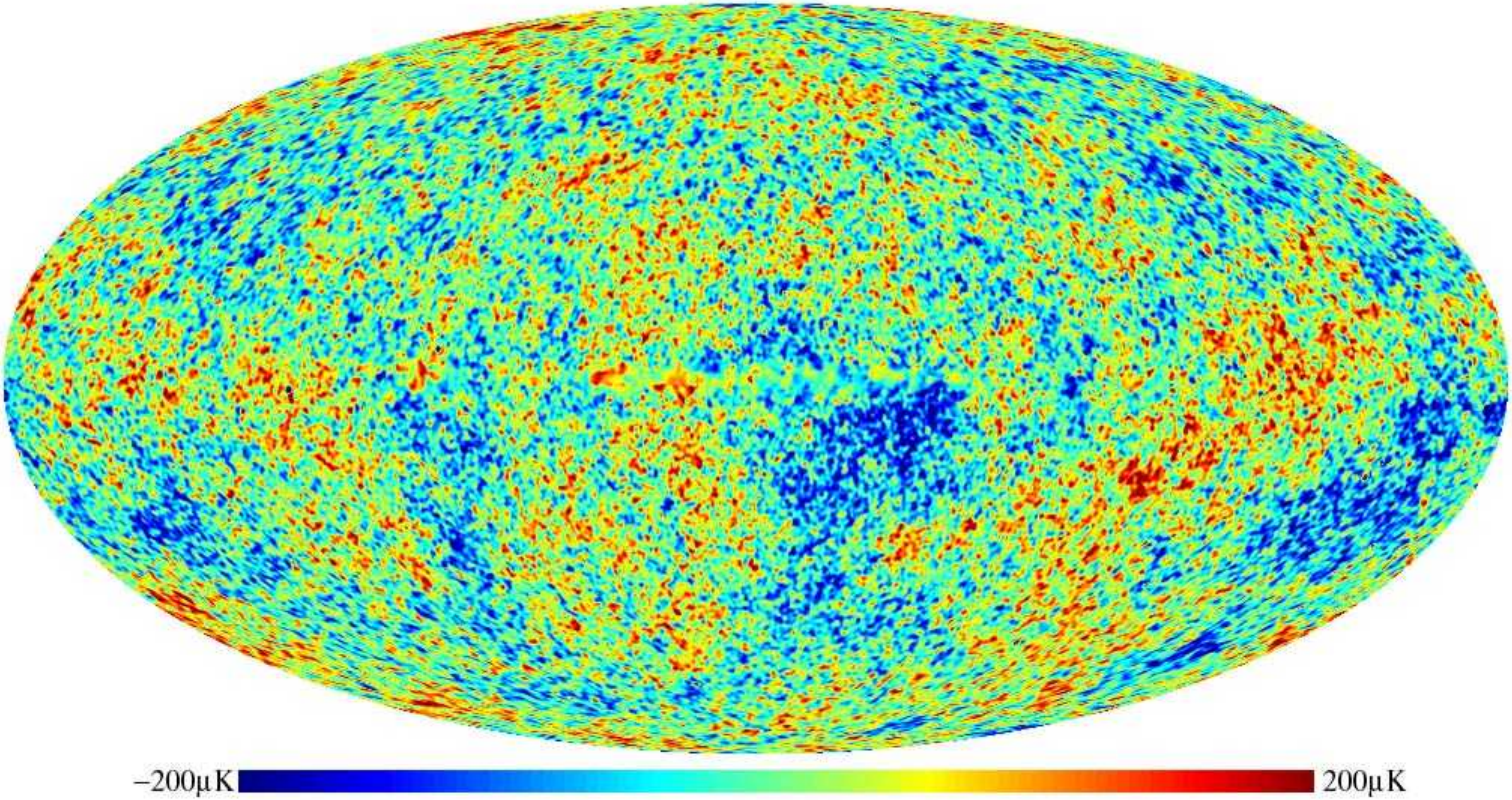
The Cosmic Microwave Background

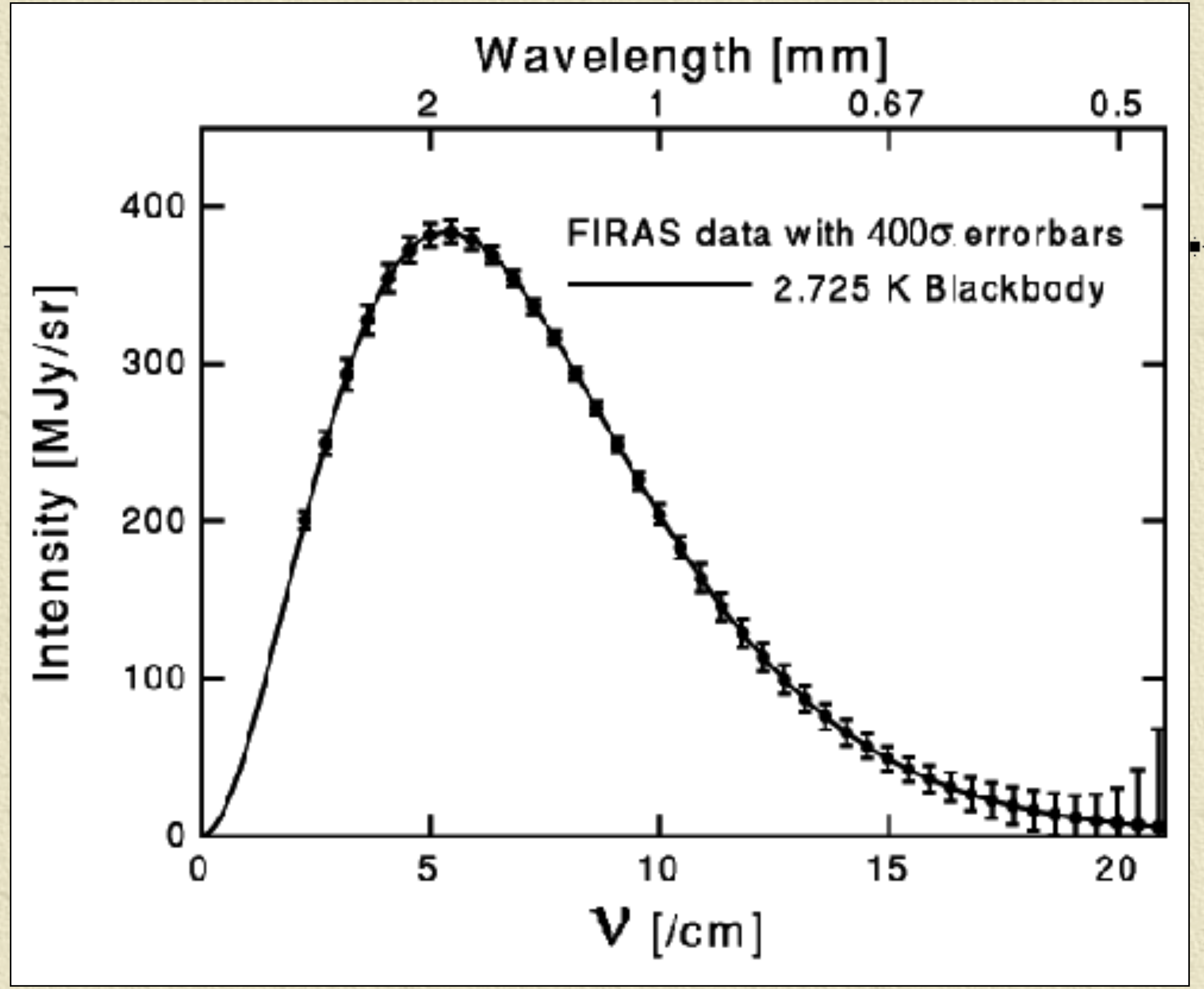
African School of Physics

Bruce Bassett


−200µK
200µK

What is the CMB?

- A photon gas at a temperature of about 2.7K that fills the Universe
- It is the most perfect blackbody ever measured



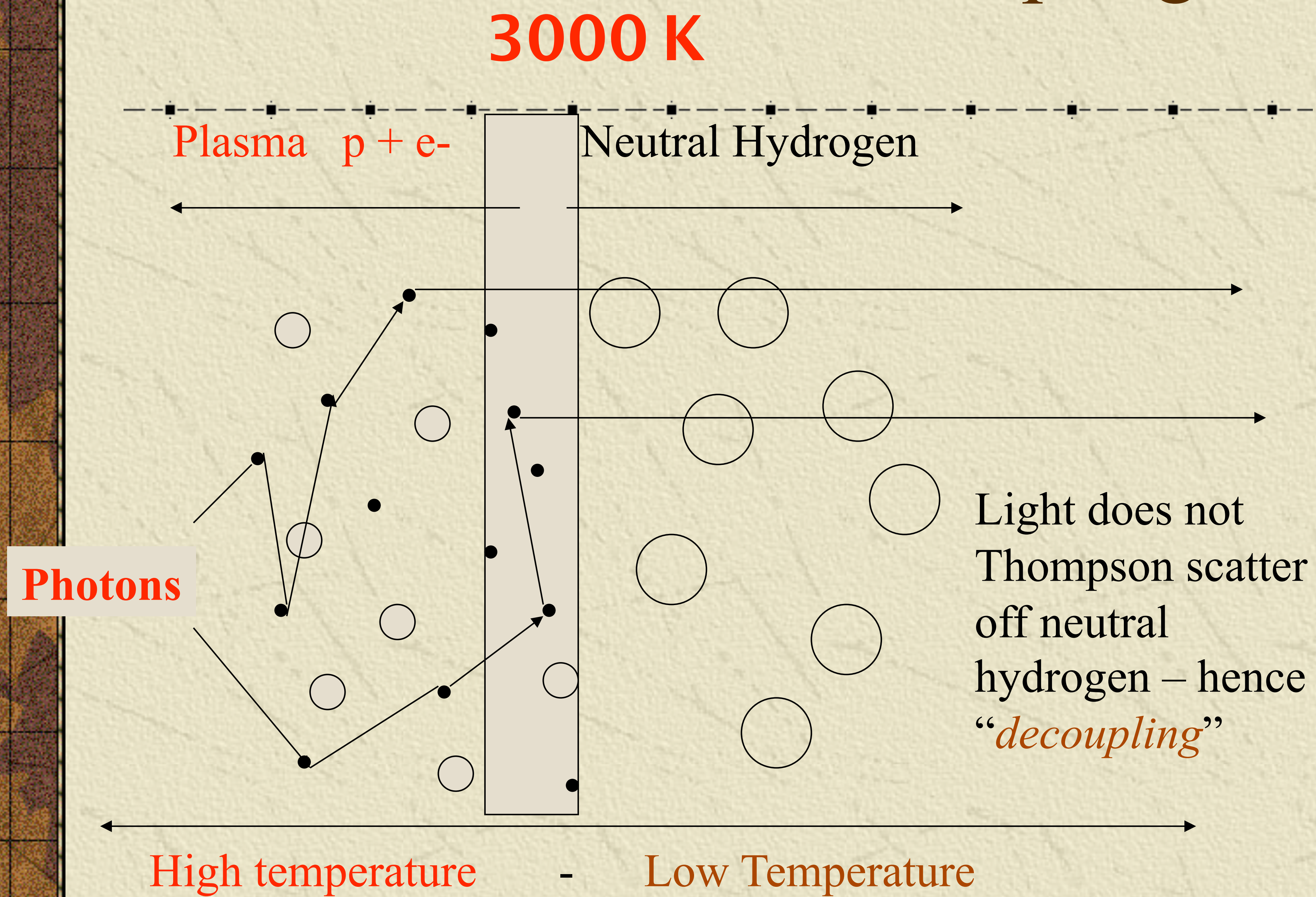
Wavelength [mm]
2
1
0.67
0.5
400
300
200
100
0
Intensity [MJy/sr]
FIRAS data with 400σ errorbars
2.725 K Blackbody
0
5
10
15
20
ν [/cm]

Predicted in the 1950's, detected in 1964

Gamow et al

Penzias and Wilson, 1964

Recombination and decoupling



The CMB in 60 seconds

- Decoupling of photons from matter and recombination of electrons and protons take place at $z \sim 1100$ when $T \sim 3000$ K
- Why?

Why are there temperature fluctuations in the CMB?

- Temperature fluctuations correspond to fluctuations in the frequency of the arriving photons (which preserve the blackbody spectrum):

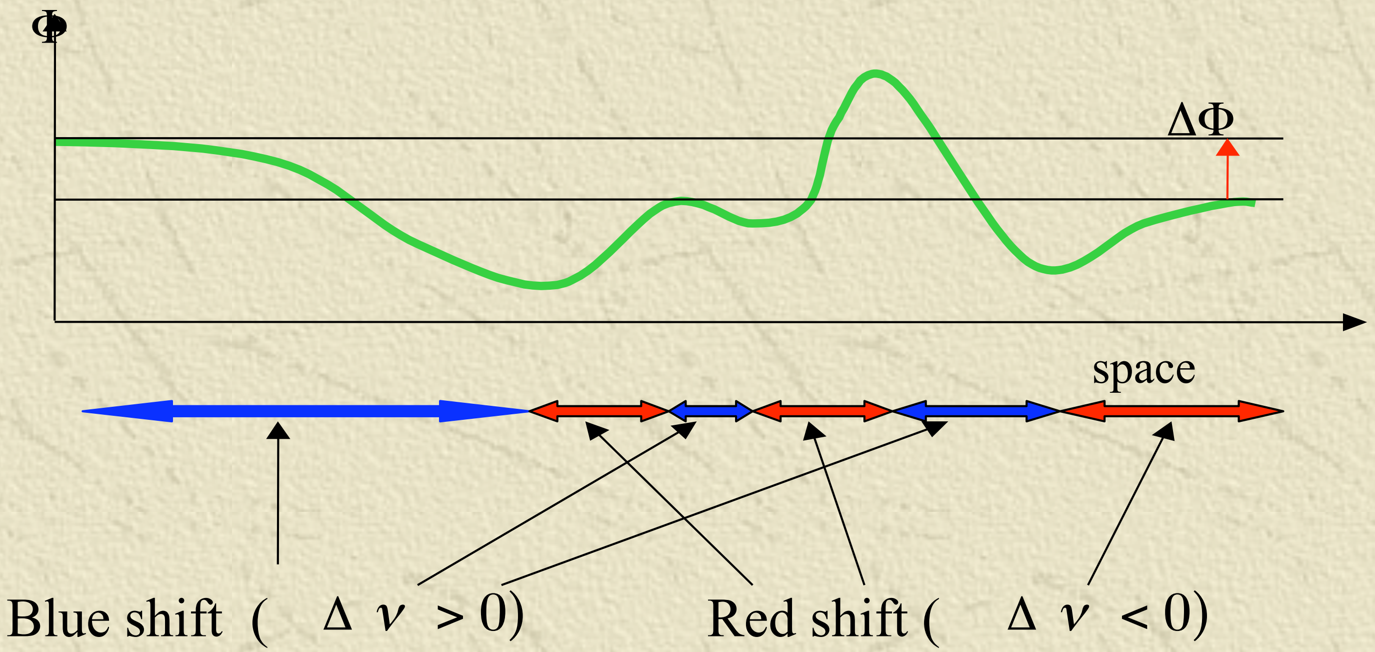
$$T_{CMB} \propto (1+z)$$

$$\Rightarrow \frac{\Delta T}{T} = \frac{\Delta z}{(1+z)} = -\frac{\Delta \nu_r}{\nu_r}$$

Frequency at reception

Gravitational red / blue shifting

Imagine a photon traveling through the spatially-dependent gravitational potential, Φ. It suffers frequency shifts due to the change in energy of the photon as it **falls into** and climbs out of gravitational potential wells on its path…



The Sachs-Wolfe Effect (1967)

- The formula for temperature anisotropies is therefore:

$$\frac{\Delta T}{T} = \frac{1}{3}\Phi\,\Big|_e^r - 2\int_e^r \frac{d\Phi}{dz}\cdot dz + \vec{v}\cdot\hat{r}$$

"Standard" Sachs-Wolfe Effect

Integrated Sachs-Wolfe Effect (ISW)

Doppler effect from velocity at last scattering

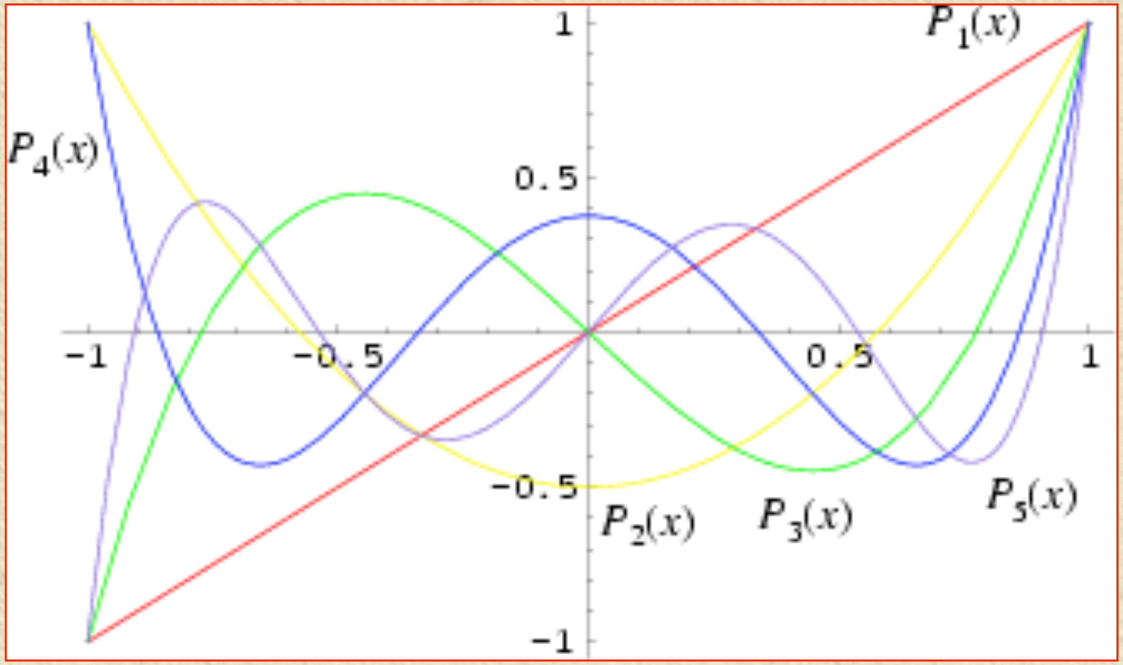
Angular Statistics

- The CMB temperature is a field on the 2-sphere
- We can describe the temperature anisotropies via the 2-point angular correlation funtion, $C(\theta)$ *(c.f. the spatial 2-point correlation function $\xi(r)$)*.
- Since $C(\theta)$ is a function of one angle we can expand it in Legendre polynomials, $P_l(\mu)$ where $\mu = \cos\theta$:

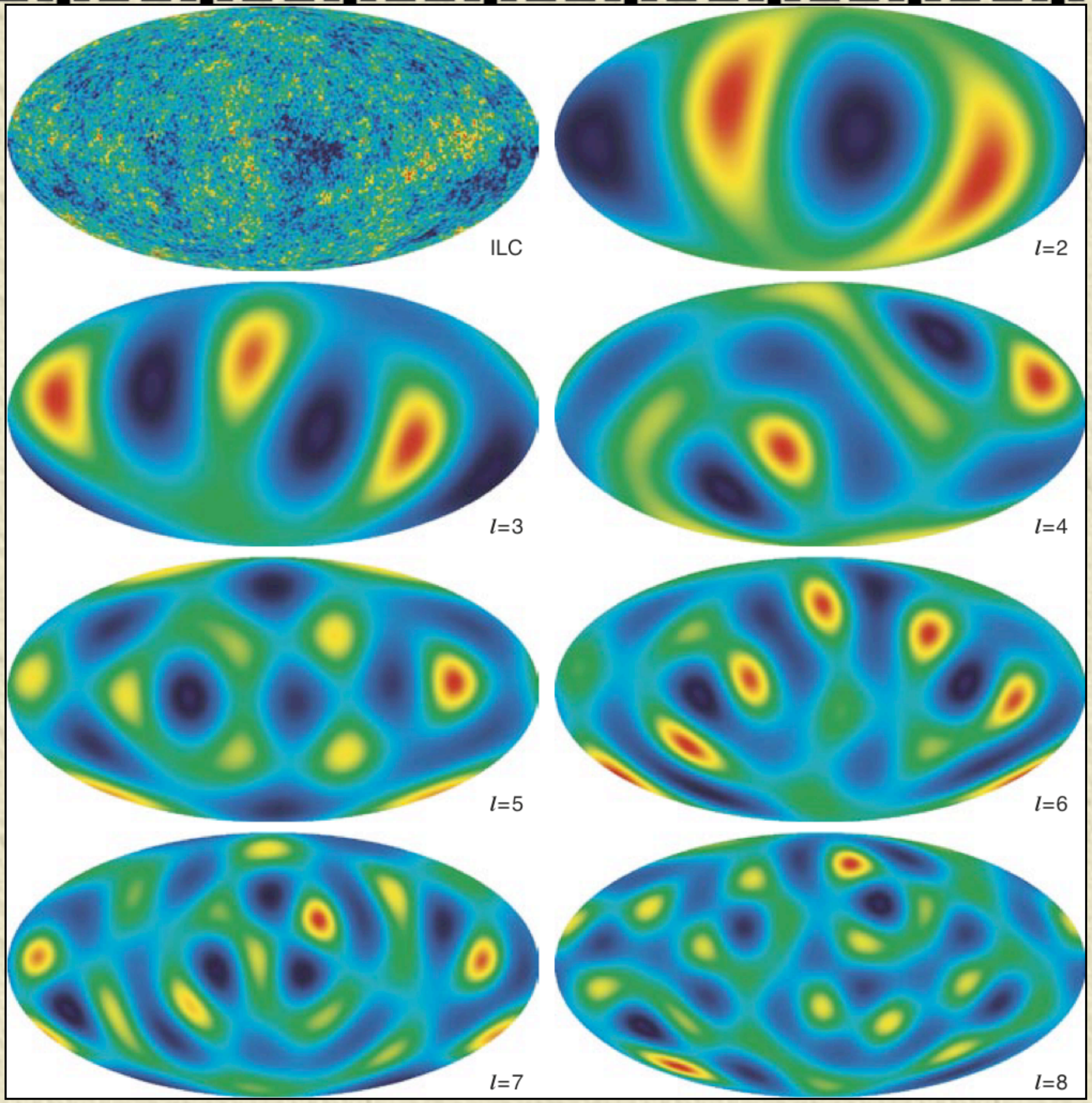
$$C(\theta) \propto \sum_{\ell} C_{\ell} P_{\ell}(\mu)$$

The Legendre Polynomials

$$P_0(x) = 1$$
$$P_1(x) = x$$
$$P_2(x) = \frac{1}{2}(3x^2 - 1)$$
$$P_3(x) = \frac{1}{2}(5x^3 - 3x)$$
$$P_4(x) = \frac{1}{8}(35x^4 - 30x^2 + 3)$$
$$P_5(x) = \frac{1}{8}(63x^5 - 70x^3 + 15x)$$
$$P_6(x) = \frac{1}{16}(231x^6 - 315x^4 + 105x^2 - 5).$$



The lower harmonics…



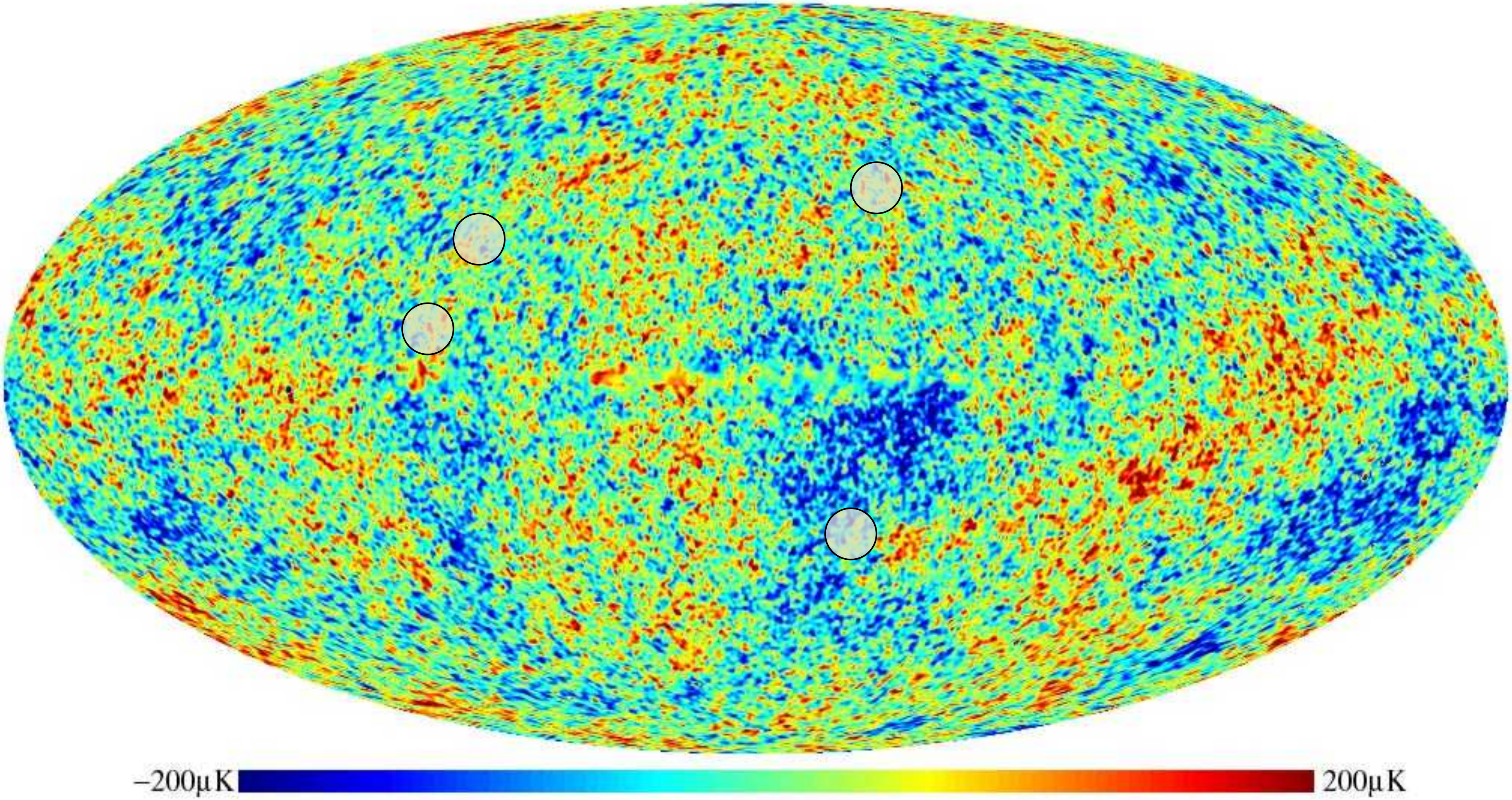
WMAP

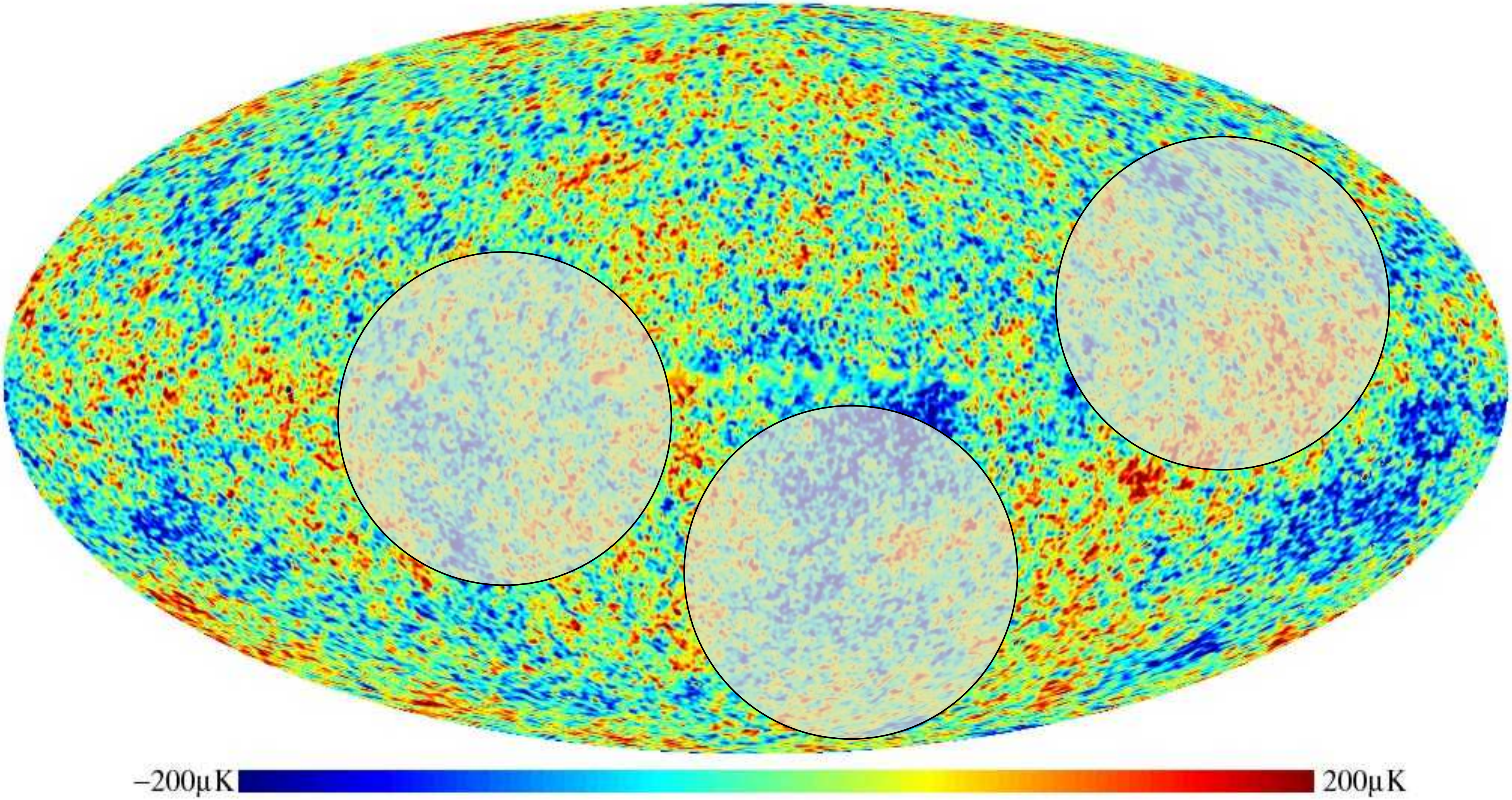
Intuition for the C_l

- The coefficients, C_l, are the key quantity for a Gaussian random field on the sphere (why?)

- Physically they represent the variance in the temperature averaged over circles of angular size $\theta \sim 200/l$ *degrees.*

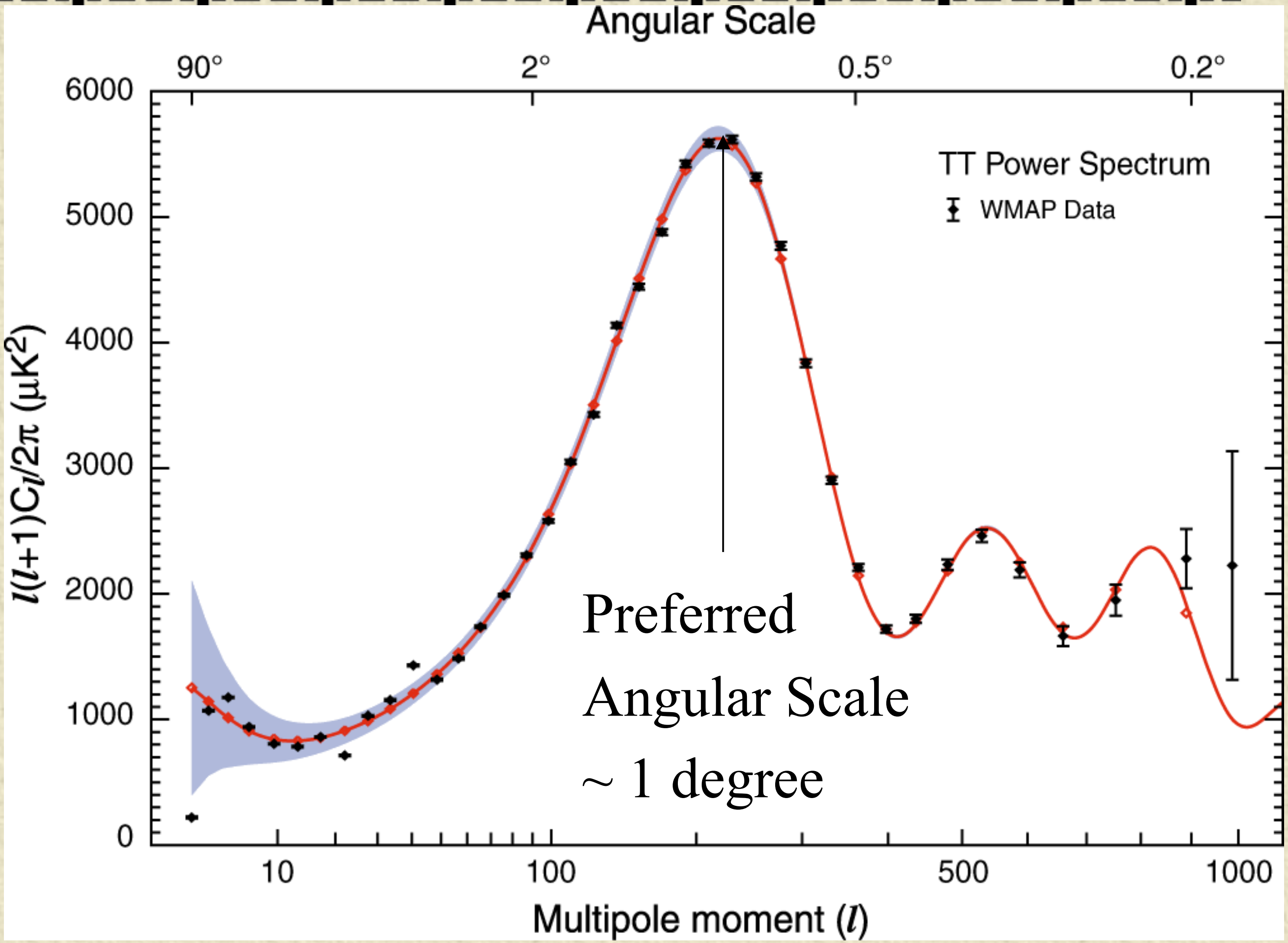
- Small l corresponds to variation on large angular scales and vice versa…

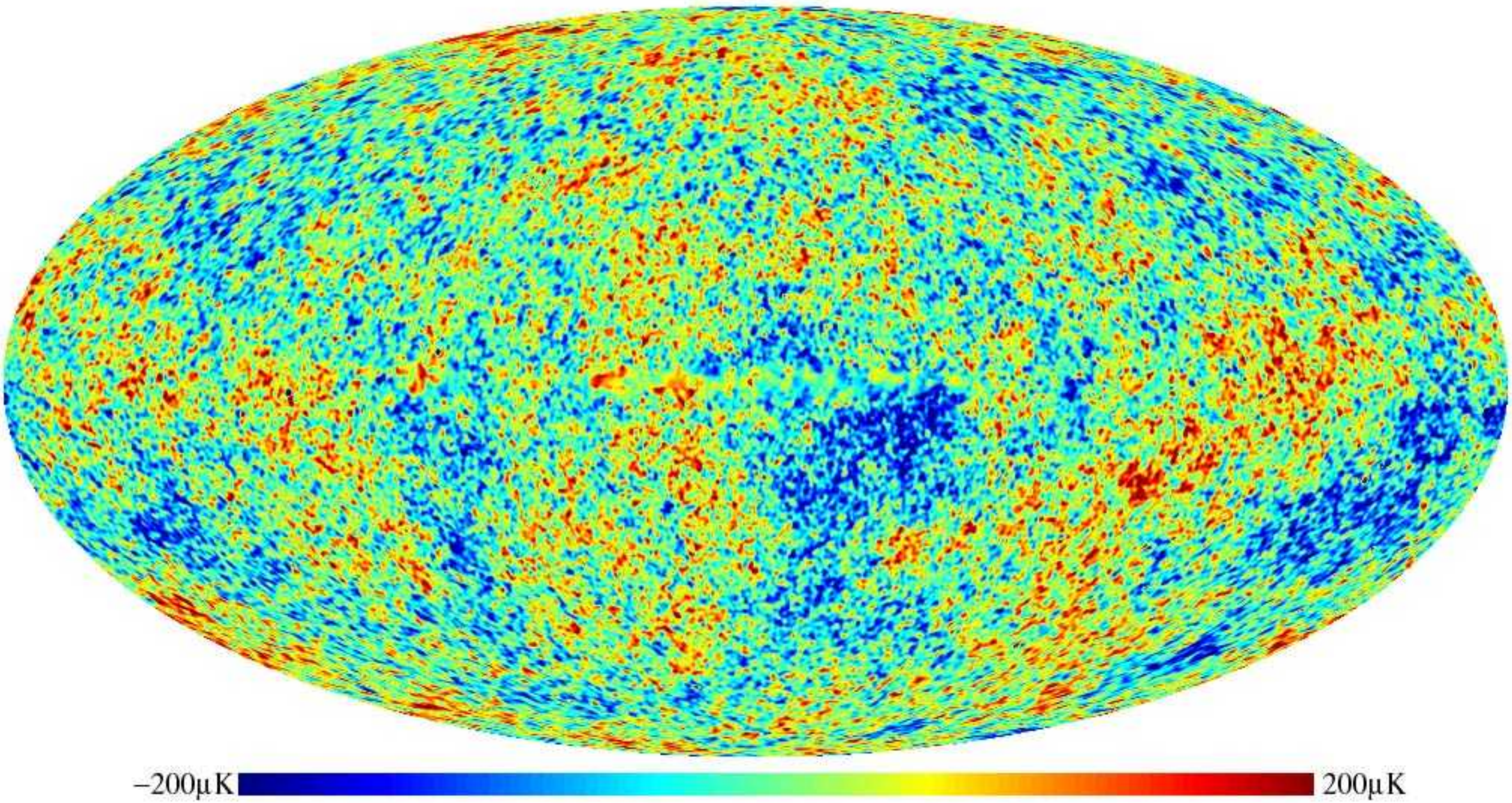

−200μK
200μK


−200μK
200μK

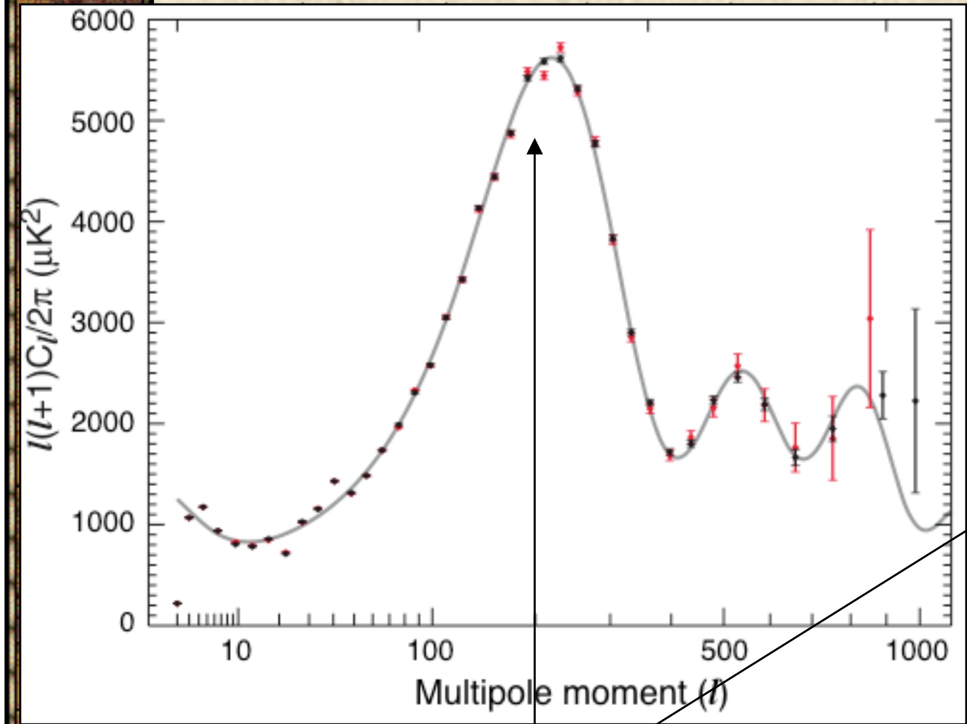
The WMAP results…

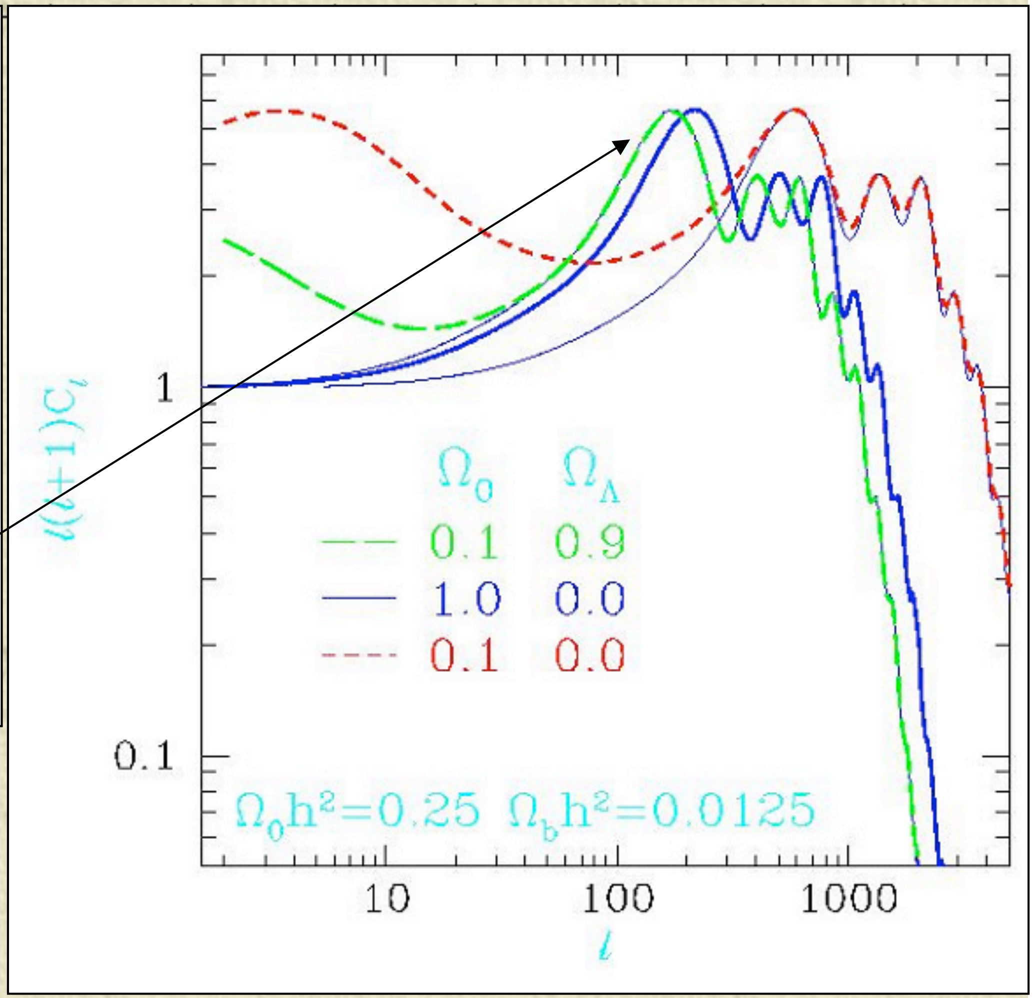
$l(l+1)\ C_l$




−200μK
200μK

Geometry of the cosmos in the CMB



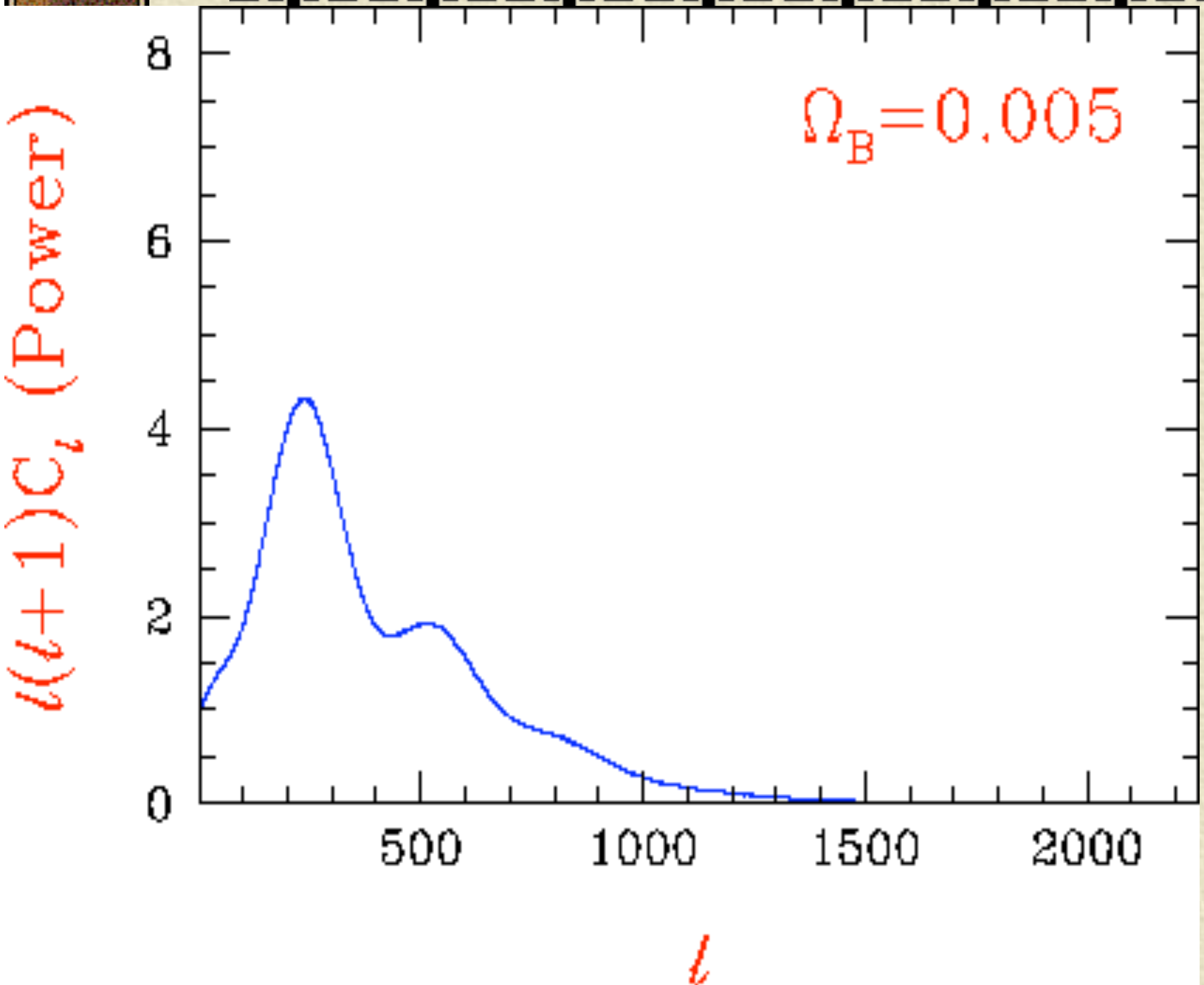


Universe is flat to within 2%

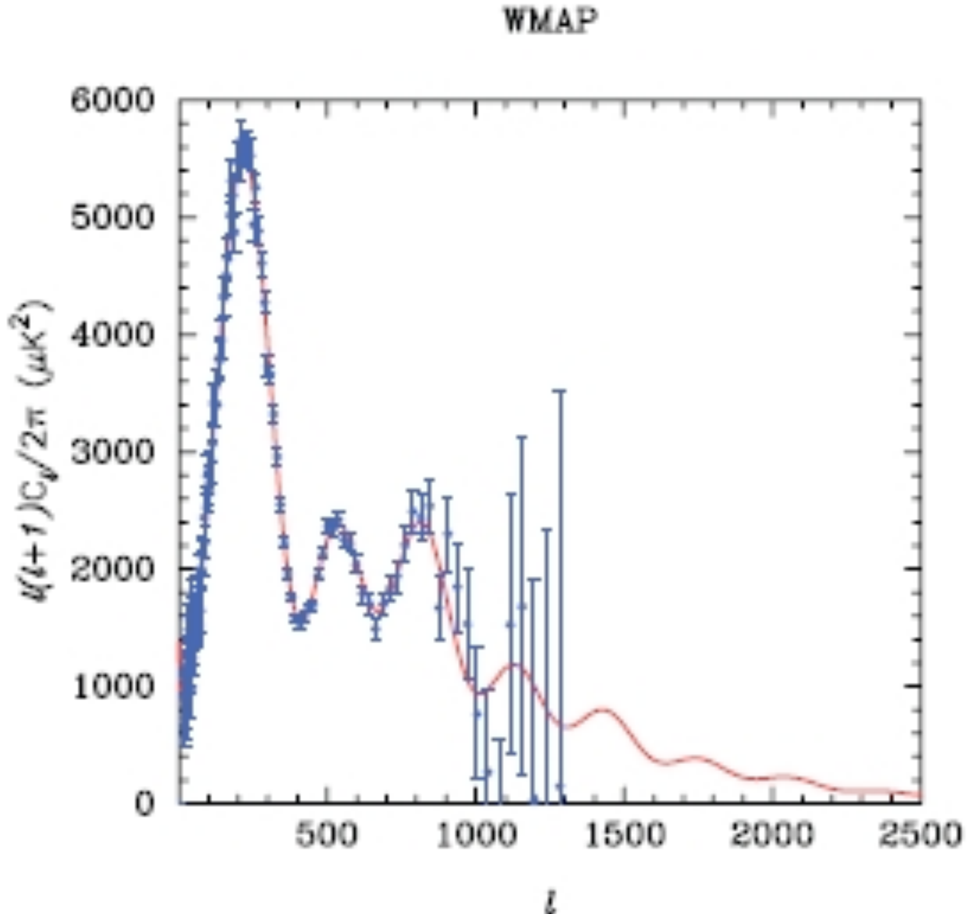
This is just a view of the BAO in photons!

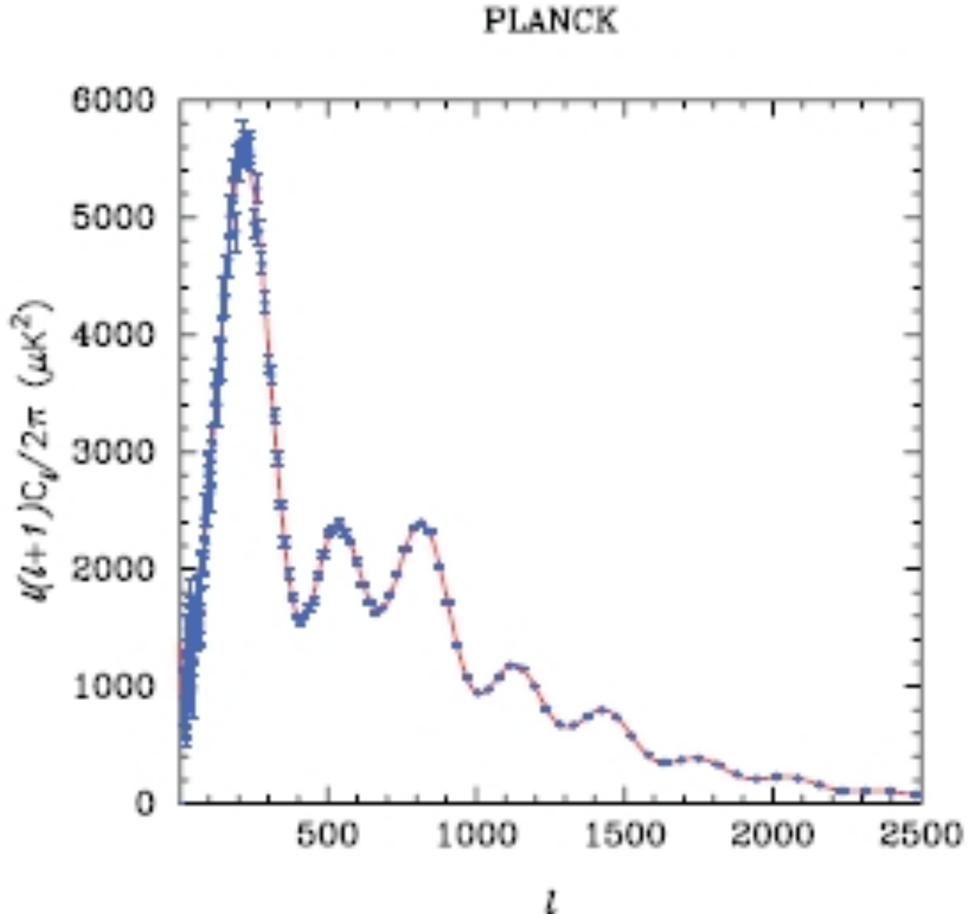
http://background.uchicago.edu/~whu/metaanim.html

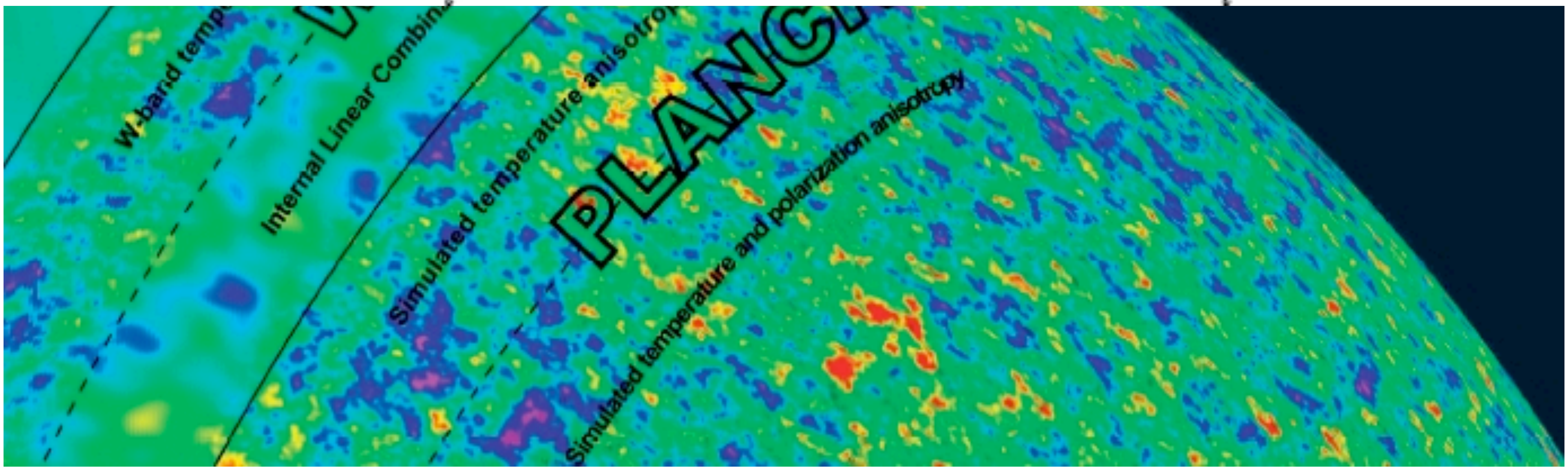
The effect of changing the amount of baryons in the universe



This illustrates the power of the CMB to constrain cosmic parameters. Each part of the angular spectrum constrains different parameters


WMAP
$\ell(\ell+1)C_\ell/2\pi$ (μK^2)
0
1000
2000
3000
4000
5000
6000
500
1000
1500
2000
2500
ℓ


PLANCK
$\ell(\ell+1)C_\ell/2\pi$ (μK^2)
0
1000
2000
3000
4000
5000
6000
500
1000
1500
2000
2500
ℓ


PLANCK
Simulated temperature and polarization anisotropy