Title: Dark Energy and Particle Physics

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Abstract: We examine the embedding of dark energy energy models based upon supergravity. We analyse the structure of the soft supersymmetry breaking terms in presence of dark energy. We pay attention to their dependence on the quintessence field and to the electroweak symmetry breaking, ie the pattern of fermions masses at low energy within the MSSM coupled to quintessence. In particular, we compute explicitly how the fermion masses generated through the Higgs mechanism depend on the quintessence field for a general model of quintessence. Fifth force and equivalence principle violations are potentially present as the vev of the Higgs bosons become quintessence field dependent. We emphasize that equivalence principle violations are a generic consequence of the fact that, in the MSSM, the fermions couple diffeently to the two Higgs doublets. Finally, we also discuss how the scaling of the cold dark and baryonic matter energy density is modified.

Dark Energy and Particle Physics

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Outline

1- Introduction

2- Quintessence field as the simplest HEP dark energy model: definition & general properties & connection with high energy physics

3- Quintessence and the rest of the world. Consequences of the interaction & illustrations on simple cases

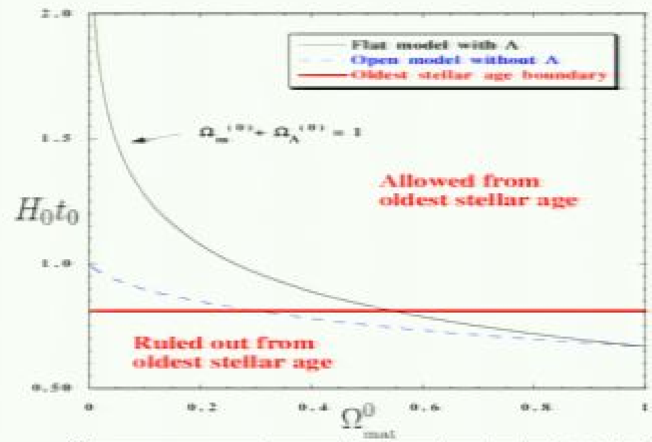
4- Dark energy & dark matter

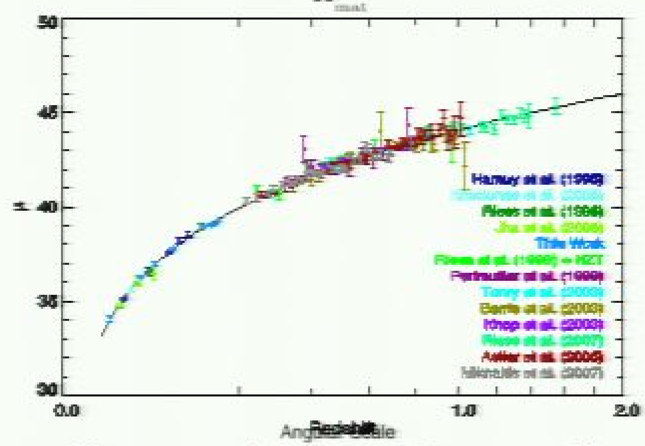
5- General conclusions

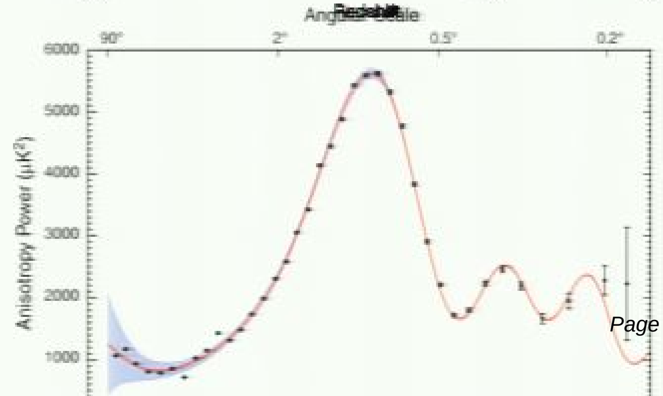
Measuring the expansion

The fact that the expansion of the Universe is accelerated is now supported by many independent measurements …

$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\ddot{a}}{a}\frac{1}{H^2} < 0$$







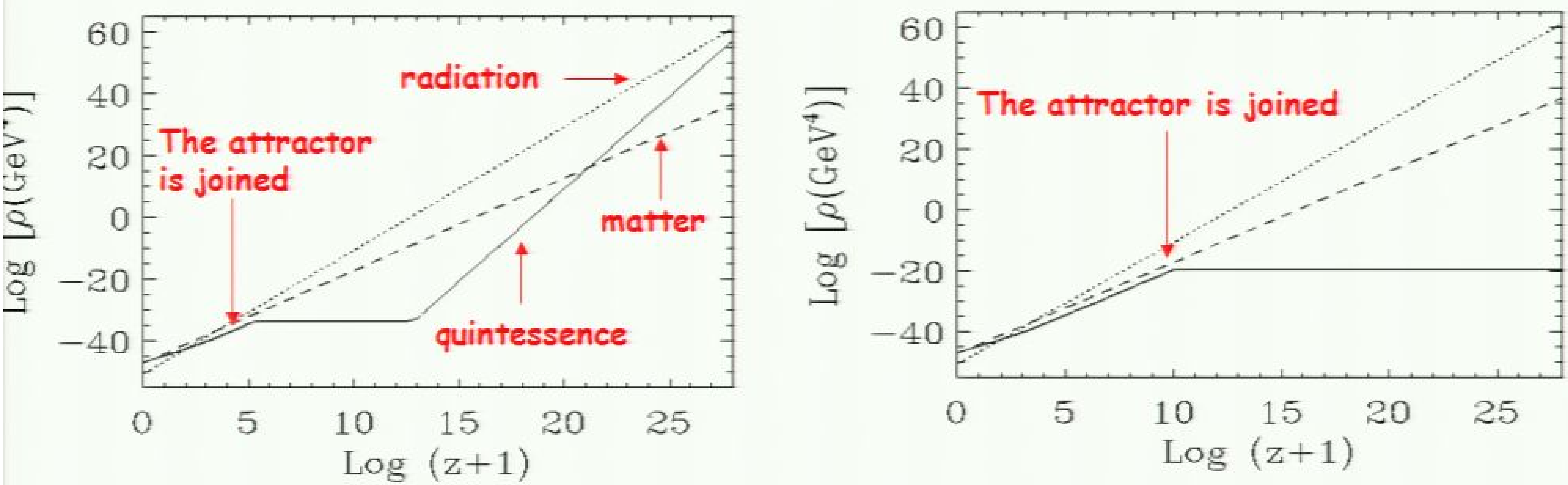
-The presence of a fluid with negative pressure (ie dark energy) and representing 70% of the total energy density in the Universe is a priori a possible explanation.

-We would like to understand the physical nature of this fluid from the high energy physics point of view in order to see whether this is a viable alternative. For this purpose, it seems natural to consider the QFT prototypical model: a scalar field (the potential energy being dominant)

NB: This does not solve the CC problem. Instead of explaining $\Omega_\Lambda = 0.7$ of the critical energy density we are just back to $\Lambda = 0$

Quintessence

A model of quintessence will be regarded as "interesting" if the present-day cosmology is independent of the initial conditions: this is the case if one of the solution of the Klein-Gordon equation is an attractor

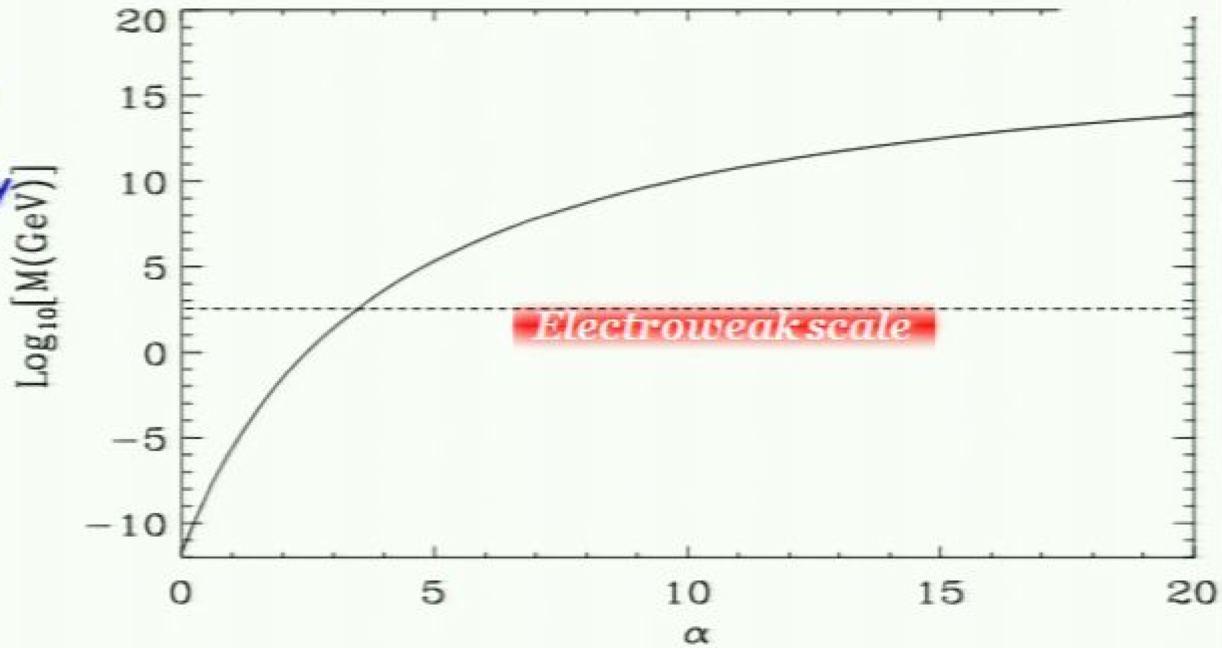


This turns out to be the case for the inverse power law potential: eg Ratra-Peebles

$$V(Q) = M^{4+\alpha} Q^{-\alpha}$$

Quintessence

- The energy scale M of the potential is fixed by the requirement that the quintessence energy density today represents 70% of the critical energy density



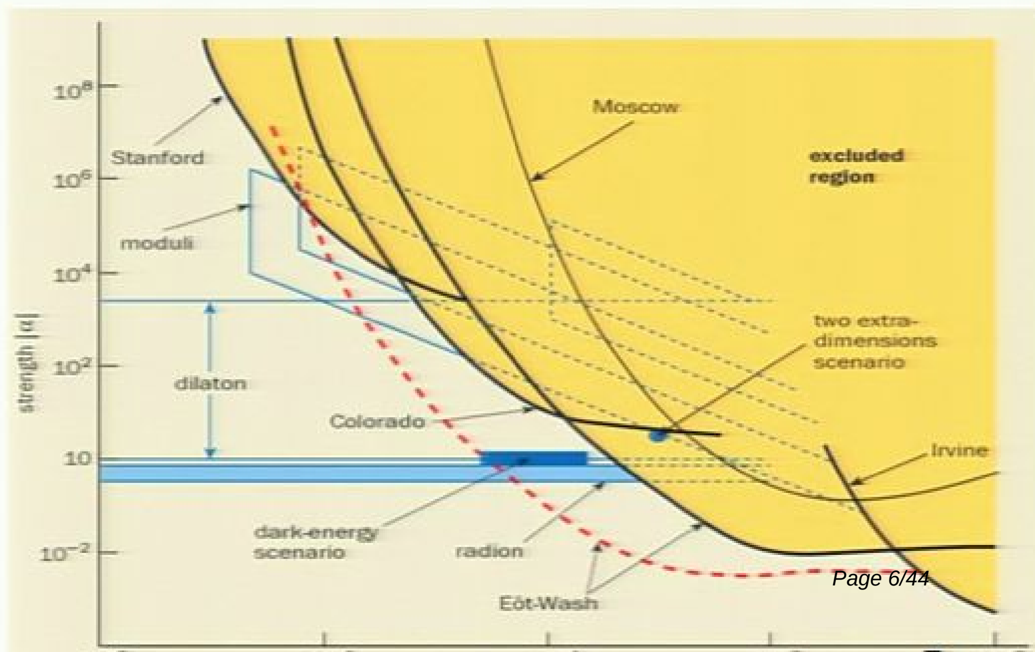
$$\frac{M^{4+\alpha}}{m_{\rm Pl}^{\alpha}} \simeq \rho_{\rm cri} \Rightarrow$$

$$\log_{10}\left[M\,(\mathrm{GeV})\right] \simeq \frac{19\alpha - 47}{\alpha + 4}$$

- The mass of the field is tiny

$$m_Q^2 = V'' = \frac{\rho_{\rm cri}}{m_{\rm Pl}^2} \sim \left(10^{-33}\mathrm{eV}\right)^2$$

ie very long range force: danger because already well constrained by various experiments



- ... but the vev is huge

$$\langle Q \rangle_{\rm today} \sim m_{\rm Pl}$$

Quintessence and particle physics

1- Can we find a candidate for the quintessence scalar field in particle physics? There is no candidate in the standard model of particle physics. Hence, we have to consider the extensions of this model. The most popular extensions are based on supersymmetry and/or supergravity.

2- Can we derive the Ratra-Peebles potential in a consistent way from particle physics? The fact that the vev of the field today is the Planck mass indicates that supergravity is the correct framework to address this question.

3- What is the influence of the quantum corrections on the shape of this potential?

4- If the dark energy is just a field, does it interact with the rest of the world? Can we compute this interaction?

5- Can we go even further and establish the link between dark energy and string theory? Can we find a candidate with a stringy interpretation?

Super-gravity & Quintessence

As argued before, we use super-gravity ... more precisely, let us consider the standard formula for the F-term potential

$$V_{\rm quint} = e^{\kappa K_{\rm quint}}\left(\left|D_Q W_{\rm quint}\right|^2 - \frac{3}{\kappa}\left|W_{\rm quint}\right|^2\right)$$

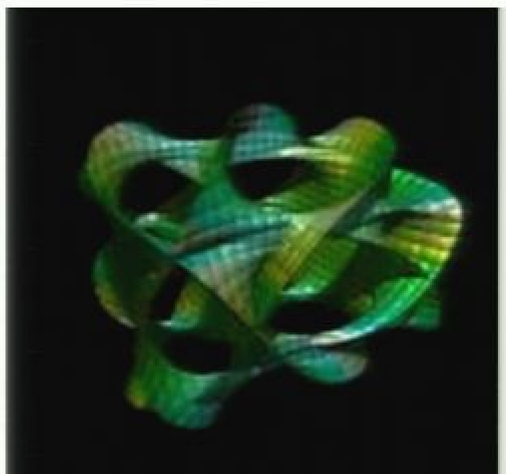
The big uncertainty is: what are the Kahler and super potentials in this sector?
It is necessary to know them in order to compute the physical effects in detail.
A priori, <u>two main possibilities</u> come to mind immediately

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

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

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

<u>No scale:moduli quintessence (connection with string theory)</u>



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

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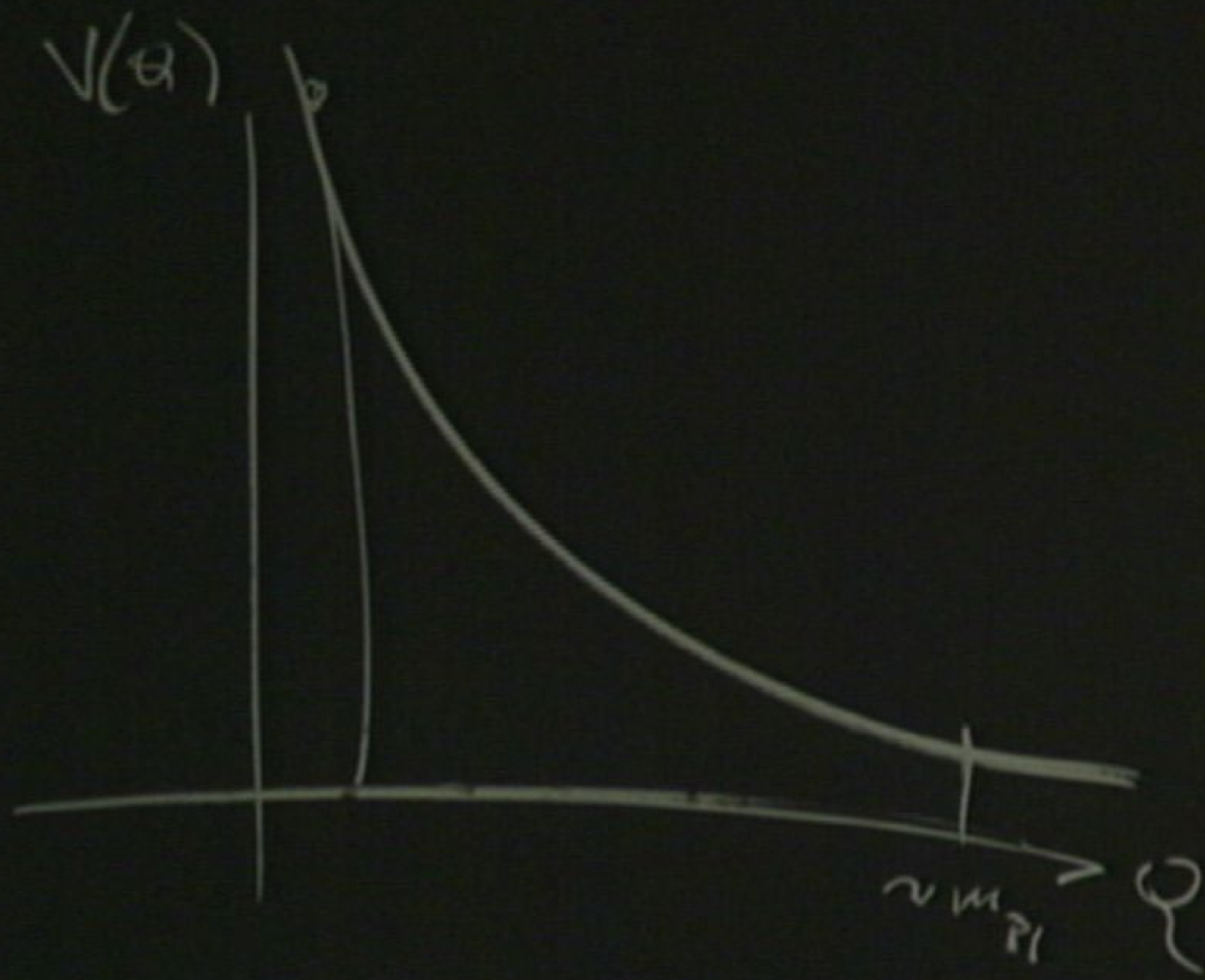
V(φ)
~ M_Pl
φ

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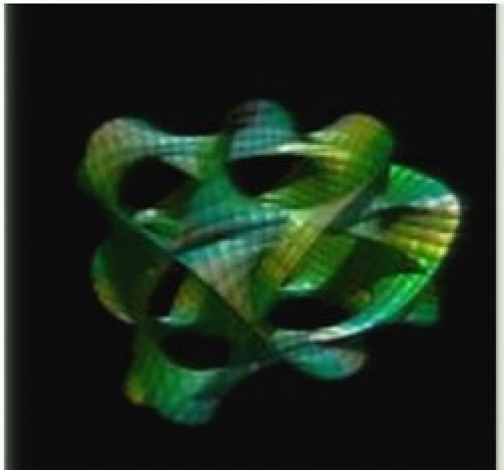

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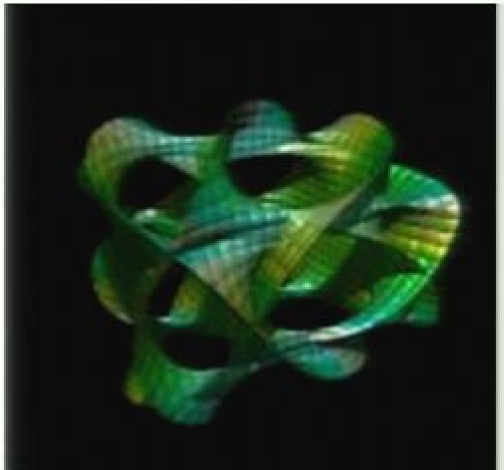

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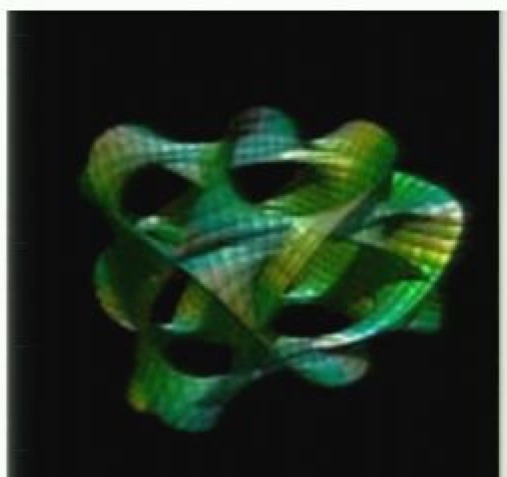

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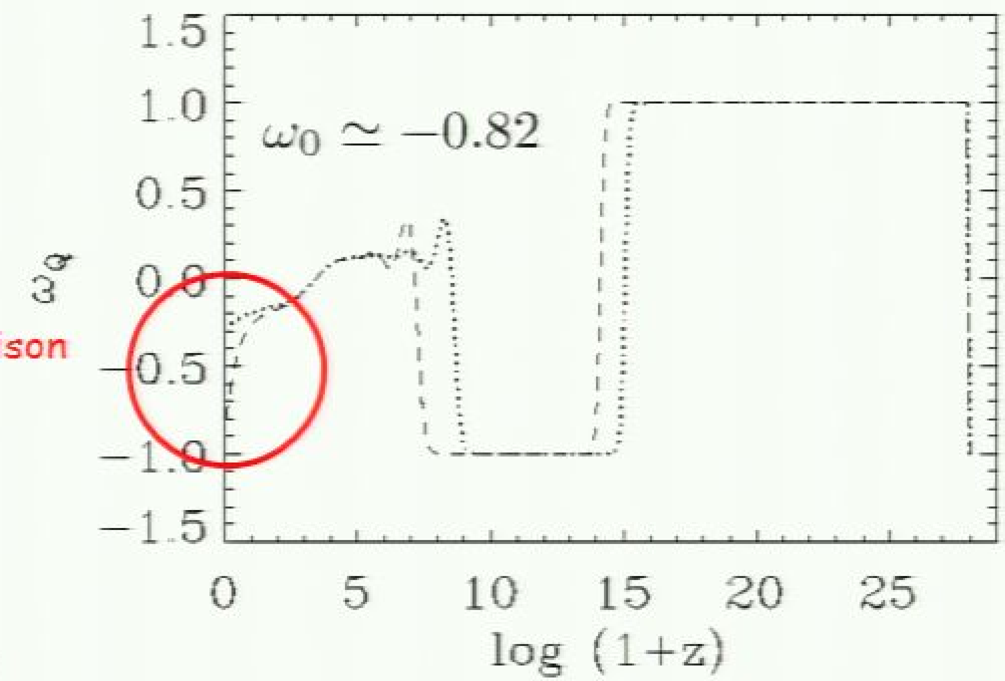
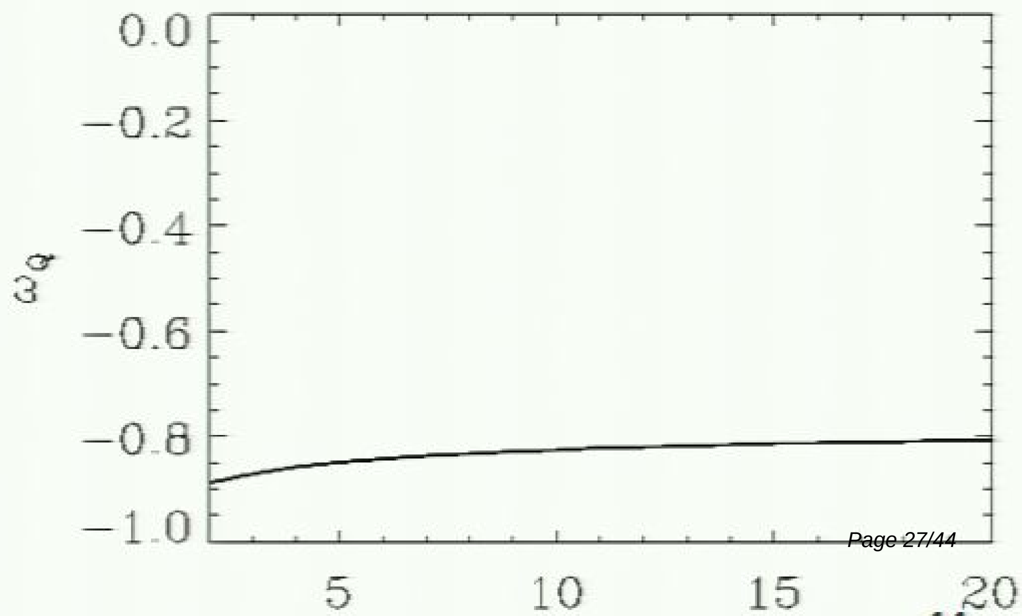


1- The attractor solution still exists since, for large redshifts, the vev of Q is small in comparison with the Planck mass

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

The "mSUGRA" framework

One has to embed dark energy in a consistent sugra framework. Let us first describe how it works for ordinary matter

Usual structure of the standard model: two sectors

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

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

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

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

where susy is broken: Poloyni field, etc ...

where the standard fields live: electrons,

The "mSUGRA" framework

In supergravity, although the sectors are separated, they communicate (through gravitation) and the fields in these separate sectors interact. The form of the interaction is completely specified.

$$K = K_{\rm obs} + K_{\rm h}$$

$$W = W_{\rm obs} + W_{\rm h}$$

The Kahler and super- potentials of each sector only depend on the fields of that sector

Then, the F-term leads to

$$V = {\rm e}^{\kappa K}\left(|DW|^2 - \frac{3}{\kappa}|W|^2\right)$$

$$V = {\rm e}^{\kappa K}\left(K^{-1}\right)^{z_i^\dagger z_j}\left(\kappa W \frac{\partial K_{\rm h}}{\partial z_j} + \frac{\partial W_{\rm h}}{\partial z_j}\right)\left(\kappa W^\dagger \frac{\partial K_{\rm h}}{\partial z_i^\dagger} + \frac{\partial W_{\rm h}^\dagger}{\partial z_i^\dagger}\right)$$
$$+ {\rm e}^{\kappa K}\left(K^{-1}\right)^{\phi_a^\dagger \phi_b}\left(\kappa W \frac{\partial K_{\rm obs}}{\partial \phi_b} + \frac{W_{\rm obs}}{\partial \phi_b}\right)\left(\kappa W^\dagger \frac{\partial K_{\rm obs}}{\partial \phi_a^\dagger} + \frac{\partial W_{\rm obs}^\dagger}{\partial \phi_a^\dagger}\right) - 3\kappa {\rm e}^{\kappa K} W W^\dagger$$

For instance, this term is an interaction between the two sectors

The "mSUGRA" framework

The hidden sector is not known but, as in the standard case, can be parameterized with a few numbers: gravitino mass, scalar mass etc …

At high energies (typically GUT scale)

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

Susy breaking scale

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

$$F_{z_i} = \frac{1}{\kappa^{1/2}} {\rm e}^{\sum_i |a_i|^2/2} M_{\rm S} (a_i + c_i) \neq 0$$

« Supersymmetry is broken »

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

The "mSUGRA" framework

The presence of the hidden sector affects the Electroweak transition. In the mSUGRA model, one has

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

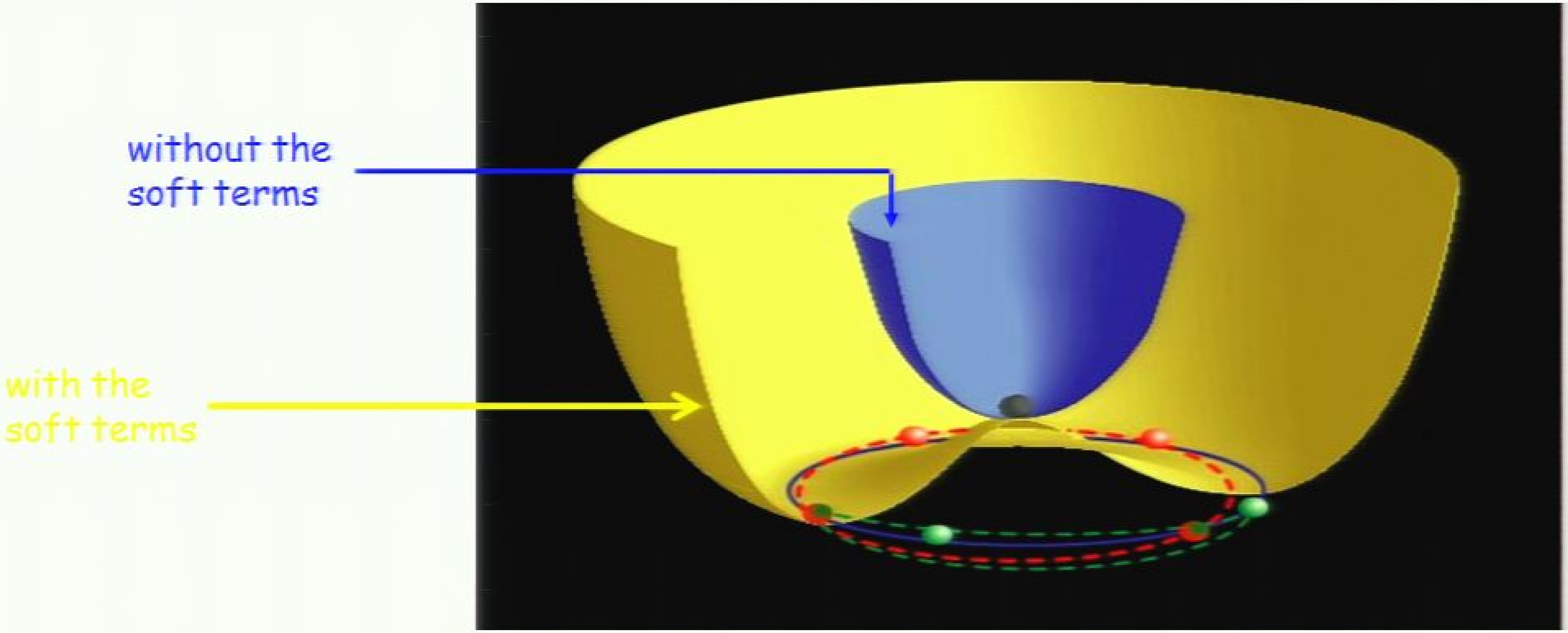
Without the breaking of SUSY, the Higgs potential only has a global minimum. The breaking of SUSY modifies the shape of the potential through the soft terms

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

$$W_{\rm obs} = \mu(H_u^+ H_d^- - H_u^0 H_d^0) + \cdots$$

Soft terms proportional to the SUSY breaking scale

The Electroweak transition is intimately linked to the breaking of SUSY

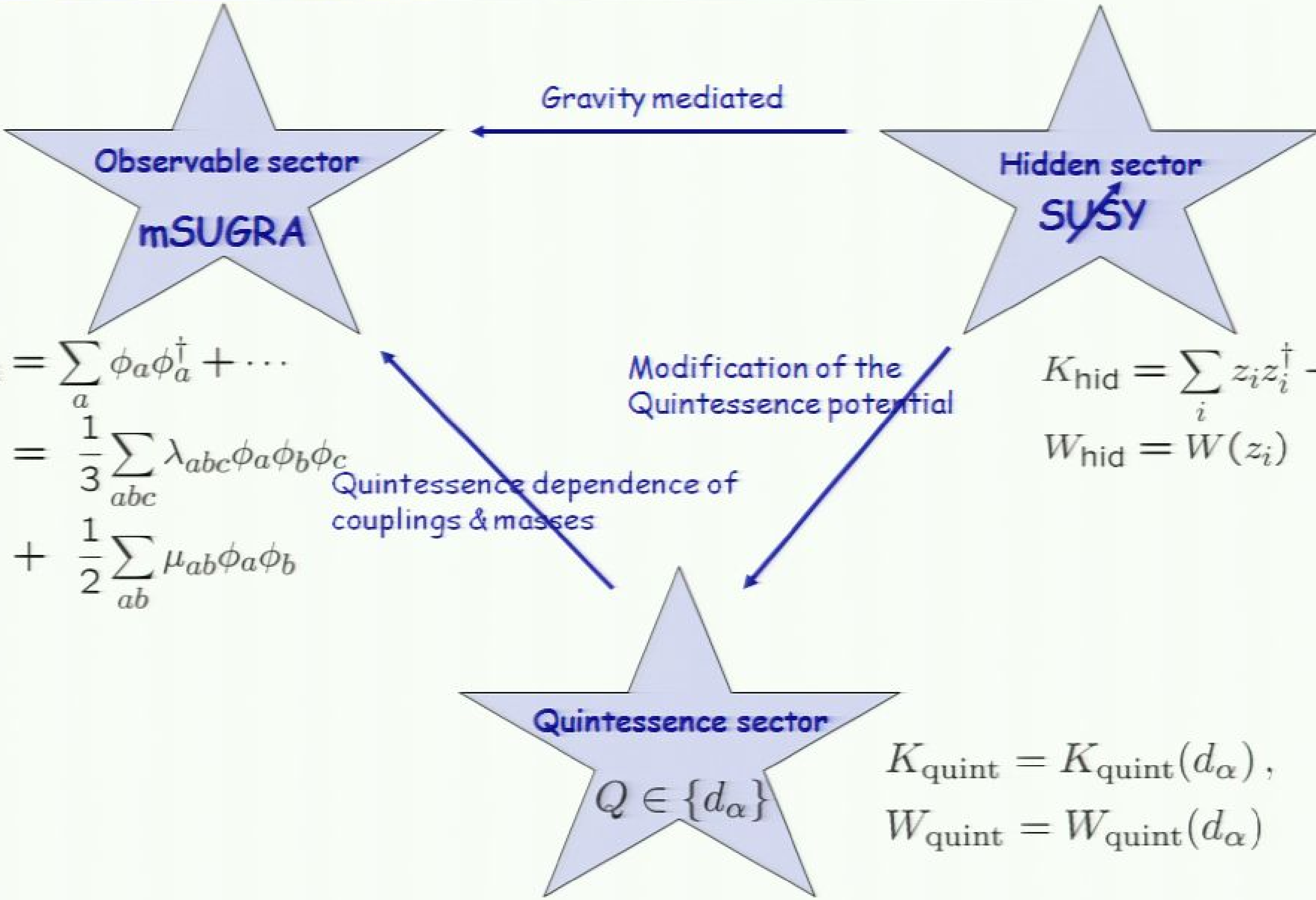


Then, the particles acquire mass when the Higgs acquire a non-vanishing vev

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

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

Quintessence & rest of the world



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

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

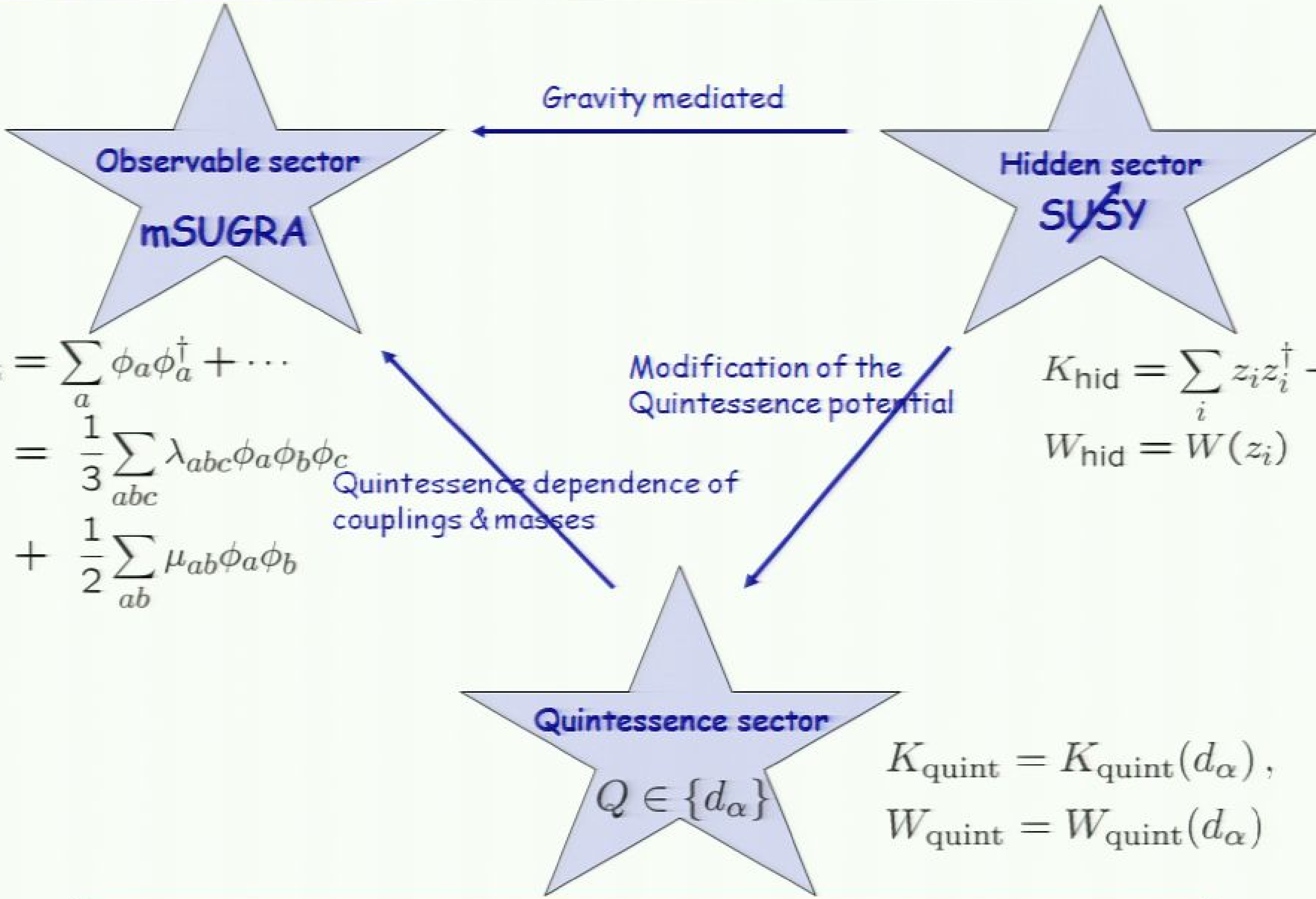
$$K_{\rm hid} = \sum_i z_i z_i^\dagger + \cdots$$

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

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

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

Quintessence & rest of the world



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

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

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

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

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

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

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

The hidden sector is not known but, as in the standard case, can be parameterized. However one has now arbitray functions!!

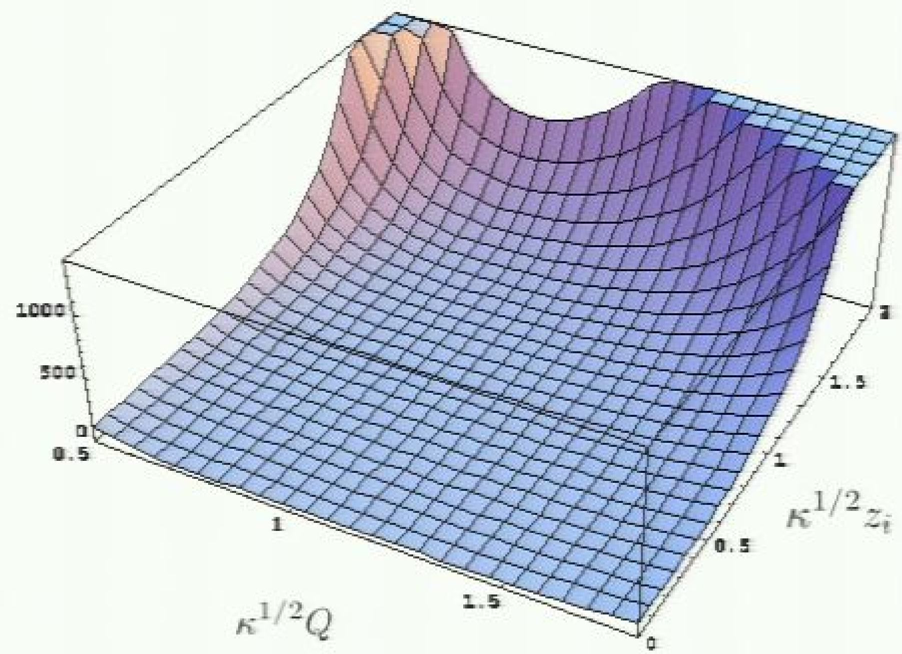
At high energies (typically GUT scale)

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

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

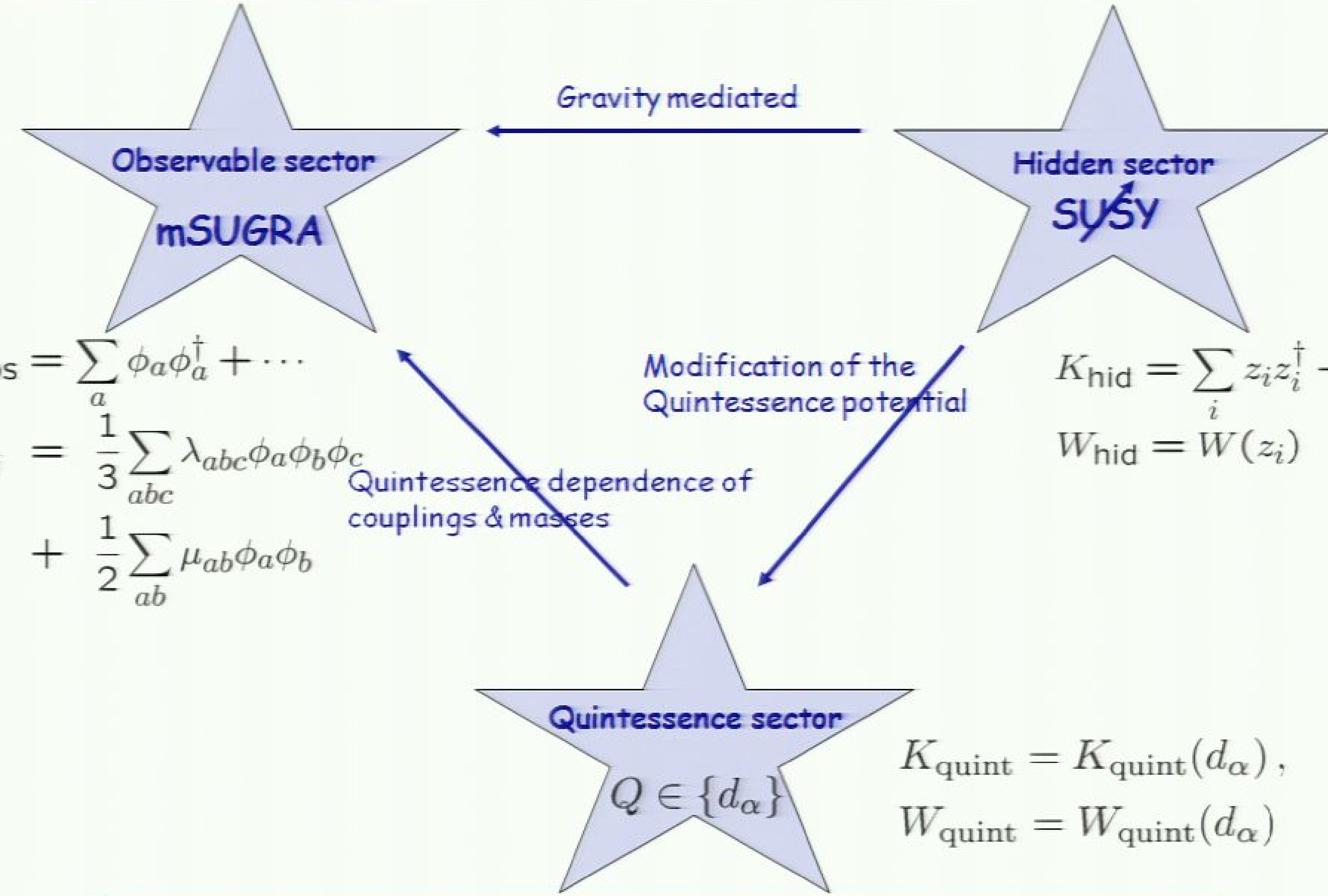
$$\kappa \, \langle W_{\rm hid} \rangle_{\rm min} \simeq M_{\rm S}(Q)$$

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



The soft terms become « dark energy dependent »

Quintessence & rest of the world



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

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

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

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

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

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

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

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

The hidden sector in presence of dark energy

The hidden sector is not known but, as in the standard case, can be parameterized. However one has now arbitray functions!!

At high energies (typically GUT scale)

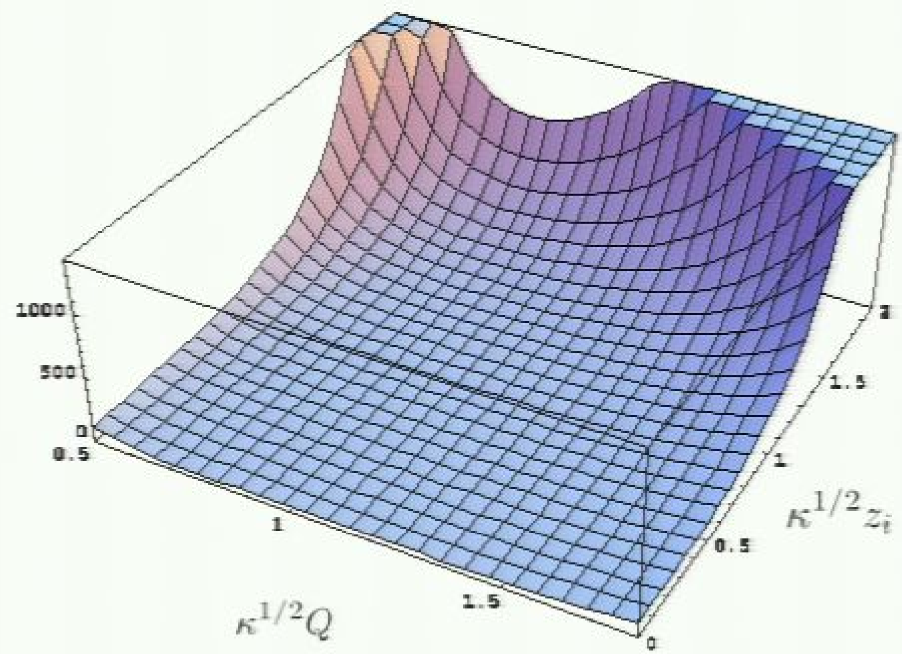
$$\partial_{z_i} V(z_j, Q, \langle \phi_a \rangle = 0) = 0$$

$$\downarrow$$

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

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

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



The soft terms become « dark energy dependent »

Consequences

Consequence I

The dark sector and the hidden sector interact. As a consequence the shape of the quintessence potential is modified: nothing but "soft terms" in the dark sector

The shape of the modified potential is model dependent, in particular it depends on the hidden sector. But as a result, one can drastically change the mass of the quintessence field and obtain

$$m_Q \gg 10^{-3}\text{eV}$$

Consequence II

Since the soft terms in the obsevable sector becomes quintessence dependent, this means the vev of the two Higgs will also become quintessence dependent and, hence, the mass of all the fermions will also functions of Q

In the case of the SUGRA model, and for an arbitrary hidden sector, the explicit form of the soft terms is given by

$$A_{abc} = \lambda_{abc} m^0_{3/2} e^{\kappa K_{\rm quint}} e^{\sum_i |a_i|^2/2} \left[1 + \frac{1}{3}\sum_i |a_i|^2 + \frac{1}{3}\sum a_i c_i + \frac{1}{3}\left(\kappa Q^2 + \kappa \xi^2 - 3\right)\right]$$

$$B_{ab} = \mu_{ab} m^0_{3/2} e^{\kappa K_{\rm quint}} e^{\sum_i |a_i|^2/2} \left[1 + \frac{1}{2}\sum_i |a_i|^2 + \frac{1}{2}\sum a_i c_i + \frac{1}{2}\left(\kappa Q^2 + \kappa \xi^2 - 3\right)\right]$$

$$m_{a\bar{b}} = m^0_{3/2} e^{\kappa K_{\rm quint}/2} \delta_{a\bar{b}}$$

-If a=c=cte, then the quintessence field acquires a large mass and the calculation of the fermion mass is not so important

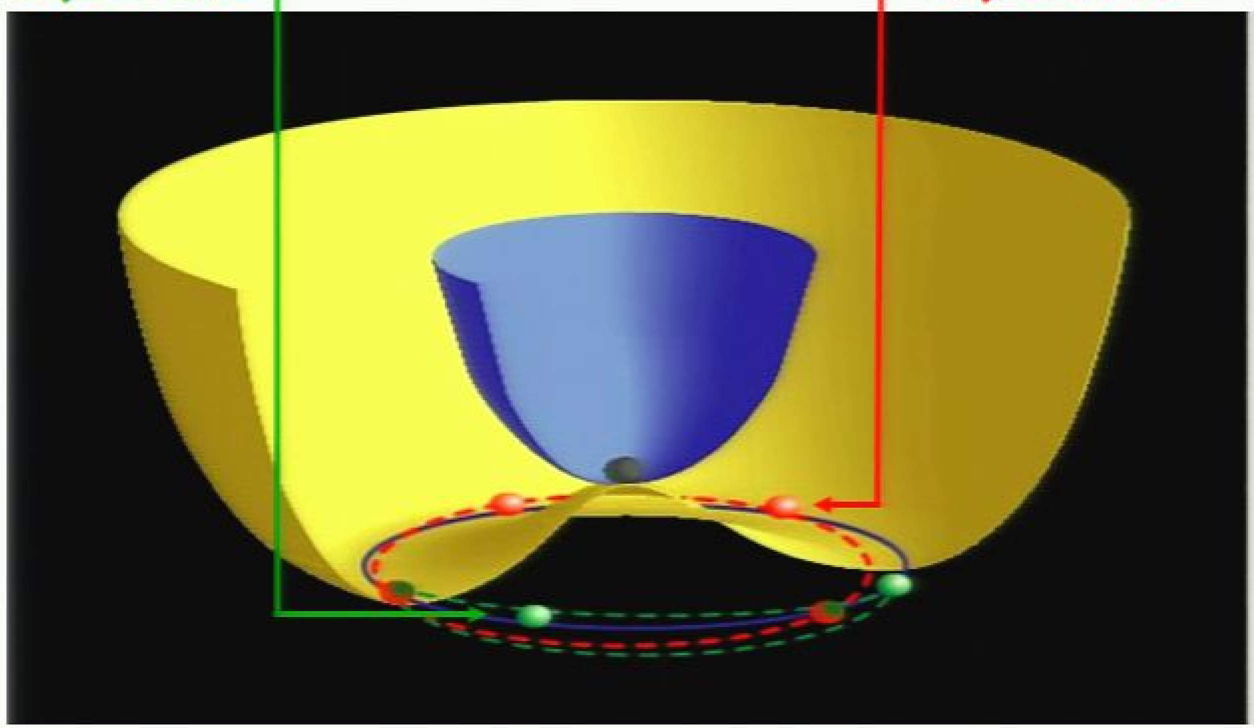
- However, if a=0 but c≠ 0, one can maybe design a model where the complicated Q-dependence of the coefficient c saves the runaway shape of the quintessence Potential. But is it fine from the gravity tests point of view??

EW transition is affected by the presence of dark energy

All the masses (fermions etc ...) become dark energy dependent. Because there are two Higgs vev, there are two types of particles:

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

"u particle" "d particle"



Through redefinitions, this type of theory can be put under the form of a scalar-tensor like theory, the difference being that there are now two coupling function:

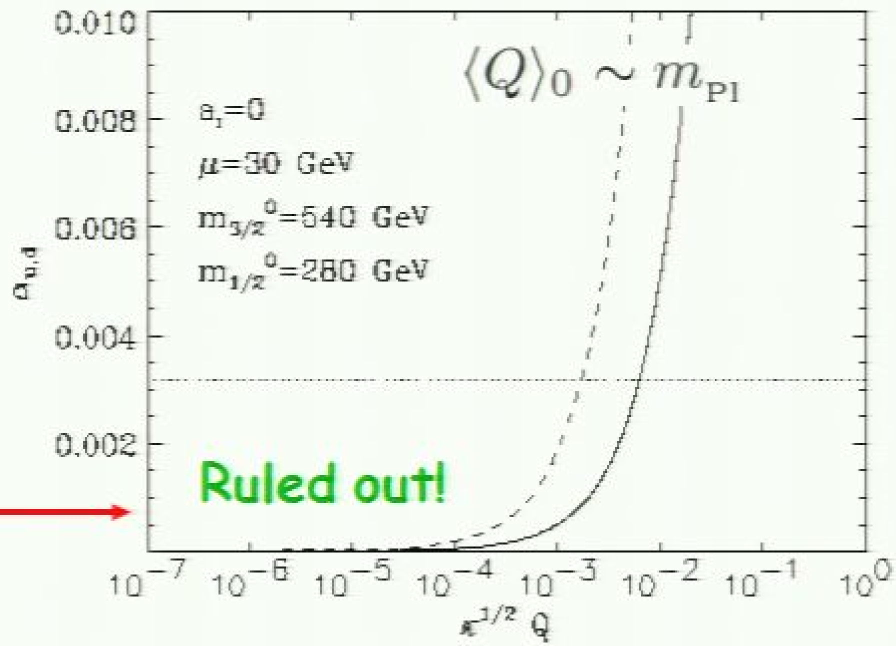
$$S=-\frac{1}{2\kappa}\int {\rm d}^4x\sqrt{-g}^{(4)}R+S_{\rm mat}\left[\tilde{\Psi}_{\rm u},A_{\rm u}^2\left(Q\right)g_{\mu\nu}\right]+S_{\rm mat}\left[\tilde{\Psi}_{\rm d},A_{\rm d}^2\left(Q\right)g_{\mu\nu}\right]+\cdots$$

Consequences:

1- Presence of a fifth force

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

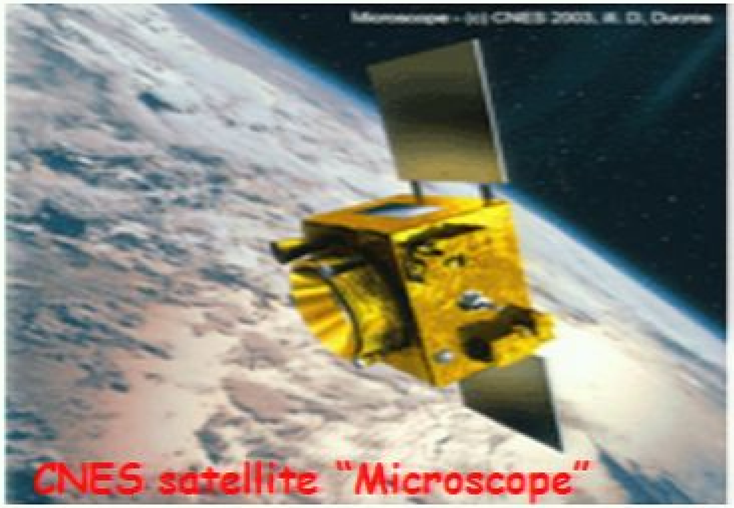
Example of the SUGRA model (no systematic exploration of the parameters space yet)



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

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

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



3- Other possible effects

Variation of constants (fine structure constant etc ...), proton to electron mass ratio, etc ...

A no-go theorem?

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- Supergravity seems to be the natural framework to build sensitive models of quintessence. It implies a non trivial coupling between the dark sector and the observable sector.

2- Many interesting consequences seem to show up: fifth force, WEP violation, Chameleon effects, variations of constants etc …

3- However, when one comes to the quantitative predictions, one faces very serious problems. In addition, these predictions are very model-dependent. The Fact that we do not the hidden sector is a serious limitation

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?

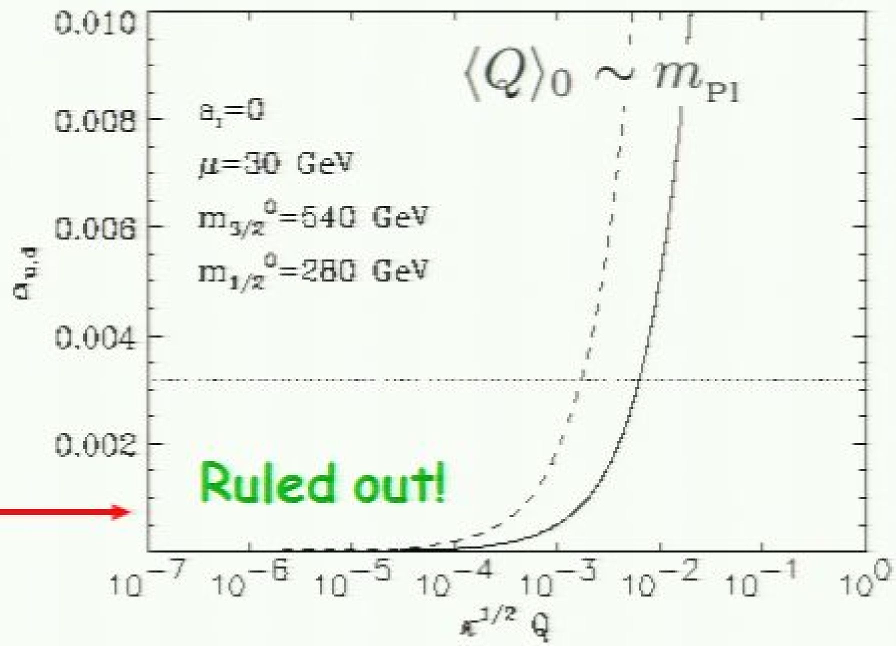
But strong assumptions on the hidden sector and on the separate sectors …

Consequences:

1- Presence of a fifth force

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

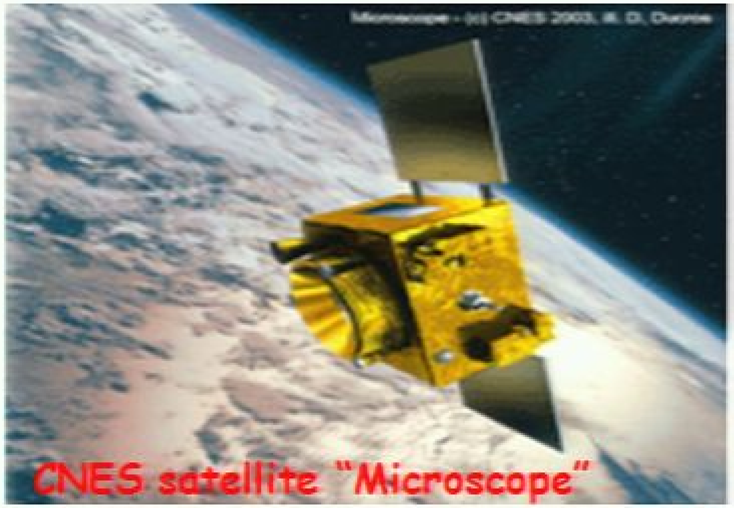
Example of the SUGRA model (no systematic exploration of the parameters space yet)



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

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

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



3- Other possible effects

Variation of constants (fine structure constant etc ...), proton to electron mass ratio, etc ...