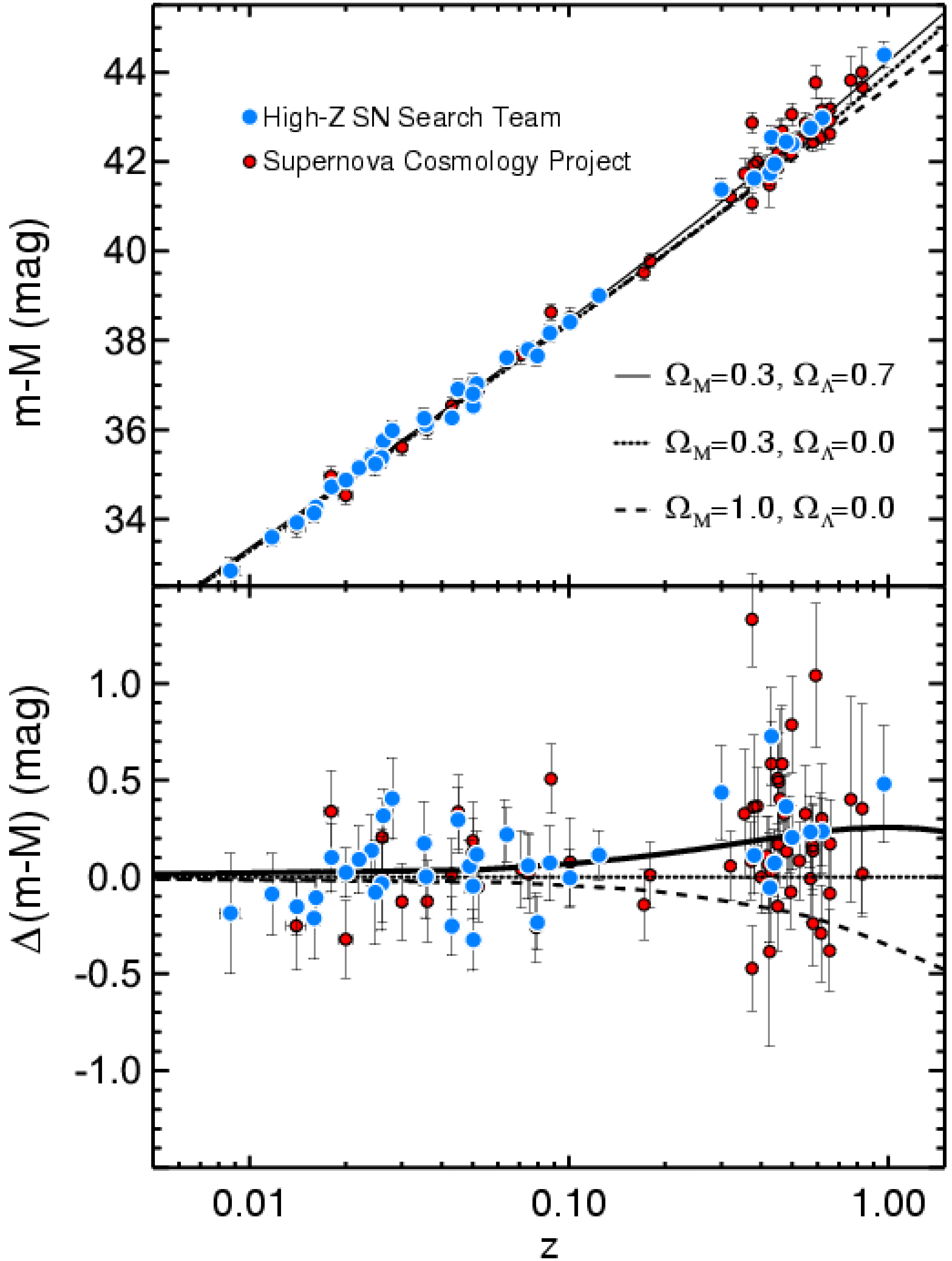


An accelerating Universe

State of the observations 2003

- Distant supernovae appear less bright than expected

↓

- Today the cosmic expansion is accelerating *not* slowing down

↓

- The dominant contribution to the cosmic mass/energy budget must have *negative* pressure

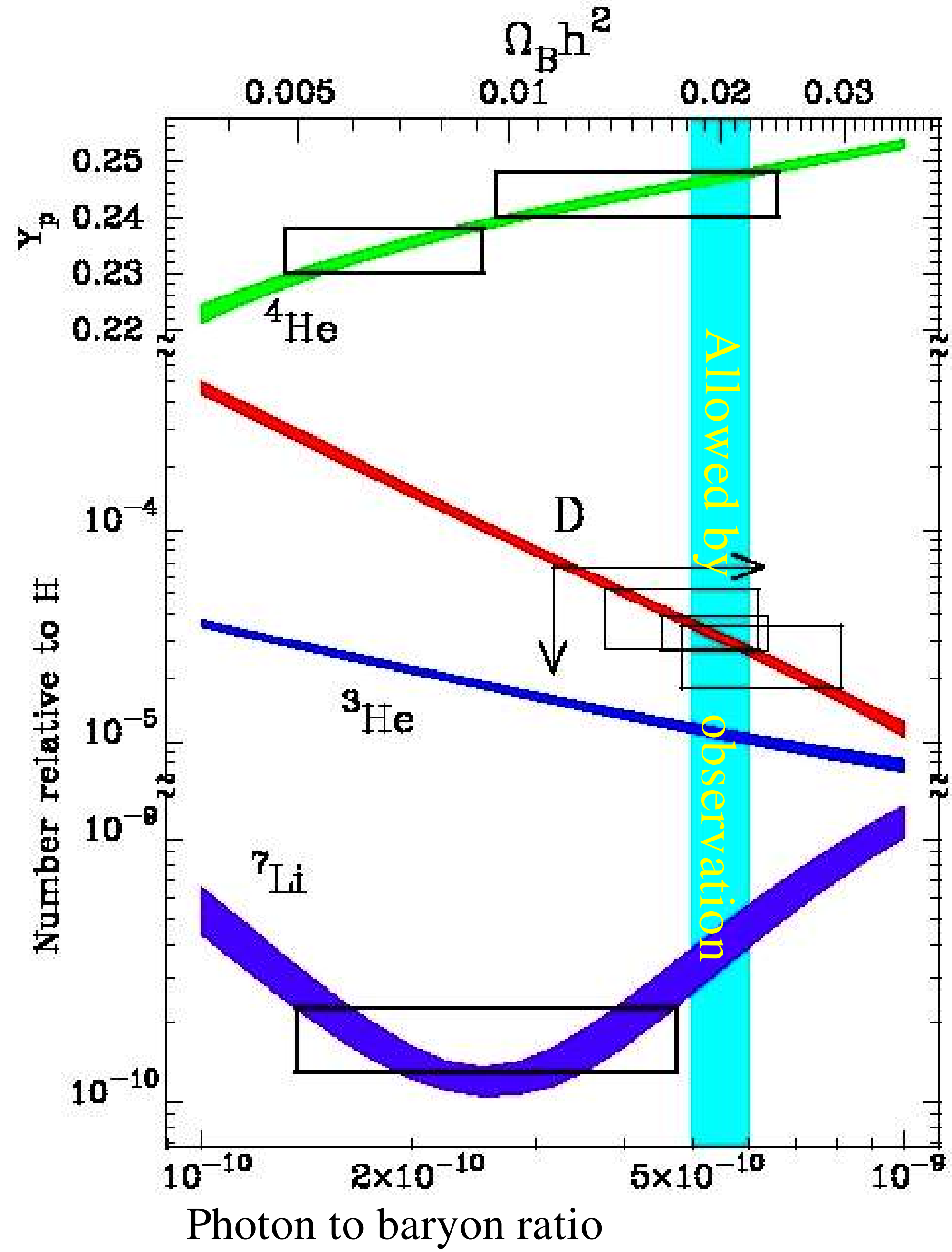
$$\ddot{R} / R = -4\pi/3\, G\, (\rho + 3\, p)$$

Dark Energy, Quintessence, a Cosmological Constant?

Element formation in the Early Universe

- During the very first 3 minutes the Universe "cools" to 10^9 C
- The nuclei of a few light elements are formed
  - Hydrogen (^1H, ^2H)
  - Helium (^3He, ^4He)
  - Lithium (^7Li)
- All the other elements formed later through nuclear reactions in stars and stellar explosions

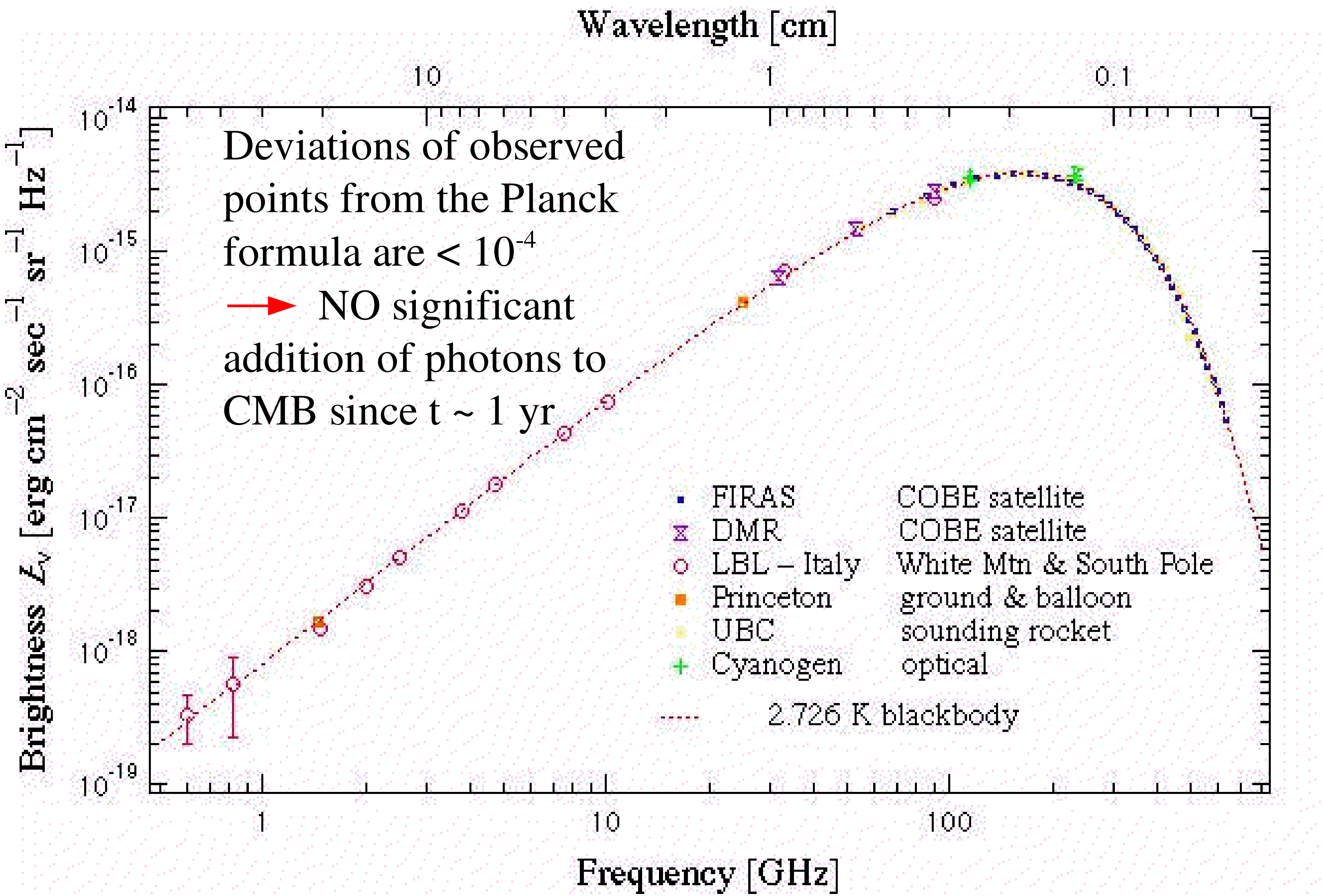
The atoms in our bodies were made in stars



COBE's spectrum of the CMB

Deviations of observed points from the Planck formula are < 10^{-4}

→ NO significant addition of photons to CMB since t ~ 1 yr

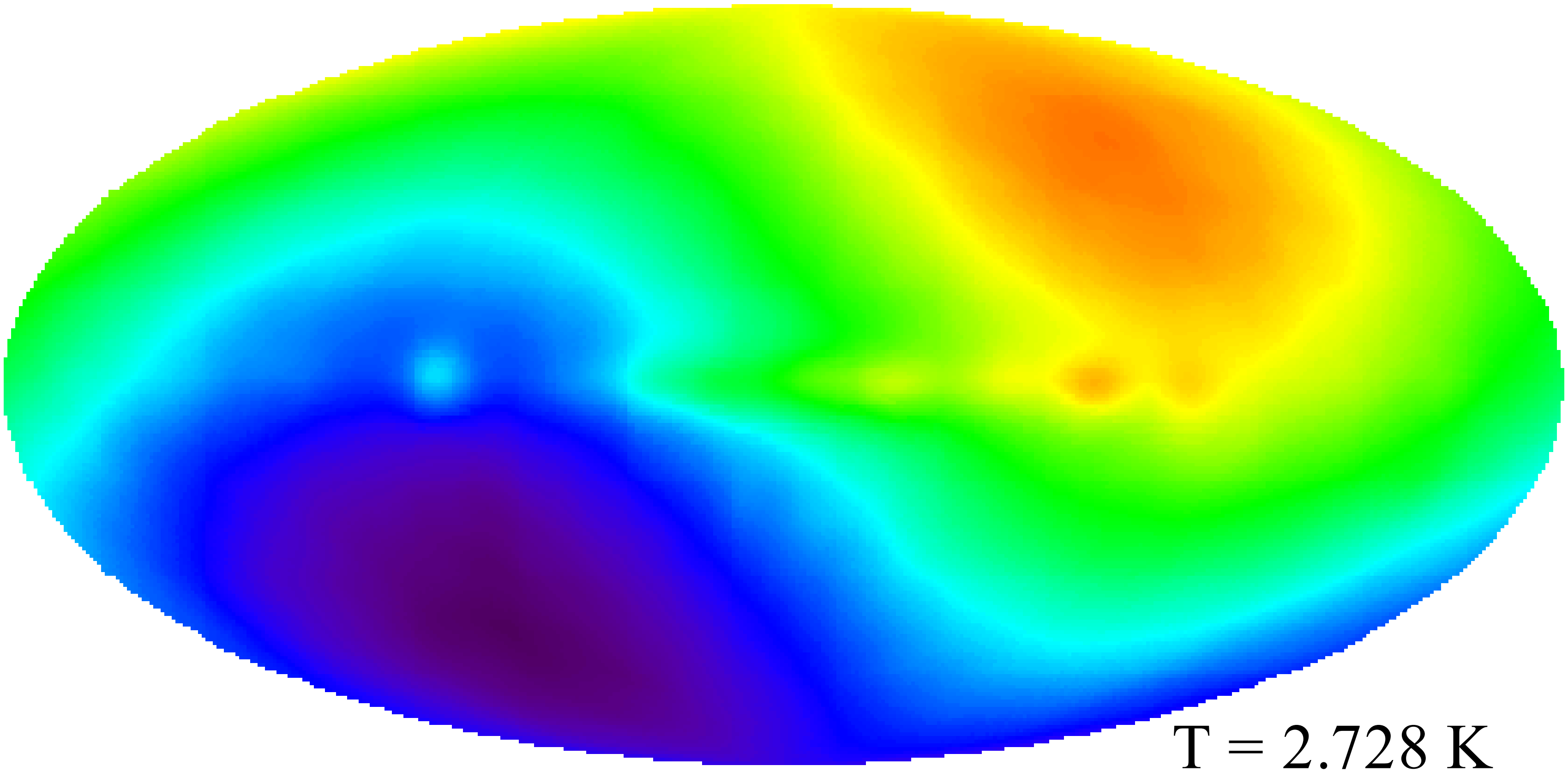


COBE's microwave map of the entire sky

$T = 2.728$ K

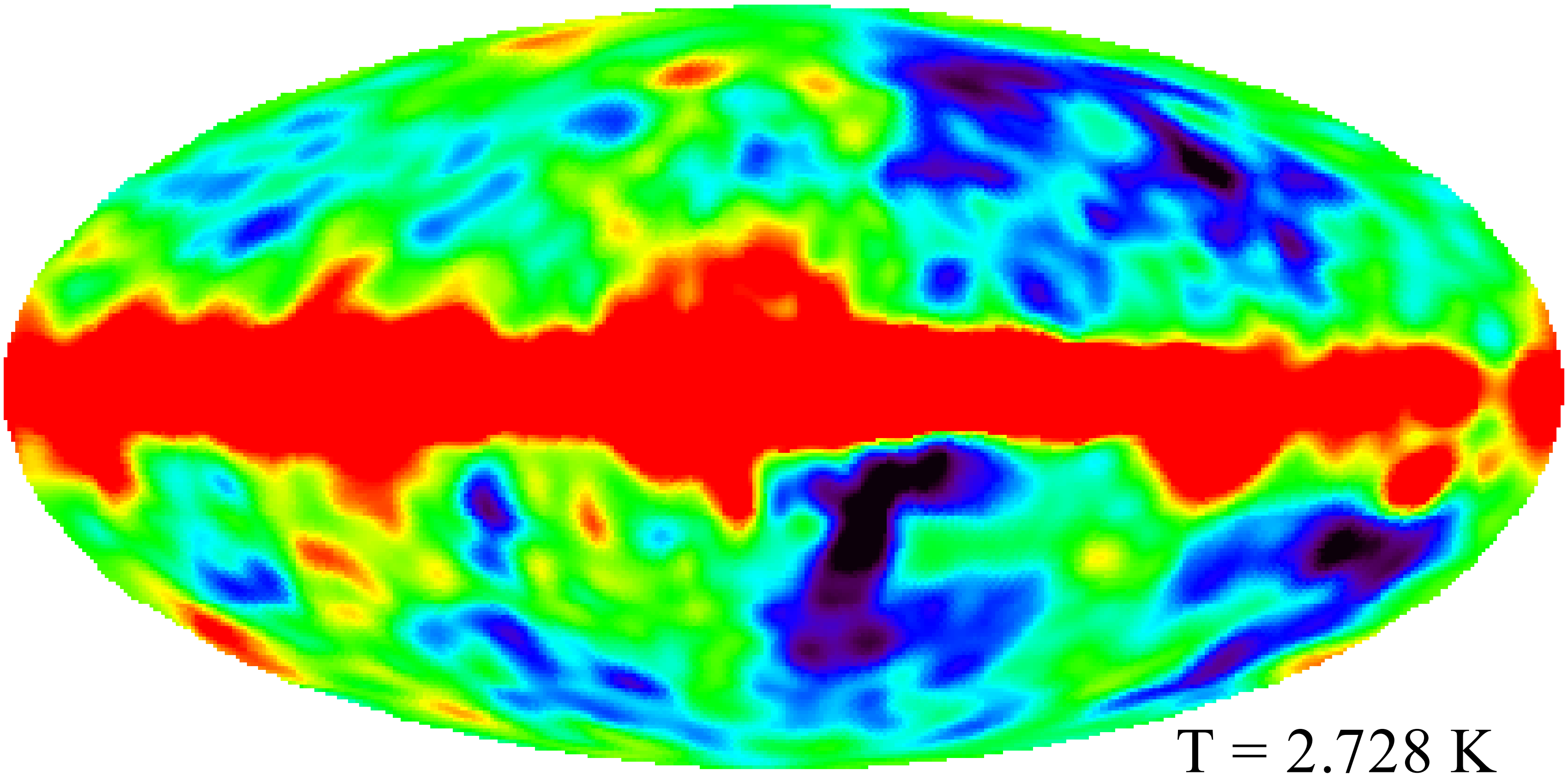
$\Delta T = 0.1$ K

COBE's microwave map of the entire sky



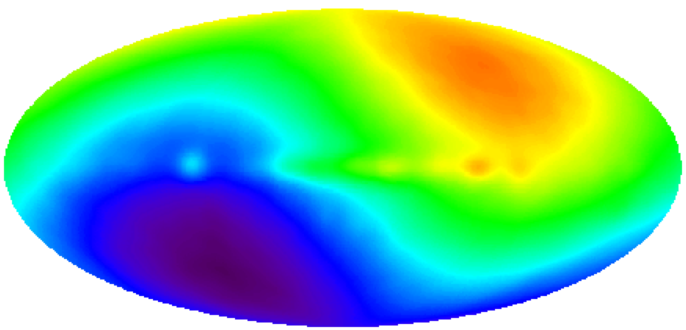
T = 2.728 K
ΔT = 0.0034 K

COBE's microwave map of the entire sky



T = 2.728 K
$\Delta T = 0.00002$ K

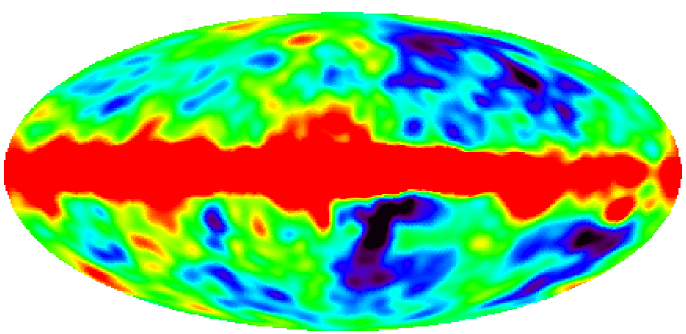
Structure in the COBE map



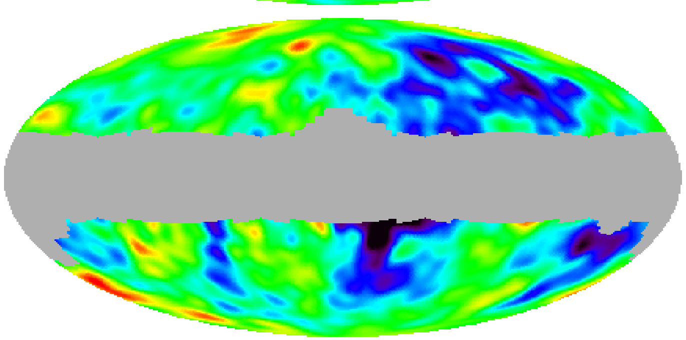
- One side of the sky is `hot', the other is `cold'

→ the Earth's motion through the Cosmos

$V_{\text{Milky Way}} = 600$ km/s

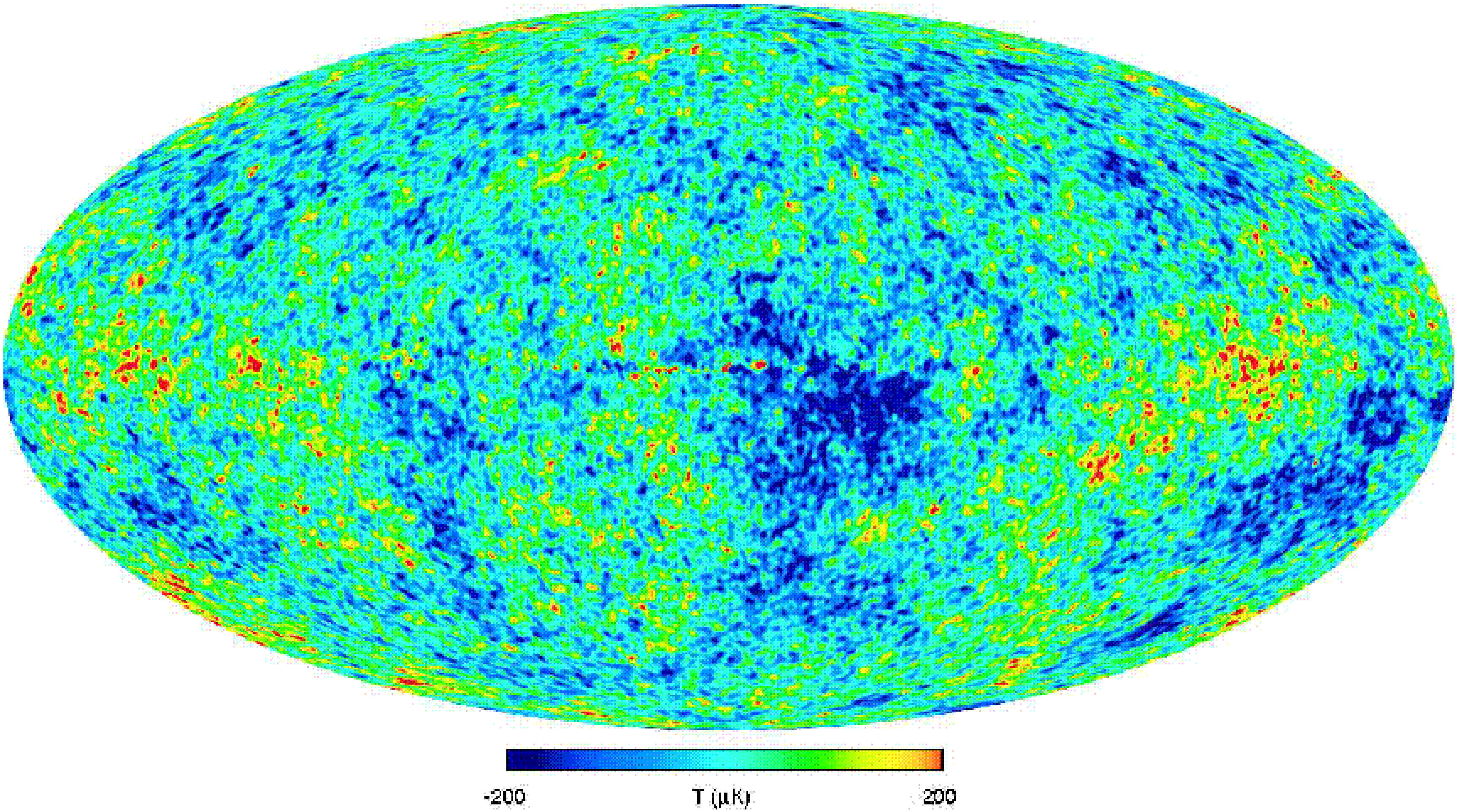


- Radiation from hot gas and dust in our own Milky Way

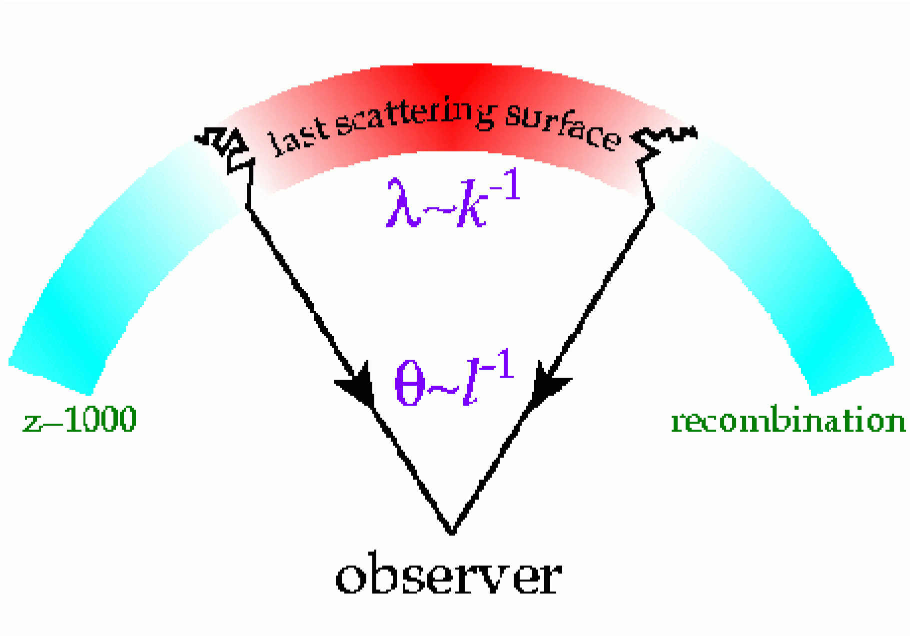


- Structure in the Microwave Background itself
  An image of structure in the `cosmic fog bank' at a distance of 40 billion light-years when the Universe was 370,000 years old

The *WMAP* of the whole CMB sky



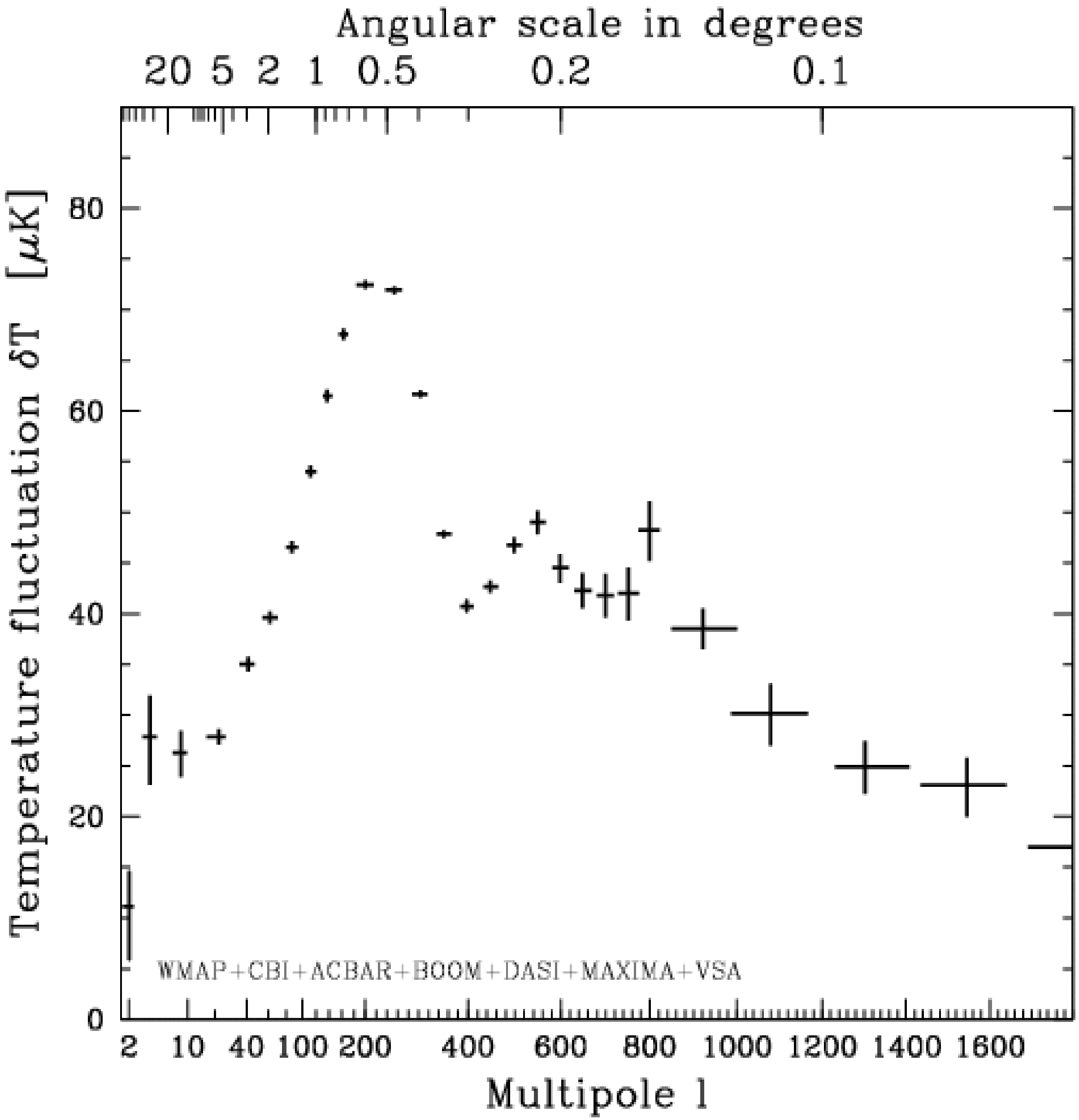
Bennett et al 2003



Observed fluctuations are gravitationally modified sound waves of amplitude ~ 10^{-5} propagating in the photon-baron-DM fluid in the last scattering surface at z ~ 1000 t ~ 370,000 yr

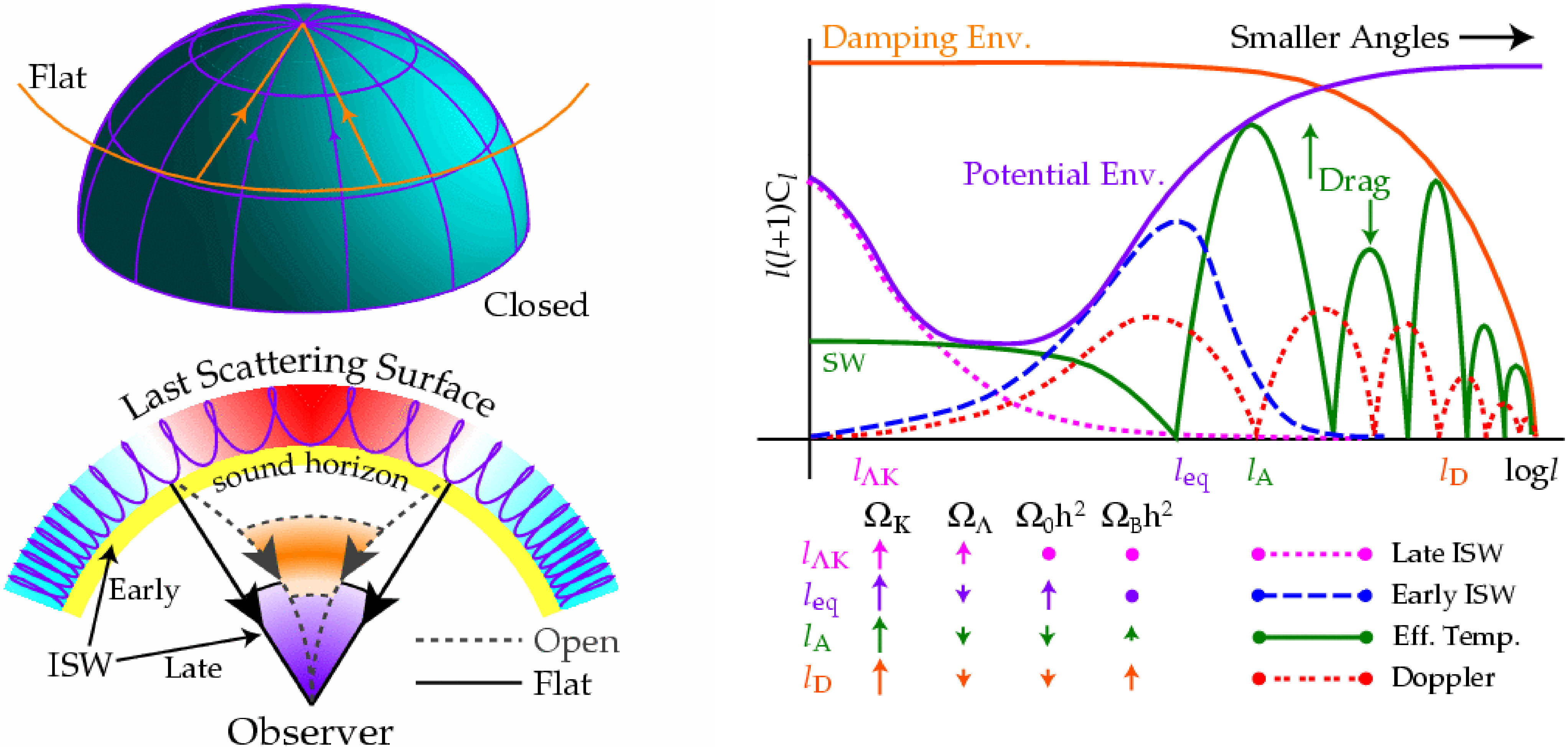
This (linear) sound wave field can be characterised by its Power Spectrum, the mean square amplitude of waves as a function of comoving spatial wavenumber $k \sim 2\pi / \lambda$

The corresponding CMB temperature fluctuation field can be characterised by its power spectrum as a function of $l \sim 2\pi / \theta$



Binned angular power spectrum of CMB temperature fluctuations for all experiments up to end of 2003

Tegmark 2004



Physical effects on the CMB power spectrum

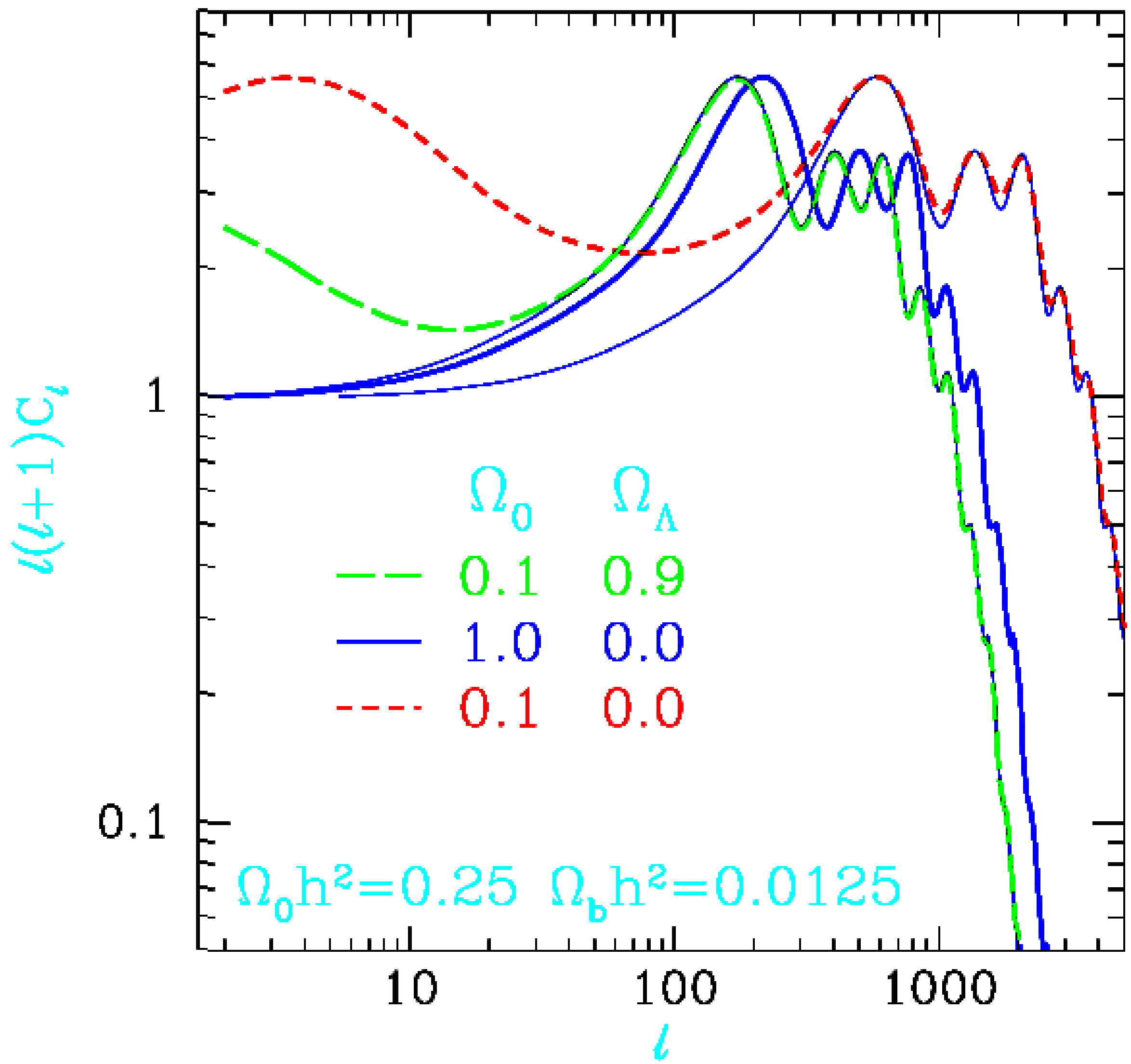
Geometry: The global geometry links physical lengths at z=1000 to angular scales on the sky → the *l*-positions of the peaks

Temperature fluctuations in the gas at z=1000 due to compression/ rarefaction in sound waves

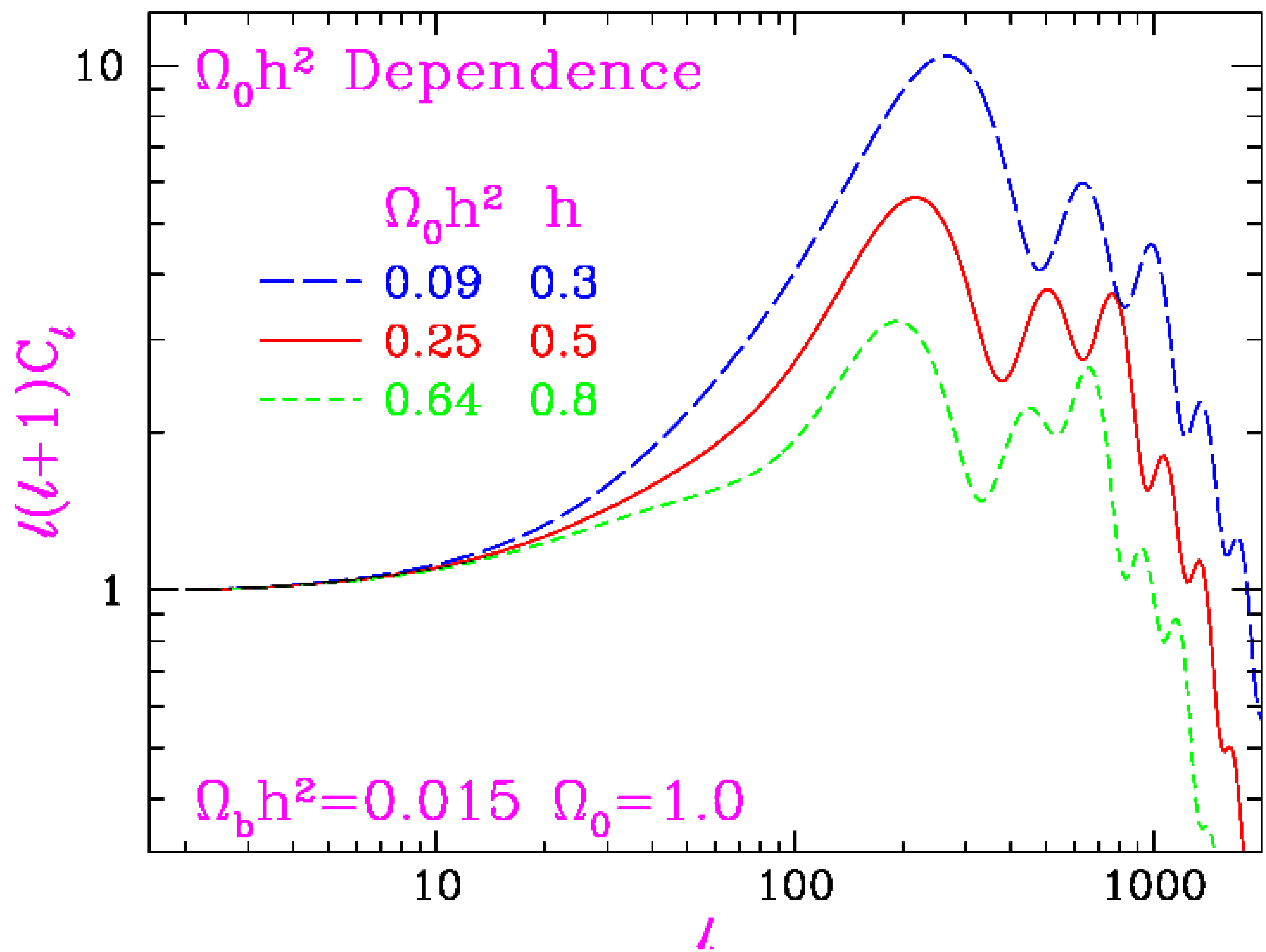
Motions in the gas at z=1000 due to the sound waves

Gravitational redshifts at z~1000 and at low z (Sachs-Wolfe effect)

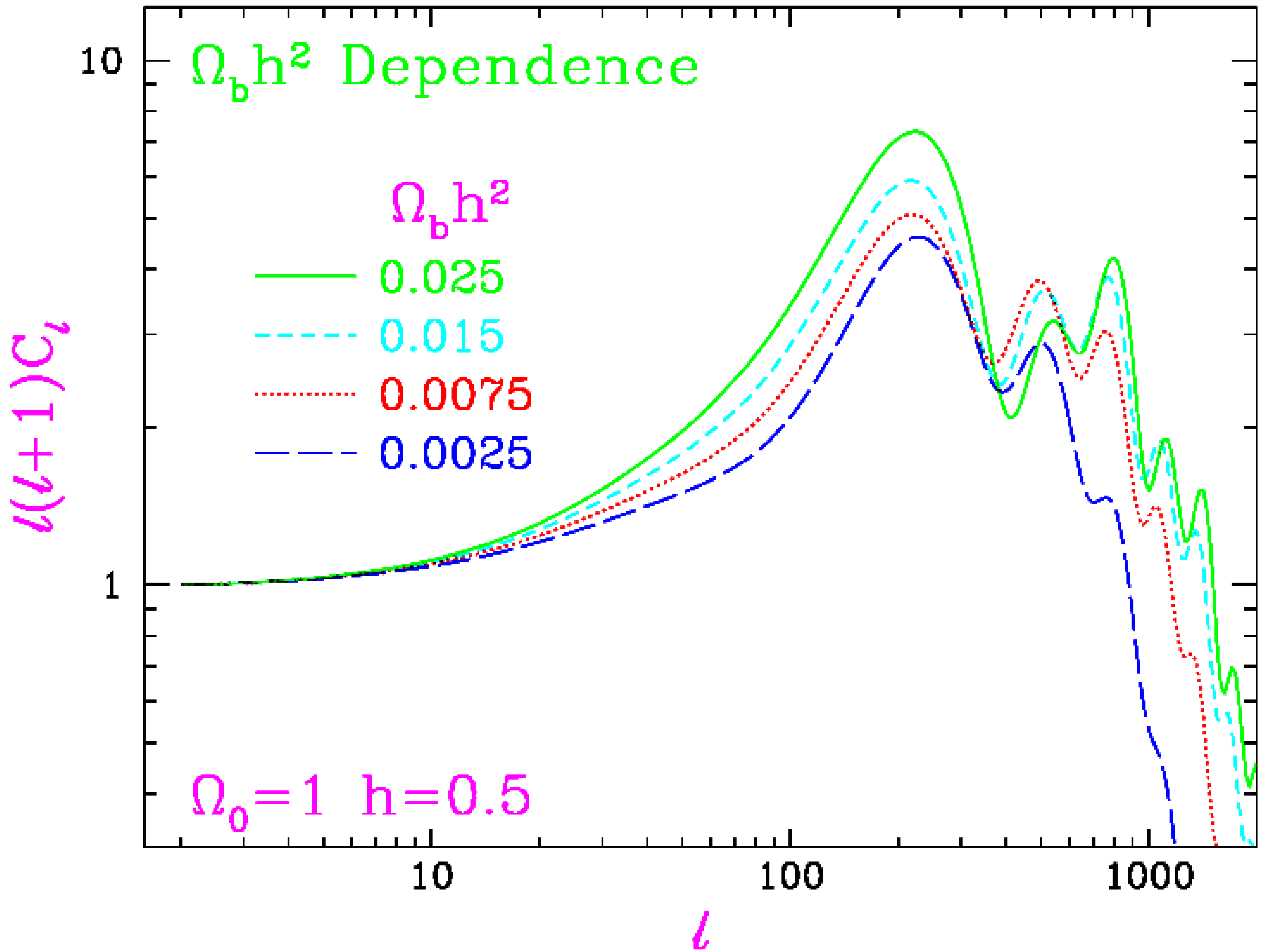
Variation of power spectrum with changing angular size distance to the last scattering surface. The change at low *l* is due to the low redshift integrated Sachs-Wolfe effect as the universe becomes curvature or Λ dominated. (See http://background.uchicago.edu/~whu)

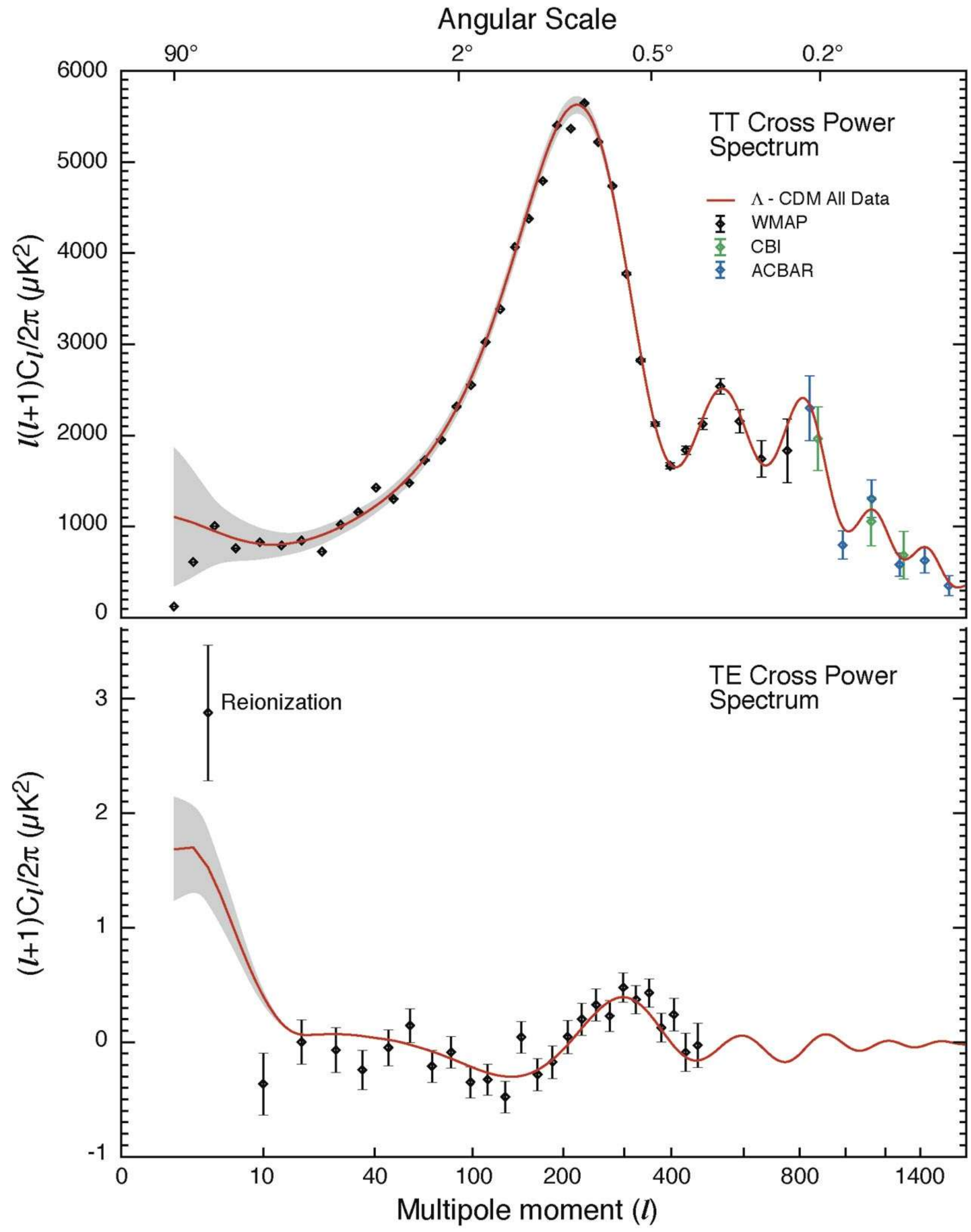


Variation of power spectrum with mass density for fixed baryon and photon density and a flat universe without Λ



Variation of the power spectrum with the baryon density. The effect at high *l* is due to diffusive damping of the short-wavelength sound waves (Silk damping).





Initial conditions for the formation of all structure

- Our Universe is flat
- It is 13.7 ± 0.2 billion years old.
- It is made of 70% dark energy, 26% cold dark matter and only 4% normal baryonic matter
- 370,000 years after the Big Bang it was nearly uniform
- All structure was imprinted in the first 10^{-30}s by quantum fluctuations of the vacuum

Cosmological parameters from the first year of WMAP data, *assuming* that the Universe is flat (Spergel et al 2003)

TABLE 1

POWER-LAW ΛCDM MODEL PARAMETERS: *WMAP* DATA ONLY

Parameter	Mean (68% Confidence Range)	Maximum Likelihood
Baryon density, $\Omega_b h^2$	0.024 ± 0.001	0.023
Matter density, $\Omega_m h^2$	0.14 ± 0.02	0.13
Hubble constant, h	0.72 ± 0.05	0.68
Amplitude, A	0.9 ± 0.1	0.78
Optical depth, τ	$0.166^{+0.076}_{-0.071}$	0.10
Spectral index, n_s	0.99 ± 0.04	0.97
$\chi^2_{\rm eff}/\nu$		1431/1342

NOTE.—Fit to *WMAP* data only.

n = 1 corresponds to the Harrison-Zel'dovich scale invariant initial spectrum

Cosmological parameters from the first year of WMAP data, *assuming* that the Universe is flat (Spergel et al 2003)

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] $l_A = \pi d_C / r_s$.

Nonlinear growth of structure in the standard ΛCDM paradigm with inflationary fluctuations adjusted to fit the WMAP data on CMB fluctuations

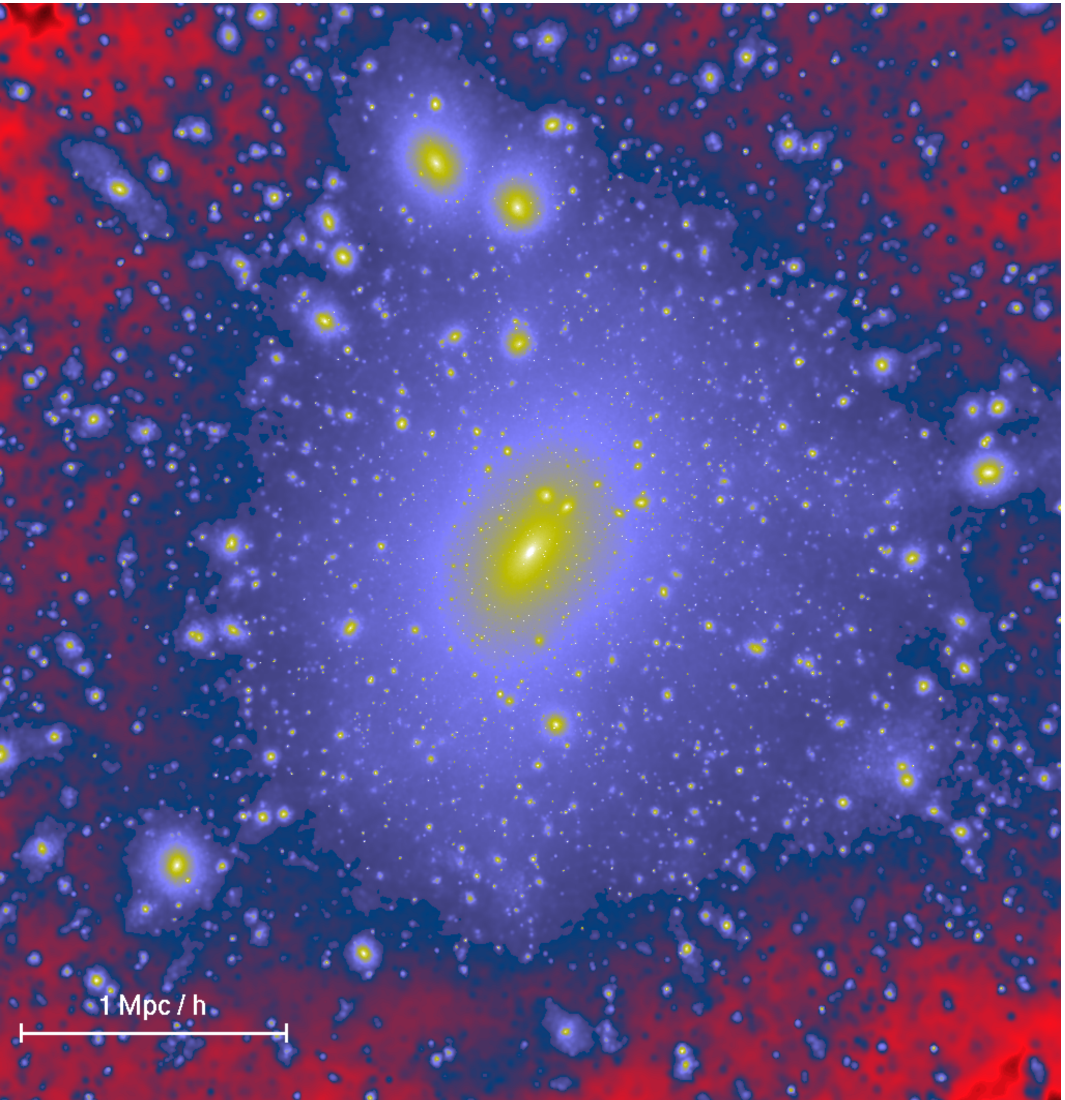
Evolution of the dark matter distribution in a thin slice centred on a galaxy cluster at z=0

Zoom into a rich cluster from a very large-scale image of the z=0 DM distribution in a thin slice

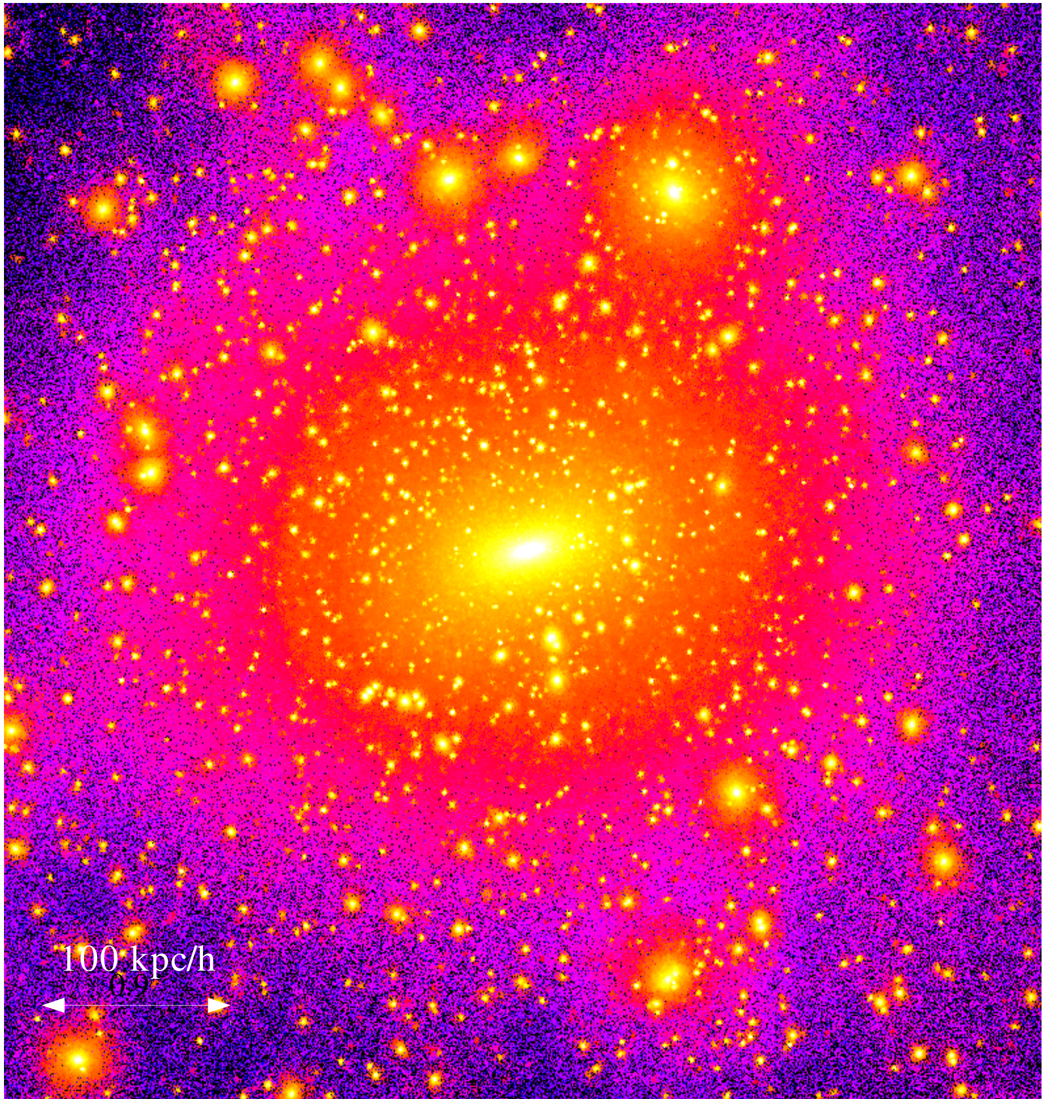
Evolution of the DM and gas distributions, the X-ray and S-Z images of a rich galaxy cluster

Small-scale structure in ΛCDM halos

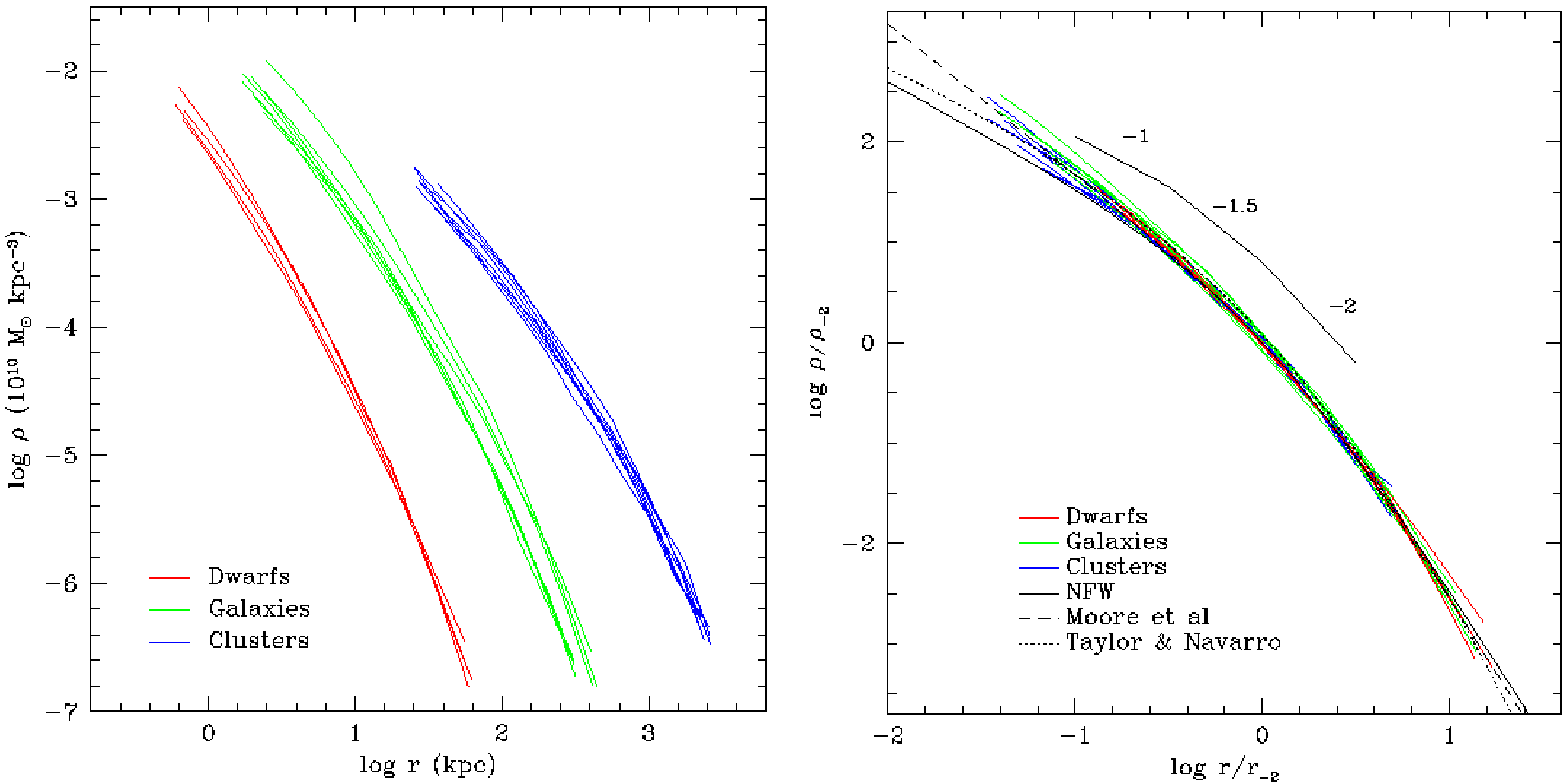
A rich galaxy cluster halo
Springel et al 2001



A 'Milky Way' halo
Power et al 2002



Profiles from high-resolution simulations

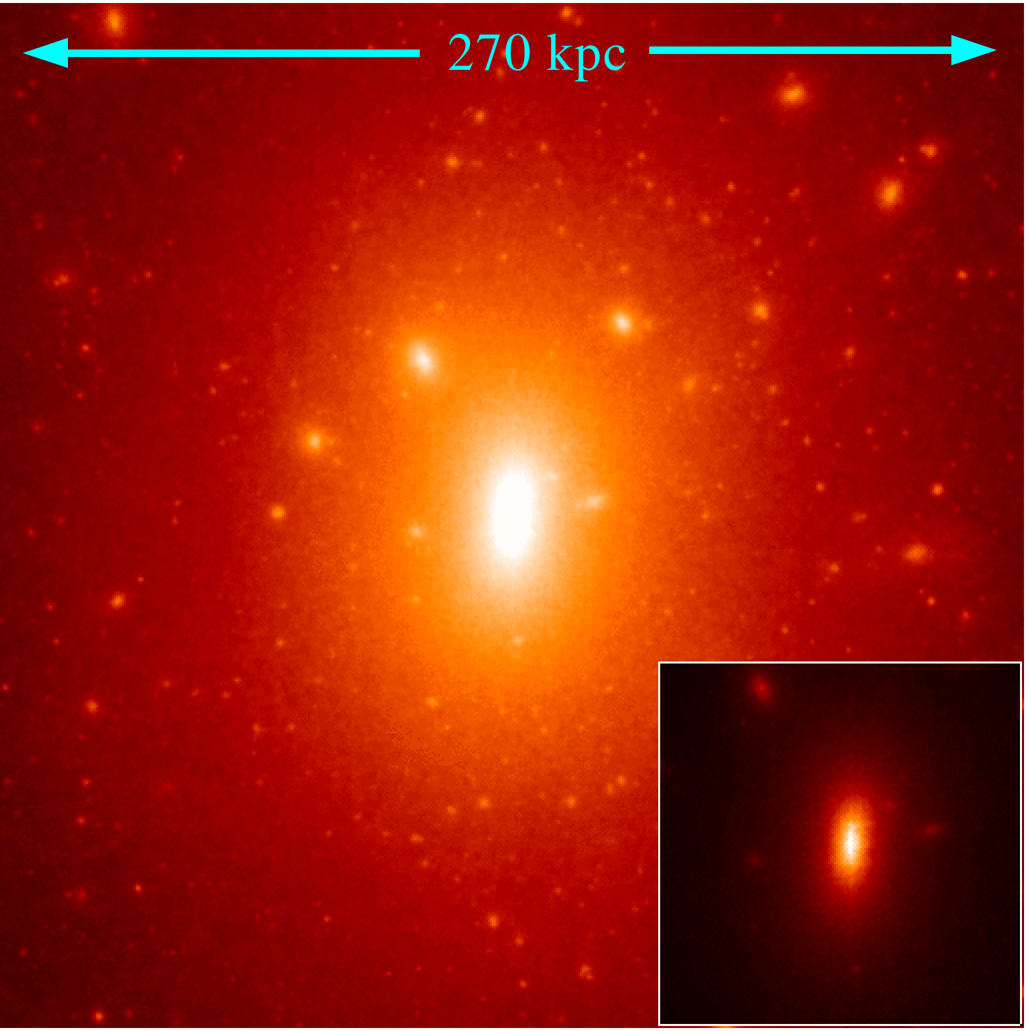


Hayashi, Navarro et al 2003

$N_{200} > 10^6$, $\epsilon \sim 0.002\ R_{200}$, convergence tested at all plotted points

γ-rays from the annihilation of DM particles

Stoehr et al 2003



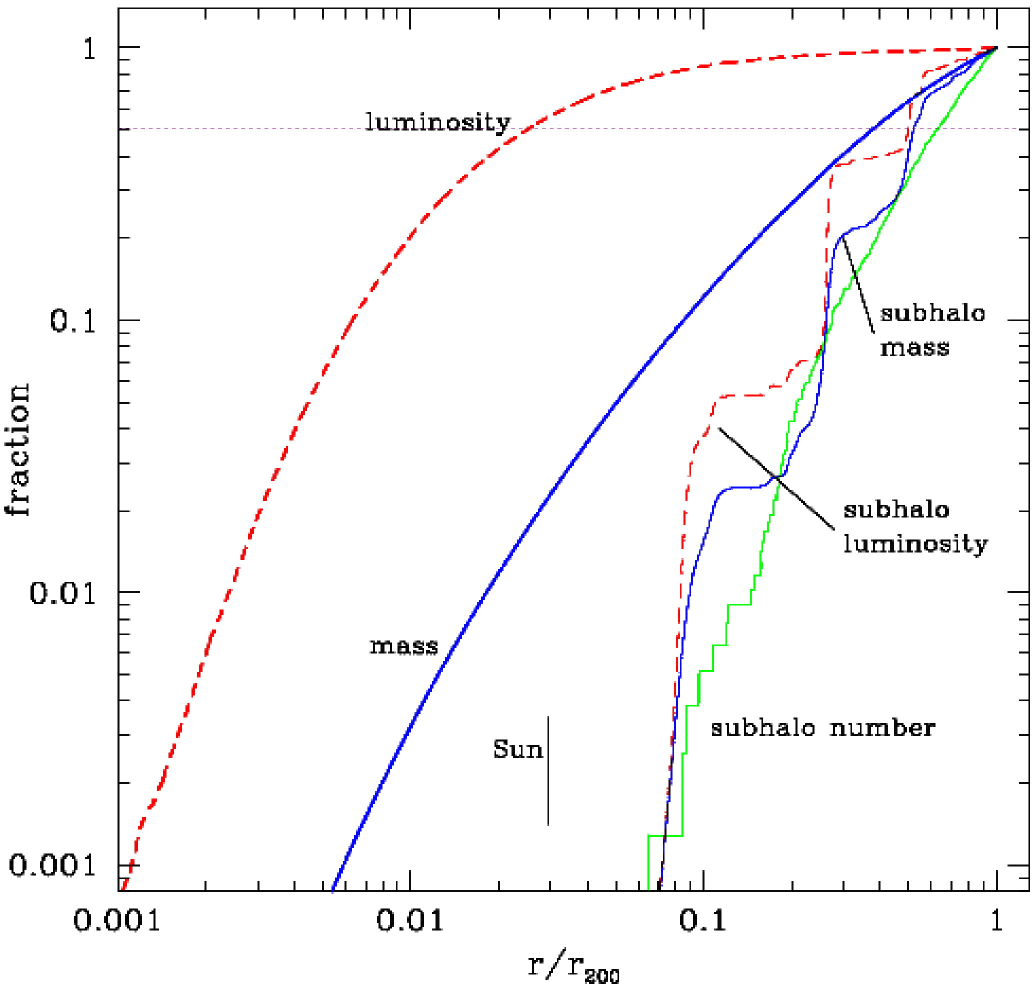
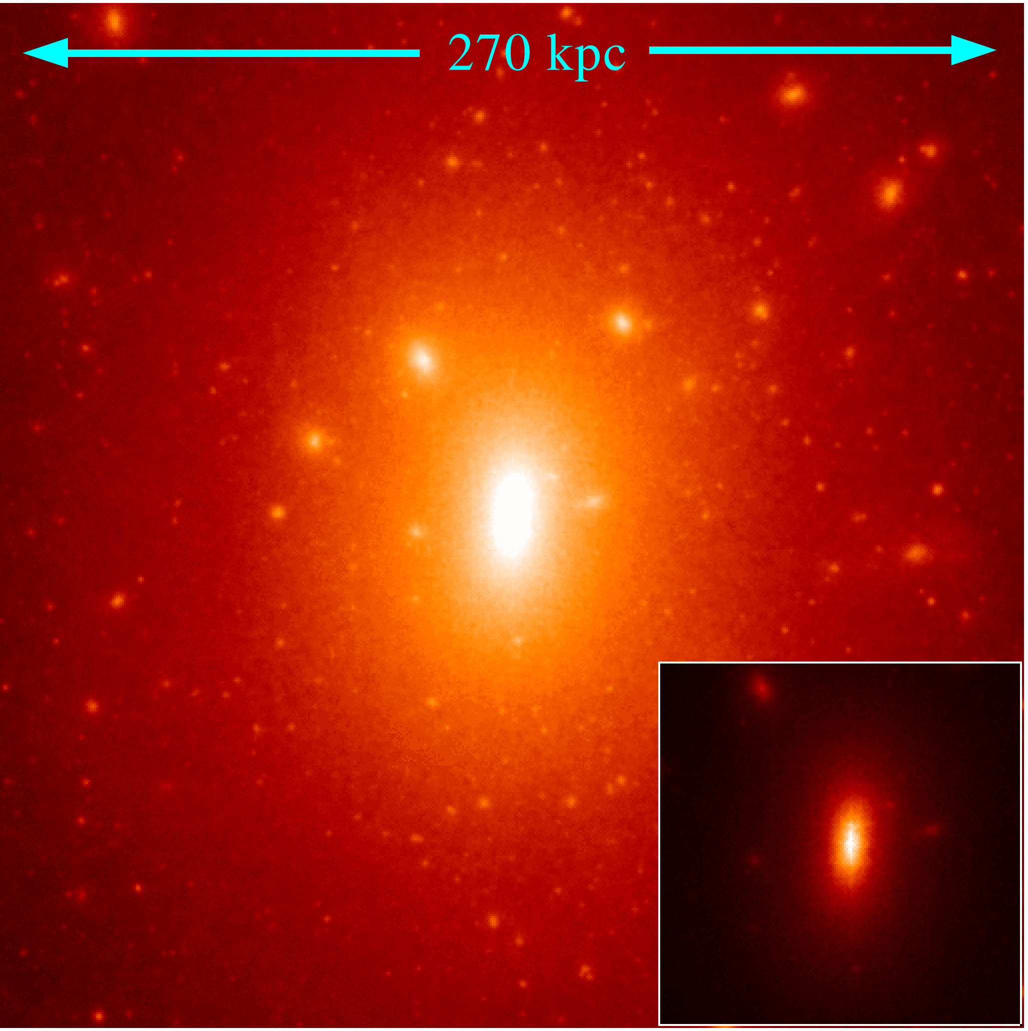


Image of a 'Milky Way' halo in annihilation radiation

Distributions of mass and of smooth and subhalo luminosity

γ-rays from the annihilation of DM particles

Stoehr et al 2003



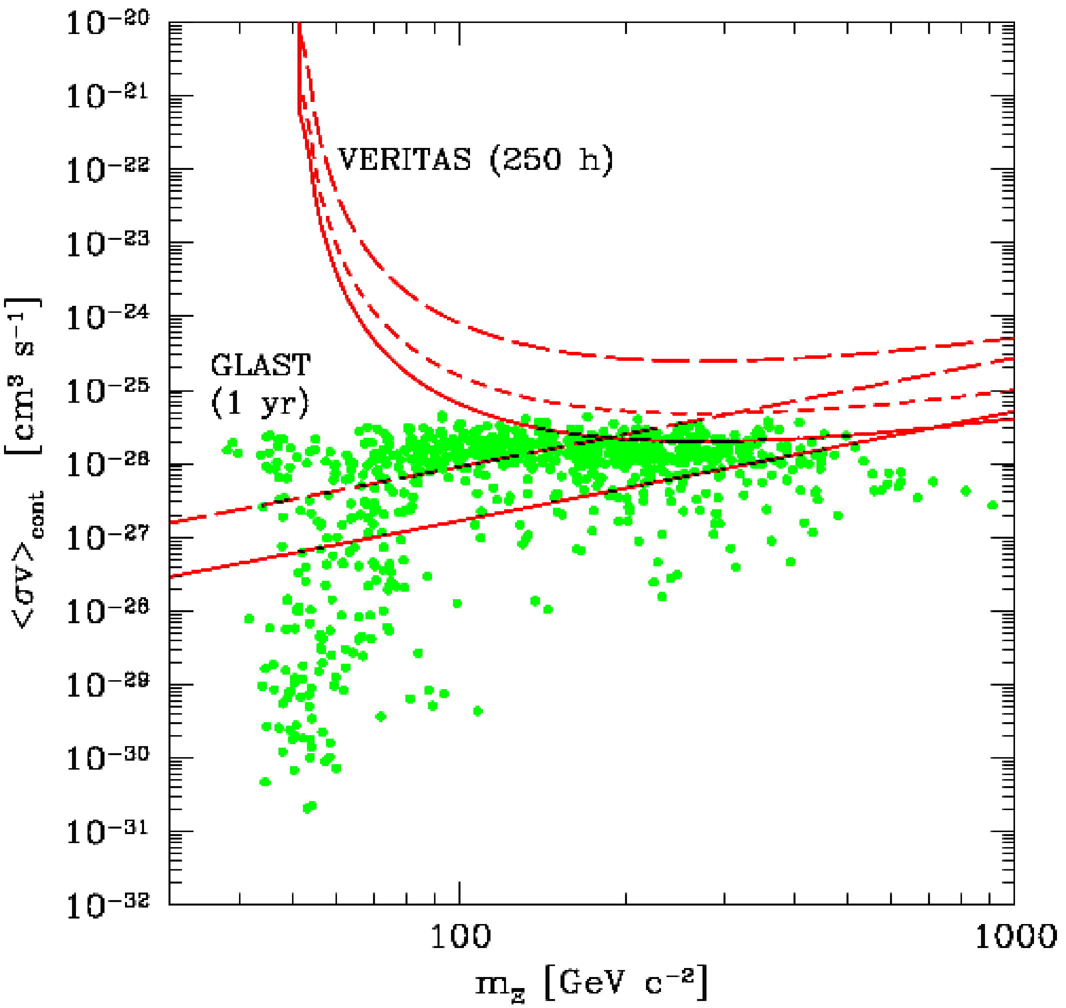


Image of a 'Milky Way' halo in annihilation radiation

Detection limits for minimal supersymmetric DM models