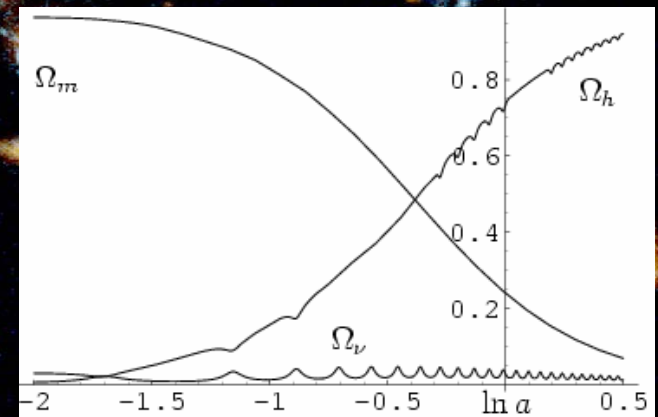
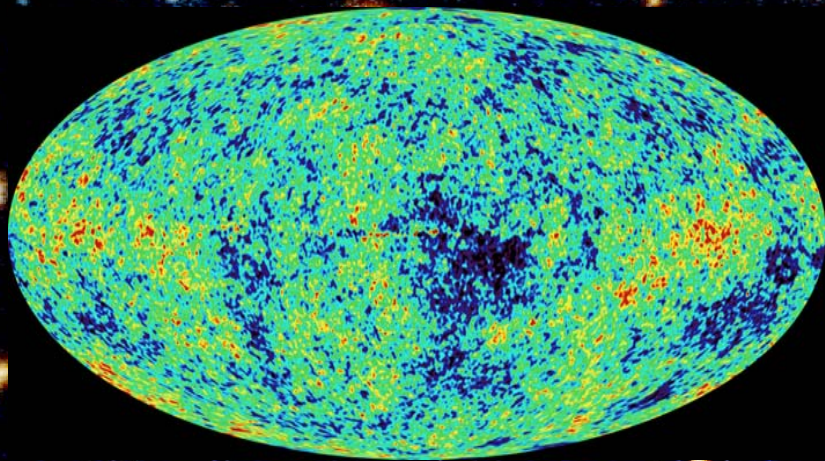


Dark Energy – a cosmic mystery



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

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

critical energy density of the universe

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

- $\Omega_b = \rho_b / \rho_c$

fraction in baryons

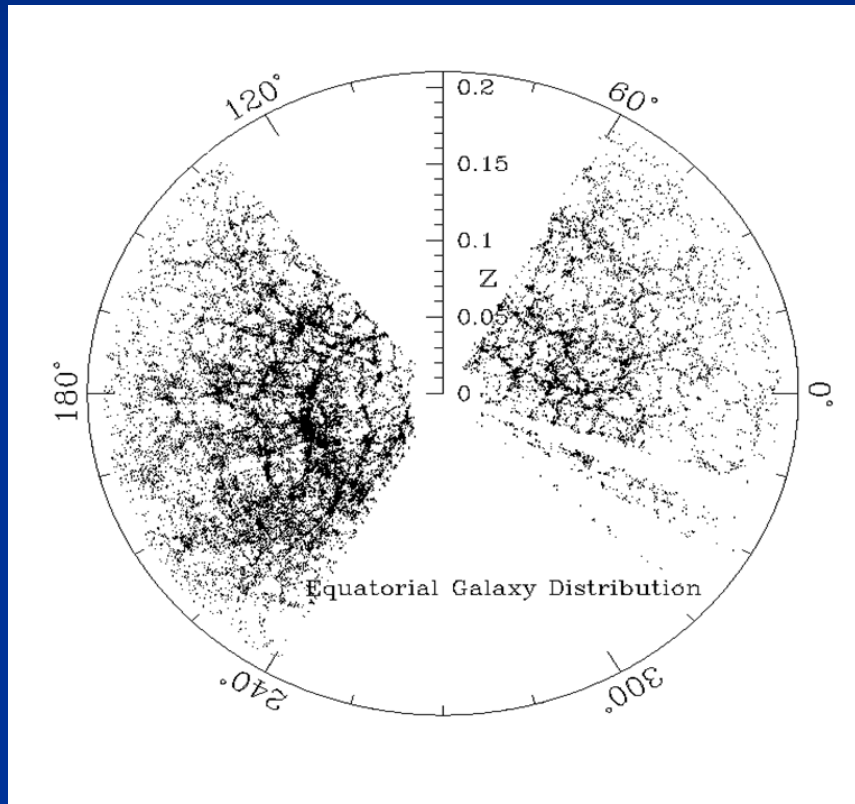
energy density in baryons over critical
energy density

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

Baryons/Atoms

SDSS

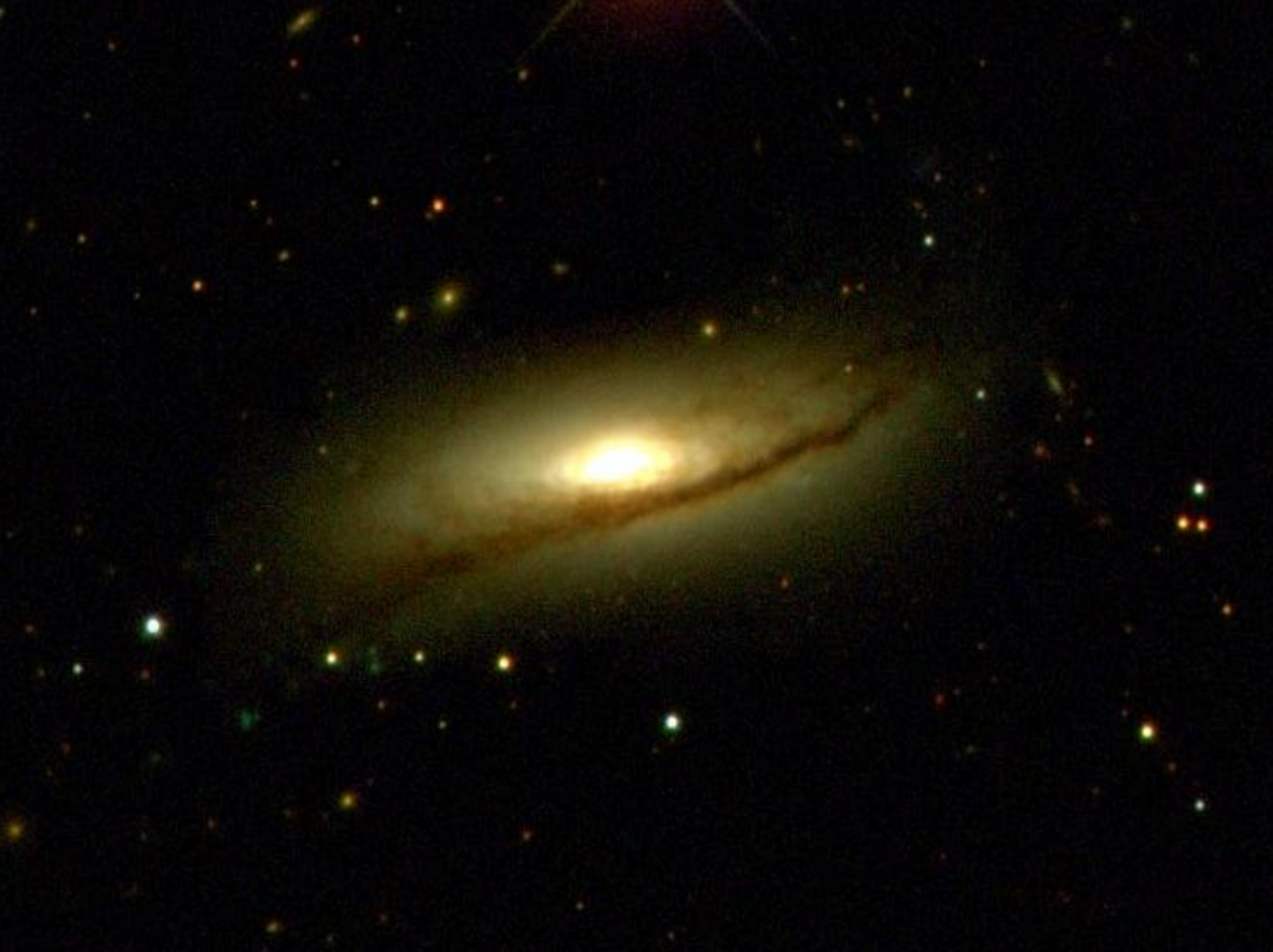
~60,000 of
>300,000
Galaxies



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

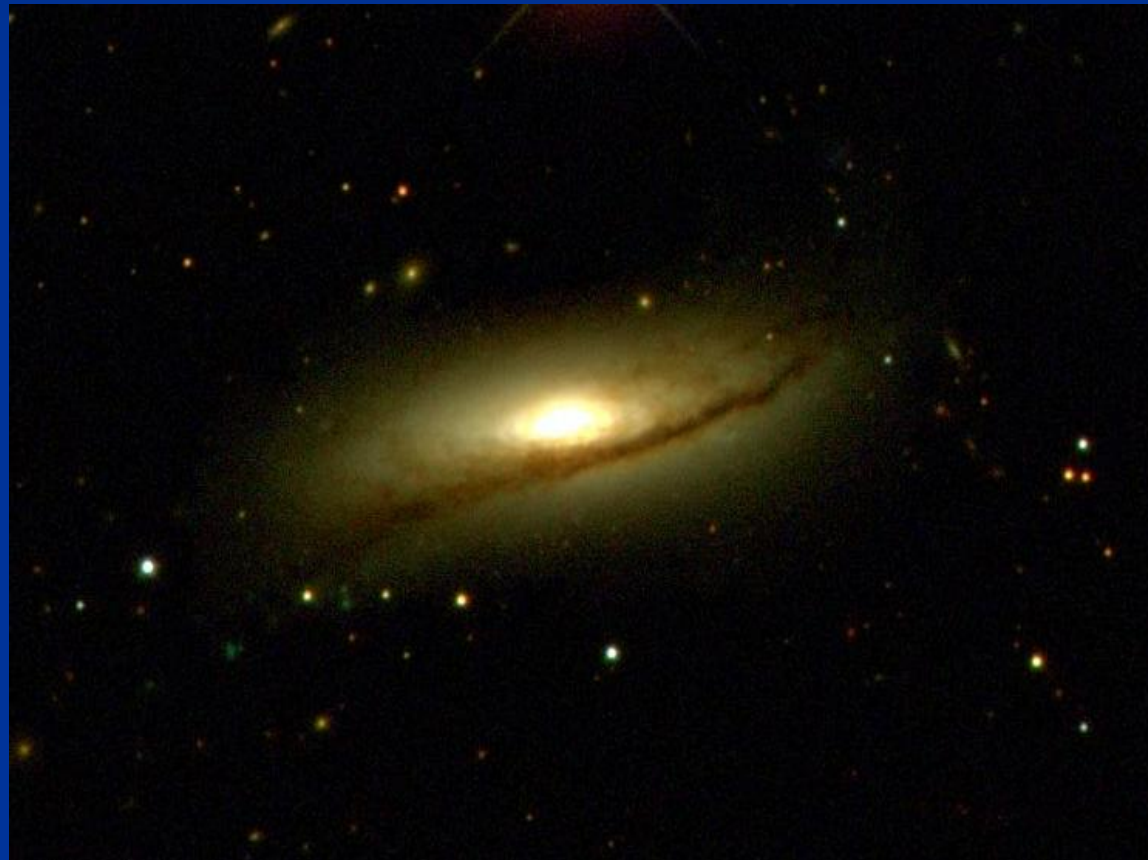


Abell 2255 Cluster
~300 Mpc



$$\Omega_b = 0.045$$

from
nucleosynthesis,
cosmic
background
radiation



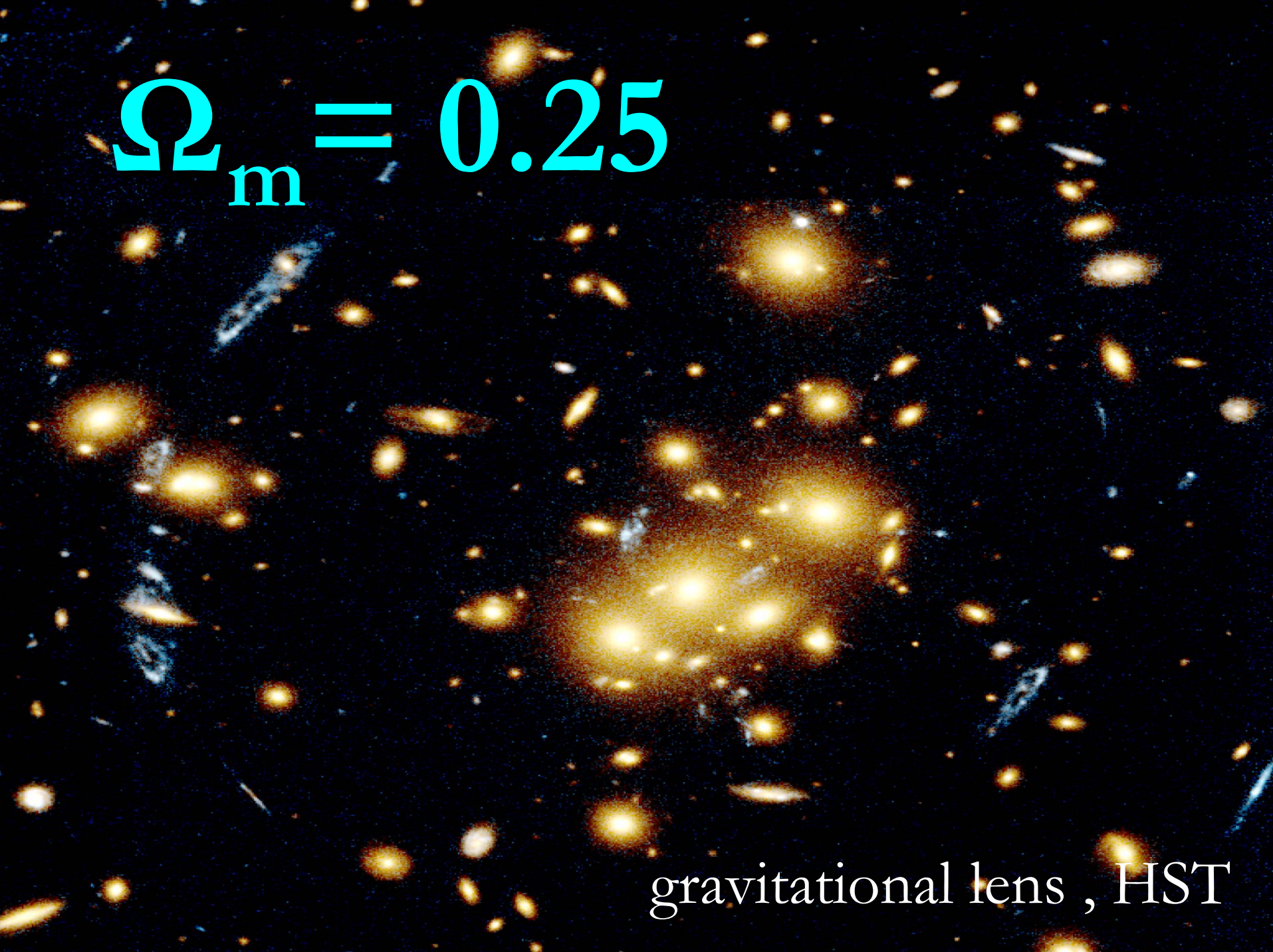
Matter : Everything that clumps



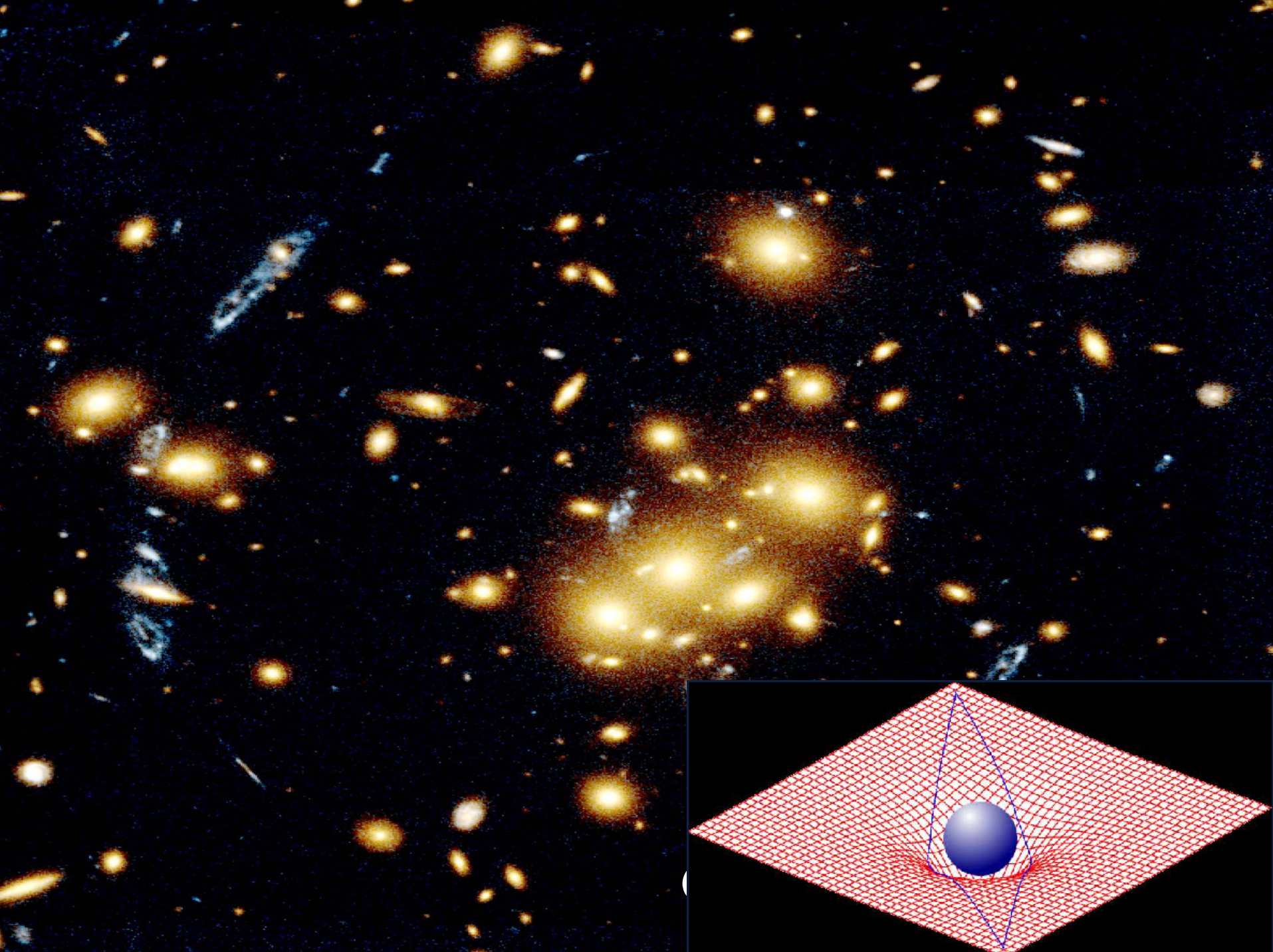
Abell 2255 Cluster
~300 Mpc

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

A deep-field astronomical image showing a large number of galaxies. In the center, there is a prominent, bright, yellowish-white galaxy cluster. Surrounding this central cluster are numerous other galaxies, many of which appear distorted or stretched, indicating they are being gravitationally lensed by the central mass. The background is dark, with some faint, blueish galaxies scattered throughout.
$$\Omega_m = 0.25$$

gravitational lens , HST





Matter : Everything that clumps

$$\Omega_m = 0.25$$

Abell 2255 Cluster
~300 Mpc

spatially flat universe

$$\Omega_{\text{tot}} = 1$$

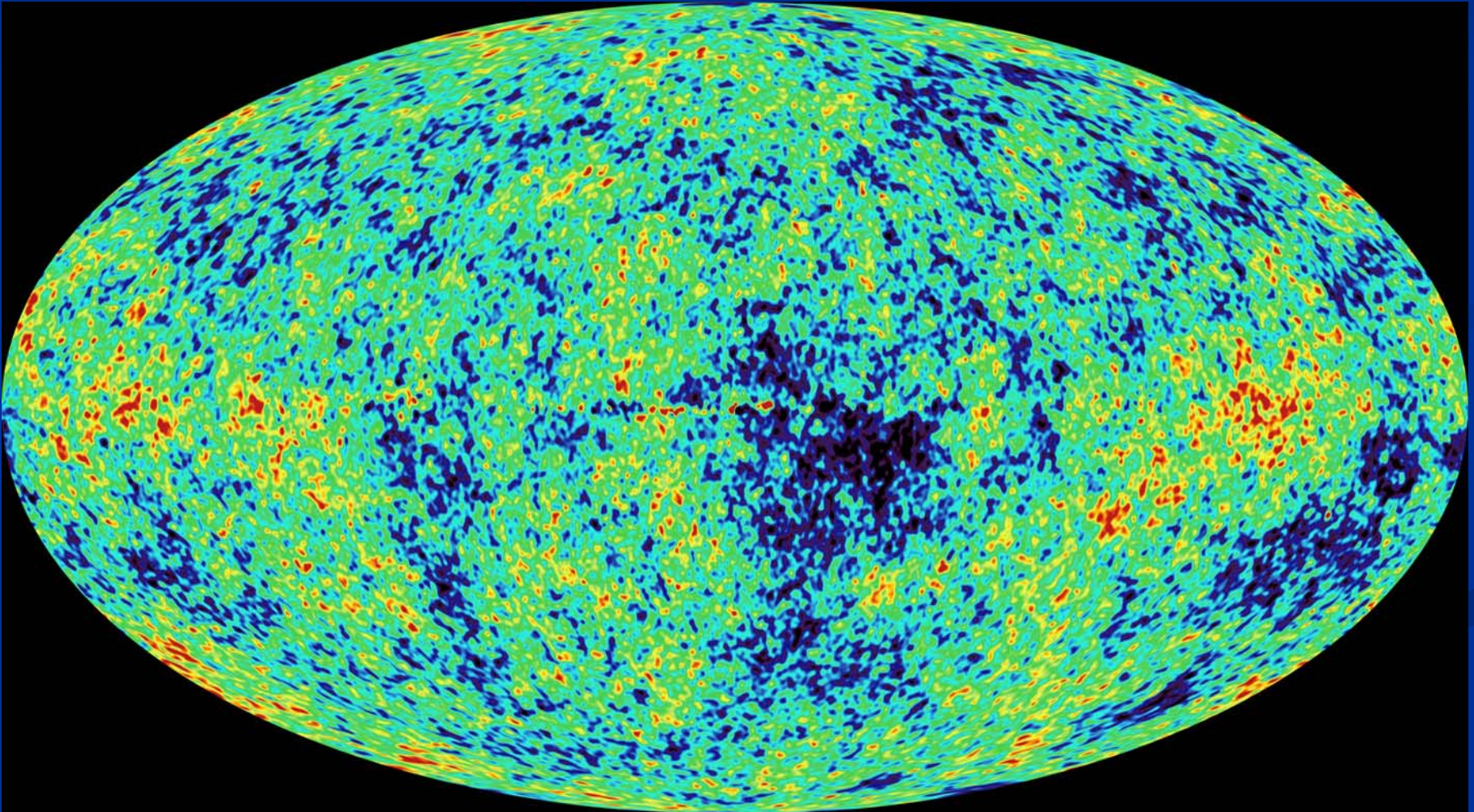
- theory (inflationary universe)

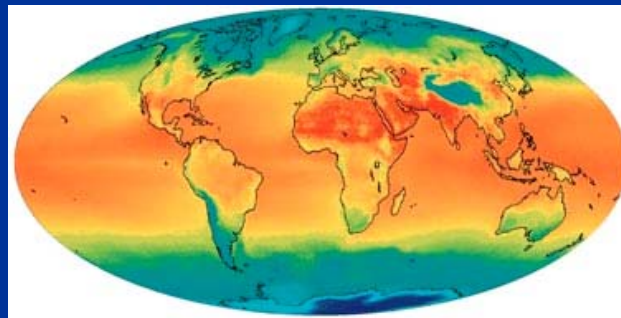
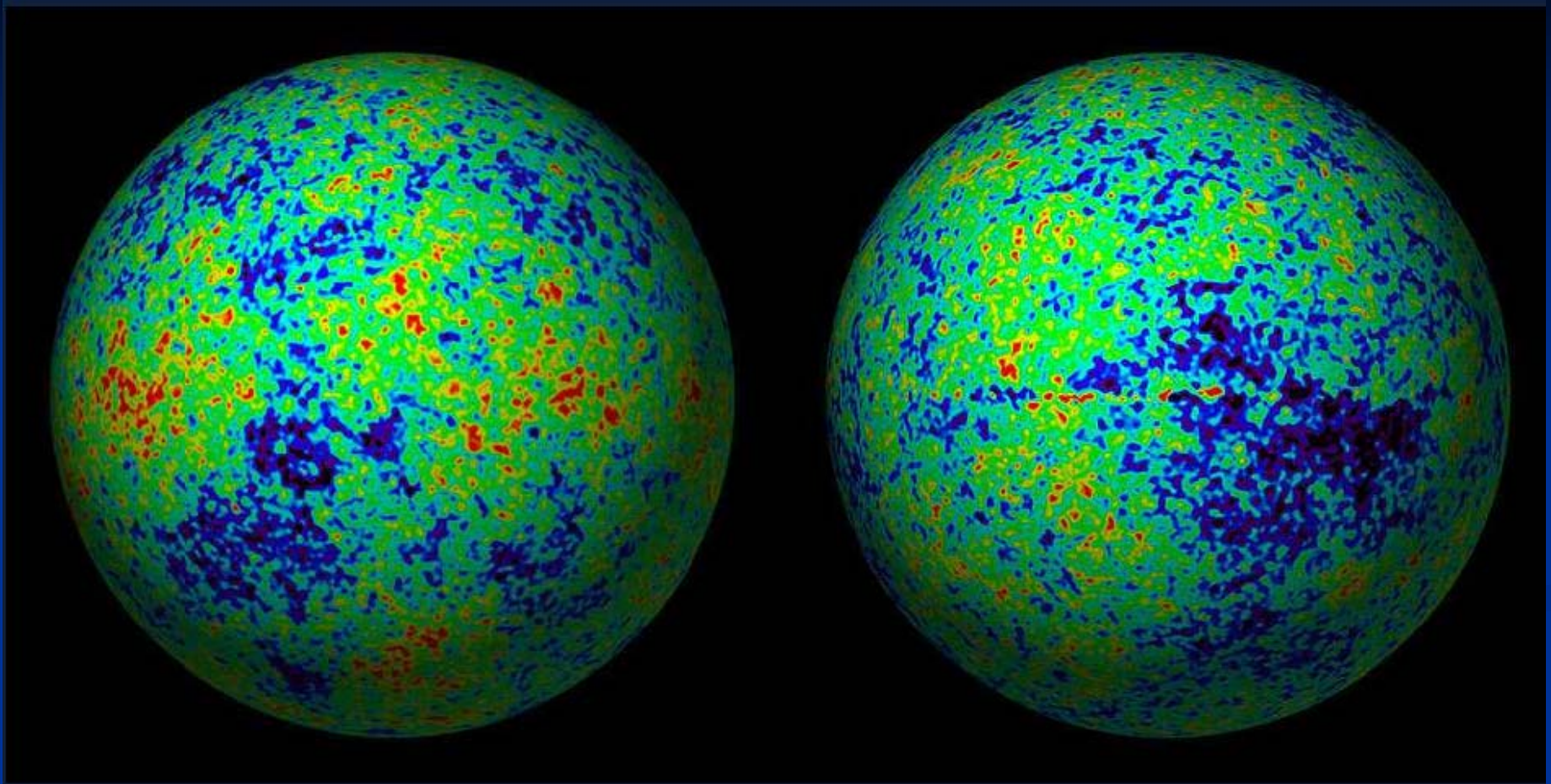
$$\Omega_{\text{tot}} = 1.0000\dots\dots\dots x$$

- observation (WMAP)

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

picture of the big bang





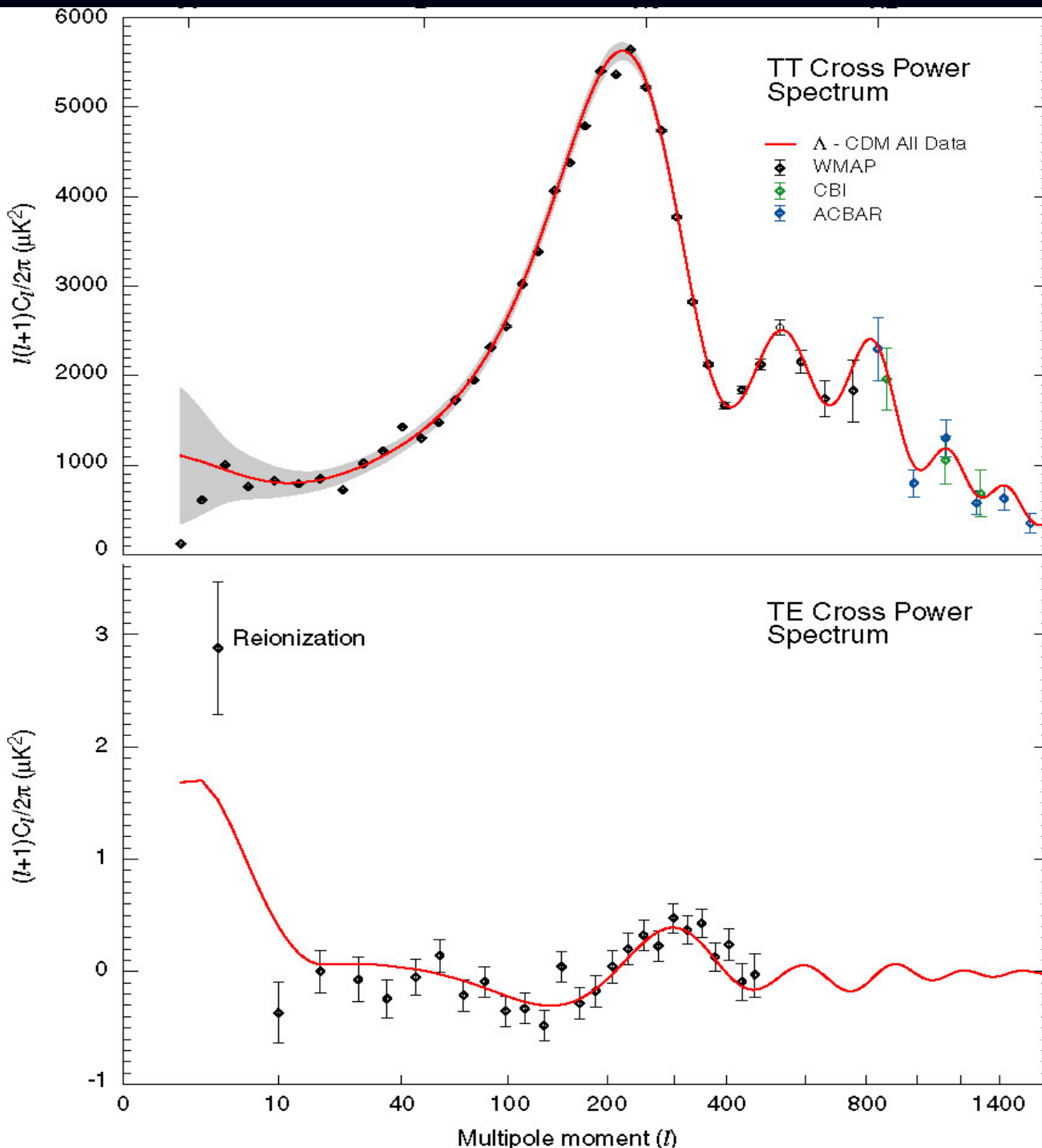
Mean values WMAP 2003

$$\Omega_{\text{tot}} = 1.02$$

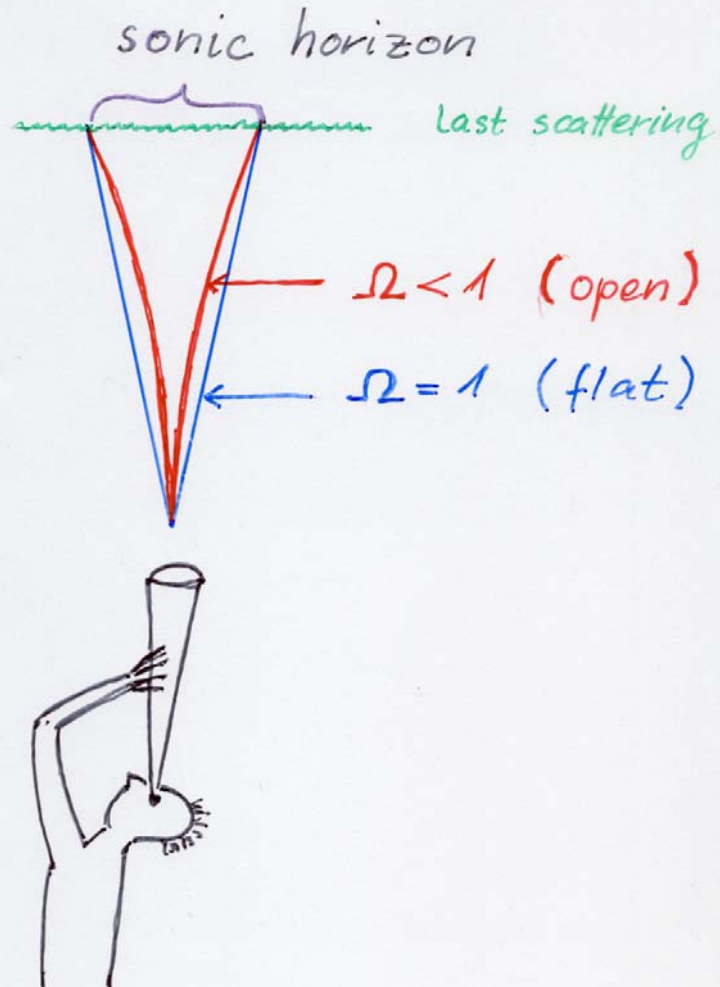
$$\Omega_{\text{m}} = 0.27$$

$$\Omega_{\text{b}} = 0.045$$

$$\Omega_{\text{dm}} = 0.225$$



$$\Omega_{\text{tot}} = 1$$



Wilkinson Microwave Anisotropy Probe

A partnership between
NASA/GSFC and Princeton

Science Team:

NASA/GSFC

Chuck Downes (PI)
Michael Gersson
Bob Hill
Gary Hinshaw
Al Kogut
Michelle Linton
Nils Odgers
Janet Weiland
Ed Wollack

Brown

Greg Tucker

UCLA

Neil Wright

UBC

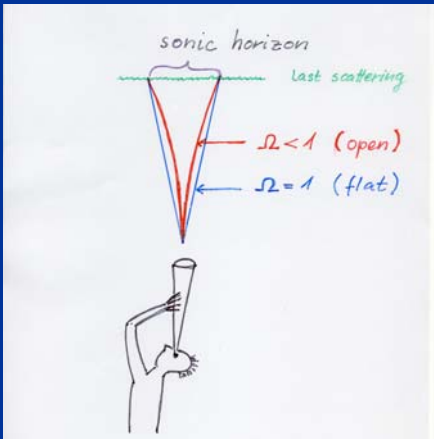
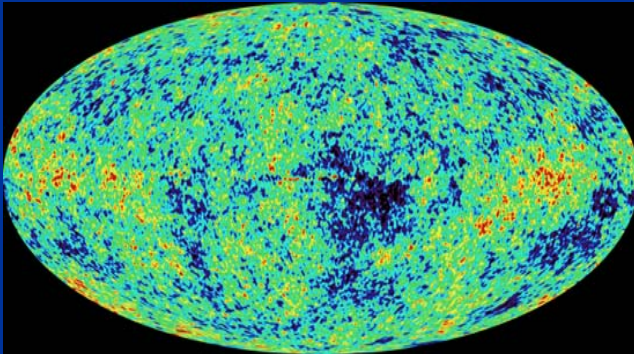
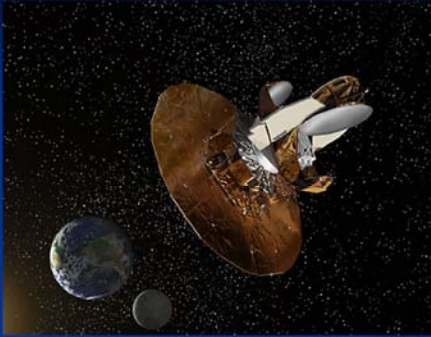
Mark Halpern

Chicago

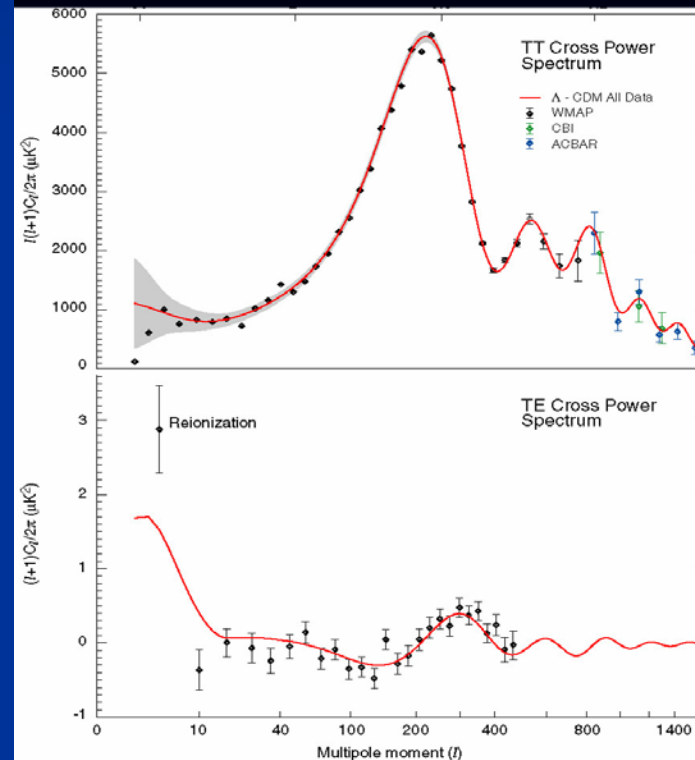
Stephan Meyer

Princeton

Chris Barnes
Norm Janotik
Eiichiro Komatsu
Michael Nolte
Lyman Page
Hiranya Peiris
David Spergel
Licia Verde



$$\Omega_{\text{tot}} = 1$$



mean values

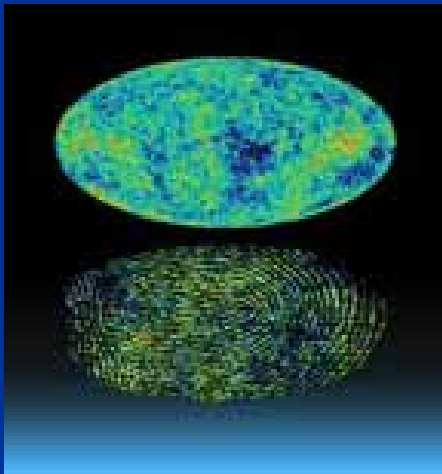
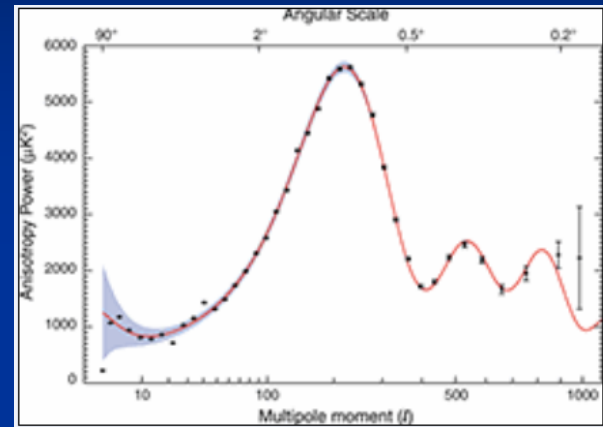
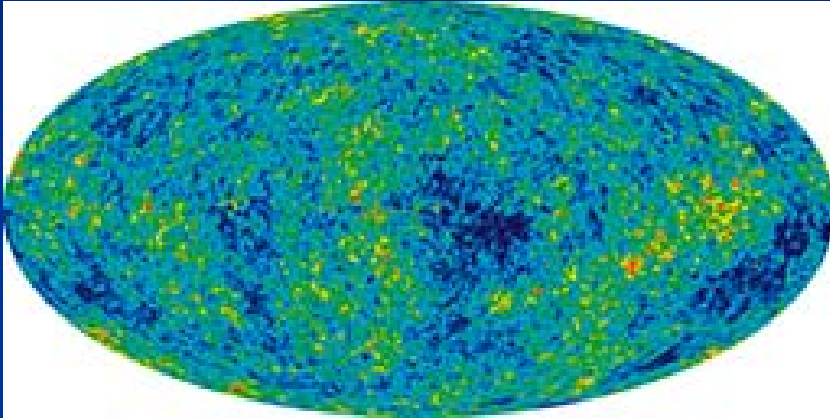
$$\Omega_{\text{tot}} = 1.02$$

$$\Omega_{\text{m}} = 0.27$$

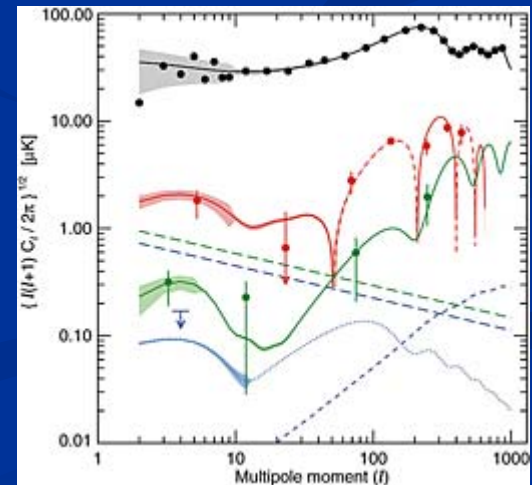
$$\Omega_{\text{b}} = 0.045$$

$$\Omega_{\text{dm}} = 0.225$$

WMAP 2006



Polarization



Dark Energy

$$\Omega_m + X = 1$$

$$\Omega_m : 25\%$$

$$\Omega_h : 75\% \quad \text{Dark Energy}$$

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**

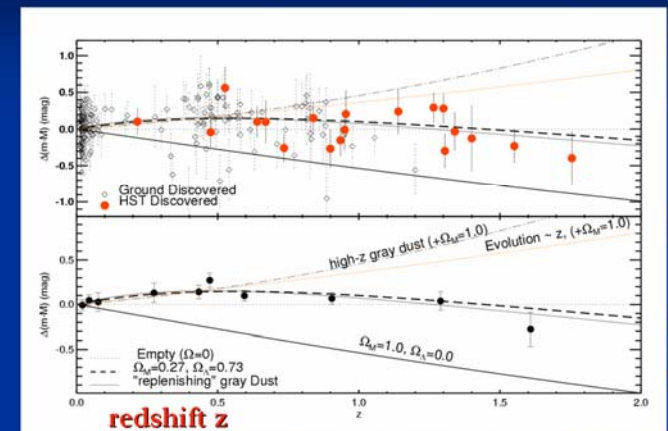
“ homogeneous “

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

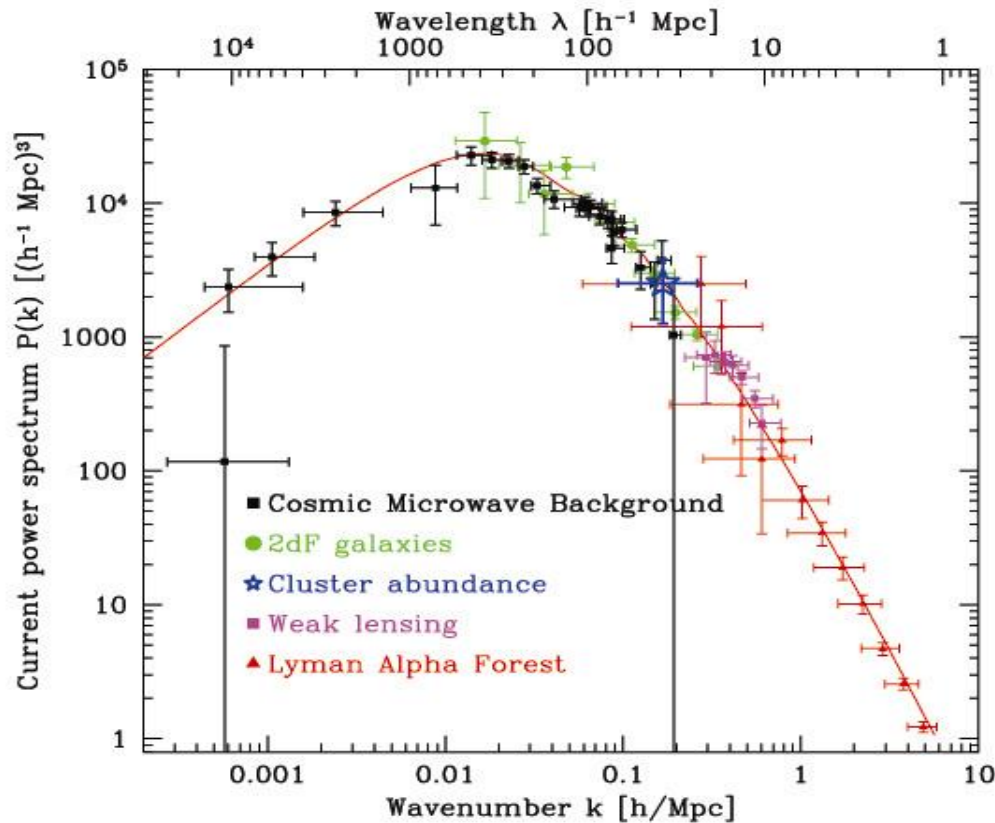
Predictions for dark energy cosmologies

*The expansion of the Universe
accelerates today !*

Supernovae 1a Hubble diagram



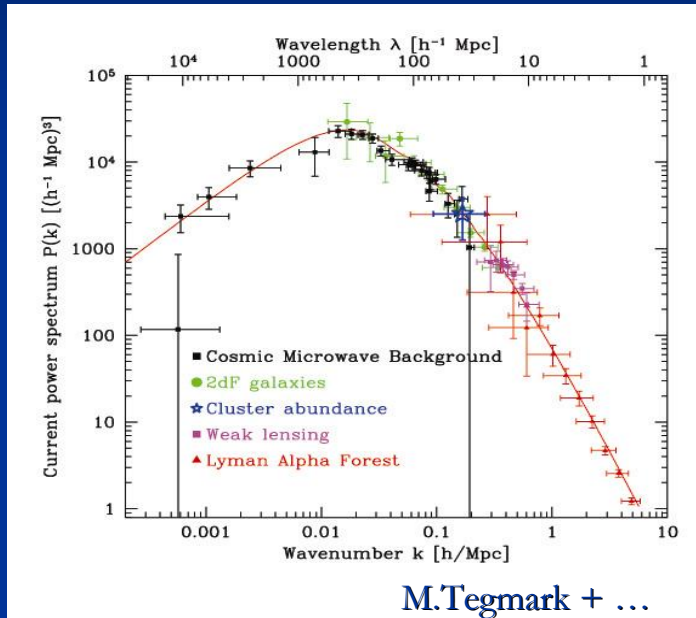
Structure formation : One primordial fluctuation spectrum



Waerbeke

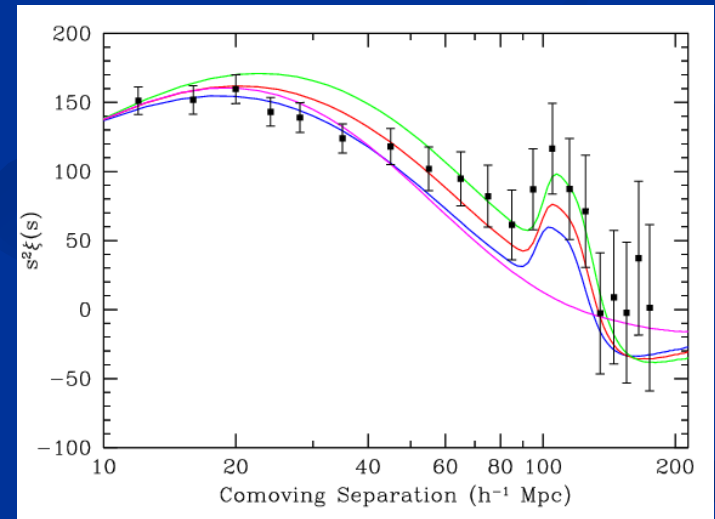
CMB agrees with
Galaxy distribution
Lyman - α
and
Gravitational
Lensing !

Power spectrum



Baryon - Peak

galaxy –
correlation –
function



Structure formation :
One primordial
fluctuation- spectrum

SDSS

Composition of the Universe

$$\Omega_b = 0.045$$

visible

clumping

$$\Omega_{dm} = 0.2$$

invisible

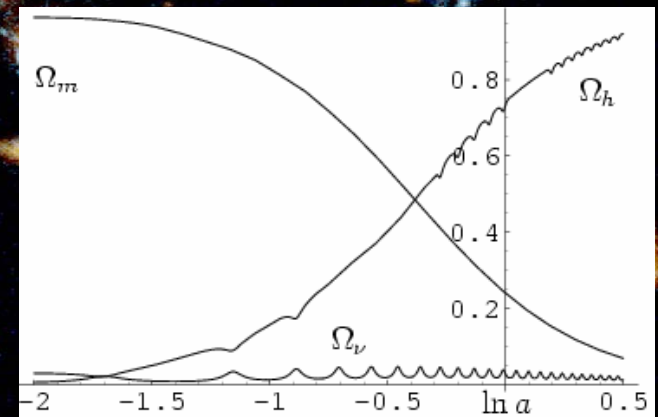
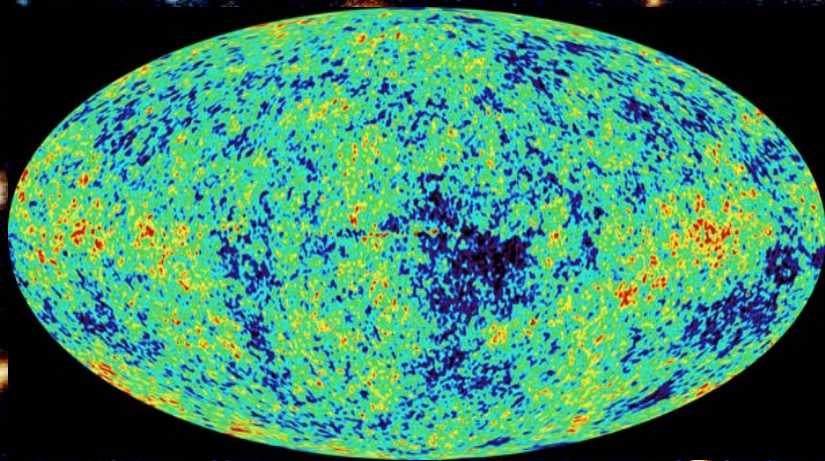
clumping

$$\Omega_h = 0.75$$

invisible

homogeneous

Dark Energy – a cosmic mystery



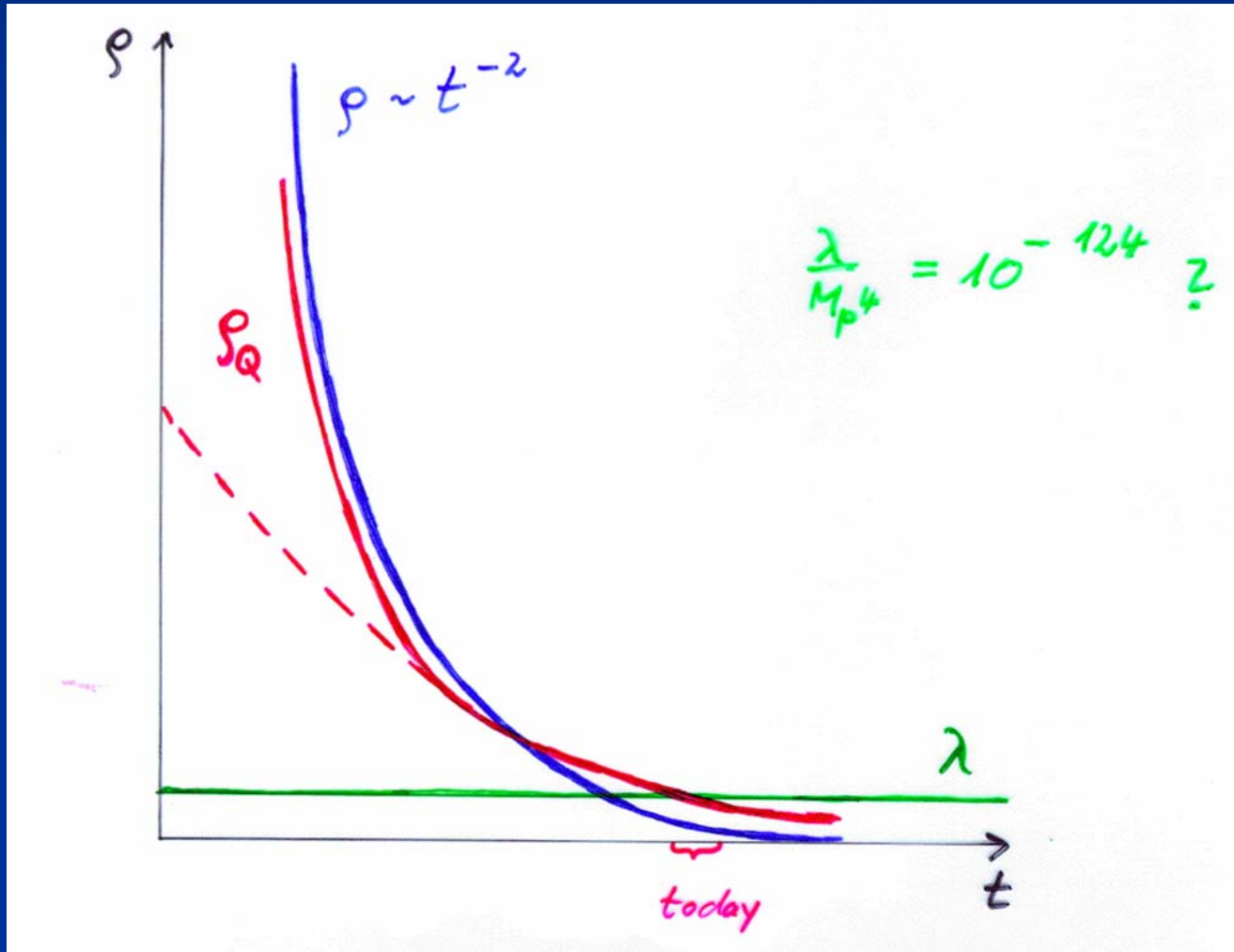
Cosmological Constant

- 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.
static

Quintessence
dynamical



Cosmological mass scales

- Energy density

$$\rho \sim (2.4 \times 10^{-3} \text{ eV})^{-4}$$

- Reduced Planck mass

$$M = 2.44 \times 10^{27} \text{ eV}$$

- Newton's constant

$$G_N = (8\pi M^2)$$

Only ratios of mass scales are observable !

homogeneous dark energy: $\rho_h/M^4 = 6.5 \cdot 10^{-121}$

matter: $\rho_m/M^4 = 3.5 \cdot 10^{-121}$

Time evolution

- $\rho_m/M^4 \sim a^{-3} \sim t^{-2}$ matter dominated universe
- $\rho_r/M^4 \sim a^{-4} \sim t^{-3/2}$ 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 $\varphi(\mathbf{x},y,z,t)$

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

Homogeneous und isotropic Universe : $\varphi(\mathbf{x},y,z,t)=\varphi(t)$

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 :
 $\rho_b(t)$ 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 $V(\varphi)$ determines details of the model

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

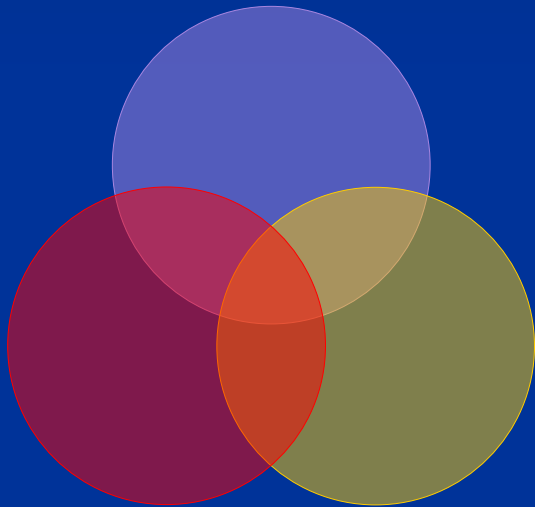
for increasing φ the potential decreases
towards zero !

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:

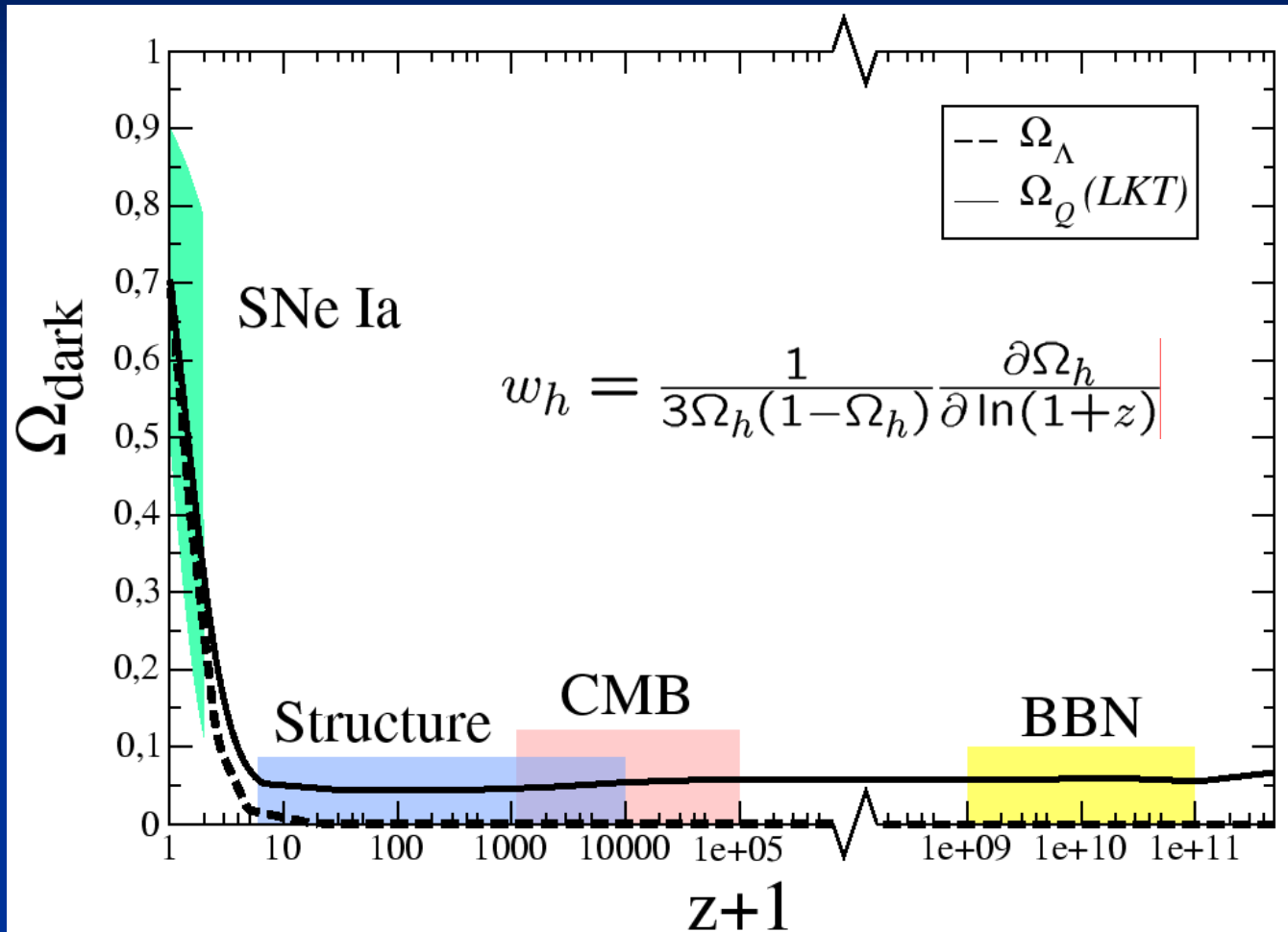
graviton

+

cosmon

observation will decide !

Time dependence of dark energy



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

Cosmic Attractors

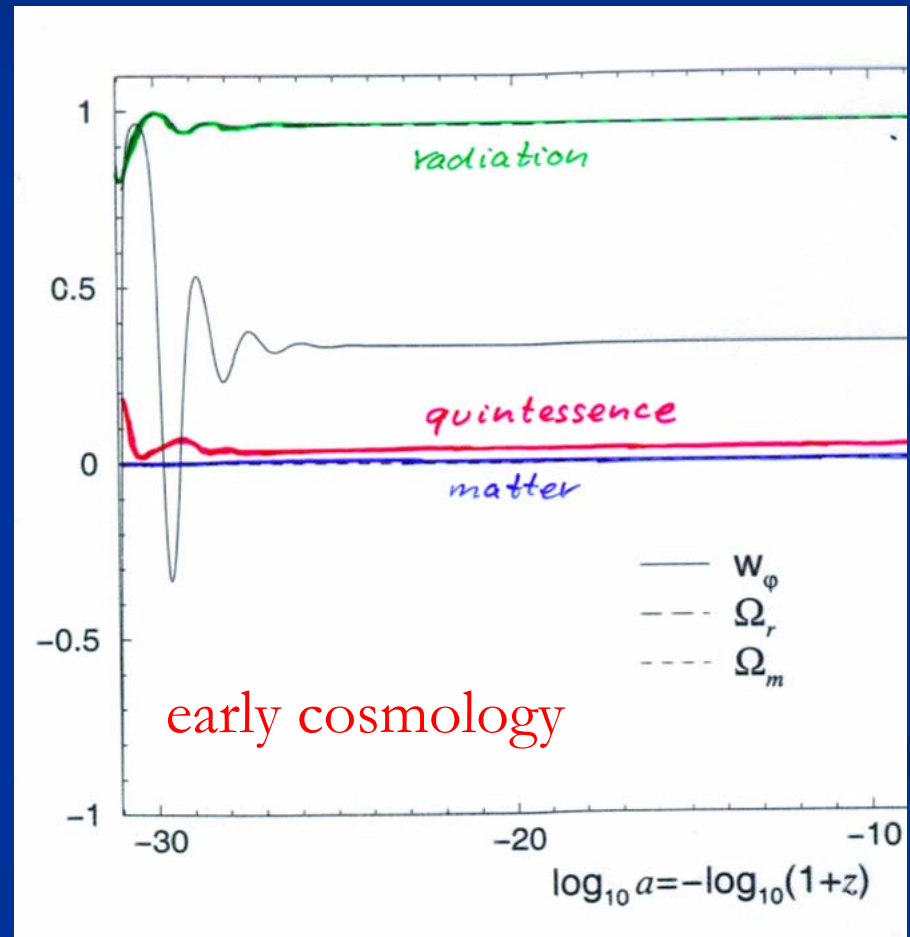
Solutions independent
of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim \text{const.}$

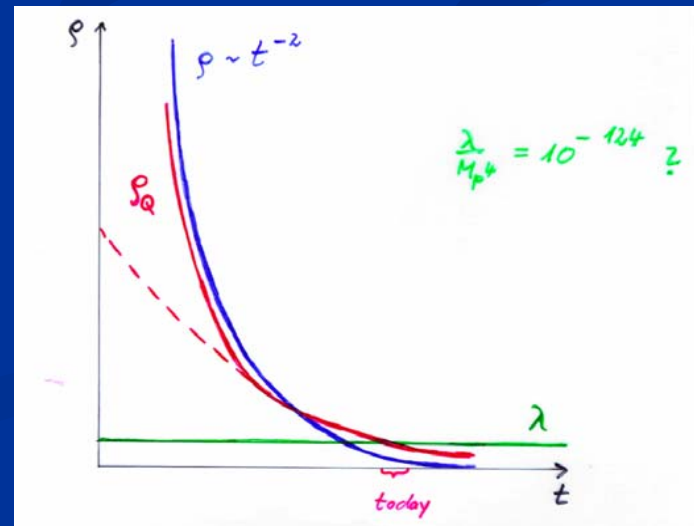
details depend on $V(\varphi)$
or kinetic term



exponential potential \longrightarrow
constant fraction in dark energy

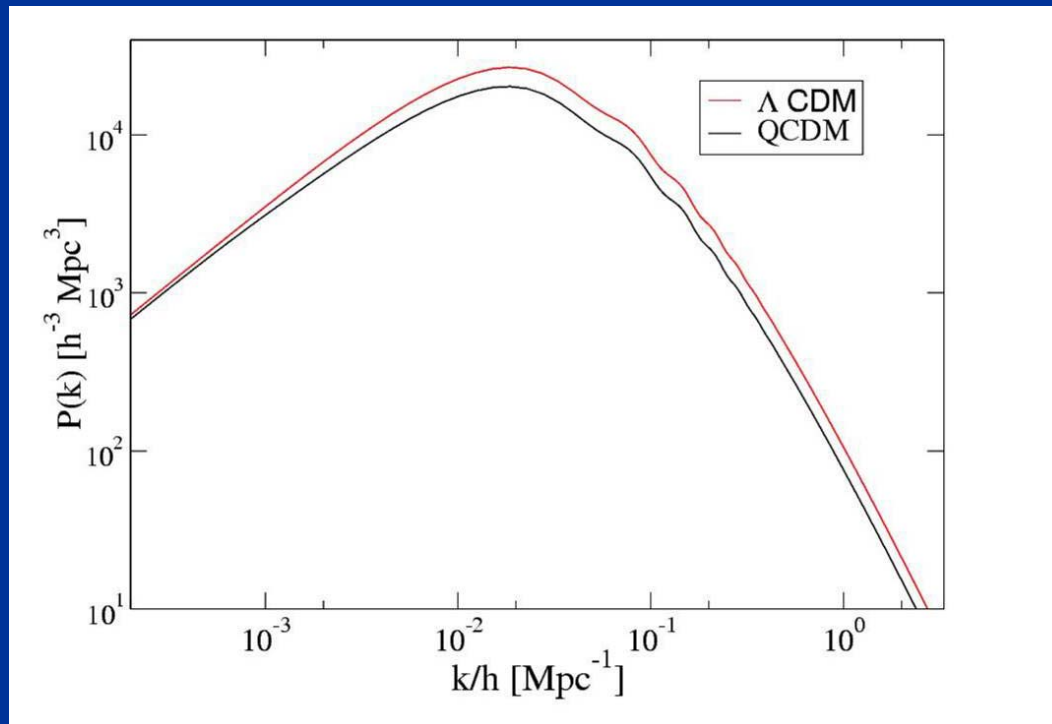
$$\Omega_h = 3/\alpha^2$$

can explain order
of magnitude
of dark energy !

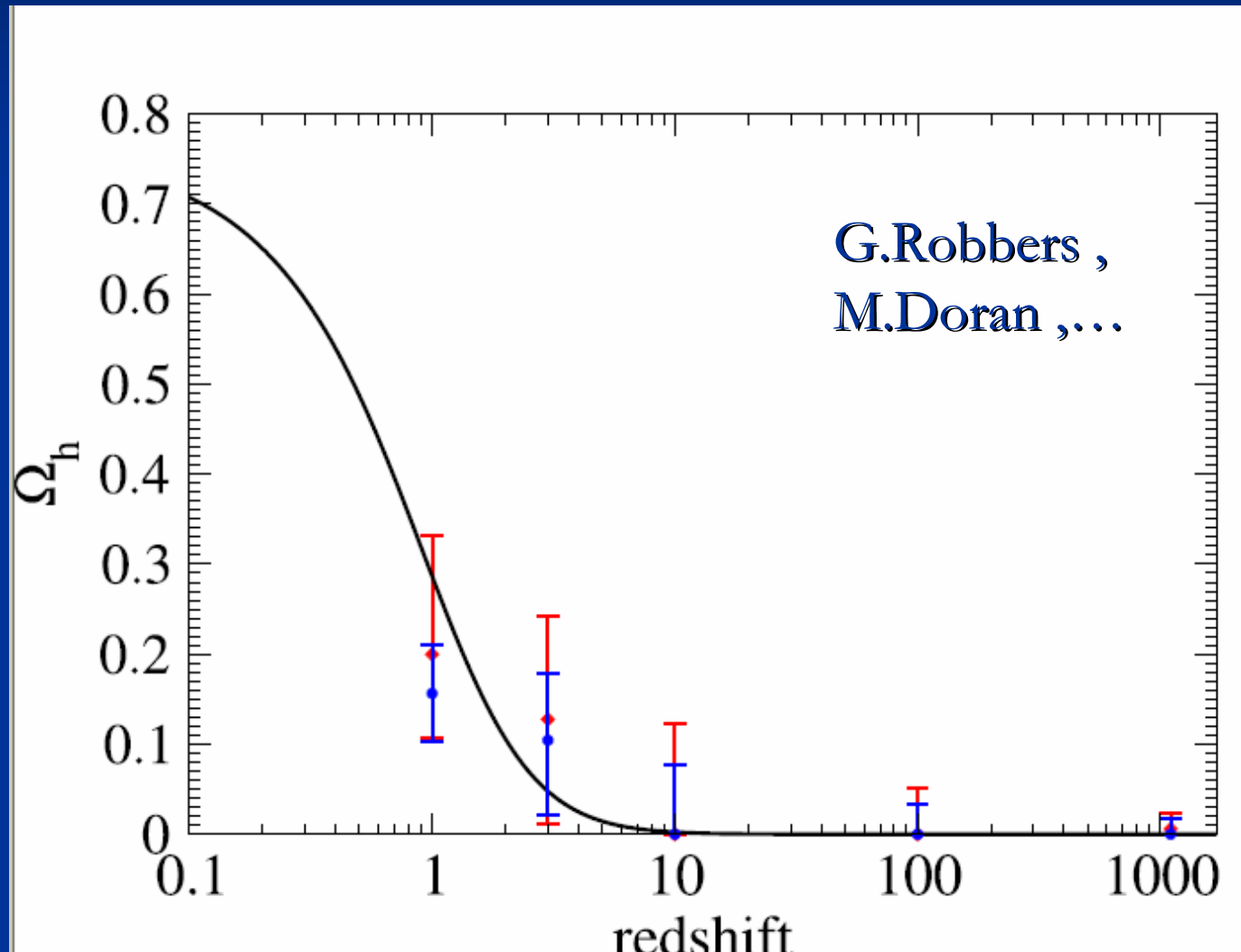


effects of early dark energy

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



observational bounds on Ω_h

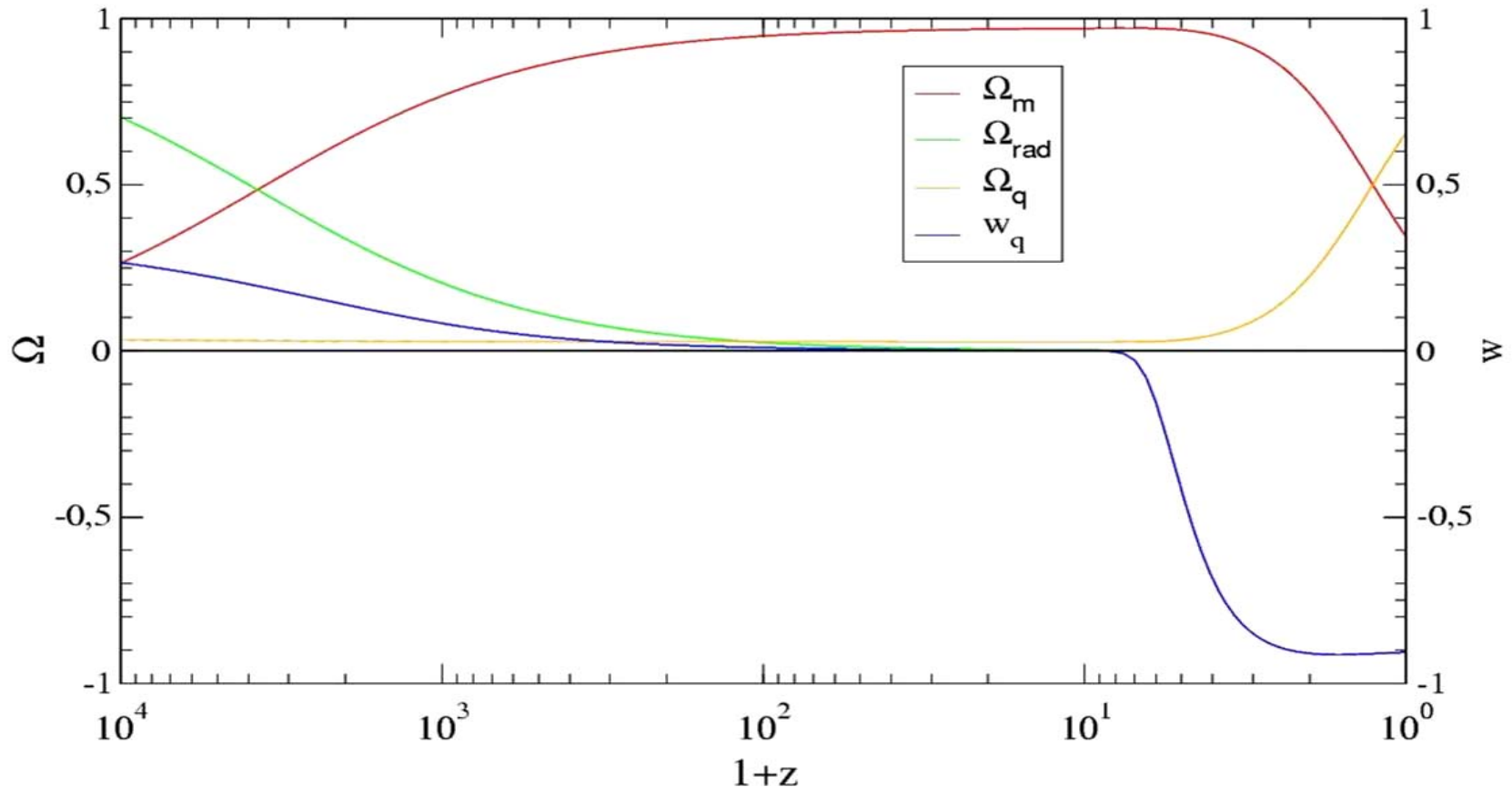


realistic quintessence

fraction in dark energy has to
increase in “recent time” !

Quintessence becomes important “today”

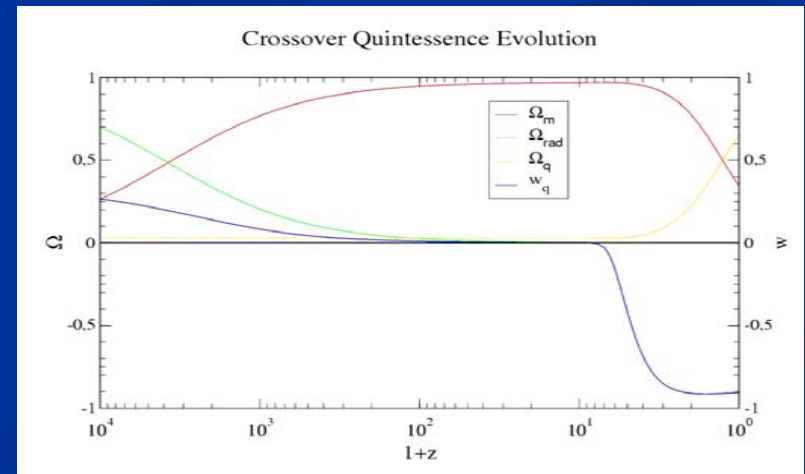
Crossover Quintessence Evolution



coincidence problem

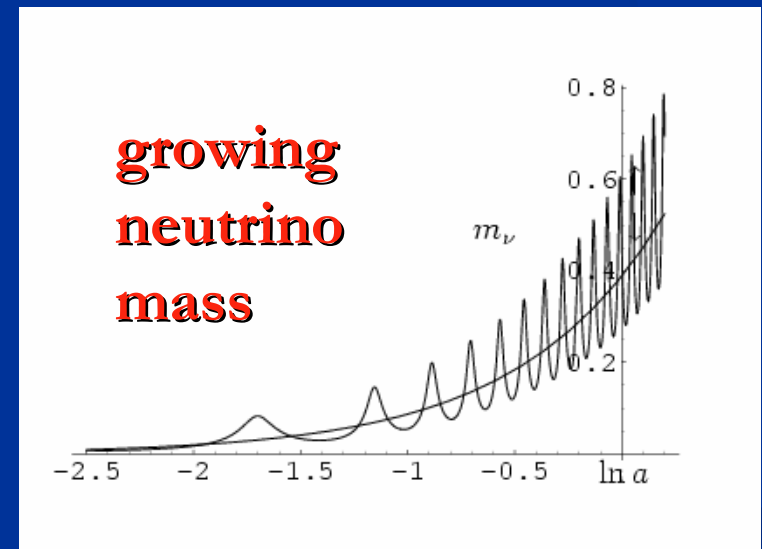
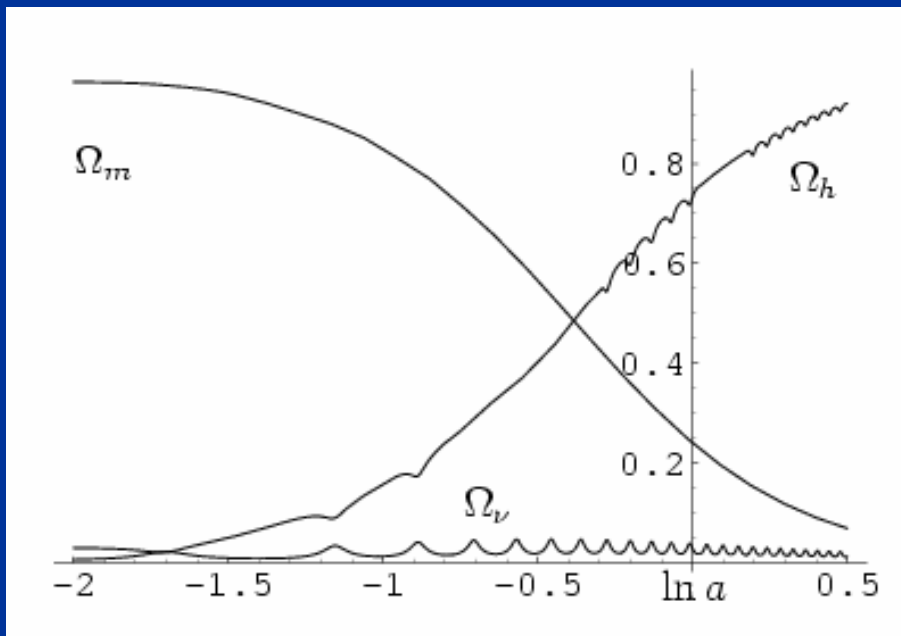
What is responsible for increase of Ω_h for $z < 6$?

Why now ?



**growing neutrino
quintessence**

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 !

connection between dark energy and neutrino properties

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.27 \left(\frac{\gamma m_\nu(t_0)}{eV} \right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density given by neutrino mass

present equation
of state given by
neutrino mass !

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

cosmological selection

- present value of dark energy density set by cosmological event :
neutrinos become non – relativistic
- not given by ground state properties !

basic ingredient :

cosmon coupling to neutrinos

Cosmon coupling to neutrinos

- can be large !

Fardon, Nelson, Weiner

- interesting effects for cosmology if neutrino mass is growing
- growing neutrinos can stop the evolution of the cosmon
- transition from early scaling solution to cosmological constant dominated cosmology

L. Amendola, M. Baldi, ...

dark energy fraction determined by neutrino mass

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

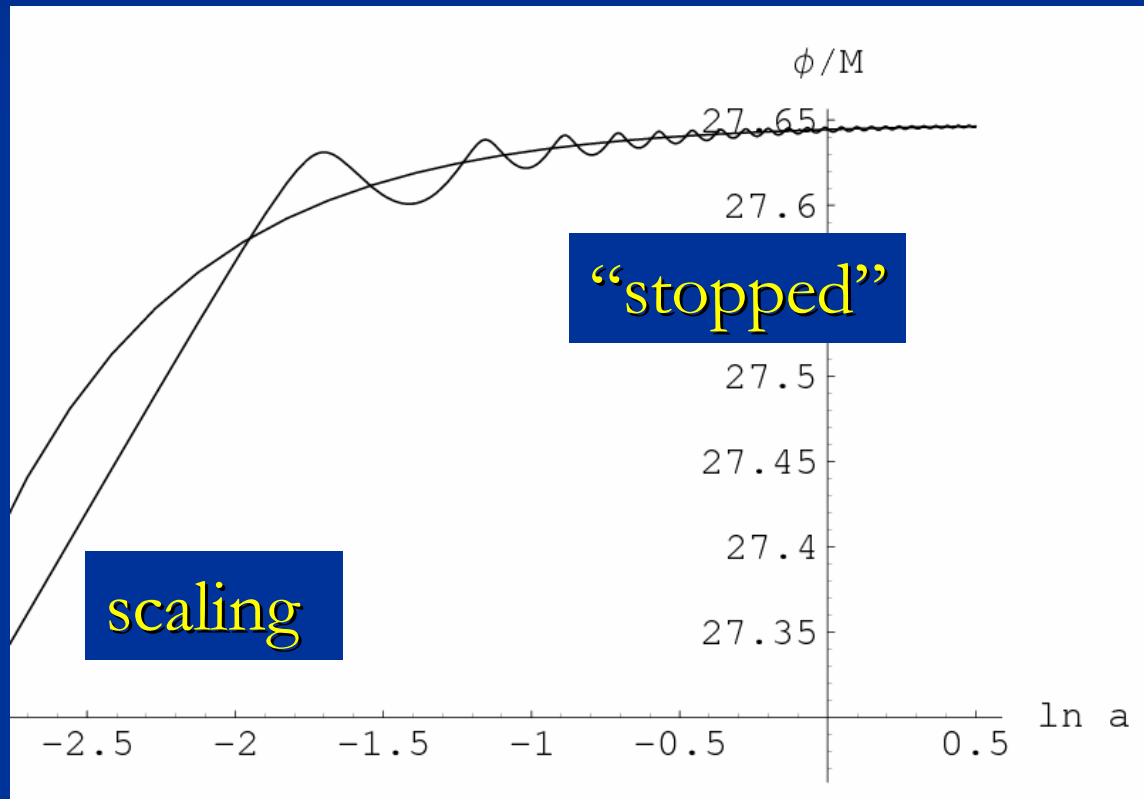
$$\gamma = -\frac{\beta}{\alpha}$$

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

cosmon evolution

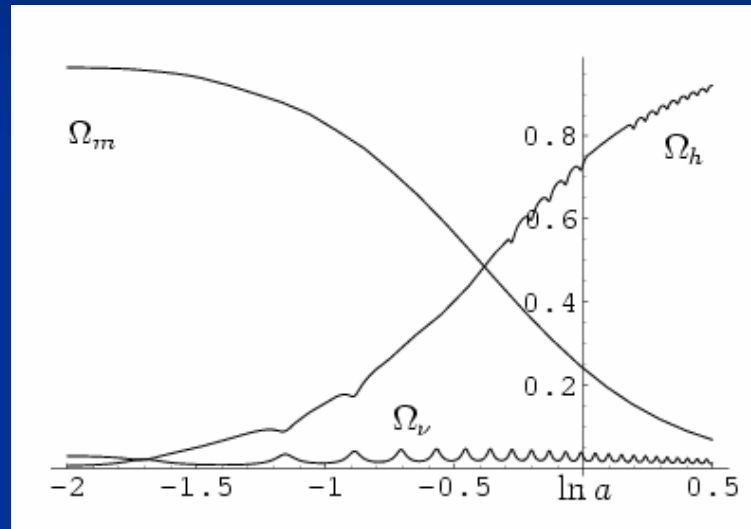


stopped scalar field
mimicks a
cosmological constant
(almost ...)

rough approximation for dark energy :

- before redshift 5-6 : scaling (dynamical)
- after redshift 5-6 : almost static
(cosmological constant)

crossover to dark energy dominated universe



starts at time when “neutrino force” becomes
important for the evolution of the cosmological field

cosmological selection !

growing neutrinos change cosmological evolution

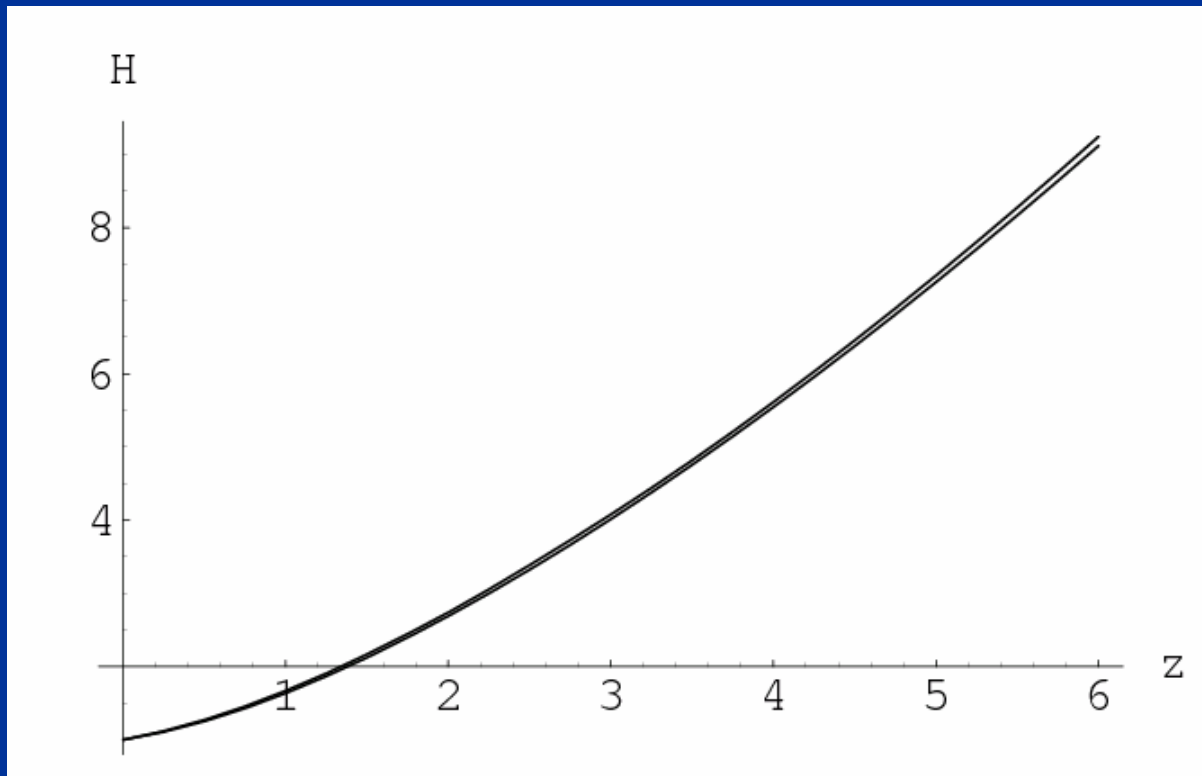
$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{\partial V}{\partial \varphi} + \frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu),$$
$$\beta(\varphi) = -M \frac{\partial}{\partial \varphi} \ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

modification of conservation equation for neutrinos

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

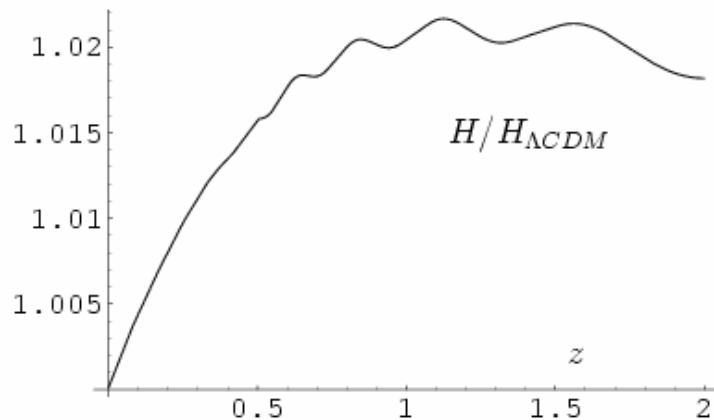
Hubble parameter

as compared to Λ CDM



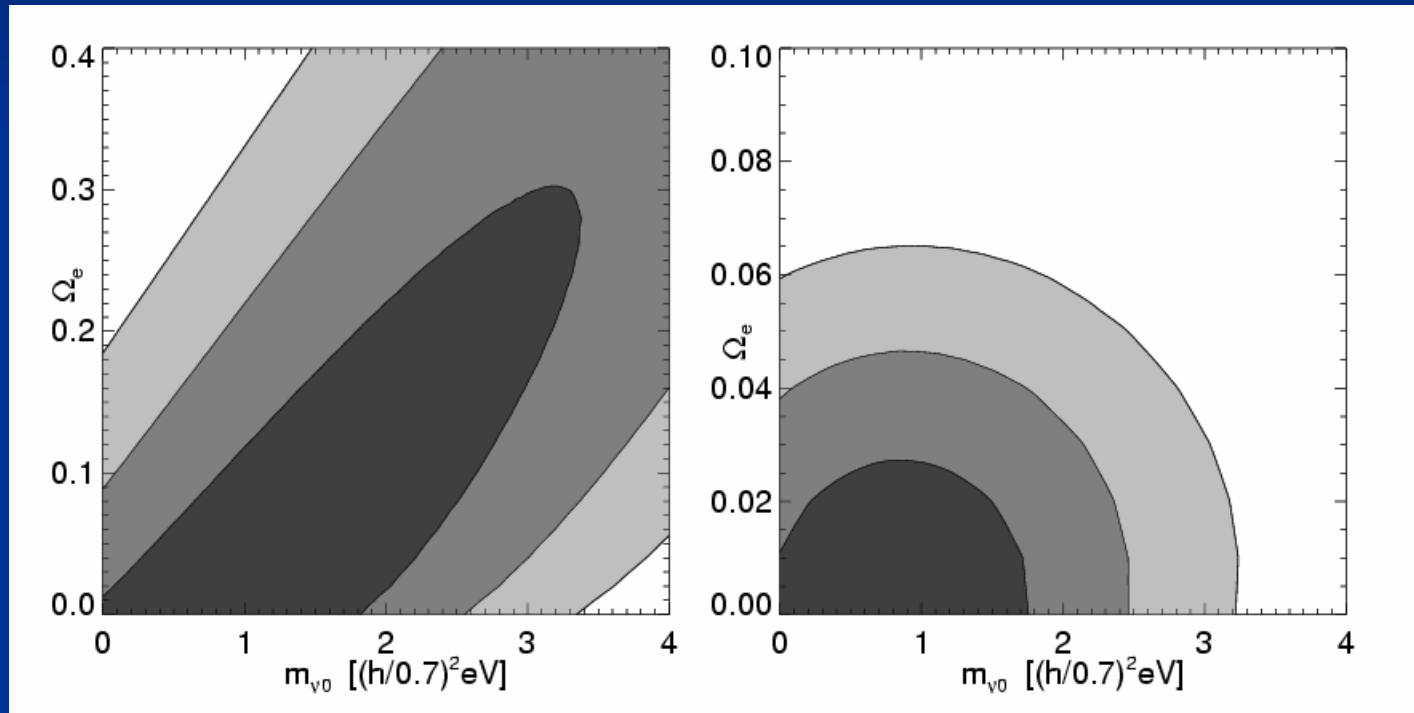
Hubble parameter ($z < z_c$)

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



only small
difference
from
 Λ CDM!

bounds on average neutrino mass



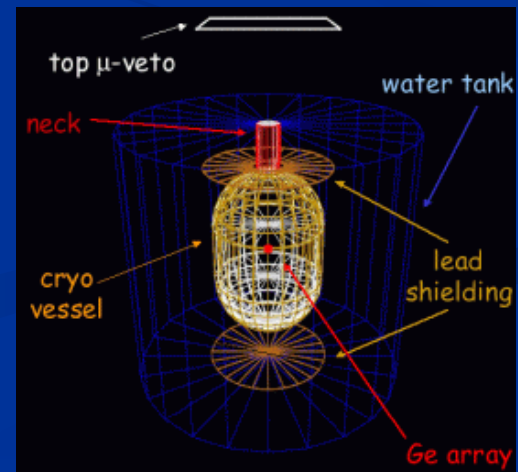
Looking Beyond Lambda with the Union Supernova Compilation

D. Rubin^{1,2}, E. V. Linder^{1,3}, M. Kowalski⁴, G. Aldering¹, R. Amanullah^{1,3}, K. Barbary^{1,2},
N. V. Connolly⁵, K. S. Dawson¹, L. Faccioli^{1,3}, V. Fadeyev⁶, G. Goldhaber^{1,2}, A. Goobar⁷,
I. Hook⁸, C. Lidman⁹, J. Meyers^{1,2}, S. Nobili⁷, P. E. Nugent¹, R. Pain¹⁰, S. Perlmutter^{1,2},
P. Ruiz-Lapuente¹¹, A. L. Spadafora¹, M. Strovink^{1,2}, N. Suzuki¹, and H. Swift^{1,2}

(Supernova Cosmology Project)

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)

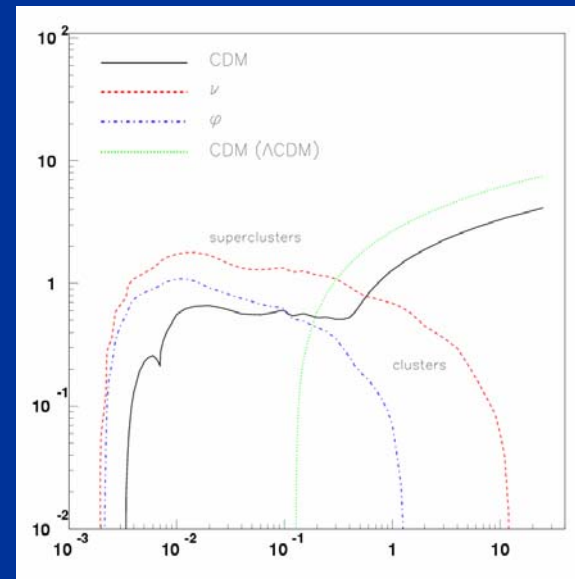
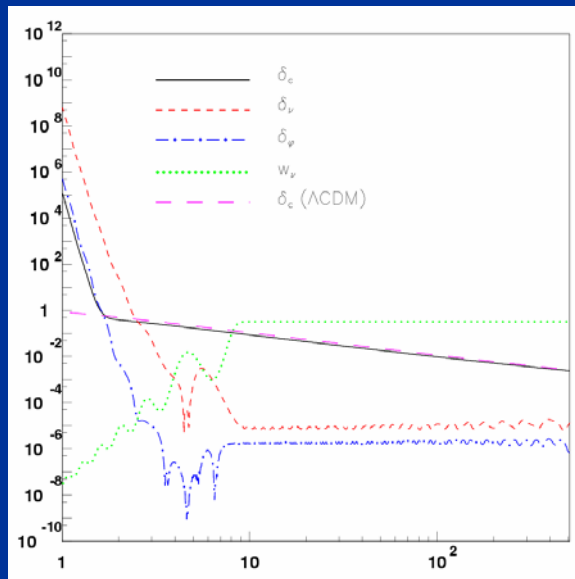


GERDA

neutrino fluctuations

neutrino structures become nonlinear at $z \sim 1$ 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 $\Omega_h(z) \iff H(z)$

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

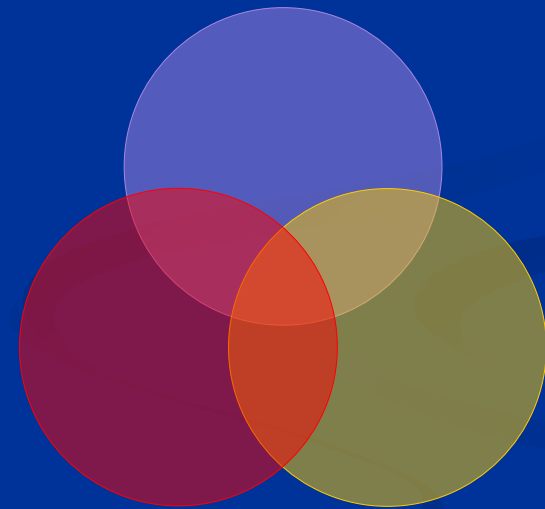
D) Possible coupling between Dark Energy and Dark Matter

Quintessence and time variation of fundamental constants

Generic prediction

Strength unknown

Strong, electromagnetic, weak interactions



gravitation

cosmodynamics

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,...

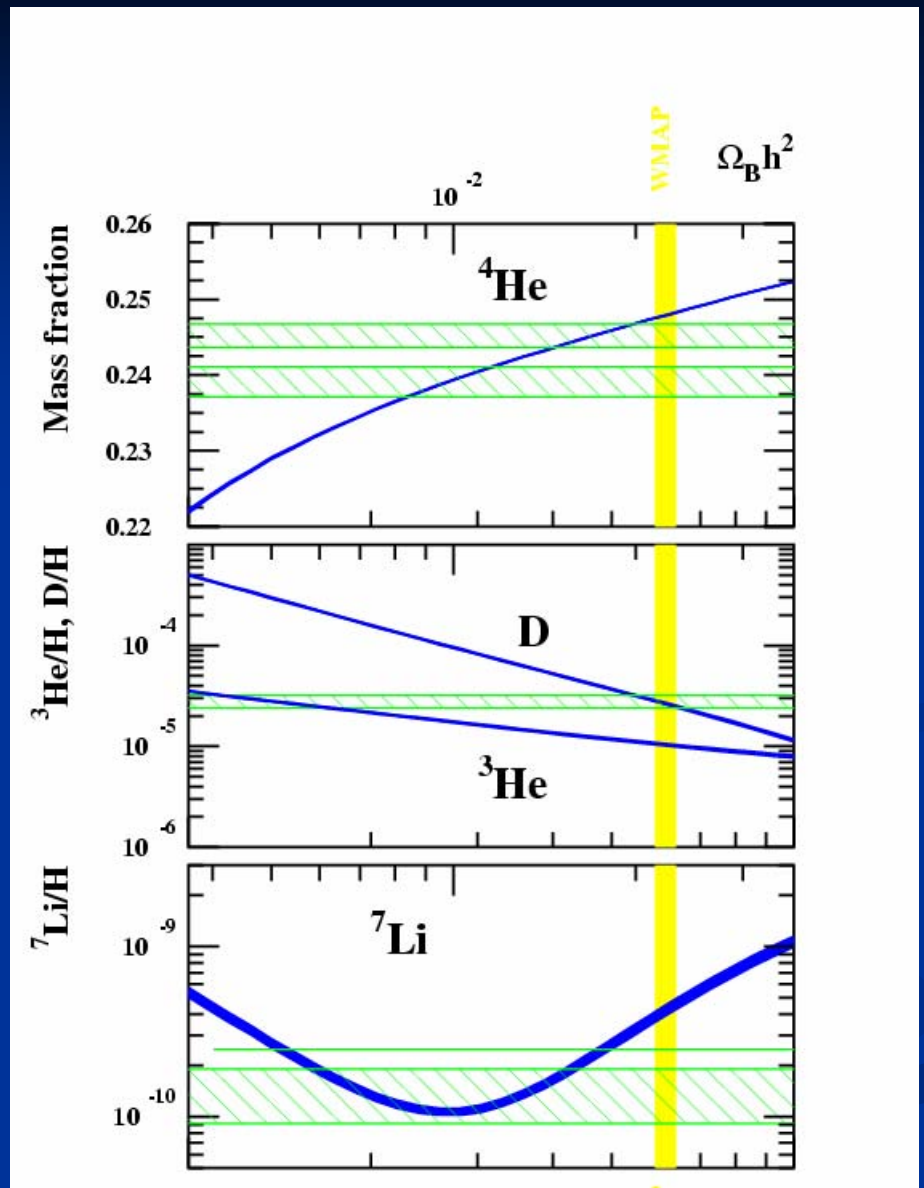


baryons :

the matter of stars and humans

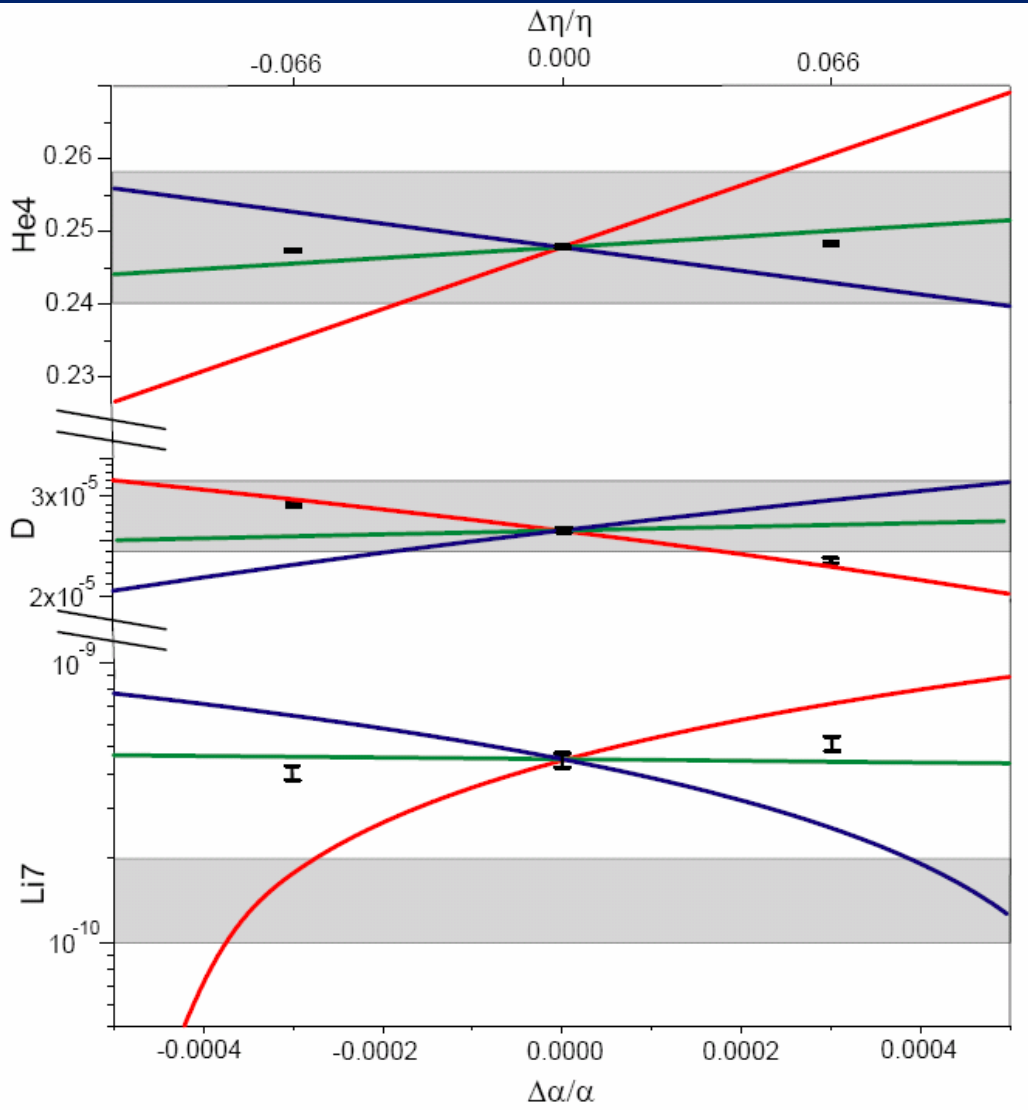
$$\Omega_b = 0.045$$

Abundancies of
primordial
light elements
from
nucleosynthesis



primordial abundances for three GUT models

He



D

Li

present
observations :
 1σ

T.Dent,
S.Stern,...

three GUT models

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

$\Delta\alpha/\alpha \approx 4 \cdot 10^{-4}$ 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

- o $\Omega_h = 0.75$
- o Q/Λ : dynamical und static dark energy will be distinguishable
- o growing neutrino mass can explain why now problem
- o 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

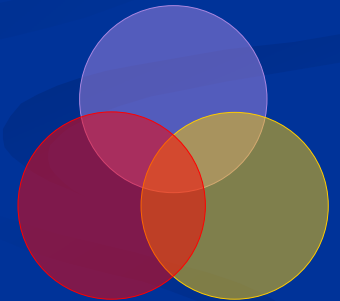
graviton

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 $\sim M^{-2}$)

- Composition dependence

→ violation of equivalence principle

- Quintessence: connected to time variation of fundamental couplings

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

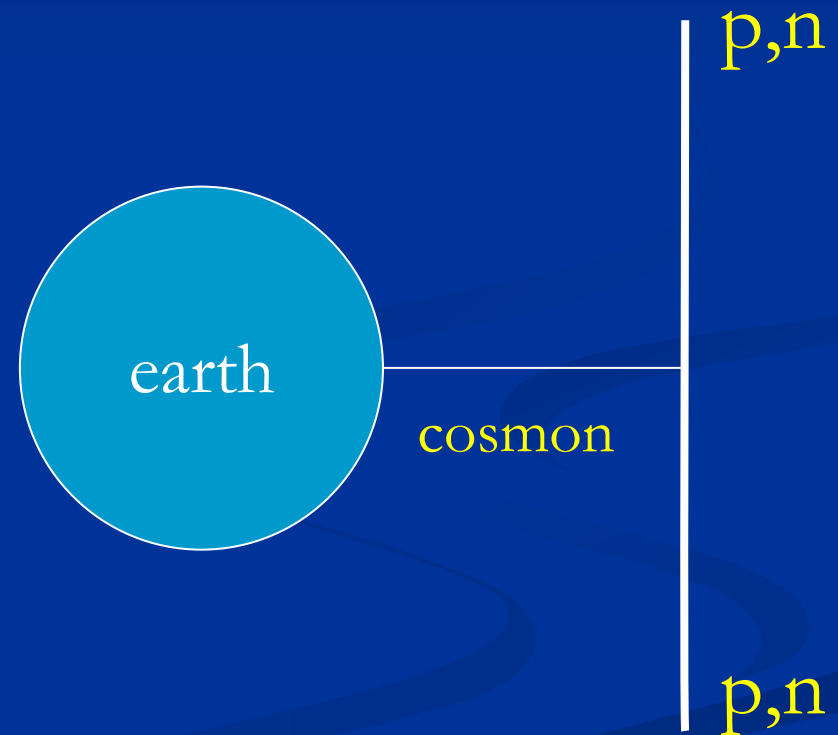
Violation of equivalence principle

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

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) :

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

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

$$\eta = \Delta a / 2a$$

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

- o $\Omega_h = 0.75$
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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,...)
- $M_p \sim \chi$, $m_{\text{proton}} \sim \chi$, $\Lambda_{\text{QCD}} \sim \chi$, $M_W \sim \chi$, ...
- 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

kinetic energy

$$\rho = T + V$$

energy density

$$T = \frac{1}{2} \dot{\phi}^2$$

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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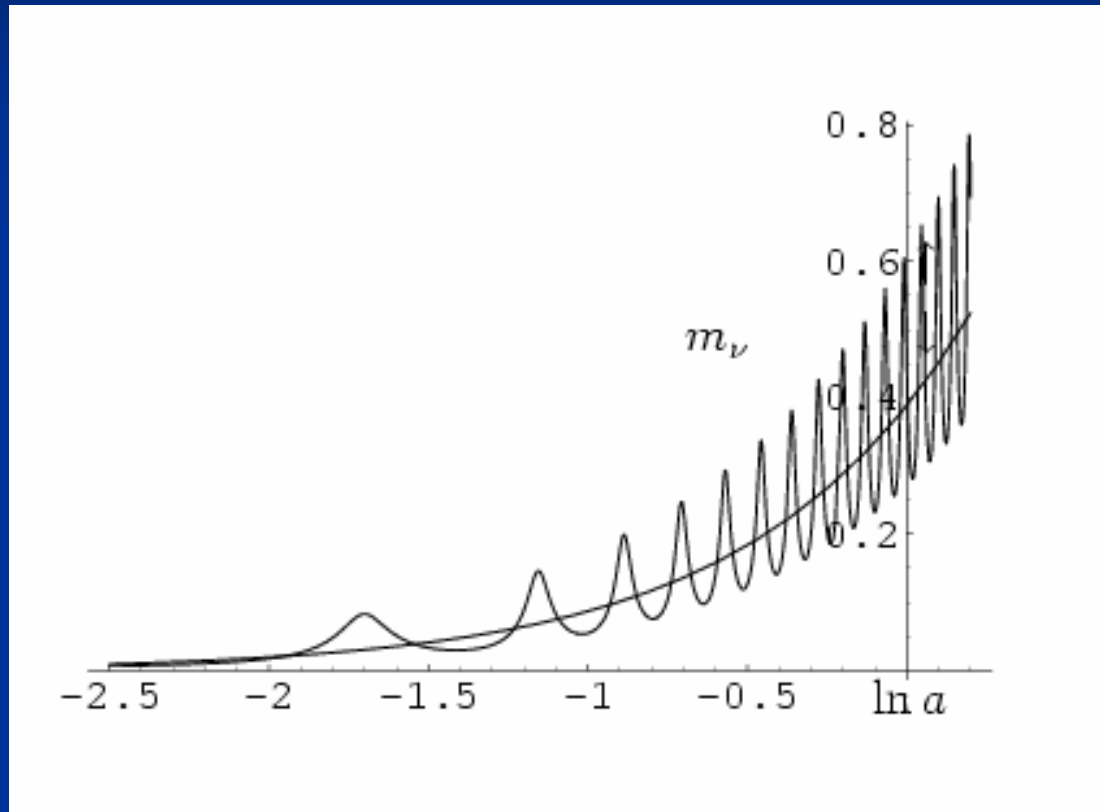
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oscillating neutrino mass



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 $z \sim 1$ for supercluster scales

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

- stable neutrino-cosmon lumps exist

N.Brouzakis , N.Tetradis , ...