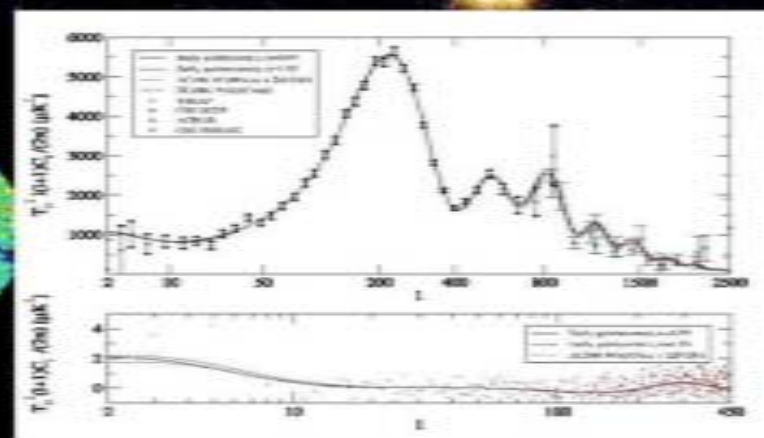
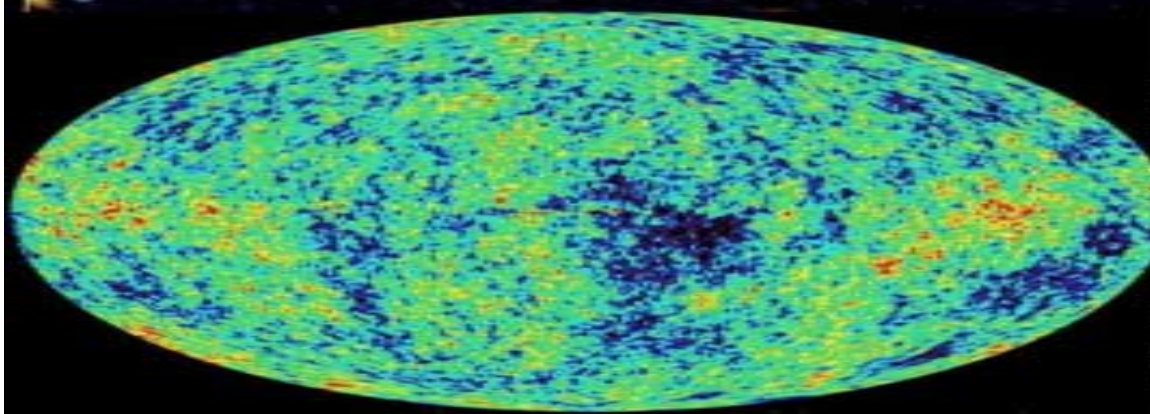


Dark Energy- a cosmic mystery



Dark Energy – a cosmic mystery

C.Wetterich

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

**What is our Universe
made of ?**

Quintessence !

fire , air,
water, soil !



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

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

Composition of the universe

$$\Omega_b = 0.045$$

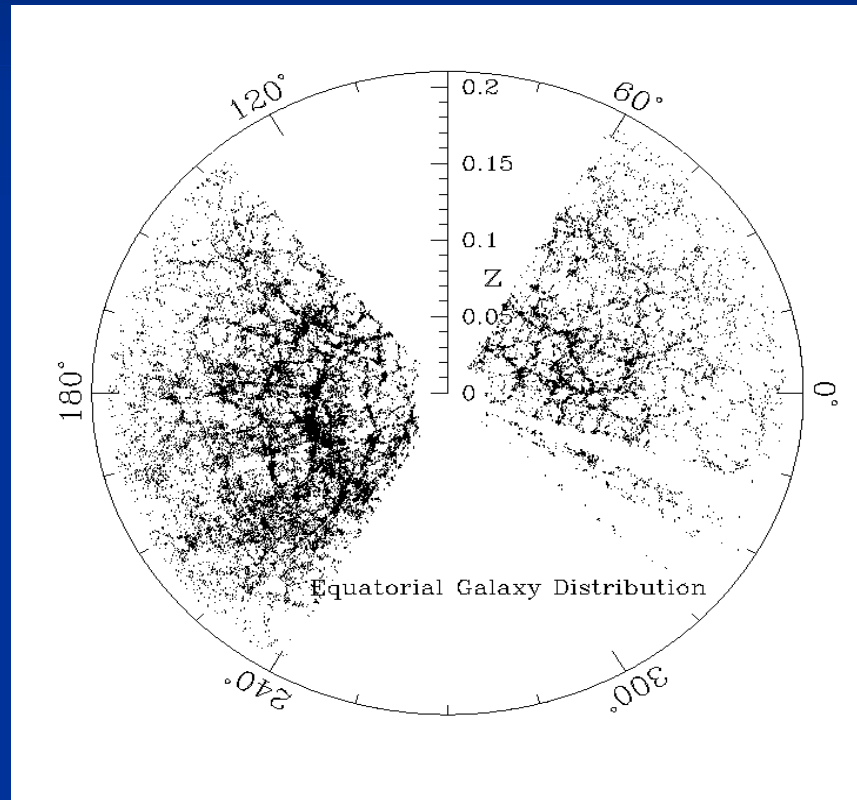
$$\Omega_{dm} = 0.225$$

$$\Omega_h = 0.73$$

baryons

SDSS

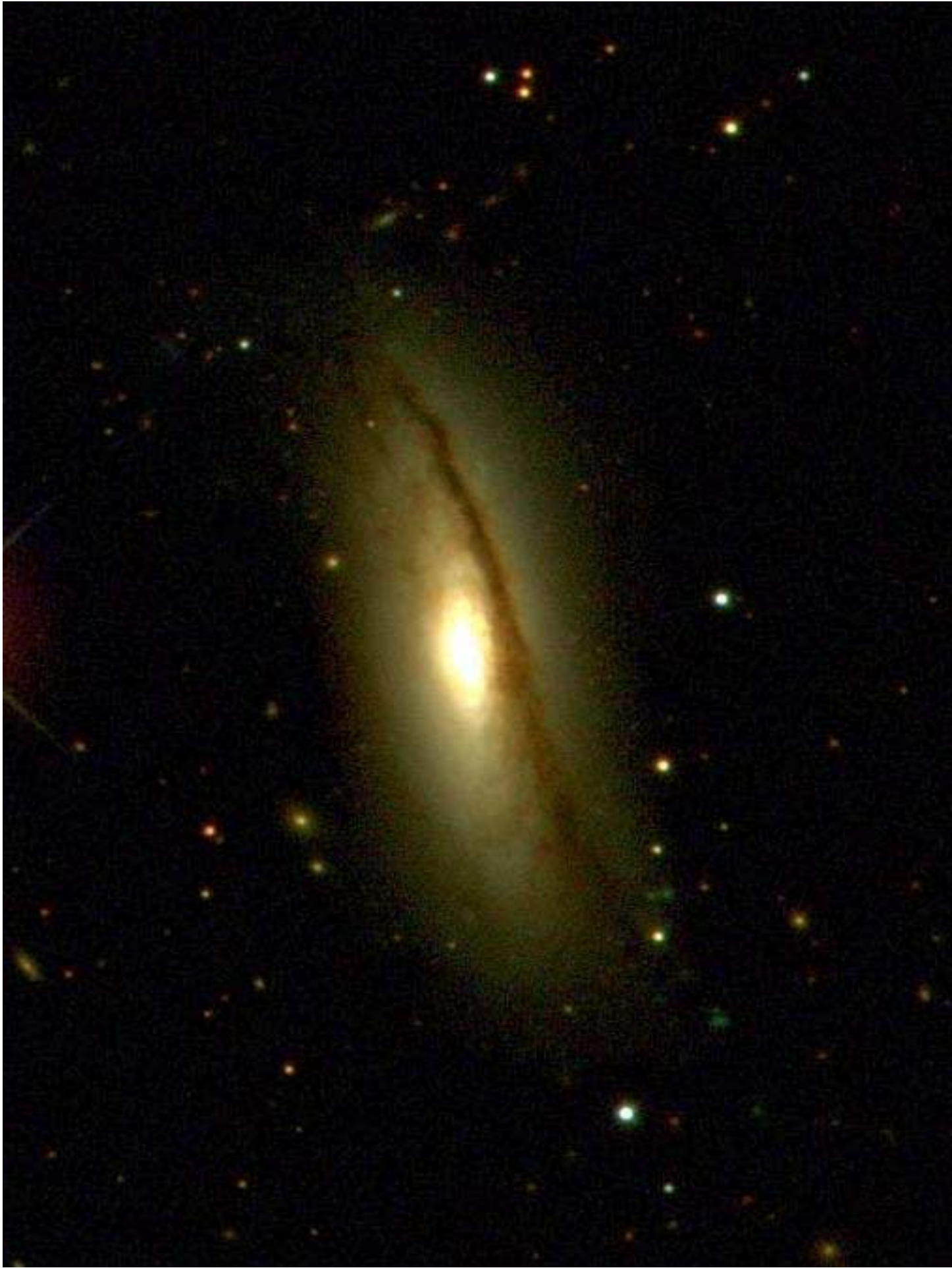
~60,000 of
>300,000
galaxies



- dust
- $\Omega_b = 0.045$
- only 5 percent of our universe consist of known matter !

This is a deep-field astronomical image of the Abell 2255 galaxy cluster. The image shows a vast field of galaxies, including many bright, yellowish-white elliptical galaxies and several smaller, bluer galaxies. Some galaxies appear as thin, curved arcs, likely due to gravitational lensing. The background is a deep black, punctuated by the light of distant celestial objects. In the bottom-left corner, there is white text identifying the cluster and its distance.

Abell 2255 Cluster
~300 Mpc

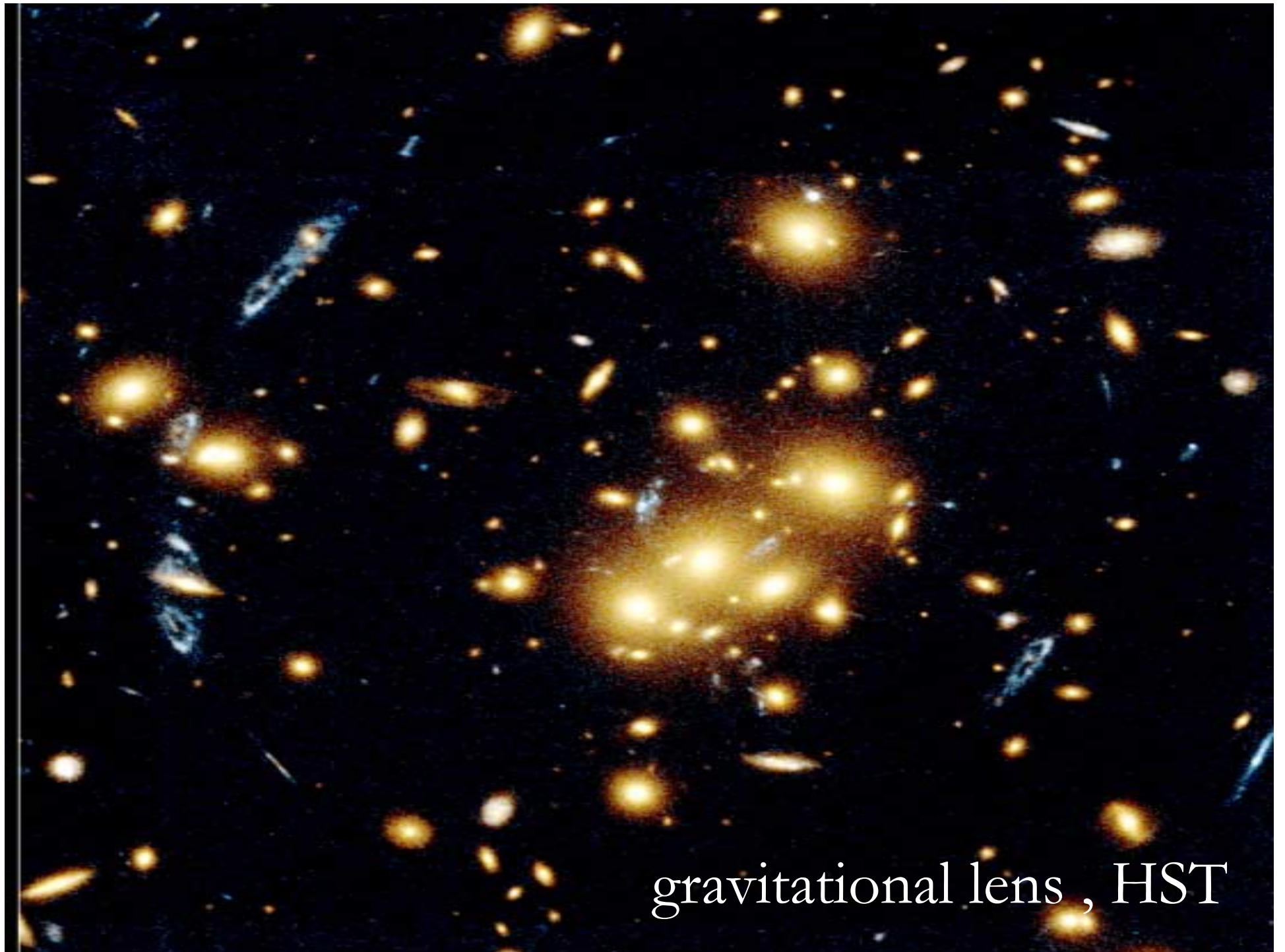


$$\Omega_b = 0.045$$

from nucleosynthesis,
cosmic background radiation

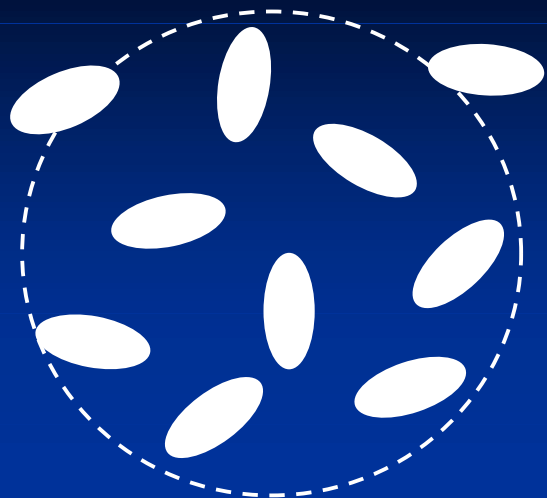
Dark Matter

- $\Omega_m = 0.27$ 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

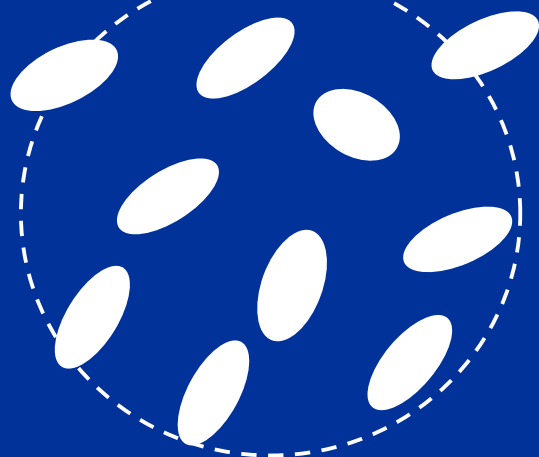


gravitational lens , HST

N Galaxies



NOT LENSED (randomly
aligned)



LENSED

Shear estimate

Averaged shape



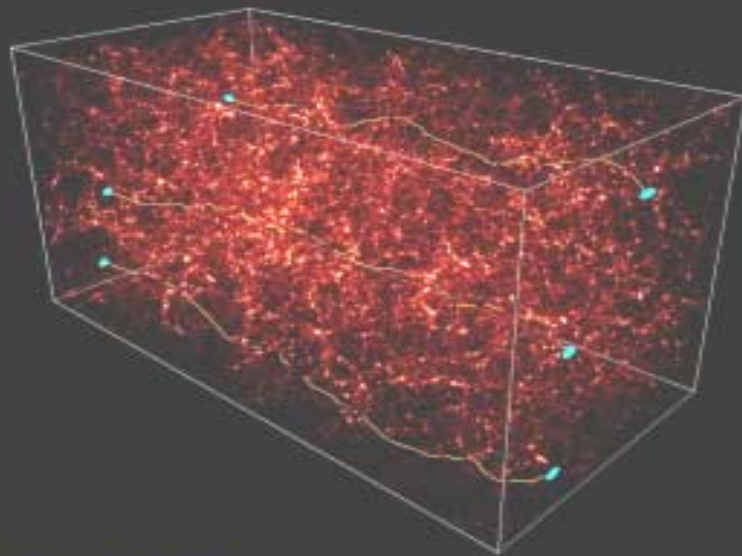
$$\langle e \rangle = 0$$



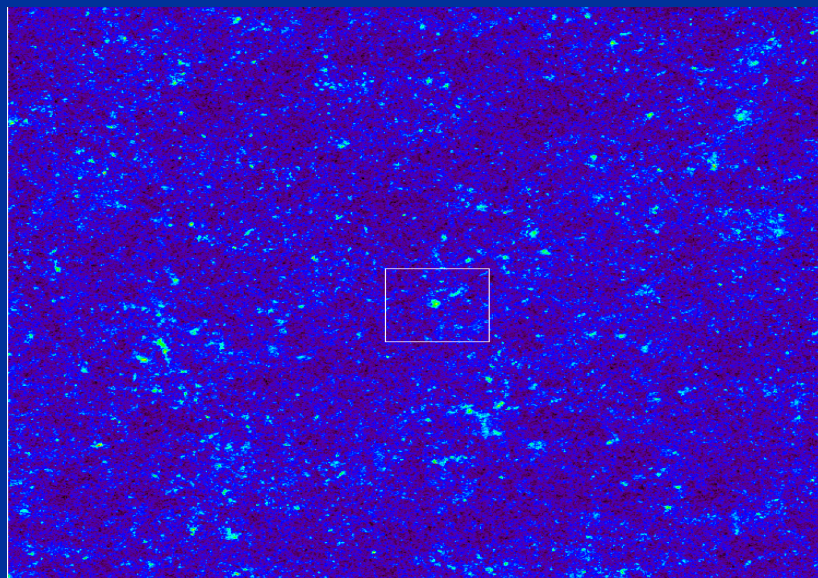
$$\langle e \rangle \approx \gamma$$

Waerbeke

DEFLECTION OF LIGHT RAYS CROSSING THE UNIVERSE, EMITTED BY DISTANT GALAXIES

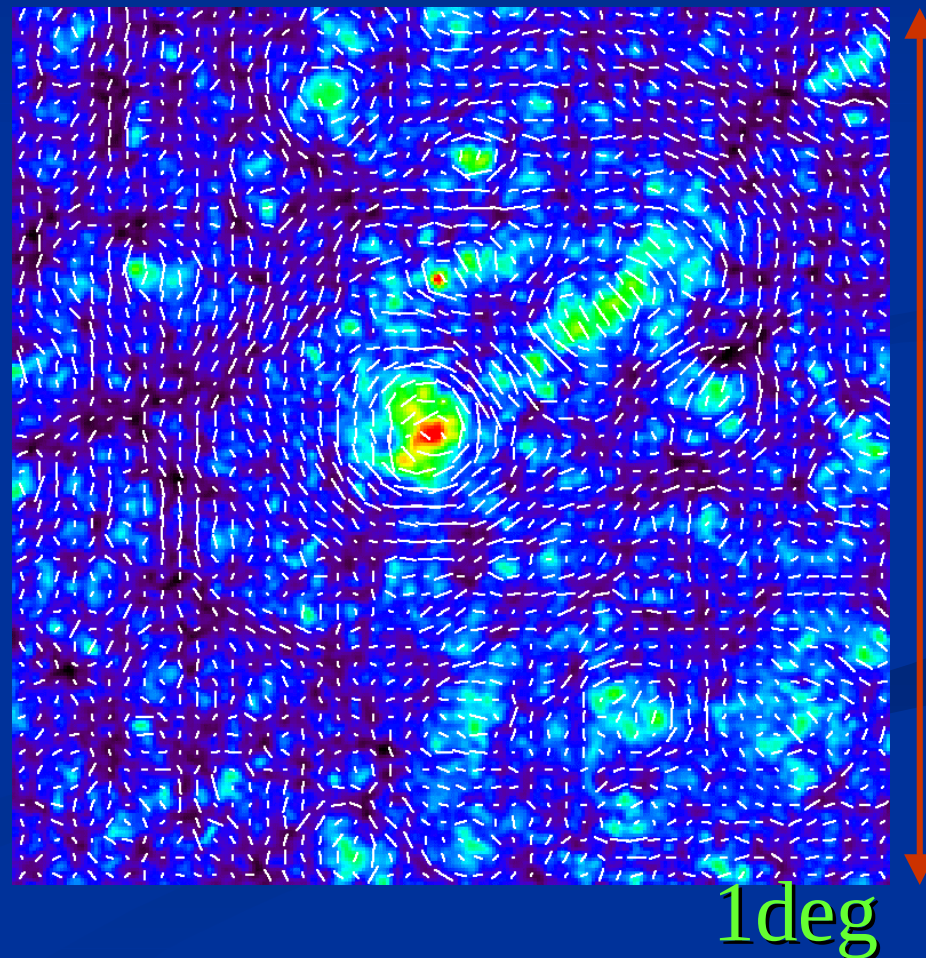


EMULATED COURTESY-HUBBARD, E. COLEMAN, IAP

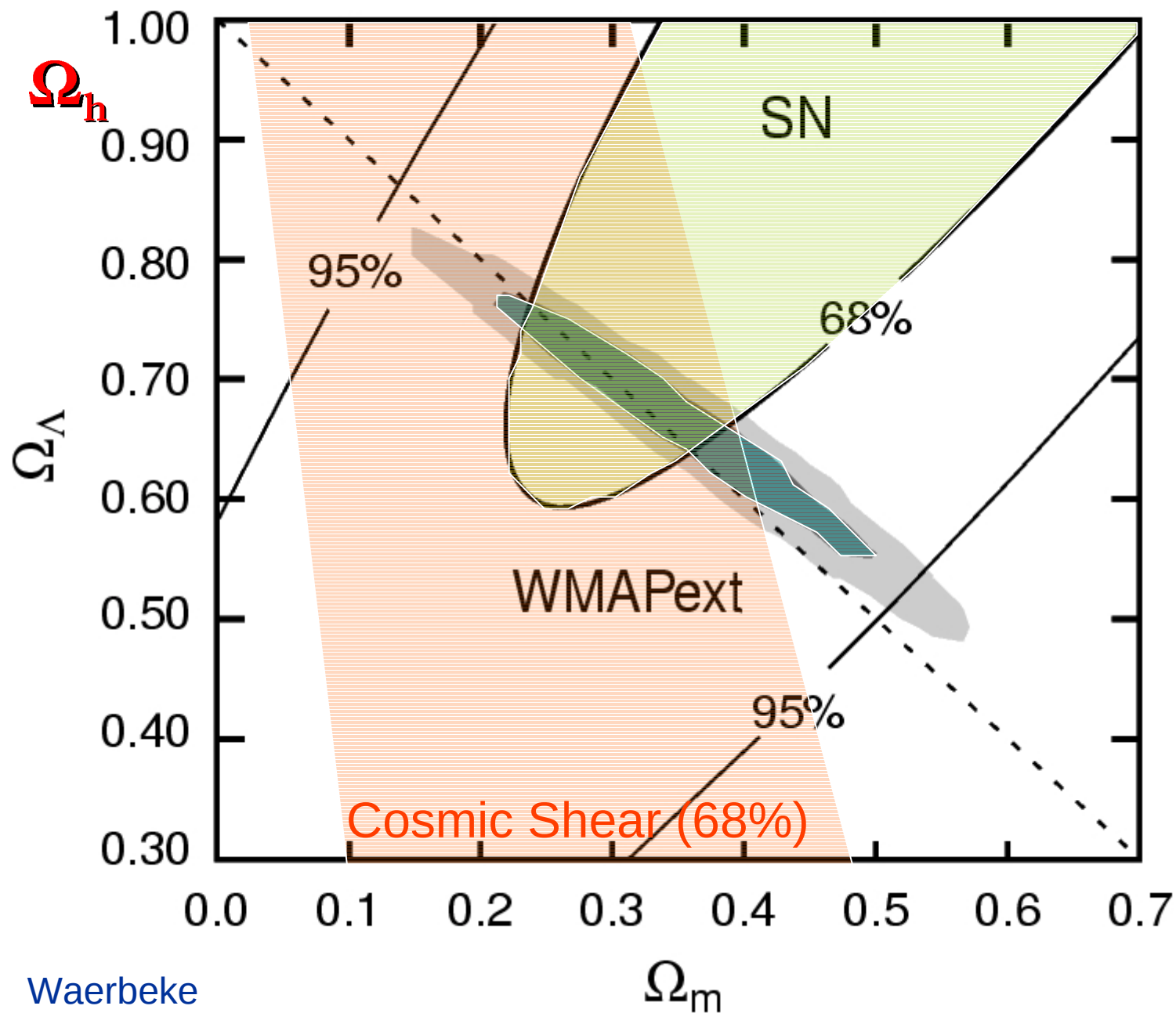


Waerbeke

cosmological weak gravitational lensing



Ranges for Ω_m , Ω_h from WMAPext, SNIa and Cosmic Shear



spatially flat universe

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

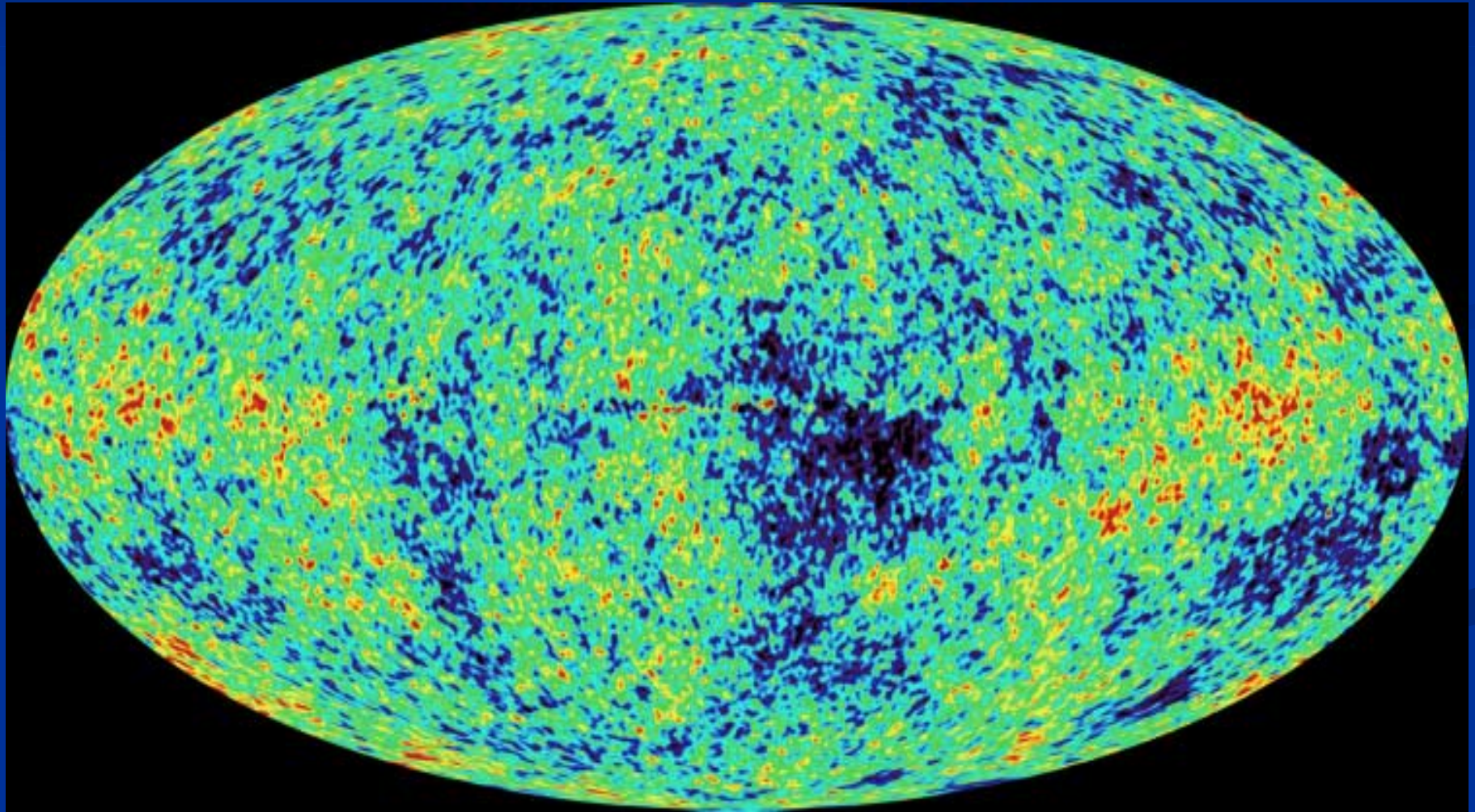
- theory (inflationary universe)

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

- observation (WMAP)

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

picture of the big bang



Wilkinson Microwave Anisotropy Probe

*A partnership between
NASA/GSFC and Princeton*

Science Team:

NASA/GSFC

Chuck Bennett (PI)

Michael Greason

Bob Hill

Gary Hinshaw

Al Kogut

Michele Limon

Nils Odegard

Janet Weiland

Ed Wollack

Brown

Greg Tucker

UCLA

Ned Wright

UBC

Mark Halpern

Chicago

Stephan Meyer

Princeton

Chris Barnes

Norm Jarosik

Eiichiro Komatsu

Michael Nolte

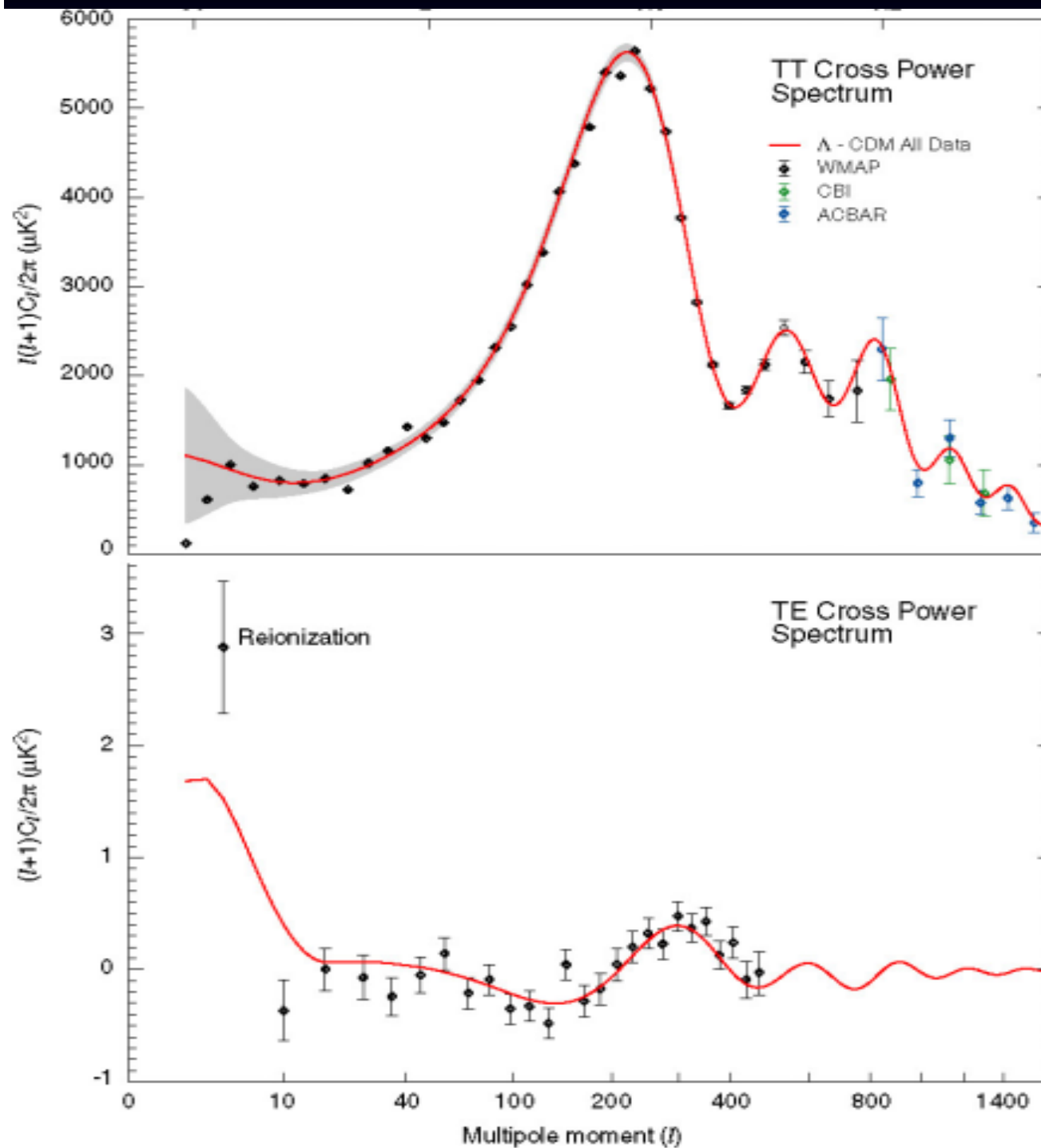
Lyman Page

Hiranya Peiris

David Spergel

Licia Verde





mean values

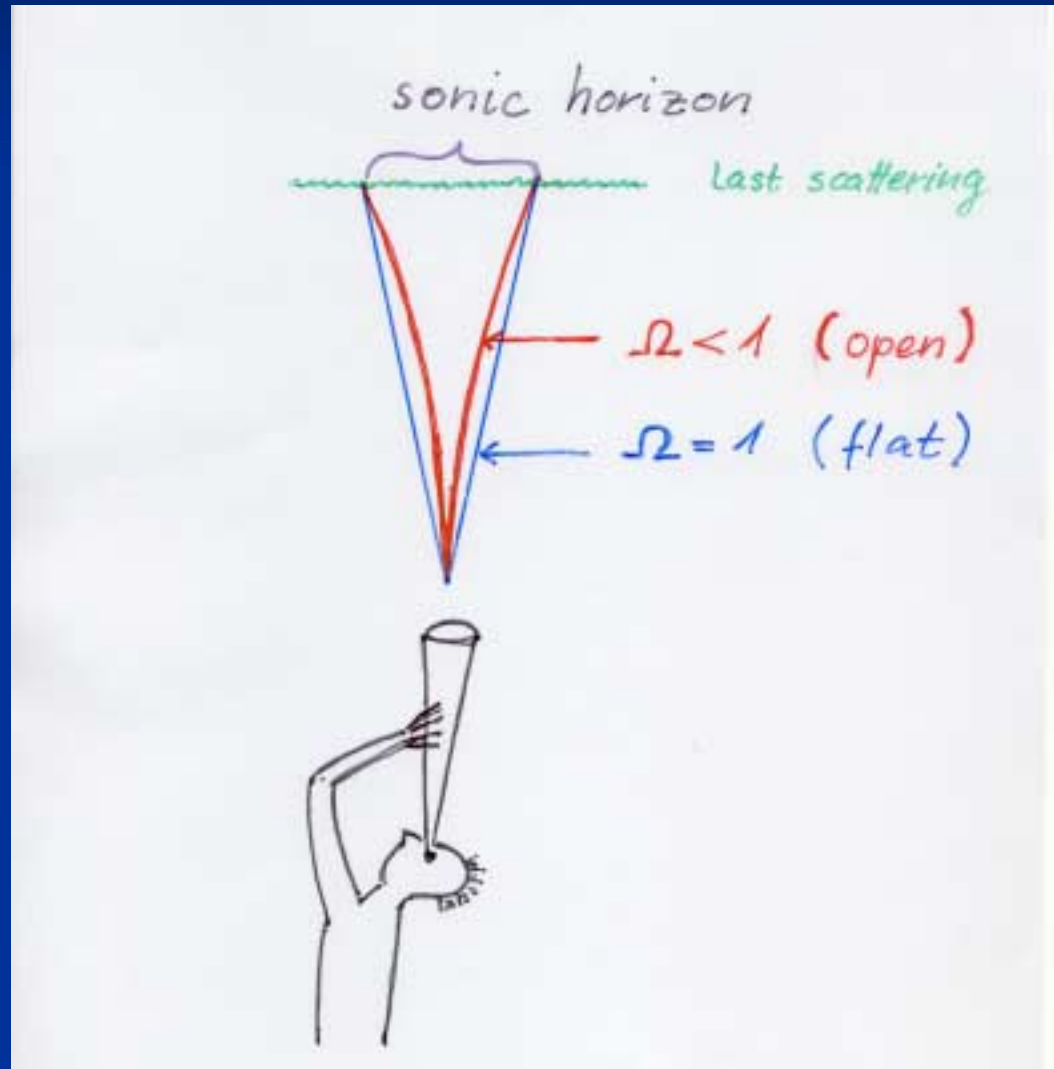
$$\Omega_{\text{tot}} = 1.02$$

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

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

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

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



Dark Energy

$$\Omega_m + X = 1$$

$$\Omega_m : 30\%$$

$$\Omega_h : 70\%$$

Dark Energy

h : homogenous , often Ω_Λ instead of Ω_h

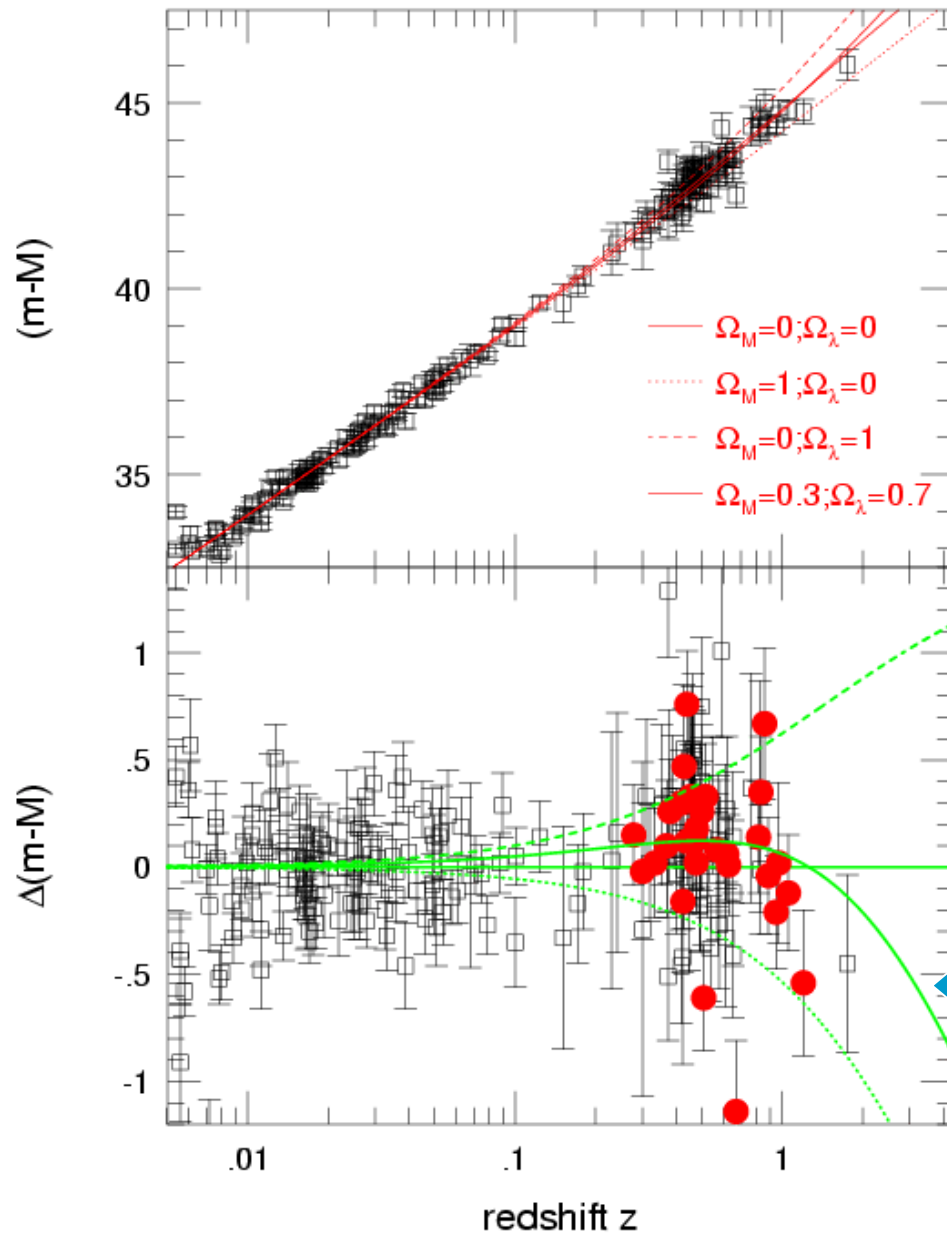
Dark Energy :
homogeneously
distributed

Dark Energy :

prediction:

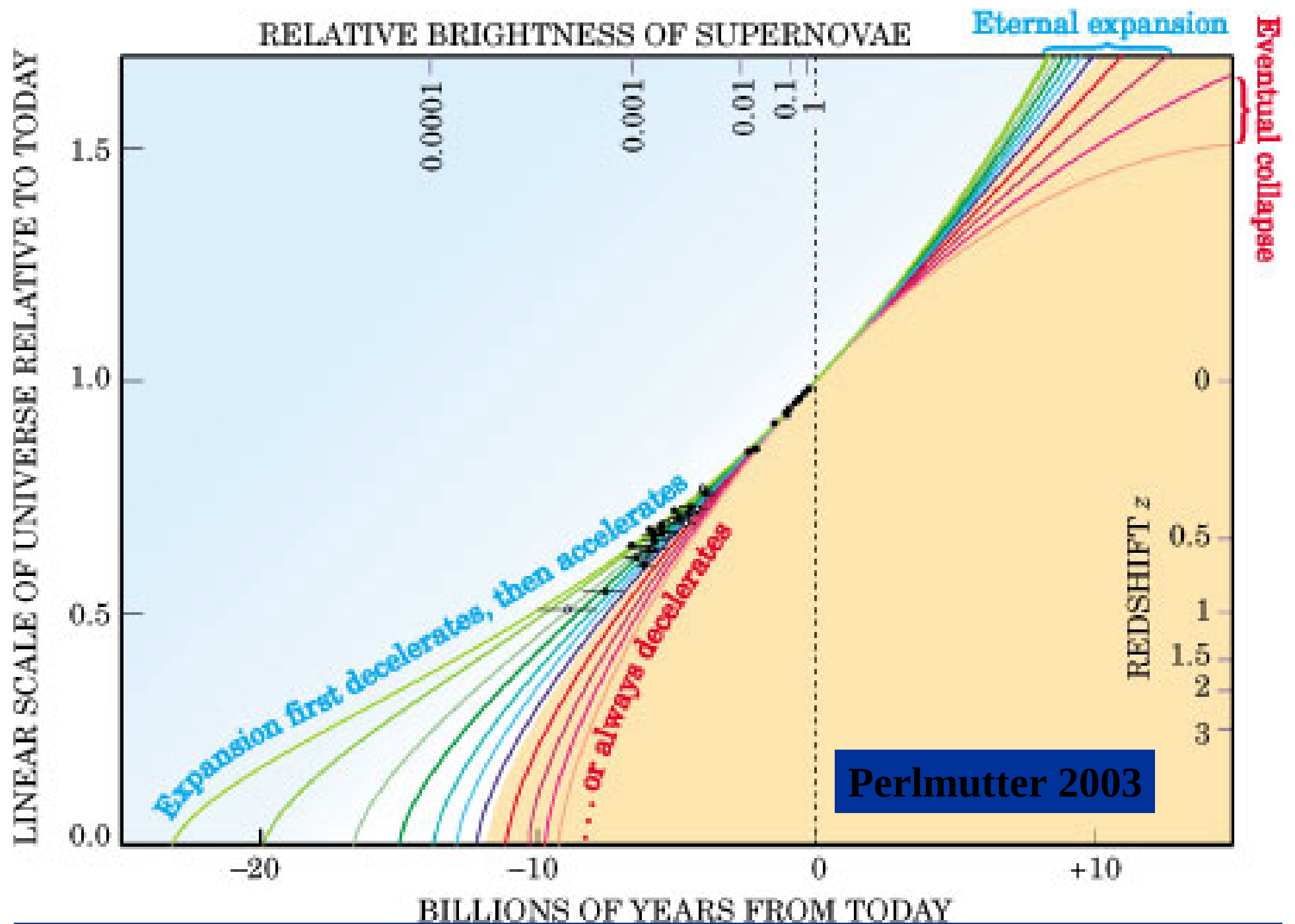
*The expansion
of the Universe
accelerates today !*

Supernova cosmology



$\Omega_h=0.7$

Tonry et al. 2003



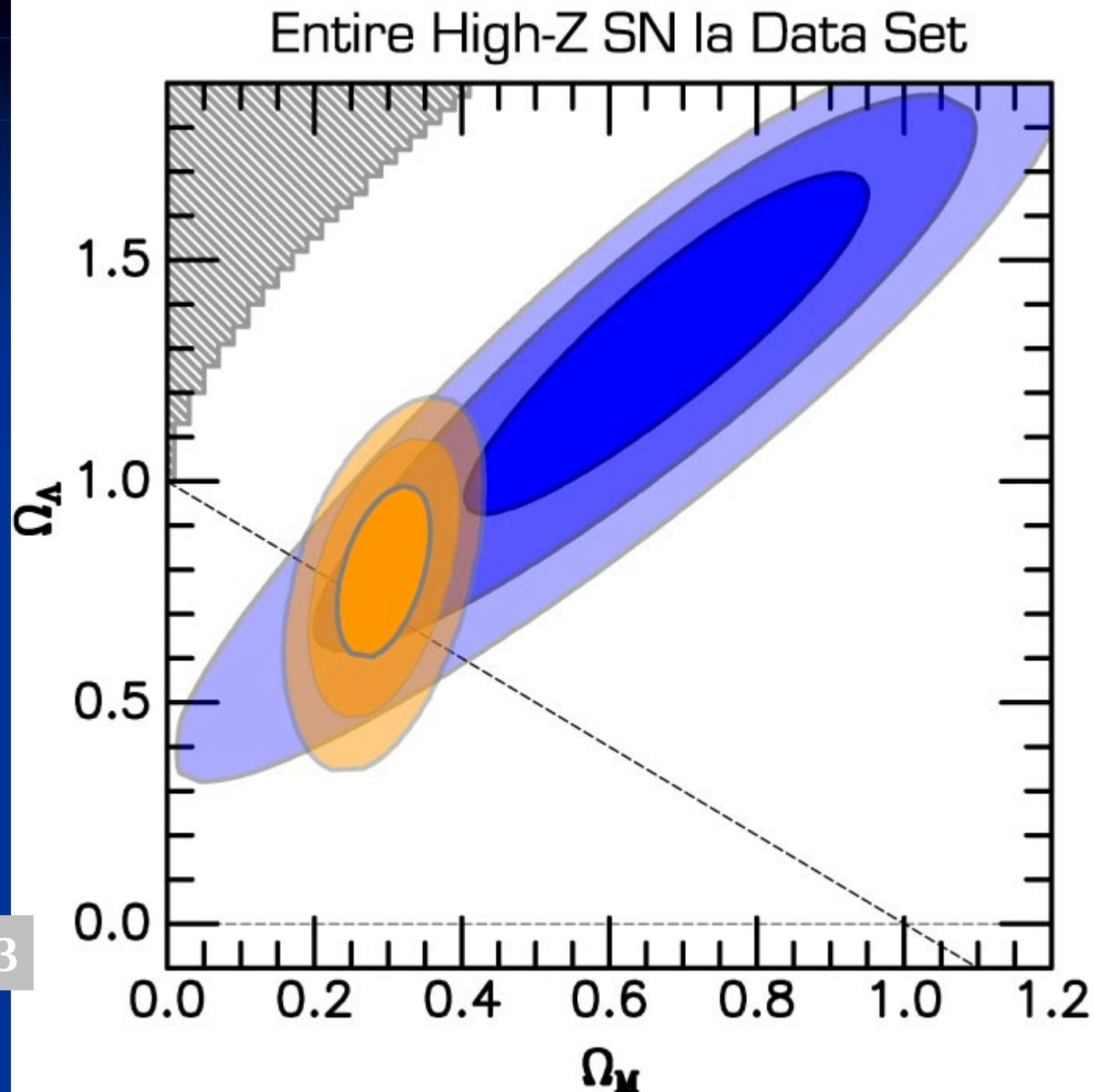
2dF:

$$\Omega_M = 0.2 \pm 0.03$$

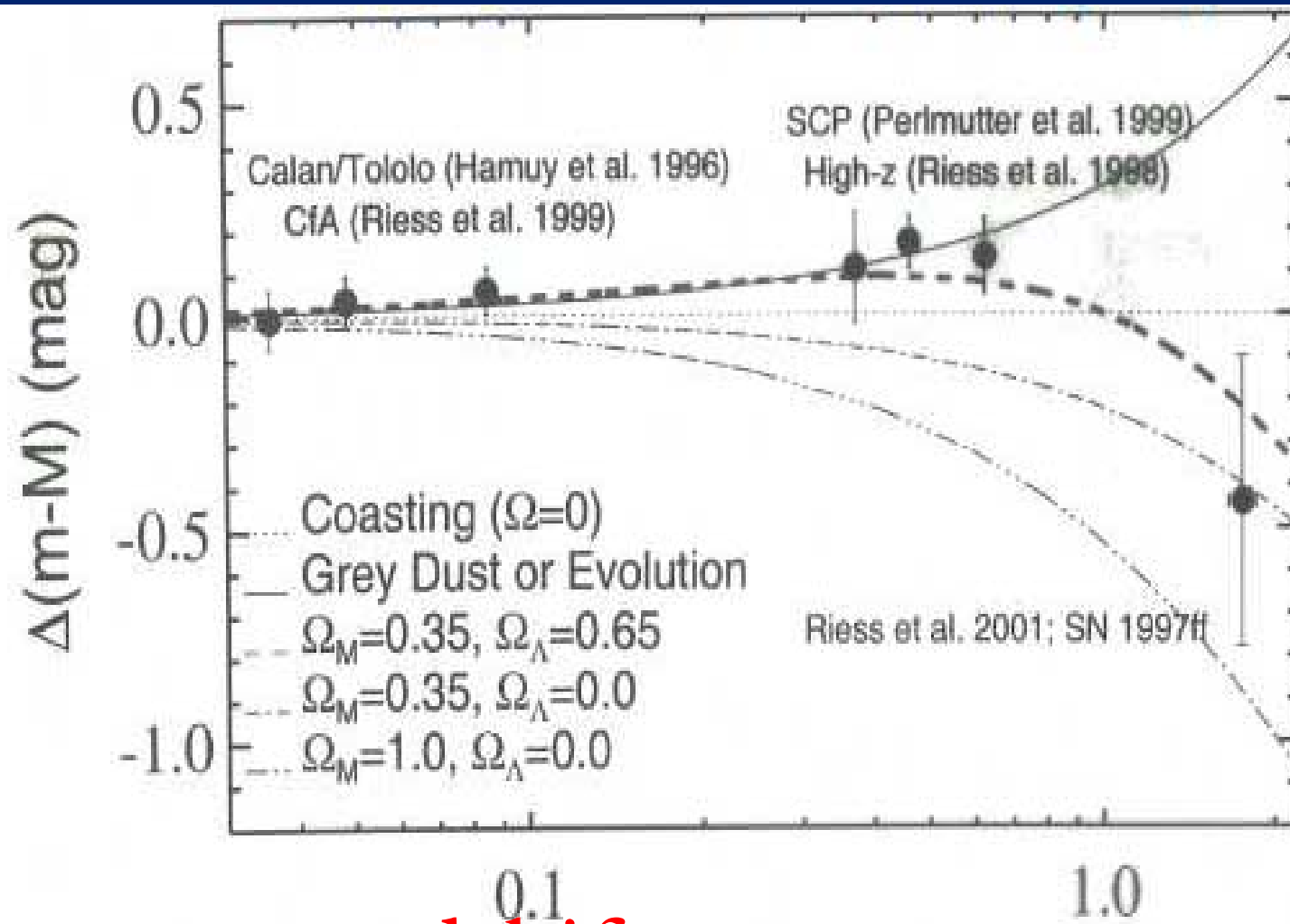
KP:

$$h = 0.72 \pm 0.08$$

Tonry et al. 2003



Supernova Ia Hubble-diagram



redshift z

Filippenko

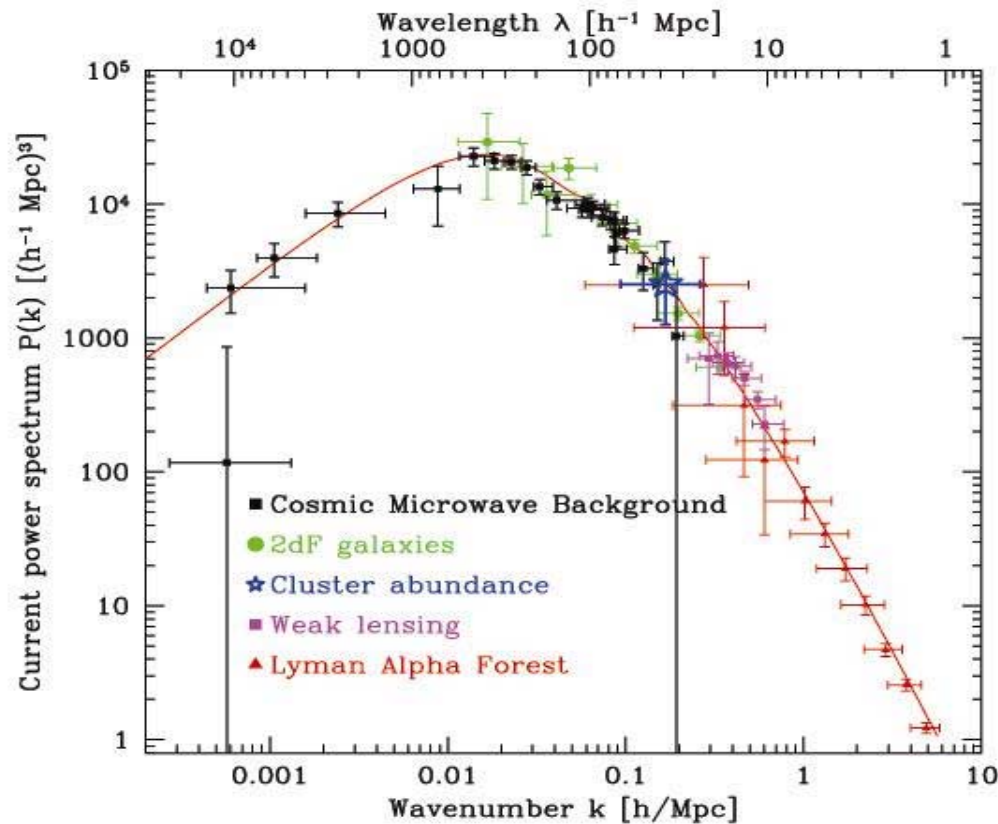
Structure formation

Structures in the Universe grow from tiny fluctuations in density distribution

stars , galaxies, clusters

One primordial fluctuation spectrum describes all correlation functions !

Structure formation : fluctuation spectrum



Waerbeke

CMB agrees with
galaxy distribution

Lyman – α forest

and

gravitational lensing
effect !

consistent cosmological model !

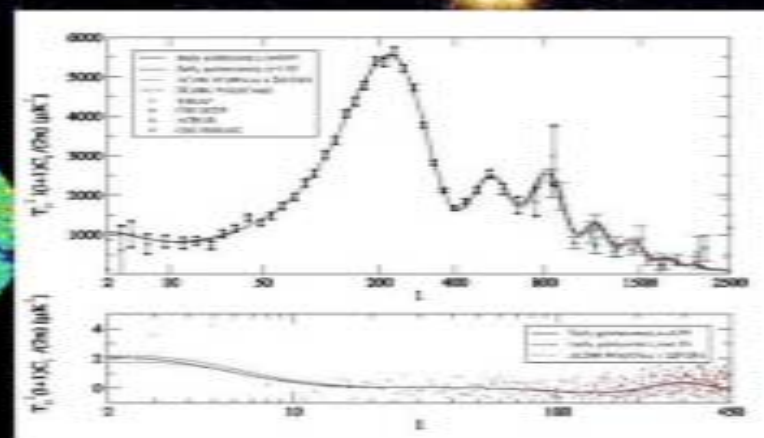
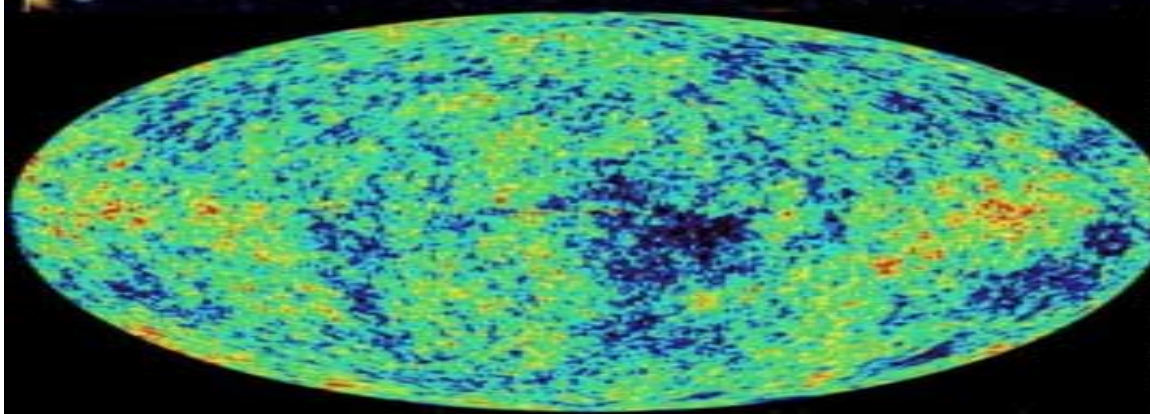
Composition of the Universe

$\Omega_b = 0.045$ visible clumping

$\Omega_{dm} = 0.225$ invisible clumping

$\Omega_h = 0.73$ invisible homogeneous

Dark Energy- a cosmic mystery



What is Dark Energy ?

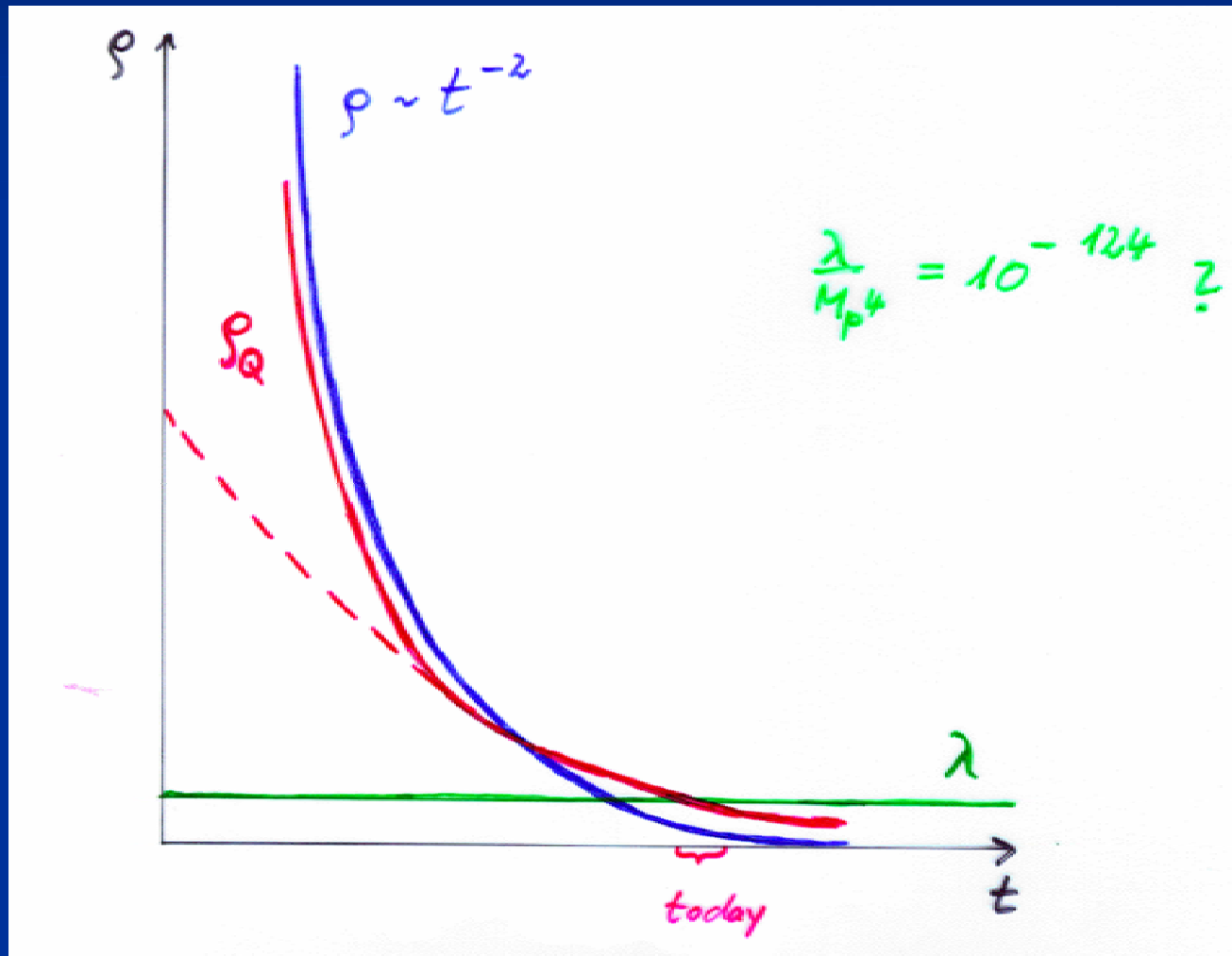
Cosmological Constant
or
Quintessence ?

Cosmological Constant

- 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

$$M = 2.44 \times 10^{18} \text{ GeV}$$

- Newton's constant

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

Only ratios of mass scales are observable !

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

matter:

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

Time evolution

- $\rho_m/M^4 \sim a^{-3} \sim \begin{matrix} t^2 & \text{matter dominated universe} \\ t^{3/2} & \text{radiation dominated universe} \end{matrix}$
- $\rho_r/M^4 \sim a^{-4} \sim t^{-2}$ 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

Cosmon

- *Scalar field changes its value even in the ~~present~~ cosmological epoch*
- *Potential und kinetic energy of cosmon contribute to the energy density of the Universe*
- *Time - variable dark energy :
 $\varrho_b(t)$ decreases with time !*

Cosmon

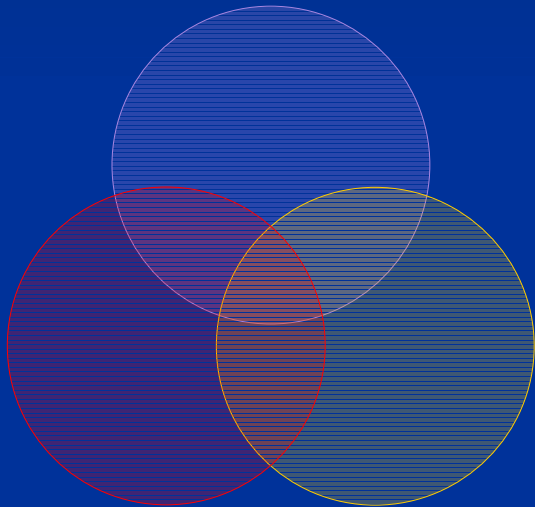
- *Tiny mass*

- $m_c \sim H$

- *New long - range interaction*

“Fundamental” Interactions

Strong, electromagnetic, weak
interactions



gravitation

cosmodynamics

On astronomical
length scales:

graviton

+

cosmon

Evolution of cosmon field

Field equation

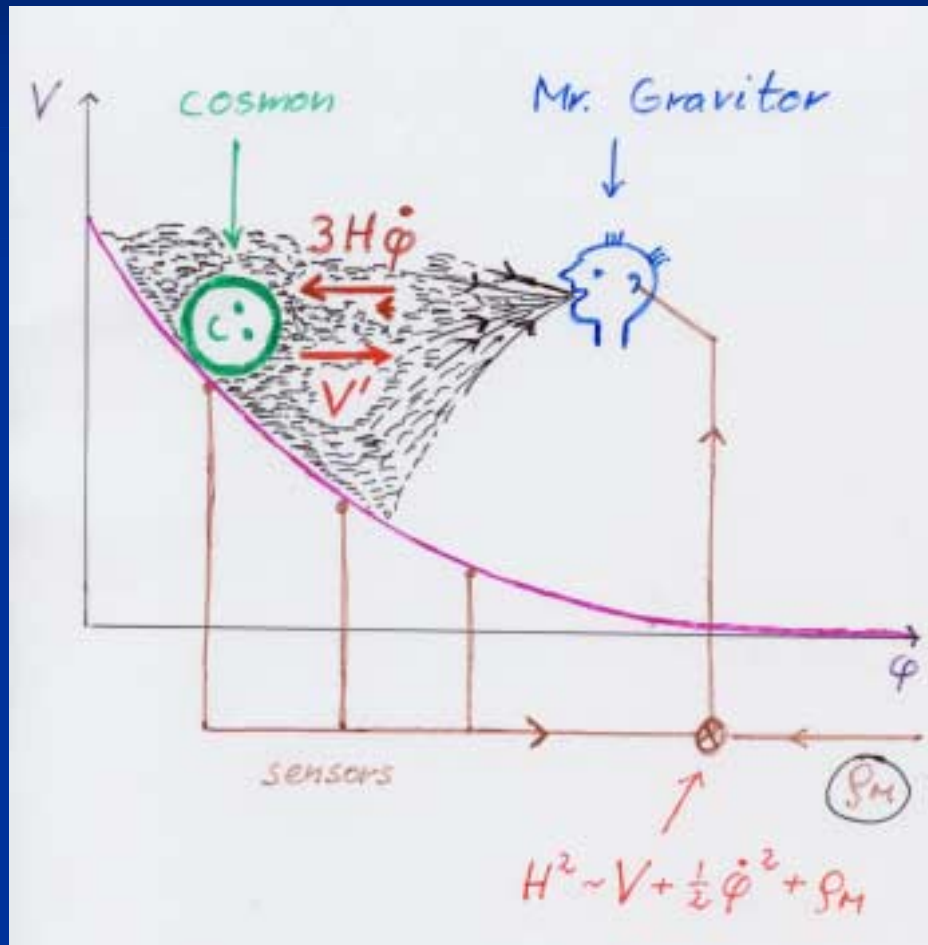
$$\ddot{\phi} + 3H\dot{\phi} = -dV/d\phi$$

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

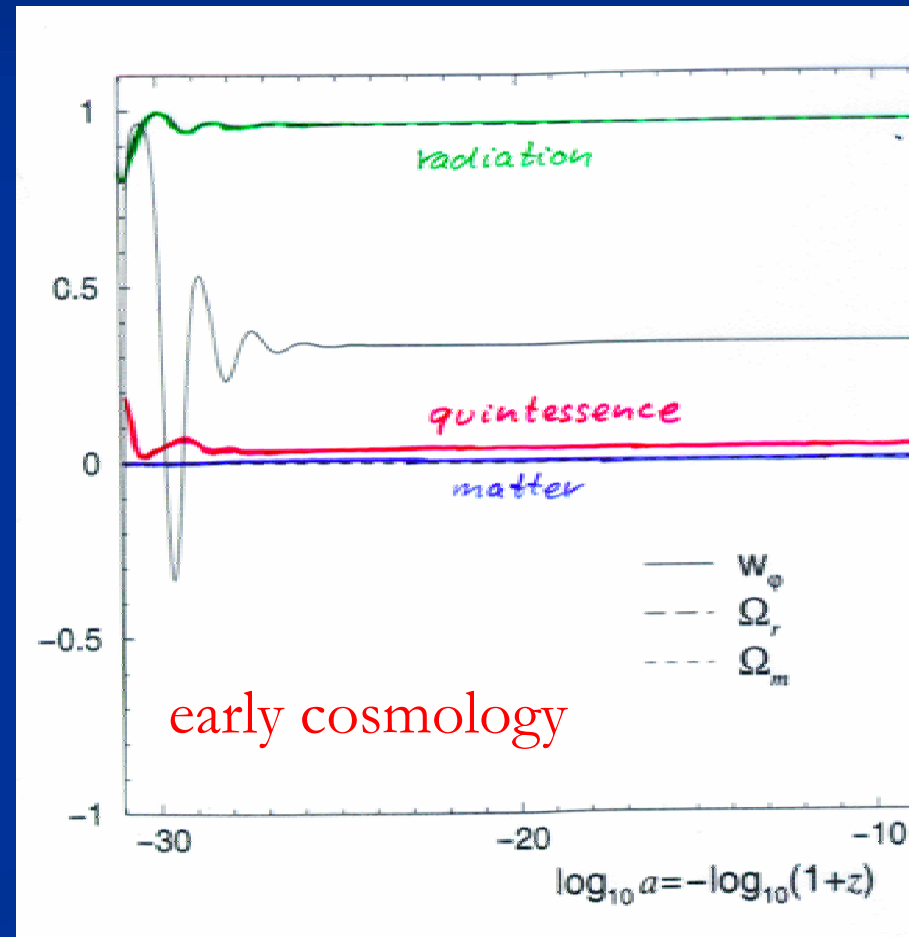
Solutions independent of
initial conditions

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

$\varphi \sim \ln(t)$

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

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



Dynamics of quintessence

- **Cosmon** ϕ : scalar singlet field
- Lagrange density $L = V + \frac{1}{2} k(f) \partial\phi \partial\phi$
(units: reduced Planck mass $M=1$)
- Potential : $V = \exp[-\phi]$
- “Natural initial value” in Planck era $\phi=0$
- today: $\phi=276$

Quintessence models

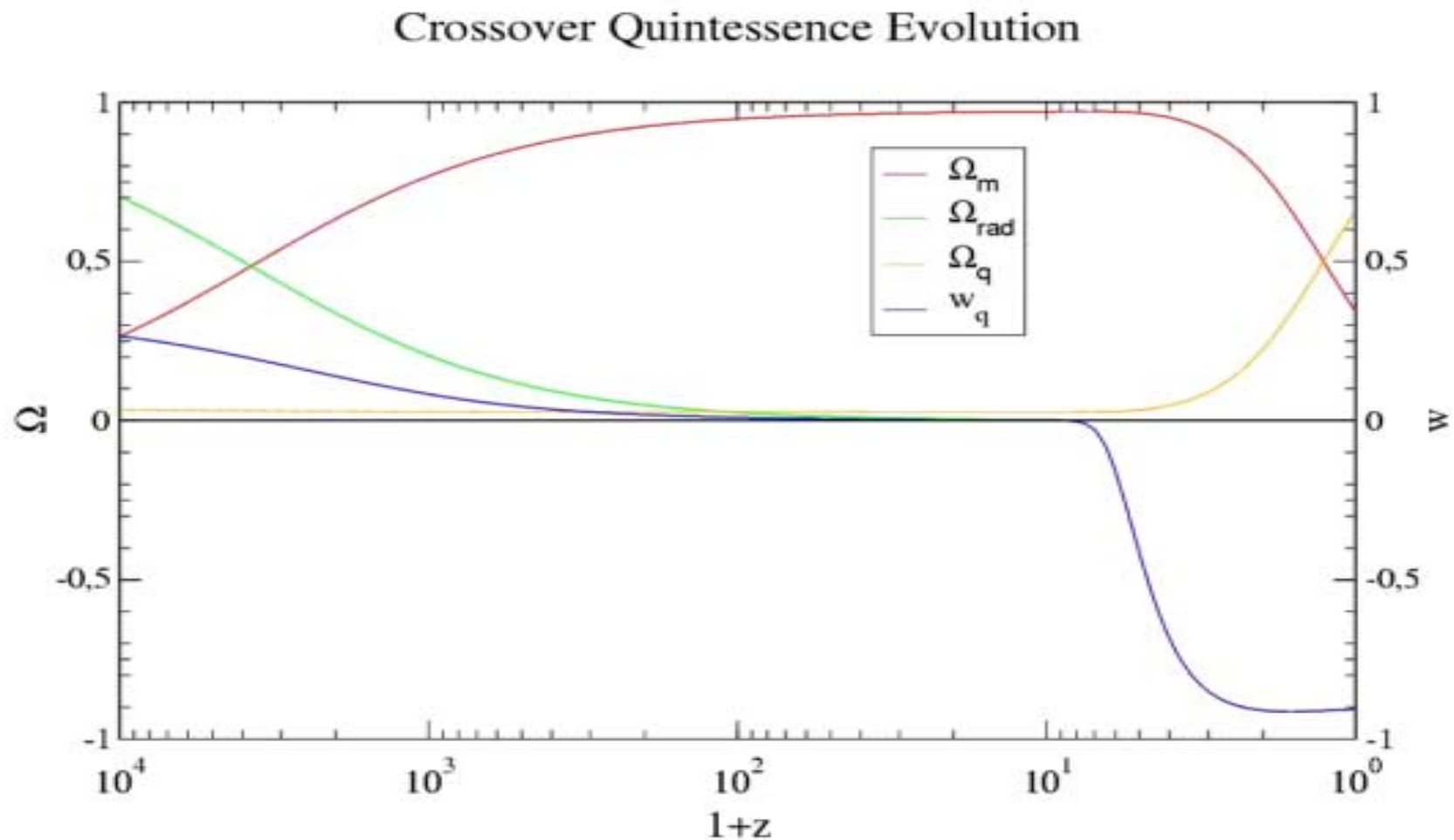
- Kinetic function $k(f)$: parameterizes the details of the model - “kinetial”
 - $k(f) = k = \text{const.}$ Exponential Q.
 - $k(f) = \exp((f - f_0)/a)$ Inverse power law Q.
 - $k^2(f) = “1/(2E(f_c - f))”$ Crossover Q.

- Naturalness criterion:

$k(f=0)/k(f_{\text{today}})$: not tiny or huge !

- else: explanation needed -

Quintessence becomes important “today”



Equation of state

$$p = T - V$$

pressure

kinetic energy

$$\rho = T + V$$

energy density

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

Equation of state

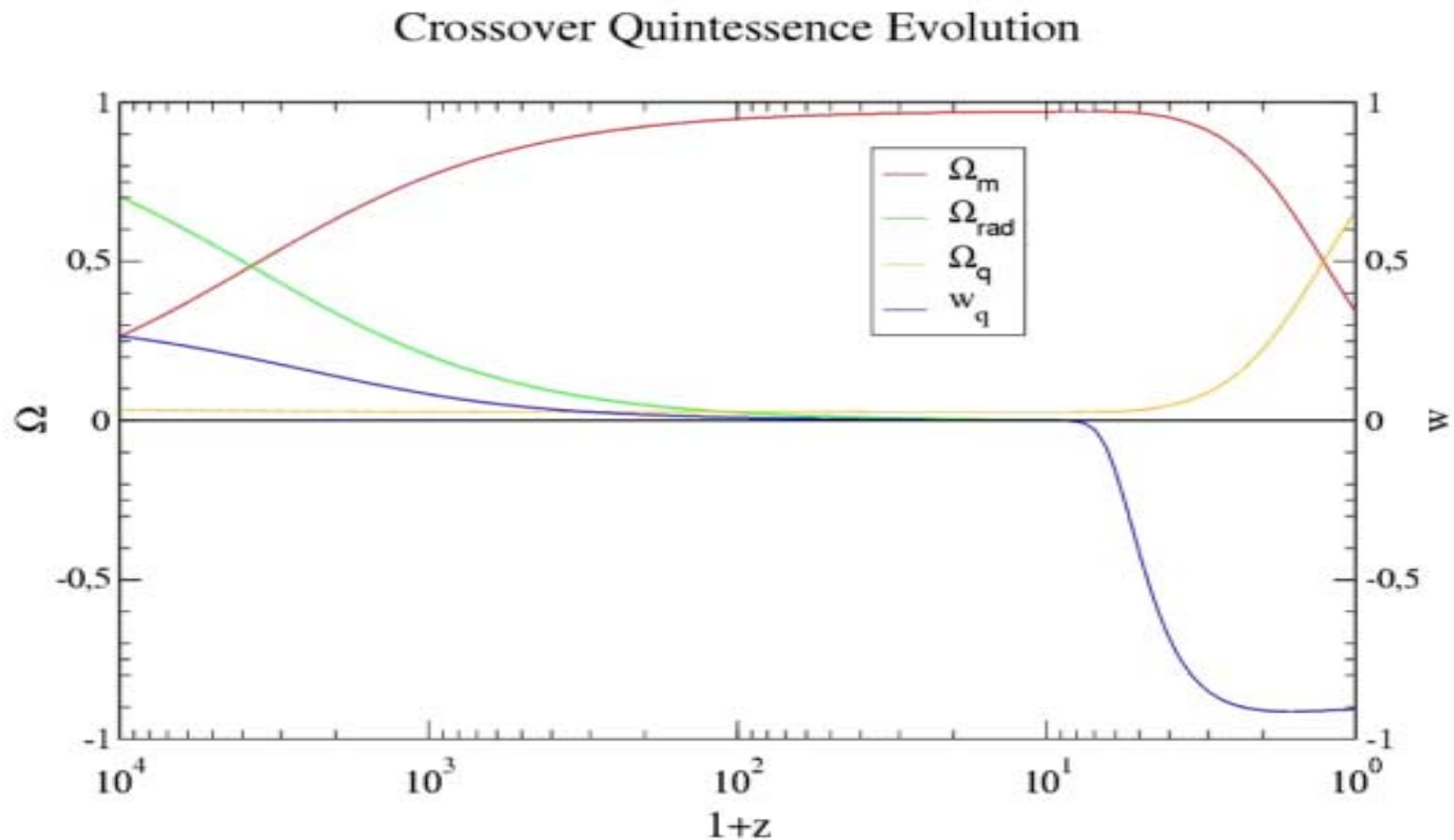
$$w = \frac{p}{\rho} = \frac{T - V}{T + V}$$

Depends on specific evolution of the scalar field

Negative pressure

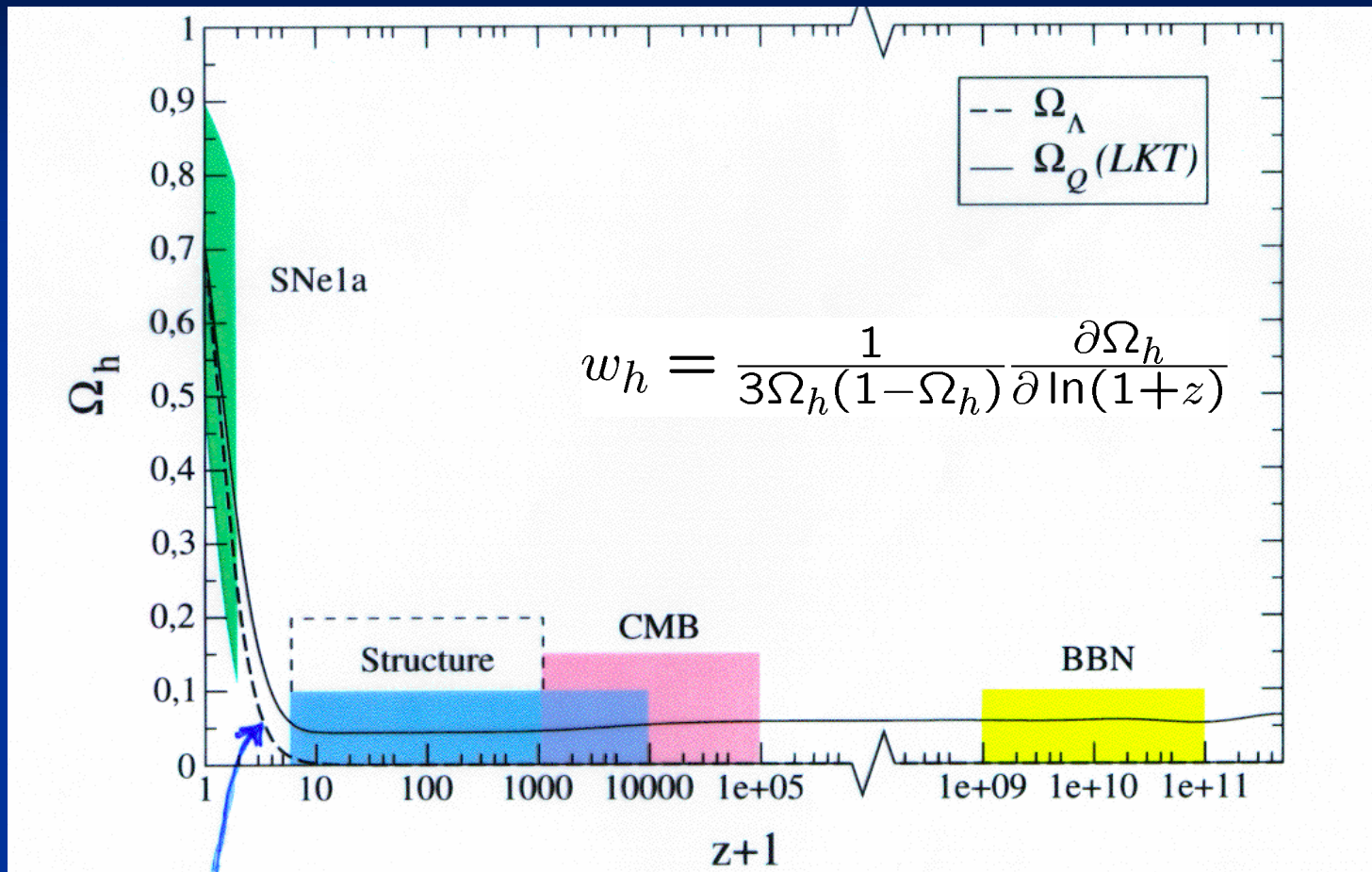
- $w < 0$ Ω_h increases
- $w < -1/3$ expansion of the Universe is accelerating
- $w = -1$ cosmological constant

Quintessence becomes important “today”



How can quintessence be
distinguished from a
cosmological constant ?

Time dependence of dark energy



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

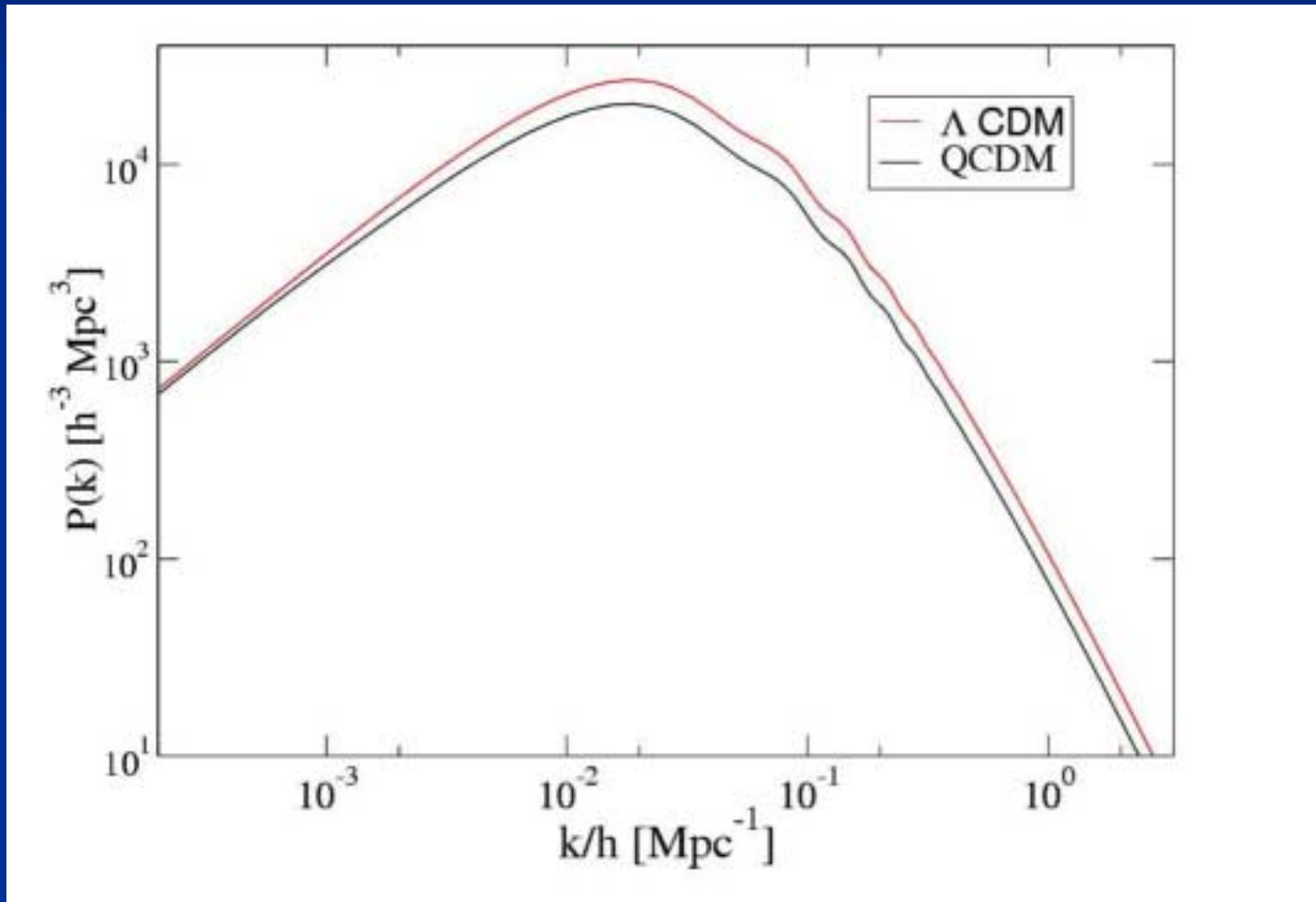
M.Doran,...

Early dark energy

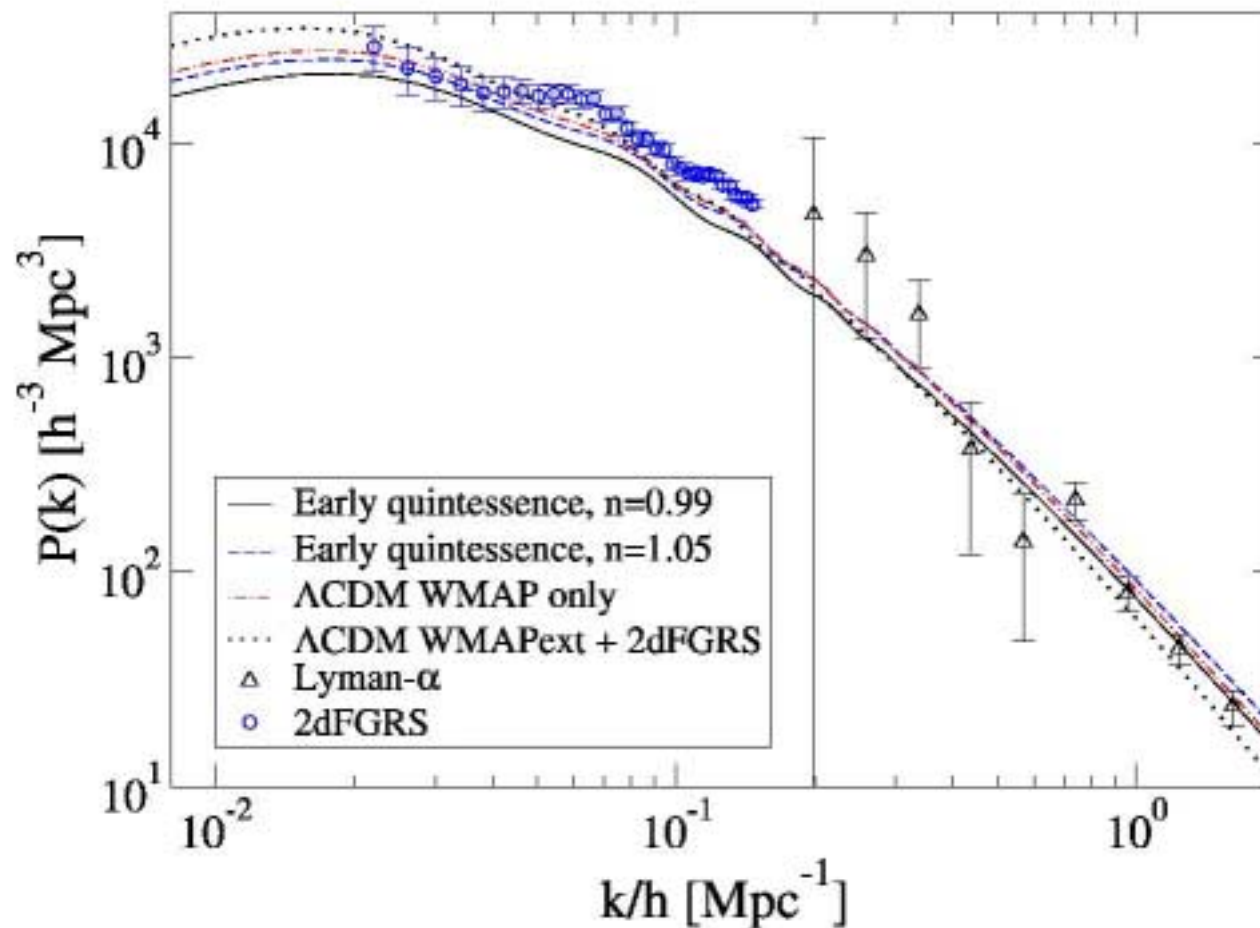
A few percent in the early Universe

Not possible for a cosmological constant

Early quintessence slows down the growth of structure

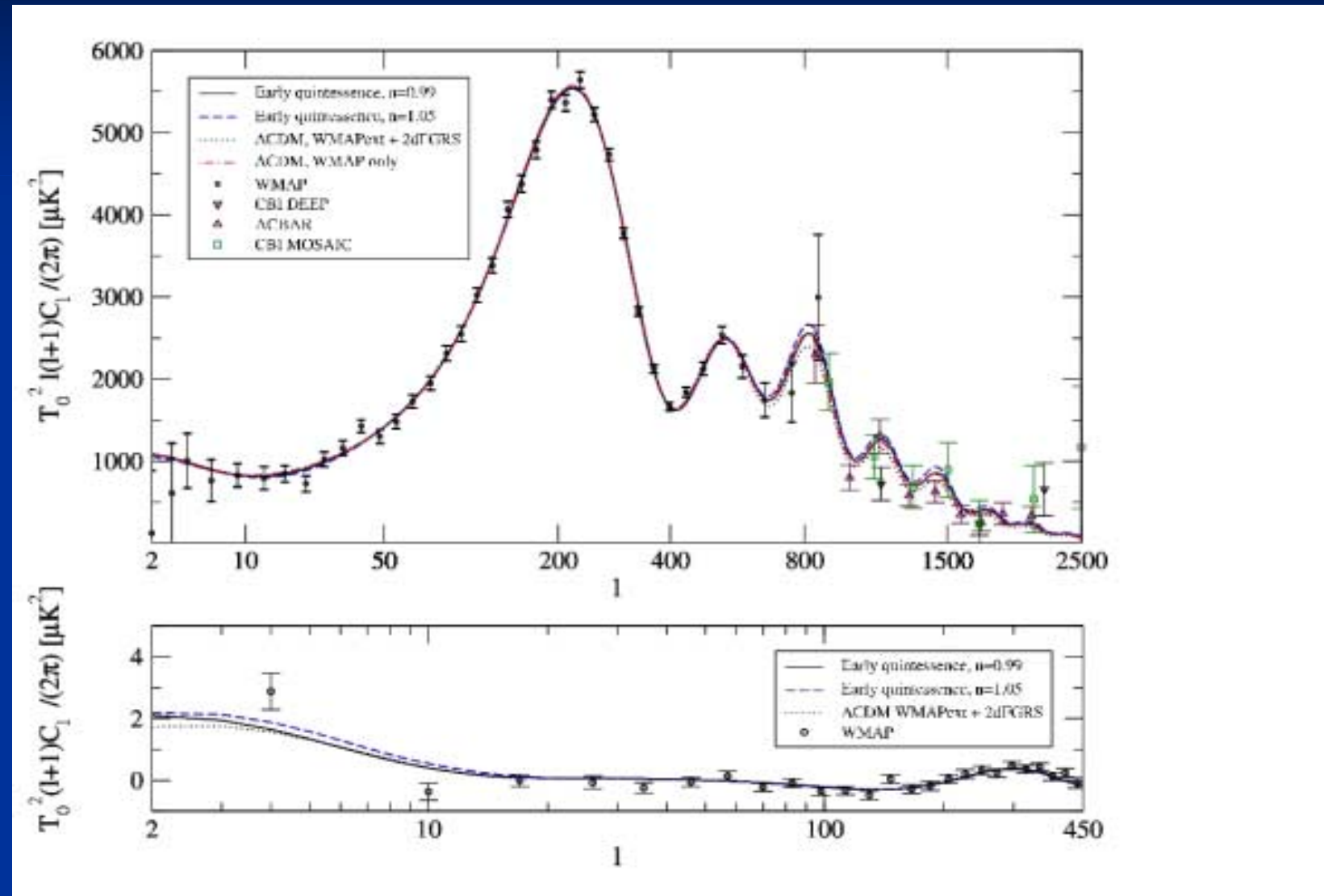


Fluctuation spectrum



Caldwell, Doran, Müller, Schäfer, ...

Anisotropy of cosmic background radiation



Caldwell, Doran, Müller, Schäfer, ...

How to distinguish Q from ? ?

A) Measurement $O_h(z) \longleftrightarrow H(z)$

- i) $O_h(z)$ 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”

Are fundamental “constants” time dependent ?

Fine structure constant α (electric charge)

Ratio nucleon mass to Planck mass

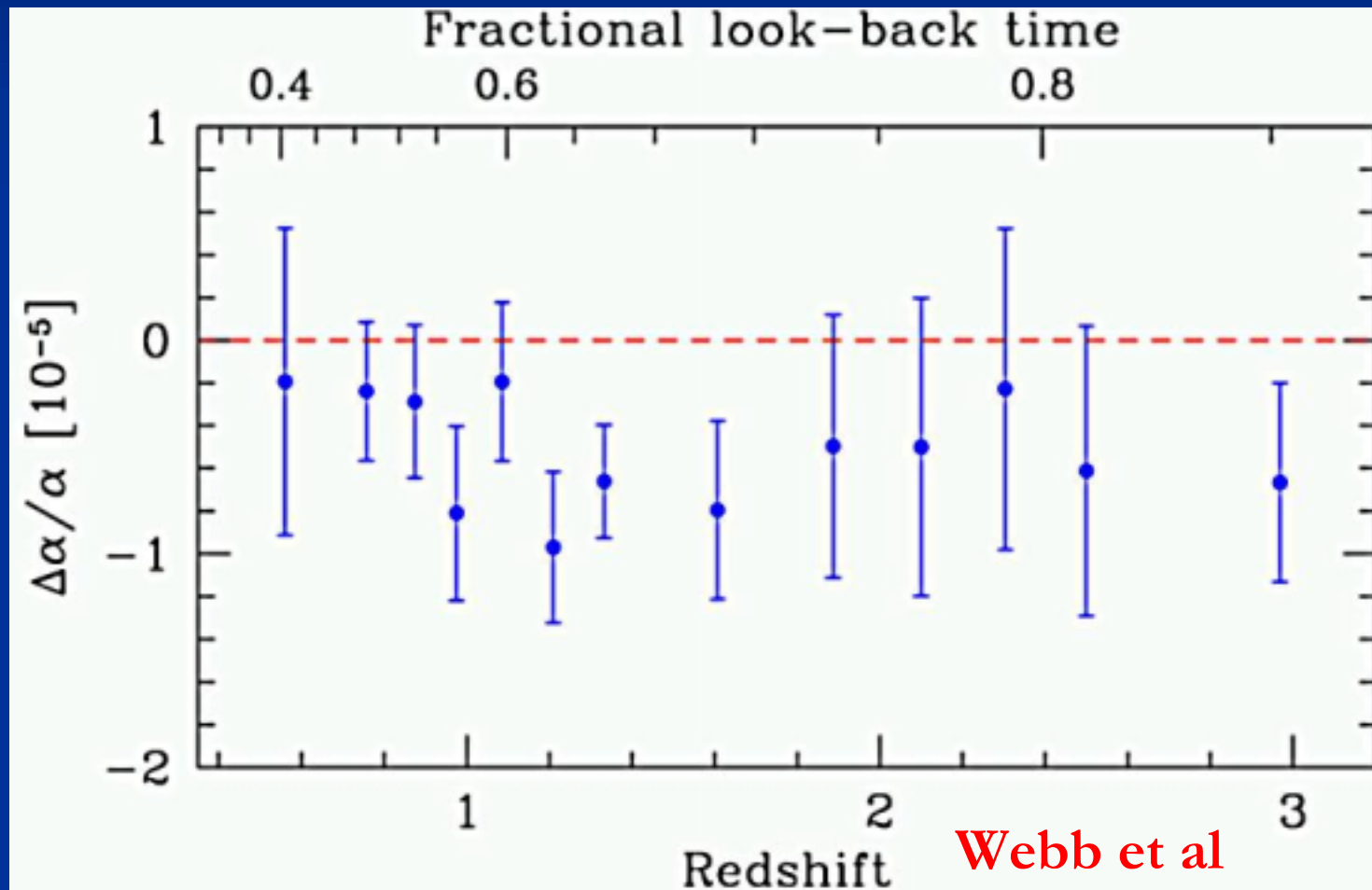
Quintessence and Time dependence of “fundamental constants”

- Fine structure constant depends on value of
cosmon field : $\alpha(f)$
- Time evolution of f 
Time evolution of α

Observation of (molecular absorption lines
in the light of quasars)

$$z=2-3 : \quad \Delta \alpha / \alpha = -0.6 \cdot 10^{-5} \quad !$$

Variation of fine structure constant as function of redshift



Webb et al

Variation of fine structure constant

Three independent data sets from Keck/HIRES

$$\Delta\alpha/\alpha = -0.54 (12) \cdot 10^{-5}$$

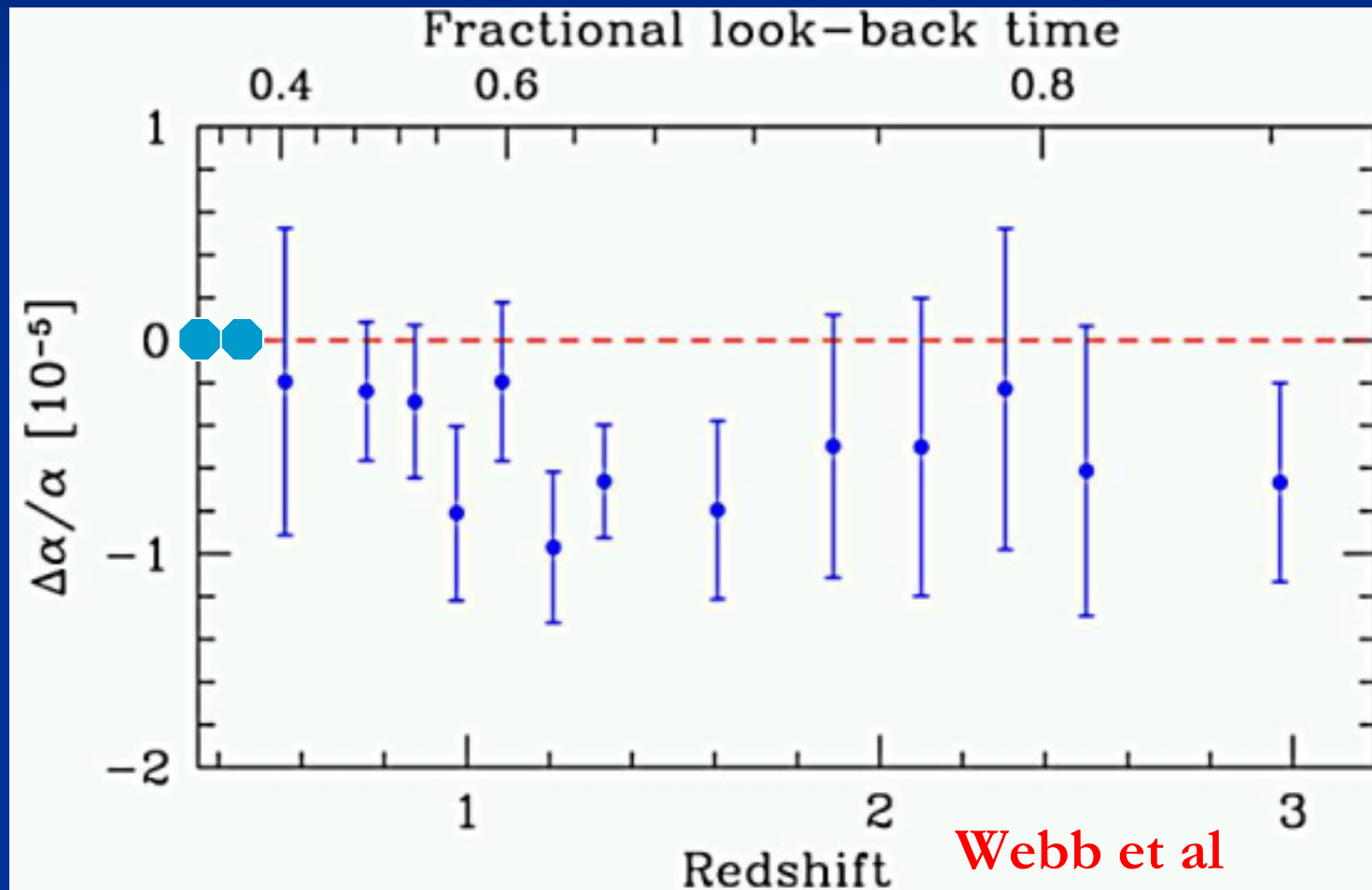
Murphy, Webb, Flammbaum, june 2003

Crossover quintessence and time variation of fundamental “constants”

Upper bounds for relative variation of the
fine structure constant

- Oklo natural reactor $\Delta\alpha/\alpha < 10^{-7}$ $z=0.13$
- Meteorites (Re-decay) $\Delta\alpha/\alpha < 3 \cdot 10^{-7}$ $z=0.45$
- Crossover Quintessence compatible with QSO
and upper bounds !

Variation of fine structure constant as function of redshift



Webb et al

Time evolution of fundamental couplings traces time evolution of quintessence

today w_h close to -1 :

- Small kinetic energy
- Slow change of f
- Slow change of a

Very small $\Delta\alpha/\alpha$ for low z !

Time variation of coupling constants
is tiny —

would be of very high significance !

Possible signal for Quintessence

Παύλος 130 χρόνια

Cosmodynamics

Cosmon mediates new long-range interaction

Range : size of the Universe – horizon

Strength : weaker than gravity

photon	electrodynamics
--------	-----------------

graviton	gravity
----------	---------

cosmon	cosmodynamics
--------	---------------

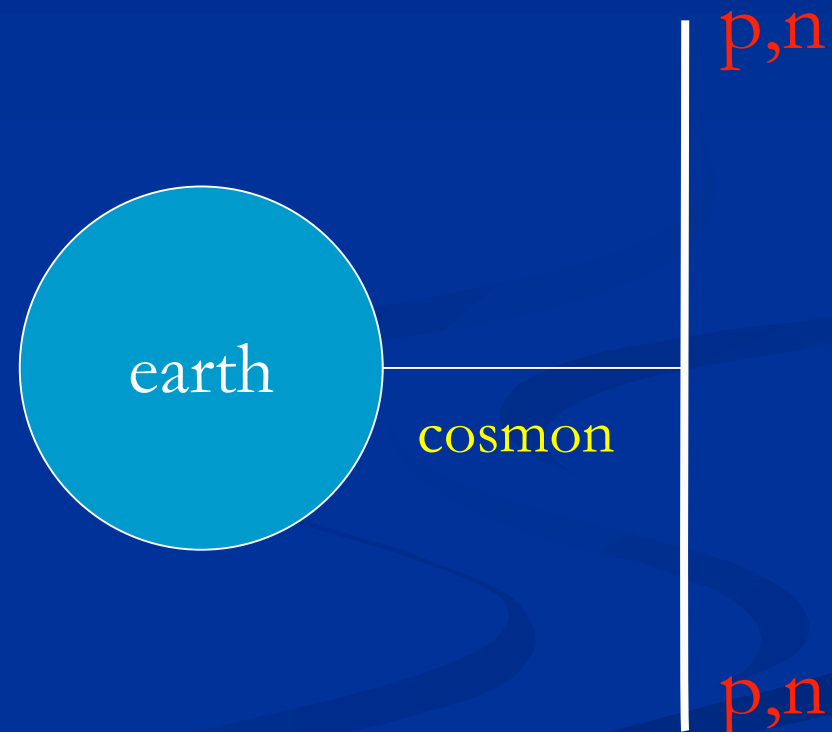
Small correction to Newton's law

Violation of equivalence principle

Different couplings of
cosmon to proton and
neutron

Differential acceleration

Violation of equivalence
principle



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 : $\eta = 10^{-14}$

Summary

- $\Omega_h = 0.7$
- Q/Λ : dynamical und static dark energy
will be distinguishable
- Q : time varying fundamental coupling “constants”

violation of equivalence principle

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

Why becomes Quintessence dominant in the present cosmological epoch ?

Are dark energy and dark matter related ?

Can Quintessence be explained in a fundamental unified theory ?

End

A few references

C.Wetterich , Nucl.Phys.B302,668(1988) , received 24.9.1987

P.J.E.Peebles,B.Ratra , Astrophys.J.Lett.325,L17(1988) , received 20.10.1987

B.Ratra,P.J.E.Peebles , Phys.Rev.D37,3406(1988) , received 16.2.1988

J.Frieman,C.T.Hill,A.Stebbins,I.Waga , Phys.Rev.Lett.75,2077(1995)

P.Ferreira, M.Joyce , Phys.Rev.Lett.79,4740(1997)

C.Wetterich , Astron.Astrophys.301,321(1995)

P.Viana, A.Liddle , Phys.Rev.D57,674(1998)

E.Copeland,A.Liddle,D.Wands , Phys.Rev.D57,4686(1998)

R.Caldwell,R.Dave,P.Steinhardt , Phys.Rev.Lett.80,1582(1998)

P.Steinhardt,L.Wang,I.Zlatev , Phys.Rev.Lett.82,896(1999)

Growth of density fluctuations

- Matter dominated universe with **constant** Ω_h :

$$\Delta\rho \sim a^{1-\frac{\epsilon}{2}}, \quad \epsilon = \frac{5}{2}\left(1 - \sqrt{1 - \frac{24}{25}\Omega_h}\right)$$

P.Ferreira,M.Joyce

- Dark energy slows down structure formation
 - $\Omega_h < 10\%$ during structure formation
- Substantial **increase** of $\Omega_h(t)$ since structure has formed!
 - **negative** w_h
- Question “why now” is back (in mild form)

“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)

Cosmon and fundamental mass scales

- 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
- m_n/M : (almost) constant - observation!

Only ratios of mass scales are observable

Dilatation symmetry

- Lagrange density:

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

- Dilatation symmetry for

$$V = \lambda \chi^4, \lambda = \text{const.}, \delta = \text{const.}, h = \text{const.}$$

- Conformal symmetry for $\delta=0$

Dilatation anomaly

- Quantum fluctuations responsible for dilatation anomaly
- Running couplings:

$$\partial\lambda/\partial\ln\chi = -A\lambda, \quad \partial\delta/\partial\ln\chi = E\delta^2$$

- $V \sim \chi^{4-A}$, $M_p(\chi) \sim \chi$
- $V/M_p^4 \sim \chi^{-A}$: decreases for increasing χ
- $E > 0$: crossover quintessence

Weyl scaling

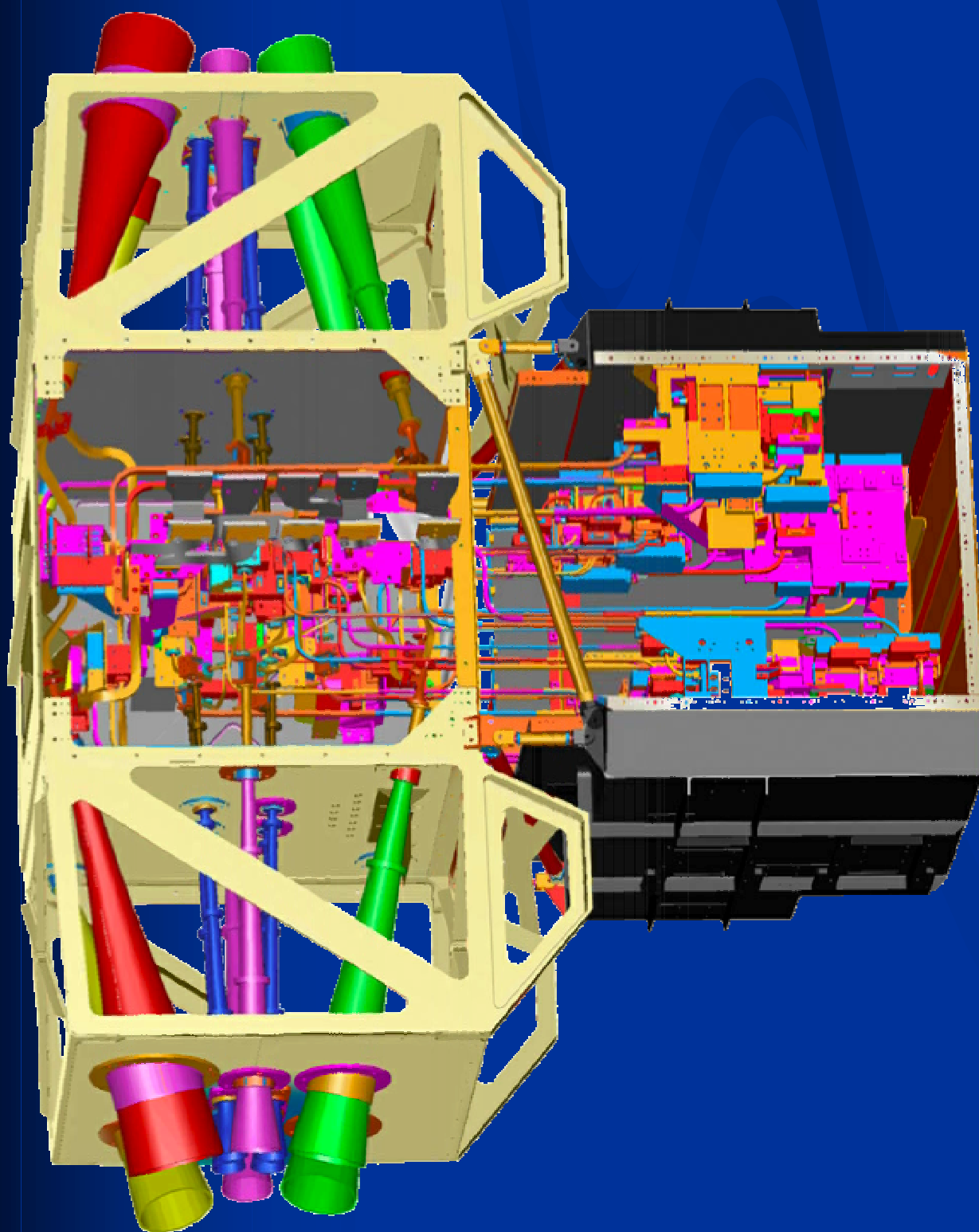
Cosmology : χ increases with time !

(“ late time cosmology explores the ultraviolet”)

Weyl scaling : $g_{\mu\nu} \rightarrow (M/\chi)^2 g_{\mu\nu}$,
 $\varphi/M = \ln (\chi^4/V(\chi))$

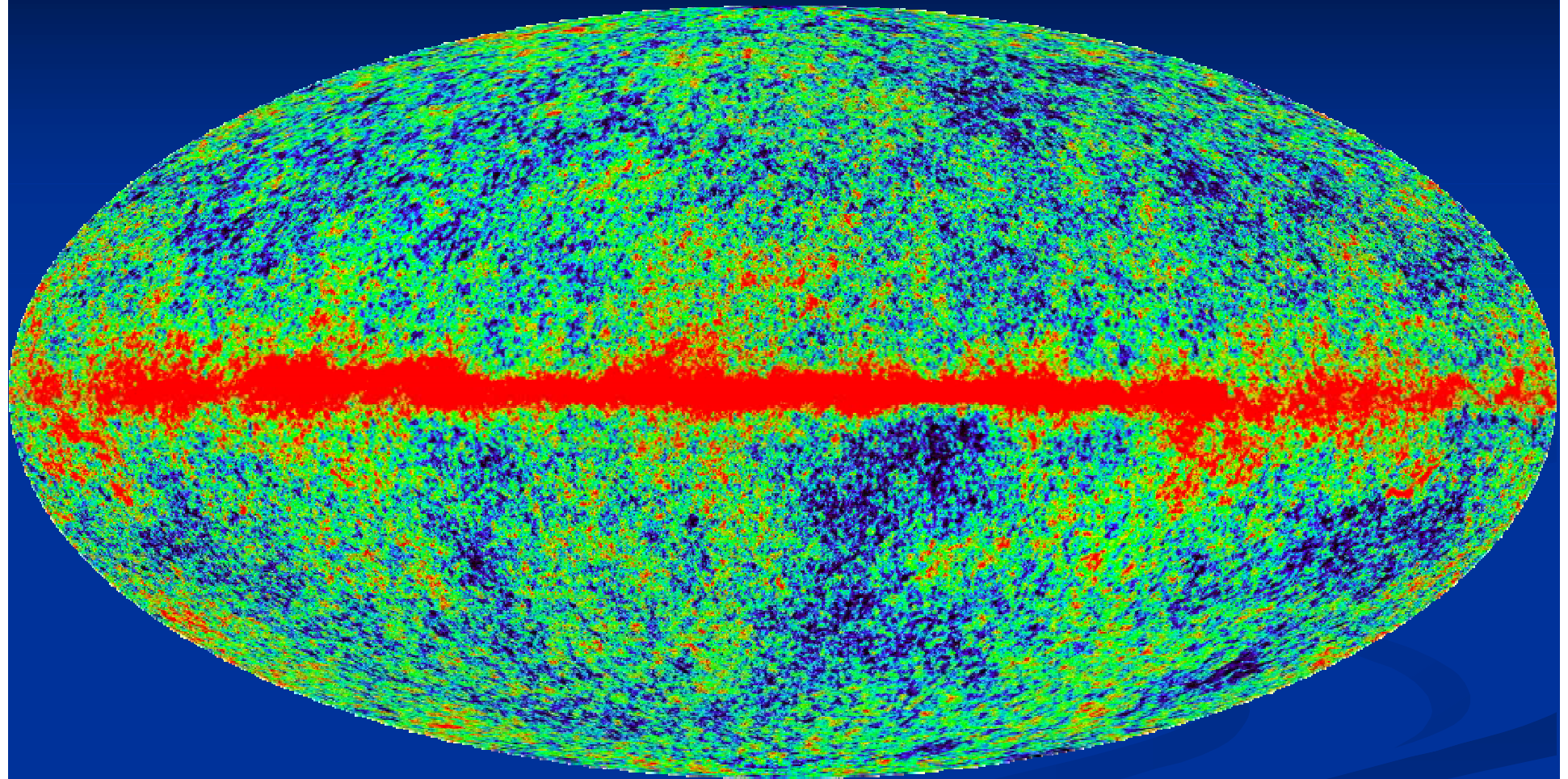
$$L = \sqrt{g} \left(-\frac{1}{2} M^2 R + \frac{1}{2} k^2 \partial^\mu \phi \partial_\mu \phi + V(\phi) + m_n \bar{\psi} \psi \right)$$

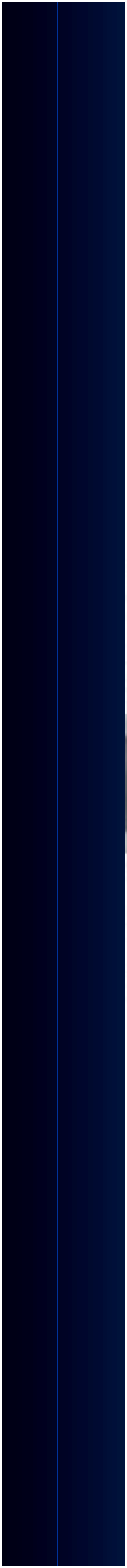
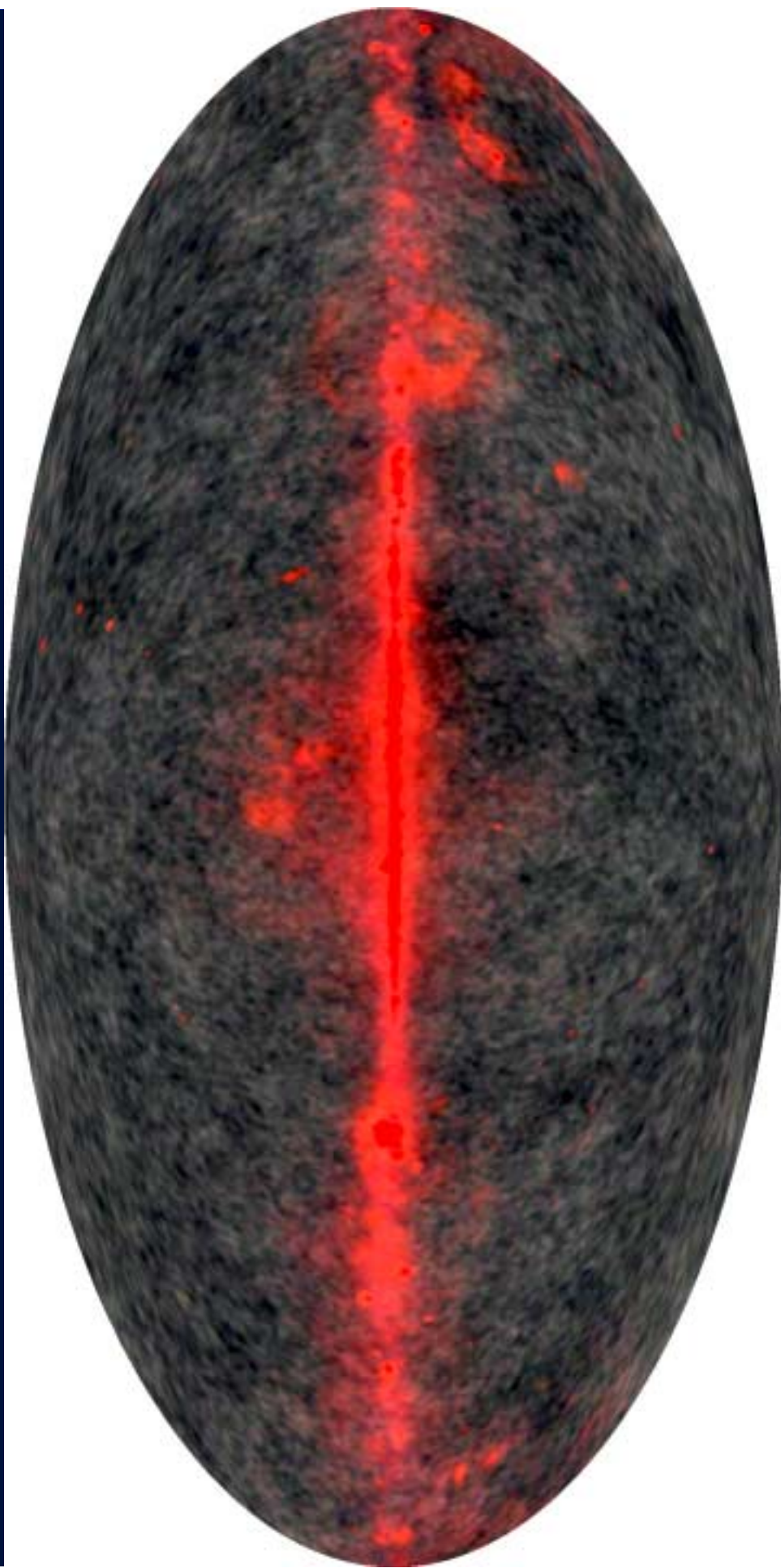
Exponential potential : $V = M^4 \exp(-\varphi/M)$



W 94 GHz

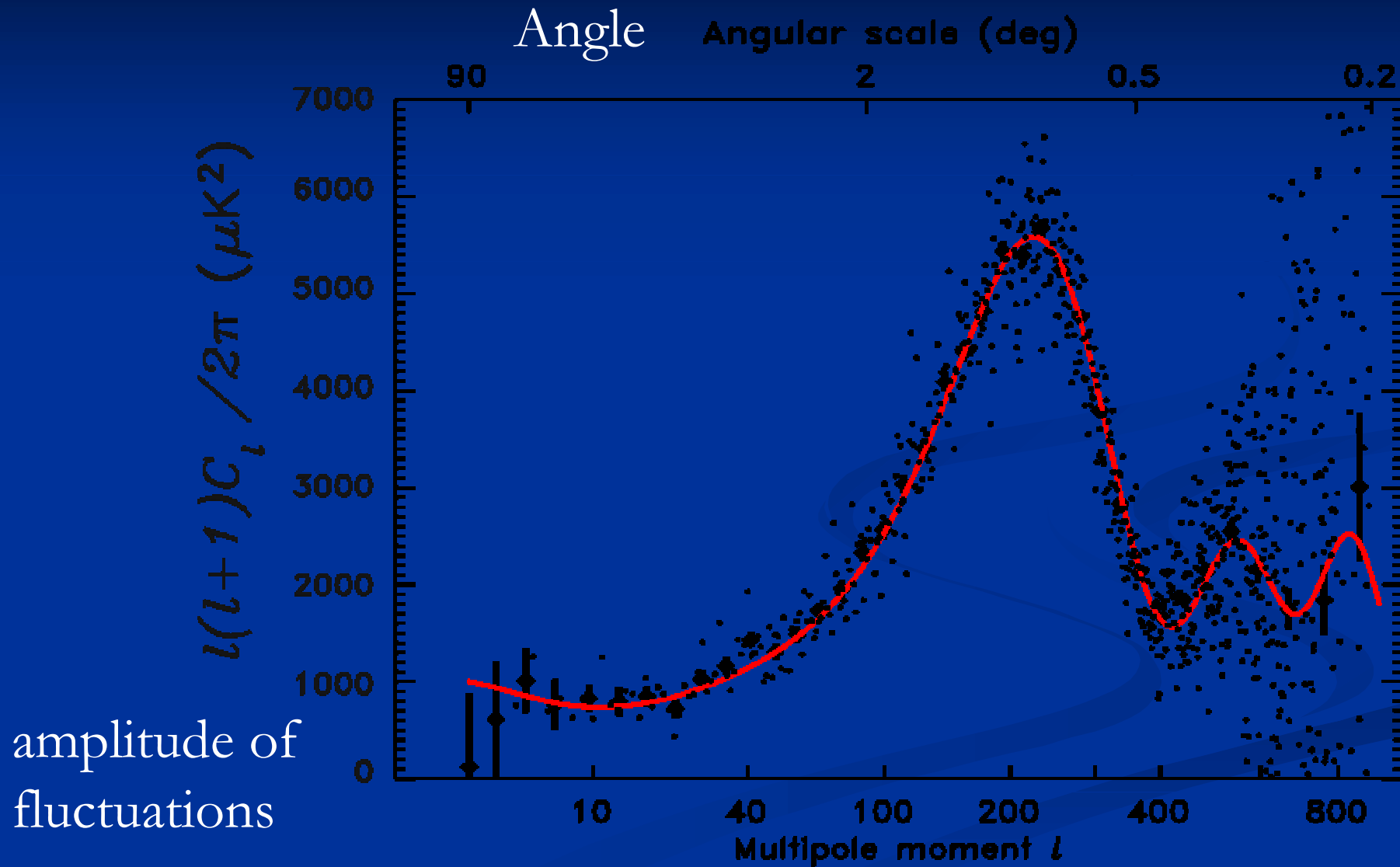
Dipole R emoved



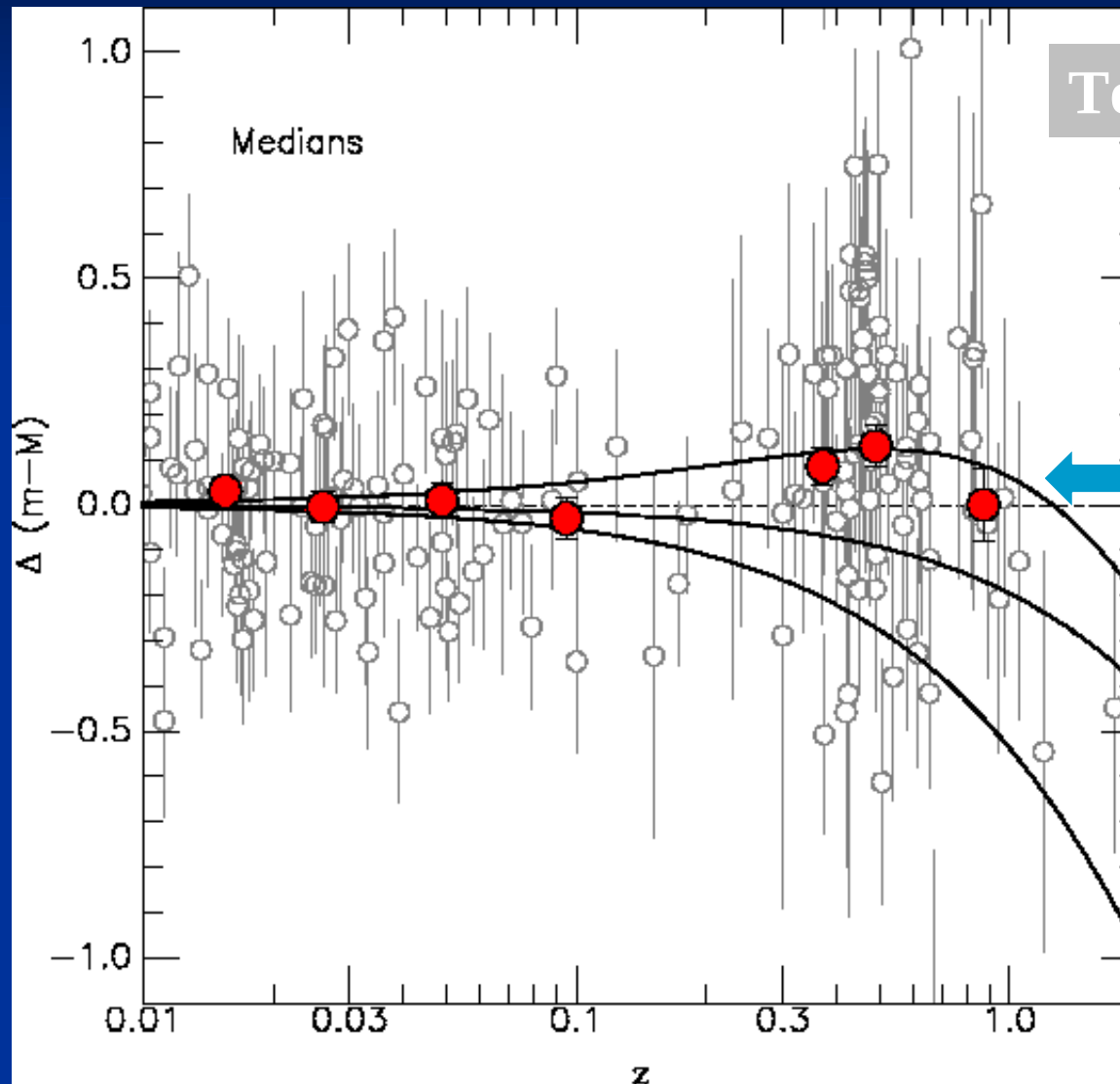


WMAP Angular Power Spectrum

Anisotropy of CMB



209 SN Ia and medians



Tonry et al. 2003

$\Omega_h = 0.7$
 $\Omega_m = 0.3$