8 The Cosmic Microwave Background

- When we say the night sky is dark, we mean that it appears dark to our eyes. The night sky is actually uniformly bright (aside from a few planets and nearby stars) at millimetre wavelengths. This "cosmic microwave background" (CMB) was discovered serendipitously discovered in the 1960s, and has several key properties:

  - the CMB spectrum is very close to that of a perfect blackbody (better than 0.01%), regardless of where in the sky we look, and the temperature is $\langle T \rangle = 2.7255\,K$

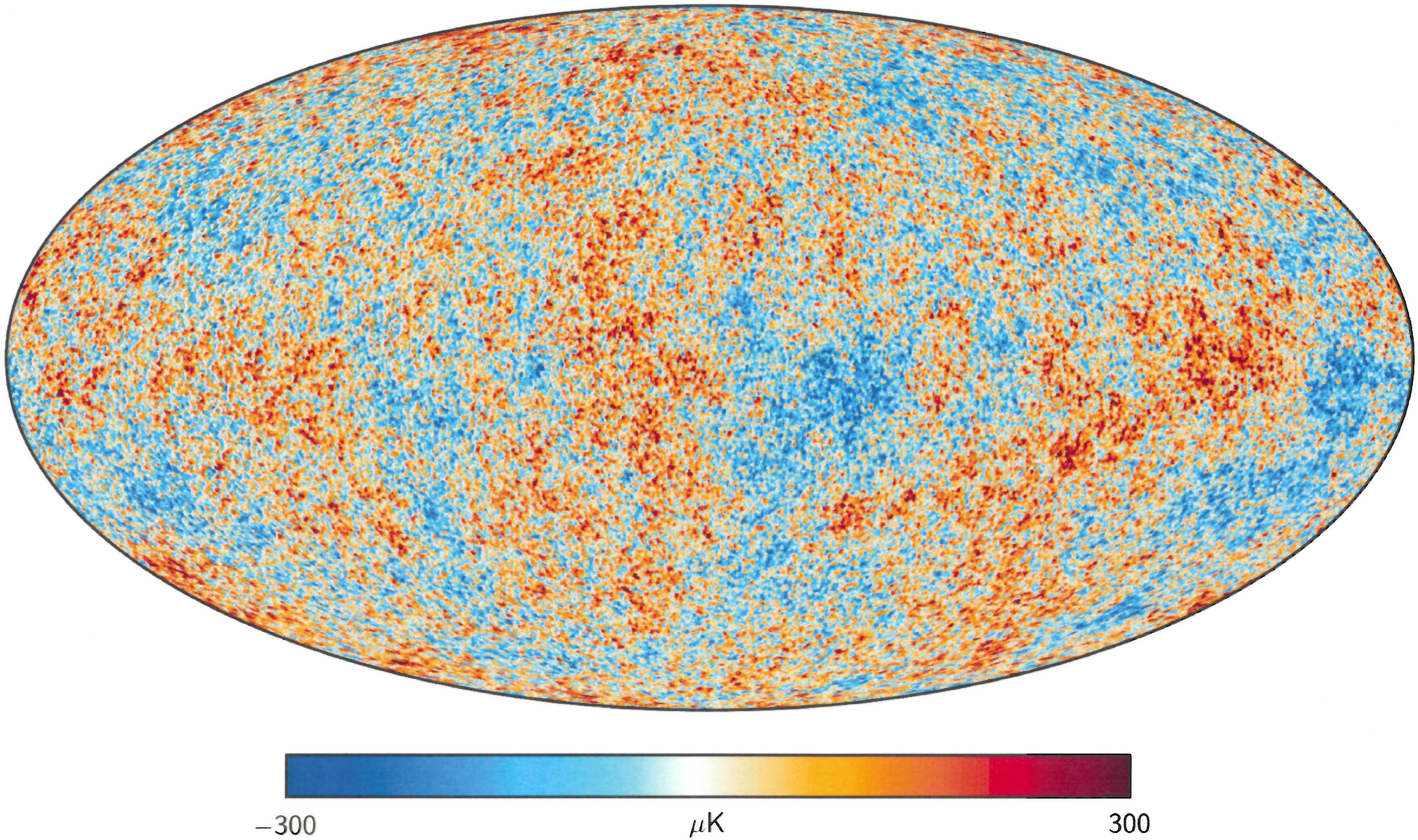
  - the CMB has a dipole distortion because the spectrum is Doppler shifted by the motion of our Local Group of galaxies towards the Hydra-Centaurus supercluster, at 0.2% of the speed of light

  - once the dipole is subtracted, there are real temperature variations across the sky, but these are small. The dimensionless variation is

$$\frac{\delta T}{T}(\theta, \phi) \equiv \frac{T(\theta,\phi) - \langle T \rangle}{\langle T \rangle} \qquad (8.1)$$

and the rms variation

$$\left\langle \left(\frac{\delta T}{T} \right)^2 \right\rangle^{1/2} = 1.1 \times 10^{-5} \qquad (8.2)$$



Map of CMB temperature variations from 2.7255K, ESA and the Planck Collaboration

- As outlined in section 2, the CMB provides evidence that the Universe was once hot, dense, opaque, and nearly homogeneous, providing support for the Hot Big Bang scenario.

- CMB photons are common, even though their energy density is low, because the energy per CMB photon is low.

$$\varepsilon_{\gamma,0} = \alpha T_0^4 = \frac{4\sigma_{SB}}{c} T_0^4 = 0.26 \text{ MeV m}^{-3} \qquad (8.3)$$

and the mean energy is $hf_{mean} = 2.7 k_B T_0 = 6.3 \times 10^{-4}$ eV, so

$$n_{\gamma,0} = 4 \times 10^8 \text{ m}^{-3} \qquad (8.4)$$

and there are roughly 10^7 CMB photons passing through you at any given moment.

The photon to baryon ratio is very high, because protons and neutrons have a much higher rest energy $E_{bary} \approx 939$ MeV.

$$\varepsilon_{bary,0} = \Omega_{bary,0}\, \varepsilon_{c,0} \approx 234 \text{ MeV m}^{-3} \qquad (8.5)$$

so the number density is

$$n_{bary,0} = \frac{\varepsilon_{bary,0}}{E_{bary}} \approx \frac{234}{939} \approx 0.25 \text{ m}^{-3} \qquad (8.6)$$

and the baryon to photon ratio

$$\eta = \frac{n_{bary,0}}{n_{\gamma,0}} = \frac{0.25}{4 \times 10^8} \approx 6 \times 10^{-10} \qquad (8.7)$$

The Origin of the CMB

- Consider the Universe at some very early time, when photons were more energetic than now (specifically, $E_\gamma \gtrsim 13.6\,eV$). Any hydrogen atom would be ionized, so we have a sea of nuclei, electrons, and photons.

  - at $z = 10^5$, $a = 10^{-5}$, and $T_\gamma \approx 3 \times 10^5\,K$ (equation 2.18), and $E_\gamma \approx 60\,eV$

  - photons primarily interact with electrons via Thomson scattering ($E_\gamma \ll m_e c^2 \approx 0.5\,MeV$, elastic scattering).

  so at this time the reactions are

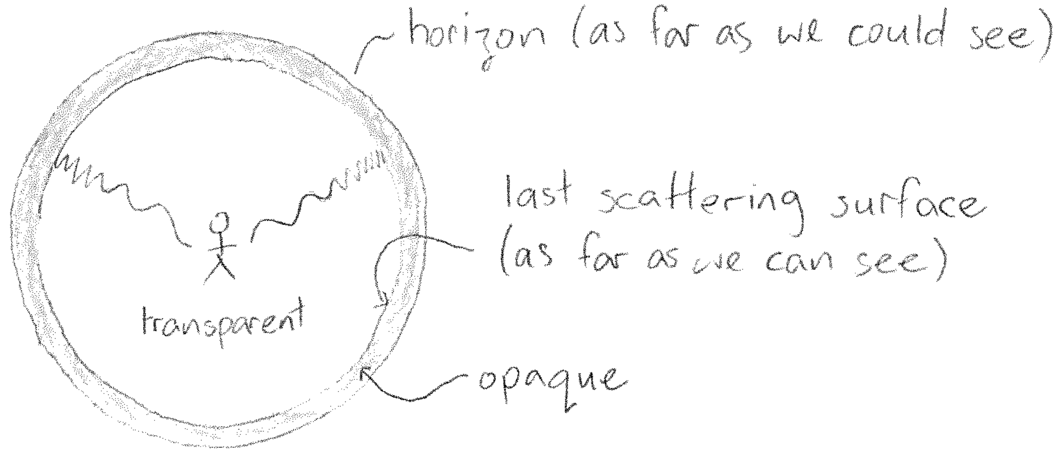
$$p + e^- \rightleftharpoons H + \gamma \qquad (8.8)$$

$$\gamma + e^- \rightarrow \gamma + e^- \qquad (8.9)$$

  and there is thermal equilibrium (frequent interactions), and the mean free path of photons is shorter than the Hubble distance, so the Universe is opaque ("optically thick").

- As the Universe expands the photon energy drops, and eventually H atoms that form cannot be ionized (just as for the photoelectric effect, it's the photon energy that matters). The point at which the baryonic component goes from ionized to neutral is called "recombination", and took place from roughly $z = 1600$ to 1100.

- Near the end of recombination, the rate at which photons scatter off electrons drops below the Hubble parameter. Any remaining electrons are being diluted by expansion faster than photons can interact with them. At this point photons and atoms "decouple", and photons undergo the "last scattering" (so are now CMB photons).



- photons originating beyond the last scattering surface did so at a time when the Universe was too dense for them to reach us (so scattered off an electron instead).

- the last scattering surface isn't special, it's just at the right distance so that those photons are reaching us now. Aliens elsewhere in the Universe would see photons originating from different large spheres for their CMB.

• Looking back, there are a few important CMB-related epochs.

event	z	T(K)	time (Myr)
radiation-matter equality	3440	9390	0.05
recombination	1380	3760	0.25
photon decoupling, last scattering	1090	2970	0.37

CMB Temperature Fluctuations

- The deviations from 2.7255 K tell us that the Universe was not perfectly homogeneous at $z = 1090$. Their angular size on the sky is related to the physical size of density and velocity fluctuations at the time of last scattering.

  - these are characterised by a power spectrum, which tells us the angular scales on which the temperature variations are strongest (i.e. a "standard ruler").

detail, skip

  - physically, the peaks are the result of standing waves (pressure vs. gravity), so the spectrum depends on the sound speed (and hence the equation of state).

  - the peak is approximately the size of the "sound horizon distance" (i.e. distance a sound wave can travel since the Big Bang, at $z = 1090$).

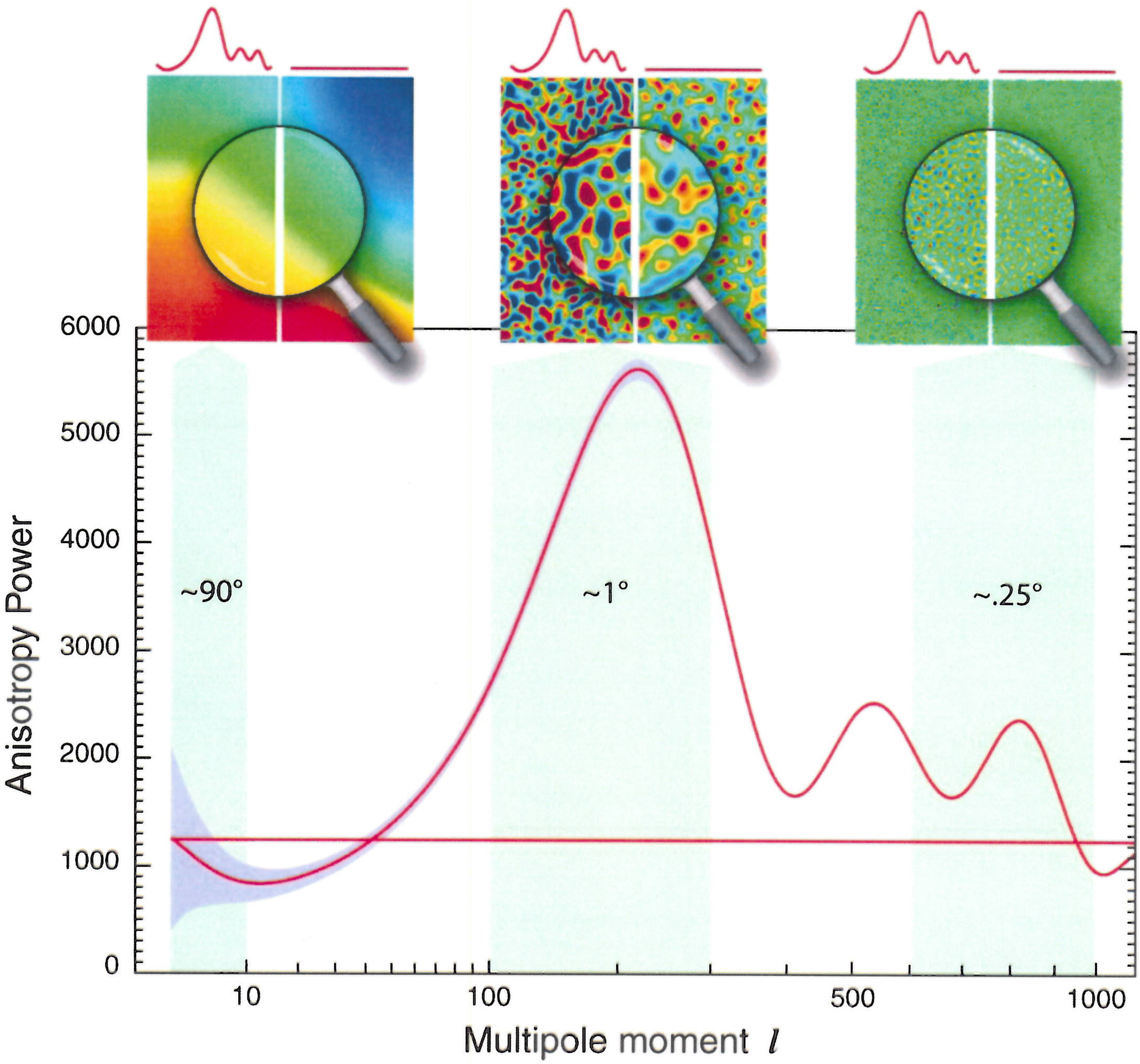
  - since we can estimate this size theoretically, we can get a constraint on κ, since curvature changes the angular size of very distant objects. We find $\kappa \approx 0$ ($\Omega = 1$, flat).

  - the sound speed depends on the photon to baryon ratio, so this can be derived from models, finding

$$\eta = \frac{n_{bary,0}}{n_{\gamma,0}} = (6.1 \pm 0.06) \times 10^{-10} \qquad (8.10)$$

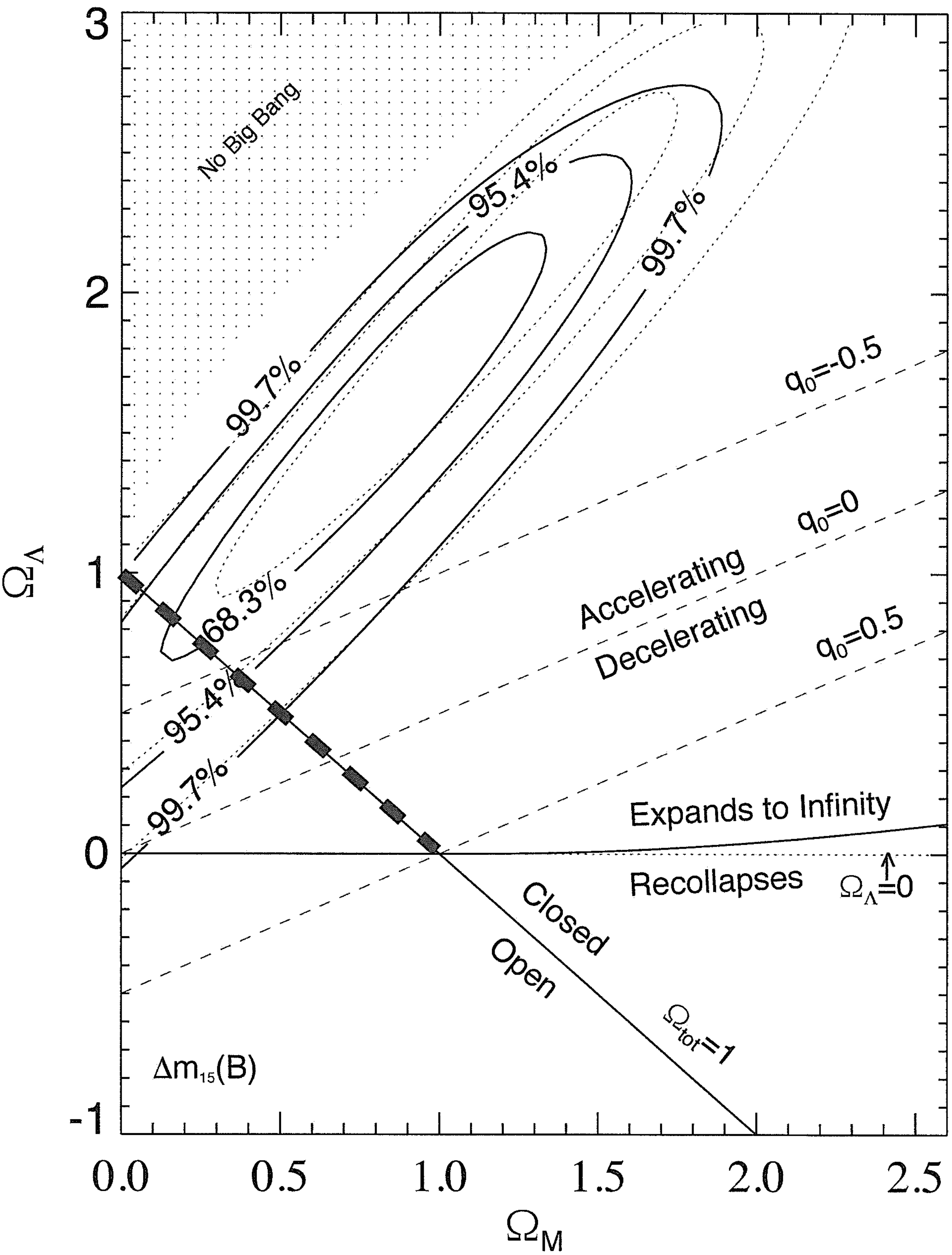
from which we then get (via 8.4 - 8.6) the density parameter for baryons

$$\Omega_{bary,0} = \frac{\varepsilon_{bary,0}}{\varepsilon_{c,0}} = 0.048 \pm 0.003 \qquad (8.11)$$



Angular power spectrum of CMB fluctuations. The magnifying glasses show what the CMB would look like for the observed (left) and flat (right) power spectra. The observed CMB tends to show temperature variations more strongly on 1-degree scales.

WMAP/GSFC



Joint constraints on the matter and cosmological constant density parameters from type Ia supernovae. If the Universe is flat (as suggested by CMB results), then the density parameters are well-constrained.

Riess et al. 1998, AJ, 116, 1009.
This paper has been cited ~11,100 times, and lead to a share of the Nobel prize