Neutrinos & Cosmology V

G. Miele

Relic neutrino properties from other observables

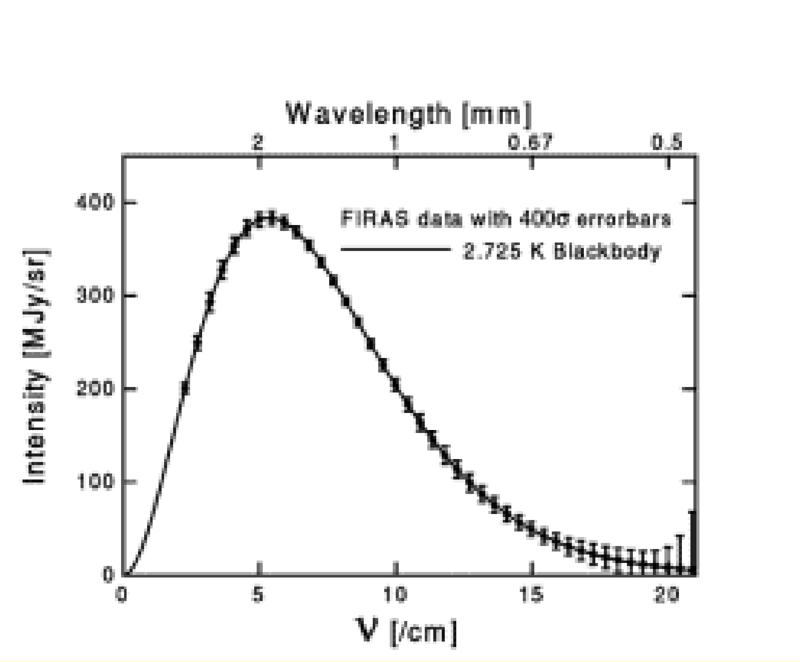
ISAPP'03

COSMIC BACKGROUND MICROWAVE RADIATION

300000 h^{-1} yr after the bang ($z \sim 1000$) photons decouple from proton and electrons, which are bound into neutral atoms

The relic photons are distributed in phase space with a black body distribution

$T = 2.725 \pm 0.001\ ^0 K$



Anisotropies are at the level of 10^{-5} only!

Main goal

Direct or indirect measurement of

Ω , Ω_b , Ω_{dm}, Ω_ν , Ω_Λ ….

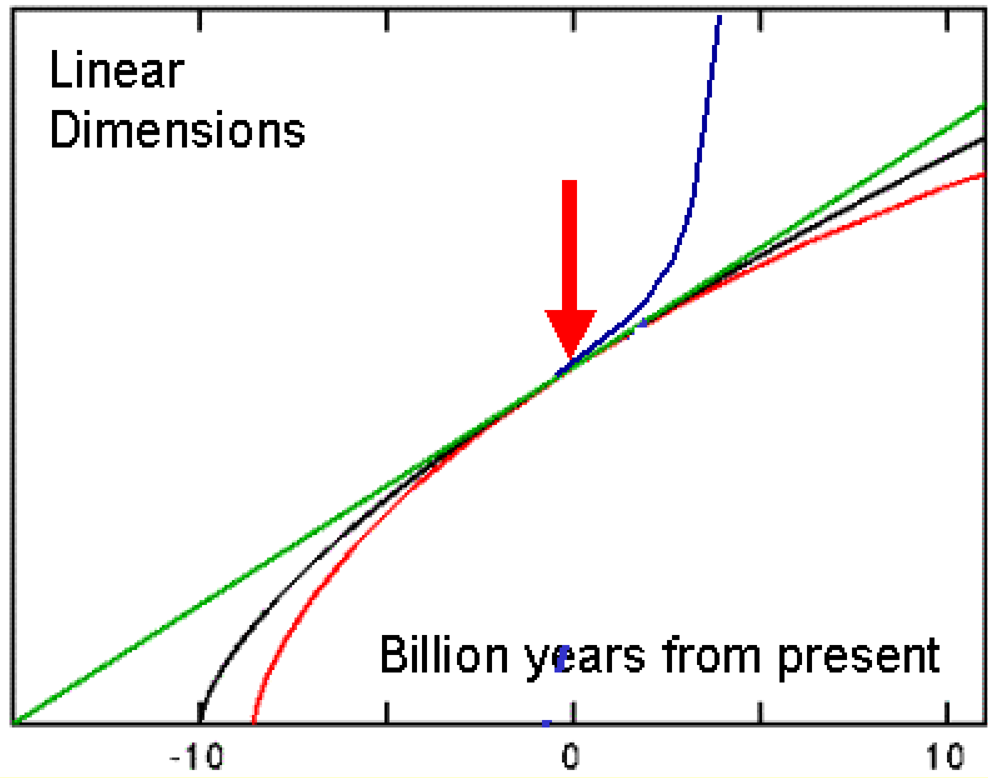
Energy density zoology

Ω_b baryons

Ω_{dm} non baryonic cold dark matter

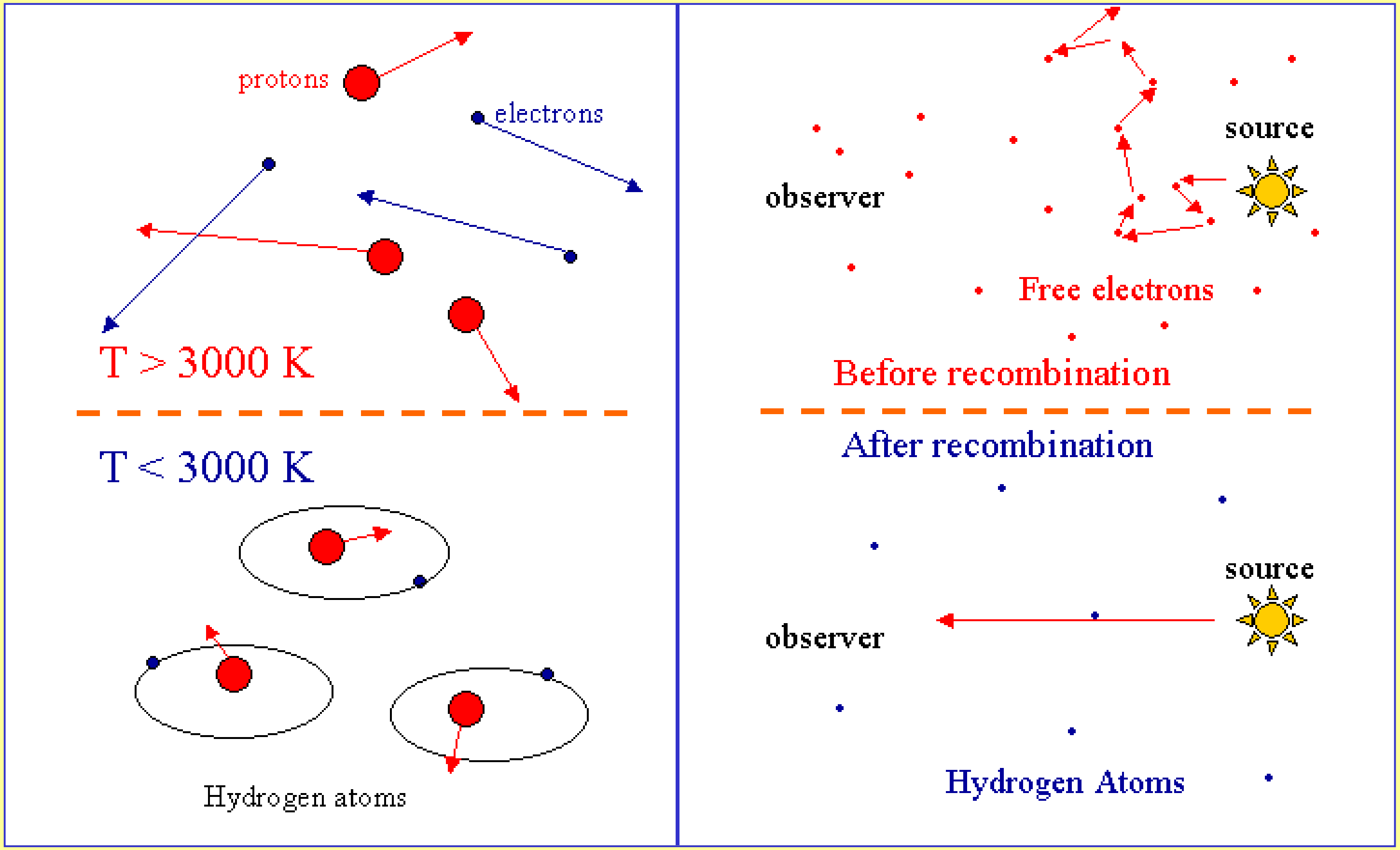
Ω_ν non baryonic hot dark matter

Ω_Λ cosmological constant



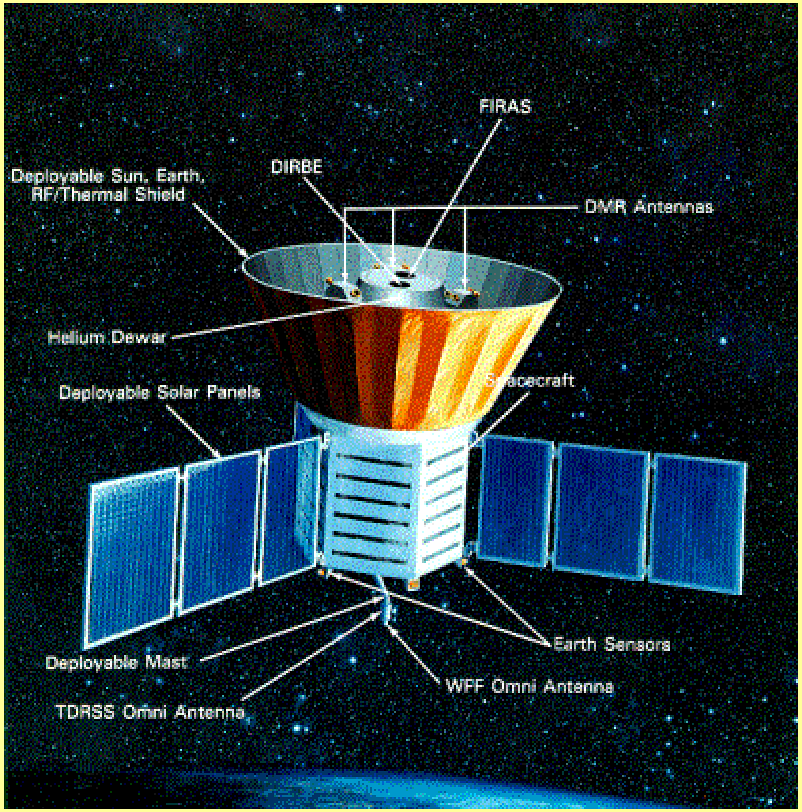
different equation of state $p = p(\rho)$

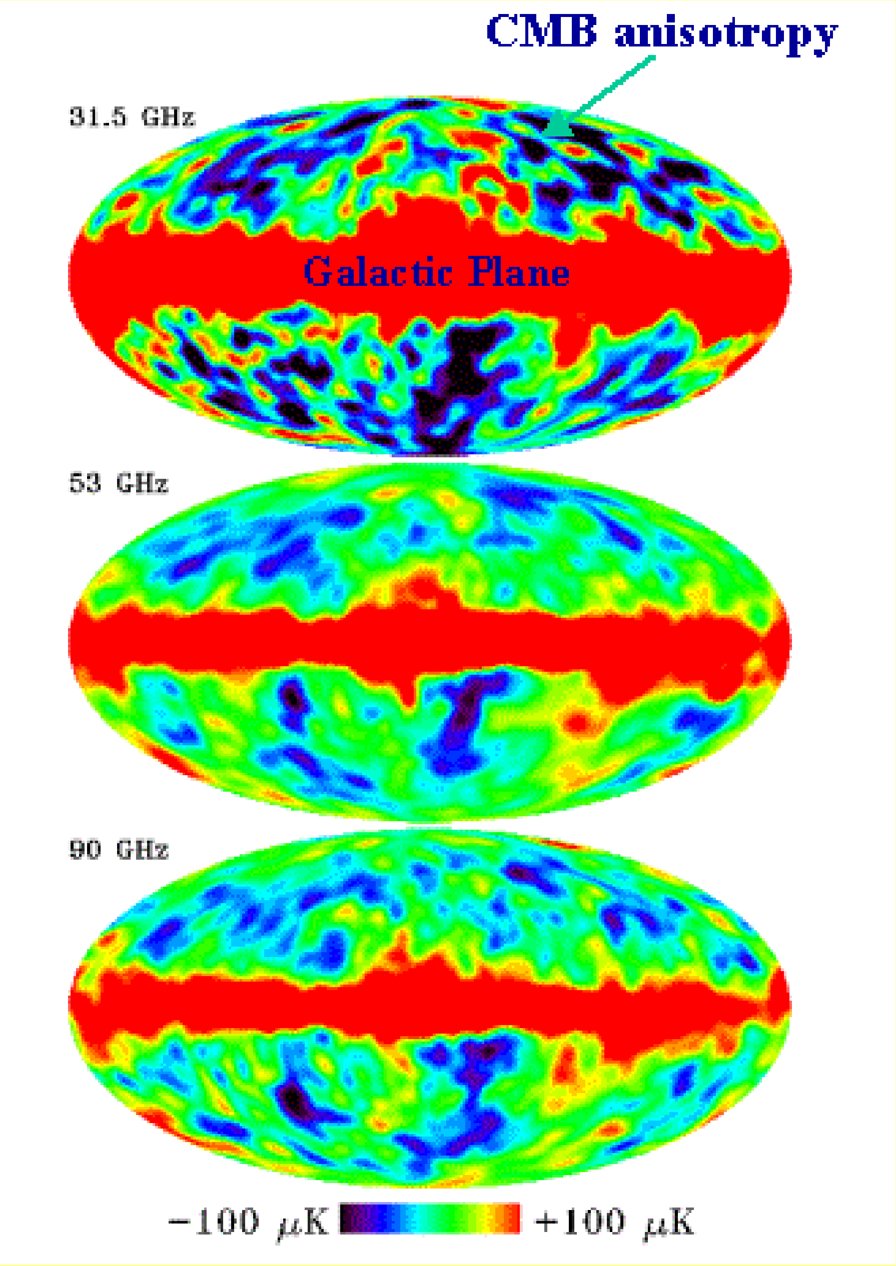
The phenomenon



After recombination photons (basically) keep their thermal distribution and now are observed as the $T \approx 3\ ^{o}K$ black body relic radiation

COBE results for CMBR anisotropy



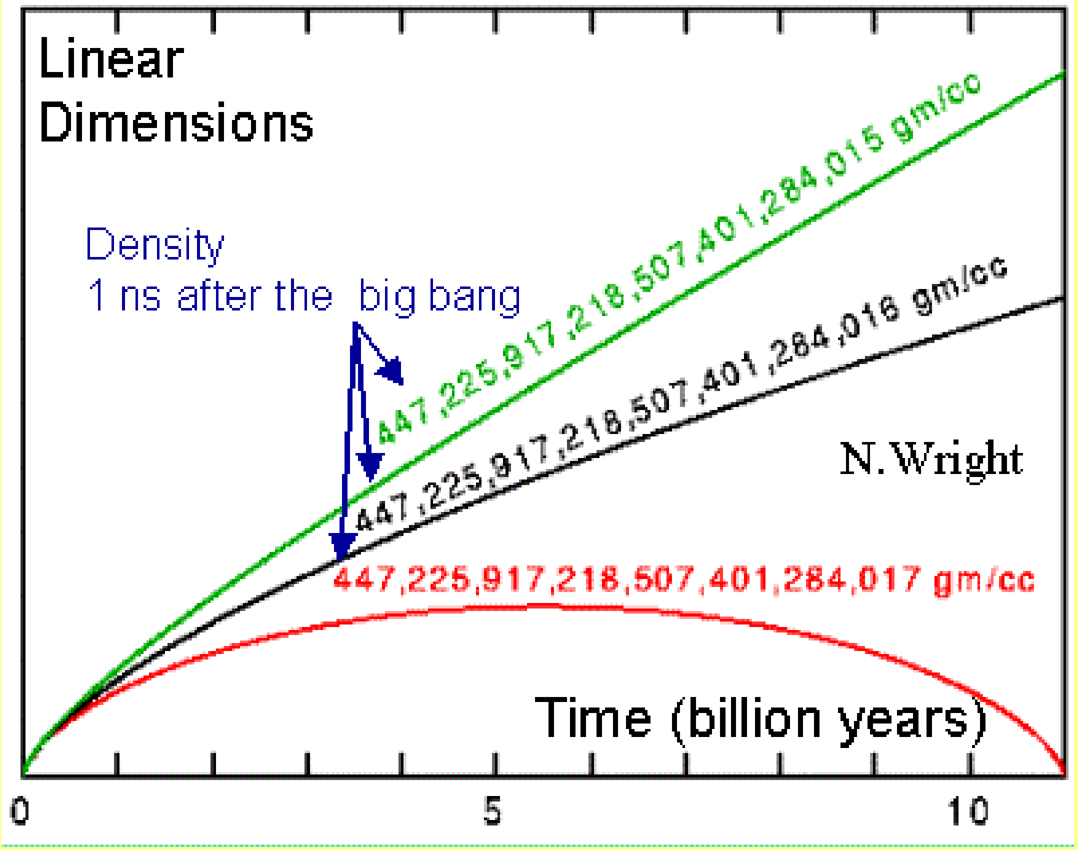


What do we know about the geometry of our universe?

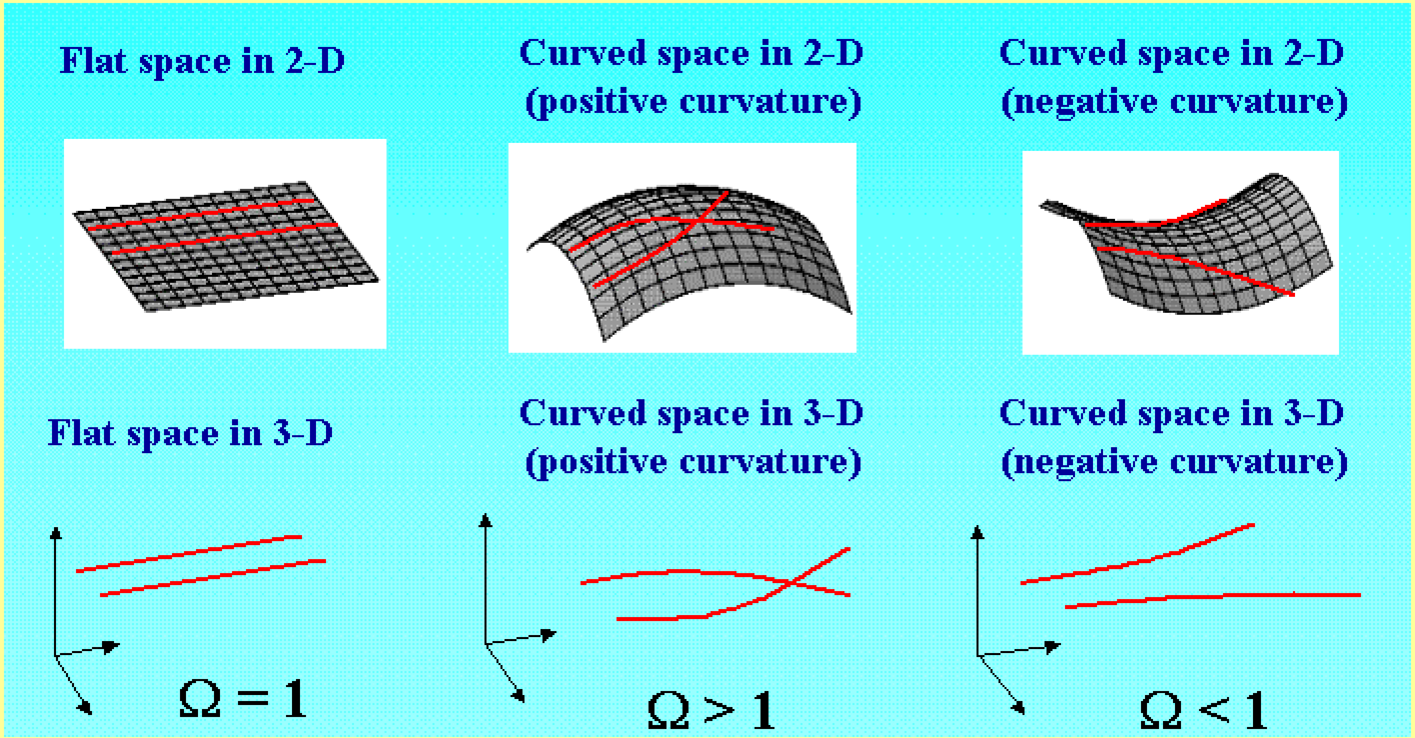
For a large scale homogeneous and isotropic universe the crucial expansion parameter is the energy density vs. the critical density:

$$\Omega = \frac{\rho}{\rho_C}$$

$$\rho_C = \frac{3H^2}{8\pi G}$$

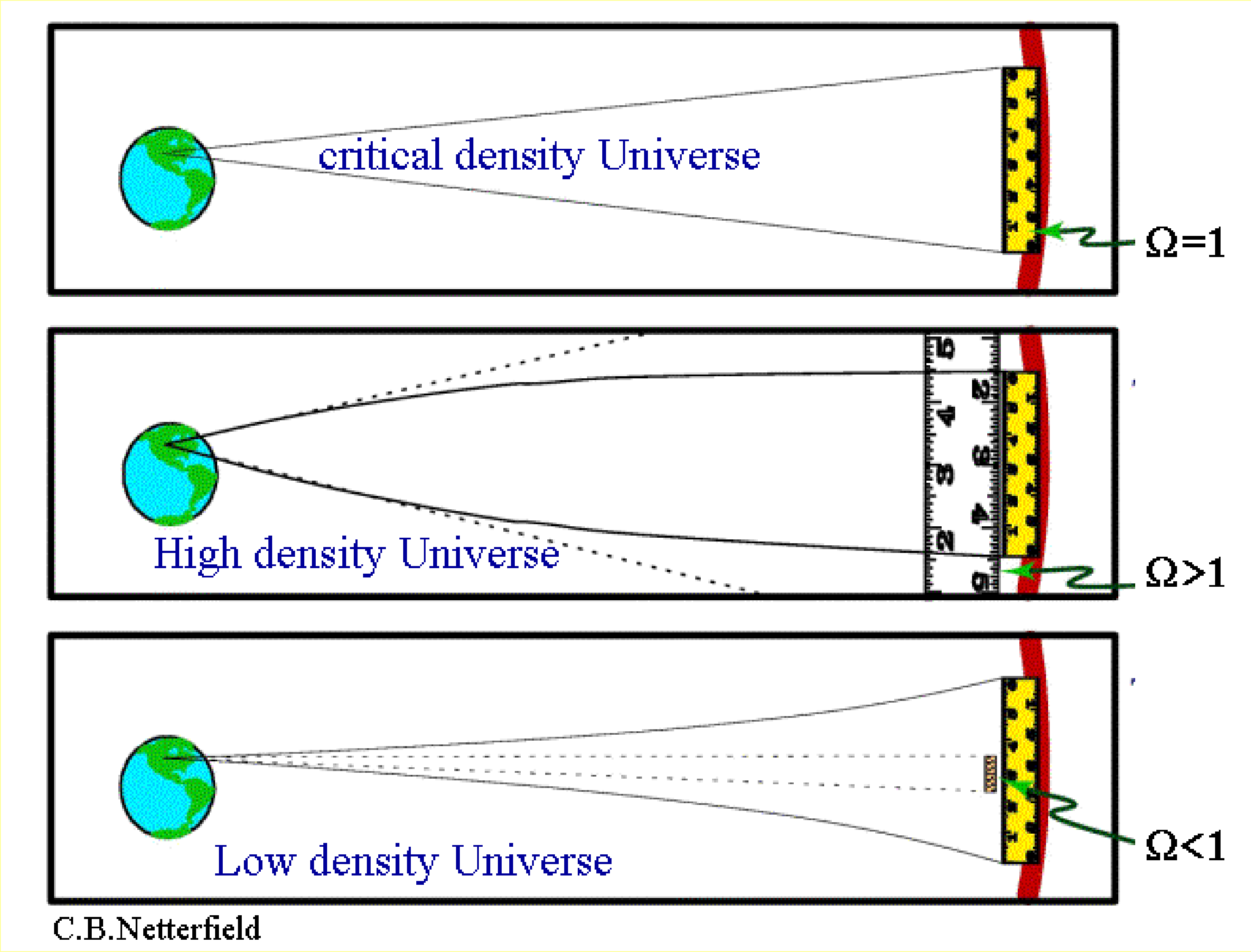


Propagation of light rays as a probe of spatial curvature
"Background lensing,,



For $\Omega \sim 1$ ⟺ tiny effect, to be observed over cosmological scales ⟶ CMBR γ's

If we had a standard “ruler,,, we could measure Ω

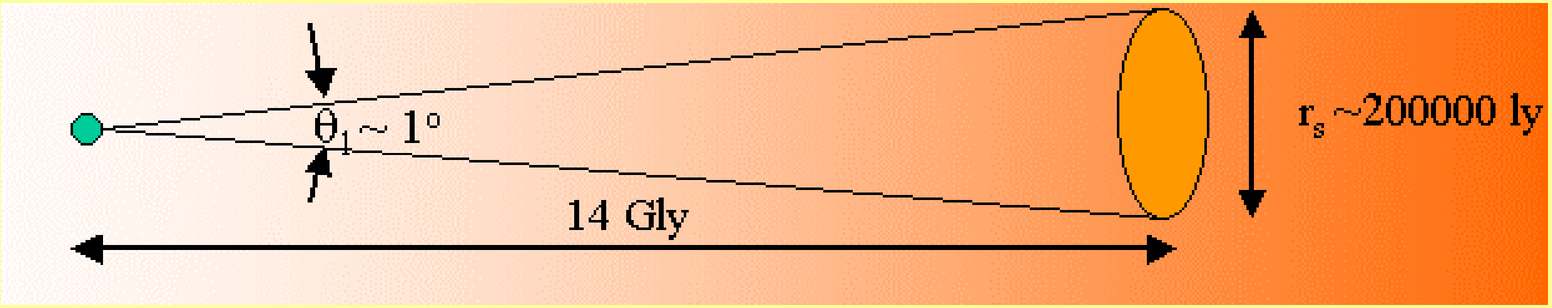


Temperature perturbations expected at the scale of the acoustic horizon r_s at recombination

r_s = distance a sound wave travels till recombination time

evaluated knowing sound velocity (and general relativity)

r_s is our standard ruler !



$$\theta_1 \sim 0.81\ \Omega^{1/2}$$

Origin of the anisotropy of the CMBR

Our Hubble volume is not homogeneous on several scales: galaxies, clusters, superclusters

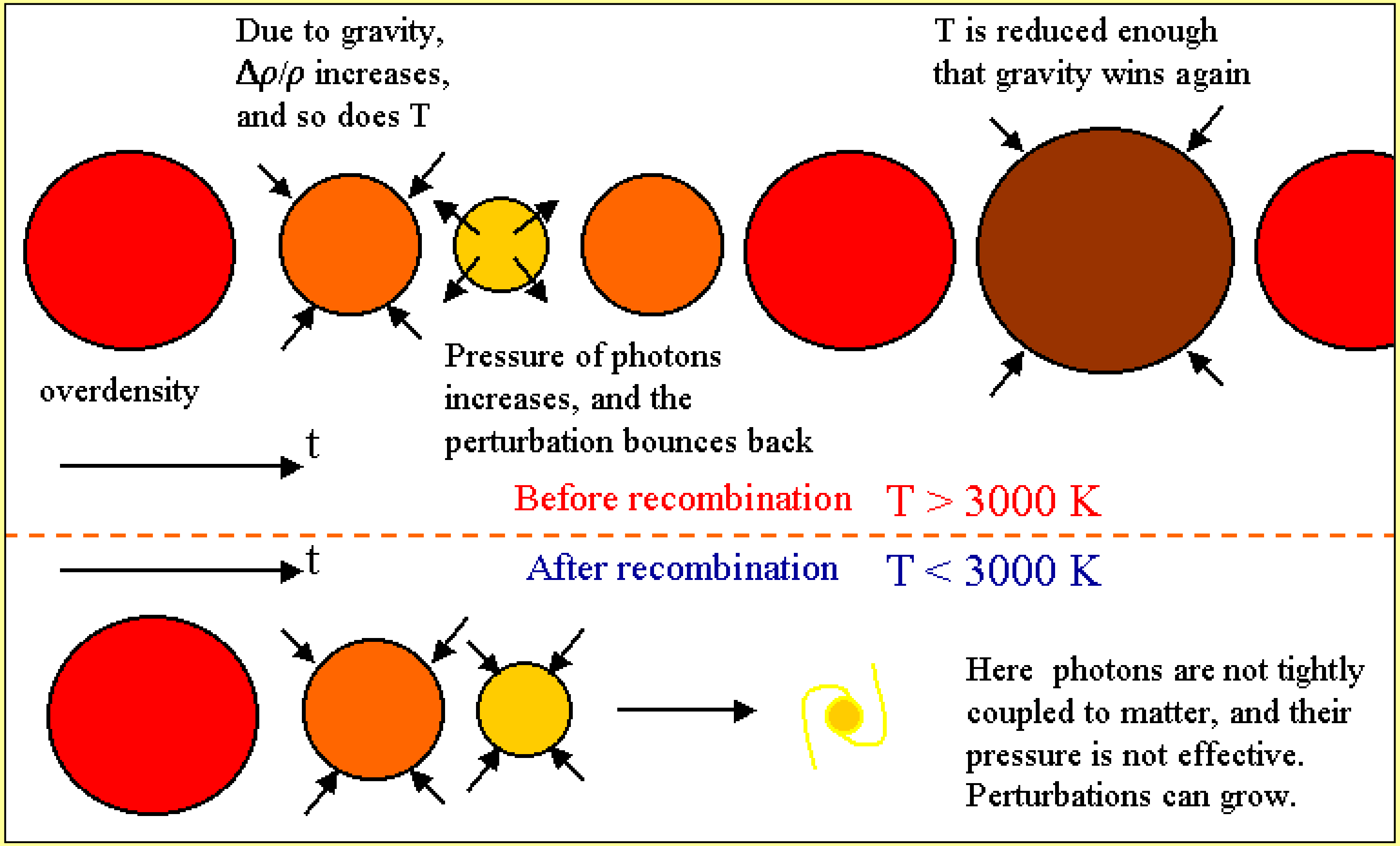
General picture

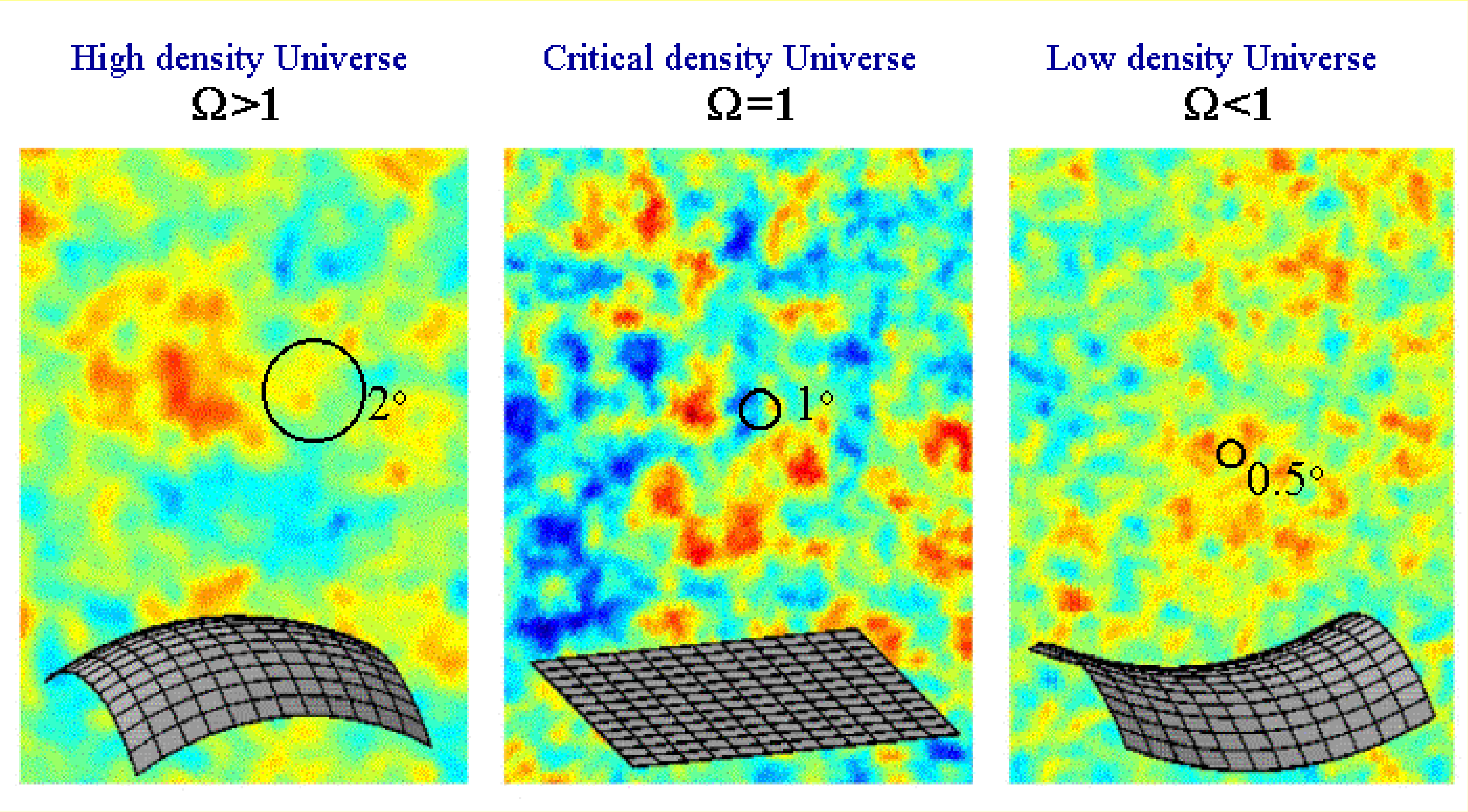
tiny density perturbations amplified by gravitational instability

Original seeds?

inflationary models: quantum perturbations grown to macroscopic scales during INFLATION

Density perturbation leave their signature on the CMBR spectrum




High density Universe
Ω>1
2°
Critical density Universe
Ω=1
1°
Low density Universe
Ω<1
0.5°

Analysis

multipole expansion of CMBR temperature

$$\delta T(\varphi,\theta) = \Sigma_{l,m} \; a_{l,m} Y^{l}_{m}(\varphi,\theta)$$

average:

$$c_l = \langle a_{l,m}^2 \rangle$$ Power spectrum

Acoustic peak: $l \sim 220 / \Omega^{1/2}$

More structures expected in the CMBR power spectrum: different perturbation scales, frozen at recombination, correspond to either compressions or decompressions.

CMBR anisotropy

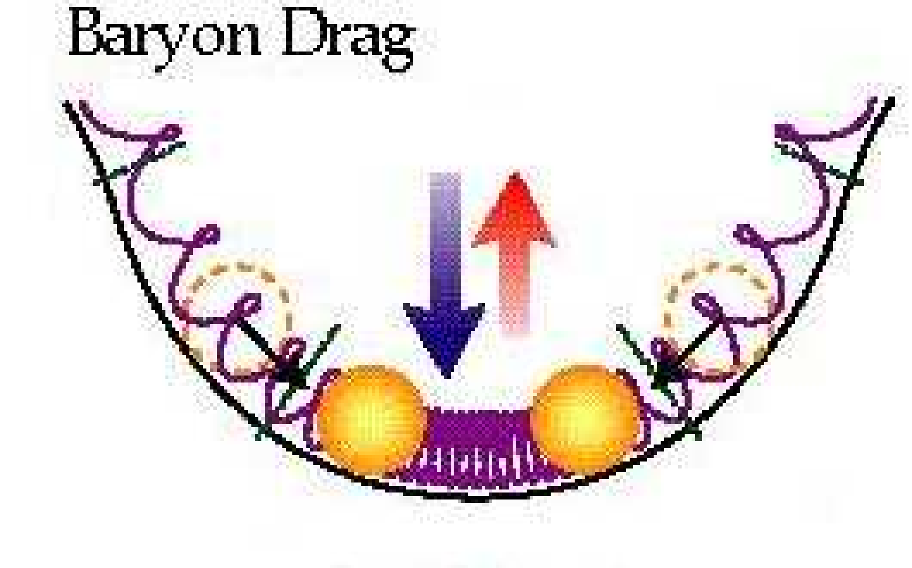
Structure of the perturbation seeds

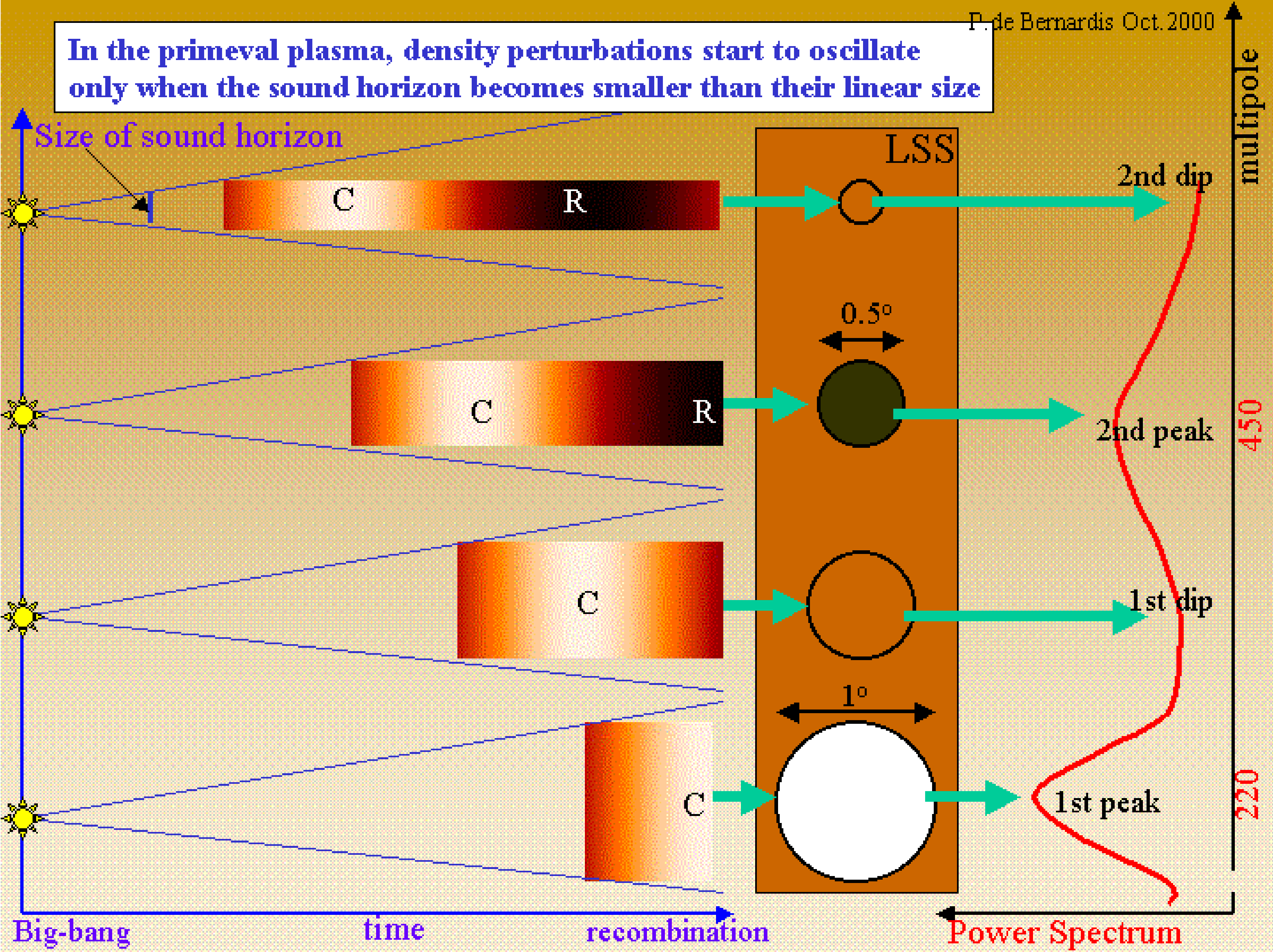
n = spectral index

n≠1 “tilted,, spectrum

Ω_b baryon fraction

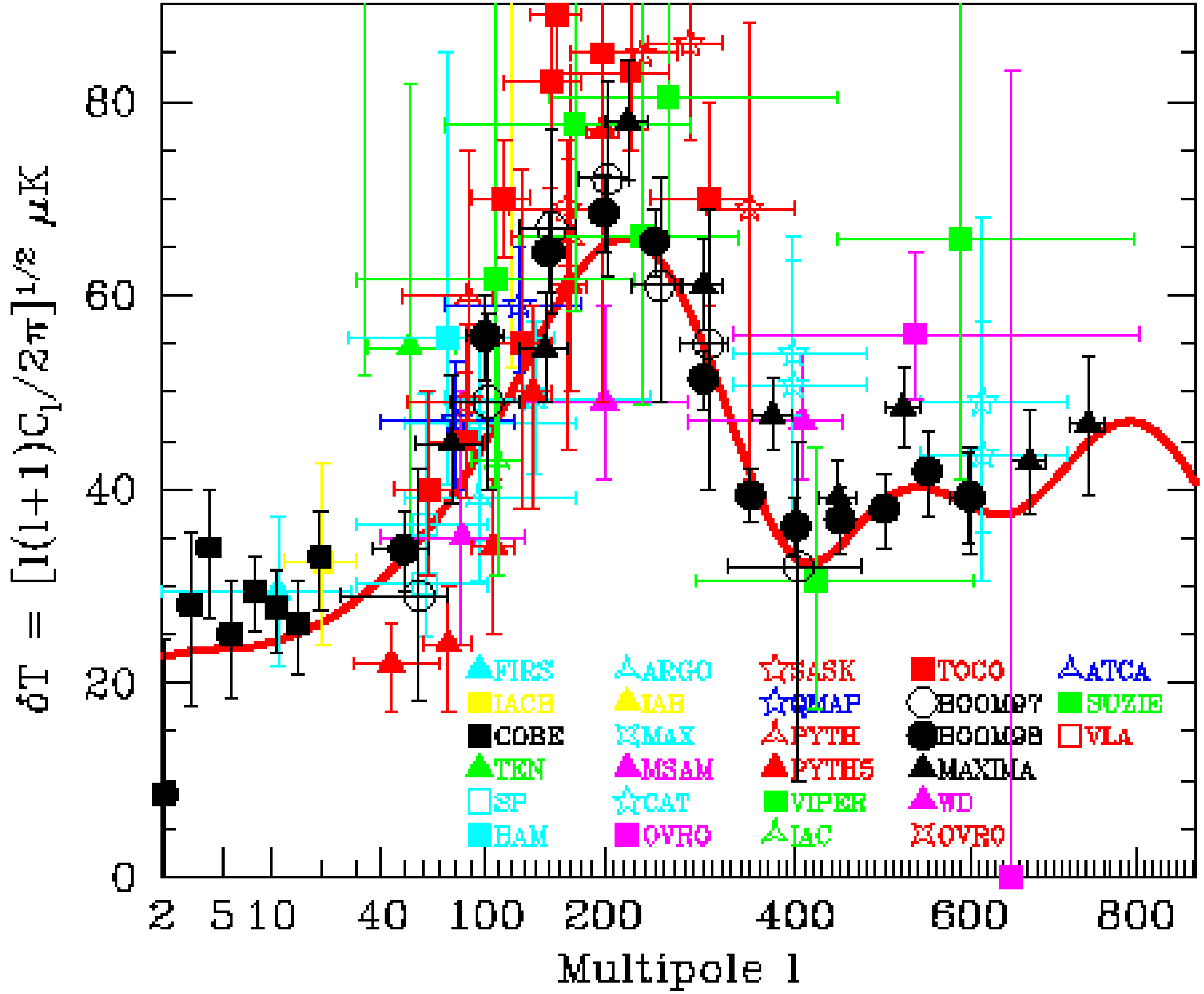
baryons increase the effective mass of the fluid: gravitational infall leads to a greater compression: higher odd peaks




P. de Bernardis Oct. 2000
In the primeval plasma, density perturbations start to oscillate only when the sound horizon becomes smaller than their linear size
Size of sound horizon
C
R
C
R
C
C
LSS
0.5°
1°
2nd dip
2nd peak
1st dip
1st peak
multipole
450
220
Big-bang
time
recombination
Power Spectrum

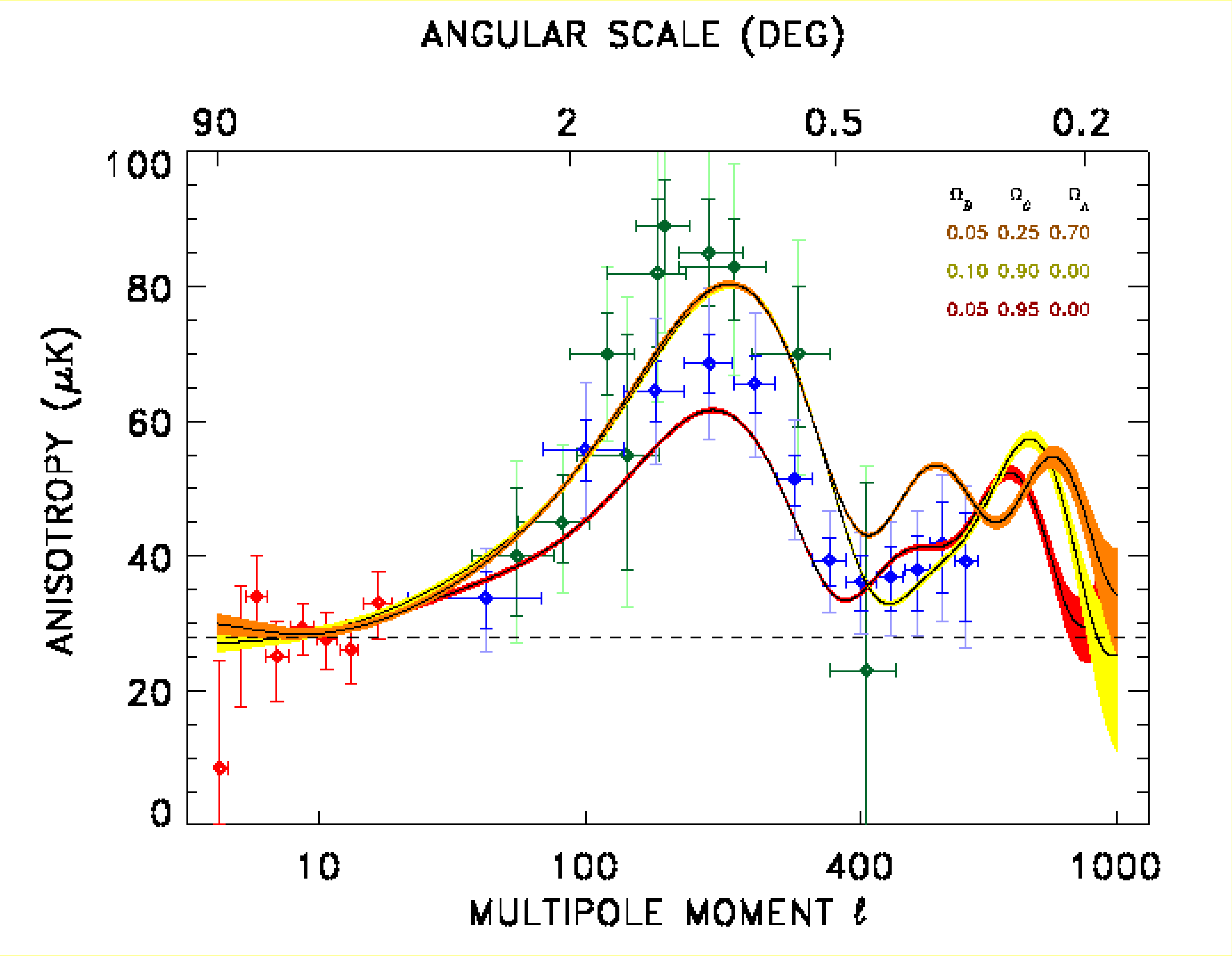
Experiments Before Wmap

Many data over several years:

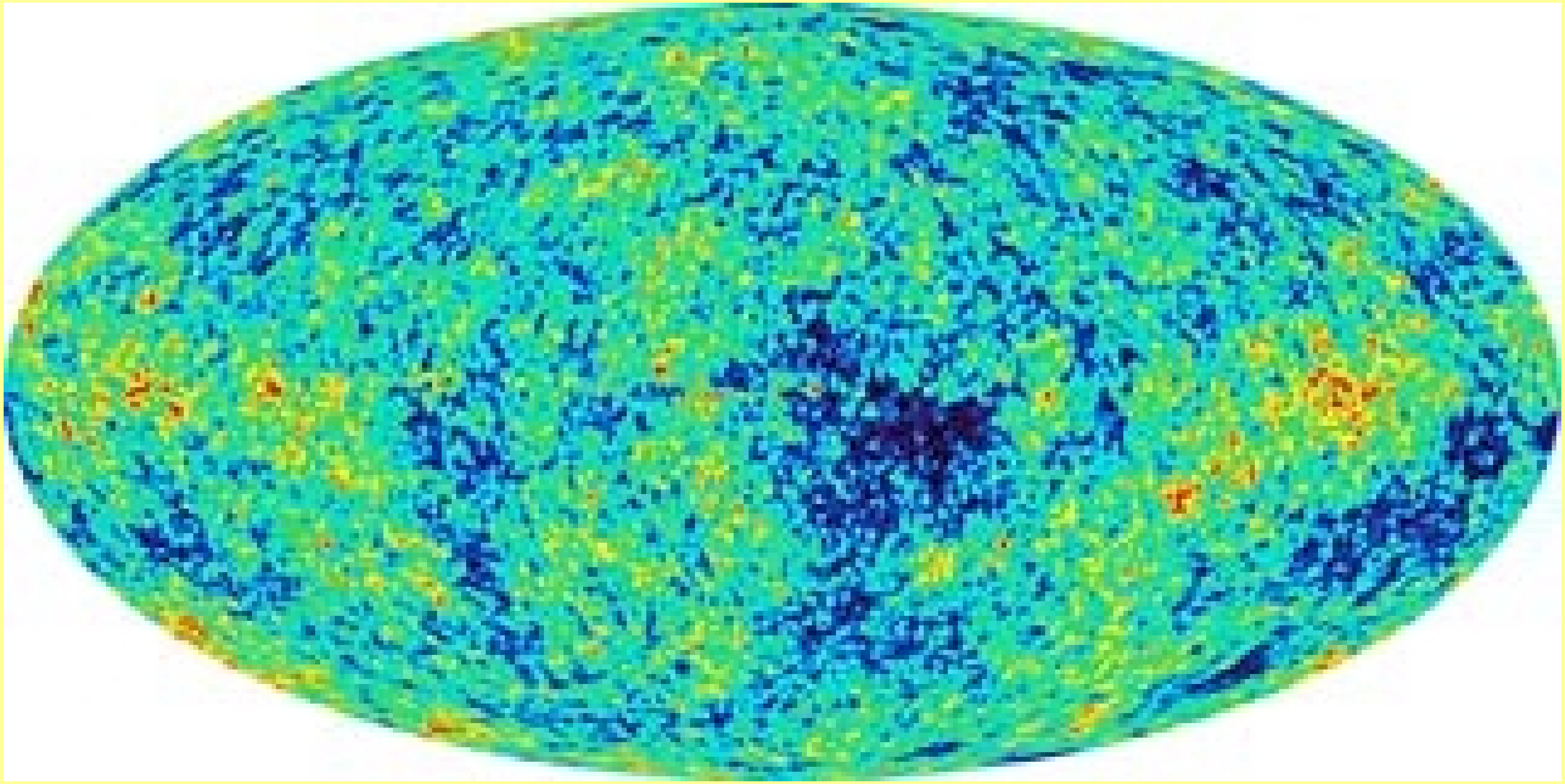


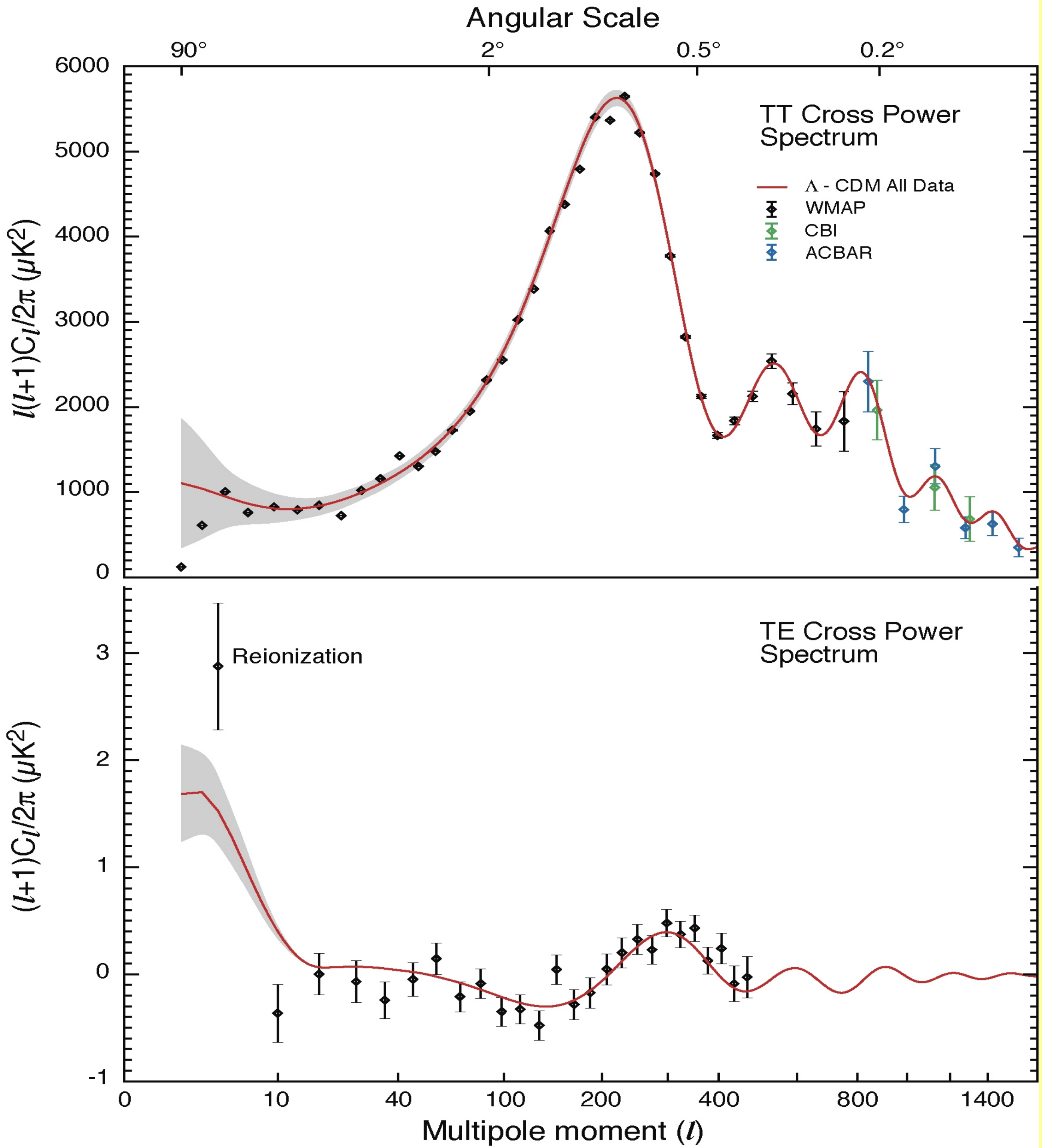
To study up to larger multipoles we need a good angular resolution

WMAP sensitivity



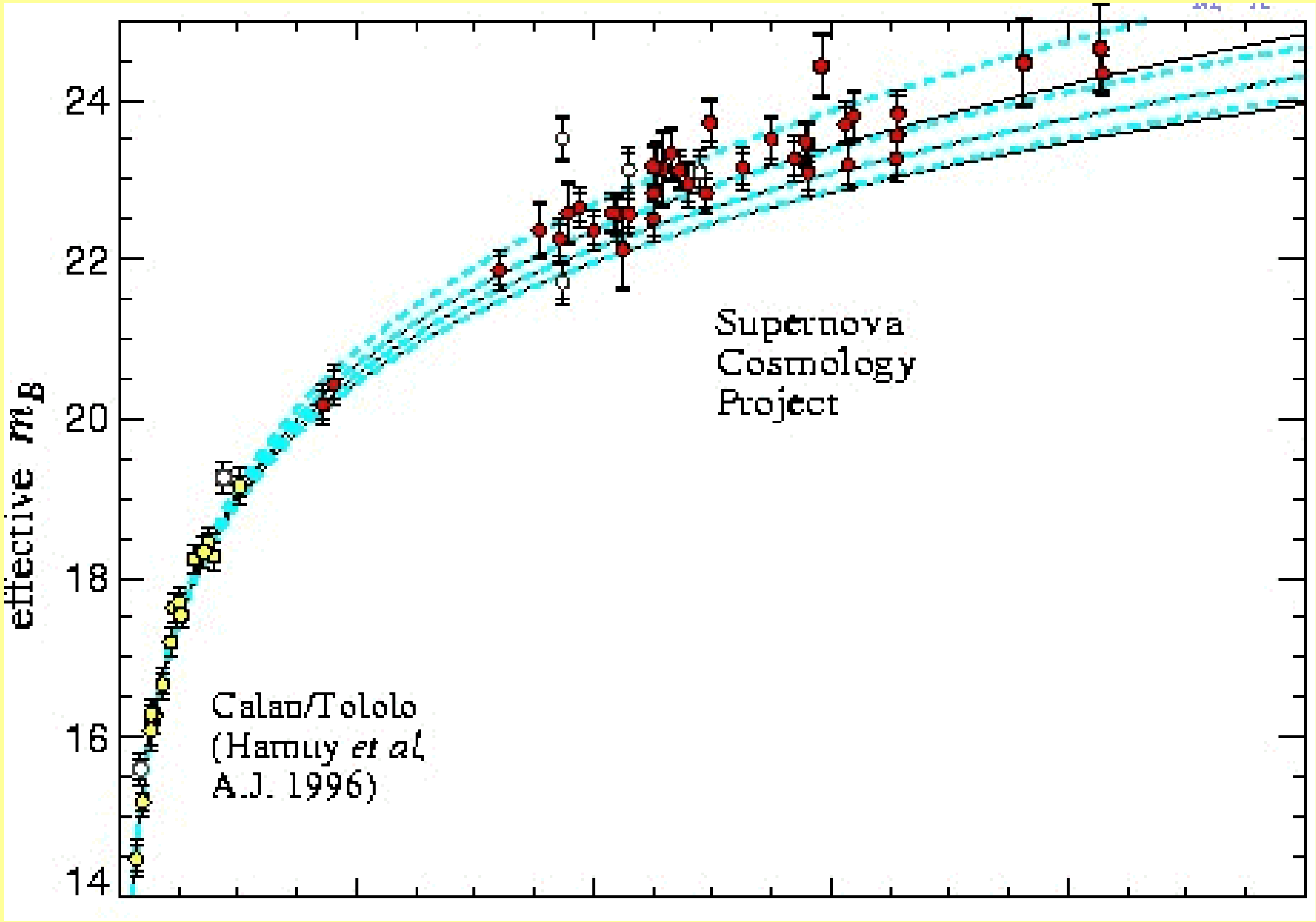
Wmap First Results

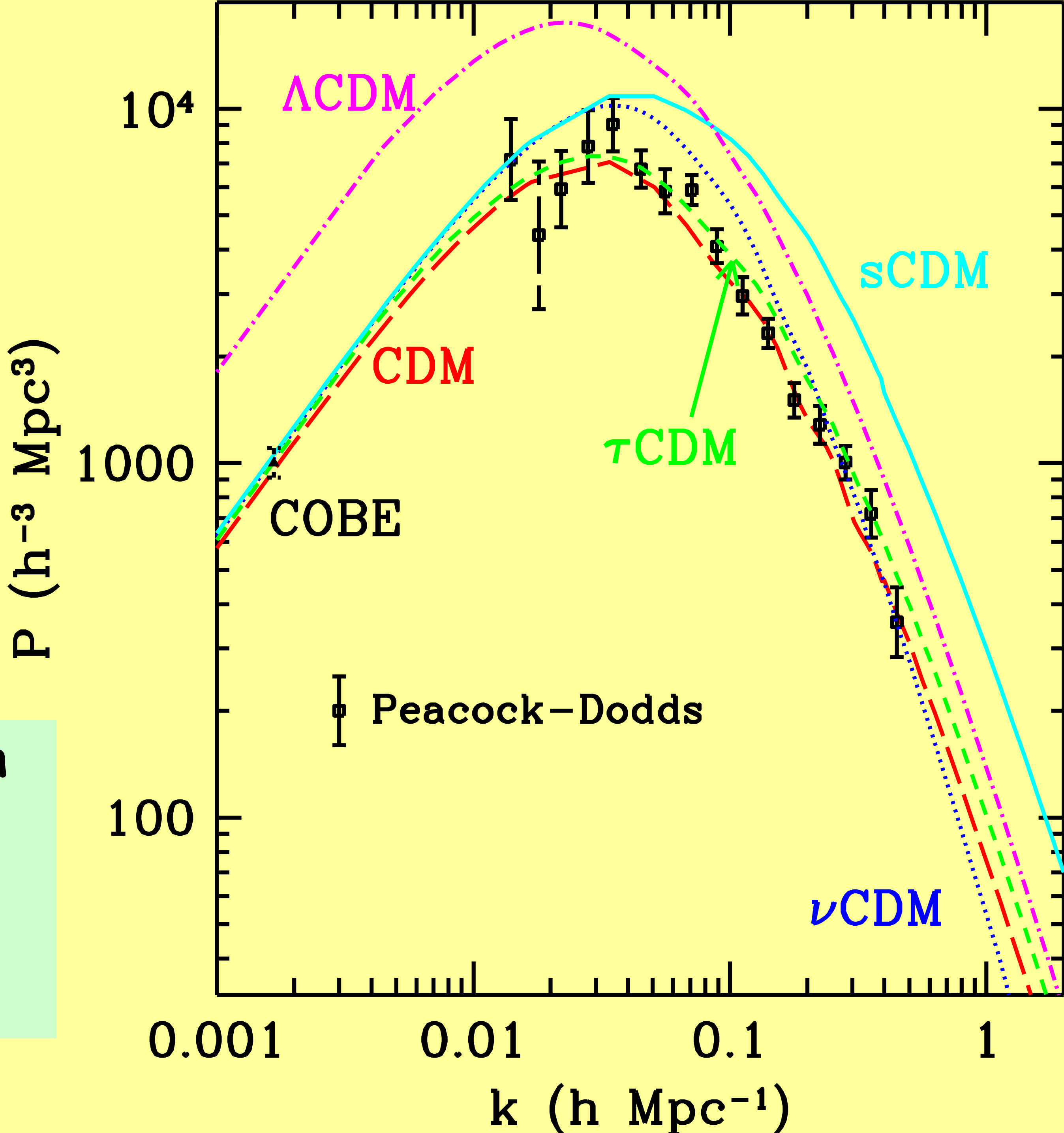



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
l(l+1)C_l/2π (μK²)
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
TE Cross Power Spectrum
Reionization
3
2
1
0
-1
(l+1)C_l/2π (μK²)
0
10
40
100
200
400
800
1400
Multipole moment (l)

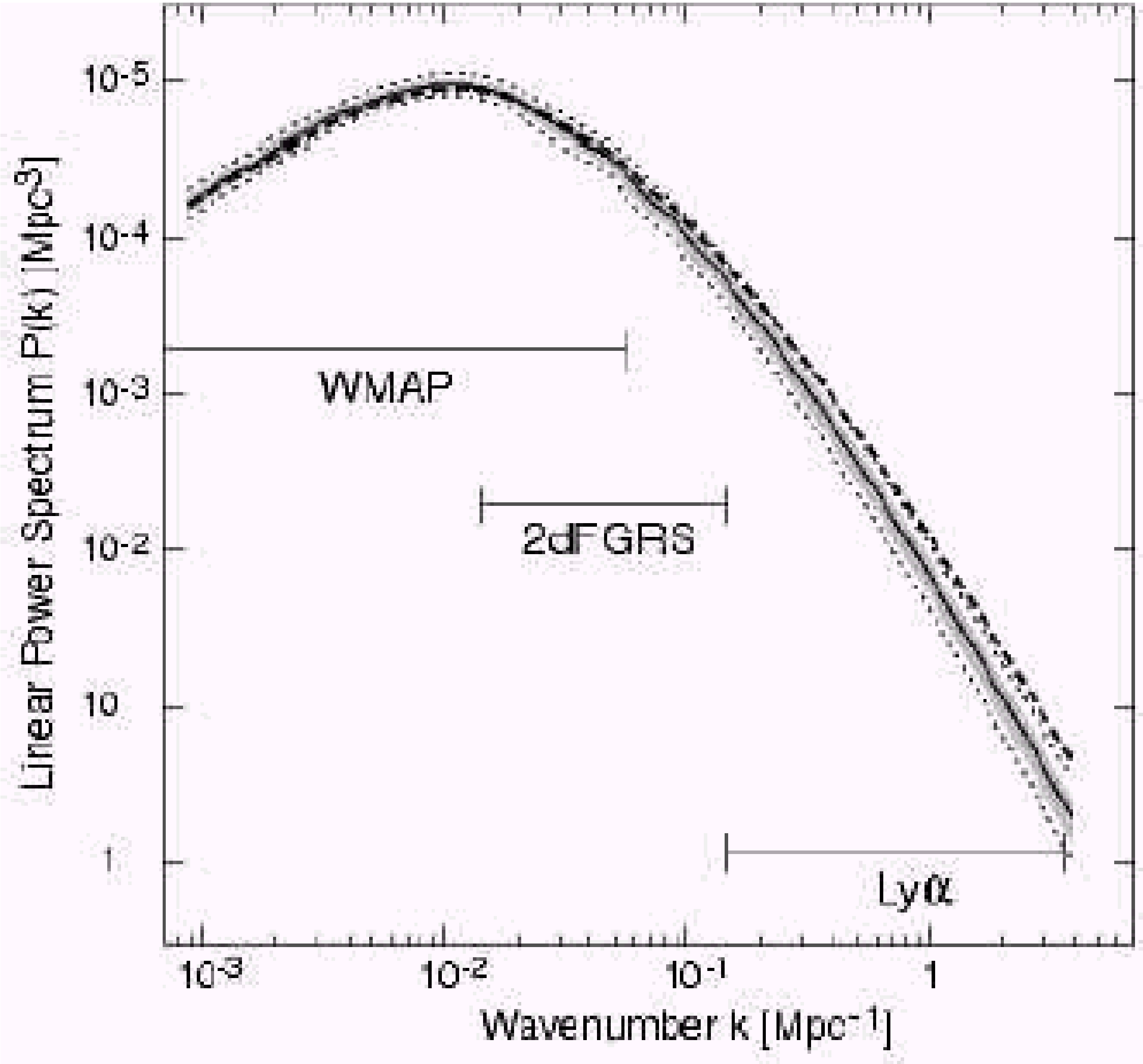
Data on CMBR + SN + LSS

Measuring the acceleration parameters with SN1a





Anglo-Australian Telescope two degree field Galaxy Redshift Survey-2dFGRS



Linear Power Spectrum P(k) [Mpc^3]
10-5
10-4
10-3
10-2
10
1
WMAP
2dFGRS
Lyα
10-3
10-2
10-1
1
Wavenumber k [Mpc-1]

ΛCDM

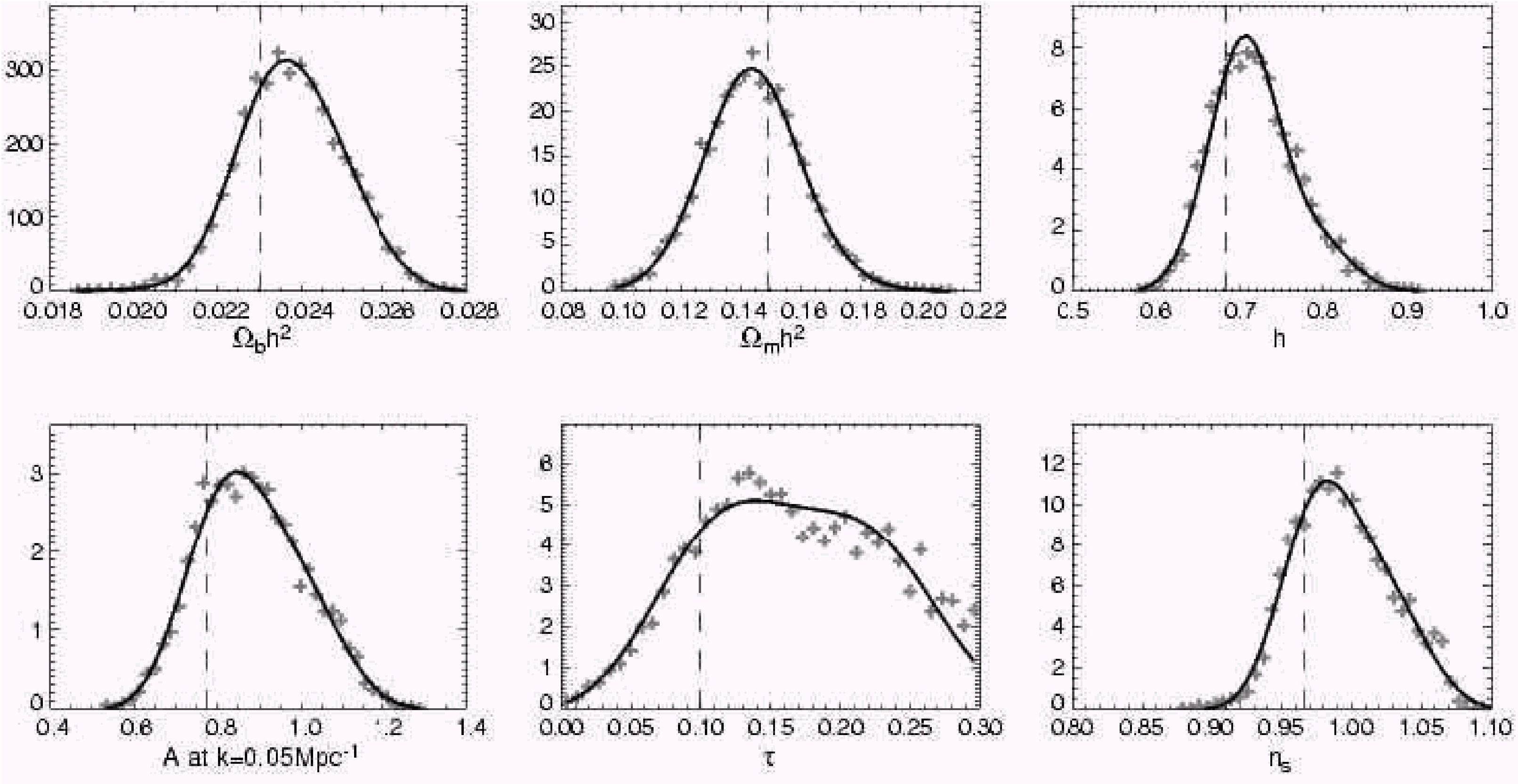


Fig. 3.— This figure shows the likelihood function of the *WMAP* TT + TE data as a function of the basic parameters in the power law ΛCDM *WMAP* model. ($\Omega_b h^2$, $\Omega_m h^2$, h, A, n_s and τ.) The points are the binned marginalized likelihood from the Markov chain and the solid curve is an Edgeworth expansion of the Markov chains points. The marginalized likelihood function is nearly Gaussian for all of the parameters except for τ. The dashed lines show the maximum likelihood values of the global six dimensional fit. Since the peak in the likelihood, x_{ML} is not the same as the expectation value of the likelihood function, $< x >$, the dashed line does not lie at the center of the projected likelihood.

Table 7. Best Fit Parameters: Power Law Λ CDM

	WMAP	WMAPext [16][a]	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	$0.75^{+0.08}_{-0.07}$
n_s	0.99 ± 0.04	0.97 ± 0.03	0.97 ± 0.03	0.96 ± 0.02
τ	$0.166^{+0.076}_{-0.071}$	$0.143^{+0.071}_{-0.062}$	$0.148^{+0.073}_{-0.071}$	$0.117^{+0.057}_{-0.053}$
h	0.72 ± 0.05	0.73 ± 0.05	0.73 ± 0.03	0.72 ± 0.03
$\Omega_m h^2$	0.14 ± 0.02	0.13 ± 0.01	0.134 ± 0.006	0.133 ± 0.006
$\Omega_b h^2$	0.024 ± 0.001	0.023 ± 0.001	0.023 ± 0.001	0.0226 ± 0.0008
χ^2_{eff}/ν	1429/1341	1440/1352	1468/1381	... [b]

[a] *WMAP* +CBI+ACBAR

[b] Since the Lyman α data points are correlated, we do not quote an effective χ^2 for the combined likelihood including Lyman α data (see Verde et al. (2003)).

running spectral index ΛCDM

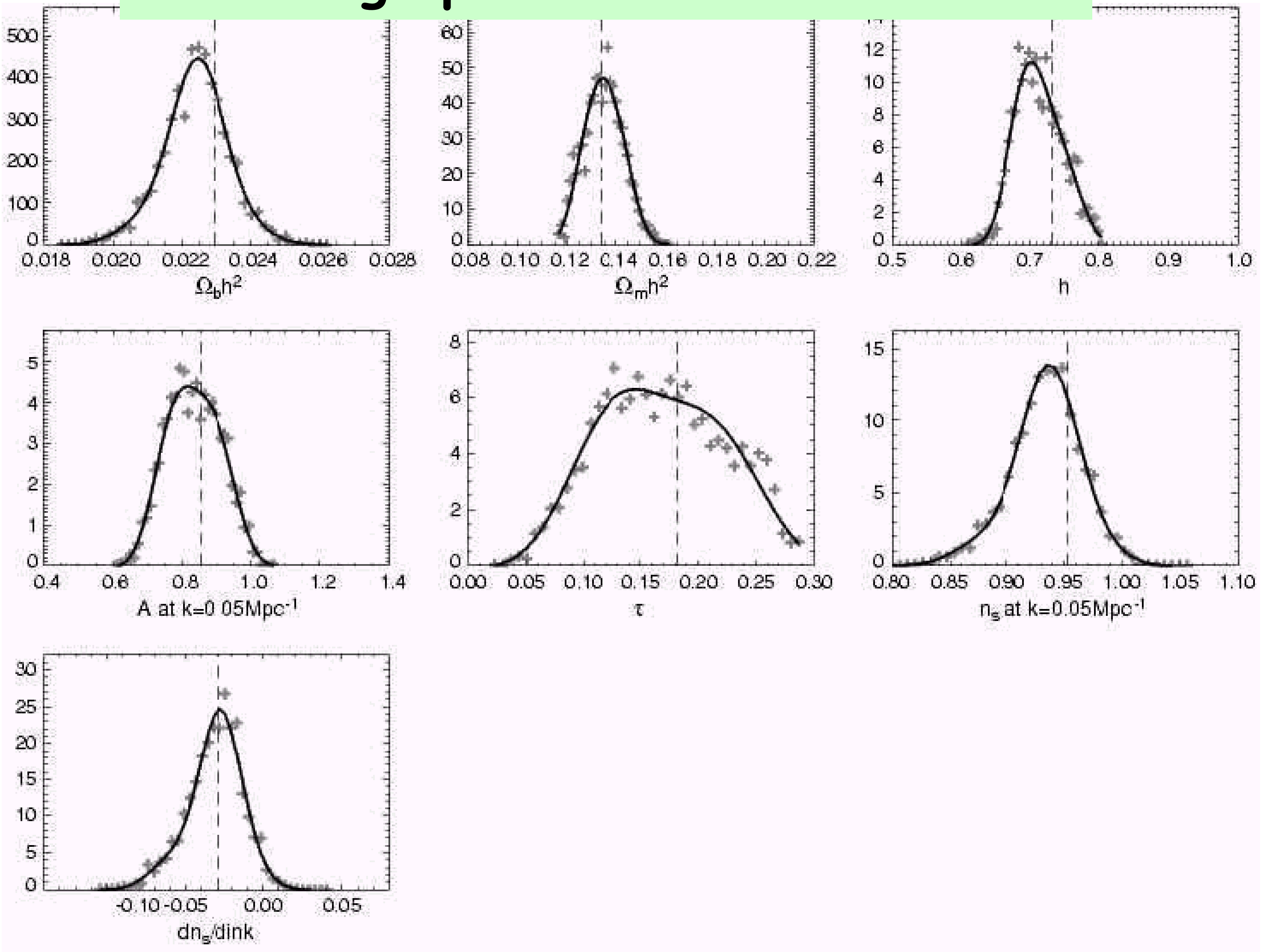


Fig. 8.— This figure shows the marginalized likelihood for various cosmological parameters in the running spectral index model for our analysis of the combined *WMAP* , CBI, ACBAR, 2dFGRS and Lyman α data sets. The dashed lines show the maximum likelihood values of the global seven dimensional fit.

Table 8. Best Fit Parameters for the Running Spectral Index ΛCDM Model

	WMAP	WMAPext	WMAPext+2dFGRS	WMAPext+ 2dFGRS+ Lyman α
A	0.92 ± 0.12	0.9 ± 0.1	0.84 ± 0.09	$0.83^{+0.09}_{-0.08}$
n_s	$0.93^{+0.07}_{-0.07}$	0.91 ± 0.06	$0.93^{+0.04}_{-0.05}$	0.93 ± 0.03
$dn_s/d\ln k$	-0.047 ± 0.04	-0.055 ± 0.038	$-0.031^{+0.023}_{-0.025}$	$-0.031^{+0.016}_{-0.017}$
τ	0.20 ± 0.07	0.20 ± 0.07	0.17 ± 0.06	0.17 ± 0.06
h	0.70 ± 0.05	0.71 ± 0.06	0.71 ± 0.04	$0.71^{+0.04}_{-0.03}$
$\Omega_m h^2$	0.14 ± 0.02	0.14 ± 0.01	0.136 ± 0.009	$0.135^{+0.008}_{-0.009}$
$\Omega_b h^2$	0.023 ± 0.002	0.022 ± 0.001	0.022 ± 0.001	0.0224 ± 0.0009
χ^2_{eff}/ν	1431/1342	1437/1350	1465/1380	*[a]

[a]Since the Lyman α data points are correlated, we do not quote χ^2_{eff} for the combined likelihood including Lyman α data (see Verde et al. (2003)).

From all these data we get

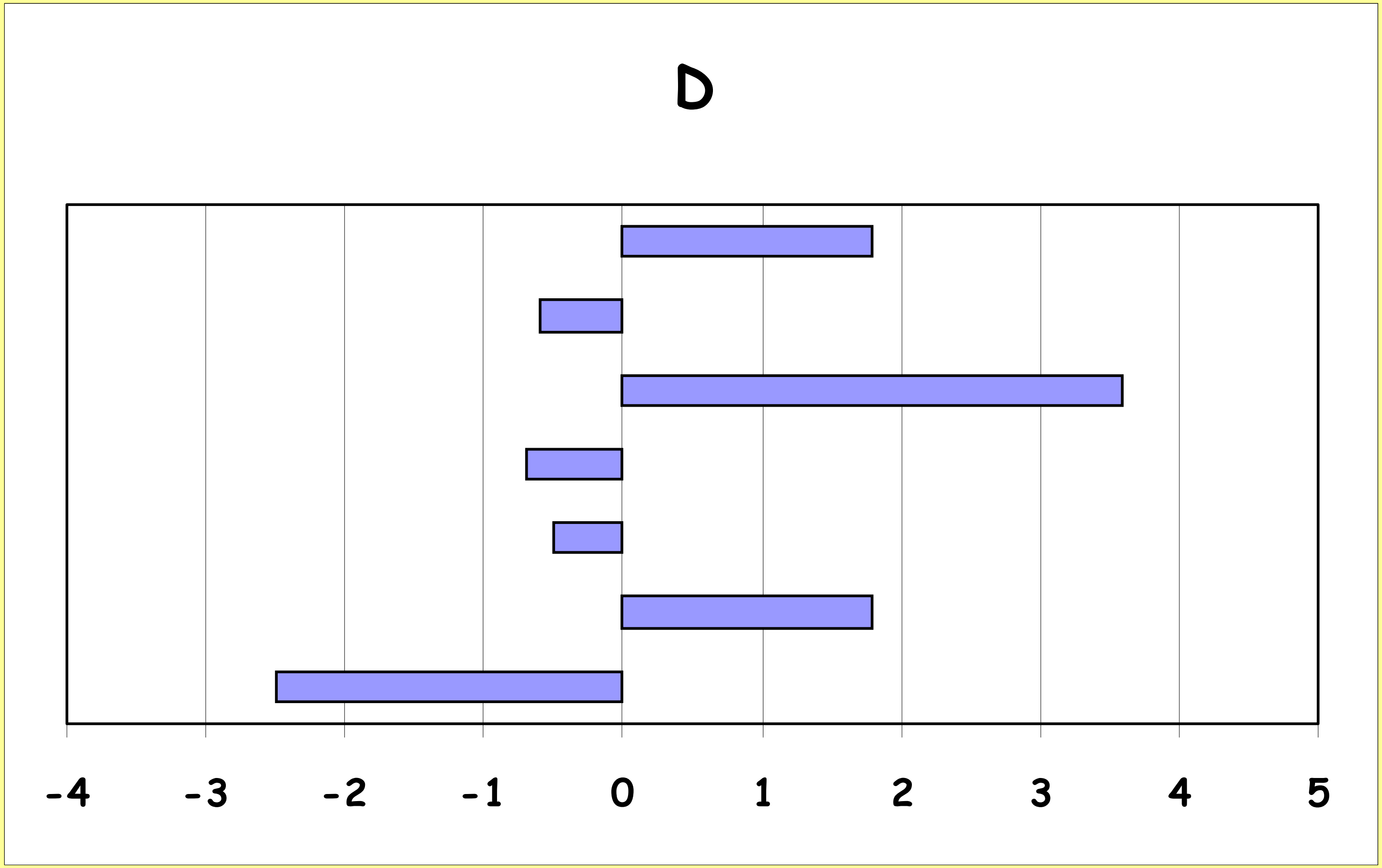
$$0.0215 \leq \Omega_B h^2 \leq 0.0234$$

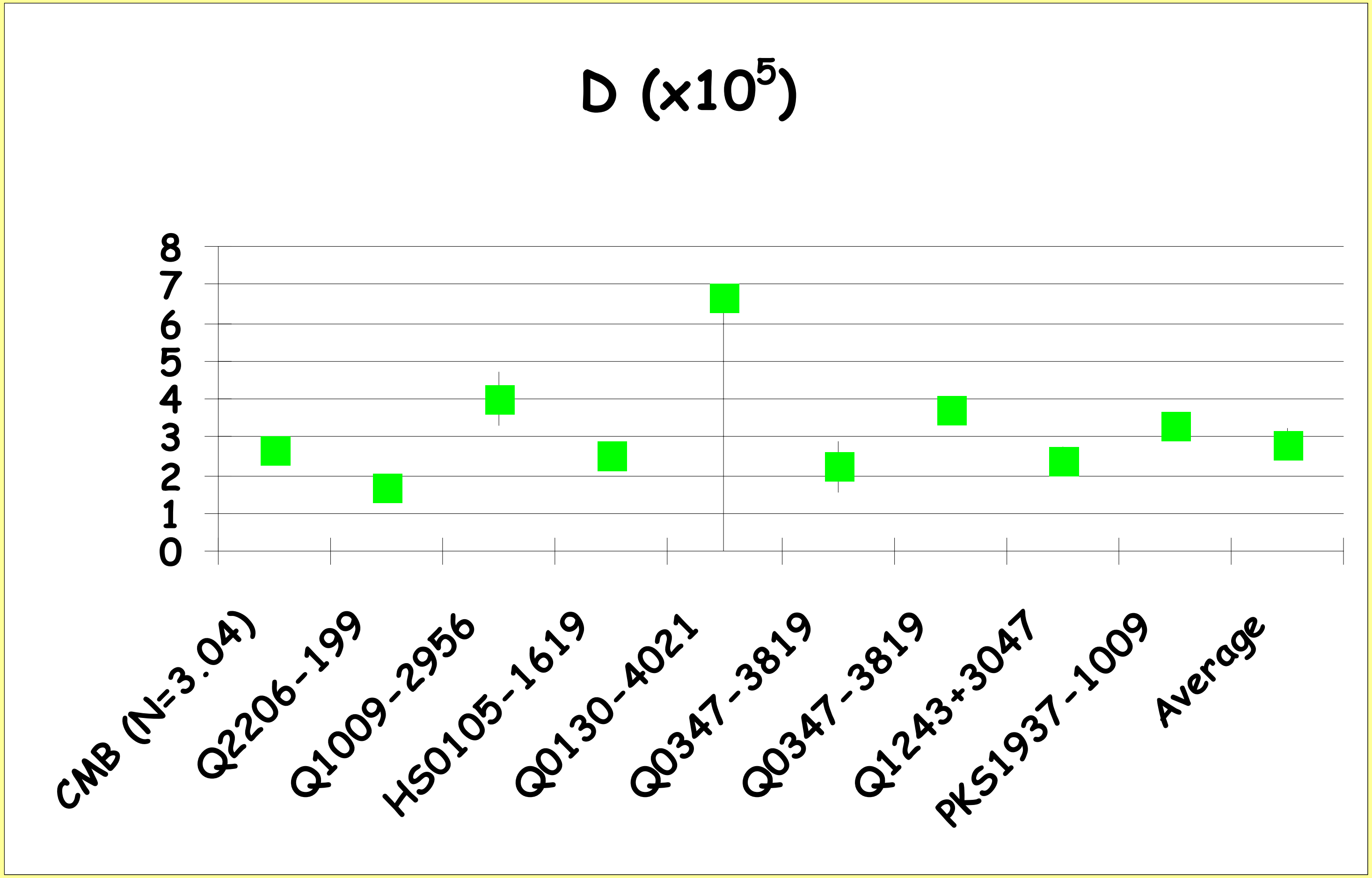
CMB+SN+LSS

vs

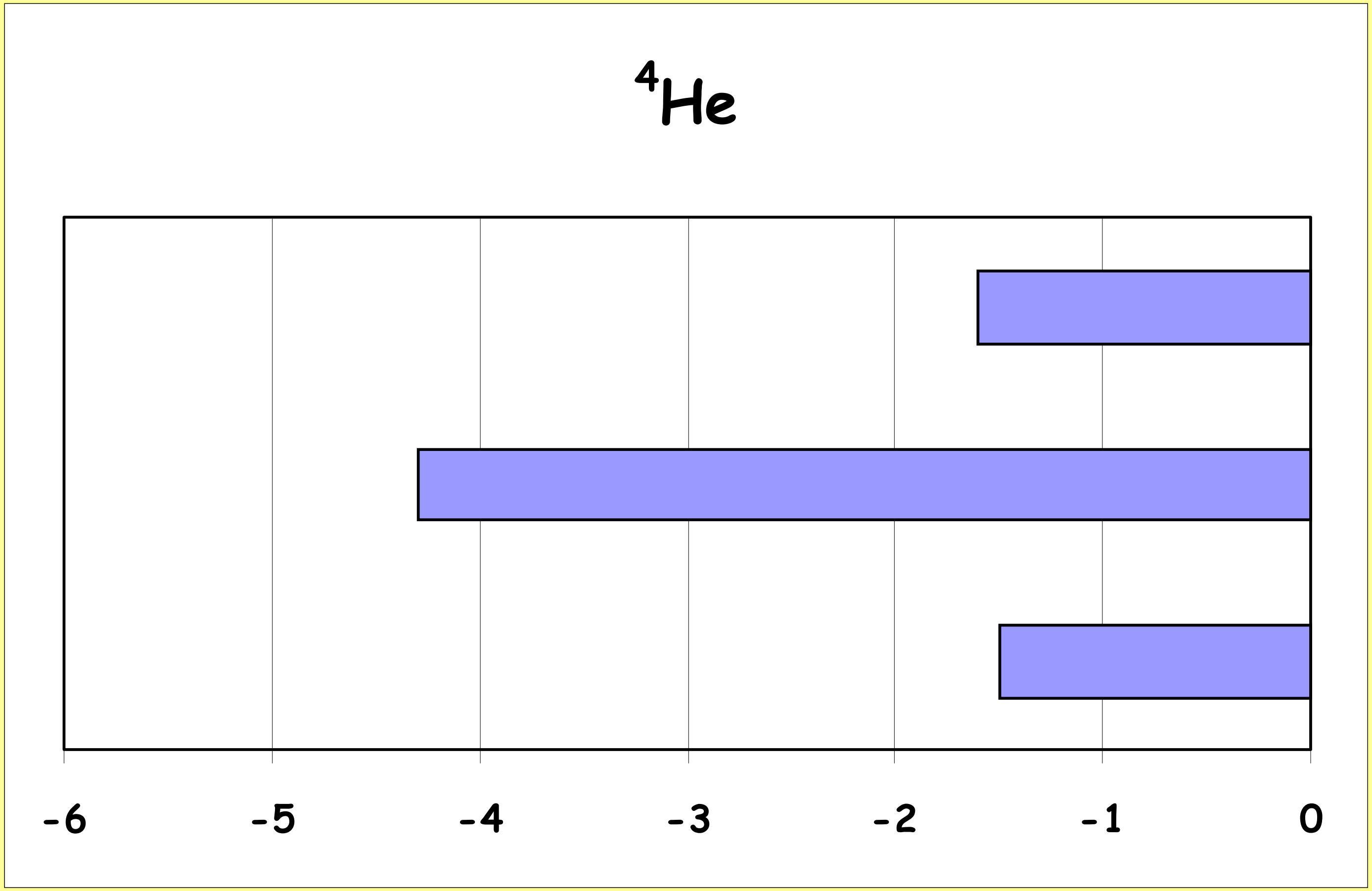
$$0.020 \leq \Omega_B h^2 \leq 0.024$$

BBN-D

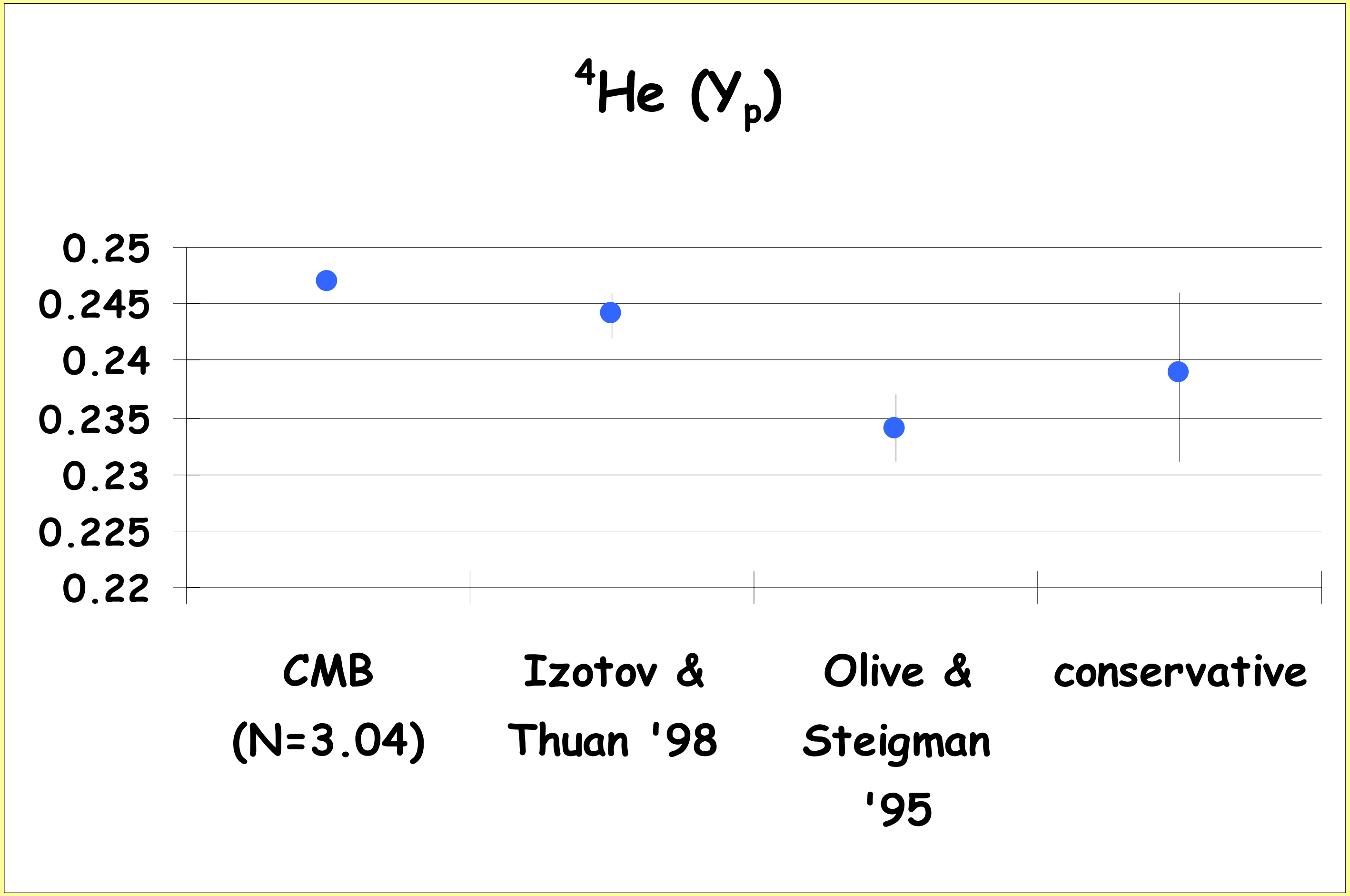

D
-4
-3
-2
-1
0
1
2
3
4
5



D (x10⁵)
8
7
6
5
4
3
2
1
0
CMB (N=3.04)
Q2206-199
Q1009-2956
HS0105-1619
Q0130-4021
Q0347-3819
Q0347-3819
Q1243+3047
PKS1937-1009
Average

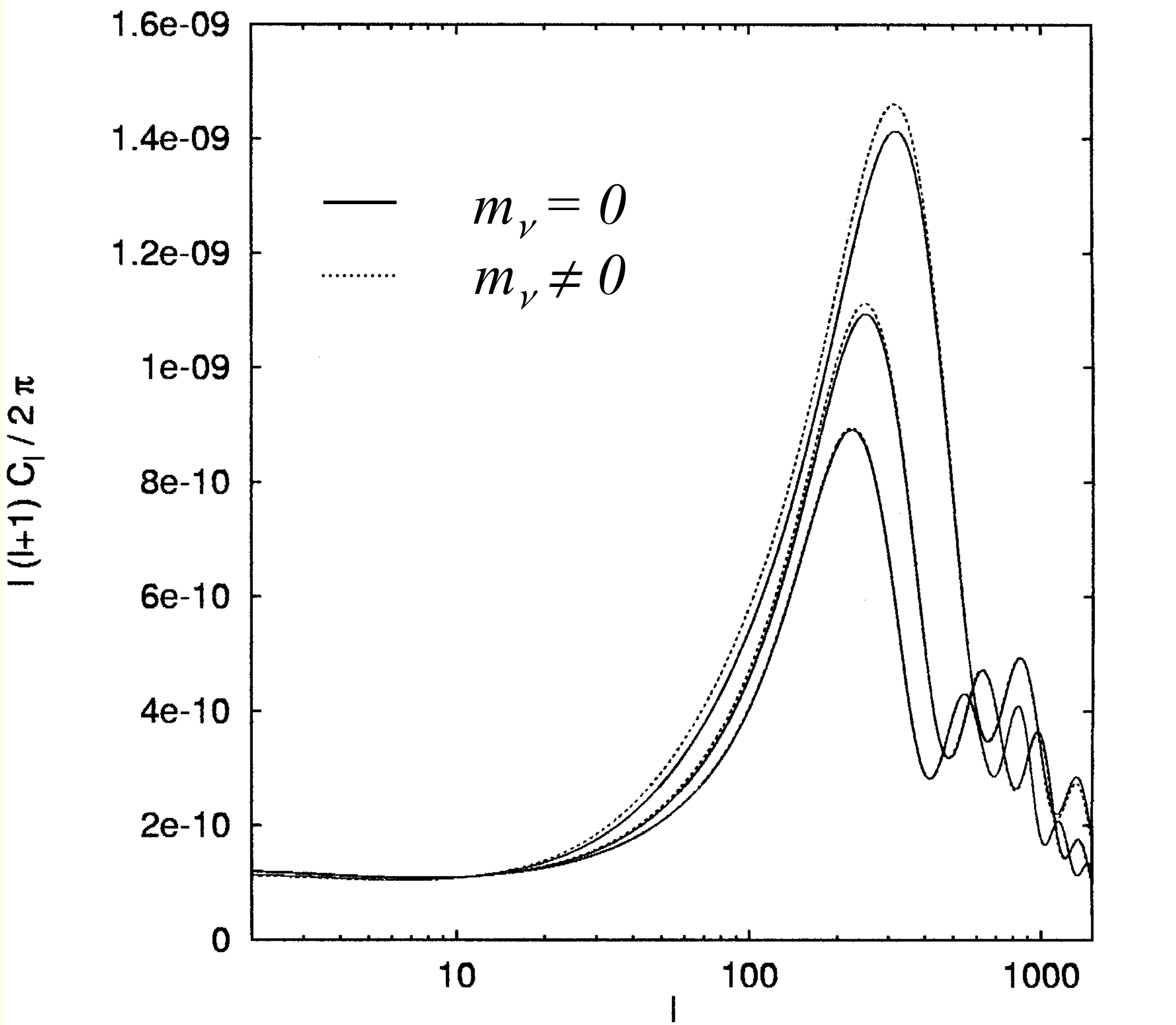


⁴He
-6
-5
-4
-3
-2
-1
0



^{4}He (Y_p)
0.25
0.245
0.24
0.235
0.23
0.225
0.22
CMB (N=3.04)
Izotov & Thuan '98
Olive & Steigman '95
conservative

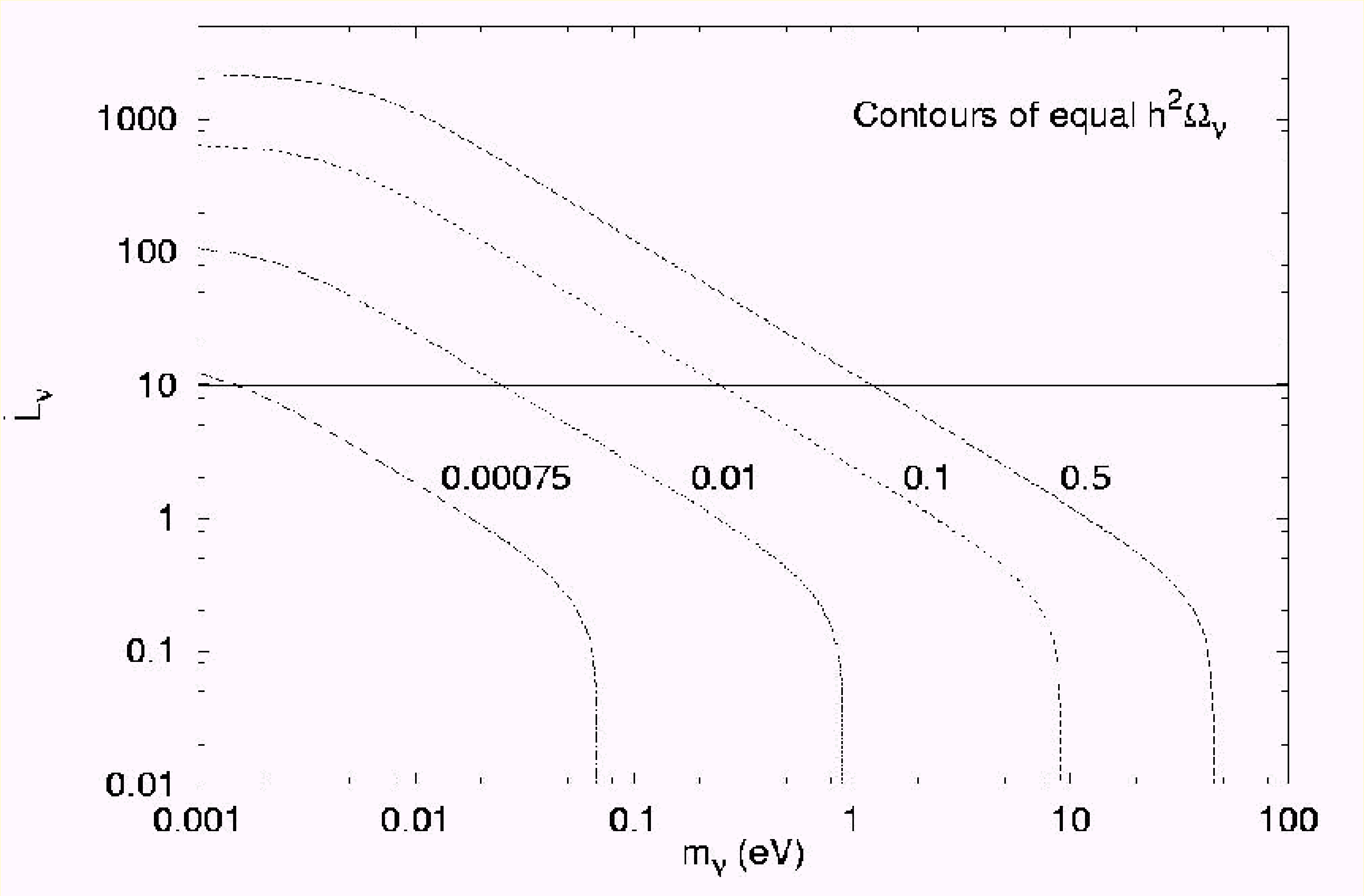
The CMB anysotropy is sensitive to N_ν^{eff} via the hight of first peak. The largest the highest



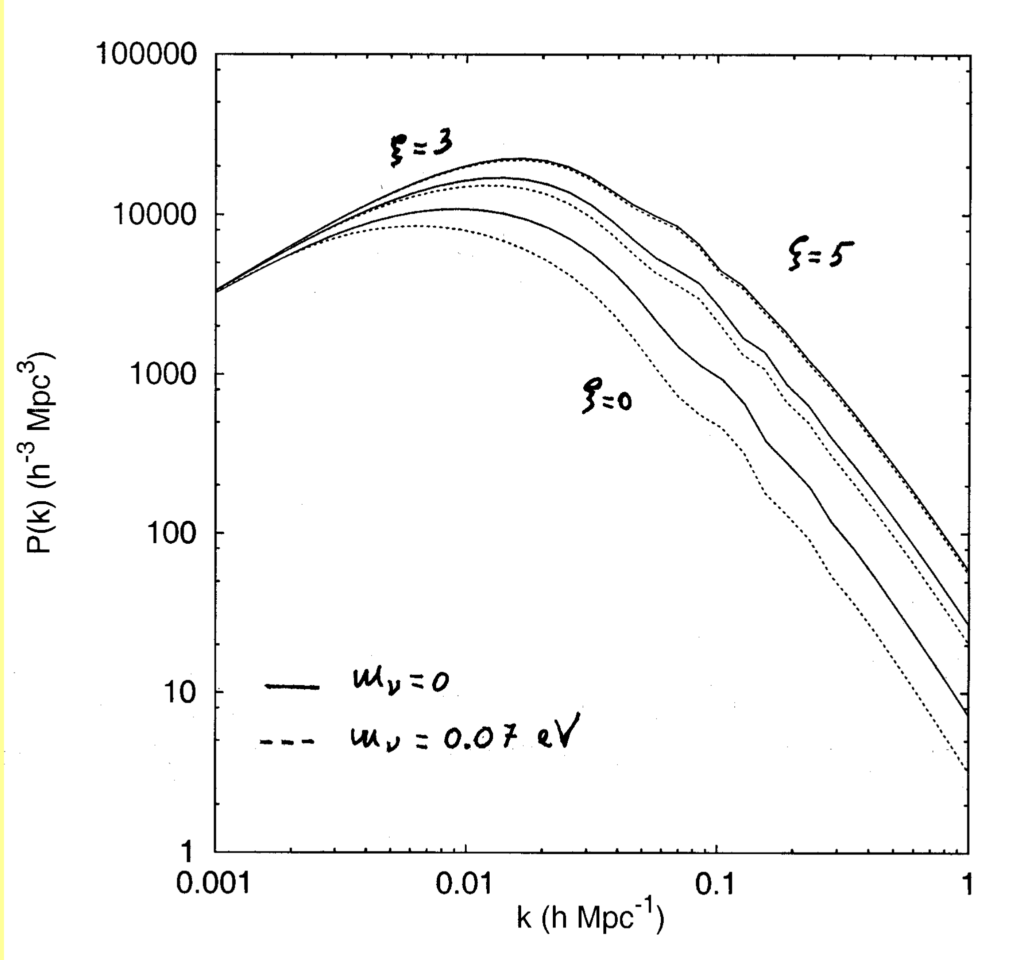
from CMB+LSS

$N_\nu^{eff} < 7$

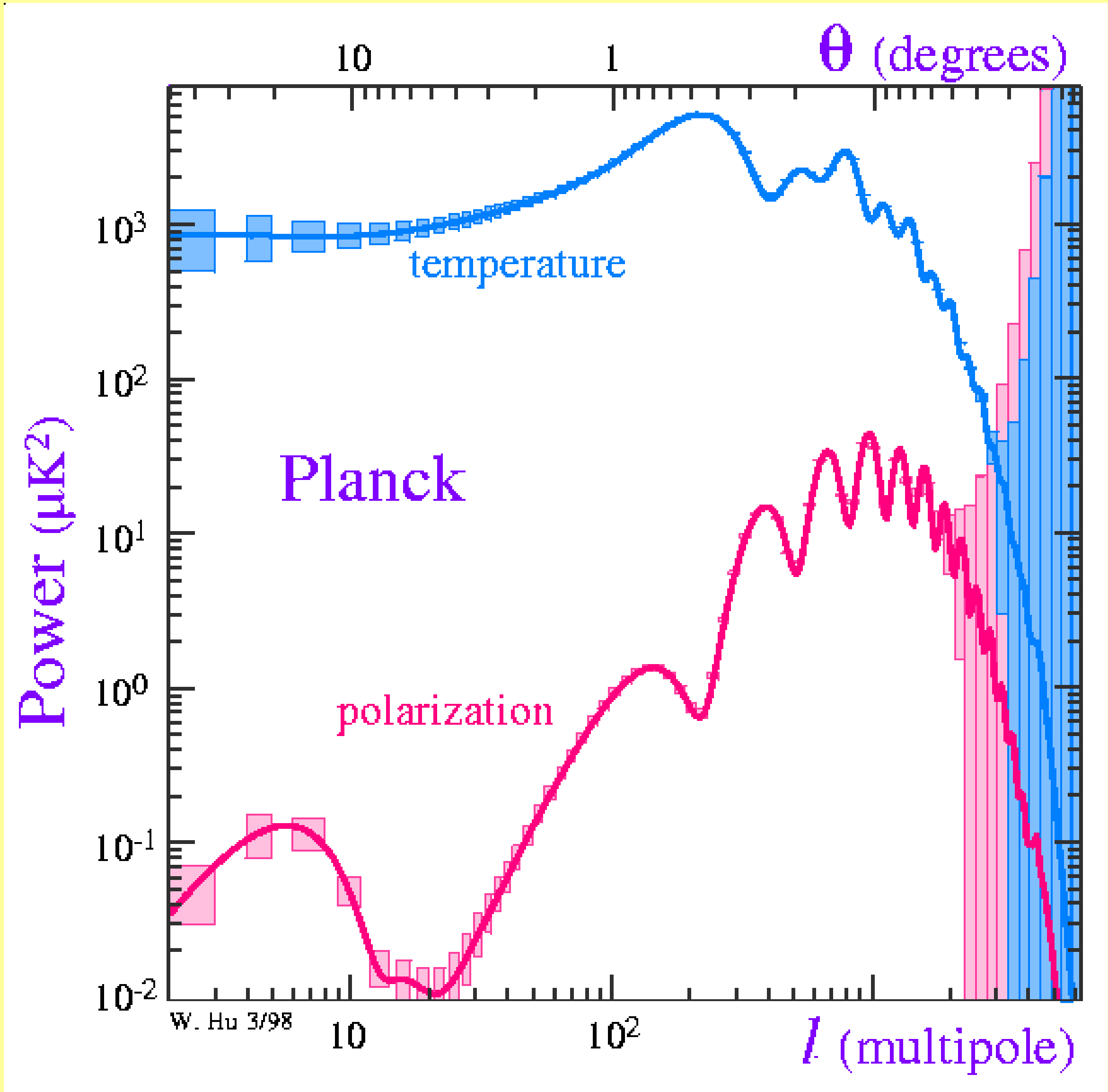
CMB is sensitive to neutrino mass via the corresponding change induced on $\Omega_\nu h^2$



LSS is more affected by neutrino mass. A lighter ν, is able to erase fluctuations (to suppress power spectrum) till later time, so to larger distances



Waiting for SDSS and PLANCK



A Dark universe

What BBN tells us about the energy content of the universe

$\Omega_b \approx 0.04$ $h = 0.71$

$\Omega_{lum} \leq 0.01$

From CMB+SNIa+Clusters:

$\Omega_m \approx 0.27$ non baryonic dark matter

$\Omega_\Lambda \approx 0.73$ non matter dark energy

Conclusions (more outlooks)

CMBR represents one of the best way to know the structure of our present universe, and its future!

Combined with other cosmological observables (BBN) provides a crucial test of our cosmological model, AND of fundamental interactions. BBN is still crucial to determine some cosmological parameters.