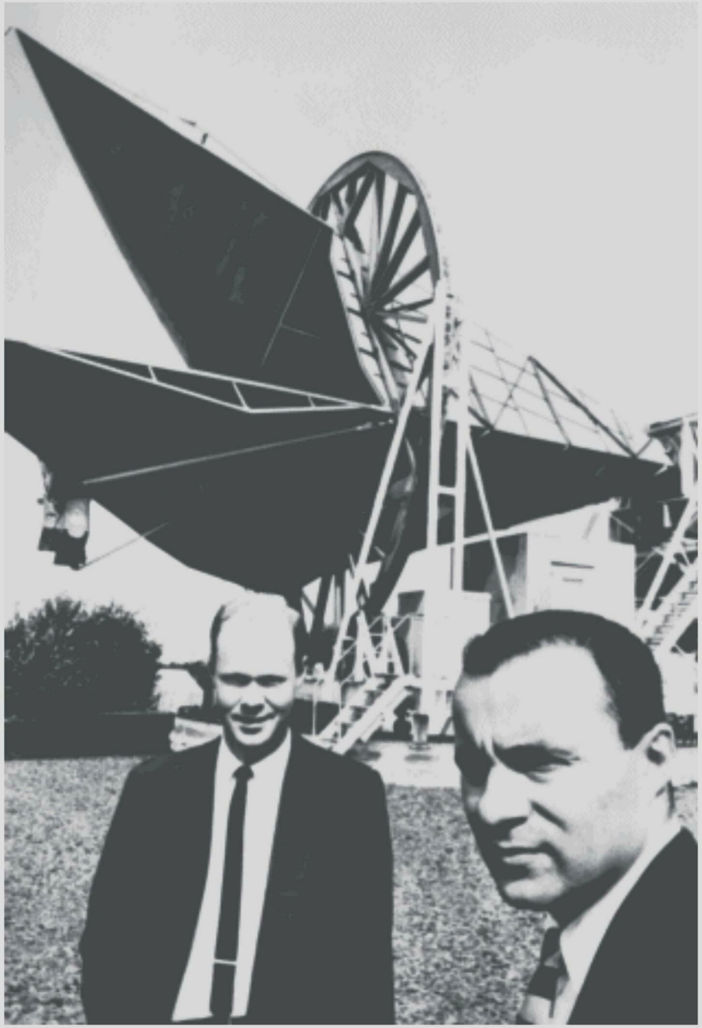
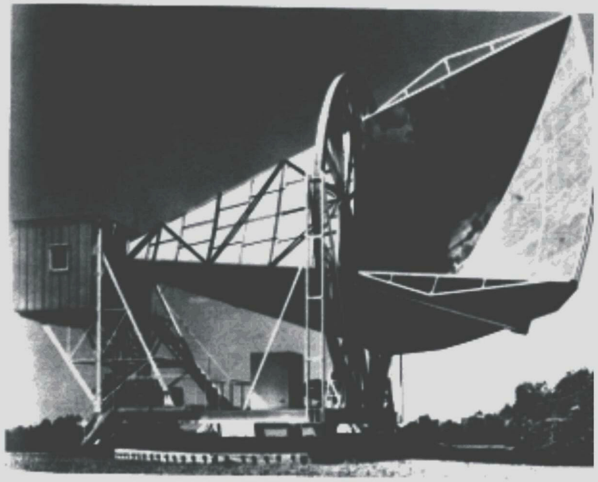
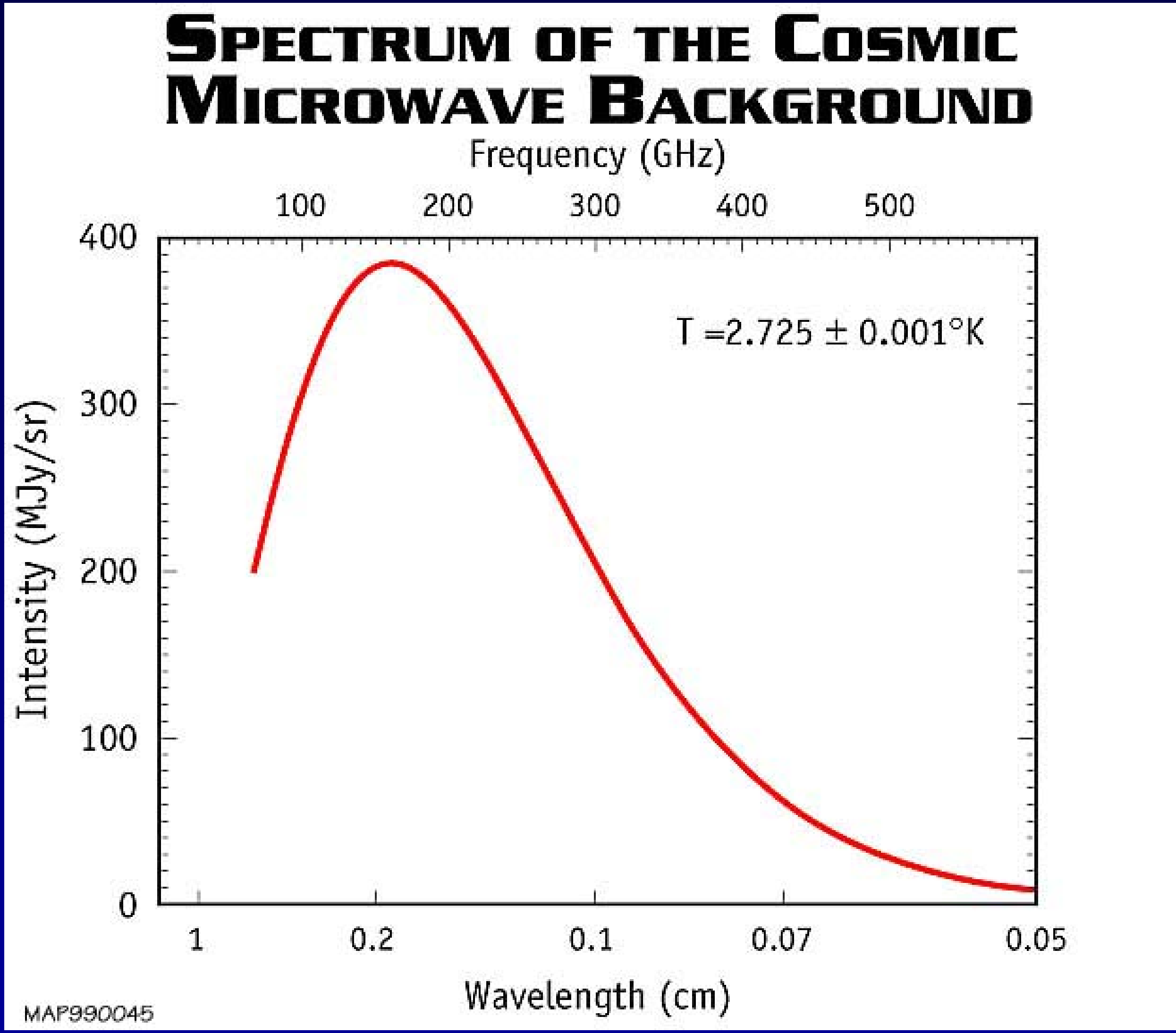
Chapter 6

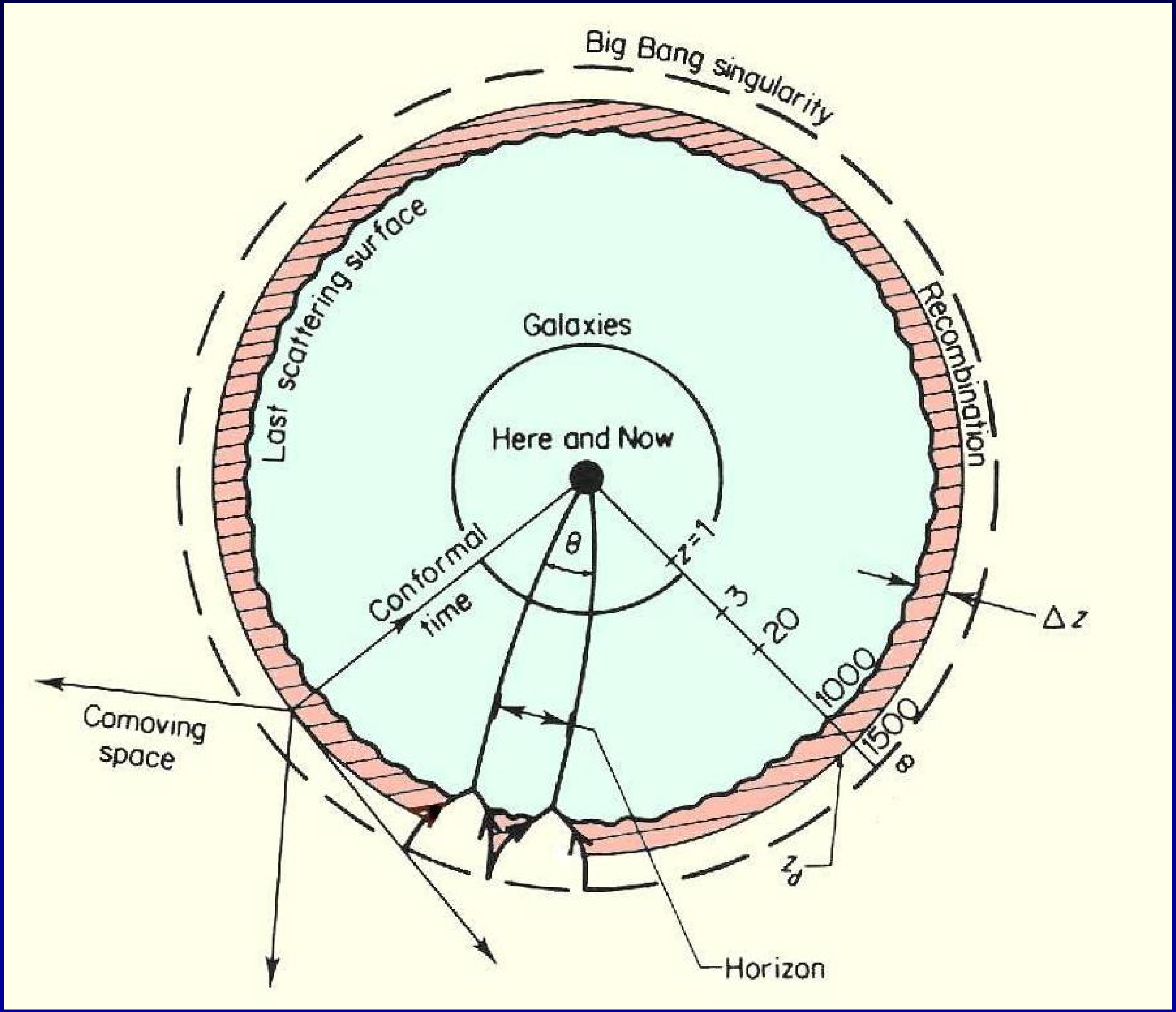
Cosmic Microwave Background

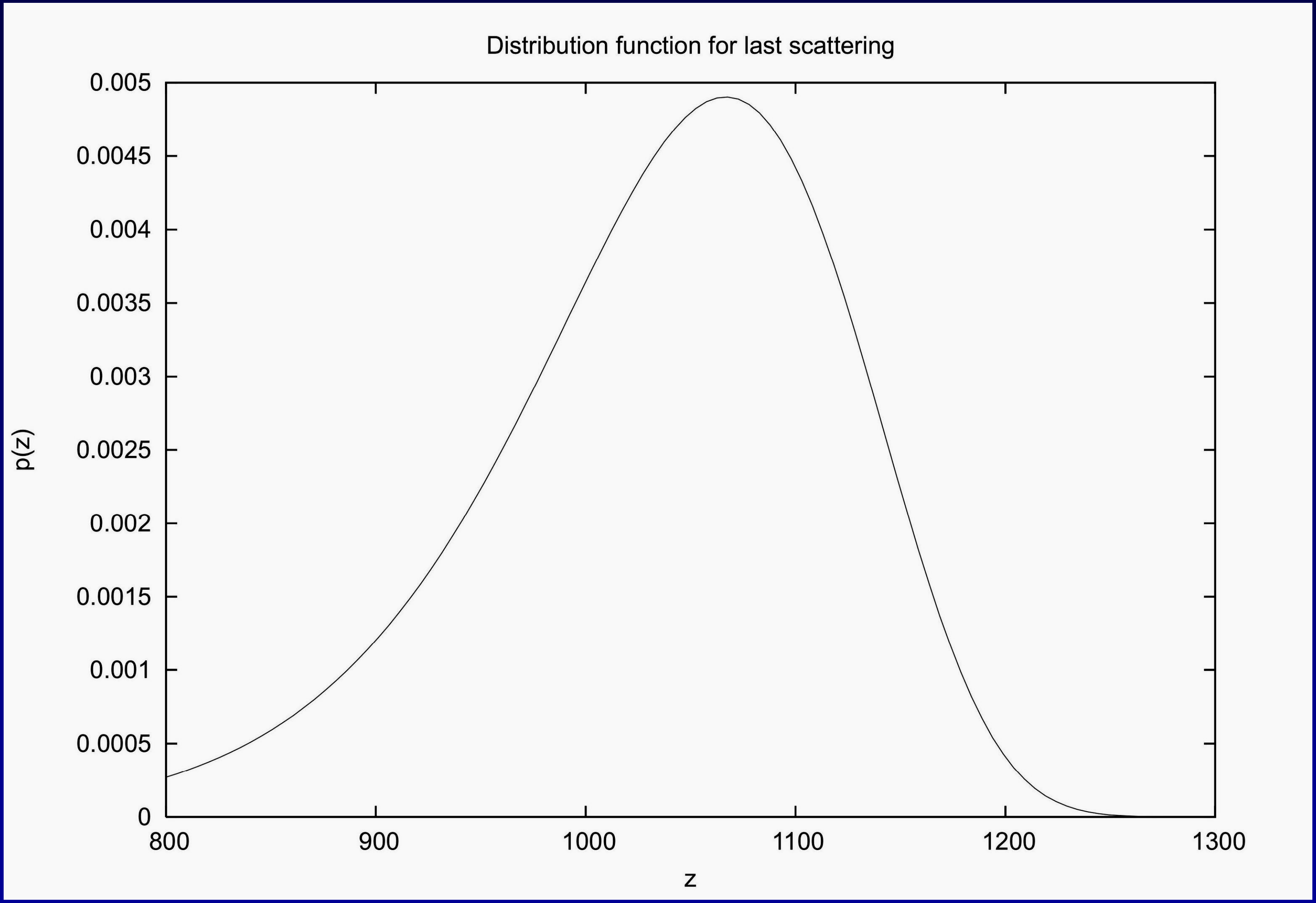




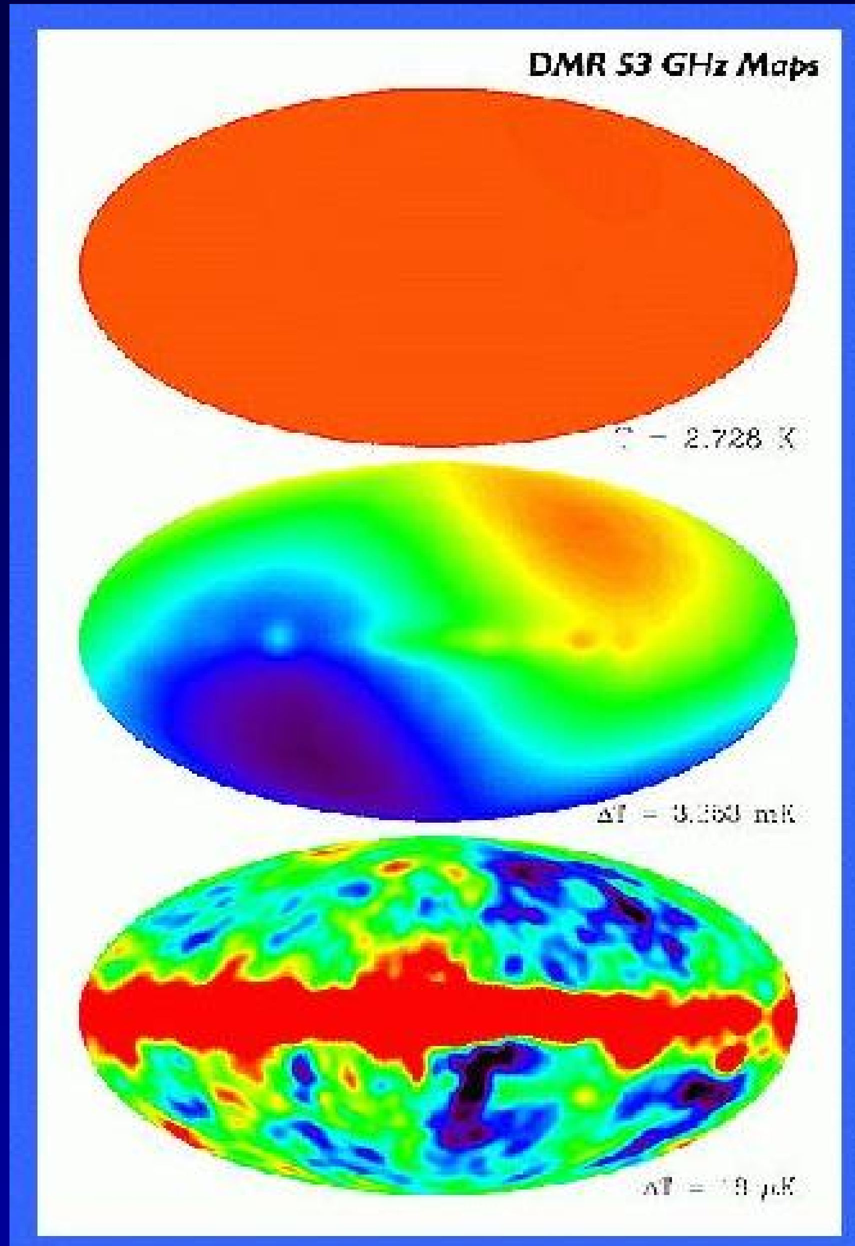


Spectrum of the Cosmic Microwave Background
Frequency (GHz)
100
200
300
400
500
400
300
200
100
0
Intensity (MJy/sr)
T =2.725 ± 0.001°K
1
0.2
0.1
0.07
0.05
Wavelength (cm)
MAP990045

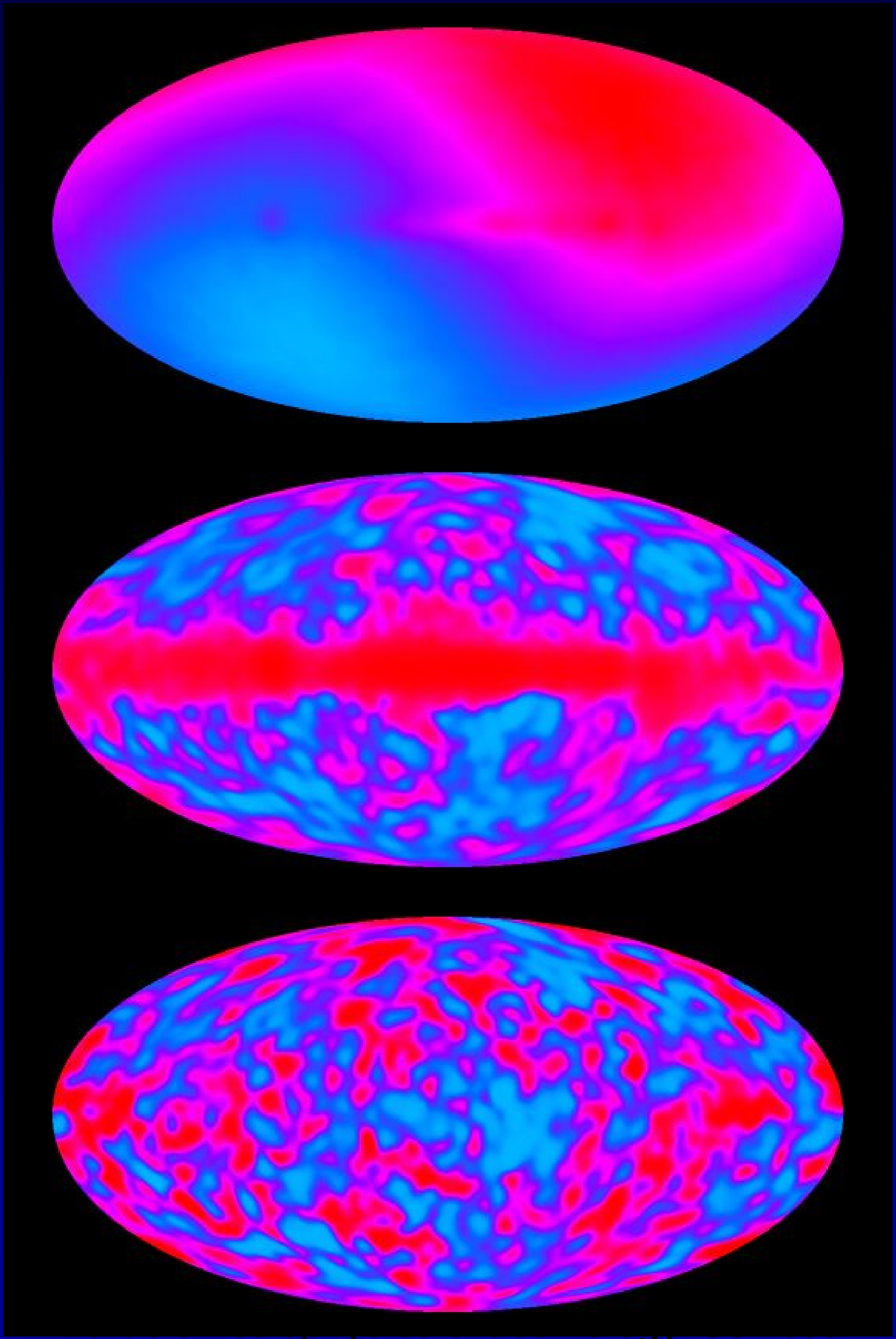

Big Bang singularity
Last scattering surface
Recombination
Galaxies
Here and Now
θ
z=1
3
20
1000
1500
∞
Δz
Conformal time
Comoving space
z_d
Horizon


Distribution function for last scattering
0.005
0.0045
0.004
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
p(z)
800
900
1000
1100
1200
1300
z

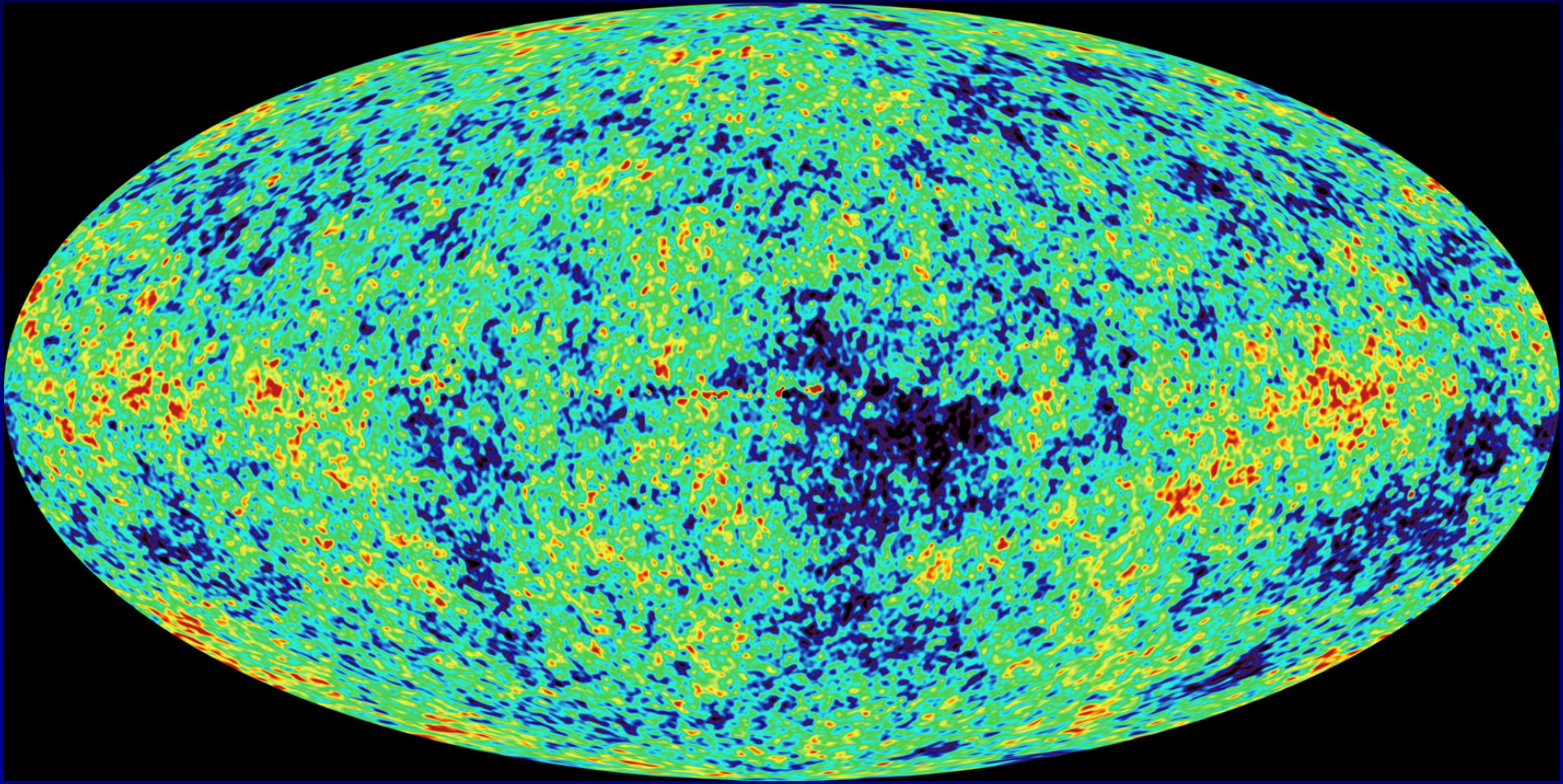
COBE



COBE

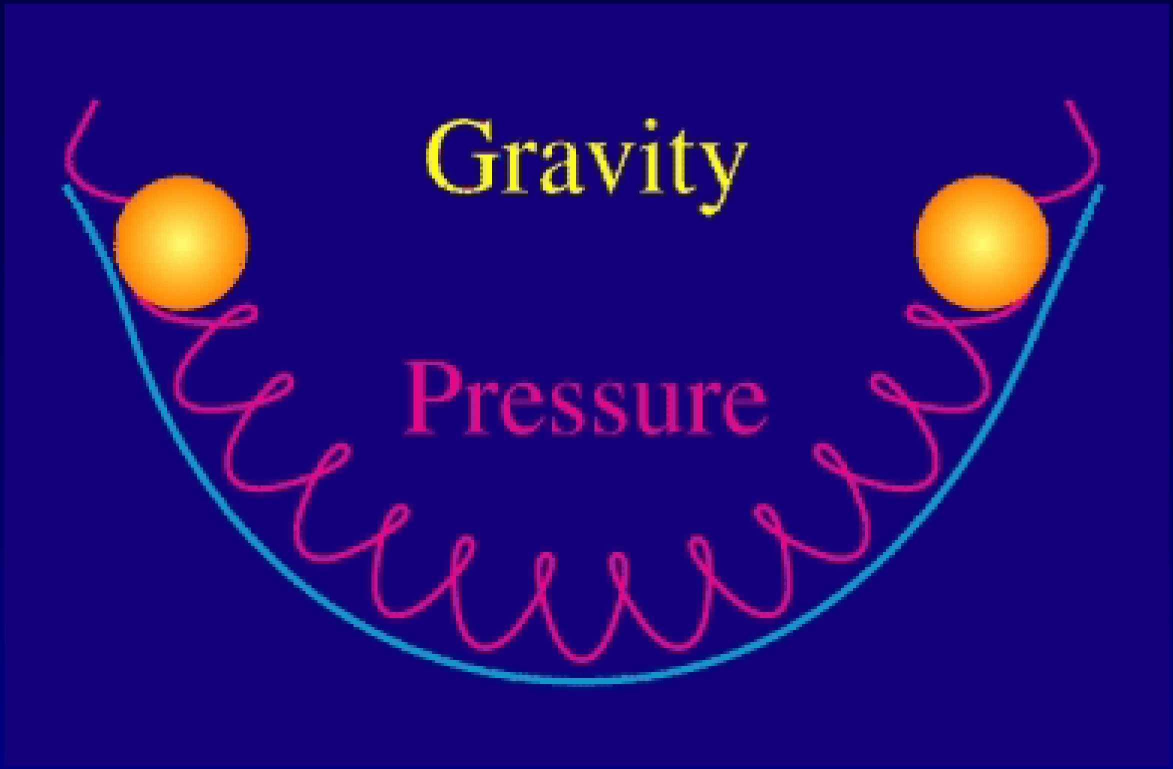


WMAP CMB anisotropy



CMB anisotropy: a toy tutorial †

† : **mainly from Wayne Hu** (http://background.uchicago.edu/~whu)



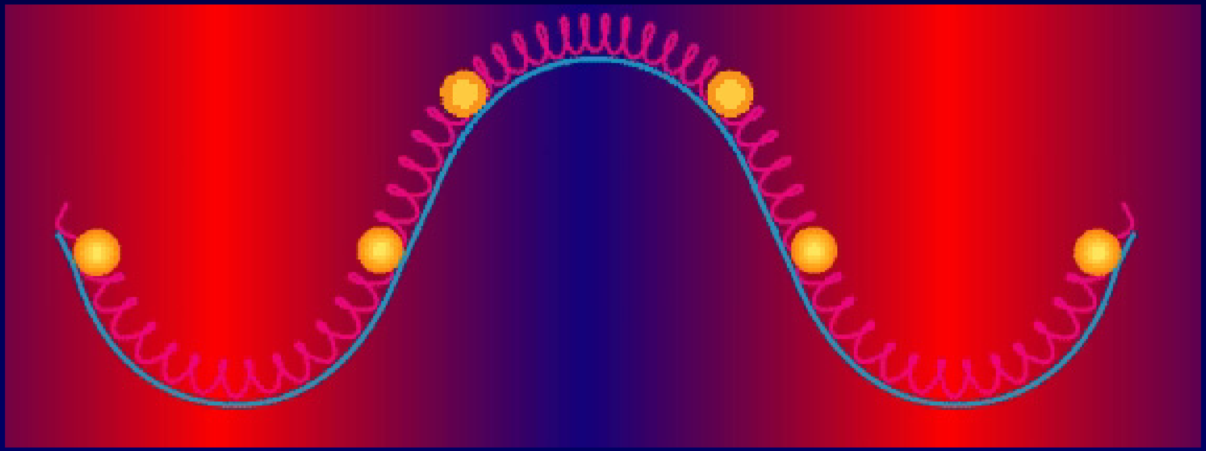
Gravity : **attracting force**
Photon pressure : **driving force**

baryonic matter coupled to photons ⇒ photon pressure prevents collapse prior to recombination (while DM is already forming structure much earlier!)

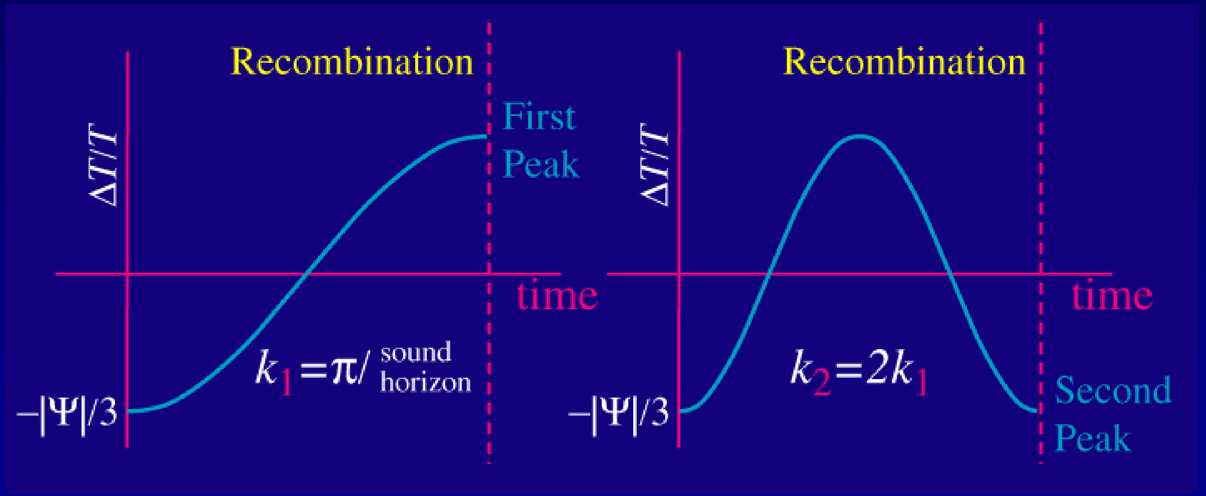
Oscillations produce

$\Delta T > 0$ or $\Delta T < 0$

blue red



Lowest mode (or wave number) corresponds to acoustic waves that managed to contract (or expand) once until recombination



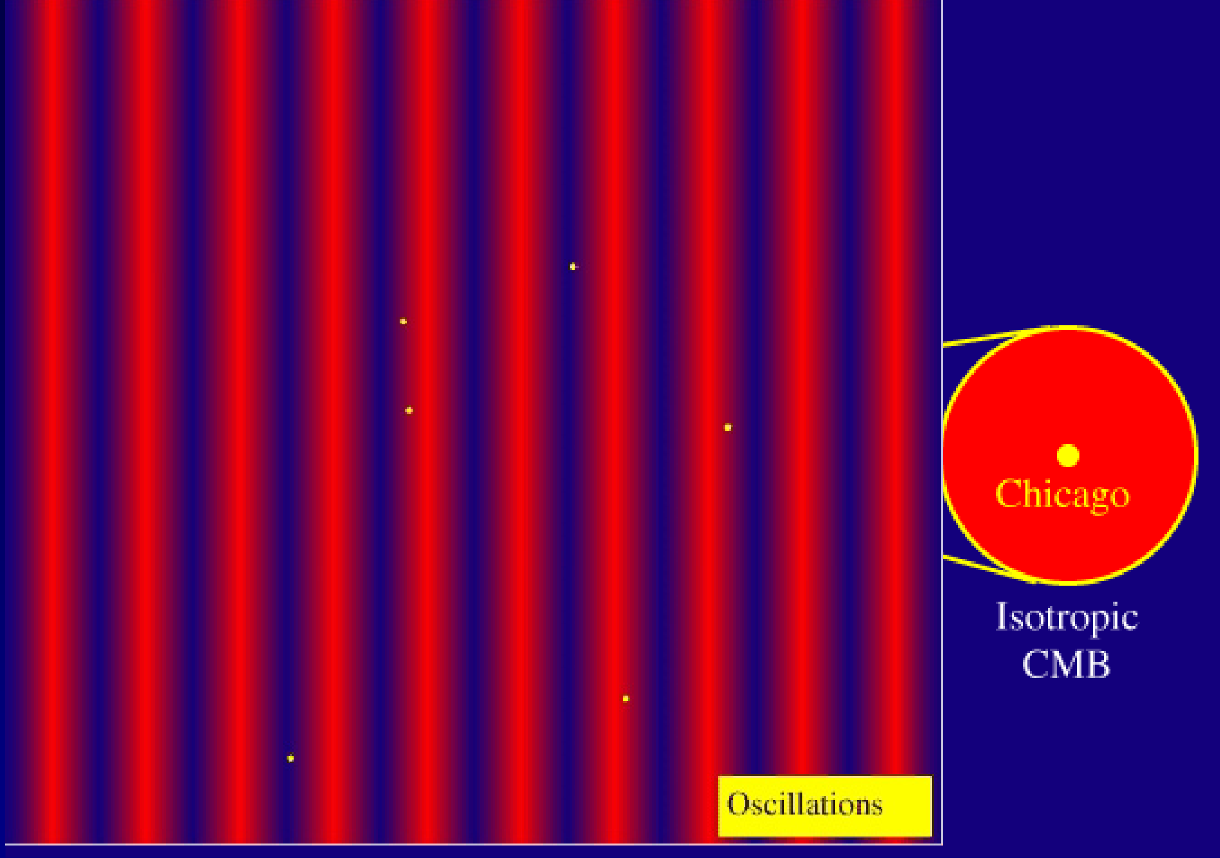
2nd mode managed to contract and expand once until recombination, a.s.o.

$\nu_n = n \cdot c_s \cdot \lambda_{s*}^{-1} = n \cdot c/\sqrt{3} \cdot \lambda_s^{-1} = n \cdot 10^{-13}$ Hz $\Rightarrow$ **not “audible” ...**

$T_n = t_{rec}/n = n^{-1} \cdot 300000$ yr

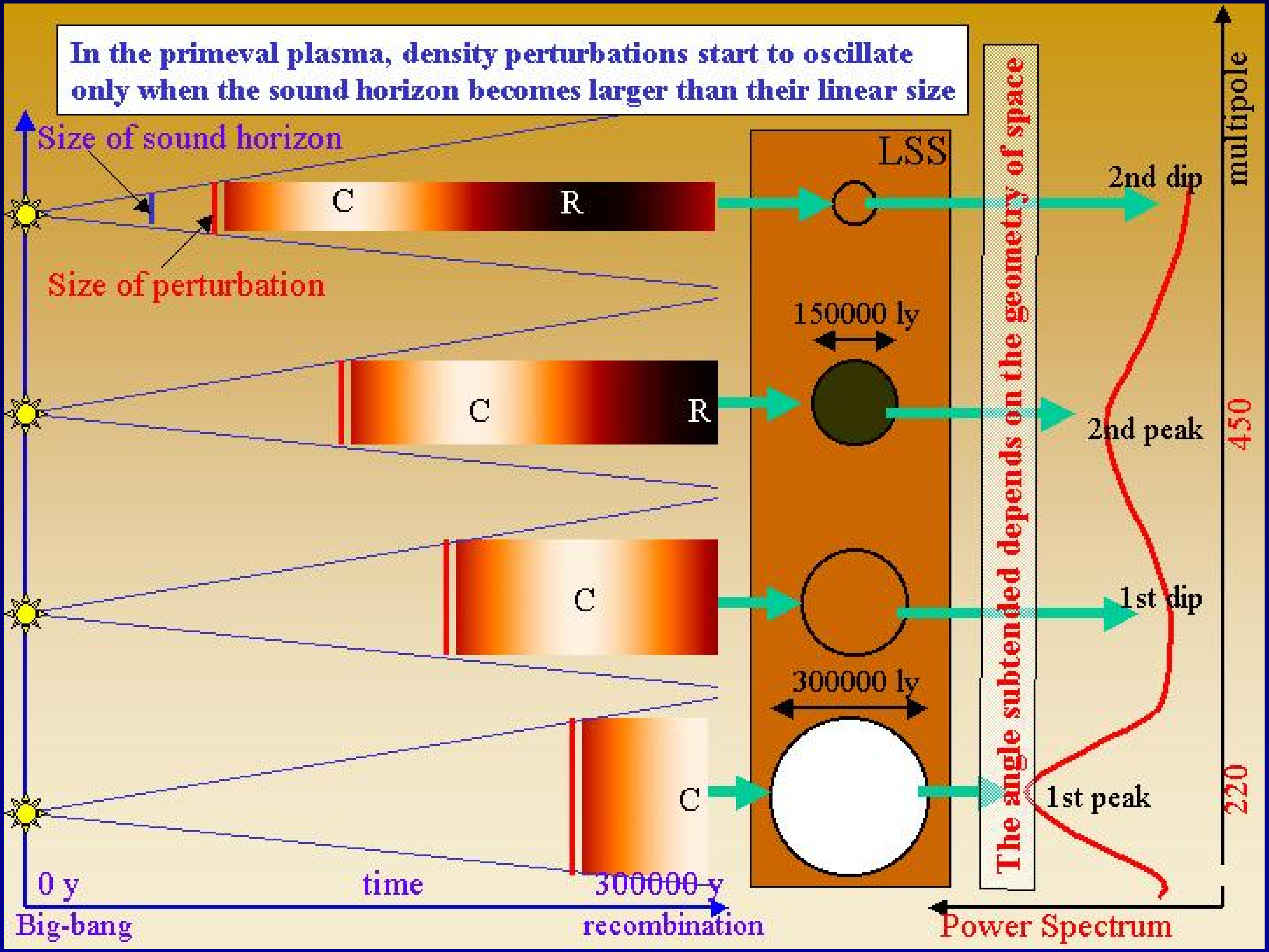
Angular distribution in the sky:

prior to recombination, photons correspond to higher and lower temp-erature

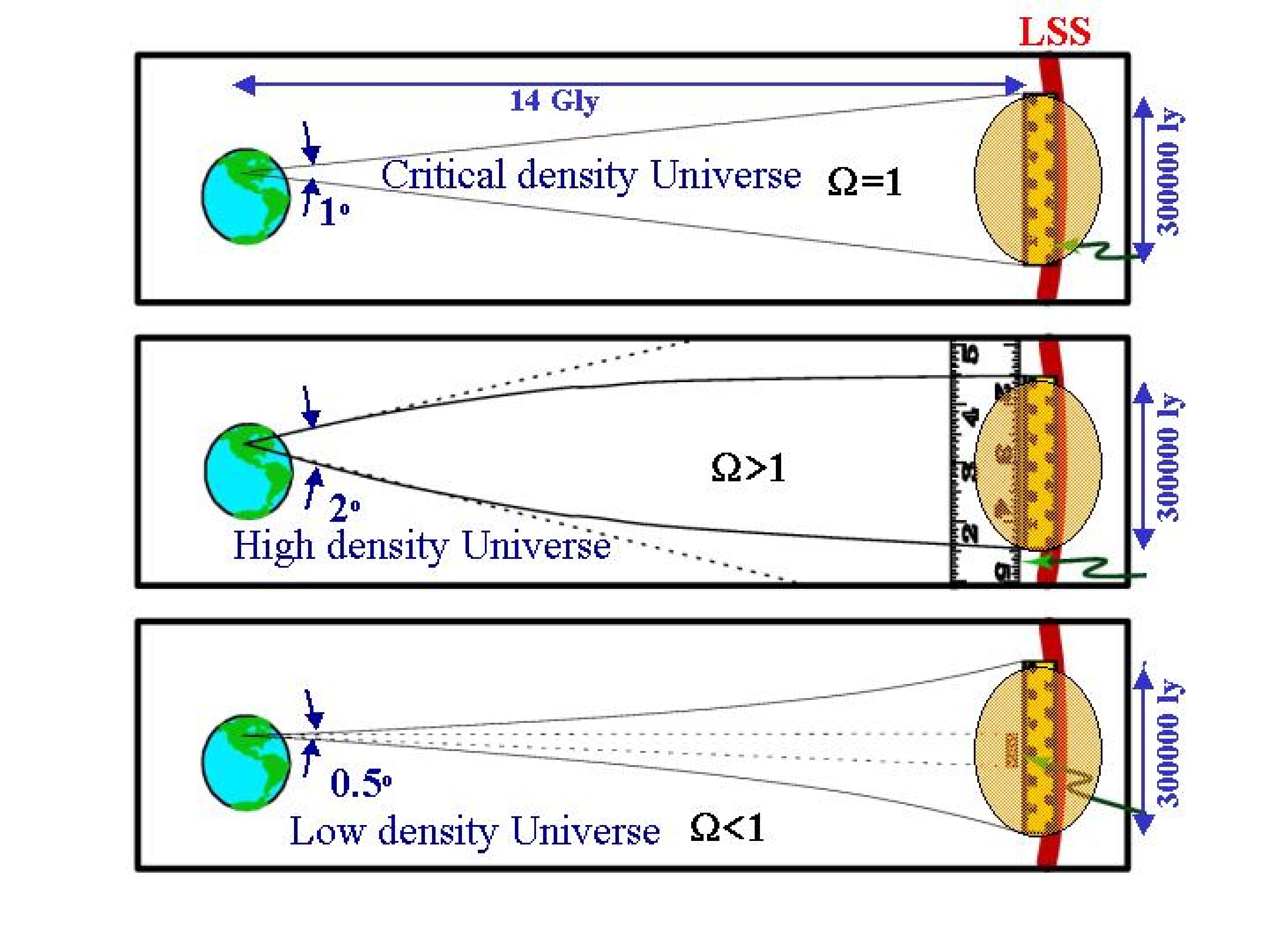


After recombination, photons travel freely and convey their last information - hot or cold, as a function of angular position - to the observer; spatial inhomogeneity is con-verted into an angular anisotropy

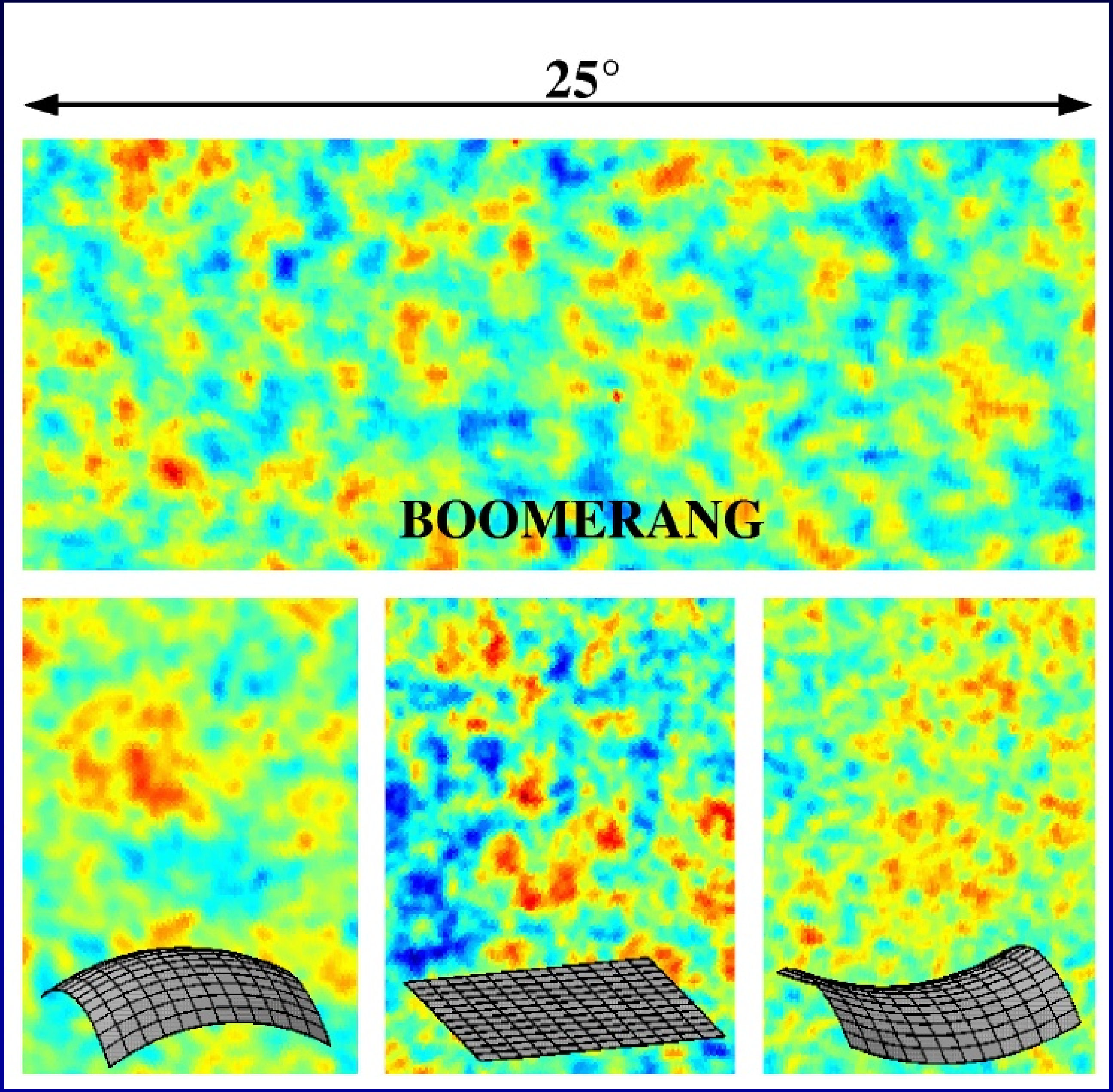
The larger the distance they arrive from, the more complex the angular pattern $\rightarrow$ higher multipoles



taken from de Bernardis



taken from de Bernardis

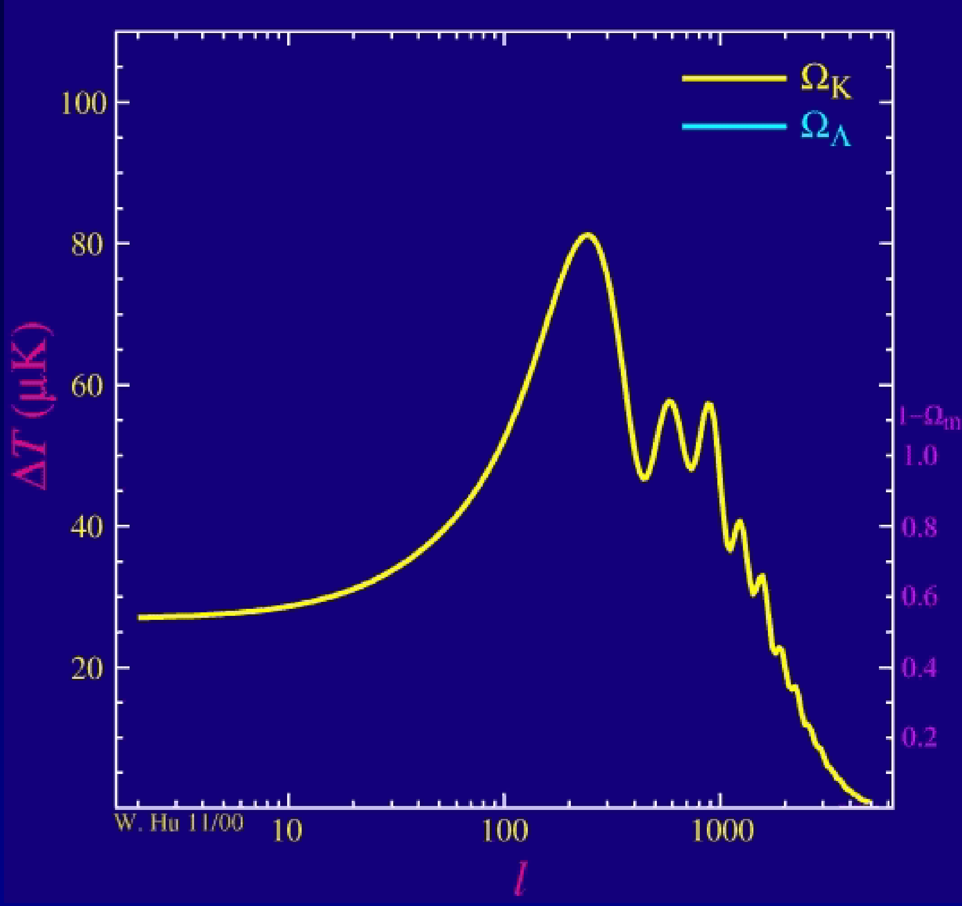

25°
BOOMERANG

The first peak: spatial curvature

Fundamental scale at recombination (the distance that sound could travel) is converted into a fundamental angular scale on the sky today

$$\theta_s \approx 0.8^\circ \cdot \Omega_0^{\frac{1}{2}}$$

$$l_1 \approx \frac{220}{(\Omega_m + \Omega_\Lambda)^{\frac{1}{2}}}$$



The first (and strongest) peak measures the geometry of the universe

caveat: change in Ω_Λ produces slight shift, too (Λ causes slight change in distance that light travels from recombination to the observer)

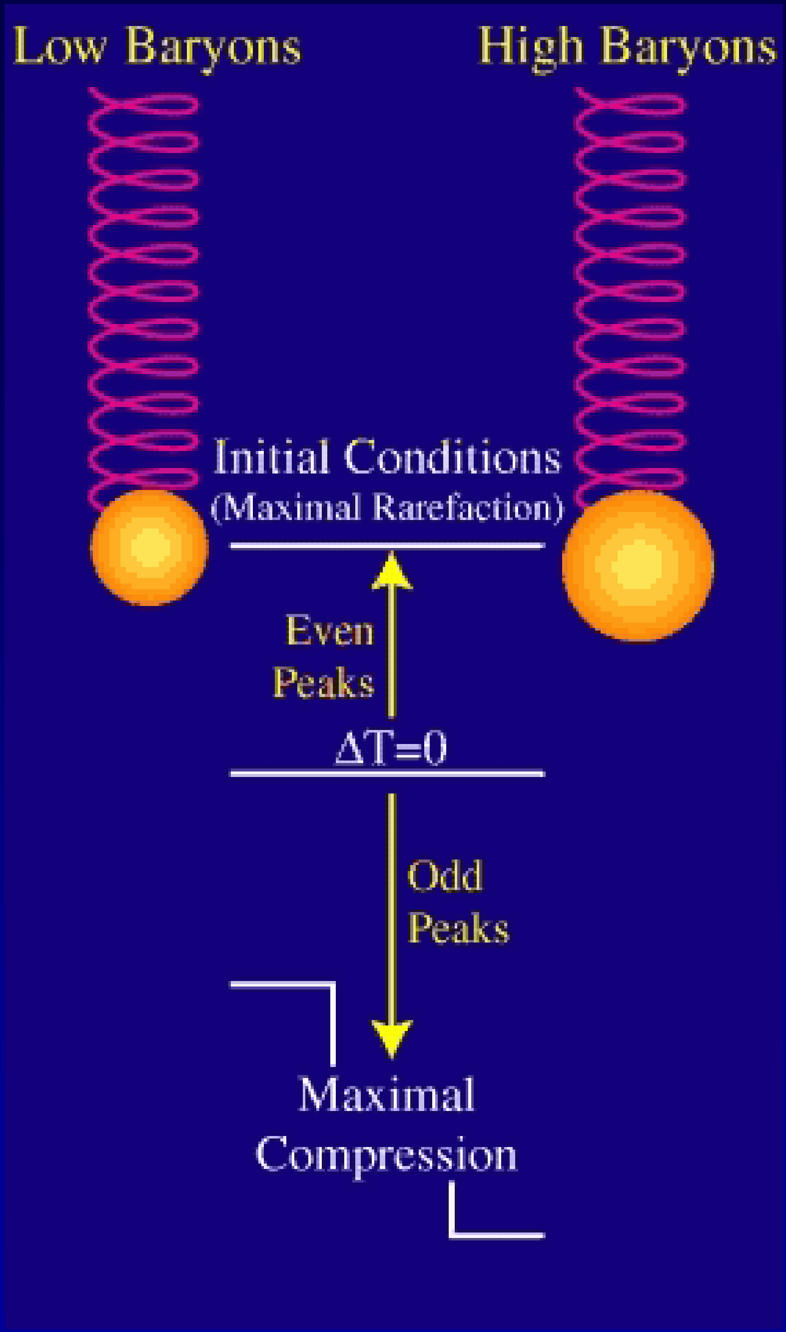
1st peak, current score: $\Omega_0 = 1.02 \pm 0.02$

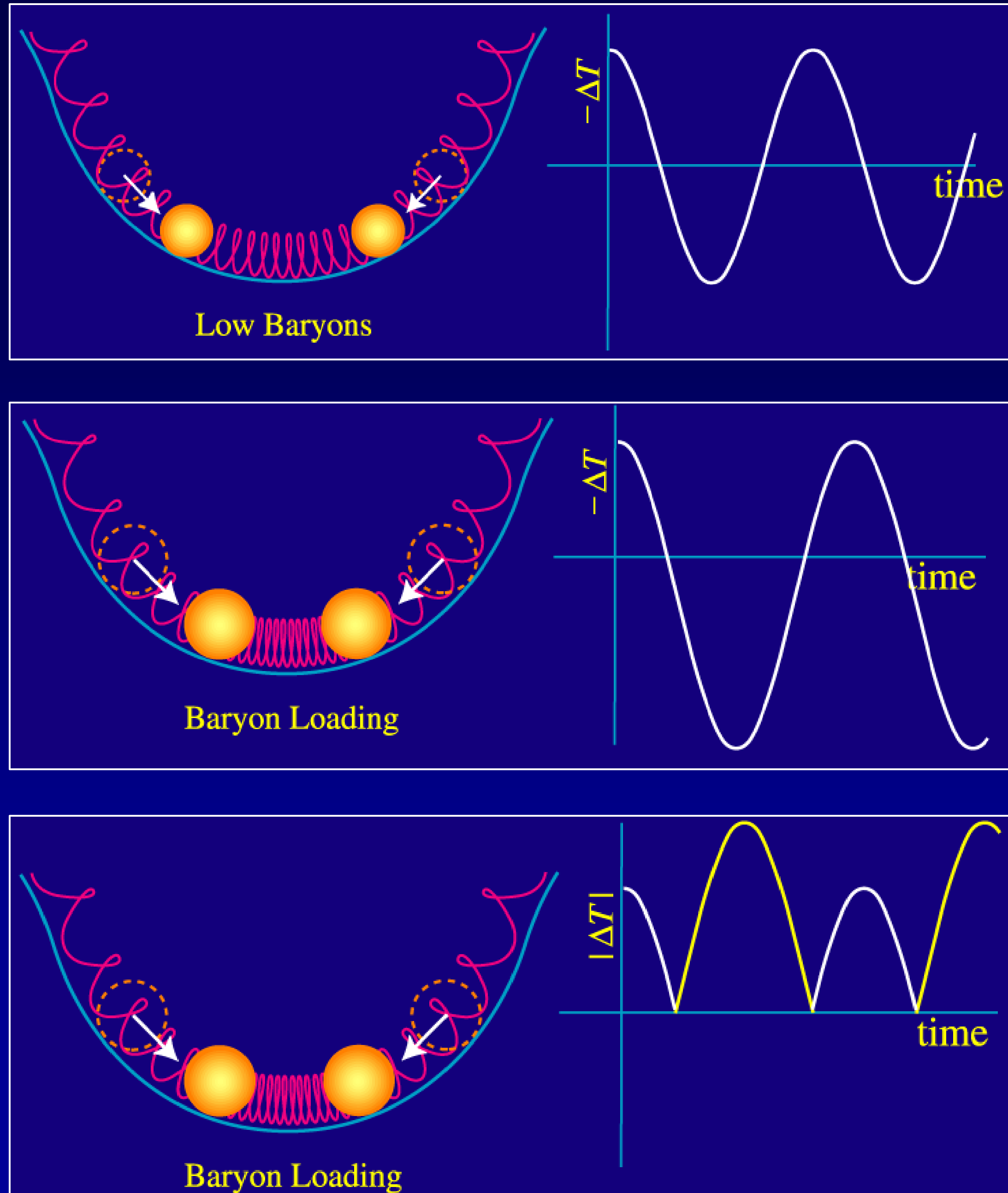
The second peak: baryons and inertia:

baryons add inertia to the plasma
⇒ contraction goes stronger, while the rarefaction remains the same!

compression	corresponds to	odd	peaks
rarefaction	corresponds to	even	peaks

⇒ higher baryon loading enhances odd over even peaks



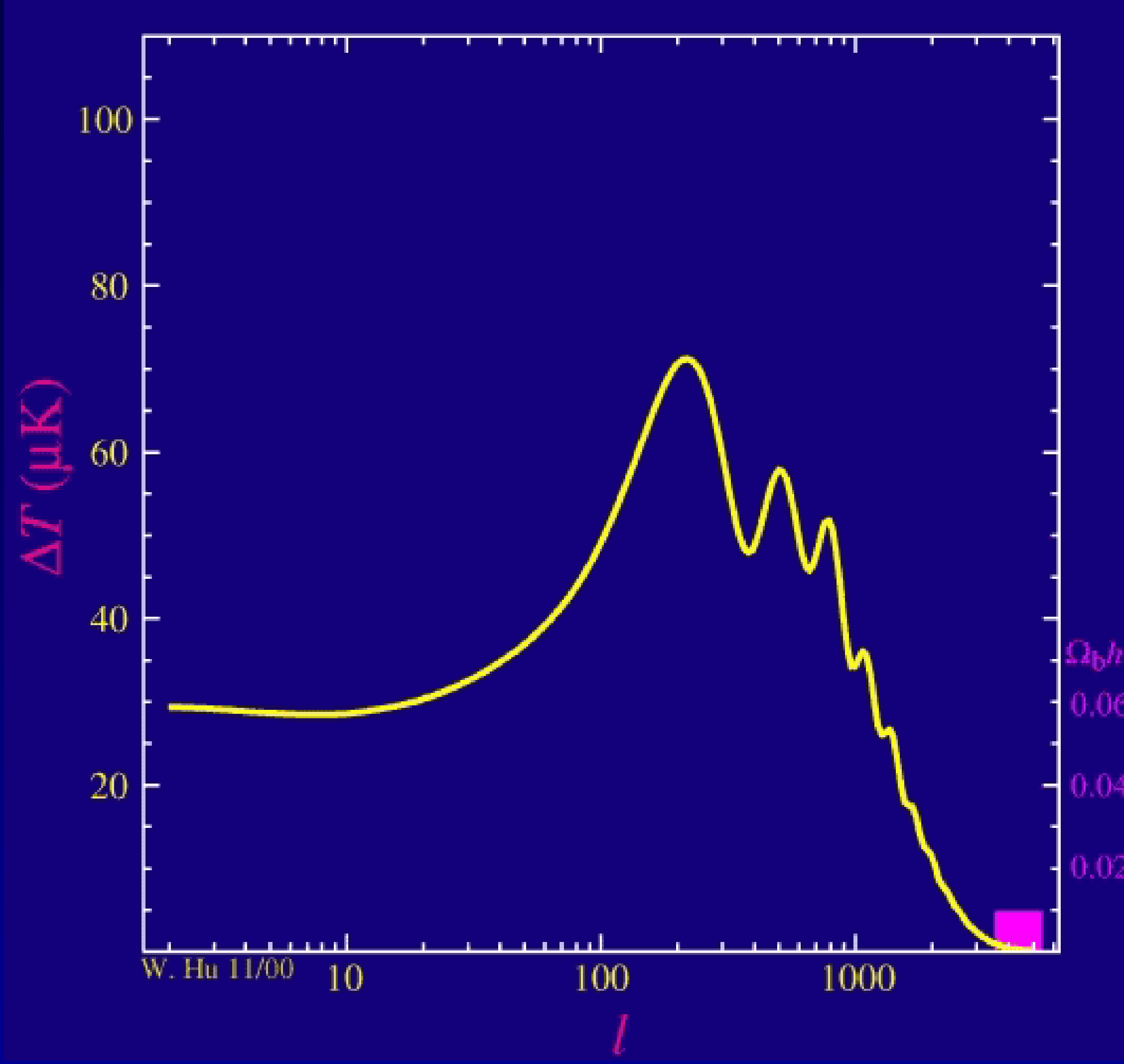


−ΔT
time
Low Baryons
−ΔT
time
Baryon Loading
|ΔT|
time
Baryon Loading

2nd peak, current score:

$\Omega_b \cdot h^2 = 0.0224 \pm 0.0009$

in nice agreement with Ω_b from deuterium abundance (QSO absorption lines)



Two more effects related to Ω_b:

(i) increasing baryon load slows oscillations down
- $\Rightarrow$ long waves don't have enough time to build up
- $\Rightarrow$ larger k preferred if Ω_b increases
- $\Rightarrow$ power spectrum pushed to slightly higher l

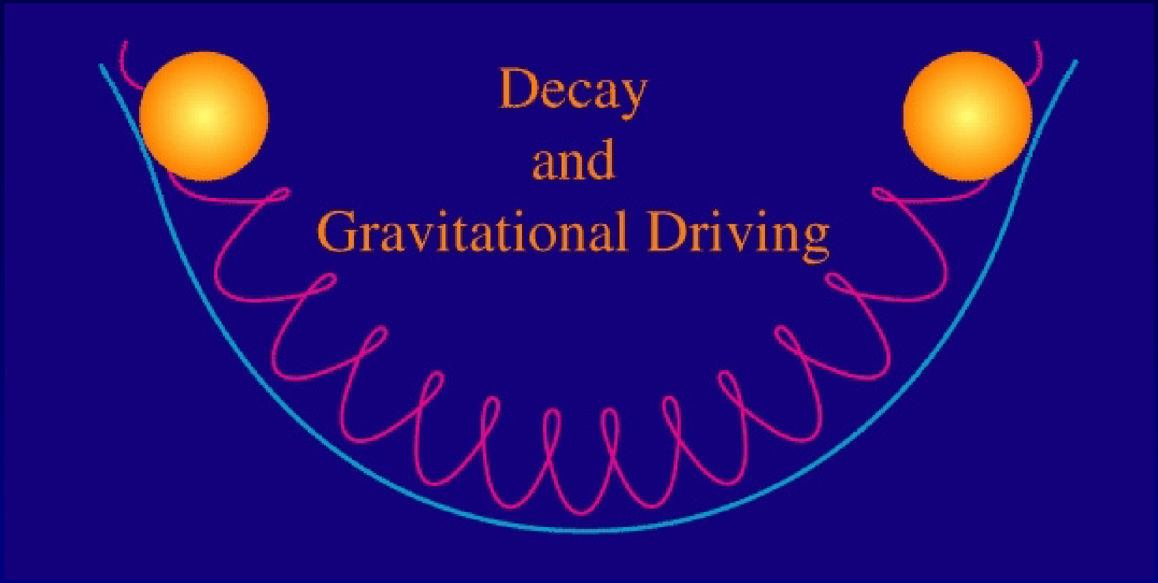
(ii) increasing Ω_b leads to more efficient damping of waves (s.b.), which is stronger for shorter wavelengths $\Rightarrow$ spectrum falls of more rapidly towards large l

(iii) decreasing Ω_m $\Rightarrow$ smaller baryon-loading effect

The third peak: decay of potentials

Poisson equation

$$\Delta\Phi = 4\pi \cdot G \cdot \rho$$



Since $\rho_r \propto R^{-4}$ and $\rho_m \propto R^{-3}$, Φ is governed by ρ_r in the state of highest compression

However, rapid expansion of the universe leads to instantaneous decay of Φ!

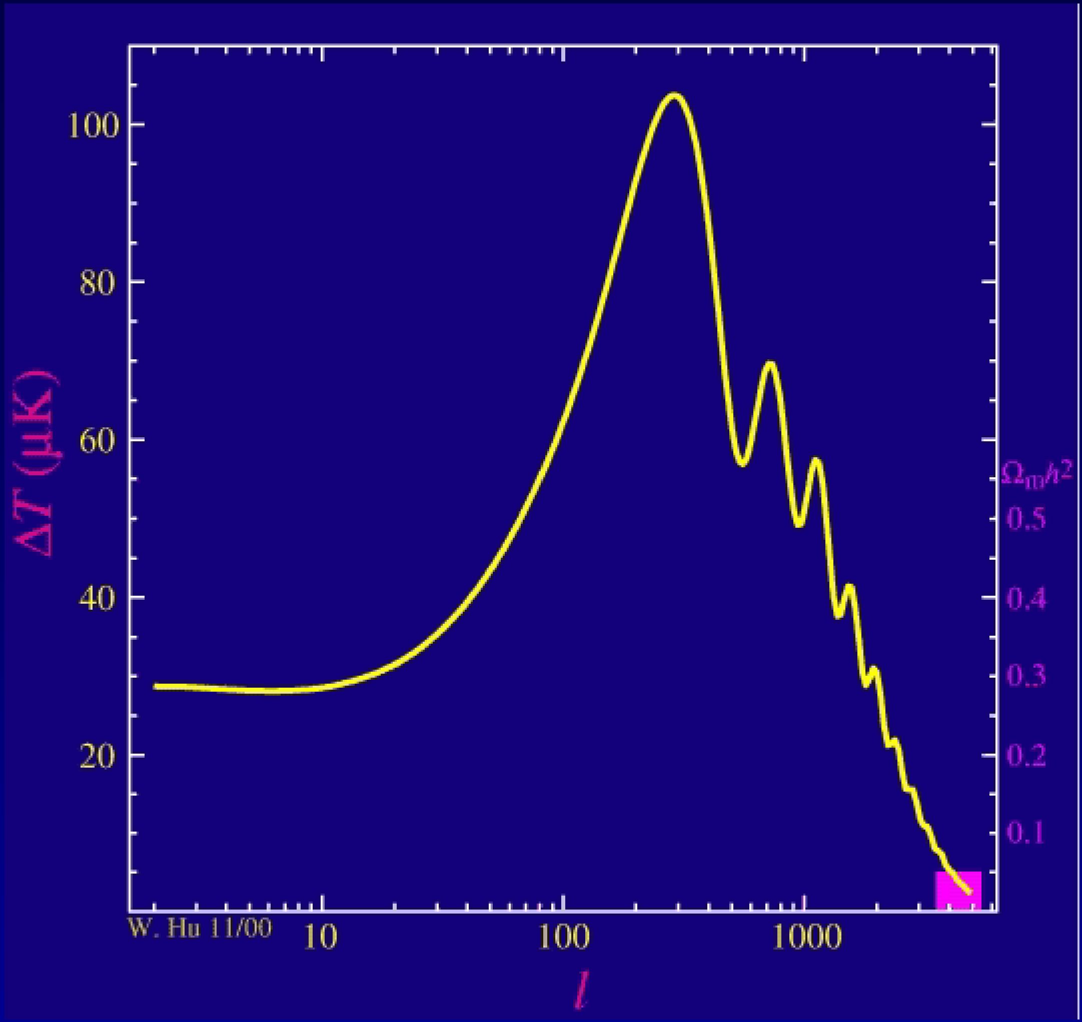
The fluid now sees no gravitation to fight against
$\Rightarrow$ amplitude of oscillations goes way up: driving force!

Driving force obviously more important in smaller (younger) universe, i.e. for $\rho_r \gg \rho_m$

Since modes with small wavelengths started first, it is the higher acoustic peaks that are more prone to this effect.

Increasing $\Omega_m \cdot h^2$ decreases the driving force $\Rightarrow$ amplitudes of waves decrease

Influence of Ω_m only separable from that of Ω_b by measuring <u>at least the first three peaks</u>

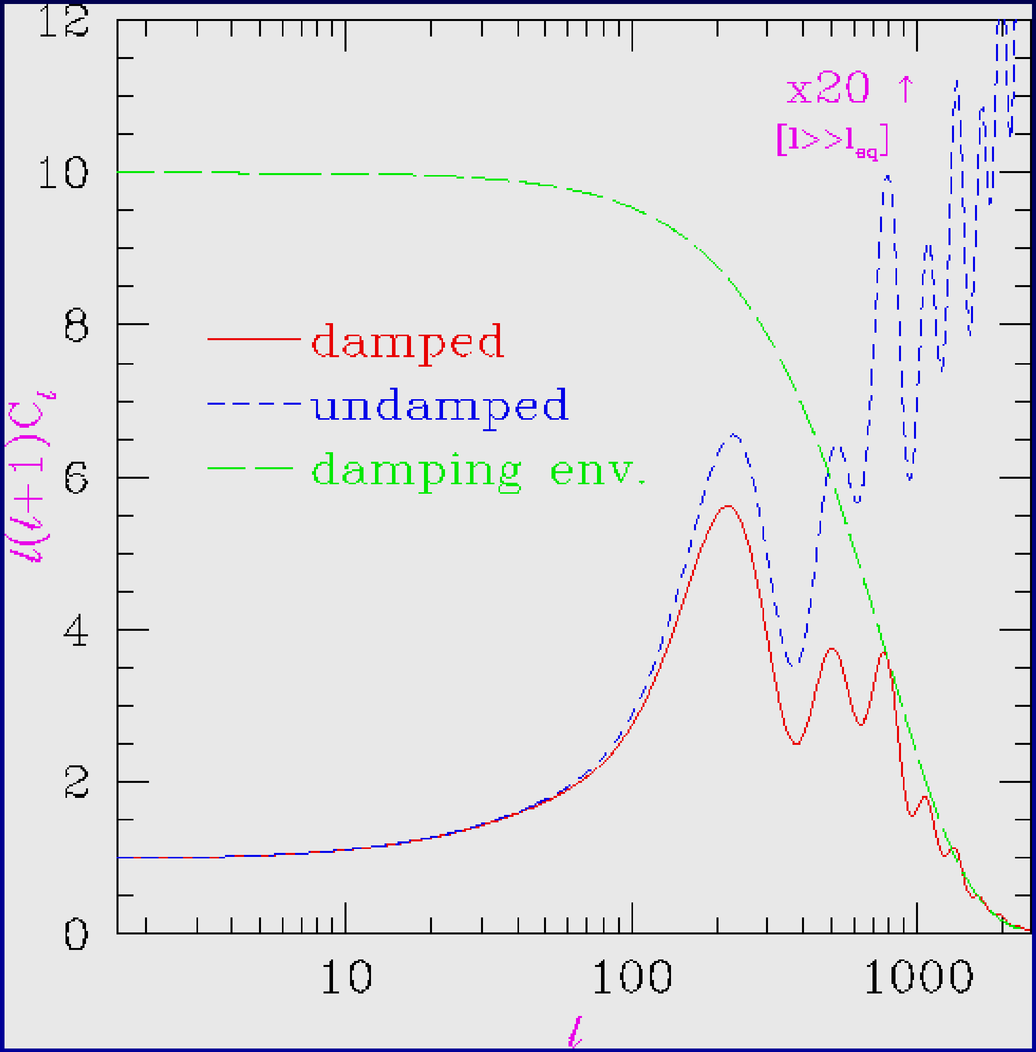


3rd peak, current score:

$\Omega_m = 0.27 \pm 0.04 \quad \Omega_\Lambda = 0.73 \pm 0.04$

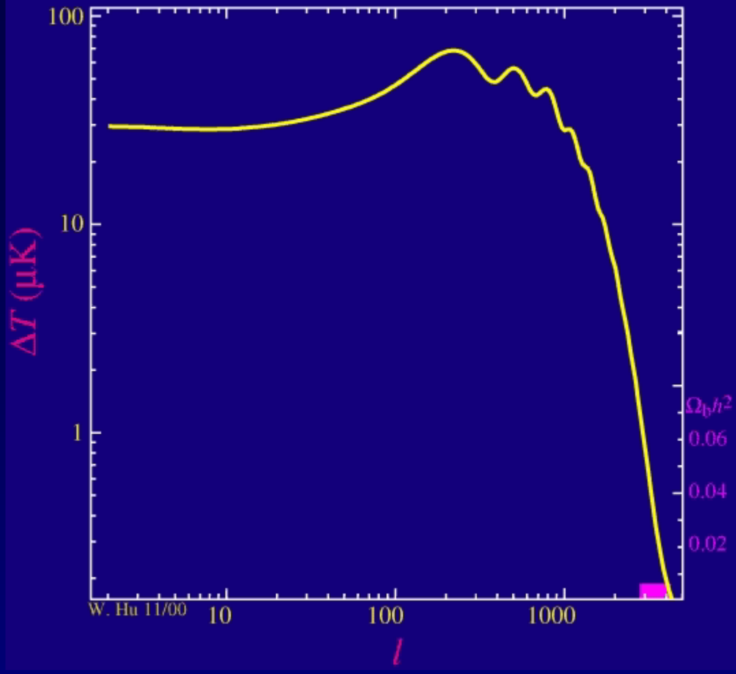
in good agreement with other, independent methods (galaxy clusters, SNe)

effect of damping

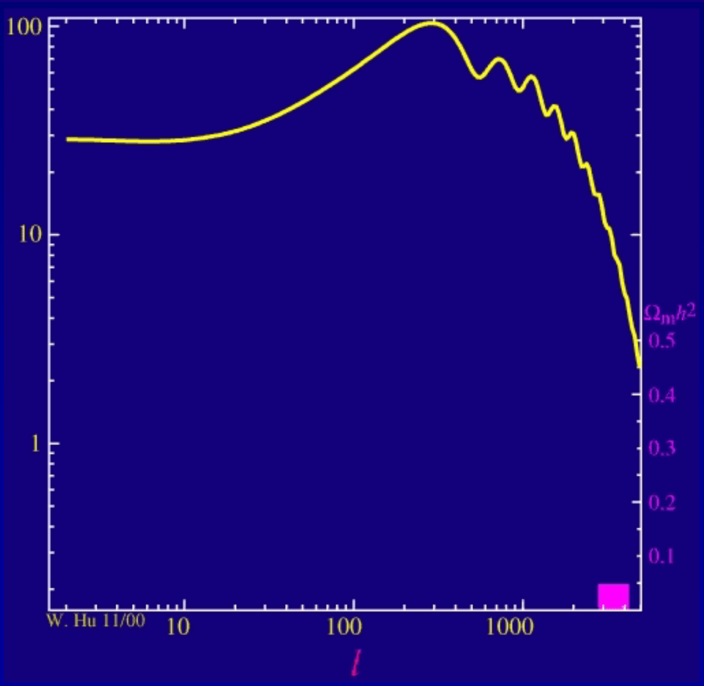


Damping depends on both, Ω_b and Ω_m

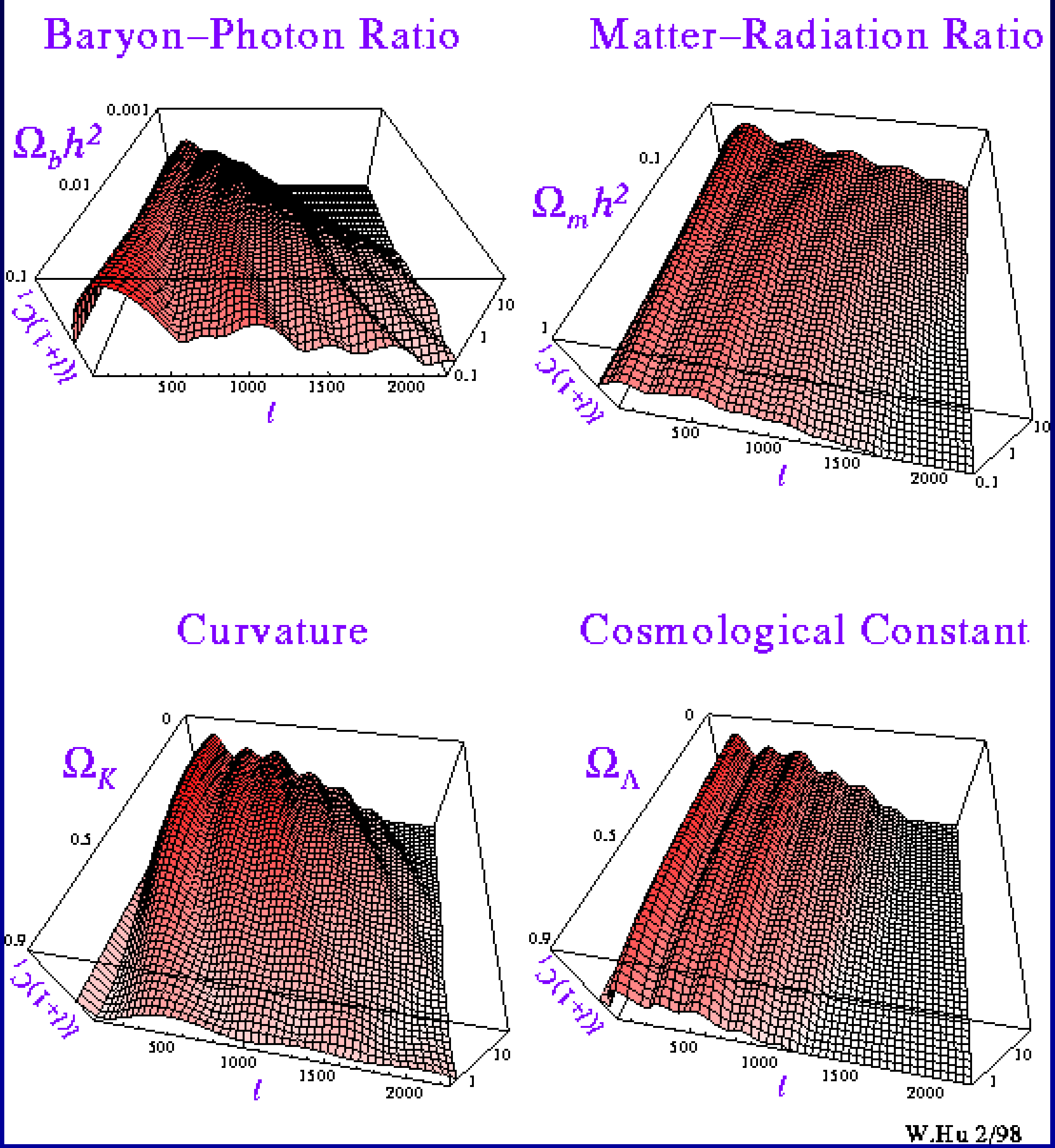
Ω_b : increasing baryon density couples the photon-baryon fluid more tightly, hence shifts the damping tail to smaller angular scales, i.e. higher l



Ω_m : increasing total matter density increases relative age of the universe, hence the angular scale of the damping is increased, shifting the damping tail to lower l

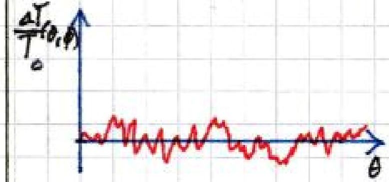
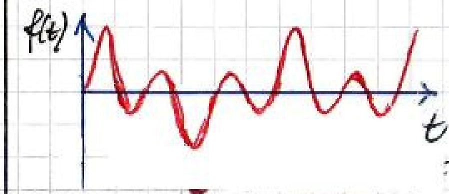
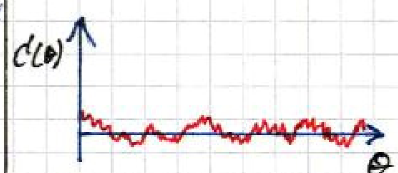
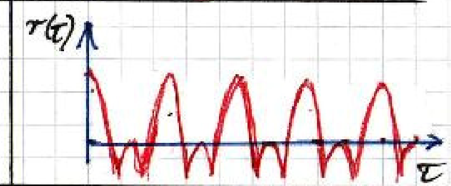
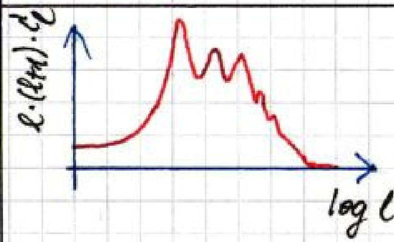


Cosmological Parameters in the CMB



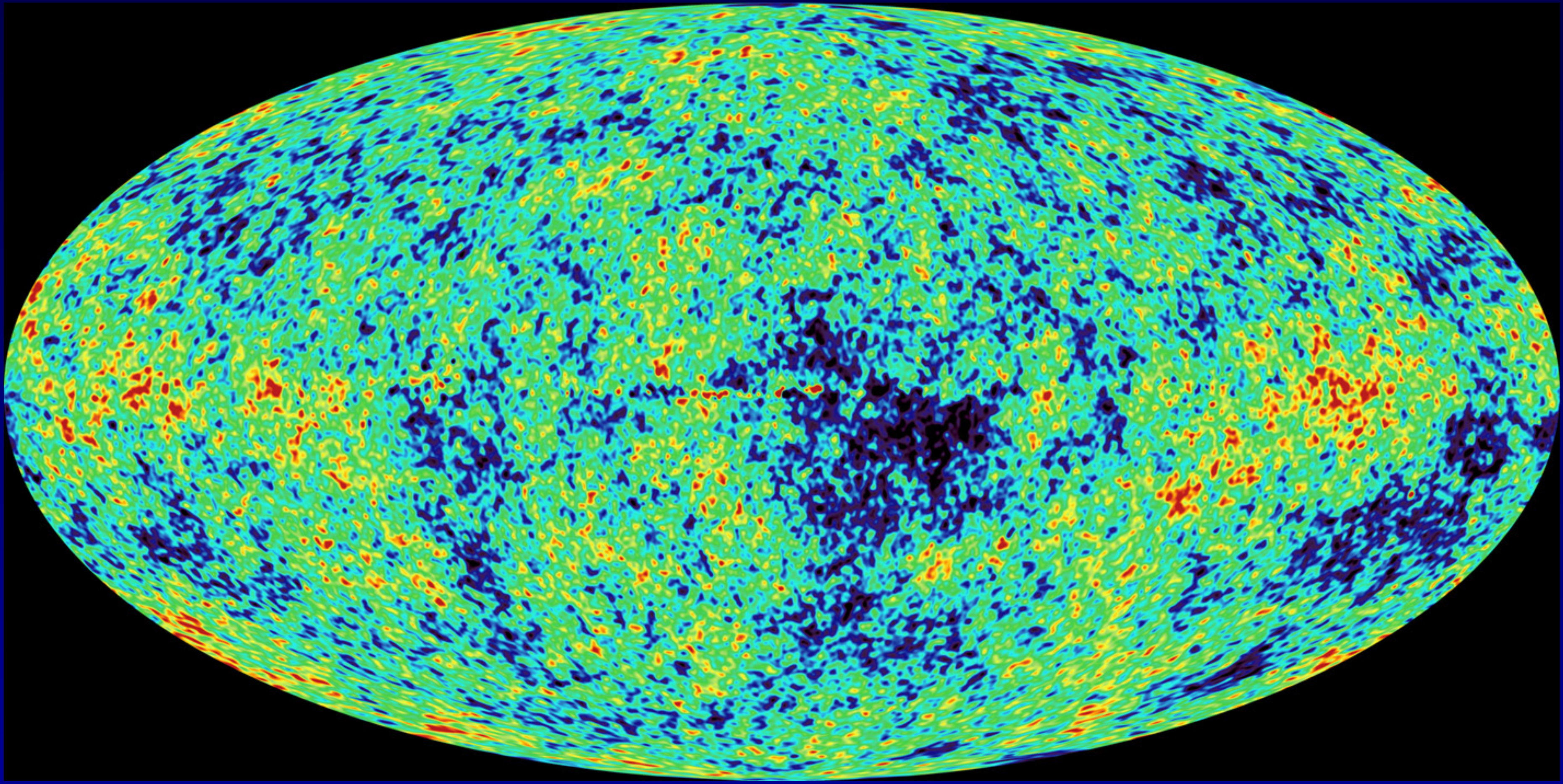
deriving the power spectrum

Analogy

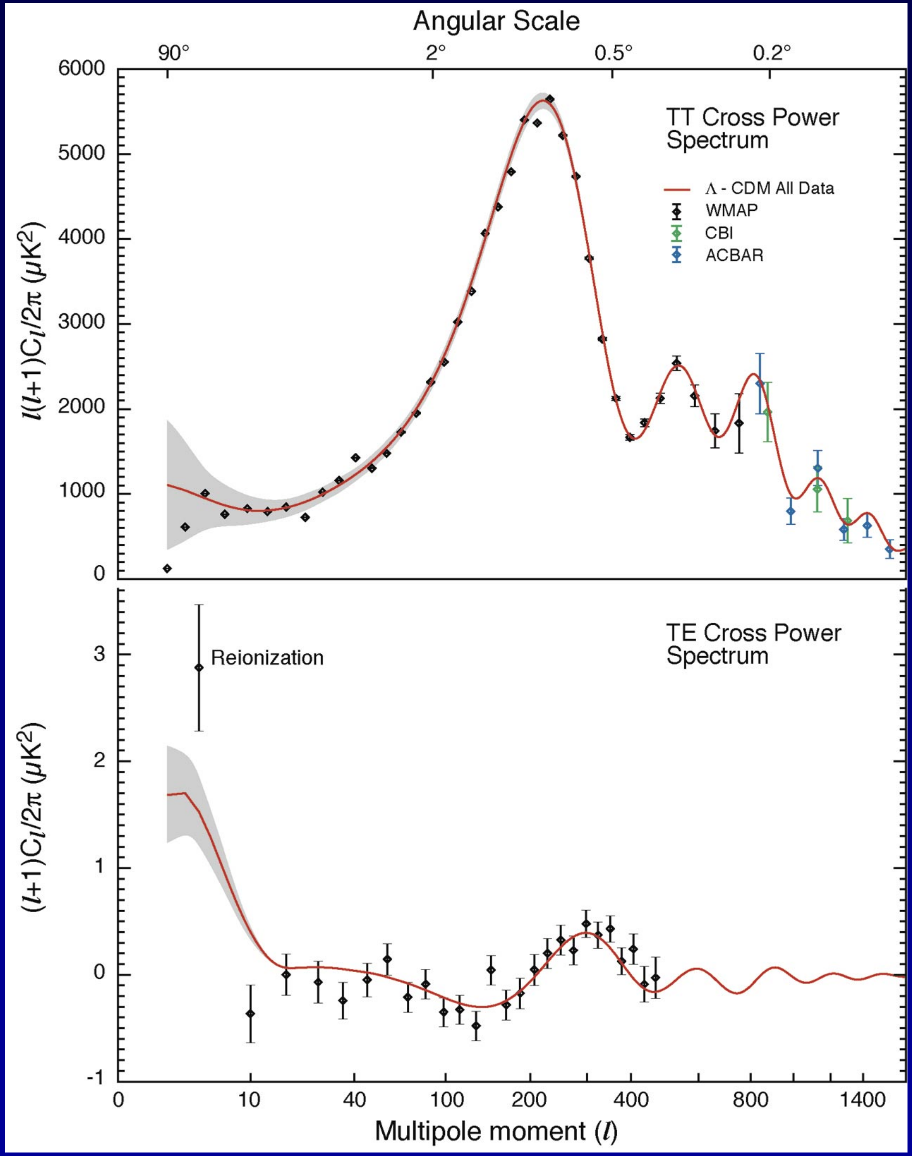
temperature fluctuations $\frac{\Delta T}{T_0}(\theta,\phi) = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{+\ell} a_{\ell m}\cdot Y_{\ell m}(\theta,\phi)$		time-dependent signal $f(t) = \sum_{n=-\infty}^{+\infty} g_n \cdot e^{-i 2\pi \cdot n \cdot \nu t}$	
2-point correlation function $C(\theta) = \left\langle \frac{\Delta T}{T_0}(\theta,\phi)\cdot\frac{\Delta T}{T_0}(\theta',\phi')\right\rangle$		autocorrelation function $r(\tau) = \frac{1}{2T}\cdot\int_{-T}^{+T} f(t)\cdot f(t-\tau)\,dt$	
coefficients of spherical harm. $a_{\ell m} = \iint_{4\pi} \frac{\Delta T}{T}(\theta,\phi)\cdot Y^*_{\ell m}(\theta,\phi)\, d\Omega$	Complex!	Fourier coefficients $g_n = \int_{-\infty}^{+\infty} f(t)\cdot e^{i 2\pi \cdot n\cdot \nu \cdot t}\, dt$	complex!
power spectrum $C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{+\ell} a_{\ell m}\cdot a^*_{\ell m} = \langle \lvert a_{\ell m}\rvert^2\rangle$		power spectrum $P(\nu) = g_n \cdot g_n^* = \lvert g_n\rvert^2$	
"autocorrelation theorem" $C(\theta) = \frac{1}{4\pi}\cdot\sum_{\ell=0}^{\infty}(2\ell+1)\cdot P_\ell(\cos\theta)\cdot C_\ell$		autocorrelation theorem $r(\tau) = \int_0^{\infty} P(\nu)\cdot e^{-i 2\pi \nu t}\, d\nu$	

↑ $\frac{1}{4\pi}$ because $Y_{\ell m} \sim \sqrt{\frac{1}{4\pi}}$

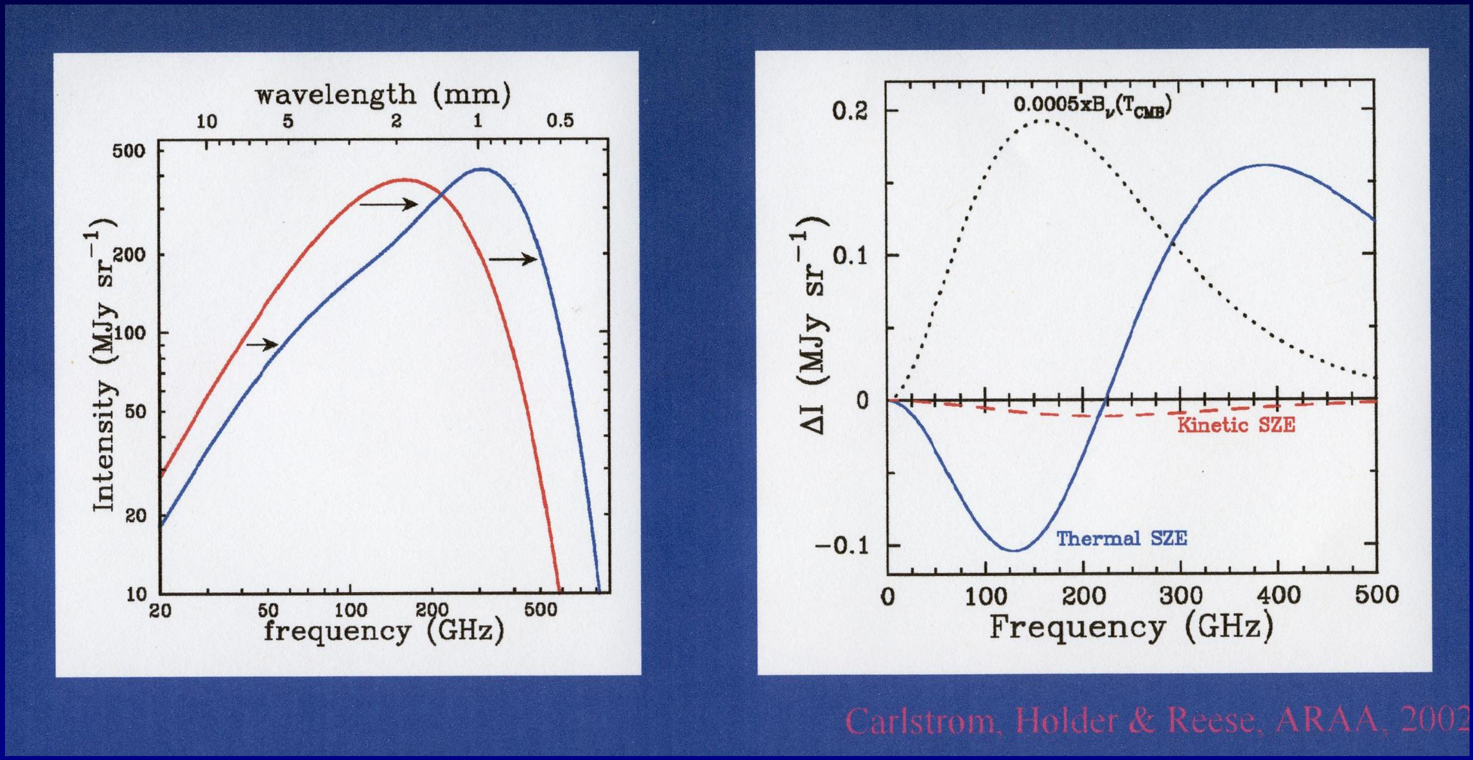
WMAP CMB anisotropy

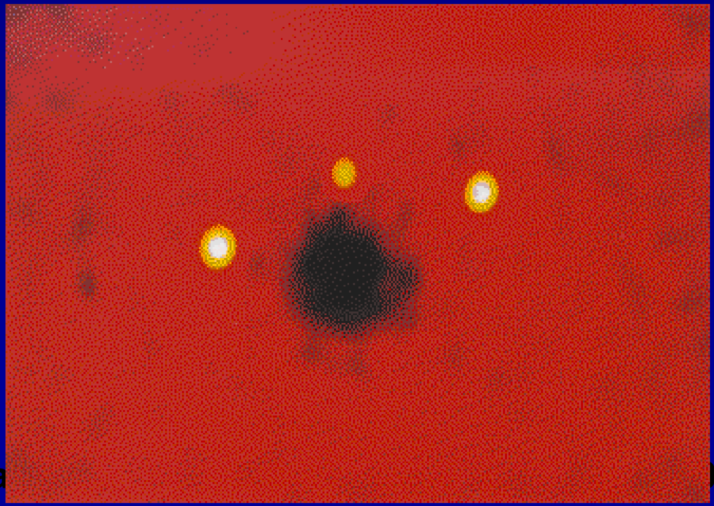


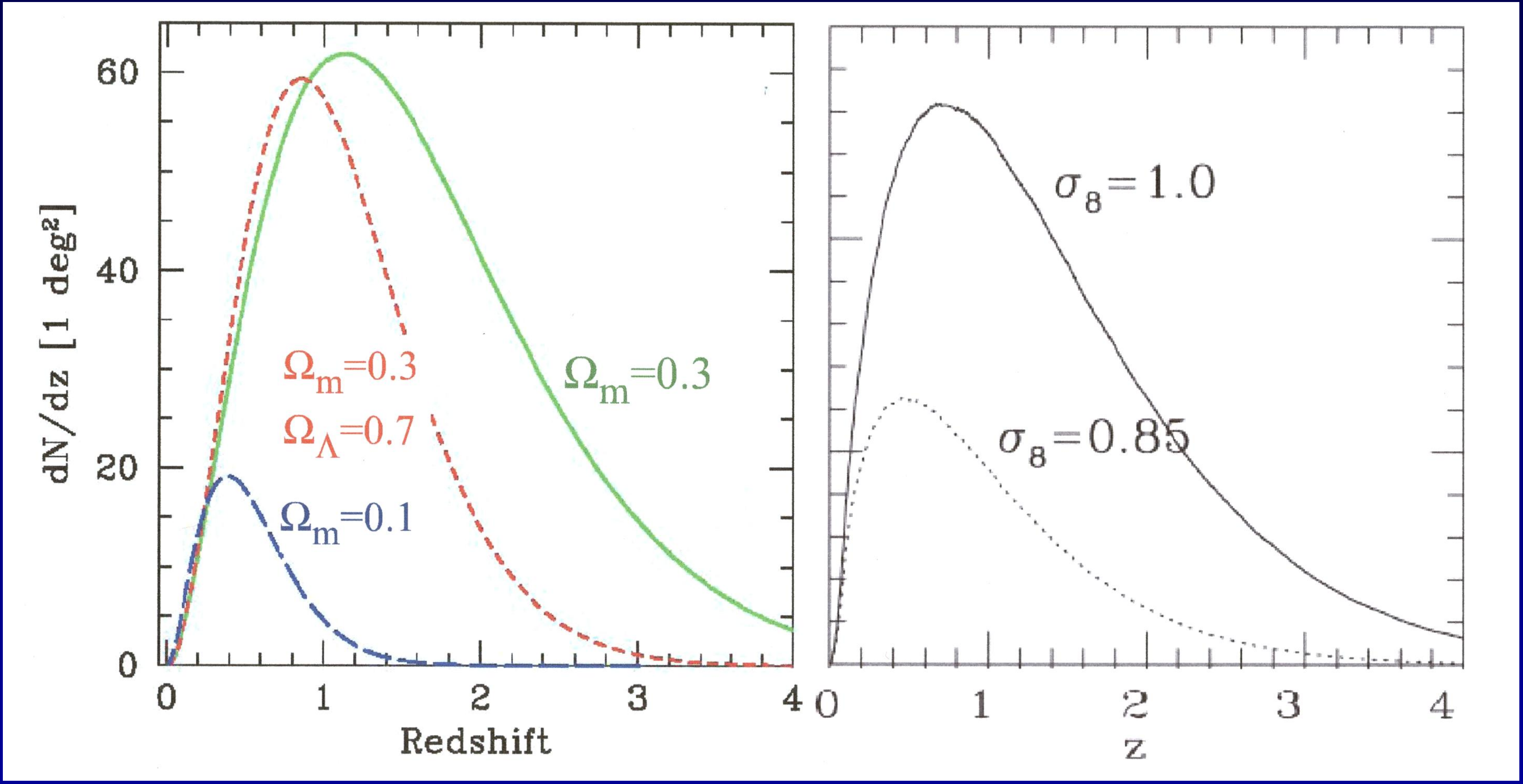
WMAP power spectrum



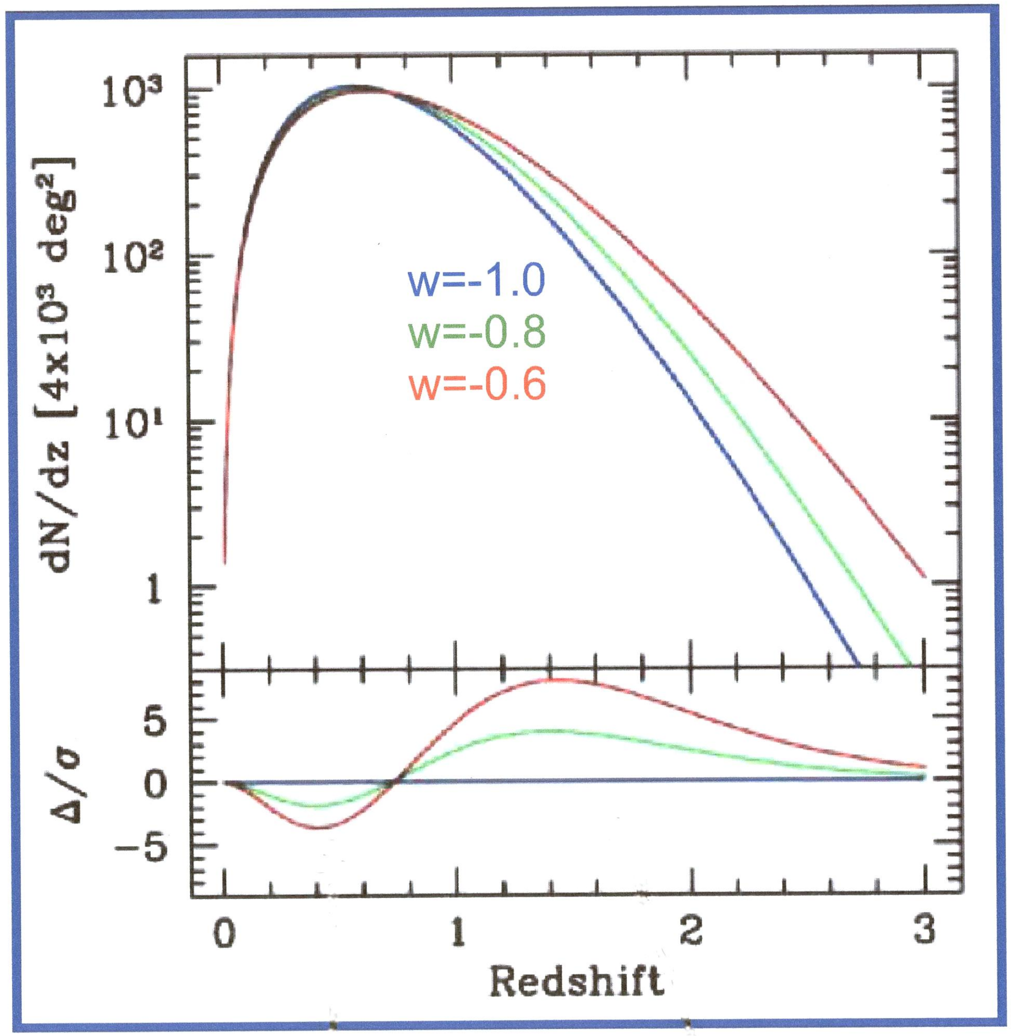
Sunyaev-Zeldovich effect







60
40
20
0
dN/dz [1 deg²]
0
1
2
3
4
Redshift
Ωm=0.3
ΩΛ=0.7
Ωm=0.3
Ωm=0.1
σ8=1.0
σ8=0.85
0
1
2
3
4
z



10³
10²
10¹
1
dN/dz [4x10³ deg²]
w=-1.0
w=-0.8
w=-0.6
5
0
−5
Δ/σ
0
1
2
3
Redshift