Cherenkov Conference-2004

Modern State of Cosmology

V.N. Lukash
Astro Space Centre of
Lebedev Physics Institute

bservational status

tructure formations

nitial conditions

osmological parameters

egeneracies

$$h\left(\frac{\Omega_m}{0.3}\right)^{1/3} = 0.7$$

$$n_S \leftrightarrow \omega_b$$

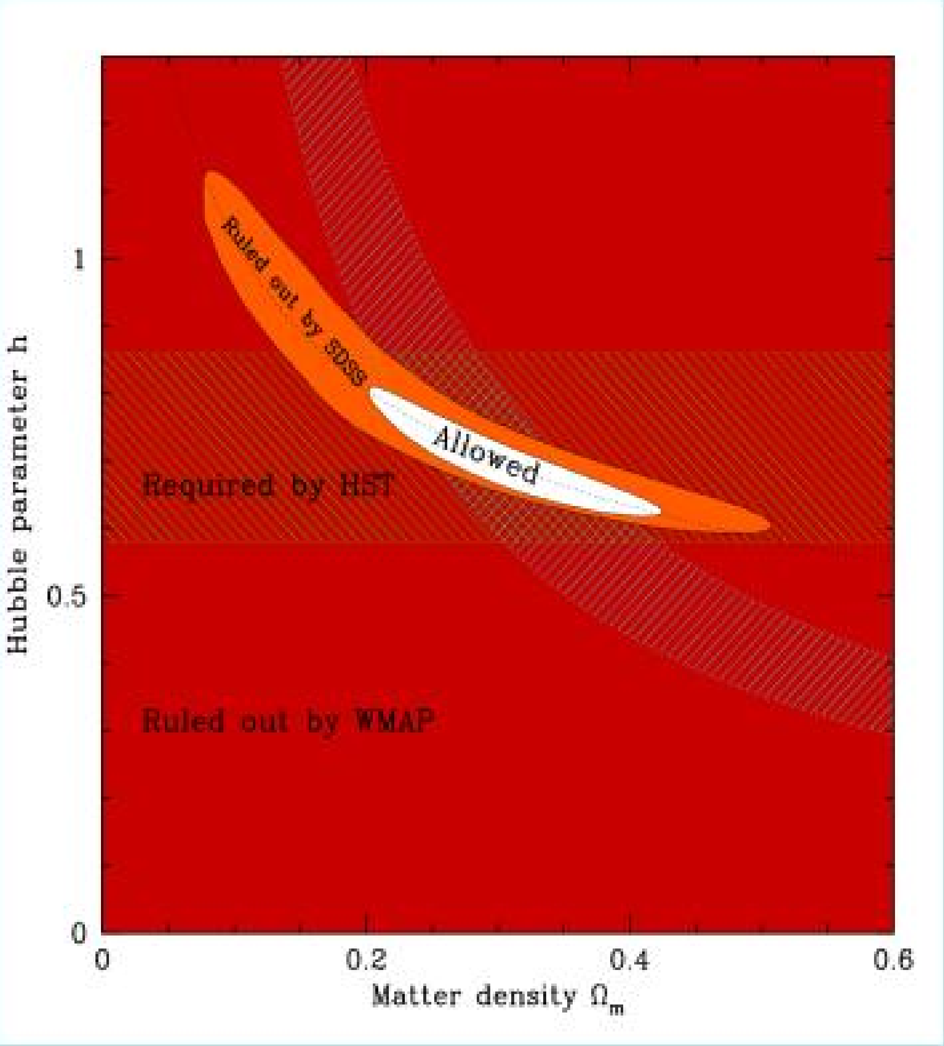
$$\sigma_8 e^{-\tau} = 0.7$$

Ω_Λ

$h \Rightarrow$ ω_{cb}, n_S

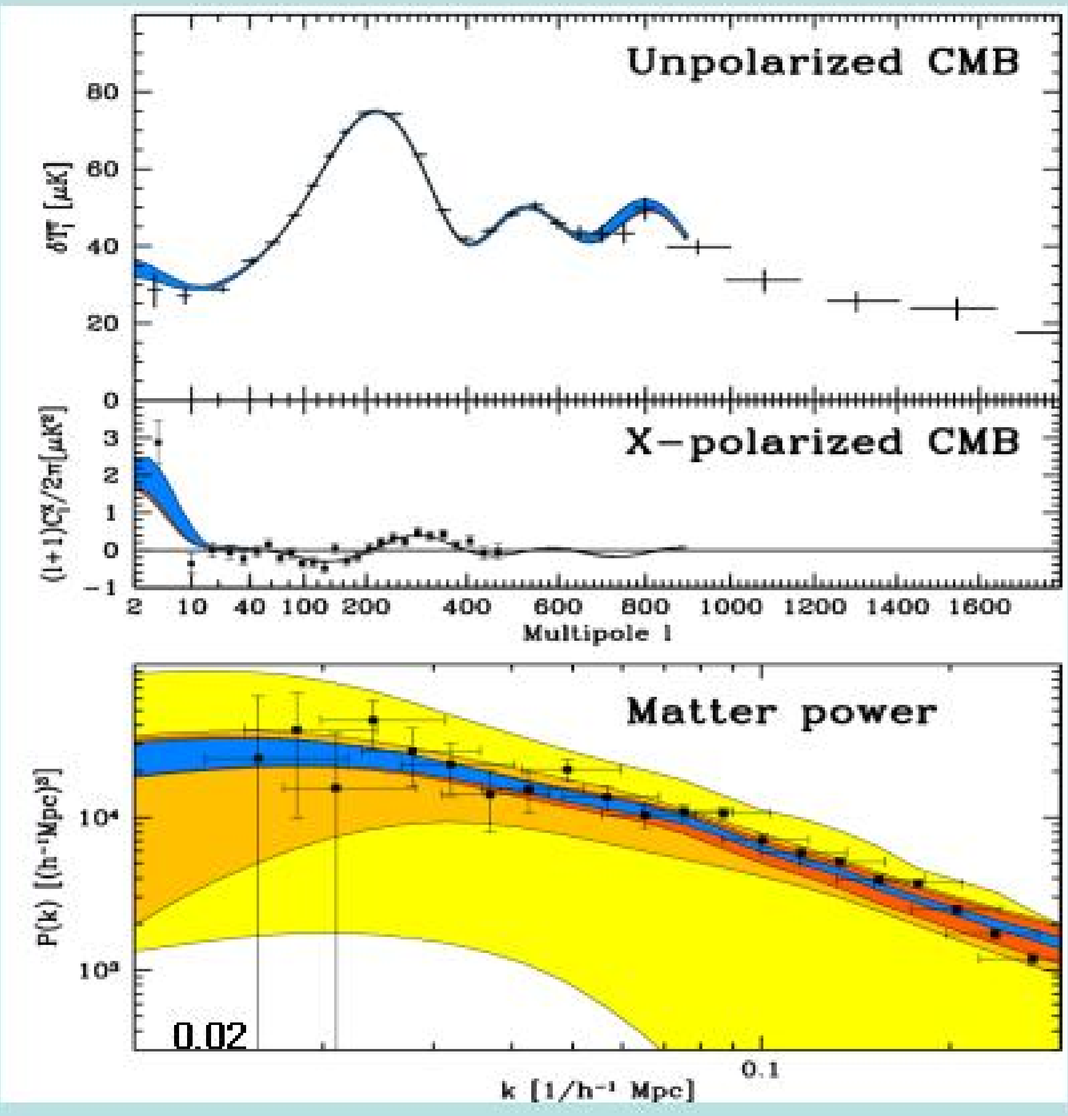
τ, σ_8

Cosmic Hubble parameter



Tegmark et al., 2003

Observational status



Coincidence between two scales:

LSS (DM) and CMB (DB)

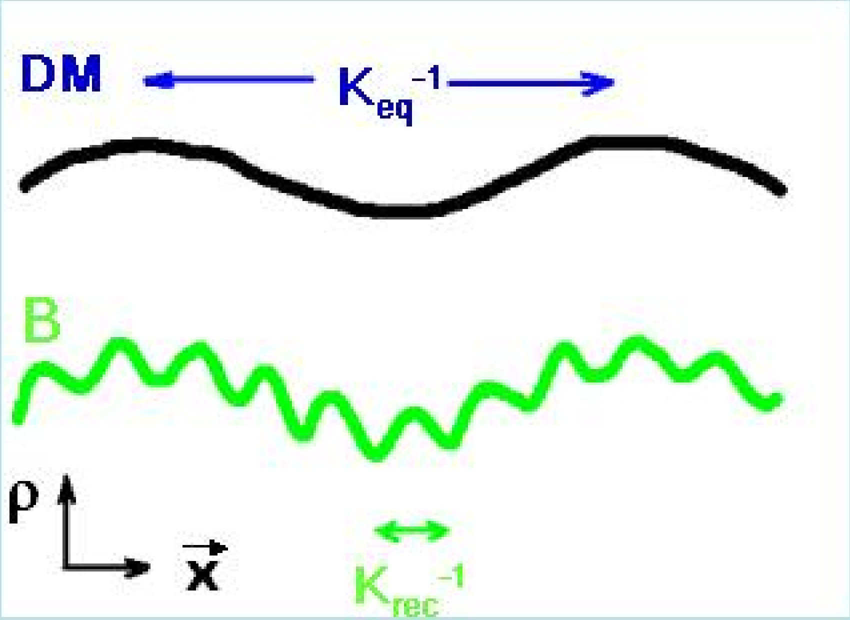
LSS and CMB scales

$z < z_{eq}$: $\quad a = \dfrac{1}{1+z} \sim \eta^2 \quad , \quad \left(\dfrac{\eta_{rec}}{\eta_{eq}}\right)^2 = \dfrac{z_{eq}}{z_{rec}} \cong \dfrac{3200}{1100} \cong \boxed{3}$

LSS : $\quad k_{eq} = \dfrac{1}{\eta_{eq}}$

CMB : $\quad k_{rec} = \dfrac{1}{c_S \eta_{rec}} \cong \dfrac{\boxed{\sqrt{3}}}{\eta_{rec}}$

$$\frac{k_{eq}}{k_{rec}} = \frac{\eta_{rec}}{\sqrt{3}\eta_{eq}} = 1$$



Message from the early Universe:

Baryon asymmetry is related to dark matter

Independent determination of initial and boundary conditions

Theory of gravitational instability

- **Zero order** $a(t)$
  (Hubble diagram)

- **First order** $P(k, z)$
  (density perturbations spectrum)

Cosmological model – in two functions

Model → FU (late) Ω_κ Ω_Λ Ω_m → f_c , f_b , f_ν Ω_X τ

Model → IU (early) A_S n_S α_S A_T n_T

LSS spectrum $\Rightarrow$ $P(k,z) = P(k) \times T^2(k,z)$

IU FU

CMB spectrum $\Rightarrow$ $C_\ell = \int P(k) \times W_\ell(k) \frac{dk}{k}$ + (T)

IU FU

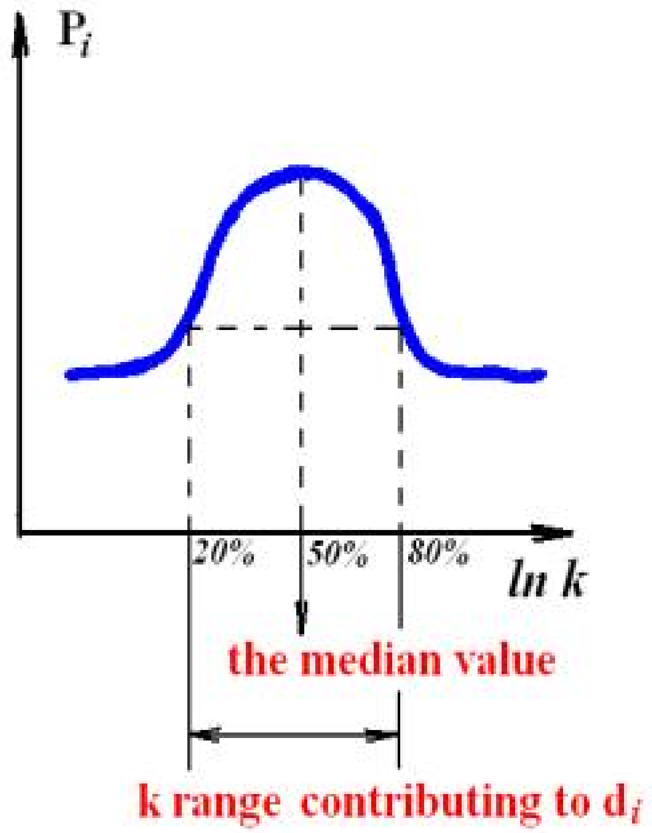
Data mapping in k-space

data point : $d_i = \int_{-\infty}^{\infty} P_i(k) \frac{dk}{k}$

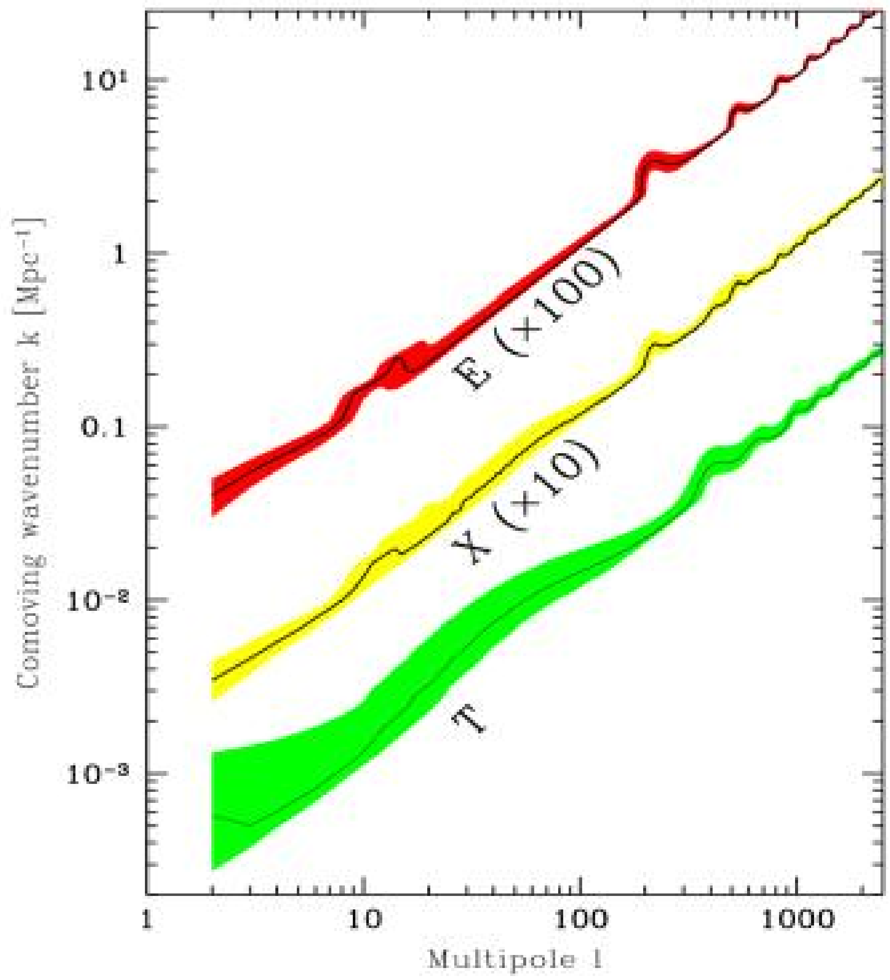
window spectrum ≡
probability distribution
in k space

CMB : $C_\ell = \int_{-\infty}^{\infty} W_\ell(k) P(k) \frac{dk}{k}$

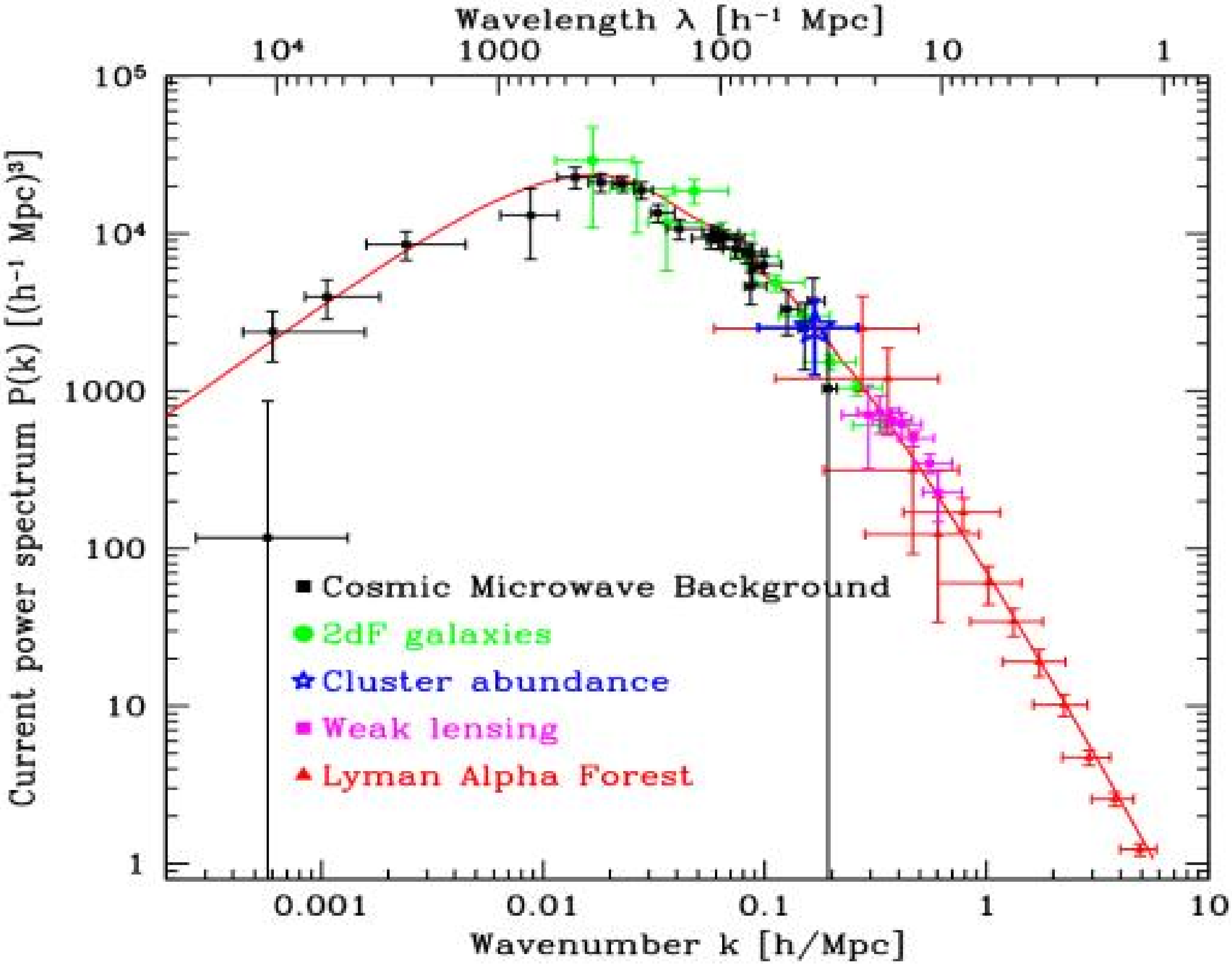
$P_\ell(k)$



$\ell \simeq 10^4\, k$



Tegmark, Zaldarriaga, 2002



Tegmark, Zaldarriaga, 2002

Cosmological initial conditions

Generation of density perturbations in the very early Universe

- Seeds – quantum vacuum fluctuations of density (phonons)
- Parametric amplification of density perturbations in the expanding Universe – spontaneous creation of phonons,

  $k \sim k_H \sim 1\ mm^{-1}$
- Stretching inhomogeneities on cosmological scales by inflation,

  $k \gg k_H \sim 1 \div 100\ Mpc^{-1}$

$$ds^2 = (1 + 2D)dt^2 + 2aC_{,\alpha}dtdx^\alpha - a^2(\delta_{\alpha\beta} + h_{\alpha\beta})dx^\alpha dx^\beta$$

$$\frac{1}{2}h_{\alpha\beta} = A\delta_{\alpha\beta} + B_{,\alpha\beta} \qquad u_i = (1 + D; v_{,\alpha})$$

$$q = Hv - A \equiv Hv - \frac{\delta a}{a}$$

$$\Phi = \frac{H}{a}\int \gamma a q dt \qquad \frac{\Delta\Phi}{a^2} = 4\pi G\delta\varepsilon_C, \qquad \delta_C \equiv \frac{\delta\varepsilon_C}{\varepsilon + p} = \frac{\dot{q}}{\beta^2 H}$$

$$\gamma \equiv -\frac{\dot{H}}{H^2} = \frac{3}{2}\frac{\varepsilon + p}{\varepsilon} \qquad \beta^2 = \frac{\dot{p}}{\dot{\varepsilon}} \qquad \alpha^2 = \frac{\gamma}{\beta^2}$$

Lagrangian theory of q field (V.N.L., 1980):

$$L = \alpha^2 \left(\dot{q}^2 - \left(\frac{\beta}{a} \right)^2 q_{,\alpha} q^{,\alpha} \right)$$

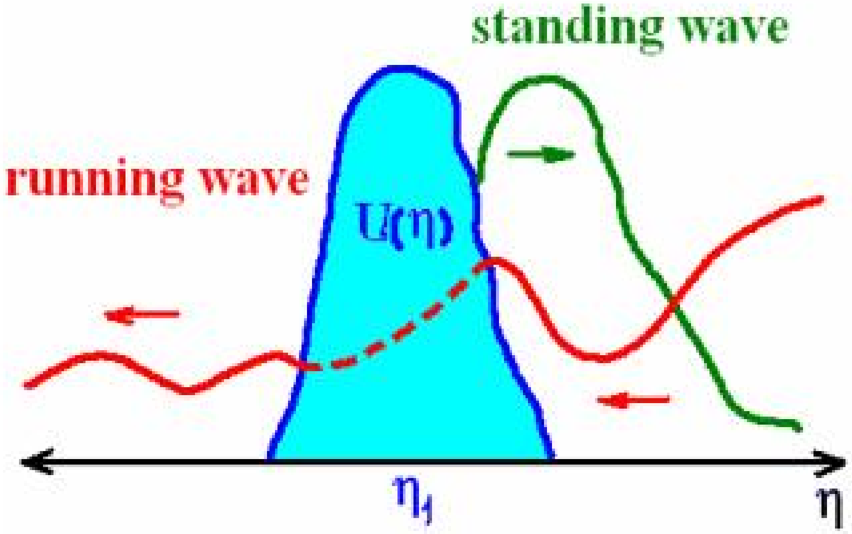
$$\ddot{q} + \left(3H + 2\frac{\dot{\alpha}}{\alpha} \right) \dot{q} - \beta^2 \frac{\Delta}{a^2} q = 0$$

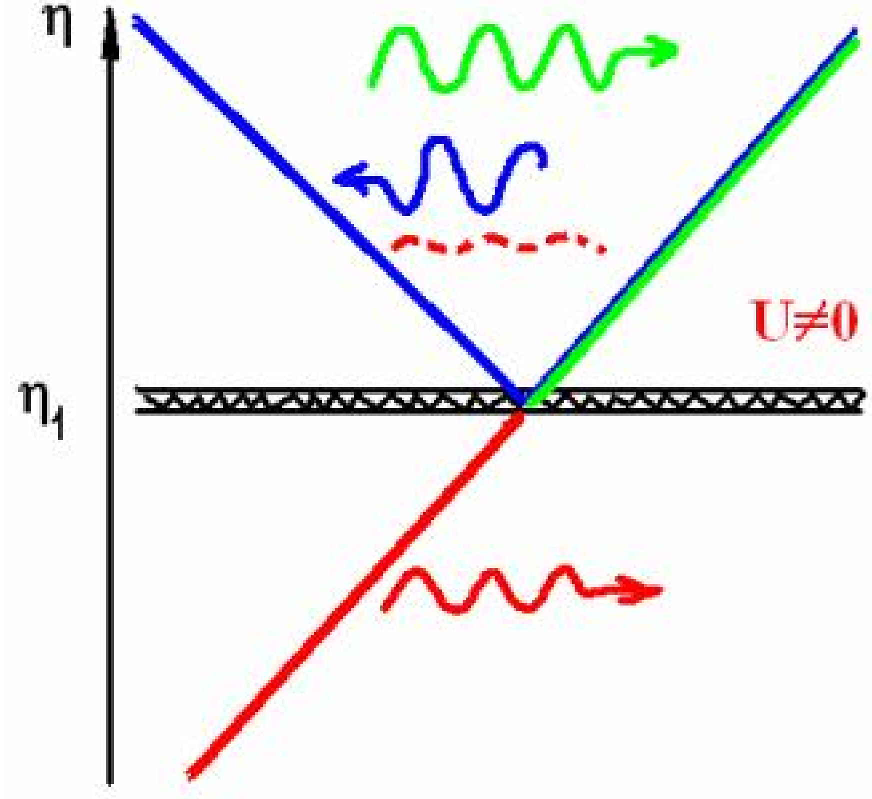
In conformal coordinates:

$$\overline{q}'' + \left(\omega^2 - U \right) \overline{q} = 0$$

$$\omega = \beta k \qquad \overline{q} = \alpha a q$$

$$U = U(\eta) = \frac{(\alpha a)''}{\alpha a}$$



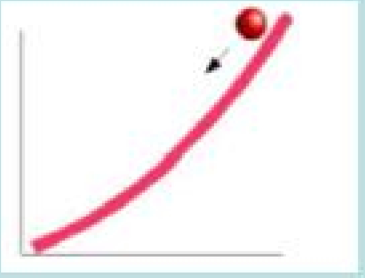


η
U≠0
η1

Observational constraints on inflationary models

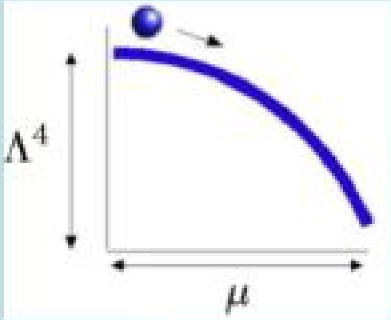
V(φ): classification of potentials

Large field inflation



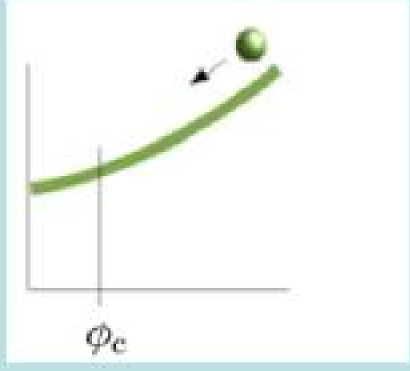
$$V'' > 0:$$
$$V(\varphi) \sim \varphi^{\kappa}$$
$$V(\varphi) \sim \exp(\varphi)$$

Small field inflation



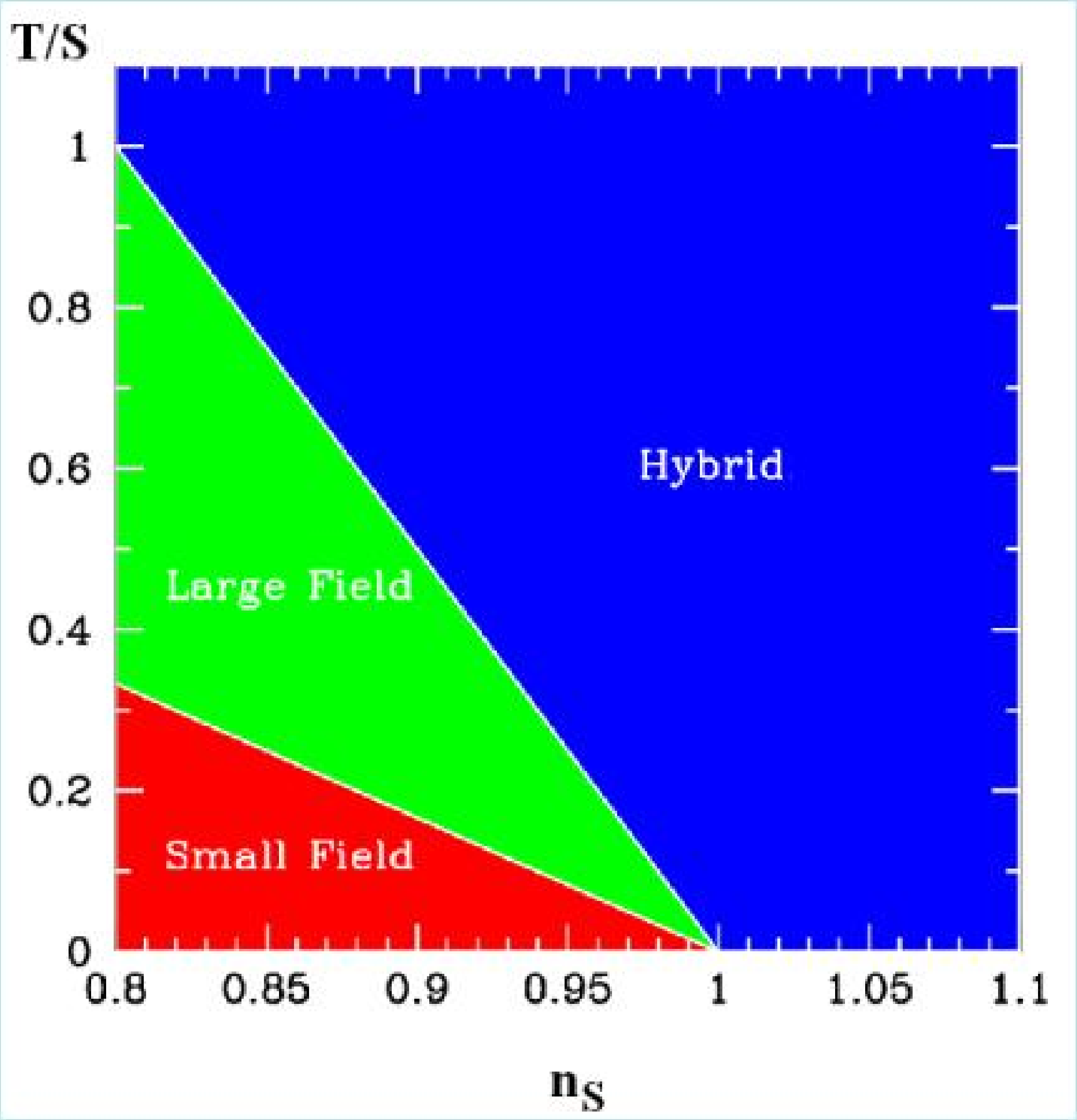
$$V'' < 0:$$
$$V(\varphi) = V_0\left(1 - \left(\frac{\varphi}{\varphi_C}\right)^{\kappa}\right)$$

Λ(hybrid)-inflation

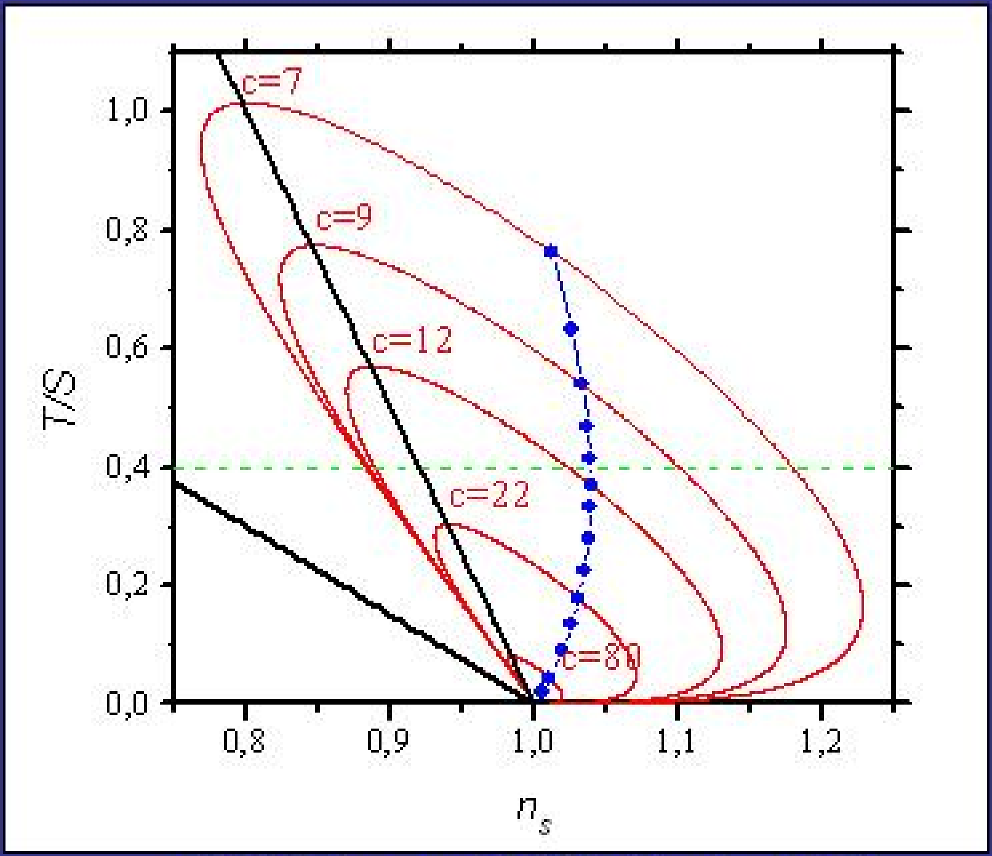


$$V'' > 0, V(0) \neq 0:$$
$$V(\varphi) = V_0\left(1 + \left(\frac{\varphi}{\varphi_C}\right)^{\kappa}\right)$$
$$\kappa = 4;\ c \equiv \frac{\varphi_C^{\,2}}{4}$$

Models and observational quantities (T/S - n_S)



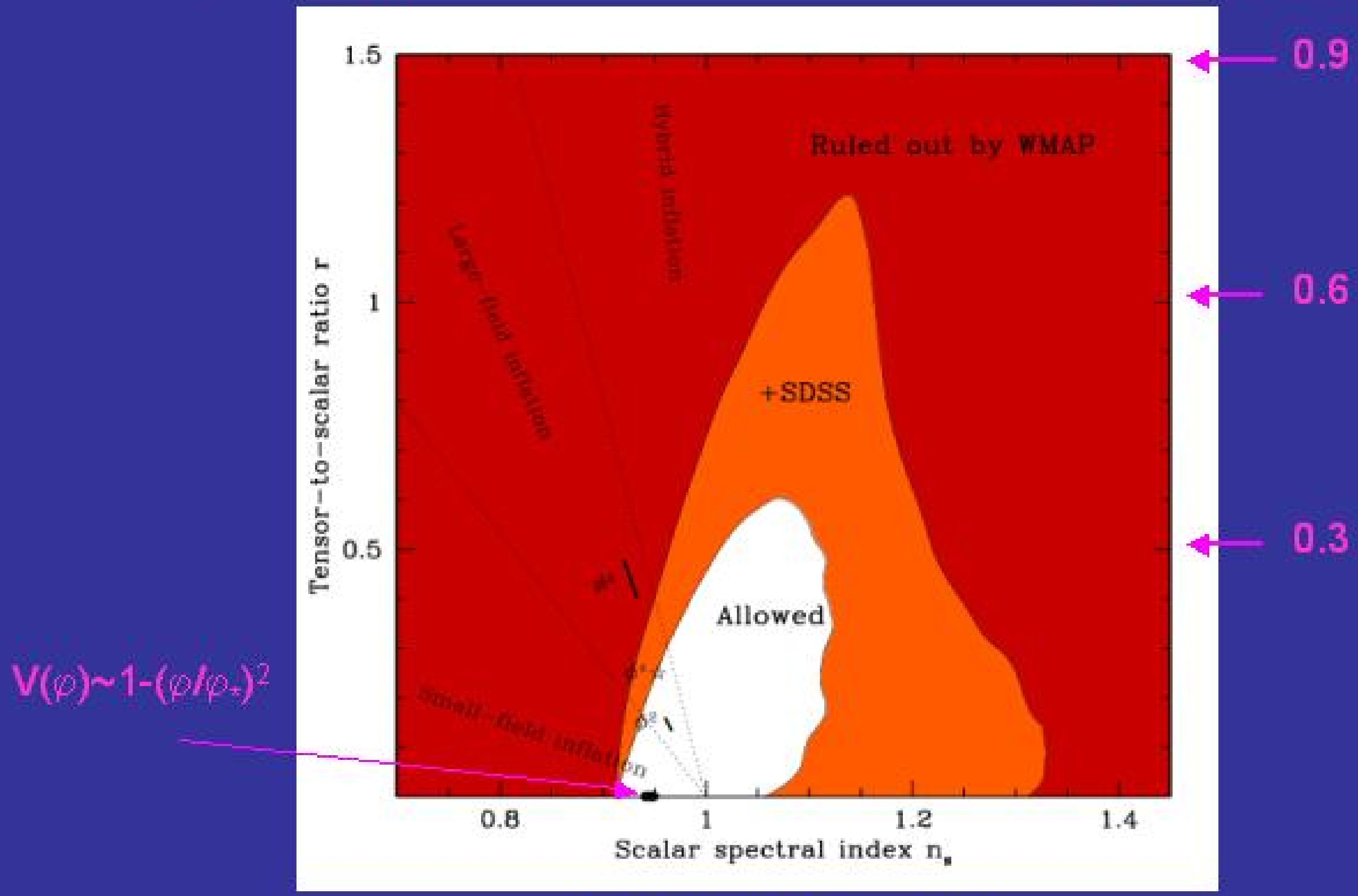
Λ-inflation (κ=4)



E.V.Mikheeva, V.N.Lukash, 2004

WMAP + SDSS

$r = -8n_T$ $T/S = 0.6\ r$



M.Tegmark et al., 2003

- Chaotic inflation:

  $m\varphi^2$ - solid grounds

  $\lambda\varphi^4$ - severe trouble

- If $n_S>1$ - Λ-inflation

  $n_S<1$ - «chaotic» or «new» or …

- Inflationary model will be recognized in the nearest future

Minimal model

$n_S=1$ $\Omega_0=1$ $T/S=0$ $f_\nu=0$

$\downarrow$ $\downarrow$ $\downarrow$

degeneracies: geometry tensor neutrino

4 parameters of MM:
(error bars <10%)

$$\tau = 0.17$$
$$\Omega_\Lambda = 0.7$$
$$\omega_c = 0.123$$
$$\omega_b = 0.023$$

$$\sigma_8 = 0.84$$

A large number of observational points (~ 2000) can be fitted by only four parameters of MM

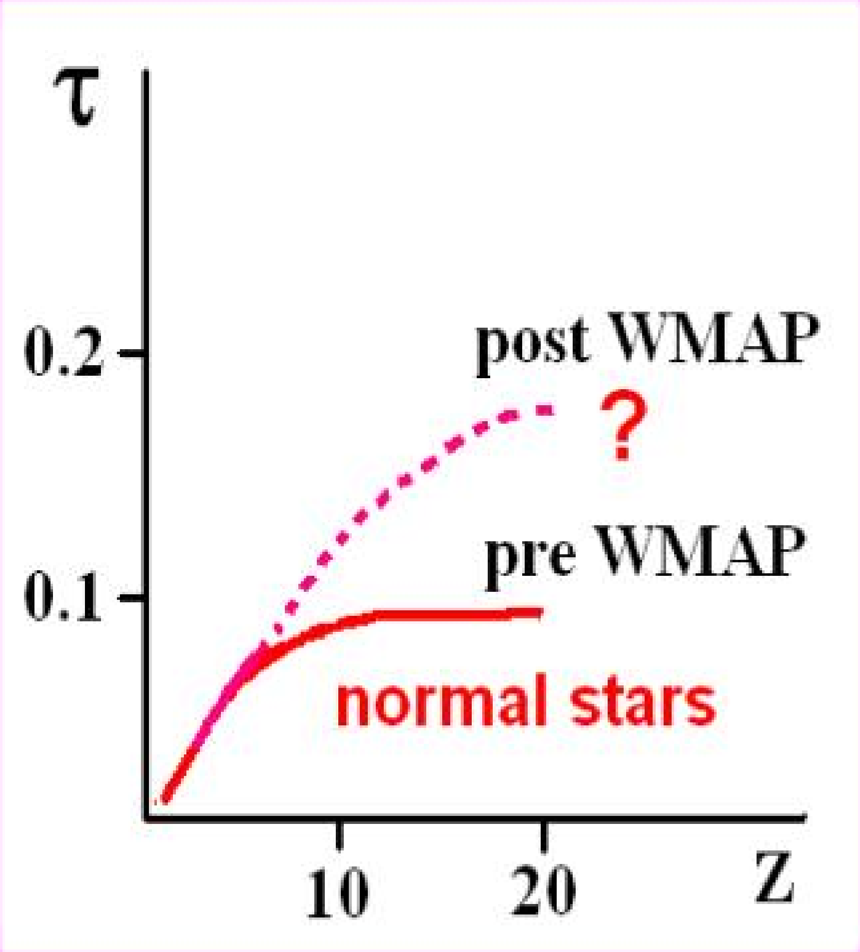
Reionization puzzle

QSO end of reionization:
z~10

Evolution of star formation:
flat out to z~6

Most distant galaxy: z~10
QSO: z=6.41

Two reionization epochs ?
z~20 (massive stars)
z~10 (normal stars, QSO)



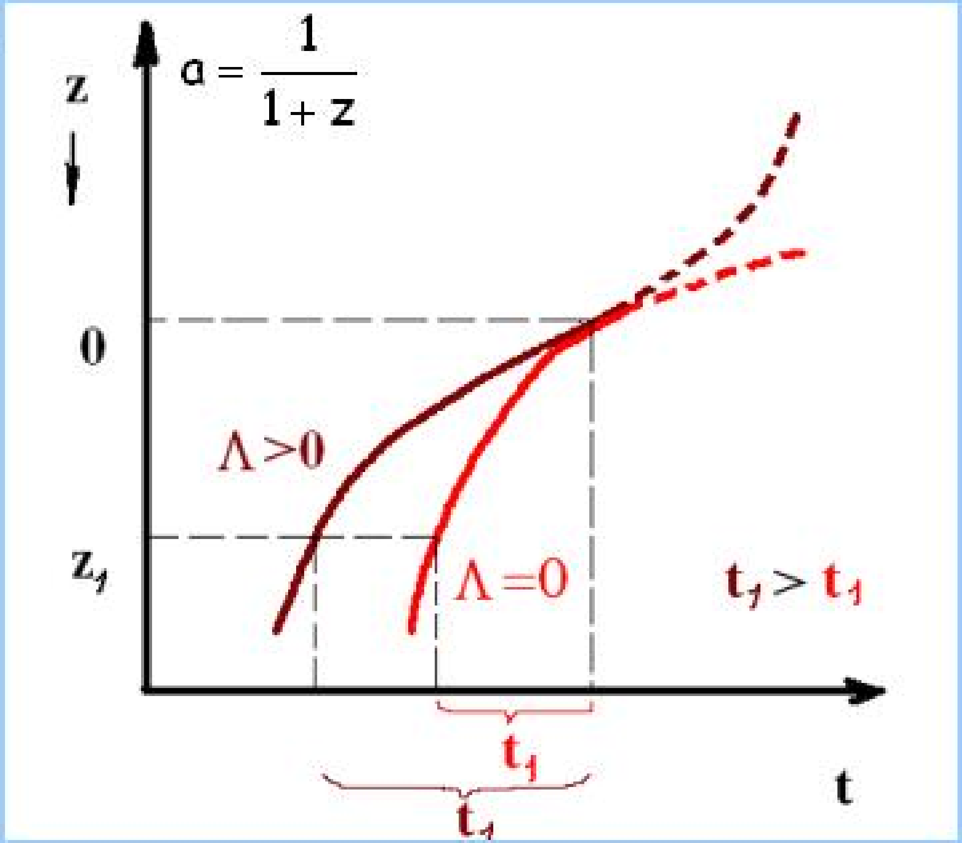
Arguments for $\Lambda>0$

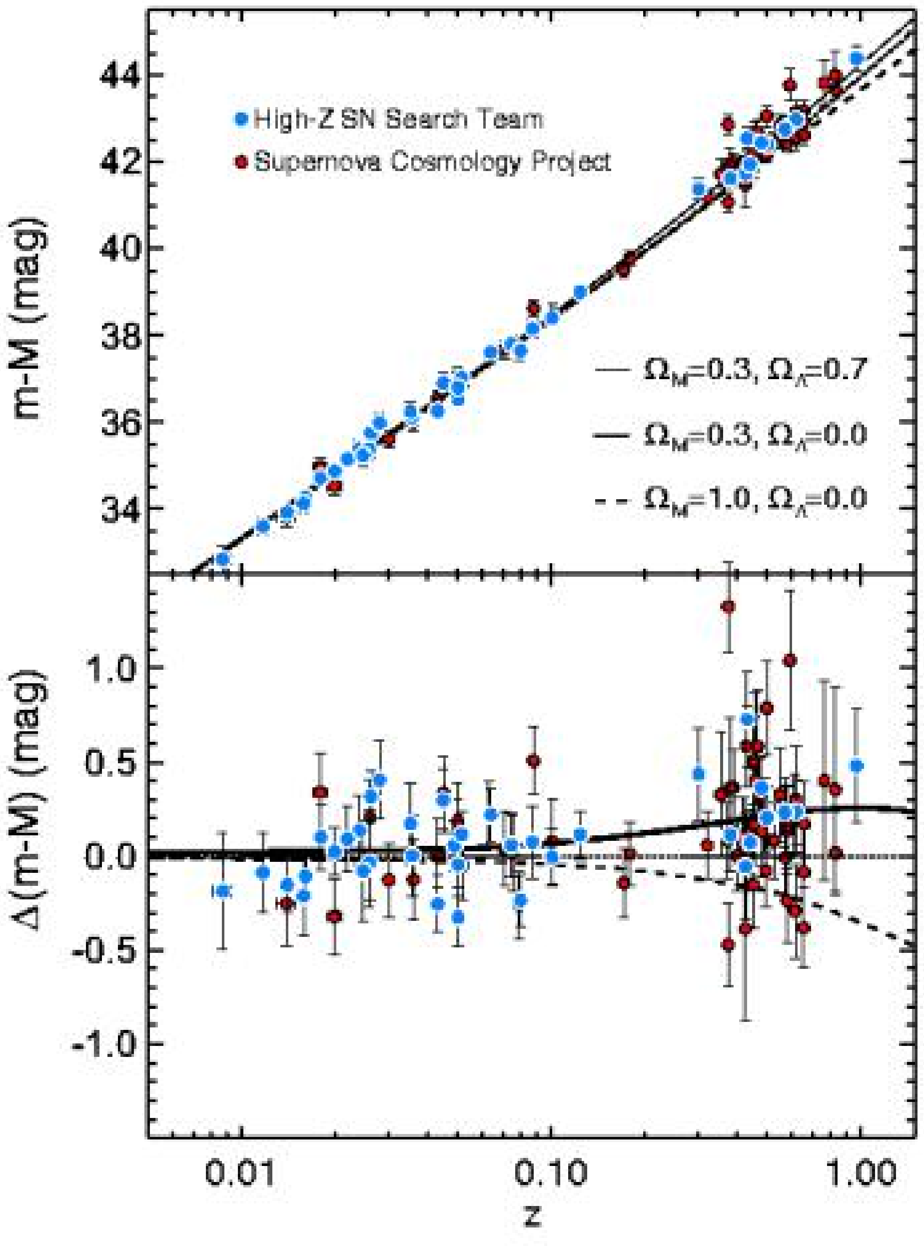
- Hubble diagram: SN Ia
  (correction for metallicity?)
- Dynamics: ISW
  (galaxies at z~0.5)
- Structure: P(k)

$$\Omega_m = \frac{\Gamma^2}{\omega_m} = \frac{(0.2)^2}{0.14} = 0.3$$

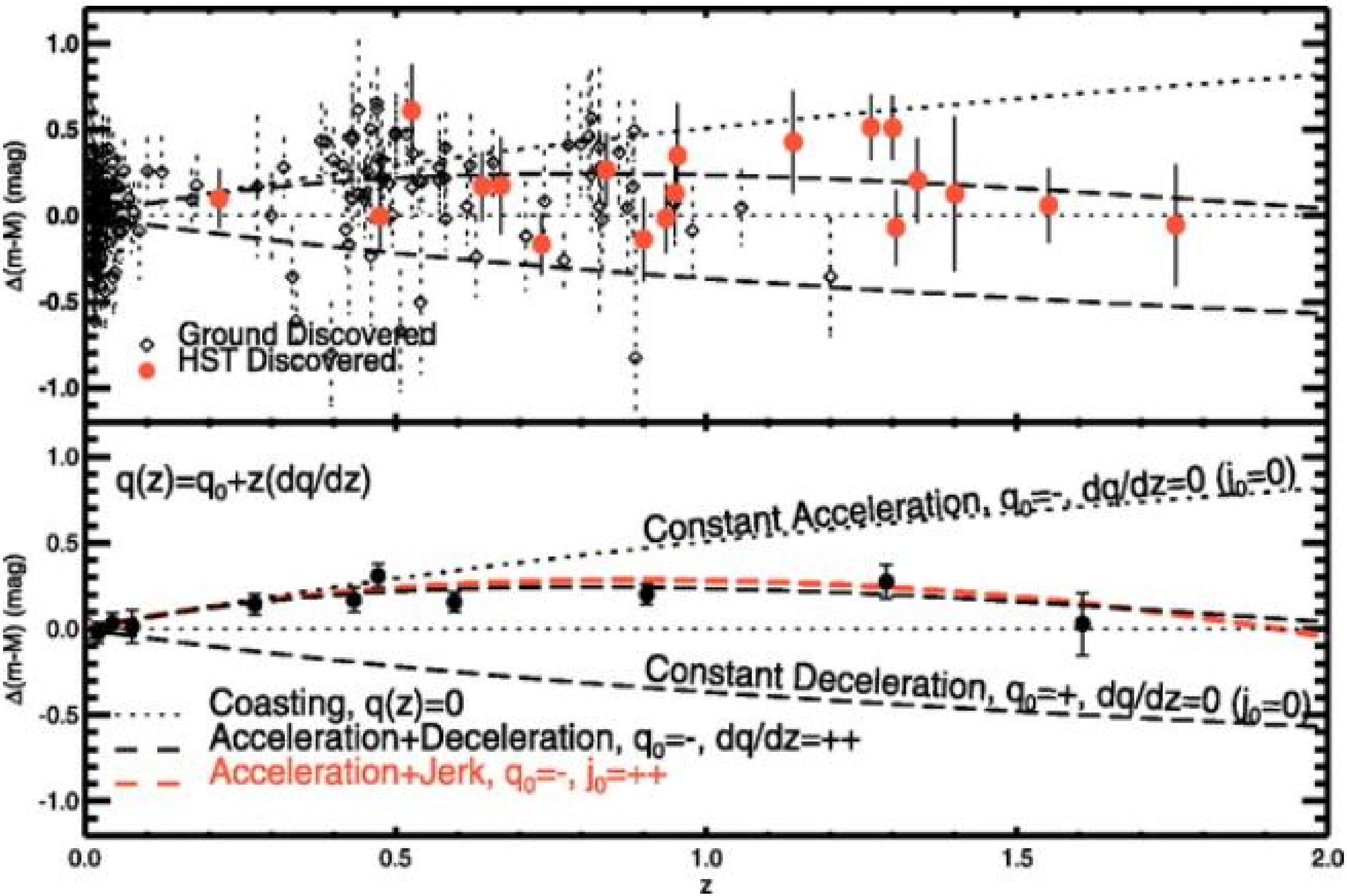
$$\Gamma = \Omega_m h \qquad \omega_m = \Omega_m h^2$$

$\uparrow$ LSS $\qquad$ $\uparrow$ CMB





Reiss et al., 2002



Riess et al., 2004

(Reprinted from Nature, Vol. 257, No. 5526, pp. 454–457, October 9, 1975)

An accelerating Universe?

James E. Gunn*

Hale Observatories, California Institute of Technology, Carnegie Institution of Washington, Pasadena, California 91125

Beatrice M. Tinsley*†

Lick Observatory, University of California at Santa Cruz, California 95060

New data on the Hubble diagram, combined with constraints on the density of the Universe and the ages of galaxies, suggest that the most plausible cosmological models have a positive cosmological constant, are closed, too dense to make deuterium in the big bang, and will expand for ever. Possible errors in the supporting arguments are discussed.

"If then, Socrates, in many respects concerning many things—the gods and the generation of the Universe—we prove unable to render an account at all points entirely consistent with itself and exact, you must not be surprised. If we can furnish accounts no less likely than any other, we must be content."

Plato, *Timaeus*

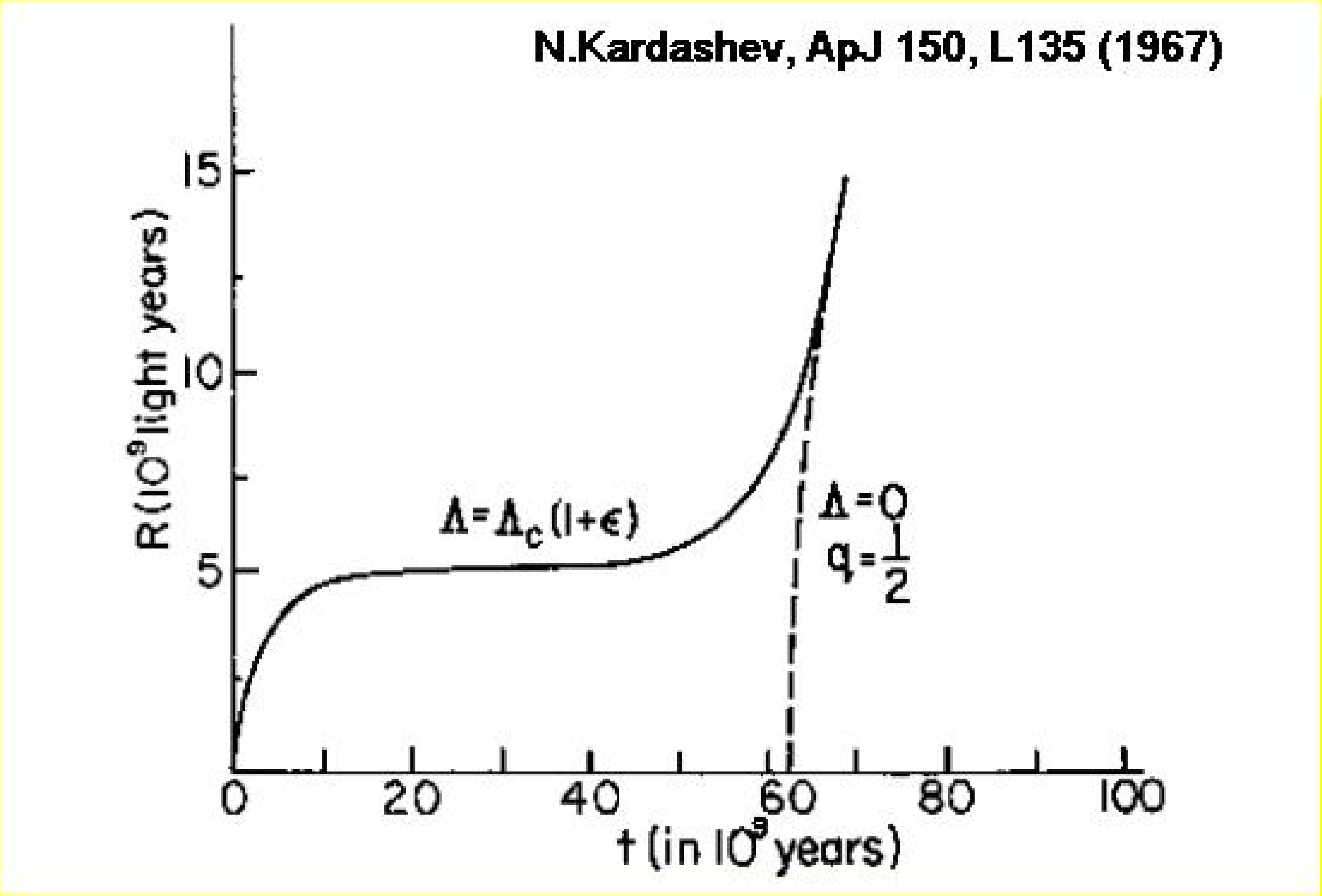
In any case, comparison of the classical Hubble diagram with density estimates based on 'local' determinations seems the best way of determining the existence of a non-zero Λ. We shall see, in fact, that the Hubble diagram alone may dictate that Λ be non-zero.

The data do not demand this conclusion, and there is the possibility that systematic errors remain, but the suggestion is strong enough that we thought it worthwhile to investigate the models in the light of other relevant observations, in the spirit of the recent work of Gott *et al.*[4] for models with $\Lambda = 0$.

Properties of Friedman models with $\Lambda \neq 0$

Three parameters specify a model completely. A set usefully related to observables is the density parameter

$$\Omega = 8\pi G\rho_0/3H_0^2$$

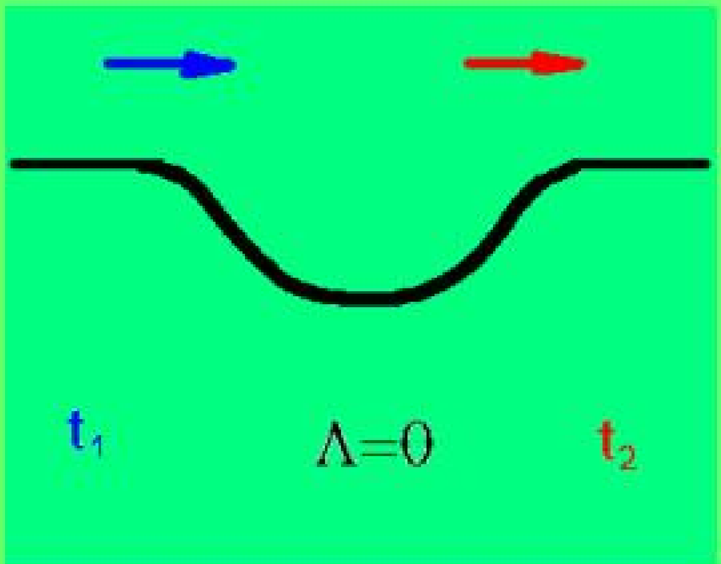


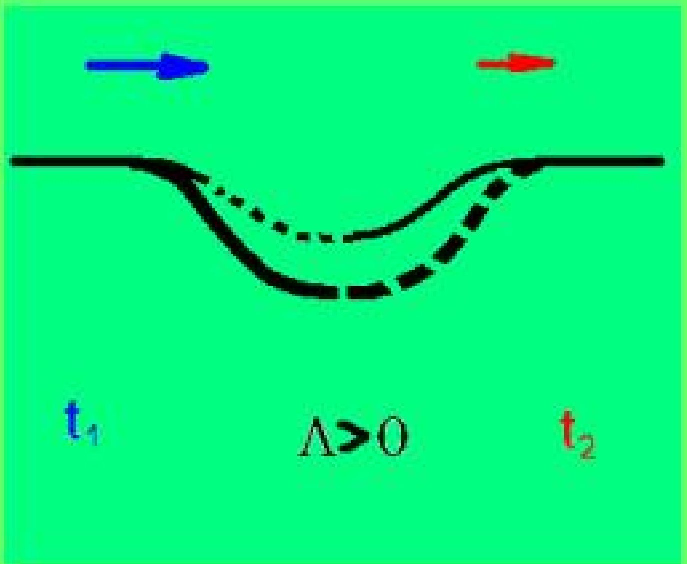
N.Kardashev, ApJ 150, L135 (1967)
15
10
5
R (10^9 light years)
Λ = Λc (1+ε)
Λ = 0
q = 1/2
0
20
40
60
80
100
t (in 10^9 years)

Dynamical impact of vacuum

cross-correlation between maps of galaxies and CMB

$$\Delta\Phi = 4\pi G\rho_m a^2\delta \sim \frac{\delta}{a} \sim \begin{cases} \text{const}, & \rho_m > \rho_\Lambda \\ a^{-1}, & \rho_m < \rho_\Lambda \end{cases}$$





Structure argument

(solid!)

$$H^2 \sim \frac{\Omega_m h^2}{a^3} + \frac{T_\gamma^4}{a^4}$$

$$\text{eq} : a^2 H^2 \sim \frac{\Omega_m h^2}{a} \sim \left(\Omega_m h^2\right)^2, \qquad \frac{1}{a} \sim \Omega_m h^2$$

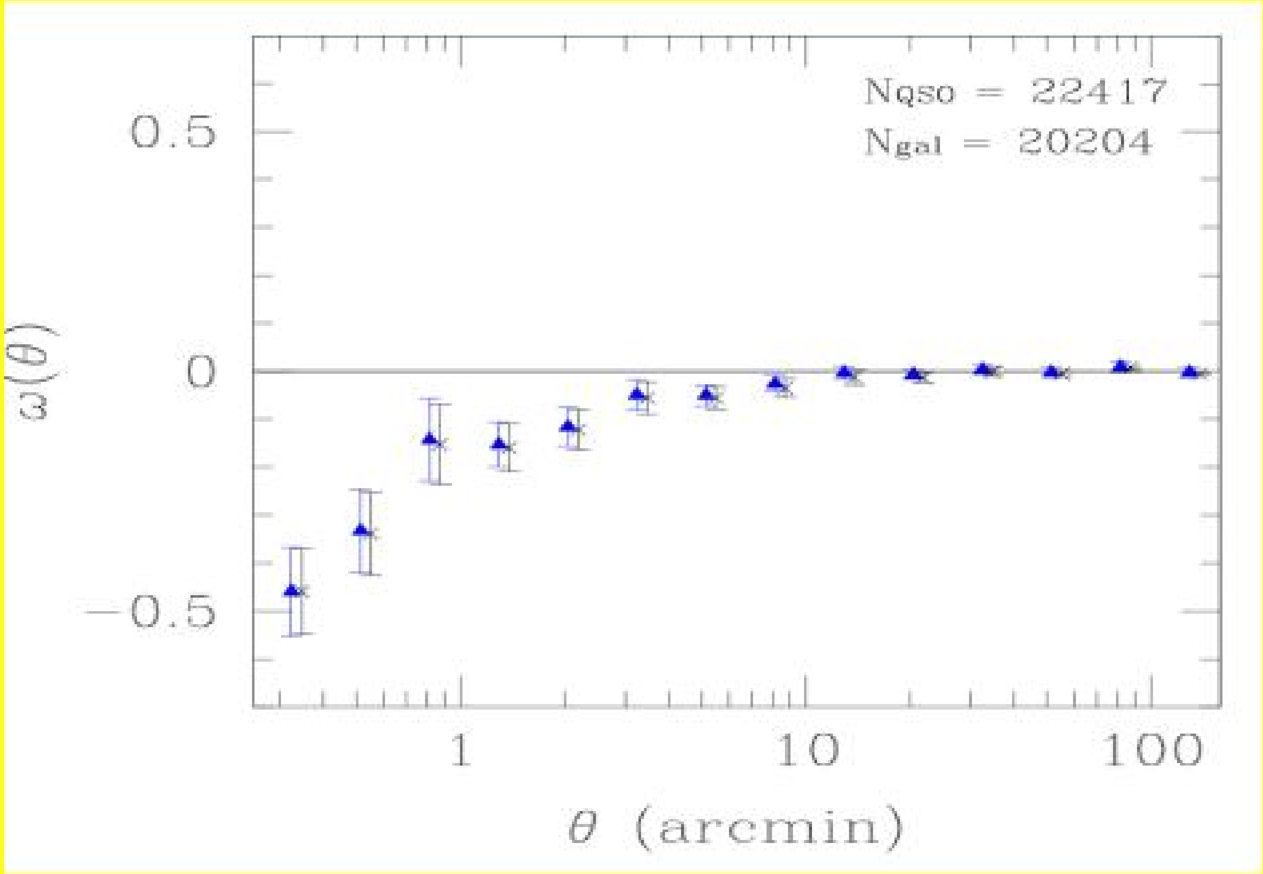
$K_{eq} = aH \sim \Omega_m h^2 = \Omega_m h$ (h/Mpc)

↑ CMB ↑ LSS

… and counter-arguments

- Weak lensing (Ω_m~1)
- Problems of ΛCDM:
  - absence of cusps in galaxy centres (stability of galaxy bars)
  - absence of substructure in galaxy halos (stability of spiral pattern in galaxy disks)
  - small number of low-massive galaxies
  - flat luminosity and correlation functions of galaxies

Angular cross-correlation between distant QSOs and nearby clusters of galaxies **(APM/SDSS)**

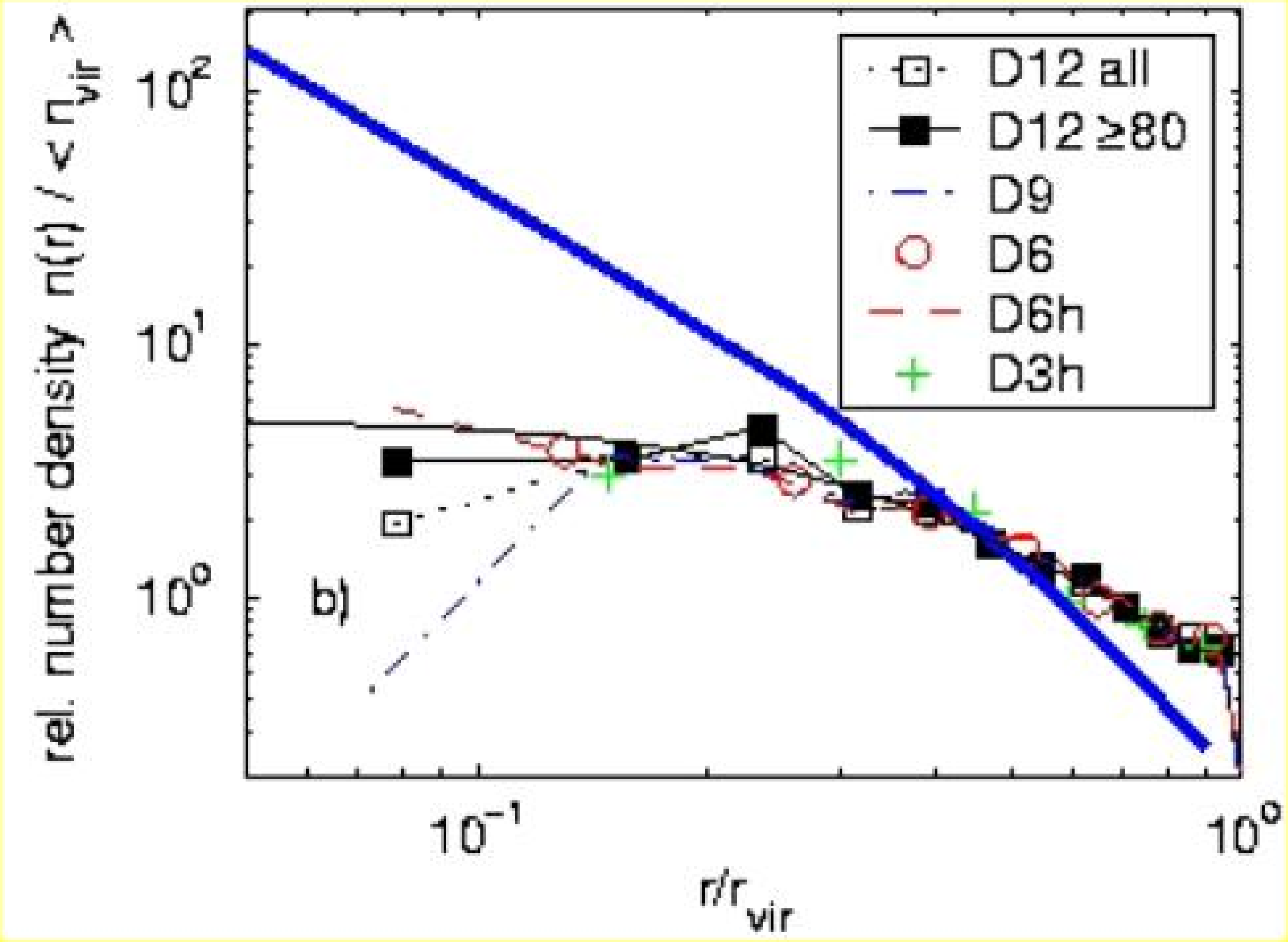


Myers et al., 2003

Substructure in galaxy halo
(simulations)

$\rho \sim r^{-\gamma}$

$\gamma \in (1, 3/2)$



Diemand et al., 2004

Among best-fit models (WMAP & 2dF)

$\Omega_m=1, \ \Omega_\Lambda=0$

$\Omega_\nu=0.2, \ \Omega_c=0.7$

$H_0= 45 \text{ km s}^{-1} \text{ Mpc}^{-1}$

↓

contradiction:

- local H_0 ($60 \div 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$)
  (SZ, gravitational lenses: 50 ± 20)
- SN Ia
- cluster evolution
- Ly_α

Degeneracies in cosmological parameter space

(reason – bad data,

region – 10 % of MM):

geometrical $(\Omega_m h^2 \sim \text{const}, \Omega_0)$

tensor $(n_S \sim f_b)$

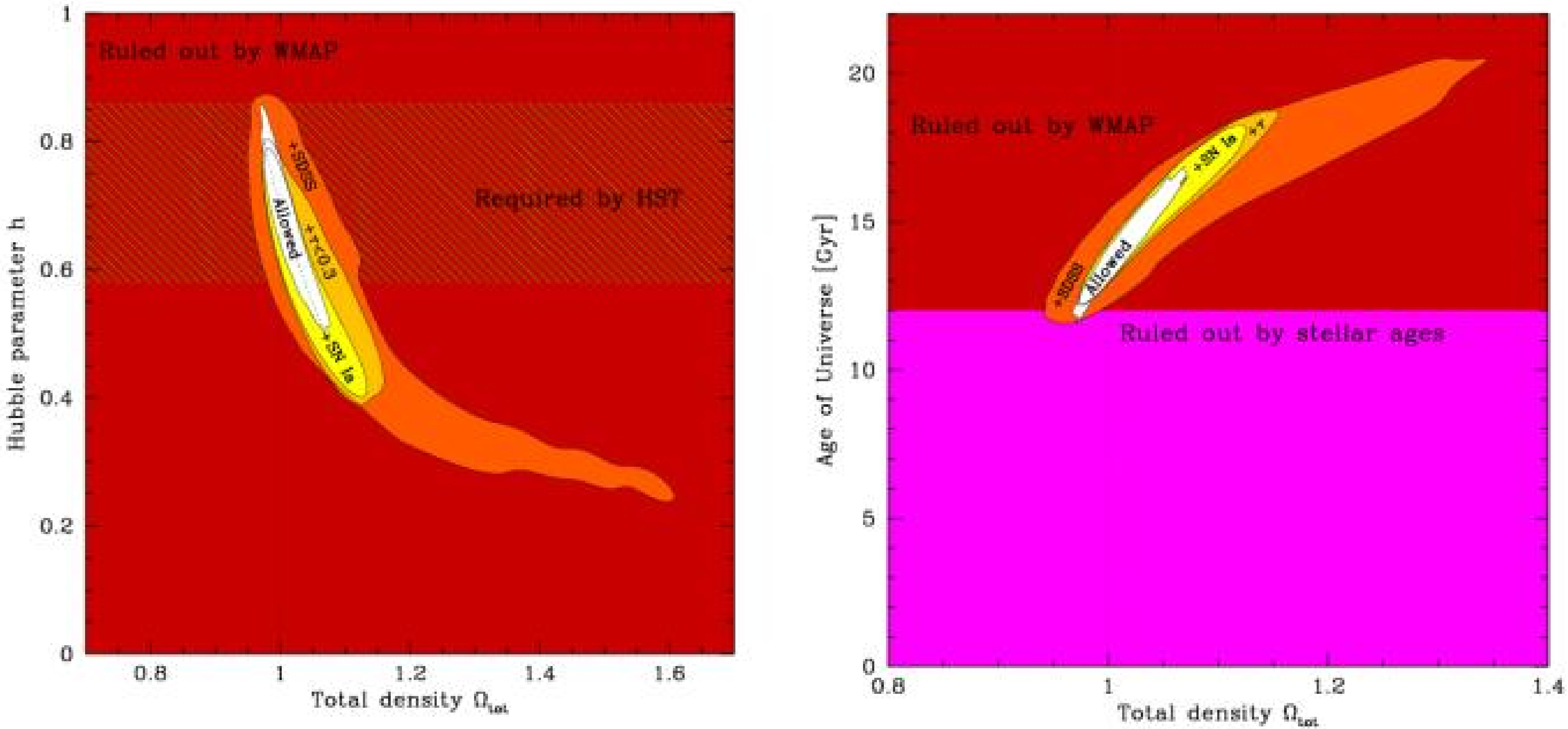
neutrino $(\Omega_m \sim f_\nu)$

Geometrical degeneracy (Ω_0=1.01$\pm$0.02)

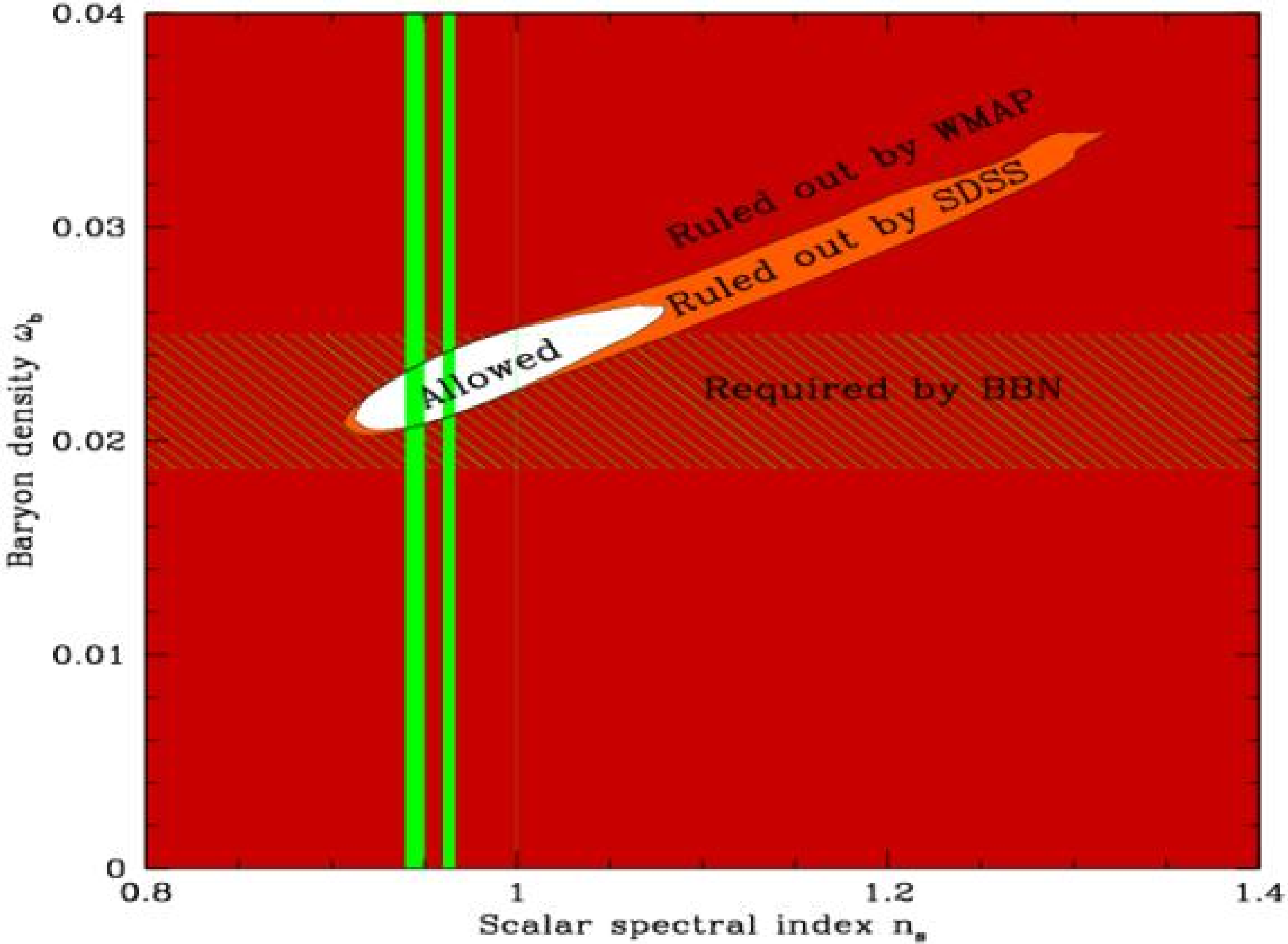
$h\Omega_0^5 = 0.7$

$T_0 = 13.5\ \Omega_0^{5/2}$ Gyrs

Hubble constant and the age of the Universe *vs* Ω_{tot}



Tegmark et al., 2003



Tegmark et al., 2003

If $m_\nu < 0.7$ eV, then

- $z_\nu < z_{rec}$ ($3T \simeq m_\nu$: $z_\nu \simeq 10^3$ [m_ν/0.7 eV])
- $\Omega_\nu h^2 = \Sigma\, m_\nu / 93\ \text{eV} < 0.02 \simeq \Omega_b h^2$
- $f_\nu \equiv \Omega_\nu / \Omega_m < 0.2$ (for $\Omega_m h^2 > 0.1$)

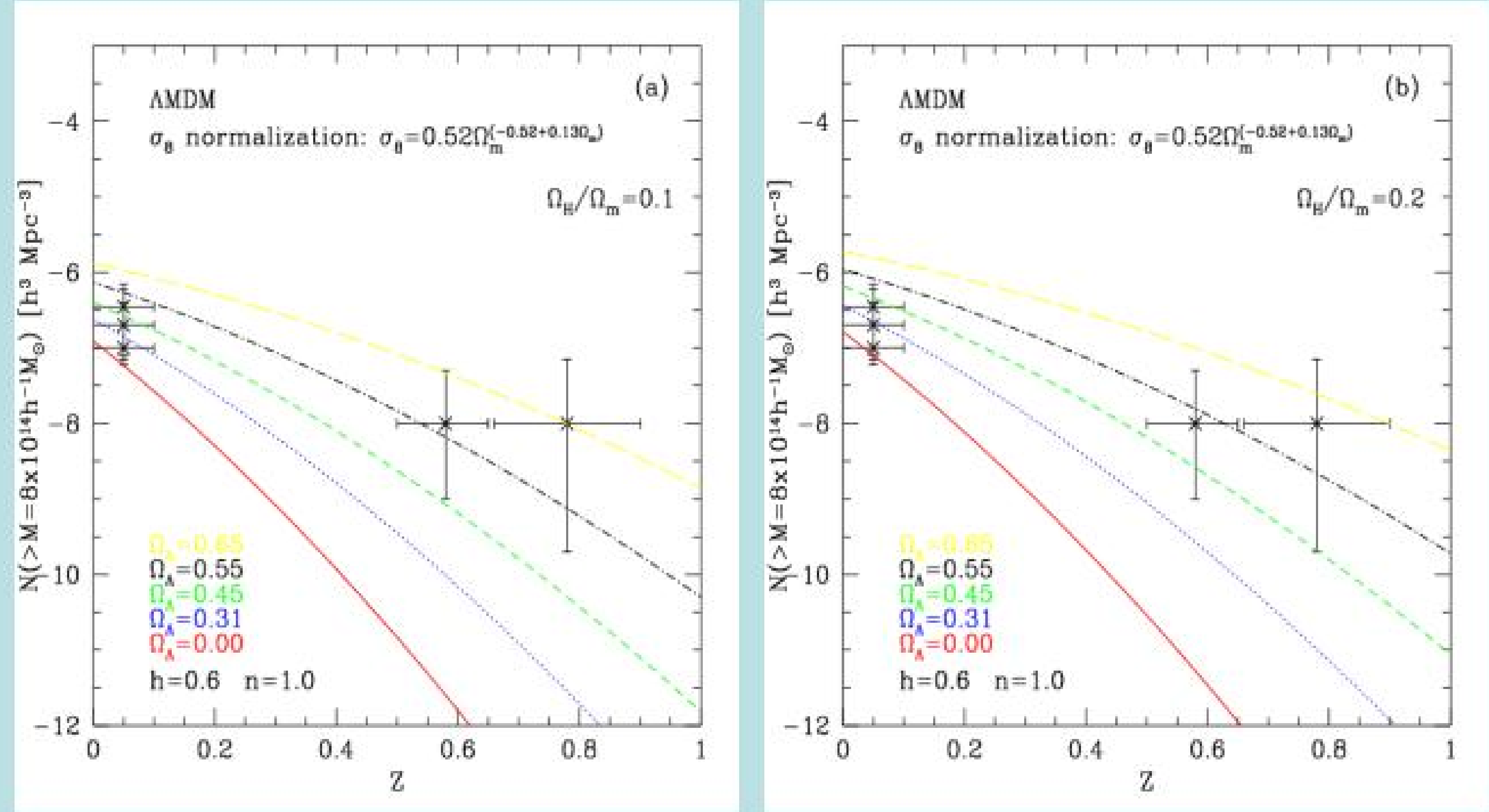
CMB $\Rightarrow \Omega_{cb} h^2$

$\Omega_m = \Omega_{cb} + \Omega_\nu$, $\Omega_m(1 - f_\nu) = \text{const} \equiv \Omega_{cb}$ (fixed by CMB)

$$\Omega_\Lambda + a f_\nu = b$$

($\Omega_m + \Omega_\Lambda = 1$, $a = \Omega_{cb}$, $b = 1 - \Omega_{cb}$)

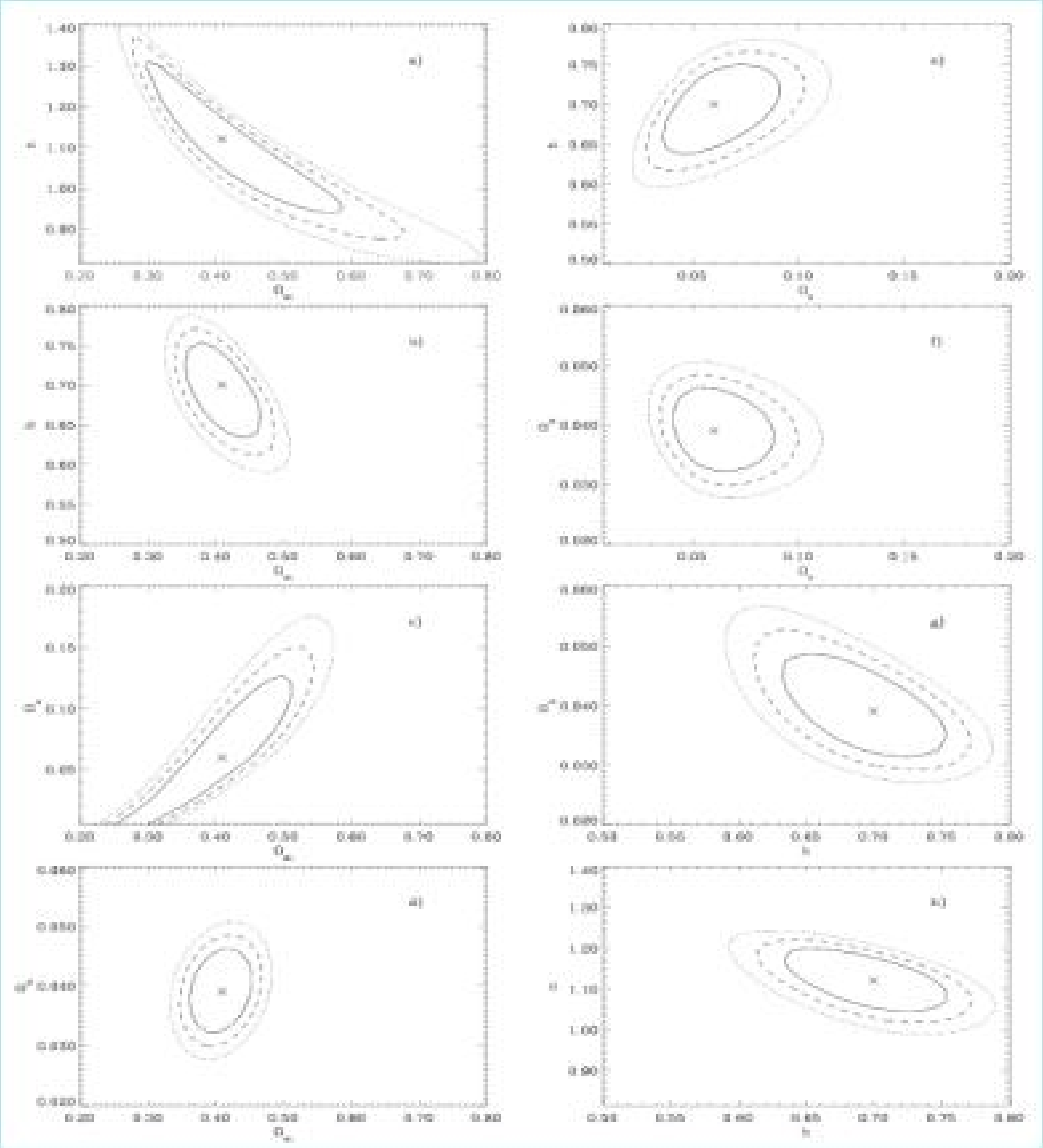
$$\Omega_\Lambda + 0.5\, f_\nu = 0.65 \pm 0.1$$



Arhipova et al., 2002

$$n\sqrt{\Omega_m} = 0.73$$

$$\Omega_\Lambda + 0.7 f_\nu = 0.66$$



Novosyadlyj et al., 2000

Cosmological parameters
CMB $\leftrightarrow$ LSS

	no GW, ν	+GW, no ν	+GW,ν,BBN
$\Omega_m h^2$	0.14	0.12	0.16
$\Omega_m h$	0.2	0.17	0.25
$\Omega_b h^2$	0.021	0.025	0.020
f_b	0.15	0.22	0.10
f_ν	-	-	0.05
n_S	1.0	1.1	1.1
T/S	-	0.2	0.3
Ω_κ	0	0	0
Ω_Λ	0.7	0.8	0.6

Conclusions

- Breaking degeneracy between initial and boundary conditions in cosmology
- Stable prediction:

$n_S \cong 1, \quad \Omega_\kappa \cong 0, \quad \Omega_\Lambda \cong 0.6 \div 0.7$

- Best-fit model: $f_\nu \sim f_b \sim 10\%$, $\Omega_m \sim 0.4$, $h \sim 0.65$

(MM: $f_b \sim 15\%$, $\Omega_m \sim 0.3$, $h \sim 0.7$)

- If $\Omega_m \leq 0.3$, then $\Omega_\nu \cong 0, \quad h \geq 0.7$

$\Omega_m > 0.3$, $\Omega_\nu \cong 0.1, \quad h < 0.7$

- ???

$m_\nu \in 0.04 \div 0.4$ eV

(f_ν<0.1: m_ν <0.4 eV)

early ionization (z~20)

$T/S \leq 0.2$

small C_2, C_3

distortions ℓ~30, 200

high χ^2

the running parameter

Unsolved fundamental problems:

- Dark matter (multicomponent):

$\Omega_b \cong \Omega_\nu,\ \Omega_c \sim \Omega_m \sim \Omega_\Lambda$

- Cosmological constant:

$\rho_\Lambda \sim M^4 = (10^{-3} eV)^4 =$

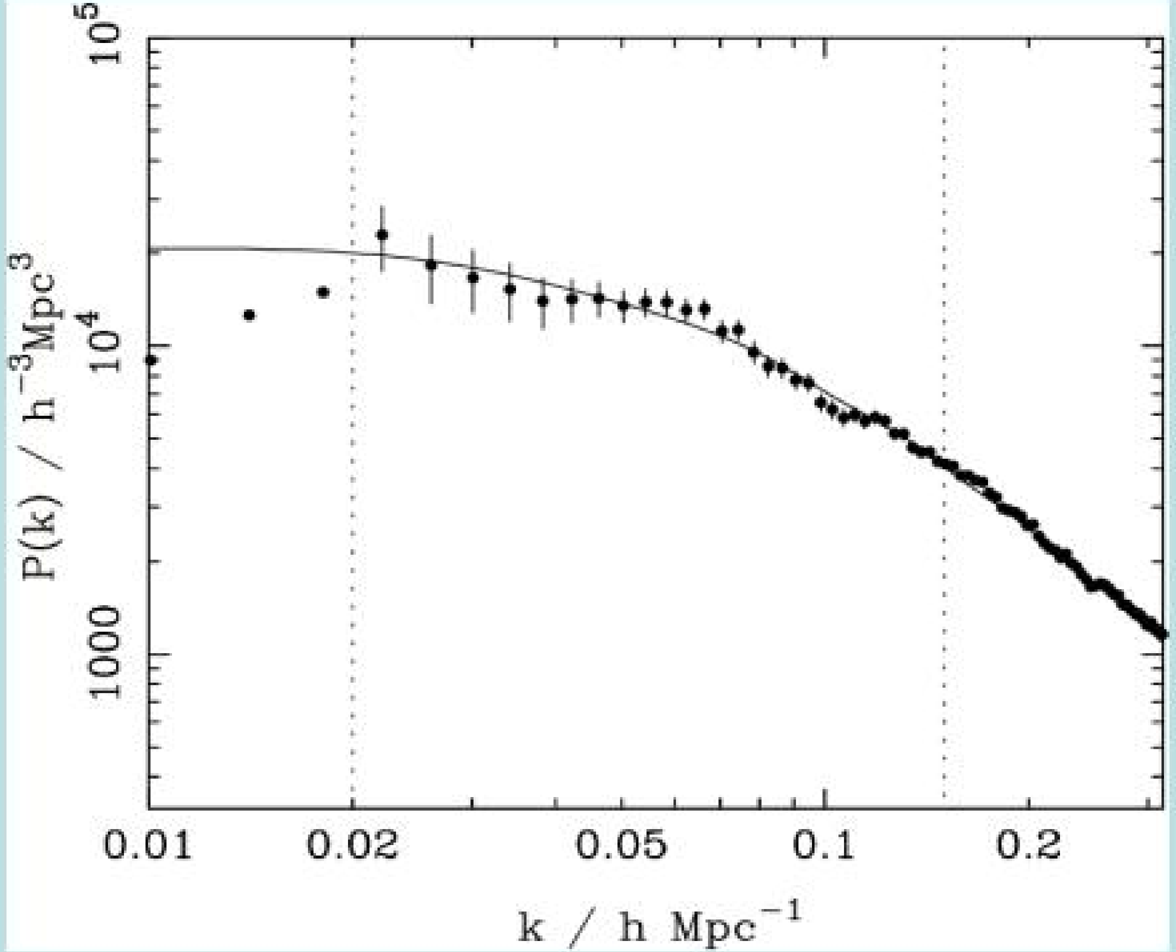
standard model:	M ~1 TeV
GUT:	$M \sim 10^{13}$ GeV
quantum gravity:	$M \sim 10^{19}$ GeV

- Coincidence of CMB and LSS scales

(relation between baryon asymmetry and dark matter)

- T/S $\rightarrow$ energy scale of inflation

2dF Galaxy Redshift Survey



O.Lahav et al., 2002

Beyond concordance model:

- τ_{opt} ~ 0.17
- Low $C_{2,3}$, deviations (>3σ) at l~30, 200
- Rolling of spectral index
- Poor χ^2 of concordance model (others in 1σ)
- Spectral excess at l~2500 (CBI, ACBAR)

QSO: end of reionization at z~6

Evolution of star formation: flat out to z~6

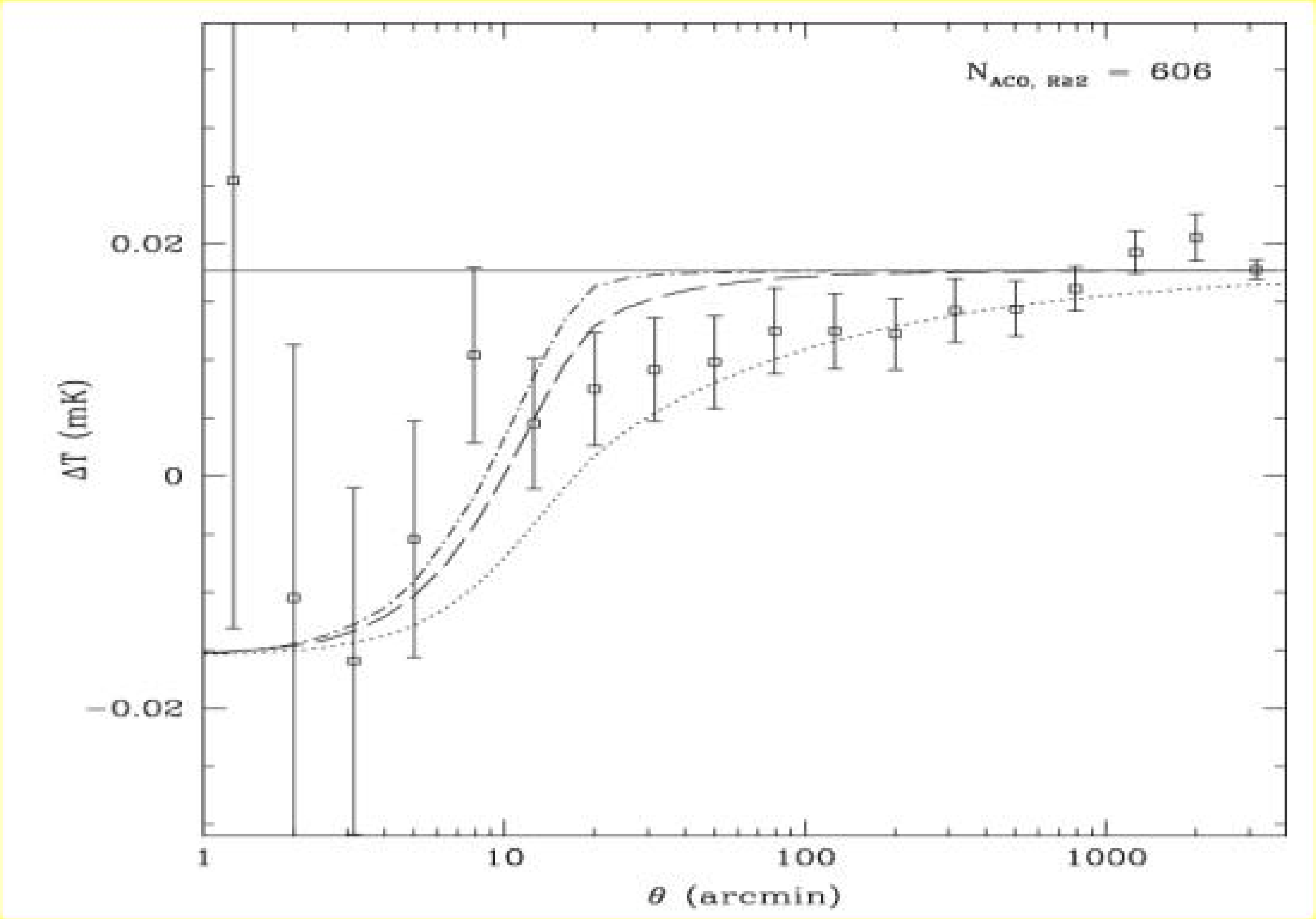
Most distant	galaxy:	z=6.56
	QSO:	z=6.41

New: two reionization epochs

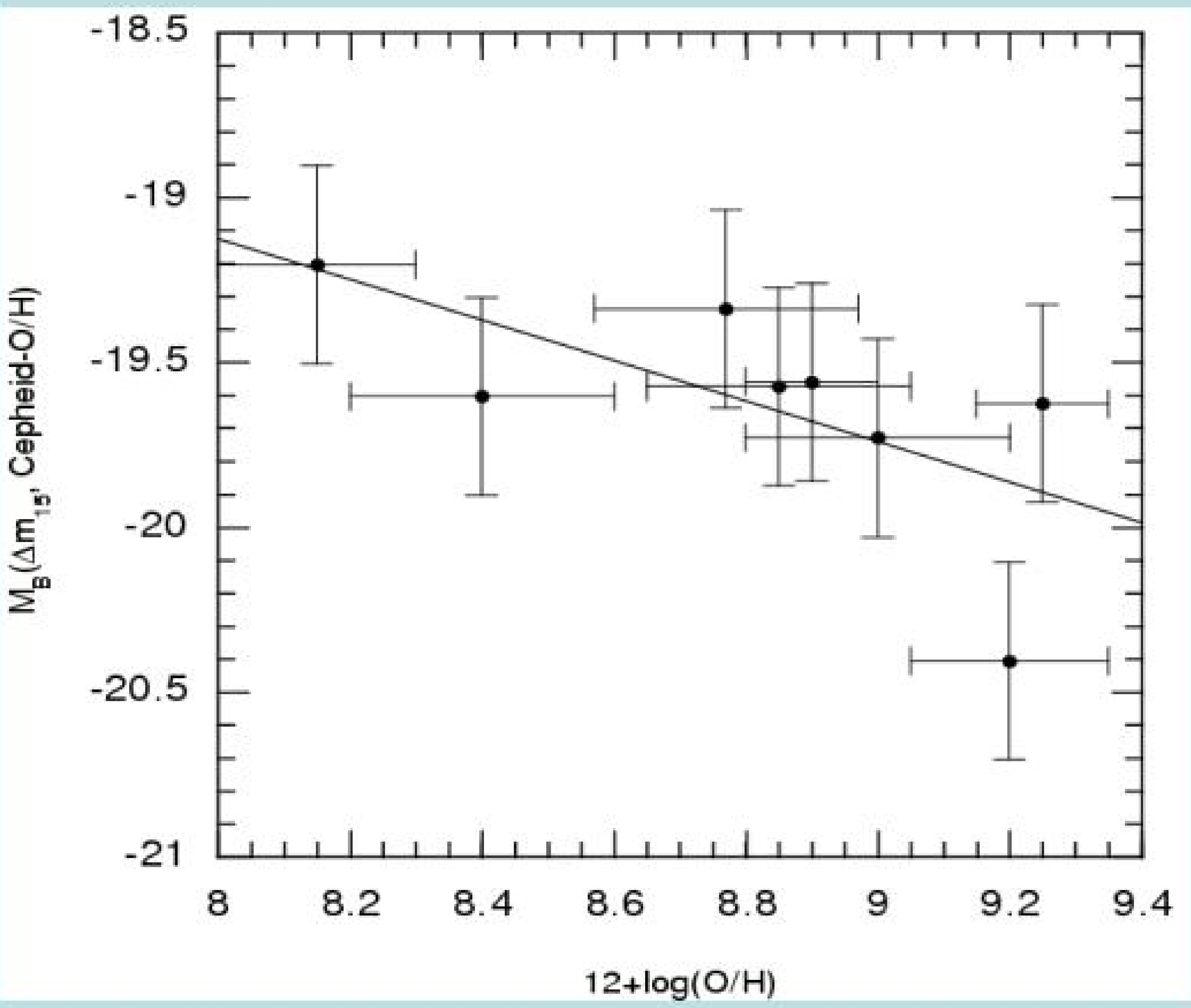
At z~20 (massive stars, QSO)

At z~6 (normal stars, QSO)

Cross-correlation between WMAP (94 GHz) and galaxy clusters (ACO, R≥2)



T.Shanks, astro-ph/0401409



T.Shanks, astro-ph/0401409