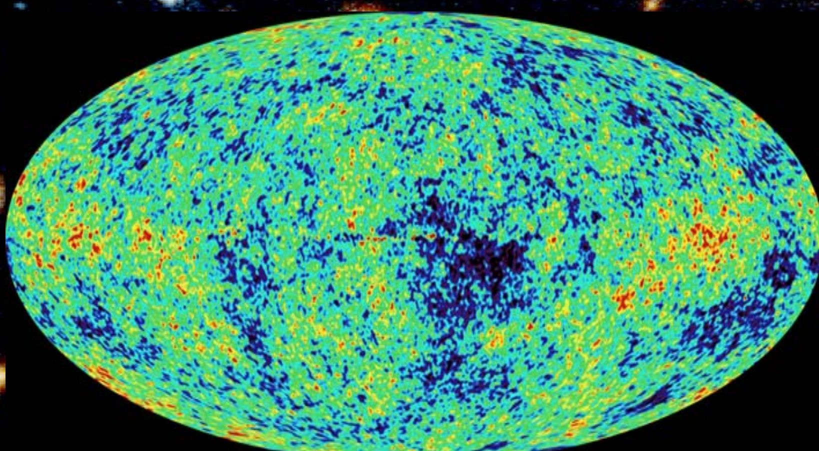
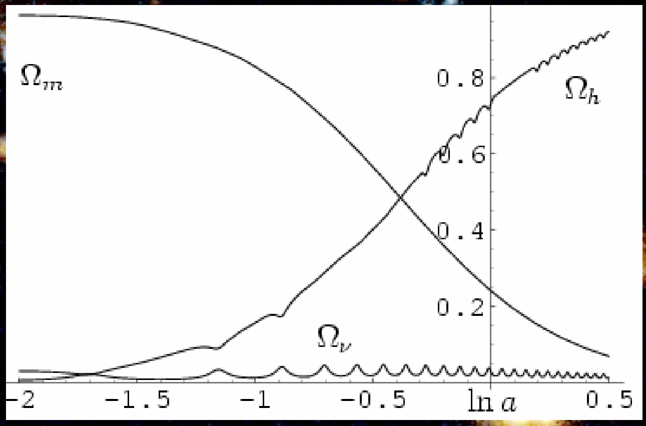
Dark Energy – a cosmic mystery





Quintessence

C.Wetterich

A.Hebecker, M.Doran, M.Lilley, J.Schwindt,
C.Müller, G.Schäfer, E.Thommes,
R.Caldwell, M.Bartelmann, K.Kharwan, G.Robbers,
T.Dent, S.Steffen, L.Amendola, M.Baldi , N.Brouzakis , N.Tetradis,
D.Mota, V.Pettorino, T.Krüger, M.Neubert

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 ?

Composition of the universe

$\Omega_b = 0.045$

$\Omega_{dm} = 0.225$

$\Omega_h = 0.73$

critical density

- $\varrho_c = 3 H^2 M^2$
  critical energy density of the universe
  (M : reduced Planck-mass , H : Hubble parameter)

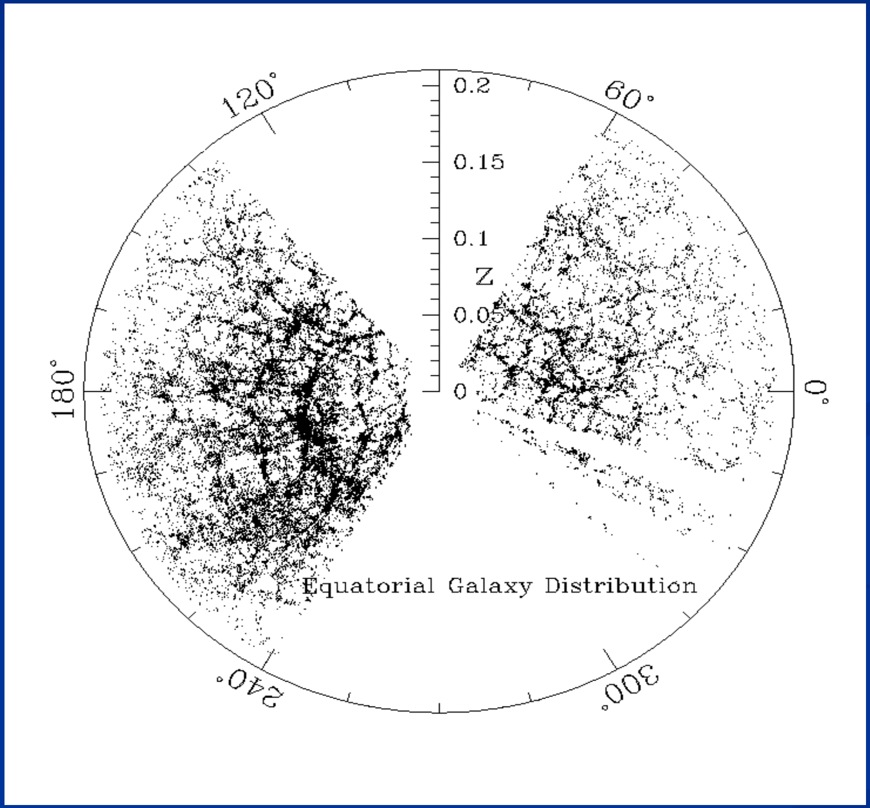
- $\Omega_b = \varrho_b / \varrho_c$
  fraction in baryons
  energy density in baryons over critical energy density

$$H = \dot{a}/a$$

Baryons/Atoms

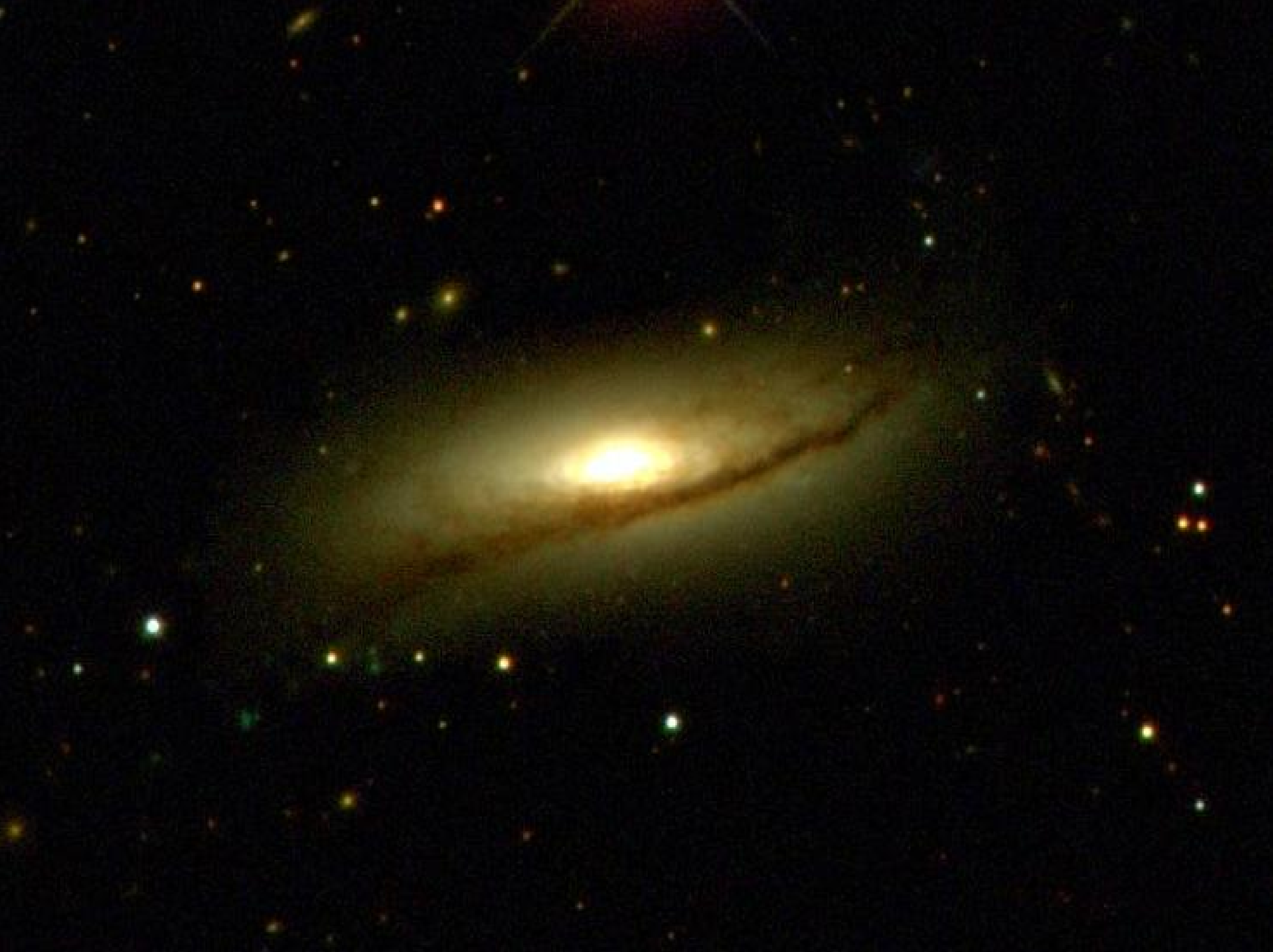
SDSS

~60,000 of
>300,000
Galaxies



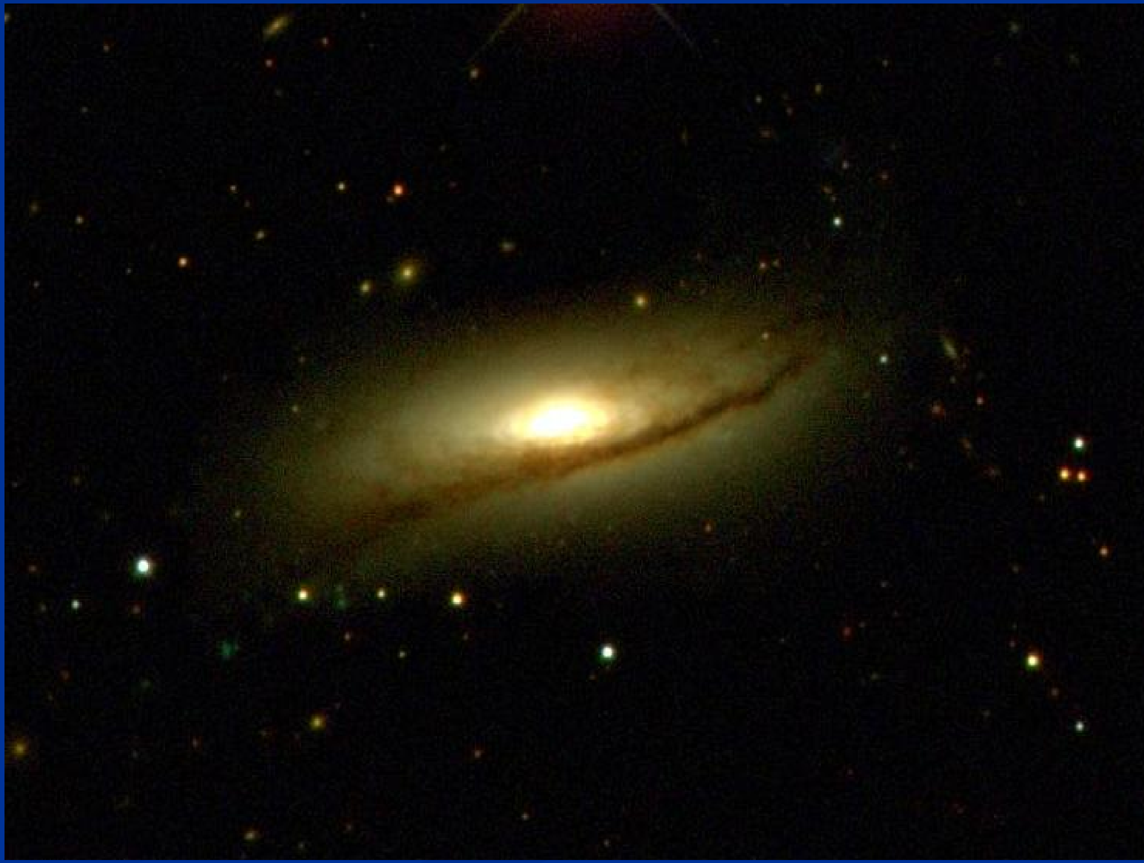
- Dust
- $\Omega_b=0.045$
- Only 5 percent of our Universe consist of known matter !


Abell 2255 Cluster
~300 Mpc



$\Omega_b = 0.045$

from nucleosynthesis, cosmic background radiation



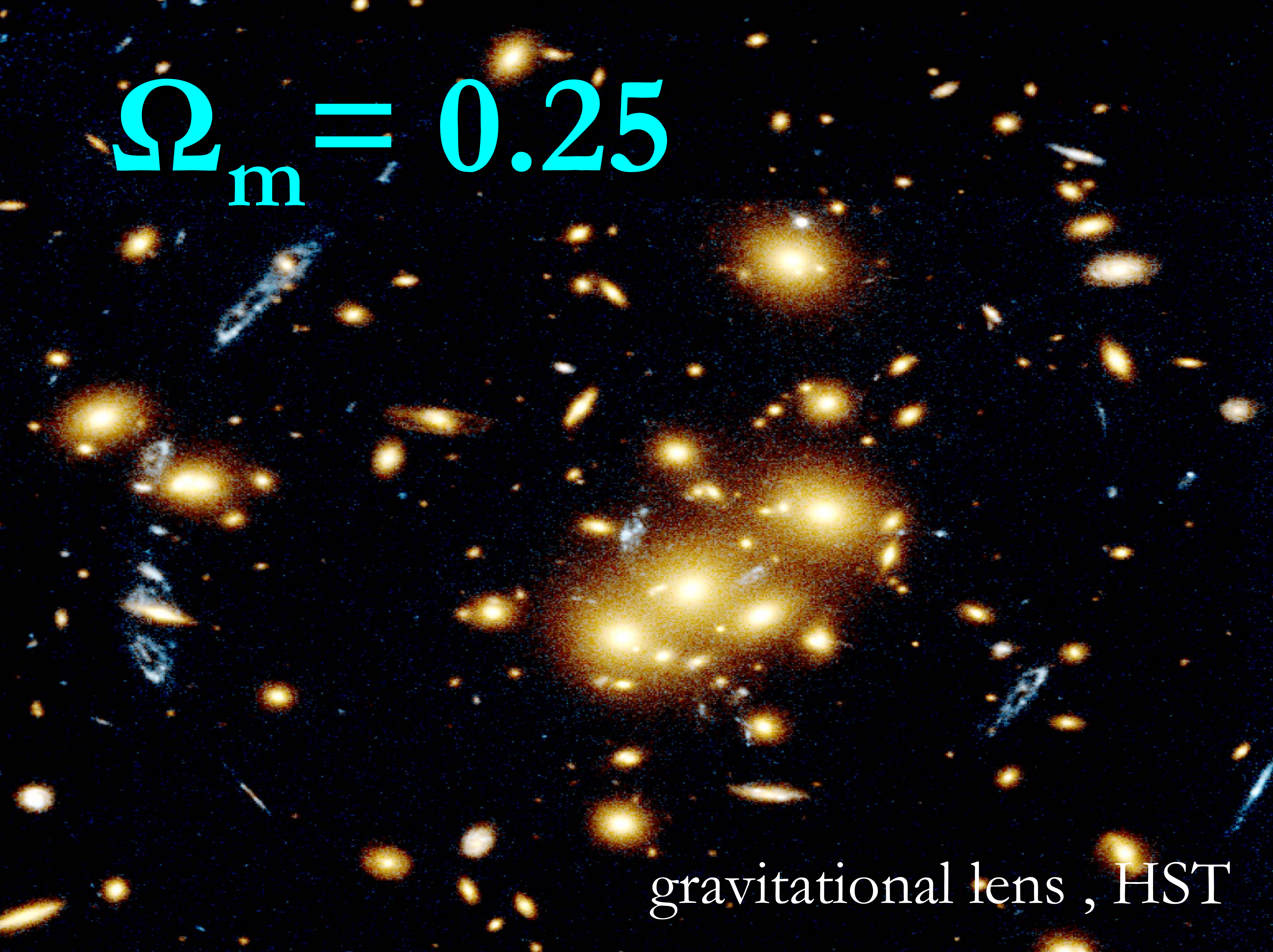
Matter : Everything that clumps

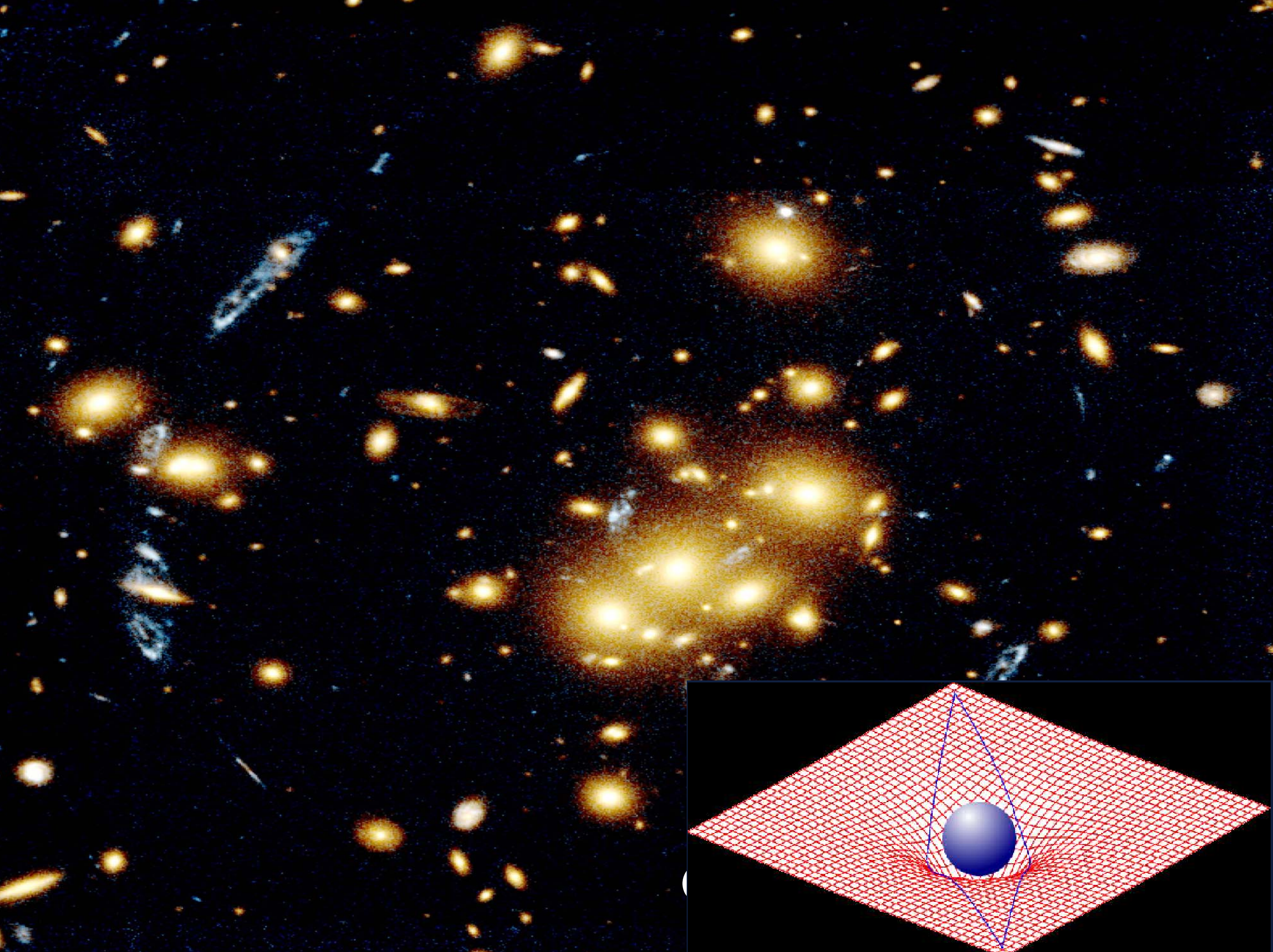
Abell 2255 Cluster
~300 Mpc

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

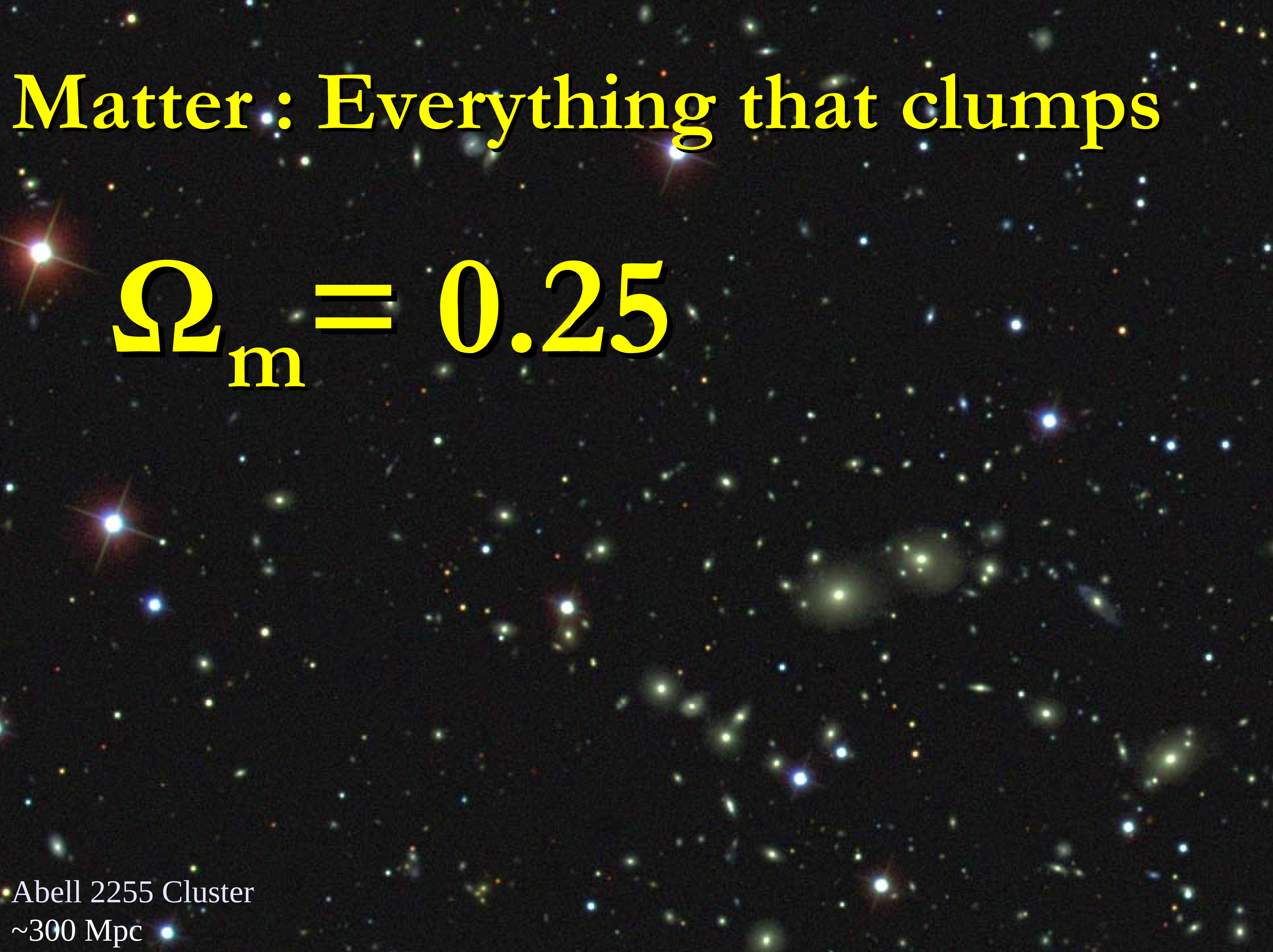
  and therefore of local matter distribution


$\Omega_m = 0.25$
gravitational lens , HST



Matter : Everything that clumps

$$\Omega_m = 0.25$$



Abell 2255 Cluster
~300 Mpc

spatially flat universe

$$\Omega_{tot} = 1$$

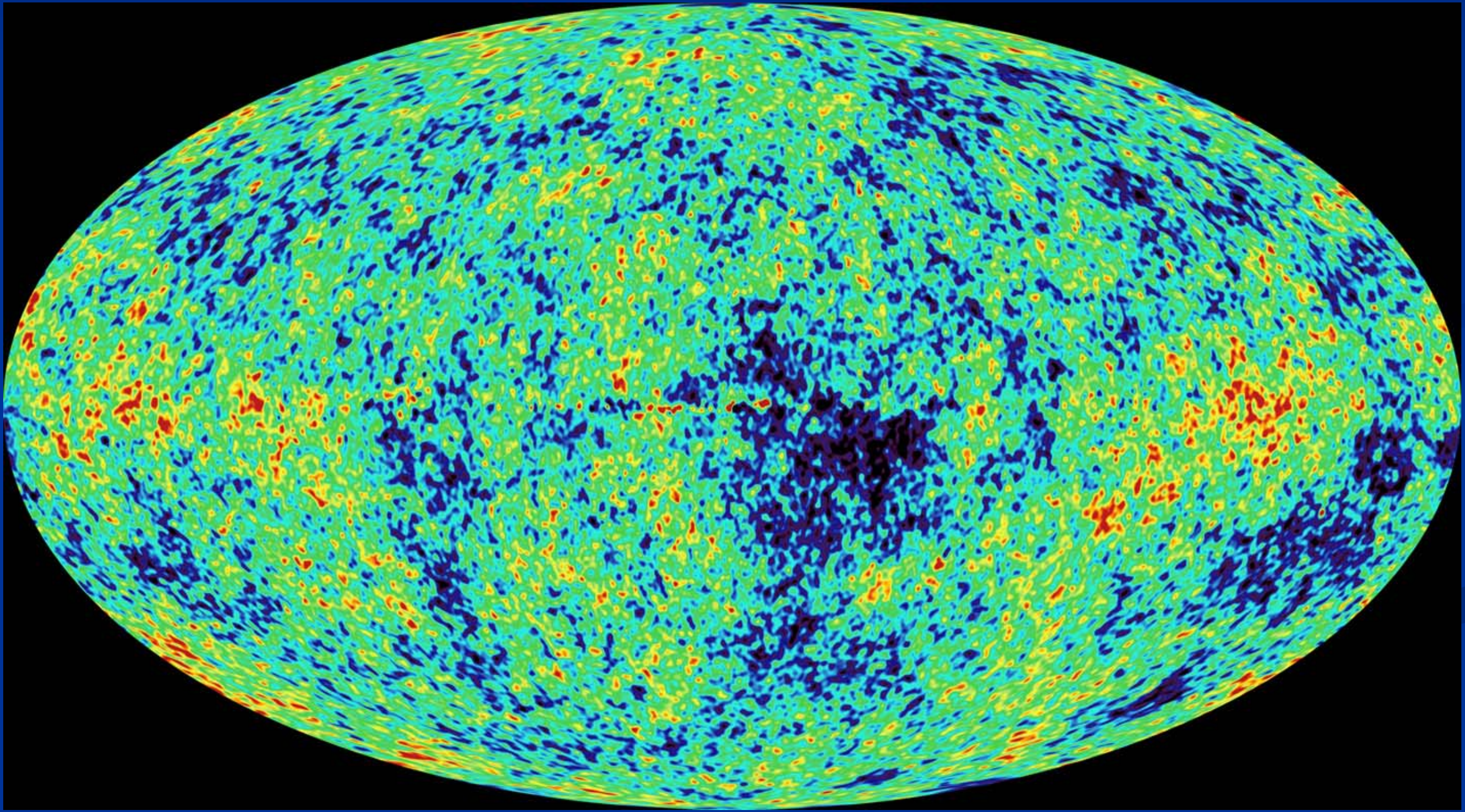
- theory (inflationary universe)

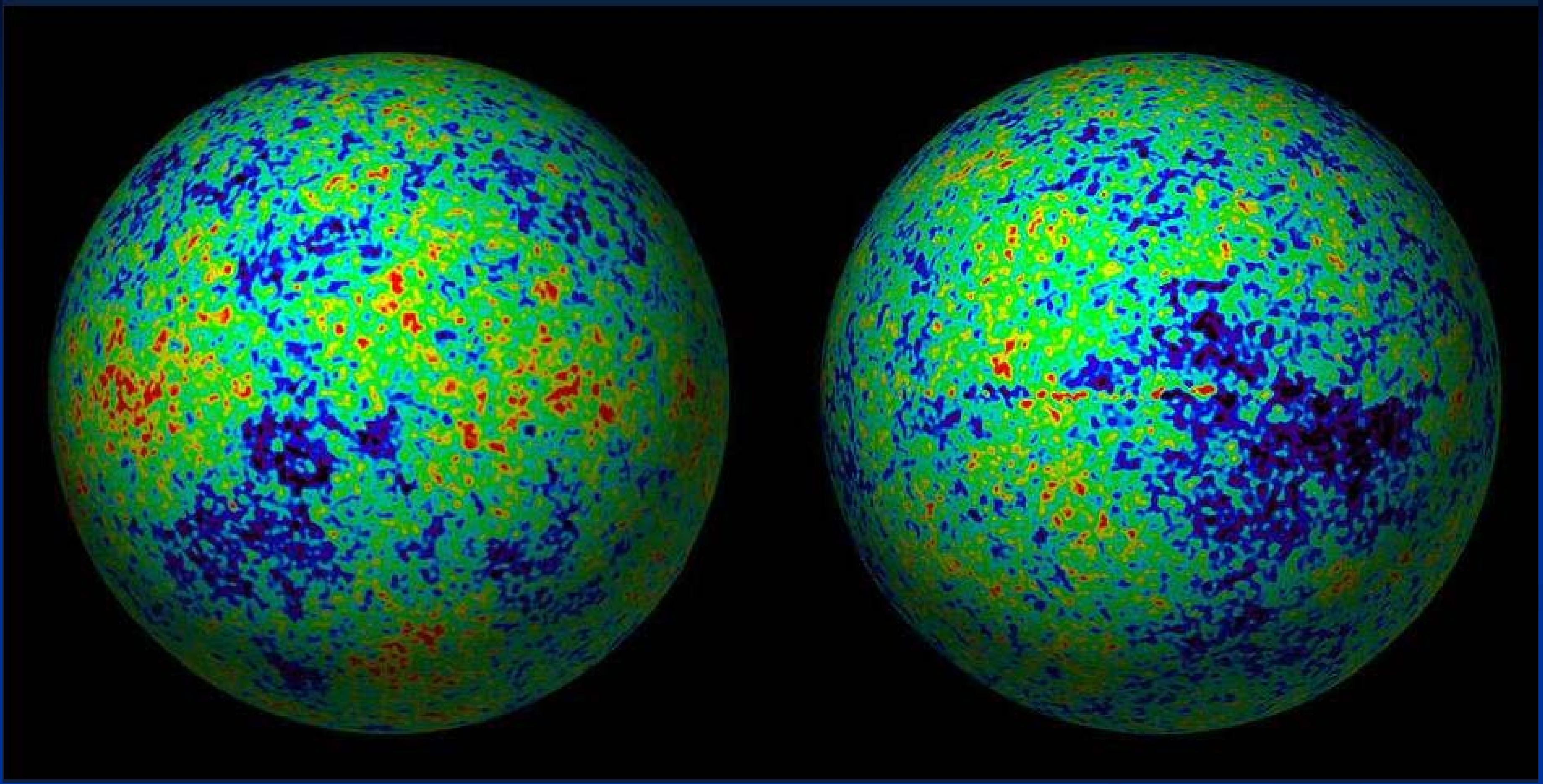
  Ω_{tot} =1.0000……….x

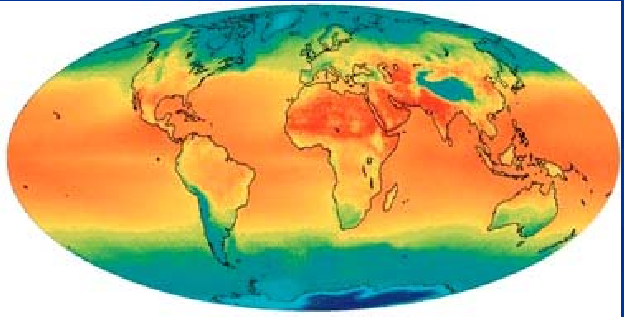
- observation (WMAP)

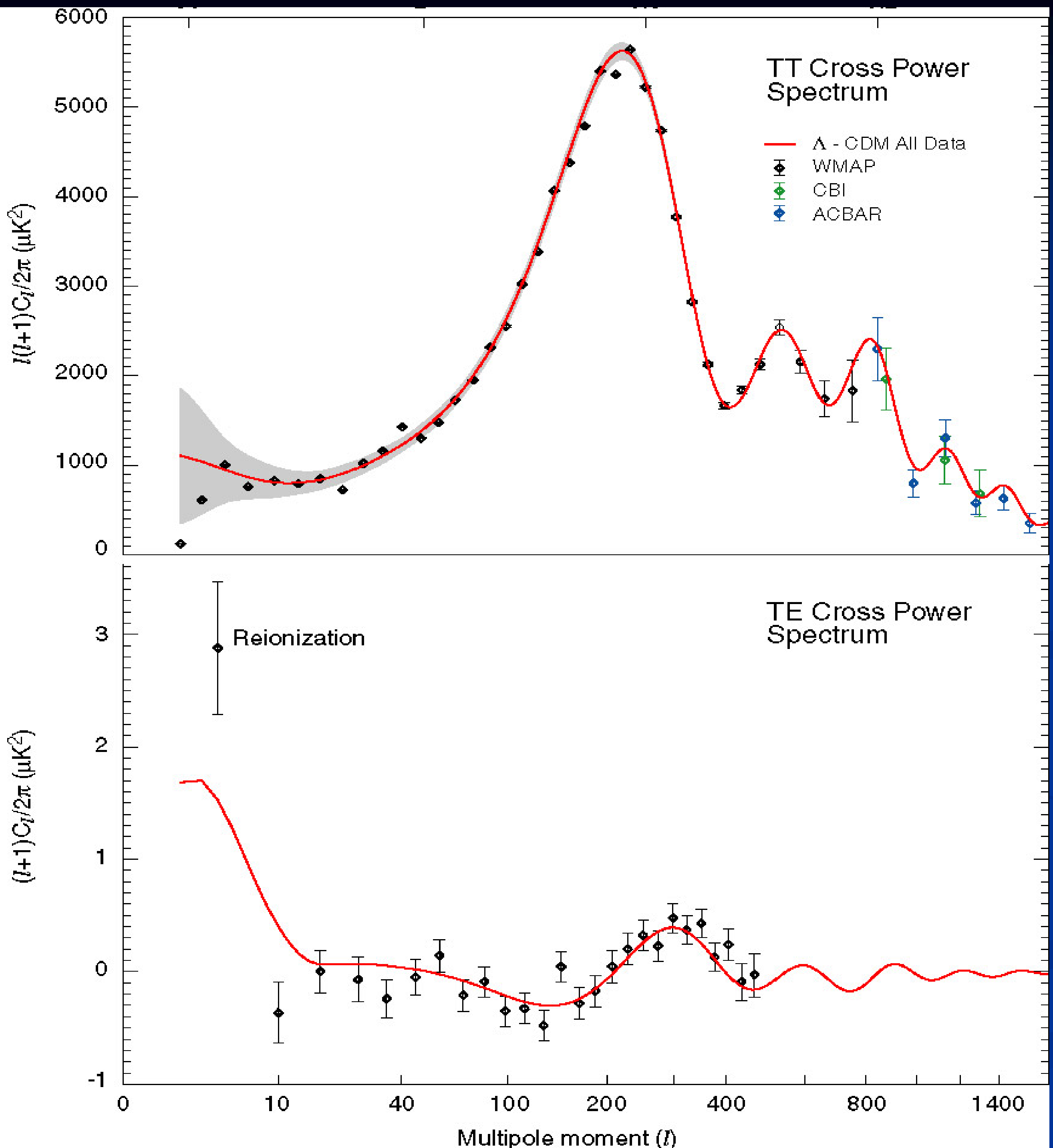
  Ω_{tot} =1.02 (0.02)

picture of the big bang









Mean values WMAP 2003

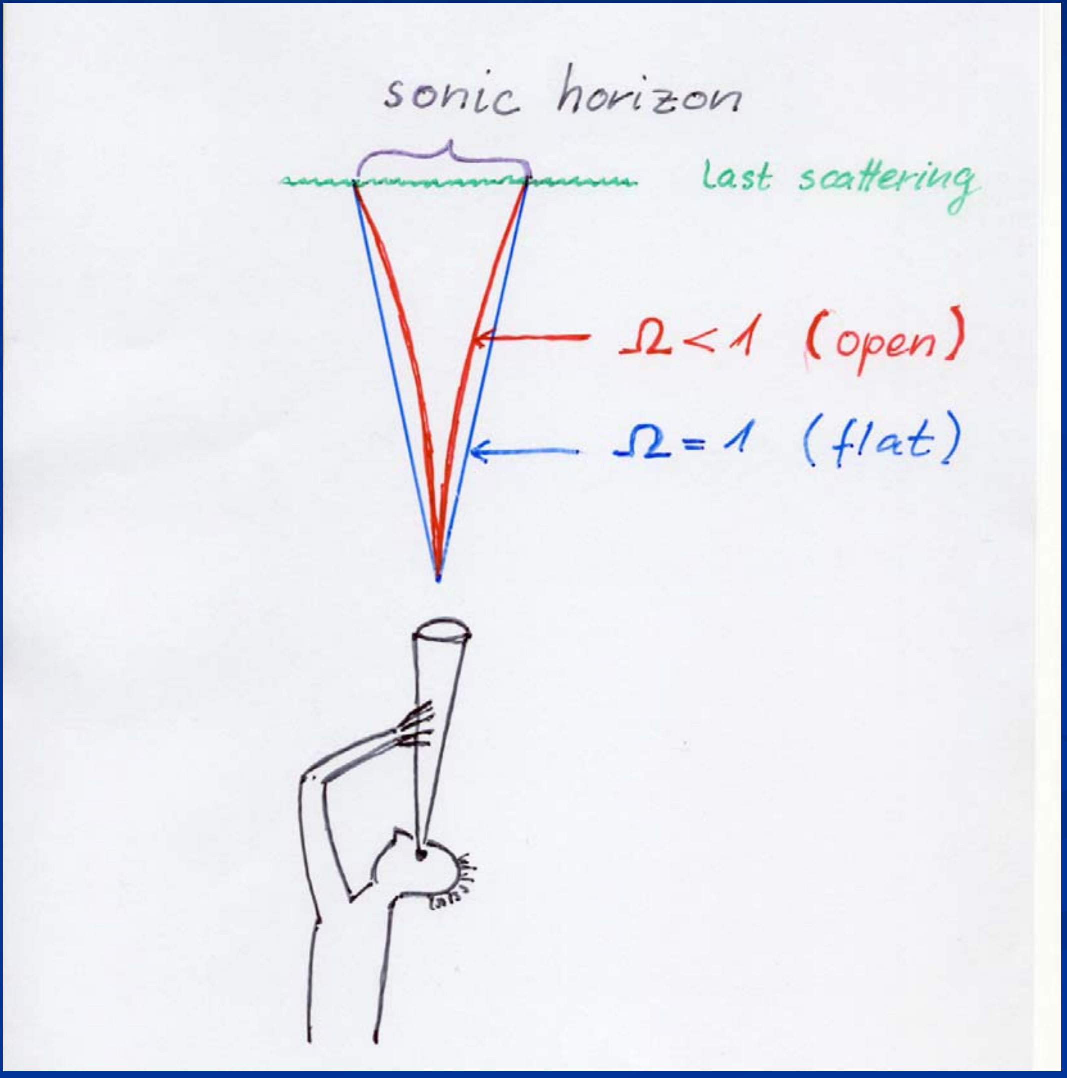
$\Omega_{tot} = 1.02$

$\Omega_{m} = 0.27$

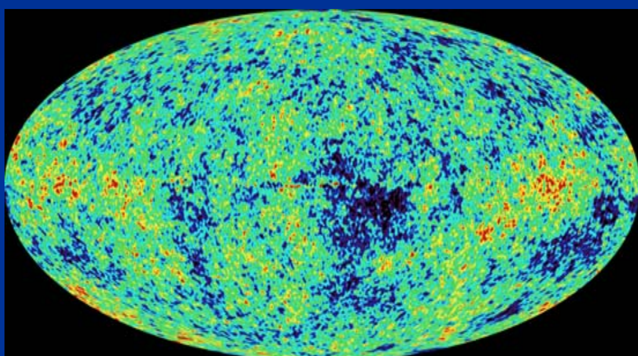
$\Omega_{b} = 0.045$

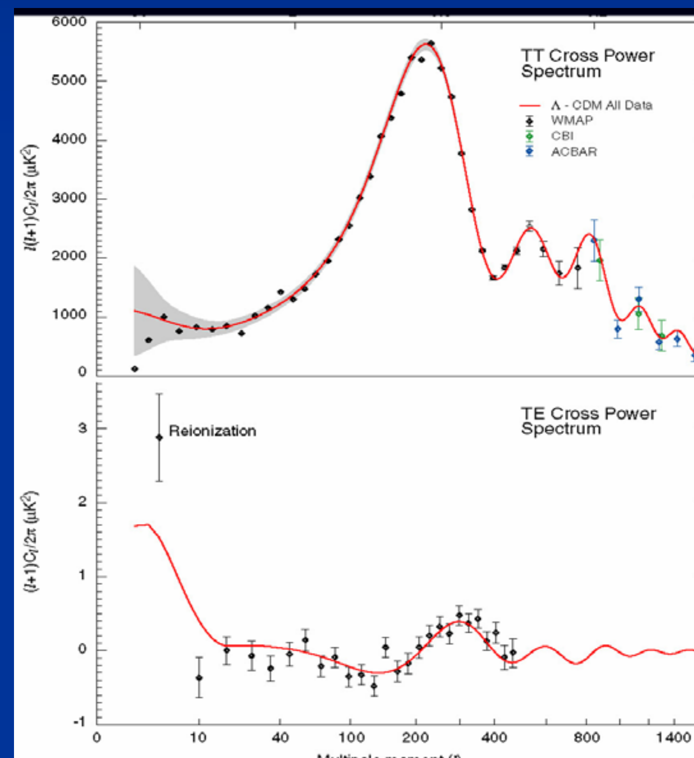
$\Omega_{dm} = 0.225$

$\Omega_{tot}=1$



$\Omega_{tot} = 1$





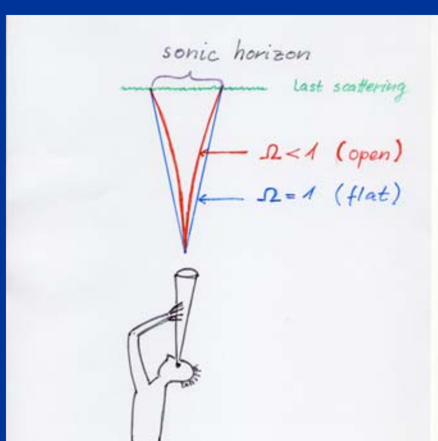
mean values

$\Omega_{tot} = 1.02$

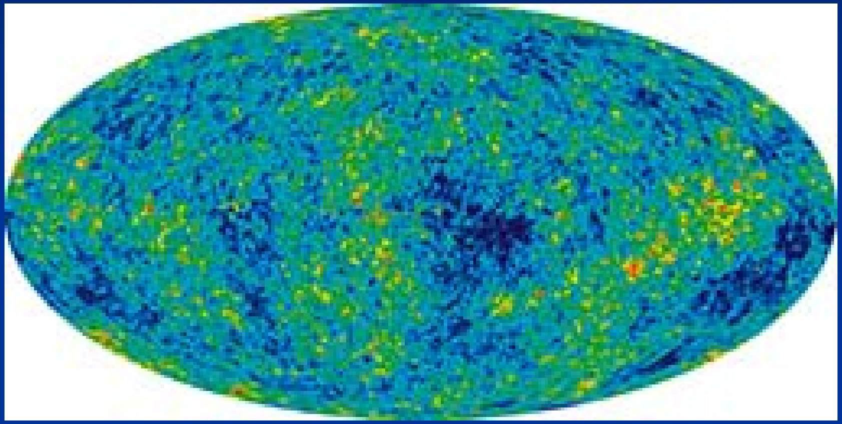
$\Omega_{m} = 0.27$

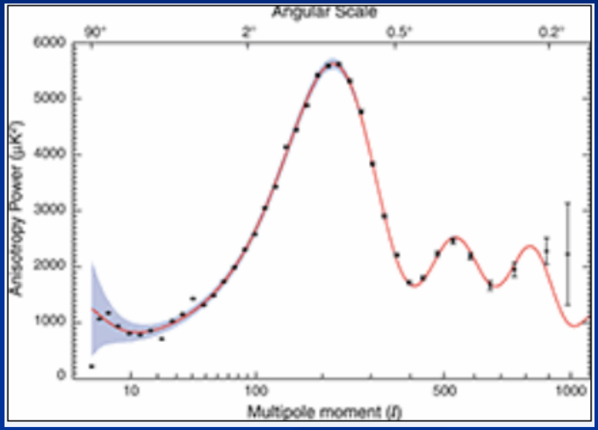
$\Omega_{b} = 0.045$

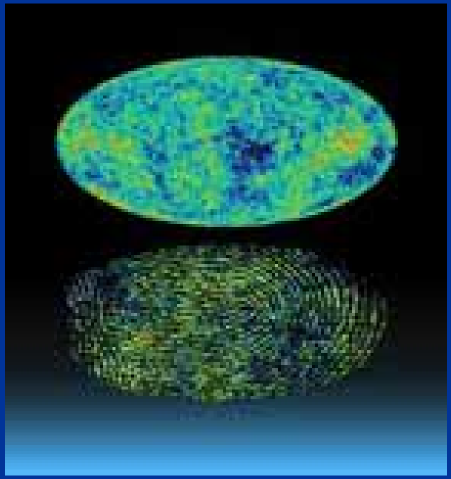
$\Omega_{dm} = 0.225$



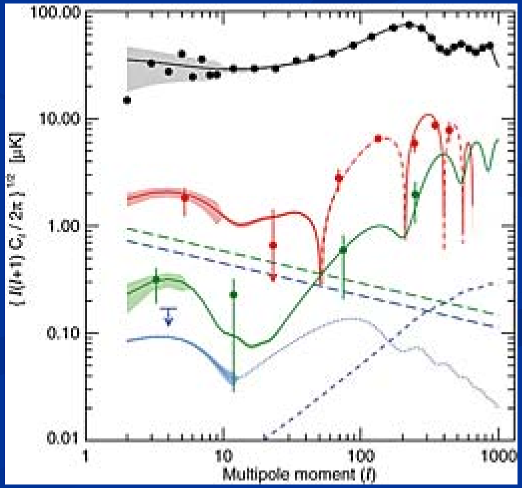
WMAP 2006







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 !

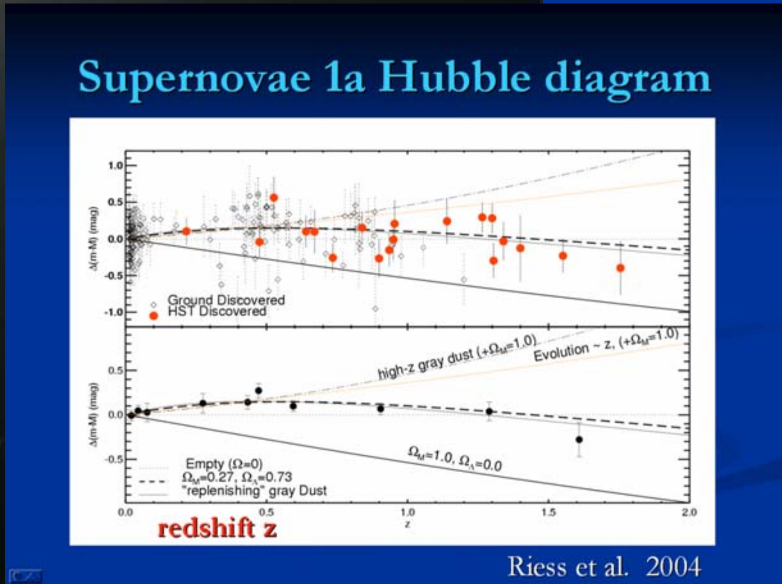
Dark Energy density is
the same at every point of space

“ homogeneous “

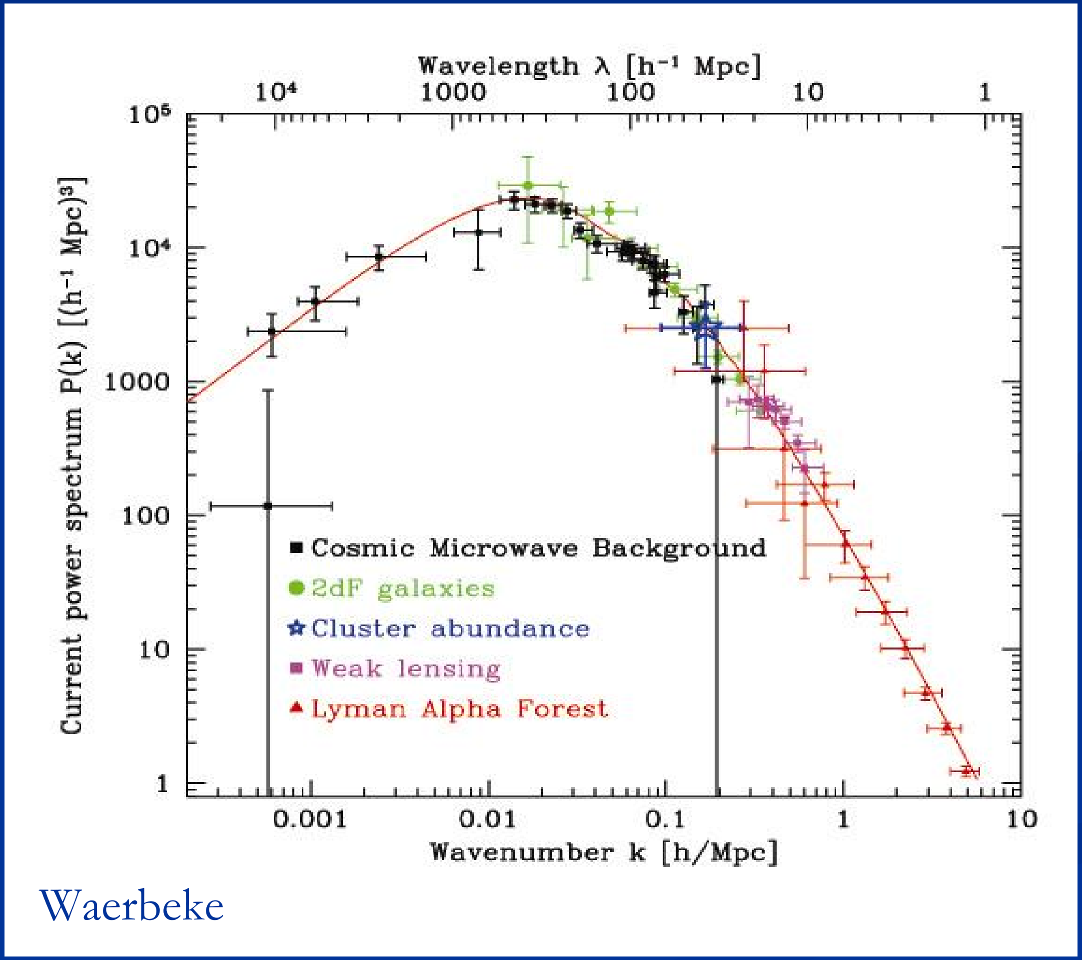
No force in absence of matter –
“ In what direction should it draw ? “

Predictions for dark energy cosmologies

The expansion of the Universe
accelerates today !



Structure formation :
One primordial fluctuation spectrum



CMB agrees with

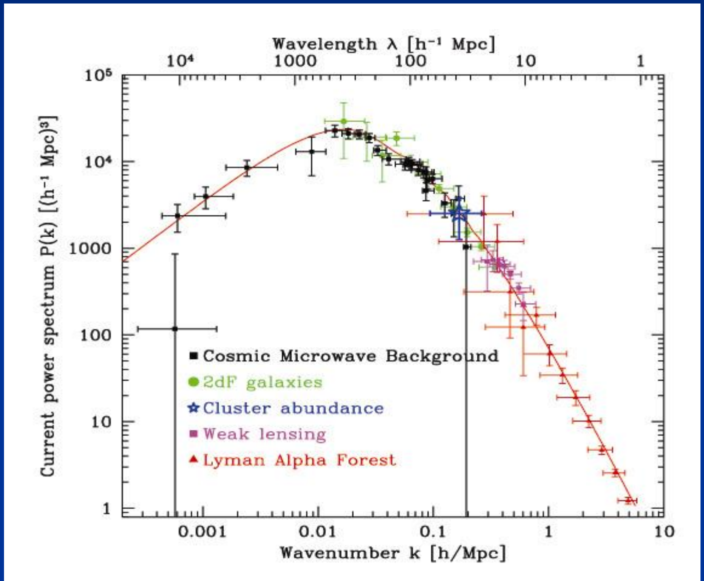
Galaxy distribution

Lyman – α

and

Gravitational Lensing !

Power spectrum

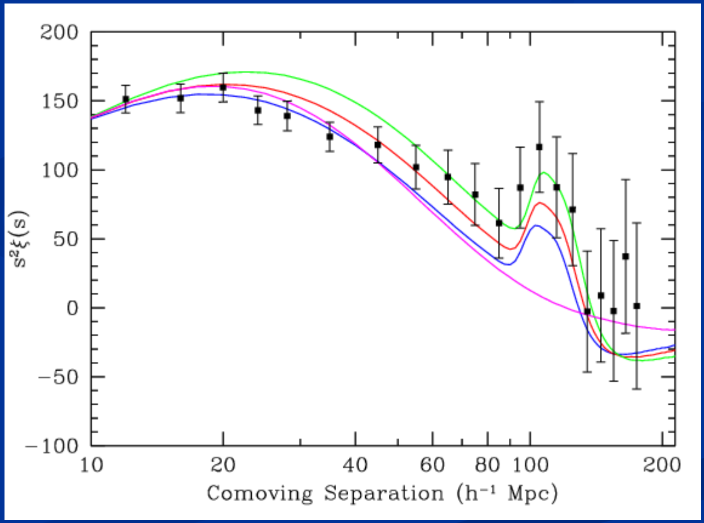


M.Tegmark + …

Structure formation :
One primordial
fluctuation- spectrum

Baryon - Peak

galaxy –
correlation –
function



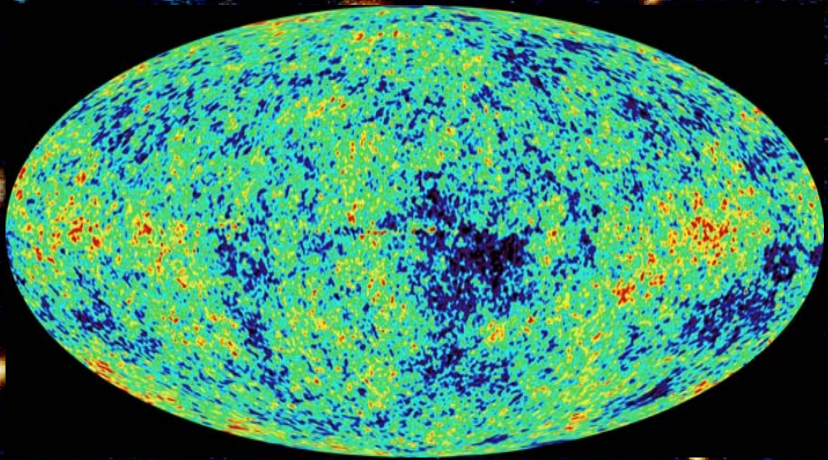
SDSS

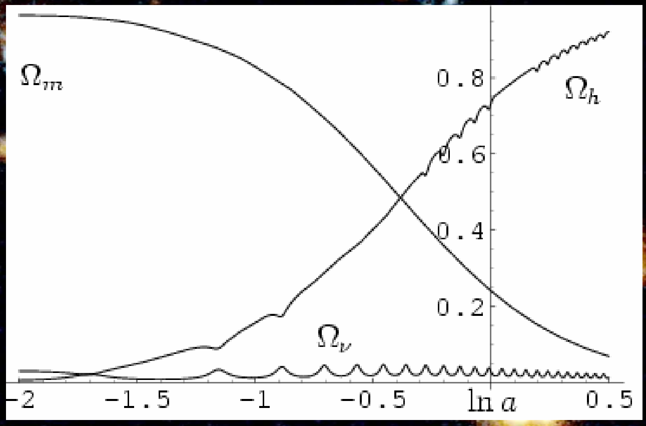
consistent cosmological model !

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 -

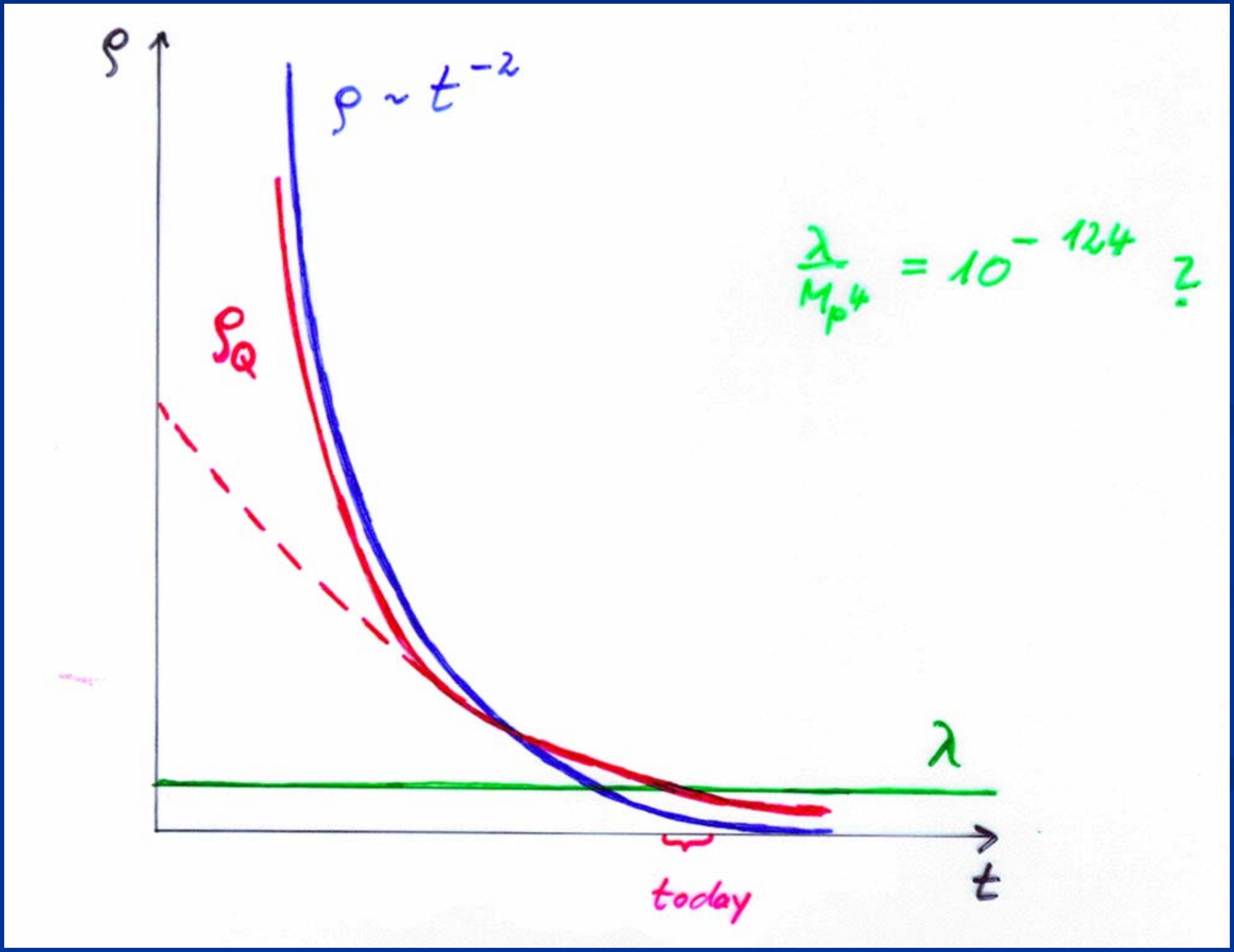
- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

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

- Why important just today ?

Cosm. Const. | Quintessence

static | dynamical



Cosmological mass scales

- Energy density

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

- Reduced Planck mass

  $M=2.44\times10^{27}\ \mathrm{eV}$

- 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 !*

Evolution of cosmon field

Field equations

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

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

Potential V(φ) determines details of the model

$V(\varphi) = M^4 \exp(-\alpha\varphi/M)$

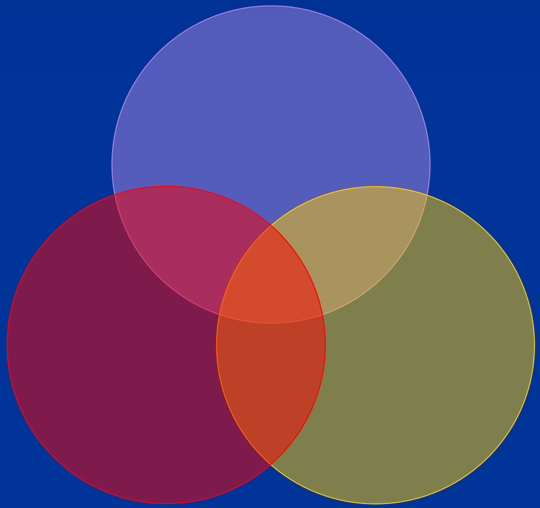
for increasing φ the potential decreases towards zero !

Cosmon

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

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

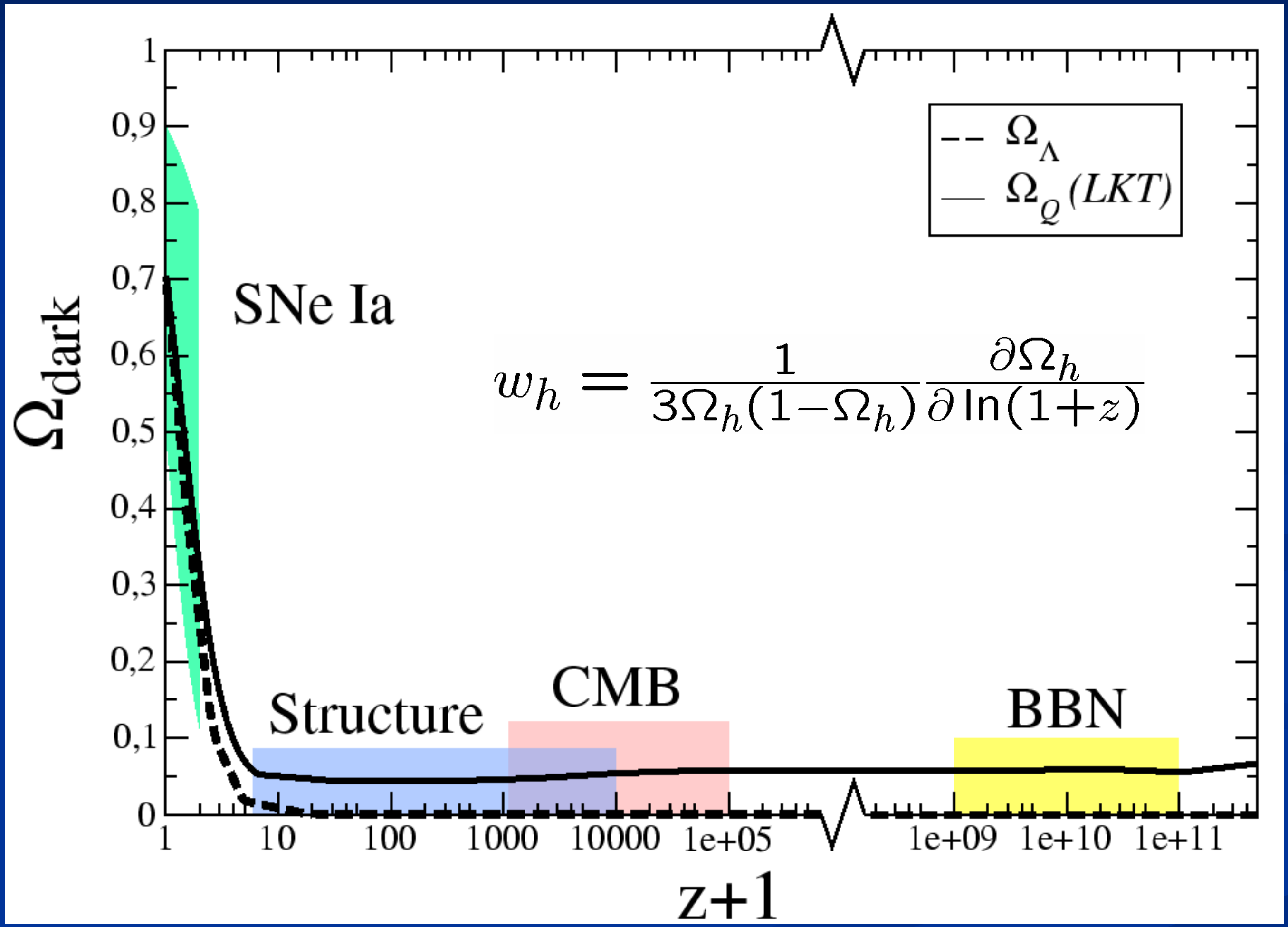
graviton

+

cosmon

observation will decide !

Time dependence of dark energy



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

M.Doran,…

Cosmic Attractors

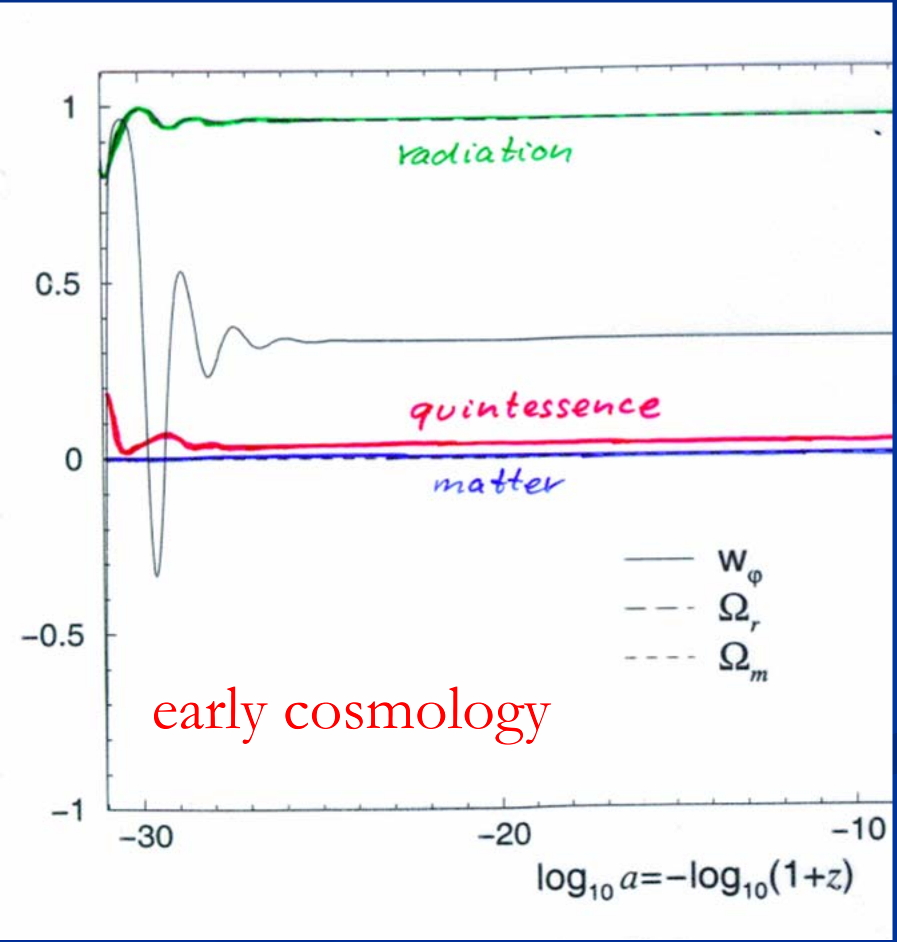
Solutions independent of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

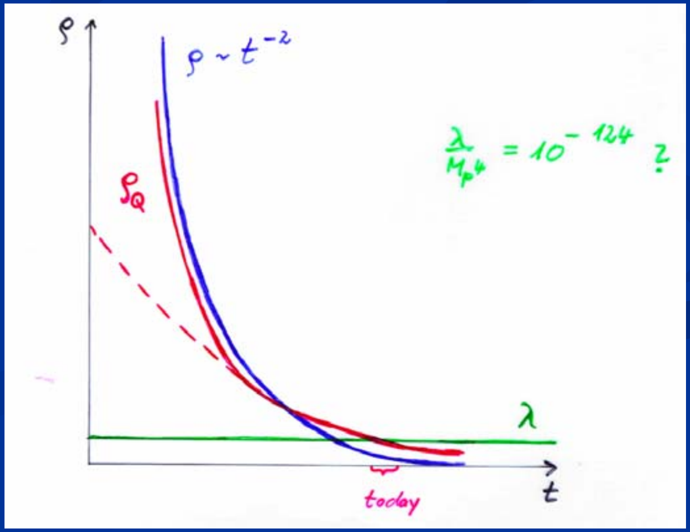
details depend on $V(\varphi)$ or kinetic term



exponential potential ⟹ constant fraction in dark energy

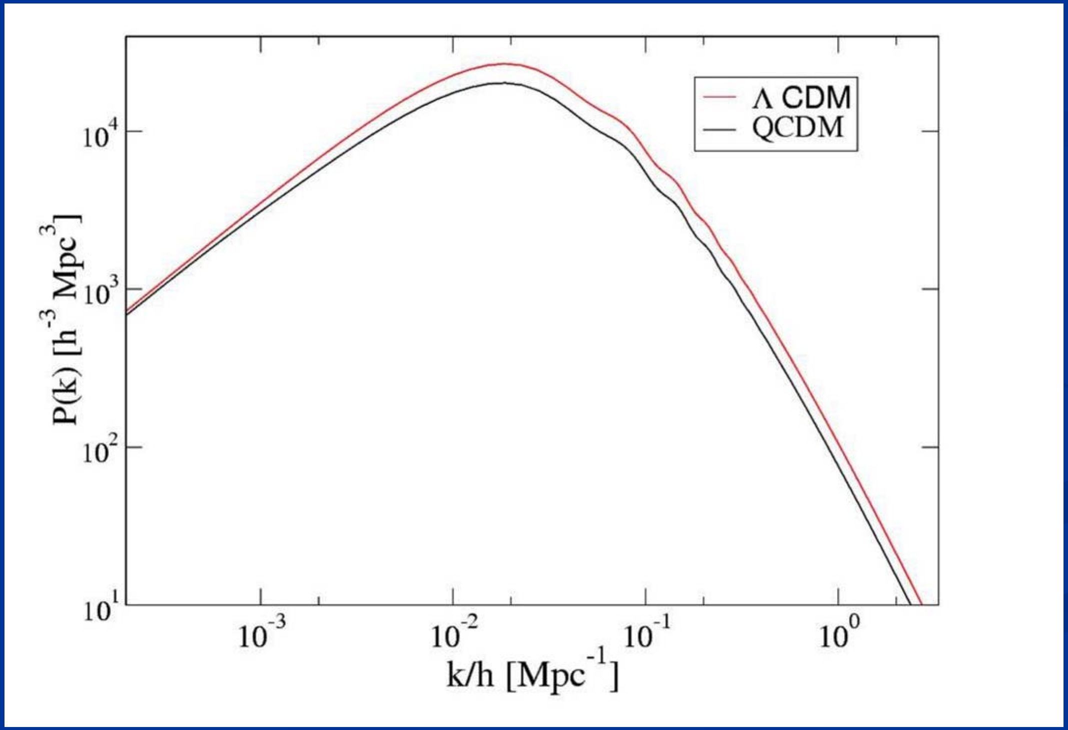
$$\Omega_h = 3/\alpha^2$$

can explain order of magnitude of dark energy !

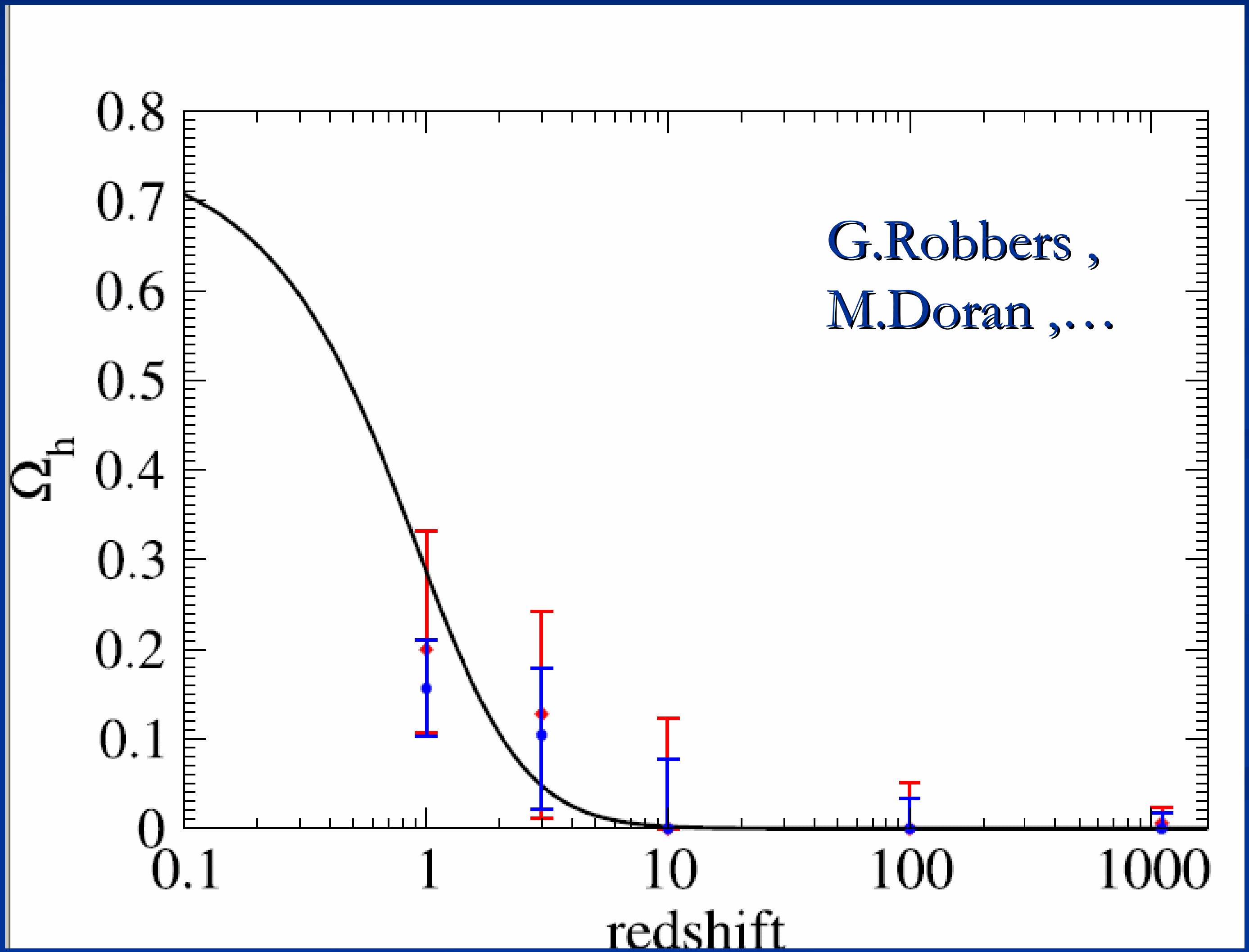


effects of early dark energy

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



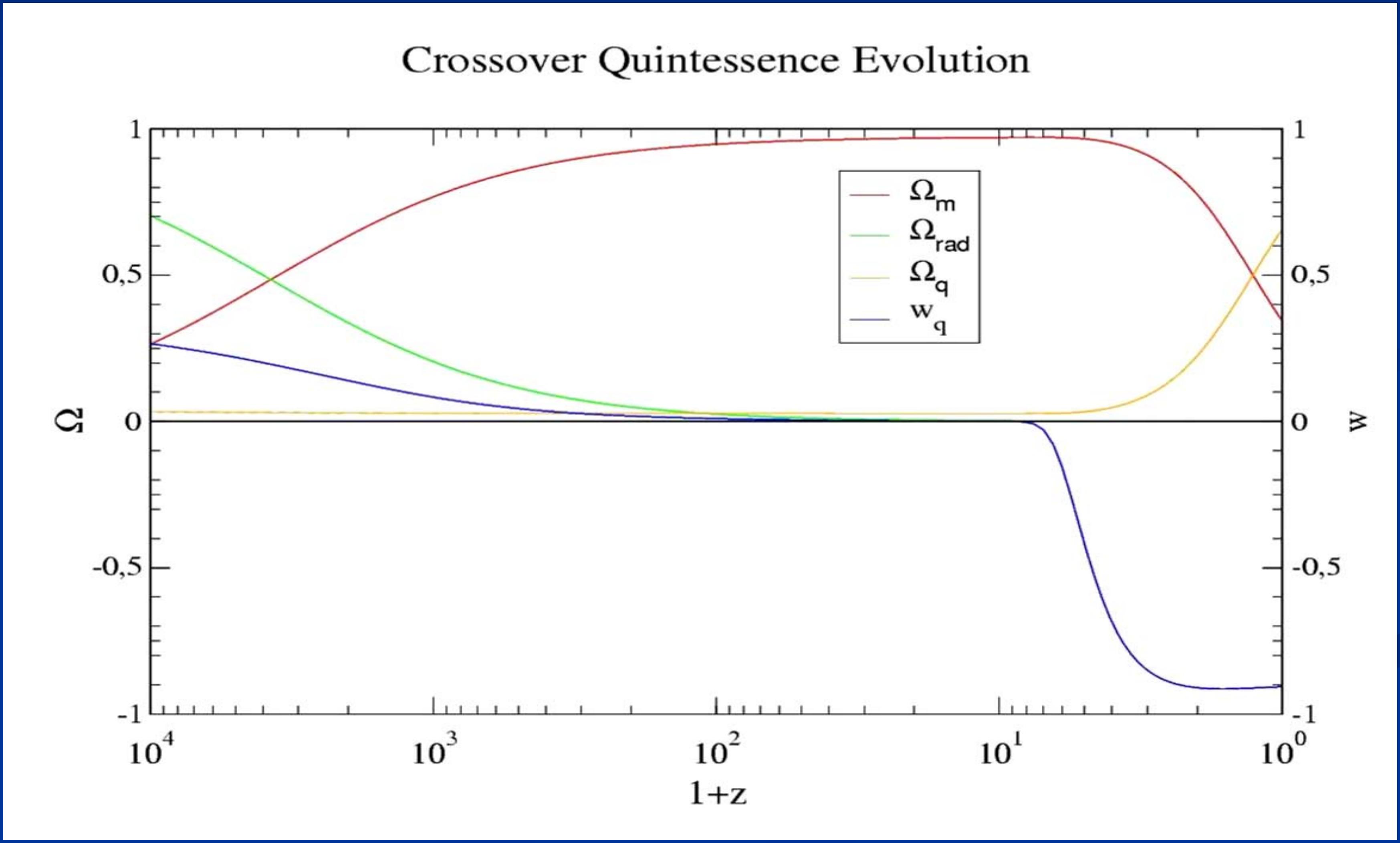
observational bounds on Ω_h



realistic quintessence

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

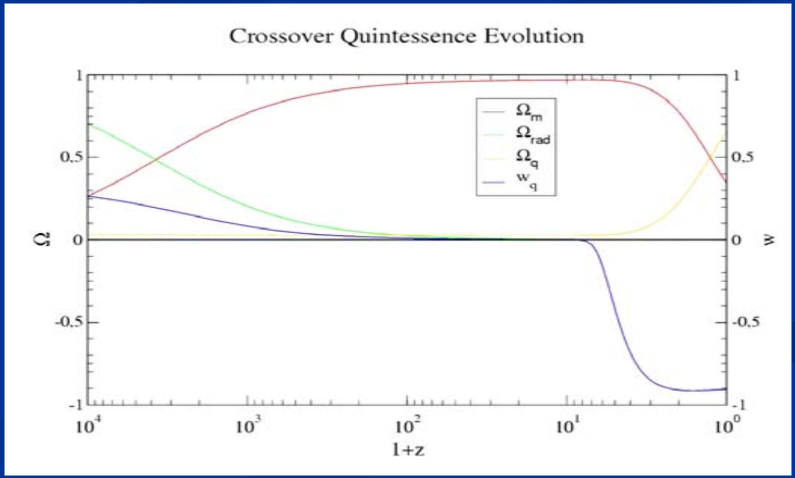
Quintessence becomes important "today"



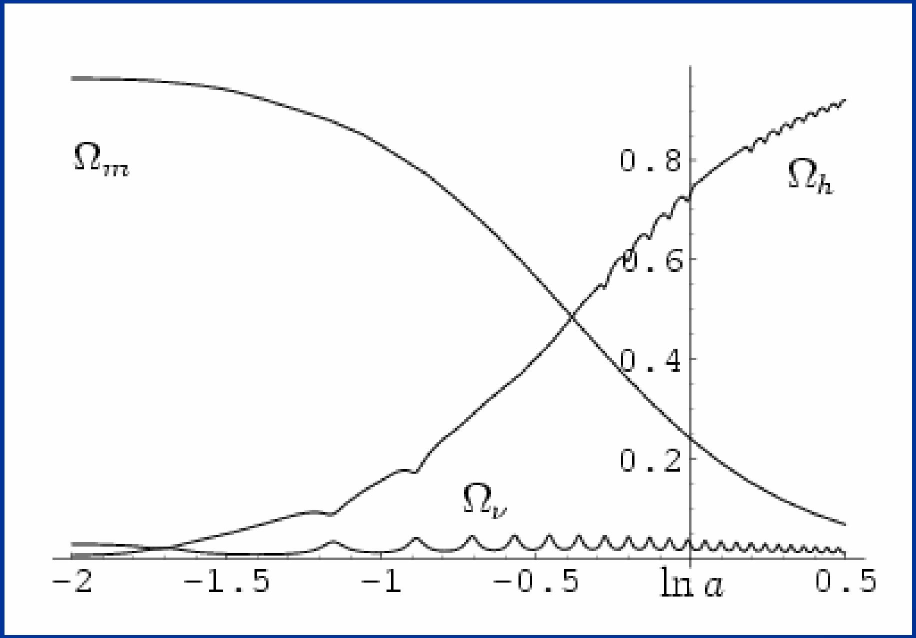
coincidence problem

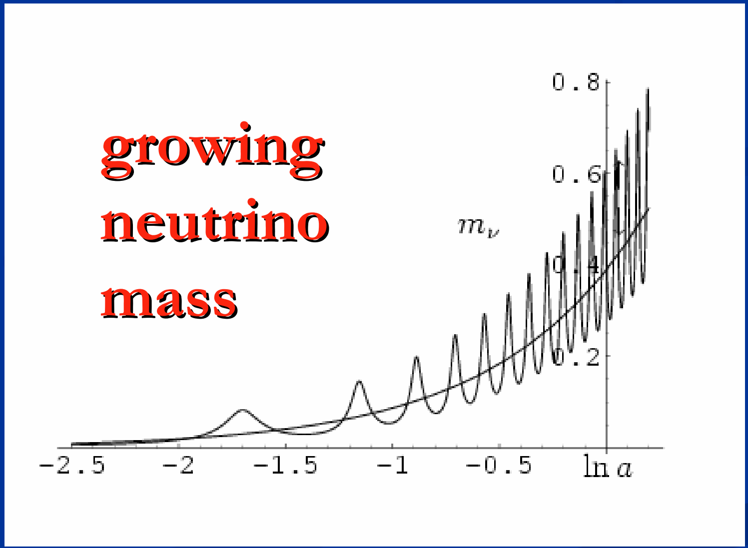
What is responsible for increase of Ω_h for $z < 6$?

Why now ?



growing neutrino mass triggers transition to almost static dark energy





L.Amendola, M.Baldi,…

effective cosmological trigger for stop of cosmon evolution : neutrinos get non-relativistic

- this has happened recently !
- sets scales for dark energy !

cosmological selection

- present value of dark energy density set by cosmological event :

  neutrinos become non – relativistic

- not given by ground state properties !

connection between dark energy and neutrino properties

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.07 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density is determined by neutrino mass !

---

present equation of state given by neutrino mass !

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\text{eV}}$$

dark energy fraction determined by neutrino mass

$$\Omega_h(t_0) \approx \frac{\gamma m_\nu(t_0)}{16eV}$$

$$\gamma = -\frac{\beta}{\alpha}$$

constant neutrino - cosmon coupling β

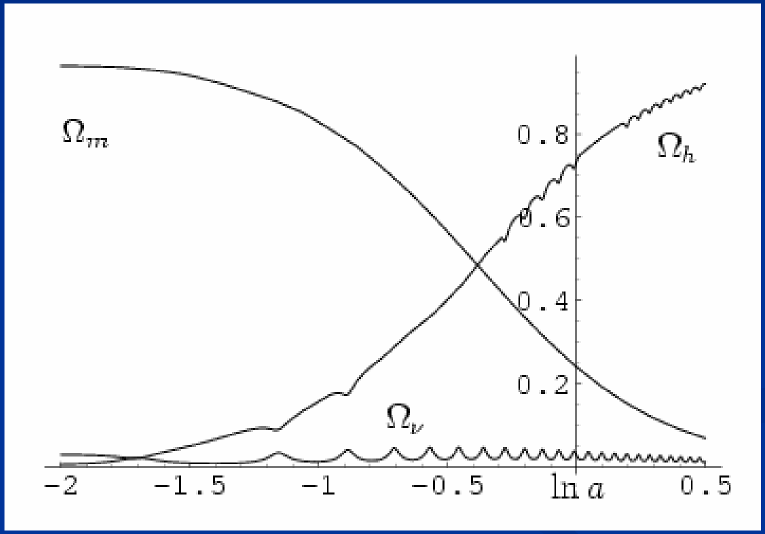
$$\Omega_h(t_0) \approx -\frac{\epsilon}{\alpha}\,\frac{m_\nu(t_0)}{\bar{m}_\nu}\,\frac{m_\nu(t_0)}{16eV}$$

variable neutrino - cosmon coupling

basic ingredient :

cosmon coupling to neutrinos

crossover to dark energy dominated universe



starts at time when "neutrino force" becomes important for the evolution of the cosmon field

cosmological selection !

growing neutrinos change cosmon evolution

$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{\partial V}{\partial \varphi} + \frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu),$$

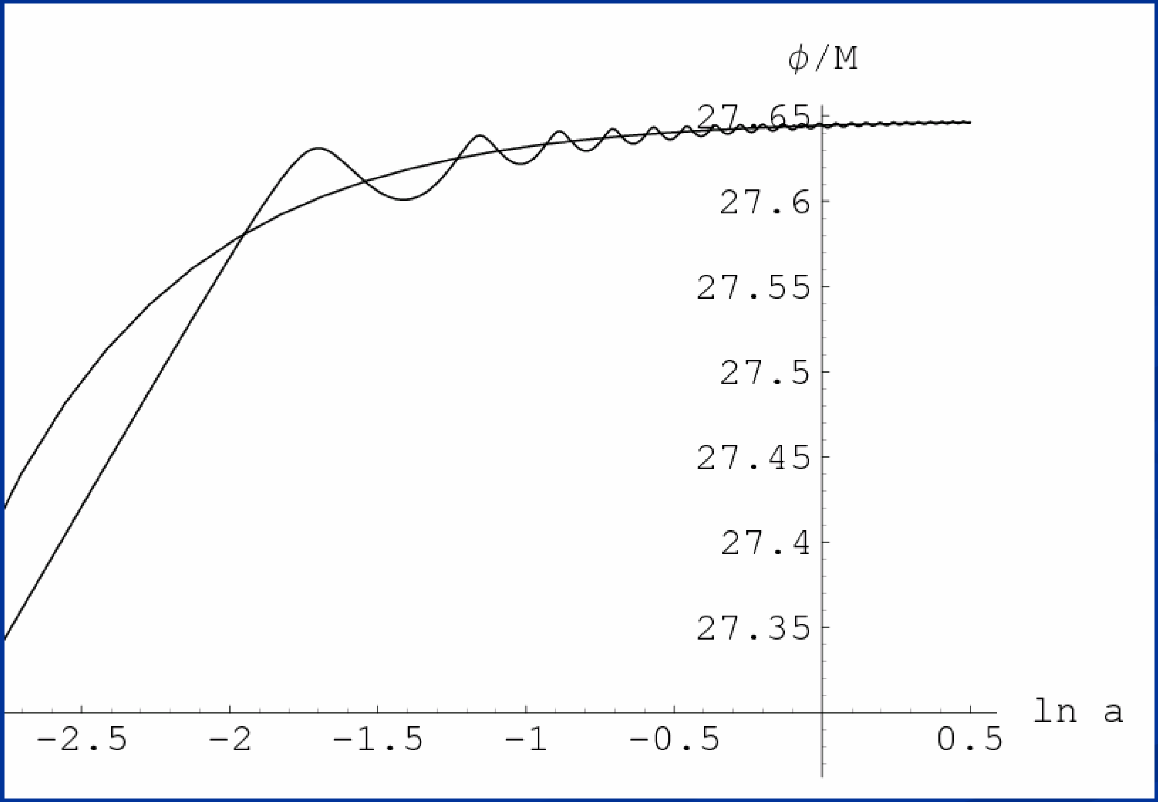
$$\beta(\varphi) = -M\frac{\partial}{\partial \varphi}\ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

modification of conservation equation for neutrinos

$$\dot{\rho}_\nu + 3H(\rho_\nu + p_\nu) = -\frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu)\dot{\varphi}$$

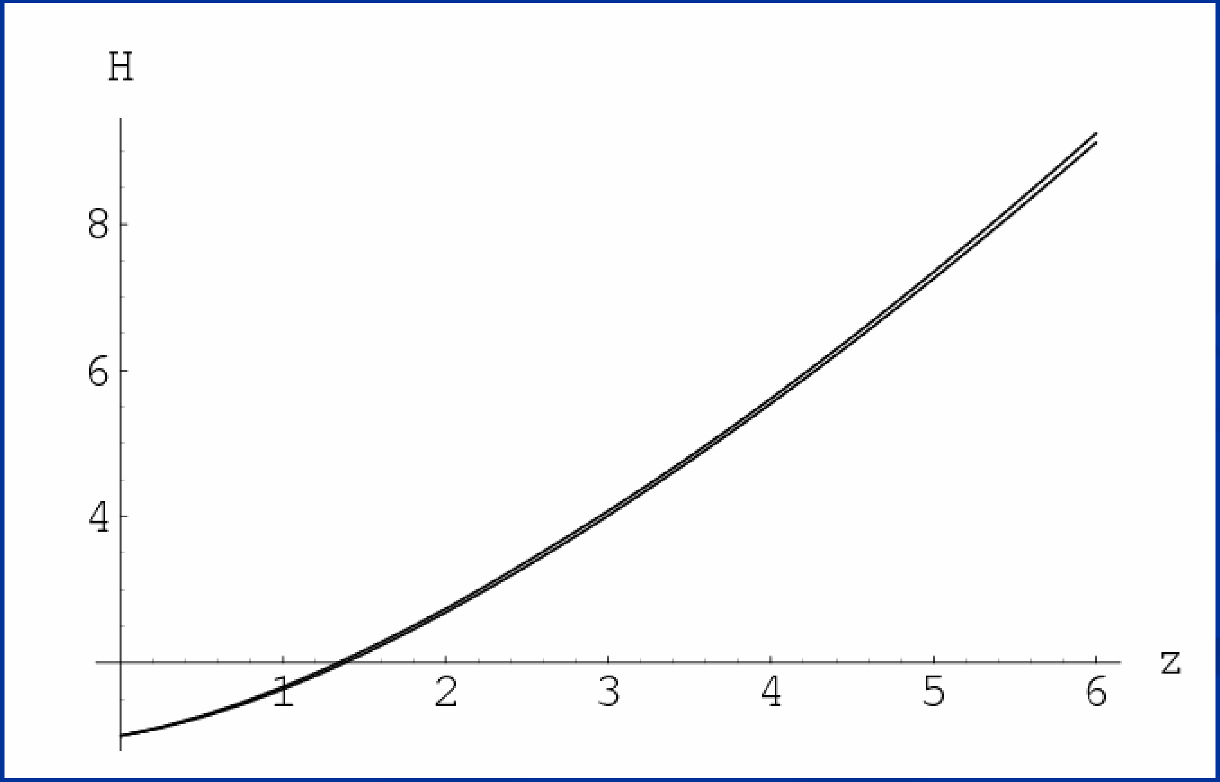
$$= -\frac{\dot{\varphi}}{\varphi - \varphi_t}(\rho_\nu - 3p_\nu)$$

cosmon evolution



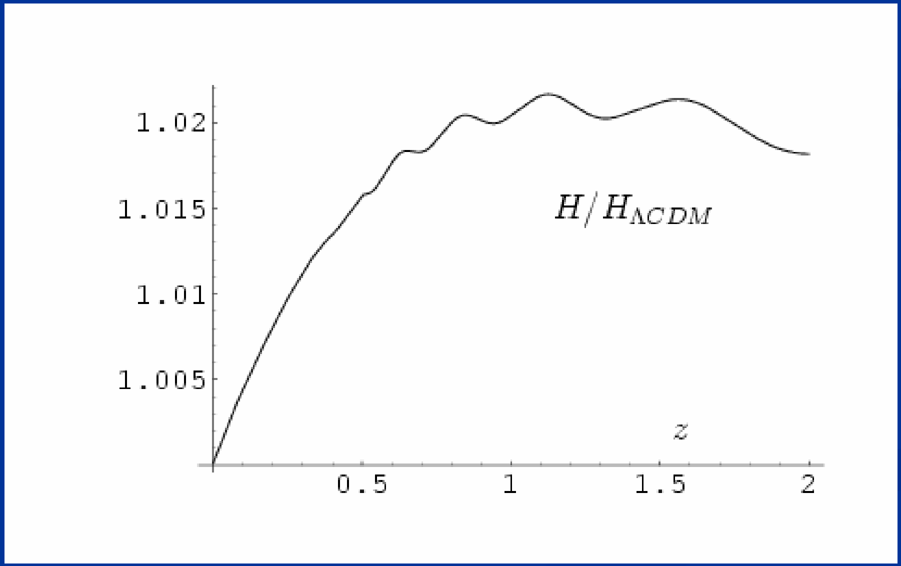
Hubble parameter

as compared to ΛCDM



Hubble parameter ($z < z_c$)

$$H^2 = \frac{1}{3M^2}\left\{V_t + \rho_{m,0}a^{-3} + 2\tilde{\rho}_{\nu,0}a^{-\frac{3}{2}}\right\}$$

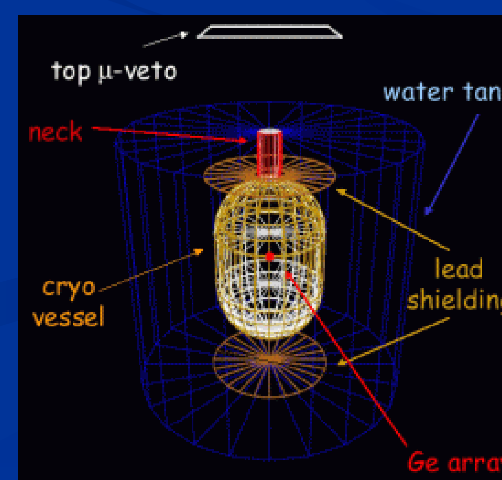


only small difference from ΛCDM !

Can time evolution of neutrino mass be observed ?

- Experimental determination of neutrino mass may turn out higher than upper bound in model for cosmological constant

(KATRIN, neutrino-less double beta decay)

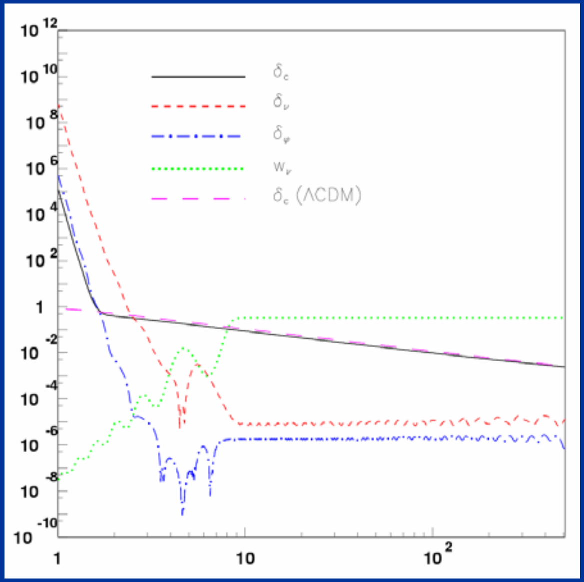


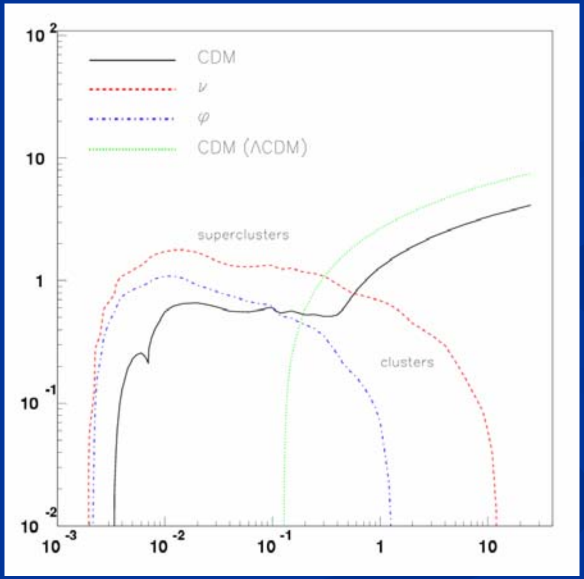
GERDA

neutrino fluctuations

neutrino structures become nonlinear at z~1 for supercluster scales

D.Mota , G.Robbers , V.Pettorino , …





stable neutrino-cosmon lumps exist

N.Brouzakis , N.Tetradis ,…

Conclusions

- Cosmic event triggers qualitative change in evolution of cosmon
- Cosmon stops changing after neutrinos become non-relativistic
- Explains why now
- Cosmological selection
- Model can be distinguished from cosmological constant

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(today) > -1

B) Time variation of fundamental "constants"

C) Apparent violation of equivalence principle

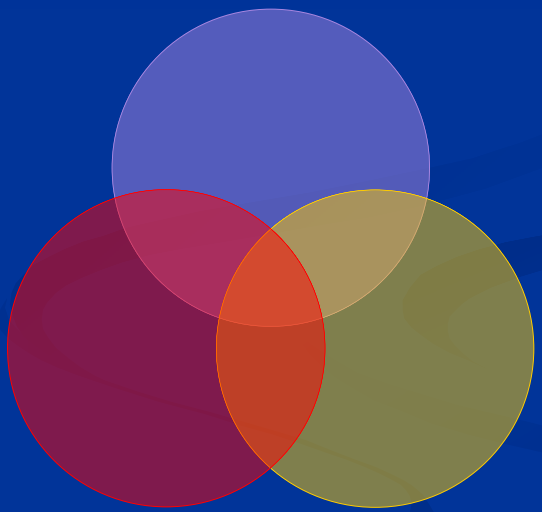
D) Possible coupling between Dark Energy and Dark Matter

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 : $\alpha(\varphi)$

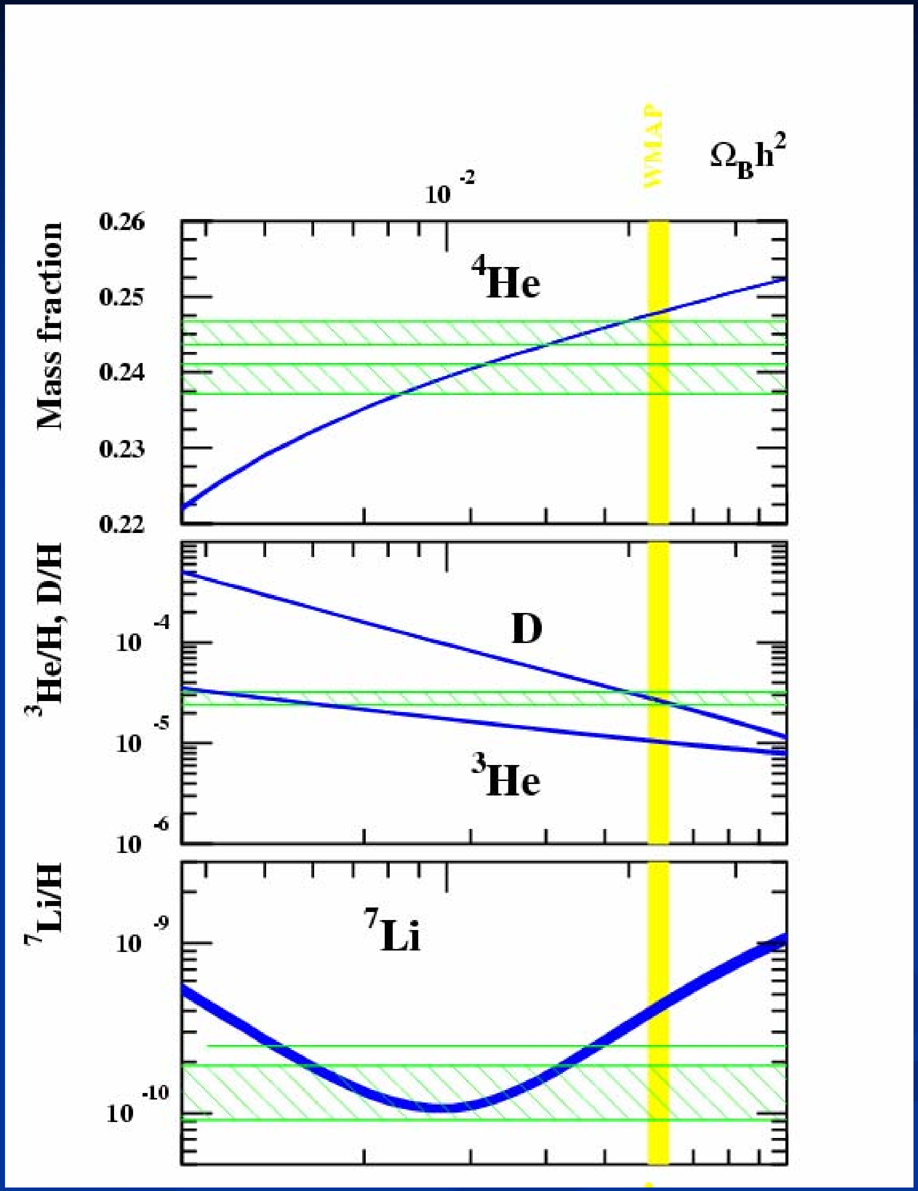
(similar in standard model: couplings depend on value of Higgs scalar field)

- Time evolution of φ ⟹ Time evolution of α

Jordan,…


baryons :
the matter of stars and humans
$\Omega_b = 0.045$

Abundancies of primordial light elements from nucleosynthesis



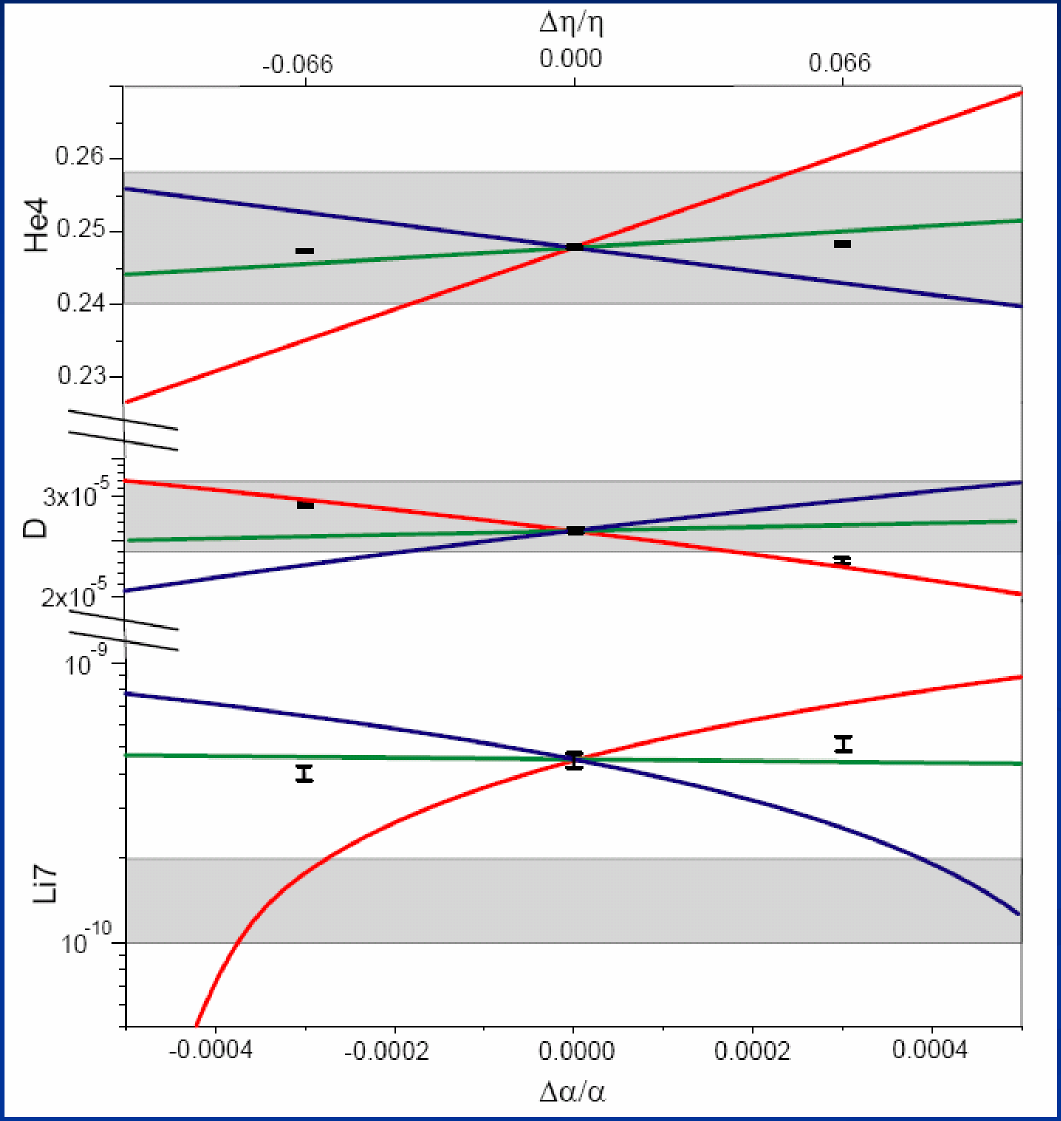
A.Coc

primordial abundances for three GUT models

He

D

Li



present observations : 1σ

T.Dent, S.Stern,…

three GUT models

- unification scale ~ Planck scale
- 1) All particle physics scales $\sim\Lambda_{QCD}$
- 2) Fermi scale and fermion masses ~ unification scale
- 3) Fermi scale varies more rapidly than Λ_{QCD}

$\Delta\alpha/\alpha \approx 4\ 10^{-4}$ allowed for GUT 1 and 3 , larger for GUT 2

$\Delta\ln(M_n/M_P) \approx 40\ \Delta\alpha/\alpha \approx 0.015$ allowed

Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

Summary

- $\Omega_h = 0.75$

- Q/Λ : dynamical und static dark energy will be distinguishable

- growing neutrino mass can explain why now problem

- Q : time varying fundamental coupling "constants"
  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

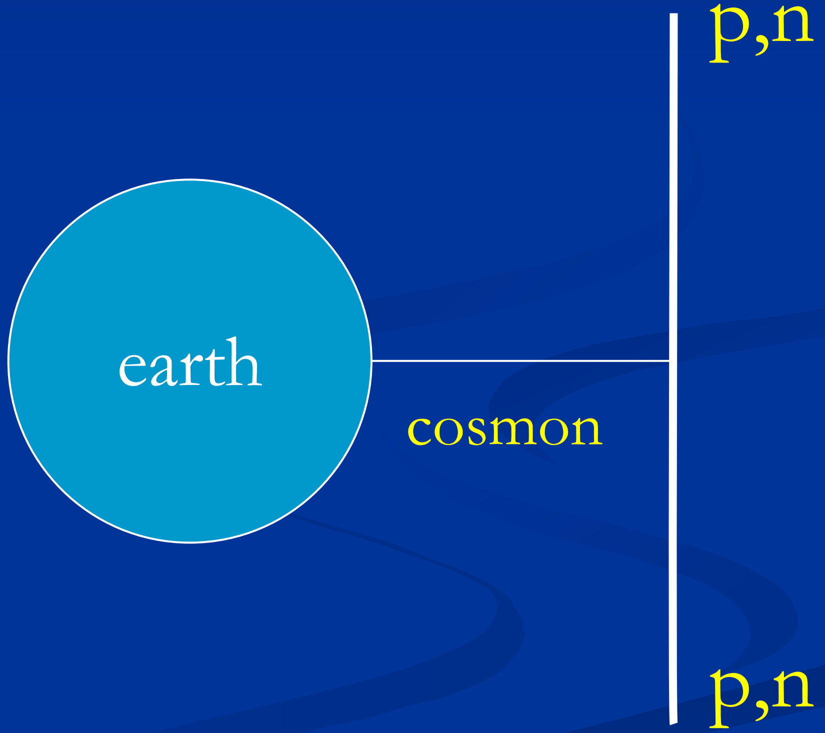
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



only apparent : new "fifth force" !

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

- $\Omega_h = 0.75$

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- growing neutrino mass can explain why now problem

- Q : time varying fundamental coupling "constants"
  violation of equivalence principle

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

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

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

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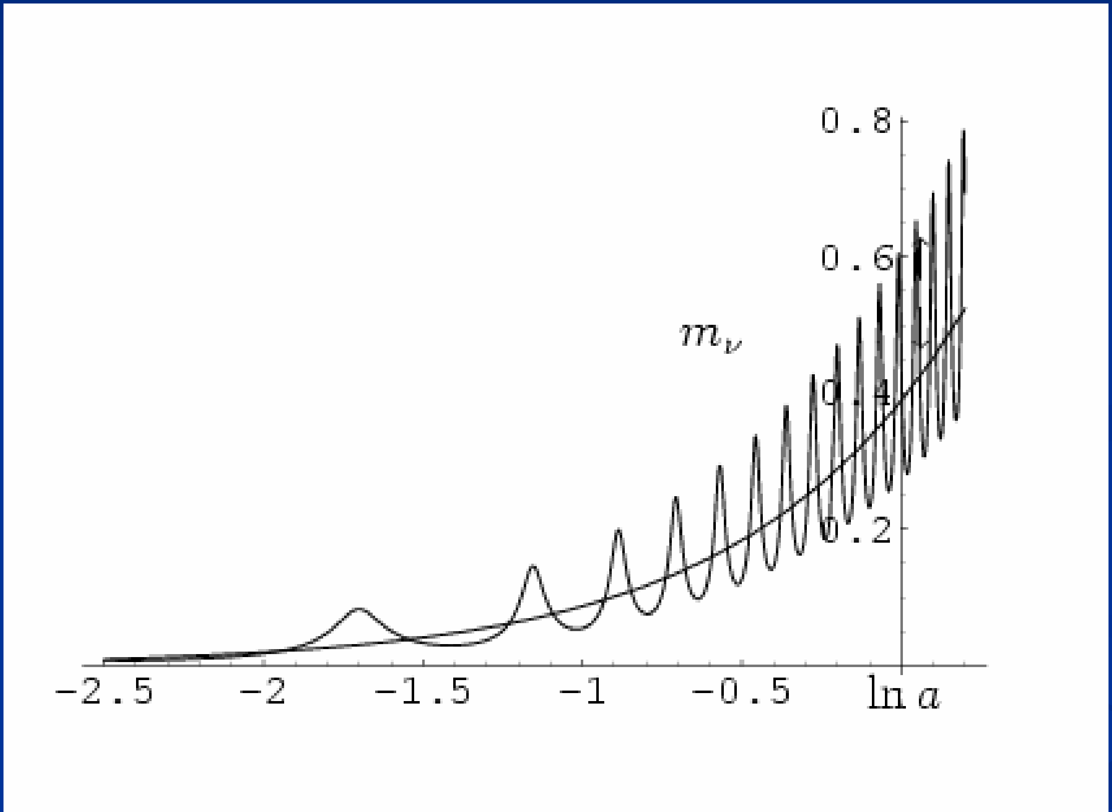
oscillating neutrino mass



neutrino fluctuations

- time when neutrinos become non – relativistic
- sets free streaming scale

$$a_R = \left(\frac{\tilde{m}_\nu(t_0)}{3T_{\nu,0}}\right)^{-\frac{2}{5}} = 0.05\left(\frac{\tilde{m}_\nu(t_0)}{eV}\right)^{-2/5}$$

- neutrino structures become nonlinear at z~1 for supercluster scales

  D.Mota , G.Robbers , V.Pettorino , …

- stable neutrino-cosmon lumps exist

  N.Brouzakis , N.Tetradis ,…

baryon acoustic peak