Dark Energy and Particle Physics

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Outline

1- General framework. Acceleration of the expansion of the Universe

2- The cosmological constant. Problems with this solution

3- The Quintessence field: definition & general properties

4- The Quintessence field during inflation

5- Quintessence model building and the importance of Supergravity

6- Quintessence and the rest of the world

7- Conclusions

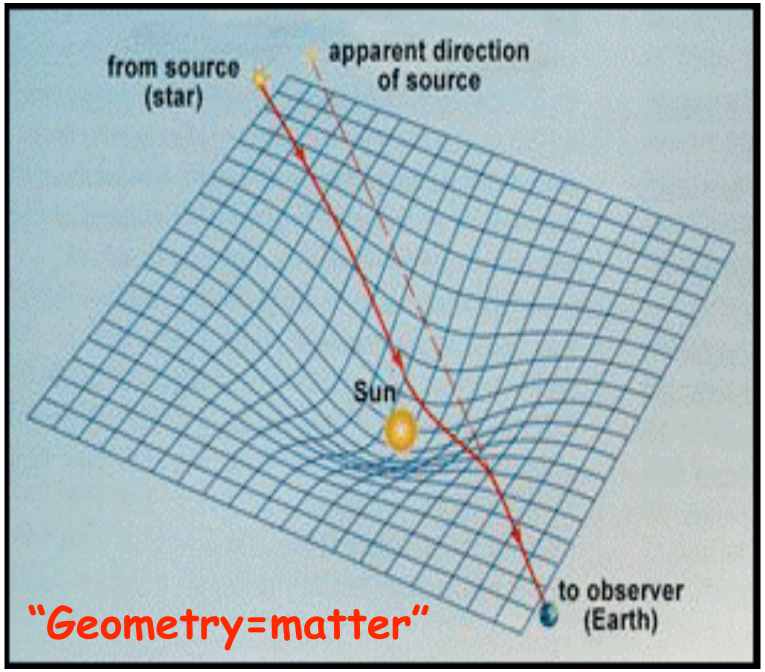
Gravity is described by General Relativity

$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = \kappa T_{\mu\nu}$$

Geometry

Matter

$$T_{\mu\nu} = (\rho + p) u_\mu u_\nu + p g_{\mu\nu}$$



Application to Cosmology (homegeneity & isotropy)

The cosmological principle implies that the geometry is

$$\mathrm{d}s^2 = -c^2 \mathrm{d}t^2 + a^2(t) \left[\mathrm{d}r^2 + r^2 (\mathrm{d}\theta^2 + \sin^2\theta \mathrm{d}\varphi^2) \right]$$

- Friedman equation: $\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{\kappa}{3}\rho$

- Conservation equation: $\dot{\rho} + 3H(\rho + p) = 0$

Observational fact: the expansion of the Univers is accelerated

$$d_{\mathrm{Lumino}}(z) = \frac{c}{H_0}\left[z + \frac{1}{2}(1 - q_0)\, z^2 + \cdots\right]$$

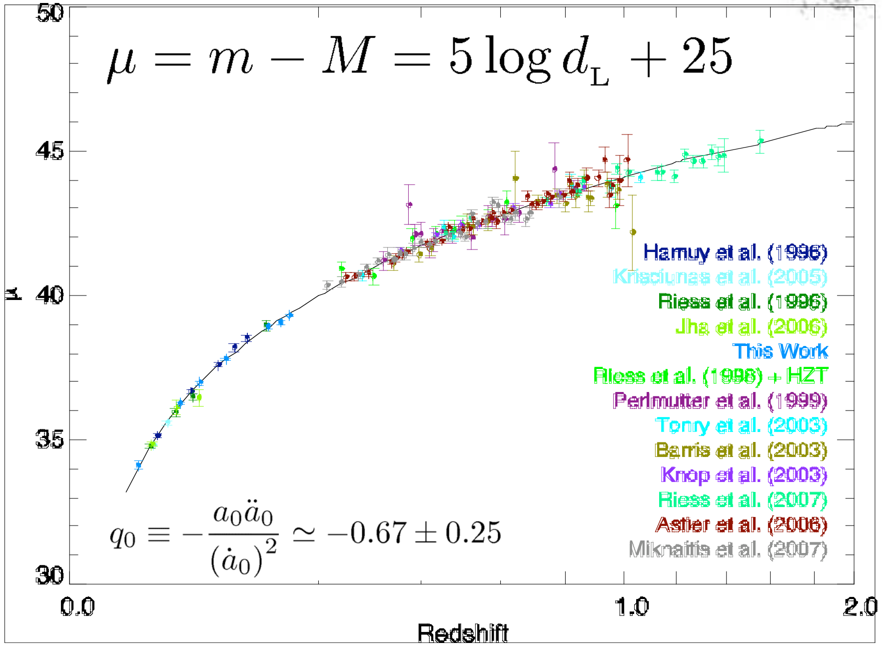
$$q_0 = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\ddot{a}}{a}\frac{1}{H^2} < 0$$

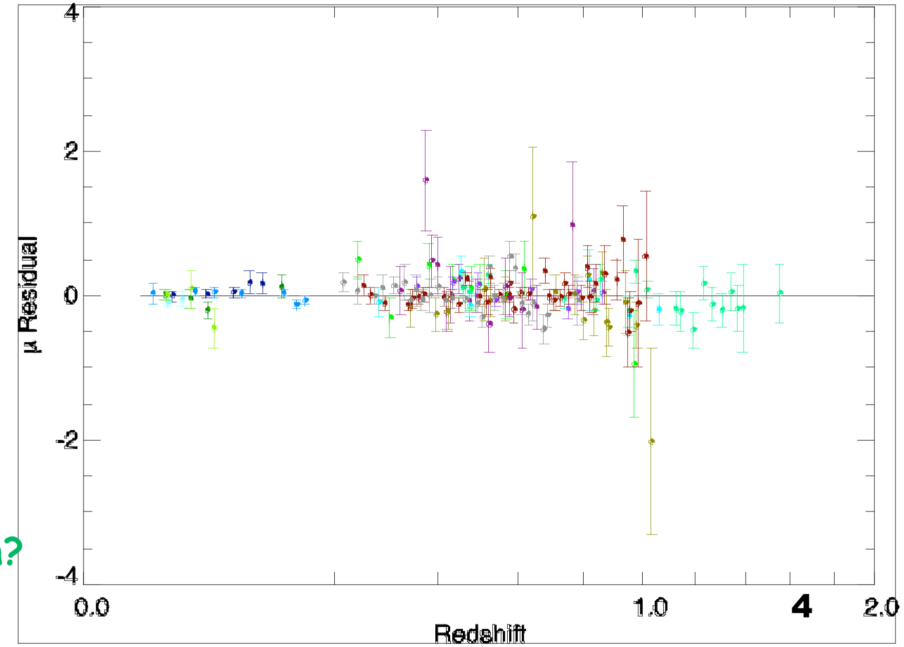
We have acceleration if the pressure is <u>negative</u>!

$$\frac{\ddot{a}}{a} = -\frac{\kappa}{6}(\rho + 3p)$$

$$p < -\frac{\rho}{3}$$

So, the question is: what is causing the acceleration?





An obvious candidate is the cosmological constant …

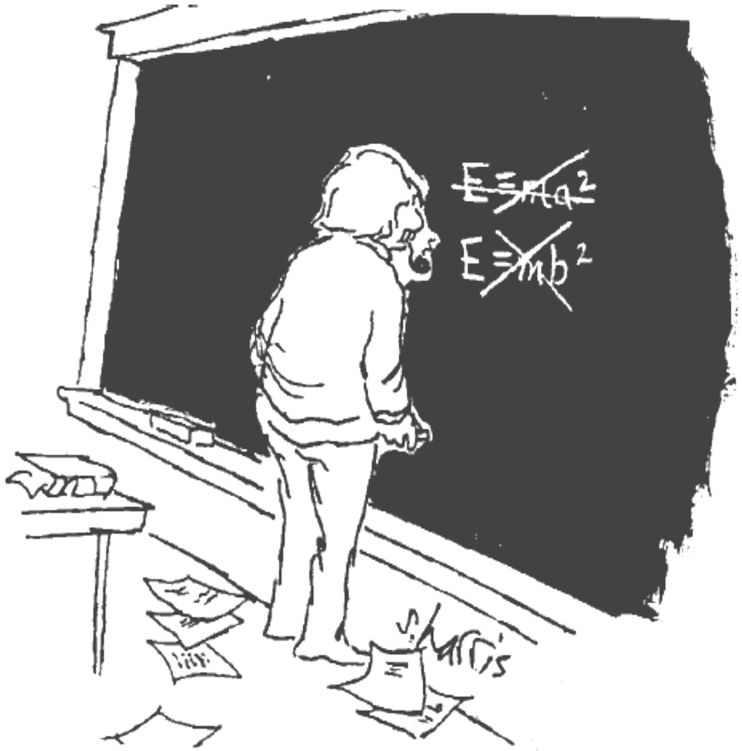
$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda_{\rm B} g_{\mu\nu} = \kappa T_{\mu\nu}$$

Bared cosmological constant (dimension m^{-2})

This term can be added because

$$\nabla^{\mu} \left(\Lambda_{\rm B} g_{\mu\nu} \right) = \Lambda_{\rm B} \nabla^{\mu} g_{\mu\nu} = 0$$

We still have a conserved stress-energy tensor



A cosmological constant can also be viewed as a fluid the stress tensor of which is given by

$$T_{\mu\nu} = -\frac{\Lambda_{\rm B}}{\kappa} g_{\mu\nu}$$

More on the last issue…

$$T_{\mu\nu} = -\frac{\Lambda_B}{\kappa} g_{\mu\nu}$$

↓

$$\rho_\Lambda = \frac{\Lambda_B}{\kappa}, \quad p_\Lambda = -\frac{\Lambda_B}{\kappa}$$

↓

$$\omega_\Lambda = \frac{p_\Lambda}{\rho_\Lambda} = -1$$

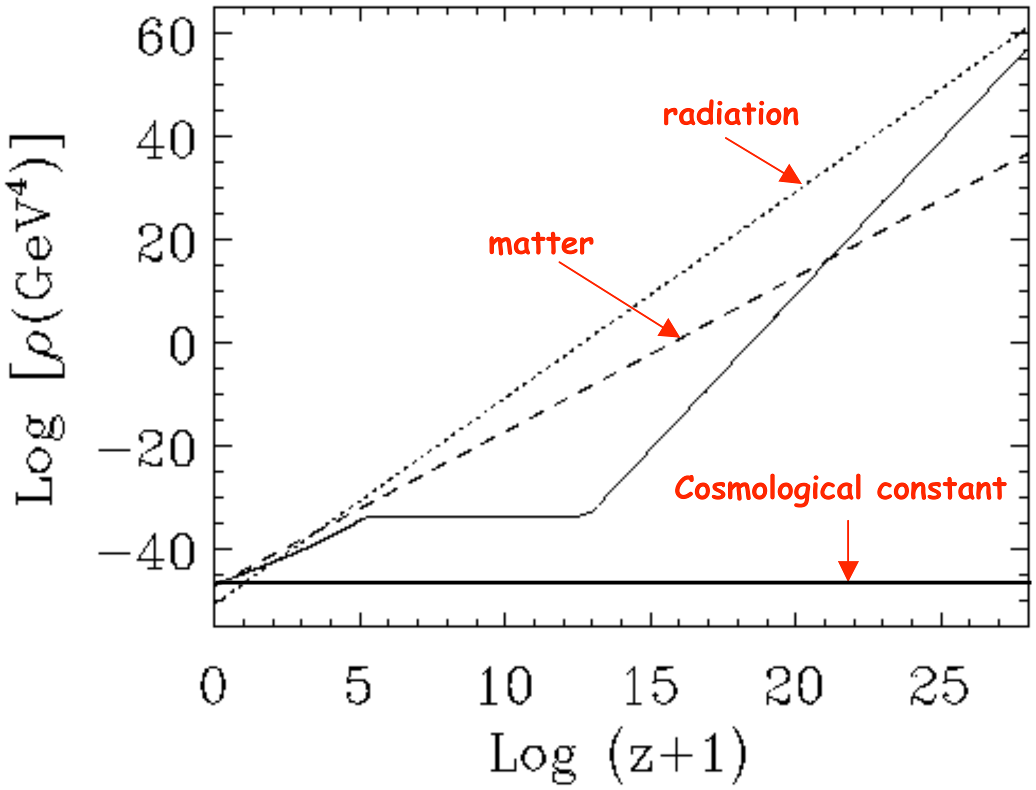
↓

$$\dot\rho + 3H(\rho + p) = \dot\rho = 0$$

The energy density associated with the cosmological constant is constant with time …!

Stress-energy tensor of a perfect fluid

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + p g_{\mu\nu}$$



Why a cosmological constant can cause acceleration??

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa}{3}\rho = \frac{\Lambda_{\rm B}}{3} = \text{constant}$$

↓

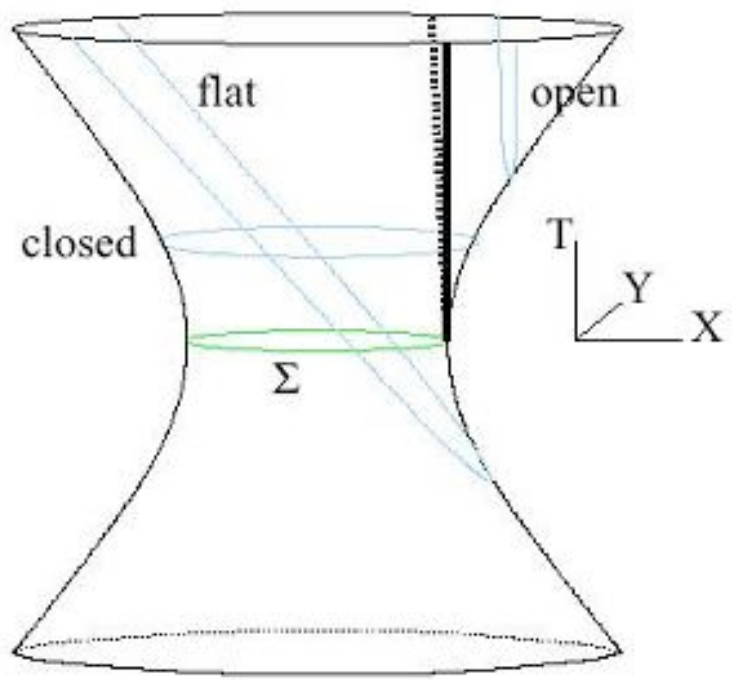
$$a(t) \propto \mathrm{e}^{Ht}$$

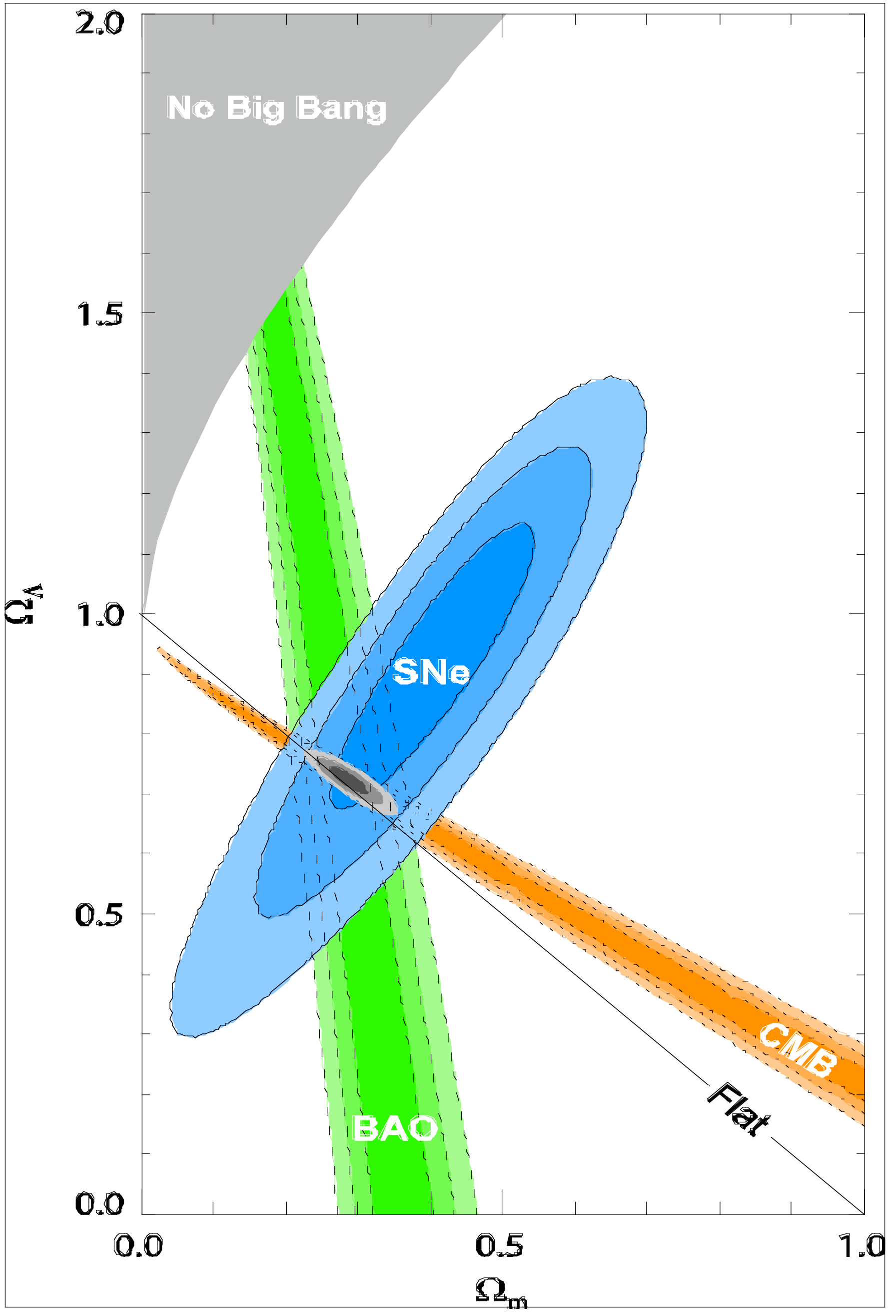
↓

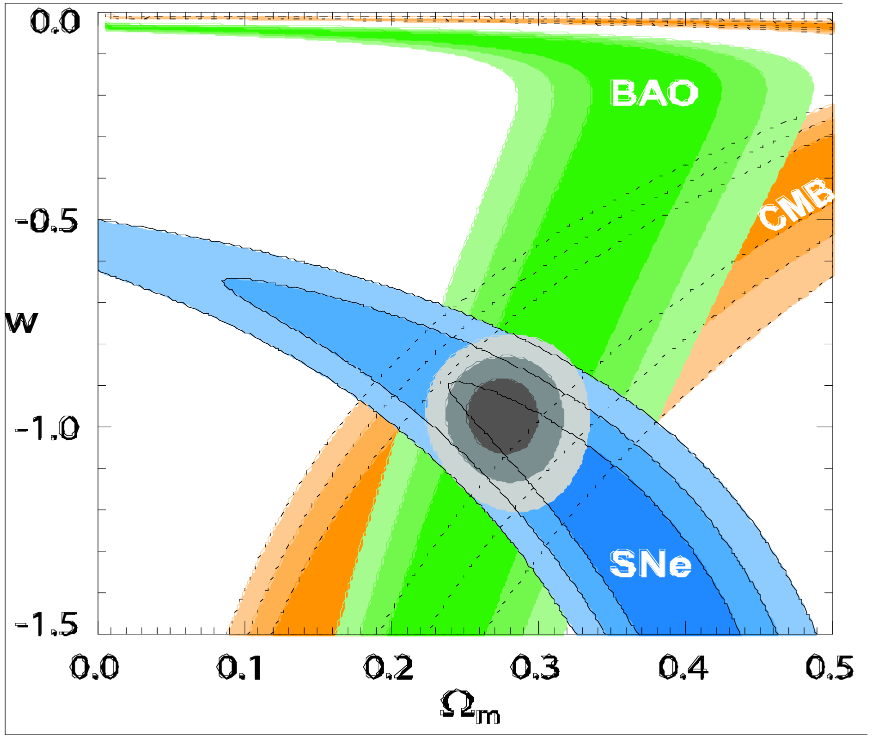
$$\frac{\ddot{a}}{a} = H^2 > 0$$

Obvious since the pressure is negative …

The corresponding spacetime is the de Sitter spacetime (as for inflation)

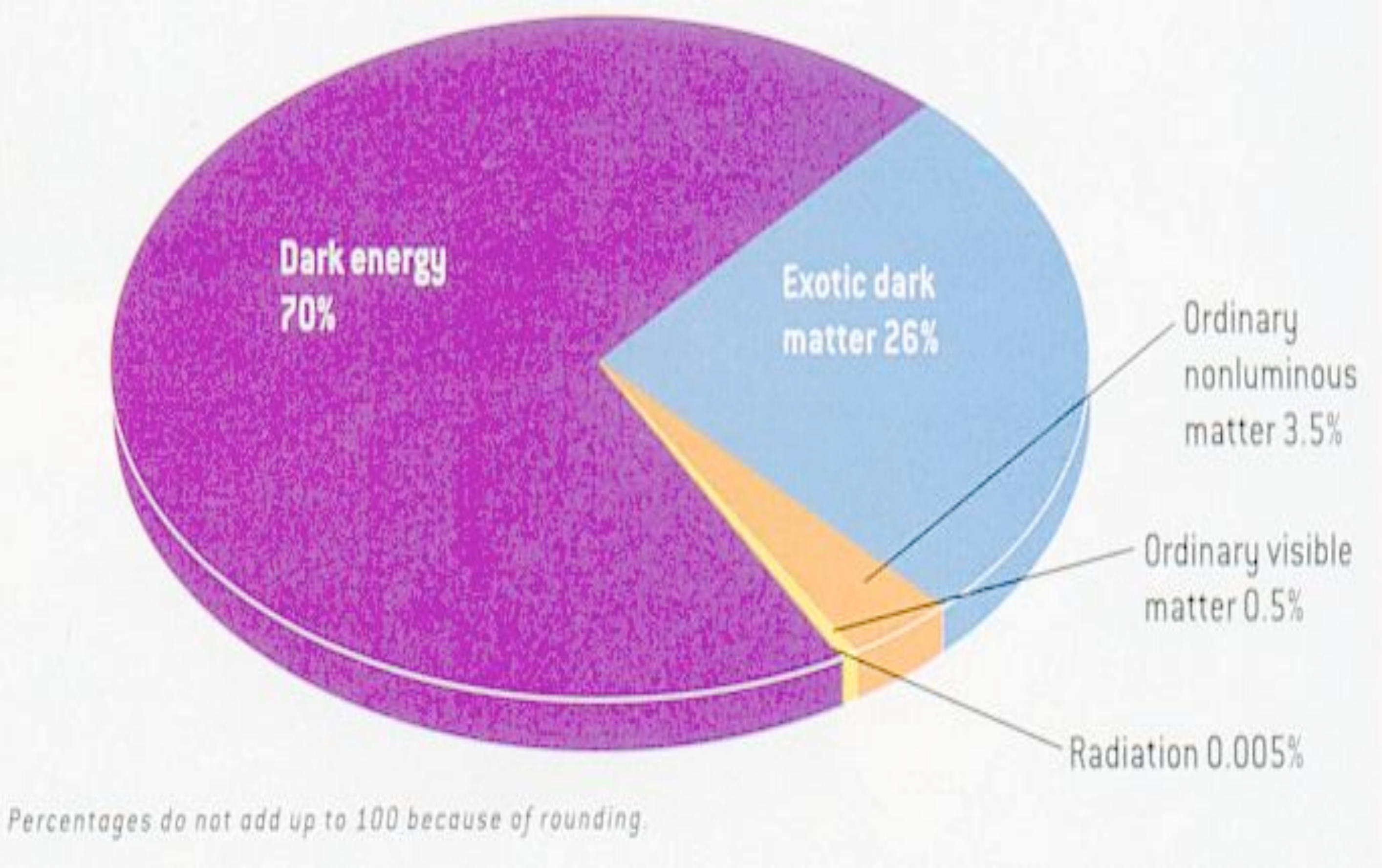






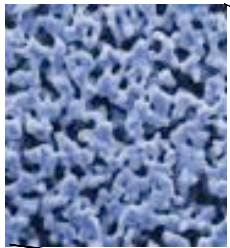
- All the data are compatible with a CC
- This introduces a new fundamental scale

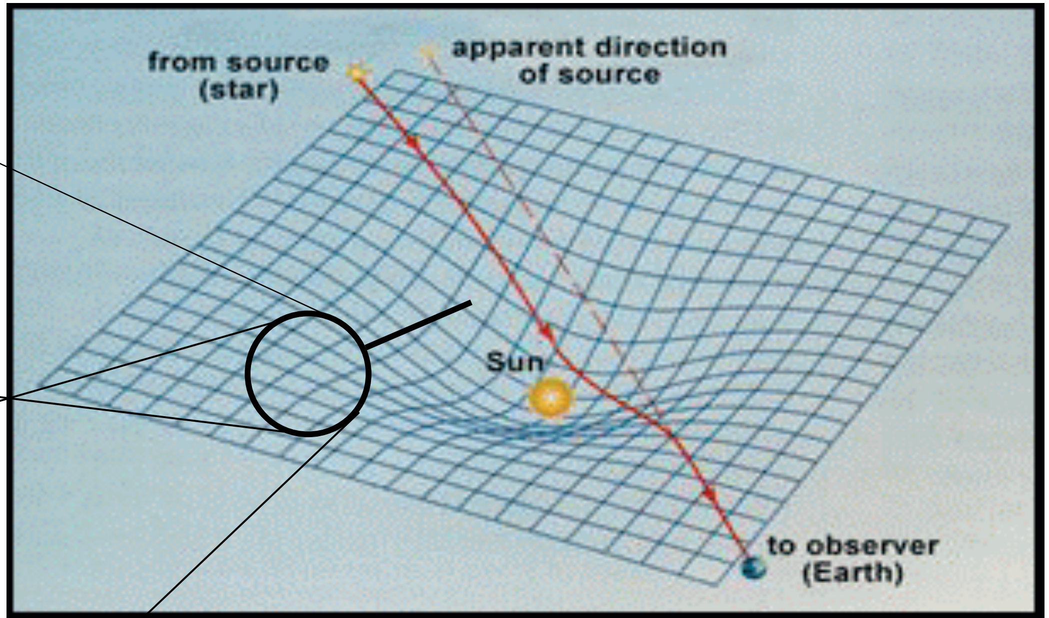
$$\rho_\Lambda \sim 10^{-47}\mathrm{GeV}^4 \sim \rho_{\mathrm{cri}}$$
$$\sim (10^{-3}\mathrm{eV})^4$$
$$L_\Lambda \sim 10^{-5}\mathrm{m}$$

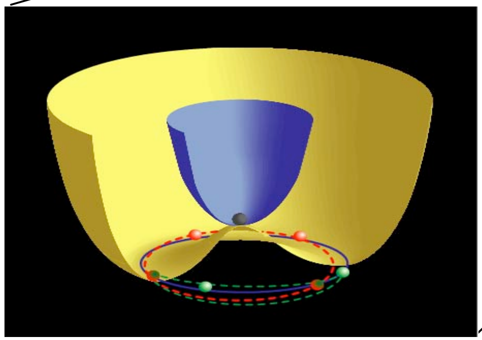

Dark energy
70%
Exotic dark
matter 26%
Ordinary
nonluminous
matter 3.5%
Ordinary visible
matter 0.5%
Radiation 0.005%
Percentages do not add up to 100 because of rounding.

… So is the problem solved? Is the CC responsible for the acceleration of the expansion of the Universe?

"The weigh of the Vacuum"







Phase transitions in the early Universe

- At the classical level, there is no problem

- At the quantum level, however there are other contributions …

$$\Lambda_{\rm eff} = \Lambda_{\rm B} + \kappa\langle\rho\rangle_{\rm vev} + \kappa\langle\rho\rangle_{\rm PT} + \cdots$$

For instance, let us calculate the contribution to the vaccum of a simple quantum scalar field in a finite box

$$\Phi(t,\mathbf{x}) = \sum_{\mathbf{k}} \frac{1}{\sqrt{2L^3\omega_{\mathbf{k}}}} \left(a_{\mathbf{k}} e^{i\mathbf{k}\cdot\mathbf{x}-i\omega t} + a_{\mathbf{k}}^\dagger e^{-i\mathbf{k}\cdot\mathbf{x}+i\omega t}\right)$$

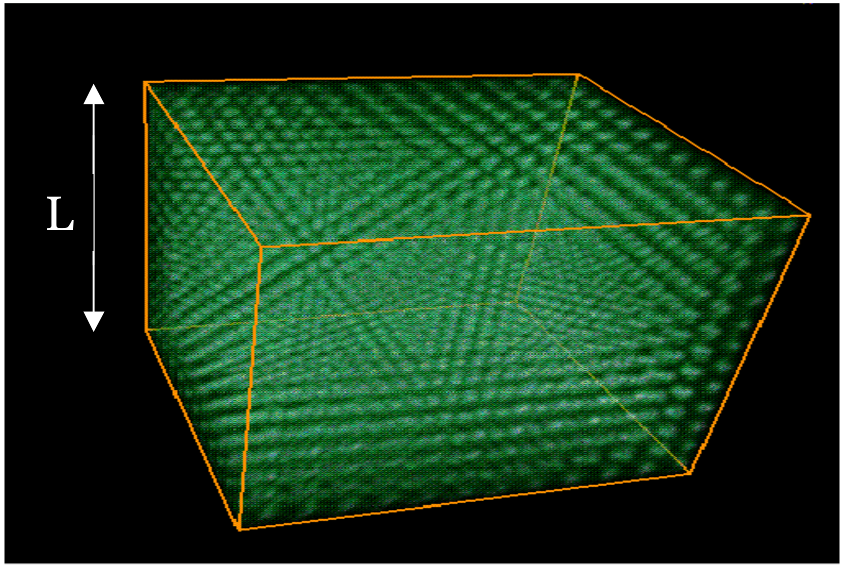
$[a_{\mathbf{k}}, a_{\mathbf{p}}^\dagger] = \delta_{\mathbf{kp}}$

$$H = \sum_{\mathbf{k}} \left(a_{\mathbf{k}}^\dagger a_{\mathbf{k}} + \frac{1}{2}\right)\omega_{\mathbf{k}}$$

Particles number

$$\omega_{\mathbf{k}} = \sqrt{\mathbf{k}^2 + m^2}$$

$$k_j = \frac{2\pi}{L} n_j$$



So the vaccum contribution is given by

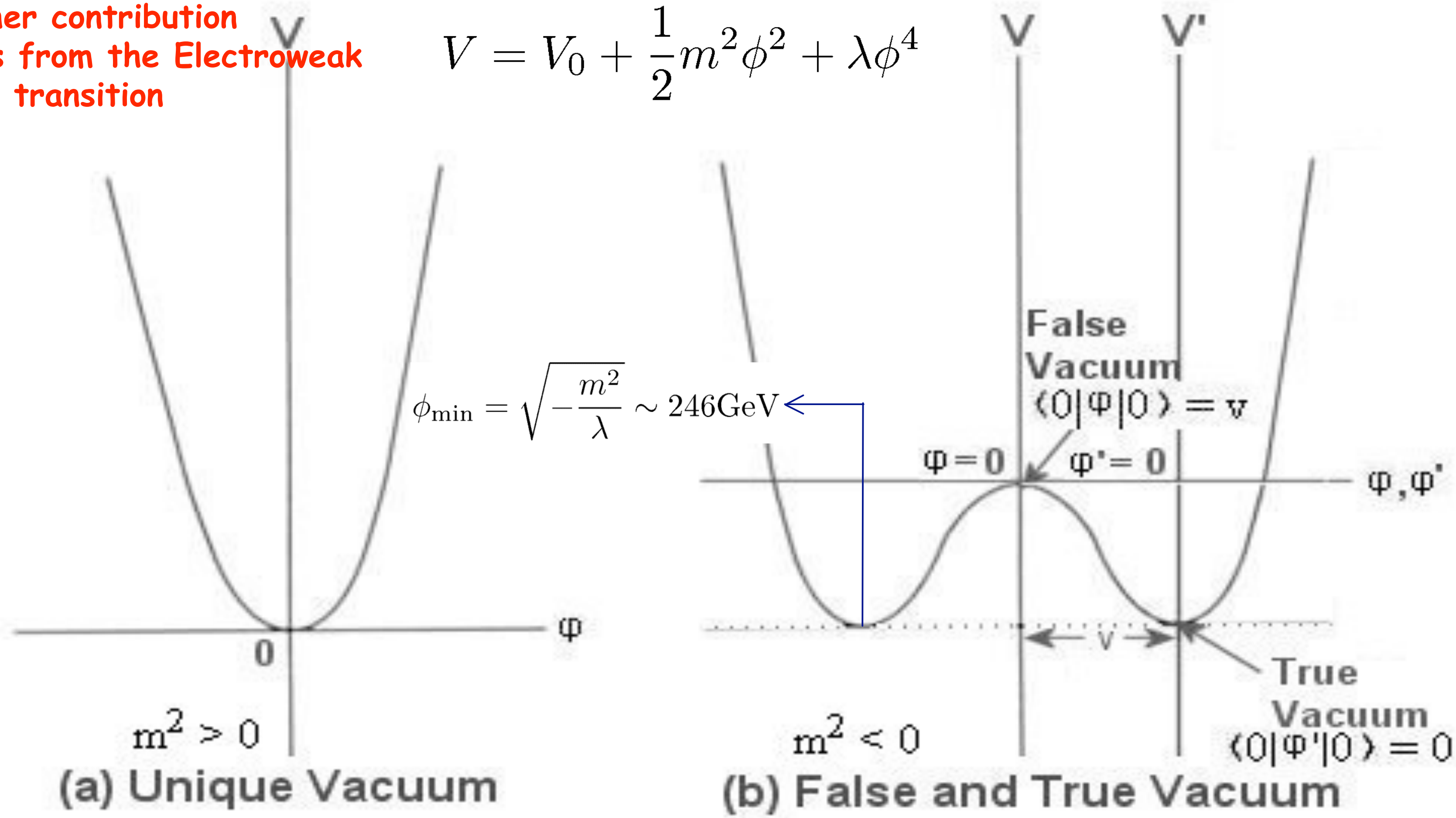
$$\langle 0|H|0\rangle = \frac{1}{2}\sum_{\mathbf{k}} \omega_{\mathbf{k}} \rightarrow \frac{1}{2}\left(\frac{L}{2\pi}\right)^3 \int \omega(k)\mathrm{d}^3\mathbf{k}$$

$$\langle\rho\rangle = \frac{1}{2}\frac{1}{(2\pi)^3}\int \mathrm{d}^3\boldsymbol{k}\sqrt{\boldsymbol{k}^2 + m^2} = \frac{M_{\mathrm{C}}^4}{16\pi^2}\left(1 + \frac{m^2}{M_{\mathrm{C}}^2} + \cdots\right) \sim 10^{122}\rho_{\mathrm{cri}}$$

(obtained with $M_{\mathrm{C}} = M_{\mathrm{Pl}}$)

Another contribution comes from the Electroweak phase transition

$$V = V_0 + \frac{1}{2}m^2\phi^2 + \lambda\phi^4$$



$$\phi_{\min} = \sqrt{-\frac{m^2}{\lambda}} \sim 246\mathrm{GeV}$$

$$\langle\rho\rangle_{\mathrm{PT}} = V_0 - \frac{m^4}{4\lambda} = V_0 - \frac{\lambda}{4}(246\,\mathrm{GeV})^4$$

Huge in comparison with the critical energy density

So the cosmological constant problem consists in the following …

- In General Relativity, the vacuum gravitates

- The vacuum energy density is made of huge disconnected pieces while the observed value is tiny

$$\Lambda_{\rm eff} = \Lambda_{\rm B} + \kappa\langle\rho\rangle_{\rm vev} + \kappa\langle\rho\rangle_{\rm PT} + \cdots$$

Small or vanishing — huge — huge

- Miraculous cancellation?

- Landscape (ie eternal inflation+string theory)?

Supersymmetry is a symmetry which relates the bosons with the fermions. The simplest example is the Wess-Zumino model

$$\mathcal{L} = \eta_{\mu\nu} \left(\partial^\mu \Phi\right)^\dagger \left(\partial^\nu \Phi\right) + i\bar{\Psi}_{\dot{\alpha}} \left(\bar{\sigma}^\mu\right)^{\dot{\alpha}\alpha} \partial_\mu \Psi_\alpha + F^\dagger F$$

This Lagrangian is invariant under the following transformation characterized by ξ

$$\delta\Phi = \sqrt{2}\xi^\alpha \Psi_\alpha$$

← From a boson, one obtains a fermion

$$\delta\Psi_\alpha = -i\sqrt{2}\left(\sigma^\mu\right)_{\alpha\dot{\beta}} \bar{\xi}^{\dot{\beta}} \partial_\mu \Phi + \sqrt{2}\xi_\alpha F$$

$$\delta F = -i\sqrt{2}\bar{\xi}_{\dot{\alpha}} \left(\bar{\sigma}^\mu\right)^{\dot{\alpha}\beta} \partial_\mu \Psi_\beta$$

This set realizes the SUSY algebra

Q_α : fermionic operator generating the SUSY transformation

$$\left\{Q_\alpha, \bar{Q}_{\dot{\beta}}\right\} = 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu$$

Two successive susy transformations » translation in spacetime

$$\left[Q_\alpha, P^\mu\right] = 0$$

$$\left[M^{\mu\nu}, Q_\alpha\right] = -i\left(\sigma^{\mu\nu}\right)_\alpha{}^\beta Q_\beta$$

In a SUSY theory, the energy of any non-vacuum state is positive definite. In the SUSY vacuum, the vacuum energy is exactly zero

$$\left\{Q_\alpha, \bar{Q}_{\dot\beta}\right\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$$

$$\to\quad 4\left\langle\psi\left|P^0\right|\psi\right\rangle = \left\langle\psi\left|Q_\alpha\left(Q_\alpha\right)^* + \left(Q_\alpha\right)^* Q_\alpha\right|\psi\right\rangle \geq 0$$

$$\to\quad \left\langle 0\left|P^0\right|0\right\rangle = 0 \quad\Longleftrightarrow\quad Q_\alpha|0\rangle = 0$$

… But SUSY has to be broken for phenomenological reasons at a scale at least (approximatively) higher than 1 TeV

$$\langle\rho\rangle = \frac{1}{2}\frac{1}{(2\pi)^3}\int \mathrm{d}^3\boldsymbol{k}\sqrt{\boldsymbol{k}^2 + m^2} = \frac{M_{\rm C}^4}{16\pi^2}\left(1 + \frac{m^2}{M_{\rm C}^2} + \cdots\right) \sim 10^{60}\rho_{\rm cri}$$

$$\downarrow\ M_{\rm C} \sim 1\mathrm{TeV}$$

We are still off by 60 orders of magnitude …

The previous difficulties have led to the search of alternatives … Can the dark energy be a (scalar) field?

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

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

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 simple "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 big 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

More on the last issue… The action of a scalar field is

$$S = -\int \mathrm{d}^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi + V\left(\Phi\right)\right]$$

$$T_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S}{\delta g^{\mu\nu}}$$

$$T^{\mu}{}_{\nu} = g^{\mu\lambda}\partial_\lambda\Phi\partial_\nu\Phi - \delta^{\mu}{}_{\nu}\left[\frac{1}{2}g^{\alpha\beta}\partial_\alpha\Phi\partial_\beta\Phi + V\left(\Phi\right)\right]$$

Neglecting the spatial derivatives (FLRW)

$$\rho = \frac{\dot{\Phi}^2}{2} + V\left(\Phi\right)$$

$$p = \frac{\dot{\Phi}^2}{2} - V\left(\Phi\right)$$

In the vacuum the derivatives should be zero …

$$\rho = +V_{\min}\left(\Phi\right) = -p$$

Variation with respect to the field

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

- No spatial gradient because FLRW…
- Damping term because the field lives in curved spacetime

One postulates the presence of a scalar field Q with a runaway potential and Λ=0. Assume that, initially the field is subdominant. This means

$$a(t) \propto t^{2/(3+3\omega_B)}$$

equation of state of the background fluid, i.e. 1/3 or 0

$$\ddot{Q} + 3\frac{2}{3(1+\omega_B)t}\dot{Q} - \alpha M^{4+\alpha}Q^{-\alpha-1} = 0$$

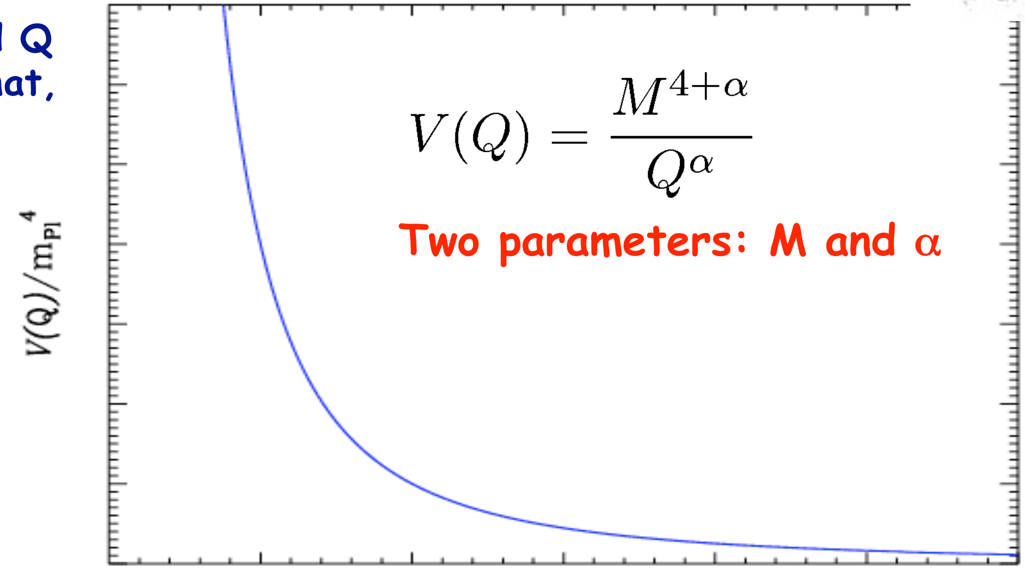
There exists a particular solution to this non-linear equation such that

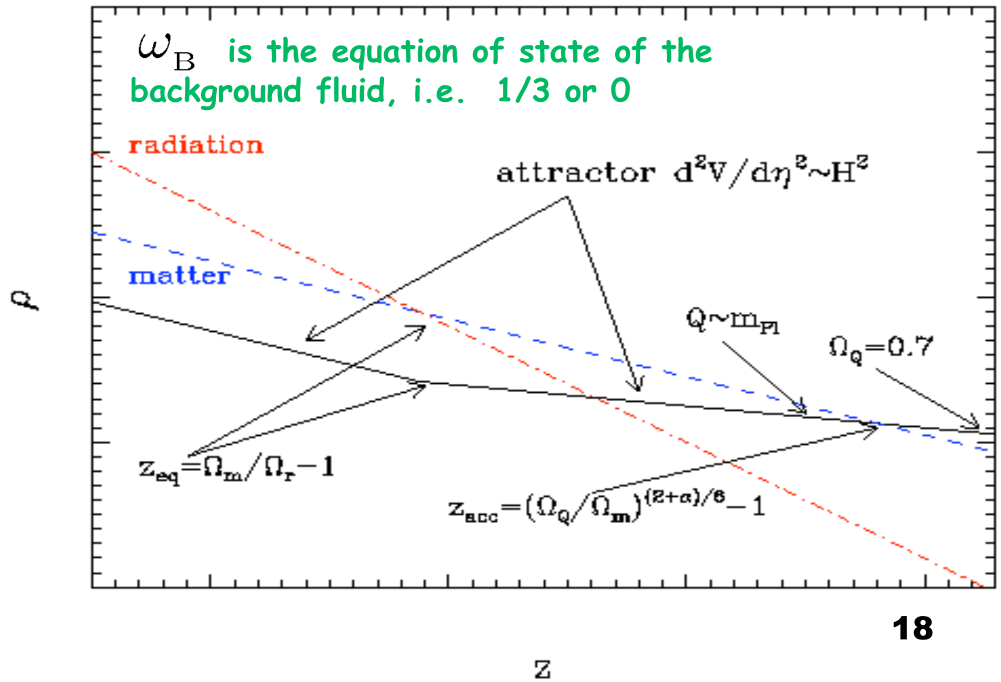
$$Q(t) = C(\alpha, \omega_B, M)t^{[4-\alpha(3\omega_B+1)]/(4+2\alpha)}$$

$$\rho_Q \propto a^{-3(1+\omega_Q)}, \ \omega_Q = \frac{-2+\alpha\omega_B}{2+\alpha}$$

-The field tracks the background ie it adapts its behaviour to the background fluid

- It scales less rapidly than the background fluid and will eventually dominate





Of course, when the field starts dominating the matter content of the Universe, the previous particular solution is no longer valid. This happens when

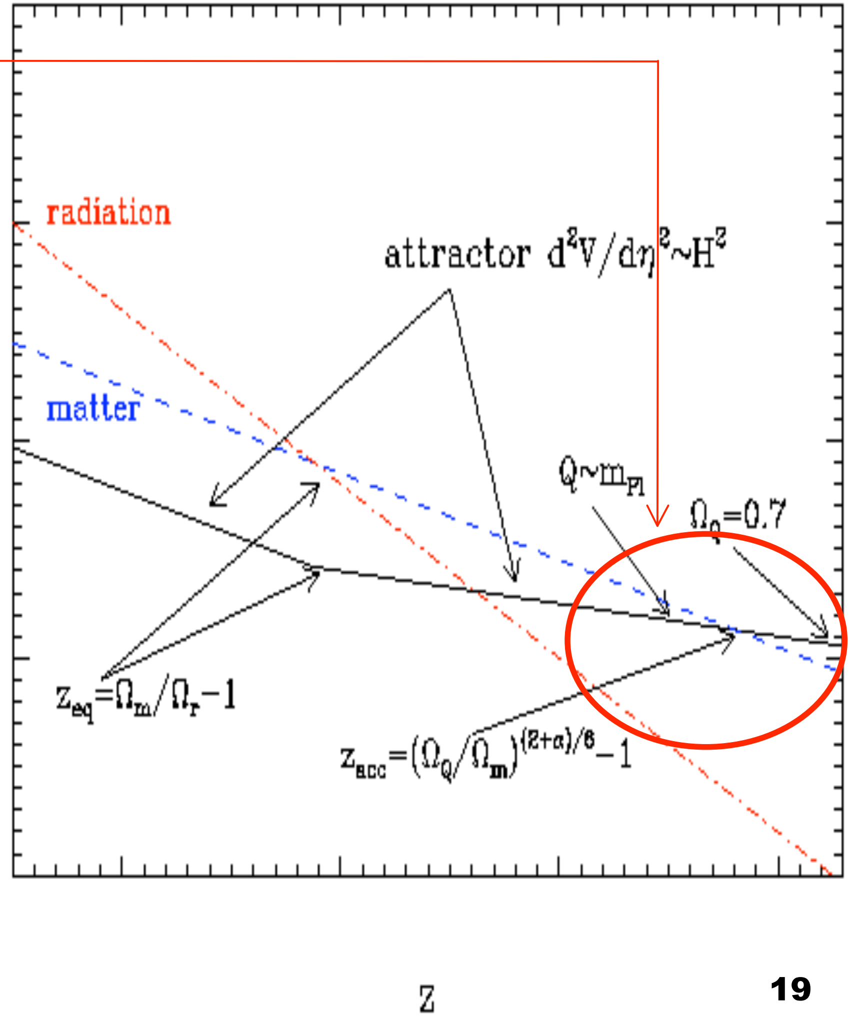
$$z_{\rm Q} = \left(\frac{\Omega_{\rm Q}}{\Omega_{\rm mat}}\right)^{(\alpha+2)/6} - 1 \simeq \mathcal{O}(1)$$

When does it happen? On the attractor, one has

$$\frac{\mathrm{d}^2 V(Q)}{\mathrm{d}Q^2} = \frac{9}{2}\frac{\alpha+1}{\alpha}\left(1-\omega_{\rm Q}^2\right)H^2$$

$$\sim \frac{\rho_{\rm Q}}{Q^2} \qquad\qquad \sim \frac{\rho_{\rm Q}}{m_{\rm Pl}^2}$$

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

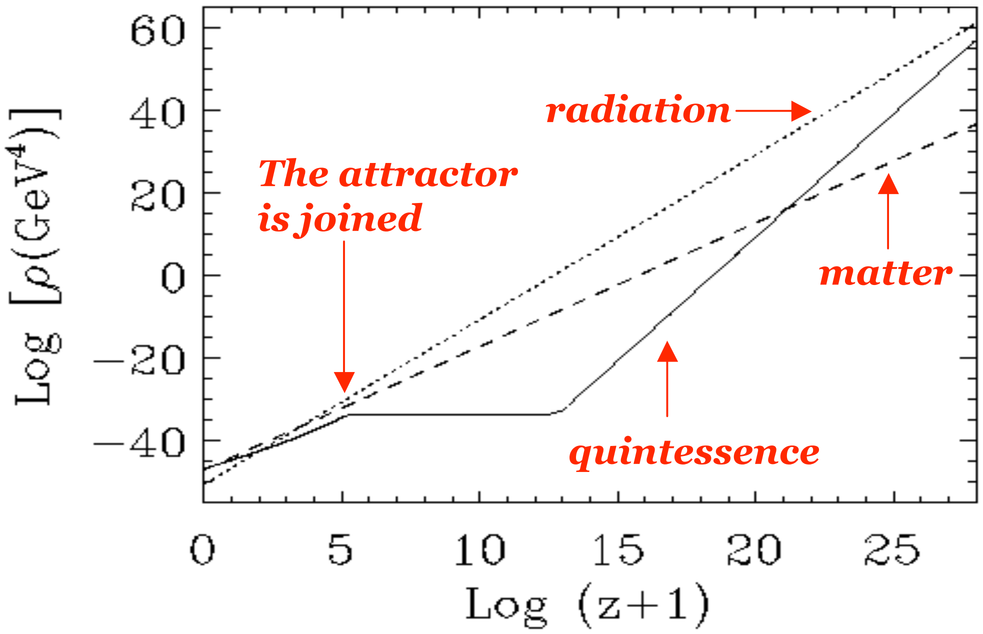


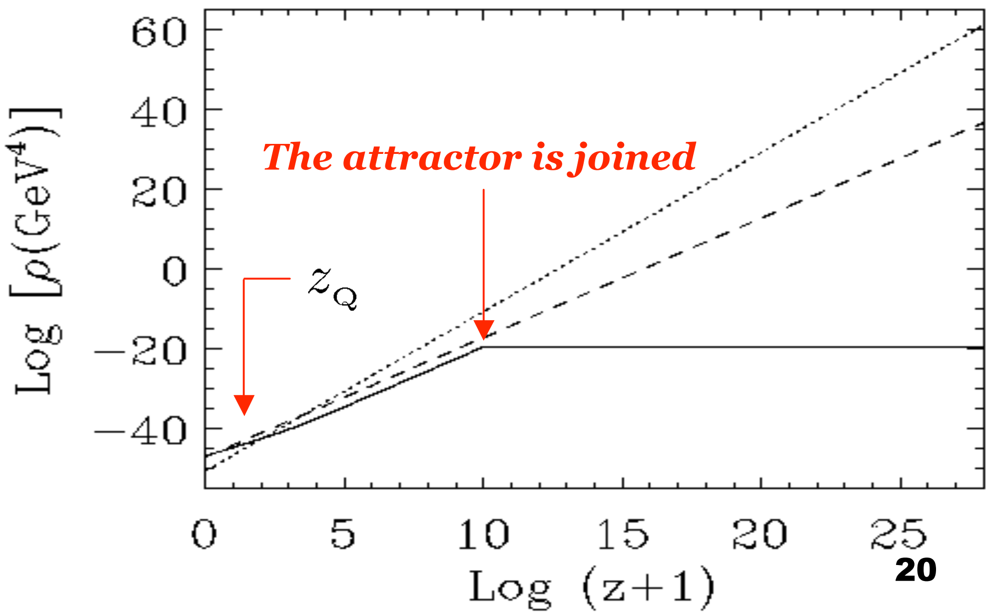
… But why is a particular solution interesting?

The particular solution is an attractor and is joined for a huge range of initial conditions

$$10^{-37}\mathrm{GeV}^4 < \rho_Q < 10^{61}\mathrm{GeV}^4$$

This is called a « tracker field » and can also be obtained for other form of the potential



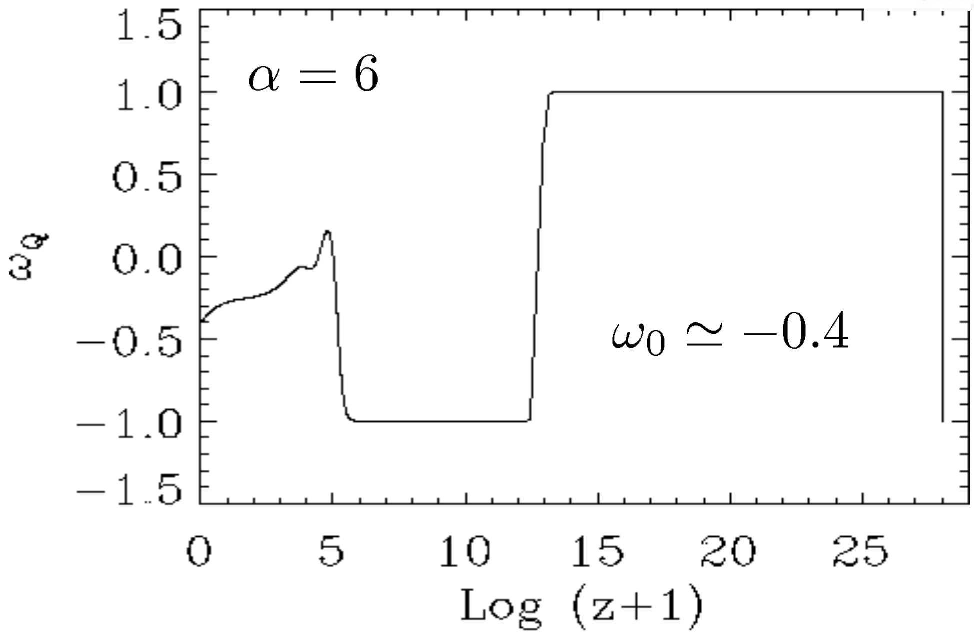


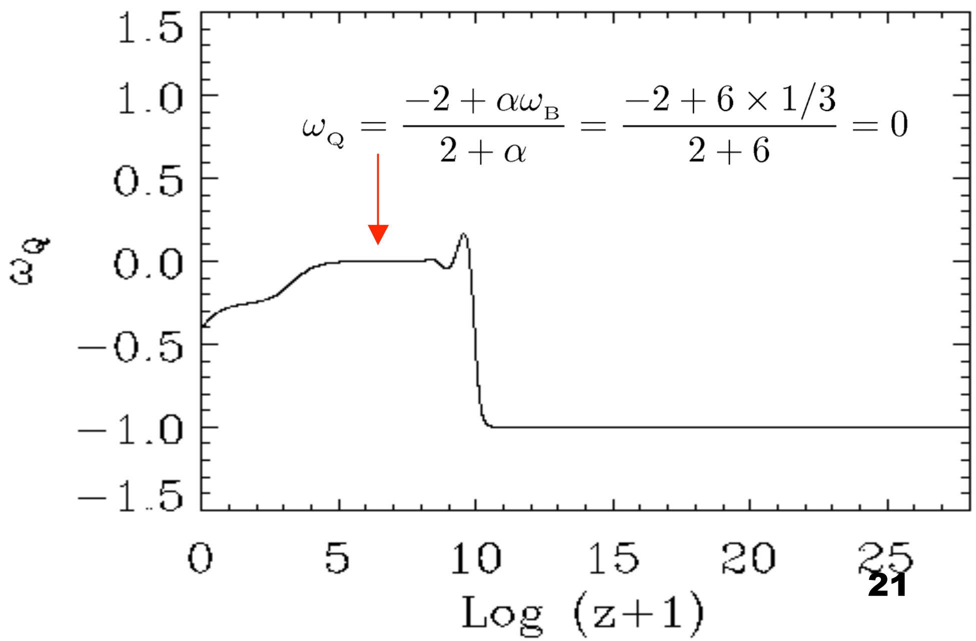
- The equation of state is a time-dependent (or redshift-dependent) quantity

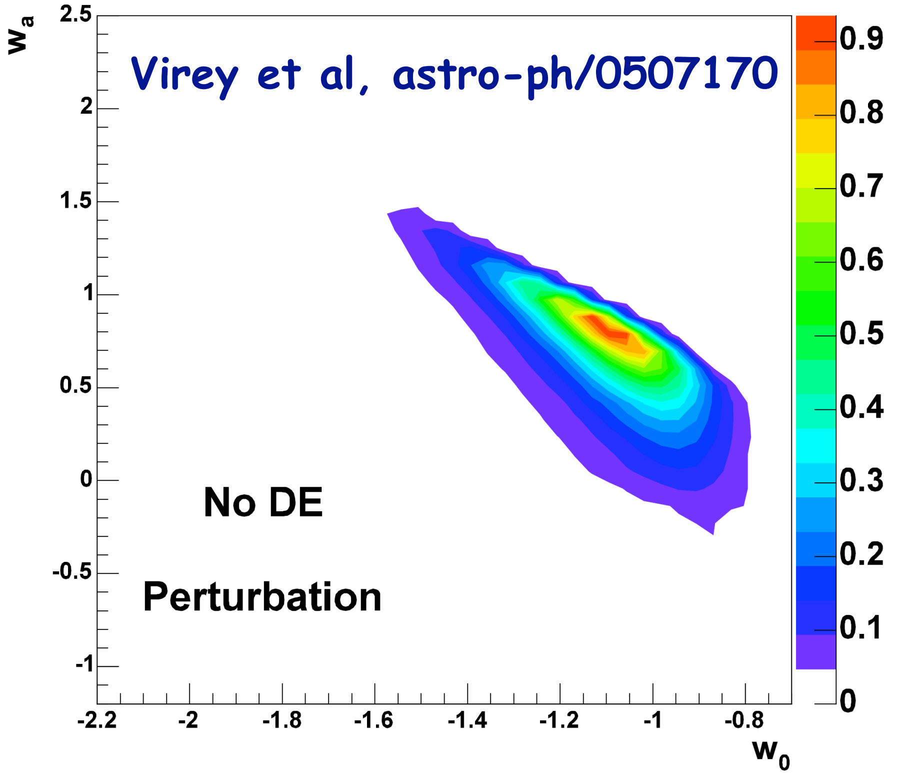
$$\omega_Q = \frac{\dot{Q}^2/2 - V(Q)}{\dot{Q}^2/2 + V(Q)} = \omega_0 + \omega_1 z + \cdots$$

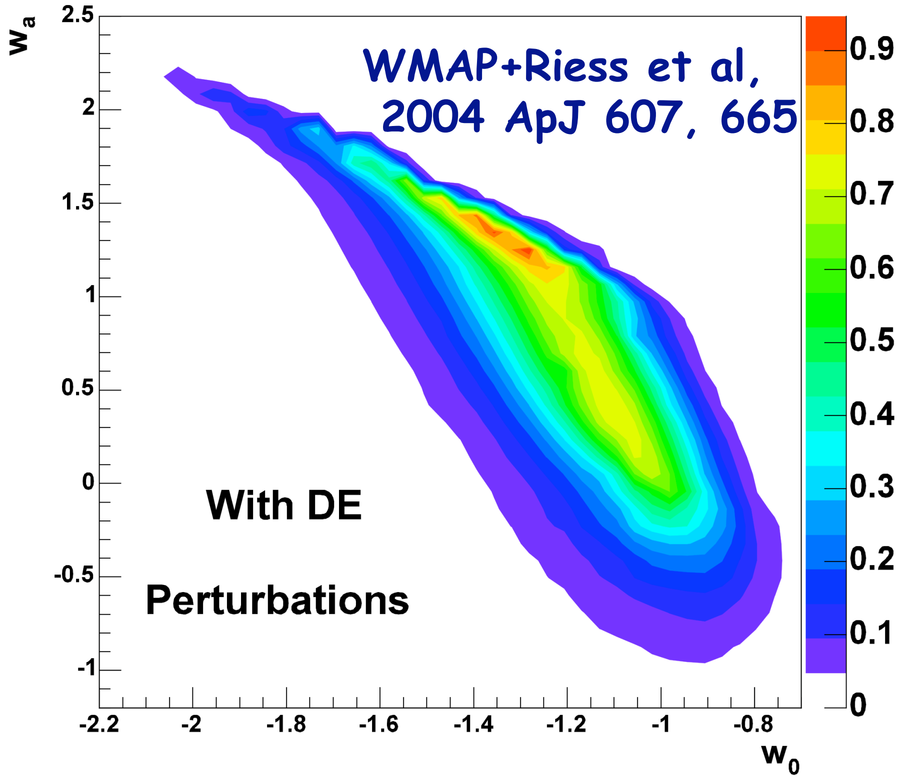
- The present value is negative and different from -1. Hence it can be distinguished from a cosmological constant

- Of course, the present value of the equation of state is also independent from the initial conditions









$$\omega(z) = \omega_0 + \omega_a(1-a) = \omega_0 + \omega_a \frac{z}{1+z}$$

Is it reliable? Caution!

- Flat fiducial models with

$$\omega(z) = \omega_0^{\rm F} + \omega_1^{\rm F} z$$

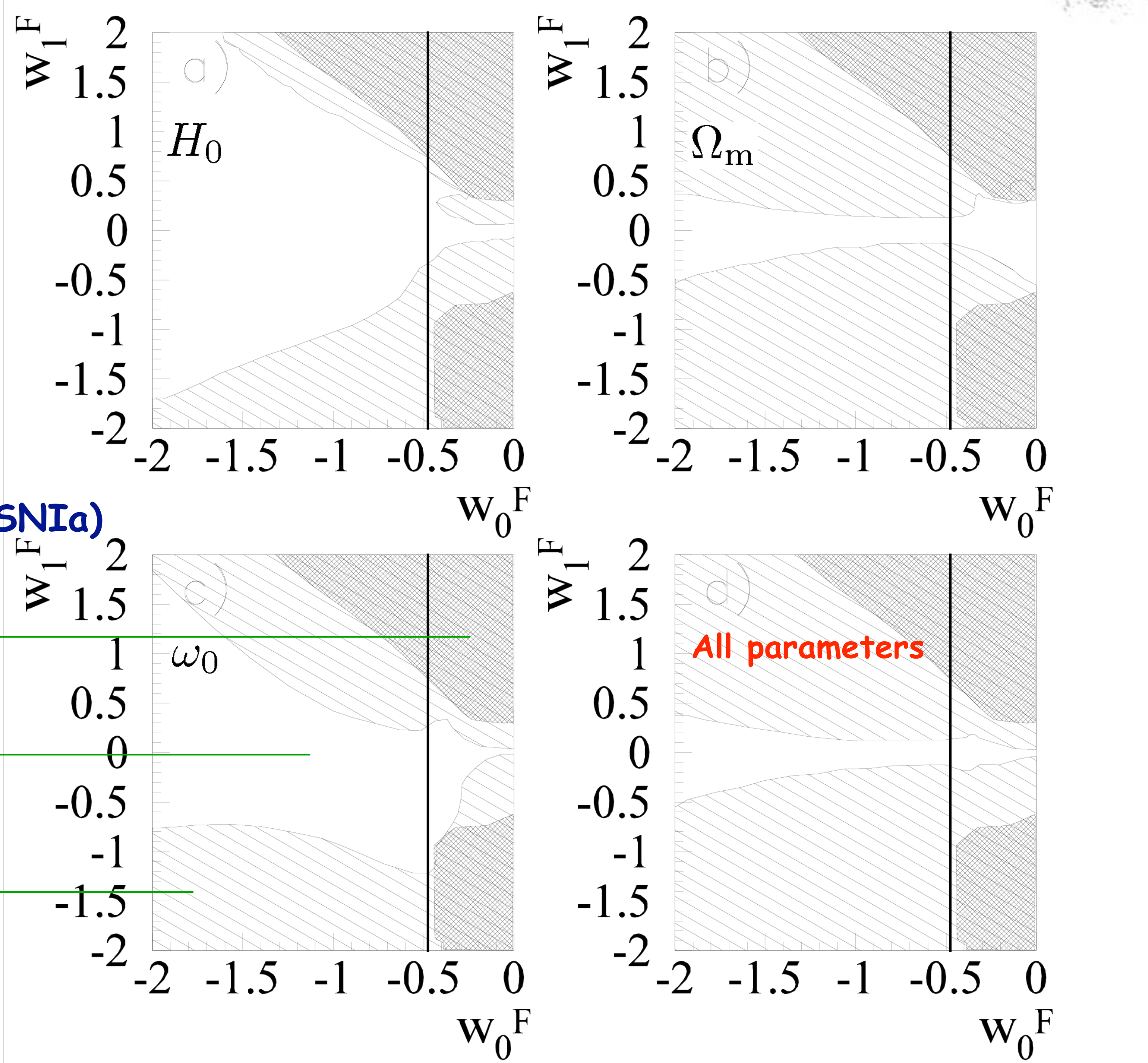
- 3-fit: H_0 , $\Omega_{\rm m}$, ω_0

- SNAP like data (~2000 SNIa)

Non-converging zone

Validity zone

Biaised zone

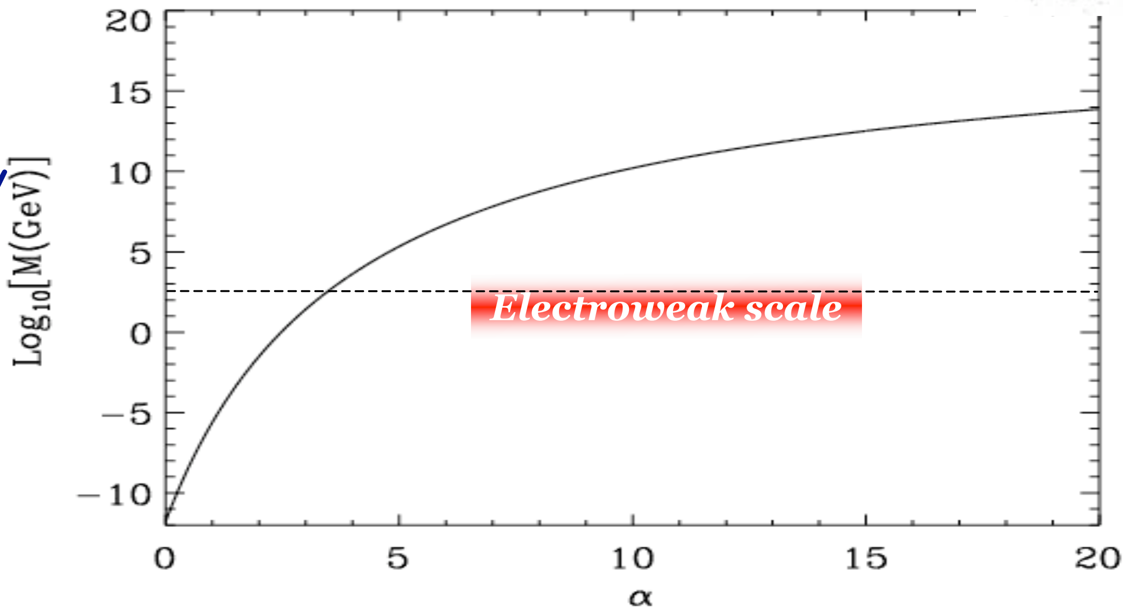


Virey JM et al, astro-ph/0403285

- 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

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

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



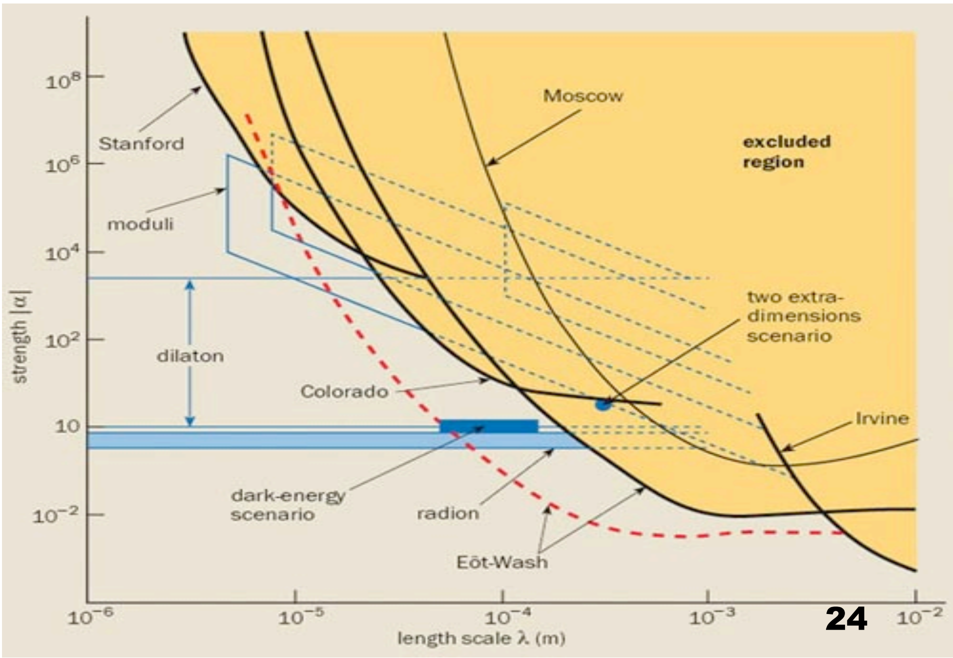
- The mass of the field is tiny

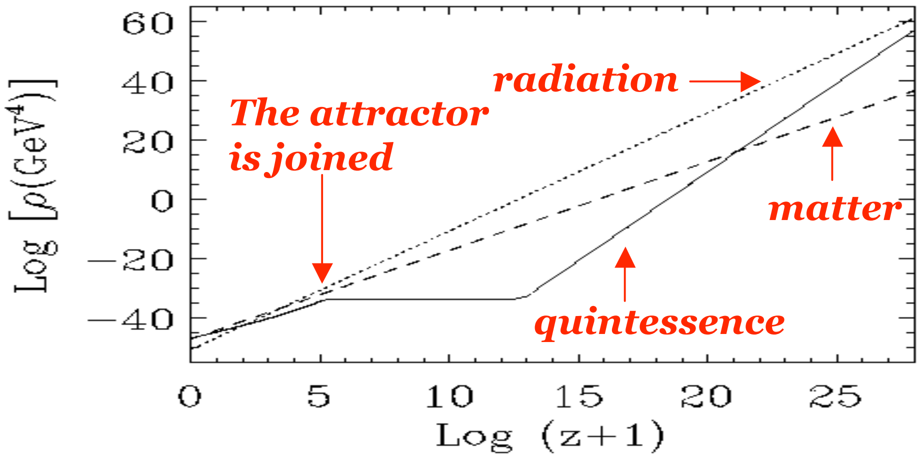
$$m_Q^2 = V'' = \frac{\rho_{\rm cri}}{m_{\rm Pl}^2} \sim \left(10^{-33}{\rm eV}\right)^2$$

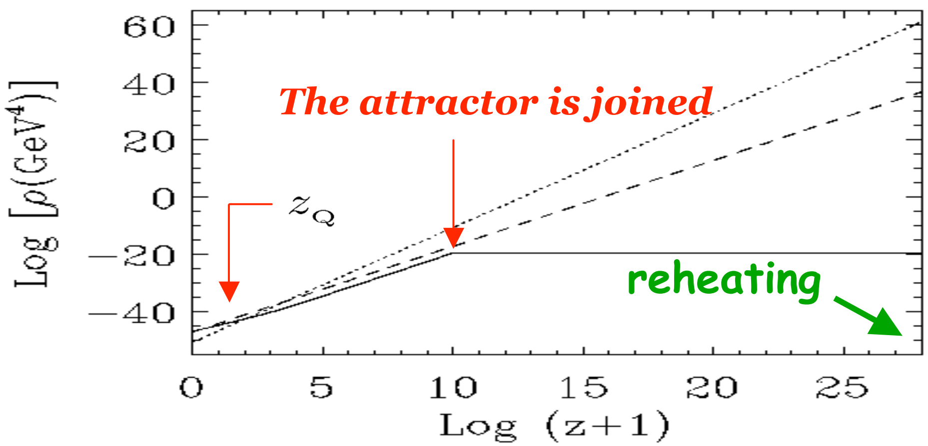
ie very long range force: danger because already well constrained by various experiments

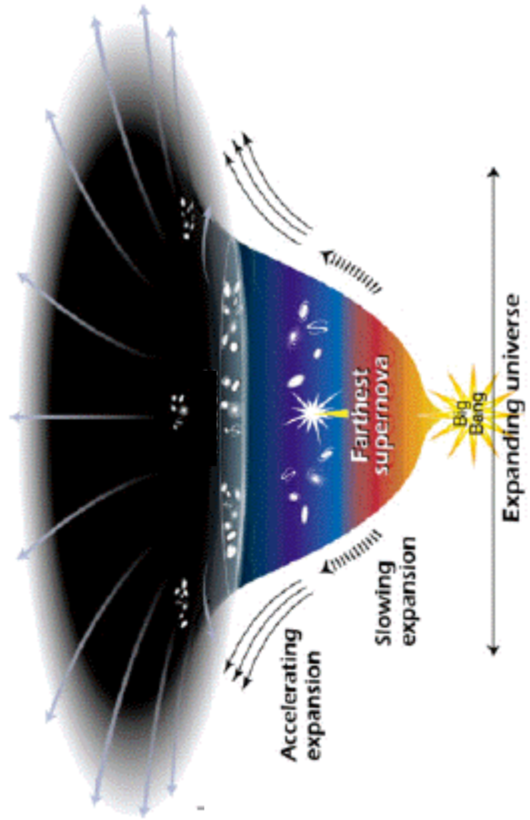
- … but the vev is huge

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









Inflation

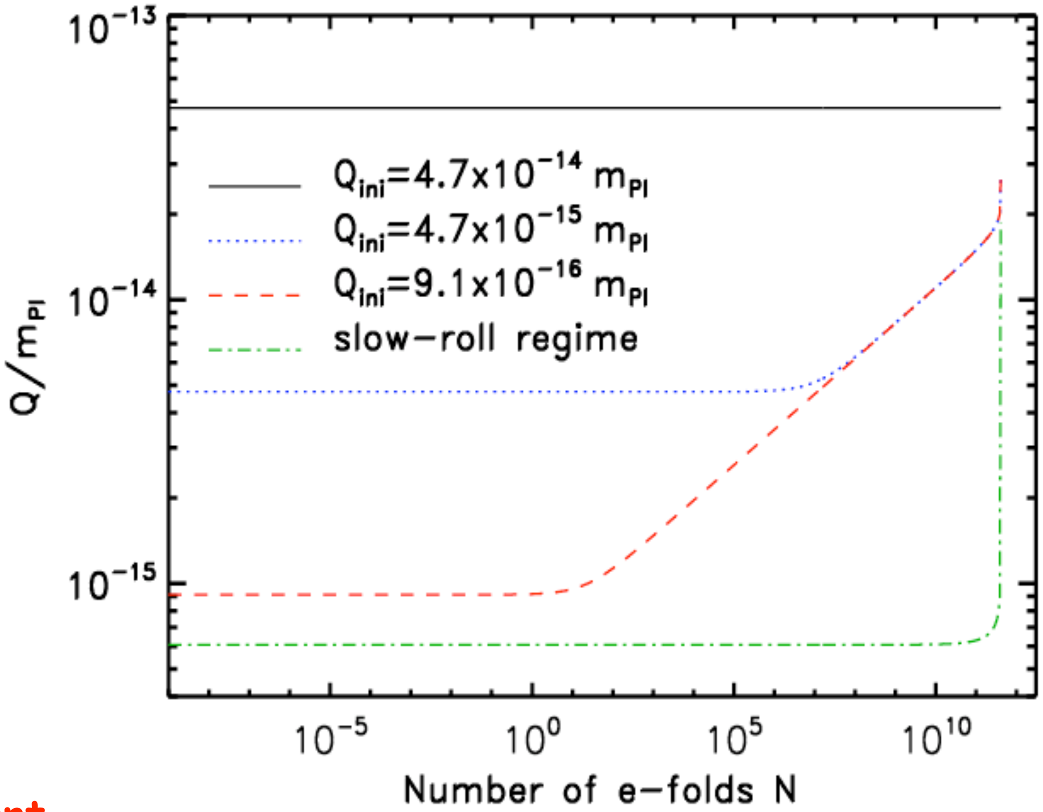
$$10^{-37}\mathrm{GeV}^4 < \rho_Q < 10^{61}\mathrm{GeV}^4$$

$$10^{-107/\alpha} < \frac{Q}{m_{\mathrm{Pl}}} < 10^{-9/\alpha}$$

- Do we have initial conditions (final conditions from the point of view of inflation) that are compatible with the attractor?

- What are the initial conditions for the quintessence field at the beginning of inflation?

Test Quintessence field in a background the evolution of which is controlled by chaotic inflation

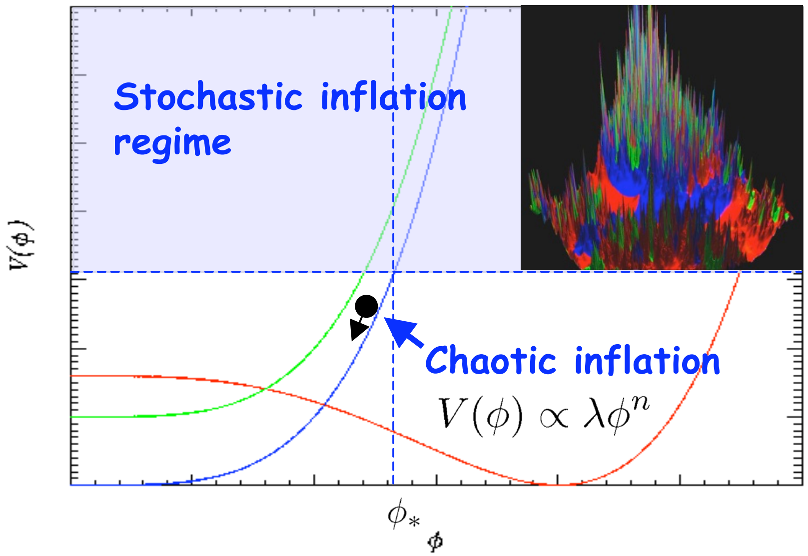


Typically, the quintessence field is frozen during inflation

However …

- Stochastic effects are important

- From high energy considerations, the inflaton and the quintessence field must interact

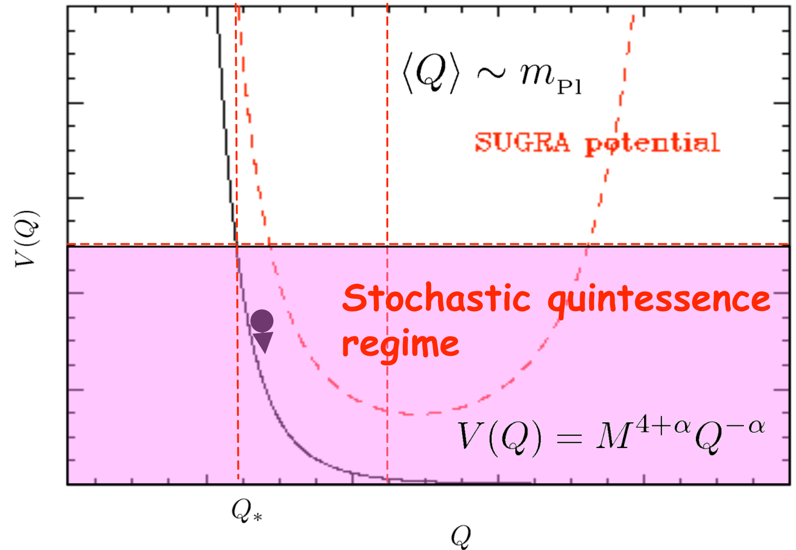


The field undergoes quantum jump H/2π every Hubble time

$$\Delta\phi_{\rm qu} \sim \frac{H}{2\pi}$$

$$\Delta\phi_{\rm cl} \sim -\frac{V_{,\phi}}{3H}\Delta t = -\frac{V_{,\phi}}{3H}\frac{1}{H}$$

$$\Delta\phi_{\rm qu} > \Delta\phi_{\rm cl} \Rightarrow \phi > \phi_* \sim \lambda^{-\frac{1}{n+2}}$$



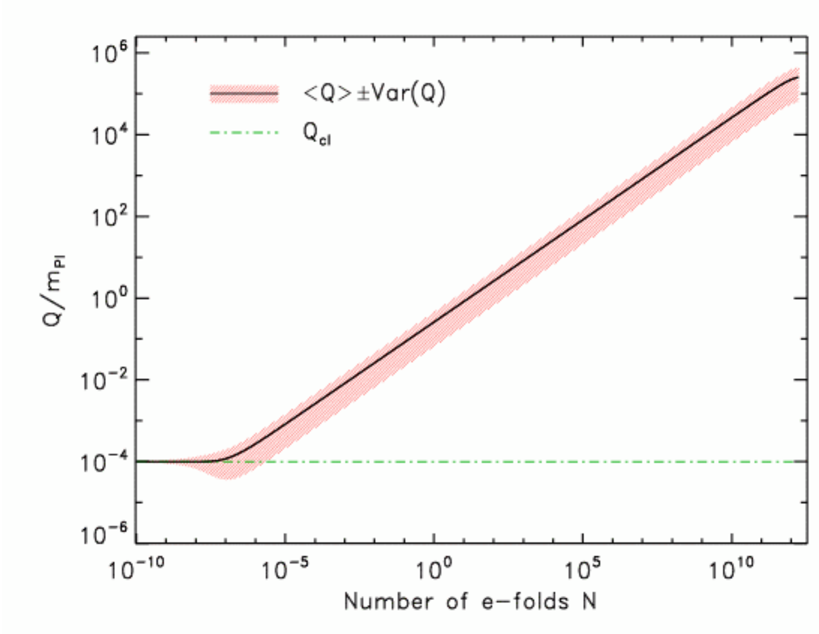
$$\Delta Q_{\rm qu} \sim \frac{H(\phi)}{2\pi}$$

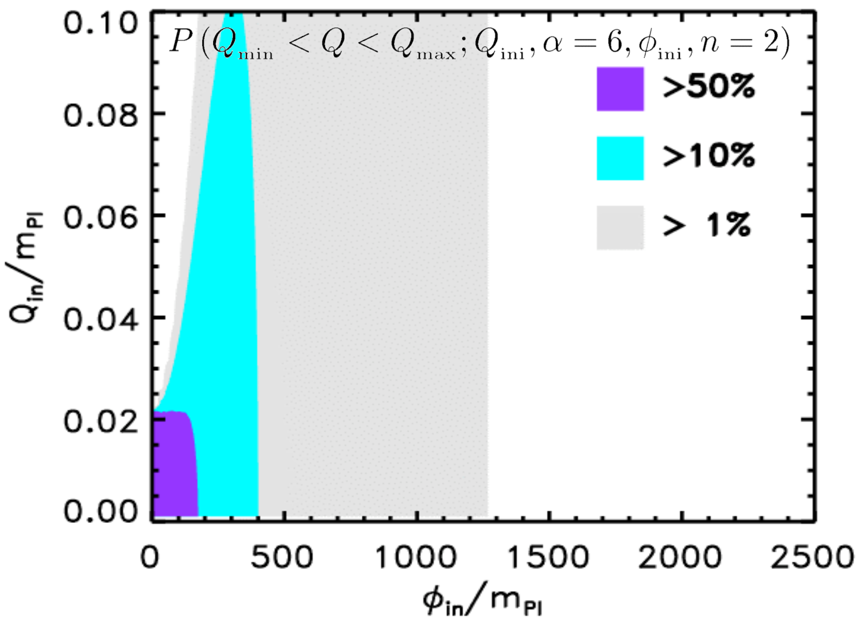
$$\Delta Q_{\rm cl} \sim -\frac{V_{,Q}}{3H(\phi)}\Delta t = -\frac{V_{,Q}}{3H(\phi)}\frac{1}{H(\phi)}$$

$$Q > Q_* \sim \left(\frac{M^{4+\alpha}}{H^3}\right)^{\frac{1}{\alpha+1}}$$

Quantum effects are important for quintessence!

M. Malquarti & A. Liddle (2002)
J. Martin & M. Musso (2004)





- The confidence region enlarges with the power index α

- A "small" number of total e-foldings is favored because otherwise the Quintessence field has too much time to drift away from the allowed range of initial conditions

J. Martin & M. Musso (2004)

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?

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

4- If the dark energy is just a field, it must 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?

Supergravity is the gauged version of super-symmetry, ie the infinitesimal susy transformations are made local

$$\delta\Phi = \sqrt{2}\xi^{\alpha}(x)\Psi_{\alpha}$$

One finds in the spectrum a graviton field (spin 2) and its supersymmetric partner, a field of spin 3/2, the gravitino

In the scalar sector, one finds that the Lagrangian can be written as

$$\mathcal{L}_{\rm SUGRA} = G_{A\bar{B}}\partial_{\mu}\Phi^{A}\partial^{\mu}\left(\Phi^{B}\right)^{\dagger} + \underbrace{\frac{1}{\kappa^{2}}{\rm e}^{G}\left(G^{\bar{A}B}G_{\bar{A}}G_{B} - 3\right)}_{\text{F-term}} + \underbrace{V_{\rm D}}_{\text{D-term}} + \cdots$$

$$G_{A\bar{B}} = \frac{\partial^{2}G}{\partial\Phi^{A}\partial\left(\Phi^{B}\right)^{\dagger}}$$

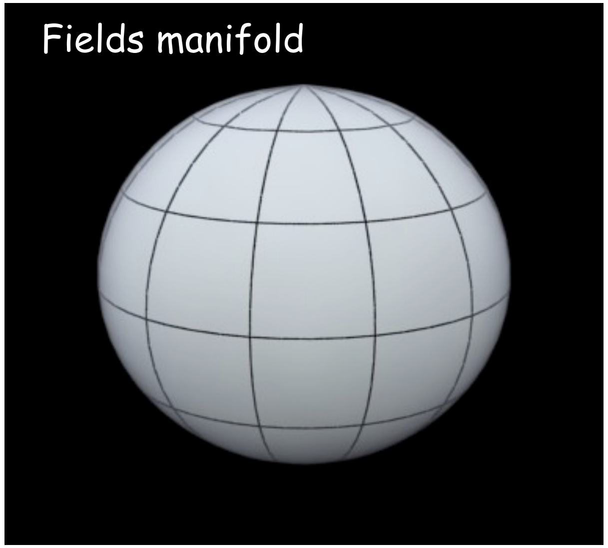
« Metric in fields space »

$$= \frac{\partial^{2}}{\partial\Phi^{A}\partial\left(\Phi^{B}\right)^{\dagger}}\left[\kappa K + \ln\left(\kappa^{3}|W|^{2}\right)\right]$$

$$= \frac{\partial^{2}\left(\kappa K\right)}{\partial\Phi^{A}\partial\left(\Phi^{B}\right)^{\dagger}}$$

Kahler potential (K)

Super-potential (W)



The SUGRA potential is no longer positive definite!

The link between the SUGRA and the global susy frameworks can be sketched as

- SUGRA = SUSY$+\mathcal{O}\left(\frac{\Phi}{m_{\rm Pl}}\right)$

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

P. Brax & J. Martin (1999)

The quintessence model building issue must be addressed in the SUGRA framework

So let us try to construct the supergravity version of the Ratra-Peebles potential. One needs to specify the Kahler and super potential. A relatively general Taylor expansion leads to

$$K_{\rm Quint} = XX^\dagger + QQ^\dagger + YY^\dagger \left[\epsilon_1 + \frac{\left(QQ^\dagger\right)^q}{m_{\rm C}^{2q}}\right] + \epsilon_2 \frac{\left(YY^\dagger\right)^p}{m_{\rm C}^{2p-2}} \mathcal{K}\left(\frac{QQ^\dagger}{m_{\rm C}^2}, \frac{XX^\dagger}{m_{\rm C}^2}\right) + \epsilon_3 \frac{\left(XX^\dagger\right)^m \left(QQ^\dagger\right)^n}{m_{\rm C}^{2m+2n-2}} + \cdots$$

Mass scale: cut-off of the effective theory used

$$W_{\rm Quint} = \lambda X^2 Y$$ (can be justified if the charges of X, Y and Q under U(1) are 1, -2 and 0)

$$\langle Y \rangle = 0 \Rightarrow \langle W_{\rm Quint} \rangle = 0$$

$$\langle X \rangle = \xi$$

Coupling constant

Furthermore, one requires that

$$\epsilon_1 = 0$$ no quadratic term in Y, p>1

$$\epsilon_3 = 0$$ no direct coupling between X and Q, otherwise the matrix is not diagonal

Straightfoward calculations (...!) lead to the following expression for the potential

$$V_{\rm Quint}(Q) = {\rm e}^{\kappa Q^2} \frac{M^{4+2q}}{Q^{2q}}$$

$$\begin{cases} M^{4+2q} = {\rm e}^{\kappa \xi^2} m_{\rm C}^{2q} \lambda^2 \xi^4 \\ \xi \simeq \frac{1}{\sqrt{\lambda}} \left(\frac{m_{\rm Pl}}{m_{\rm C}}\right)^{q/2} \rho_{\rm cri}^{1/4} \end{cases}$$

$$K_{\rm Quint} = XX^\dagger + QQ^\dagger + YY^\dagger \left[\epsilon_1 + \frac{(QQ^\dagger)^q}{m_{\rm C}^{2q}}\right] + \epsilon_2 \frac{(YY^\dagger)^p}{m_{\rm C}^{2p-2}} \mathcal{K}\left(\frac{QQ^\dagger}{m_{\rm C}^2}, \frac{XX^\dagger}{m_{\rm C}^2}\right)$$

SUGRA corrections $\kappa Q^2 \sim \frac{Q^2}{m_{\rm Pl}^2} = \mathcal{O}(1)$

One does not recover exactly the Ratra-Peebles potential

In particular, one can determine the mass scale of the potential in terms of the microscopic parameters

$$M^{4+2q} = e^{\kappa \xi^2} m_{\rm C}^{2q} \lambda^2 \xi^4$$

With this simple model, one can see that the scenario has important problems

$$\lambda \sim 1\,,\; m_{\rm C} = 10^{15}\,{\rm GeV} < m_{\rm Pl}\,,\; q \sim 7 \Rightarrow \;\xi > 10^2\,{\rm GeV}$$

… But how to control terms like $\displaystyle\sum_n^{\infty} \frac{(QQ^\dagger)^n}{m_{\rm C}^{2n}}$ with $\langle Q \rangle \sim m_{\rm Pl}$

$$\lambda \sim 1\,,\;\; m_{\rm C} = m_{\rm Pl} \;\Rightarrow \xi \simeq 10^{-23.5}\,{\rm GeV} \simeq 10^{-30} m_{\rm Pl}$$

… But, in some sense, the fine-tuning problem reappears …

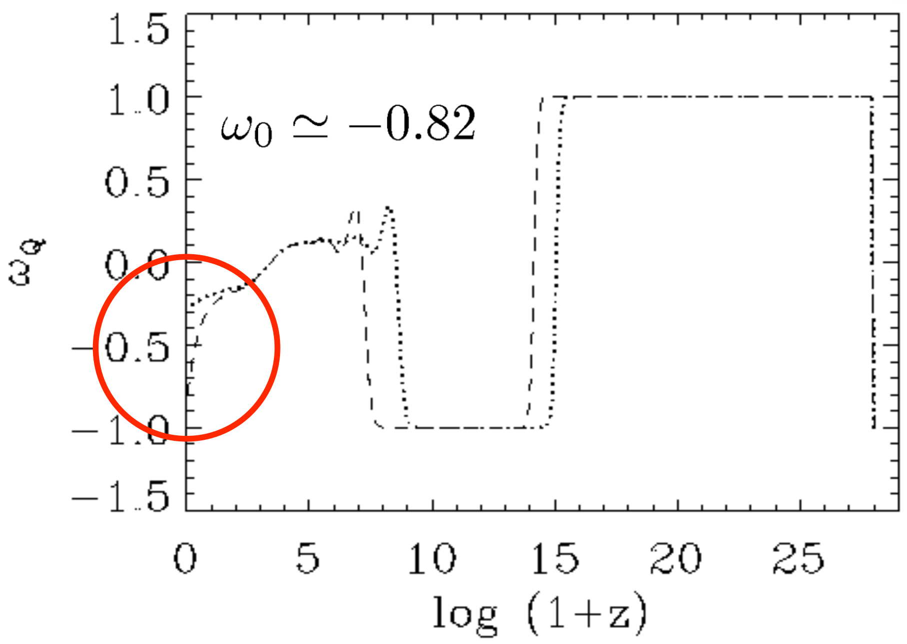
What are the effects of the SUGRA corrections?

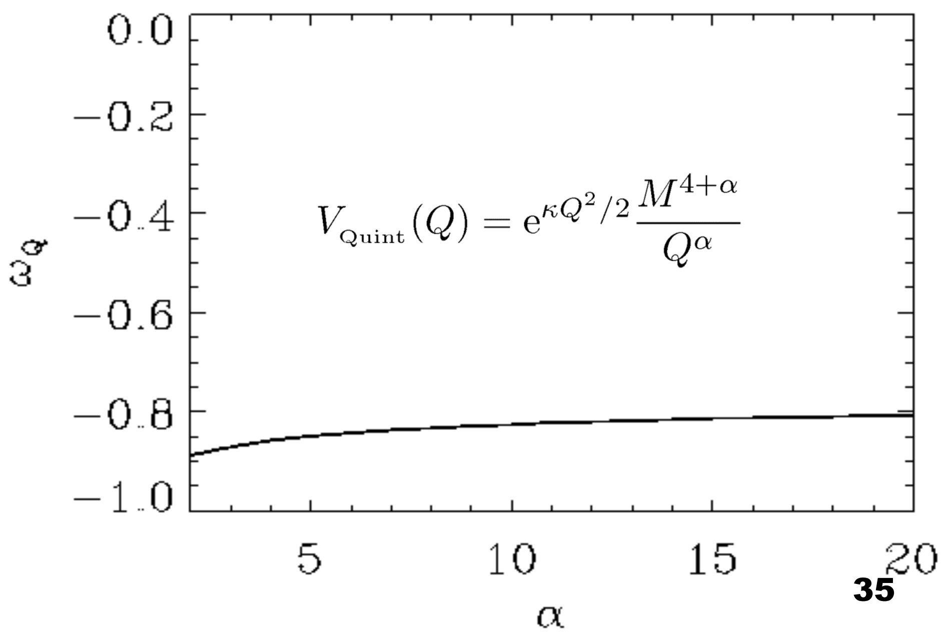
1- The attractor solution still exists since, for large redshifts, the vev of Q is small in comparison with the Planck mass

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



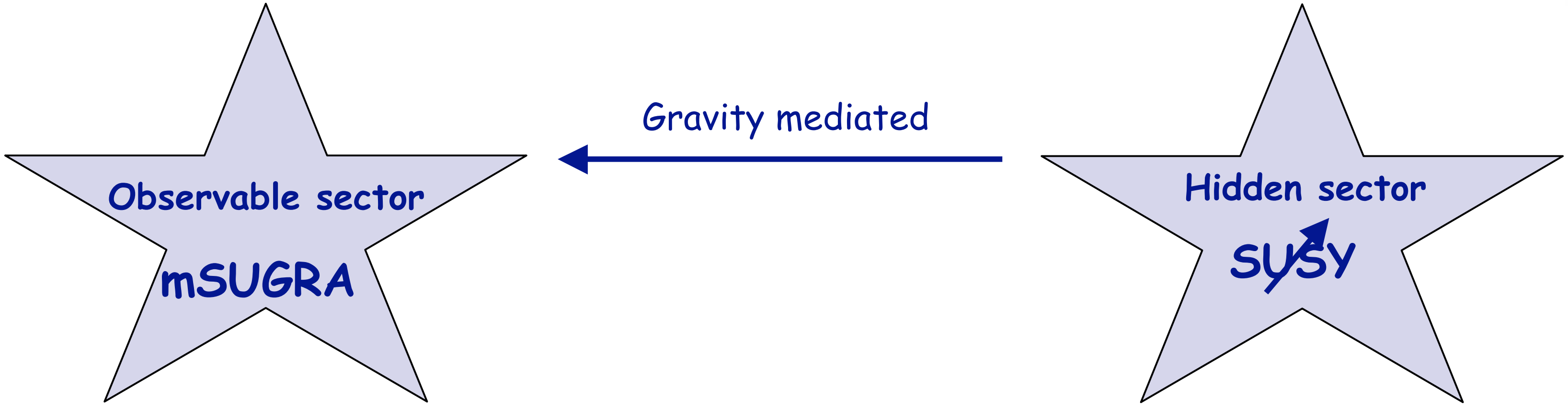


- So far, we have treated the quintessence field as isolated from the rest of the world.

- This is clearly not very realistic!

- What are the properties of this interaction, its strength etc …??

- The problem is not easy technically because we must adress it in the framework of SUGRA (cf before)



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

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

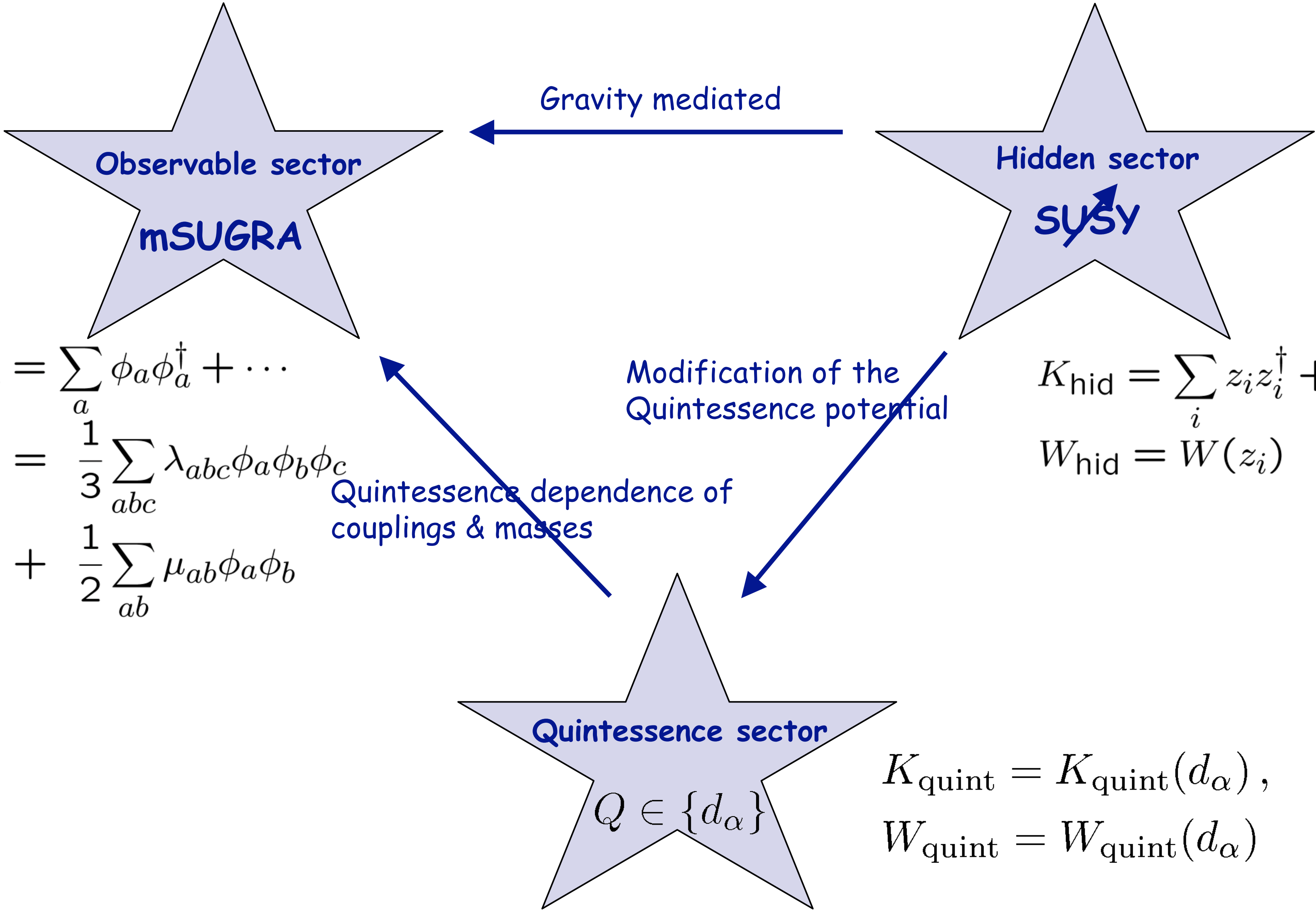
where the standard fields live: electrons, quarks, dark matter etc ...

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

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

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

Usual structure of the standard model: two sectors



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

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

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

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

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

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

The presence of dark energy will affect the Electroweak transition. In the mSUGRA model, one has

- There are two Higgs doublet instead of one

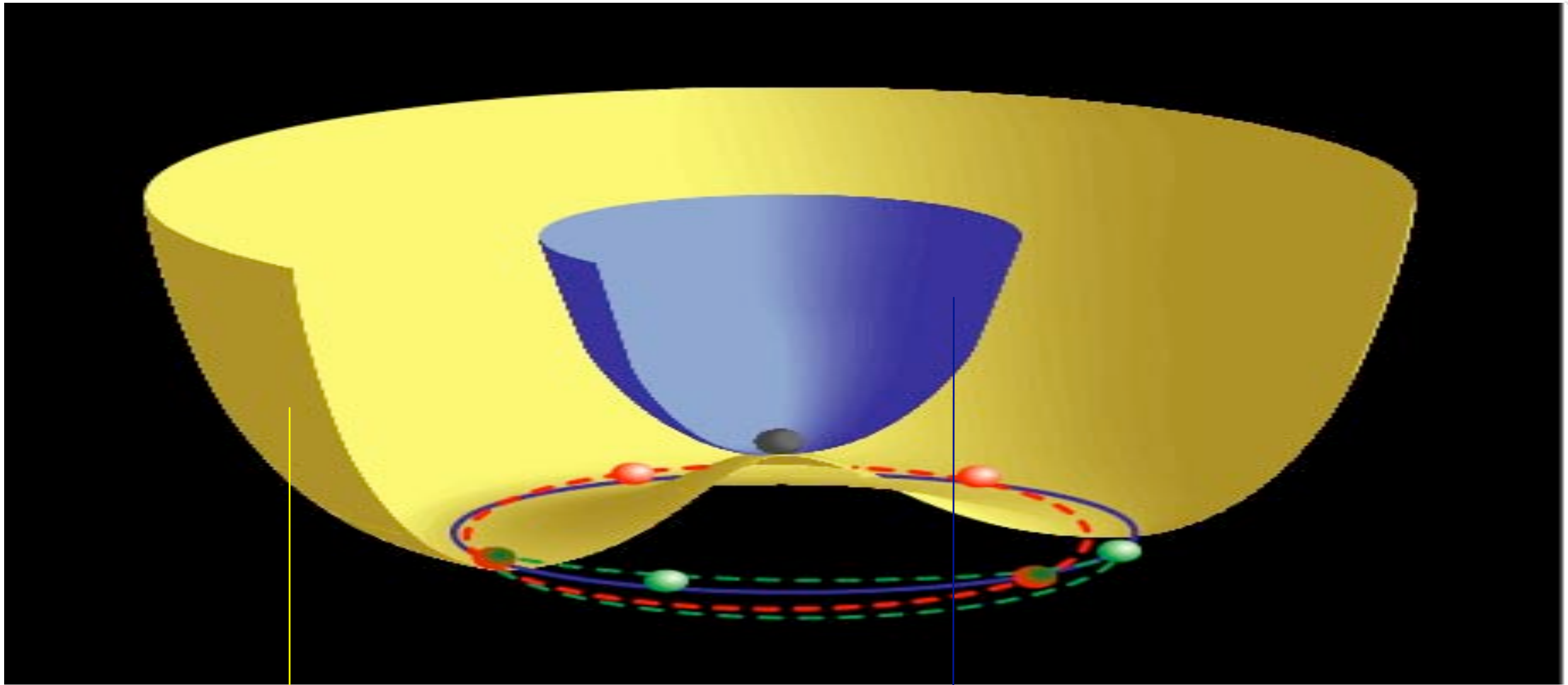
- The EW transition is intimately linked to the breaking of SUSY

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

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

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

Soft terms



With the soft terms

without the soft terms

Then, the particles acquire mass when the Higgs acquire a non-vanishing vev. One gets two "types" of particle

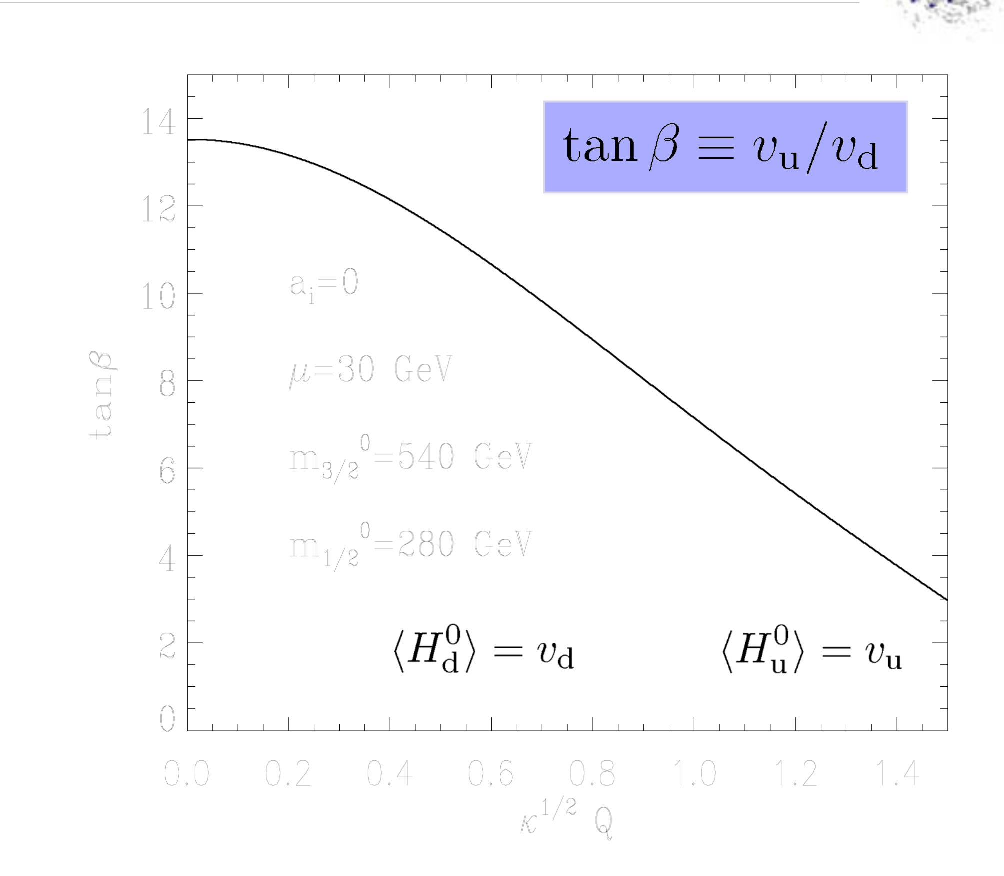
$$\begin{cases} m_{\rm u} = \lambda_{\rm u} \langle H_{\rm u}^0 \rangle \\ m_{\rm d} = \lambda_{\rm d} \langle H_{\rm d}^0 \rangle \end{cases}$$

In presence of dark energy, the vev's of the Higgs become Q-dependent

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

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

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



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.

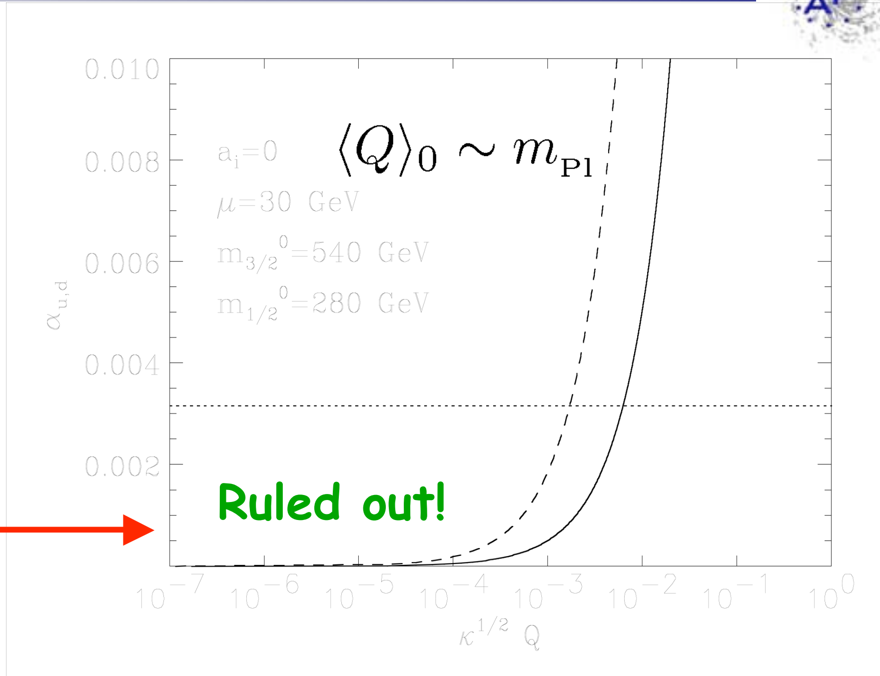
Derived from the SUGRA model+ mSUGRA

Consequences:

1- Presence of a fifth force

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

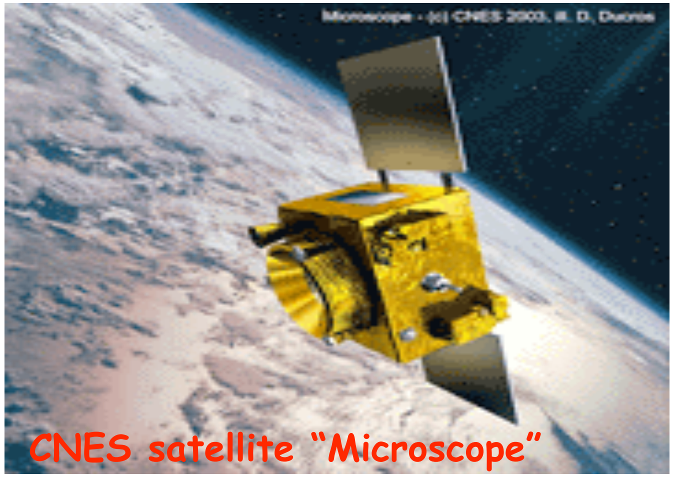
Example of the SUGRA model (no systematic exploration of the parameters space yet)



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



CNES satellite "Microscope"

3- Other possible effects

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

- The expansion of the Universe is accelerated. It is now a fact. The cosmological constant seems to be a natural candidate but it is difficult to understand its magnitude. Even SUSY cannot really help.

- Quintessence is a model of dark energy where a scalar field is supposed to be responsible for the accelerated expansion of the Universe. It has some nice properties like the ability to "solve" the coincidence problem. In addition, The Quintessence equation of state now is not -1 as for the cosmological constant and is red-shift dependent: this would be a clear observational signature.

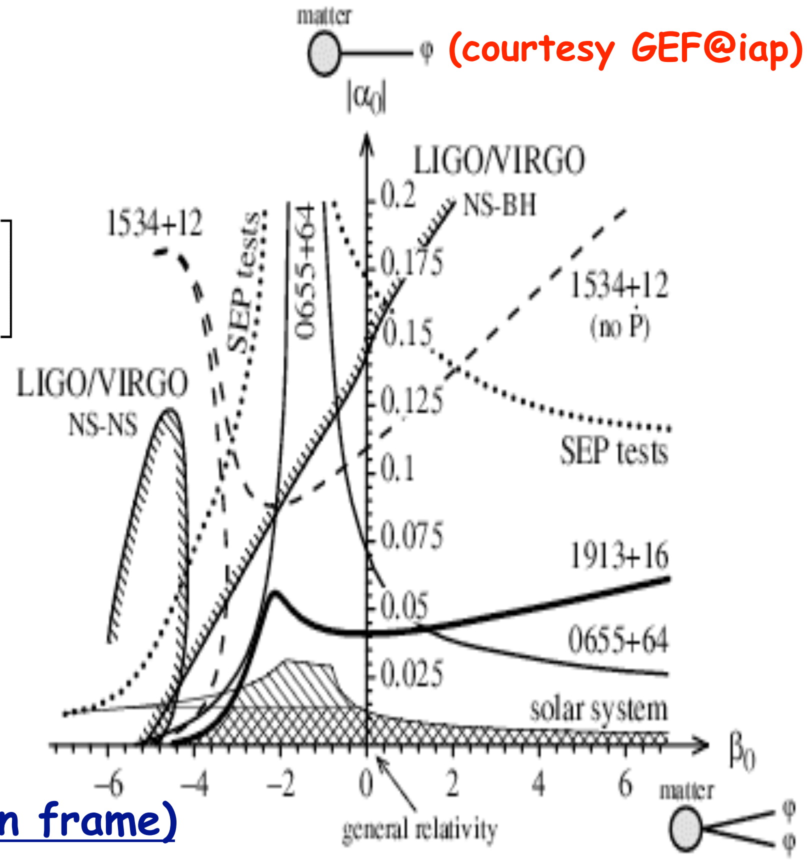
- However, implementing Quintessence in high energy physics is difficult and no fully satisfactory model exists at present.

- The interaction of Quintessence with the rest of the world is non trivial and can lead to interesting phenomena and/or constraints. Probing dark energy is not only measuring the equation of state … Local gravity tests in the solar system are also important.

Consider ϕ, a "matter" field (in fact it should be a fermion). Because of its coupling with the quintessence field, its mass can change

$$S_{\rm mat}[\phi] = -\frac{1}{2}\int {\rm d}^4x\sqrt{-g}\left[g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + m^2\left(\frac{Q}{M_{\rm Pl}}\right)\phi^2\right]$$

Variation of the mass



Through the redefinitions

$$\tilde{g}_{\mu\nu} = A^2 g_{\mu\nu}\,, \quad \tilde{\phi} = \frac{\phi}{A}\,, \quad m(Q) = \frac{A(Q)}{A(0)}$$

We obtain a scalar-tensor theory (in the Einstein frame)

$$S_{\rm mat}[\tilde{\phi}, A^2 g_{\mu\nu}] = -\frac{1}{2}\int {\rm d}^4x\sqrt{-\tilde{g}}\left[\tilde{g}^{\mu\nu}\partial_\mu\tilde{\phi}\partial_\nu\tilde{\phi} + m^2(0)\,\tilde{\phi}^2\right]$$

$$\alpha = \frac{{\rm d}\ln A}{{\rm d}Q}$$

$$\beta = \frac{{\rm d}\alpha}{{\rm d}Q}$$

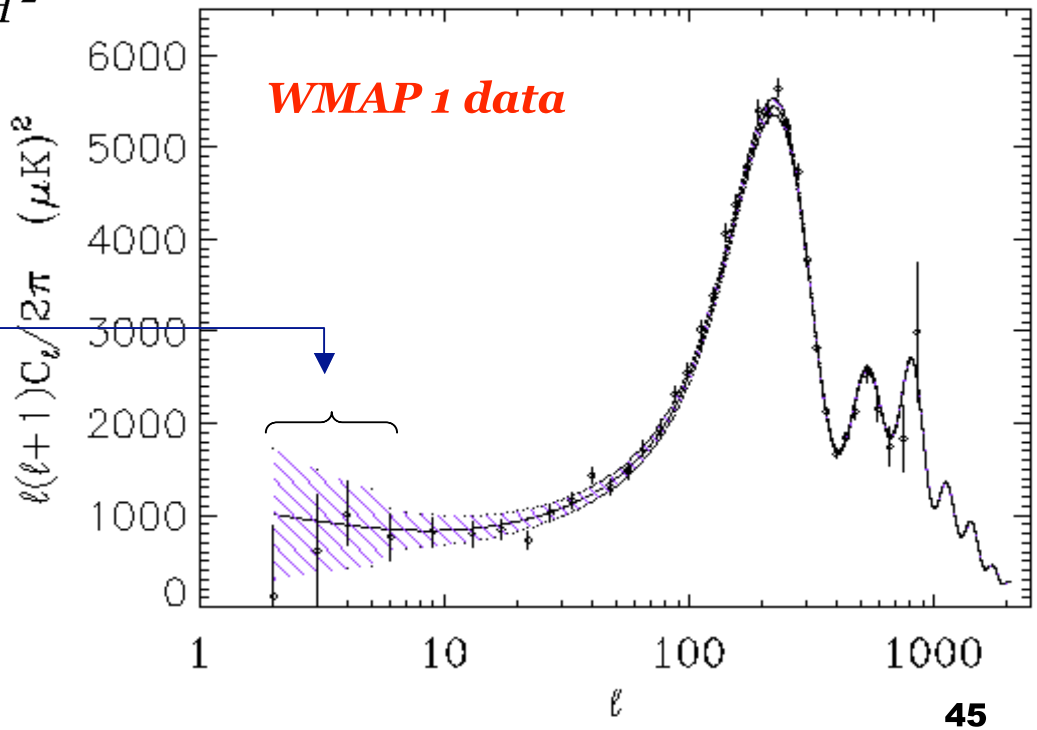
Constrained by solar system and/or pulsar tests

- The evolution of the small inhomogeneities is controlled by the perturbed Klein-Gordon equation

$$\delta Q''_{\mathbf{k}} + 2\frac{a'}{a}\delta Q'_{\mathbf{k}} + \left[k^2 + a^2\frac{\mathrm{d}^2V(Q)}{\mathrm{d}Q^2}\right]\delta Q_{\mathbf{k}} = -2a^2\frac{\mathrm{d}V}{\mathrm{d}Q}\Phi_{\mathbf{k}} + 4Q^2\Phi'_{\mathbf{k}}$$

$$\frac{\mathrm{d}^2V(Q)}{\mathrm{d}Q^2} = \frac{9}{2}\frac{\alpha+1}{\alpha}\left(1-\omega_{\mathrm{Q}}^2\right)H^2$$

$$\ell_{\mathrm{Jeans}} \sim H^{-1}$$



Clustering of quintessence only on scales of the order of the Hubble radius