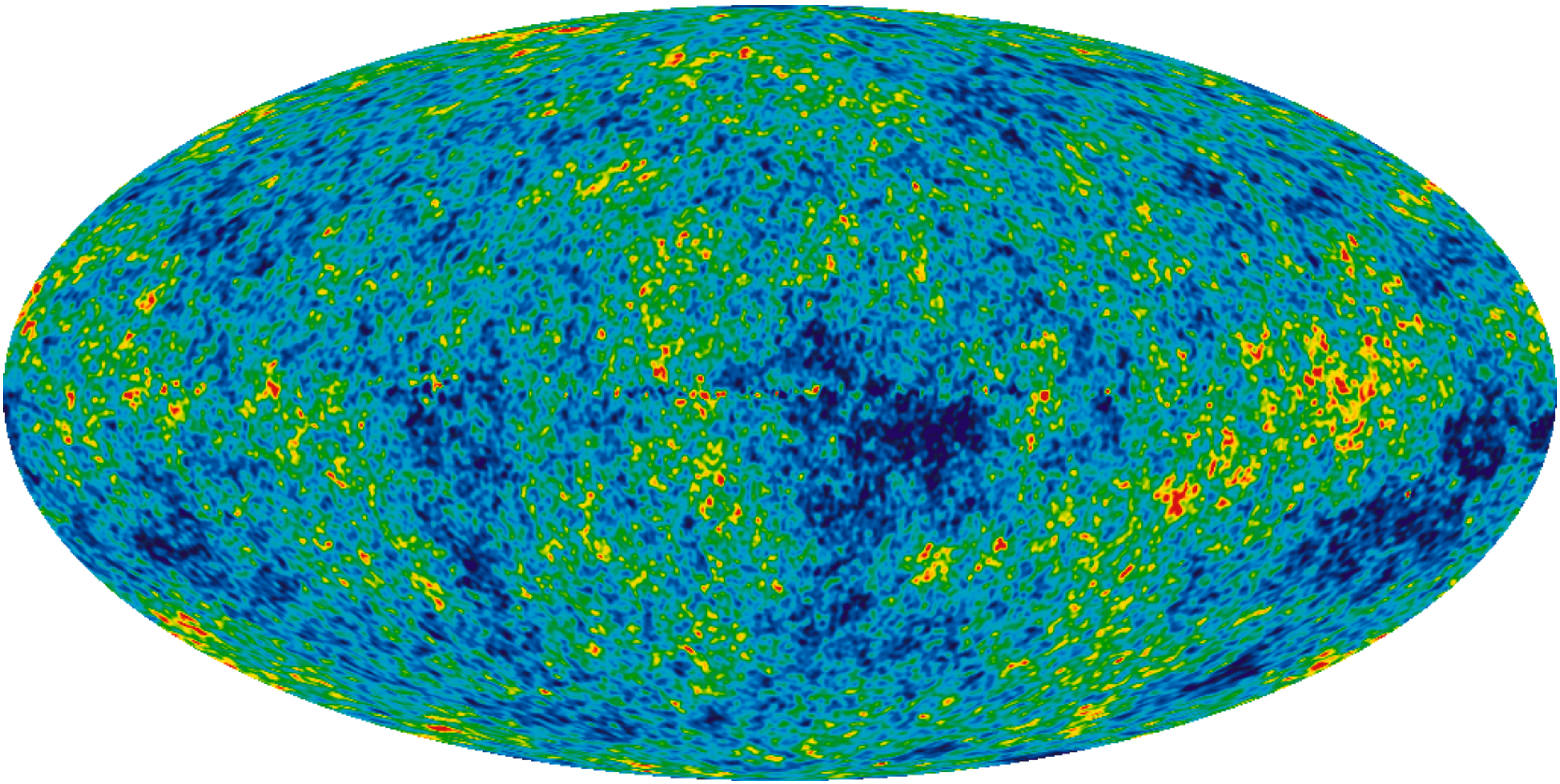
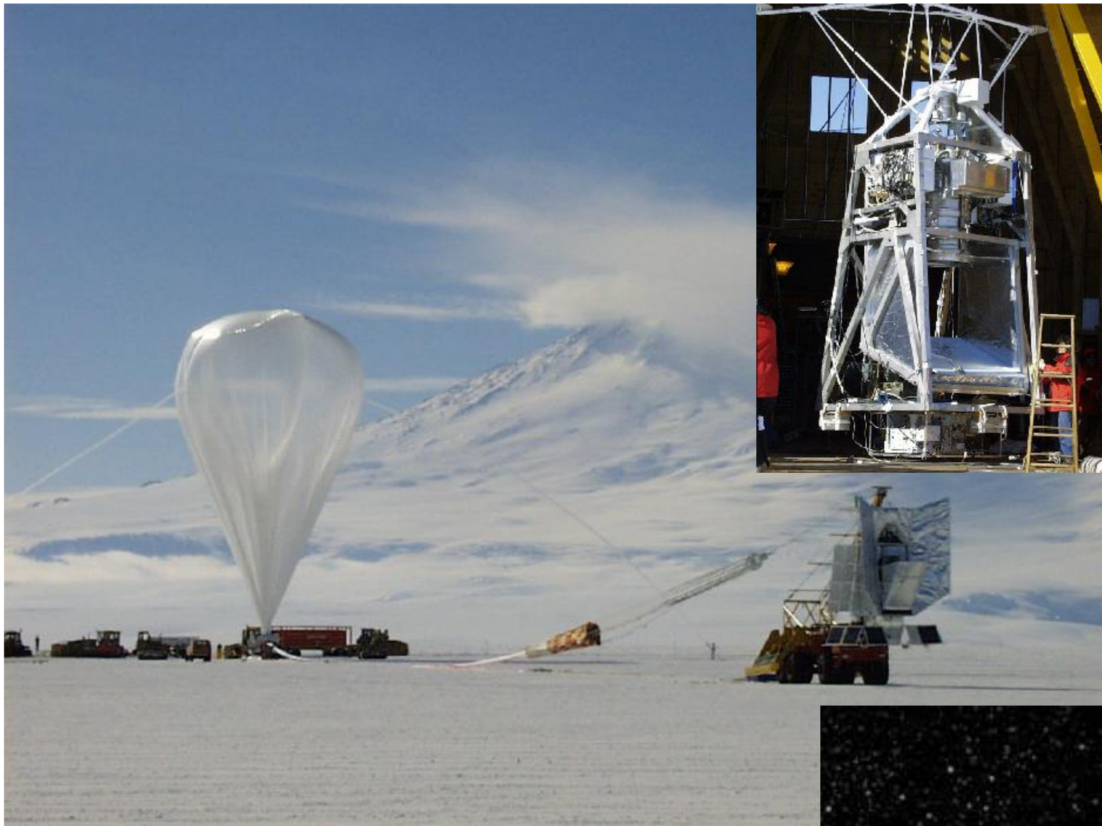
Cosmology With the Cosmic Microwave Background



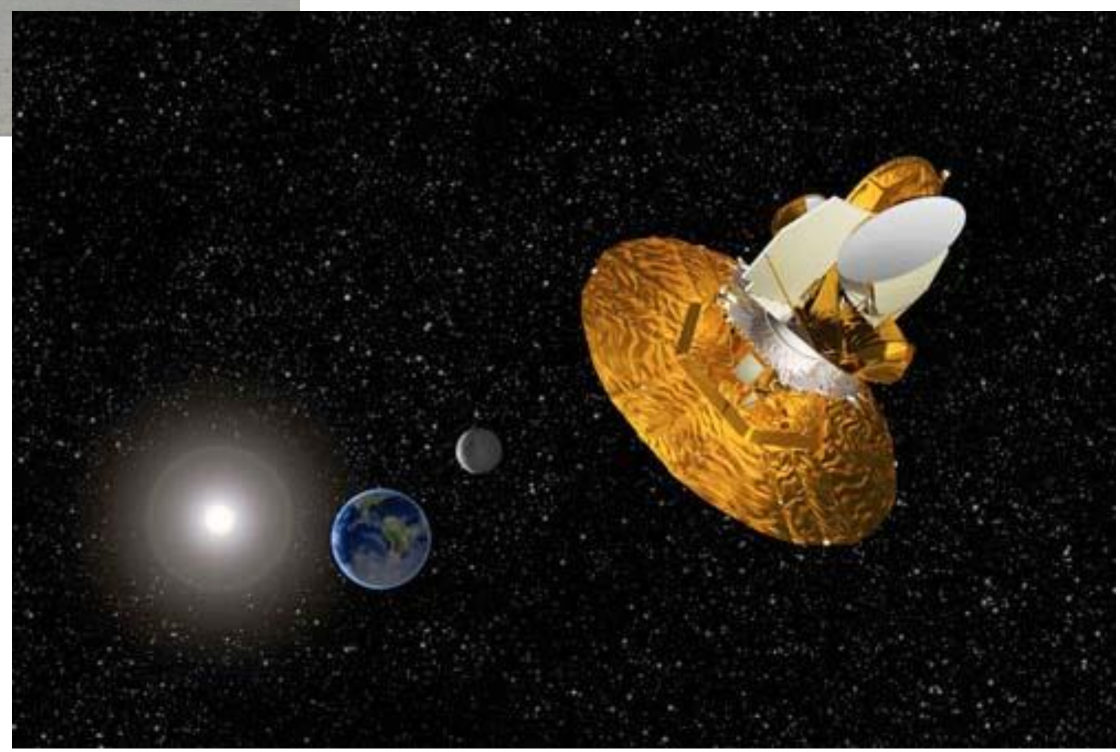
The Modern Angular Diameter Test: CMBR Fluctuations

- Uses the size of the particle horizon at the time of the recombination (the release of the CMBR) as a standard ruler
- This governs the largest wavelength of the sound waves produced in the universe then, due to the infall of baryons into the large-scale density fluctuations
- These sound waves cause small fluctuations in the temperature of the CMB ($\Delta T/T \sim 10^{-5}$ - 10^{-6}) at the appropriate angular scales (~ a degree and less)
- They are measured as the angular power spectra of temperature fluctuations of the CMBR

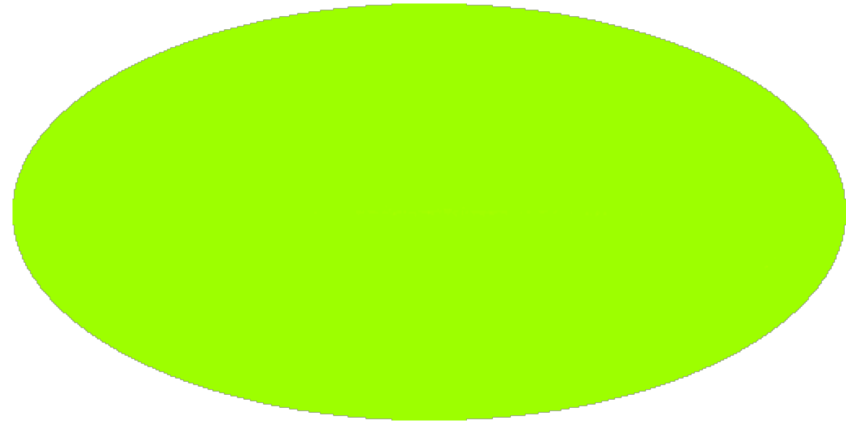


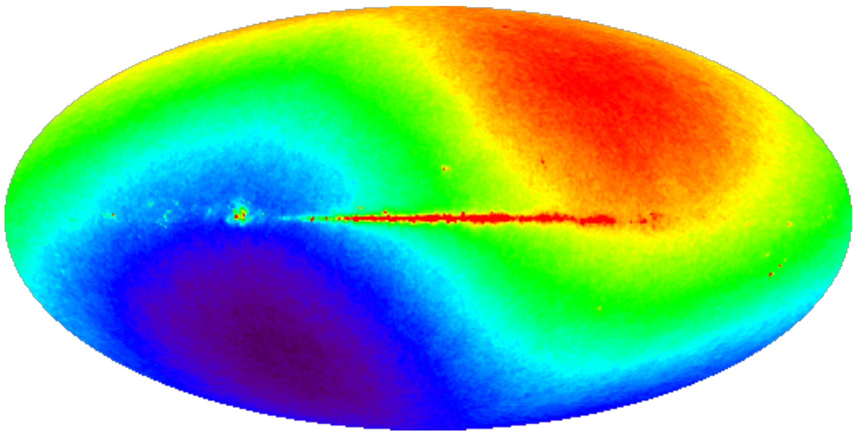
BOOMERANG
(1998)

WMAP
(2001 - 2010



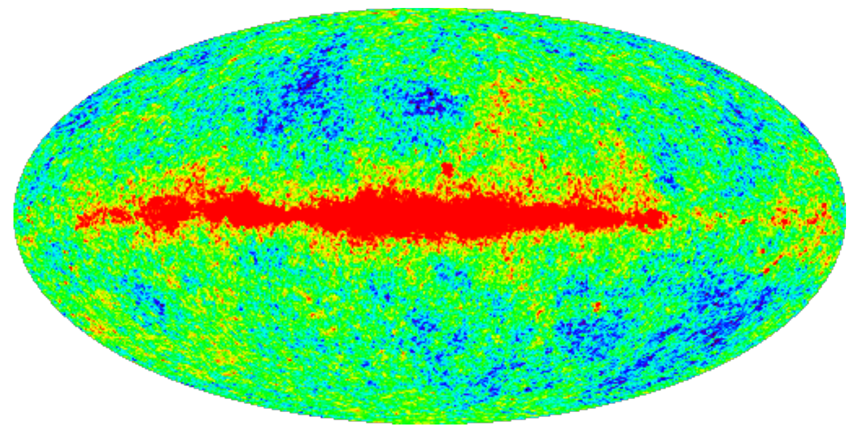
The CMBR sky from WMAP ➡

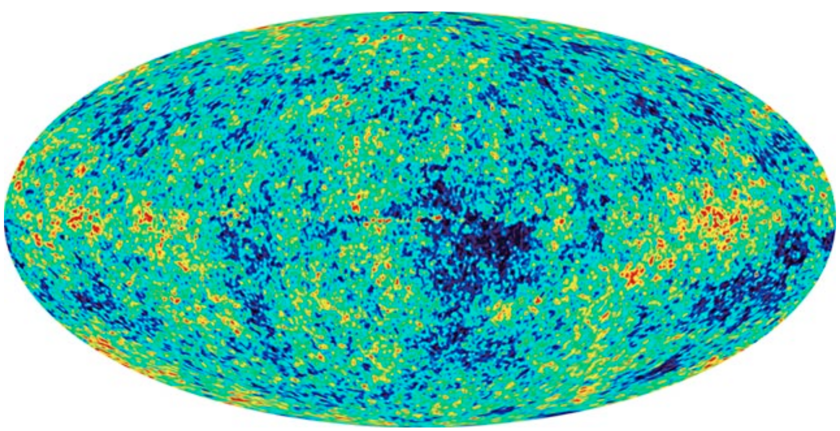




⬅ Enhance the conttrast by 10^3

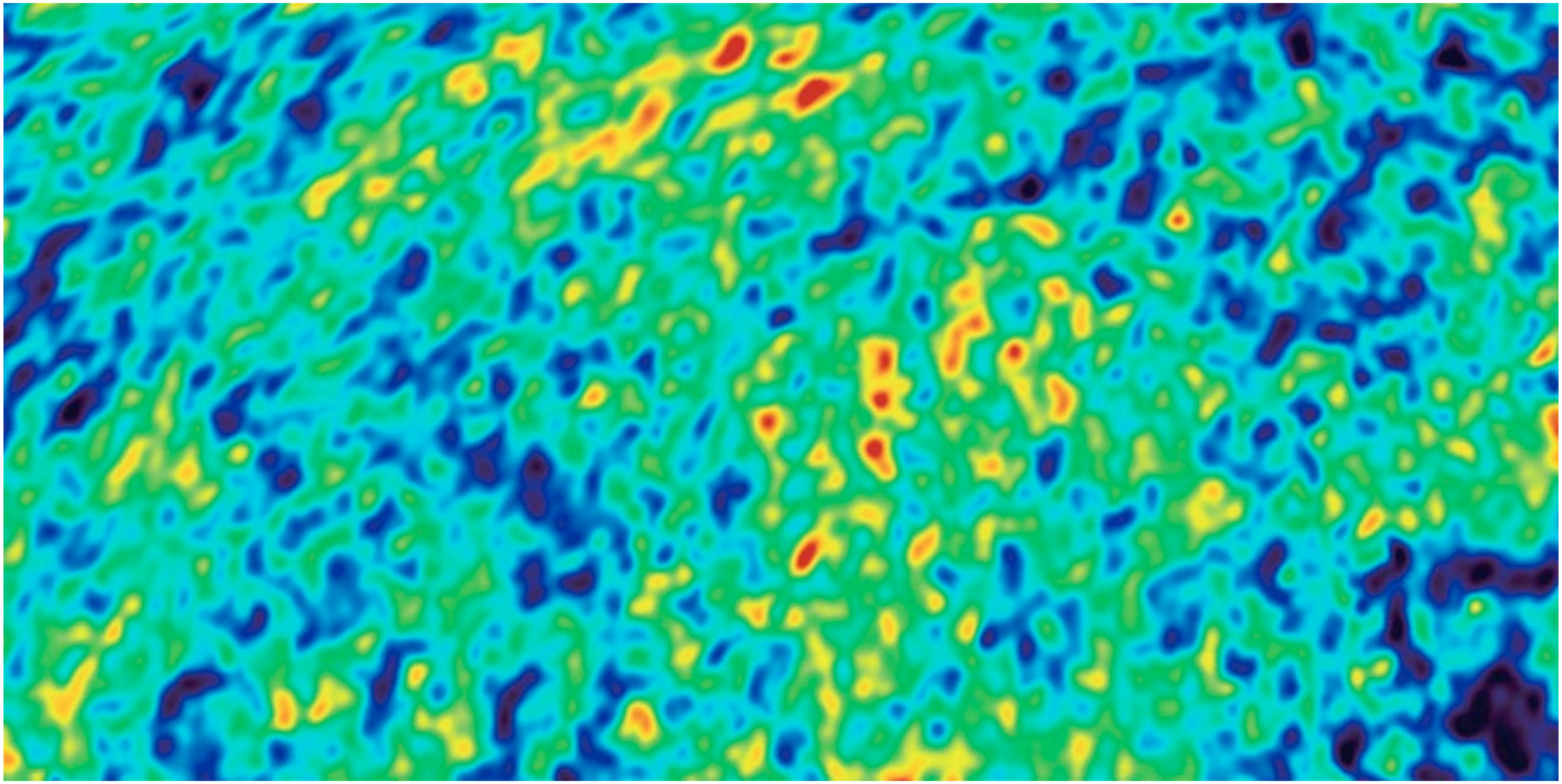
Remove the dipole and
enhance the contrast to 10^5 ➡





⬅ Remove the Galaxy, the
contrast is 10^5 and see the
primordial density fluctuations

A characteristic Fluctuation Scale Exists of ~ 1 degree

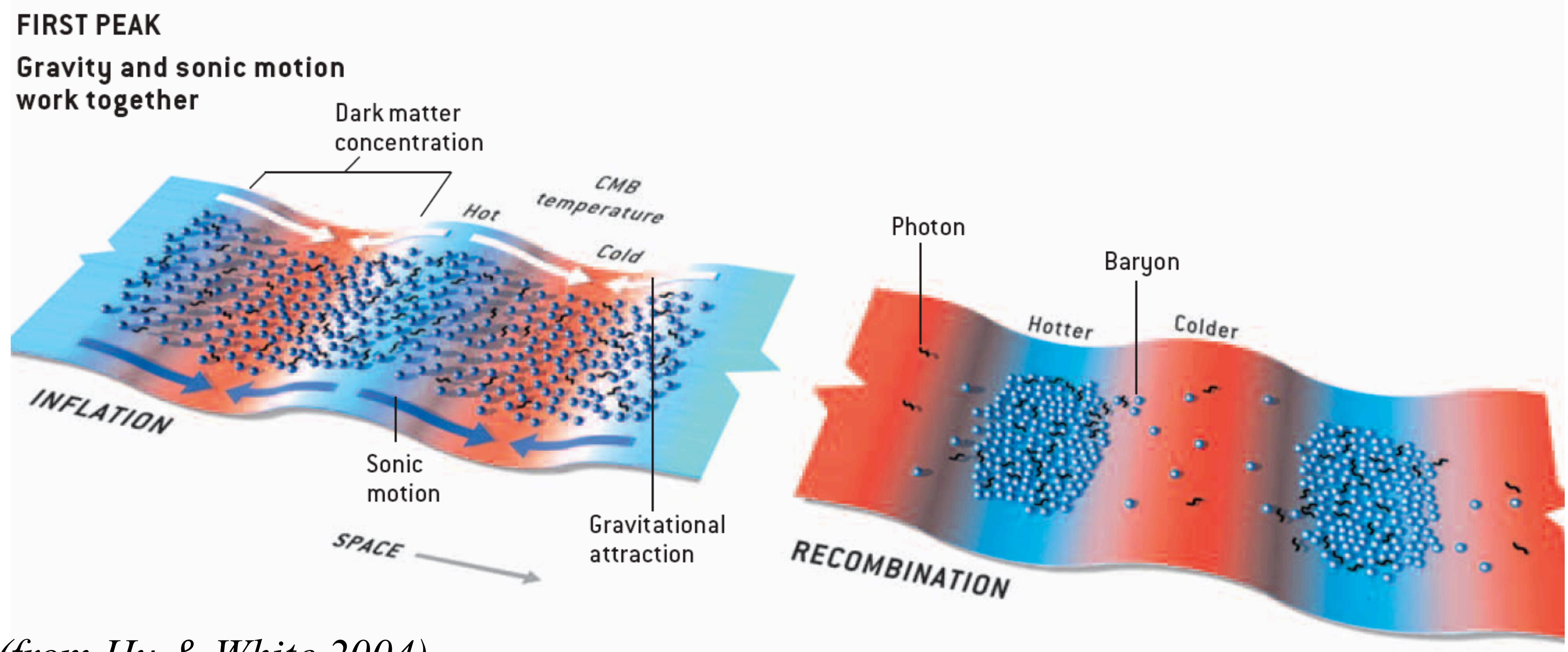


This corresponds to the size of the particle horizon at the decoupling, and thus to the longest sound wavelength which can be present

The Cosmic Sound

Large-scale density fluctuations in the early universe attract baryons and photons. Their streaming motion, compression, generate sound waves.

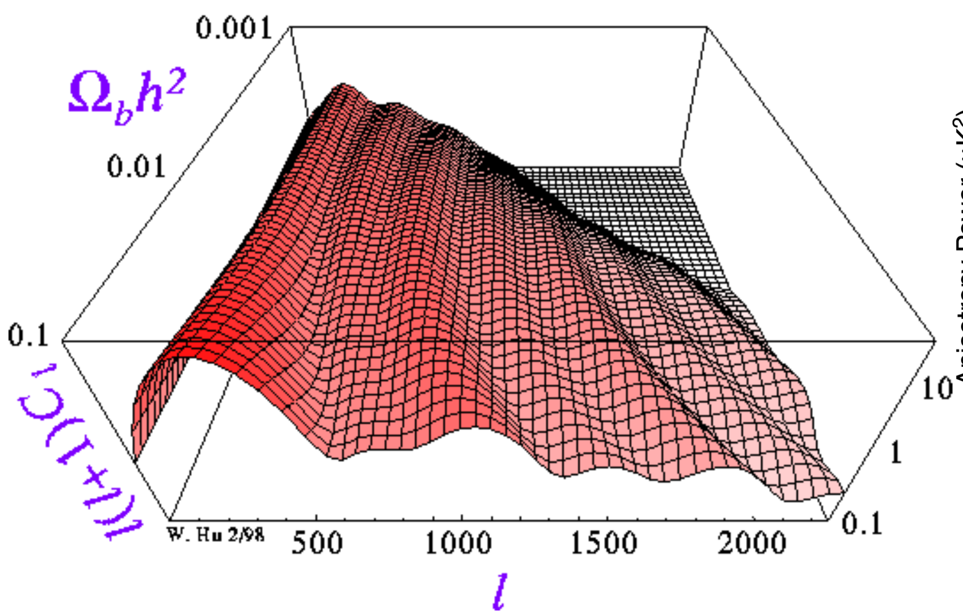
INFLUENCE OF DARK MATTER modulates the acoustic signals in the CMB. After inflation, denser regions of dark matter that have the same scale as the fundamental wave (*represented as troughs in this potential-energy diagram*) pull in baryons and photons by gravitational attraction. (The troughs are shown in red because gravity also reduces the temperature of any escaping photons.) By the time of recombination, about 380,000 years later, gravity and sonic motion have worked together to raise the radiation temperature in the troughs (*blue*) and lower the temperature at the peaks (*red*).



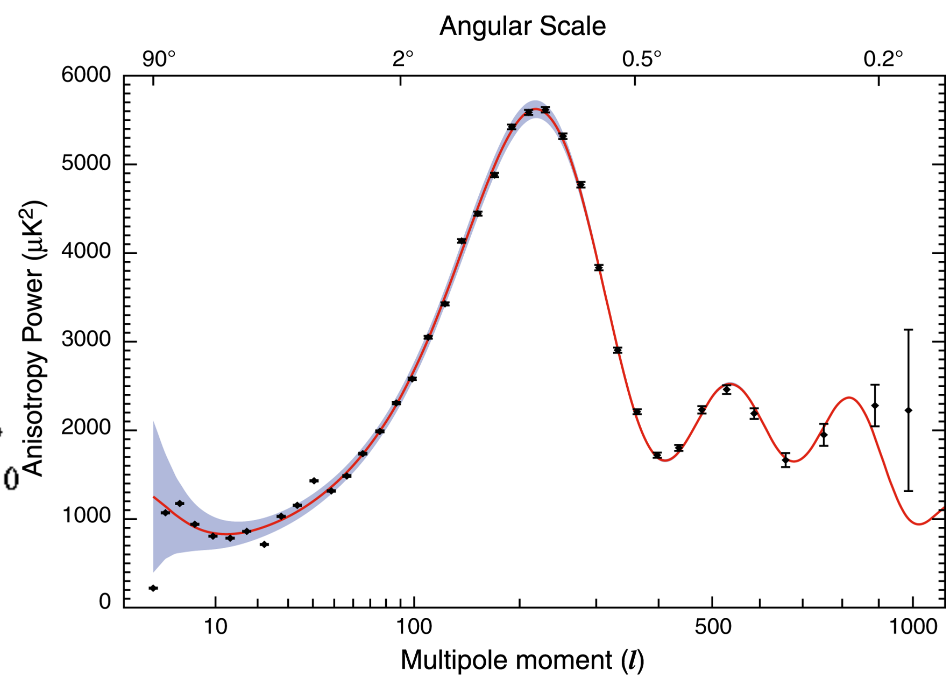
(from Hu & White 2004)

Acoustic Peaks in the CMBR

- The largest wavelength corresponds to the size of the particle horizon at the time
- Higher overtones incorporate a more complex interplay of baryons, dark matter, and radiation pressure
- The pattern is frozen in the CMB temperature fluctuations at the time of the decoupling



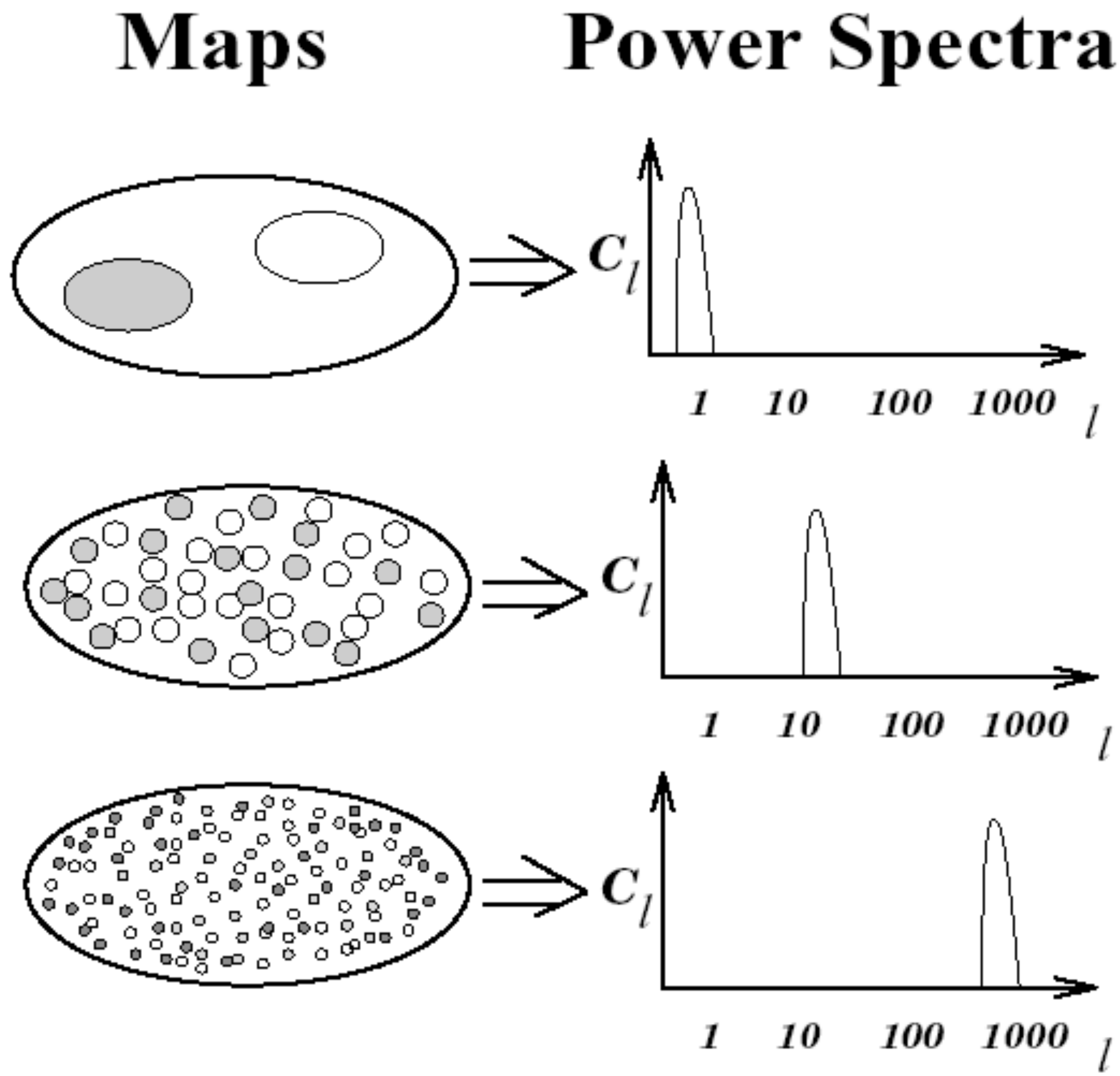
(from W.Hu)



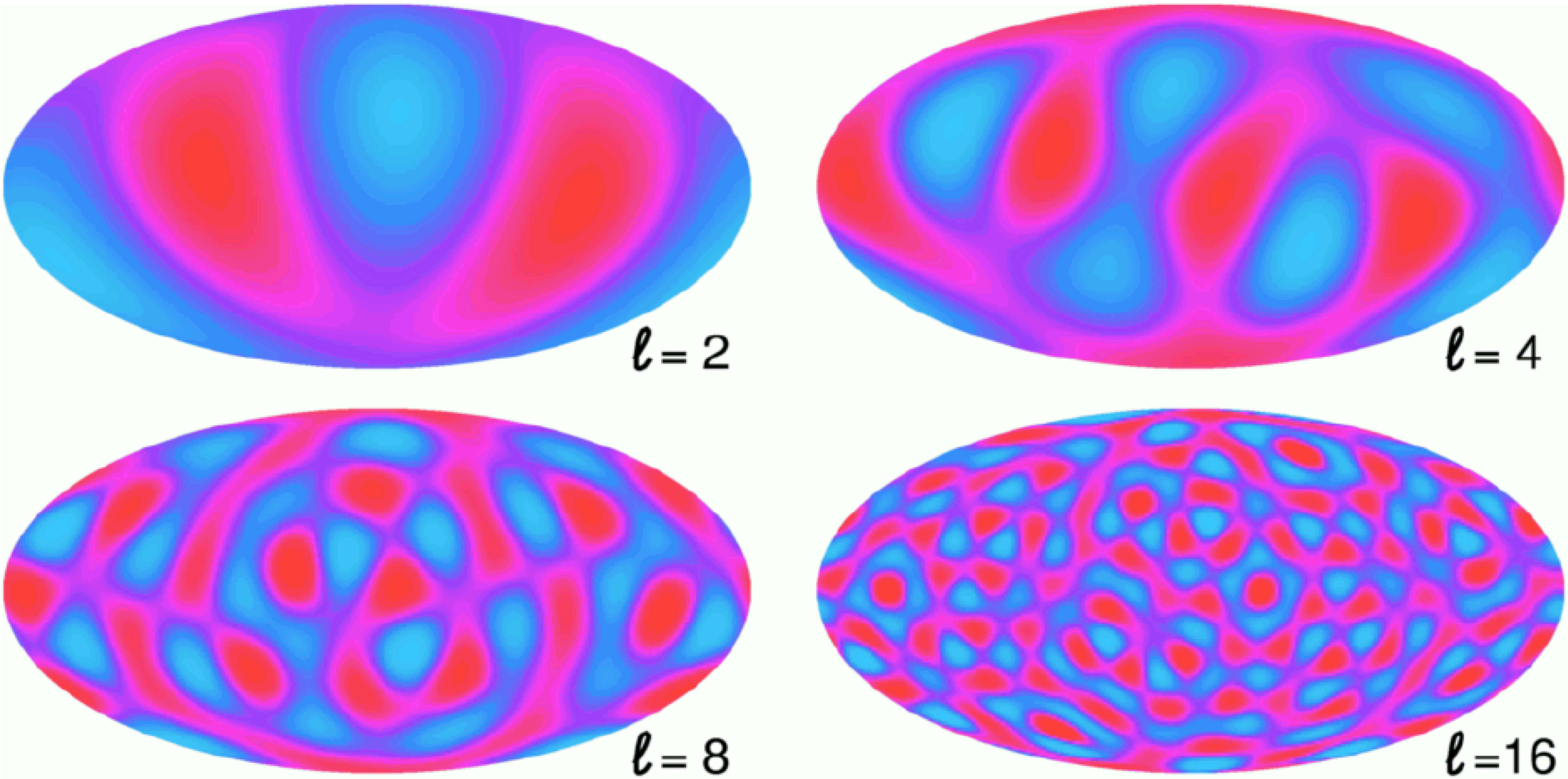
WMAP year 3 results

The Angular Power Spectrum

To quantify this, we evaluate the angular (spherical harmonic) power spectra



Spherical Harmonic Decomposition



(from N. Wright)

Spherical Harmonics

Any quantity which varies with position on the surface on a sphere can be written as the sum of spherical harmonics:

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi)$$

measured anisotropy map as function of spherical polar angles θ and ϕ

weight - how much of the signal is accounted for by this particular mode

spherical harmonic function

The spherical harmonic functions themselves are just increasingly complicated trignometric functions, e.g.:

$$Y_{22}(\theta,\phi) = \sqrt{\frac{5}{96\pi}}\, 3\sin^2\theta e^{2i\phi}$$

Spherical Harmonics

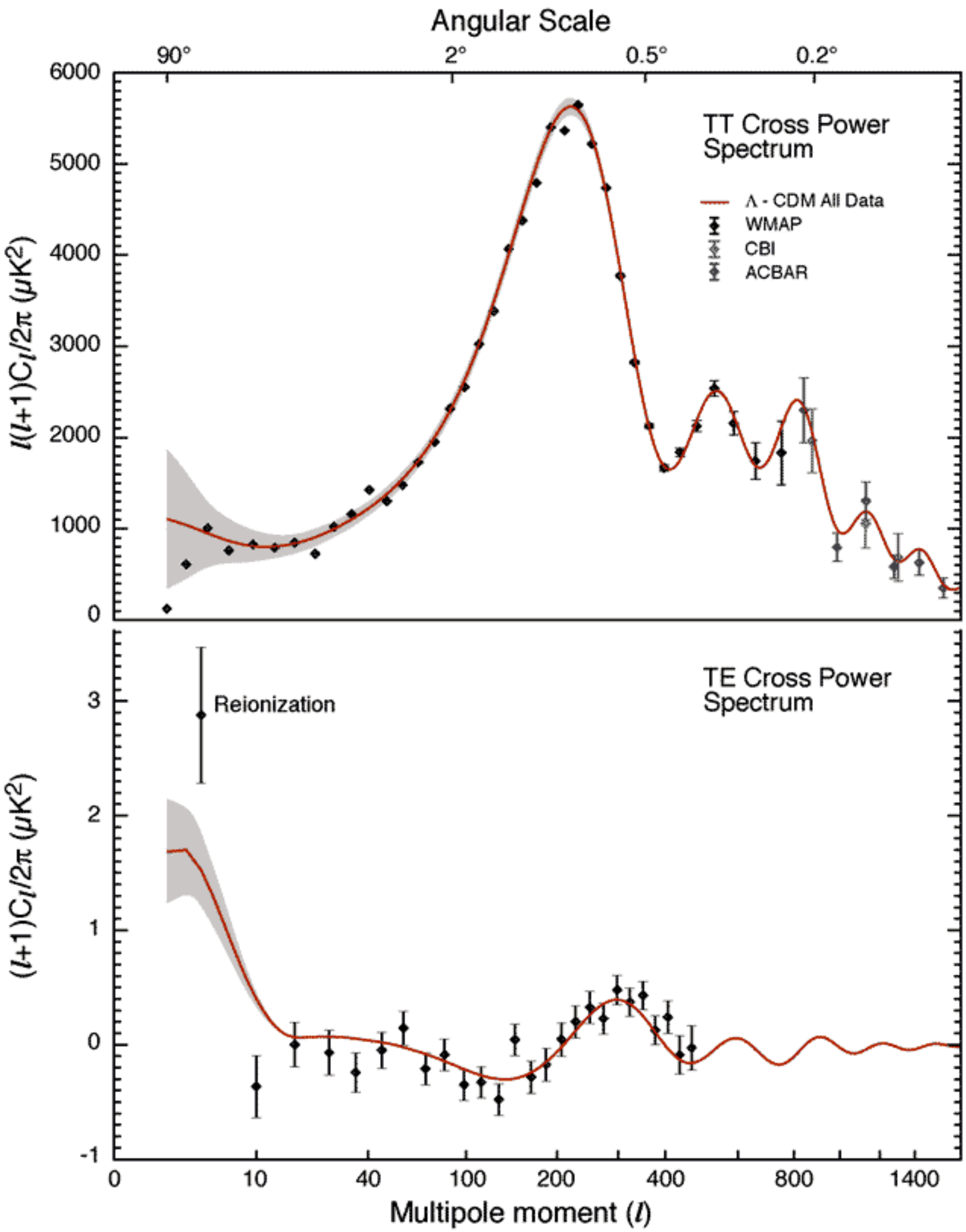
Having decomposed the observed map into spherical harmonics, result is a large set of coefficients a_{lm}. Next we compute the average magnitude of these coefficients as a function of l:

$$C_l \equiv \left\langle \left| a_{lm} \right|^2 \right\rangle$$

Plot of C_l as a function of l is described as the ***angular power spectrum*** of the microwave background. Each C_l measures how much anisotropy there is on a particular angular scale, given by:

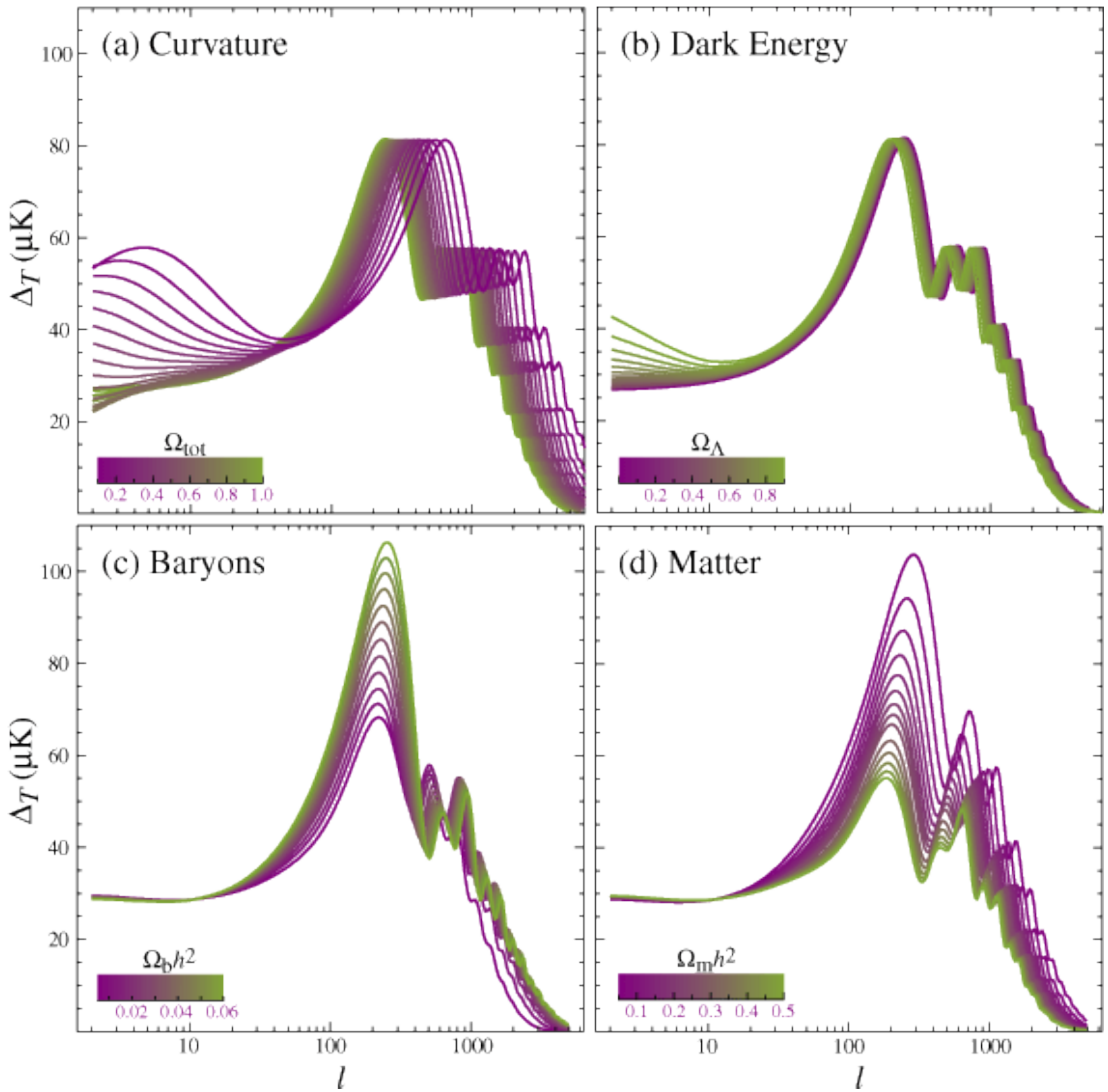
$$\theta \sim \frac{180^\circ}{l}$$

The results look like this:



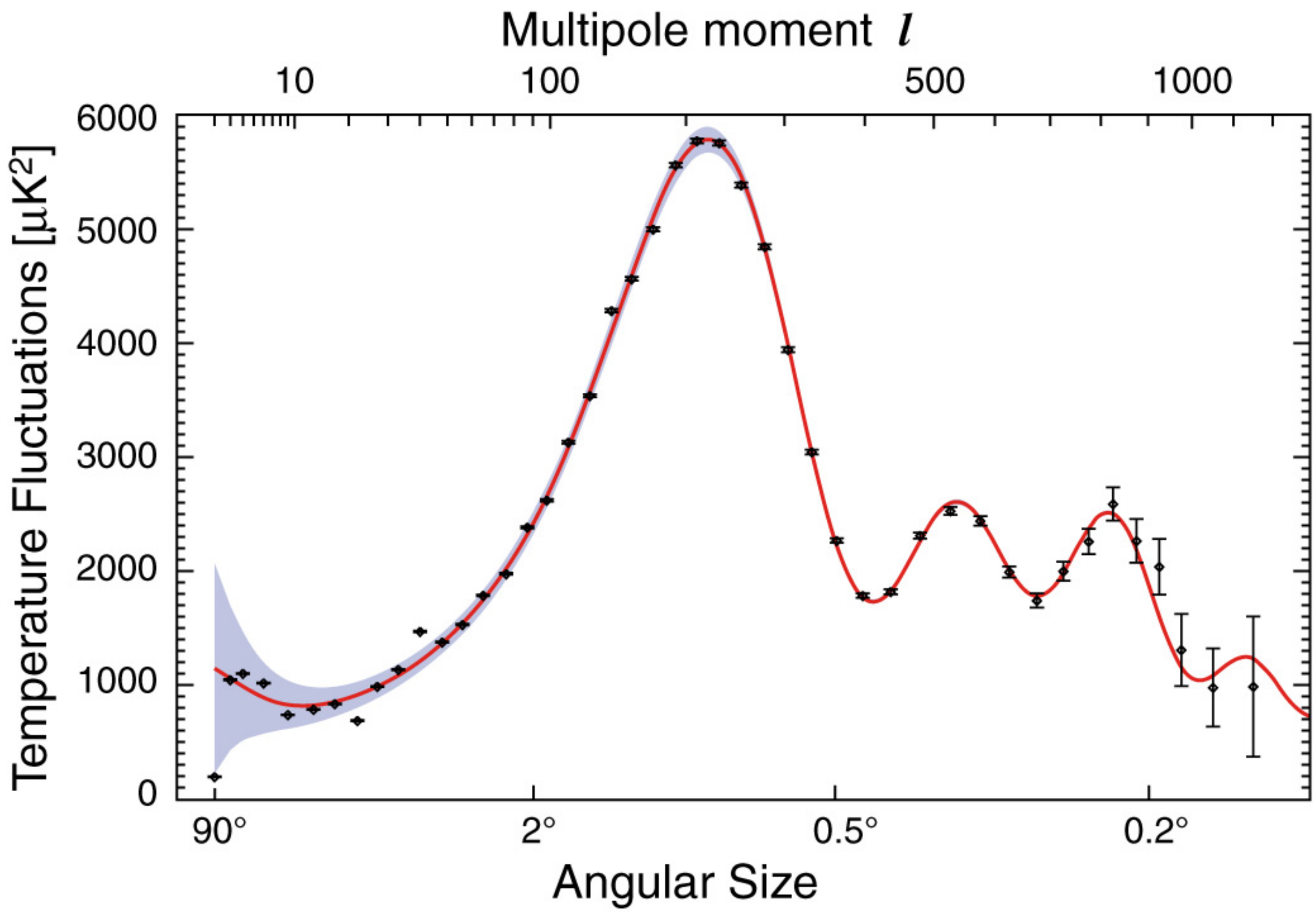
WMAP, angular power spectrum, Bennett et al. 2003

Positions and amplitudes of peaks depend on a variety of cosmological parameters in a complex fashion



Is the Universe Flat, Open, or Closed?

Doppler peaks define a physical scale of the particle horizon at recombination. The corresponding angular size depends on the geometry of the universe



WMAP
7 yr data

Observed position of the first peak is at:

$$l = 220 \Rightarrow \Omega_{total} = 1.02 \pm 0.02$$

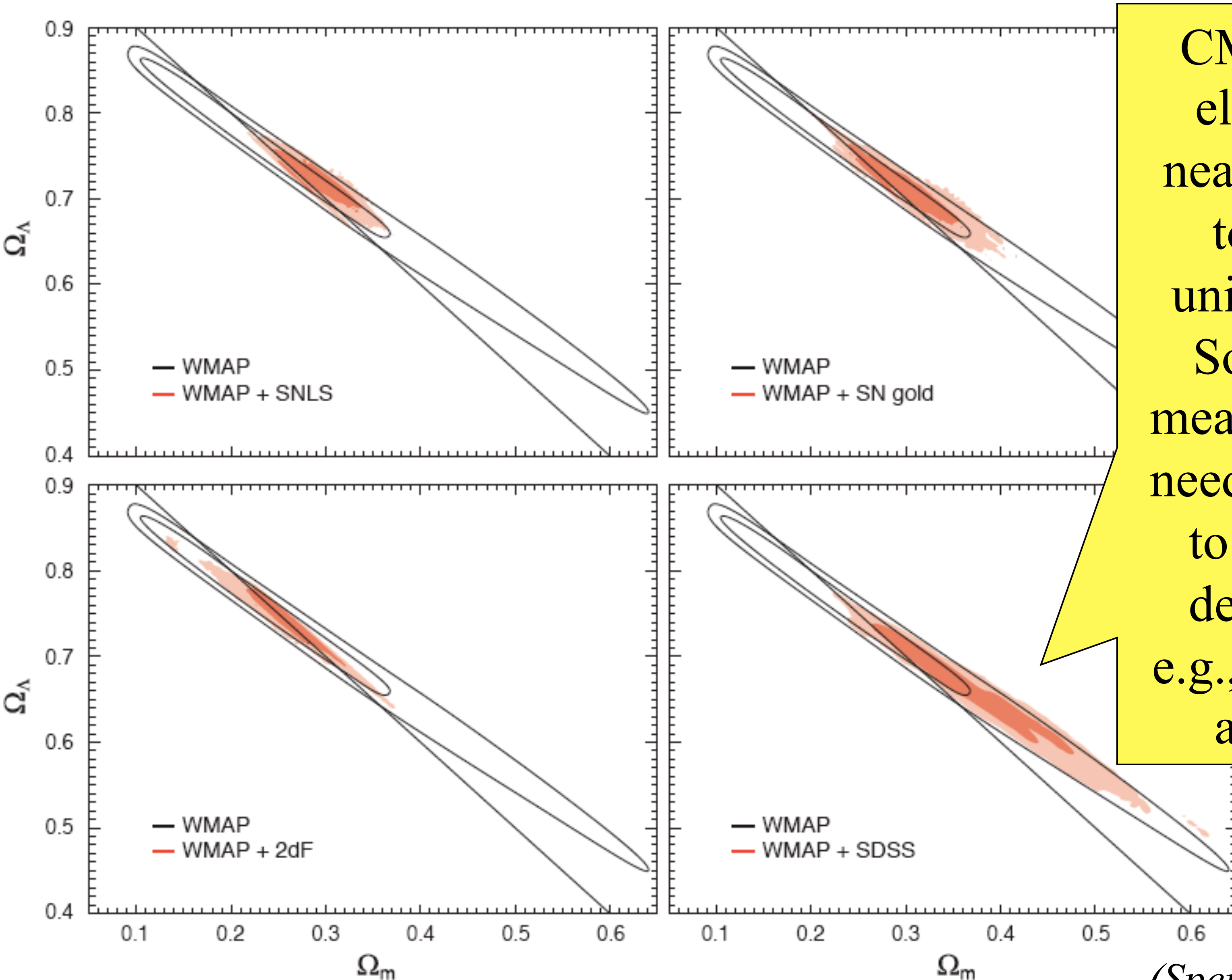
i.e., **the Universe is flat (or very close to being flat)**

What does this imply about the cosmological constant?

Directly: almost nothing - CMB anisotropy is mainly sensitive to the *total* energy density, not to the individual contributions from matter and cosmological constant

Indirectly: estimate (by other means) that the total matter density is perhaps $\Omega_m = 0.3$ (mostly dark matter). Need something else to make up the inferred value of $\Omega_{total} = 1$. A cosmological constant with $\Omega_\Lambda \sim 0.7$ as deduced from SN is consistent with this

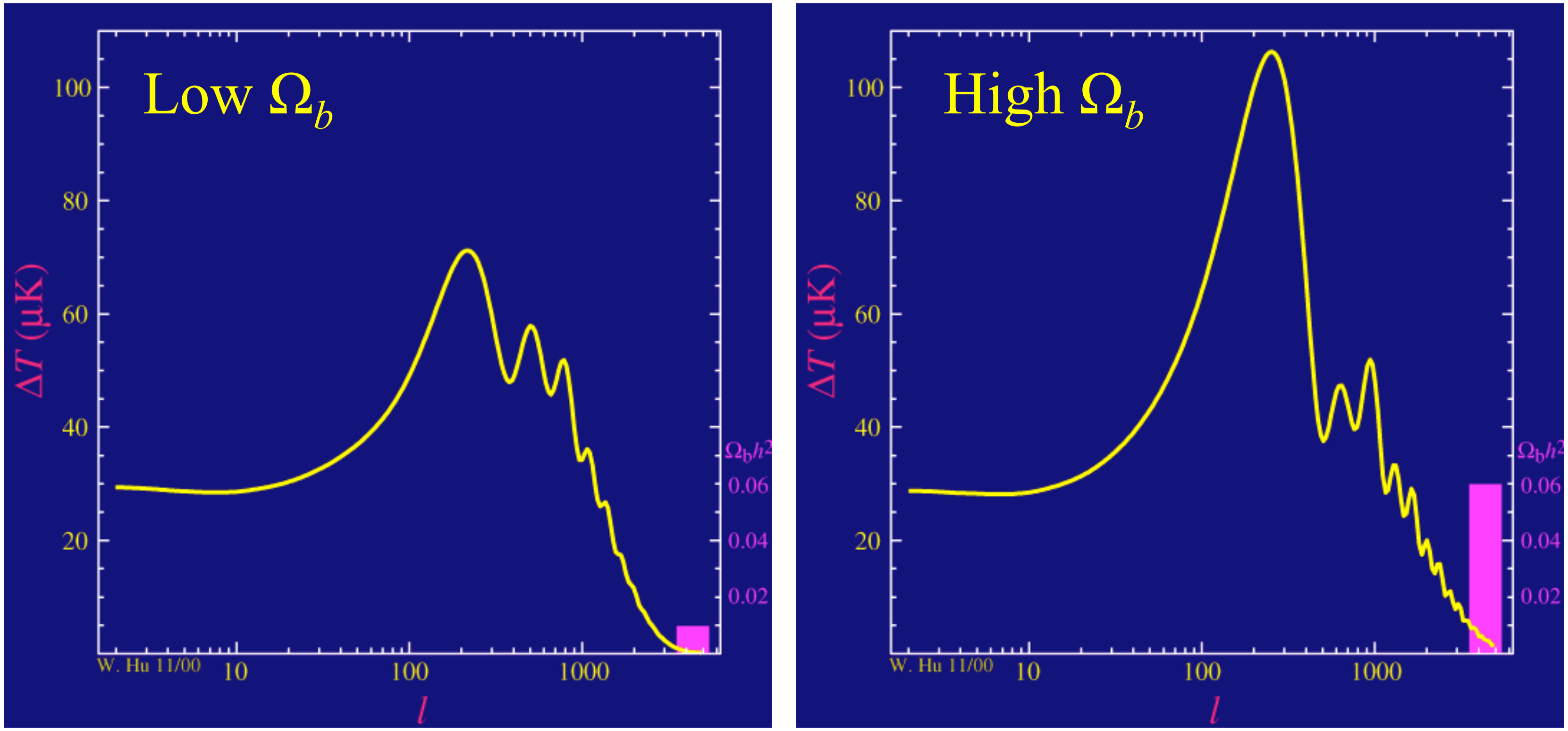
CMBR Parameter Degeneracy



CMBR error ellipses are nearly parallel to the flat universe line. Some other measurement is needed in order to break the degeneracy, e.g., SNe, LSS, ages, etc.

(Spergel et al. 2006)

Baryon Content of the Universe



(from W. Hu)

Increasing the fraction of baryons:

- Increases the amplitude of the Doppler peaks
- Changes the *relative* strength of the peaks - odd peaks (due to compressions) become stronger relative to the even peaks (due to rarefactions)

Baryon Content of the Universe

WMAP results give:

$$\Omega_{baryons}h^2 = 0.024 \pm 0.001$$

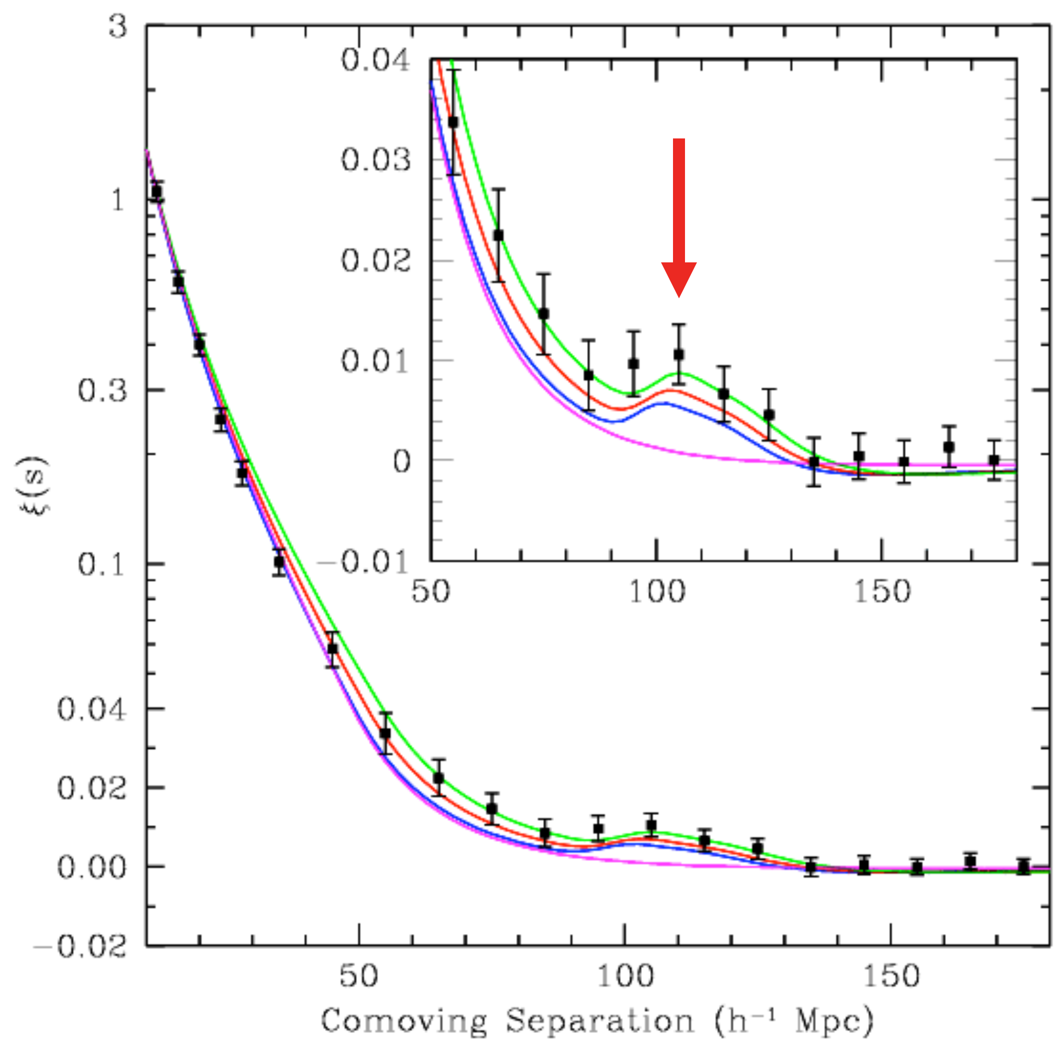
Estimates based on nucleosynthesis and the measured abundance of deuterium give a range:

$$\Omega_{baryons}h^2 = 0.021 \rightarrow 0.025$$

Good consistency between the two independent measurements (different physics, different methodology) of the baryon abundance!

Baryon Acoustic Oscillations (BAO)

Eisenstein et al. 2005 (using SDSS red galaxies); also seen by the 2dF redshift survey



The 1st Doppler peak seen in the CMBR imprints a preferred scale for clustering of galaxies.

Detection of this feature in galaxy clustering at $z \sim 0.3$ gives us another instance of a "standard ruler" for an angular diameter test, at redshifts $z < 1100$

Future redshift surveys can do much better yet

TABLE 2

DERIVED COSMOLOGICAL PARAMETERS

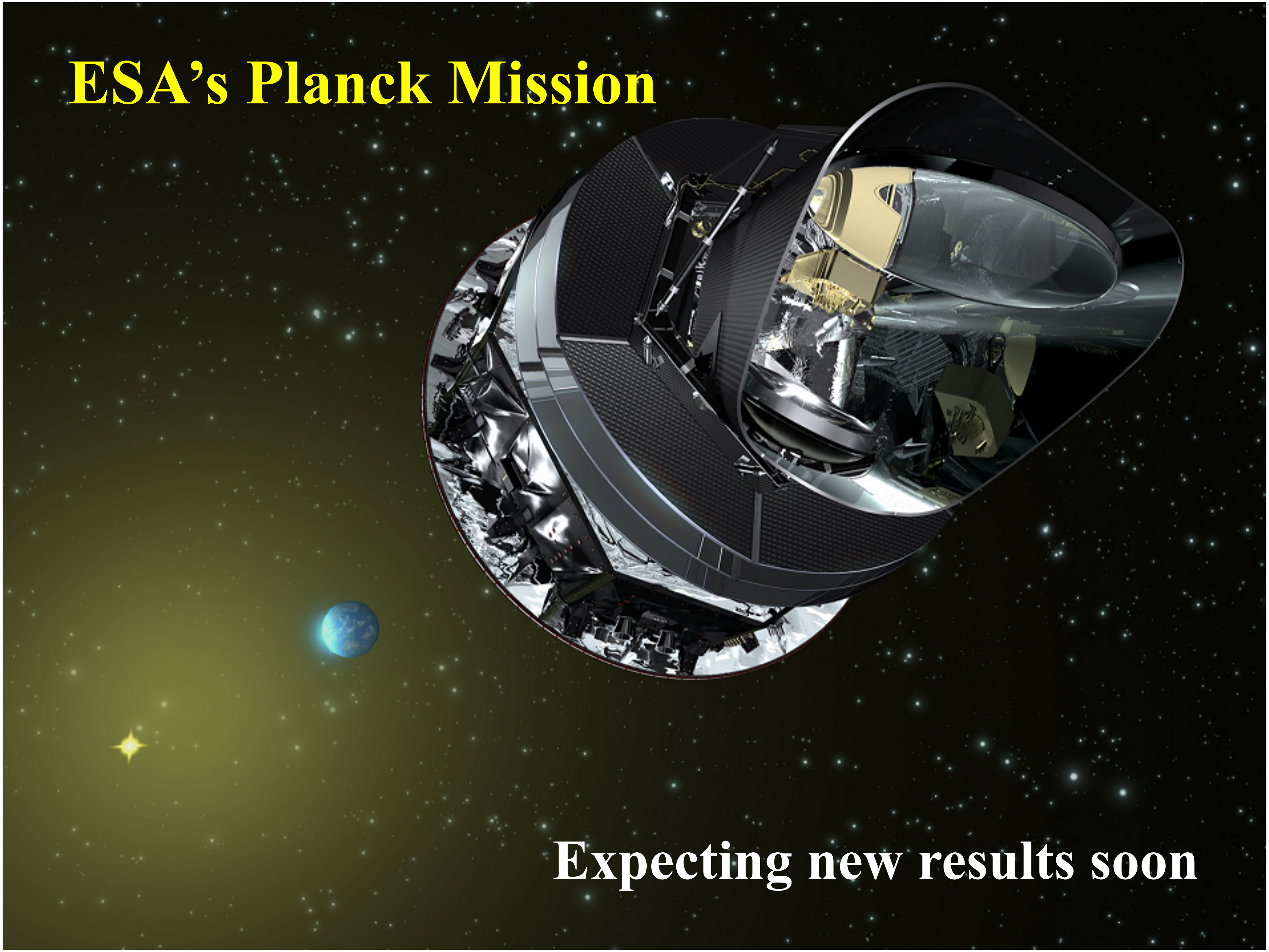
Parameter	Mean (68% Confidence Range)
Amplitude of galaxy fluctuations, σ_8	0.9 ± 0.1
Characteristic amplitude of velocity fluctuations, $\sigma_8 \Omega_m^{0.6}$	0.44 ± 0.10
Baryon density/critical density, Ω_b	0.047 ± 0.006
Matter density/critical density, Ω_m	0.29 ± 0.07
Age of the universe, t_0	13.4 ± 0.3 Gyr
Redshift of reionization,[a] z_r	17 ± 5
Redshift at decoupling, $z_{\rm dec}$	1088^{+1}_{-2}
Age of the universe at decoupling, $t_{\rm dec}$	372 ± 14 kyr
Thickness of surface of last scatter, $\Delta z_{\rm dec}$	194 ± 2
Thickness of surface of last scatter, $\Delta t_{\rm dec}$	115 ± 5 kyr
Redshift at matter/radiation equality, $z_{\rm eq}$	3454^{+385}_{-392}
Sound horizon at decoupling, r_s	144 ± 4 Mpc
Angular diameter distance to the decoupling surface, d_A	13.7 ± 0.5 Gpc
Acoustic angular scale,[b] ℓ_A	299 ± 2
Current density of baryons, n_b	$(2.7 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/photon ratio, η	$(6.5^{+0.4}_{-0.3}) \times 10^{-10}$

NOTE.—Fit to the *WMAP* data only.

[a] Assumes ionization fraction, $x_e = 1$.

[b] $l_A = \pi d_C / r_s$.

WMAP results,
Spergel et al. 2003


ESA's Planck Mission
Expecting new results soon

Next:

Source Counts:
A Proxy for the Volume-Redshift Test