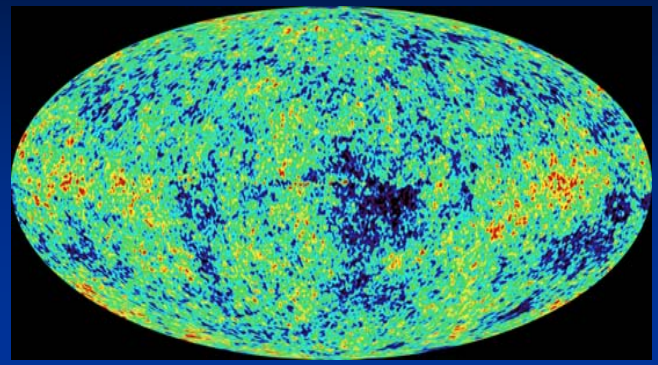
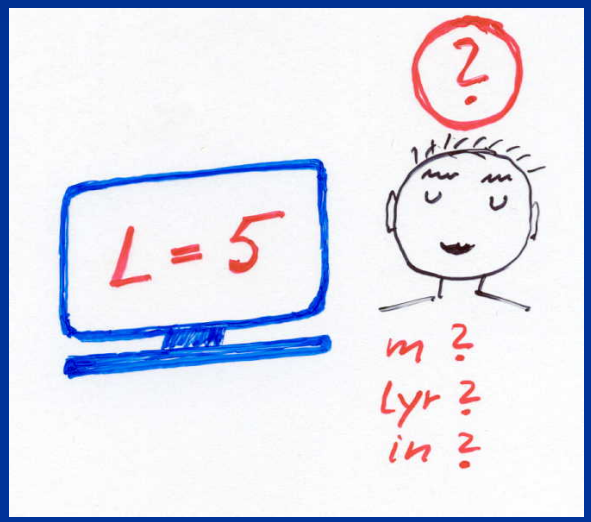
Quintessence - a fifth force from variation of the fundamental scale

$\Omega_m + X = 1$





?

Ω_m : 25%

Ω_h : 75%

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

Dark Energy dominates the Universe

Energy - density in the Universe

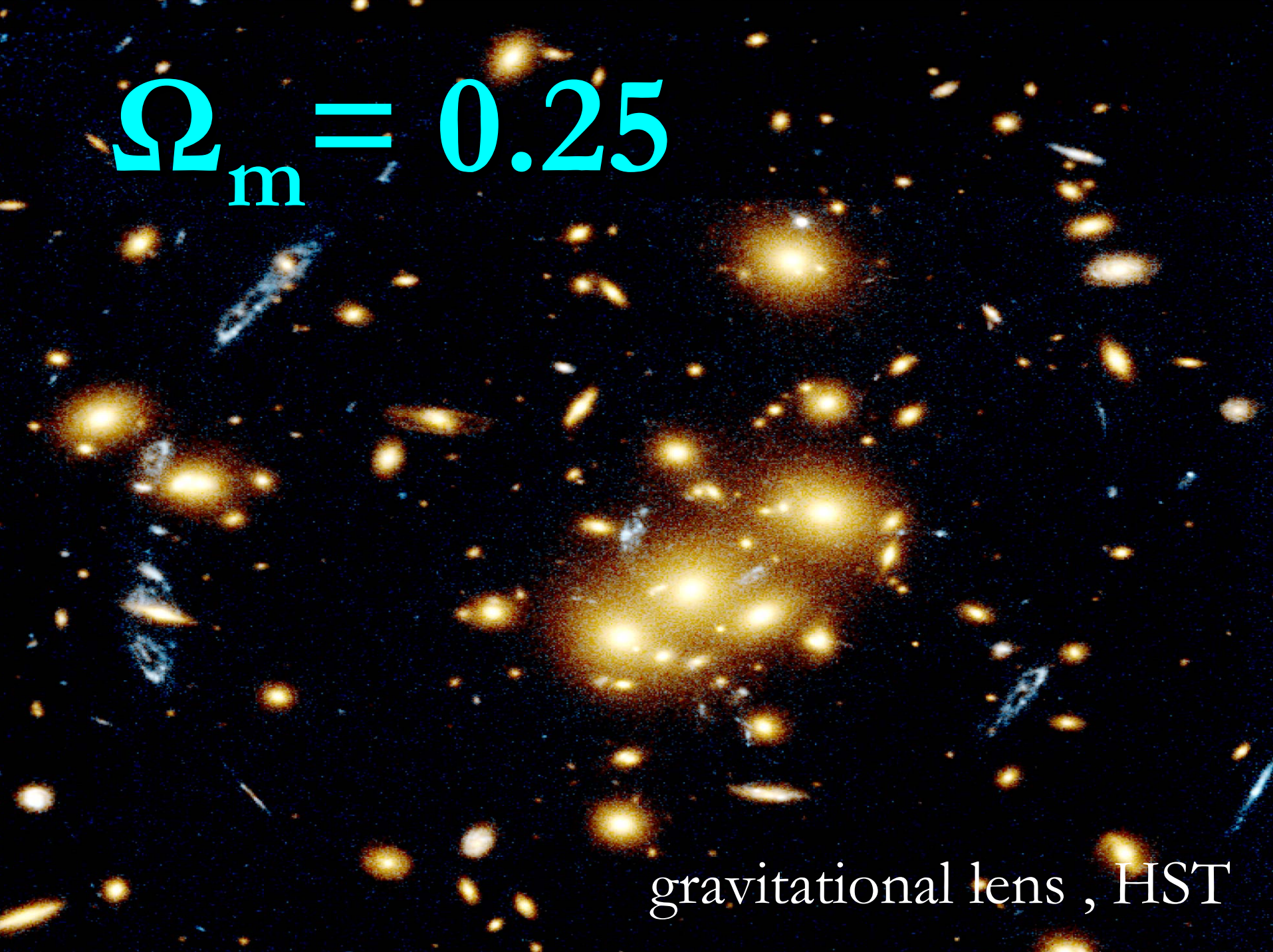
=

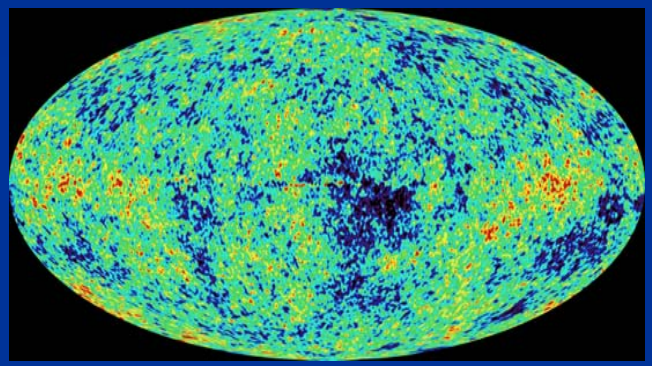
Matter + Dark Energy

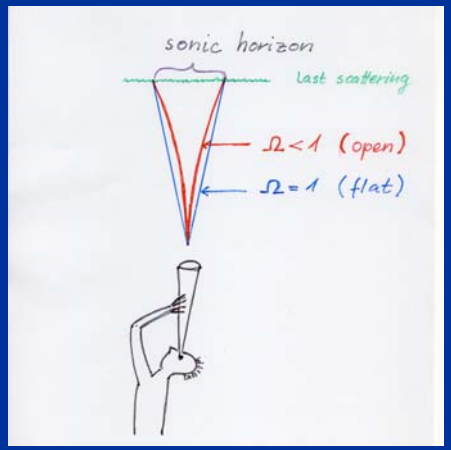
25 % + 75 %

Matter : Everything that clumps

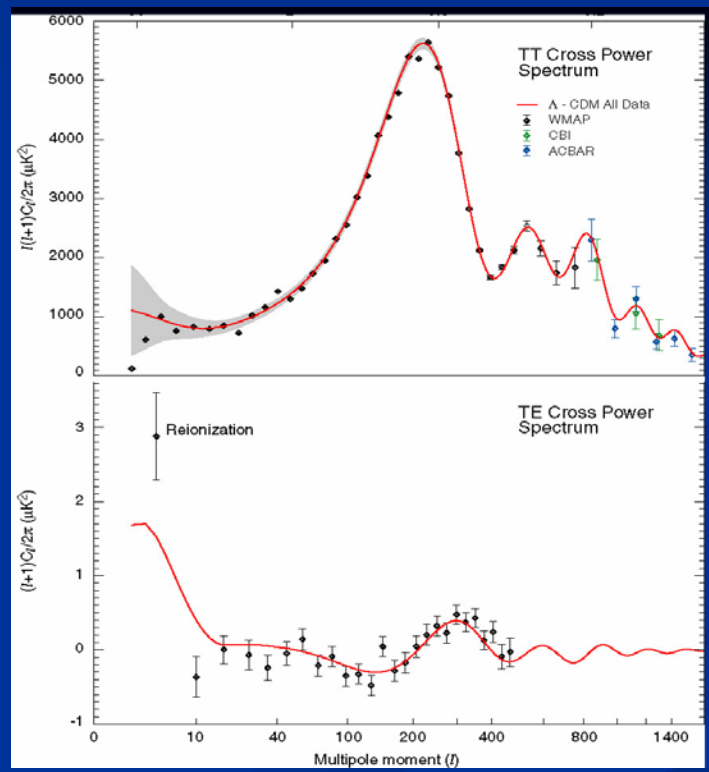
Abell 2255 Cluster
~300 Mpc


$\Omega_m = 0.25$
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 : 25%

Ω_h : 75% 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 “

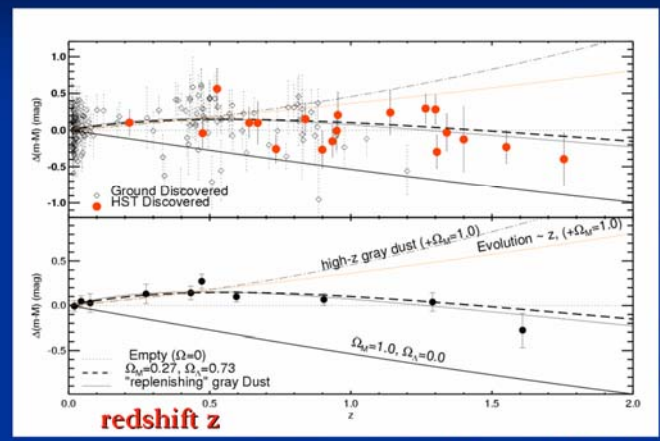
Ω_h

Predictions for dark energy cosmologies

The expansion of the Universe

accelerates today !

Supernovae 1a Hubble diagram



Riess et al. 2004

What is Dark Energy ?

Cosmological Constant

or

Quintessence ?

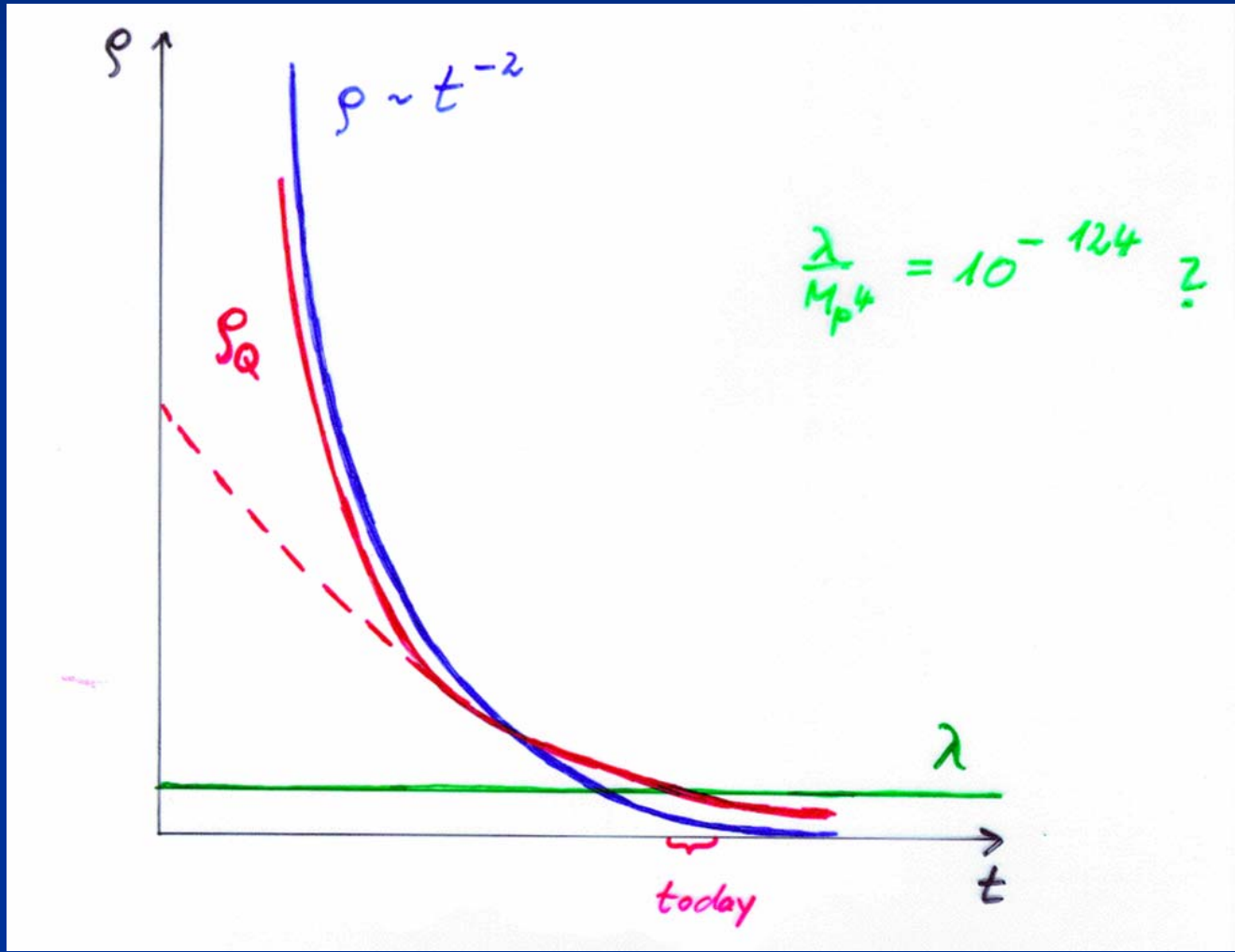
Cosmological Constant
- Einstein -

- 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



Quintessence and solution of cosmological constant problem should be related !

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 ?

Time dependent Dark Energy : Quintessence

- What changes in time ?
- **Only dimensionless ratios of mass scales are observable !**
- V : potential energy of scalar field or cosmological constant
- V/M^4 is observable
- **Imagine the Planck mass M increases …**

Quintessence from time evolution of fundamental mass scale

Fundamental mass scale

- Unification fixes parameters with dimensions

- Special relativity : c
- Quantum theory : h
- Unification with gravity :

fundamental mass scale

(Planck mass , string tension , …)

Fundamental mass scale

- Fixed parameter or dynamical scale ?
- Dynamical scale $\longleftrightarrow$ Field
- Dynamical scale compared to what ?

momentum versus mass

(or other parameter with dimension)

Cosmon and fundamental mass scale

- Assume all mass parameters are proportional to scalar field χ (GUTs, superstrings,…)
- $M_p \sim \chi$, $m_{proton} \sim \chi$, $\Lambda_{QCD} \sim \chi$, $M_W \sim \chi$,…

- χ may evolve with time : **cosmon**
- m_n/M : (almost) constant - ***observation*** !

Only ratios of mass scales are observable

Example :

Field χ denotes scale of transition
from higher dimensional physics
to effective four dimensional description
in theory without fundamental mass parameter

(except for running of dimensionless couplings…)

Dilatation symmetry

- Lagrange density:

$$L = \sqrt{g}(-\frac{1}{2}\chi^2 R + \frac{1}{2}(\delta - 6)\partial^\mu \chi \partial_\mu \chi + V(\chi) + h\chi\overline{\psi}\psi)$$

- Dilatation symmetry for

$$V = \lambda\chi^4\,,\ \lambda = const.,\ \delta = const.,\ h = const.$$

- Conformal symmetry for δ=0

Dilatation anomaly

- Quantum fluctuations responsible for dilatation anomaly
- Running couplings: **hypothesis**

$$\partial\lambda/\partial \ln \chi = -A\lambda\,,\ \partial\delta/\partial \ln \chi = E\delta^2$$

- Renormalization scale μ : (momentum scale)
- $\lambda \sim (\chi/\mu)^{-A}$
- E > 0 : crossover Quintessence

Dilatation anomaly and quantum fluctuations

- Computation of running couplings (beta functions) needs unified theory !
- Dominant contribution from modes with momenta $\sim\chi$!
- No prejudice on "natural value " of anomalous dimension should be inferred from tiny contributions at QCD- momentum scale !

Cosmology

Cosmology : χ increases with time !

(due to coupling of χ to curvature scalar)

for large χ the ratio V/M^4 decreases to zero

Effective cosmological constant vanishes asymptotically for large t !

Asymptotically vanishing effective "cosmological constant"

- Effective cosmological constant ~ V/M^4
- $\lambda \sim (\chi/\mu)^{-A}$
- $V \sim (\chi/\mu)^{-A}\ \chi^4$
- $M = \chi$

$$\mathbf{V/M^4 \sim (\chi/\mu)^{-A}}$$

Weyl scaling

Weyl scaling : $g_{\mu\nu} \rightarrow (M/\chi)^2 g_{\mu\nu}$,

$\varphi/M = \ln(\chi^4/V(\chi))$

$$L = \sqrt{g}(-\frac{1}{2}M^2R + \frac{1}{2}k^2(\phi)\partial^\mu\phi\partial_\mu\phi + V(\phi) + m(\phi)\overline{\psi}\psi)$$

Exponential potential : $V = M^4 \exp(-\varphi/M)$

No additional constant !

Without dilatation – anomaly :

V= const.

Massless Goldstone boson = dilaton

Dilatation – anomaly :

$V(\varphi)$

Scalar with tiny time dependent mass :

cosmon

Crossover Quintessence

$$\partial\delta/\partial \ln \chi = E\delta^2$$ (like QCD gauge coupling)

critical χ where δ grows large
critical φ where k grows large $k^2(\varphi) = \delta(\chi)/4$

$k^2(\varphi) =$ "$1/(2E(\varphi_c - \varphi)/M)$"

if $\varphi_c \approx 276/M$ (tuning !) :

this will be responsible for relative increase of dark energy in present cosmological epoch

Realistic cosmology

Hypothesis on running couplings yields realistic cosmology for suitable values of A , E , φ_c

Quintessence cosmology

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 (i.e. E > 0)

Quintessence

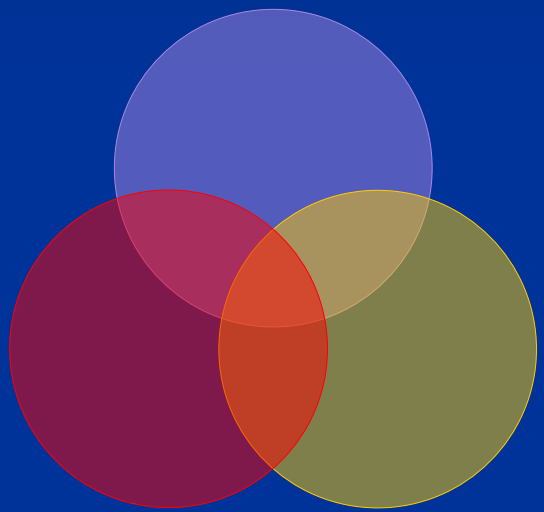
Cosmon – Field $\varphi(x,y,z,t)$

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

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: $\varphi=276$

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 -

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*

cosmon mass changes with time !

for standard kinetic term

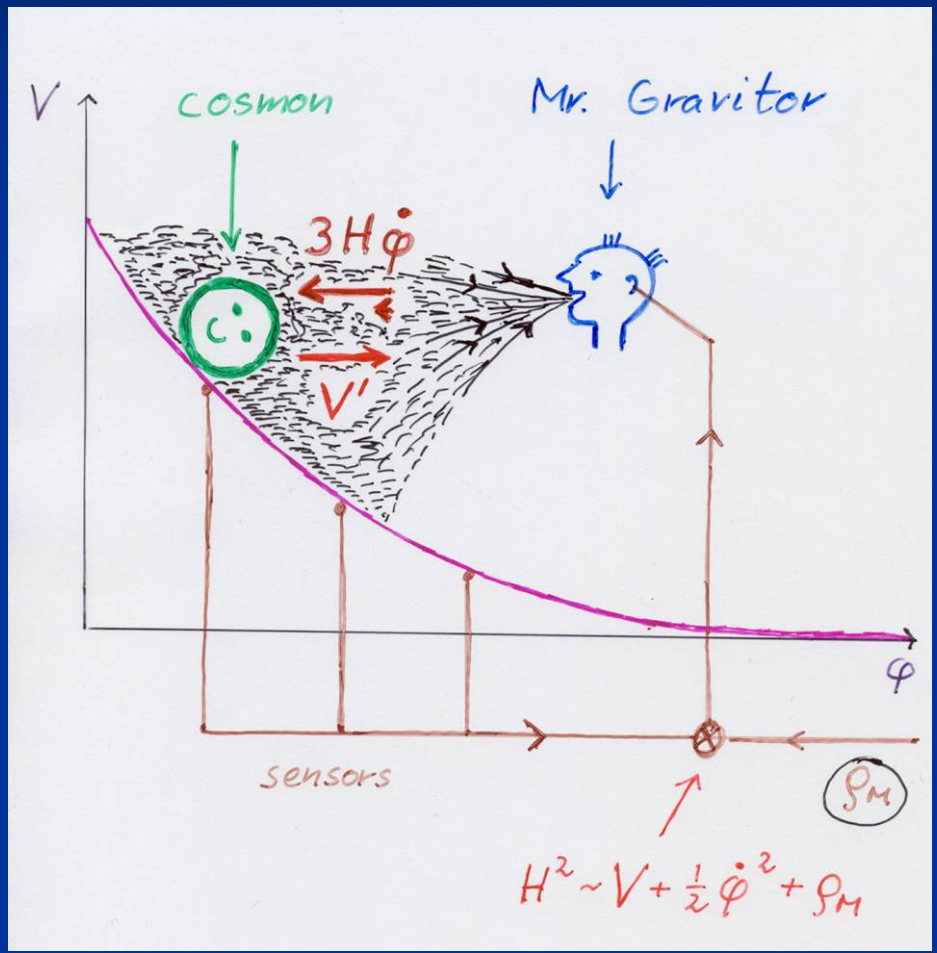
- $m_c^2 = V''$

for standard exponential potential , k ≈ const.

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

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

Cosmological equations



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

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

Cosmic Attractors

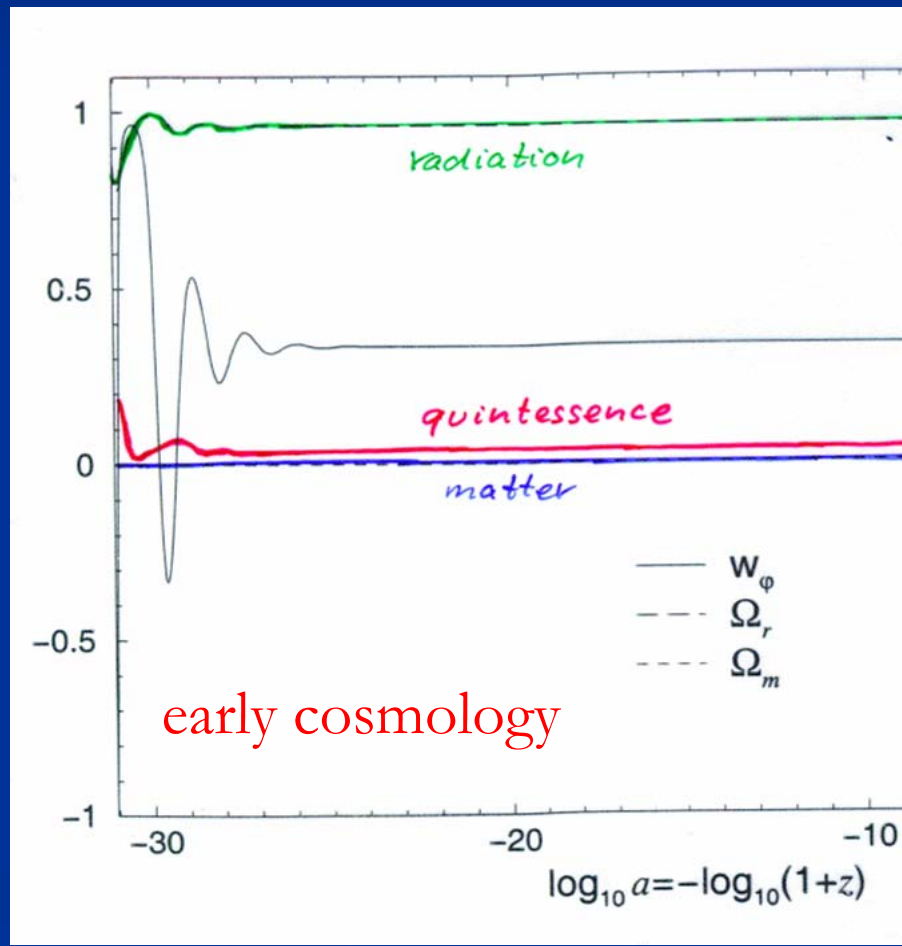
Solutions independent of initial conditions

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

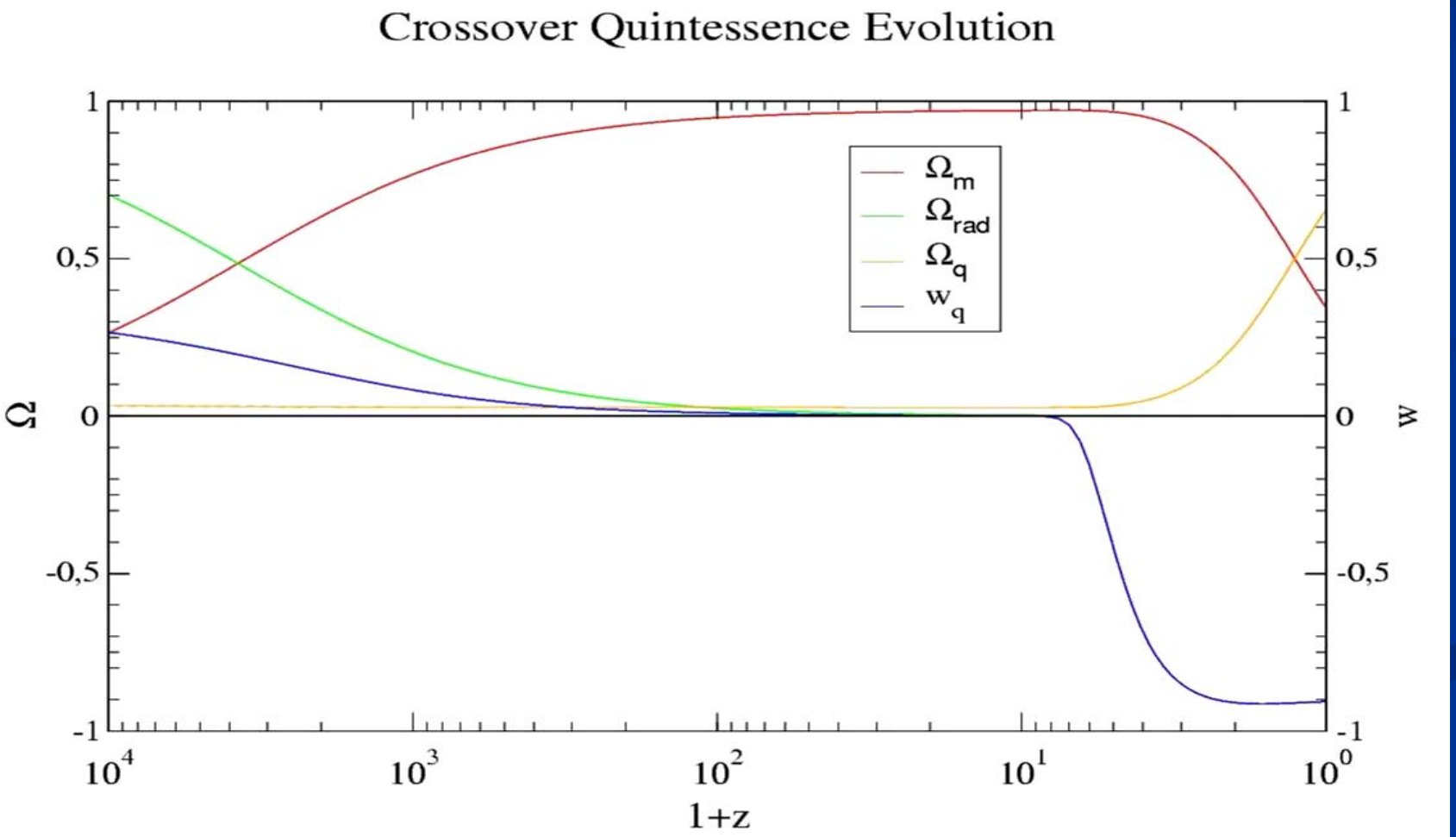
$\varphi \sim \ln(t)$

$\Omega_h \sim$ 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)

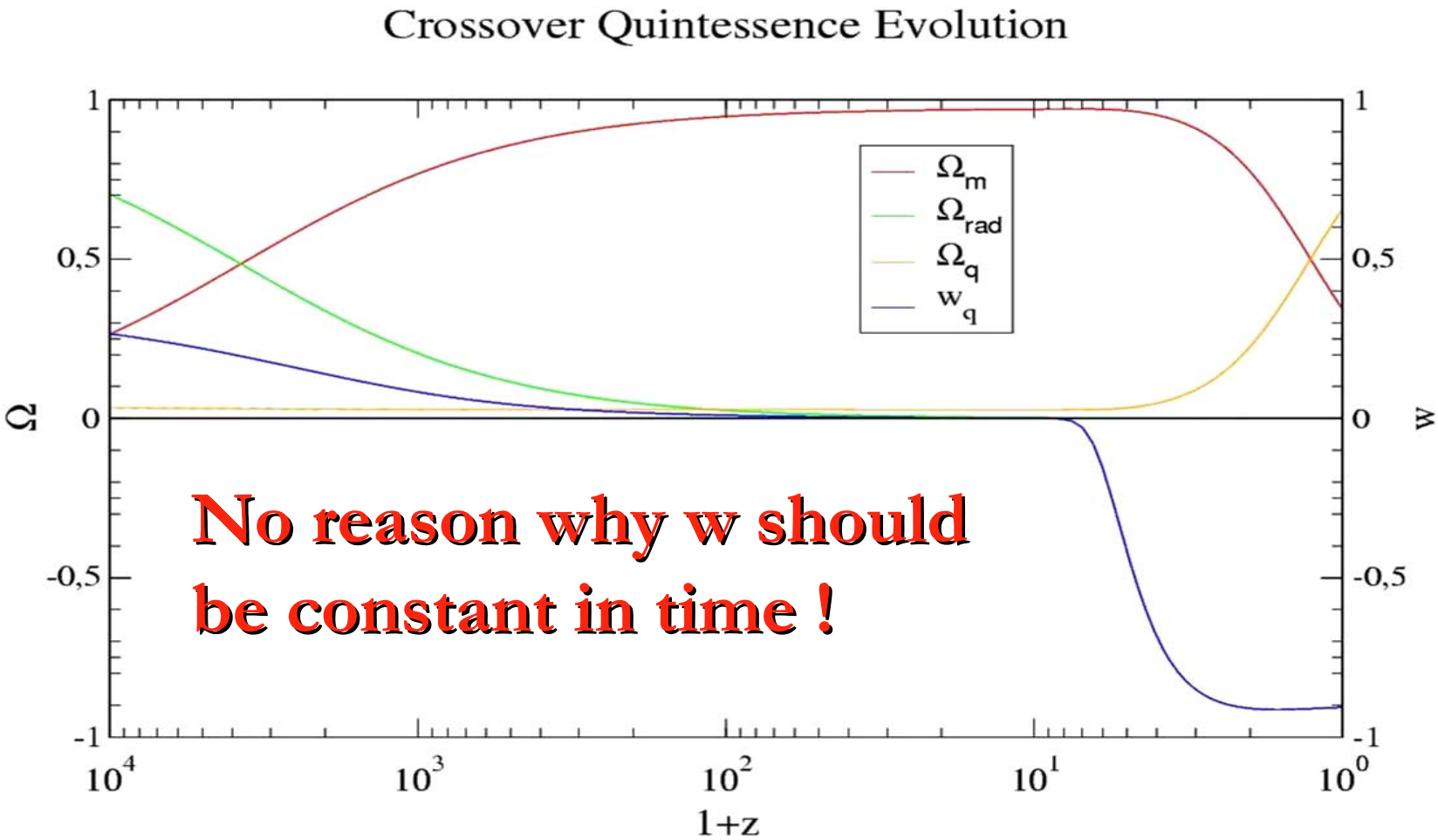
late universe with
small radiation component :

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

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

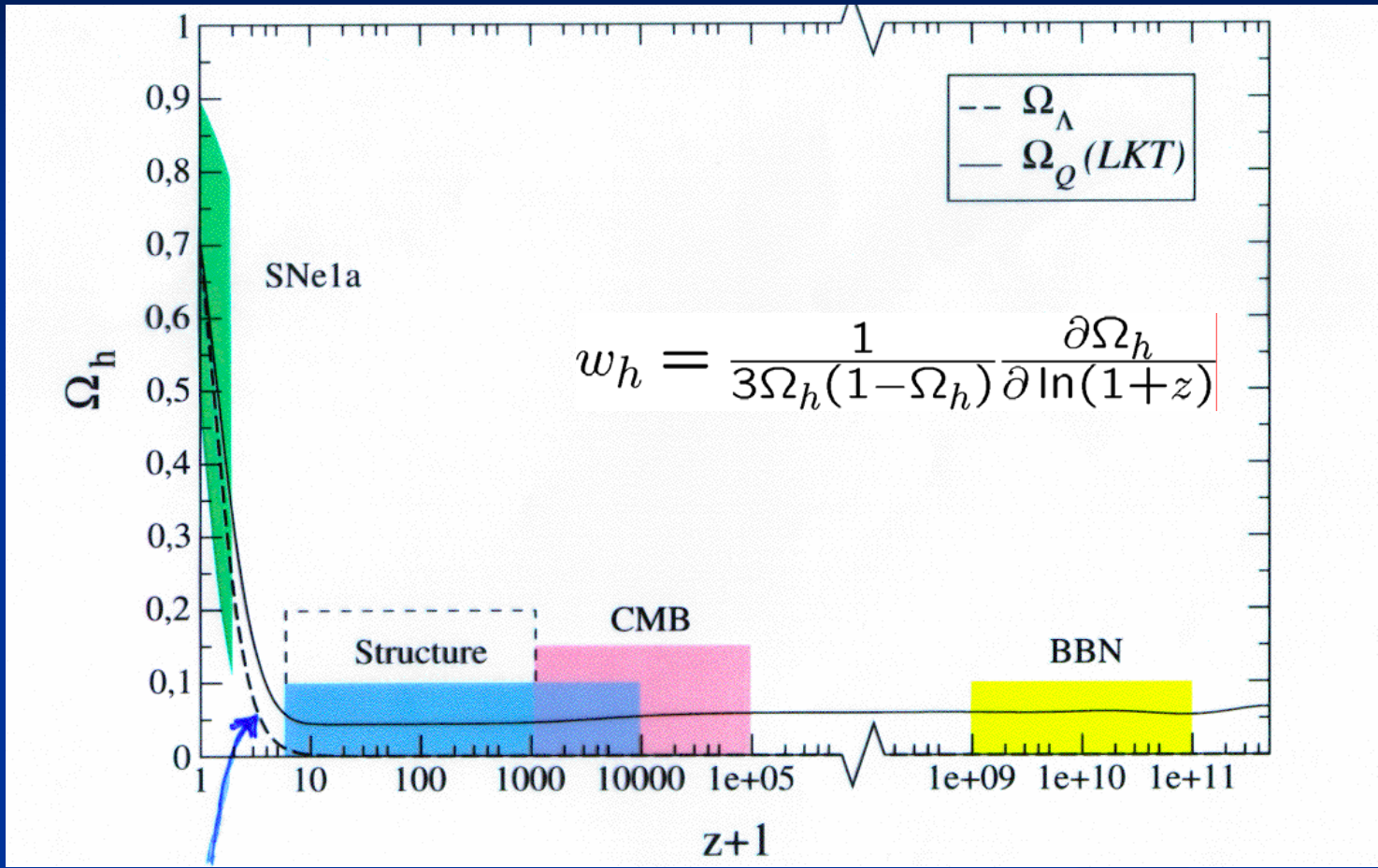
- $w = -1$ cosmological constant

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,…

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

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

Early dark energy

A few percent in the early Universe

Not possible for a cosmological constant

A few percent Early Dark Energy

If linear power spectrum fixed today (σ_8) :

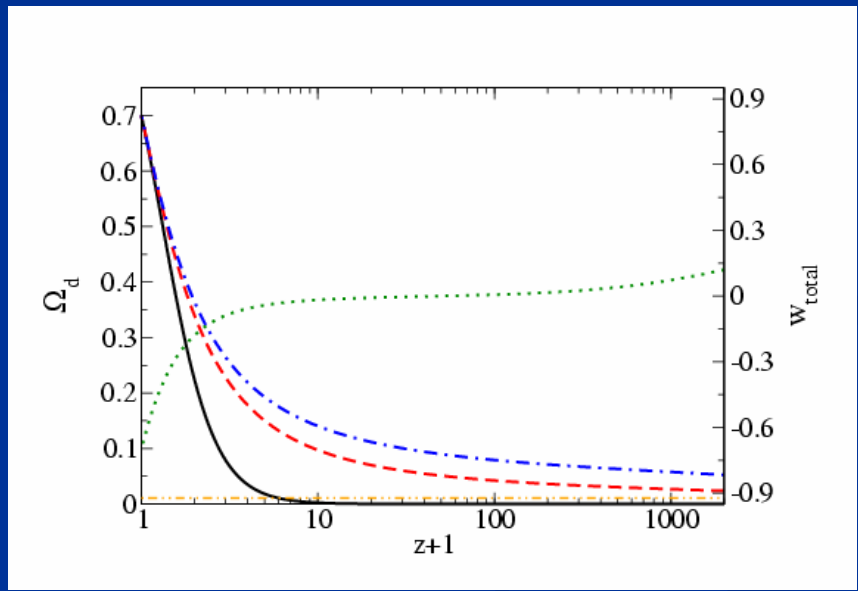
More Structure at high z !

Bartelmann,Doran,…

Early Dark Energy

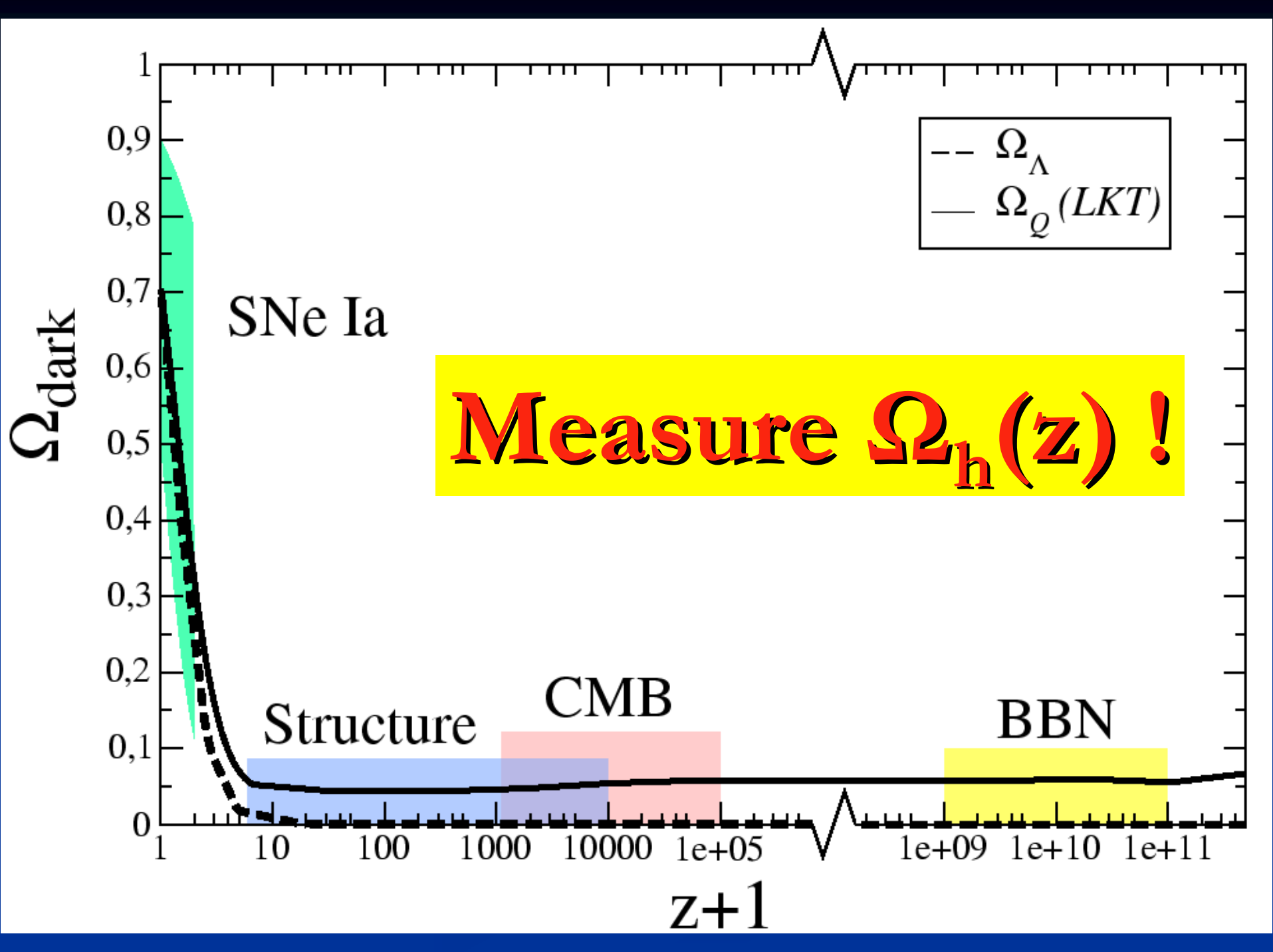
A few percent in the early Universe

Not possible for a cosmological constant



1σ and 2σ limits

Doran,Karwan,..


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 $\Omega_h(z)$!

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

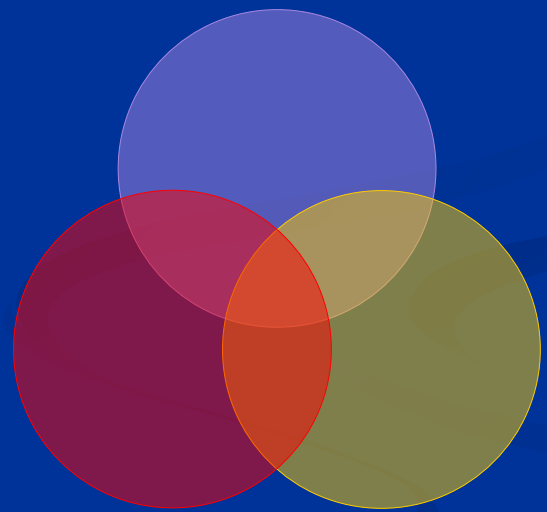
Quintessence and time variation of fundamental constants

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 !

Quintessence from higher dimensions

work with J. Schwindt

hep-th/0501049

Quintessence from higher dimensions

An instructive example:

Einstein – Maxwell theory in six dimensions

$$S = \int d^6x\sqrt{-g}\left\{-\frac{M_6^4}{2}R + \lambda_6 + \frac{1}{4}F^{AB}F_{AB}\right\}$$

Warning : not scale - free !

Dilatation anomaly replaced by explicit mass scales.

Metric

Ansatz with particular metric (not most general !)

which is consistent with

d=4 homogeneous and isotropic Universe

and internal U(1) x Z_2 isometry

$$ds^2 = \exp\left(-\frac{\phi(t)}{\bar{M}}\right)\{-dt^2 + a^2(t)d\vec{x}d\vec{x}\}$$

$$+\exp\left(\frac{\phi(t)}{\bar{M}}\right) r_0^2\{d\rho^2 + B^2\sin^2\rho\, d\theta^2\}$$

$$r_0^2 = \frac{\bar{M}^2}{4\pi B M_6^4}$$

B ≠ 1 : football shaped internal geometry

Exact solution

$$A_\theta = \frac{m}{2e_6}(1-\cos\rho)$$

m : monopole number (integer)

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

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

cosmology with scalar

and potential V :

$$V(\phi) = \bar{M}^4 \left\{ \frac{\lambda_6}{M_6^4 \bar{M}^2}\, e^{-\frac{\phi}{\bar{M}}} - 4\pi B \frac{M_6^4}{\bar{M}^4}\, e^{-\frac{2\phi}{\bar{M}}} + 2\pi^2 m^2 \frac{M_6^4}{e_6^2 \bar{M}^6}\, e^{-\frac{3\phi}{\bar{M}}} \right\}$$

Asymptotic solution for large t

$$H = 2t^{-1}, \quad \phi = 2\bar{M} \ln \frac{t}{\sqrt{10} M_6^2 \lambda_6^{-1/2}}$$

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

$$V + \frac{1}{2}\dot{\phi}^2 \propto t^{-2}$$

Naturalness

- No tuning of parameters or integration constants
- Radiation and matter can be implemented
- Asymptotic solution depends on details of model, e.g. solutions with constant $\Omega_h \neq 1$

problem :

time variation of fundamental constants

Are fundamental "constants" time dependent ?

Fine structure constant α (electric charge)

Ratio electron to proton mass

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 :

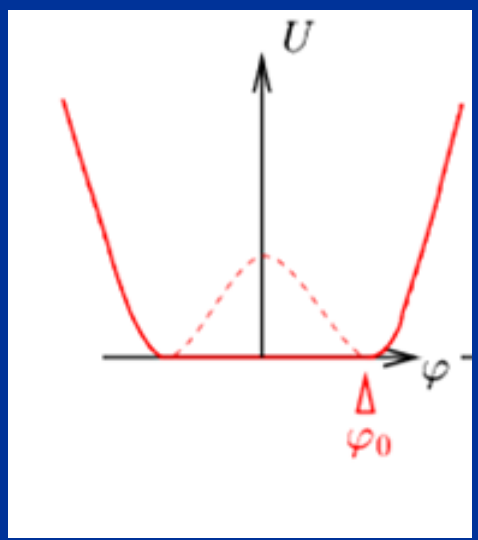
$$m_{electron} = h_{electron} * \varphi_H \quad \text{etc.}$$

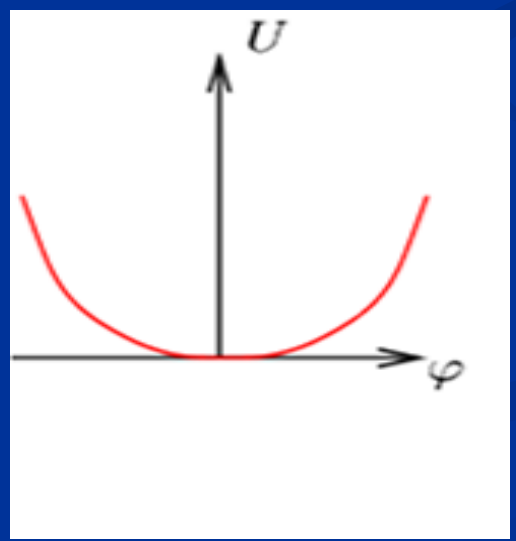
Restoration of symmetry at high temperature in the early Universe

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 :

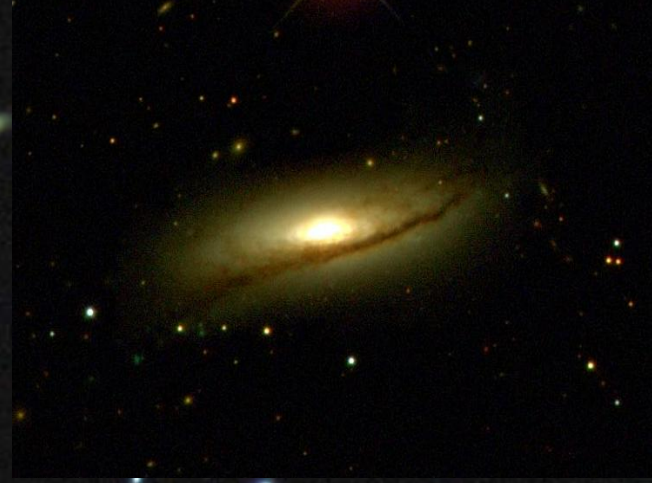
No difference in mass for electron and muon !

Quintessence :
Couplings are still varying now !

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

Where to look for time variation of fundamental couplings ?

- Nucleosynthesis
- Molecular absorption lines in the light of distant Quasars
- Oklo natural reactor
- Atomic clocks
- CMB

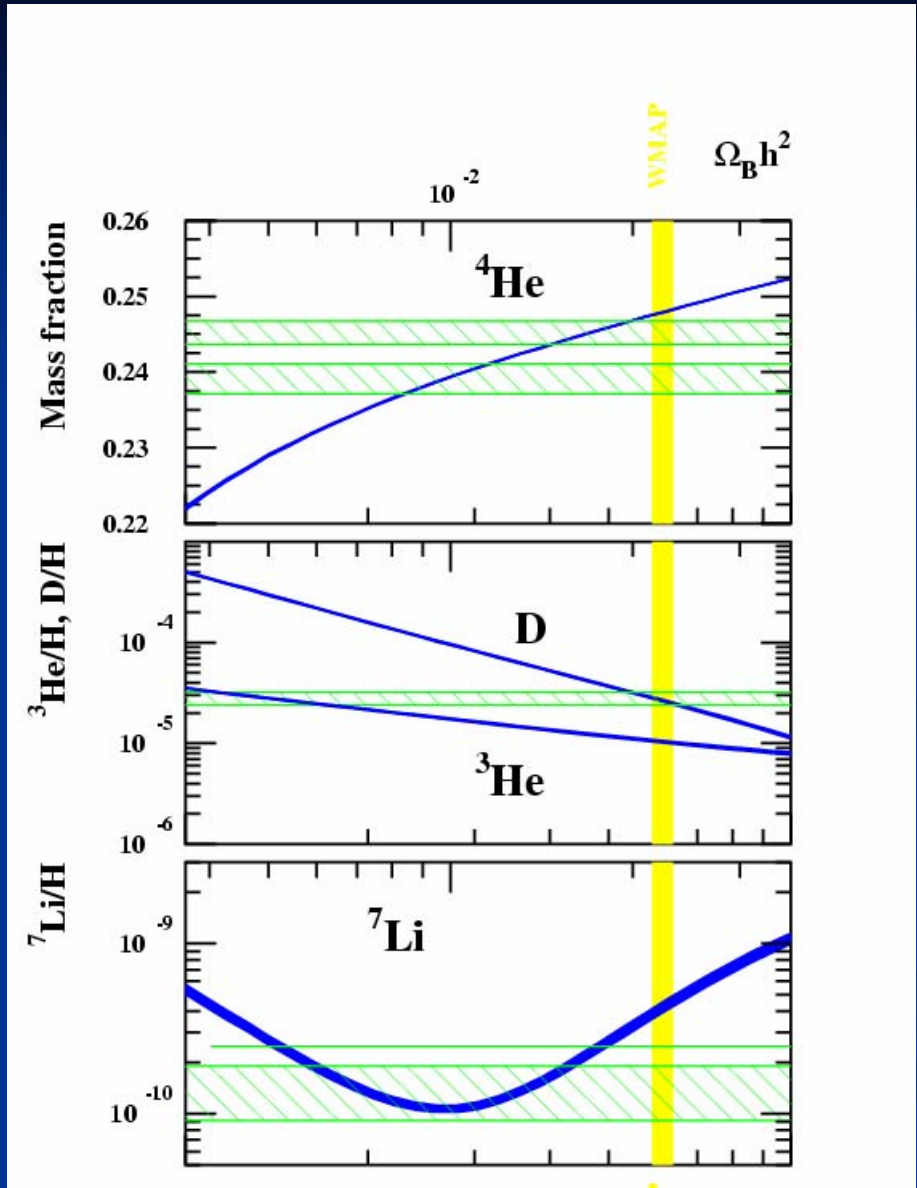


baryons :

the matter of stars and humans

$\Omega_b = 0.045$

Abundancies of primordial light elements from nucleosynthesis



A.Coc

Allowed values for variation of fine structure constant :

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

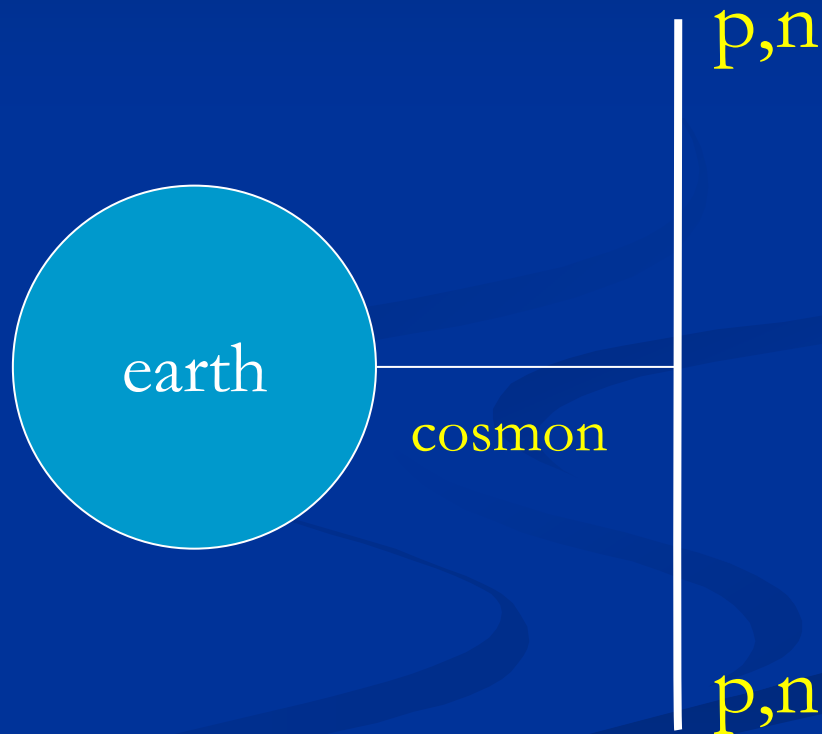
Possible signal for Quintessence

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

Apparent violation of equivalence principle

and

time variation of fundamental couplings

measure both the

cosmon – coupling to ordinary matter

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

Summary

- $\Omega_h = 0.75$
- Q/Λ : dynamical und static dark energy
  will be distinguishable
- Q : time varying fundamental coupling “constants”

  violation of equivalence principle

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

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

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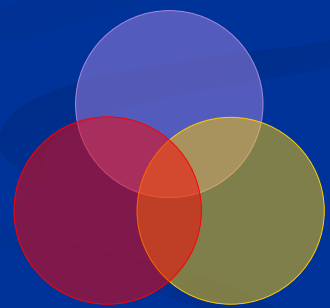
Cosmodynamics

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

Time evolution of fundamental couplings traces time evolution of quintessence

today w_h close to -1 :

- Small kinetic energy
- Slow change of φ
- Slow change of α

Very small $\Delta\alpha/\alpha$ for low z !

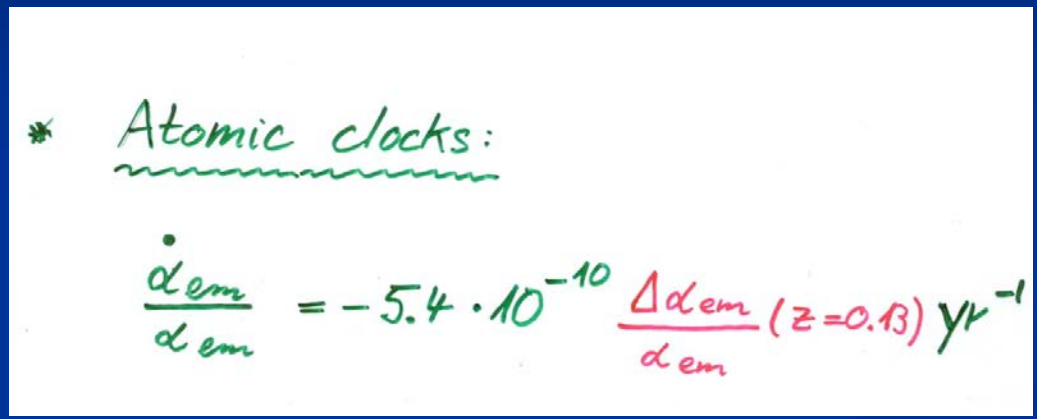
Crossover quintessence and time variation of fundamental "constants"

Upper bounds for relative variation of the fine structure constant

- Oklo natural reactor $\Delta\alpha/\alpha < 10^{-7}$ $z=0.13$
- Meteorites (Re-decay) $\Delta\alpha/\alpha < 3\ 10^{-7}$ $z=0.45$

- Crossover Quintessence compatible with QSO and upper bounds !

Atomic clocks and OKLO

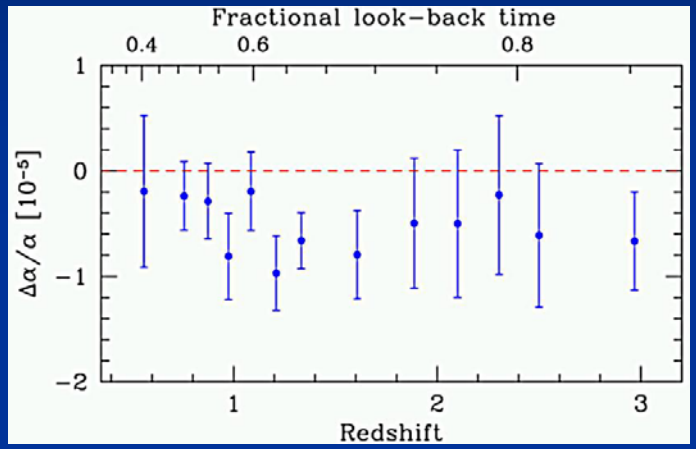


assumes that both effects are dominated by change of fine structure constant

Observation : $|\Delta\alpha/\alpha| < 2 * 10^{-15} / yr$

Munich group

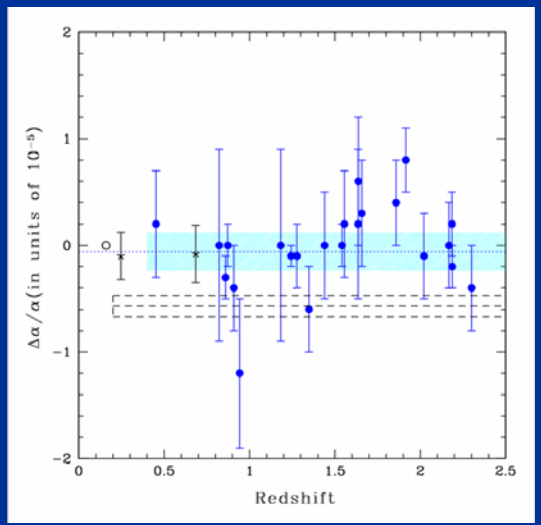
Variation of fine structure constant as function of redshift



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

$z \approx 2$

Cosmon and time variation of couplings : fixed points

- small coupling of cosmon to matter due to fixed points behavior

α_X : unified gauge coupling at unification scale $M_X \sim \chi$

running $\alpha_X(\chi)$:

$$\frac{\partial \alpha_X}{\partial \ln \chi} = b_2 \alpha_X - b_4 \alpha_X^2$$

$b_2, b_4 > 0$

UV – fixed point reached for $\chi \gg m$

$$\alpha_{X*} = \frac{b_2}{b_4} \approx \frac{1}{40}$$

close to fixed point :
small time evolution of couplings
coupling to matter weaker
than gravitational strength

Field equations

$$R_{AB} - \frac{1}{2} R g_{AB} = M_6^{-4} (T_{AB}^{(F)} + T_{AB}^{(M)} - \lambda_6 g_{AB}),$$

$$\partial_A (\sqrt{-g} F^{AB}) = 0.$$

Energy momentum tensor

$$T^{(F)}_{AB} = F_{AC}F_B{}^C - \frac{1}{4}F_{CD}F^{CD}g_{AB}$$

$$R_{AB} - \frac{1}{2}Rg_{AB} = M_6^{-4}(T^{(F)}_{AB} + T^{(M)}_{AB} - \lambda_6 g_{AB}),$$

$$\partial_A(\sqrt{-g}F^{AB}) = 0.$$

Free integration constants

M , B , $\Phi(t=0)$, $(d\Phi/dt)(t=0)$: continuous

m : discrete

Conical singularities

deficit angle $\Delta = 2\pi(1 - B)$

singularities can be included with
energy momentum tensor on brane

$$(T^{(B)})^{\nu}_{\mu} = \frac{B-1}{B r_0^2 e^{\phi/\bar{M}}} M_6^4 \left(\frac{\delta(\rho)}{\rho} + \frac{\delta(\rho-\pi)}{\pi-\rho} \right) \delta^{\nu}_{\mu}$$

bulk point of view : describe everything in terms of bulk geometry (no modes on brane without tail in bulk)

Dimensional reduction

$$L^{(4)} = -\frac{\bar{M}^2}{2}R + \frac{Z_1(\phi)}{4}F^{(1)}_{\mu\nu}F^{\mu\nu(1)}$$

$$+\frac{Z_2(\phi)}{4}F^{(2)}_{\mu\nu}F^{\mu\nu(2)}$$

$$+i\sum_j \bar{\psi}_j\gamma^\mu(\partial_\mu - iQ^{(1)}_j\bar{e}_1A^{(1)}_\mu - iQ^{(2)}_j\bar{e}_2A^{(2)}_\mu)\psi_j$$

$$+\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + V(\phi)$$

Time dependent gauge coupling

$$e_{1(2)} = \frac{\bar{e}_{1(2)}}{\sqrt{Z_{1(2)}}}$$

$$Z_1 = e^{\phi/\bar{M}}, \quad Z_2 = e^{2\phi/\bar{M}}$$

Realistic model : Crossover Quintessence

$$\partial\delta/\partial \ln \chi = E\delta^2$$ (like QCD gauge coupling)

critical χ where δ grows large
critical φ where k grows large $k^2(\varphi) = \delta(\chi)/4$

$k^2(\varphi)$ = "$1/(2E(\varphi_c - \varphi)/M)$"

if $\varphi_c \approx 276/M$ (tuning !)

Relative increase of dark energy in present cosmological epoch