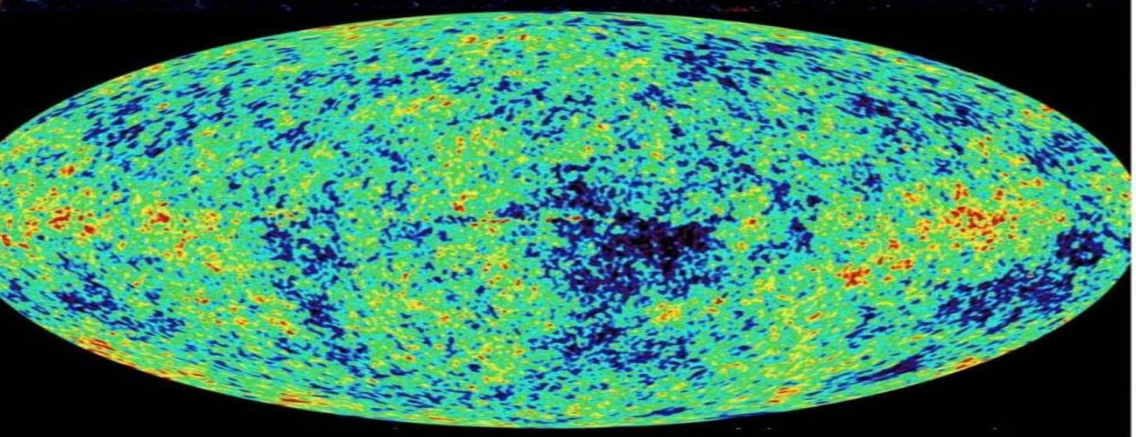
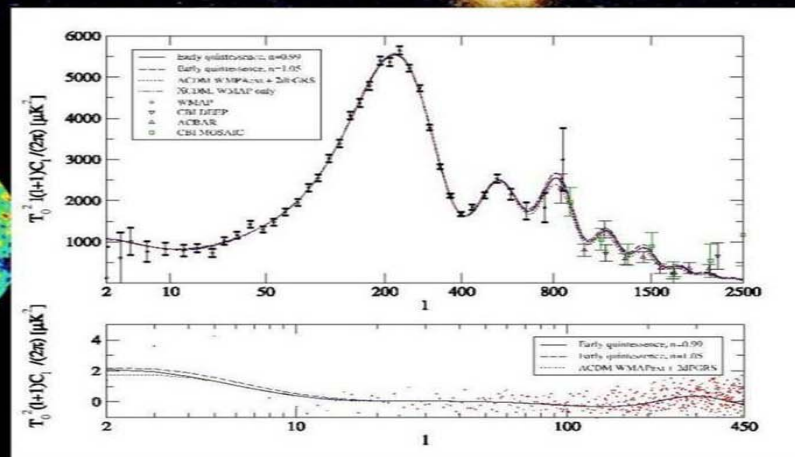
Quintessence-
a dynamical Dark Energy





Quintessence

C.Wetterich

A.Hebecker,M.Doran,M.Lilley,J.Schwindt,
C.Müller,G.Schäfer,E.Thommes,
R.Caldwell,M.Bartelmann,K.Karwan

What is our universe made of ?

Dark Energy dominates the Universe

Energy - density in the Universe

=

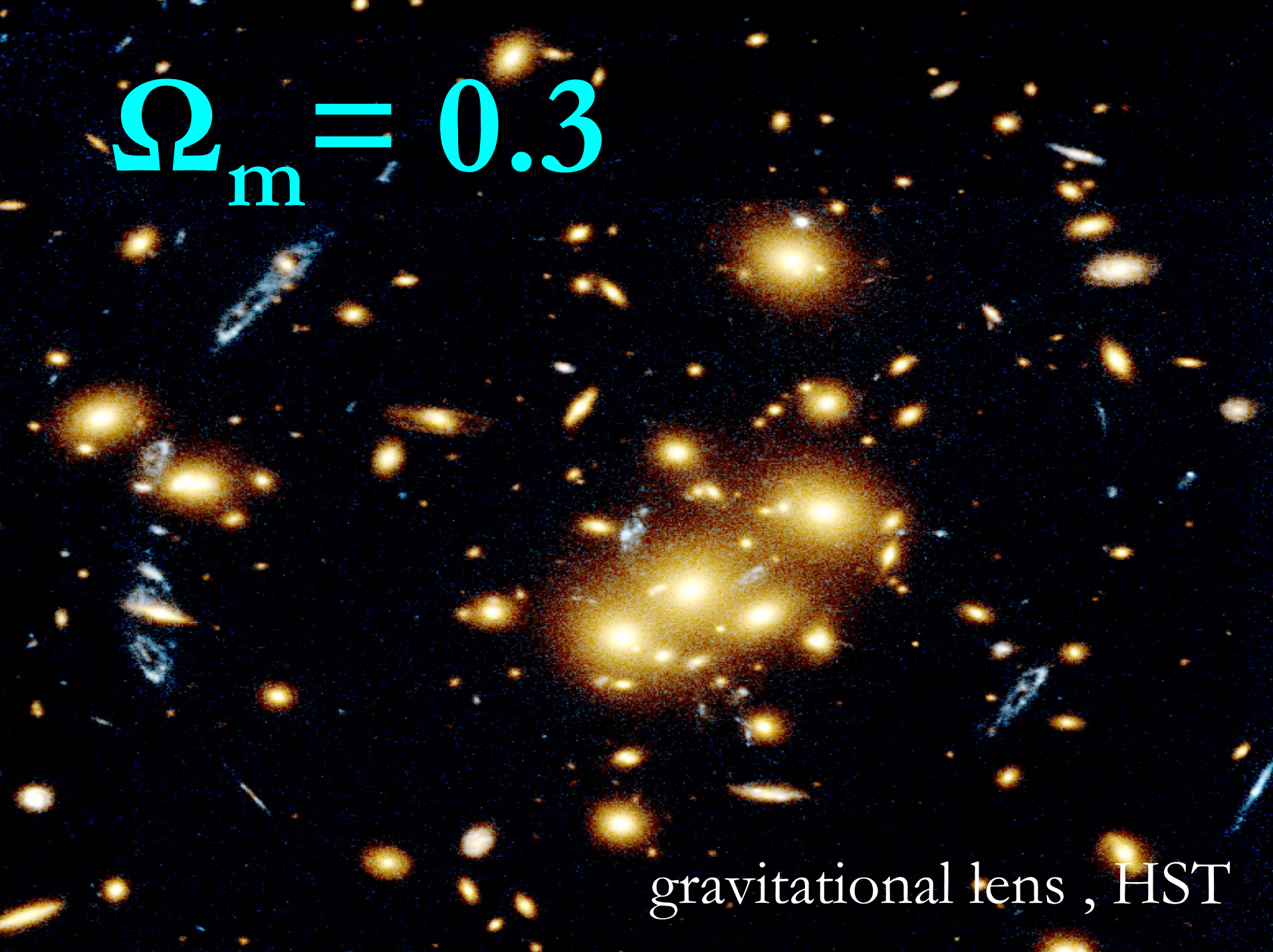
Matter + Dark Energy

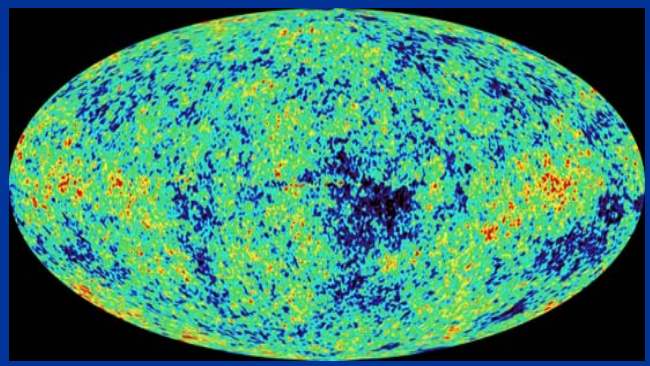
30 % + 70 %

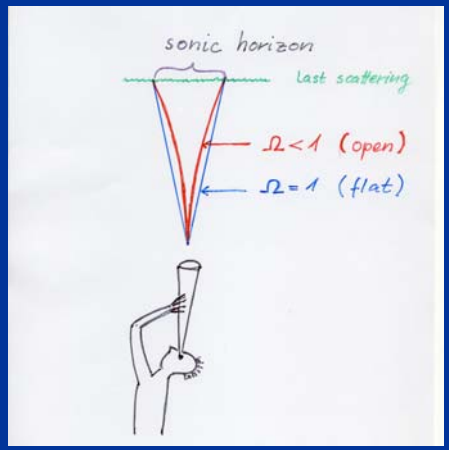
What is Dark Energy ?

Matter : Everything that clumps

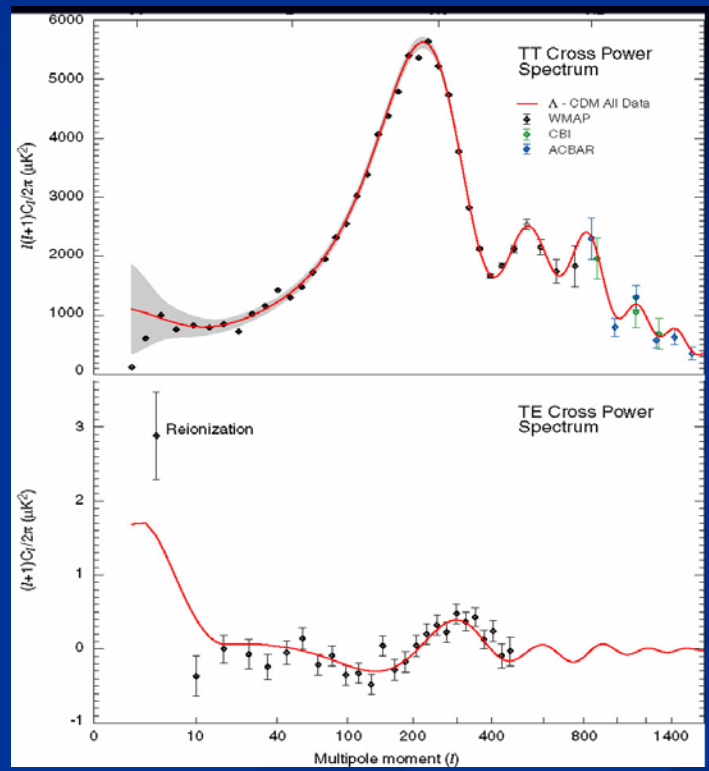
Abell 2255 Cluster
~300 Mpc


$\Omega_m = 0.3$
gravitational lens , HST





$\Omega_{tot}=1$



mean values

$\Omega_{tot}=1.02$

$\Omega_{m}=0.27$

$\Omega_{b}=0.045$

$\Omega_{dm}=0.225$

Dark Energy

$\Omega_m + X = 1$

Ω_m : 30%

Ω_h : 70% Dark Energy

h : homogenous , often Ω_Λ instead of Ω_h

Space between clumps is not empty :

Dark Energy !

Dark Energy density is the same at every point of space

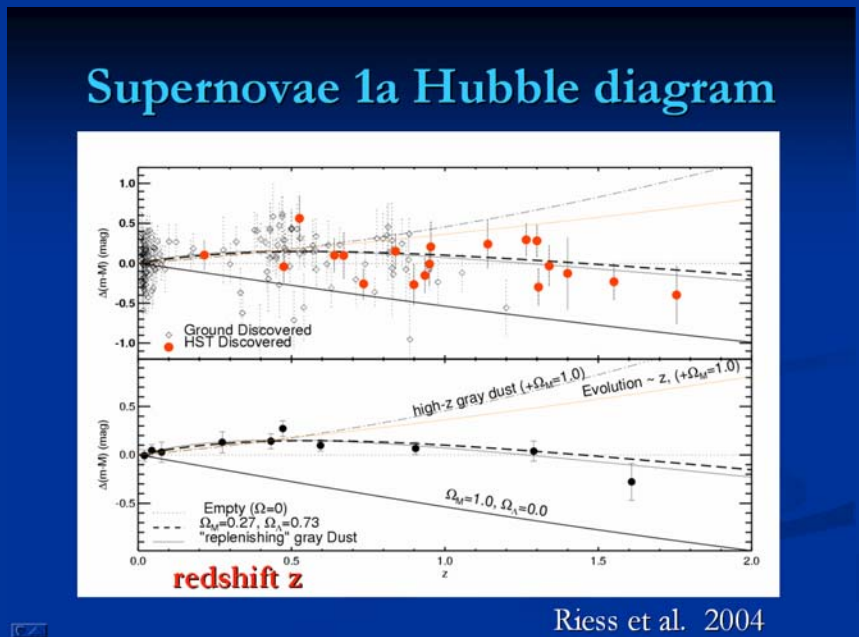
“ homogeneous “

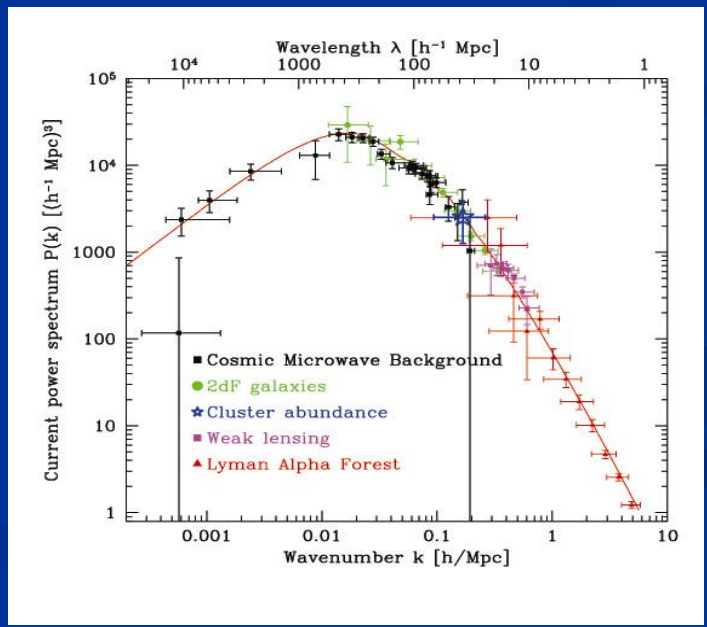
No force –
“ In what direction should it draw ? “

Two important predictions

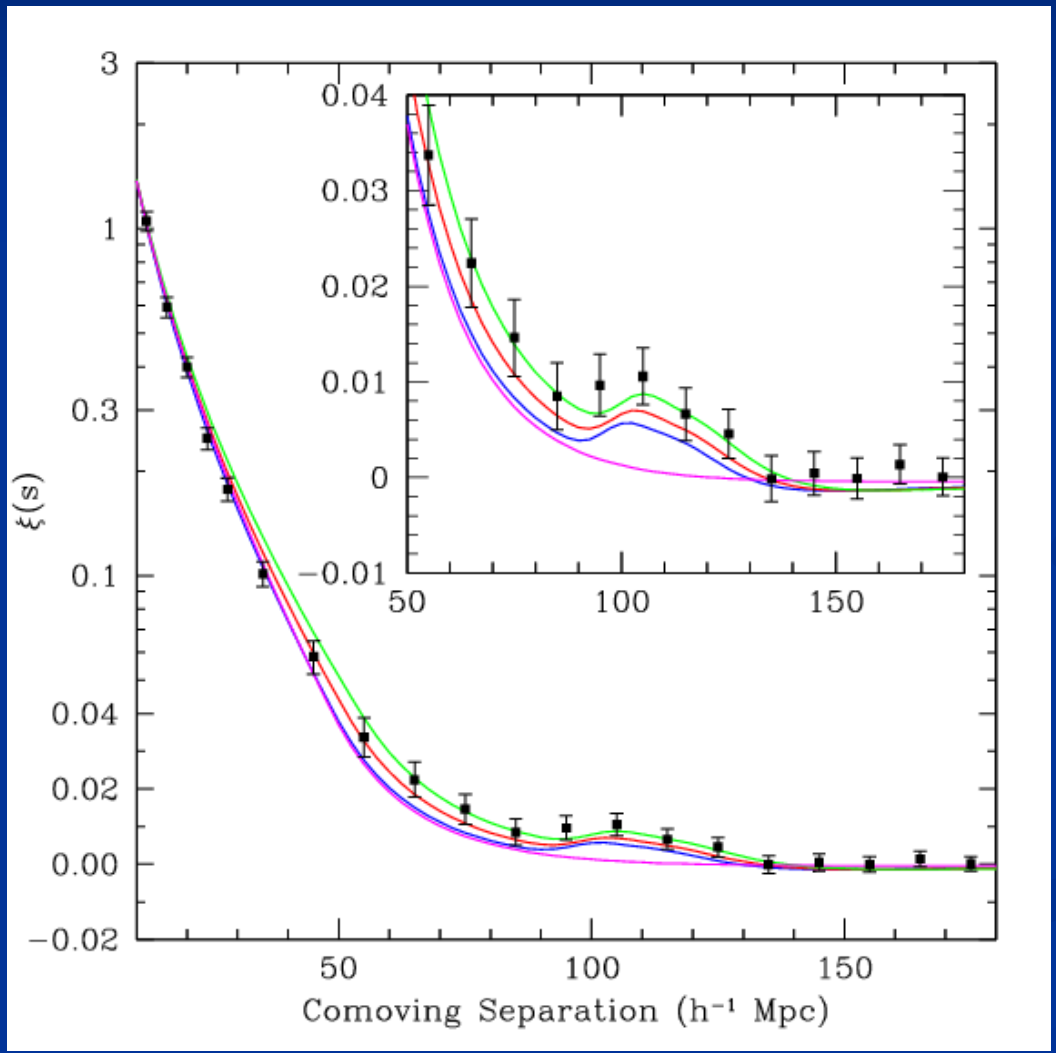
The expansion of the Universe accelerates today !

Structure formation : One primordial fluctuation- spectrum

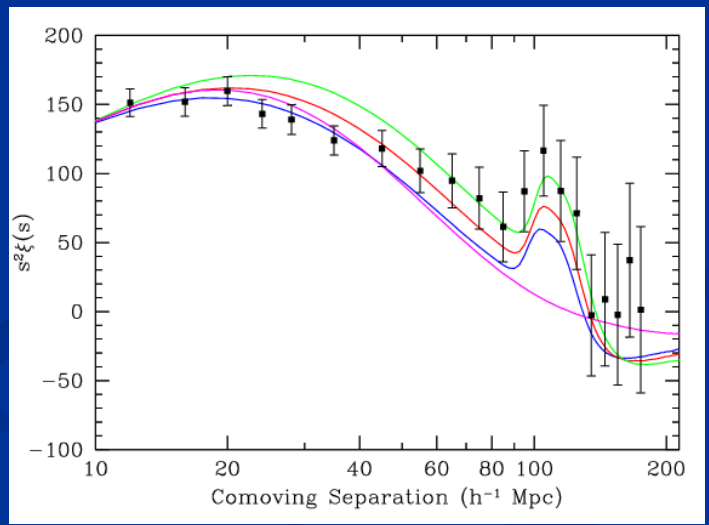




Baryon - Peak



SDSS



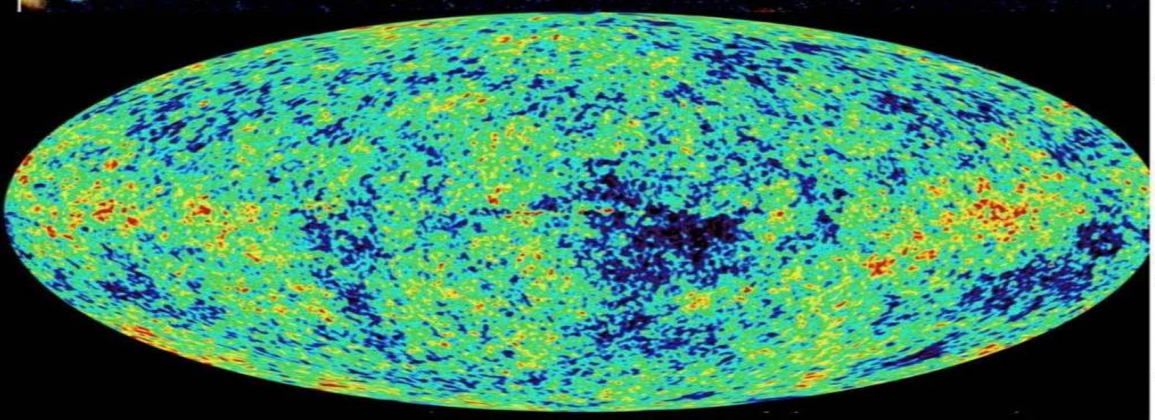
galaxy – correlation – function

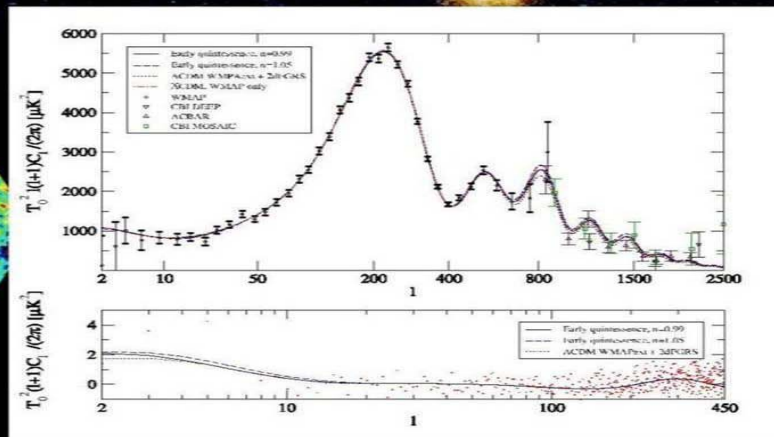
consistent cosmological model !

Composition of the Universe

$\Omega_b = 0.045$	visible	clumping
$\Omega_{dm} = 0.22$	invisible	clumping
$\Omega_h = 0.73$	invisible	homogeneous

Dark Energy- a cosmic mystery





What is Dark Energy ?

Cosmological Constant

or

Quintessence ?

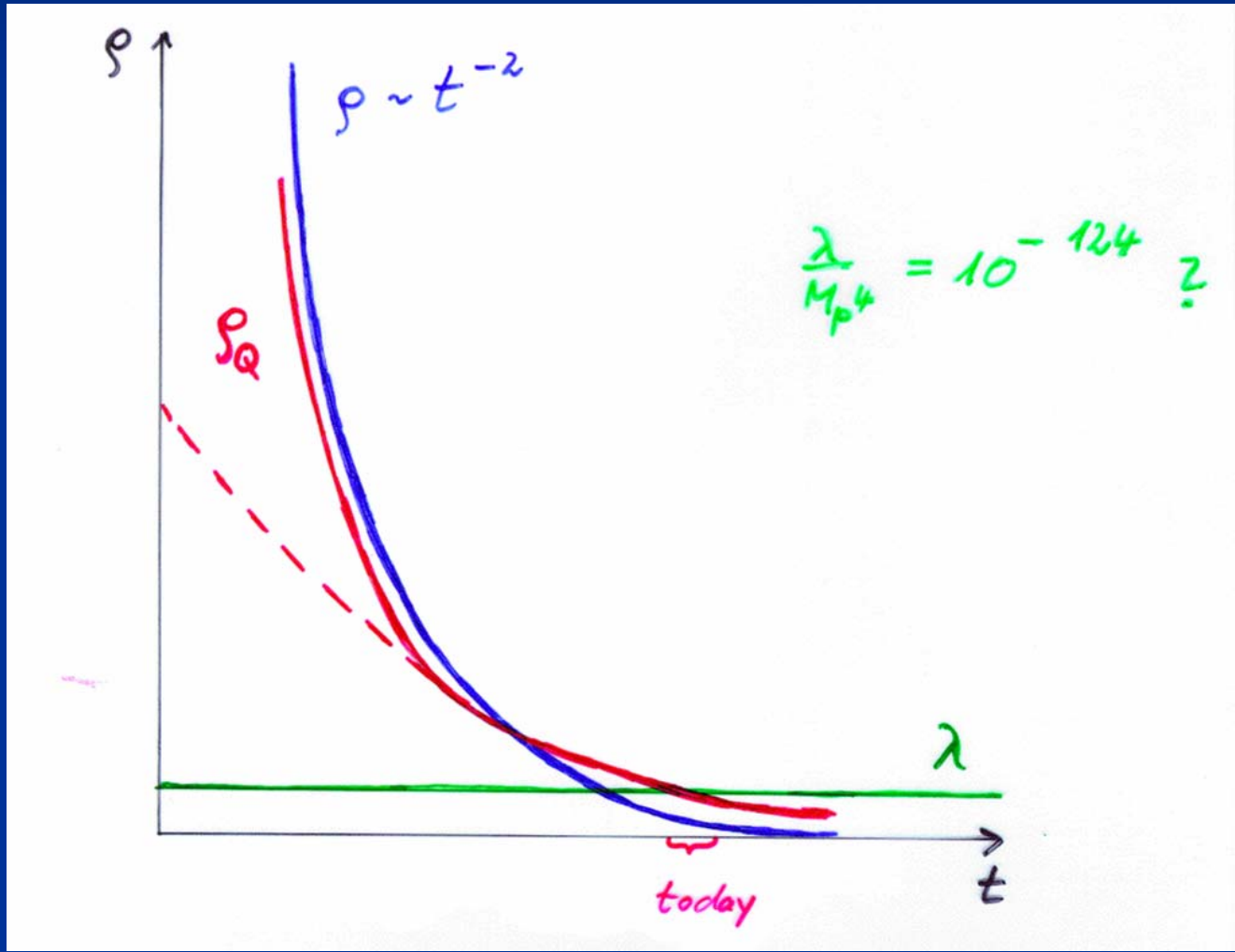
Cosmological Constant
- Einstein -

- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

- Why so small ? $\lambda/M^4 = 10^{-120}$

- Why important just today ?

Cosm. Const.	Quintessence
static	dynamical



Cosmological mass scales

- Energy density

  $\rho \sim (2.4 \times 10^{-3}\ \mathrm{eV})^{-4}$

- Reduced Planck mass

  $M = 2.44 \times 10^{18}\ \mathrm{GeV}$

- Newton's constant

  $G_N = (8\pi M^2)$

Only ratios of mass scales are observable !

homogeneous dark energy: $\rho_h / M^4 = 6.5\ 10^{-121}$

matter: $\rho_m / M^4 = 3.5\ 10^{-121}$

Time evolution

- $\rho_m/M^4 \sim a^{-3} \sim$ t^{-2} matter dominated universe
  $t^{-3/2}$ radiation dominated universe
- $\rho_r/M^4 \sim a^{-4} \sim t^{-2}$ radiation dominated universe

Huge age ⇨ small ratio

Same explanation for small dark energy?

Quintessence

Dynamical dark energy ,
generated by scalar field

(cosmon)

C.Wetterich,Nucl.Phys.B302(1988)668, 24.9.87
P.J.E.Peebles,B.Ratra,ApJ.Lett.325(1988)L17, 20.10.87

Prediction :

homogeneous dark energy influences recent cosmology

- of same order as dark matter -

Original models do not fit the present observations …. modifications

Quintessence

Cosmon – Field $\varphi(x,y,z,t)$

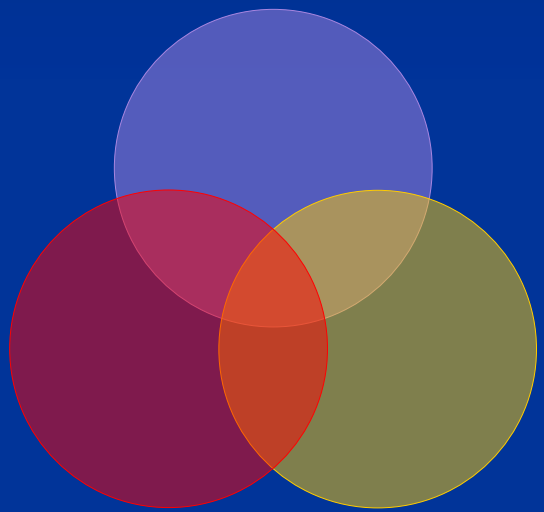
similar to electric field , but no direction (scalar field)

Homogeneous und isotropic Universe : $\varphi(x,y,z,t)=\varphi(t)$

Potential und kinetic energy of the cosmon -field
contribute to a dynamical energy density of the Universe !

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

Evolution of cosmon field

Field equations

$$\ddot{\phi} + 3H\dot{\phi} = -dV/d\phi$$

$$3M^2H^2 = V + \frac{1}{2}\dot{\phi}^2 + \rho$$

Potential V(φ) determines details of the model

e.g. $V(\varphi) = M^4 \exp(-\varphi/M)$

for increasing φ the potential decreases towards zero !

Cosmon

- *Scalar field changes its value even in the **present** cosmological epoch*
- *Potential und kinetic energy of cosmon contribute to the energy density of the Universe*
- *Time - variable dark energy :*

  $\varrho_h(t)$ *decreases with time !*

Cosmon

- *Tiny mass*
- $m_c \sim H$
- *New long - range interaction*

Dynamics of quintessence

- Cosmon φ : scalar singlet field
- Lagrange density $L = V + \frac{1}{2}\, k(\varphi)\, \partial\varphi\, \partial\varphi$

  (units: reduced Planck mass M=1)
- Potential : $V=\exp[-\varphi]$
- "Natural initial value" in Planck era $\varphi=0$
- today: $\varphi=276$

cosmon mass changes with time !

for standard kinetic term

- $m_c^2 = V''$

for standard exponential potential , k = const.

- $m_c^2 = V''/ k^2 = V/(k^2 M^2)$

  $= 3 \Omega_h (1 - w_h) H^2 /(2 k^2)$

Quintessence models

- Kinetic function $k(\varphi)$: parameterizes the details of the model - "kinetial"
  - $k(\varphi) = k=\text{const.}$ Exponential Q.
  - $k(\varphi) = \exp((\varphi - \varphi_1)/\alpha)$ Inverse power law Q.
  - $k^2(\varphi) =$ "$1/(2E(\varphi_c - \varphi))$" Crossover Q.
- possible naturalness criterion:

$k(\varphi=0)/\ k(\varphi_{today})$: not tiny or huge !

- else: explanation needed -

More models …

- Phantom energy (Caldwell)
  negative kinetic term ($w < -1$)
  consistent quantum theory ?

- K – essence (Amendariz-Picon, Mukhanov, Steinhardt)
  higher derivative kinetic terms
  why derivative expansion not valid ?

- Coupling cosmon / (dark) matter (C.W., Amendola)
  why substantial coupling to dark matter and not to ordinary matter ?

- Non-minimal coupling to curvature scalar – $f(\varphi)\, R$ -
  can be brought to standard form by Weyl scaling !

kinetial

$$\mathcal{L}(\varphi) = \frac{1}{2}(\partial\varphi)^2 k^2(\varphi) + \exp[-\varphi]$$

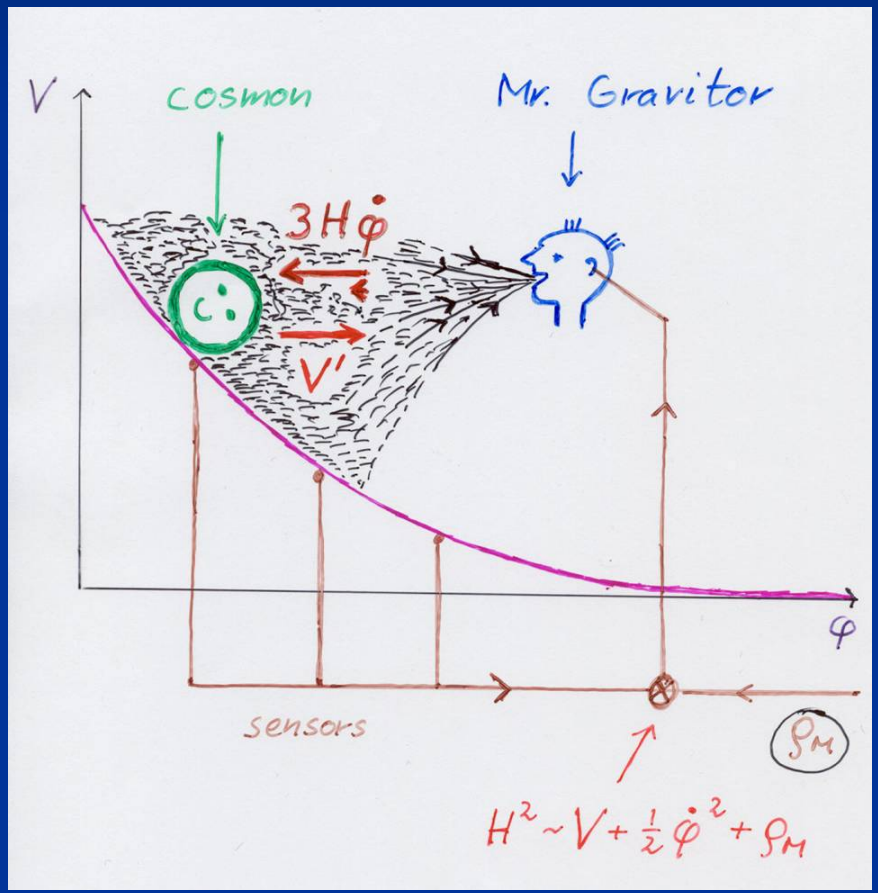
Small almost constant k :

- Small almost constant Ω_h

Large k :

- Cosmon dominated universe (like inflation)

cosmological equations



use scale factor a as time variable:

matter : $\dfrac{d\ln\rho_m}{d\ln a} = -3$

radiation : $\dfrac{d\ln\rho_r}{d\ln a} = -4$

$$\frac{d\ln\rho_\varphi}{d\ln a} = -3(1+w_\varphi)$$

$$\frac{d\varphi}{d\ln a} = \sqrt{\frac{6\,(\rho_\varphi - V(\varphi))}{k^2\,(\varphi)(\rho_m+\rho_r+\rho_\varphi)}}$$

Cosmic Attractors

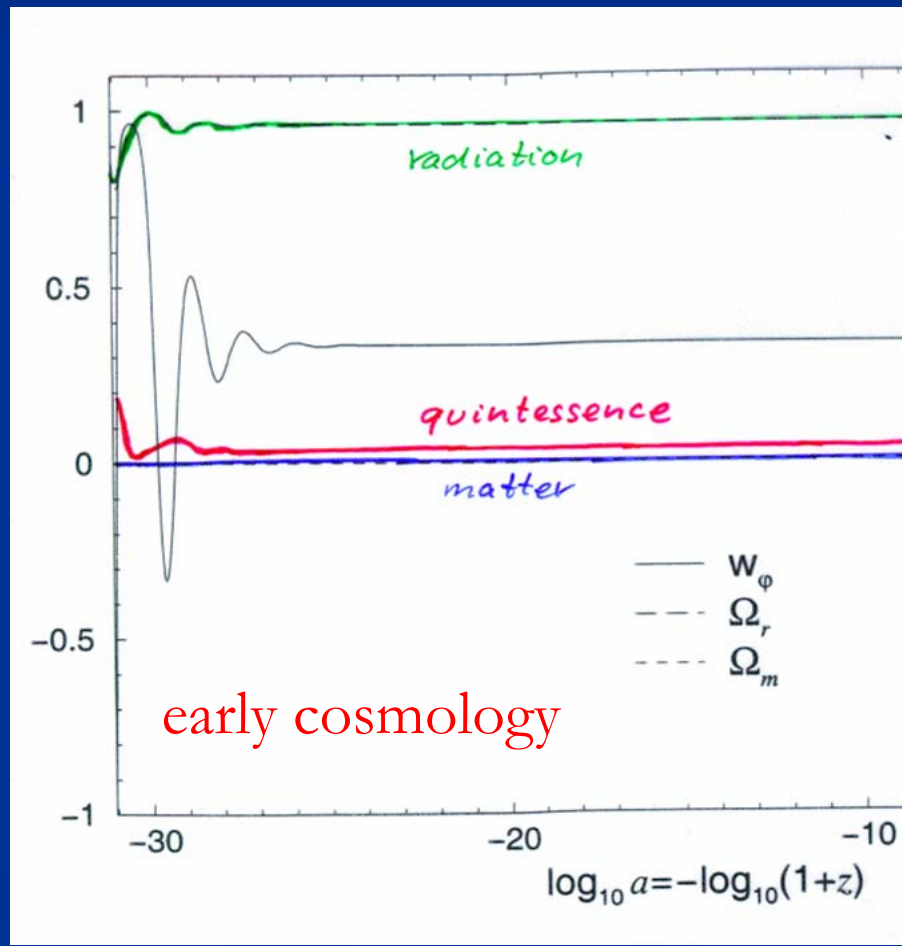
Solutions independent of initial conditions

typically $V \sim t^{-2}$

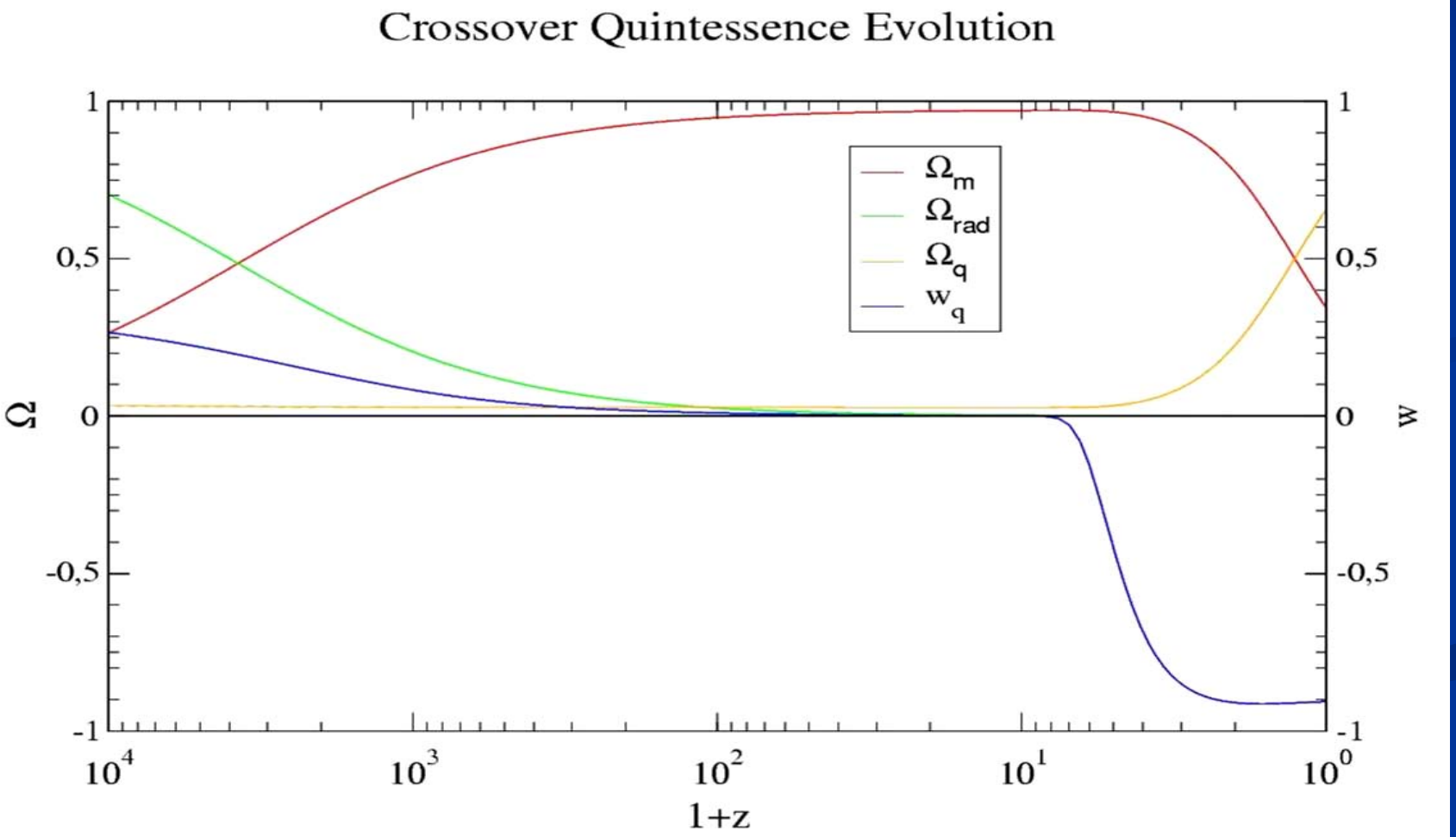
$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

details depend on $V(\varphi)$ or kinetic term



Quintessence becomes important "today"



Equation of state

p=T-V pressure

ϱ=T+V energy density

kinetic energy

$T = \frac{1}{2}\dot{\phi}^2$

Equation of state

$$w = \frac{p}{\rho} = \frac{T-V}{T+V}$$

Depends on specific evolution of the scalar field

Negative pressure

- $w < 0$ Ω_h increases (with decreasing z)

late universe with
small radiation component :

$$w_h = \frac{1}{3\Omega_h(1-\Omega_h)} \frac{\partial \Omega_h}{\partial \ln(1+z)}$$

- $w < -1/3$ expansion of the Universe is accelerating

- $w = -1$ cosmological constant

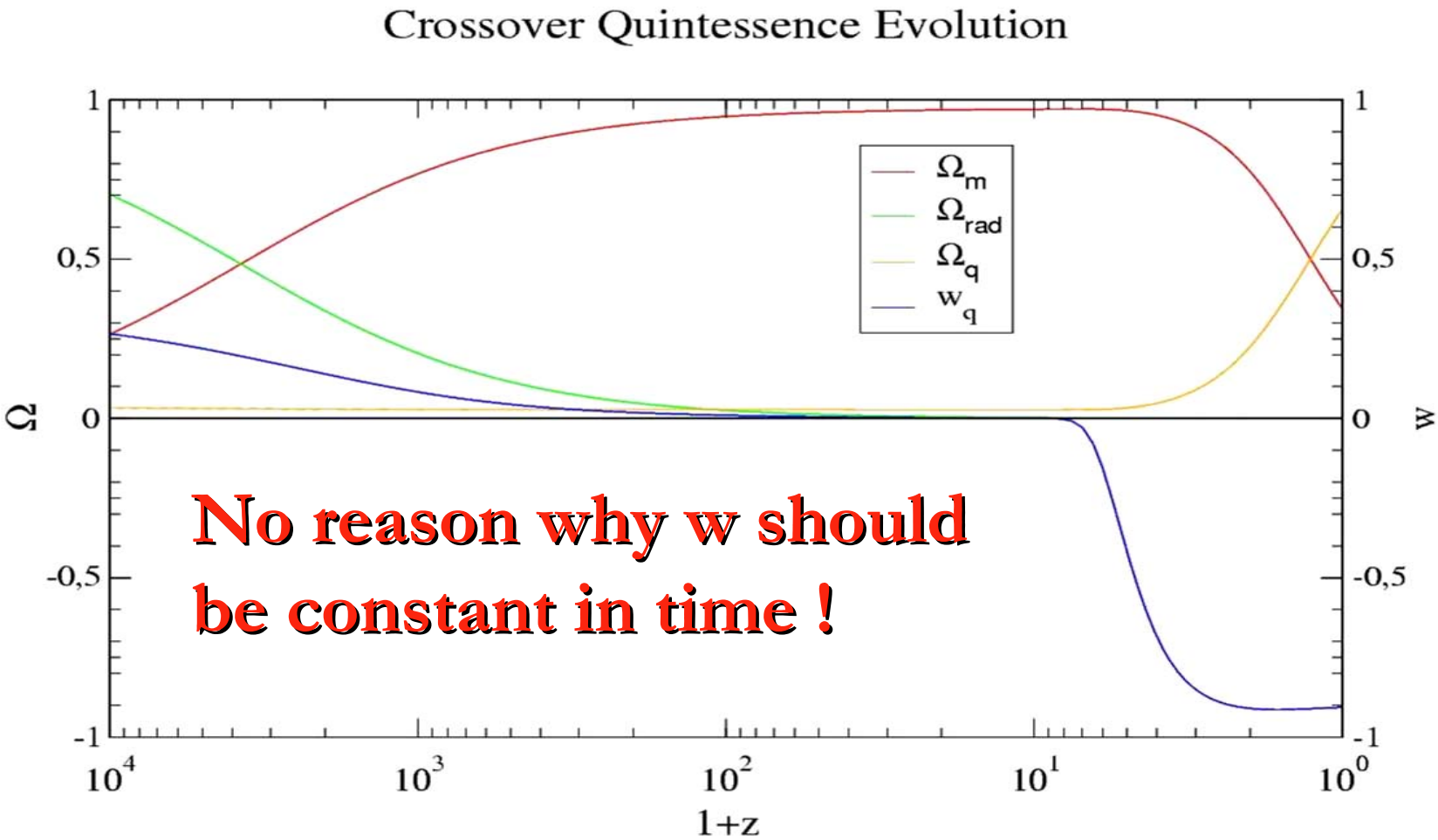
small early and large present dark energy

fraction in dark energy has substantially increased since end of structure formation

expansion of universe accelerates in present epoch

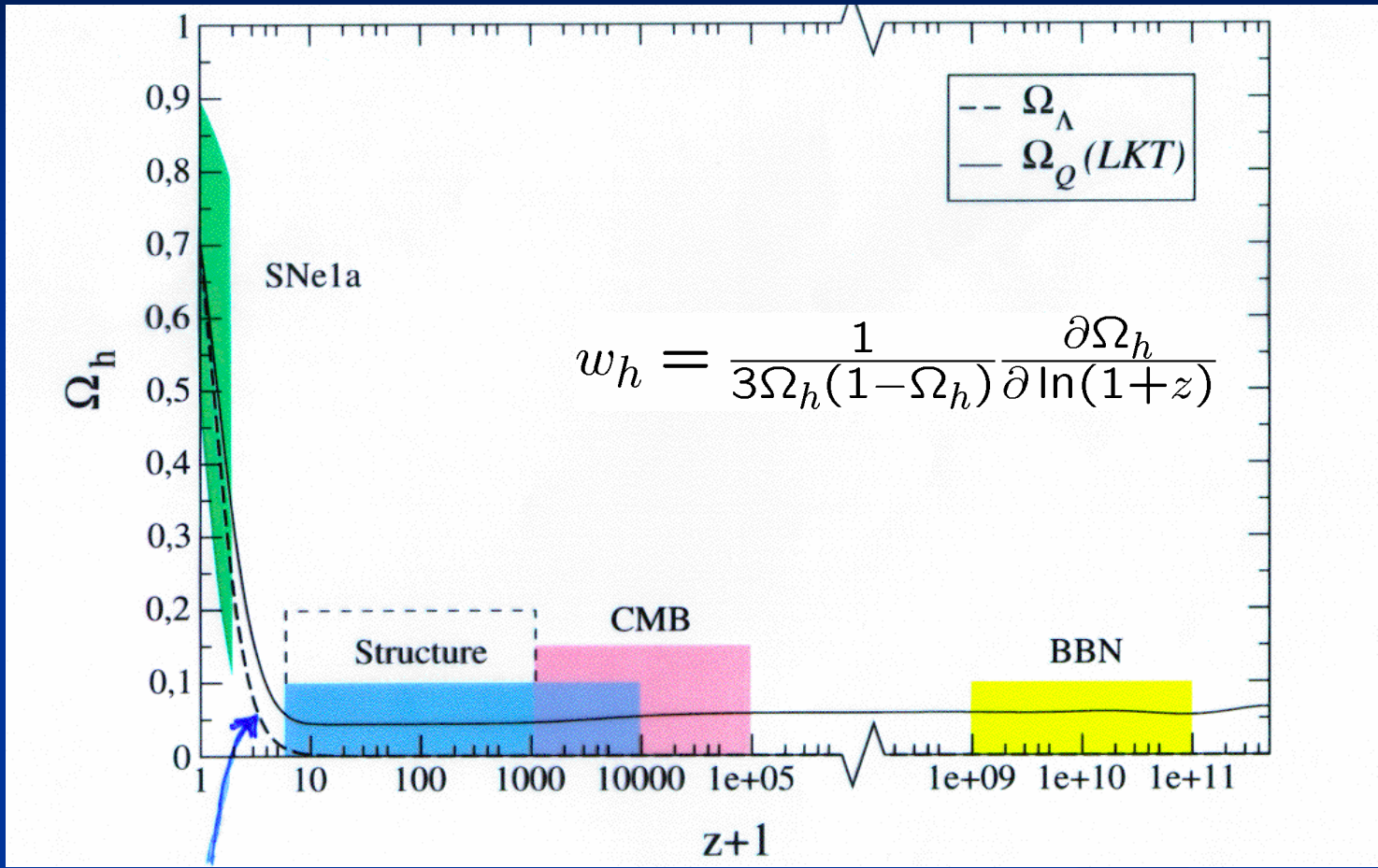
$$w_h = \frac{1}{3\Omega_h(1-\Omega_h)} \frac{\partial \Omega_h}{\partial \ln(1+z)}$$

Quintessence becomes important "today"



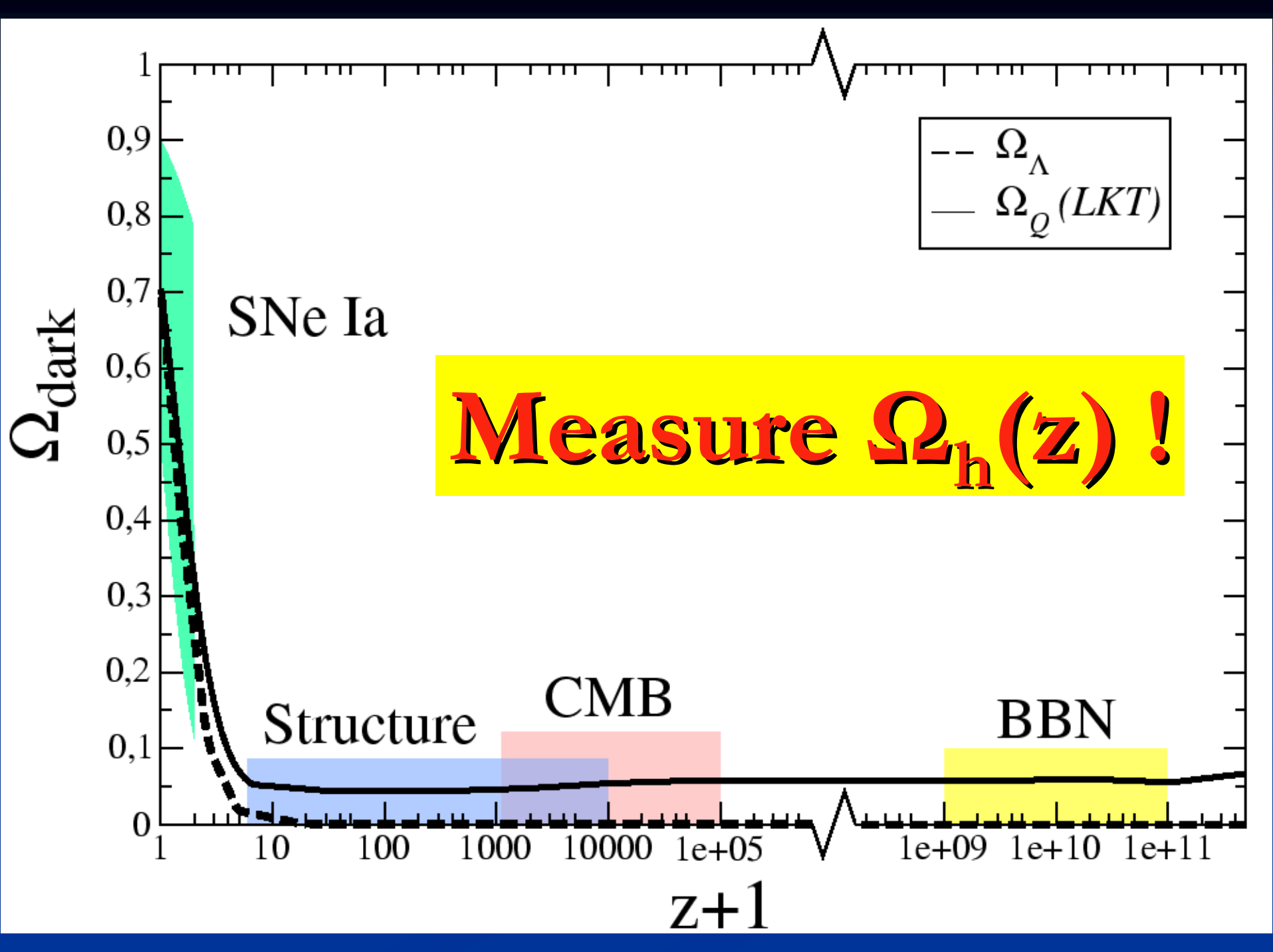
How can quintessence be distinguished from a cosmological constant ?

Time dependence of dark energy



cosmological constant : $\Omega_h \sim t^2 \sim (1+z)^{-3}$

M.Doran,…

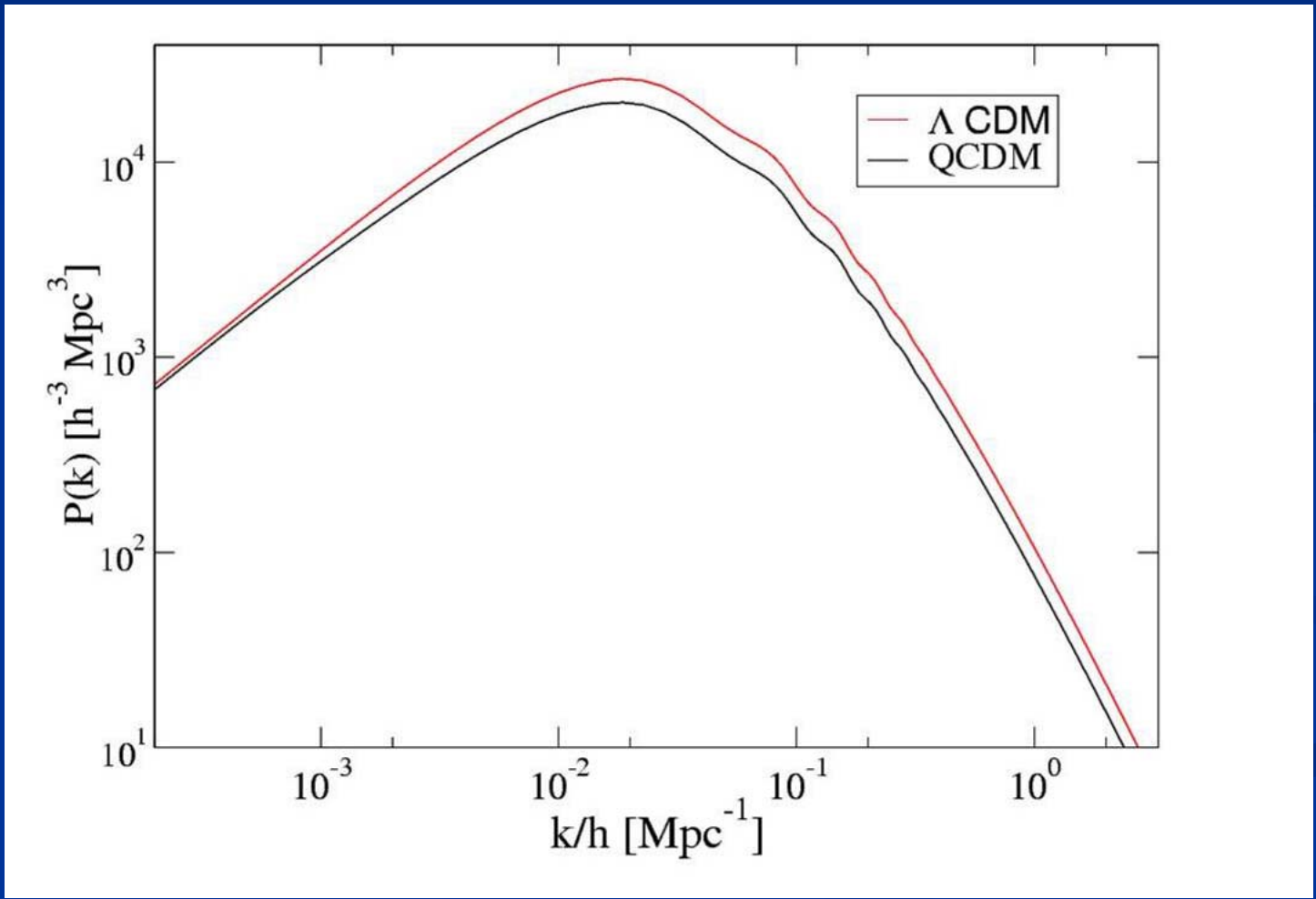

Ω_{dark}
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
1
10
100
1000
10000
1e+05
1e+09
1e+10
1e+11
z+1
Ω_Λ
Ω_Q (LKT)
SNe Ia
Structure
CMB
BBN
Measure $\Omega_h(z)$!

Early dark energy

A few percent in the early Universe

Not possible for a cosmological constant

Early quintessence slows down the growth of structure



Growth of density fluctuations

- Matter dominated universe with constant Ω_h :

$$\Delta\rho \sim a^{1-\frac{\epsilon}{2}}\ ,\ \epsilon = \frac{5}{2}\left(1-\sqrt{1-\frac{24}{25}\Omega_h}\right)$$

P.Ferreira,M.Joyce

- Dark energy slows down structure formation

  ⟹ Ω_h < 10% during structure formation

- Substantial increase of $\Omega_h(t)$ since structure has formed!

  ⟹ negative w_h

- Question "why now" is back (in mild form)

A few percent Early Dark Energy

If linear power spectrum fixed today (σ_8) :

More Structure at high z !

Bartelmann,Doran,…

How to distinguish Q from Λ ?

A) Measurement $\Omega_h(z)$ $\Longleftrightarrow$ $H(z)$

i) $\Omega_h(z)$ at the time of structure formation , CMB - emission or nucleosynthesis

ii) equation of state $w_h(\text{today}) > -1$

B) Time variation of fundamental "constants"

C) Apparent violation of equivalence principle

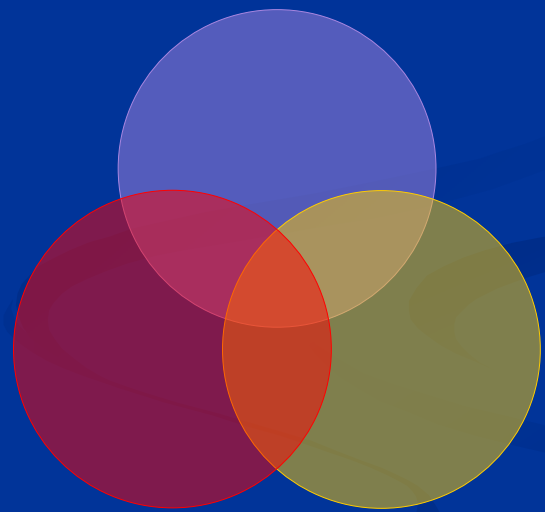
Quintessence and time variation of fundamental constants

Generic prediction

Strength unknown

C.Wetterich , Nucl.Phys.B302,645(1988)

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

Time varying constants

- It is not difficult to obtain quintessence potentials from higher dimensional or string theories
- Exponential form rather generic

  (after Weyl scaling)
- But most models show too strong time dependence of constants !

Are fundamental “constants” time dependent ?

Fine structure constant α (electric charge)

Ratio nucleon mass to Planck mass

Quintessence and Time dependence of "fundamental constants"

- **Fine structure constant depends on value of cosmon field : $\alpha(\varphi)$**

  (similar in standard model: couplings depend on value of Higgs scalar field)

- **Time evolution of φ ⟹ Time evolution of α**

Jordan,…

Standard – Model of electroweak interactions : Higgs - mechanism

- The masses of all fermions and gauge bosons are proportional to the (vacuum expectation) value of a scalar field φ_H (Higgs scalar)
- For electron, quarks , W- and Z- bosons :

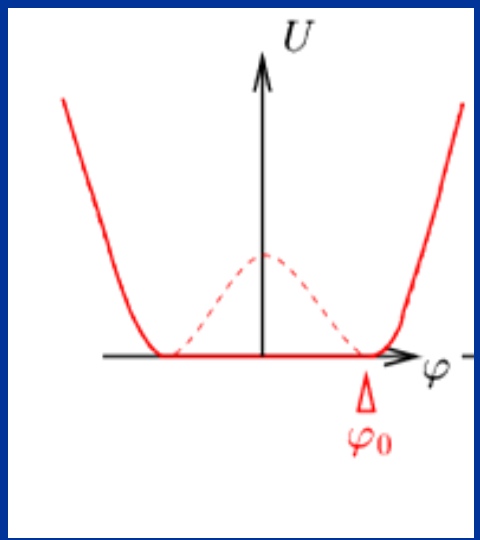
$$m_{electron} = h_{electron} * \varphi_H \quad \text{etc.}$$

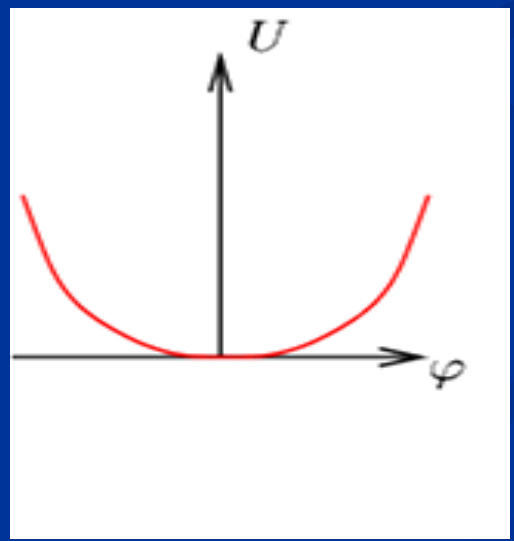
Restoration of symmetry at high temperature in the early Universe

Low T
SSB
$<\varphi_H>=\varphi_0 \neq 0$

High T
SYM
$<\varphi_H>=0$

high T :
less order
more symmetry

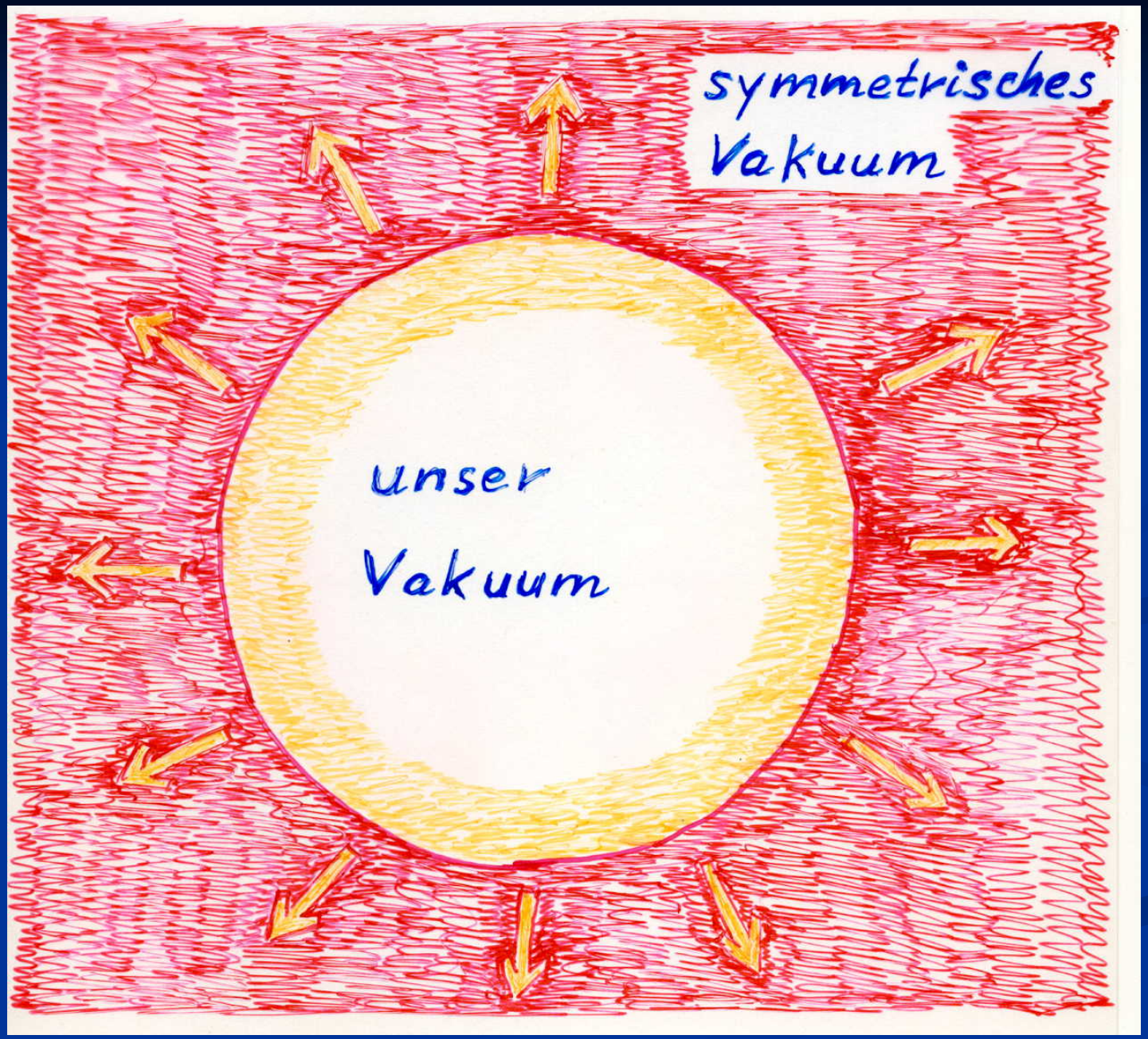




example:
magnets

In the hot plasma
of the early Universe :

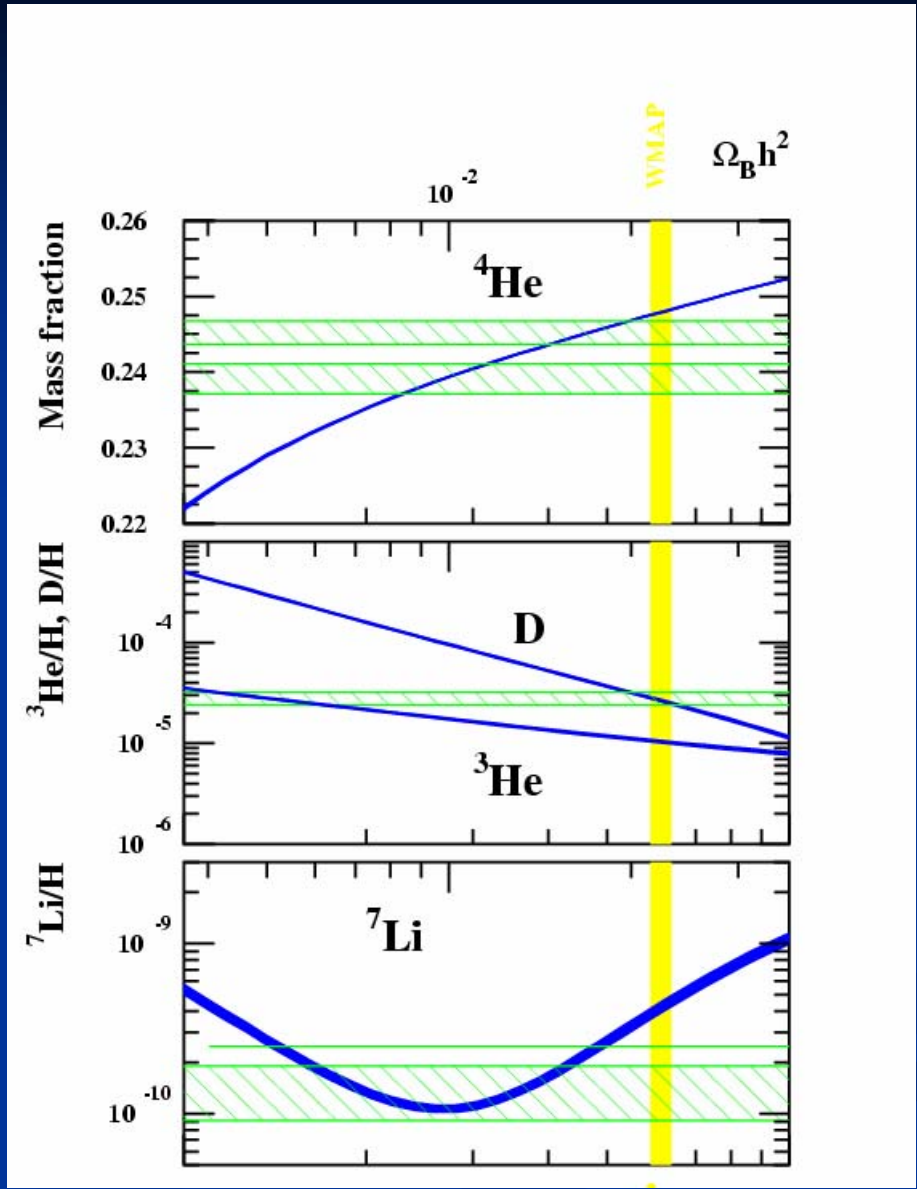
No difference in mass for electron and myon !


symmetrisches
Vakuum
unser
Vakuum

Quintessence :
Couplings are still varying now !

Strong bounds on
the variation of couplings -
interesting perspectives for
observation !

Abundancies of primordial light elements from nucleosynthesis



A.Coc

if present 2-sigma deviation of He –abundance from CMB/nucleosynthesis prediction would be confirmed :

$\Delta\alpha/\alpha\ (z=10^{10}) = -1.0\ 10^{-3}$ GUT 1

$\Delta\alpha/\alpha\ (z=10^{10}) = -2.7\ 10^{-4}$ GUT 2

C.Mueller,G.Schaefer,…

Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

Παντα ρει

Everything is flowing

Summary

- $\Omega_h = 0.7$
- Q/Λ : dynamical und static dark energy
  will be distinguishable
- Q : time varying fundamental coupling “constants”

  violation of equivalence principle

Quintessence and solution of cosmological constant problem should be related !

??????????????????????

Why becomes Quintessence dominant in the present cosmological epoch ?

Are dark energy and dark matter related ?

Can Quintessence be explained in a fundamental unified theory ?

End

A few references

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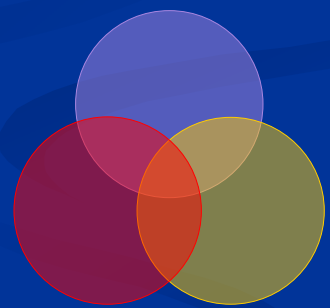
Cosmodynamics

Cosmon mediates new long-range interaction

Range : size of the Universe – horizon

Strength : weaker than gravity

photon	electrodynamics
graviton	gravity
cosmon	cosmodynamics



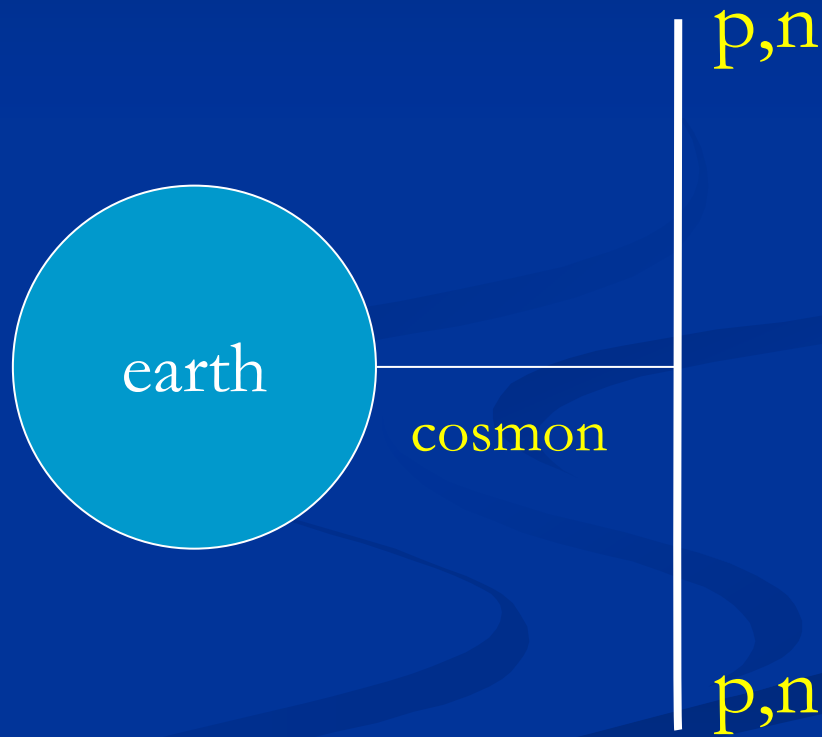
Small correction to Newton's law

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

Differential acceleration η

For unified theories (GUT) :

$$\eta = -1.75\ 10^{-2} \Delta R_z \left(\frac{\partial \ln \alpha}{\partial z}\right)^2 \frac{1+\tilde{Q}}{\Omega_h (1+w_h)}$$

$$\Delta R_z = \frac{\Delta Z}{Z+N} \approx 0.1$$

η=Δa/2a

Q : time dependence of other parameters

Link between time variation of α

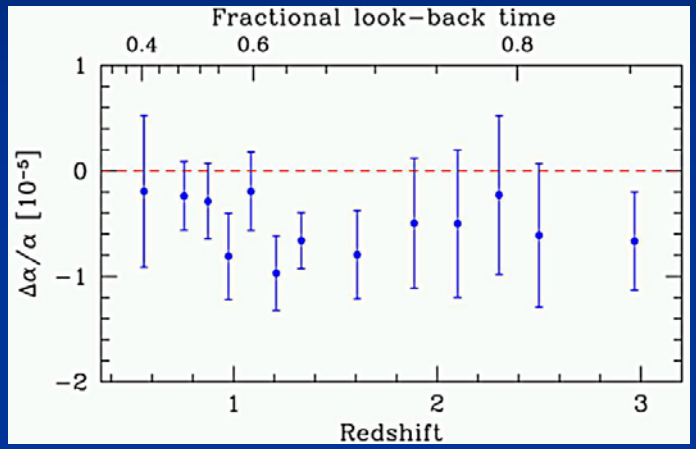
and violation of equivalence principle

typically : $\eta = 10^{-14}$

if time variation of α near Oklo upper bound

to be tested by MICROSCOPE

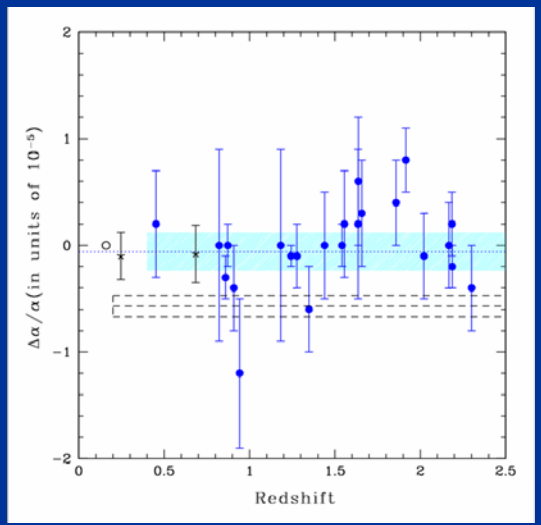
Variation of fine structure constant as function of redshift



Three independent data sets from Keck/HIRES

$$\Delta\alpha/\alpha = -0.54\ (12)\ 10^{-5}$$

Murphy,Webb,Flammbaum, june 2003



VLT

$$\Delta\alpha/\alpha = -0.06\ (6)\ 10^{-5}$$

Srianand,Chand,Petitjean,Aracil, feb.2004

$z \approx 2$