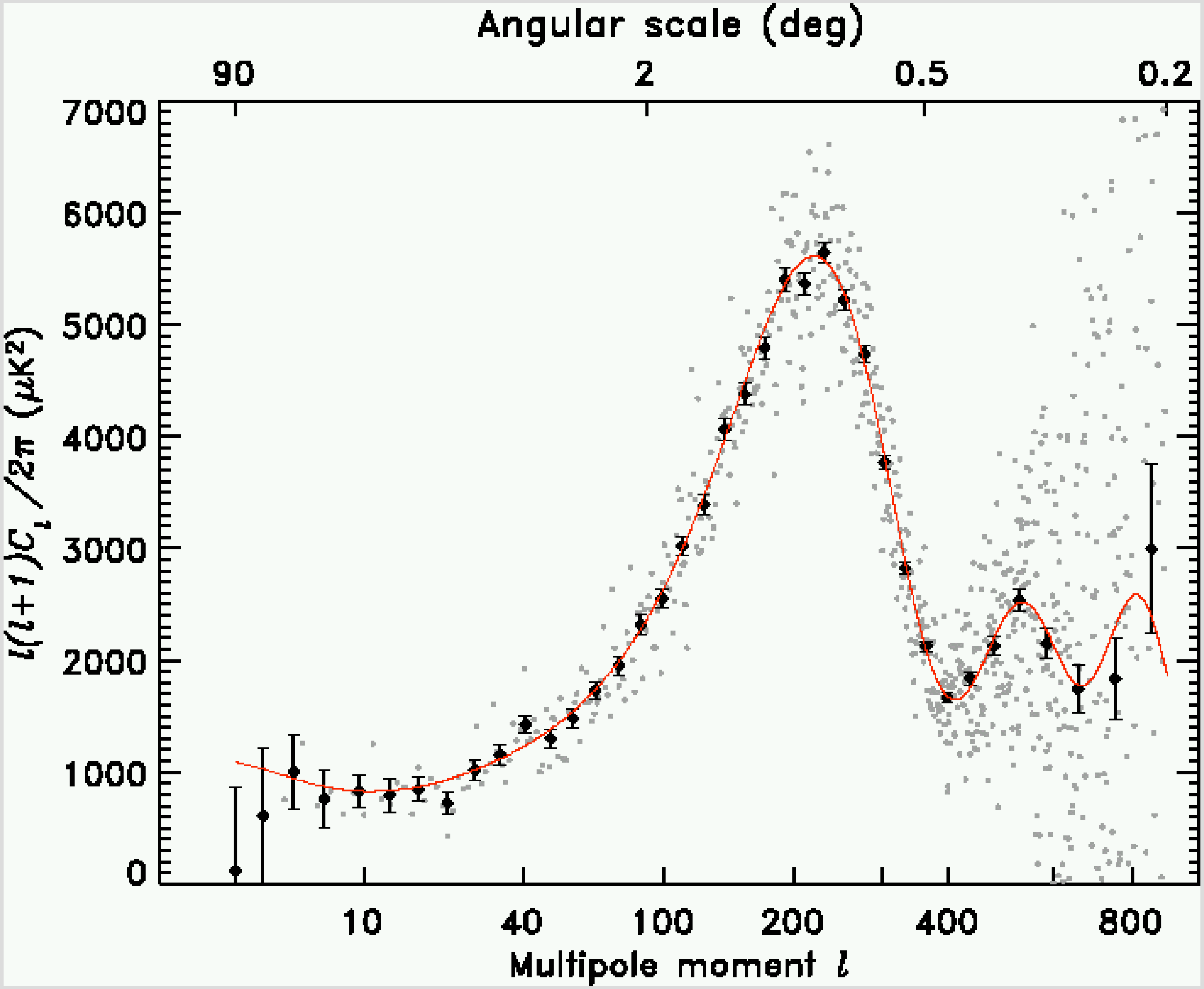
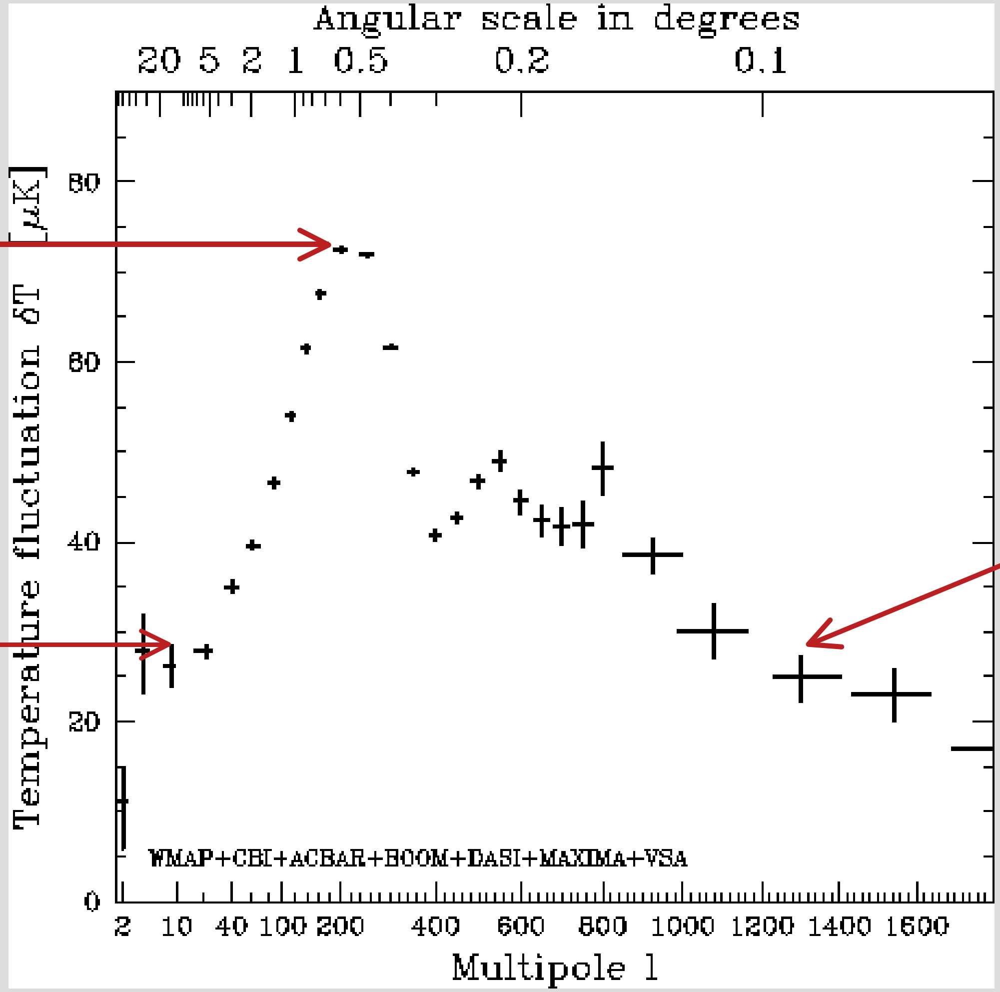
Observational determinations of CMB anisotropy



2003 data

Results from the WMAP satellite 1st year data

Compilation of all available data by Max Tegmark includes WMAP and some ground based / balloon experiments sensitive to smaller angular scales:



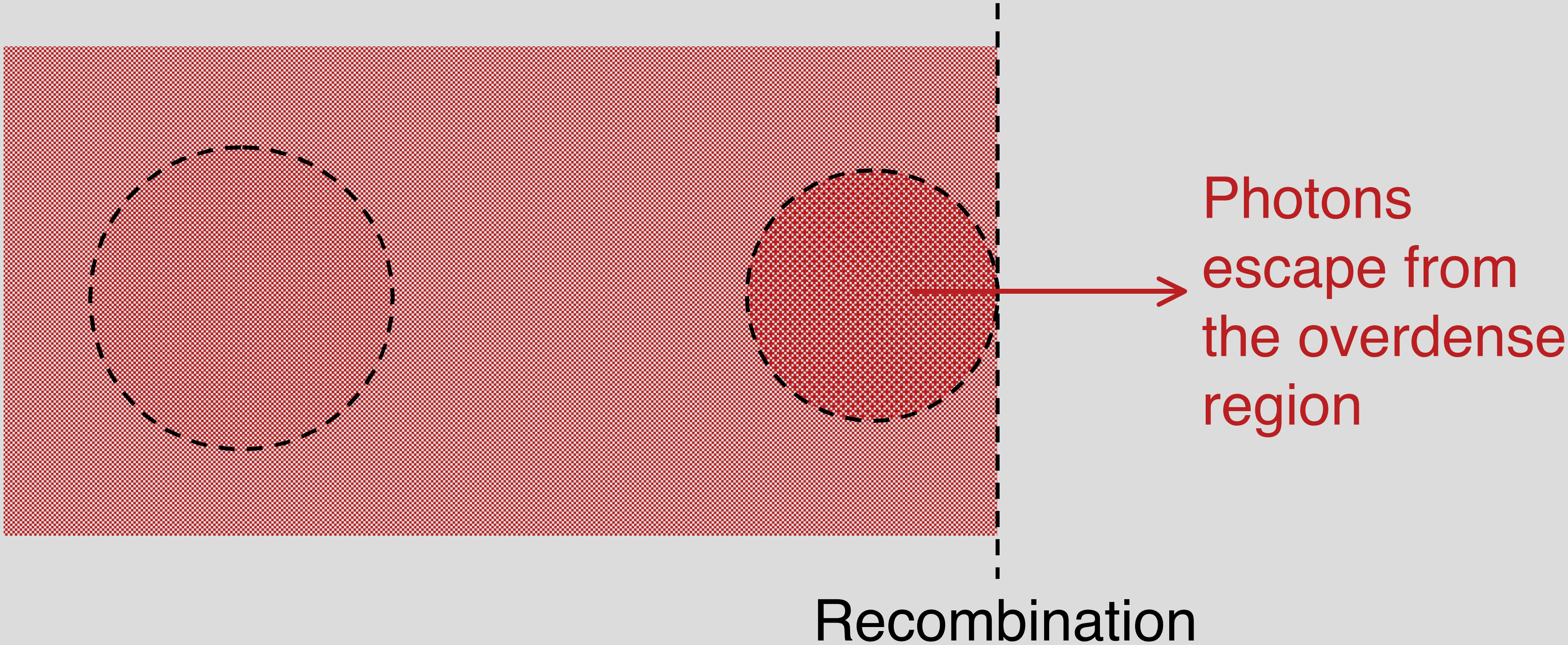
Peak at degree scales

Plateau at large scales

Decline toward very small scales

Want to understand physical origin of each of these features

Most of the anisotropy power spectrum reflects fluctuations in the density at the time of recombination:



Consider a slight overdensity collapsing during the radiation dominated phase. Photons escaping at recombination:

- Escape from a hotter, denser region
- Are redshifted escaping from a deeper potential well
- Have a Doppler shift due to relative velocity

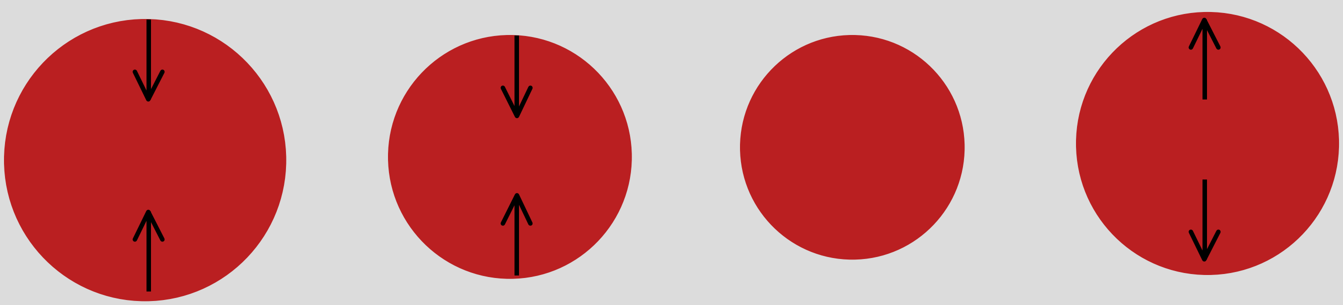
How this works in detail depends upon the scale of the fluctuations:

Largest scales (low l)

On the largest scales, perturbations have not had time to collapse significantly prior to recombination. At low l, directly see the fluctuations generated at an earlier epoch.

Intermediate scales (~degree)

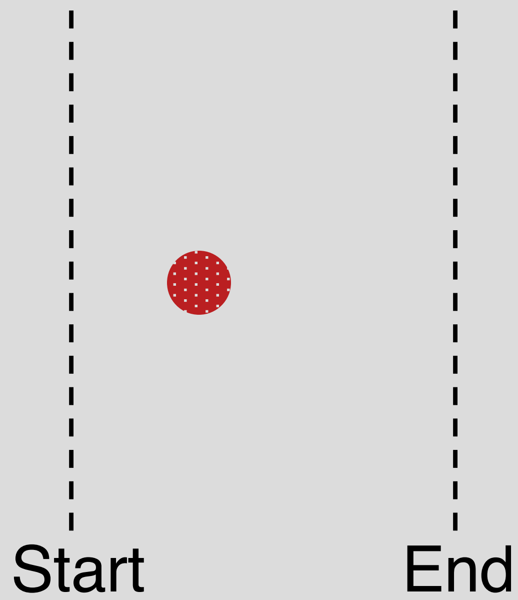
Overdensities start to collapse, but increased pressure causes them to bounce - leading to oscillations.



Maxima and minima of these oscillations lead to the strongest signals in the microwave background:

- Doppler peaks
- First peak (compression) occurs at degree scales

Small scales



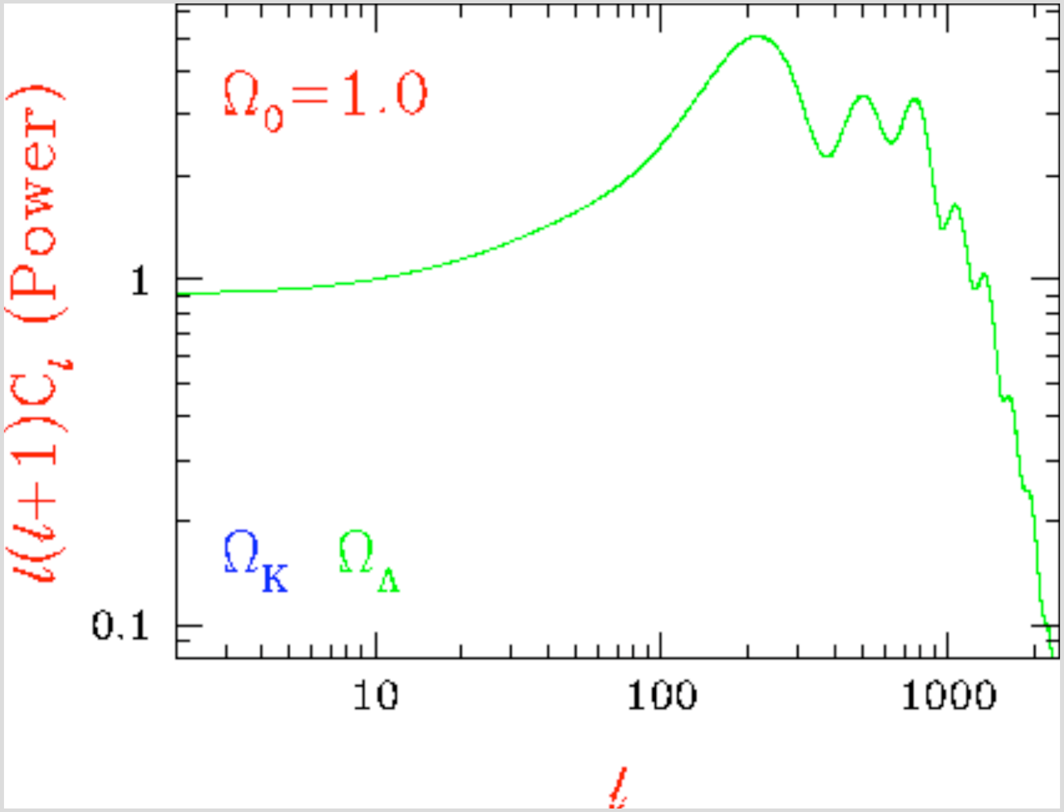
Recombination is not instantaneous
Photons will `leak' out of small over / under-densities during the process - damping very small scale fluctuations

Exponential suppression of anisotropy at the smallest scales

Dependence on cosmology

1. Is the Universe flat, open, or closed?

Doppler peaks define a physical scale at recombination
Angular scale this corresponds to depends upon the geometry of the Universe:



Blue curve: effect of changing the geometry

Open universe - position of the peaks is shifted to smaller angular scales (i.e. larger multipole l)

Animations from Wayne Hu

Observed position of the first peak is at:

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

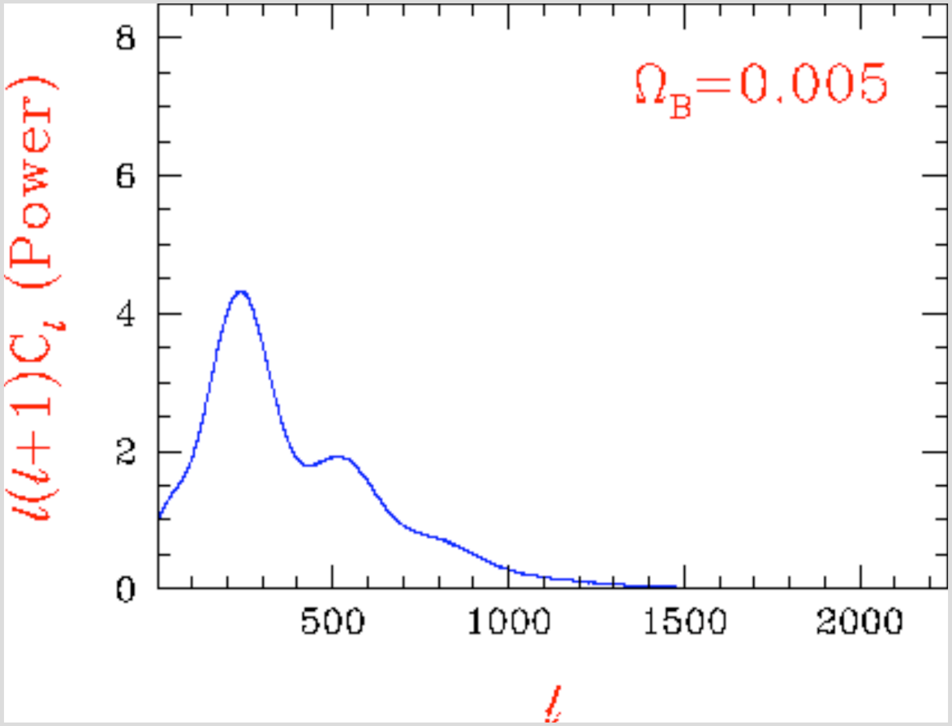
i.e. the Universe is flat (or very close to being flat)

<u>What does this imply about the cosmological constant?</u>

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.

2. Baryon content of the Universe



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)

WMAP results give:

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

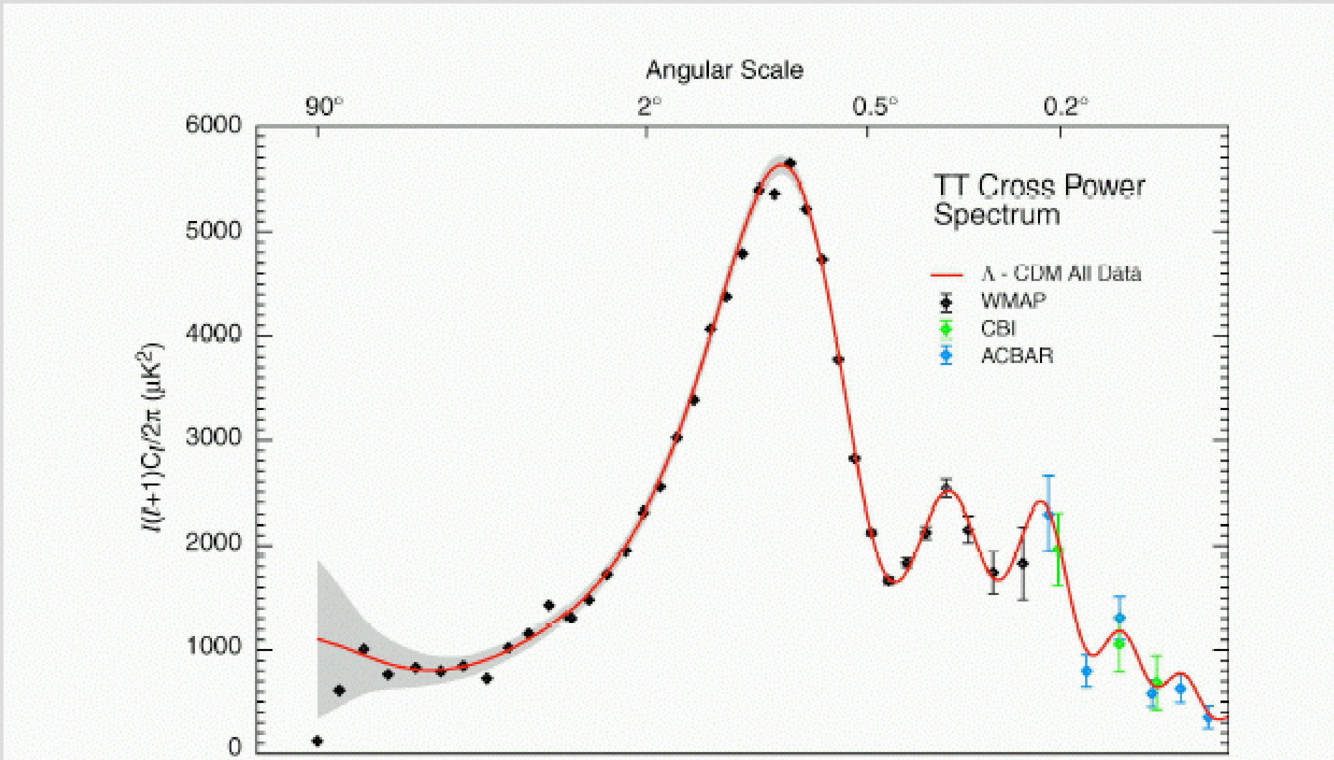
Hubble constant in units of 100 km s^{-1} Mpc^{-1}

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

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

Good consistency between two independent measurements of the baryon abundance.

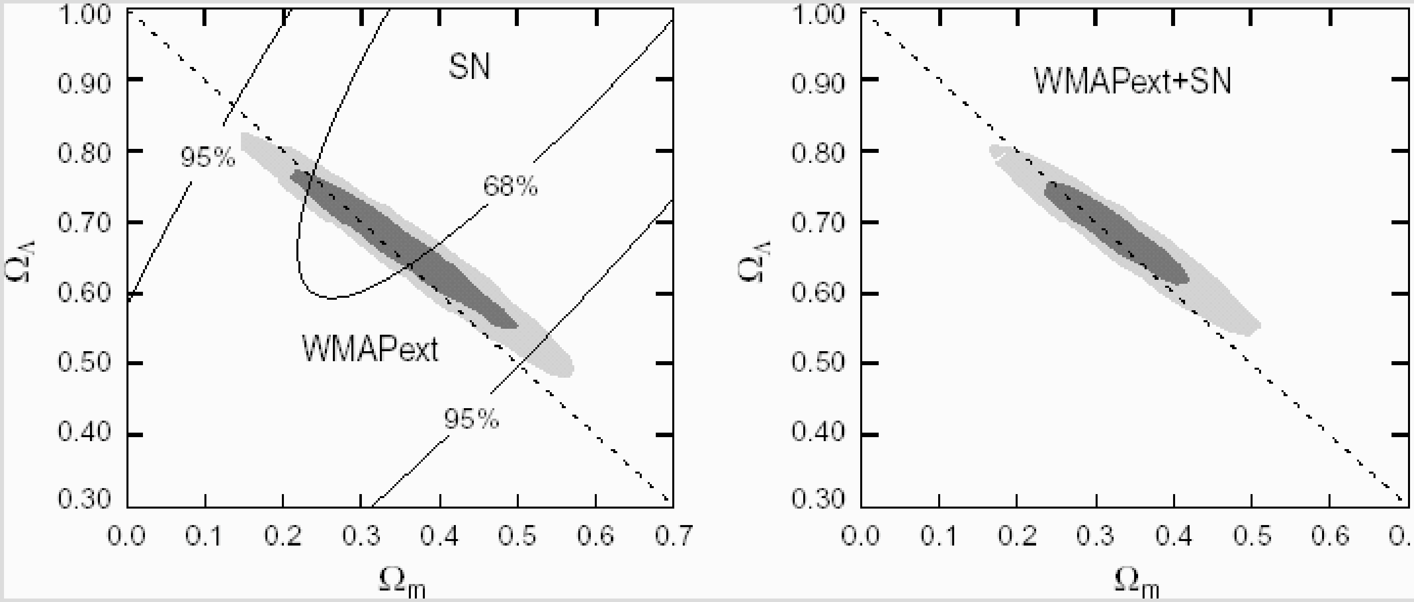
Full power spectrum from WMAP and other experiments is consistent with the predictions of ΛCDM (i.e. the family of cosmological models that include dark matter plus a cosmological constant):



Simplest such models have 6 free parameters:

- Being able to fit the data is a genuine success!
- Parameters are mostly well constrained by the data

Adding in other cosmological information e.g. from the supernovae measurements, further constrains the model:



Important information provided by:

- **Microwave background** (WMAP, eventually Planck)
- **Type 1a Supernovae**
- **Nucleosynthesis**
- **Lyman-α forest, galaxy clustering** (2dF, Sloan Digital Sky Survey), **weak gravitational lensing**

Summary:

- The Universe is **flat**, and will expand forever
- Ordinary matter (stars, gas, dark baryons) is negligible
- **Cold dark matter** and **dark energy** dominate the evolution of the Universe, and currently make roughly equal contributions to the total energy density

Suggests that the Universe at the time of recombination is now very well understood - we know the initial conditions that eventually gave rise to galaxies, stars, quasars etc…

Discuss on Wednesday where the initial conditions (may) have come from…