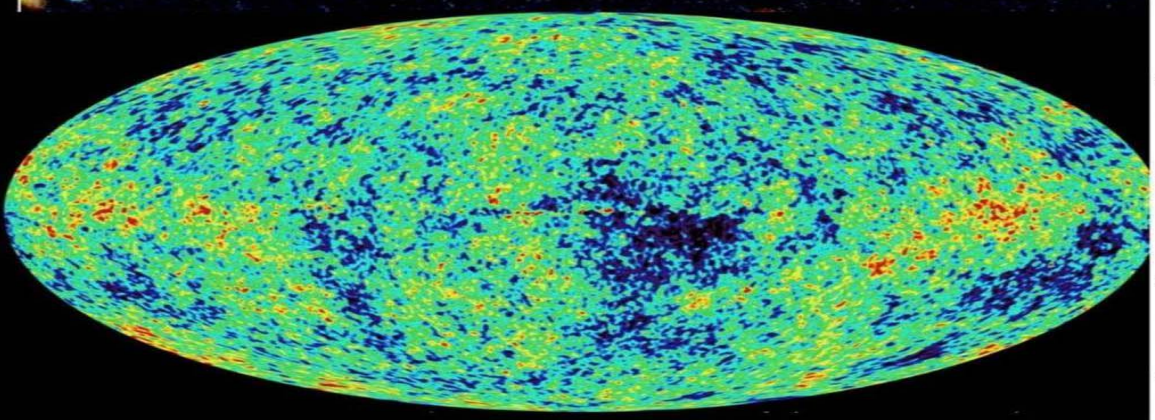
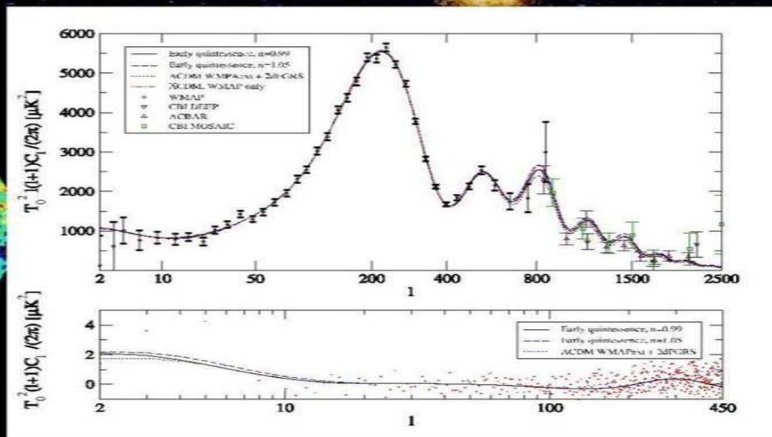
Dark Energy- a cosmic mystery





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

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

  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

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

Composition of the universe

$$\Omega_b = 0.045$$

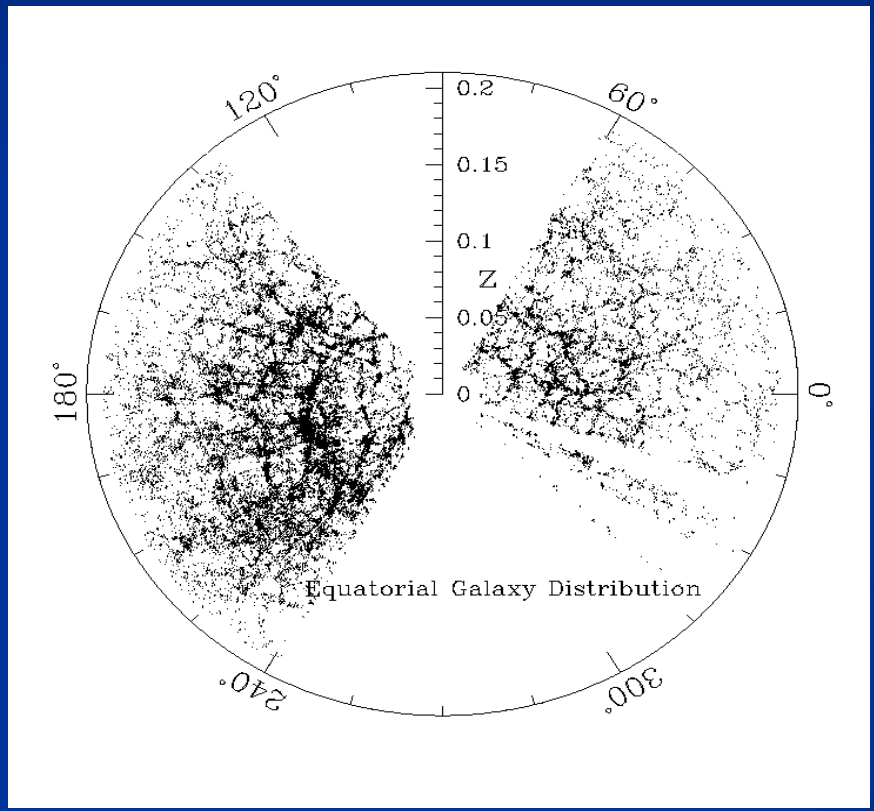
$$\Omega_{dm} = 0.225$$

$$\Omega_h = 0.73$$

baryons

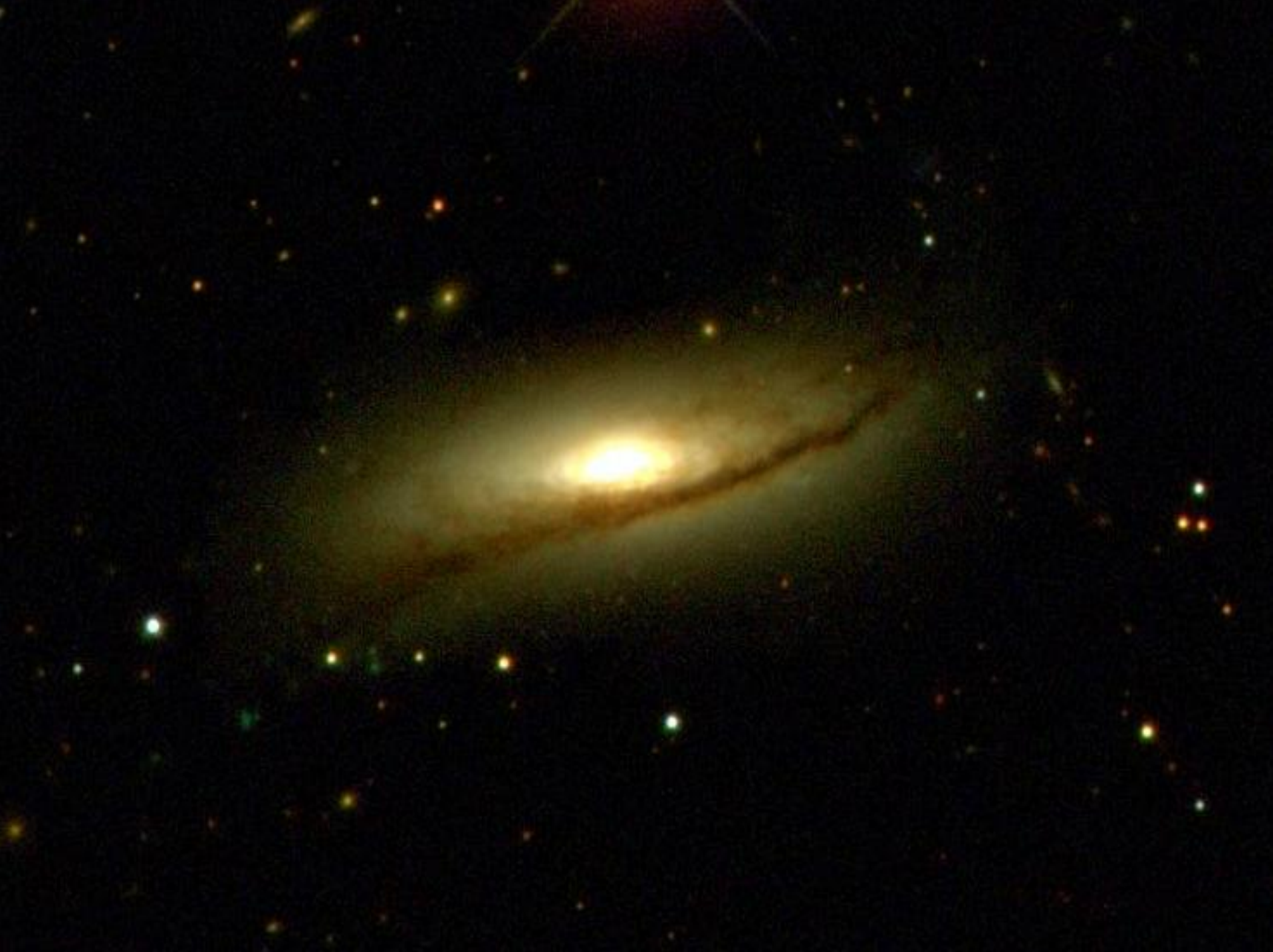
SDSS

~60,000 of >300,000 galaxies



- dust
- Ω_b=0.045
- only 5 percent of our universe consist of known matter !


Abell 2255 Cluster
~300 Mpc



$\Omega_b = 0.045$

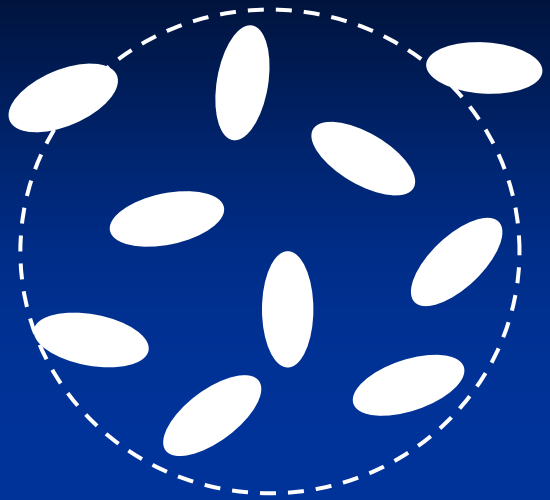
from nucleosynthesis,
cosmic background radiation

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

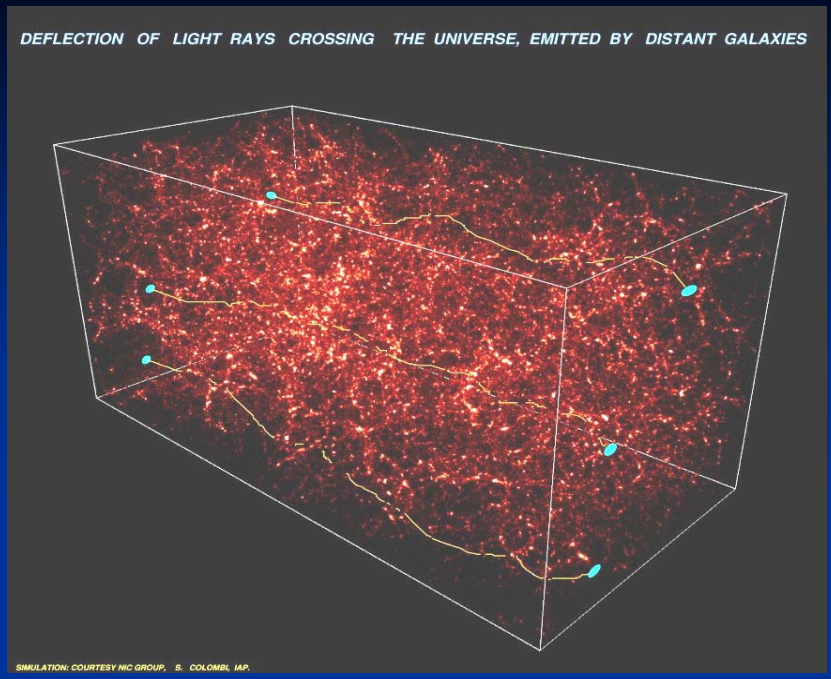
Averaged shape

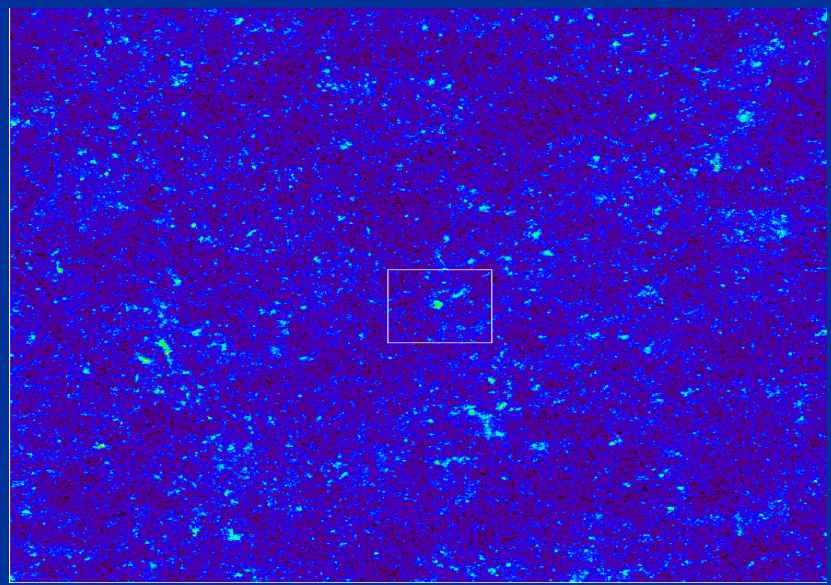
$\langle e \rangle = 0$

$\langle e \rangle \approx \gamma$

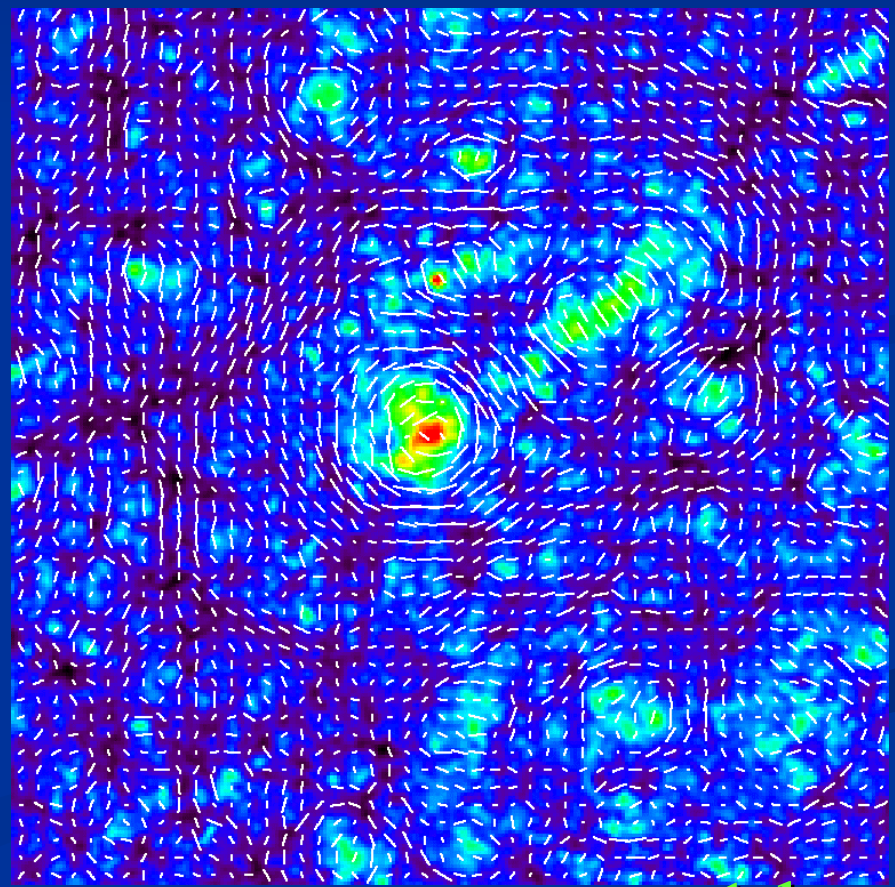
Waerbeke

cosmological weak gravitational lensing



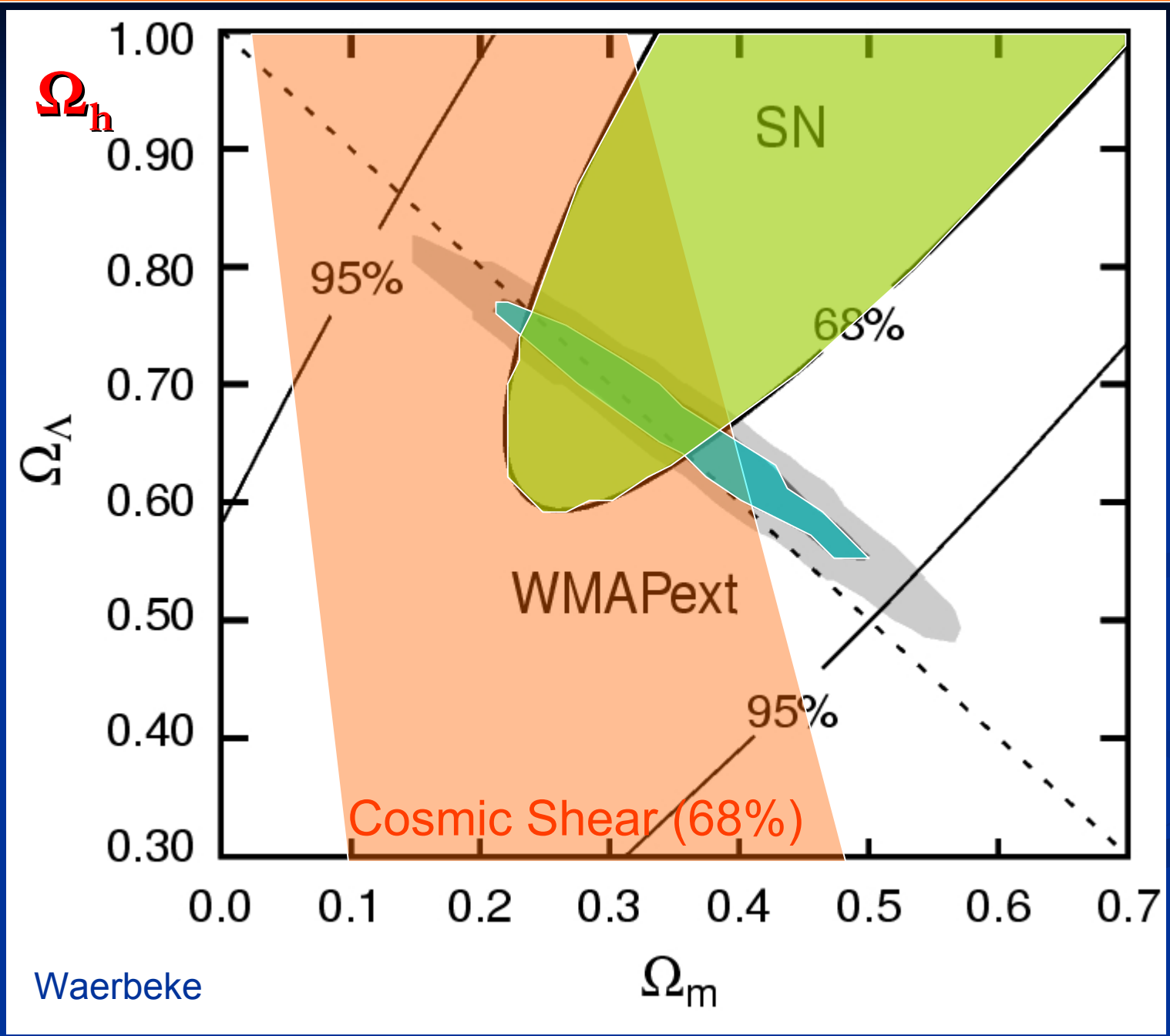


Waerbeke



1deg

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



Waerbeke

spatially flat universe

$$\Omega_{tot} = 1$$

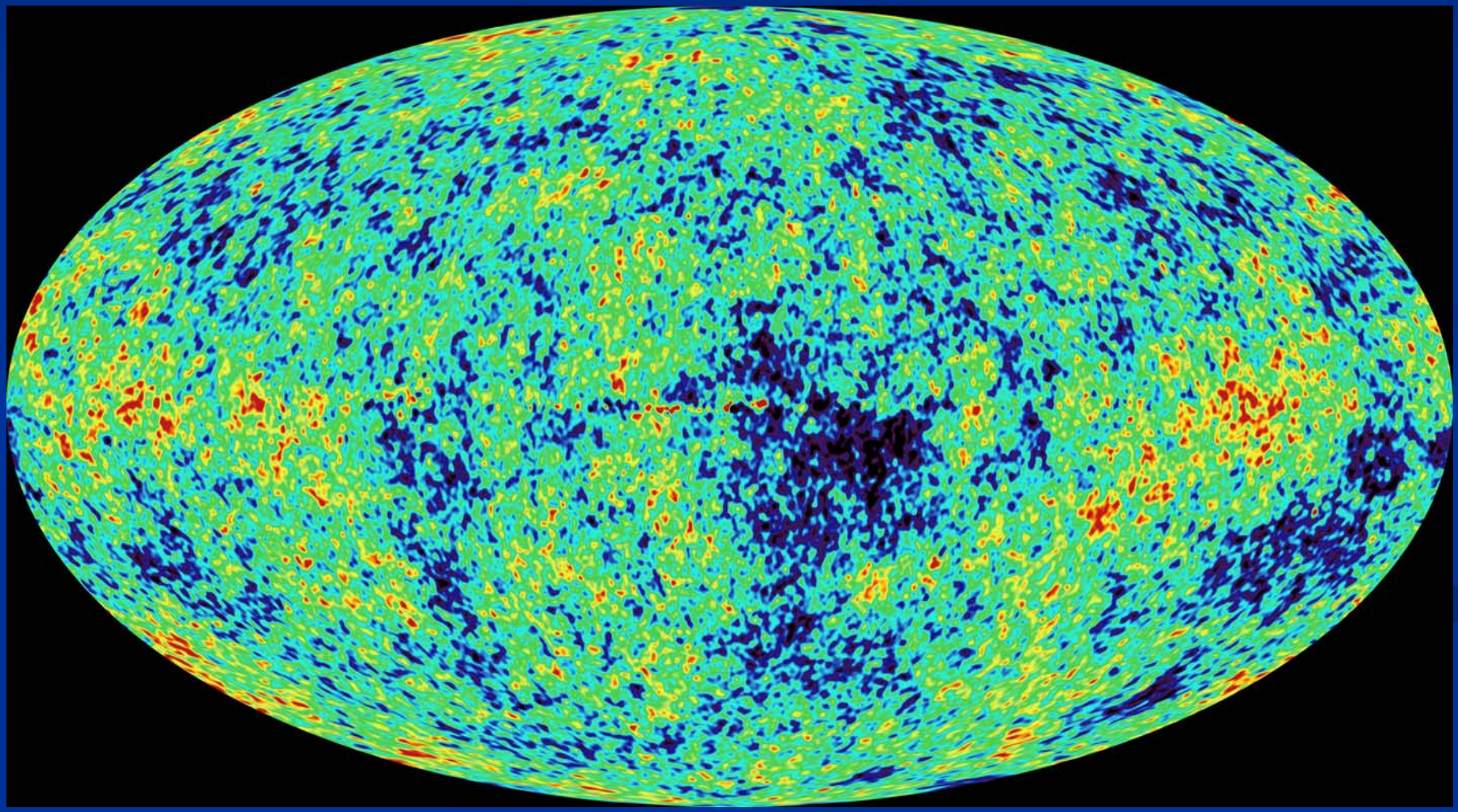
- theory (inflationary universe)

  Ω_{tot} =1.0000……x

- observation (WMAP)

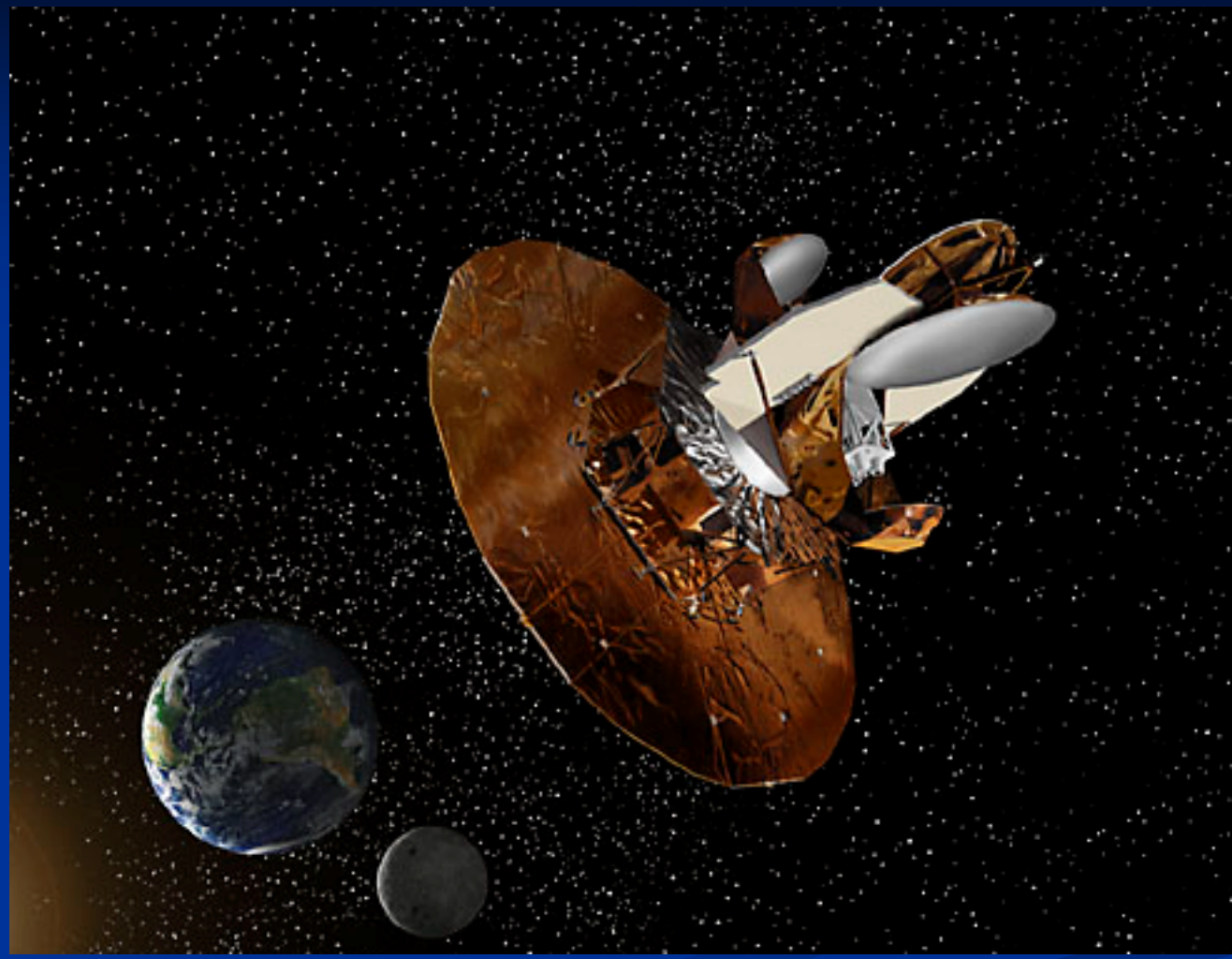
  Ω_{tot} =1.02 (0.02)

picture of the big bang



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

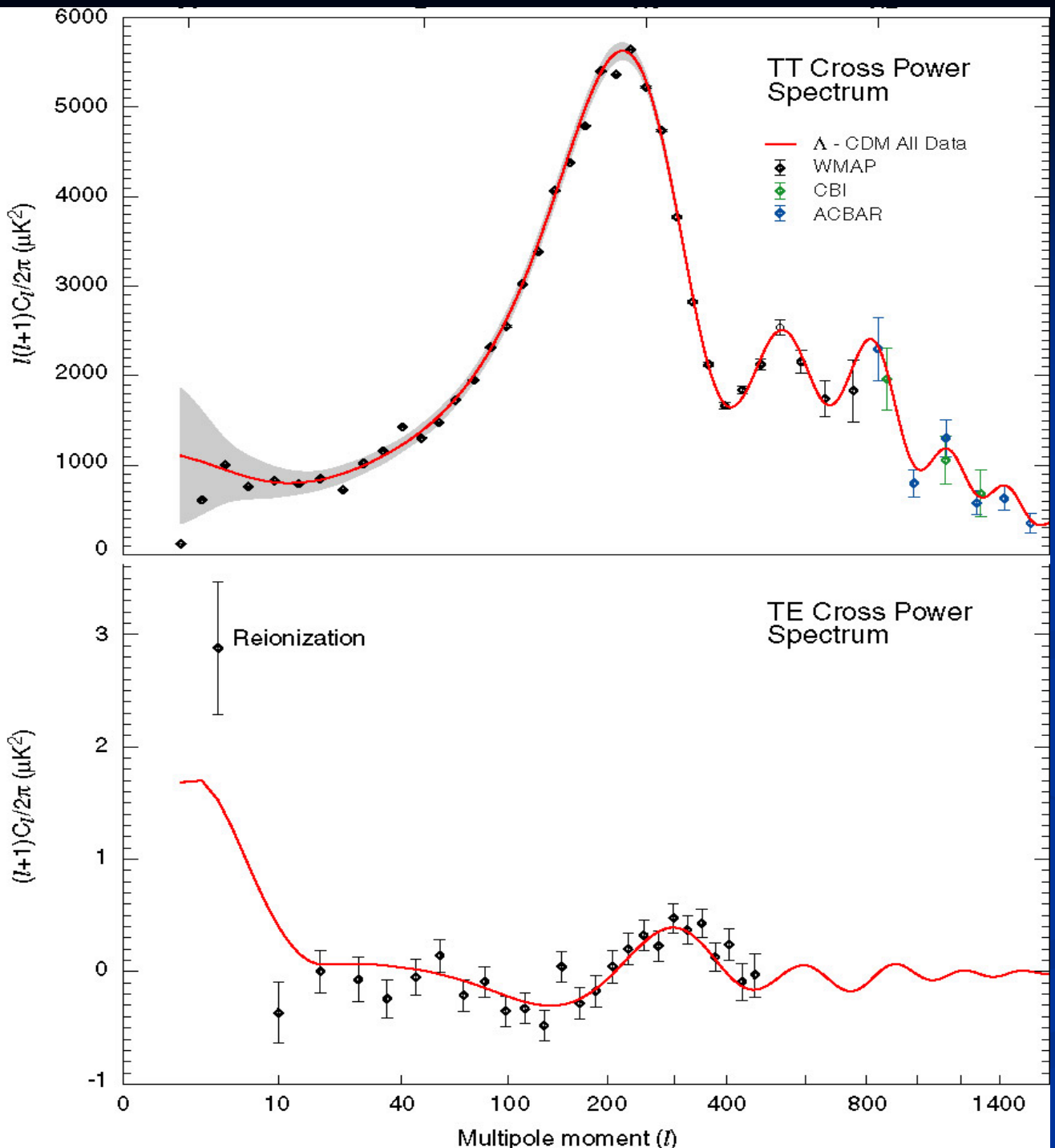
Brown
Greg Tucker

UCLA
Ned Wright

UBC
Mark Halpern

Chicago
Stephan Meyer

Princeton
Chris Barnes
Norm Jarosik
Eiichiro Komatsu
Michael Nolta
Lyman Page
Hiranya Peiris
David Spergel
Licia Verde



mean values

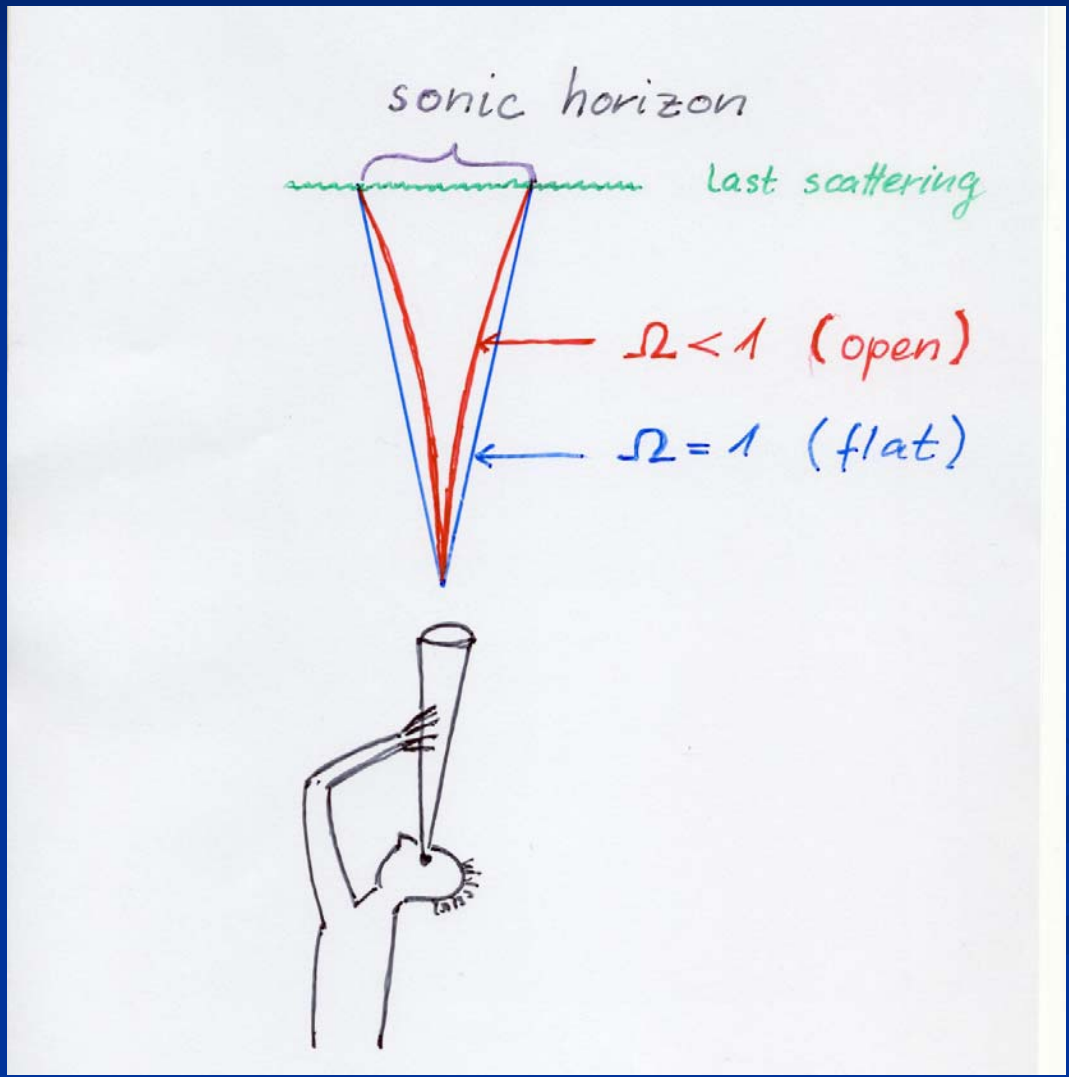
$\Omega_{tot} = 1.02$

$\Omega_{m} = 0.27$

$\Omega_{b} = 0.045$

$\Omega_{dm} = 0.225$

$\Omega_{tot}=1$



Dark Energy

$\Omega_m + X = 1$

Ω_m : 30%

Ω_h : 70% Dark Energy

h : homogenous , often Ω_Λ instead of Ω_h

Dark Energy :

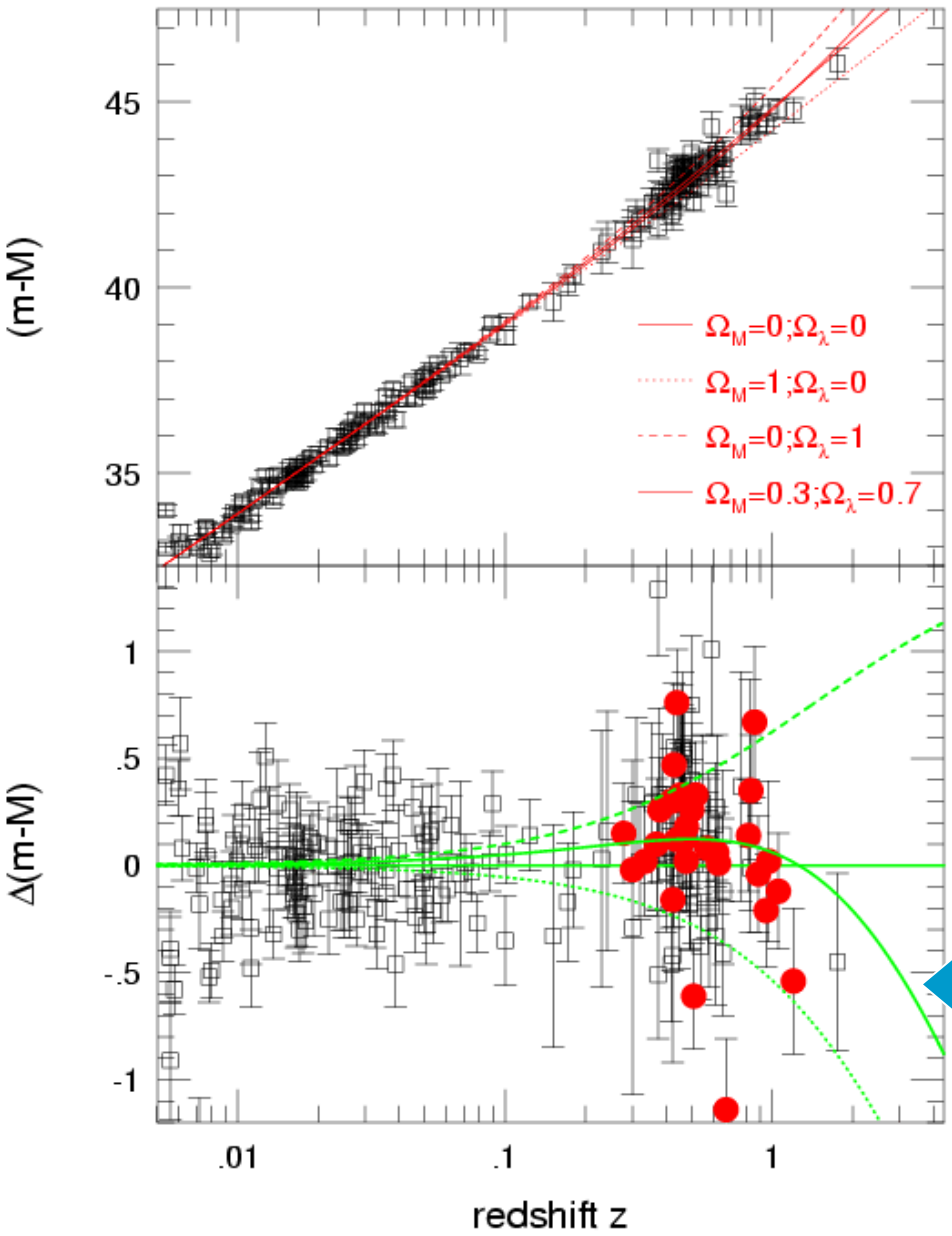
homogeneously distributed

Dark Energy :

prediction:

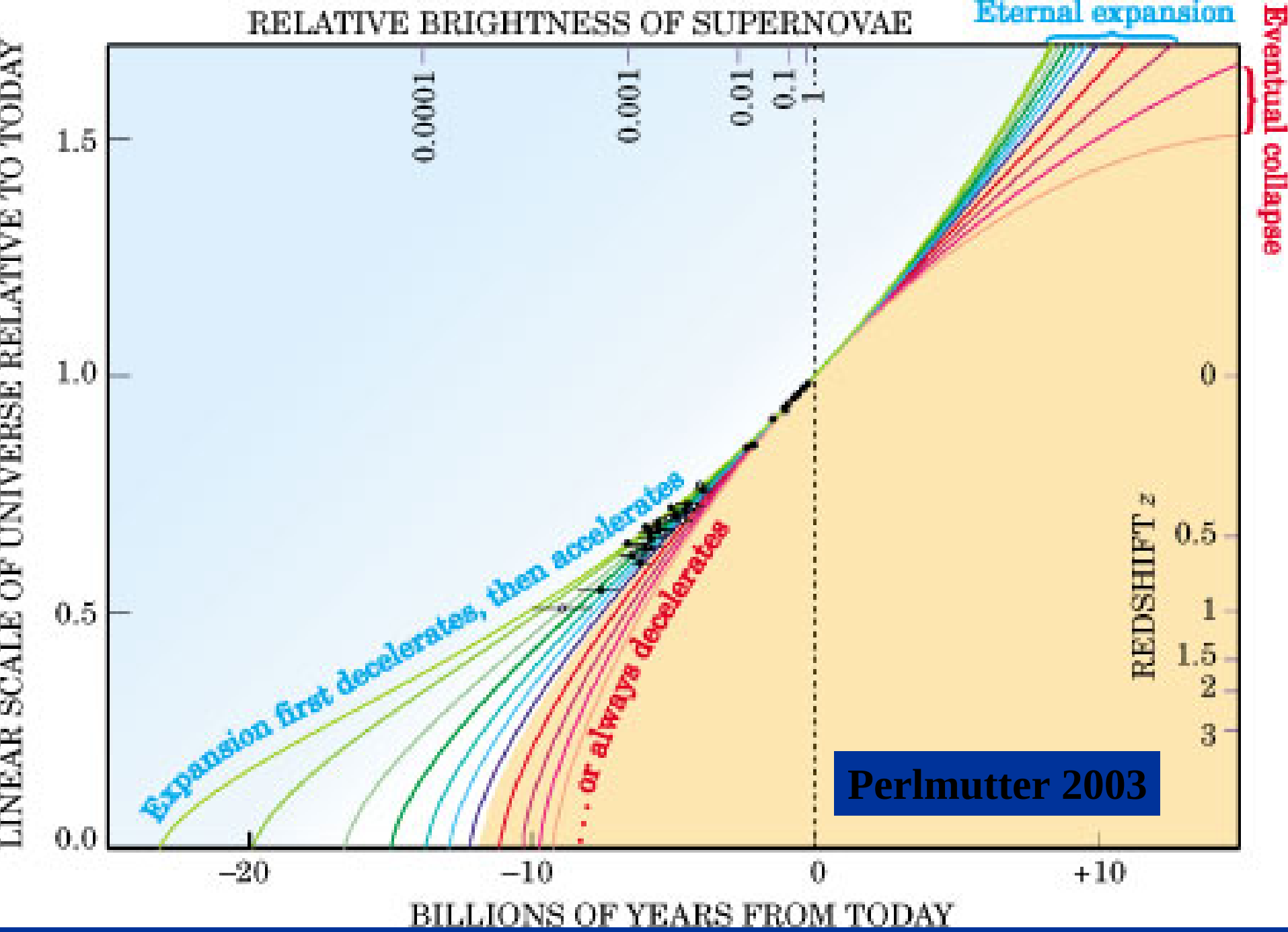
The expansion of the Universe accelerates today !

Supernova cosmology



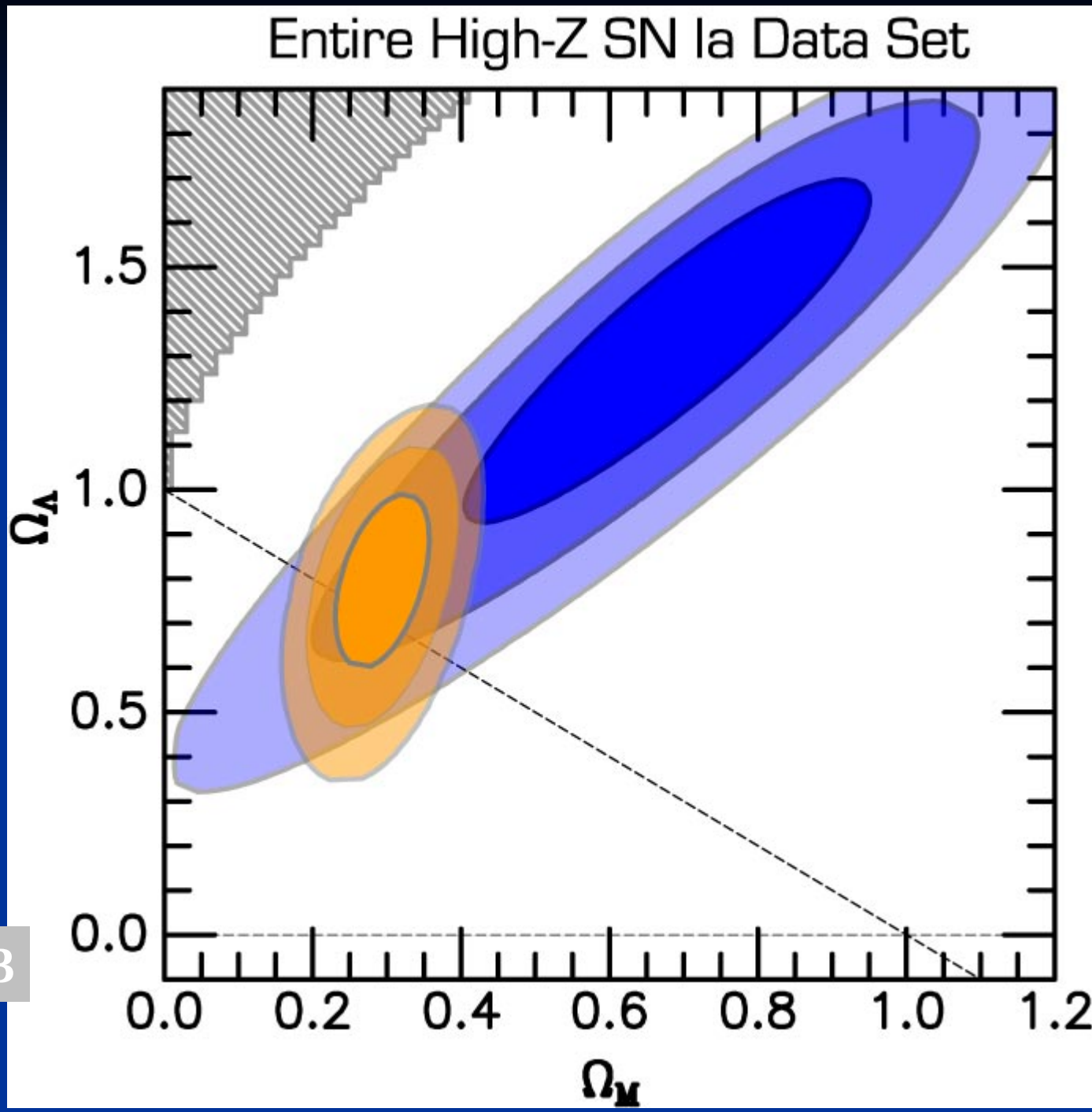
Ω_h=0.7

Tonry et al. 2003


RELATIVE BRIGHTNESS OF SUPERNOVAE
Eternal expansion
Eventual collapse
0.0001
0.001
0.01
0.1
1
LINEAR SCALE OF UNIVERSE RELATIVE TO TODAY
1.5
1.0
0.5
0.0
Expansion first decelerates, then accelerates
. . . or always decelerates
REDSHIFT z
0
0.5
1
1.5
2
3
Perlmutter 2003
−20
−10
0
+10
BILLIONS OF YEARS FROM TODAY

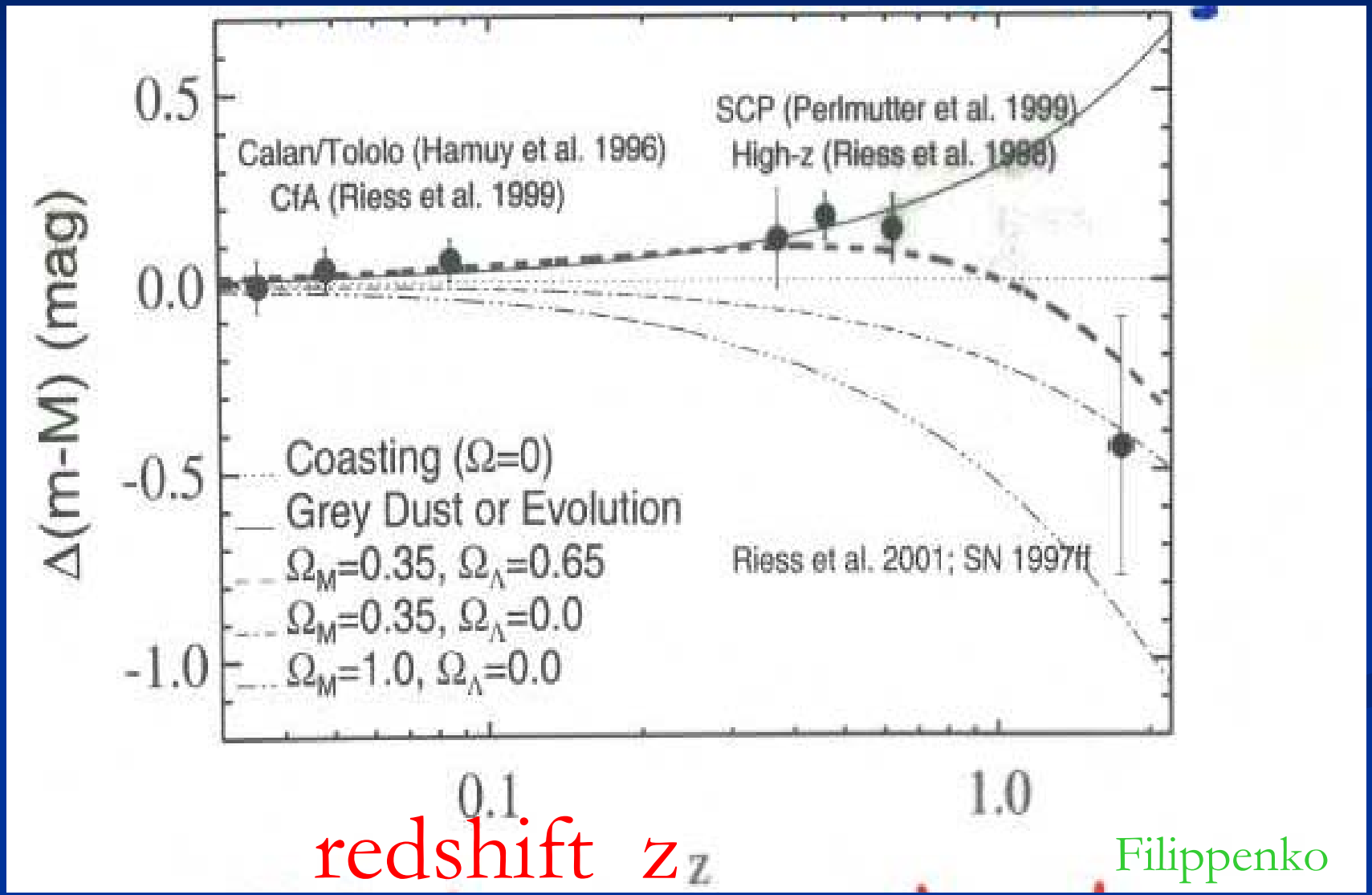
2dF:
Ω_M=0.2±0.03

KP:
h = 0.72 ± 0.08



Tonry et al. 2003

Supernova Ia Hubble-diagram



Filippenko

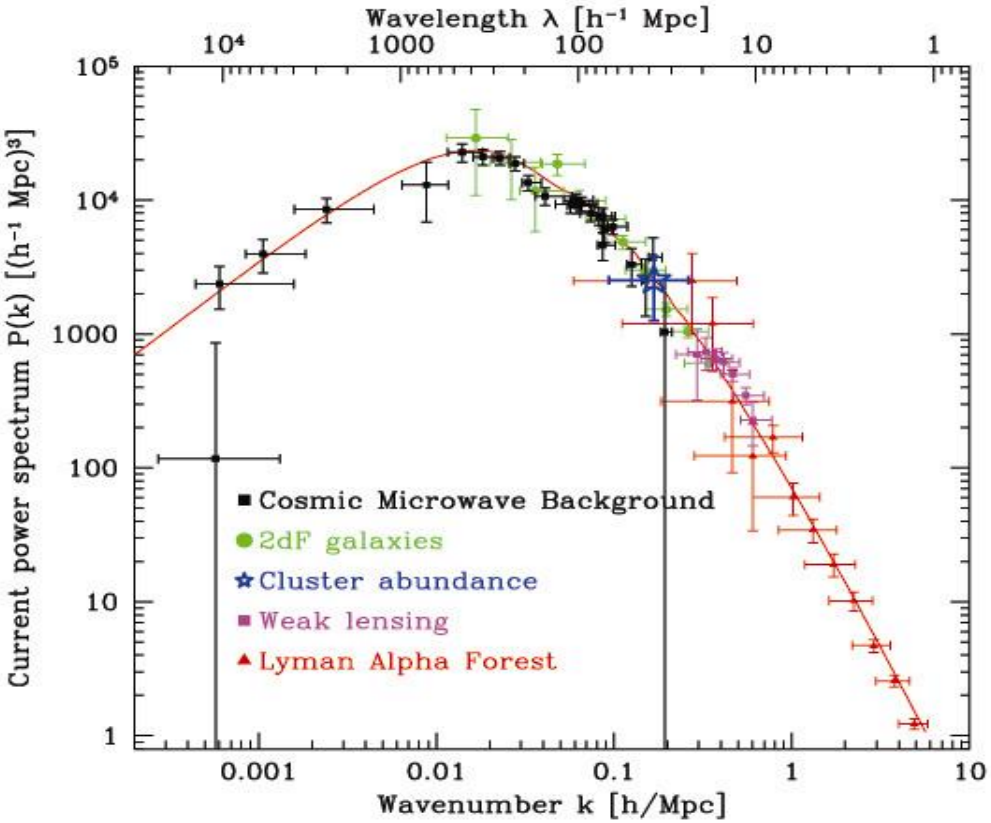
Structure formation

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

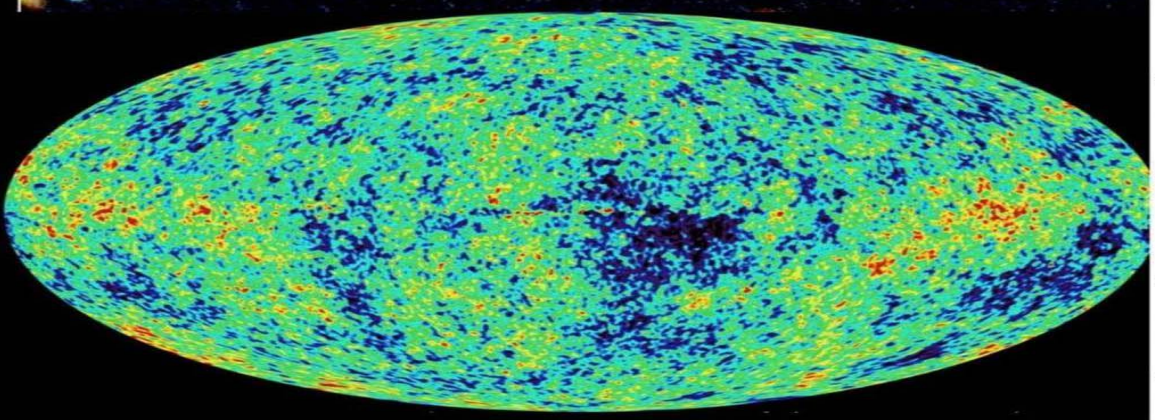
gravitational lensing effect !

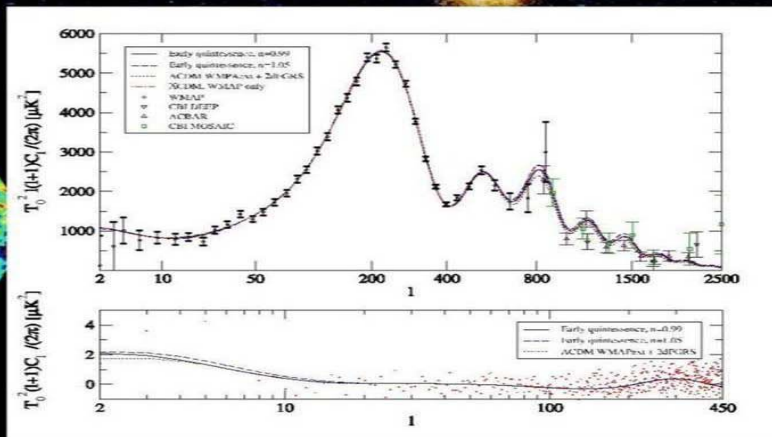
consistent cosmological model !

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 ?

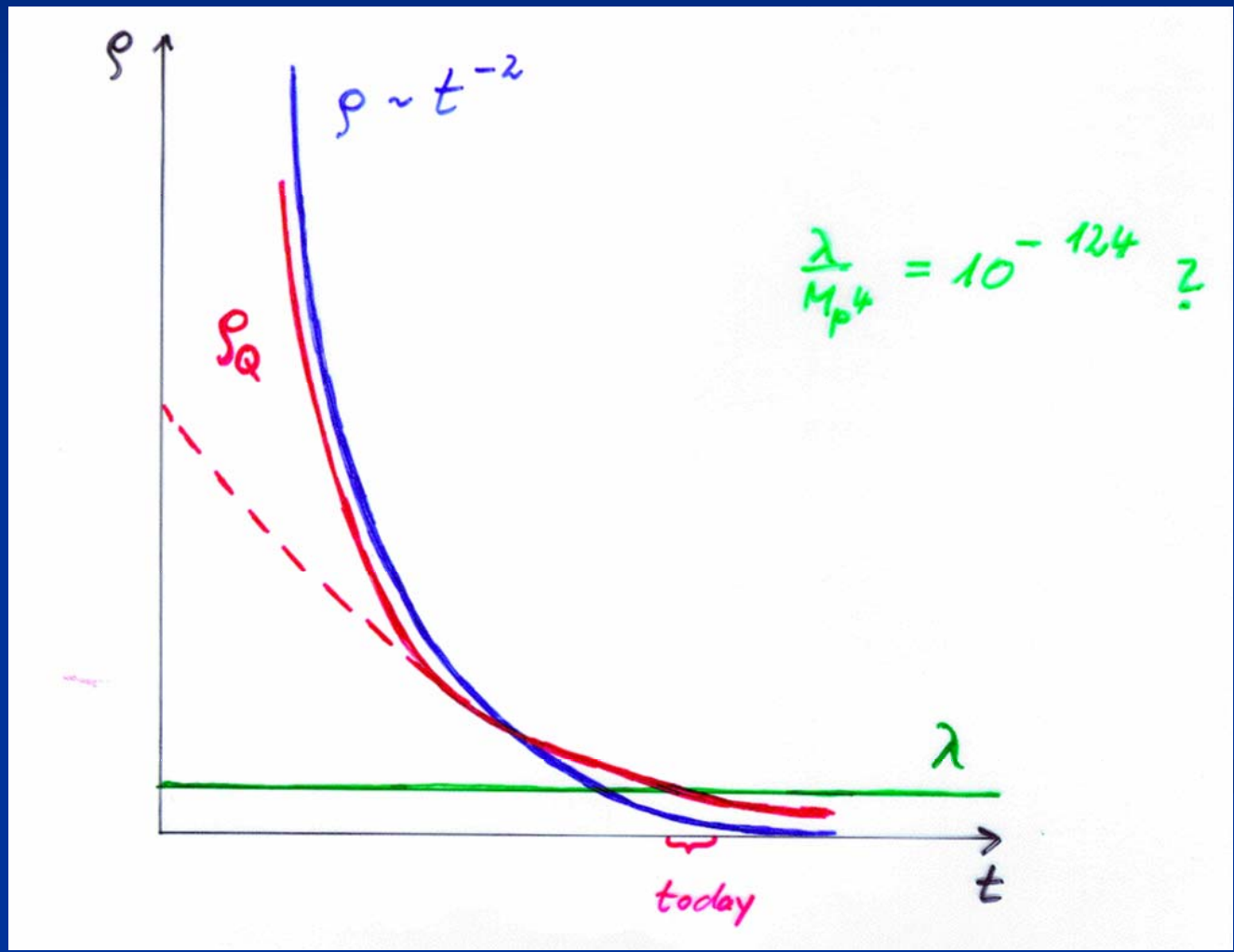
Cosmological Constant

- 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.	Quintessence
static	dynamical



Cosmological mass scales

- Energy density

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

- Reduced Planck mass

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

- Newton's constant

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

Only ratios of mass scales are observable !

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

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

Time evolution

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

Huge age ⇨ 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 :*

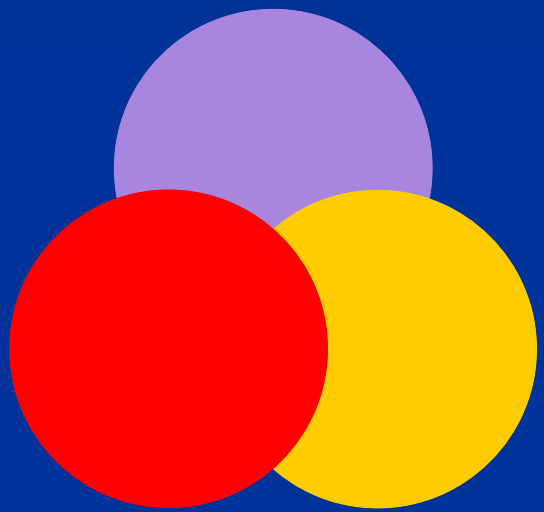
  $\varrho_h(t)$ *decreases with time !*

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 equation

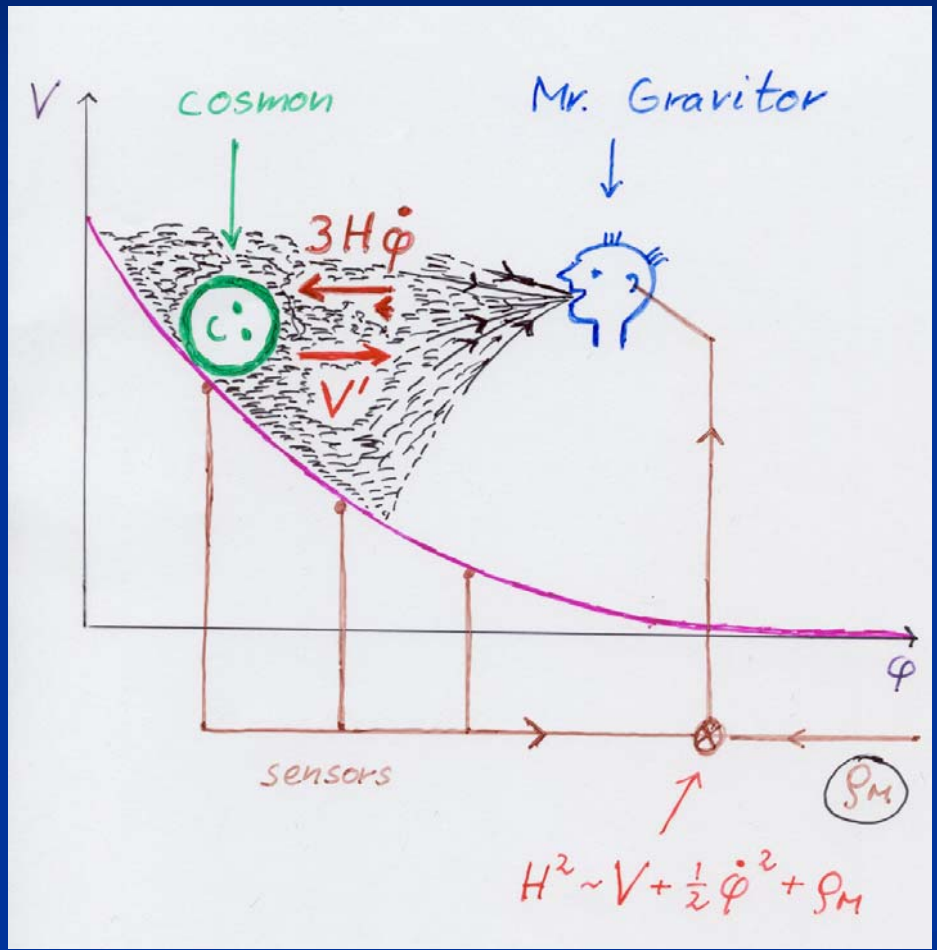
$$\ddot{\phi} + 3H\dot{\phi} = -dV/d\phi$$

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



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

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

Cosmic Attractors

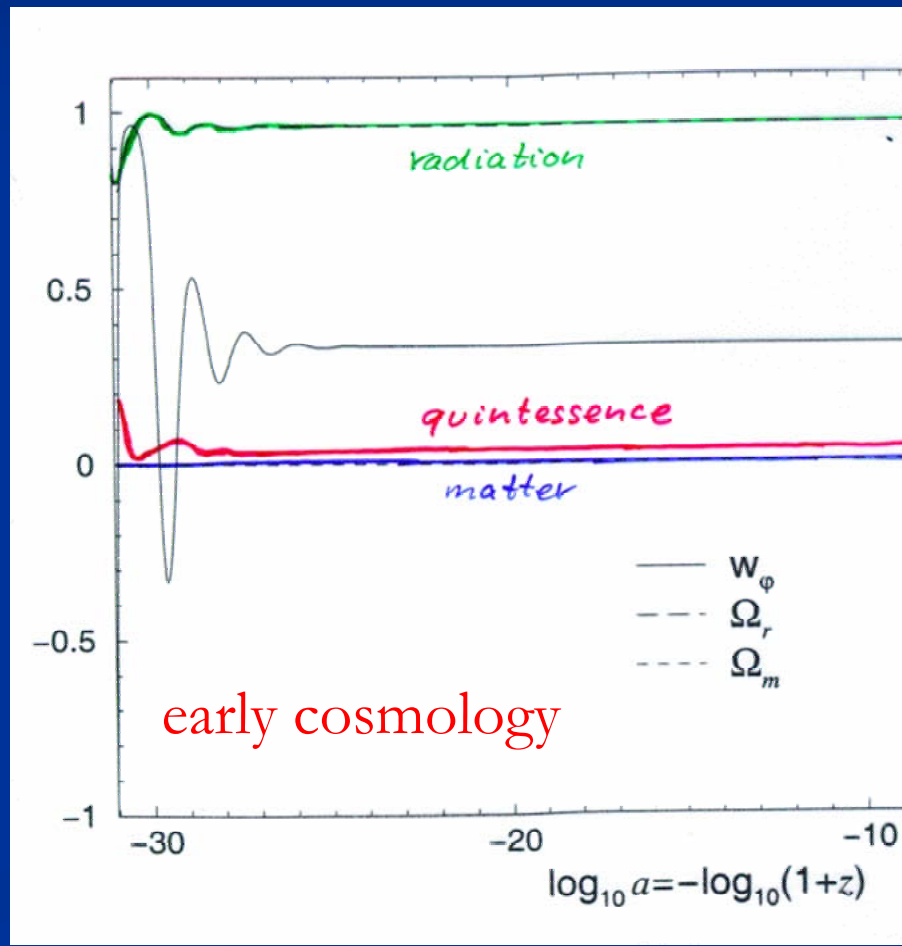
Solutions independent of initial conditions

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

$\varphi \sim \ln(t)$

$\Omega_h \sim$ const.

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



Dynamics of quintessence

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

  (units: reduced Planck mass M=1)
- Potential : $V=\exp[-\varphi]$
- "Natural initial value" in Planck era $\varphi=0$
- today: $\varphi=276$

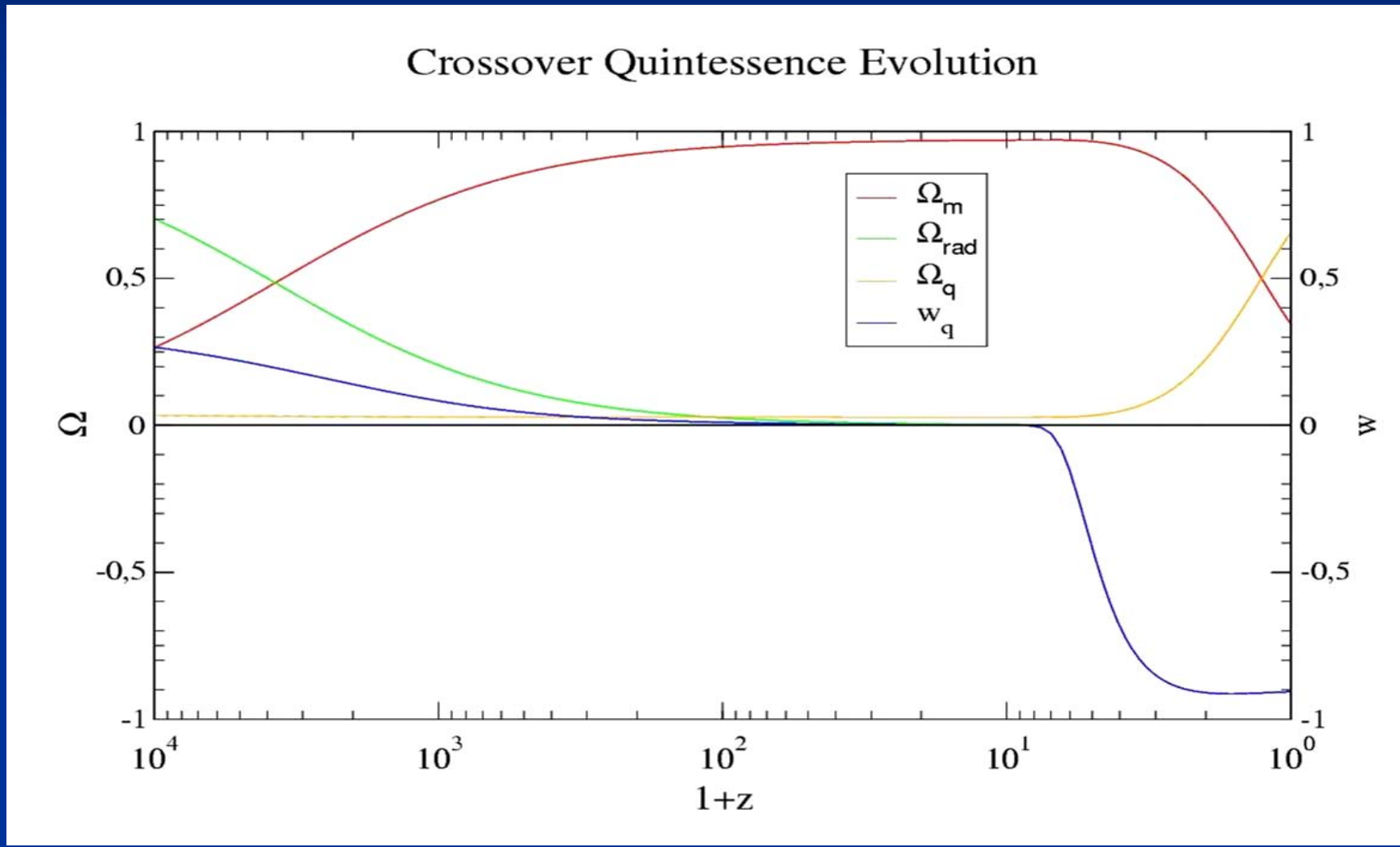
Quintessence models

- 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.
- Naturalness criterion:

$k(\varphi=0)/\ k(\varphi_{today})$: not tiny or huge !

- else: explanation needed -

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

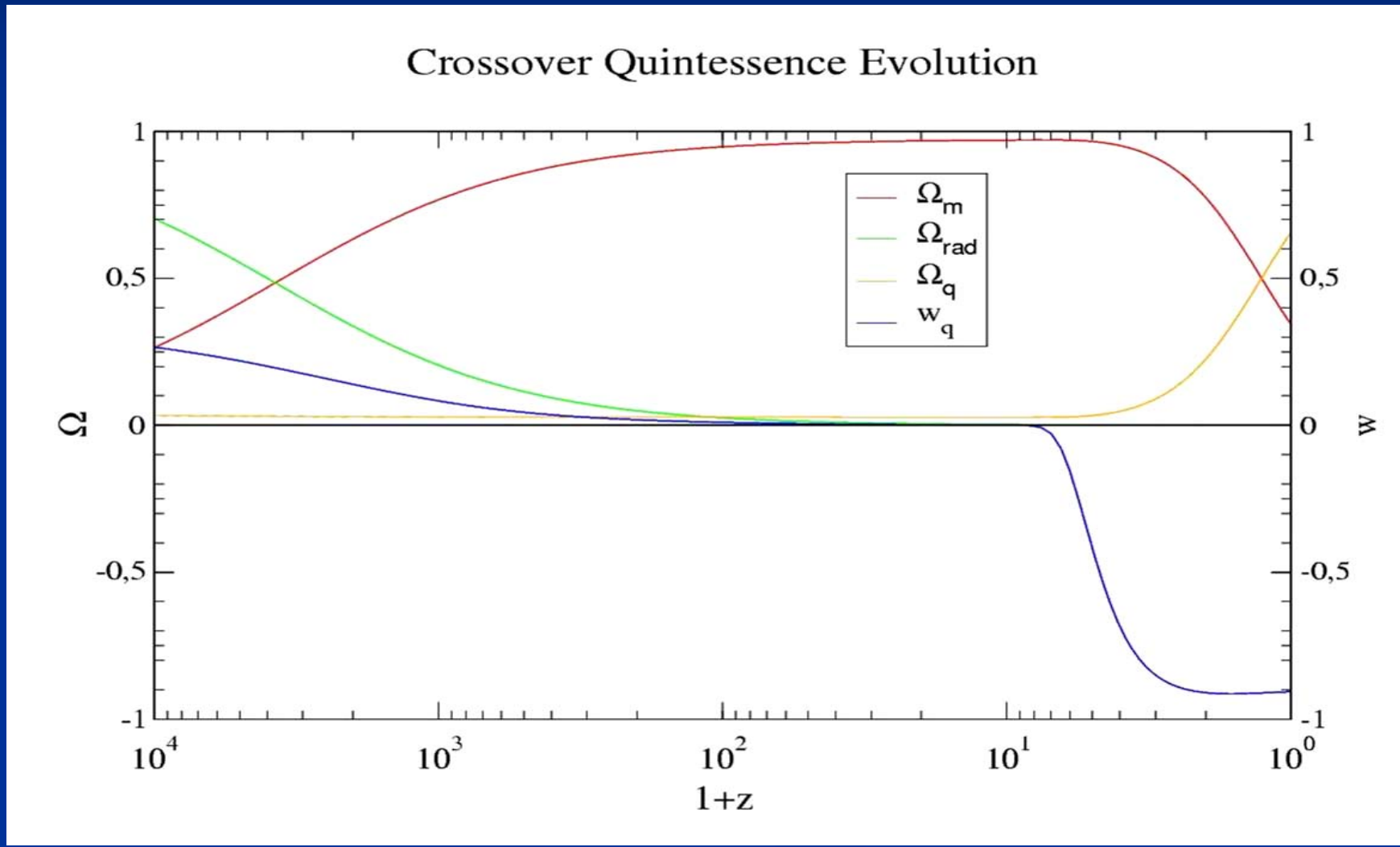
$$w = \frac{p}{\rho} = \frac{T-V}{T+V}$$

Depends on specific evolution of the scalar field

Negative pressure

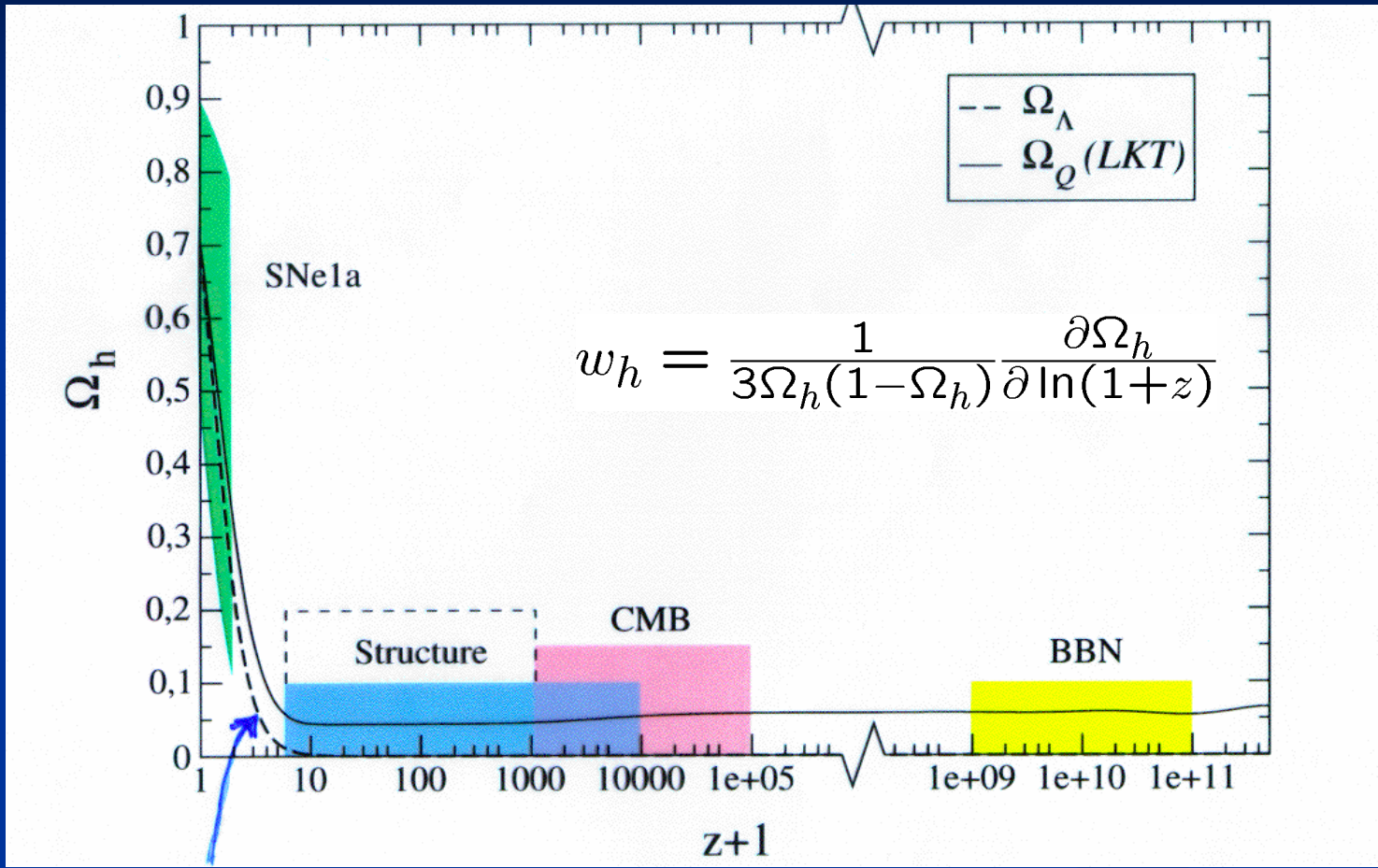
- $w < 0$ Ω_h increases
- $w < -1/3$ expansion of the Universe is accelerating
- $w = -1$ cosmological constant

Quintessence becomes important "today"



How can quintessence be distinguished from a cosmological constant ?

Time dependence of dark energy



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

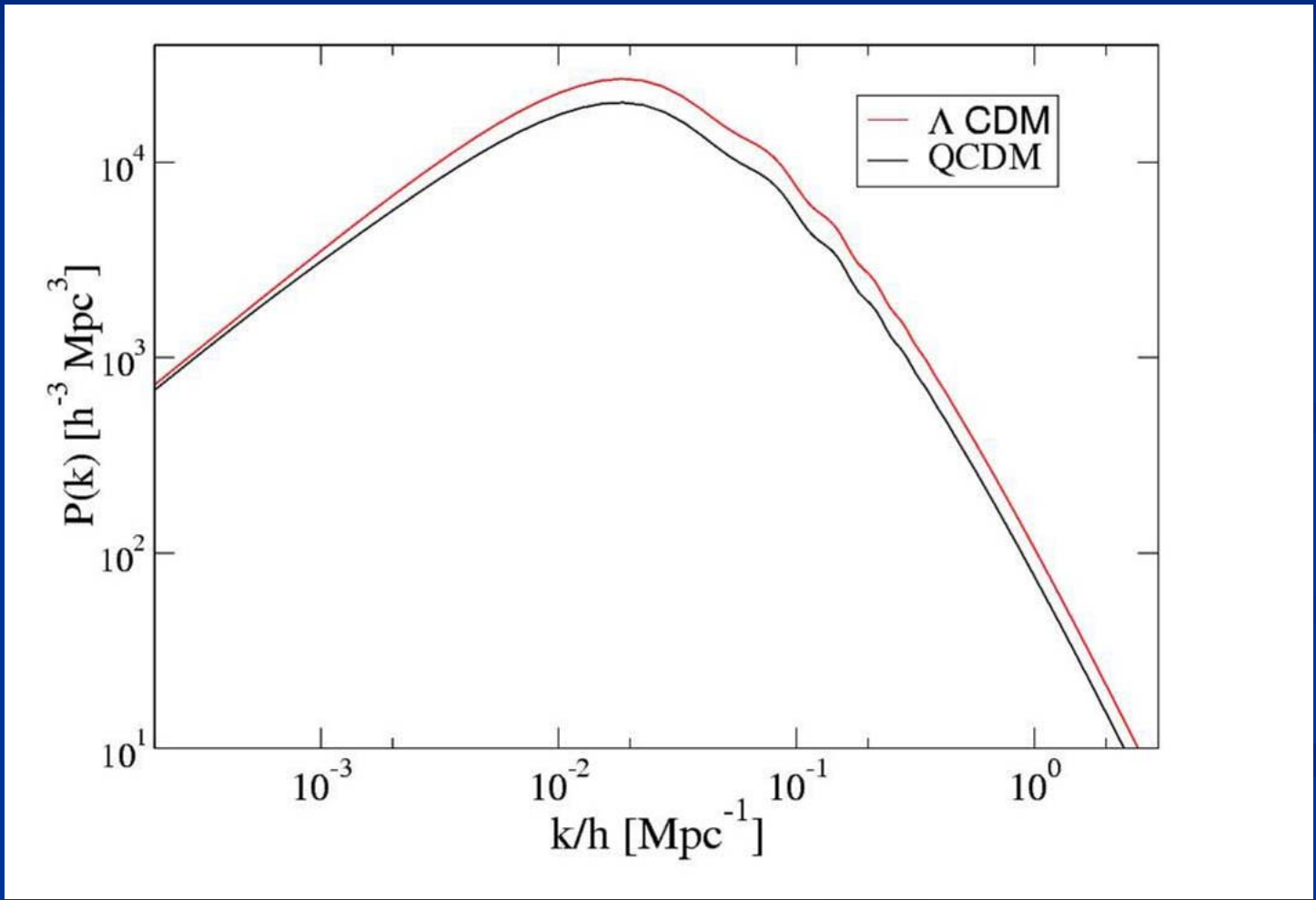
M.Doran,…

Early dark energy

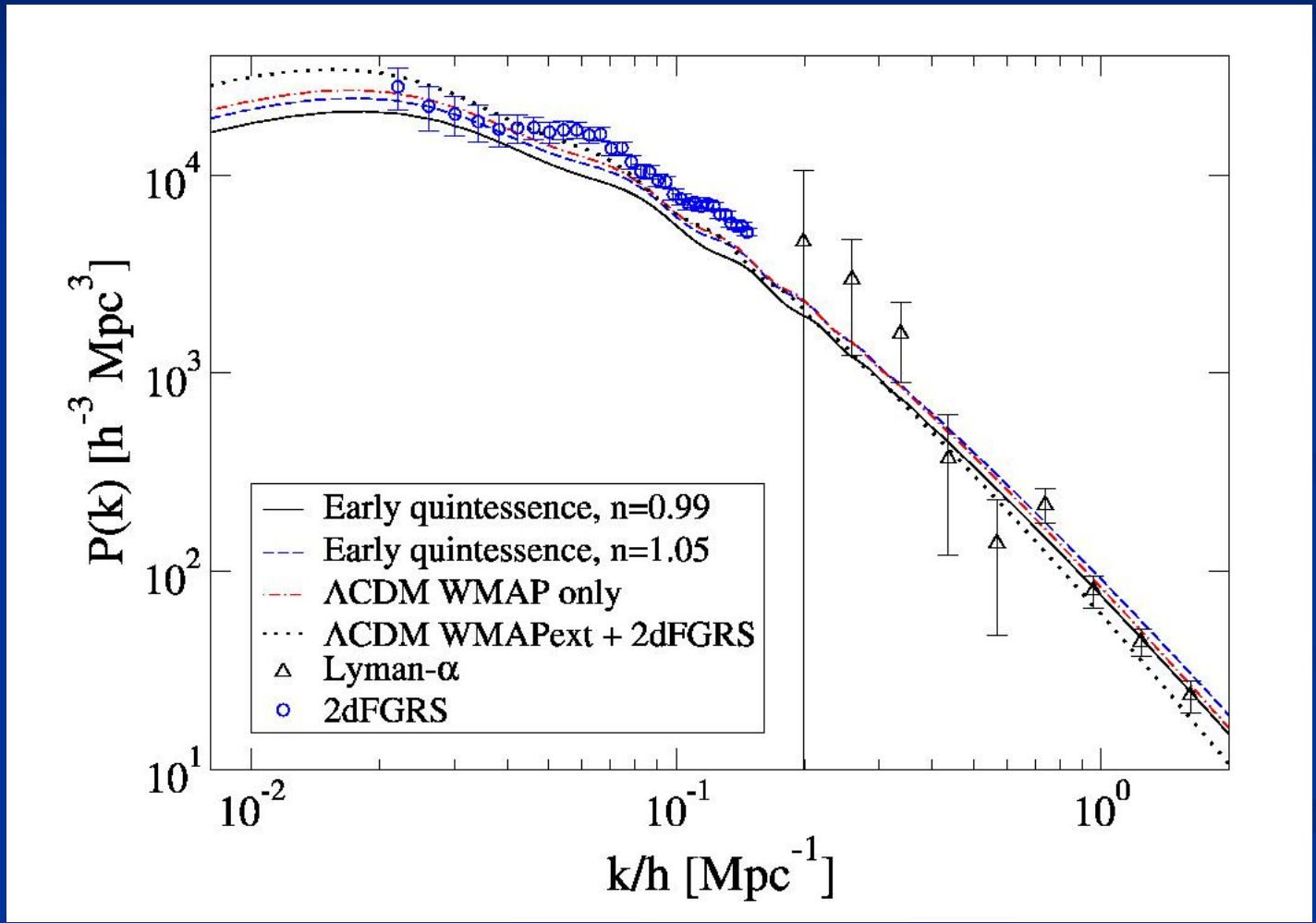
A few percent in the early Universe

Not possible for a cosmological constant

Early quintessence slows down the growth of structure

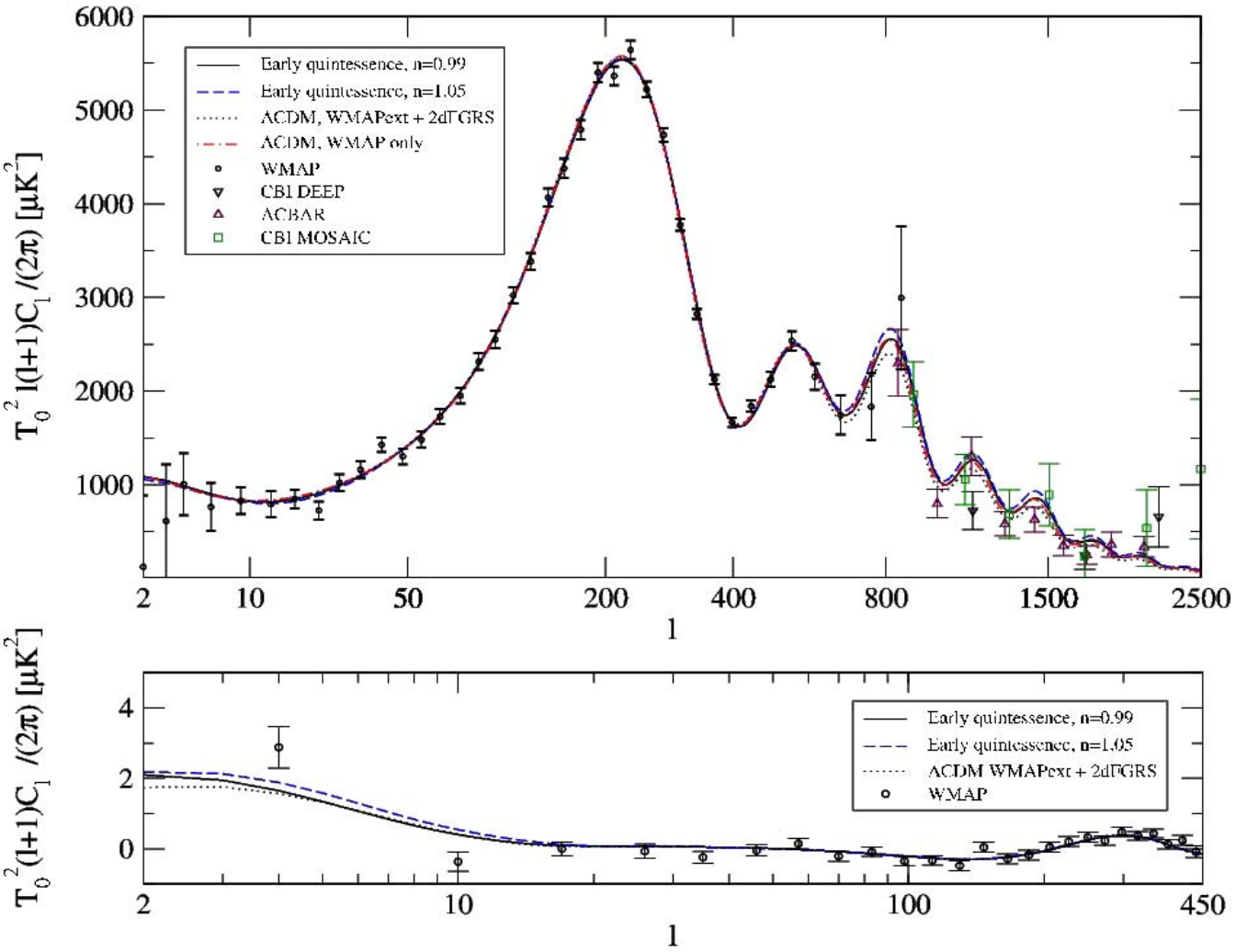


Fluctuation spectrum



Caldwell,Doran,Müller,Schäfer,…

Anisotropy of cosmic background radiation



Caldwell,Doran,Müller,Schäfer,…

How to distinguish Q from 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"

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 : $\alpha(\varphi)$

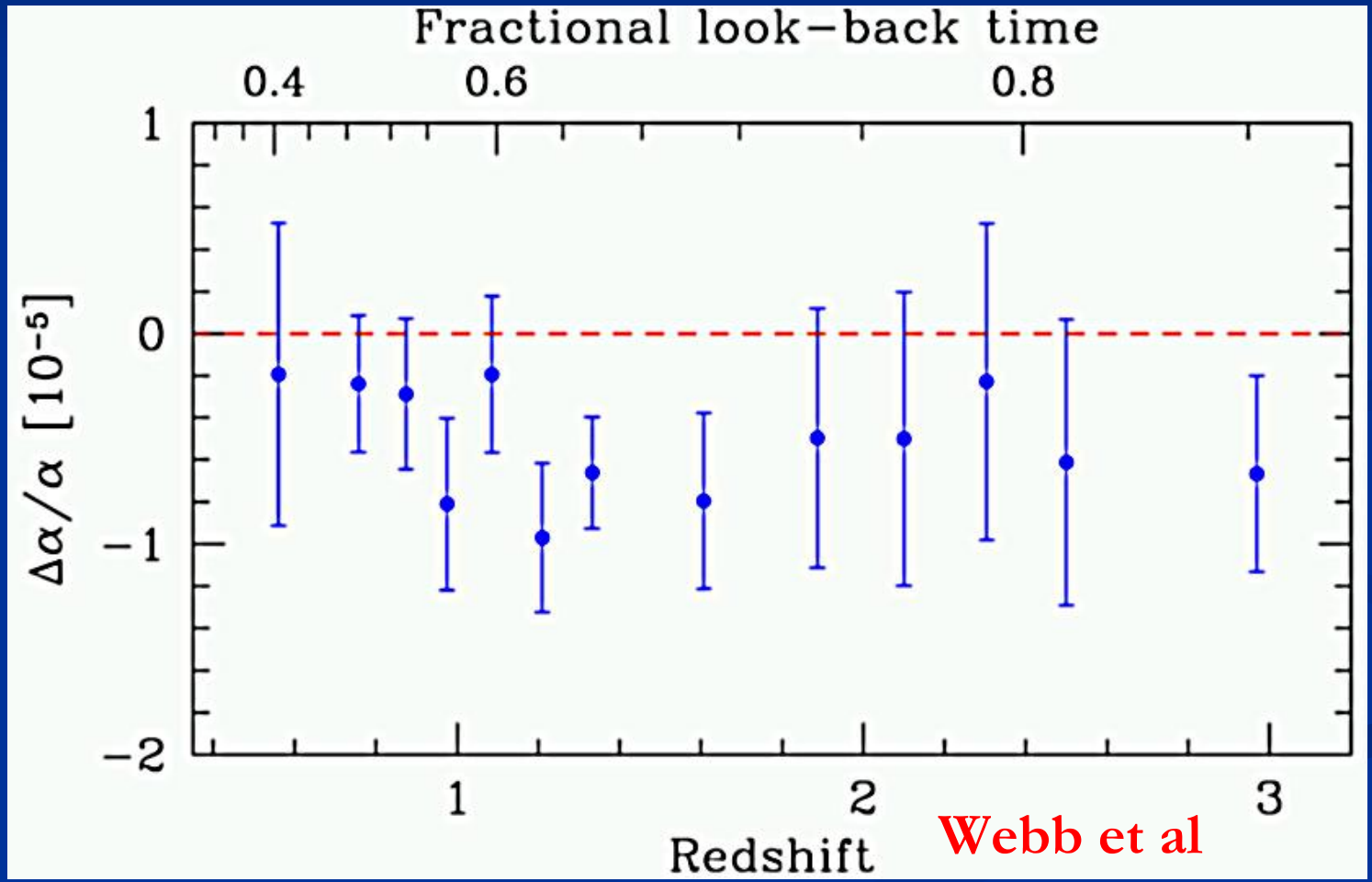
- Time evolution of φ ⇒ Time evolution of α

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

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

Webb et al

Variation of fine structure constant as function of redshift



Variation of fine structure constant

Three independent data sets from Keck/HIRES

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

Murphy,Webb,Flammbaum, june 2003

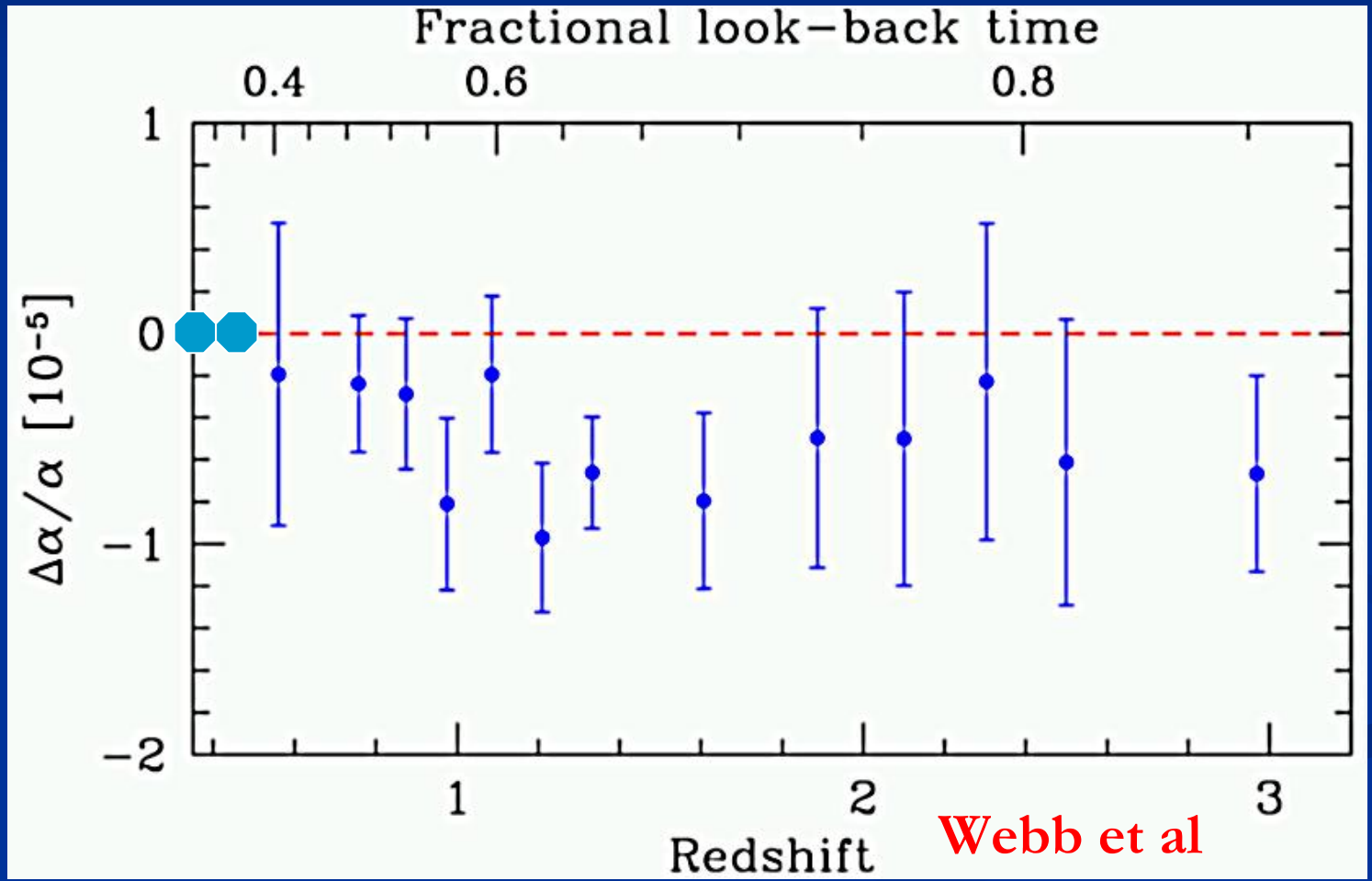
Crossover quintessence and time variation of fundamental "constants"

Upper bounds for relative variation of the fine structure constant

- Oklo natural reactor $\Delta\alpha/\alpha < 10^{-7}$ $z=0.13$
- Meteorites (Re-decay) $\Delta\alpha/\alpha < 3\ 10^{-7}$ $z=0.45$

- Crossover Quintessence compatible with QSO and upper bounds !

Variation of fine structure constant as function of redshift



Time evolution of fundamental couplings traces time evolution of quintessence

today w_h close to -1 :

- Small kinetic energy
- Slow change of φ
- Slow change of α

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

Παντα ρει

Cosmodynamics

Cosmon mediates new long-range interaction

Range : size of the Universe – horizon

Strength : weaker than gravity

photon	electrodynamics
graviton	gravity
cosmon	cosmodynamics

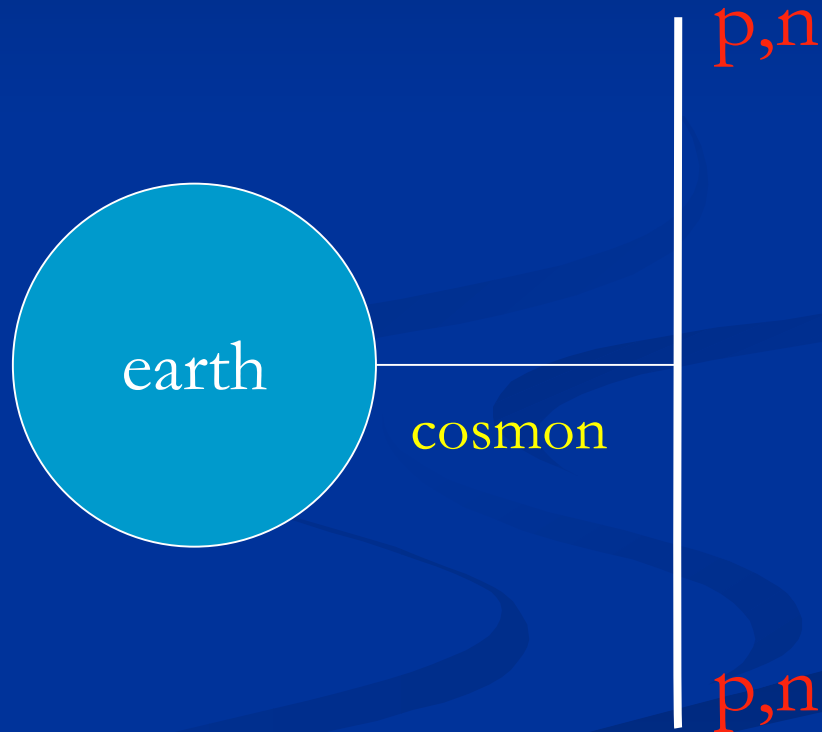
Small correction to Newton's law

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) :

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

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

η=Δa/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

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Growth of density fluctuations

- Matter dominated universe with constant Ω_h :

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

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 ~ 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,…)
- $M_p \sim \chi$, $m_{proton} \sim \chi$, $\Lambda_{QCD} \sim \chi$, $M_W \sim \chi$,…
- χ may evolve with time
- m_n/M : (almost) constant - ***observation*** !

Only ratios of mass scales are observable

Dilatation symmetry

- Lagrange density:

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

- Dilatation symmetry for

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

- Conformal symmetry for δ=0

Dilatation anomaly

- Quantum fluctuations responsible for dilatation anomaly
- Running couplings:

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

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

Weyl scaling

Cosmology : χ increases with time !

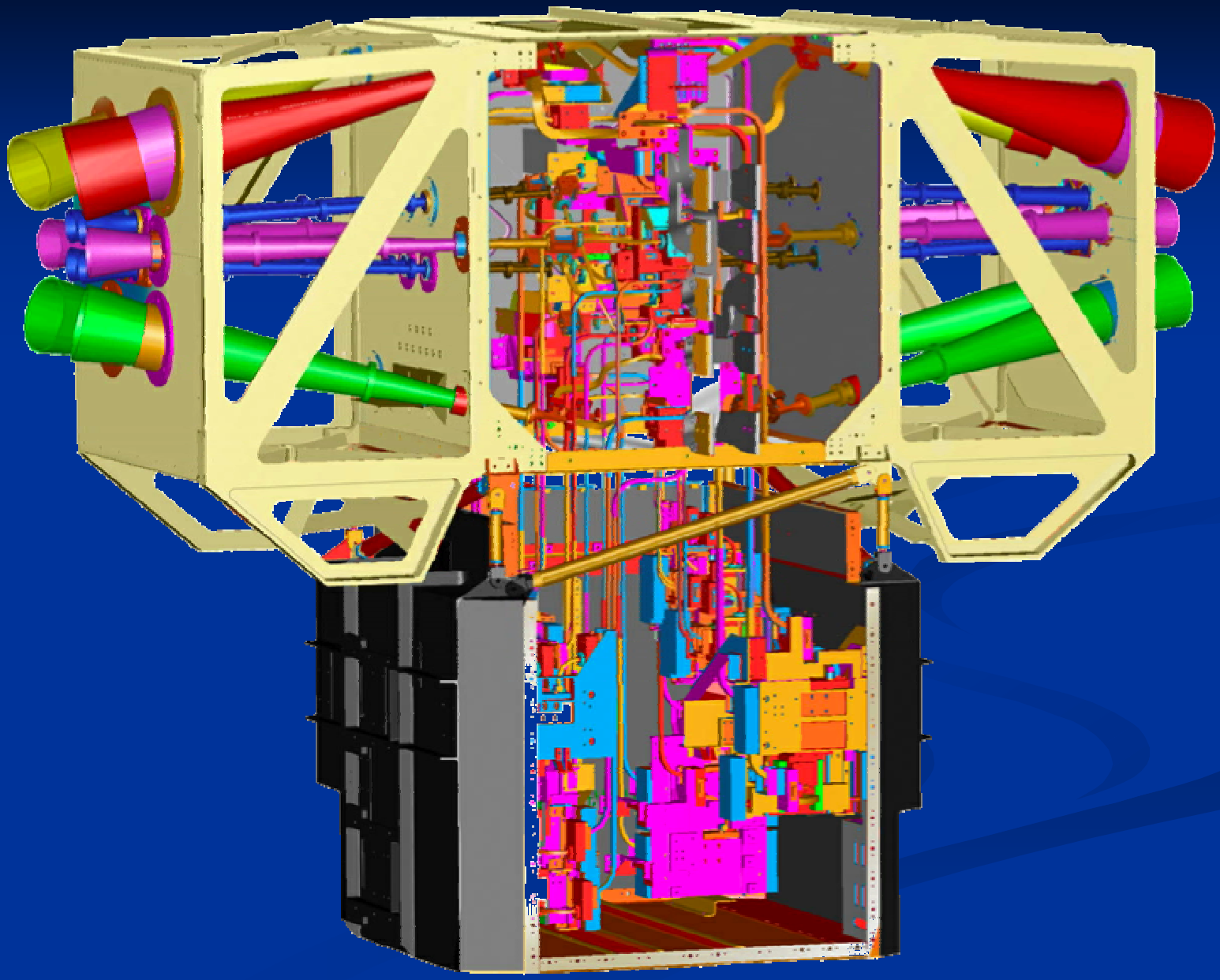
(" late time cosmology explores the ultraviolet")

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

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

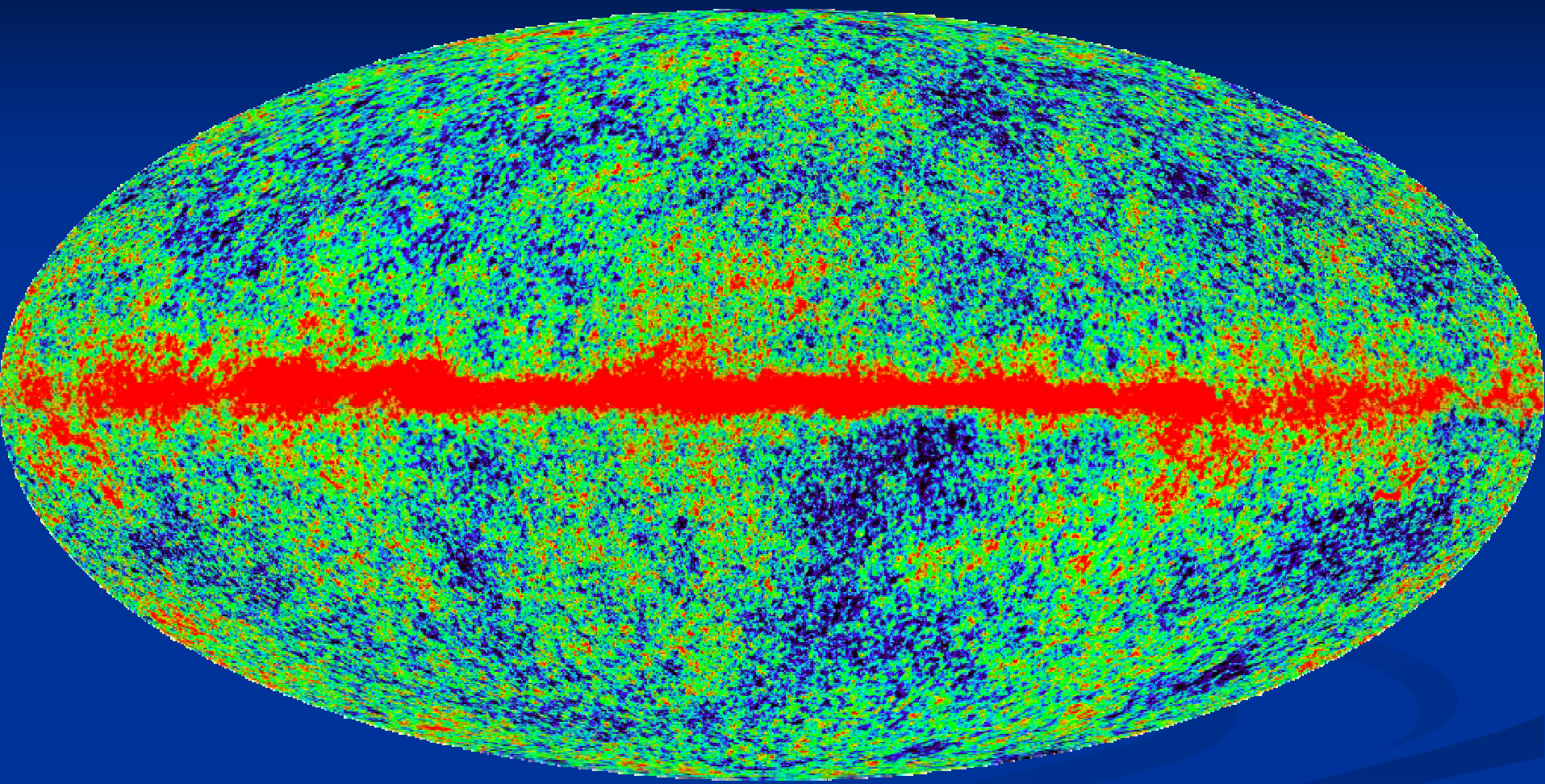
$$L = \sqrt{g}(-\frac{1}{2}M^2R + \frac{1}{2}k^2\partial^\mu\phi\partial_\mu\phi + V(\phi) + m_n\overline{\psi}\psi)$$

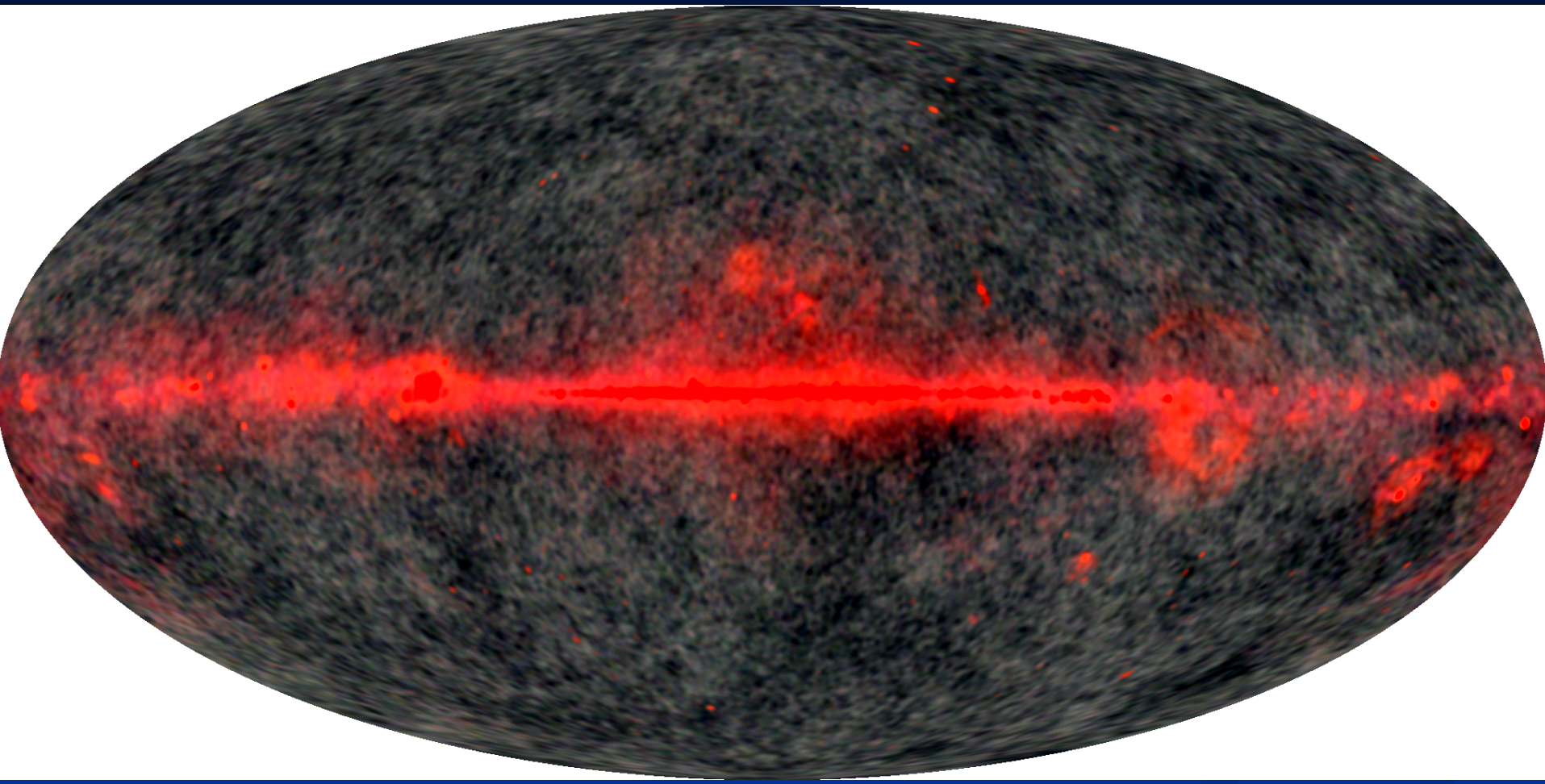
Exponential potential : $V = M^4 \exp(-\varphi/M)$



W 94 GHz

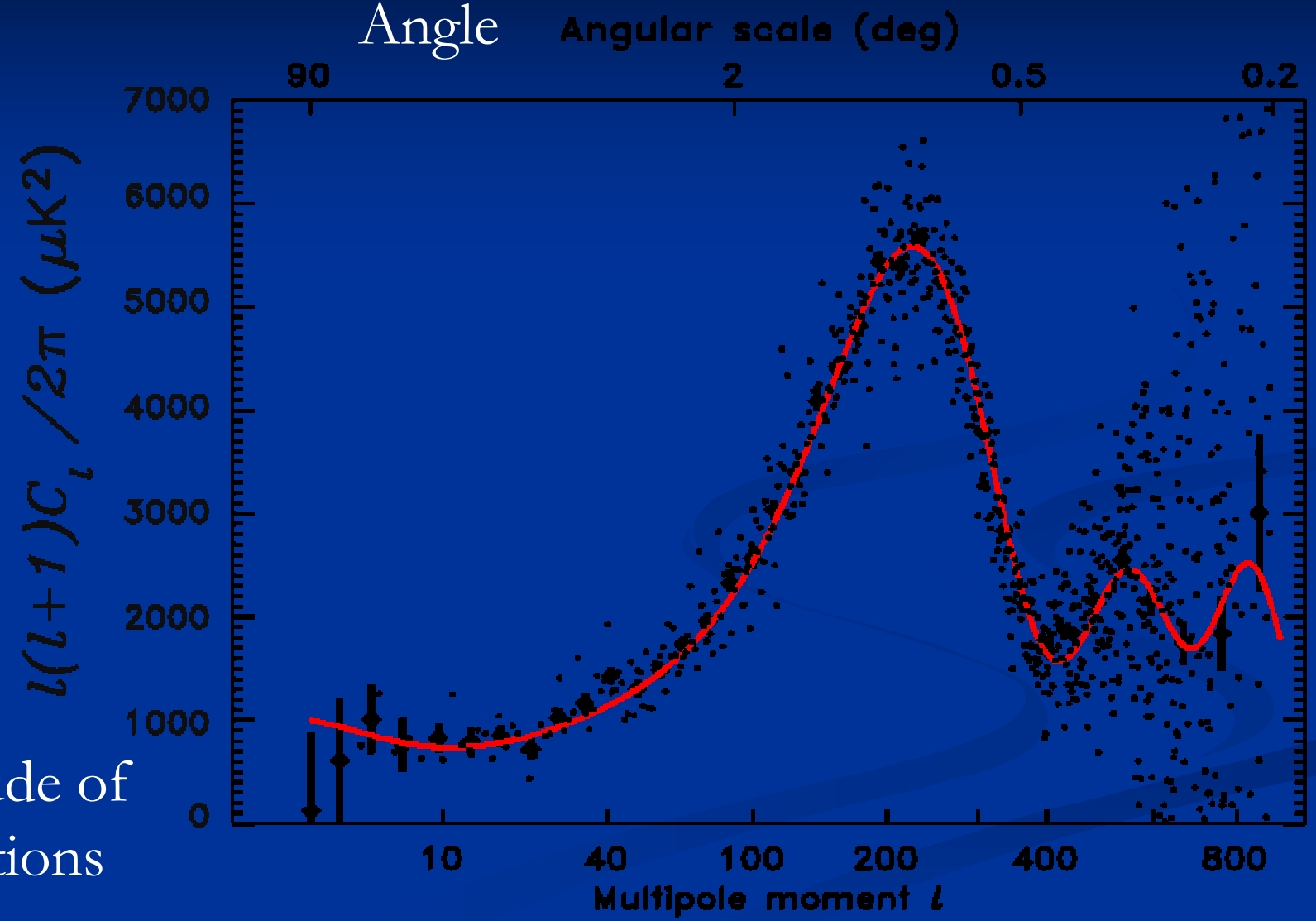
Dipole Removed





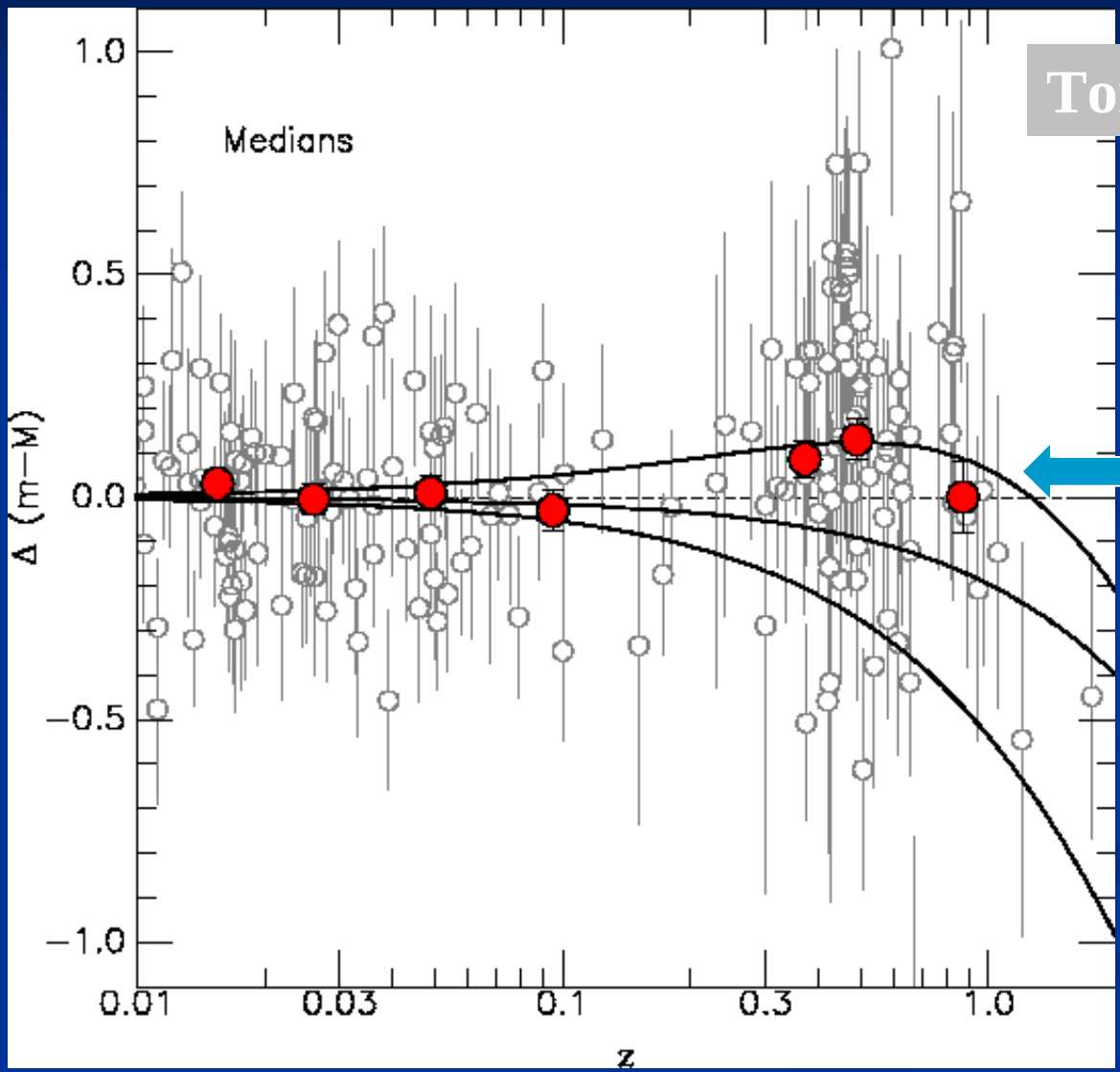
WMAP Angular Power Spectrum

Anisotropy of CMB



amplitude of fluctuations

209 SN Ia and medians



Tonry et al. 2003

$\Omega_h = 0.7$

$\Omega_m = 0.3$