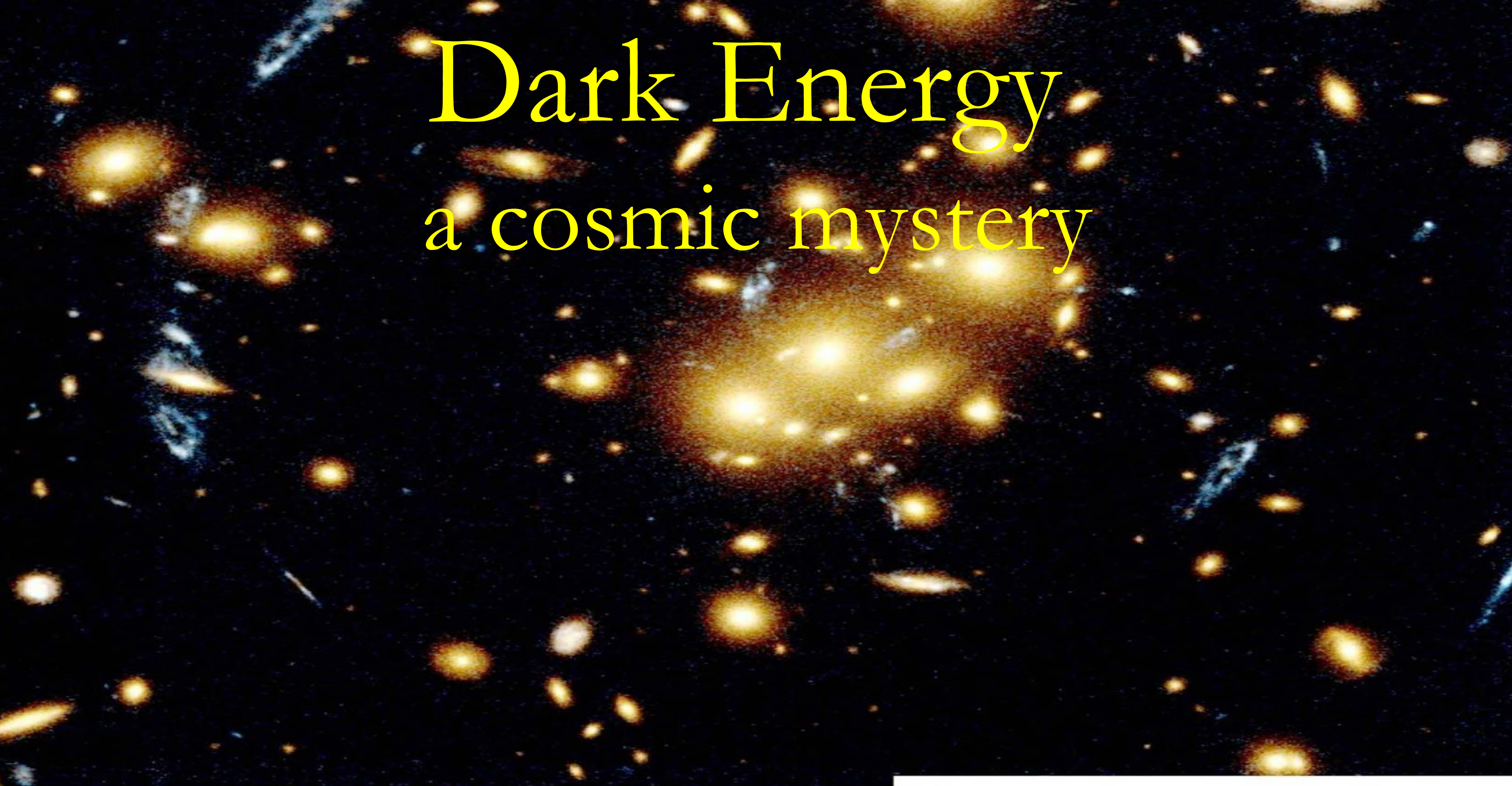
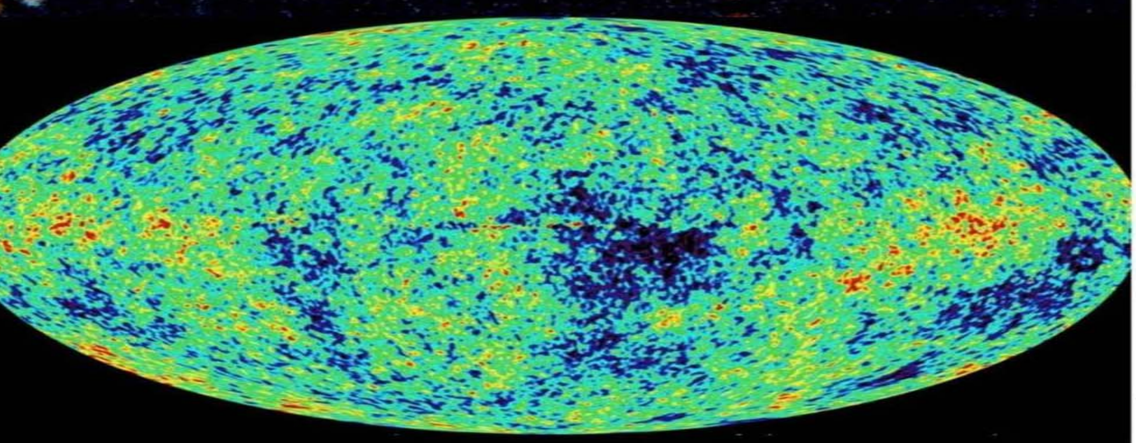
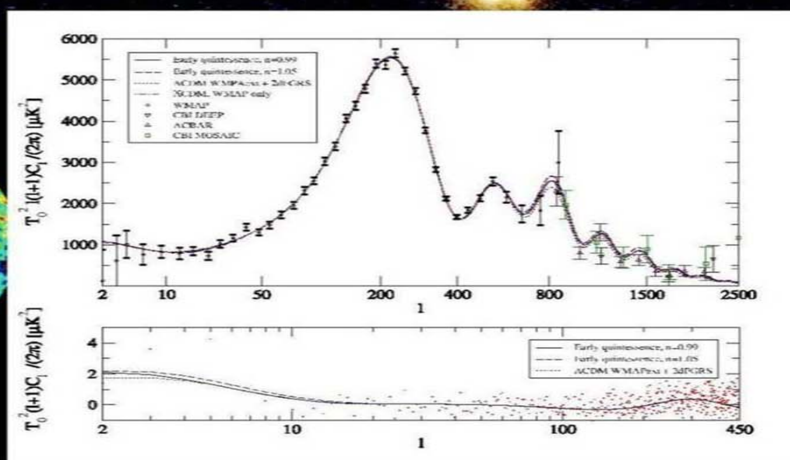
Dark Energy
a cosmic mystery







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 %

critical density

- $\varrho_c = 3 H^2 M^2$

  critical energy density of the universe

  (M : reduced Planck-mass , H : Hubble parameter)

- $\Omega_b = \varrho_b / \varrho_c$

  $H = \dot{a}/a$

  fraction in baryons

  energy density in baryons over critical energy density

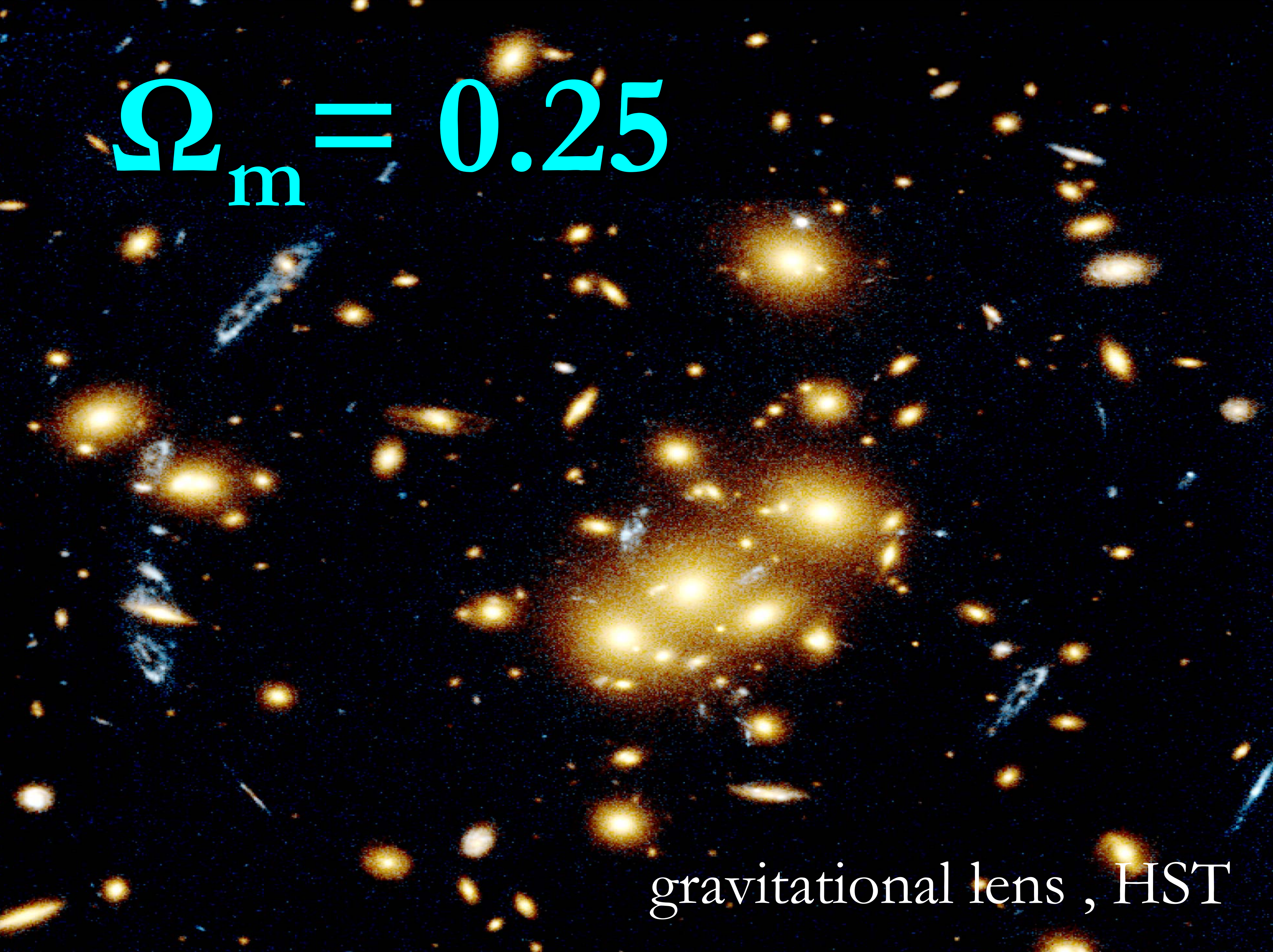
What is Dark Energy ?

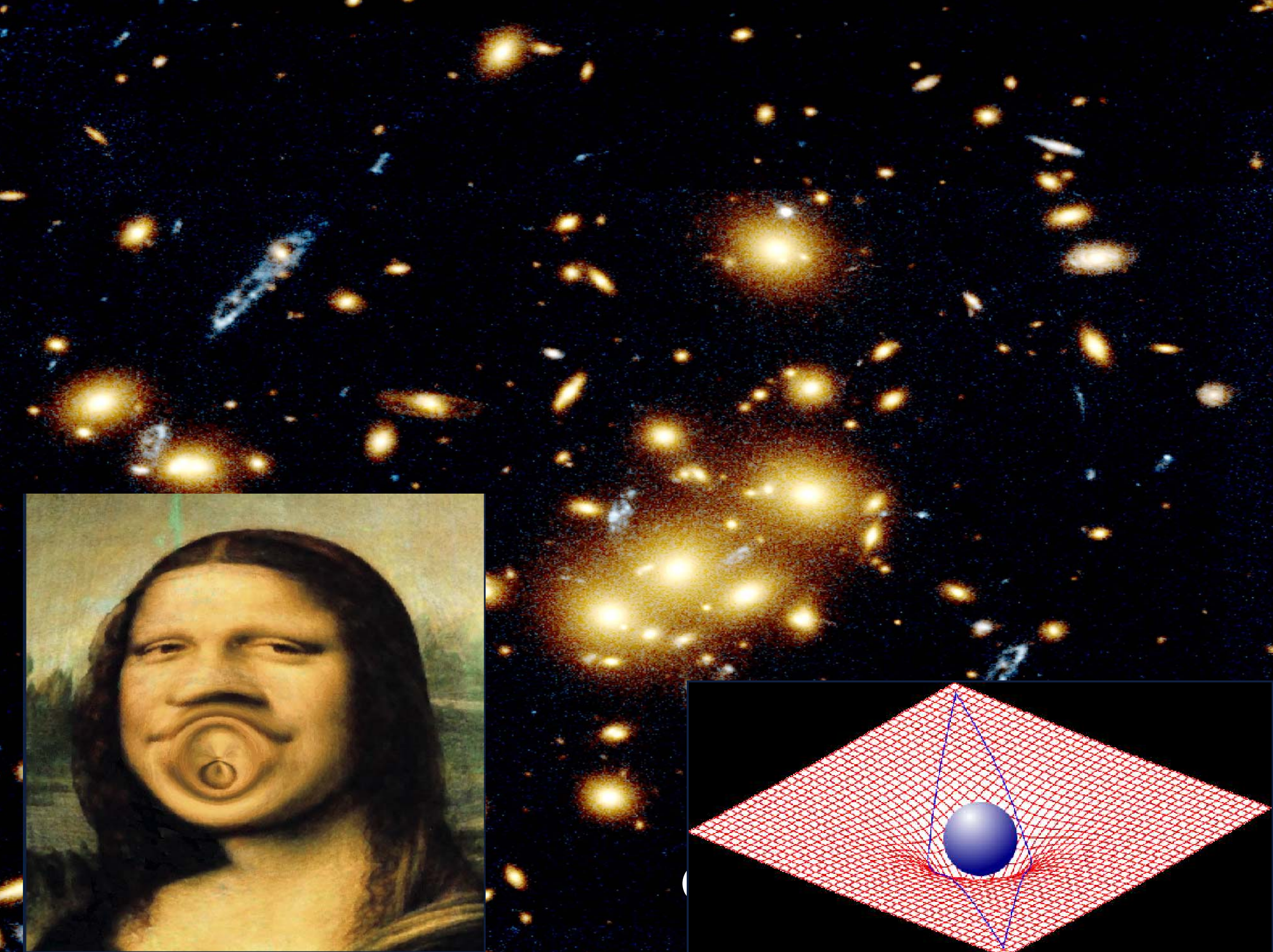

Matter : Everything that clumps
Abell 2255 Cluster
~300 Mpc

Dark Matter

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

  and therefore of local matter distribution


$\Omega_m = 0.25$
gravitational lens , HST



spatially flat universe

$$\Omega_{tot} = 1$$

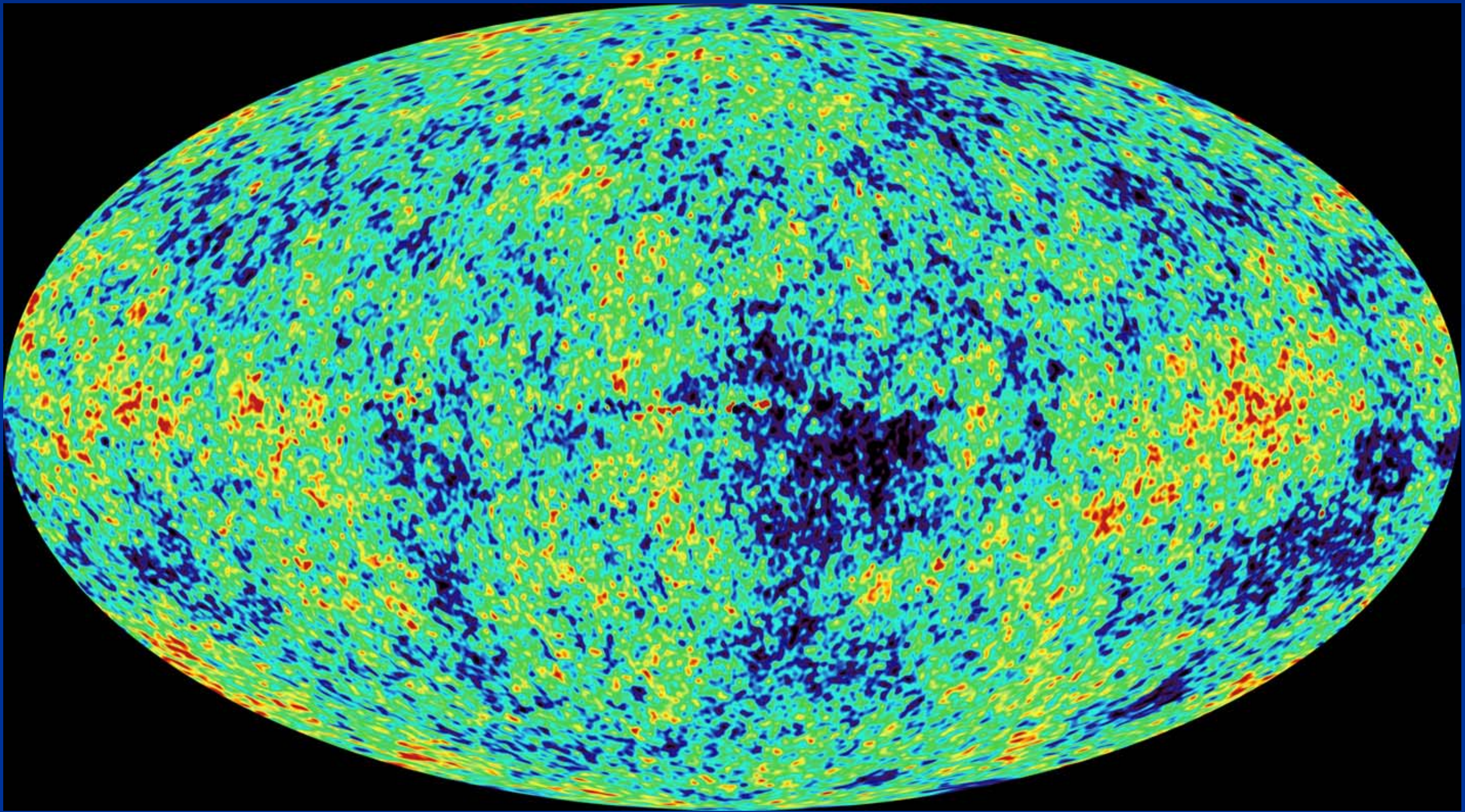
- theory (inflationary universe)

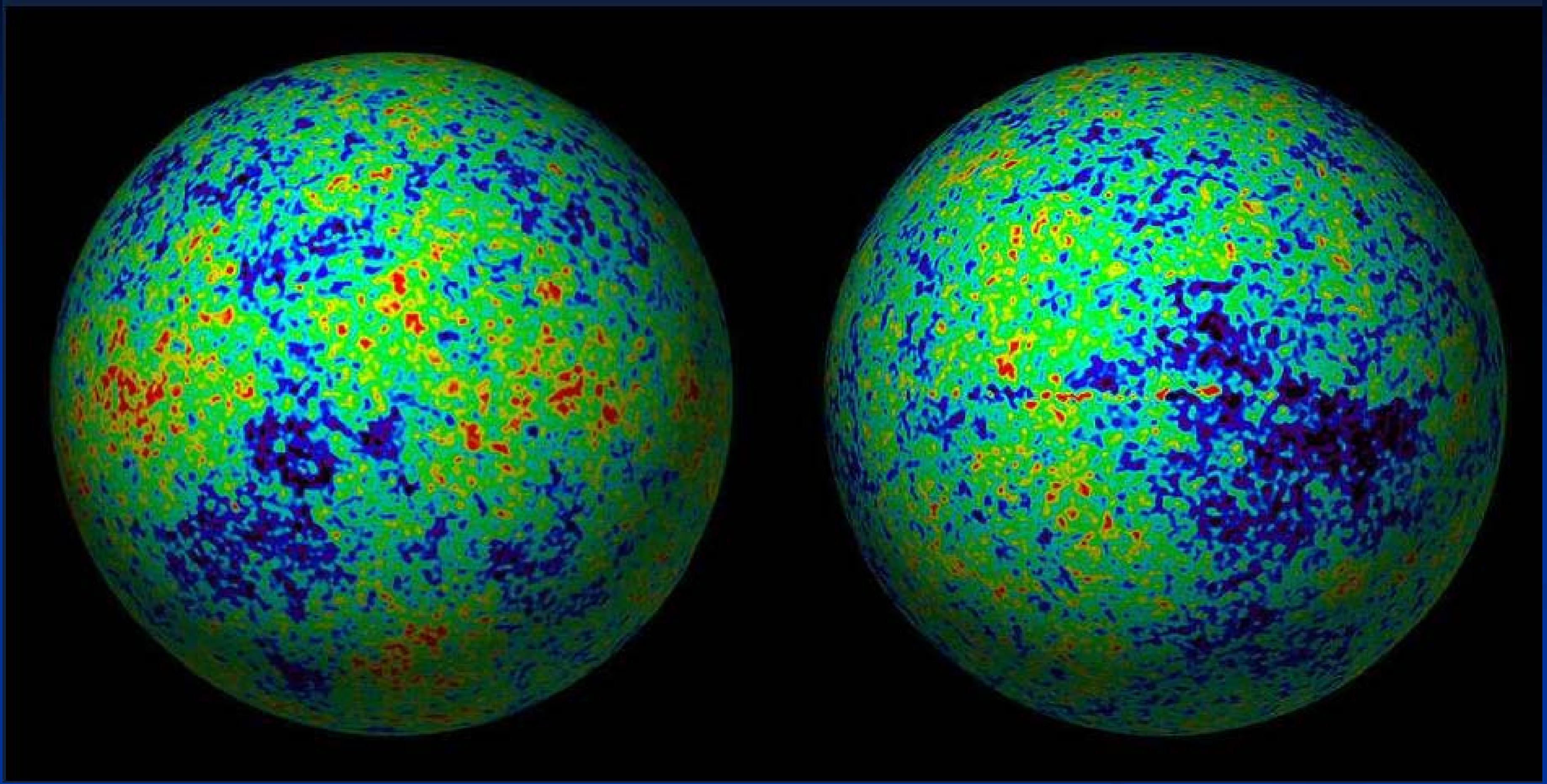
  Ω_{tot} =1.0000……….x

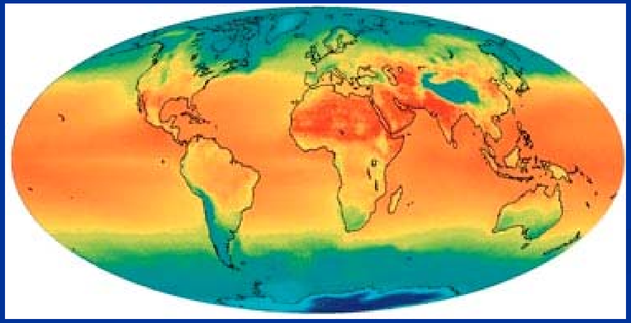
- observation (WMAP)

  Ω_{tot} =1.02 (0.02)

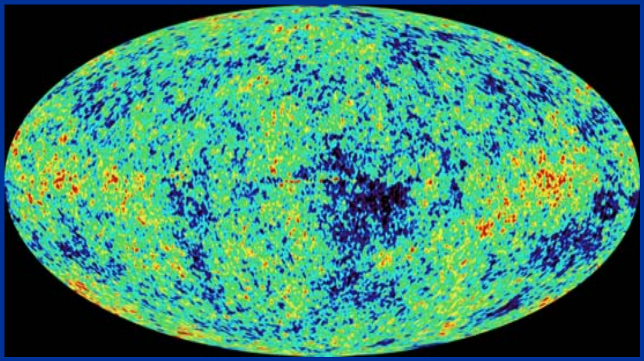
picture of the big bang

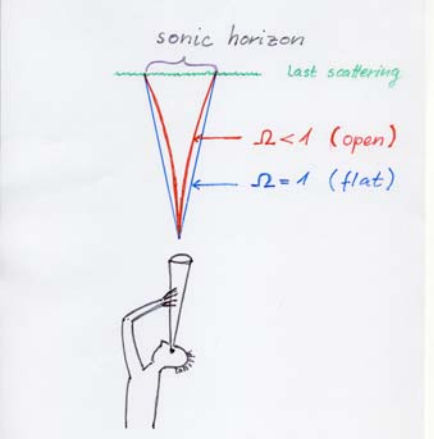


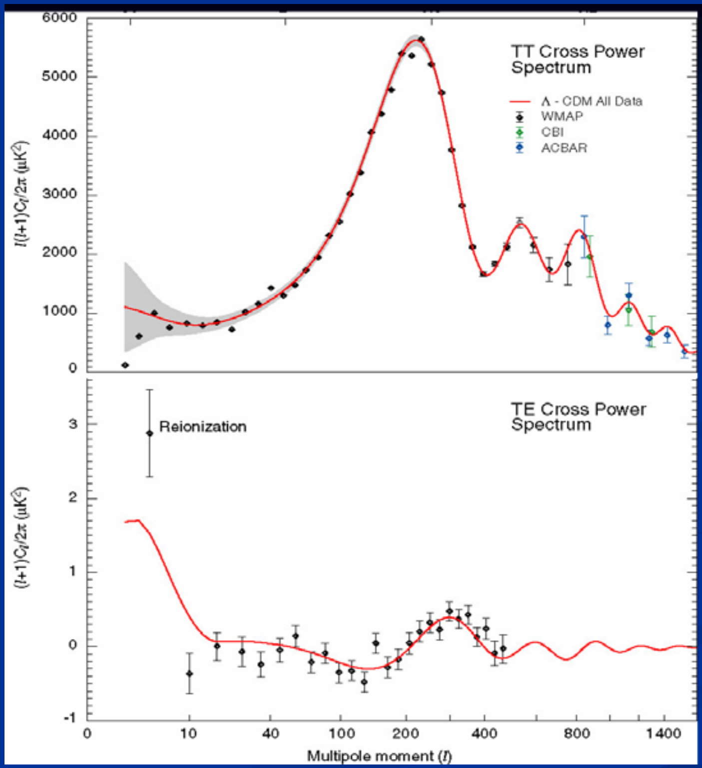




$\Omega_{tot}=1$







mean values

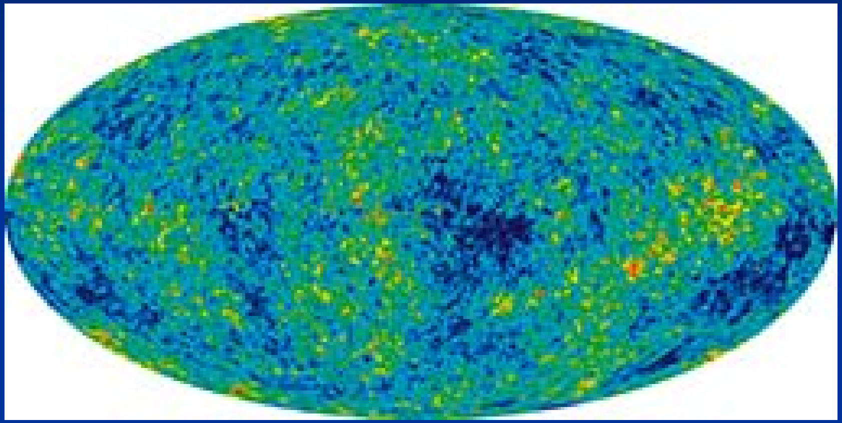
Ω_{tot} =1.02

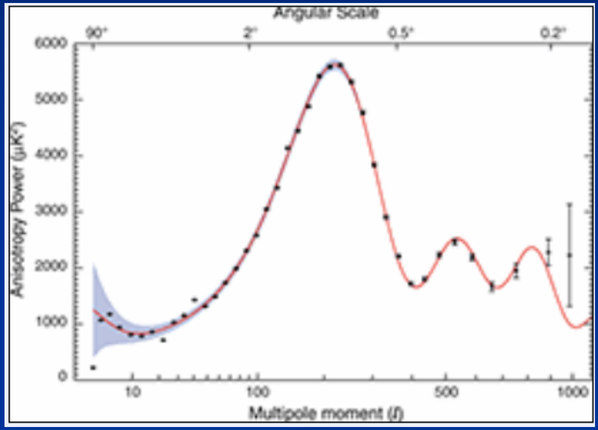
Ω_m =0.27

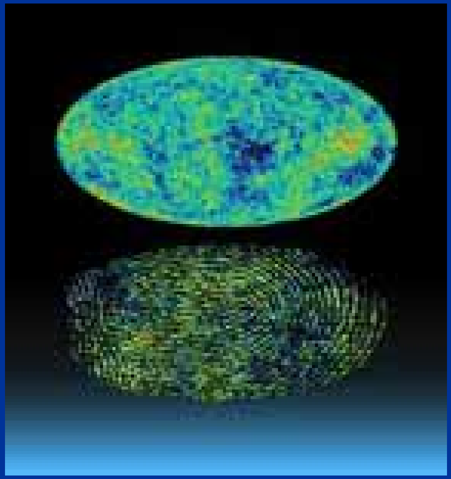
Ω_b =0.045

Ω_{dm} =0.225

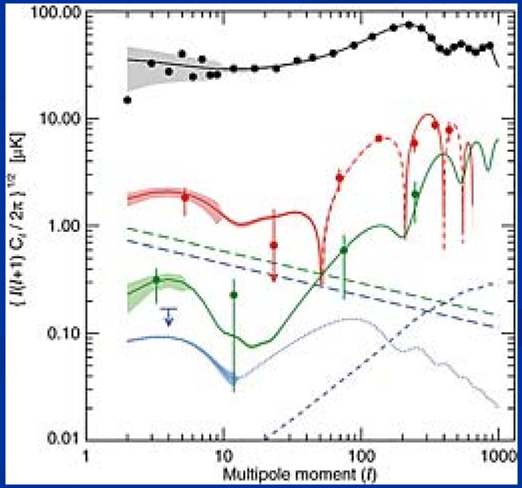
WMAP 2006







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 !

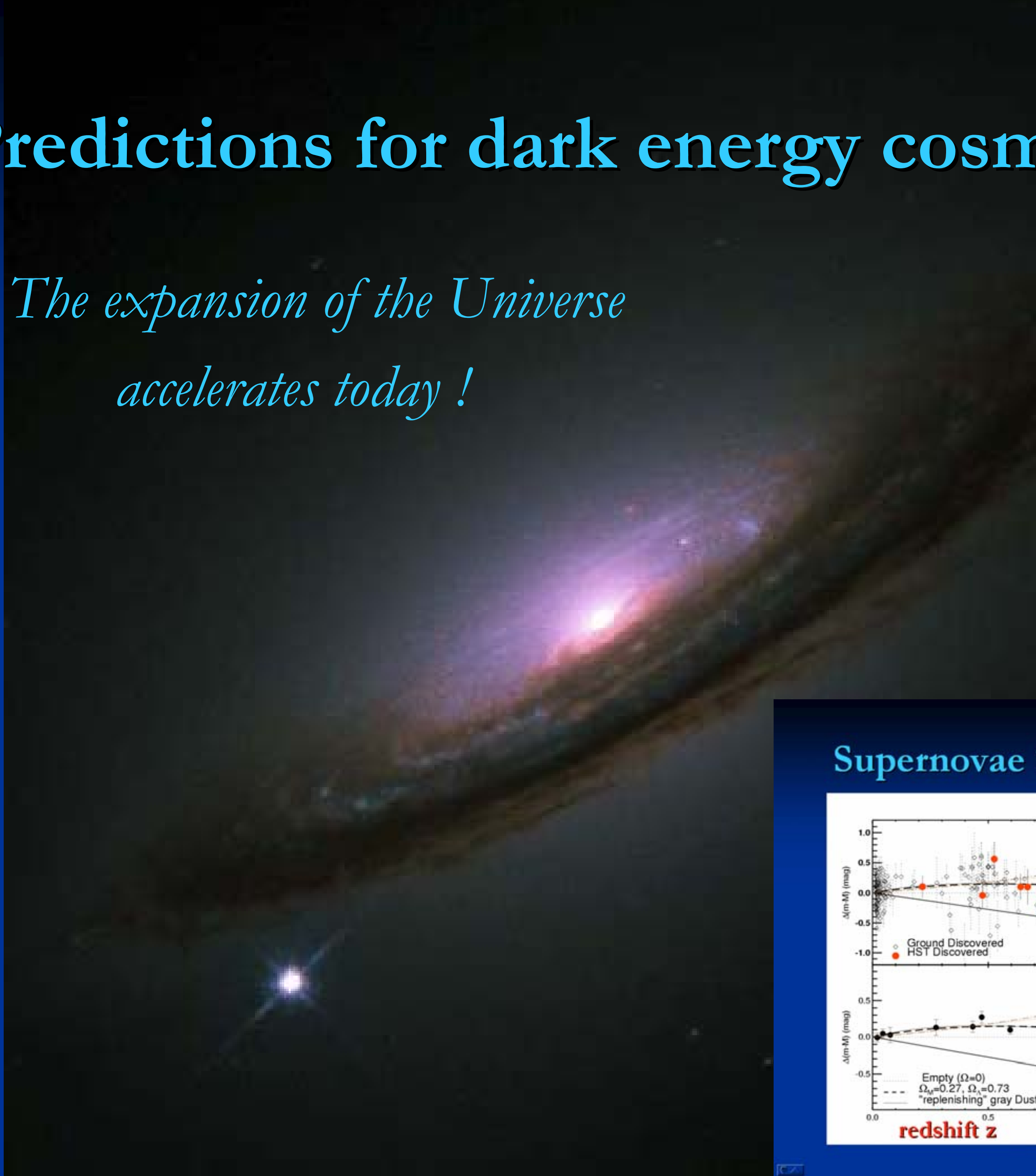
Dark Energy density is
the same at every point of space

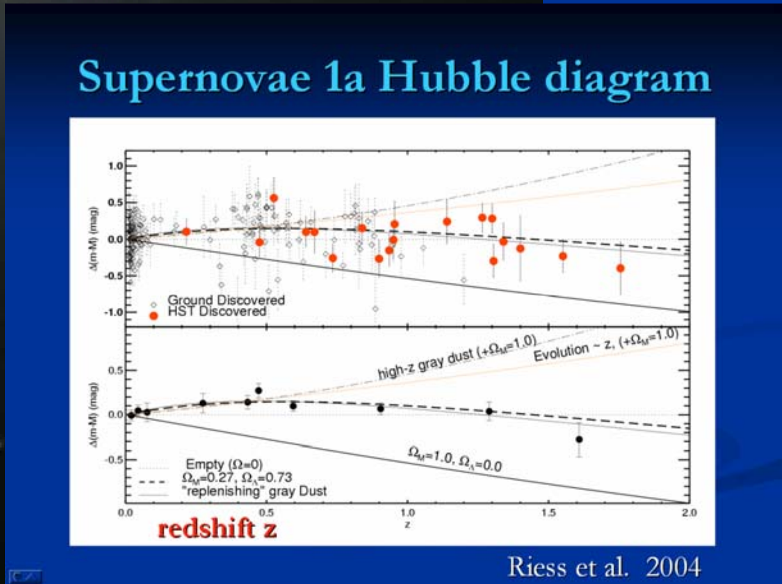
“ homogeneous “

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

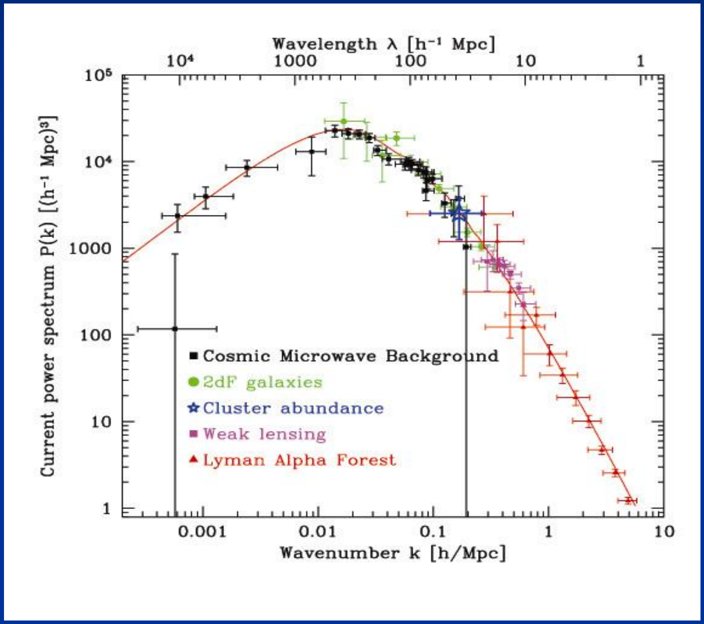
Predictions for dark energy cosmologies

The expansion of the Universe accelerates today !





Power spectrum

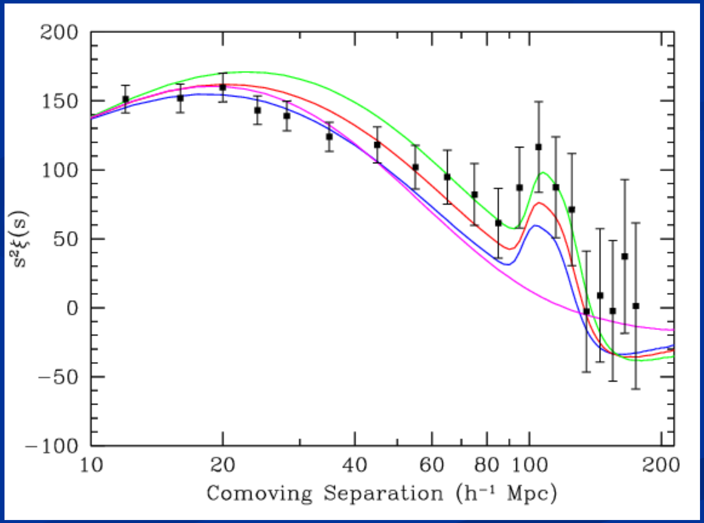


Structure formation :

One primordial fluctuation- spectrum

Baryon - Peak

galaxy – correlation – function



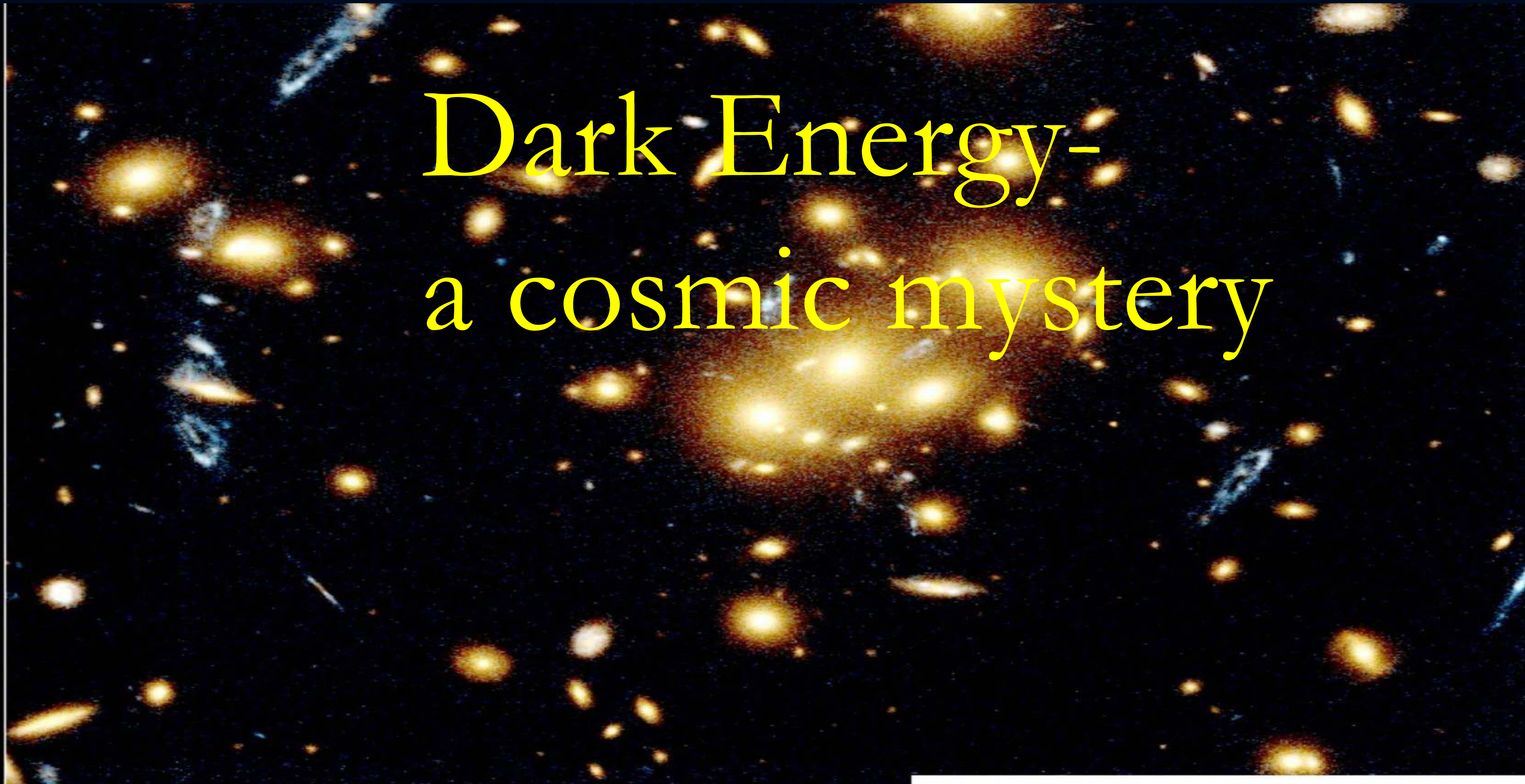
SDSS

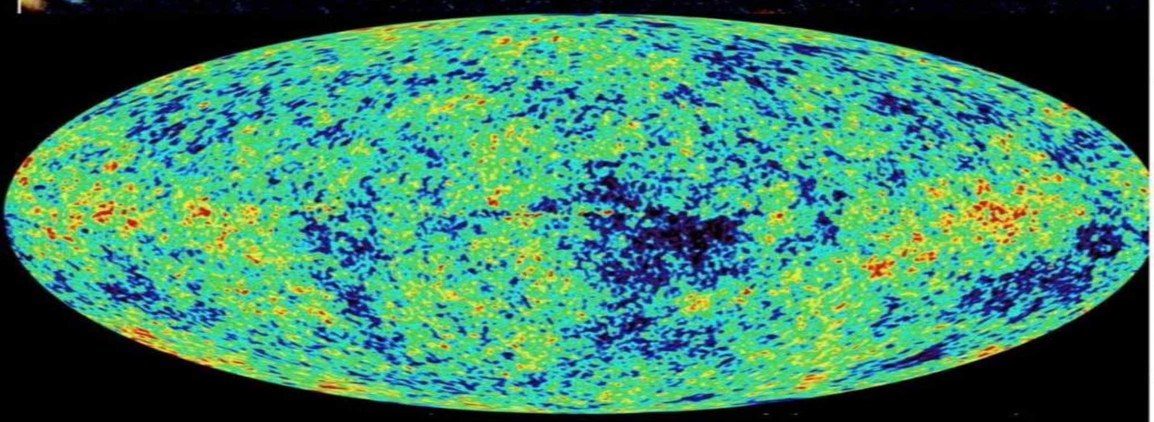
consistent cosmological model !

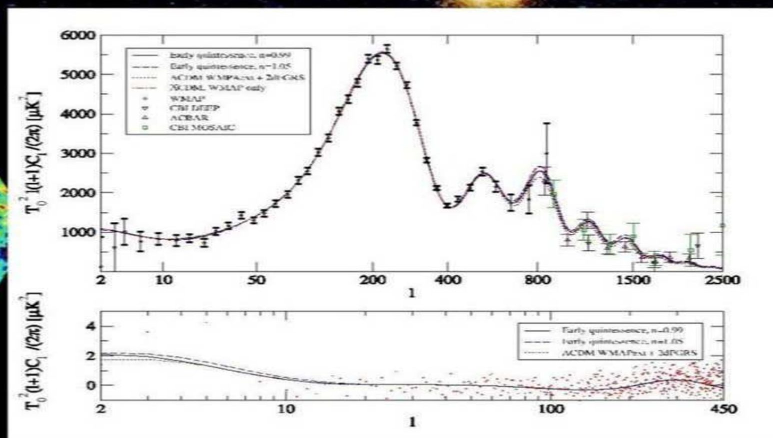
Composition of the Universe

$\Omega_b = 0.045$	visible	clumping
$\Omega_{dm} = 0.2$	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 ?

Einstein equation

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = -\frac{8\pi}{M_p^2} T_{\mu\nu}$$

$$M_p = 1.22 \cdot 10^{19}\,\mathrm{GeV} = G_N^{-1/2}$$

Energy-momentum-tensor

$$T_{\mu\nu} = T_{\mu\nu}^{(\mathrm{baryon})} + T_{\mu\nu}^{(\mathrm{radiation})}$$

$$+ T_{\mu\nu}^{(\mathrm{dark\ matter})}$$

$$+ T_{\mu\nu}^{(\mathrm{homogeneous})}$$

$$T_{\mu\nu}^{(\text{homogenous})} \overset{?}{=}$$

$$\begin{cases} \lambda\, g_{\mu\nu} & : \text{cosmological const.} \\ T_{\mu\nu}^{(q)} & : \text{quintessence} \end{cases}$$

scalar field ?

nonlocal gravity ?

⋮

Gravitational action

$$S = + \int d^4x \, g^{1/2} \left(- \frac{M_p^2}{16\pi} R + \lambda \right)$$

λ : cosmological constant

Field equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi}{M_p^2} \left(T^M_{\mu\nu} - \lambda g_{\mu\nu} \right)$$

$M_p \approx 10^{19}$ GeV : Planck mass

$T^M_{\mu\nu}$: matter energy momentum tensor

accounts for nonvanishing entropy in the universe

without matter:

$$R = + \frac{32\pi}{M_p^2} \lambda$$

Cosmological constant

$$T_{\mu\nu} = T^{M}_{\mu\nu} - \lambda g_{\mu\nu}$$

$$\rho \rightarrow \rho + \lambda = \rho + \rho_\lambda$$

$$p \rightarrow p - \lambda = p + p_\lambda$$

$$\rho + p \rightarrow \rho + p$$

„Equation of state"

$$p_\lambda / \rho_\lambda = -1$$

Friedman universe $(\lambda = 0)$

Einstein equations $\rightarrow$

(i) $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_p^2}\,\rho \quad - \frac{k}{a^2}$

(evolution equation)

(ii) $\dot{\rho} \quad + 3H(\rho + p) = 0$

(energy-momentum-conservation)

$\Leftrightarrow \frac{d}{dt}\left[a^3(\rho + p)\right] = a^3 \frac{d}{dt}\,p$

radiation $(p = \frac{1}{3}\rho)$ $\quad \rho \sim a^{-4}$

matter $(p = 0)$ $\quad \rho \sim a^{-3}$

$k = 0$ (always applicable for early universe)

Field equations involve only the Hubble-parameter $H = \dot{a}/a$

$\lambda \neq 0$

Einstein equations →

(i) $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_P^2}(\varrho + \lambda) - \frac{k}{a^2}$

(evolution equation)

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$k = 0$ (always applicable for early universe)

Field equations involve only the Hubble-parameter $H = \dot{a}/a$

Only minor modification for

$\lambda \ll \rho$

For $t \to \infty$: $\lambda \neq 0$ has always important effects !

asymptotic solution for cosmological constant (k=0)

$\lambda > 0$

$$H^2 \to \frac{8\pi}{3M_p^2}\lambda \qquad a \sim \exp H_0 t$$

$\lambda = 0$

$$H \to \eta t^{-1} \qquad a \sim t^{\eta}$$

$\lambda < 0$

$$H \to \left(\frac{8\pi}{3M_p^2}|\lambda|\right)^{1/2} tg\,(c_1 - c_2 t)$$

e.g. a expands to maximal a_0
and shrinks subsequently

For

$$|\lambda| \ll \frac{3 M_p^2 H^2}{8\pi} \quad :$$

only small corrections to

standard cosmology

—

$$\lambda \approx (0.6 - 0.7)\, \rho_c$$

good candidate for dark energy !

compatible with observation !

problems with small λ

- no symmetry explanation for $\lambda/M^4 = 10^{-120}$
- quantum fluctuations contribute

Zero point energies for normal modes of field with mass m, for wave numbers $|k| < \Lambda$ $(m^2 \ll \Lambda^2)$

$$\langle \rho \rangle_{vac} = \int_0^{\Lambda} \frac{4\pi k^2\, dk}{(2\pi)^3} \cdot \frac{1}{2}\sqrt{k^2+m^2} \simeq \frac{\Lambda^4}{16\pi^2}$$

In QED, zero point energies are measured by Casimir effect

—

detection of cosmological constant:

Link between quantum fluctuations and gravity !

Anthropic principle

For

$$\lambda \lesssim -\frac{1}{2}\rho_c$$

or

$$\lambda > (10-100)\,\rho_c$$

we simply would not exist !

Banks
Weinberg
Linde

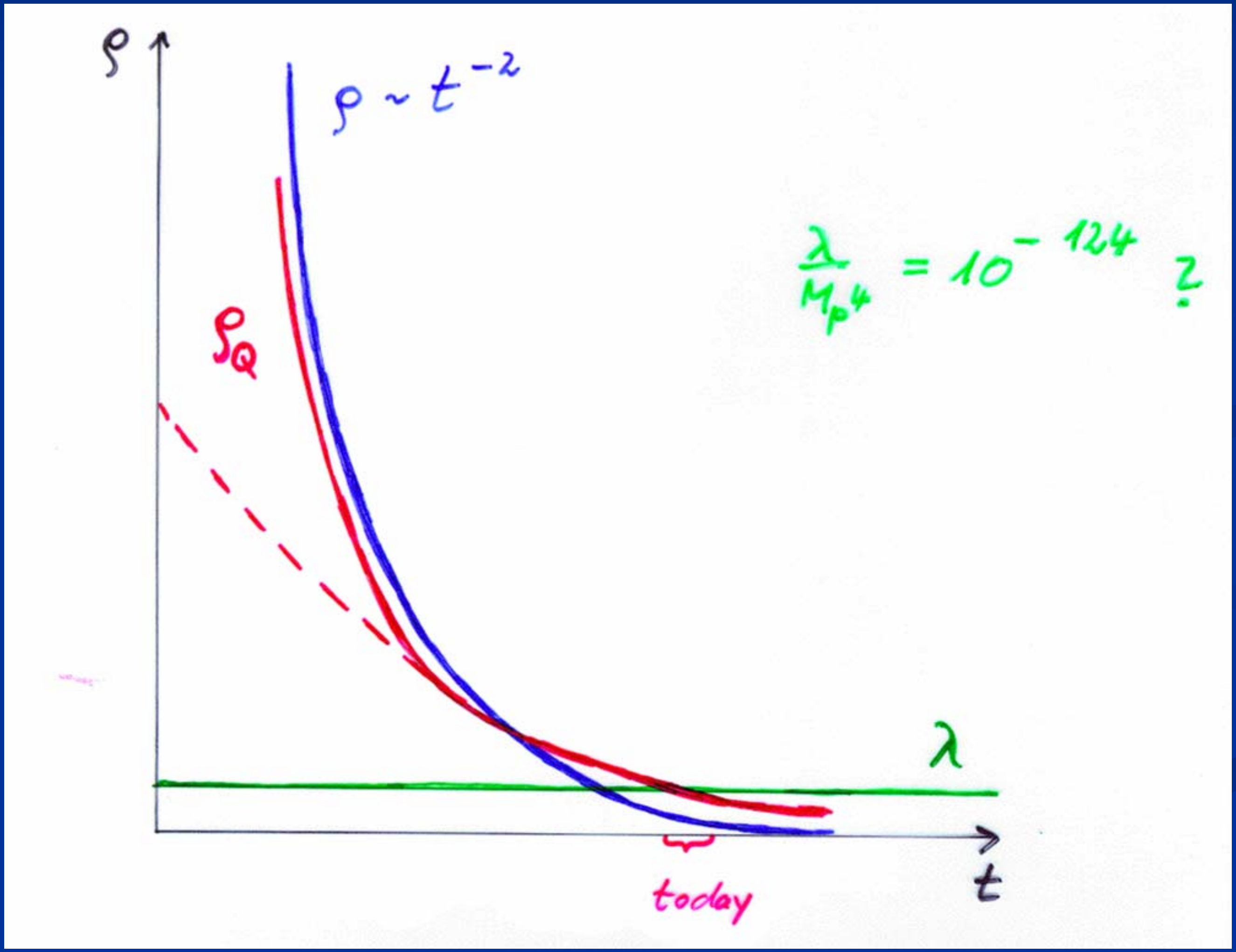
Cosmological Constant
- Einstein -

- 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 !

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 :*

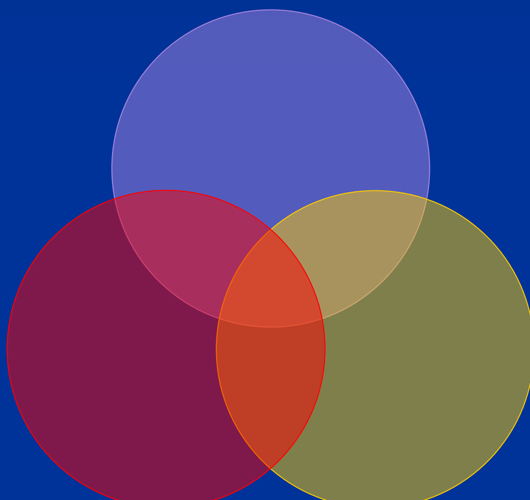
  $\rho_h(t)$ *decreases with time !*

Cosmon

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

"Fundamental" Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

Evolution of cosmon field

Field equations

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

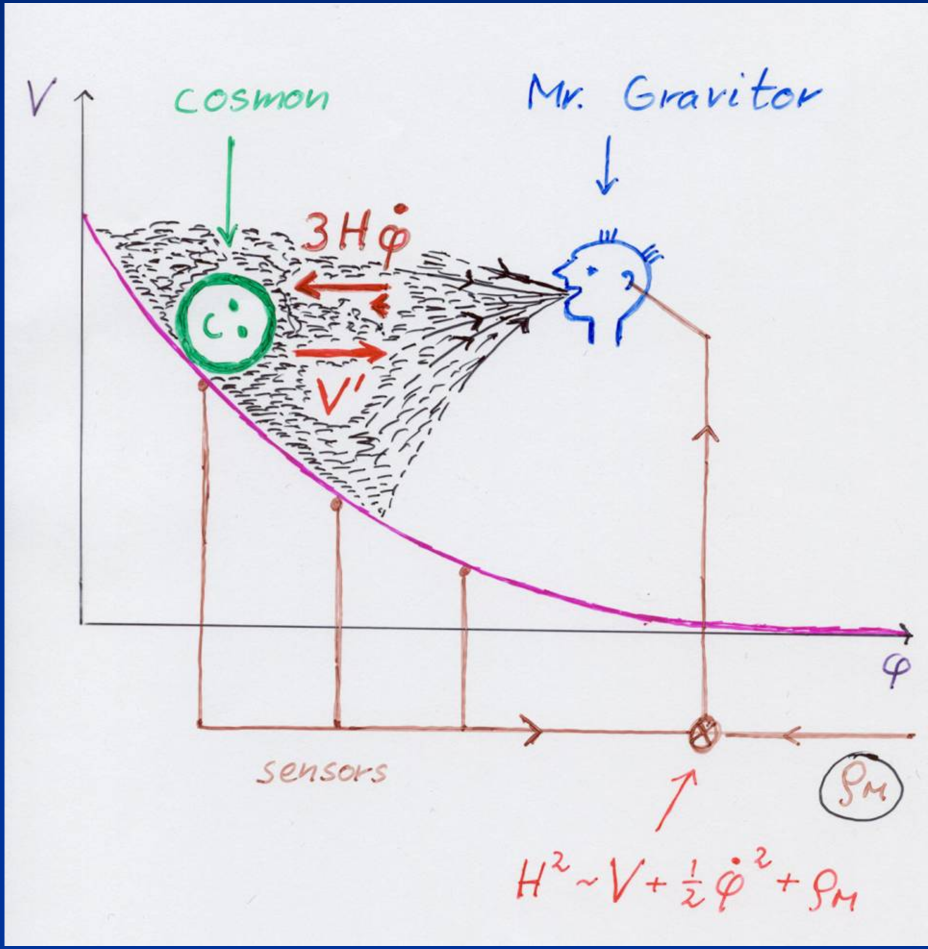
$$3M^2H^2 = V + \frac{1}{2}\dot{\phi}^2 + \rho$$

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 !

Cosmological equations



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

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

Cosmic Attractors

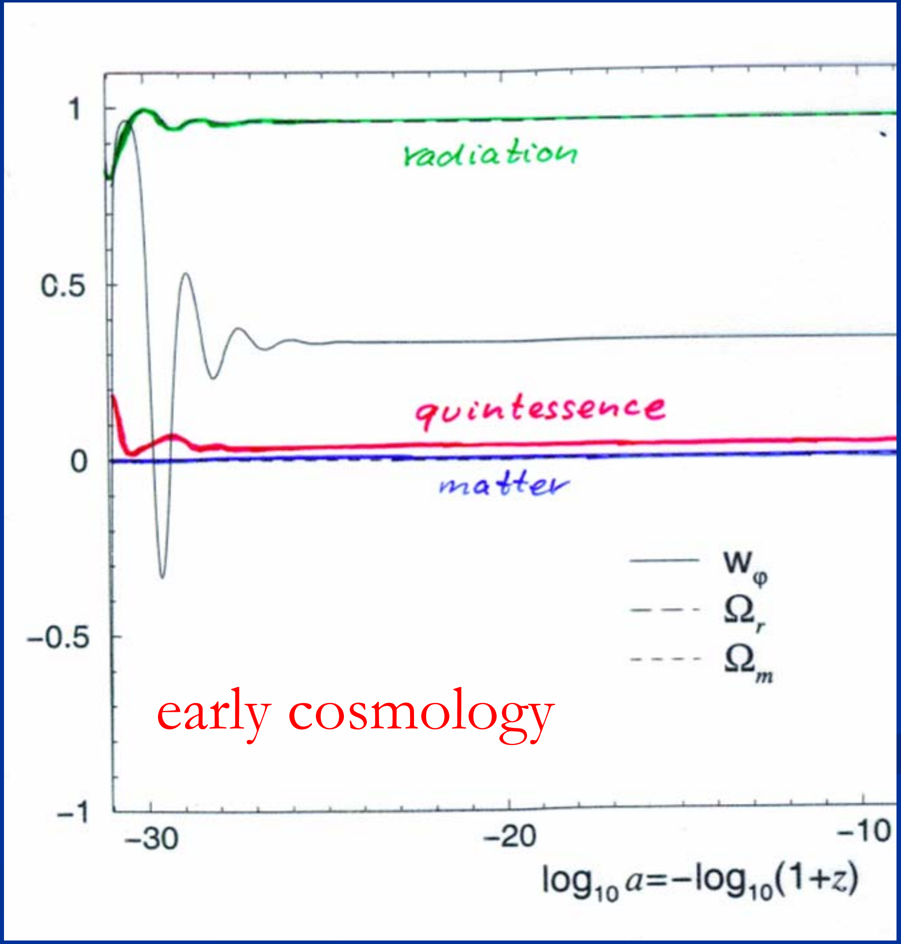
Solutions independent of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

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



Cosmological equations

$$\mathcal{L} = \sqrt{g}\left\{\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi + V(\phi)\right\}$$

(homogeneous and isotropic Robertson-Walker metric , $k=0$)

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

matter/radiation

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

$$\dot{\rho}_M + 3H(\rho_M + p_M) = 0$$

$$p_M = \frac{n-3}{3}\rho_M$$

asymptotic solution for large time

Cosmological solutions with scalar field (cosmon)

for exponential potential $V \sim \exp(-a\frac{\varphi}{M})$

$$\Longrightarrow$$

asymptotic solution for $t \to \infty$:

$$V \sim t^{-2} \quad , \quad \dot{\varphi}^2 \sim t^{-2}$$

$$\varphi = \frac{2M}{a} \ln t$$

stable attractor!

independent of initial conditions
"tracker solution"

$$\Omega_{hom} = \frac{3}{2a^2}$$

fixed fraction in dark energy!

$$H^2 = \frac{1}{6M^2}(\rho_M + V(\varphi) + \frac{1}{2}\dot{\varphi}^2)$$

$$\dot{\rho}_M + 3H(\rho_M + p_M) = 0$$

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

$$p_M = \frac{n-3}{3}\rho_M$$

$$V = \bar{V}_0 \exp\{-a\frac{\varphi}{M}\}$$

$$\phi = \frac{2M}{\alpha}\ln(t/\bar{t}) \ , \quad \frac{1}{2}\dot{\phi}^2 = \frac{2M^2}{\alpha^2}t^{-2} \ , \quad V = \frac{2M^2}{\alpha^2}\frac{(6-n)}{n}t^{-2}$$

$$H = \frac{2}{n}t^{-1} \quad , \quad \rho \sim t^{-2}$$

$$\Omega_d = (V + \frac{1}{2}\dot{\phi}^2)/\rho_c = \rho_\phi/\rho_c = \frac{n}{2\alpha^2}$$

$M \to \hat{}M$

exponential potential → constant fraction in dark energy

$$\Omega_M = 1 - \frac{n}{2a^2}$$

$$\Omega_V = \frac{V}{\rho_c} = \frac{n(6-n)}{12a^2}$$

$$\Omega_{kin} = \frac{\dot{\varphi}^2}{2\rho_c} = \frac{n^2}{12a^2}$$

$$\Omega_h = \Omega_V + \Omega_{kin} = \frac{n}{2a^2}$$

asymptotic solution

for $t \to \infty$

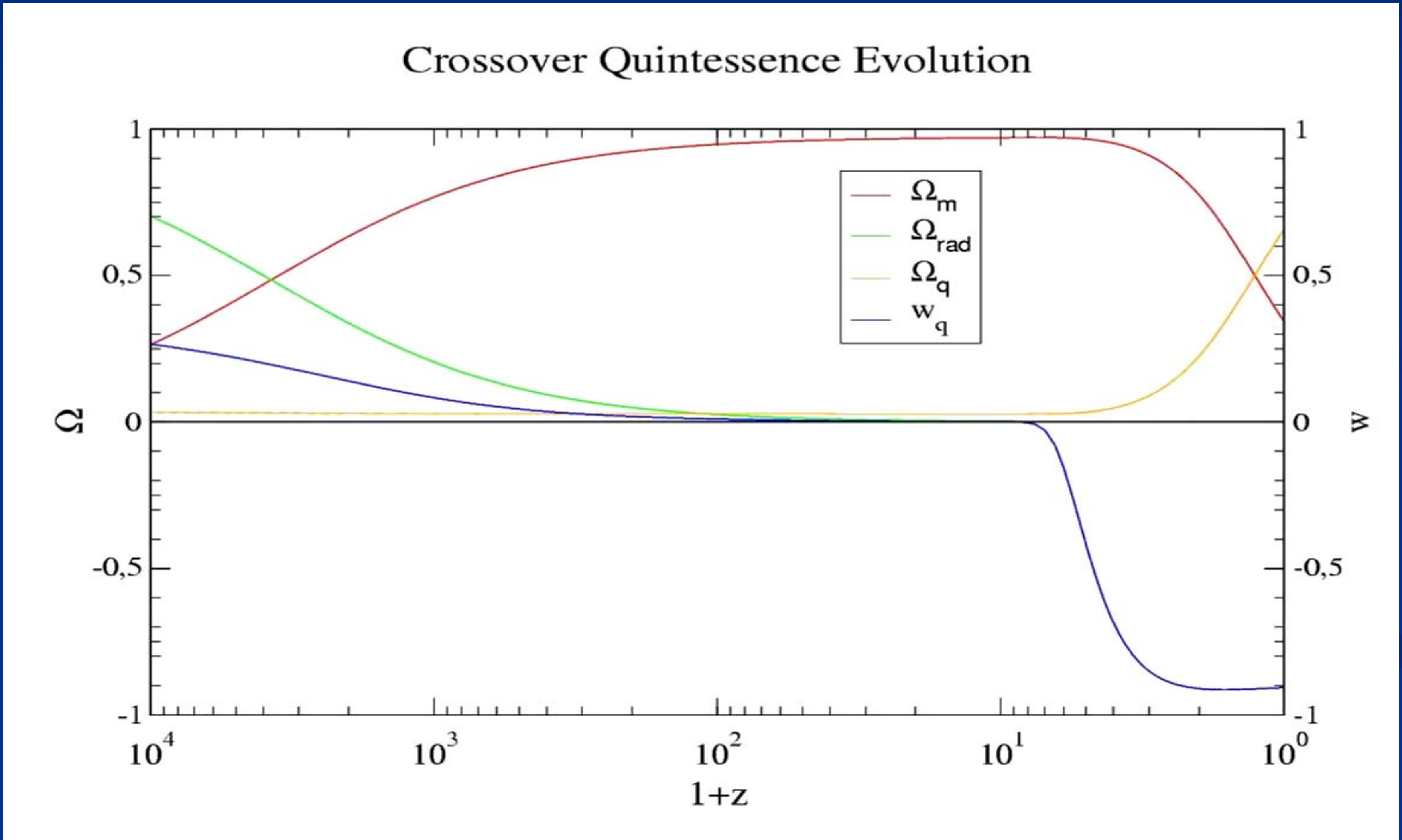
"attractor" for $a^2 > \frac{n}{2}$

$$\Omega_x = \frac{8\pi}{3} \frac{\rho_x}{M_p^2 H^2}$$

realistic quintessence

fraction in dark energy has to increase in "recent time" !

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)

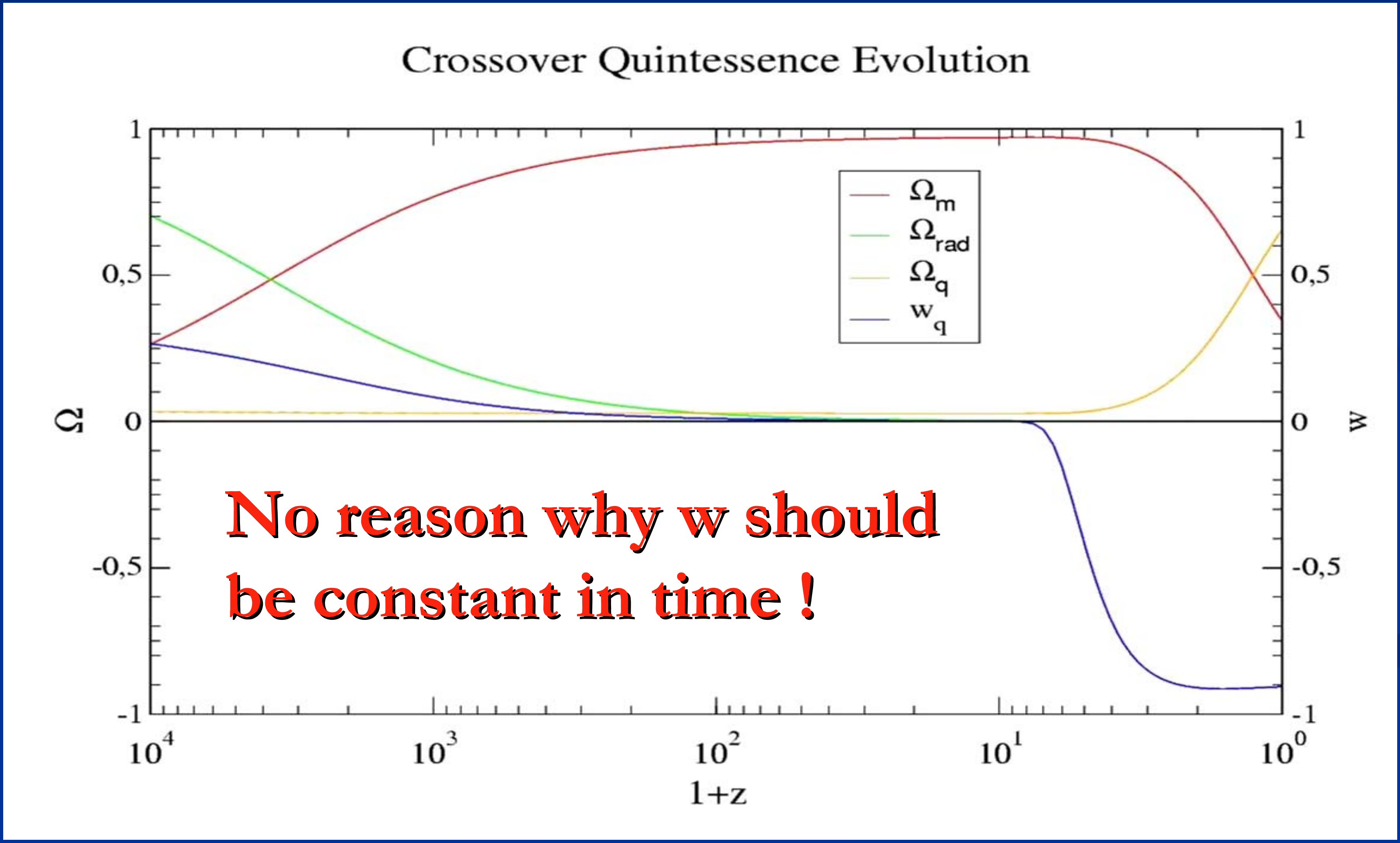
late universe with
small radiation component :

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

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

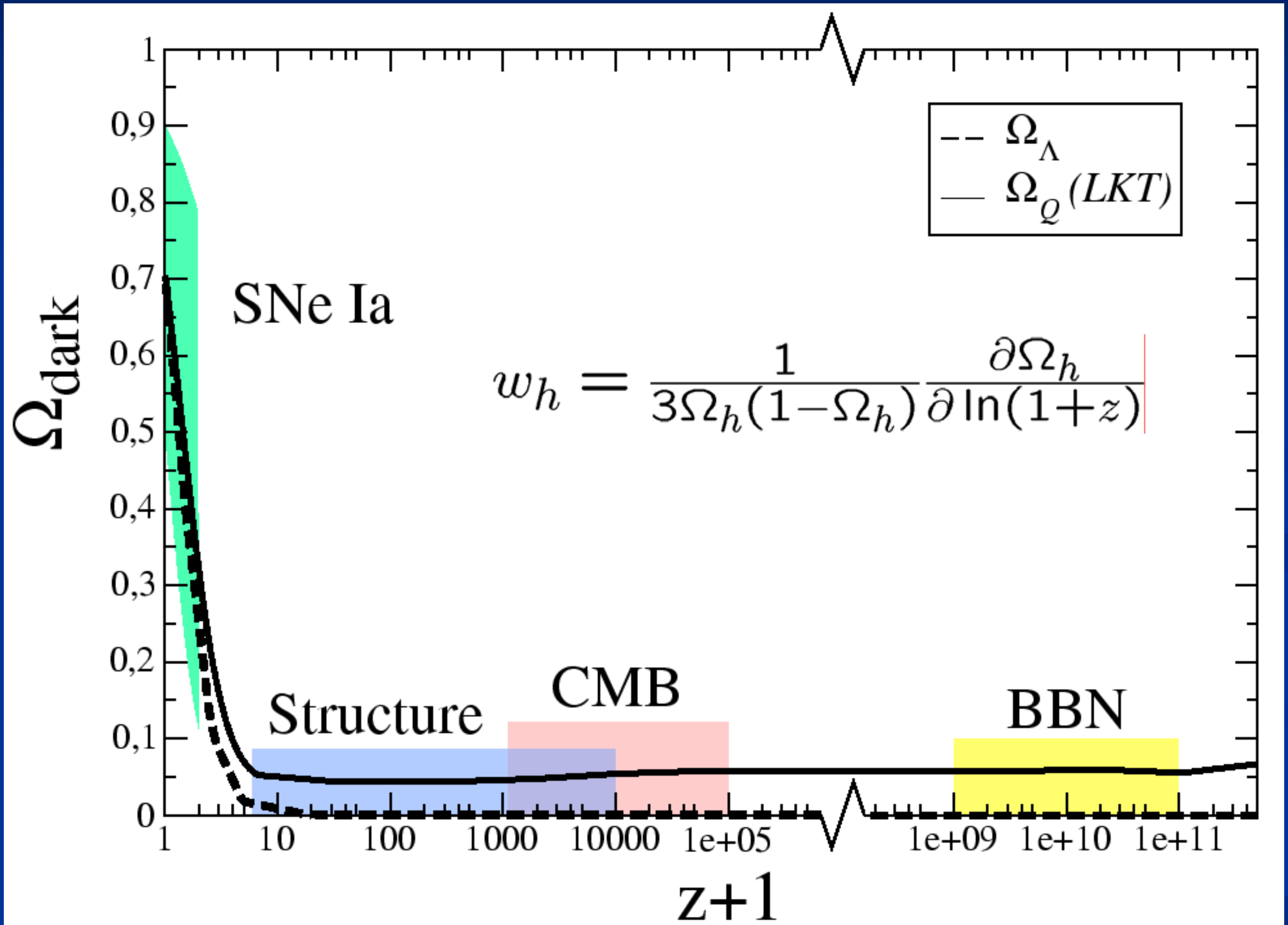
- w = -1 cosmological constant

Quintessence becomes important "today"



How can quintessence be distinguished from a cosmological constant ?

Time dependence of dark energy



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

M.Doran,…

small early and large present dark energy

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

→

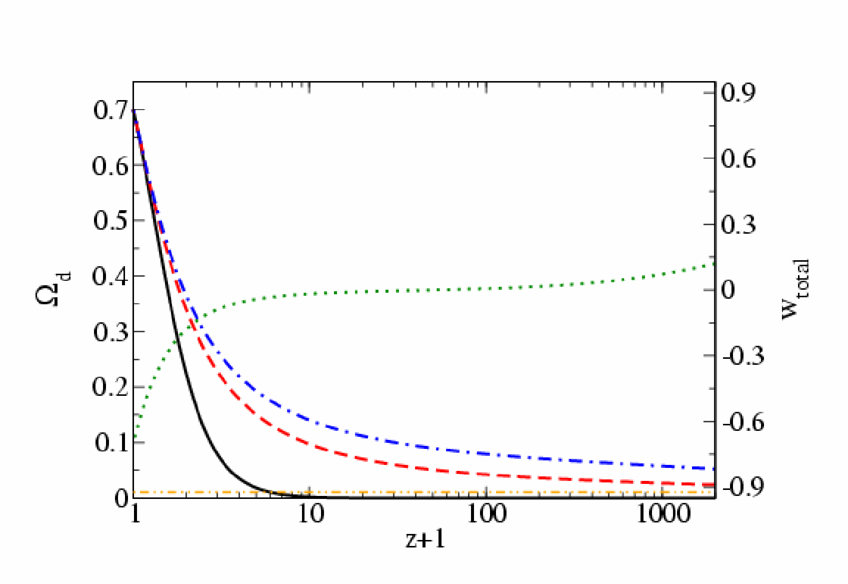
expansion of universe accelerates in present epoch

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

Early Dark Energy

A few percent in the early Universe

Not possible for a cosmological constant



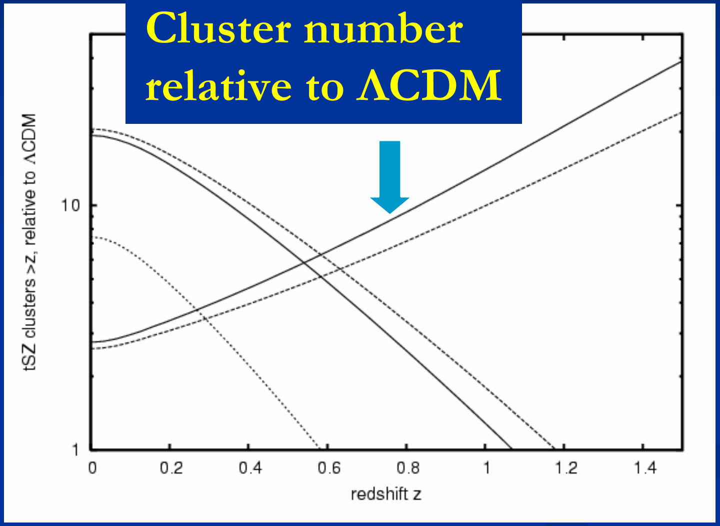
1σ and 2σ limits

Doran,Karwan,..

Little Early Dark Energy can make large effect !

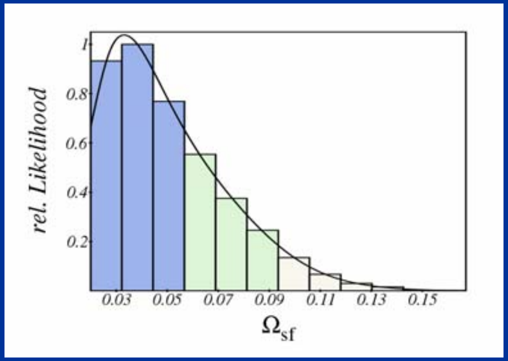
More clusters at high redshift

Cluster number relative to ΛCDM

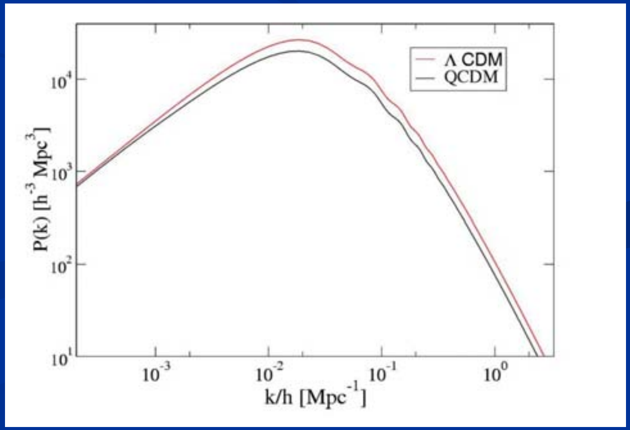


Two models with
4% Dark Energy
during structure formation

Fixed σ_8
(normalization dependence !)



Early Quintessence slows downs the growth of structure



How to distinguish Q from Λ ?

A) Measurement $\Omega_h(z)$ ⟺ $H(z)$

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

D) Possible coupling between Dark Energy and Dark Mater

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

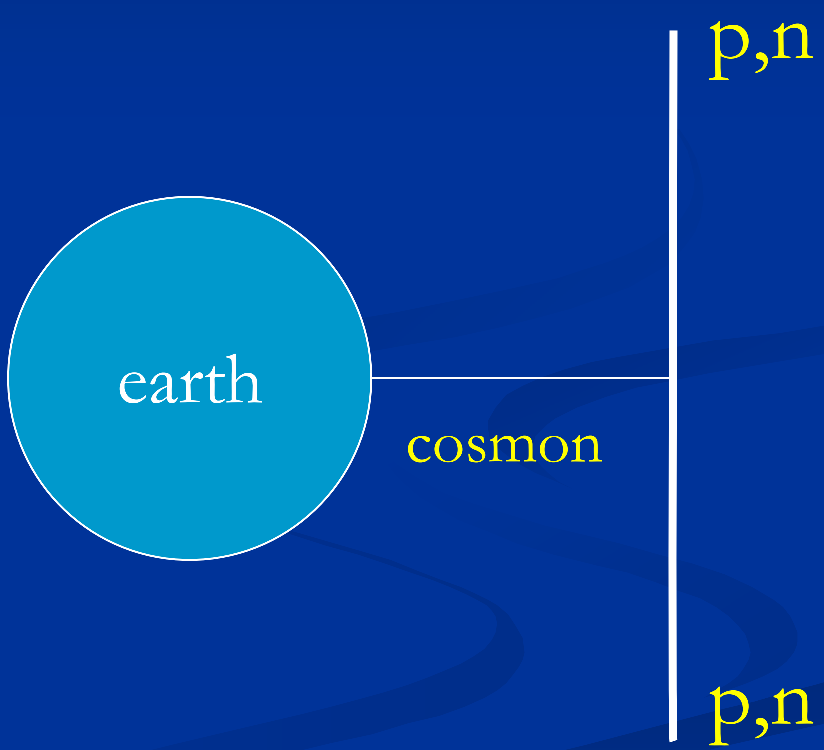
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

(1) $\alpha_X(\varphi) \rightarrow \Lambda_{QCD}(\varphi) \rightarrow m_n(\varphi)$

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

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

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

(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 !

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

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.

Cosmon coupling to Dark Matter

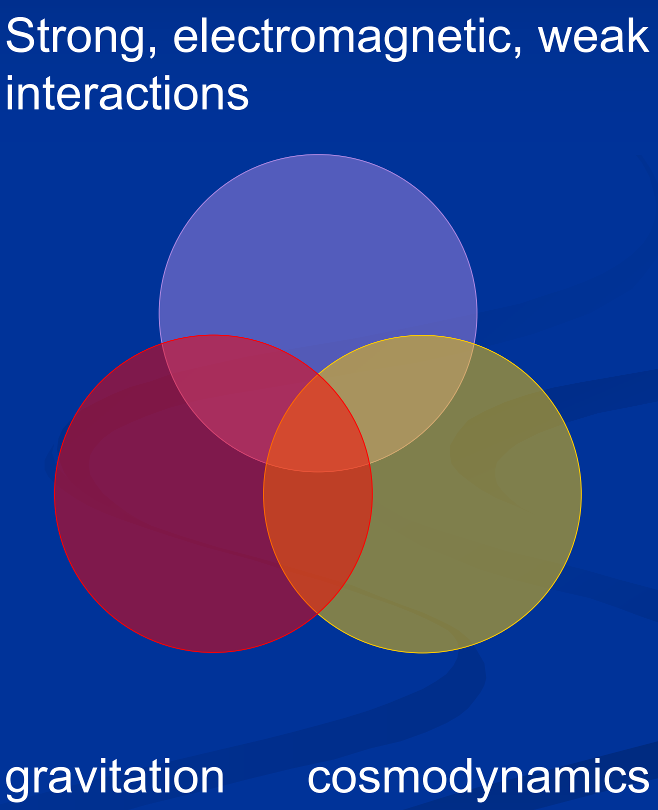
- Only bounded by cosmology
- Substantial coupling possible
- Can modify scaling solution and late cosmology
- Role in clustering of extended objects ?

L. Amendola

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 → 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 :

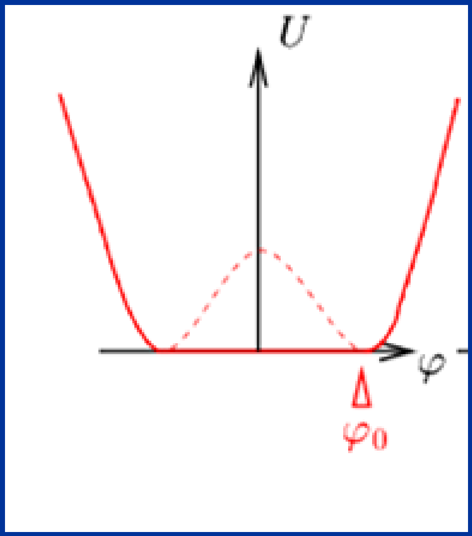
$$m_{electron} = h_{electron} * \varphi_H$$ etc.

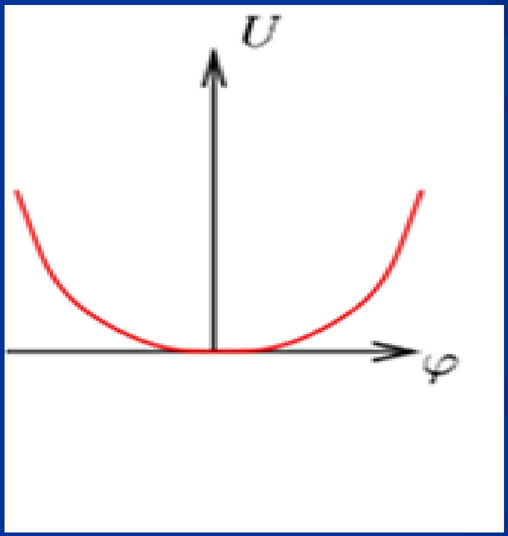
Restoration of symmetry at high temperature in the early Universe

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

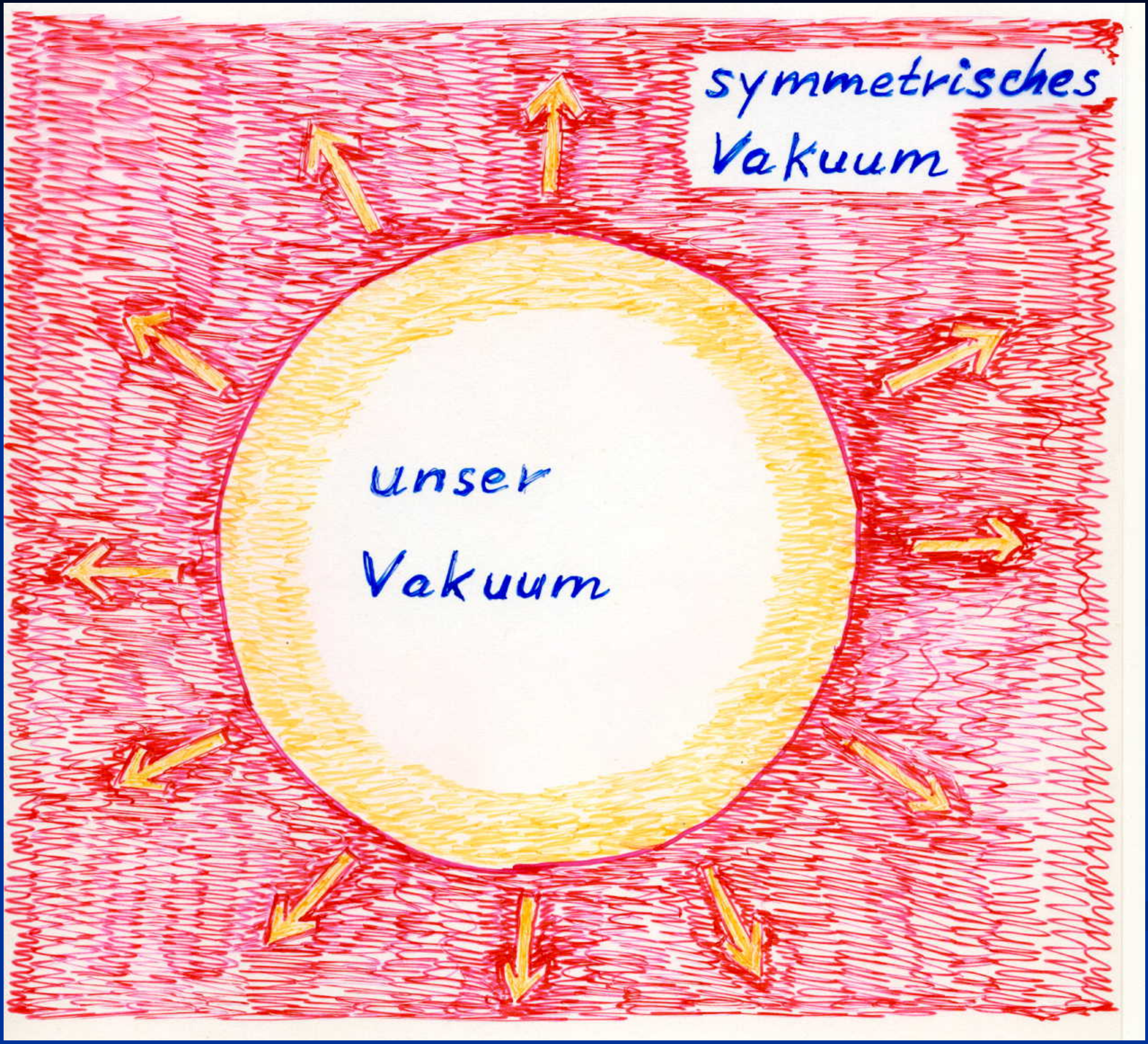




example:
magnets

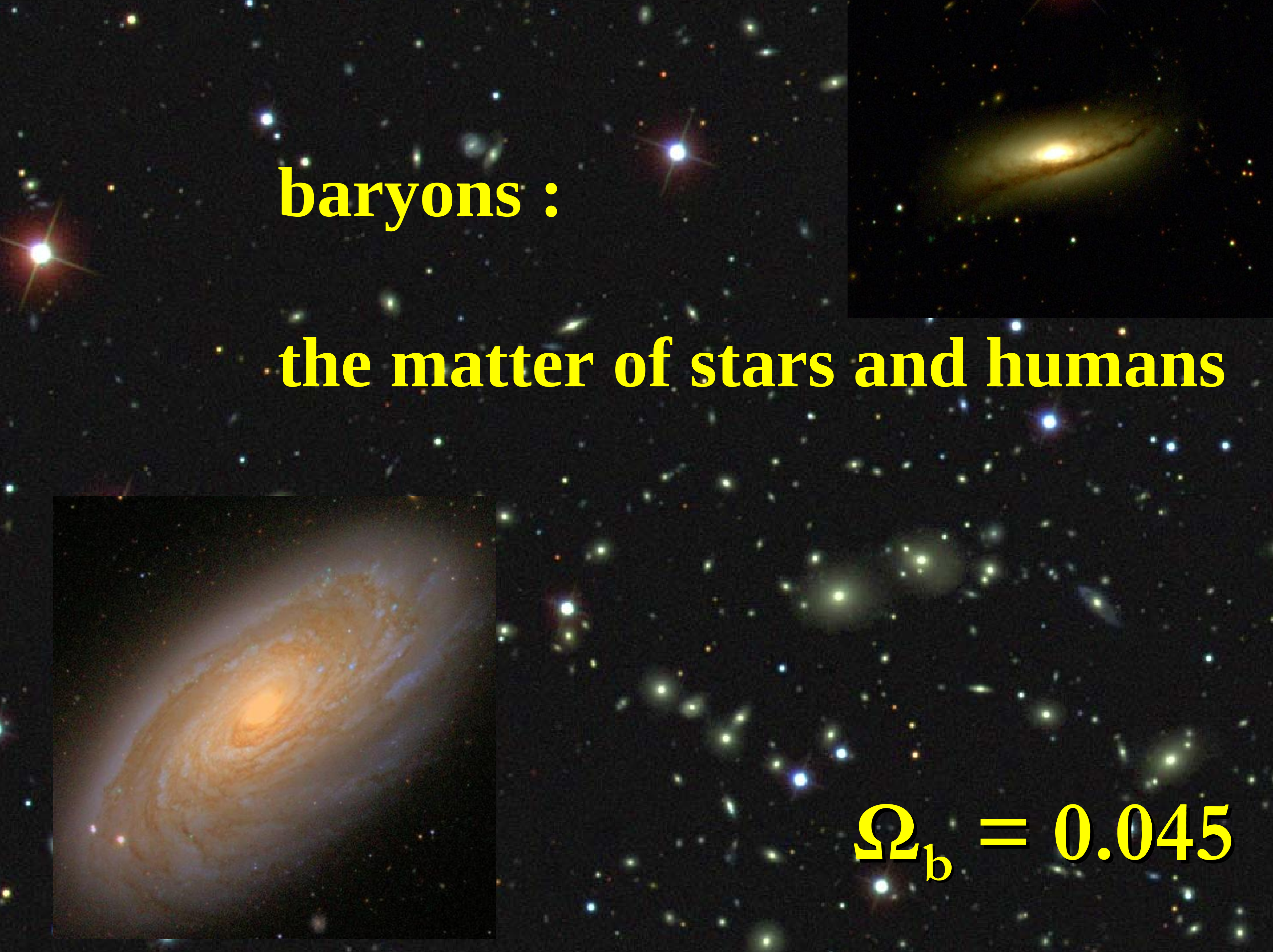
In the hot plasma
of the early Universe :

No difference in mass for electron and muon !

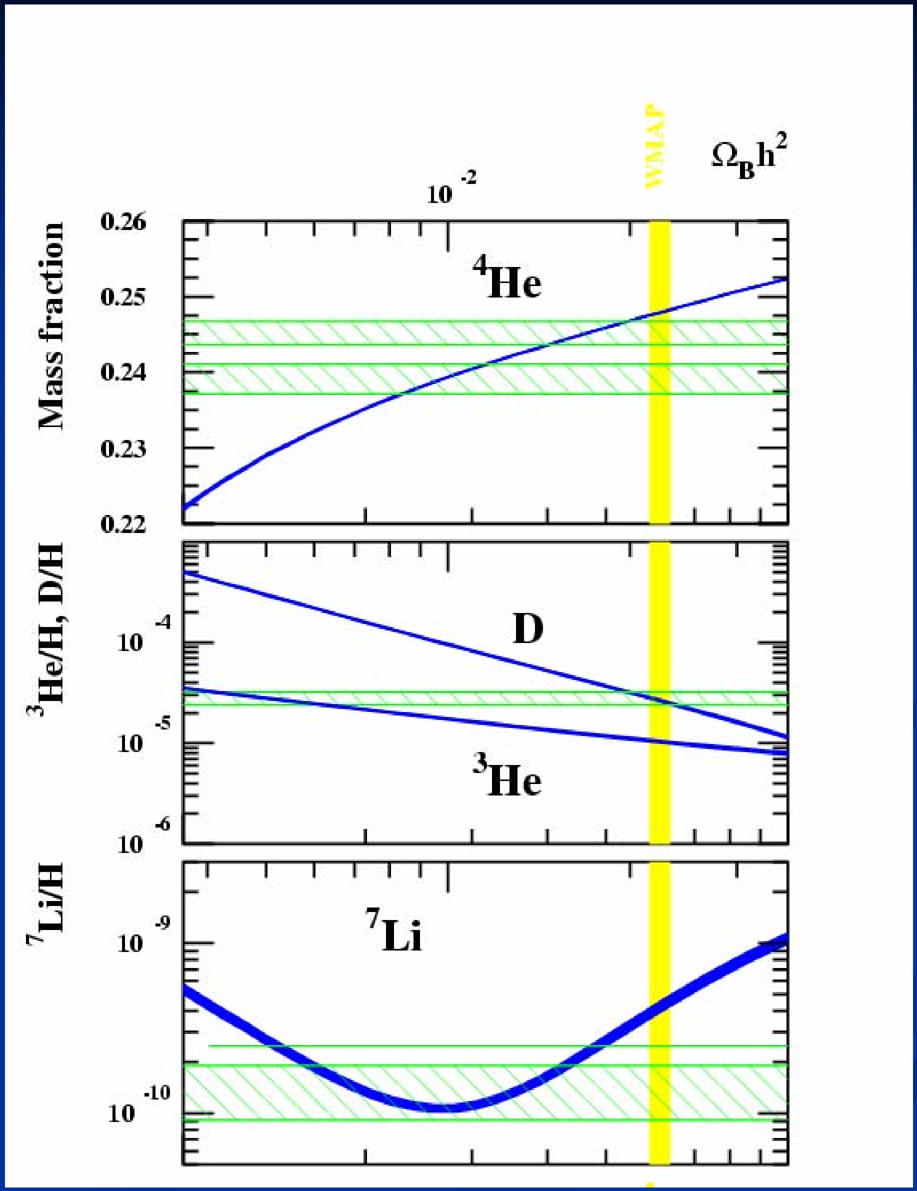

symmetrisches
Vakuum
unser
Vakuum

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

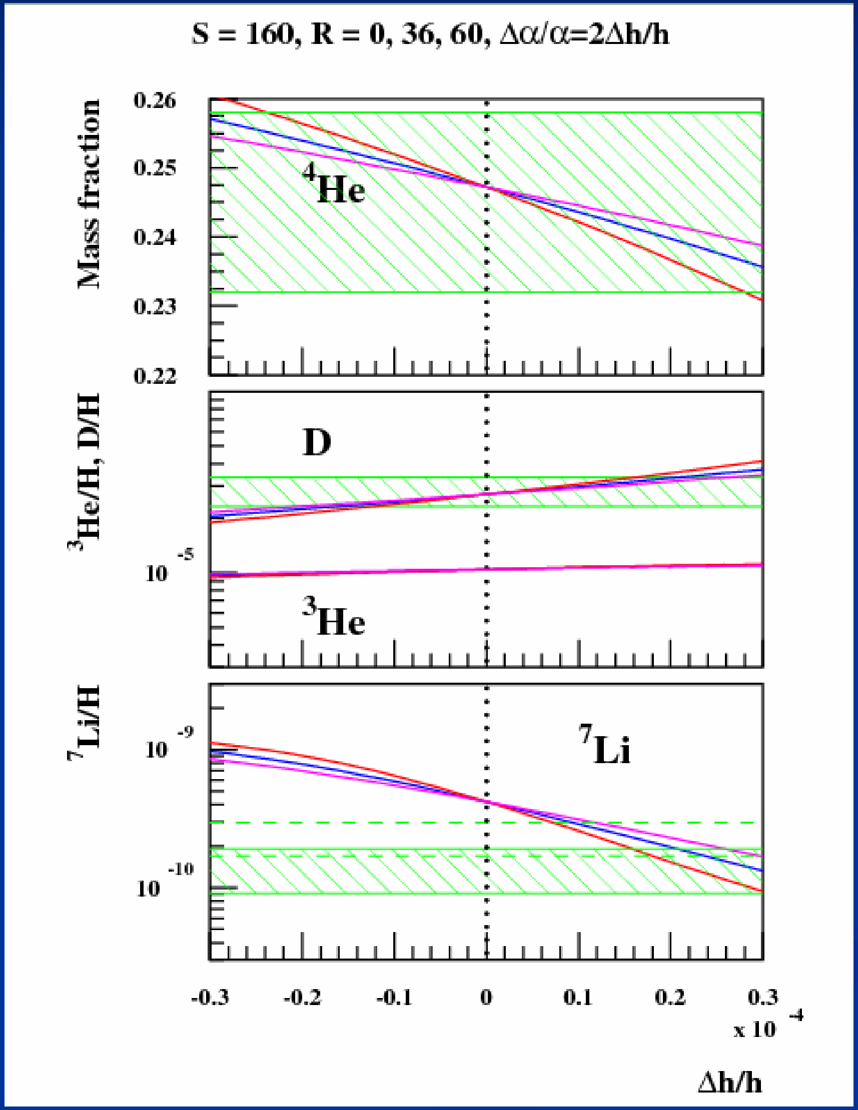
Allowed values for variation of fine structure constant :

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

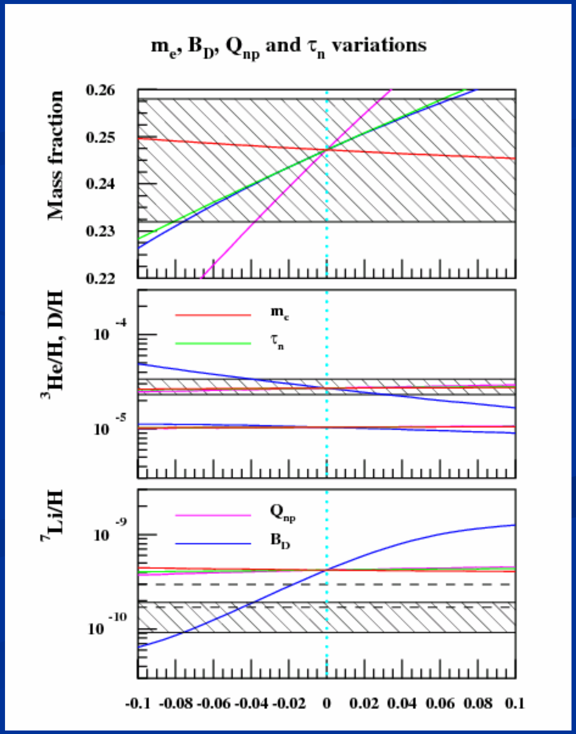
$\Delta\alpha/\alpha\ (z=10^{10}) = -2.7\ 10^{-4}$ GUT 2

C.Mueller,G.Schaefer,…

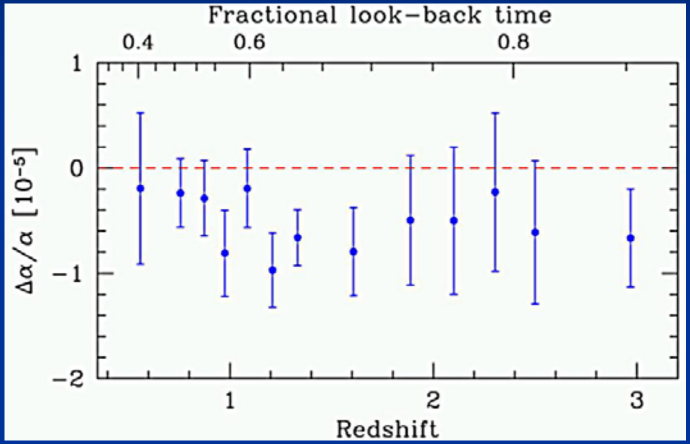
variation of Li- abundance



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



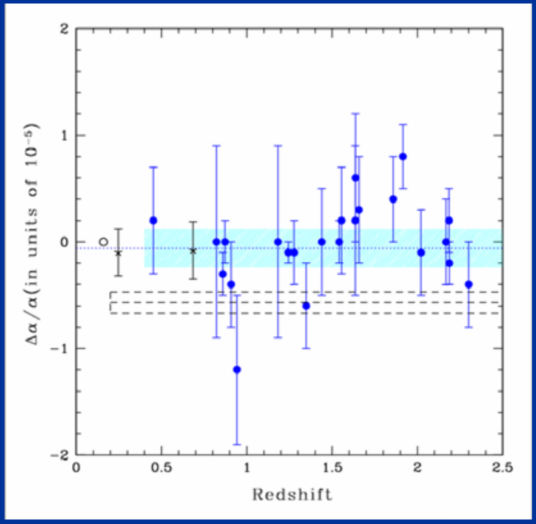
Variation of fine structure constant as function of redshift



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

$z \approx 2$

Atomic clocks and OKLO

* Atomic clocks:

$$\frac{\dot{\alpha}_{em}}{\alpha_{em}} = -5.4 \cdot 10^{-10} \, \frac{\Delta \alpha_{em}}{\alpha_{em}}(z=0.13) \, yr^{-1}$$

observation $\frac{\dot{\alpha}_{em}}{\alpha_{em}} = (4.2 \pm 6.9) \cdot 10^{-15} \, yr^{-1}$

Sortais et al.

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

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) :

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

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

$\eta = \Delta a / 2a$

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 , …)

small change of couplings in space

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

for $r = 2\ R_E$

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

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

A few references

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Dynamics of quintessence

- Cosmon φ : scalar singlet field
- Lagrange density $L = V + ½\, k(\varphi)\, \partial\varphi\, \partial\varphi$

  (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(φ) 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)