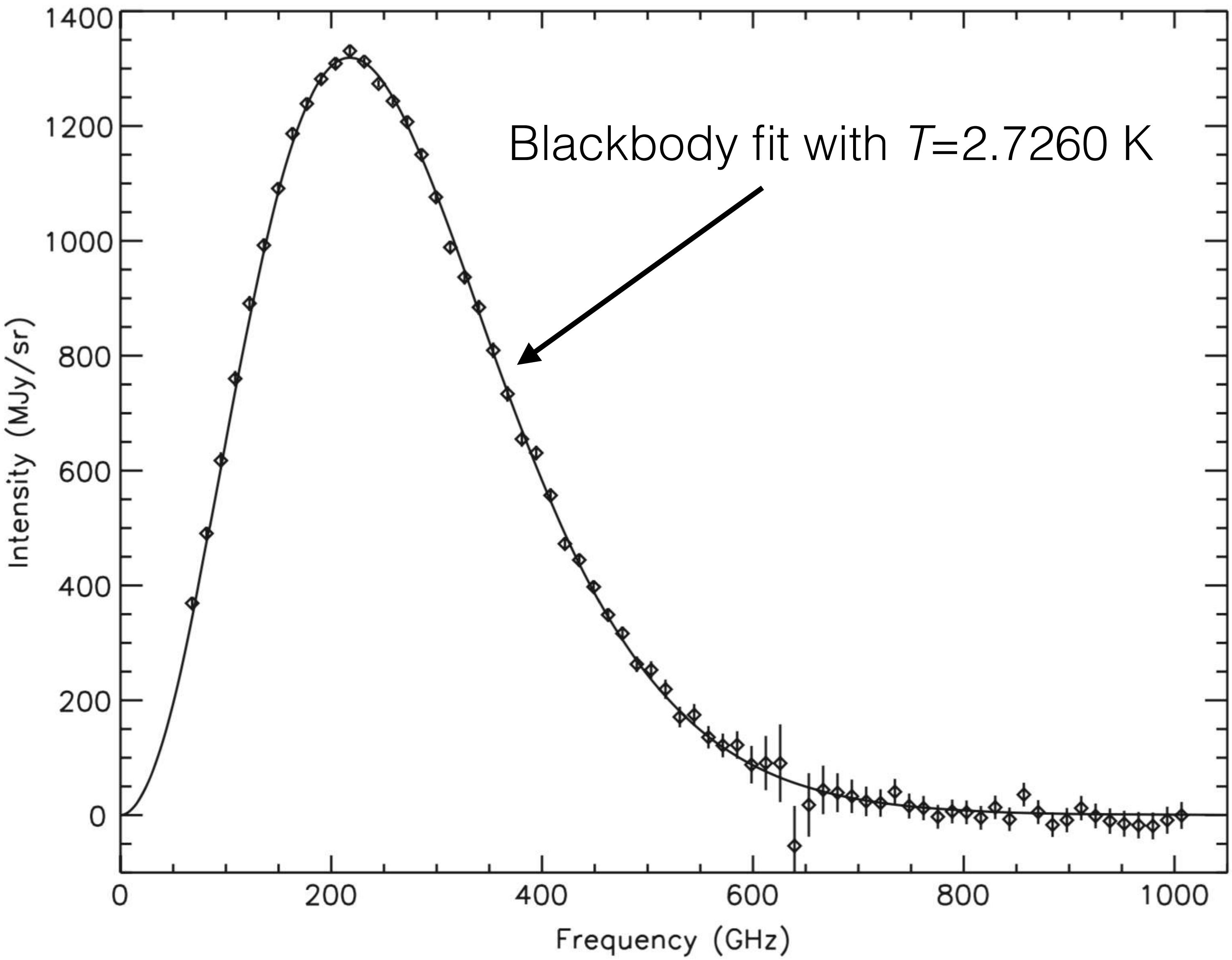
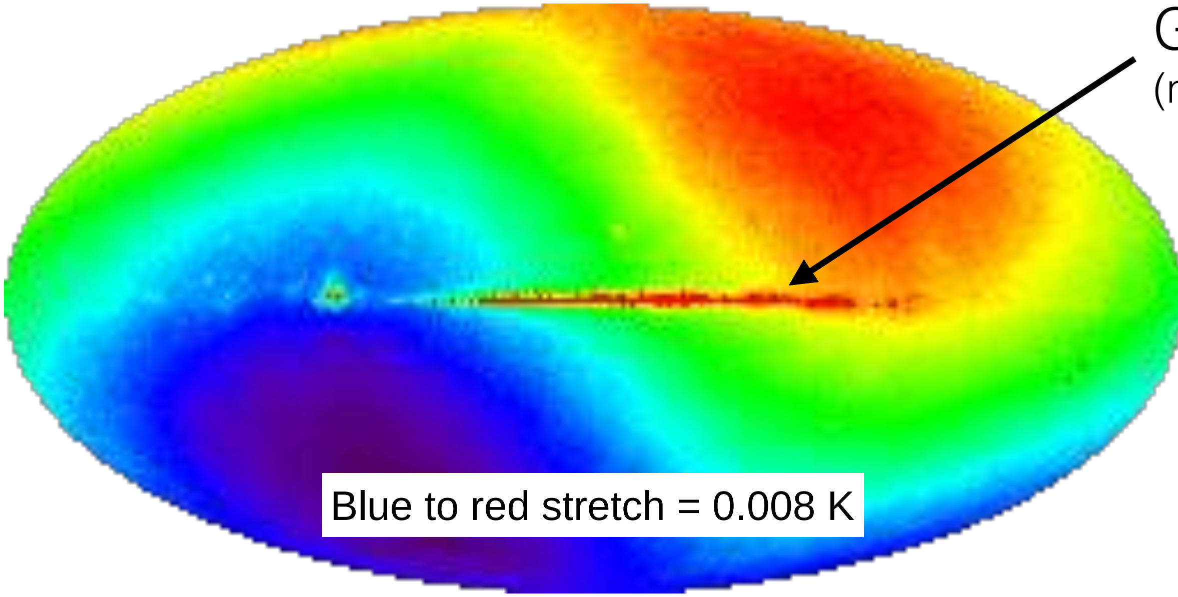
Cosmic microwave background

Mean CMB spectrum



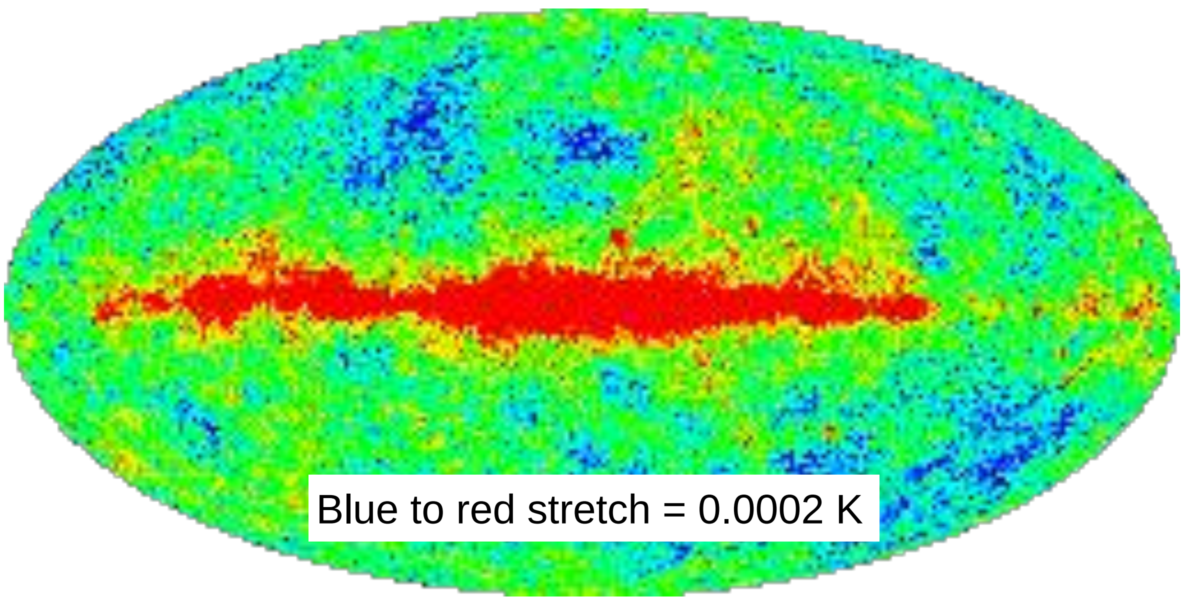
Fixsen 09

CMB anisotropies



Galaxy
(must subtract for cosmological analysis)

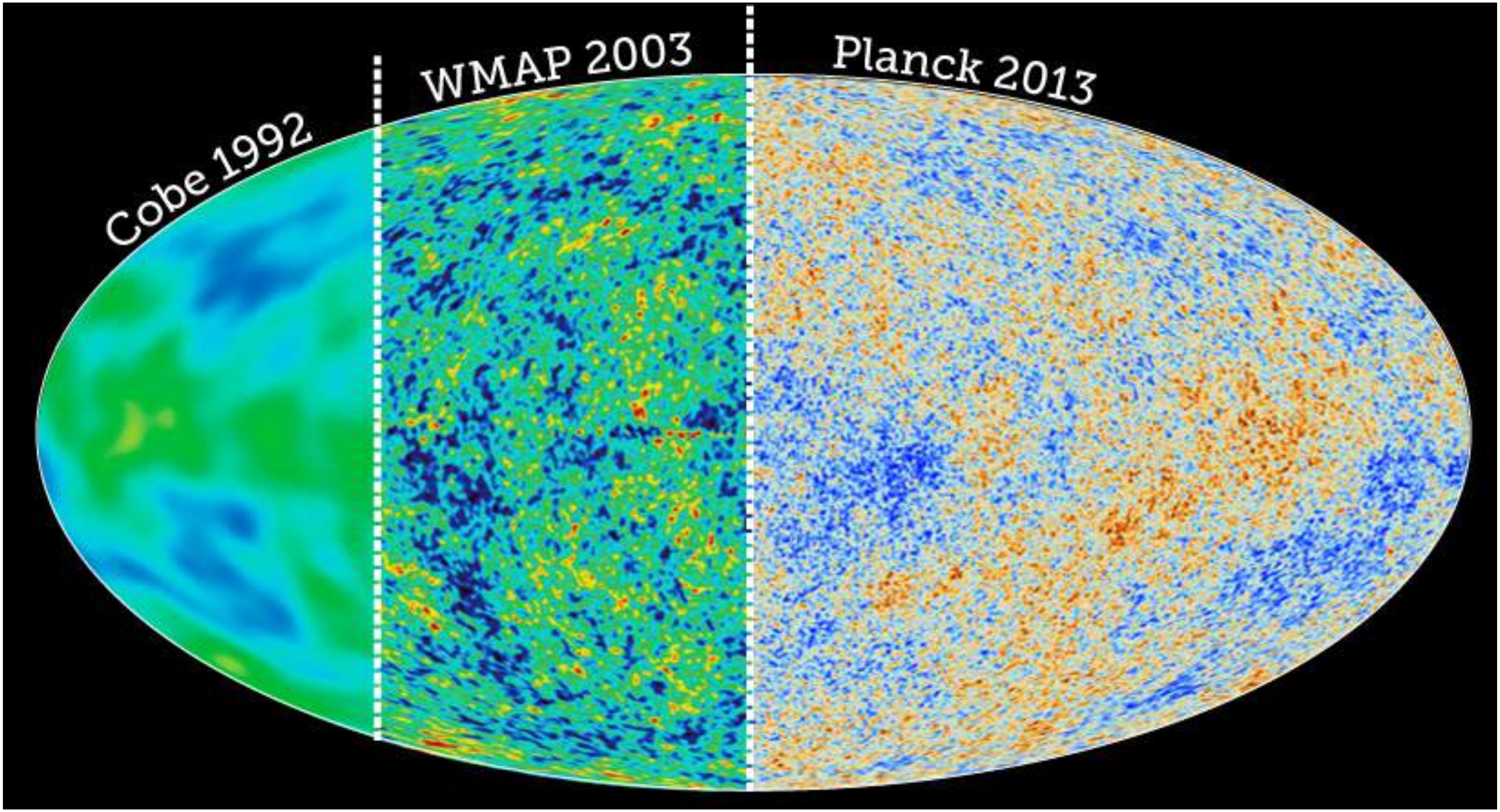
$\Delta T/T \sim 10^{-3}$ dipole anisotropy from bulk motion of Local Group relative background photon sea



$\Delta T/T \sim 10^{-5}$ fluctuations after subtracting dipole

WMAP

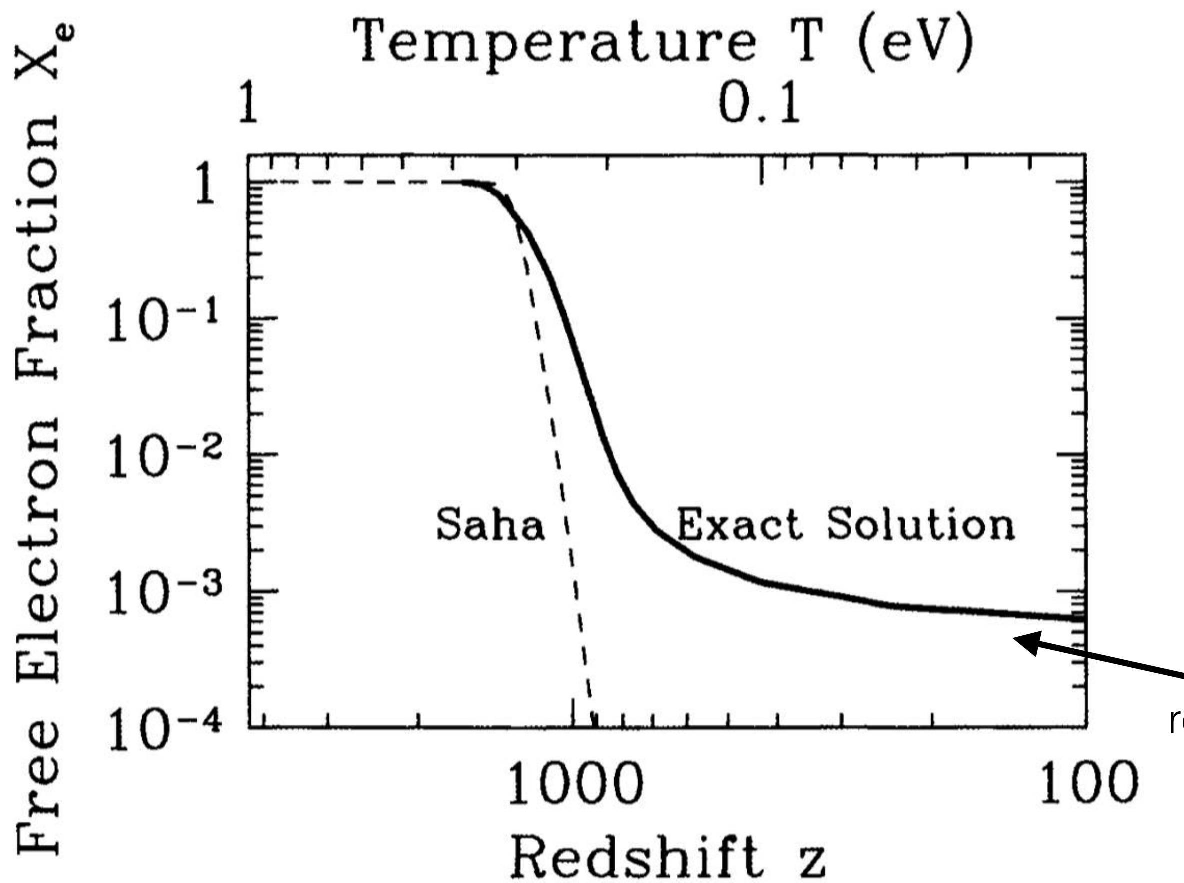
Three satellites have provided full-sky maps of CMB anisotropies



There are also ground- and balloon-based CMB experiments. Ground-based provide the best angular resolution (diffraction limit $\Theta \sim \lambda/D$) but cannot map the whole sky.

Cosmological recombination and last scattering

Saha correctly predicts z_{rec} but incorrect in detail



non-equilibrium effects, e.g.
recombination rate drops as $X_e \to 0$

Figure 3.4. Free electron fraction as a function of redshift. Recombination takes place suddenly at $z \sim 1000$ corresponding to $T \sim 1/4$ eV. The Saha approximation, Eq. (3.37), holds in equilibrium and correctly identifies the redshift of recombination, but not the detailed evolution of X_e. Here $\Omega_b = 0.06, \Omega_m = 1, h = 0.5$.

Dodelson 03

Visibility function quantifies probability of last scattering redshift

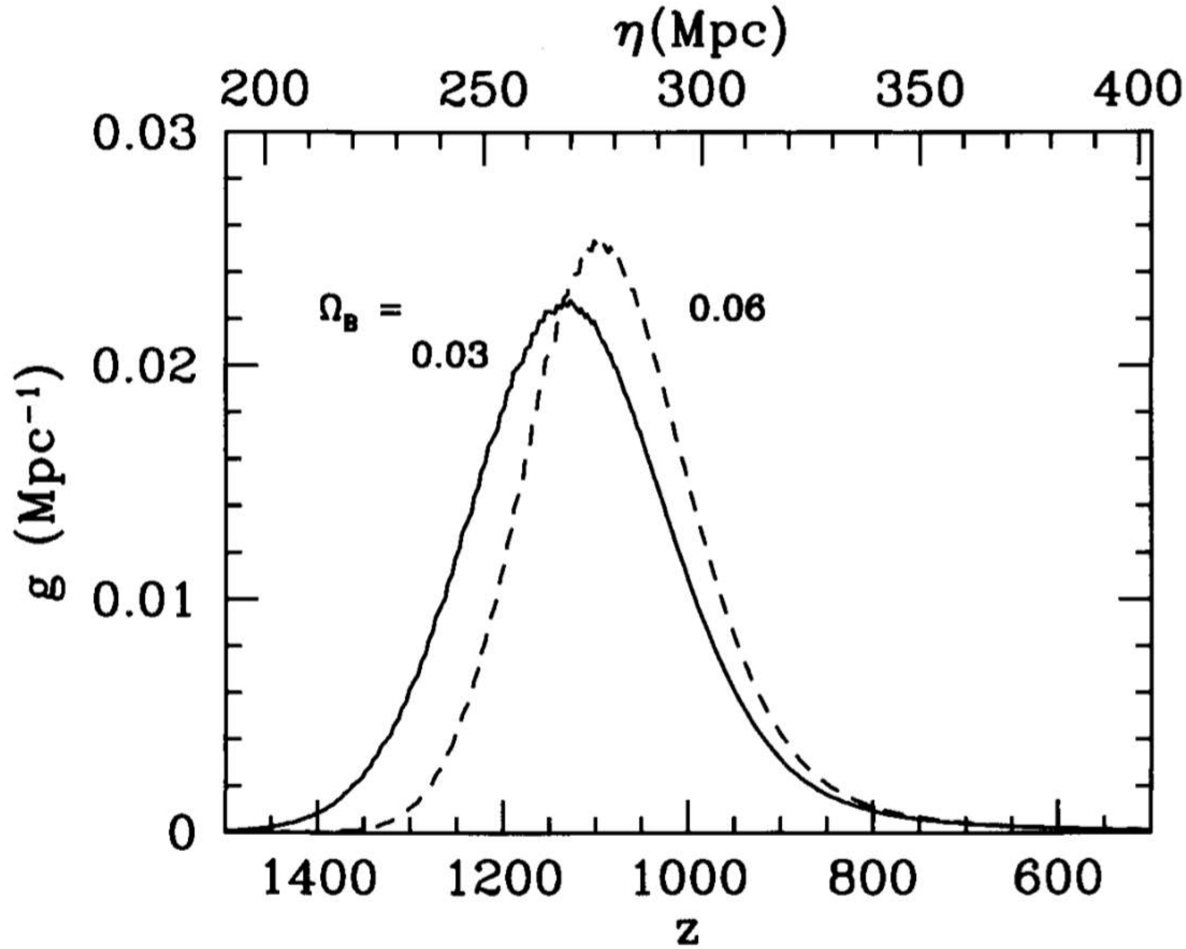


Figure 8.9. The visibility function. Most electrons last scatter at around $z \simeq 1100$ with little dependence on the baryon density. Note that the integral of g over conformal time is 1. Here $h = 0.5$.

$$g(\eta) \equiv -\dot{\tau} e^{-\tau}$$

η=comoving distance

Dodelson 03

The CMB power spectrum

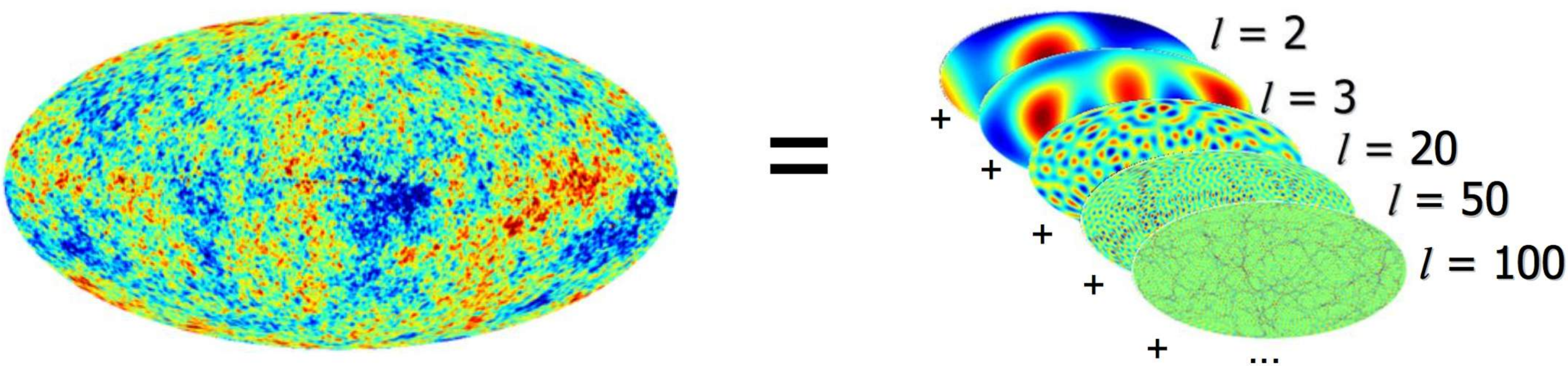
Spherical harmonics representation of the CMB sky

- Orthonormal basis so can use to represent any scalar field on the sky
- Spherical analog of Fourier decomposition
- Apply to CMB temperature

$$T(\hat{n}) = \sum_{\ell=0}^{\ell_{\max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n})$$

$$a_{\ell m} = \int_{4\pi} T(\hat{n}) Y^*_{\ell m}(\hat{n}) d\Omega$$

$$\sqrt{\frac{2\ell+1}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}} P_{\ell m}(\cos\theta) e^{im\phi} \equiv Y_{\ell m}(\theta,\phi)$$

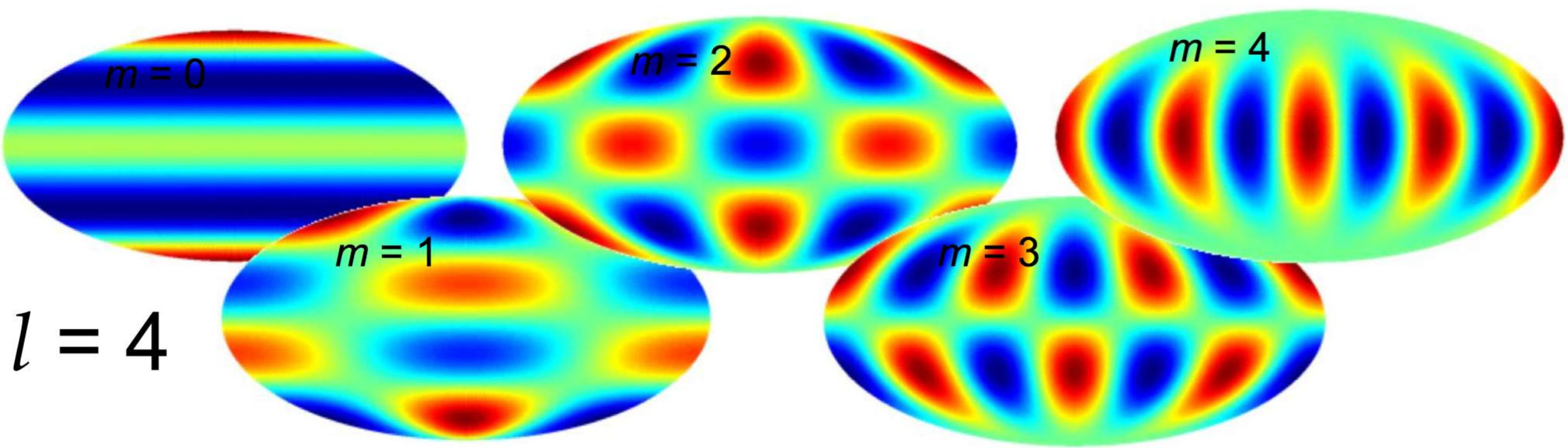


Eriksen 11

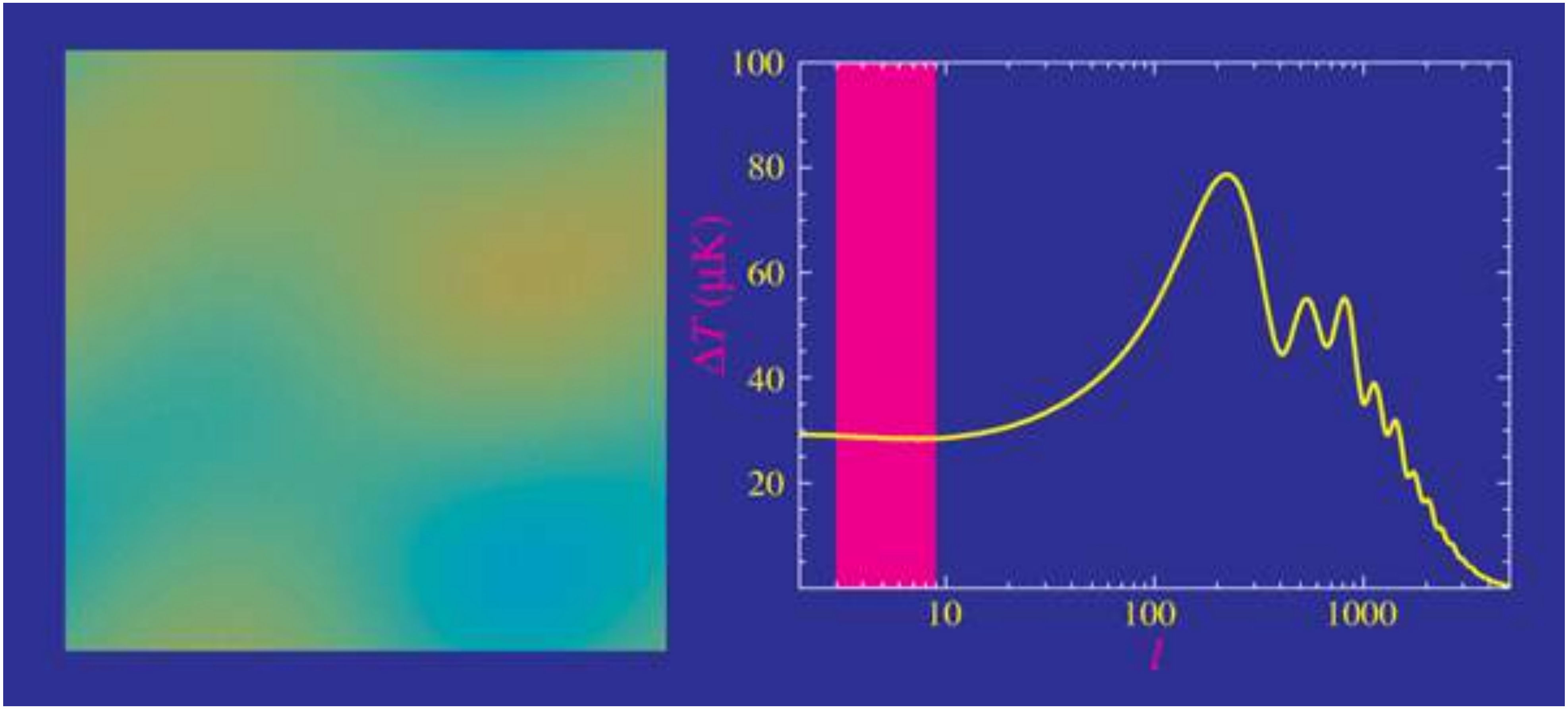
Angular power spectrum

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2$$

- *l* determines the wavelength of the mode (number of waves along meridian)
- *m* determines the "shape" of the mode (number of modes along equator)



Low *l* = large angular scales, high *l*=small scales

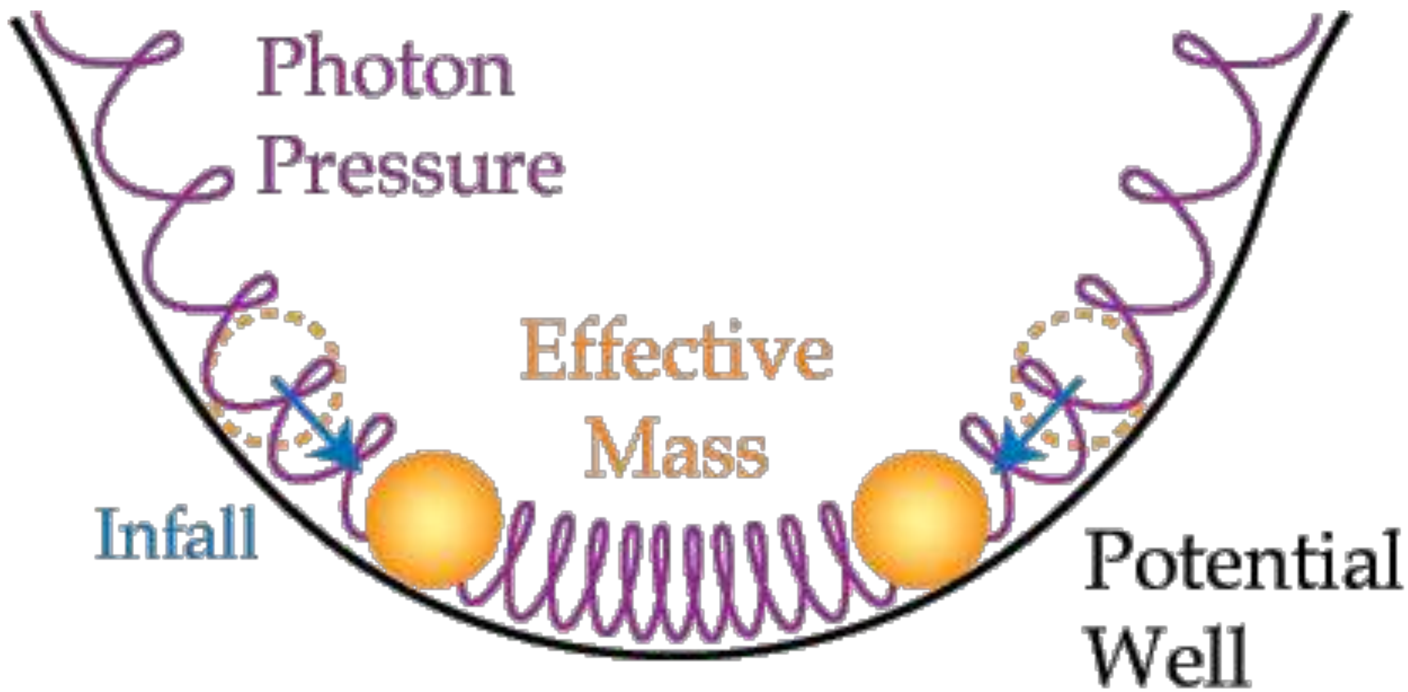


Magenta band on the right represents a filter on the angular size of features in the map on the left. The filter starts on the 10 degree scale similar to the original COBE measurements. As the filter passes through the first peak in the power spectrum, the spots are degrees in scale and most intense.

Hu & White 04

Acoustic oscillations

Photon-baryon fluid oscillates in dark matter potential wells at surface of last scattering



At last scattering: $\rho_{\rm DM} : \rho_{\rm rad} : \rho_{\rm b} = 6.4 : 1.4 : 1$

Cartoon credit: W. Hu

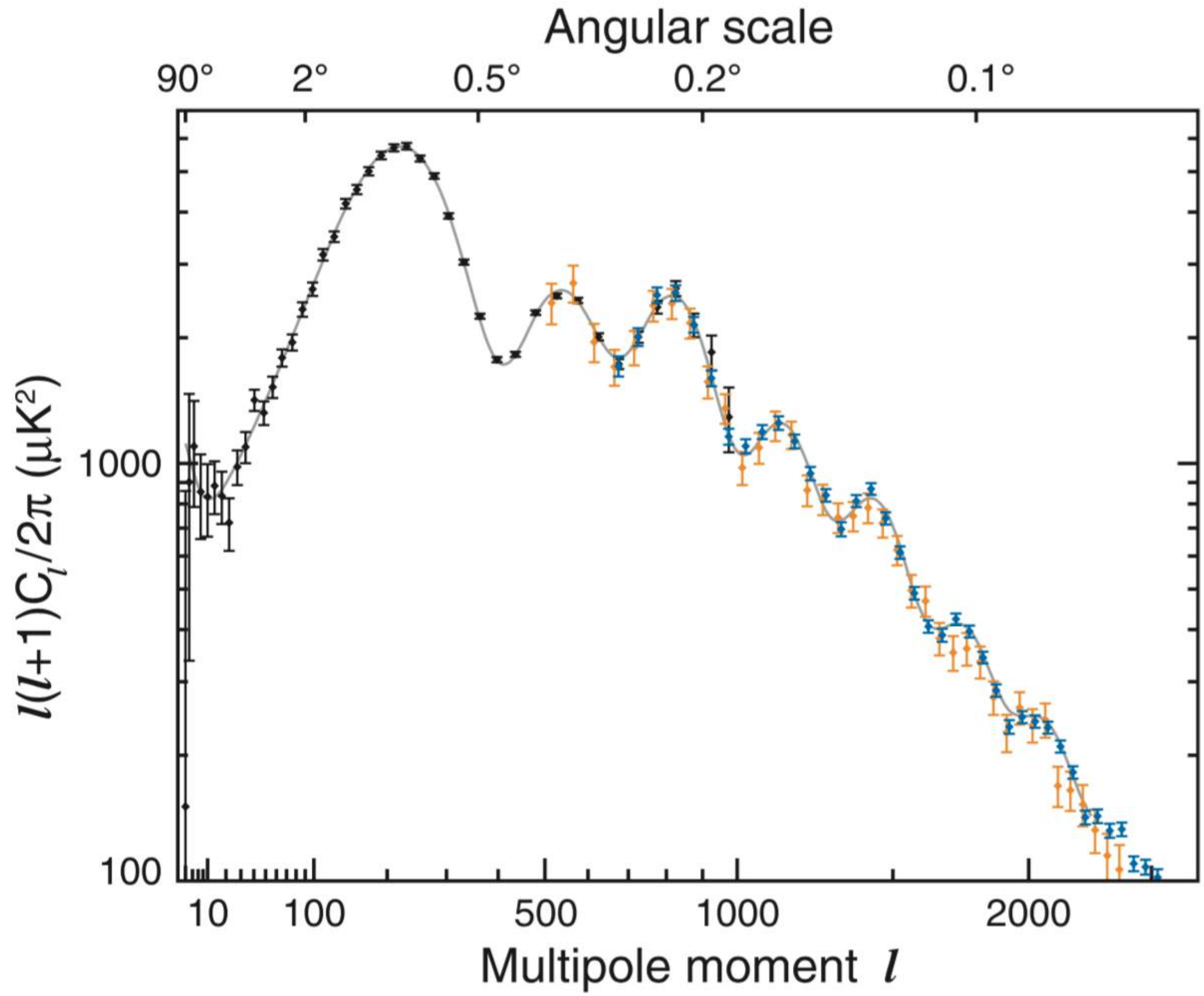
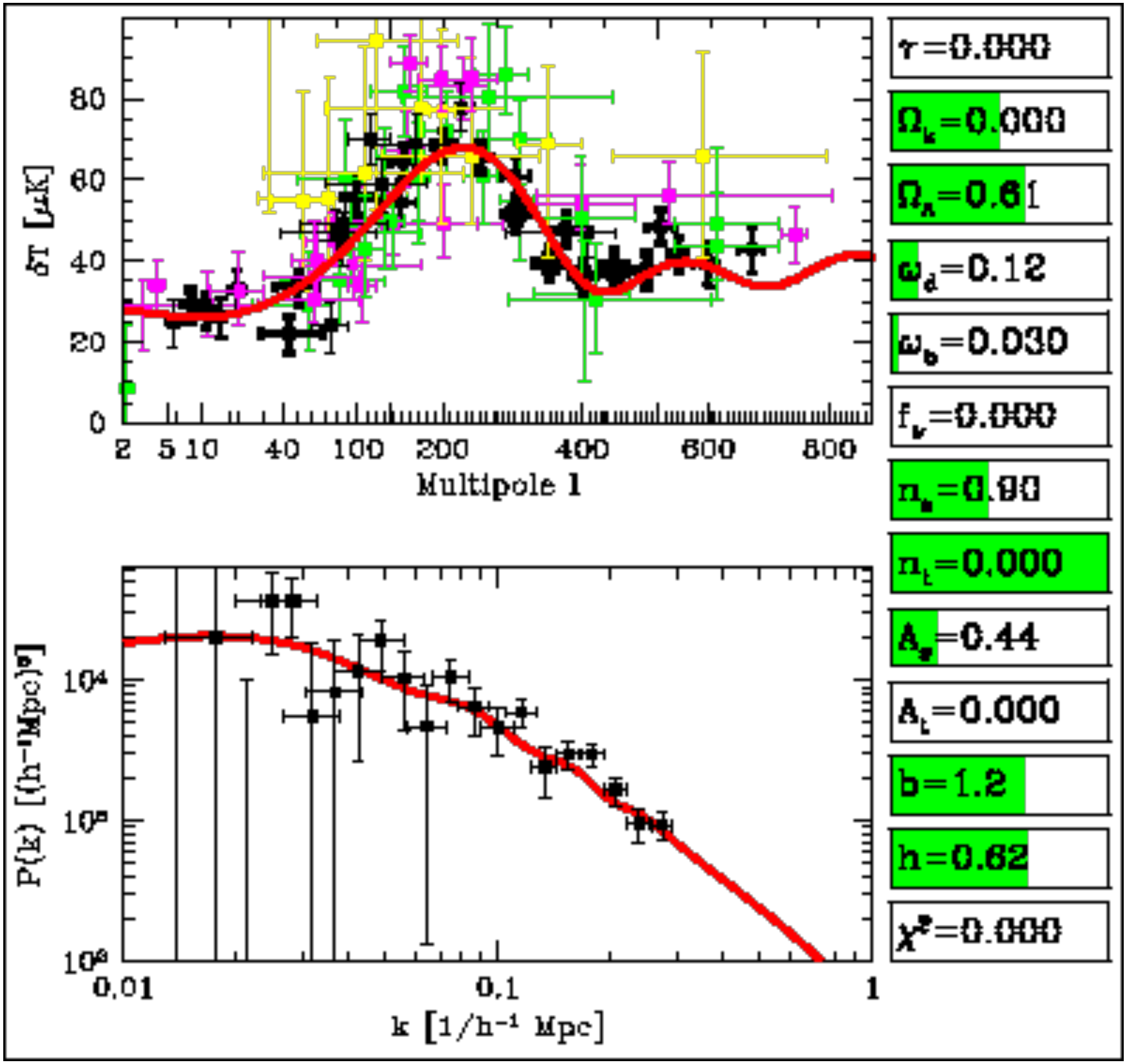


Figure 1. Compilation of the CMB data used in the nine-year *WMAP* analysis. The *WMAP* data are shown in black, the extended CMB data set—denoted "eCMB" throughout—includes SPT data in blue (Keisler et al. 2011) and ACT data in orange, (Das et al. 2011b). We also incorporate constraints from CMB lensing published by the SPT and ACT groups (not shown). The ΛCDM model fit to the *WMAP* data alone (shown in gray) successfully predicts the higher-resolution data.

WMAP 9-year

Cosmological parameter estimation from the CMB power spectrum

Varying baryon fraction

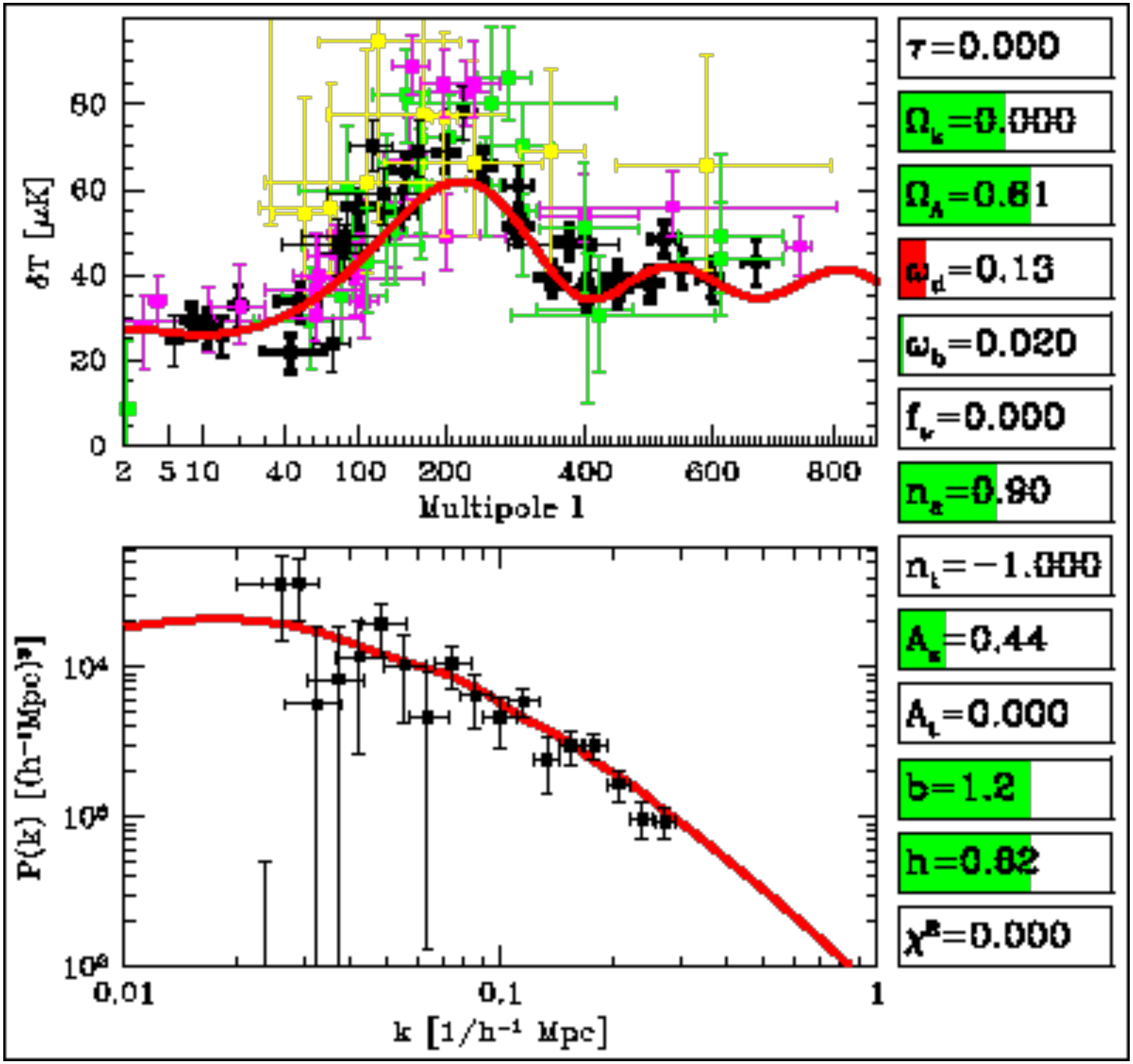


$\omega_X \equiv \Omega_X h^2$

more baryons → higher peaks

Credit: M. Tegmark

Varying dark matter mass density

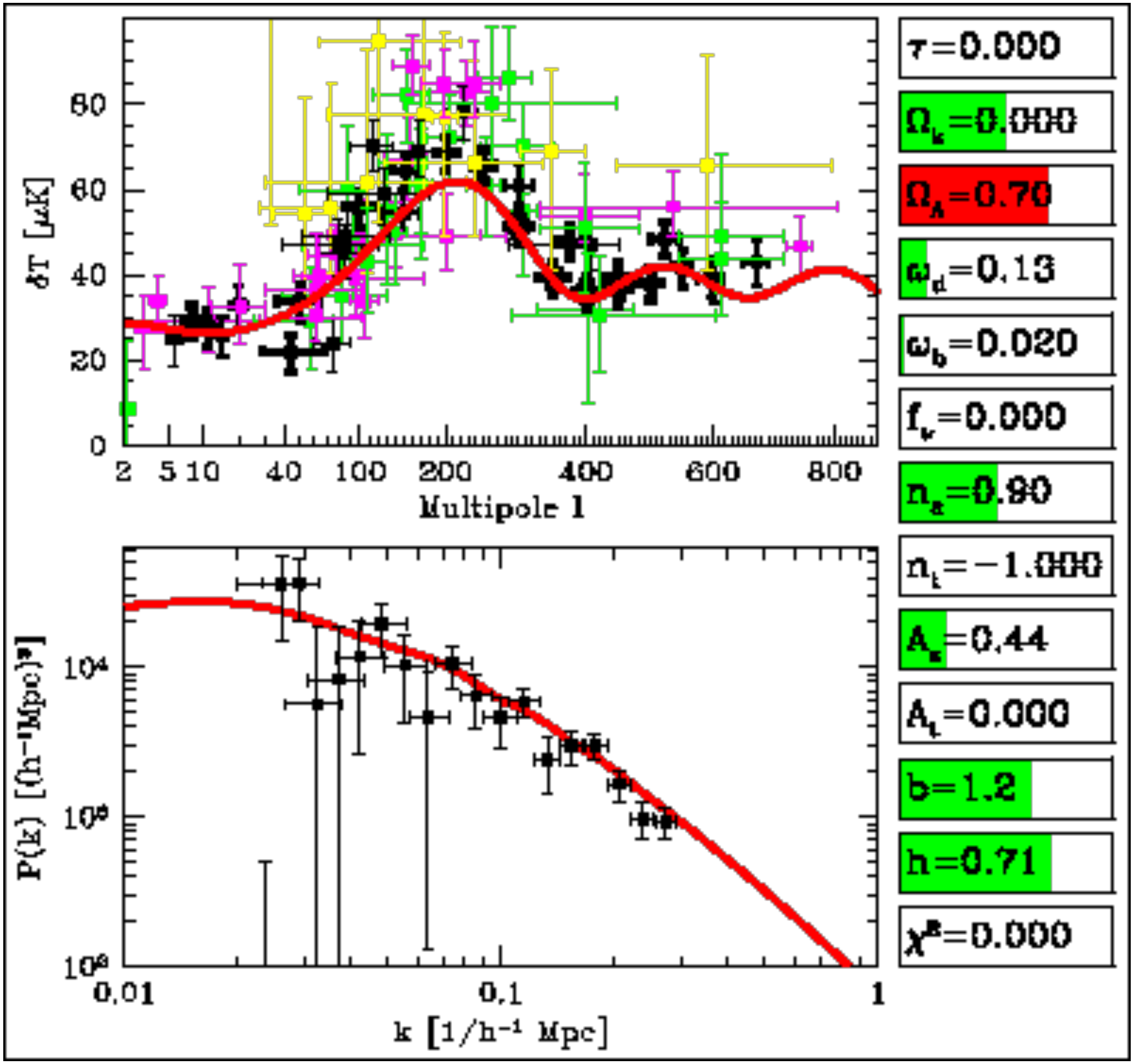


$\omega_X \equiv \Omega_X h^2$

more dark matter → lower peaks

Credit: M. Tegmark

Varying cosmological constant



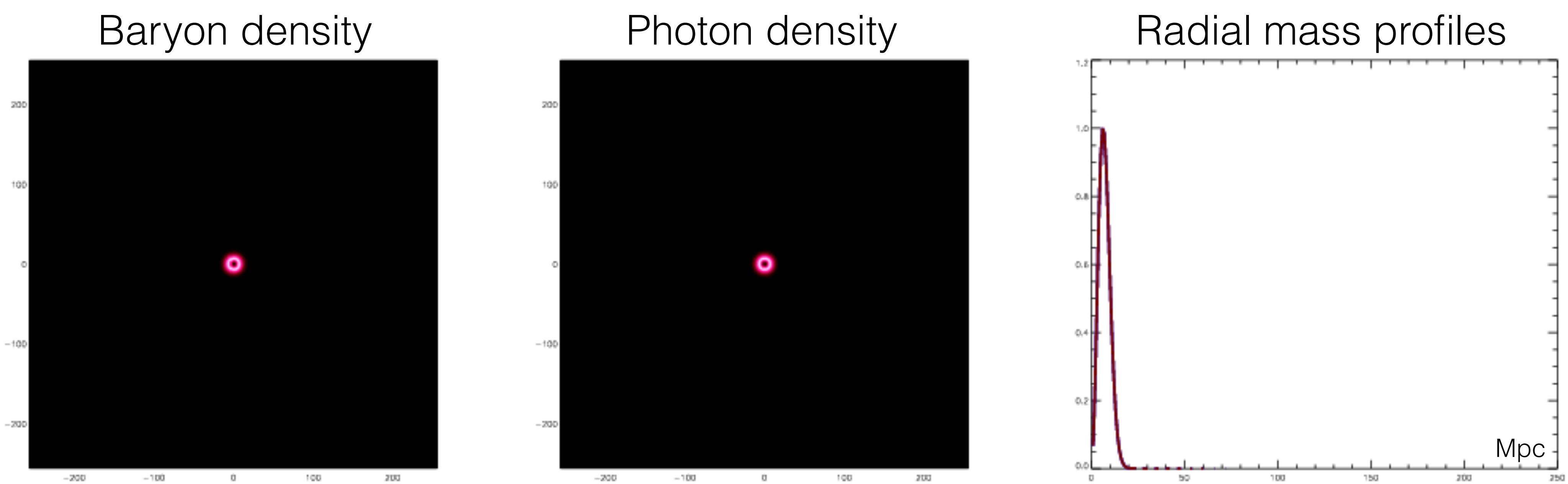
$\omega_X \equiv \Omega_X h^2$

Λ dynamically unimportant at LS but changes $d_{\rm diam}(z_{\rm LS})$

Credit: M. Tegmark

Baryon acoustic oscillations in galaxy distribution

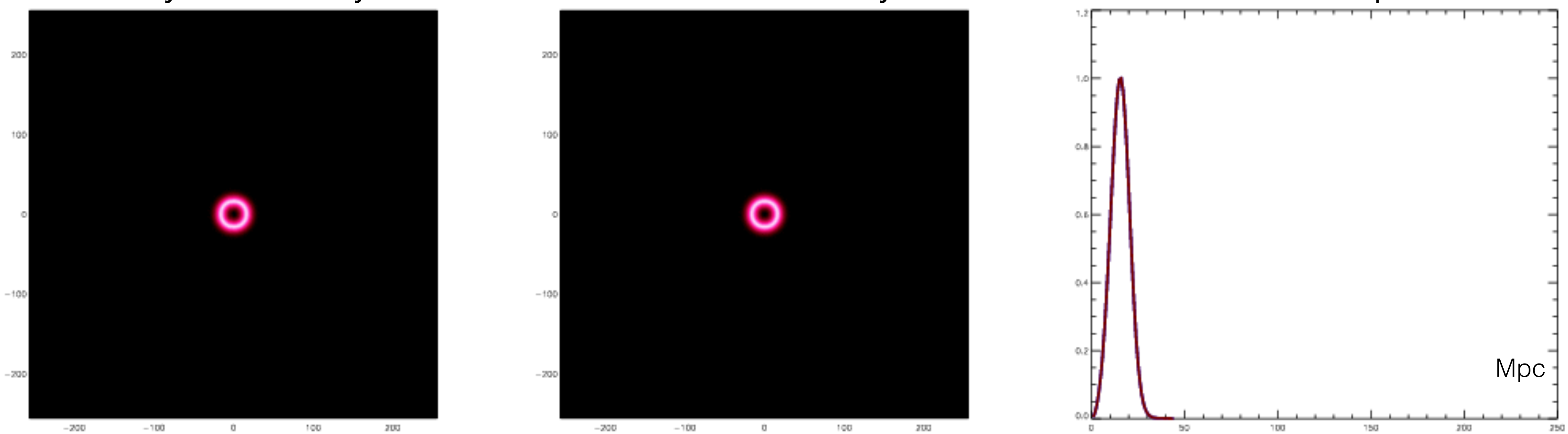
Consider the early Universe, which was composed of a coupled plasma of photons, ionized hydrogen, and dark matter. Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin. High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Credit: M. White

Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light

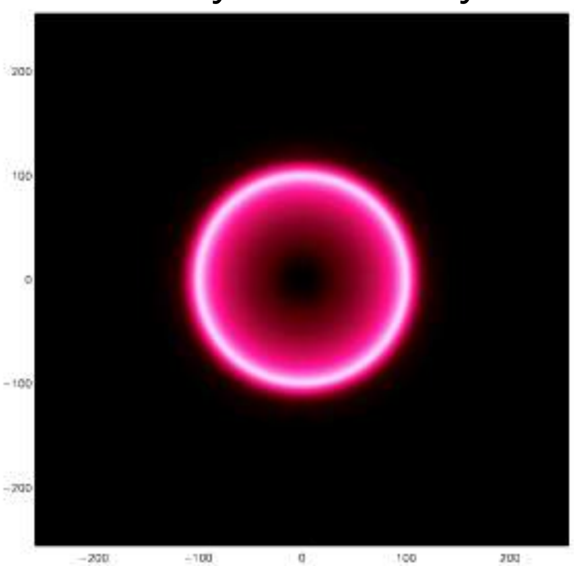
Baryon density Photon density Radial mass profiles



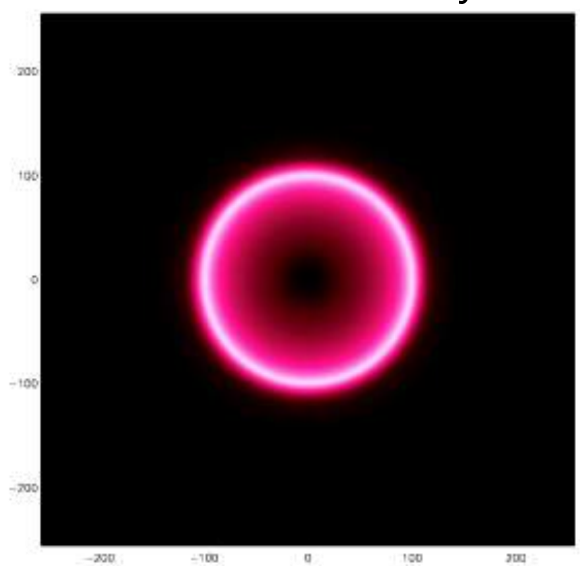
Credit: M. White

This expansion continues for ~300,000 years

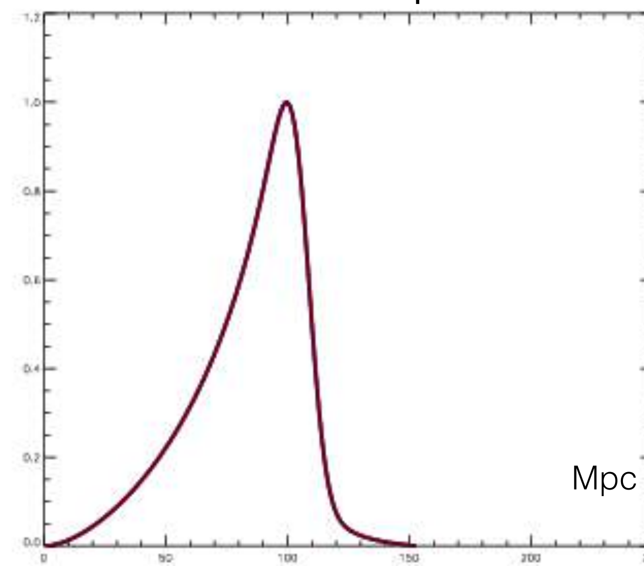
Baryon density



Photon density



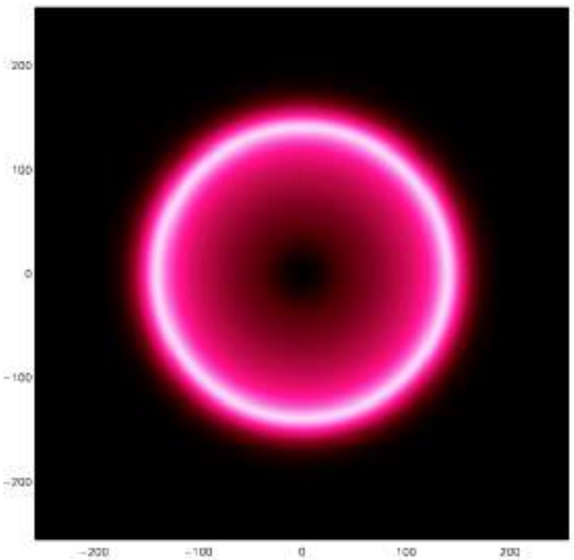
Radial mass profiles



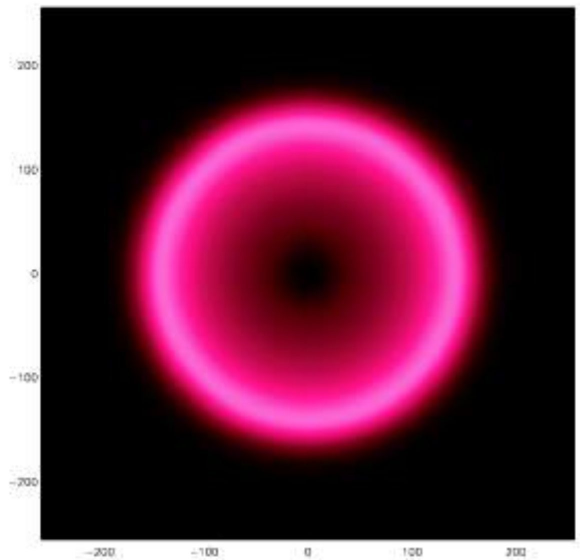
Credit: M. White

After ~300,000 years, the Universe has cooled enough the protons capture the electrons to form neutral hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.

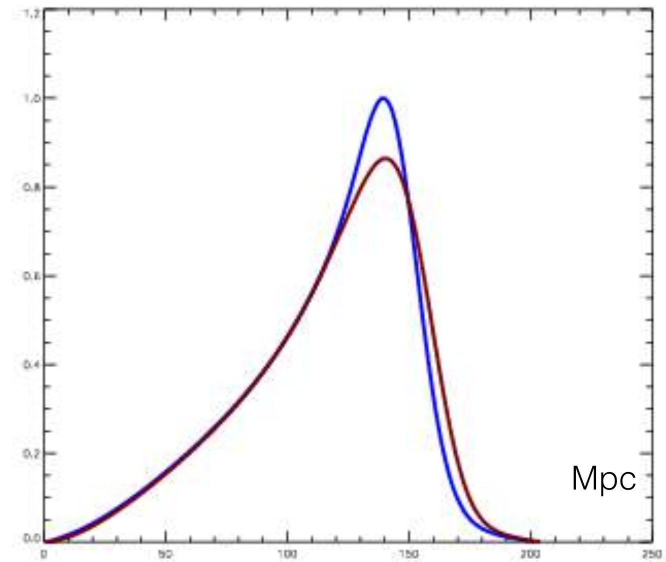
Baryon density



Photon density



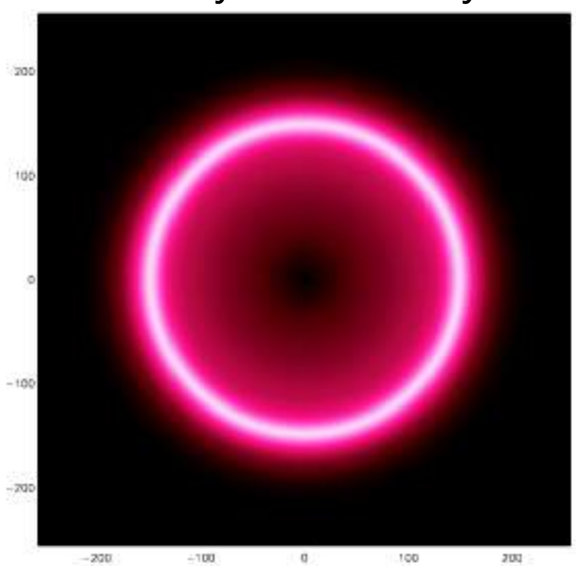
Radial mass profiles



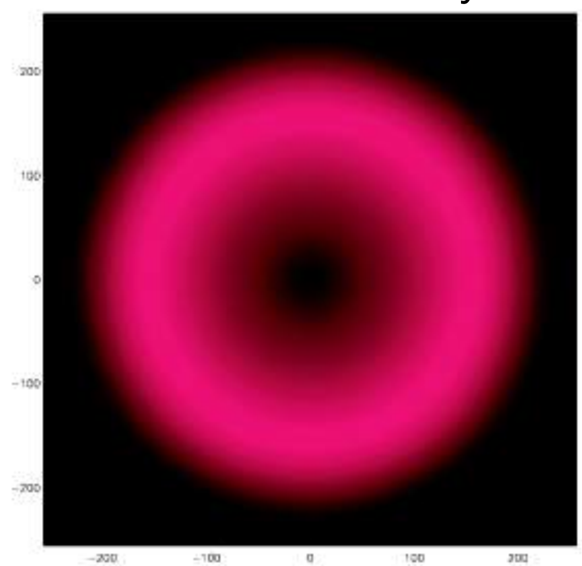
Credit: M. White

The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.

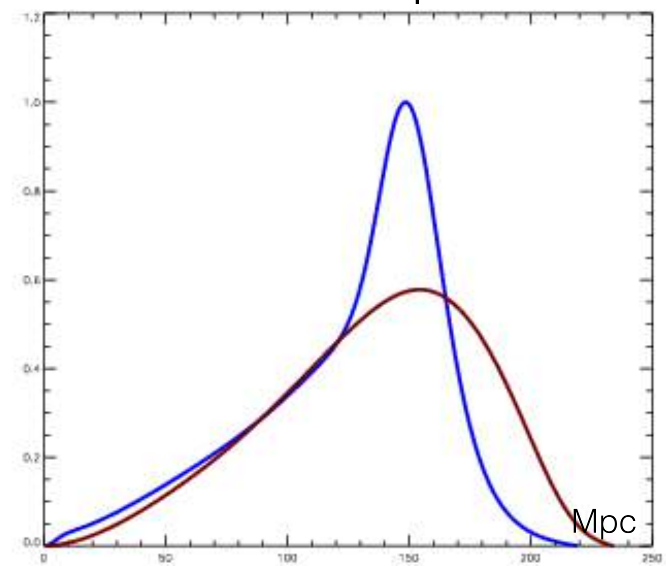
Baryon density



Photon density



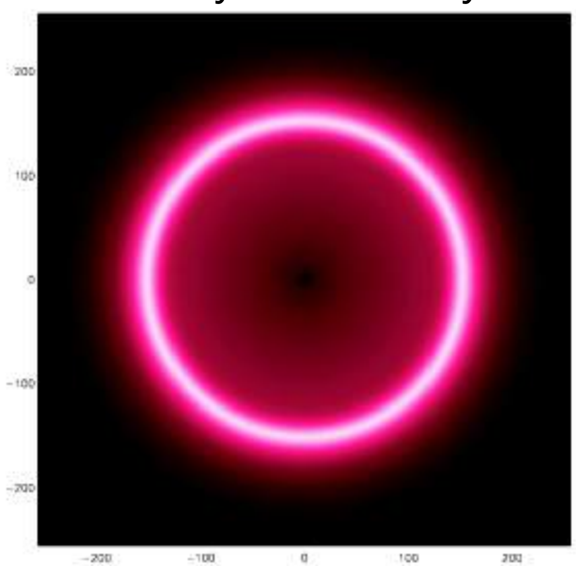
Radial mass profiles



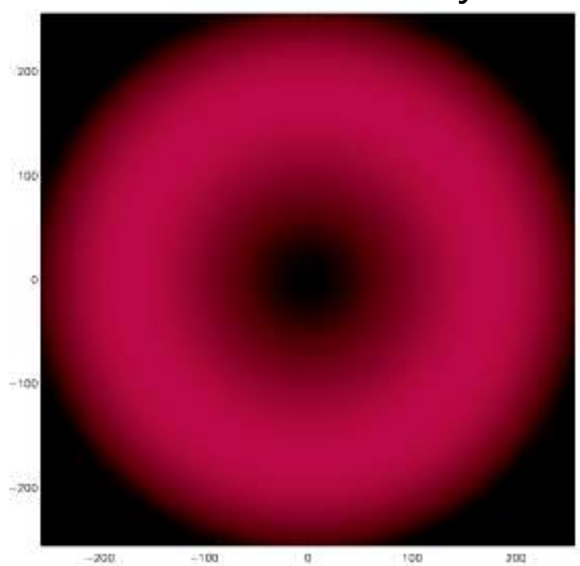
Credit: M. White

Decoupled evolution of photons and baryons continue for a while…

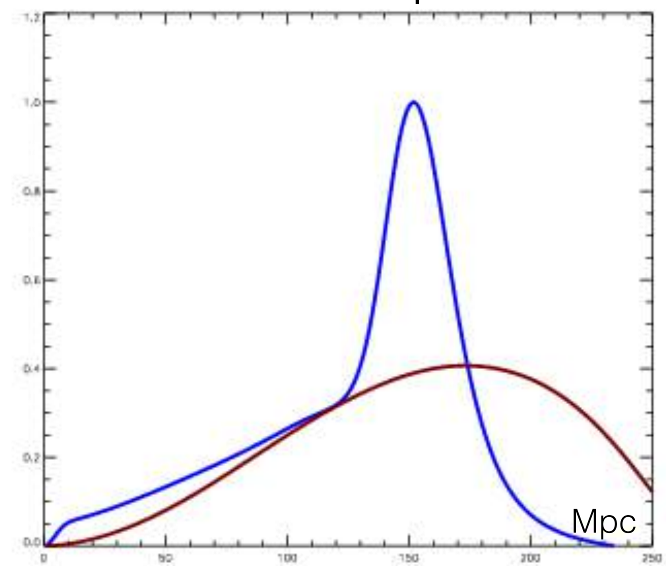
Baryon density



Photon density



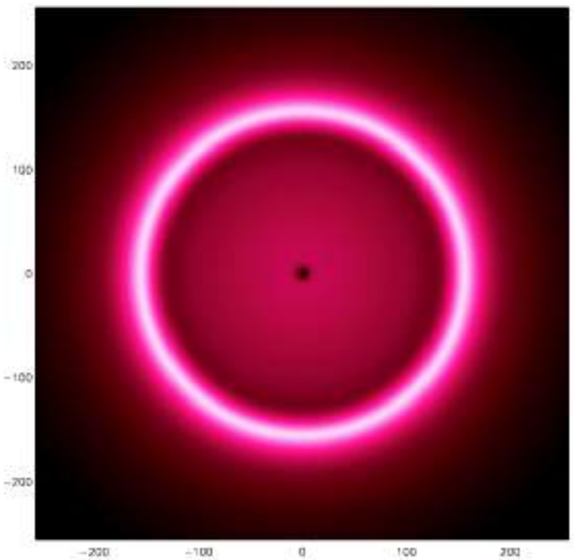
Radial mass profiles



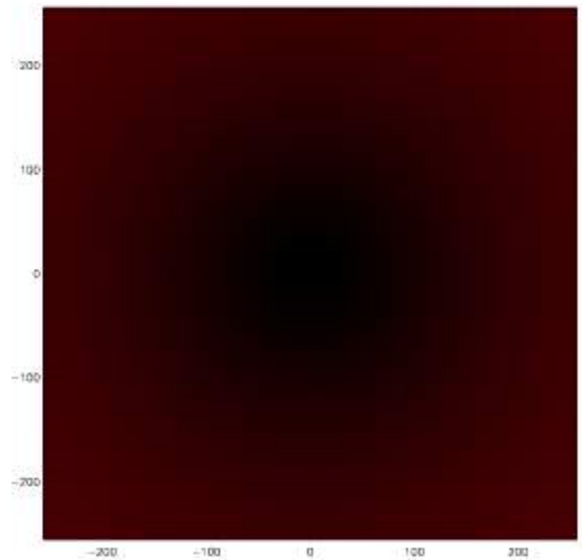
Credit: M. White

The photons have become almost completely uniform, but the baryons remain overdense in a shell ~150 Mpc (comoving) in radius. In addition, the large gravitational potential well which we started with starts to draw material back into it.

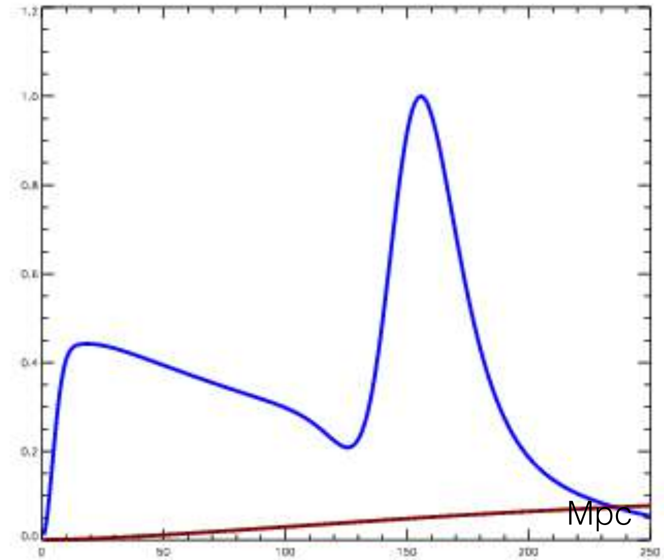
Baryon density



Photon density



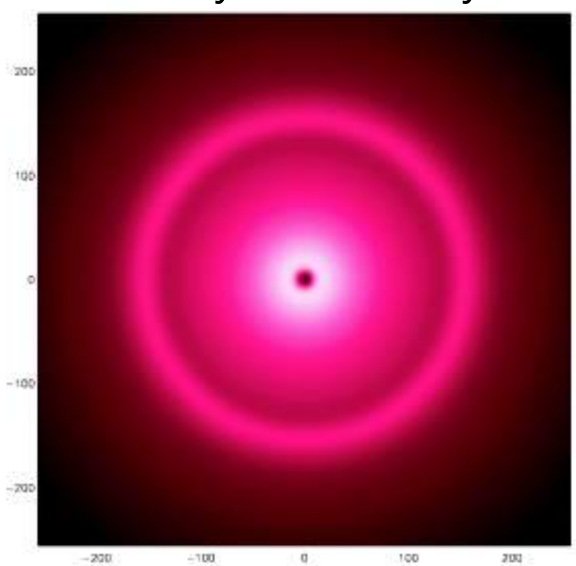
Radial mass profiles



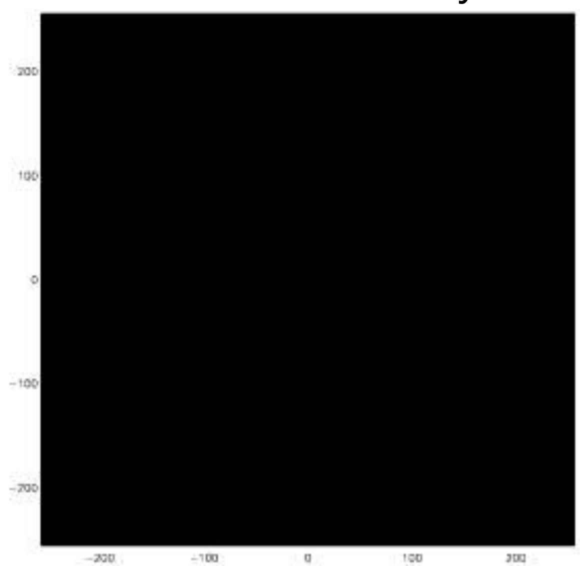
Credit: M. White

As the perturbation grows by O(1,000) the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m. The final configuration is our original peak at the center (which was put in by hand) and an echo in a shell ~150 Mpc in radius. The radius of this shell is known as the sound horizon.

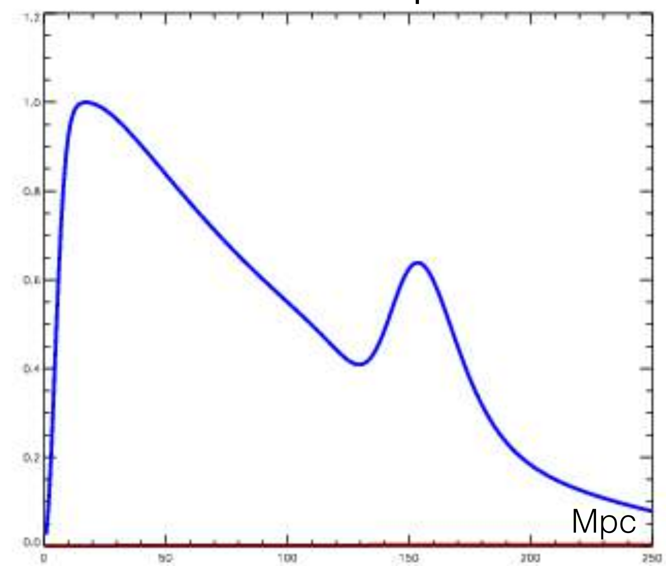
Baryon density



Photon density



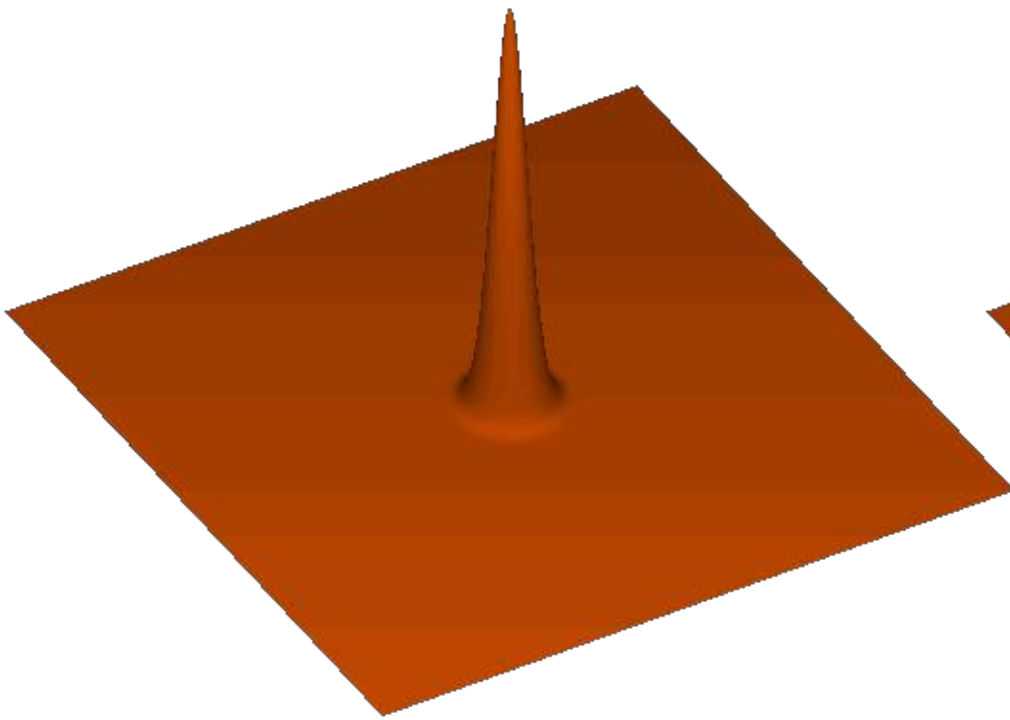
Radial mass profiles



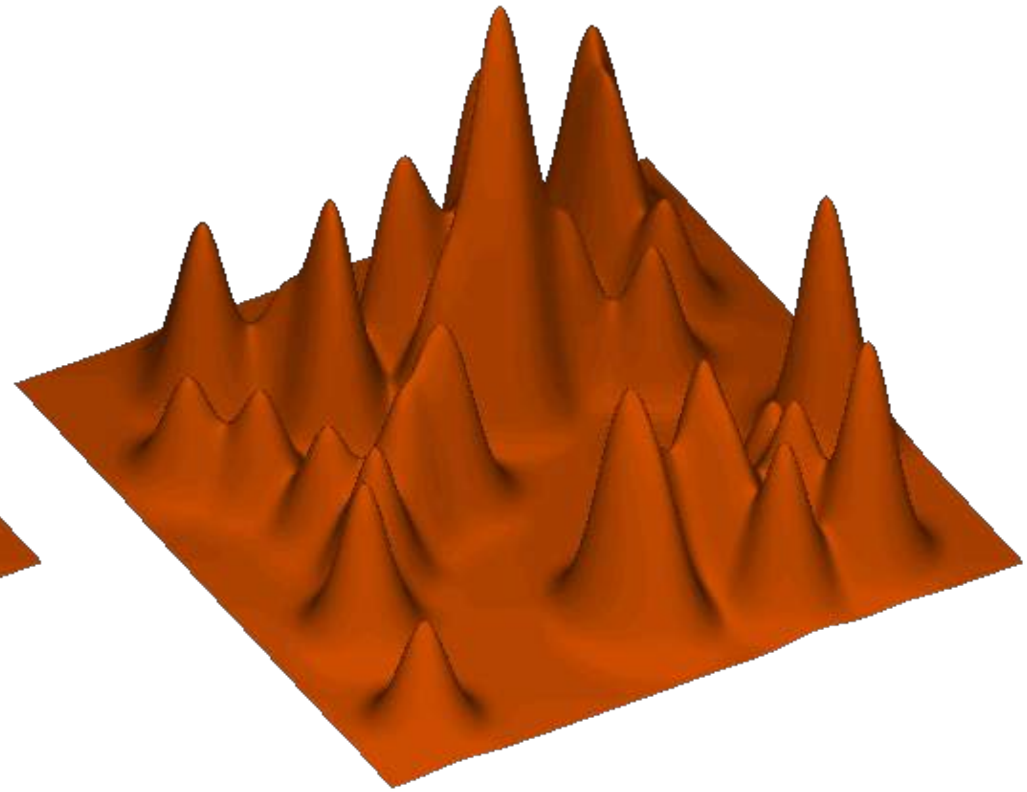
Credit: M. White

Single vs. superposed waves in baryons

One wave



Multiple waves

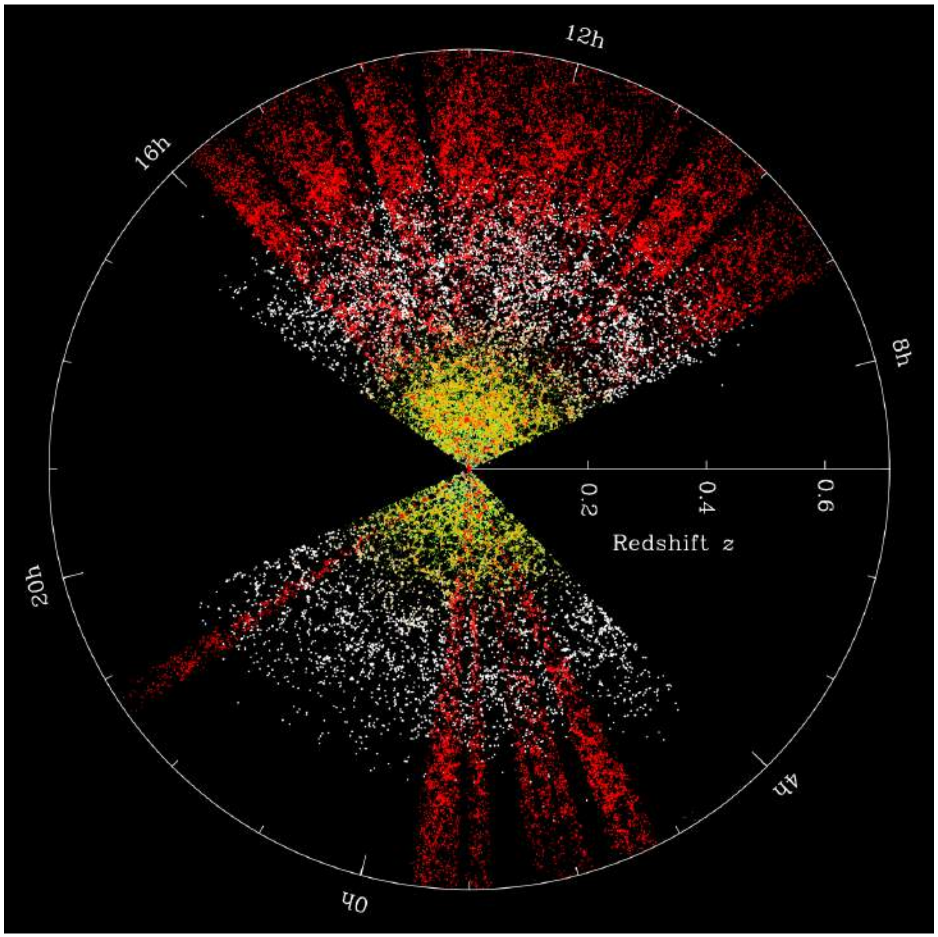


Color = transition
from neutral to
ionized

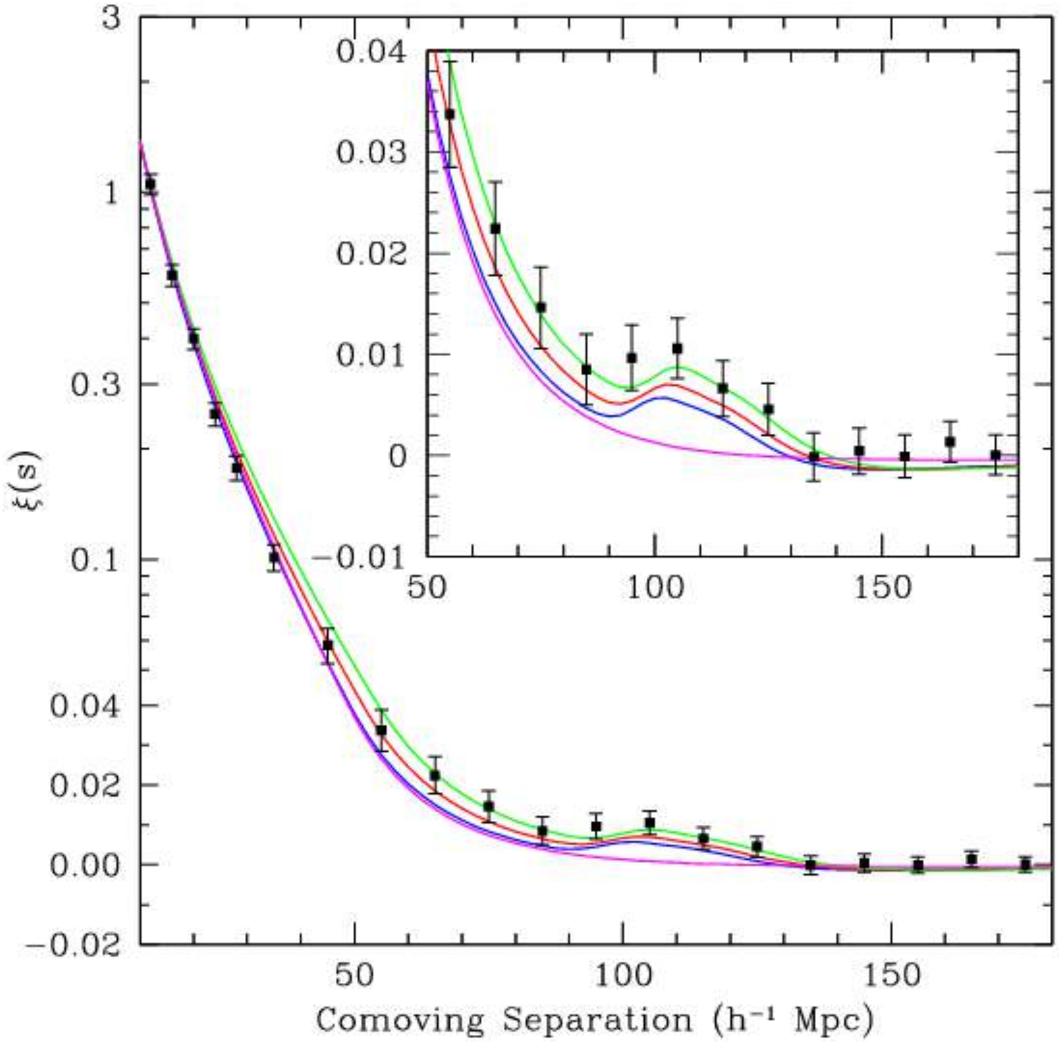
Credit: D. Eisenstein

CMB fluctuations grow into “baryonic acoustic oscillations” in the galaxy distribution

Baryonic Oscillation Spectroscopy Survey (BOSS) galaxy map



Luminous red galaxy (LRG) correlation function



Eisenstein+05

Breaking degeneracies by combining different cosmological measurements

CMB+BAO+SNe constraints