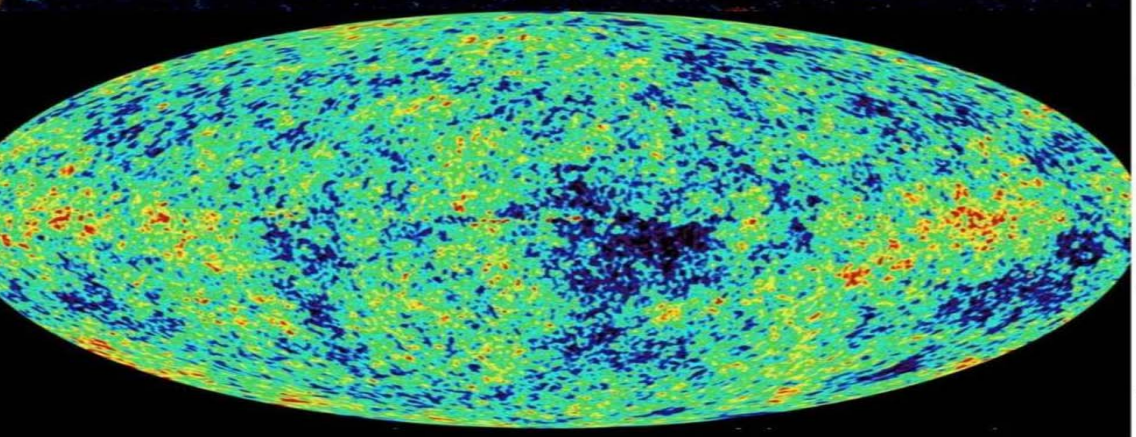
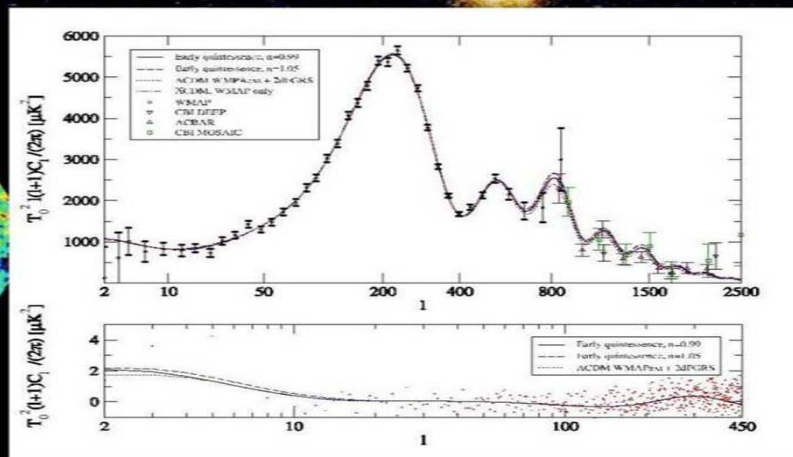
Dark Energy
a cosmic mystery





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

=

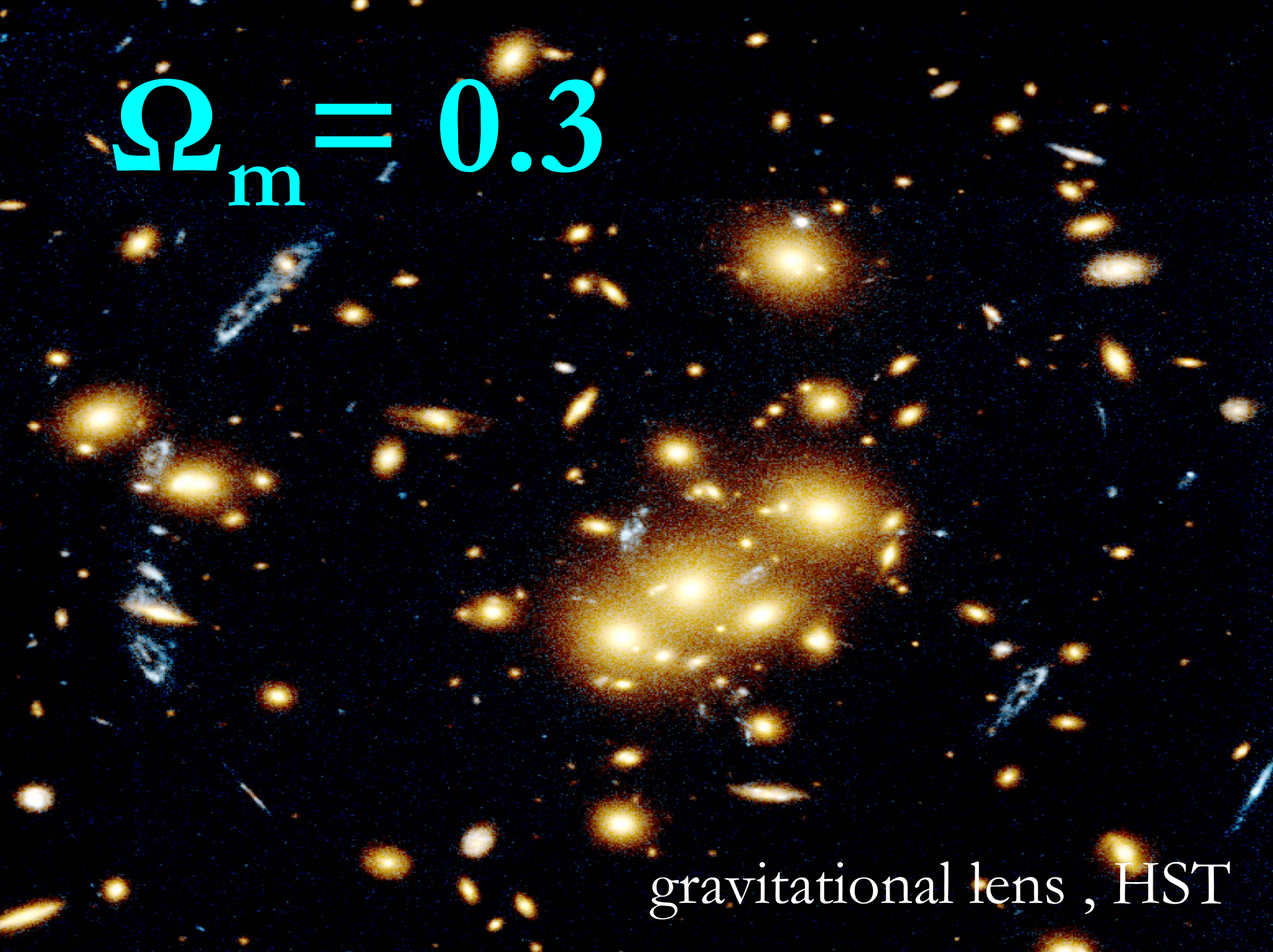
Matter + Dark Energy

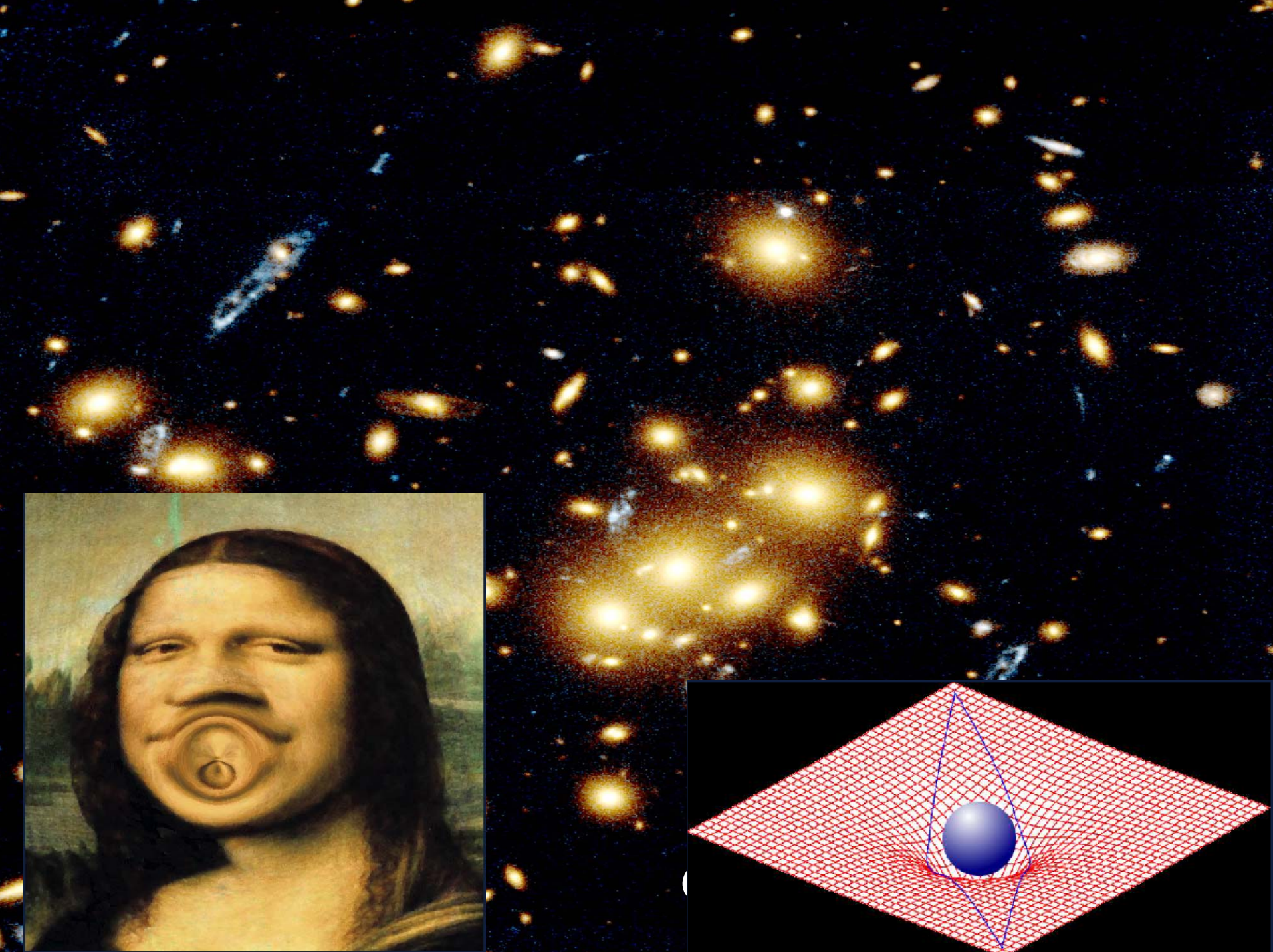
30 % + 70 %

What is Dark Energy ?

Matter : Everything that clumps

Abell 2255 Cluster
~300 Mpc


$\Omega_m = 0.3$
gravitational lens , HST



spatially flat universe

$$\Omega_{tot} = 1$$

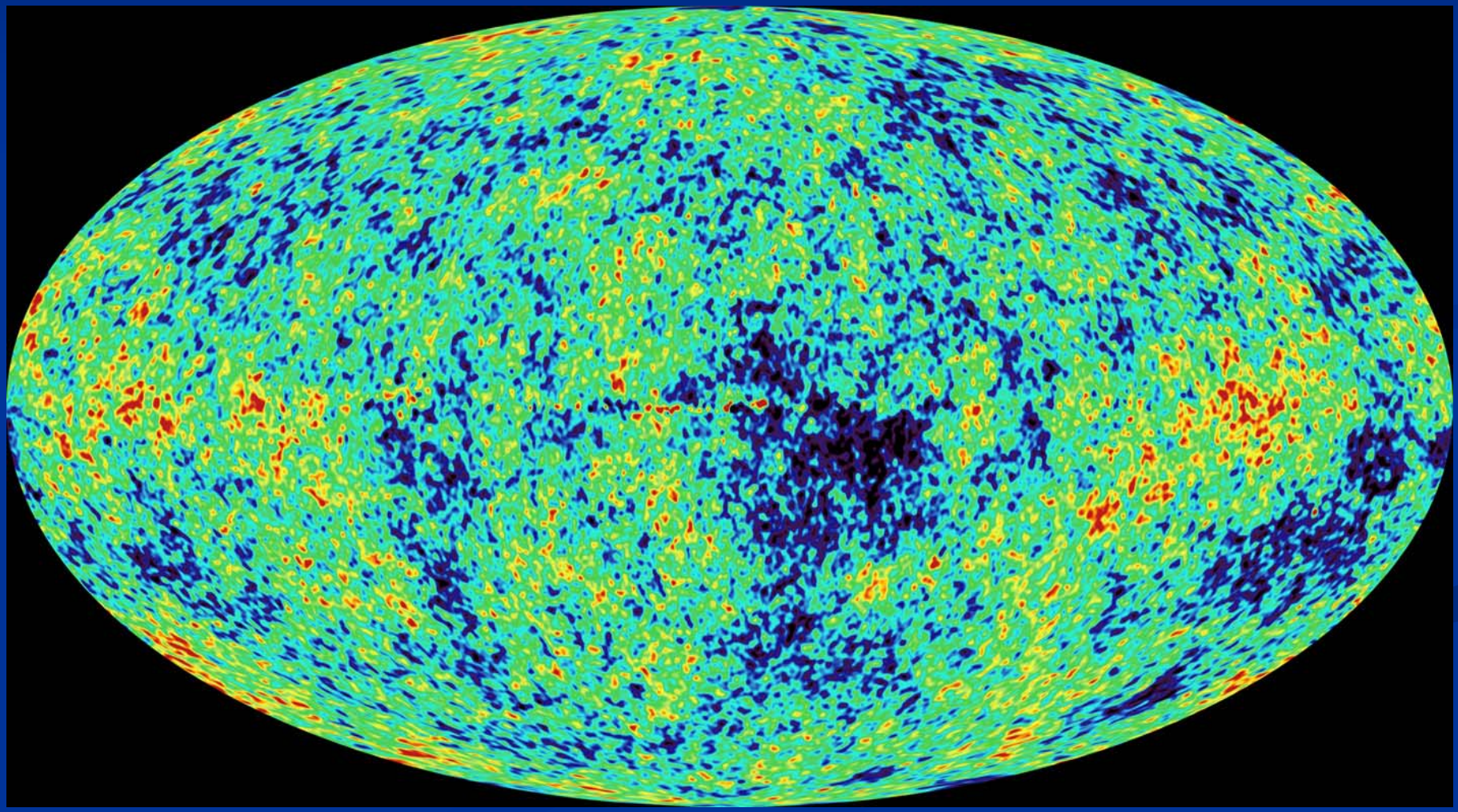
- theory (inflationary universe)

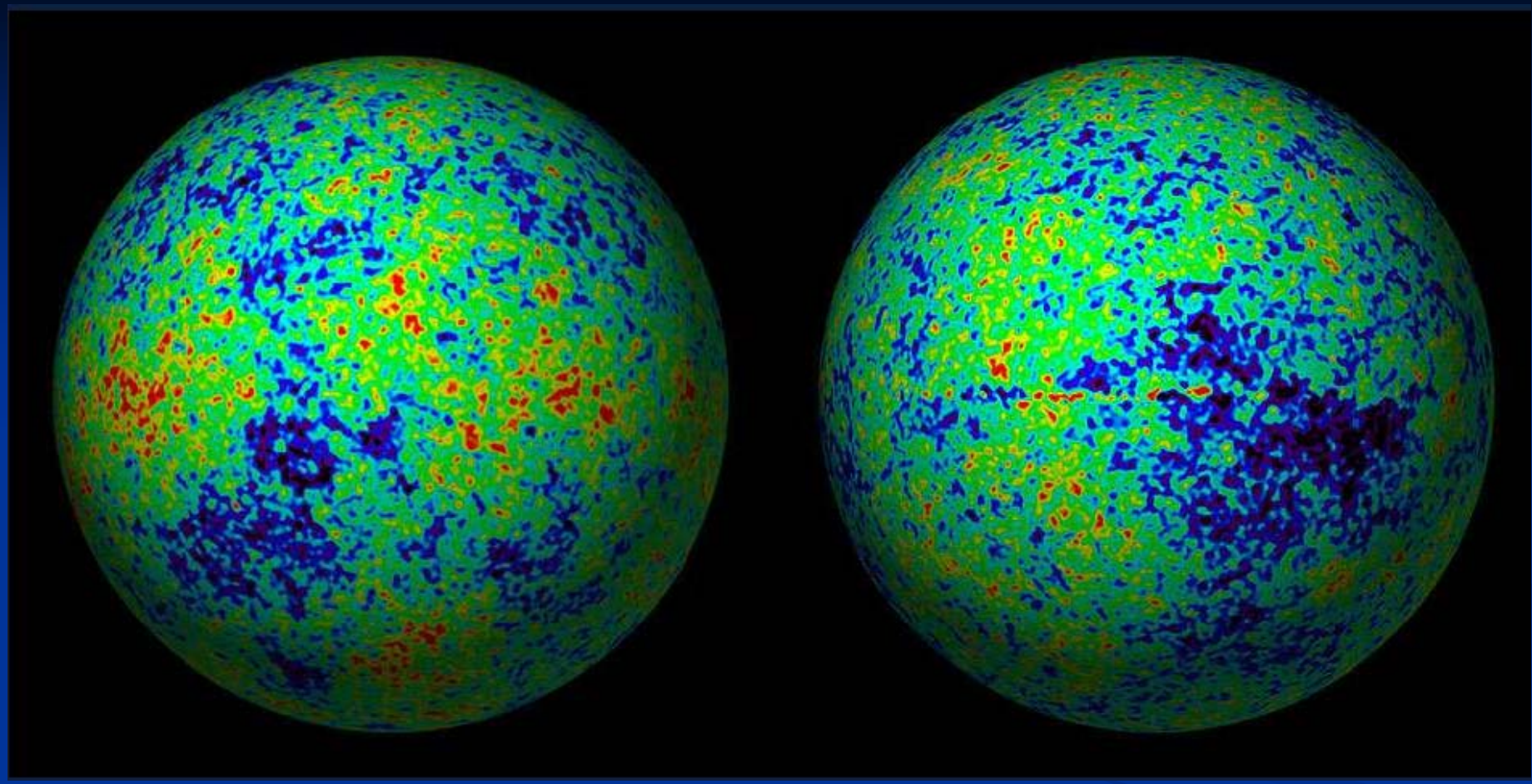
  Ω_{tot} =1.0000…….x

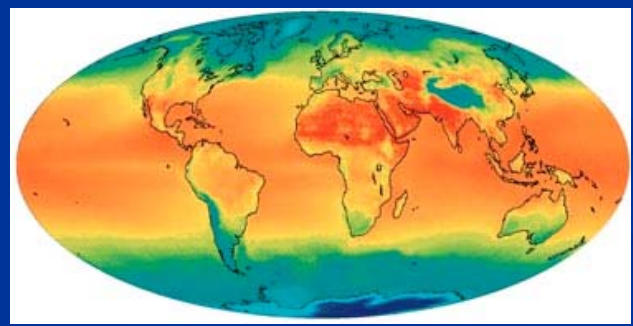
- observation (WMAP)

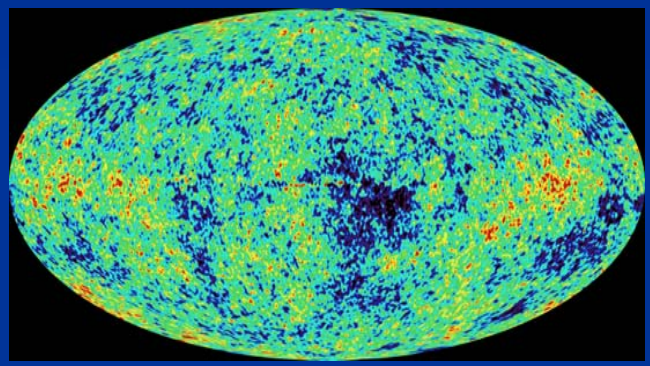
  Ω_{tot} =1.02 (0.02)

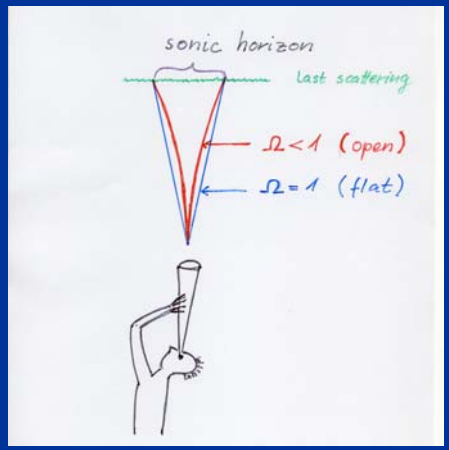
picture of the big bang



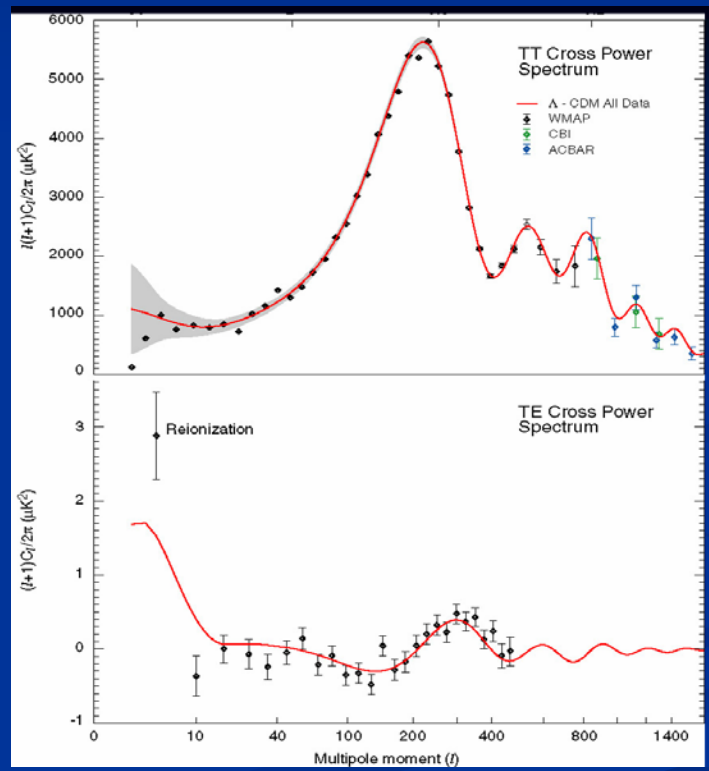








$\Omega_{tot}=1$



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 “

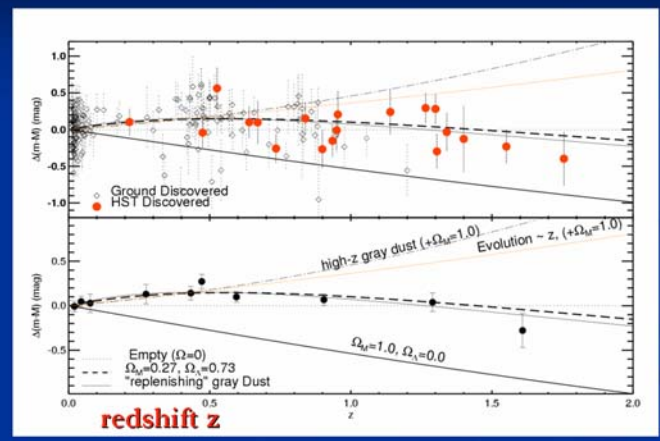
No force in absence oc matter –
“ In what direction should it draw ? “

Predictions for dark energy cosmologies

The expansion of the Universe

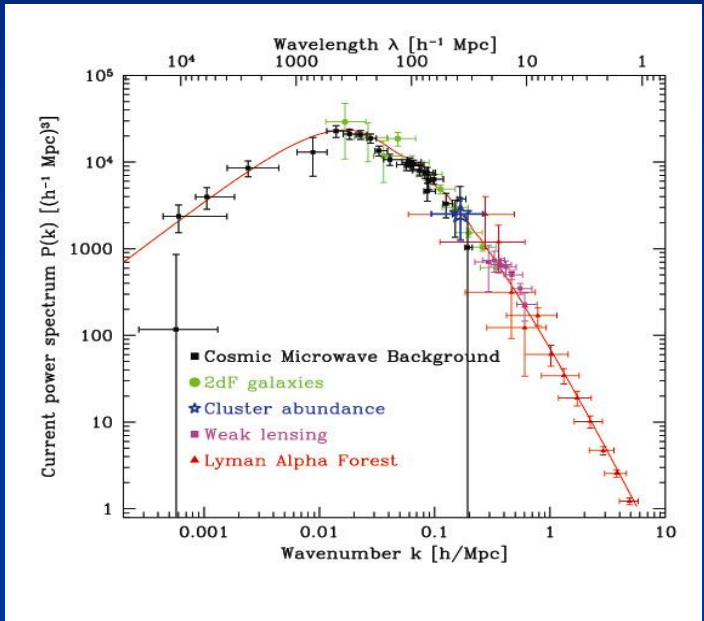
accelerates today !

Supernovae 1a Hubble diagram



Riess et al. 2004

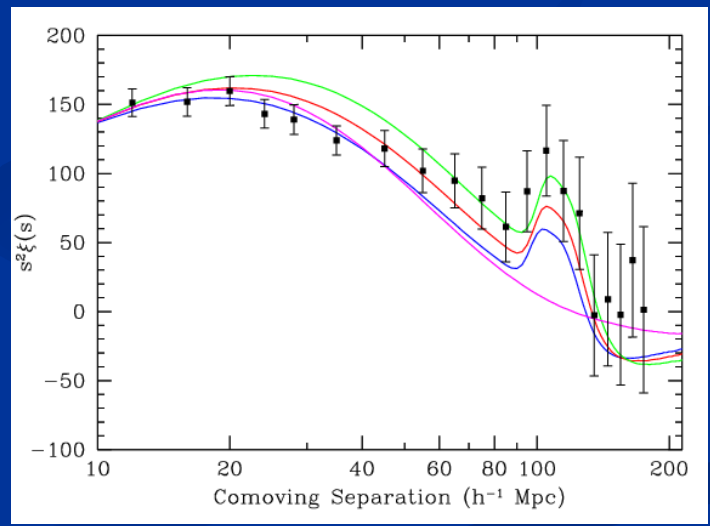
Power spectrum



Structure formation :
One primordial fluctuation- spectrum

Baryon - Peak

galaxy – correlation – function



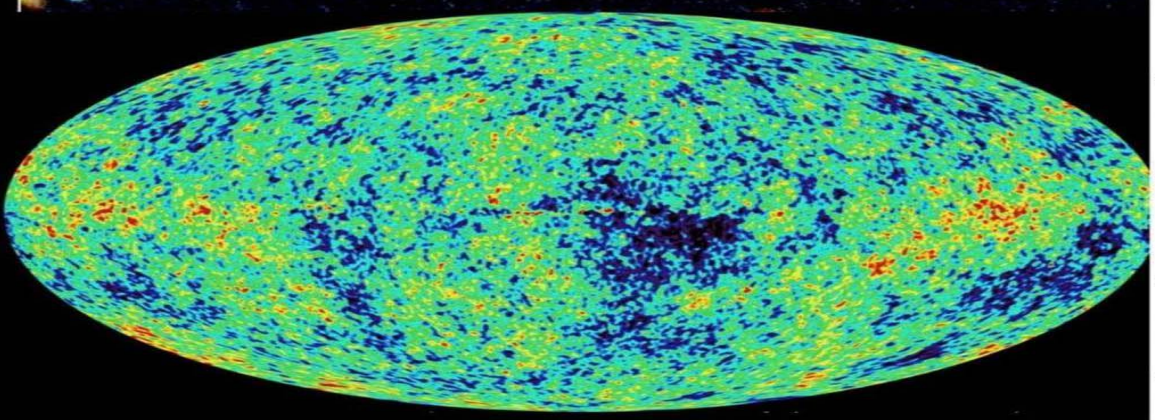
SDSS

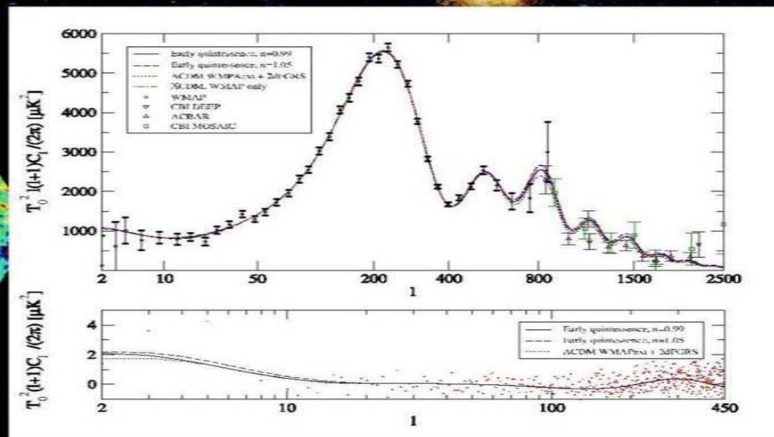
consistent cosmological model !

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 ?

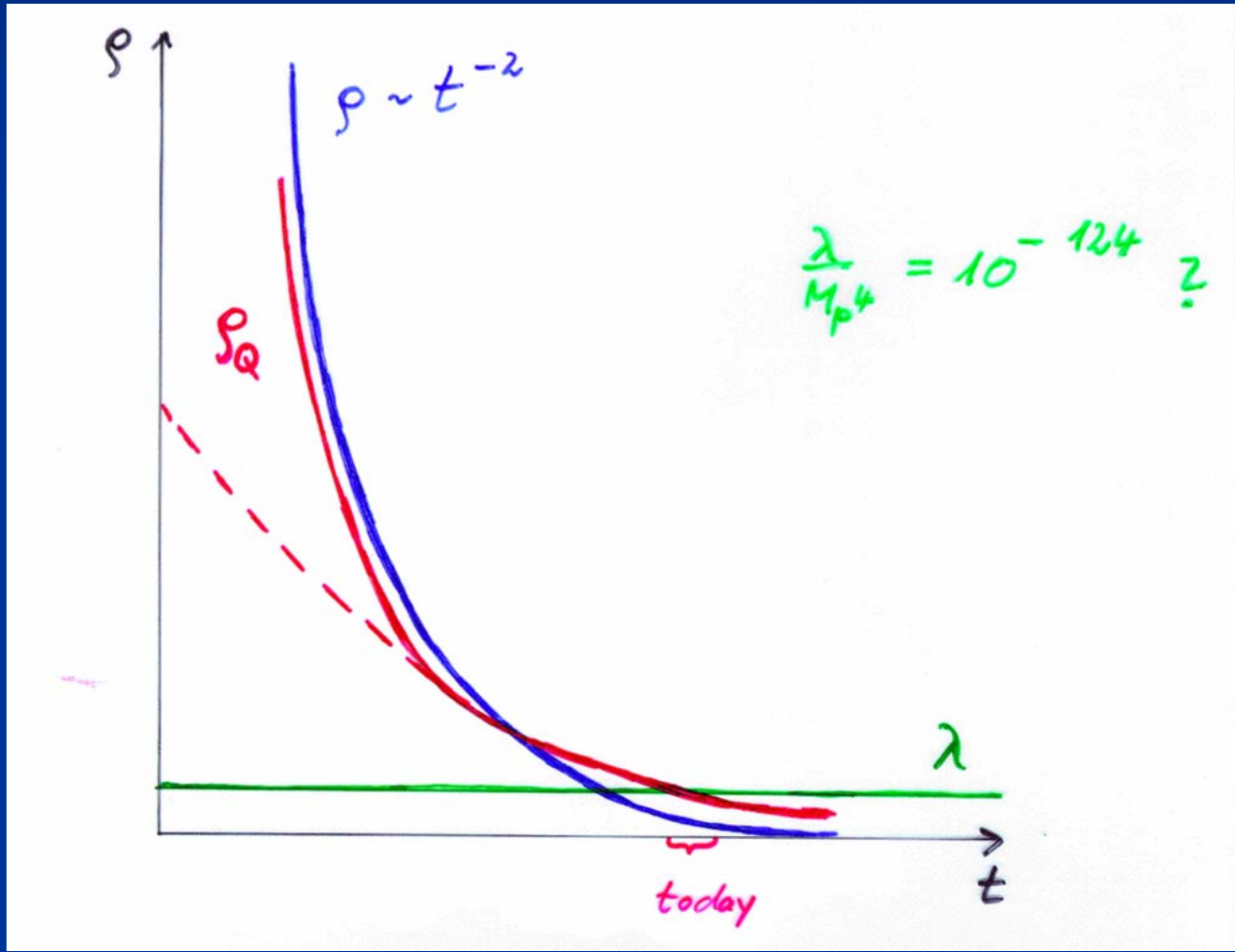
Cosmological Constant
- Einstein -

- 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 $\varphi(x,y,z,t)$

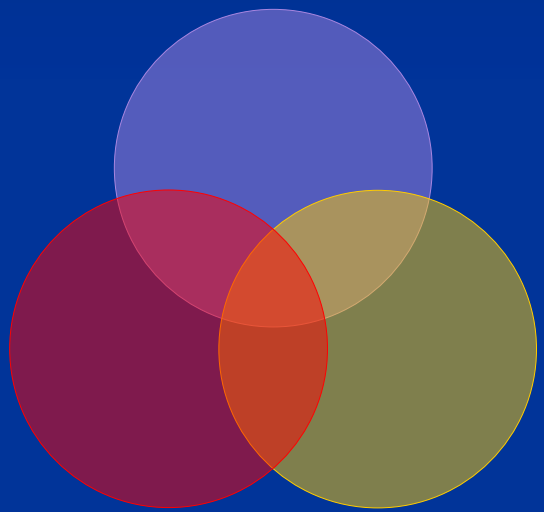
similar to electric field , but no direction (scalar field)

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 $V(\varphi)$ determines details of the model

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

for increasing φ the potential decreases towards zero !

Cosmon

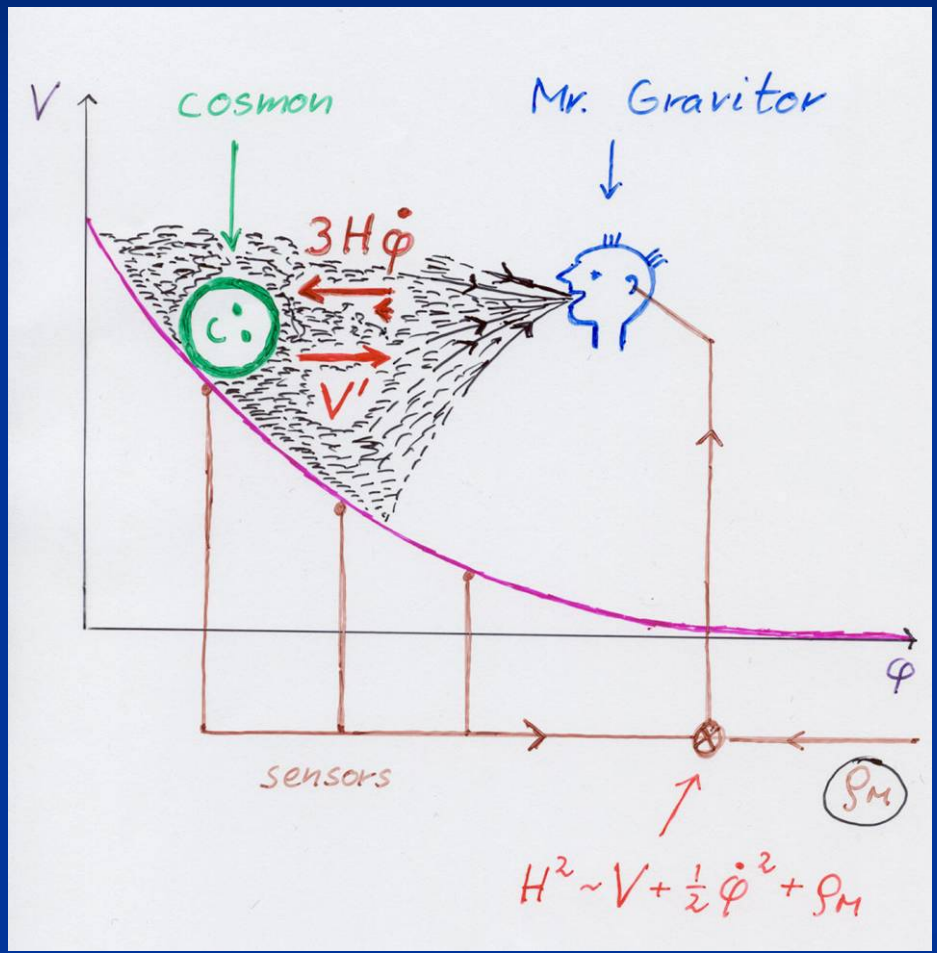
- *Scalar field changes its value even in the **present** cosmological epoch*
- *Potential und kinetic energy of cosmon contribute to the energy density of the Universe*
- *Time - variable dark energy :*

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

Cosmon

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

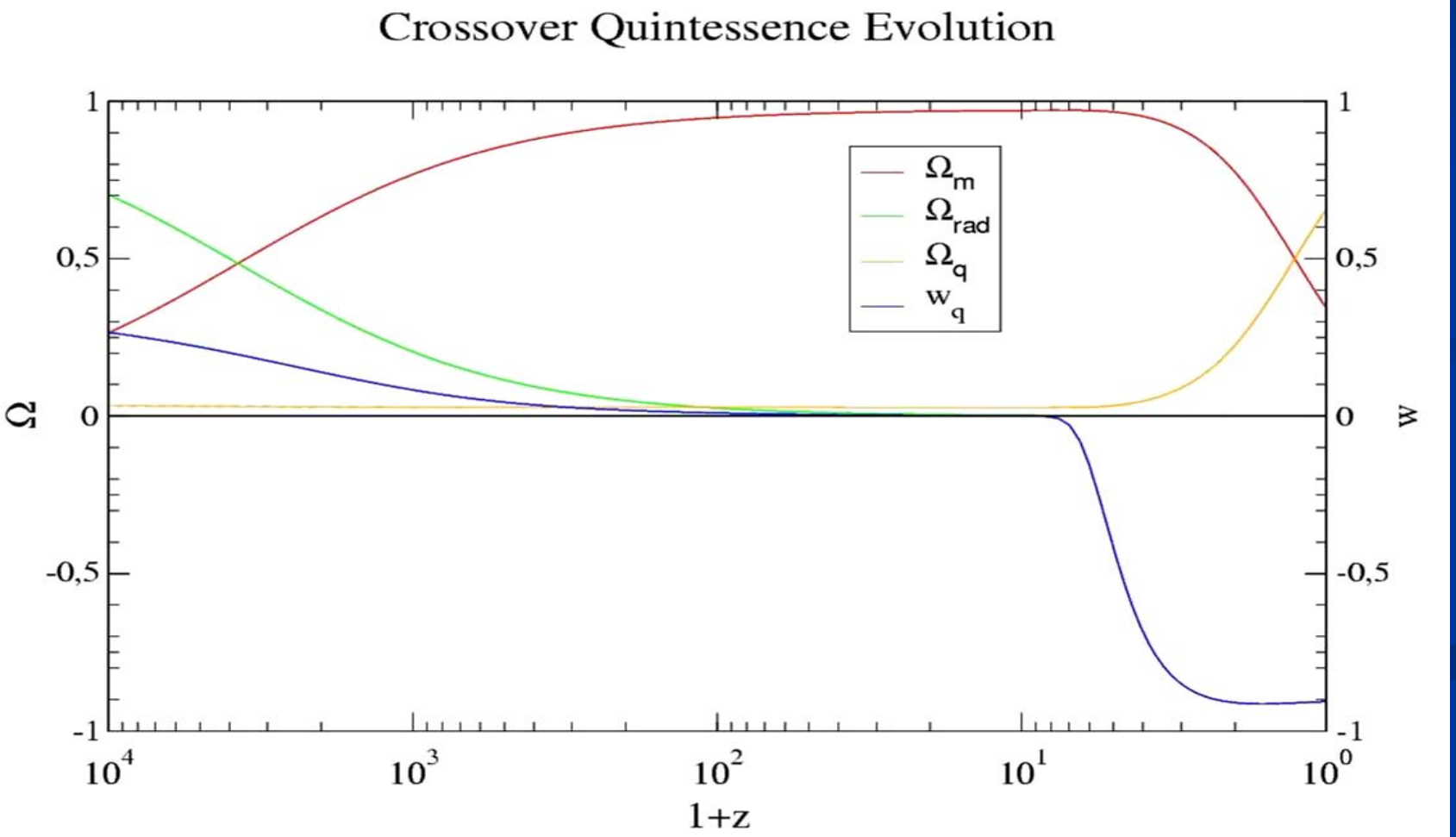
Cosmological equations



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

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

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)

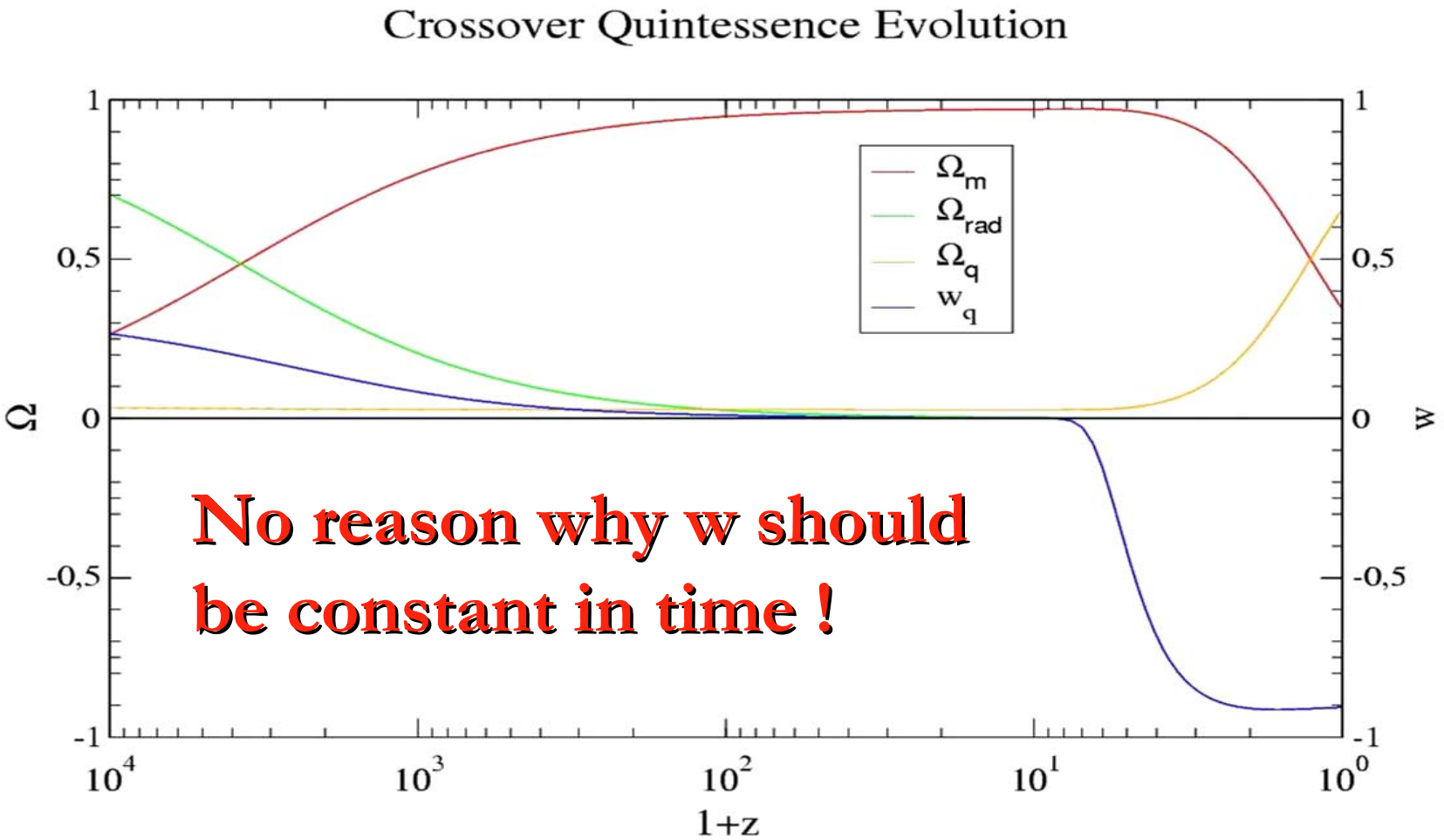
late universe with
small radiation component :

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

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

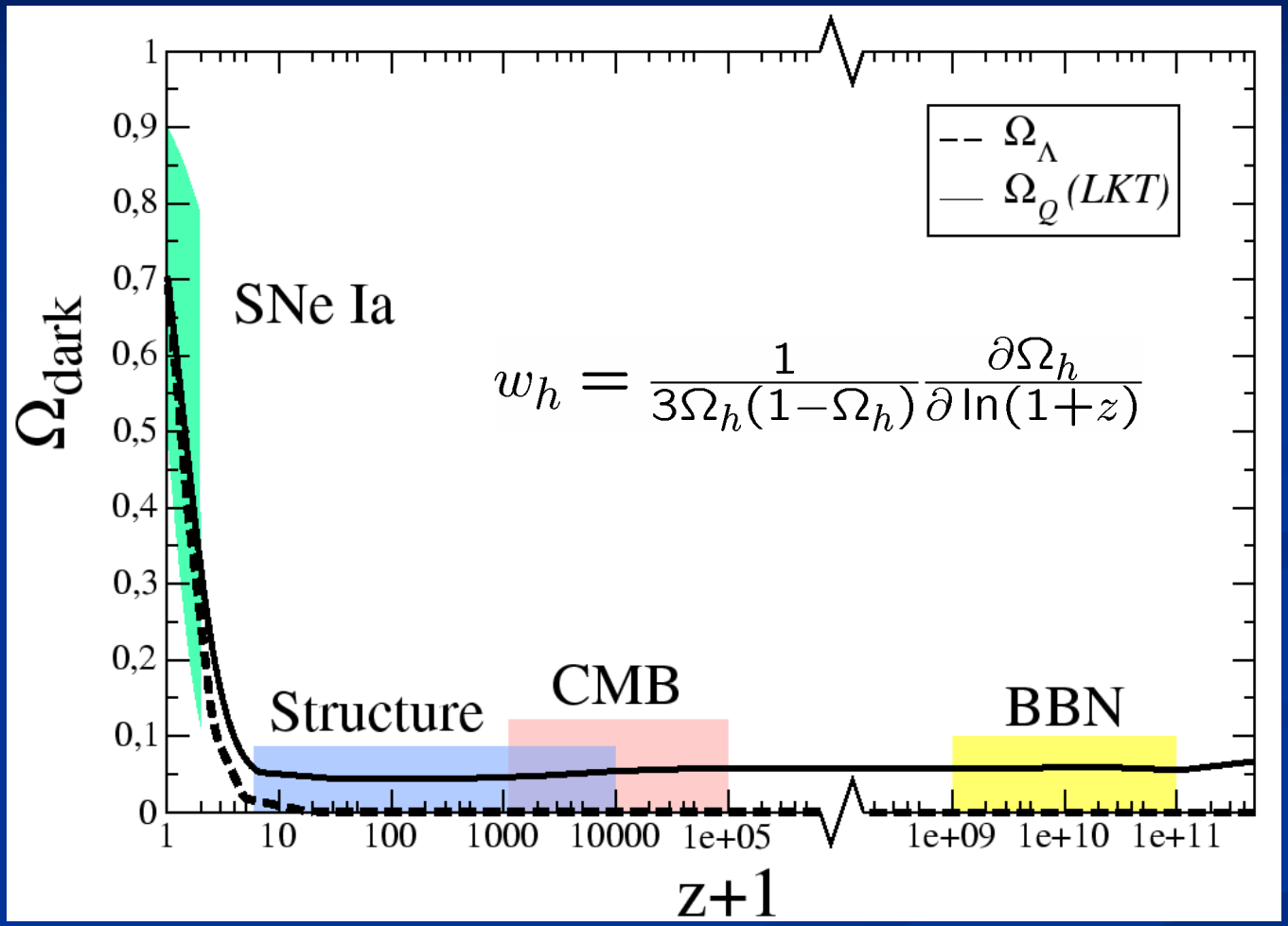
- w = -1 cosmological constant

Quintessence becomes important "today"



How can quintessence be distinguished from a cosmological constant ?

Time dependence of dark energy



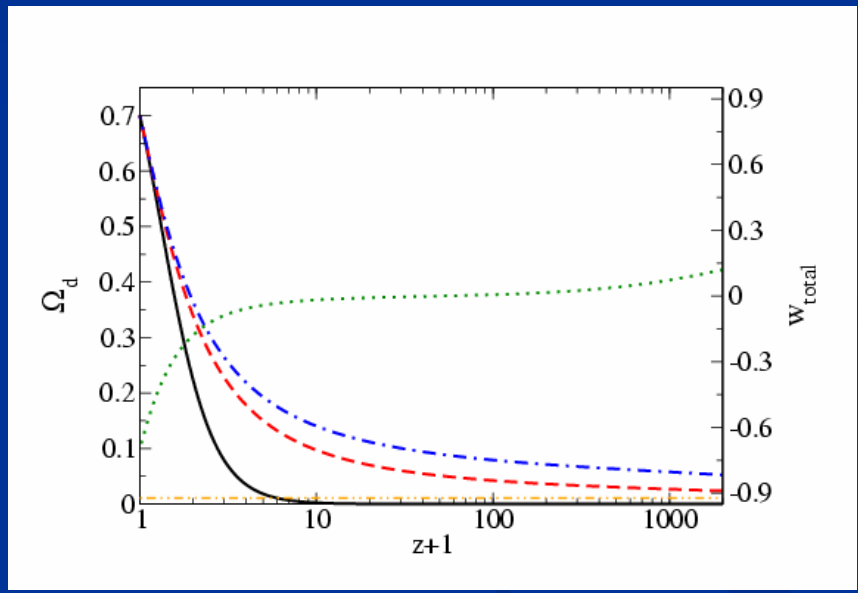
cosmological constant : $\Omega_h \sim t^2 \sim (1+z)^{-3}$

M.Doran,…

Early Dark Energy

A few percent in the early Universe

Not possible for a cosmological constant

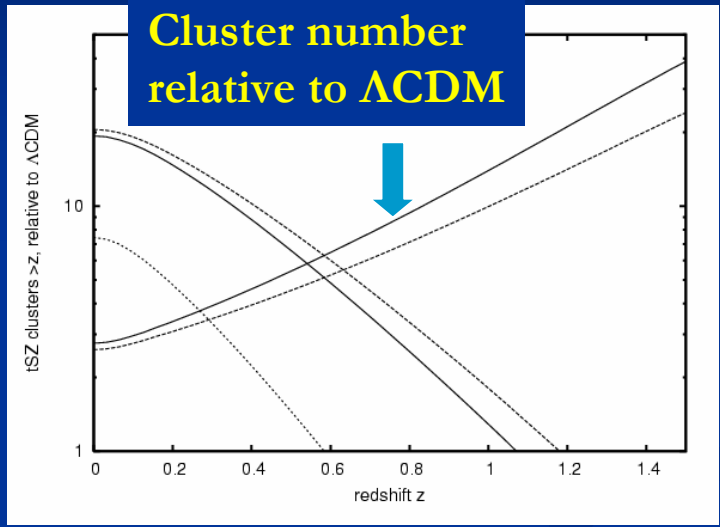


1σ and 2σ limits

Doran,Karwan,..

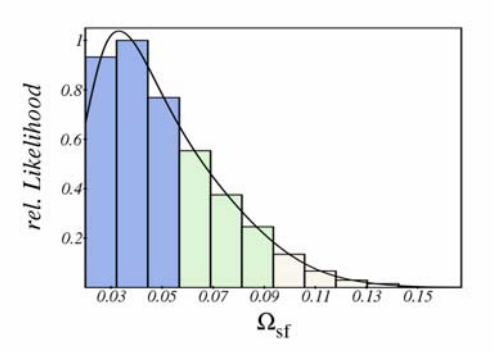
Little Early Dark Energy can make large effect !

More clusters at high redshift

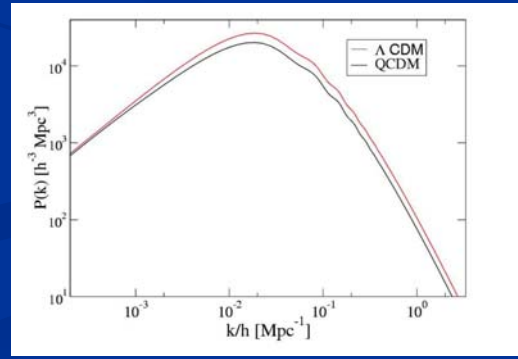


Two models with
4% Dark Energy
during structure formation

Fixed σ_8
(normalization dependence !)



Early Quintessence
slows downs
the growth
of structure



Dark Energy during structure formation

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

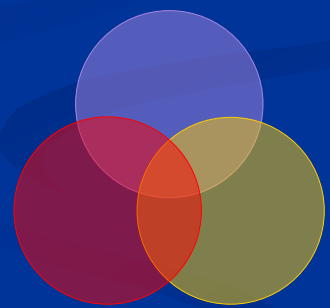
Cosmodynamics

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

"Fifth Force"

- Mediated by scalar field

R.Peccei,J.Sola,C.Wetterich,Phys.Lett.B195,183(1987)

- Coupling strength: weaker than gravity

  (nonrenormalizable interactions ~ M^{-2})

- Composition dependence

  ⟹ violation of equivalence principle

- Quintessence: connected to time variation of fundamental couplings

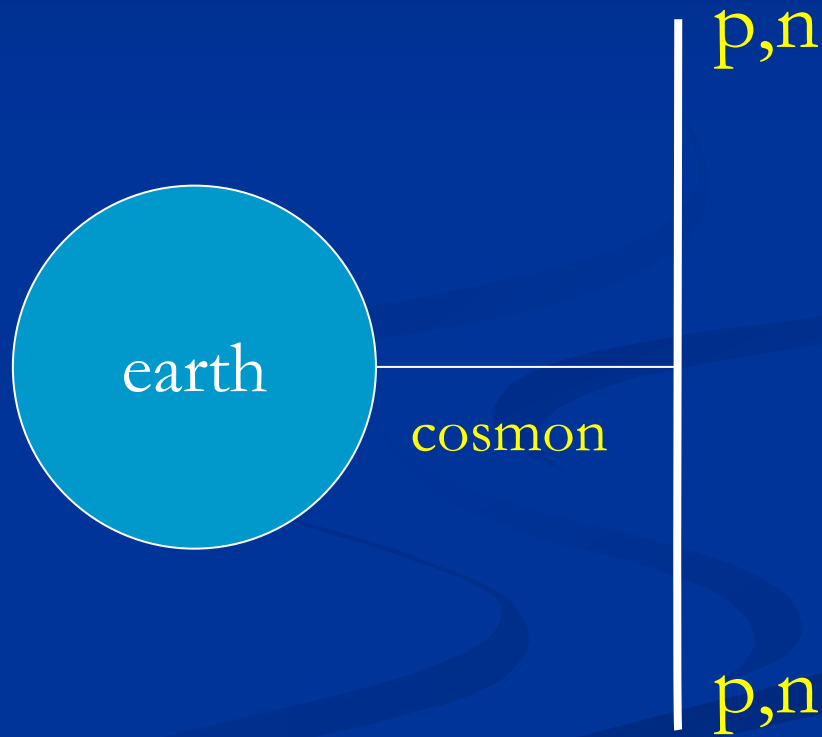
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

(1) $\alpha_x(\varphi) \to \Lambda_{QCD}(\varphi) \to m_n(\varphi)$

nucleon mass depends on value of the cosmon field (and therefore on time)

(2) expand around cosmological value $\varphi_0(t)$:

$$\varphi(\vec{x}, t) = \varphi_0(t) + \delta\varphi(\vec{x}, t)$$

$$m_n = m_n(\varphi_0) + \frac{\partial m_n}{\partial \varphi}\Big|_{\varphi_0} \delta\varphi$$

$\Rightarrow$ cosmon - nucleon vertex $\sim \bar{n} n \delta\varphi$

$\Rightarrow$ earth is source for surrounding local cosmon field $\delta\varphi(|\vec{r}|)$

(3) Test body carries effective

„cosmon charge"

$$Q_c = k^{-1} \frac{\partial m_t}{\partial \varphi}$$

to be compared with „gravitational charge"

$$Q_g = \frac{m_t}{\sqrt{2}\, \bar{M}_p}$$

⇒ Correction to Newtonian potential

$$V_N = - \frac{G_N M m_t}{r} (1 + \alpha_t)$$

$$\alpha_t = \frac{2 \bar{M}_p^2}{k^2} \frac{\partial \ln M}{\partial \varphi} \frac{\partial \ln m_t}{\partial \varphi}$$

(4) Protons and neutrons have different cosmon charges, $\frac{\partial m_p}{\partial \varphi} \neq \frac{\partial m_n}{\partial \varphi}$

Differential acceleration

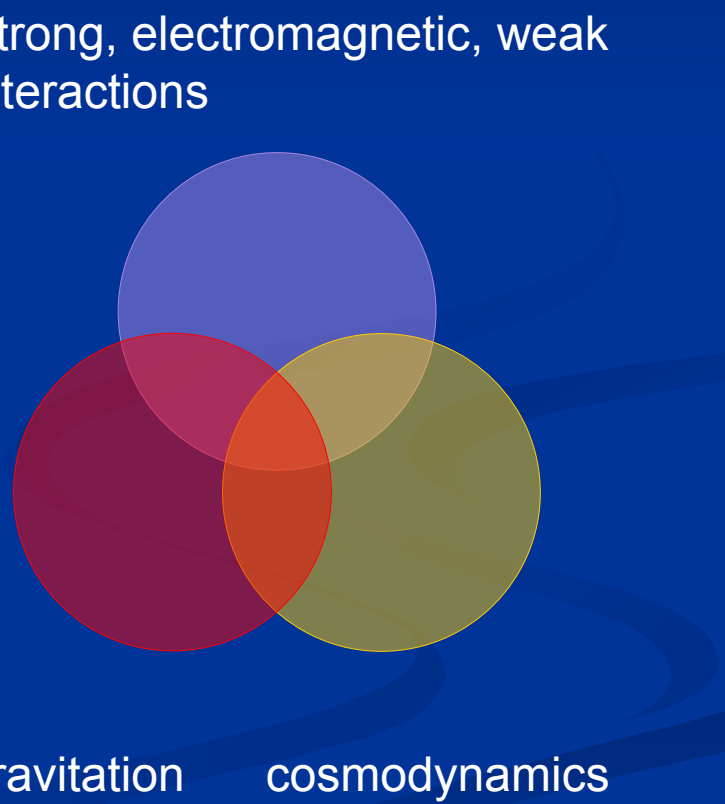
Two bodies with equal mass experience a different acceleration !

$$\eta = (a_1 - a_2) / (a_1 + a_2)$$

Quintessence and time variation of fundamental constants

Generic prediction

Strength unknown



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

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 :

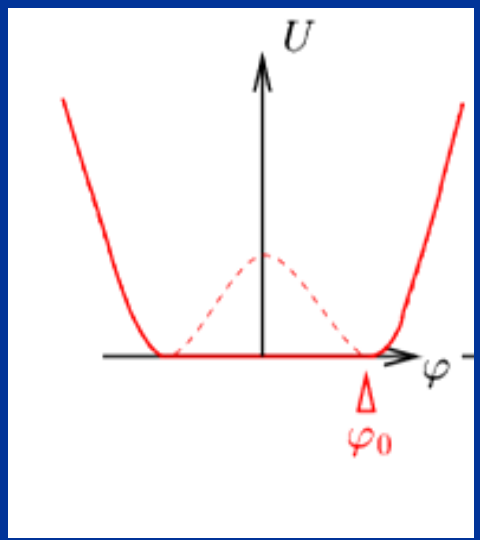
$$m_{electron} = h_{electron} * \varphi_H \quad \text{etc.}$$

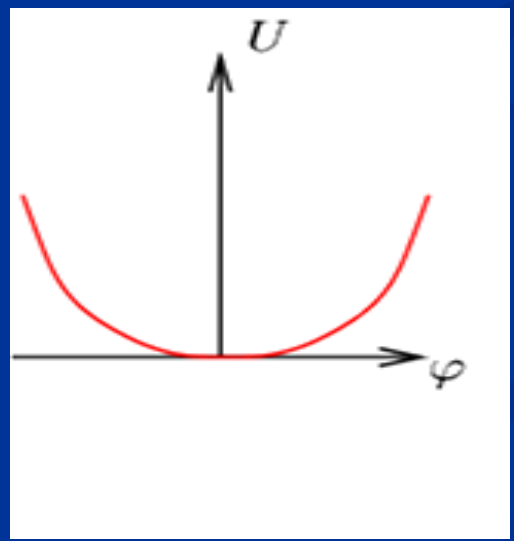
Restoration of symmetry at high temperature in the early Universe

Low T
SSB
$\langle \varphi_H \rangle = \varphi_0 \neq 0$

High T
SYM
$\langle \varphi_H \rangle = 0$

high T :
less order
more symmetry

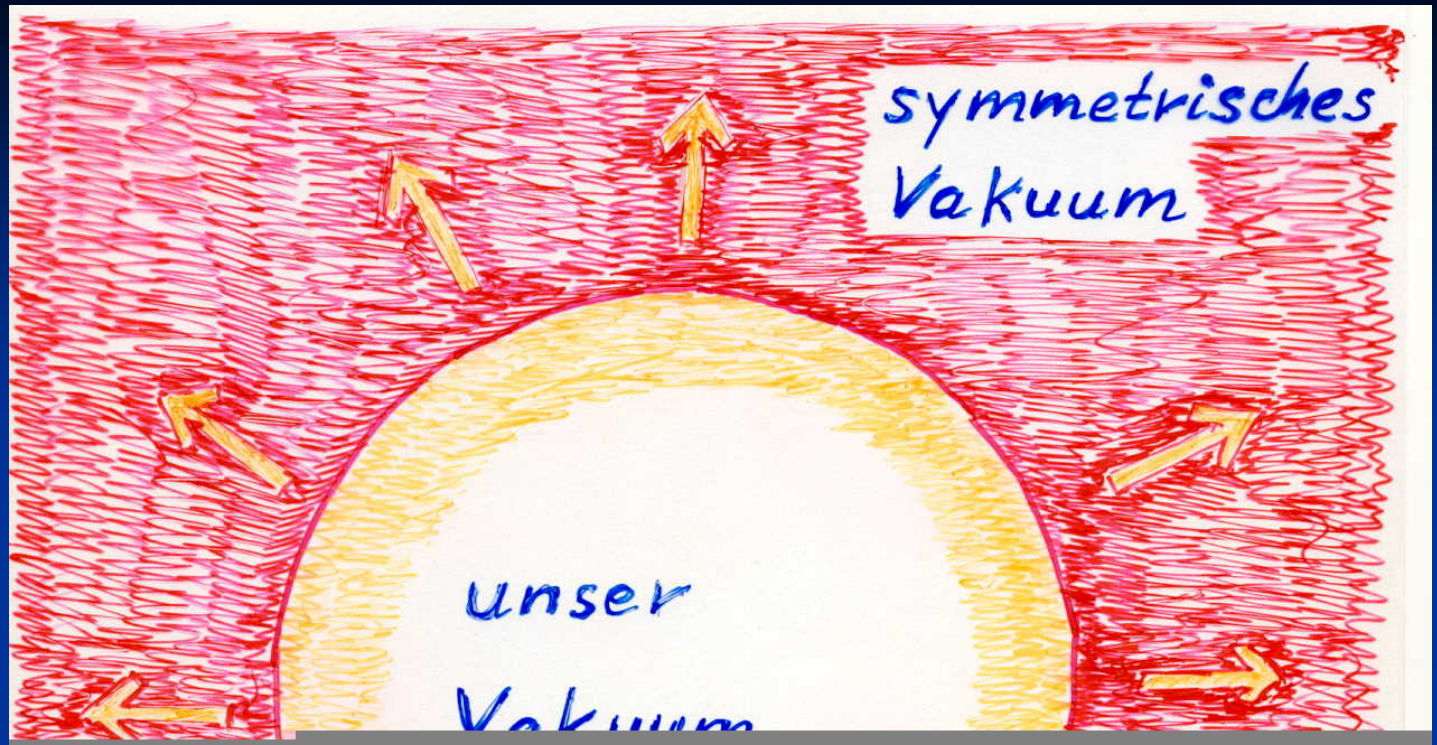




example:
magnets

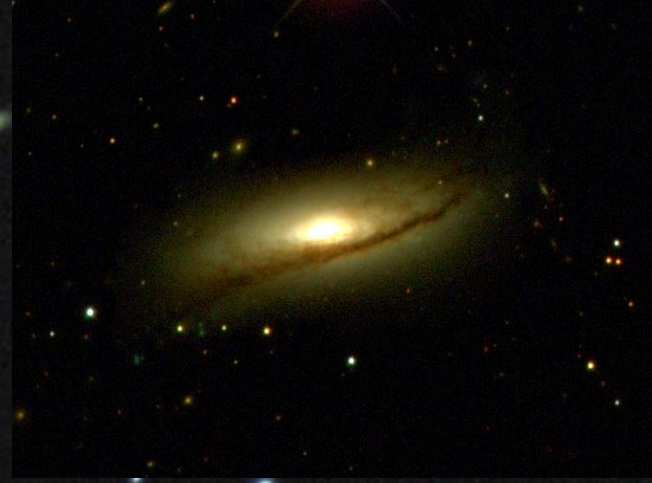
In the hot plasma
of the early Universe :

No difference in mass for electron and myon !


symmetrisches
Vakuum
unser

Quintessence :
Couplings are still varying now !

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

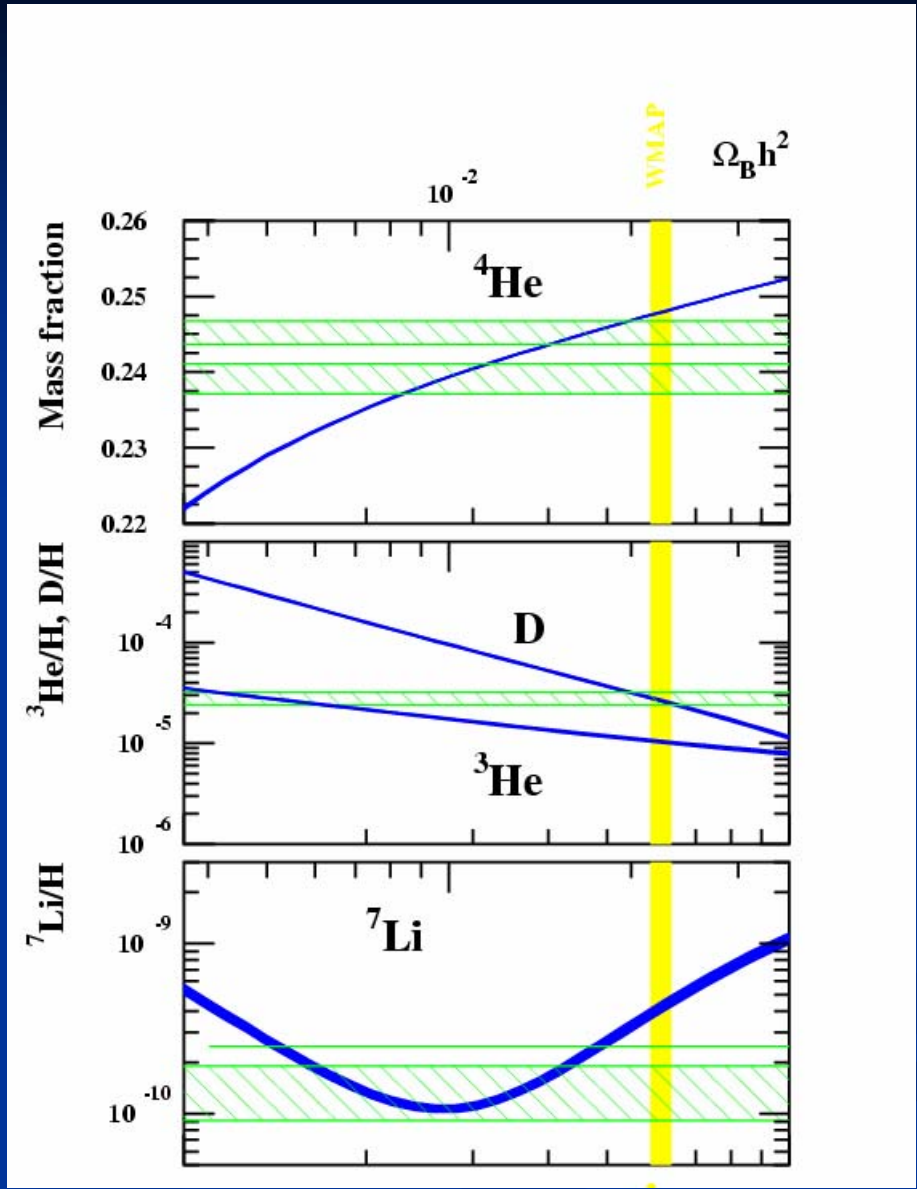


baryons :

the matter of stars and humans

$\Omega_b = 0.045$

Abundancies of primordial light elements from nucleosynthesis



A.Coc

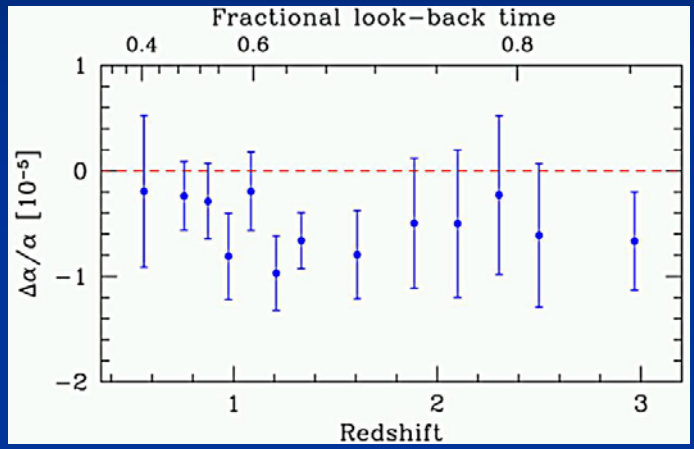
if present 2-sigma deviation of He –abundance from CMB/nucleosynthesis prediction would be confirmed :

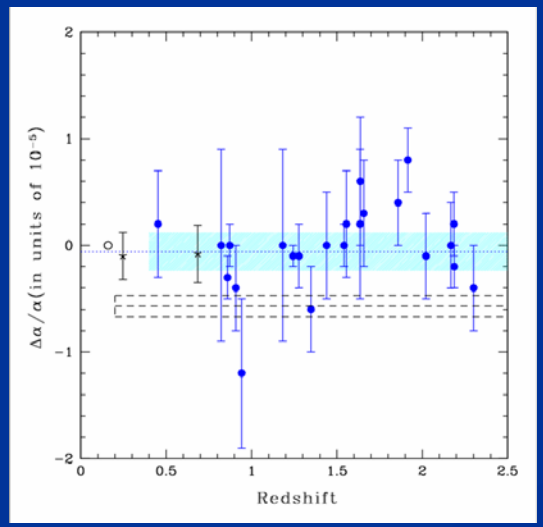
$\Delta\alpha/\alpha\ (z=10^{10}) = -1.0\ 10^{-3}$ GUT 1

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

C.Mueller,G.Schaefer,…

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

$z \approx 2$

Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

Παντα ρει

Everything is flowing

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 (MICROSCOPE , …)

small change of couplings in space

- Fine structure constant depends on location in space
- Experiments with satellites ?

for $r = 2\ R_E$

$$\delta\ \alpha_{em} / \alpha_{em} = 3\ \ 10^{-19} / k^2$$

Quintessence and solution of cosmological constant problem should be related !

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

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

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 !

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

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

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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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)

Cosmic Attractors

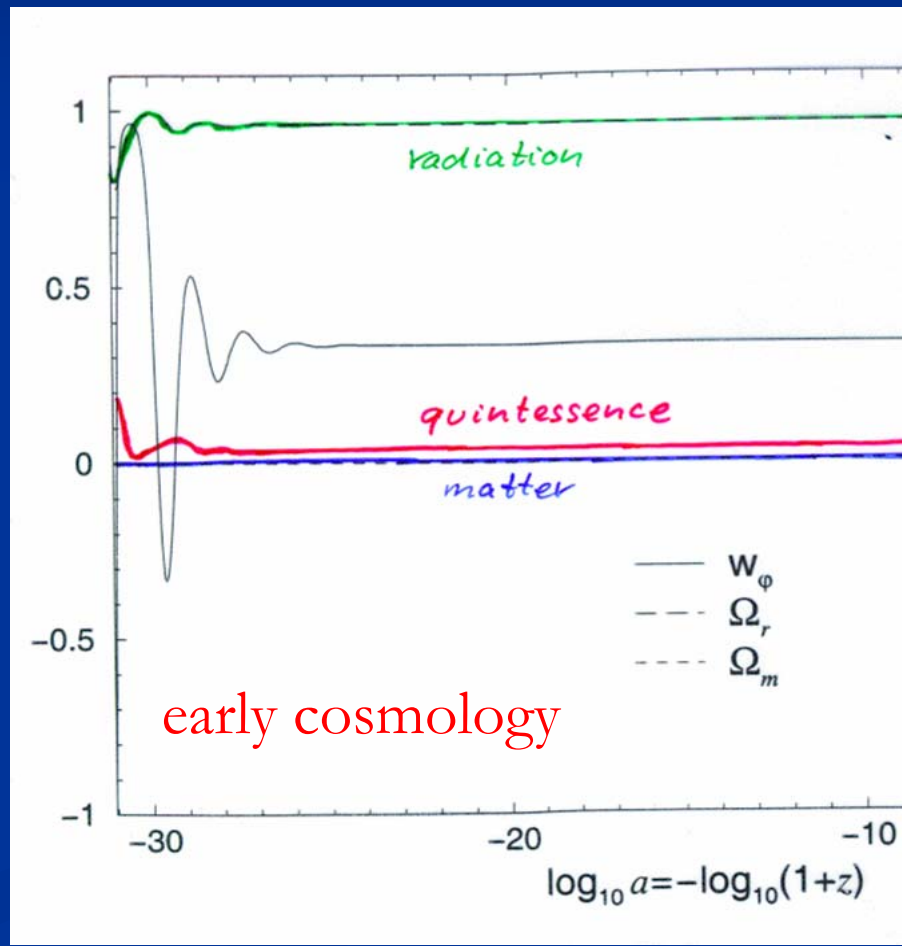
Solutions independent of initial conditions

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

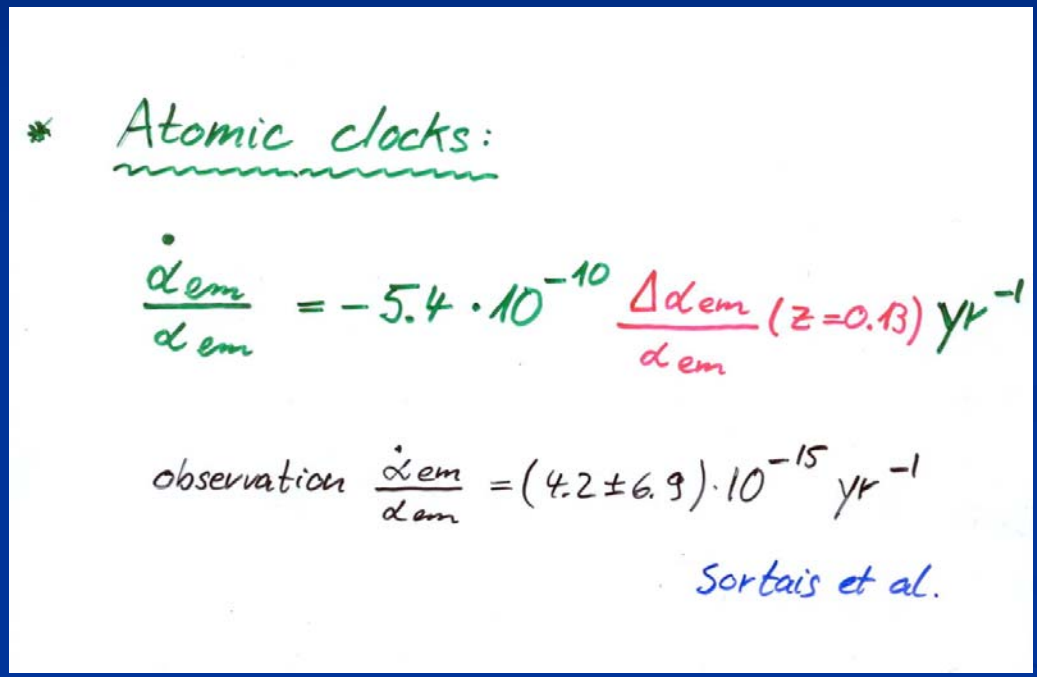
$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

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



Atomic clocks and OKLO



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