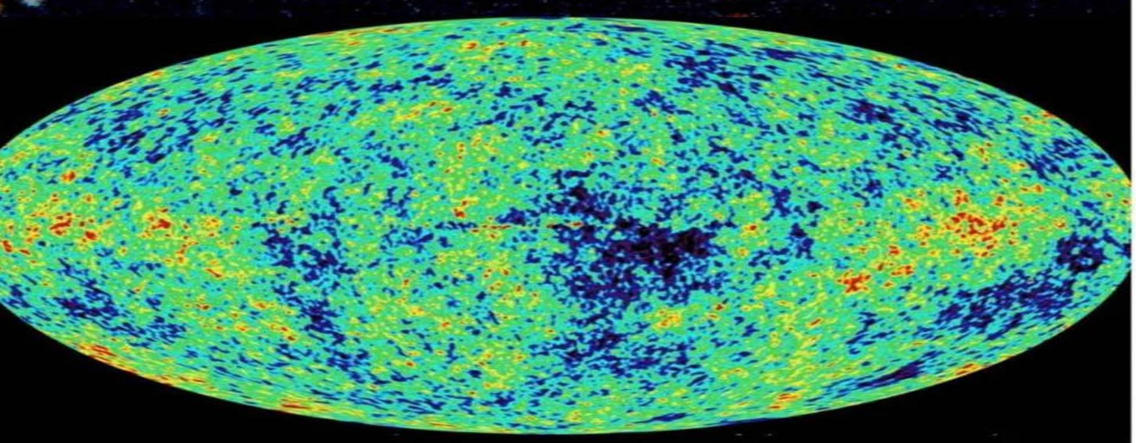
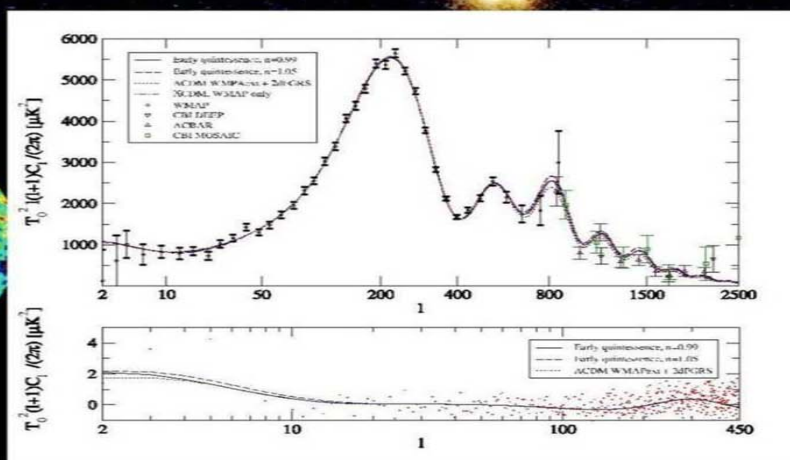
Dark Energy – a cosmic mystery





Quintessence

C.Wetterich

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

What is our universe made of ?

Dark Energy dominates the Universe

Energy - density in the Universe

=

Matter + Dark Energy

25 % + 75 %

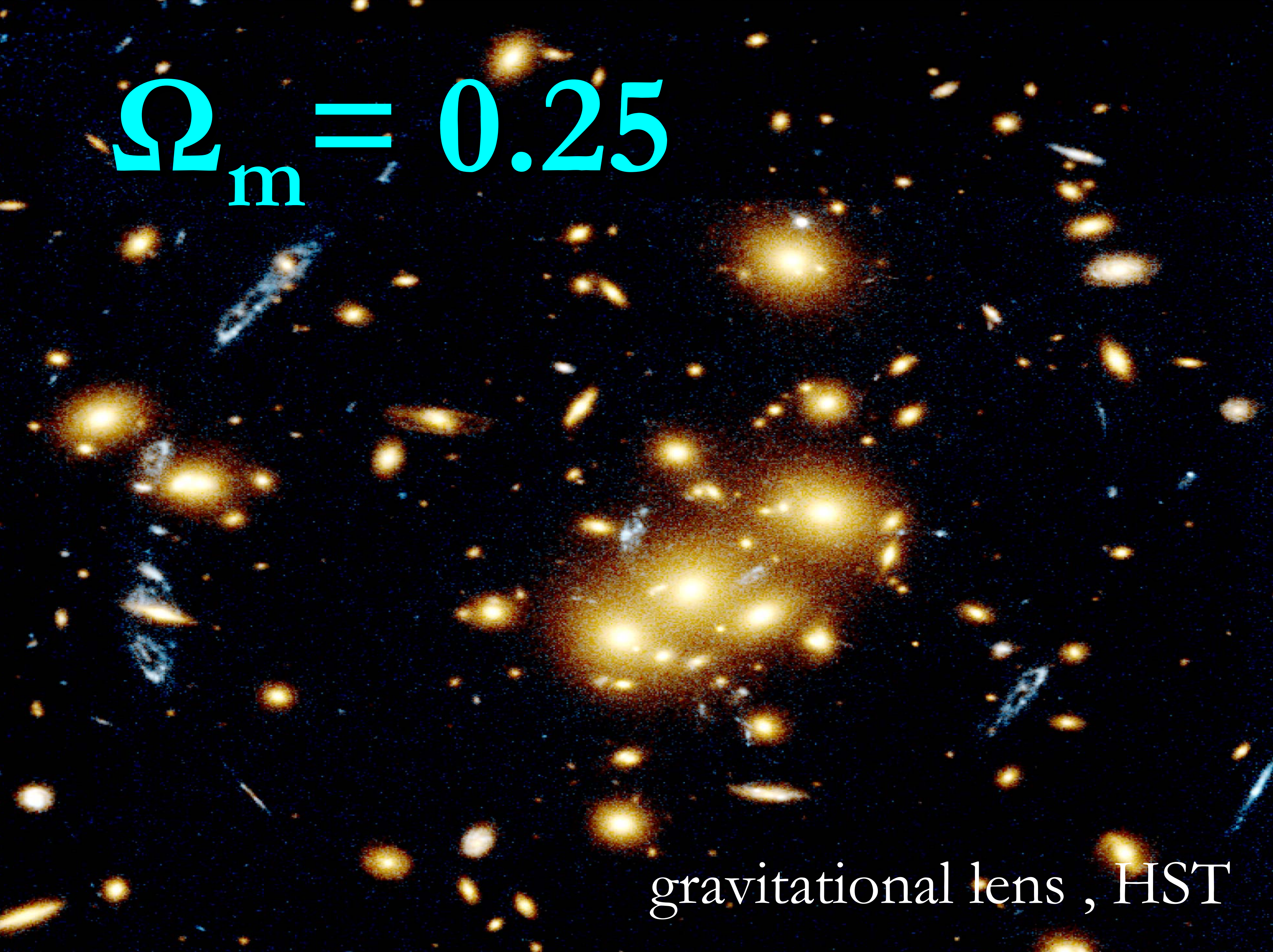
What is Dark Energy ?

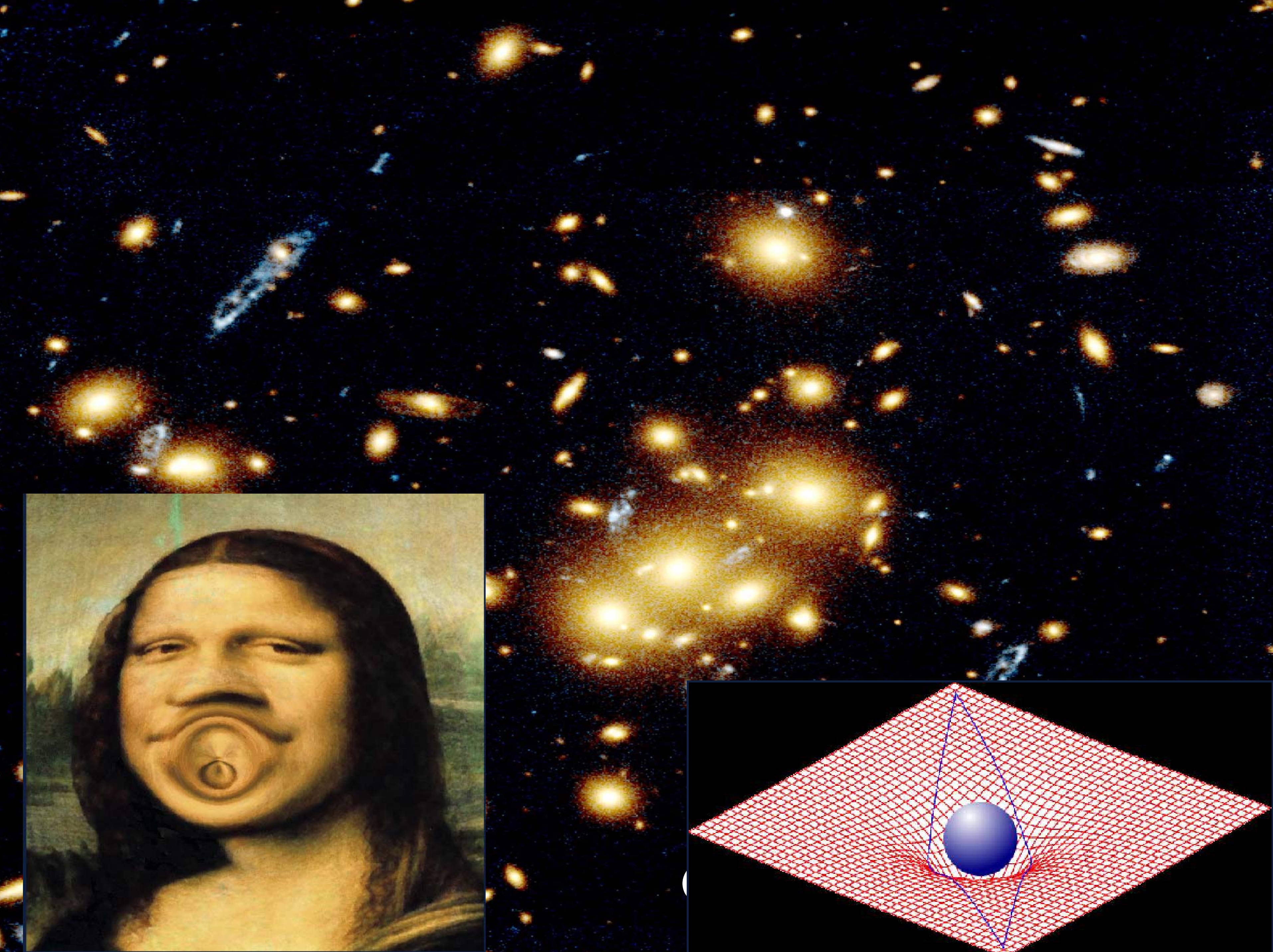
Matter : Everything that clumps

Dark Matter

- $\Omega_m = 0.25$ total "matter"
- Most matter is dark !
- So far tested only through gravity
- Every local mass concentration $\Longrightarrow$ gravitational potential
- Orbits and velocities of stars and galaxies $\Longrightarrow$ measurement of gravitational potential

  and therefore of local matter distribution


$\Omega_m = 0.25$
gravitational lens , HST



spatially flat universe

$$\Omega_{tot} = 1$$

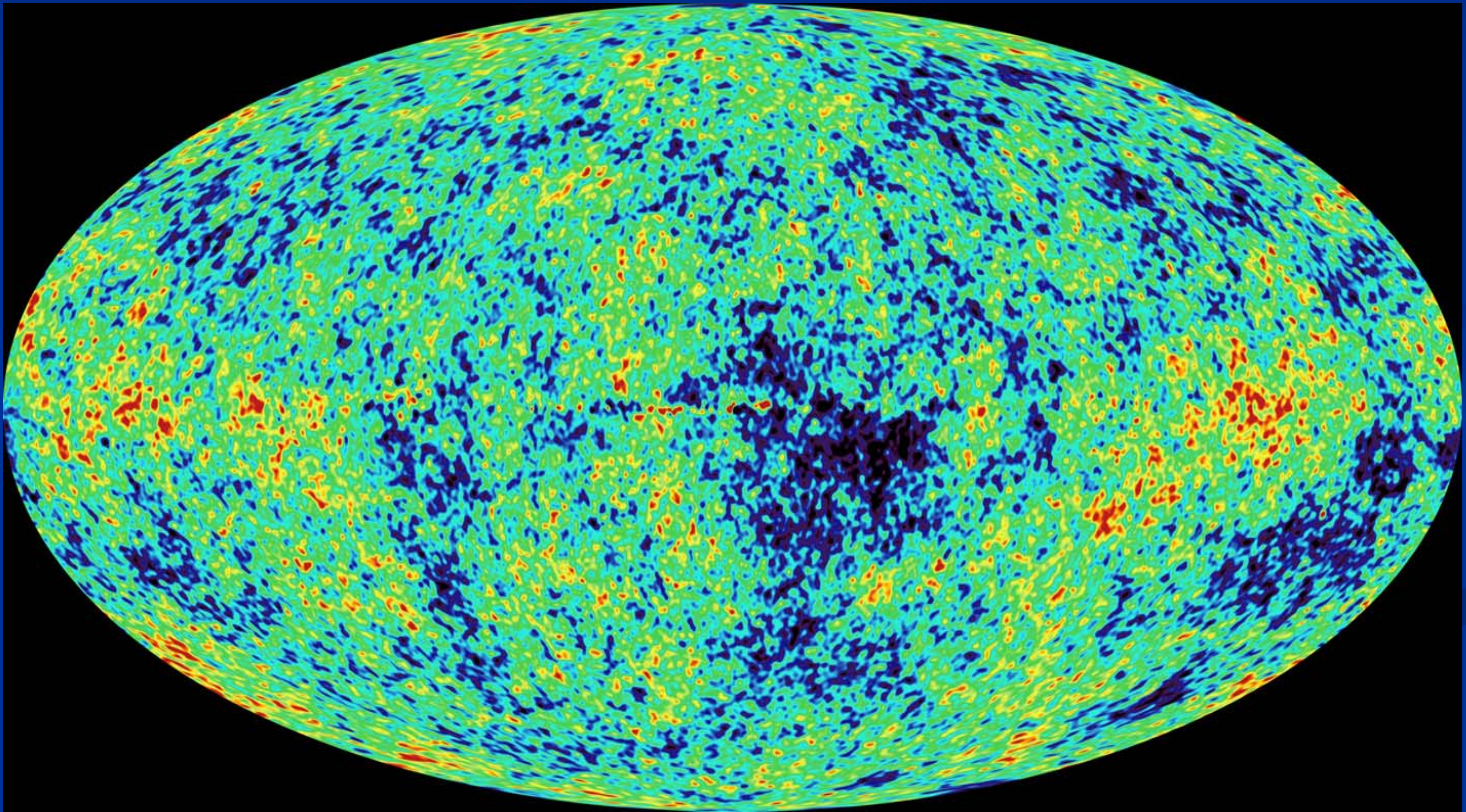
- theory (inflationary universe)

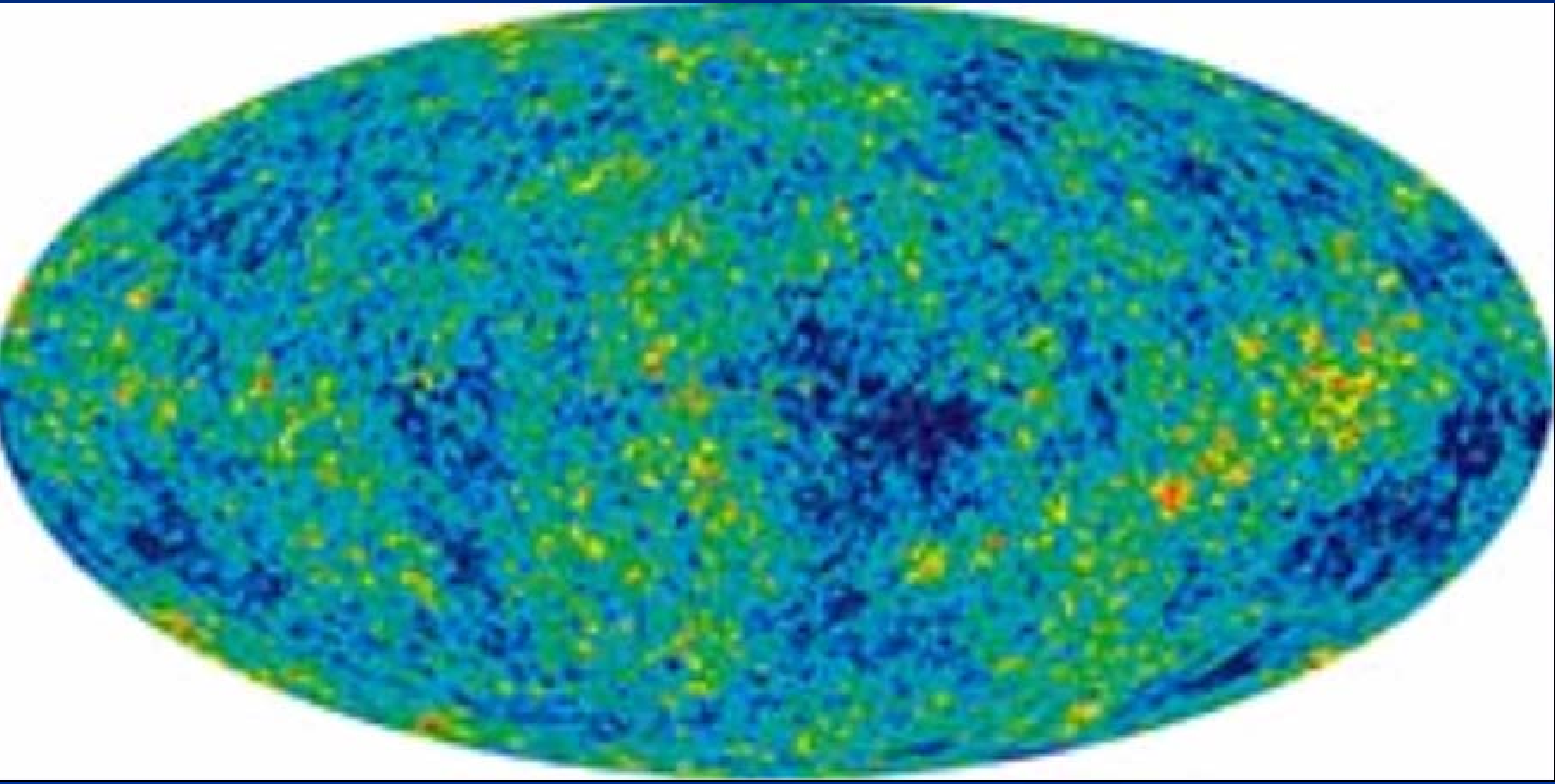
  $\Omega_{tot} = 1.0000..........x$

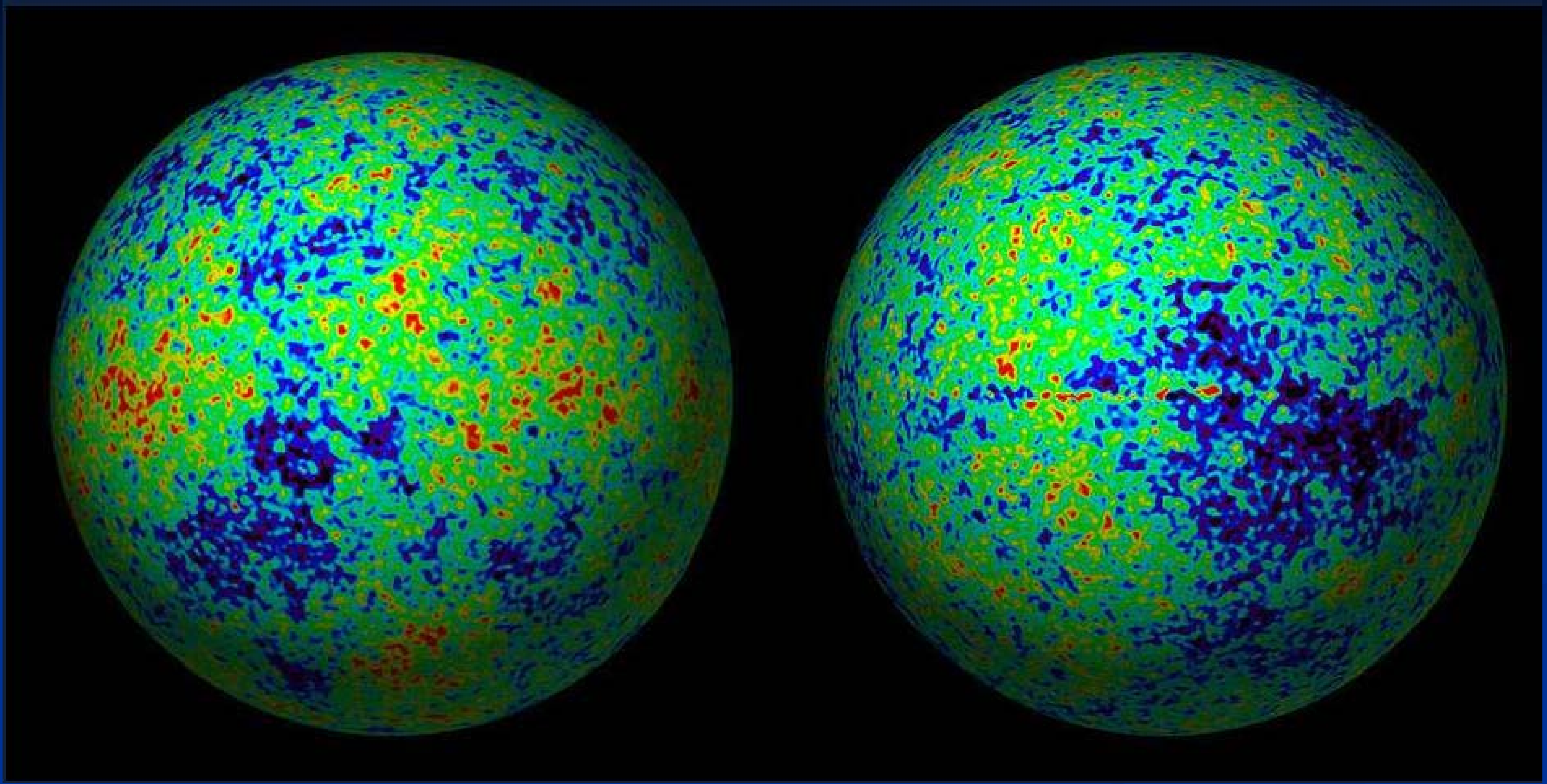
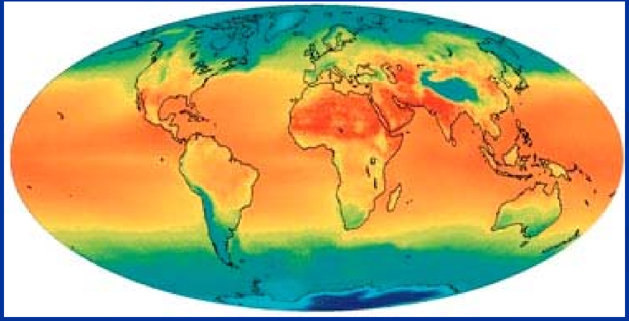
- observation (WMAP)

  $\Omega_{tot} = 1.02\ (0.02)$

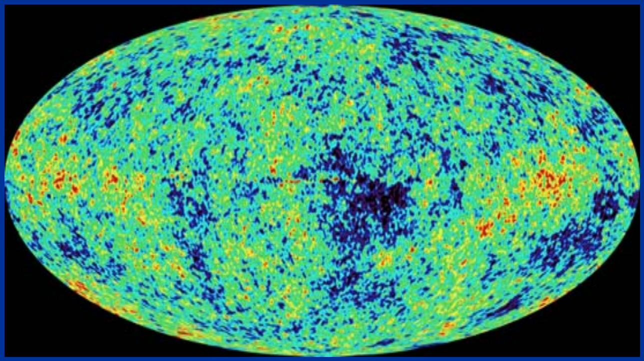
picture of the big bang

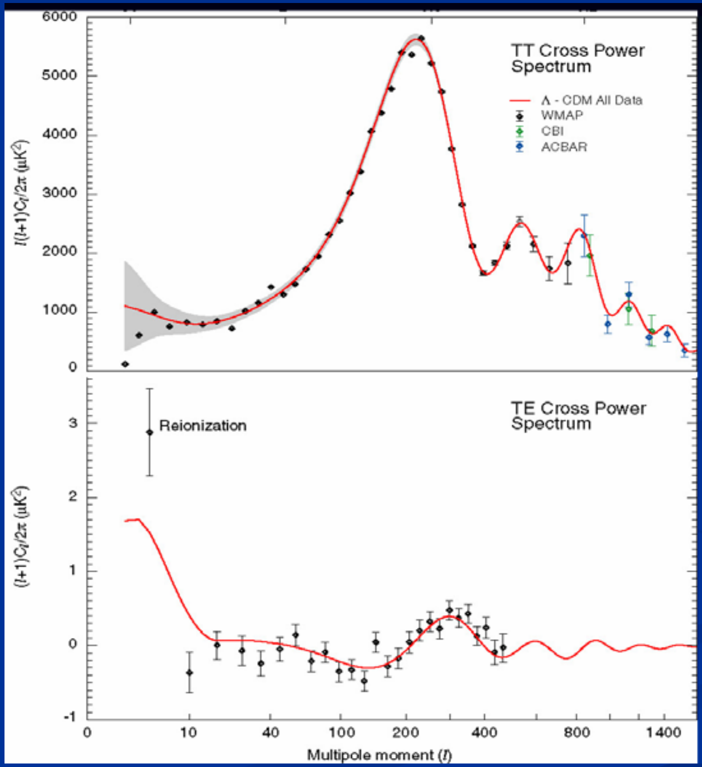




$\Omega_{tot}=1$





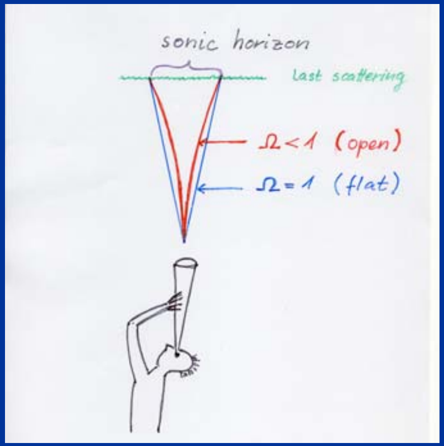
mean values

$\Omega_{tot} = 1.02$

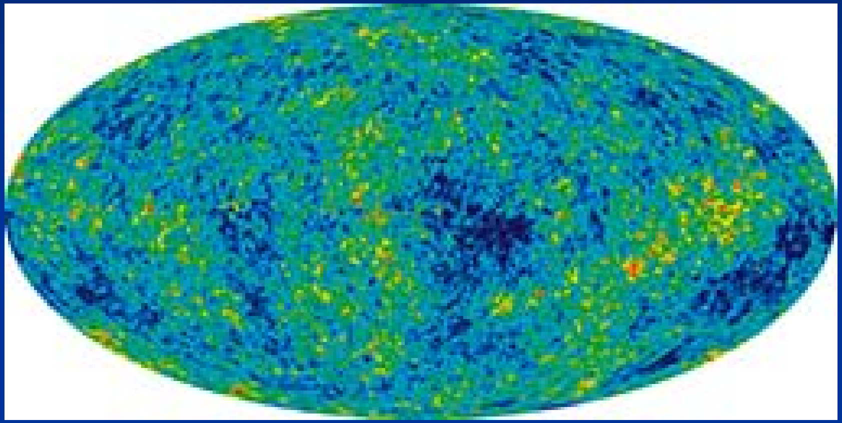
$\Omega_{m} = 0.27$

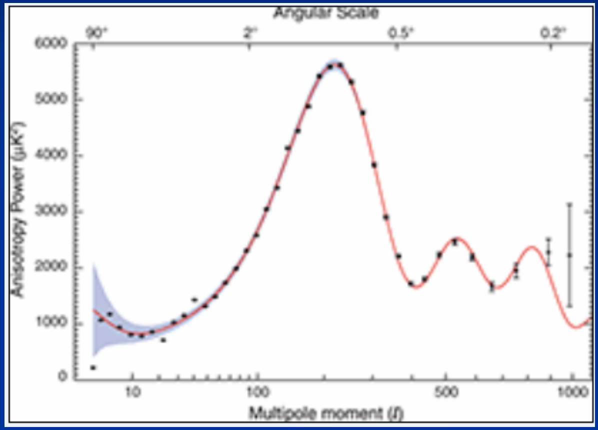
$\Omega_{b} = 0.045$

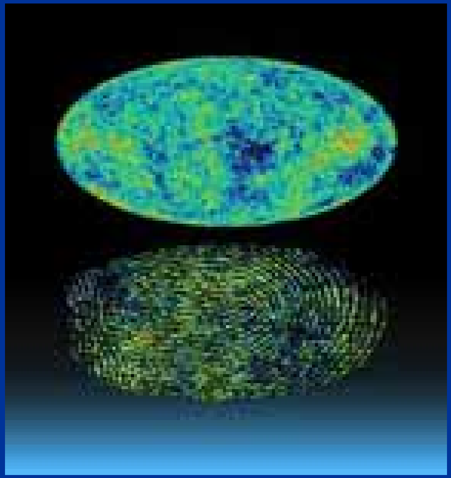
$\Omega_{dm} = 0.225$



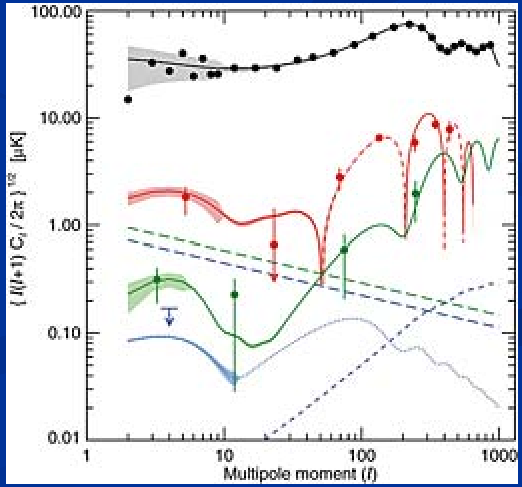
WMAP 2006







Polarization



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 !

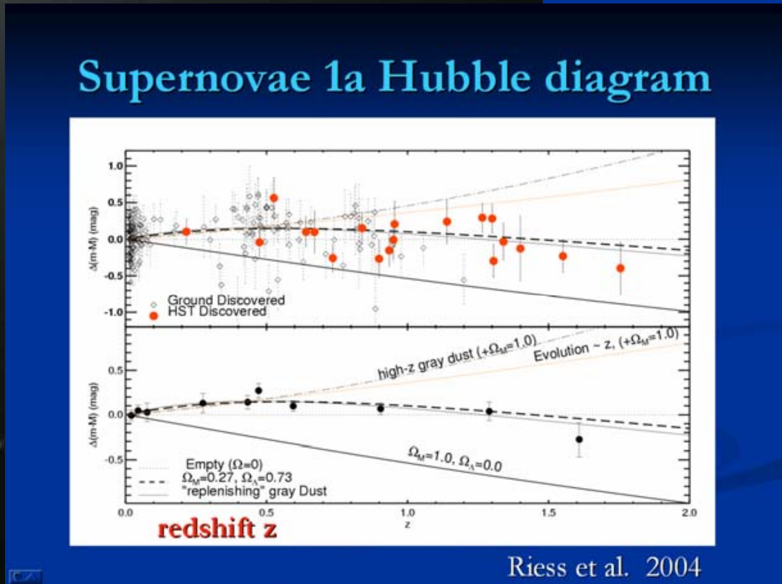
Dark Energy density is
the same at every point of space

“ homogeneous “

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

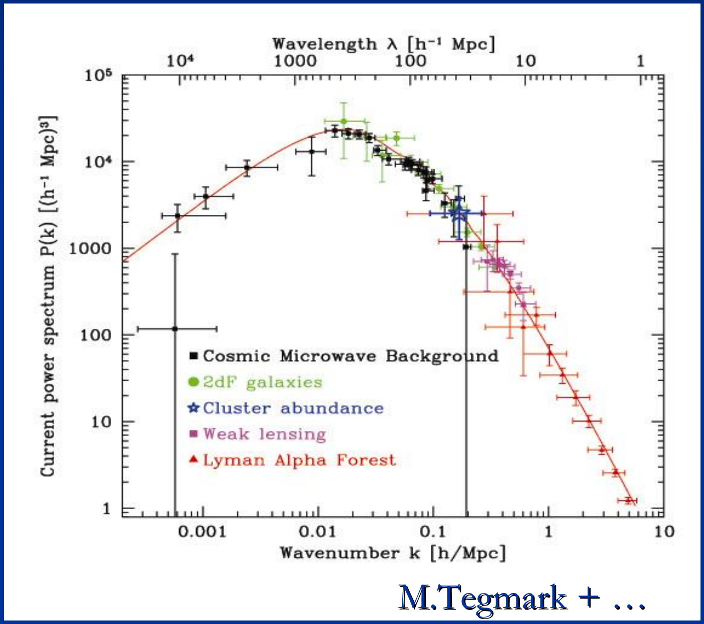
Predictions for dark energy cosmologies

The expansion of the Universe
accelerates today !

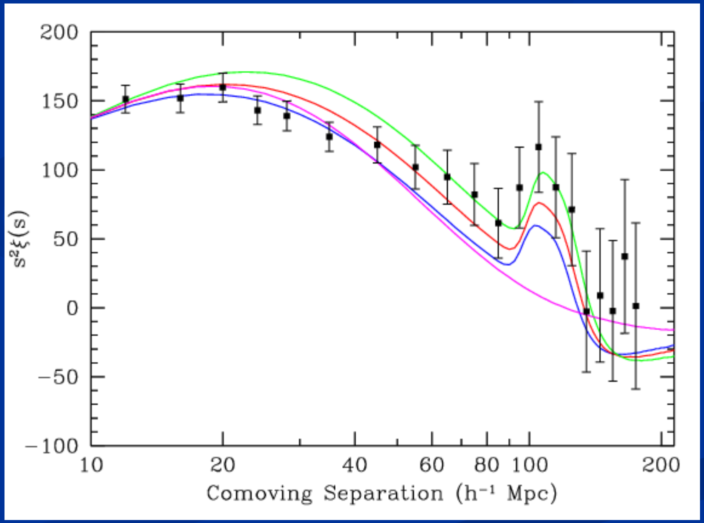


Power spectrum

Baryon - Peak



galaxy – correlation – function

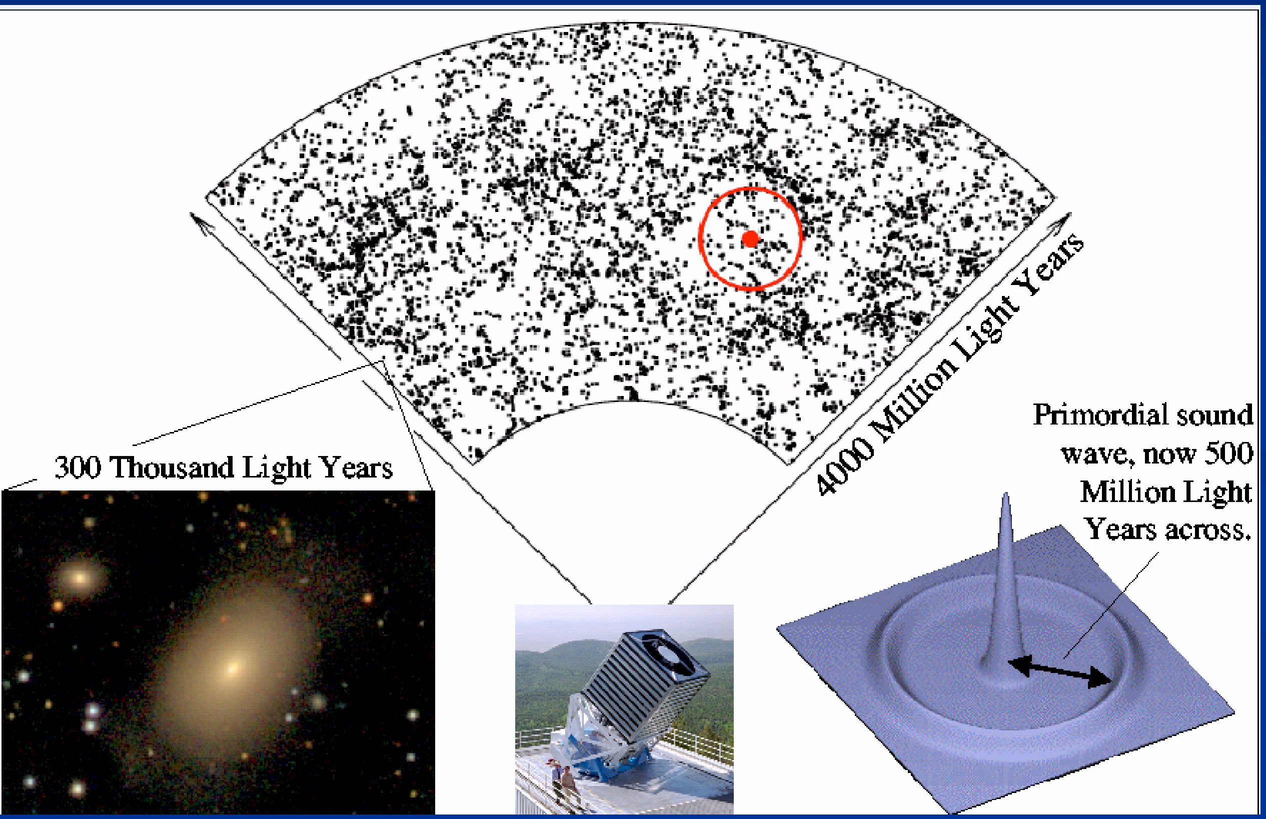


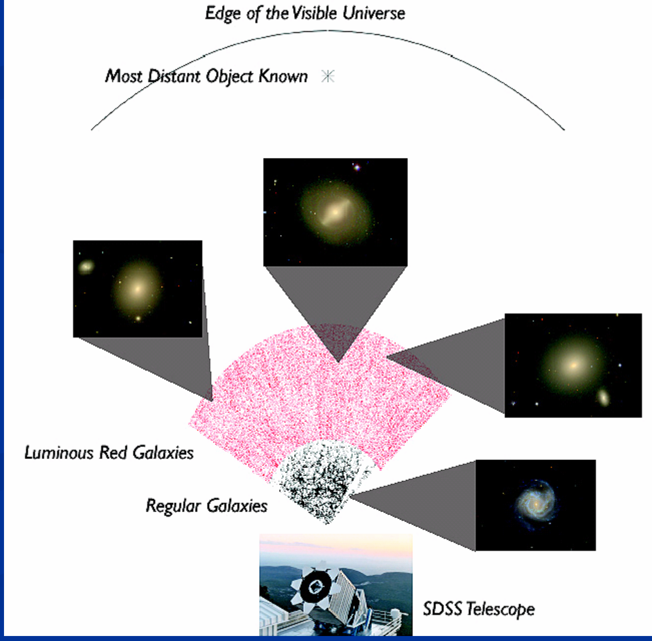
Structure formation :

One primordial fluctuation- spectrum

SDSS

baryon acoustic peak



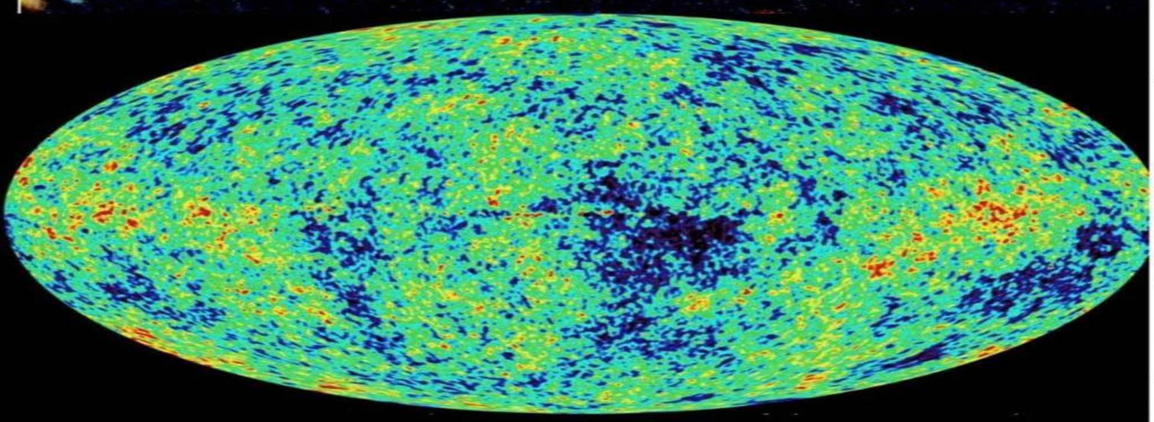


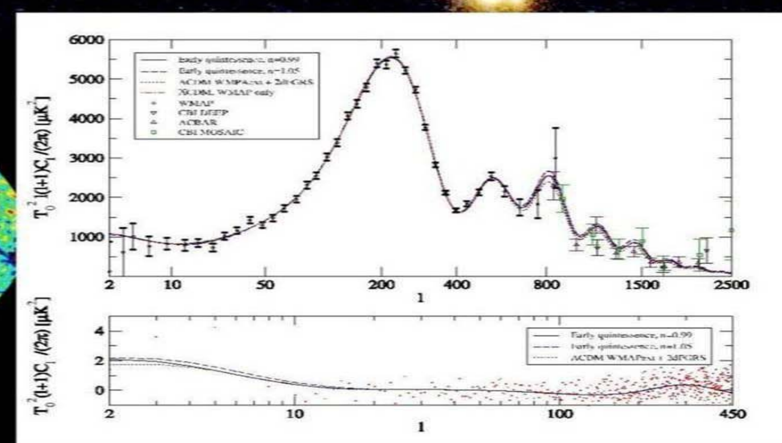
consistent cosmological model !

Composition of the Universe

$\Omega_b = 0.045$	visible	clumping
$\Omega_{dm} = 0.2$	invisible	clumping
$\Omega_h = 0.75$	invisible	homogeneous

Dark Energy- a cosmic mystery





What is Dark Energy ?

Cosmological Constant

or

Quintessence ?

Cosmological Constant
- Einstein -

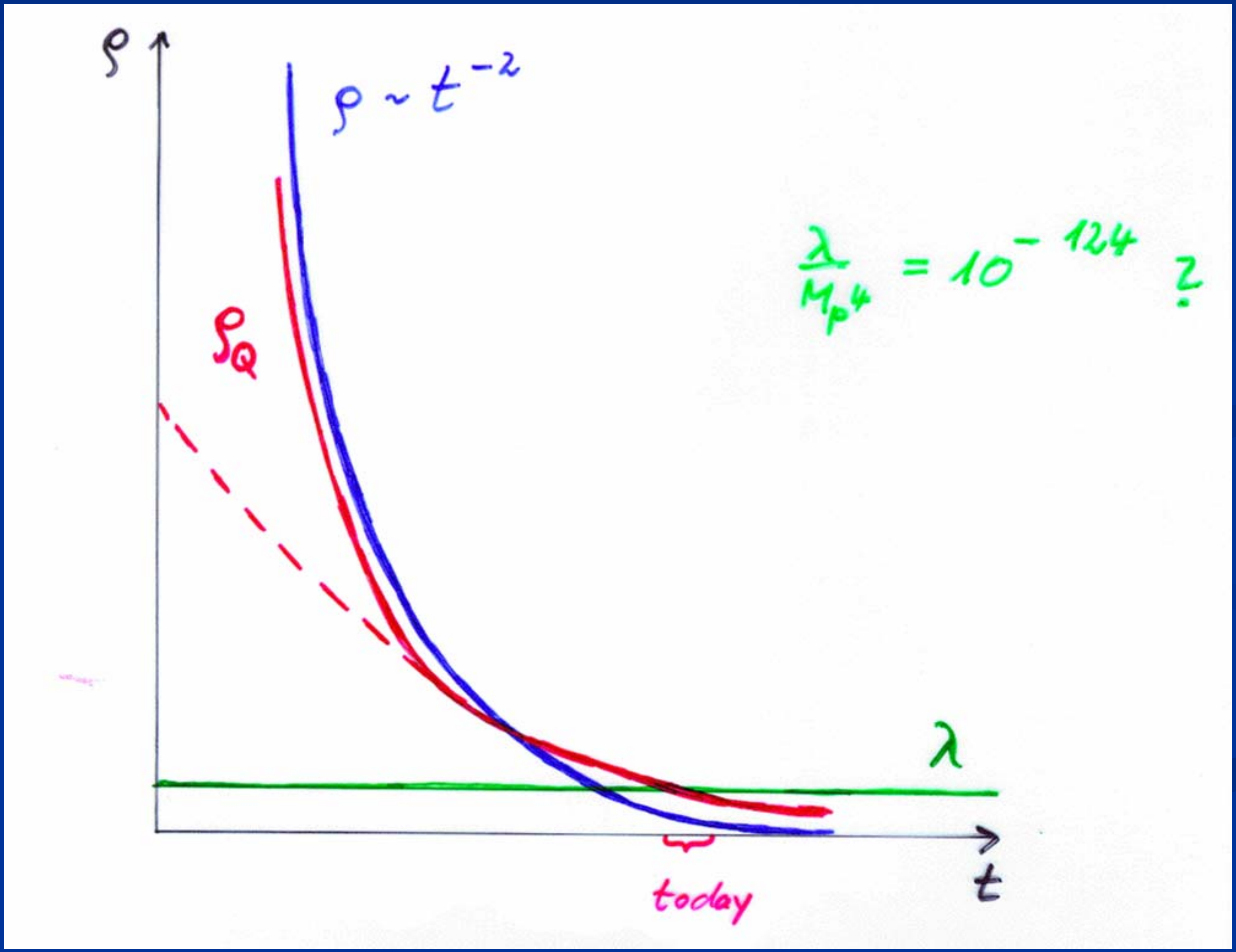
- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

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

- Why important just today ?

Cosm. Const. | Quintessence

static | dynamical



Cosmological mass scales

- Energy density

  $\rho \sim (\ 2.4\times10^{\ -3}\ \mathrm{eV}\ )^{-\ 4}$

- Reduced Planck mass

  $M=2.44\times10^{18}\mathrm{GeV}$

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

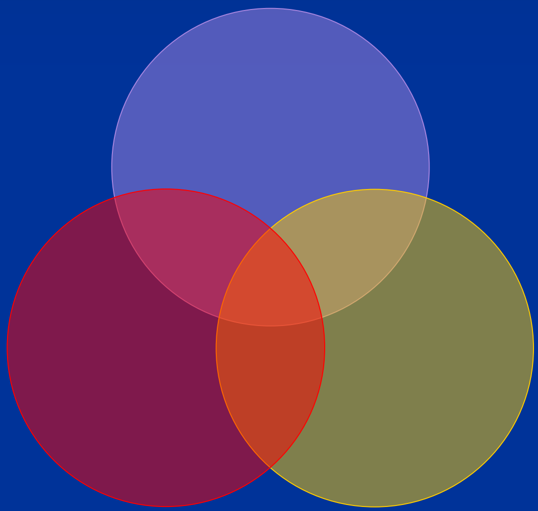
similar to electric field , but no direction (scalar field)

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. $\mathbf{V(\varphi) = M^4 \exp(-\varphi/M)}$

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 :*

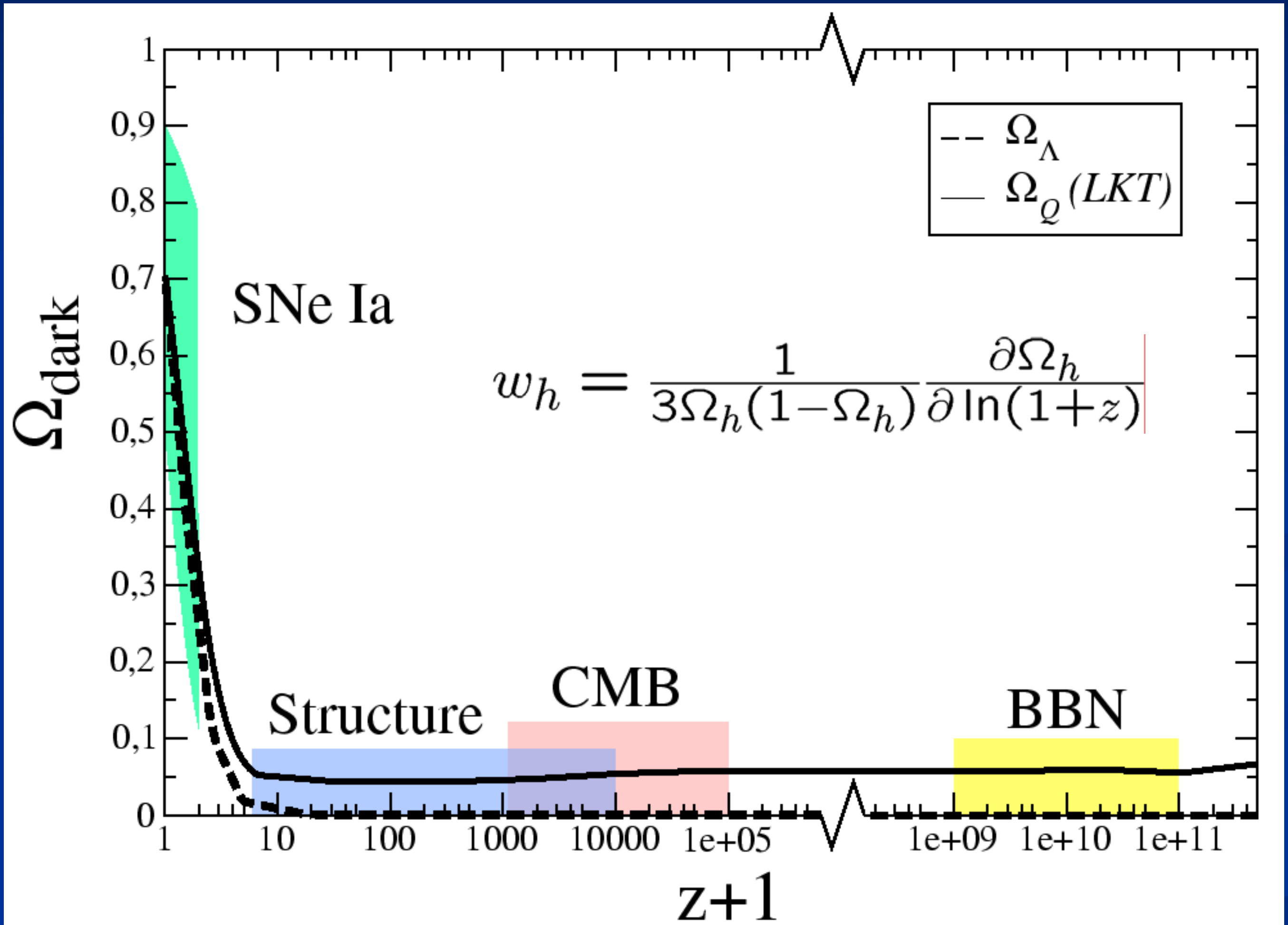
  $\rho_h(t)$ *decreases with time !*

Cosmon

- *Tiny mass*
- $m_c \sim H$ *(depends on time !)*
- *New long - range interaction*

observation will decide !

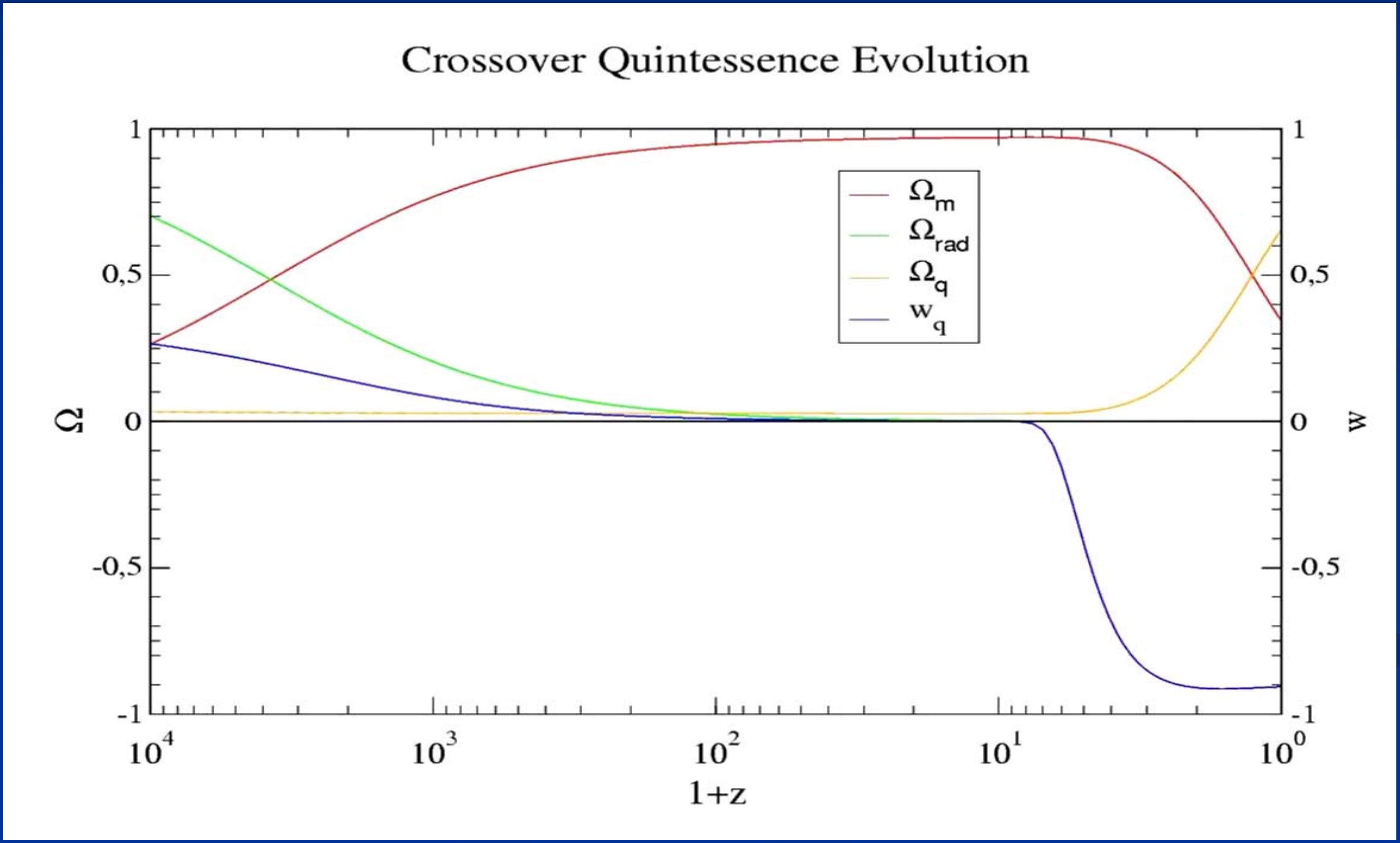
Time dependence of dark energy



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

M.Doran,…

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

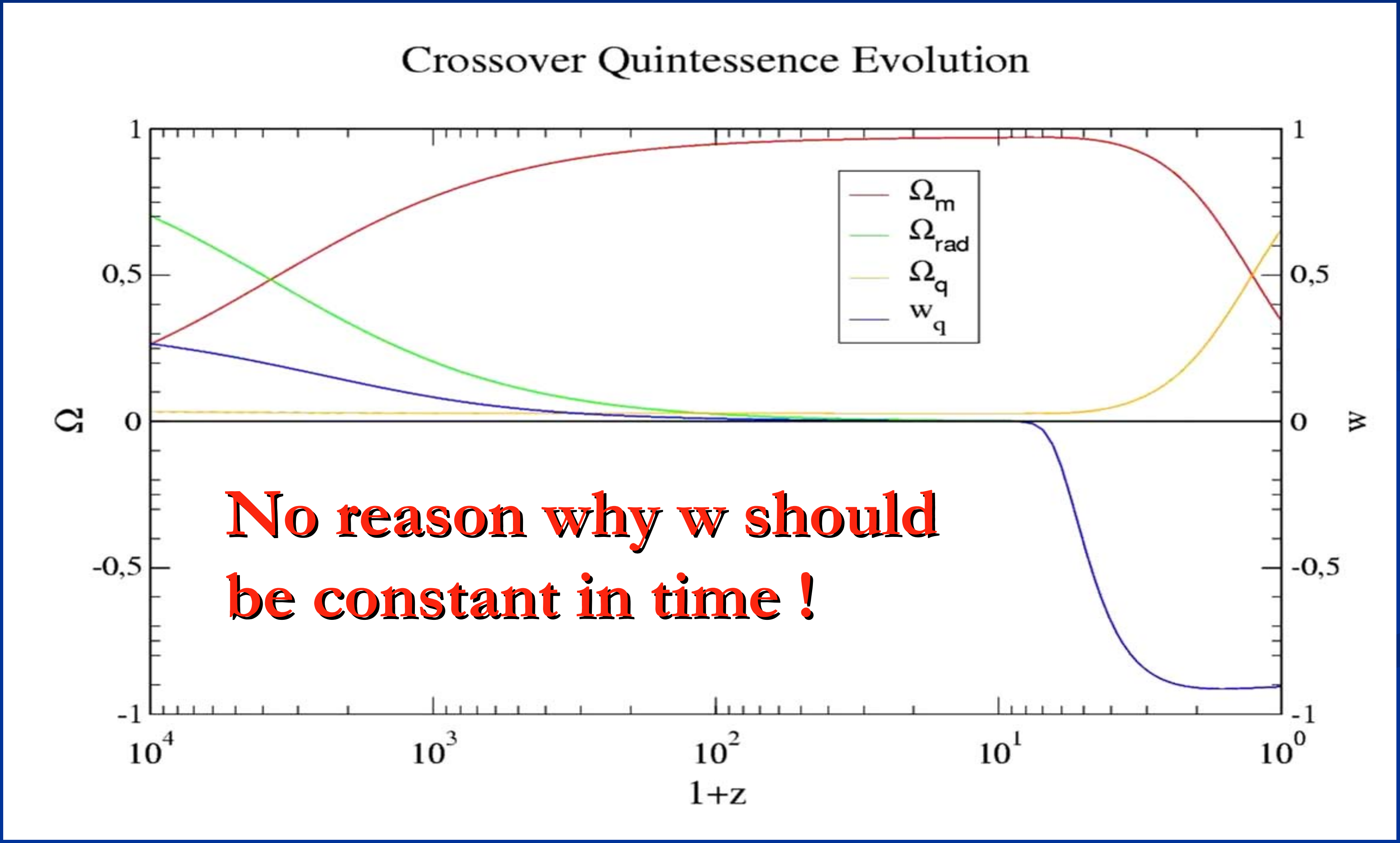
fraction in dark energy has substantially increased since end of structure formation

→

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"



coincidence problem

What is responsible for increase of Ω_h for $z < 10$?

a) Properties of cosmon potential or kinetic term

Late quintessence

- w close to -1
- Ω_h negligible in early cosmology
- needs tiny parameter, similar to cosmological constant

Early quintessence

- Ω_h changes only modestly
- w changes in time

transition

- special feature in cosmon potential or kinetic term becomes important "now"
- tuning at ‰ level

Dynamics of quintessence

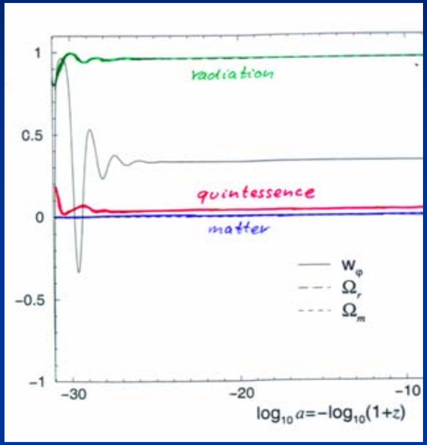
- **Cosmon** φ : scalar singlet field
- Lagrange density $L = V + \frac{1}{2}\, \mathbf{k(\varphi)}\, \partial\varphi\, \partial\varphi$

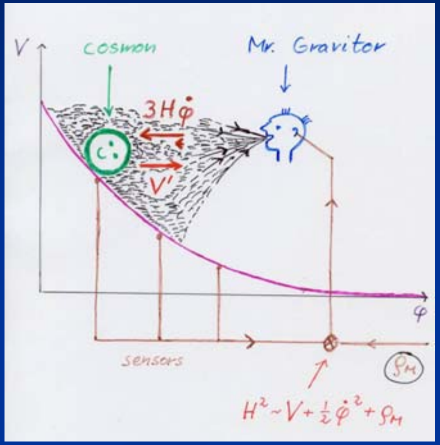
  (units: reduced Planck mass M=1)
- Potential : $V=\exp[-\varphi]$
- "Natural initial value" in Planck era $\varphi=0$
- today: $\varphi=276$
- models characterized by "kinetial" $\mathbf{k(\varphi)}$

attractor solutions

Small almost constant k :

- Small almost constant Ω_h





⇨ This can explain tiny value of Dark Energy !

Large k :

- Cosmon dominated universe (like inflation)

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

Transition to cosmon dominated universe

- Large value k >> 1 : universe is dominated by scalar field
- k increases rapidly : evolution of scalar fied essentially stops
- Realistic and natural quintessence:

  k changes from small to large values after structure formation

b) Quintessence reacts to some special event in cosmology

- Onset of
  matter dominance

  K- essence

  Amendariz-Picon, Mukhanov, Steinhardt

  needs higher derivative kinetic term

- Appearance of
  non-linear structure

  Back-reaction effect

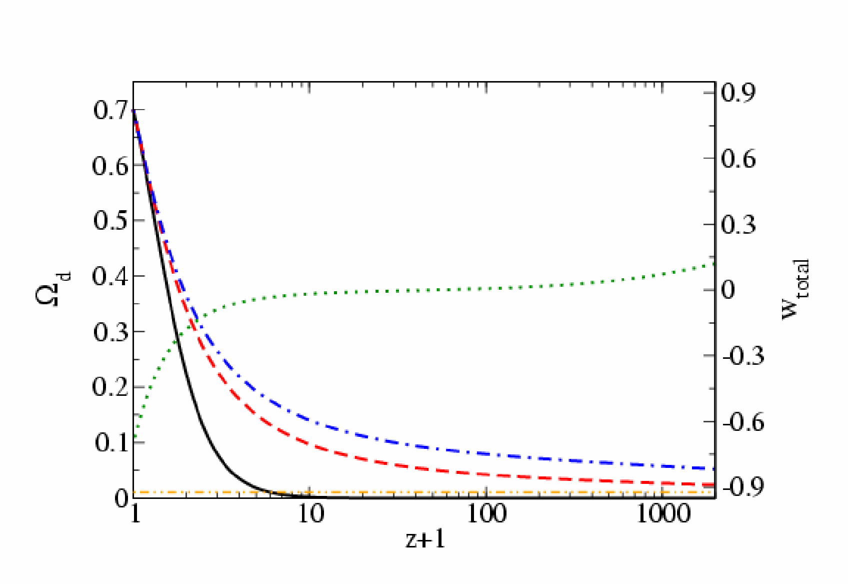
  needs coupling between Dark Matter and Dark Energy

How can quintessence be distinguished from a cosmological constant ?

Early Dark Energy

A few percent in the early Universe

Not possible for a cosmological constant



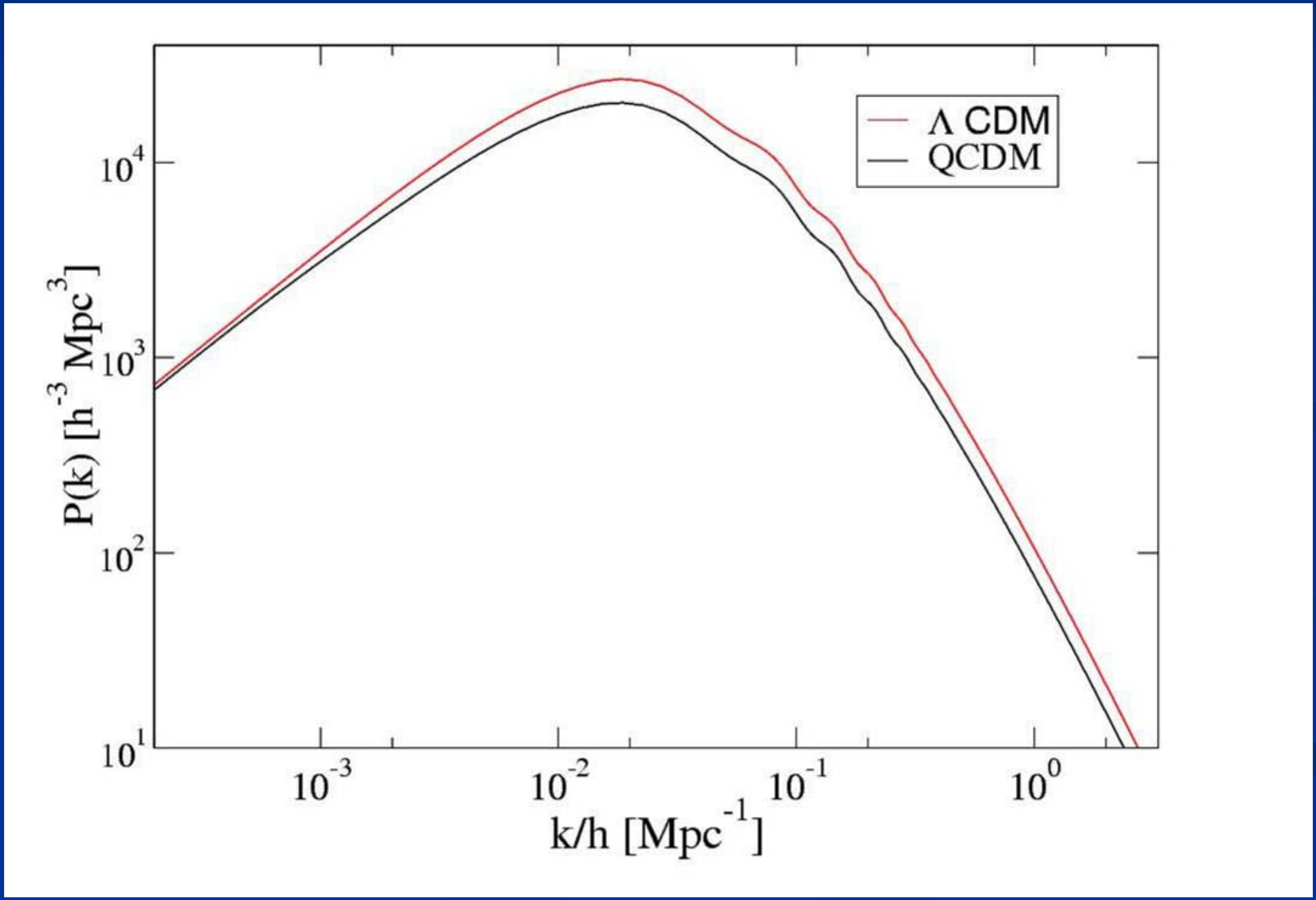
1σ and 2σ limits '05

Doran,Karwan,..

effects of early dark energy

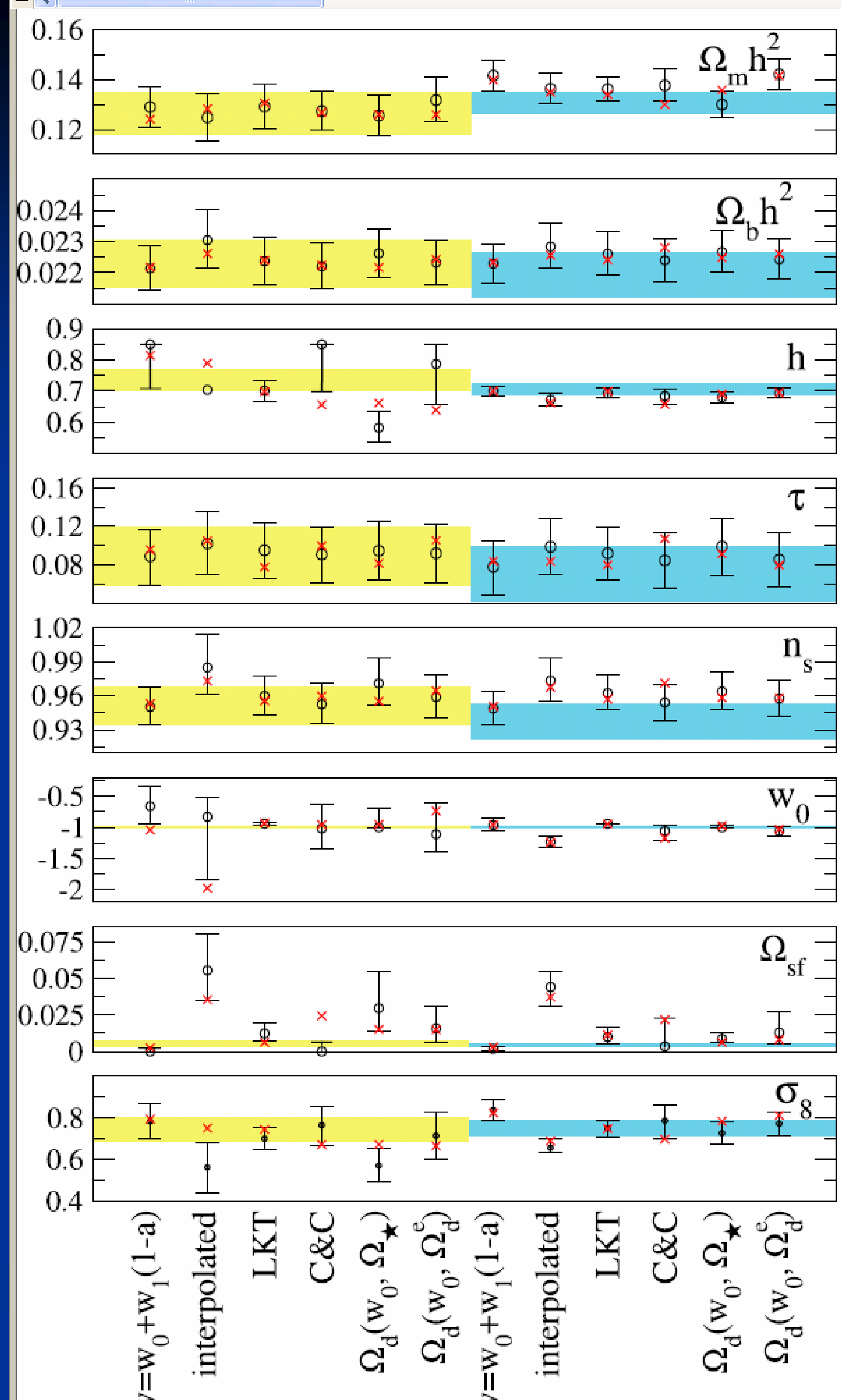
- modifies cosmological evolution (CMB)
- slows down the growth of structure

Early quintessence slows down the growth of structure

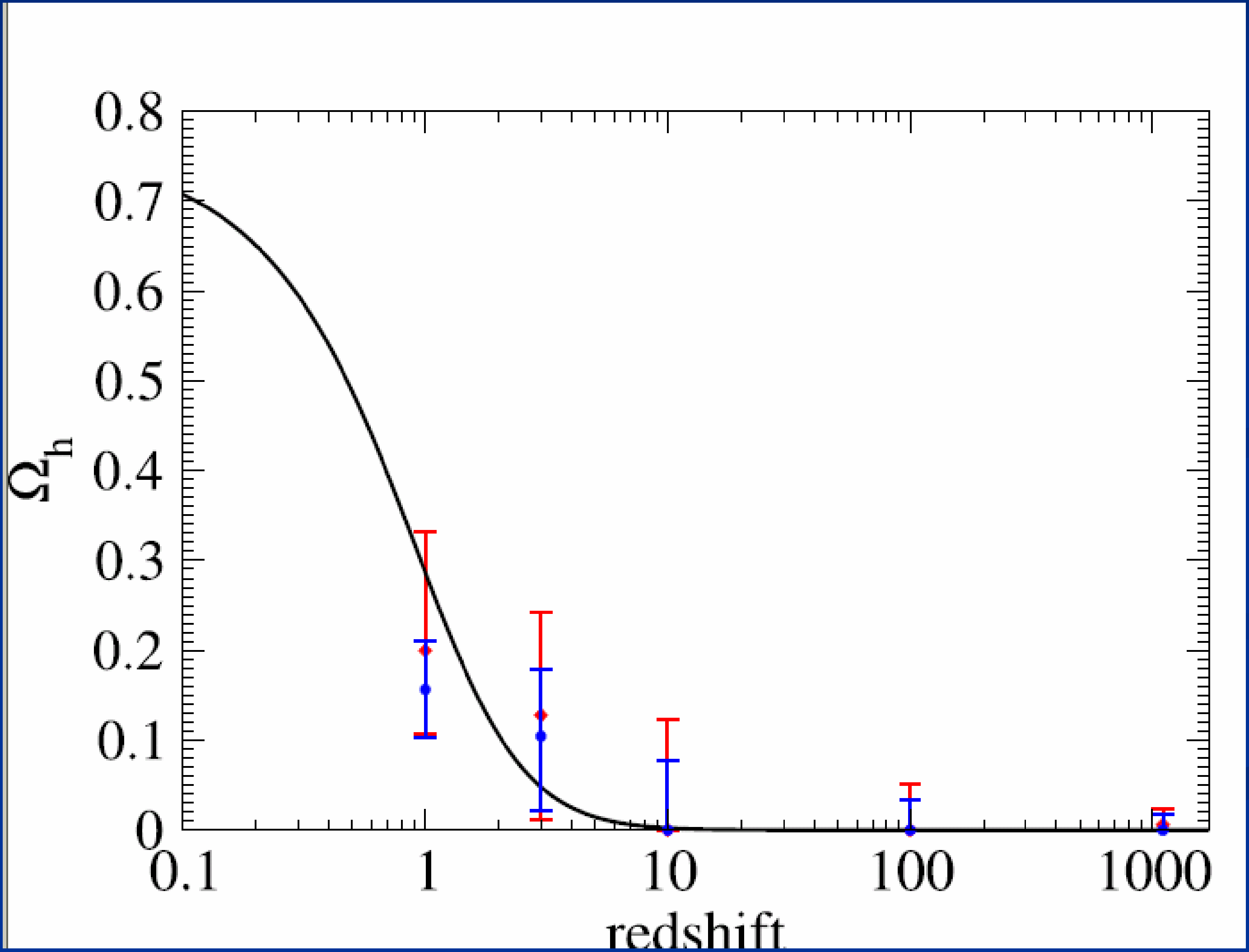


bounds on
Early Dark Energy
after WMAP’06

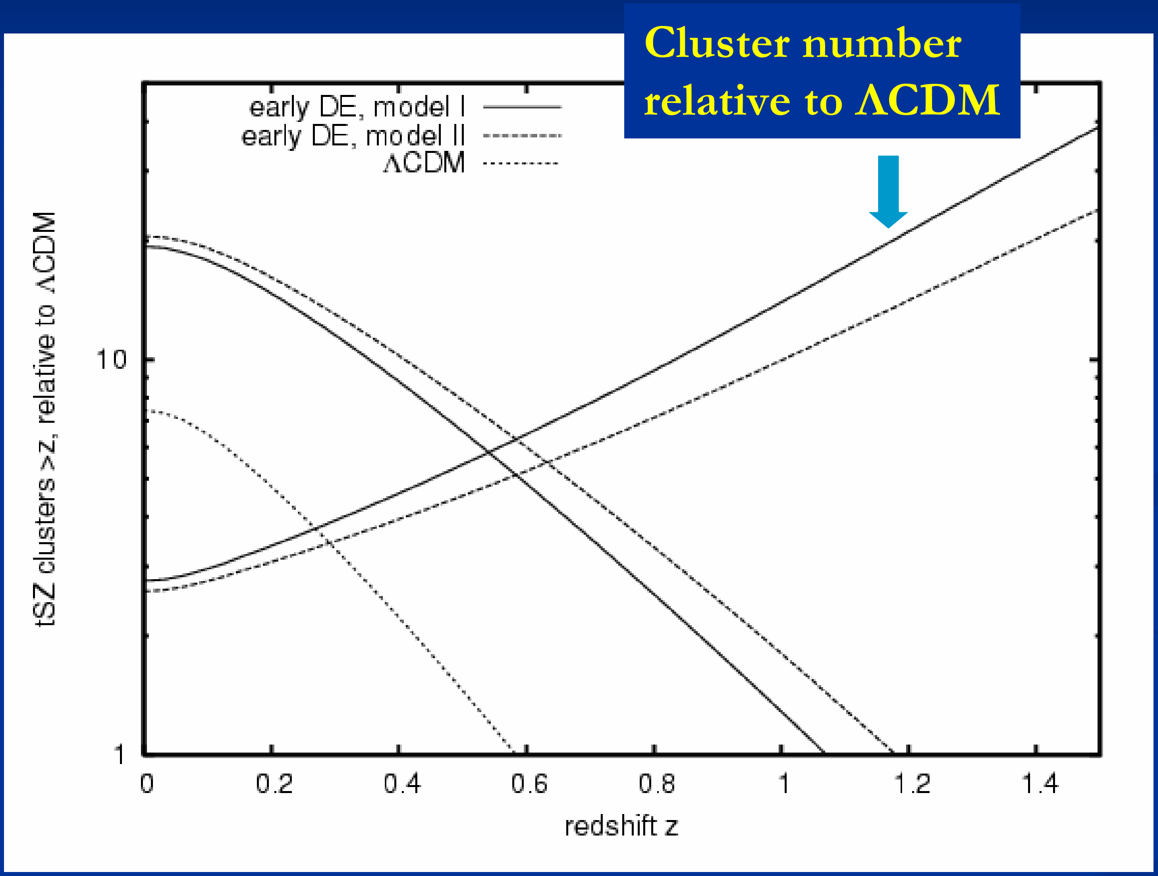
G.Robbers,M.Doran,…



interpolation of Ω_h



Little Early Dark Energy can make large effect ! Non – linear enhancement



Two models with 4% Dark Energy during structure formation

Fixed σ_8 (normalization dependence !)

More clusters at high redshift !

Bartelmann,Doran,…

How to distinguish Q from Λ ?

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

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

ii) equation of state w_h(today) > -1

B) Time variation of fundamental "constants"

C) Apparent violation of equivalence principle

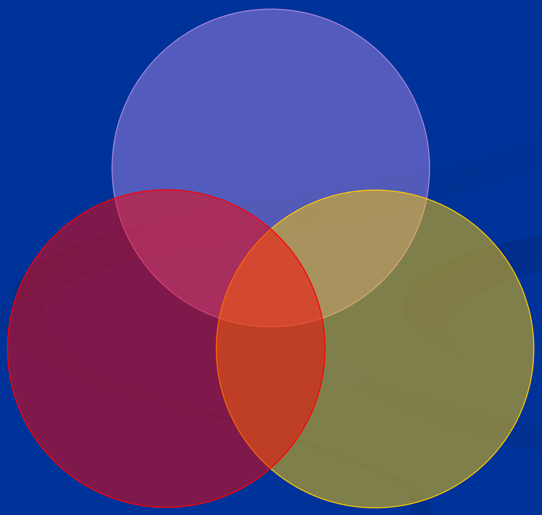
D) Possible coupling between Dark Energy and Dark Mater

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 electron mass to proton mass

Ratio nucleon mass to Planck mass

Quintessence and Time dependence of "fundamental constants"

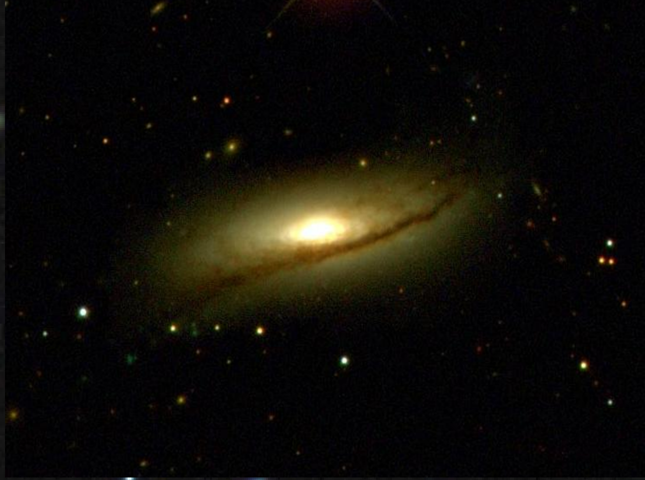
- Fine structure constant depends on value of cosmon field : $\alpha(\varphi)$

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

- Time evolution of φ $\Rightarrow$ Time evolution of α

Jordan,…

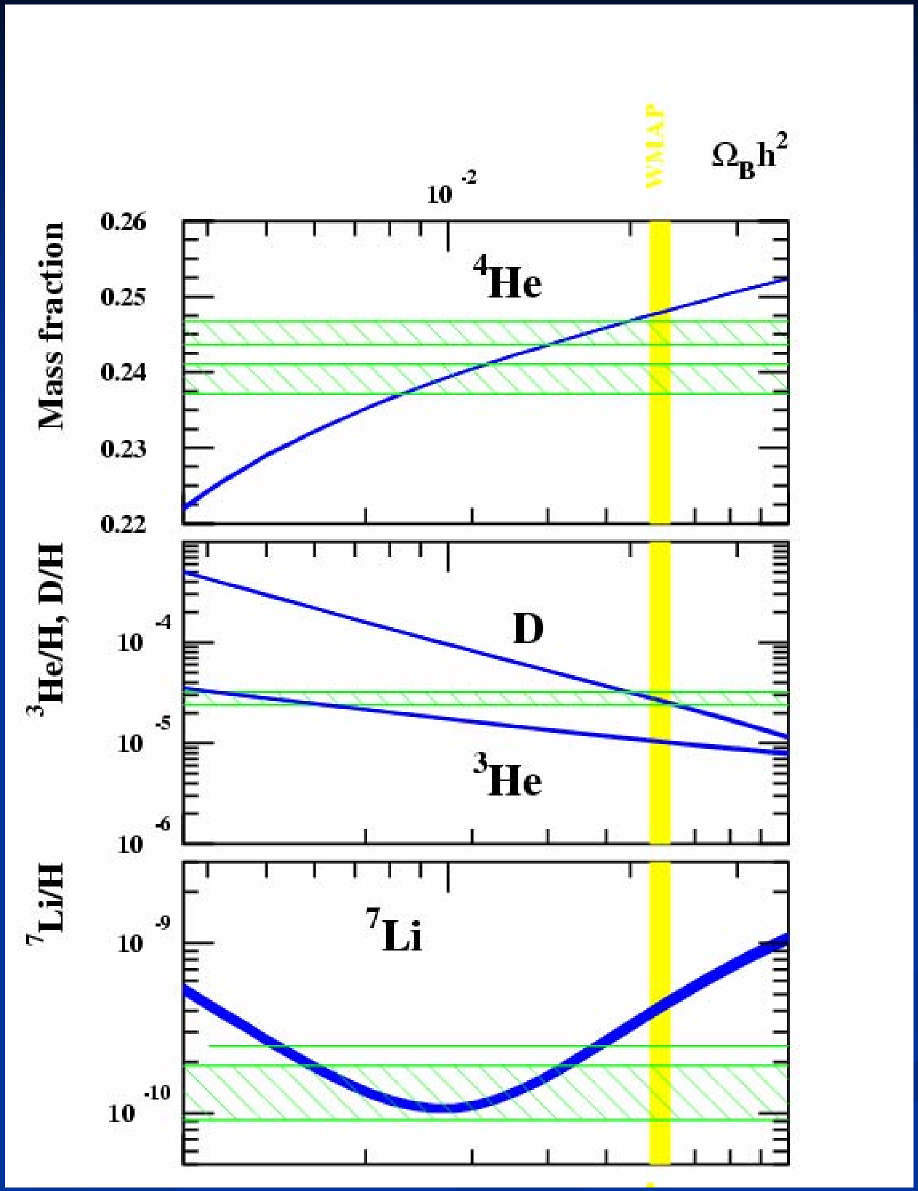
baryons :



the matter of stars and humans

$$\Omega_b = 0.045$$

Abundancies of primordial light elements from nucleosynthesis



A.Coc

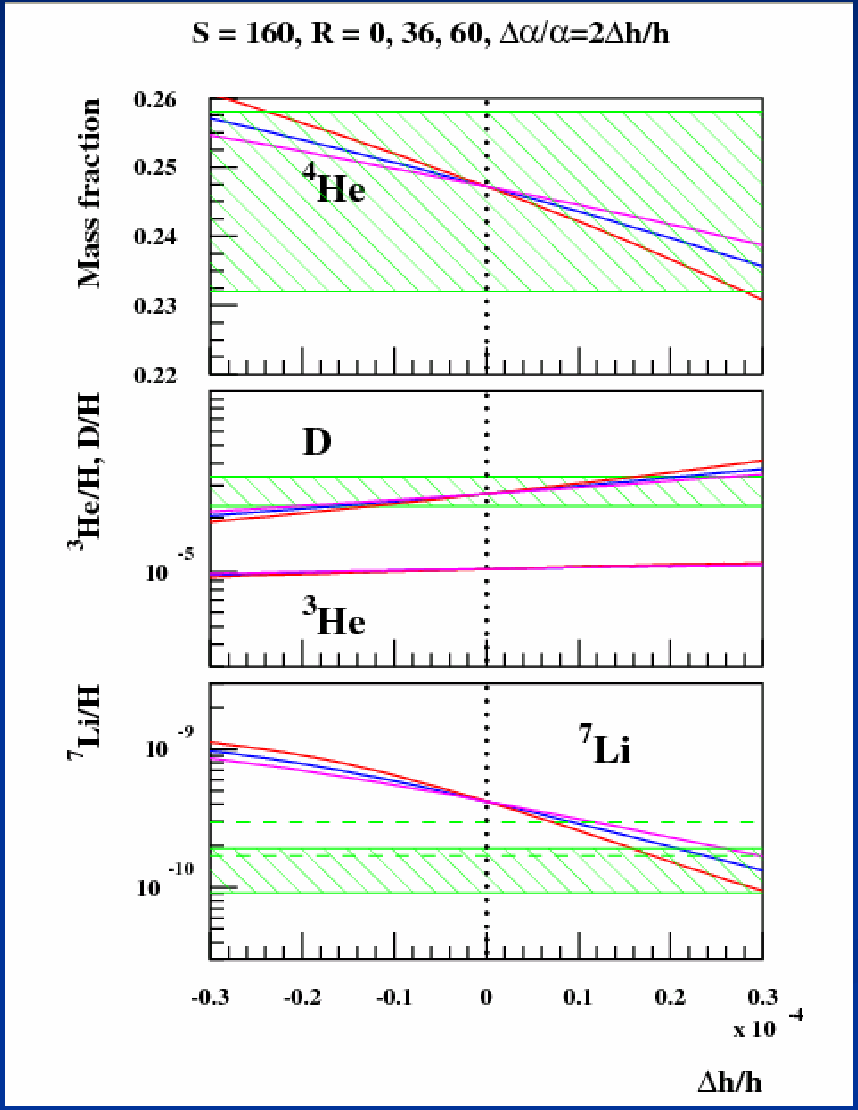
Allowed values for variation of fine structure constant :

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

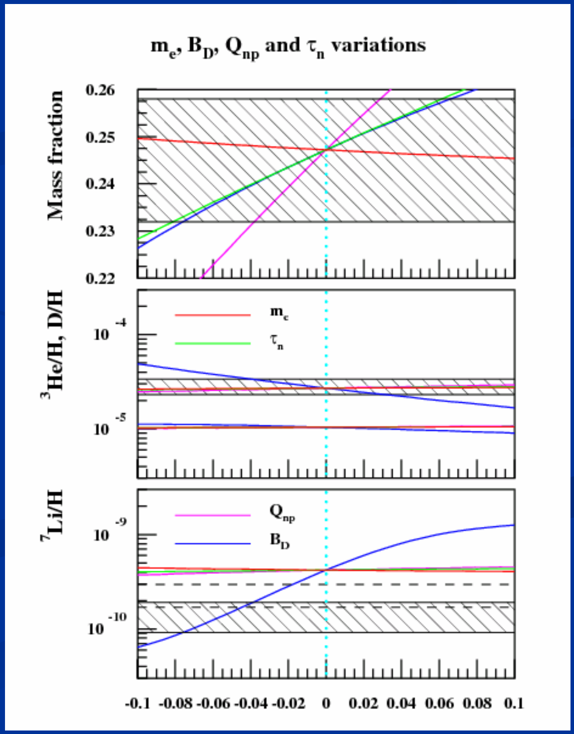
$$\Delta\alpha/\alpha \; (z=10^{10}) = -2.7 \; 10^{-4} \quad \text{GUT 2}$$

C.Mueller,G.Schaefer,…

variation of Li- abundance



Coc,Nunes,Olive, Uzan,Vangioni 10/06



Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

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

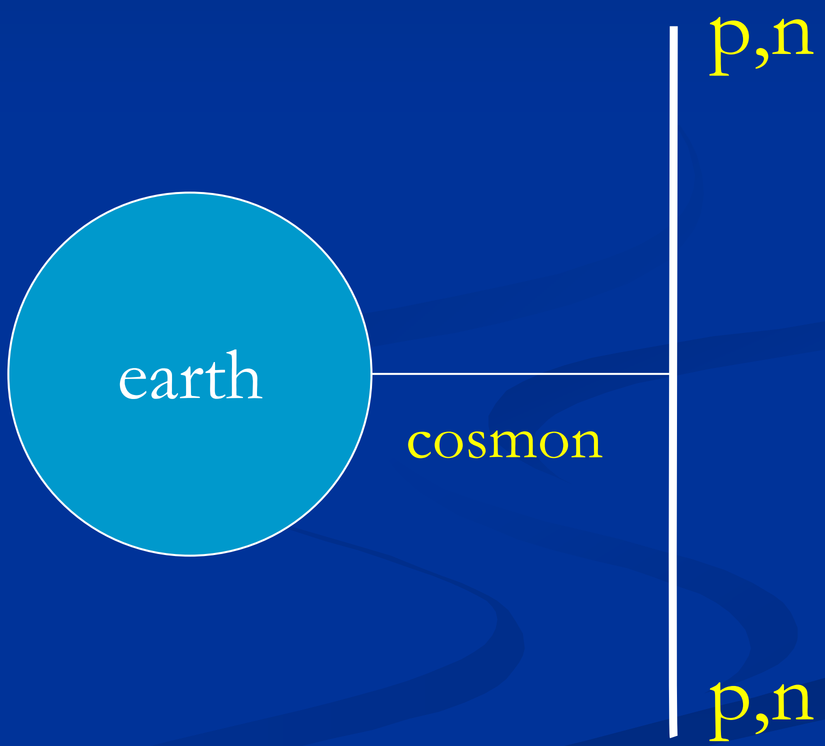
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

Differential acceleration

Two bodies with equal mass experience
a different acceleration !

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

bound : $\eta < 3\ 10^{-14}$

Cosmon coupling to atoms

- Tiny !!!
- Substantially weaker than gravity.
- Non-universal couplings bounded by tests of equivalence principle.
- Universal coupling bounded by tests of Brans-Dicke parameter ω in solar system.
- Only very small influence on cosmology.

(All this assumes validity of linear approximation)

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) :

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

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

$\eta = \Delta a / 2a$

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 , …)

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 ?

Quintessence and solution of cosmological constant problem should be related !

End

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:

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

- 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

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

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

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

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

No additional constant !

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Quintessence models

- Kinetic function $k(\varphi)$: parameterizes the details of the model - "kinetial"
  - $k(\varphi) = k = const.$ 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 !

crossover quintessence

k(φ) increase strongly for φ corresponding to present epoch

Example (LKT) :

$$k(\varphi) = k_{min} + \tanh(\varphi - \varphi_1) + 1$$

$$(\text{with } k_{min} = 0.1\,, \quad \varphi_1 = 276.6\,)$$

exponential quintessence:

$$k = \frac{1}{\sqrt{2}\alpha}$$

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

  $\Longrightarrow$ Ω_h < 10% during structure formation

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

  $\Longrightarrow$ negative w_h

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

cosmon mass changes with time !

for standard kinetic term

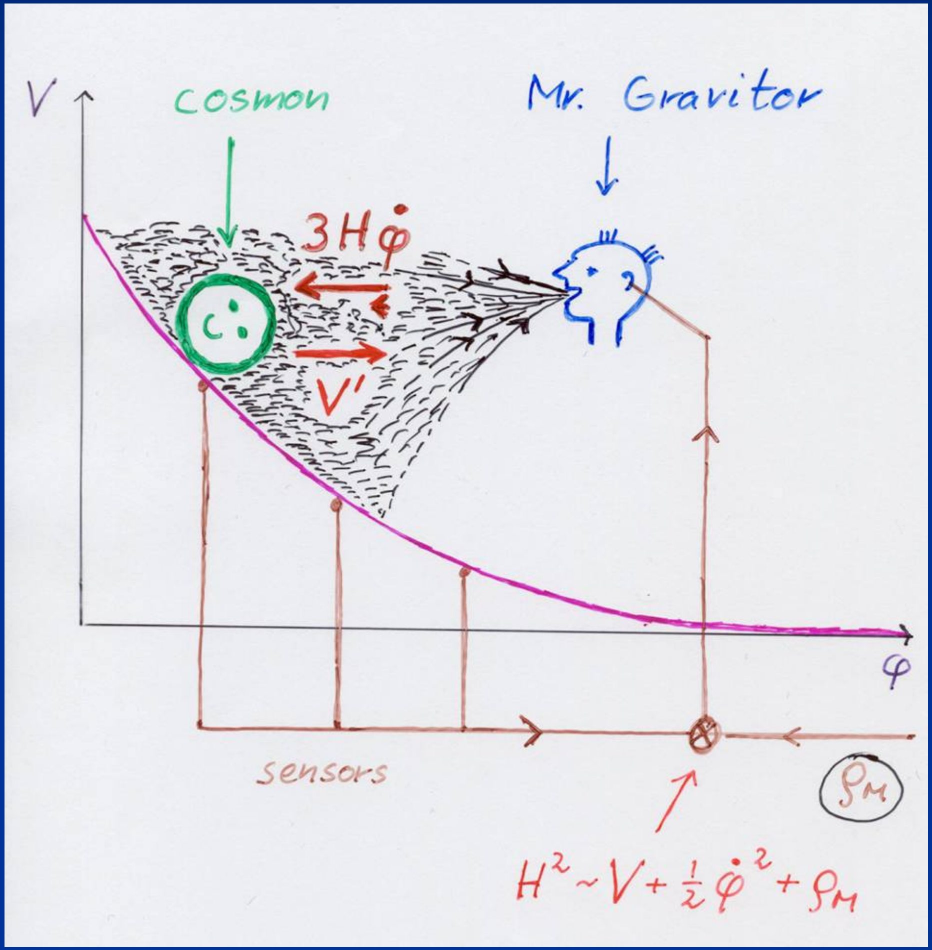
- $m_c^2 = V''$

for standard exponential potential , $k \approx$ 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



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

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

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