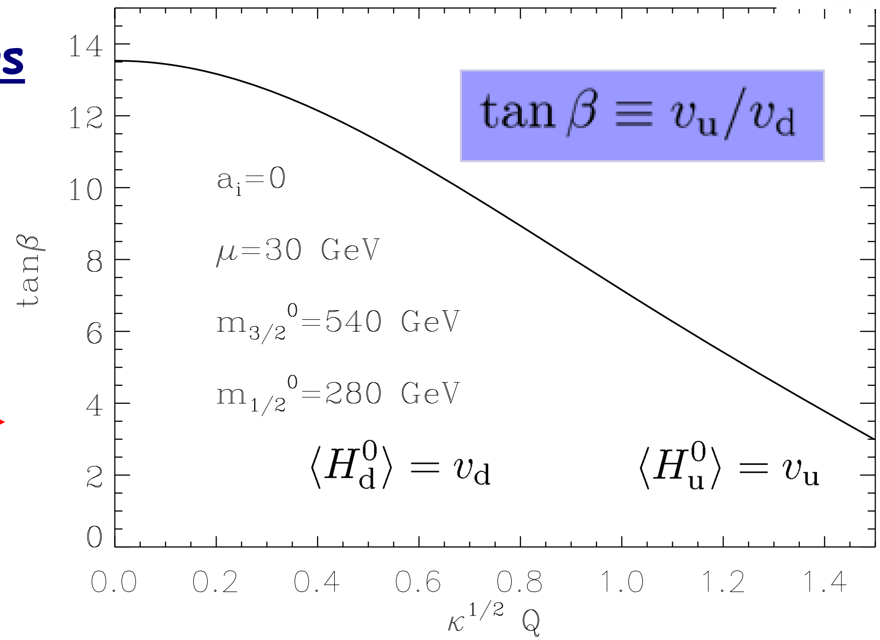
$$m_{\rm u} = \lambda_{\rm u}\langle H_{\rm u}^0 \rangle$$

$$m_{\rm d} = \lambda_{\rm d}\langle H_{\rm d}^0 \rangle$$



As a consequence, the vev's of the Higgs become Q-dependent

$$v_{\rm u} = \frac{v \tan\beta}{\sqrt{1+\tan^2\beta}}\,, \qquad v_{\rm d} = \frac{v}{\sqrt{1+\tan^2\beta}}$$



Completely calculable in a given model (here the SUGRA model)

$$\tan\beta = \frac{2|\mu|^2 e^{\sum_i |a_i|^2} + m_{H_{\rm u}}^2(Q) + m_{\rm d}^2(Q)}{2\mu B(Q)}\left(1 \pm \sqrt{1 - 4\mu^2 B^2(Q)\left[2|\mu|^2 e^{\sum_i |a_i|^2} + m_{\rm H_u}^2 + m_{\rm H_d}^2\right]^{-2}}\right)$$

Yukawa couplings

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

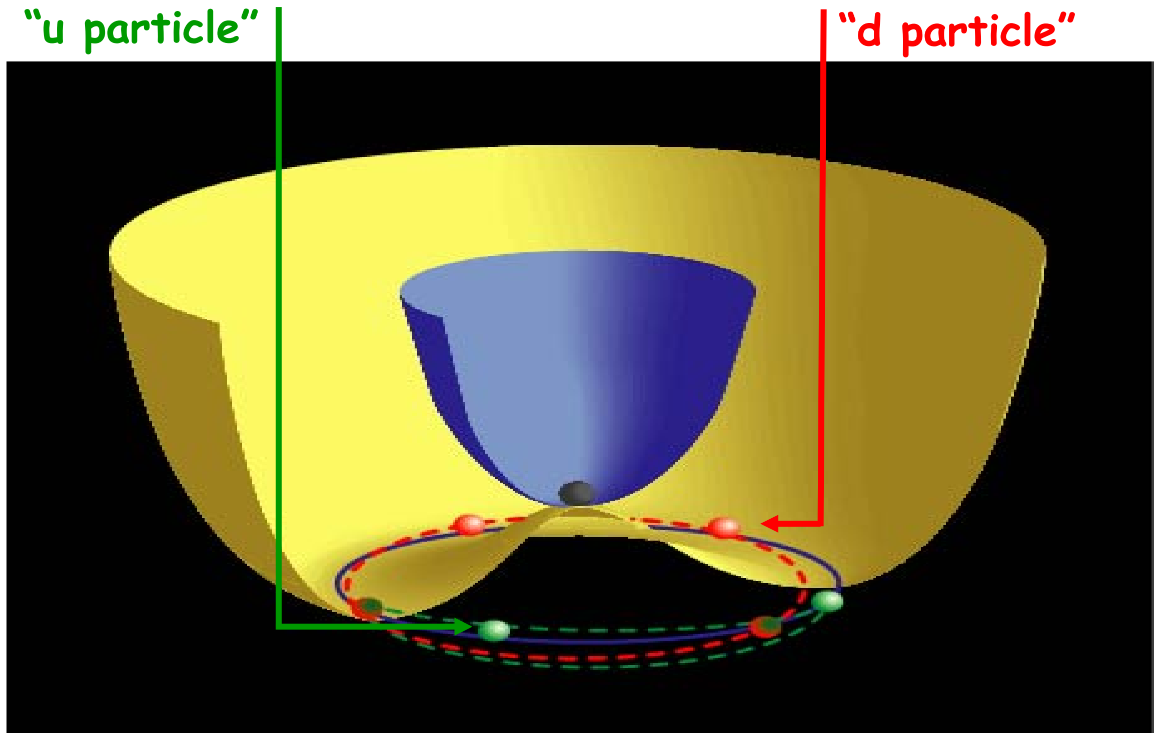
$$m_{\rm d}(Q) = \lambda_{\rm d} e^{\kappa K_{\rm quint}/2 + \sum_i |a_i|^2/2} v_{\rm d}(Q)$$

Main Result:

The fermions pick up a Q-dependent mass which is not the same for the "u" or "d" particles. This is calculable entirely from SUGRA.

Consequences:

$$S_{\mathrm{mat}}[\phi_{\mathrm{u}}, \phi_{\mathrm{d}}, g_{\mu\nu}] = -\frac{1}{2}\int \mathrm{d}^4x\sqrt{-g}\,\left[g^{\mu\nu}\partial_\mu\phi_{\mathrm{u}}\partial_\nu\phi_{\mathrm{u}} + m_{\mathrm{u}}^2\left(Q\right)\phi_{\mathrm{u}}^2 + g^{\mu\nu}\partial_\mu\phi_{\mathrm{d}}\partial_\nu\phi_{\mathrm{d}} + m_{\mathrm{d}}^2\left(Q\right)\phi_{\mathrm{d}}^2\right] + \cdots$$



Through redefinitions, this type of theory can be put under the form of a scalar-tensor theory

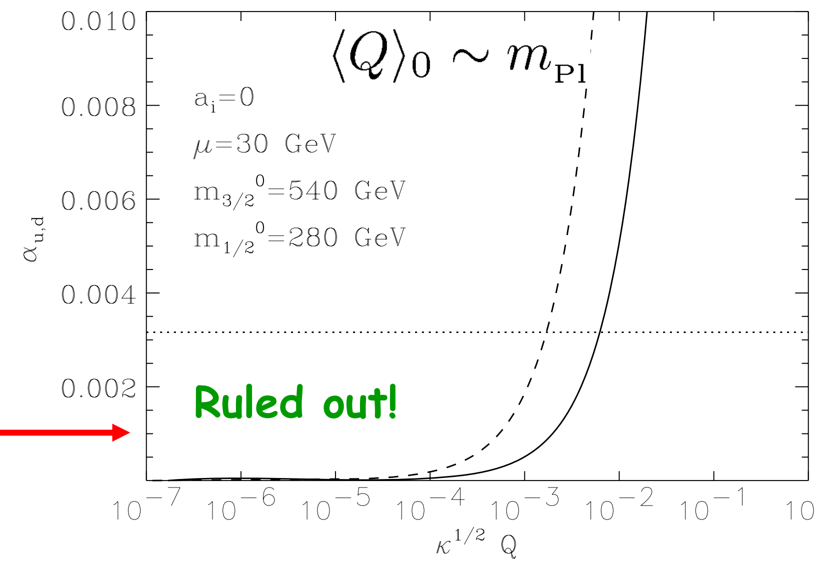
$$S = -\frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}^{(4)}R + S_{\mathrm{mat}}\left[\tilde{\Psi}_{\mathrm{u}}, A_{\mathrm{u}}^2\left(Q\right)g_{\mu\nu}\right] + S_{\mathrm{mat}}\left[\tilde{\Psi}_{\mathrm{d}}, A_{\mathrm{d}}^2\left(Q\right)g_{\mu\nu}\right] + \cdots$$

Consequences:

1- Presence of a fifth force

$$\alpha_{\mathrm{u,d}}(Q) = \left| \frac{1}{\kappa^{1/2}} \frac{\mathrm{d} \ln m_{\mathrm{u,d}}(Q)}{\mathrm{d}Q} \right| < 10^{-2.5}$$

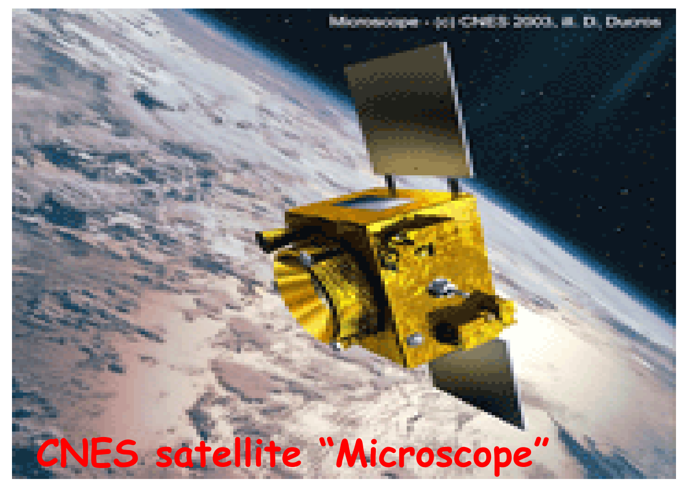
Example of the SUGRA model (no systematic exploration of the parameters space yet)



2- Violation of the (weak) equivalence principle (because there are two Higgs!)

$$\eta_{\mathrm{AB}} \equiv \left(\frac{\Delta a}{a}\right)_{\mathrm{AB}} = 2\frac{a_{\mathrm{A}} - a_{\mathrm{B}}}{a_{\mathrm{A}} + a_{\mathrm{B}}} \sim \frac{1}{2}\alpha_{\mathrm{E}}\left(\alpha_{\mathrm{A}} - \alpha_{\mathrm{B}}\right)$$

Current limits: $\eta_{\mathrm{AB}} = (+0.1 \pm 2.7 \pm 1.7) \times 10^{-13}$



3- Other possible effects

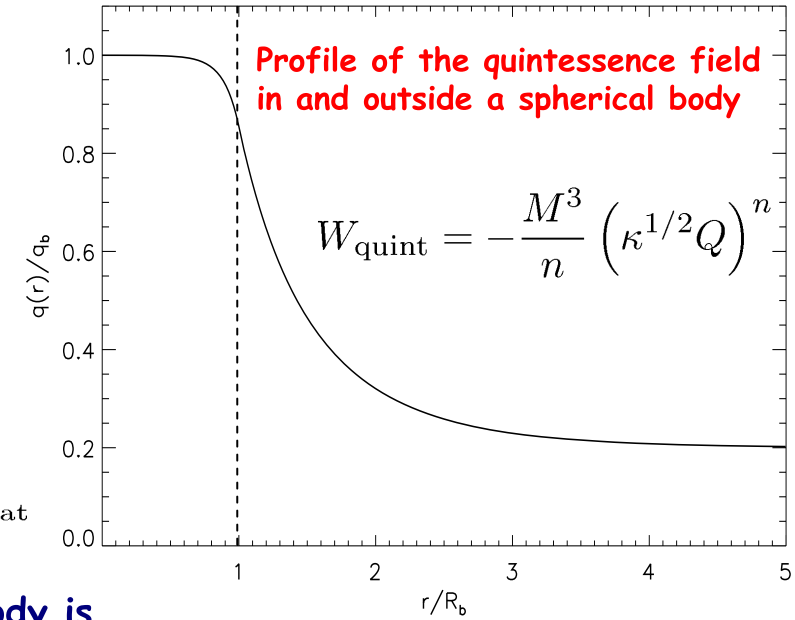
Variation of constants (fine structure constant etc …), proton to electron mass ratio, Chameleon model (hence, one can have $\omega < -1$)

The no-scale case is quite specific because

1- There is a universal dependence of the masses $\propto Q^{-3}$

2- There is a Chameleon mechanism

$$\begin{aligned} V_{\rm eff}(Q) &= V_{\rm DE}(Q) + {\rm e}^{\sqrt{6}q}\rho_{\rm mat} \\ &\simeq \frac{1}{2} M_{\rm S} M^3 {\rm e}^{-(n-3)\sqrt{2/3}q} + {\rm e}^{\sqrt{6}q}\rho_{\rm mat} \end{aligned}$$



The acceleration felt by a test particle outside the body is

$$a = -\frac{G m_{\rm b}}{r^2}\left[1 + \frac{\alpha_q\left(q_\infty - q_{\rm b}\right)}{\Phi_{\rm N}}\right]$$

$$\alpha_q \to \sqrt{6}$$

$$q_\infty \to q_{\rm min} \sim \ln\left[\frac{(n-3)M_{\rm S}M^3}{6\rho_{\rm mat}}\right]$$

$$\Phi_{\rm N} = \frac{G m_{\rm b}}{R_{\rm b}}$$

Compatibility with gravity tests is not only controlled by α_q but also by the profile of the field : thin shell effect

In the no scale case, one can show that the mechanism is not efficient enough : no scale ruled out.

Quintessence and the rest of the world

The quintessence potential is modified by the hidden sector

The fermions mass pick up a quintessence dependence

The potential is still of the runaway type and its mass is $m_Q \sim H_0 \ll 10^{-3}$ eV

The potential acquires a minimum and the mass of Q typically becomes the gravitino mass $m_{3/2} \gg 10^{-3}$eV

The model is safe from the gravity experiments point of view but is not interesting from the cosmological point of view

One has to check whether the model is safe from the gravity experiments point of view.

"Polynomial models" : not compatible (chameleon if hidden Sec. not trivial??)

"No scale models" : not compatible despite the chameleon

Conclusions:

1- Coupling Dark energy to the observable fields predicts a bunch of different effects. In particular, violation of the EP is directly linked to the fact that they are two Higgs in the MSSM.

2- Probing dark energy is not only measuring the equation of state (cosmological test). Gravity ("local") tests are important.

3- Detailed predictions require detailed models. Can be used to rule out models. More in hep-th/0605228, astro-ph/0606306

Punch-line: Either the model is fine from the gravity point of view because its mass is large (gravitino mass) but uninteresting from the cosmological point of view or it is fine from the cosmological point of view because its mass is small (Hubble length) but, then, the corresponding range of the force is large and it is difficult to build a model consistent from the gravity experiments point of view. Quintessence no-go theorem?

But strong assumptions on the hidden sector and on the separate sectors …