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SUMMER SCHOOL IN COSMOLOGY AND ASTROPARTICLE PHYSICS

28 June - 10 July 2004

An introduction to CMB anisotropies (I)

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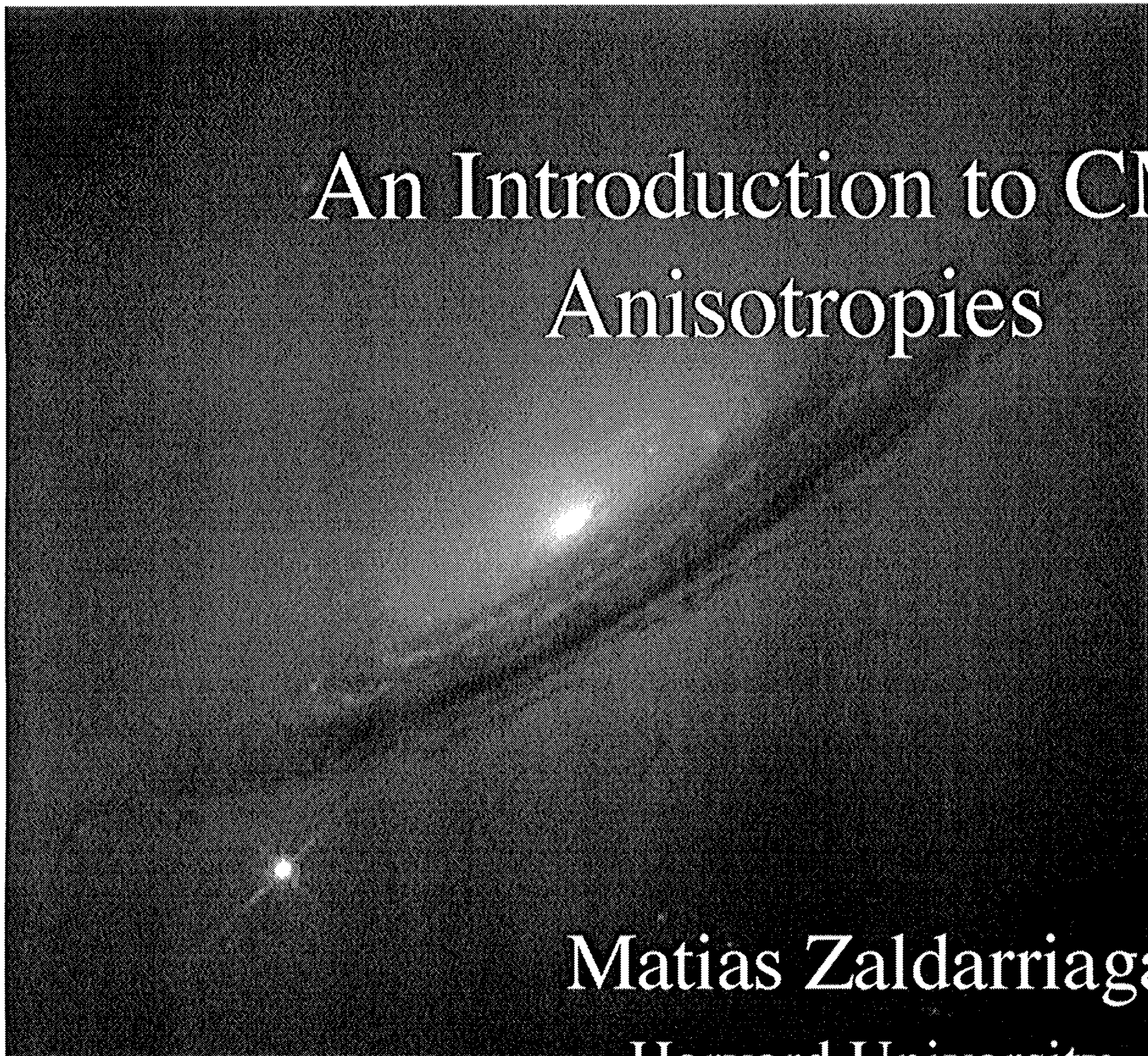
Please note: These are preliminary notes intended for internal distribution only.

An Introduction to CMB Anisotropies



Matias Zaldarriaga
Harvard University

Summer 2004

Basic Questions in Cosmology:

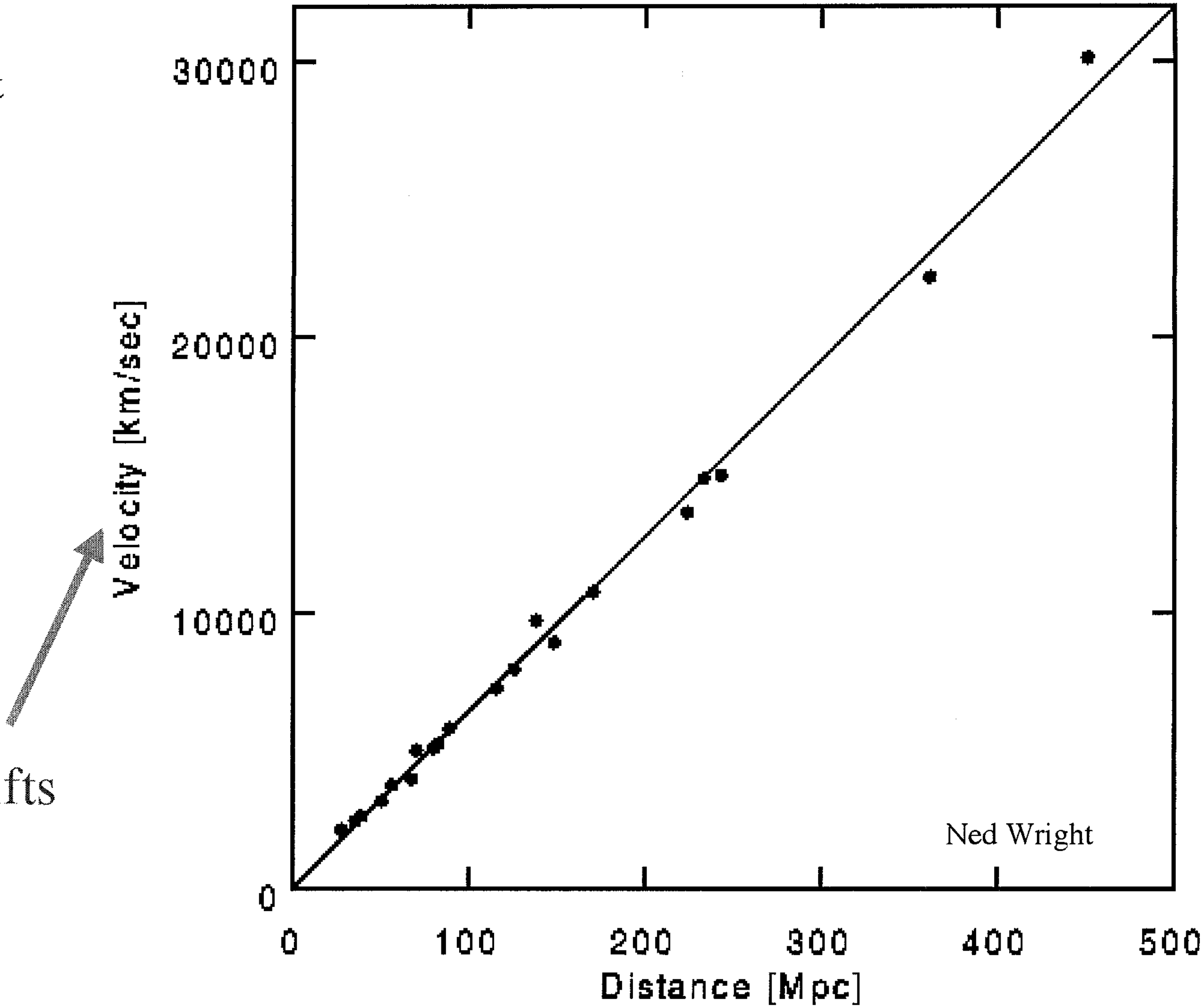
- How does the Universe evolve?
- What is the universe made off?
- How is matter distributed?
- How did structure form? Generation and evolution

Cosmology: Background

- Dynamics of the Expansion of the Universe
- Matter Components
- Recombination & Decoupling
- Basic Timeline

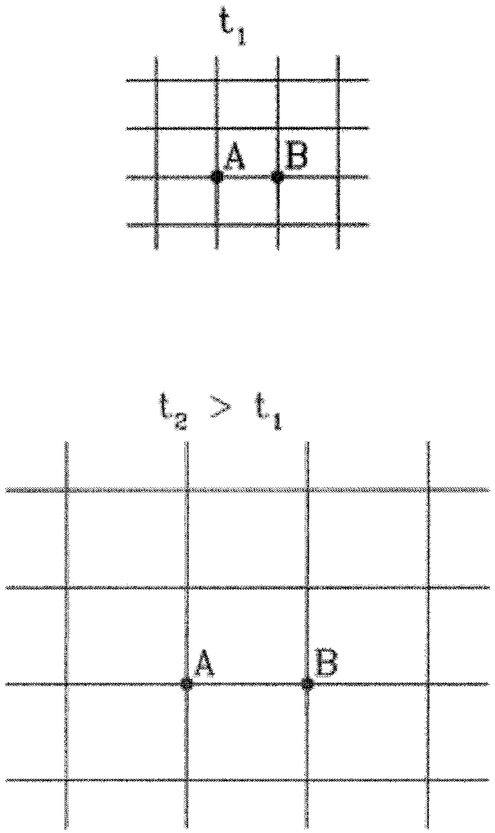
The Expansion of the Universe

Type Ia SNe
Riess, Press &
Kirshner '96



Measured
using redshifts

Expansion of the Universe



Basic Cosmology and Notation

We describe the expansion of the universe using the scale factor $a(t)$

$$r_{AB}(t) = a(t)x_{AB}, \tag{1}$$

which follows Friedmann equation,

$$(\frac{1}{a}\frac{da}{dt})^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{K}{a^2}, \tag{2}$$

Basic Cosmology and Notation

The Hubble constant $H_0 \equiv (a^{-1}da/dt)|_{t_0}$ characterizes the expansion rate at the present epoch. The critical density is defined as

$$\begin{aligned}\rho_{\rm crit} &\equiv \frac{3H_0^2}{8\pi G} \\ &= 1.9\;10^{-29}\;h^2 \text{grams cm}^{-3} \\ &= 2.8\;10^{11}\;h^2 M_\odot\;\text{Mpc}^{-3} \\ &= 1.1\;10^{-5}\;h^2 \text{protons cm}^{-3}. \end{aligned} \tag{3}$$

Consequences of the Expansion

The Universe is not always the same.

The Universe was denser in the past.

The Universe was hotter in the past.

The Universe has several components

- Radiation
- Normal matter (protons, electrons, neutrinos, etc)
- Dark matter
- Dark “energy”

They all contribute th the right hand side of the Friedmann equation

Density vs a

$$p = w\rho \quad \begin{cases} w &= 0 \quad \text{non-relativistic matter} \\ w &= 1/3 \quad \text{radiation} \\ w &= -1 \quad \text{vaccum energy} \end{cases}$$

$$d(a^3\rho) = -pda^3 \quad \Rightarrow \quad \rho \propto a^{-3(1+w)}$$

Different species dominate at different times

$$H^2 = \frac{\rho}{M_{pl}^2}$$

Matter equal radiation when $a \sim 3 \times 10^{-4}$

$$\frac{\ddot{a}}{a} = -\frac{2}{M_{pl}^2}(\rho + 3p) = -\frac{2}{M_{pl}^2}\rho(1 + 3w)$$

Acceleration if $w < -1/3$

Basic Cosmology and Notation

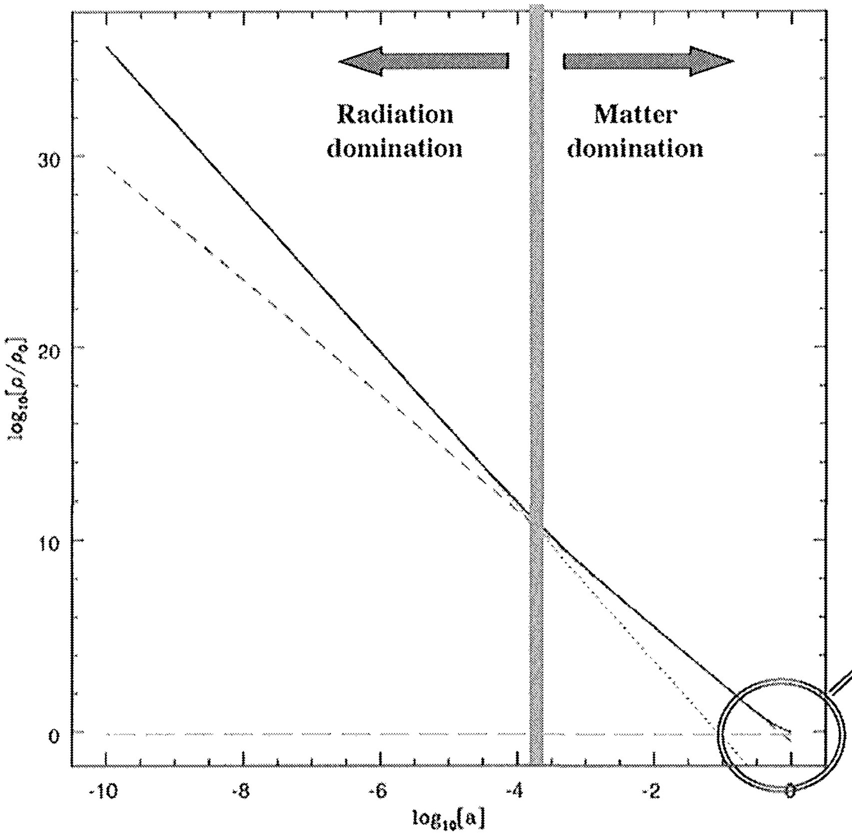
We can rewrite (2) in terms of the different densities at the present epoch measured in terms of the critical density ($\Omega_i = \rho_{i0}/\rho_{\rm crit}$),

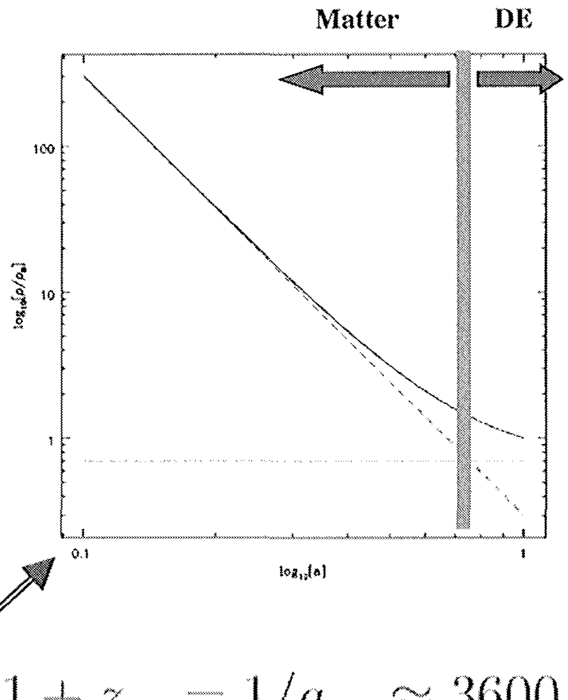
$$\begin{aligned} \left(\frac{1}{a}\frac{da}{dt}\right)^2 &= H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_v + \Omega_K a^{-2}] \\ 1 &= \Omega_m + \Omega_r + \Omega_v + \Omega_K. \end{aligned} \qquad (4)$$

We have introduced $\Omega_K = K/\rho_{\rm crit}$. The second line in equation (4) follows from evaluating the first at t_0, it is true by definition.

$$\rho_{i0} = \Omega_i \rho_{\rm crit} = \Omega_i \frac{3H_0^2}{8\pi G} \propto \Omega_i h^2, \qquad (5)$$

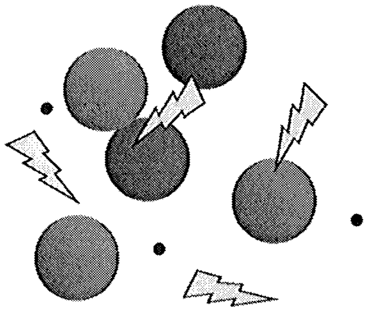
Evolution of the density



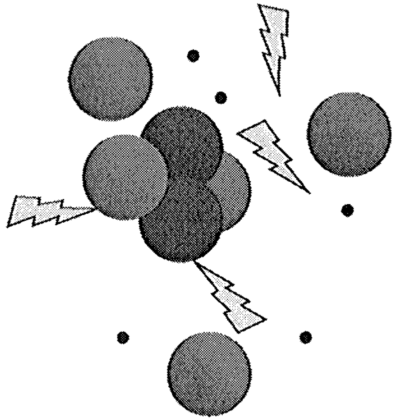


$$1 + z_{eq} = 1/a_{eq} \approx 3600$$

$$\Omega_m = 0.3\ ;\ \Omega_v = 0.7$$



Expansion

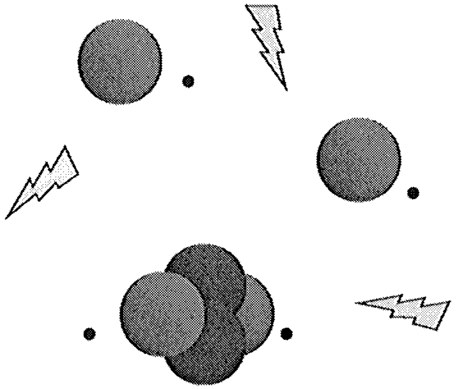


Expansion

Primordail "soup": protons, neutrons, electrons, photons. Temperature too high to form nuclei.

<u>Nucleosynthesis</u>

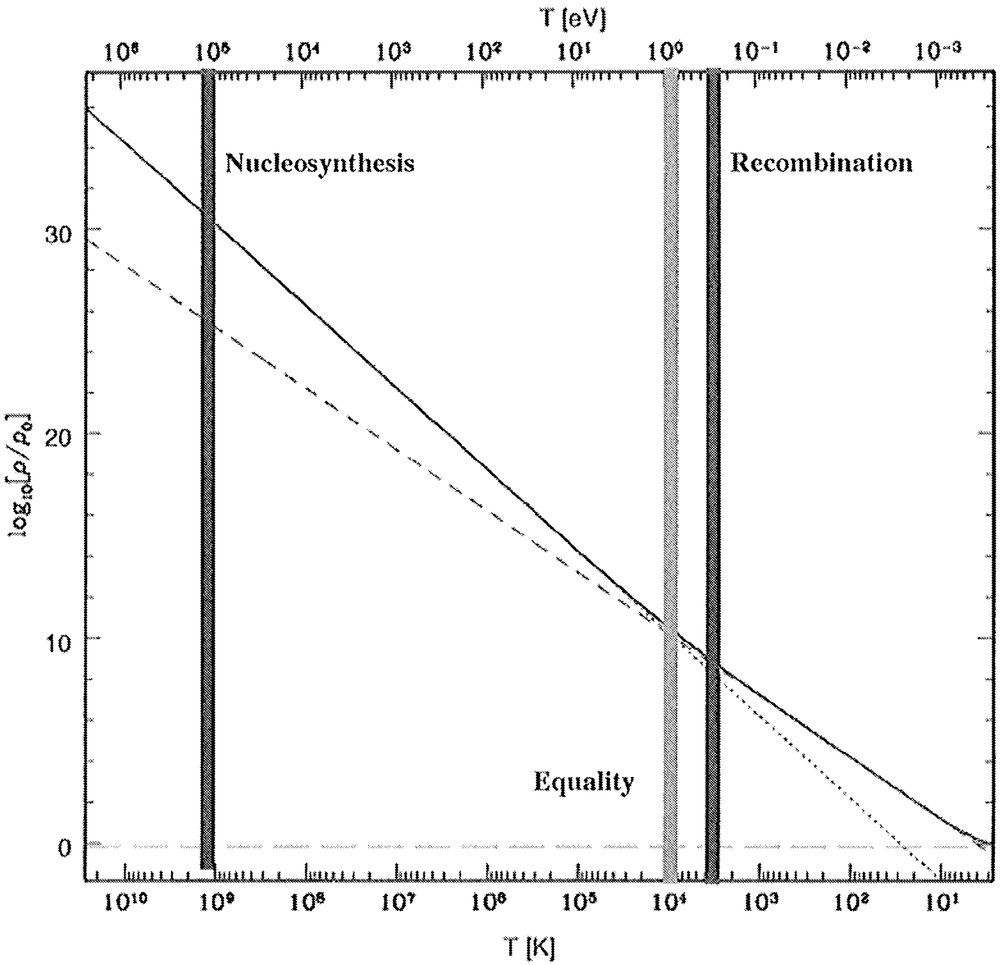
First minutes after the Big Bang: formation of Helium, Deuterium and Lithium.



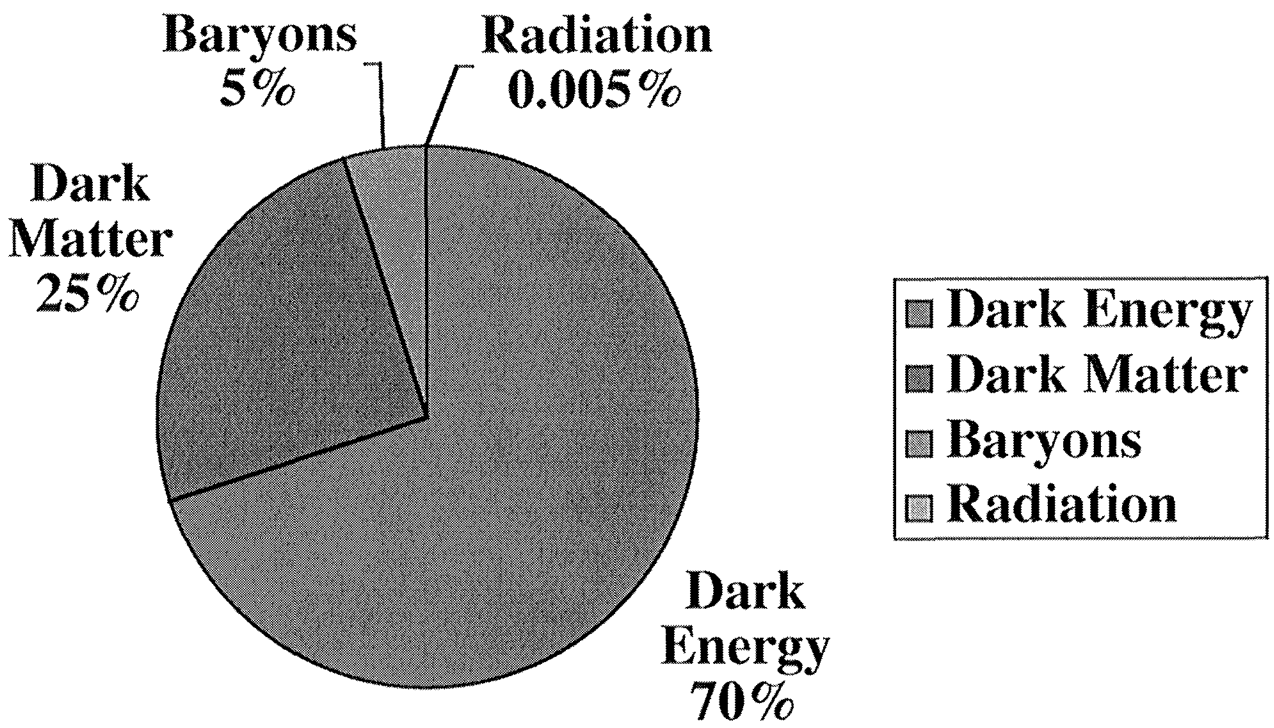
<u>Recombination</u>

300,000 after the Big Bang. Universe cools enough to form neutral hydrogen. The universe becomes transparent to photons.

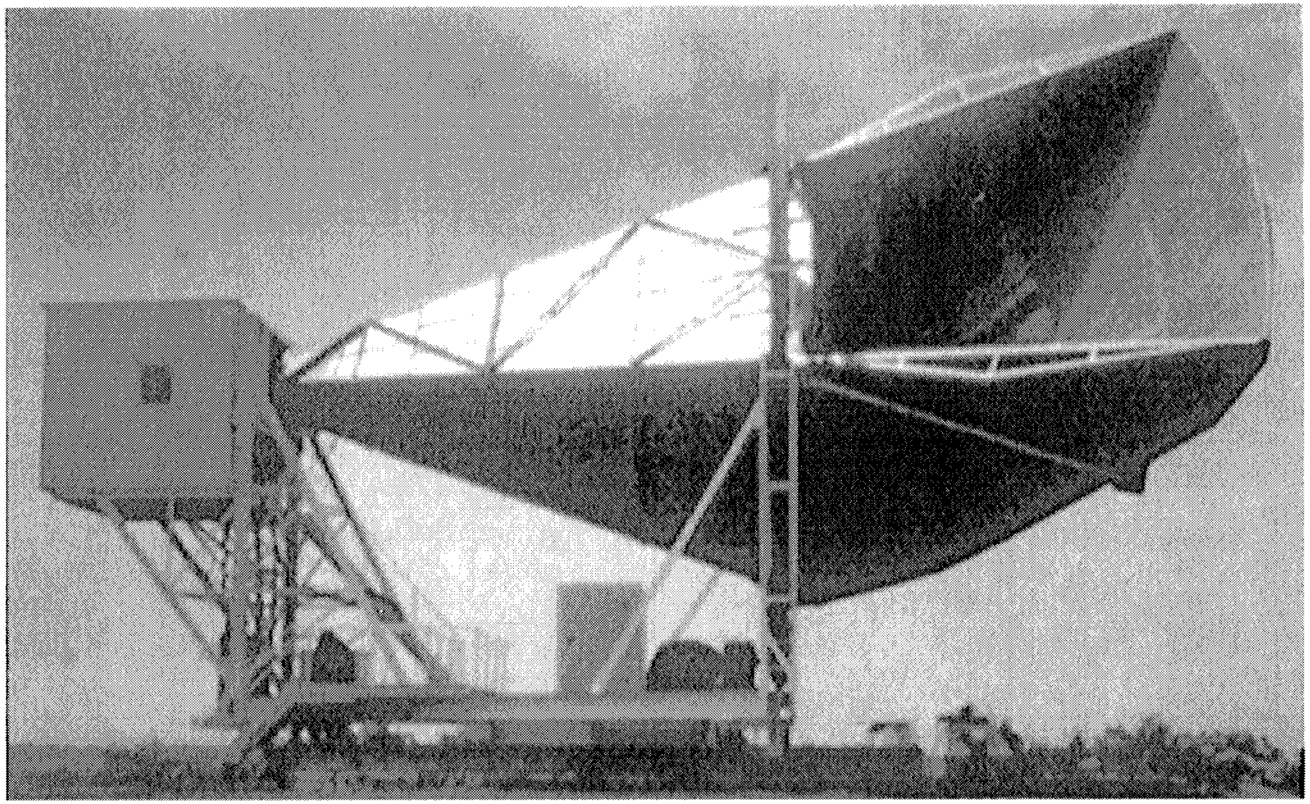
Thermal History



Matter content of the Universe



Photons: The Cosmic Microwave Background



Penzias & Wilson 1965

The Spectrum of the CMB

$n_\gamma \approx 422\ cm^{-3}$
$\Omega_\gamma \approx 5\ 10^{-5}$

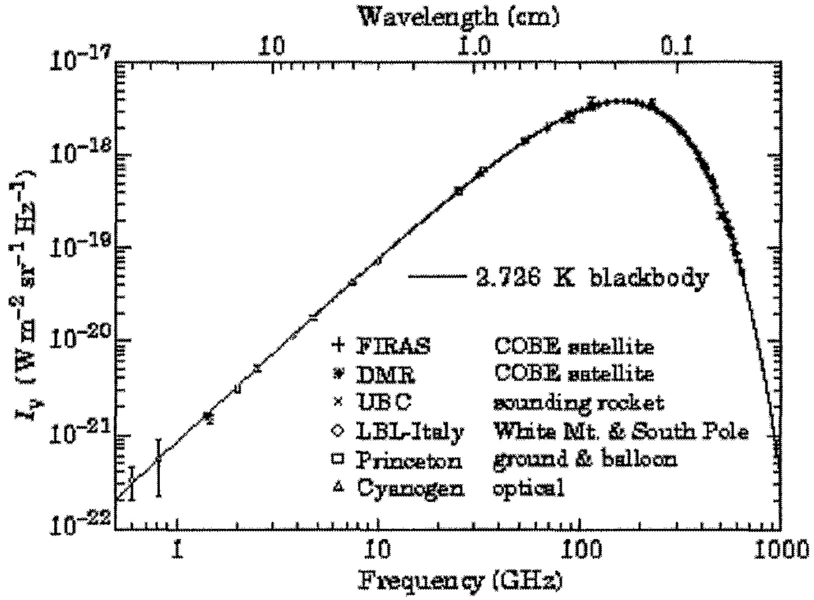
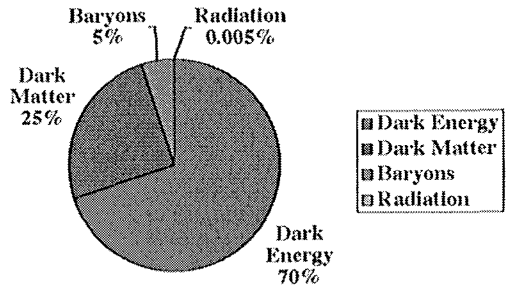


Figure 1. Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at frequencies of 3 GHz and below (10 cm and longer wavelengths). (References for this figure are at the end of this section under "CMB Spectrum References.")

Smoot & Scott
'98

Baryons:



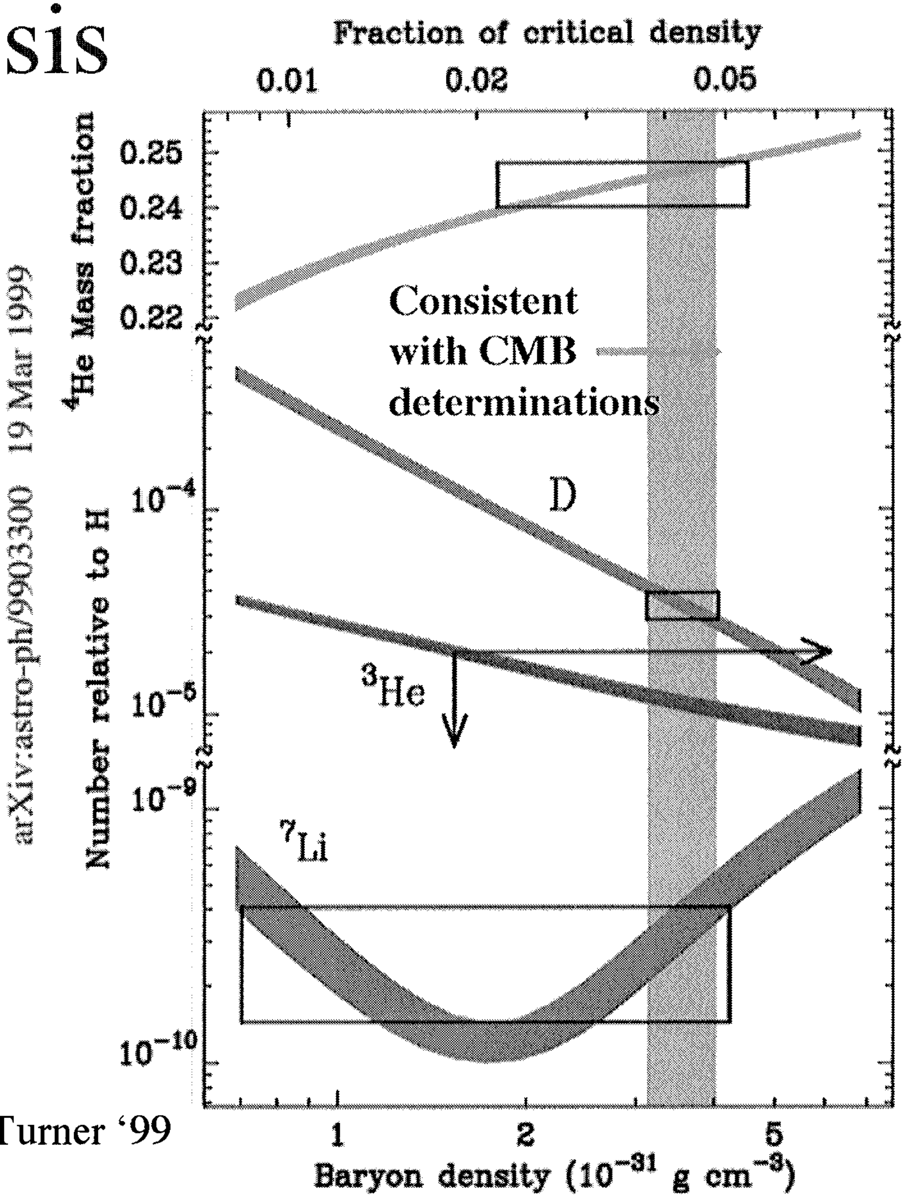
Stars, gas, etc. Seen by their emission and absorption of light

The best ways to count baryons are BBN and the CMB anisotropies.

There are approximately 2×10^9 CMB photons for every baryon.

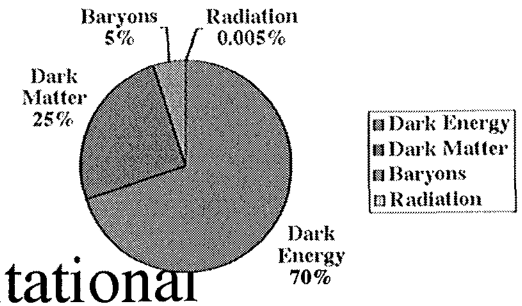
Nucleosynthesis

Light elements were created when the temperature of the CMB was in the MeV range, roughly a minute after the Big Bang.



Burles, Nollet & Turner '99

Dark matter:



Indirectly detected through its gravitational effect in systems such as galaxies, cluster of galaxies.

The best ways to estimate the mean density of dark matter are the CMB anisotropies.

The density of DM is roughly 5 times larger than the baryon density.

Good Particle physics candidates: LSP thermally produced, Axion

Dark Matter in Galaxies

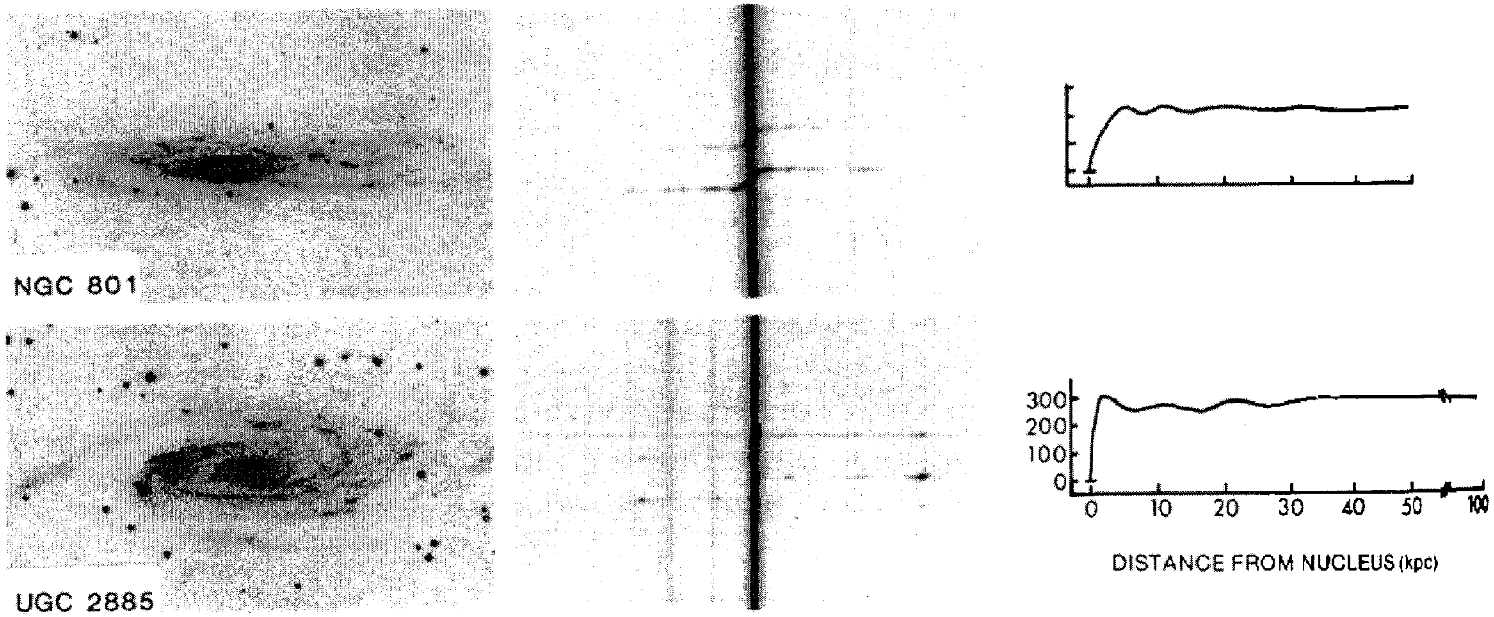
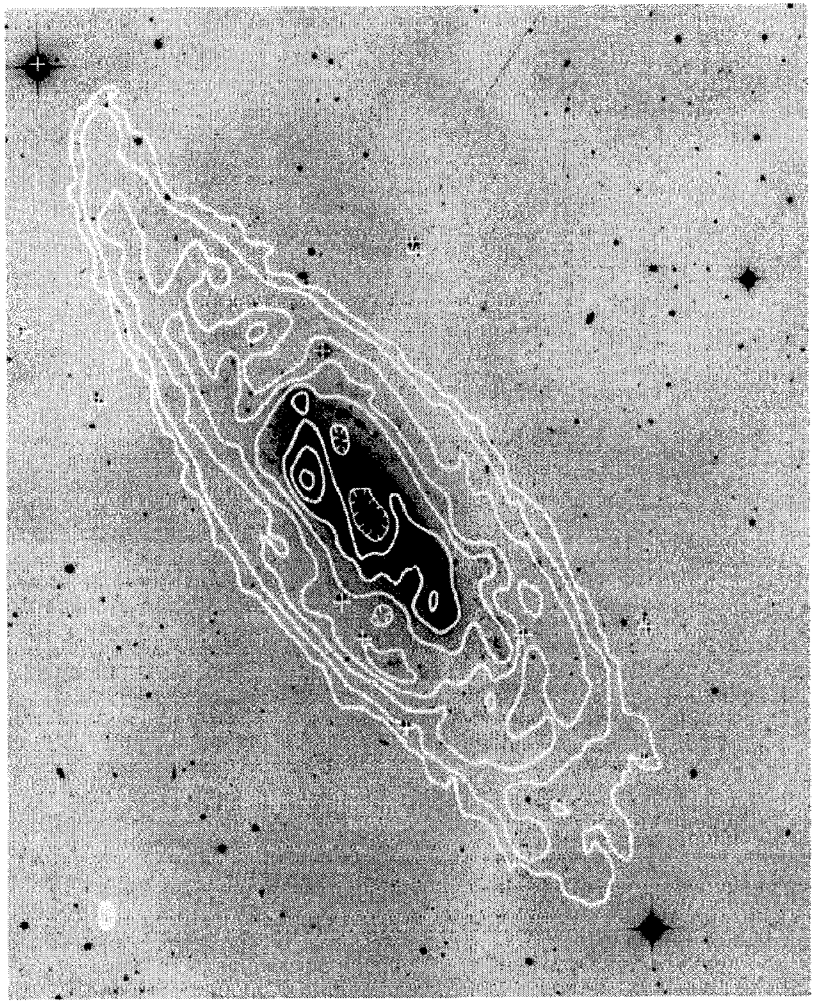


Figure 10-1. Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each spectrum is continuum emission from the nucleus. The distance scales are based on a Hubble constant $h = 0.5$. Reproduced from Rubin (1983), by permission of *Science*.

see: Binney, Tremaine (1994) *Galactic Dynamics* p.600



see: van Albada et al. (1985) *ApJ*, **295**, 305

NGC 3198 (optical and radio emission)
HI measured using 21cm transition

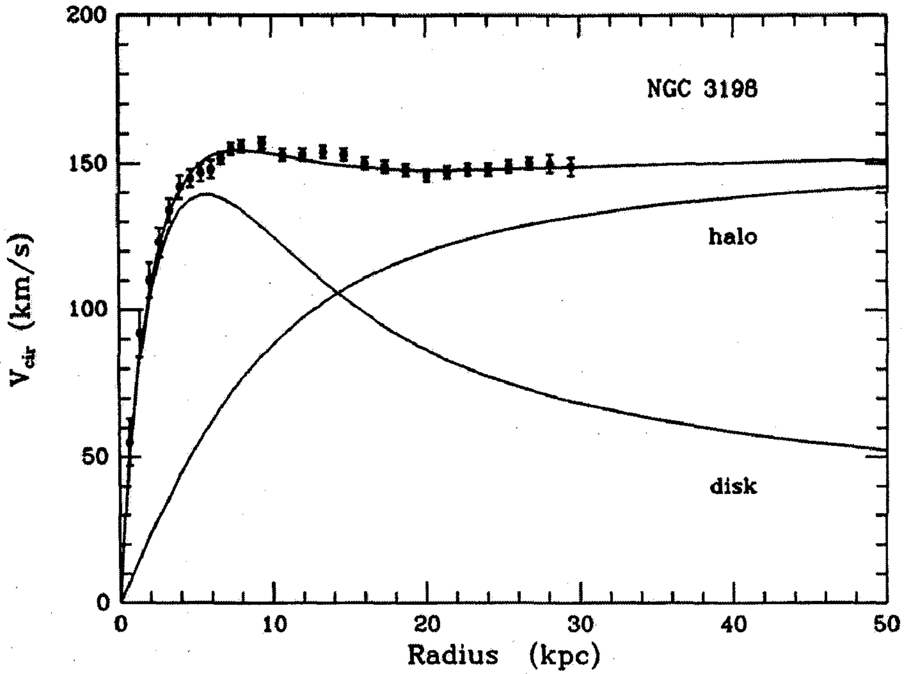


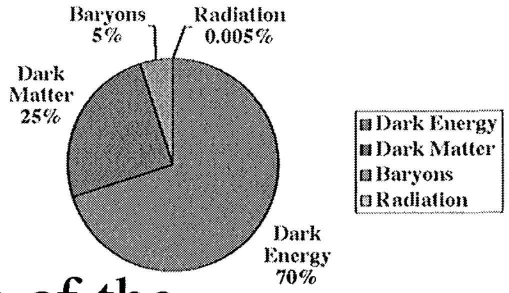
FIG. 4.—Fit of exponential disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the disk has been taken equal to that of the light distribution (60″, corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0) = 0.0040\ M_\odot\ pc^{-3}$.

see: van Albada et al. (1985) *ApJ*, **295**, 305

There are other ways to infer the presence of dark matter

Gravitational Lensing
Effect on the CMB
Gravitational effect in clusters of galaxies

Dark Energy:



Only indirectly detected through its gravitational effect on the expansion of the universe

The best ways to estimate the current energy density are type Ia SN and the CMB anisotropies.

The present energy density in DE is roughly 70% of the total.

NO Particle physics understanding

The Friedman equation:

The rate of expansion is related to the energy density

$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\bar{\rho} - \frac{K}{a^2},$$

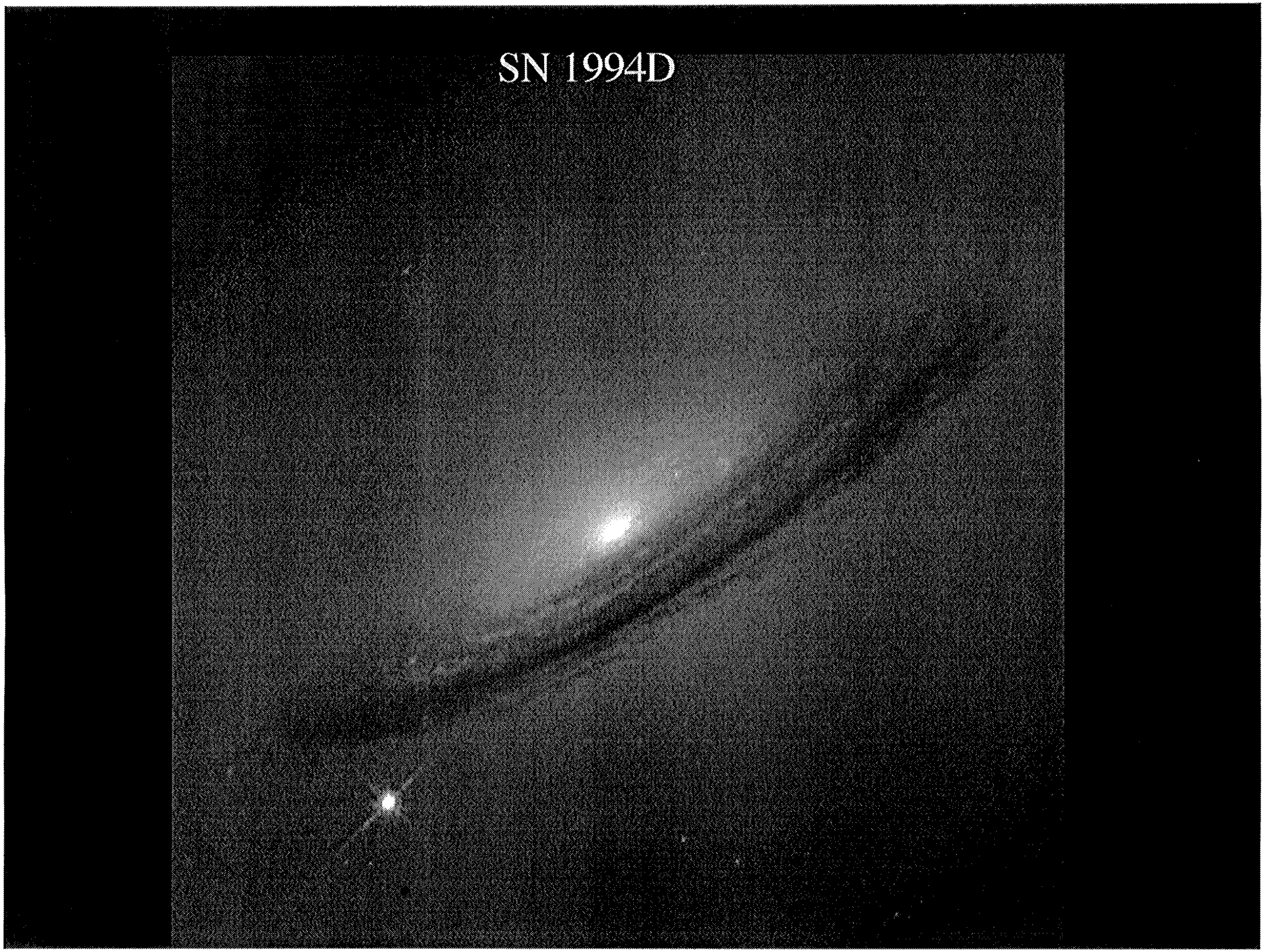
$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_v + \Omega_K a^{-2}]$$

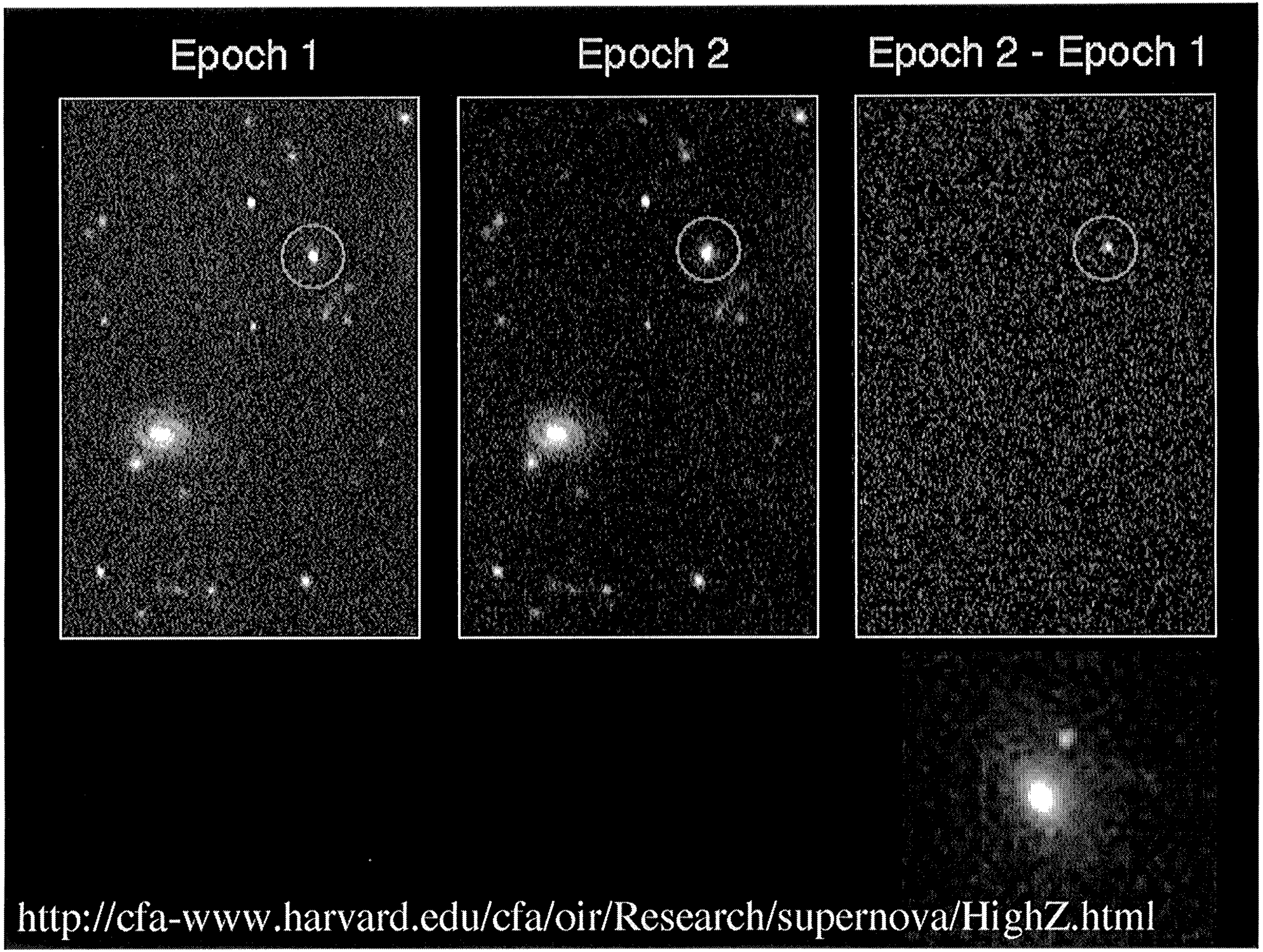
$$1 = \Omega_m + \Omega_r + \Omega_v + \Omega_K.$$

The time it takes the universe to expand by a certain factor depends on its matter content.

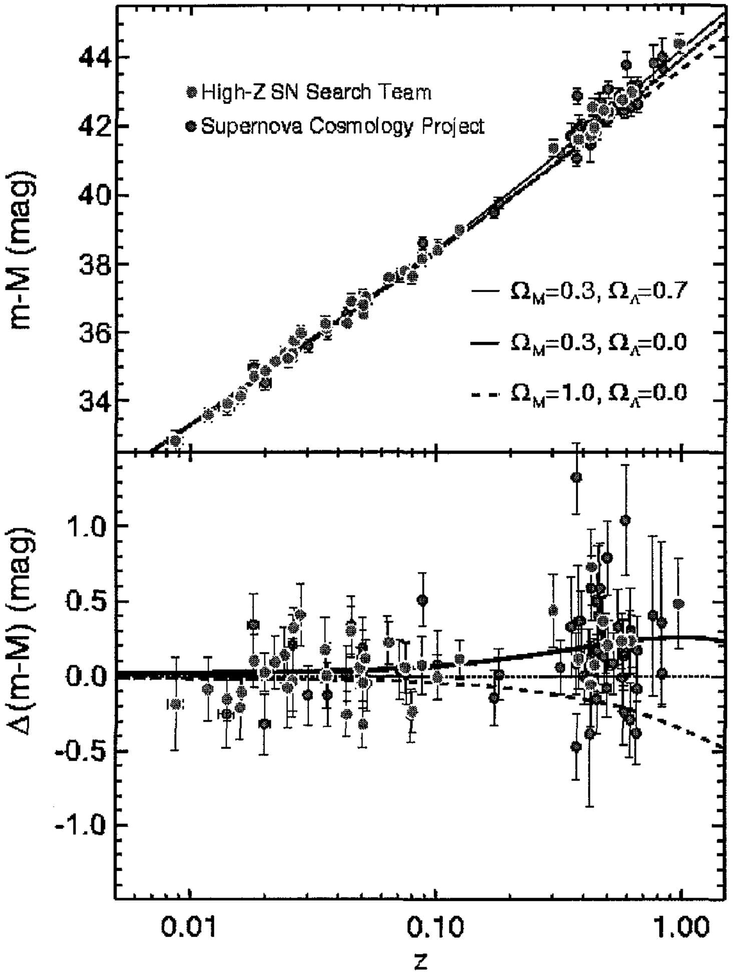
The distance light can travel while the universe expands from a_1 to a_2 depends on the matter content (a_2/a_1 is measured by the redshift).

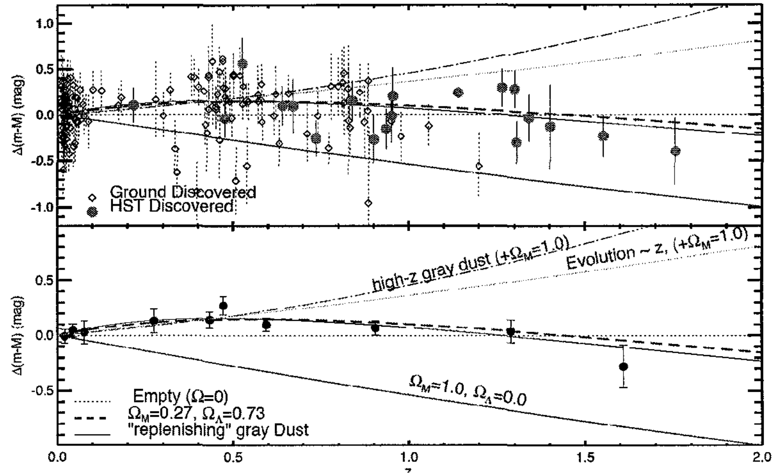
The apparent brightness of an object depends on the matter content.

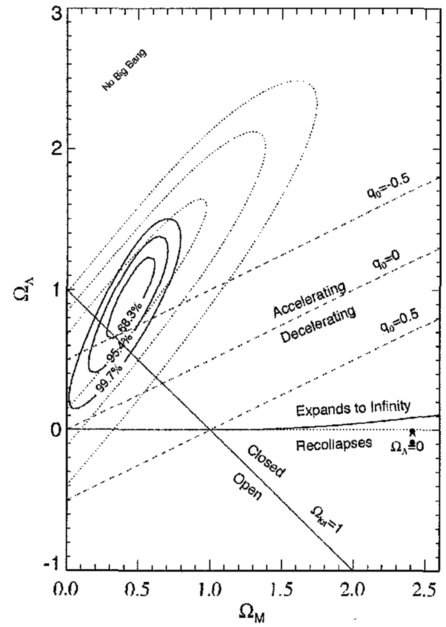

SN 1994D


Epoch 1
Epoch 2
Epoch 2 - Epoch 1
http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html

Supernovae results







Could GR be wrong ?

How is matter distributed?

Matter is not distributed uniformly

It forms structure on many scales

The level of structure evolves with time

Hubble Deep Field

Hubble Space Telescope • WFPC2

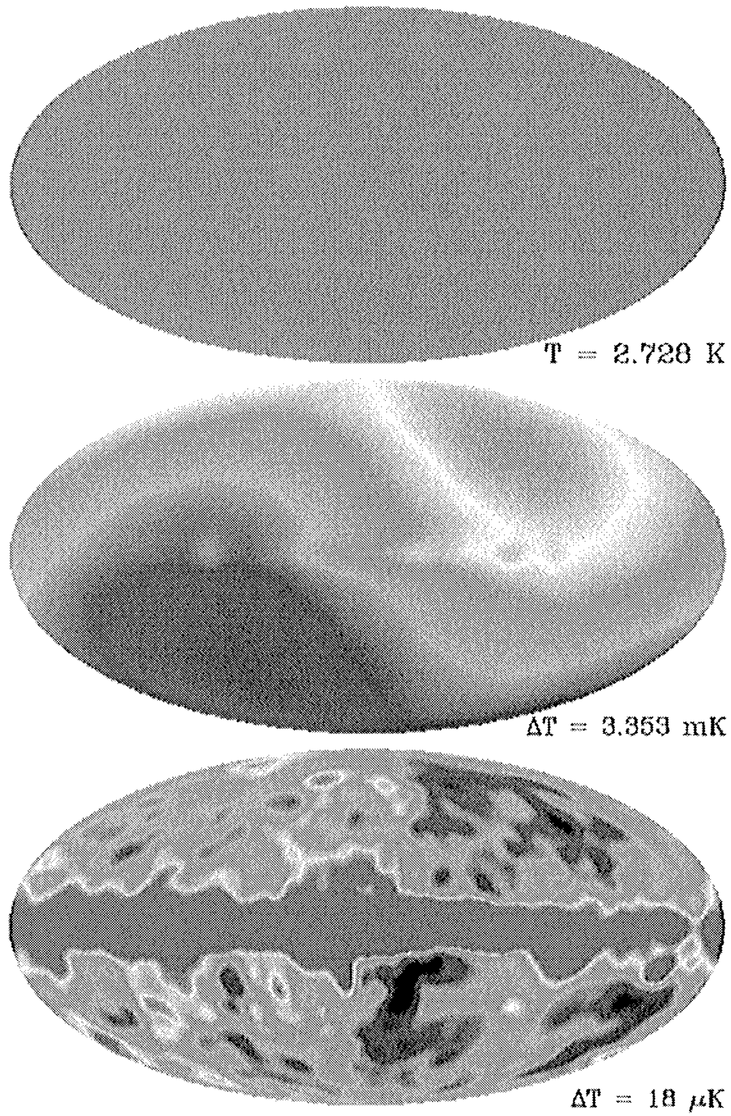
PRC96-01a • ST ScI OPO • January 15, 1995 • R. Williams (ST ScI), NASA

Probes of Large Scale Structure

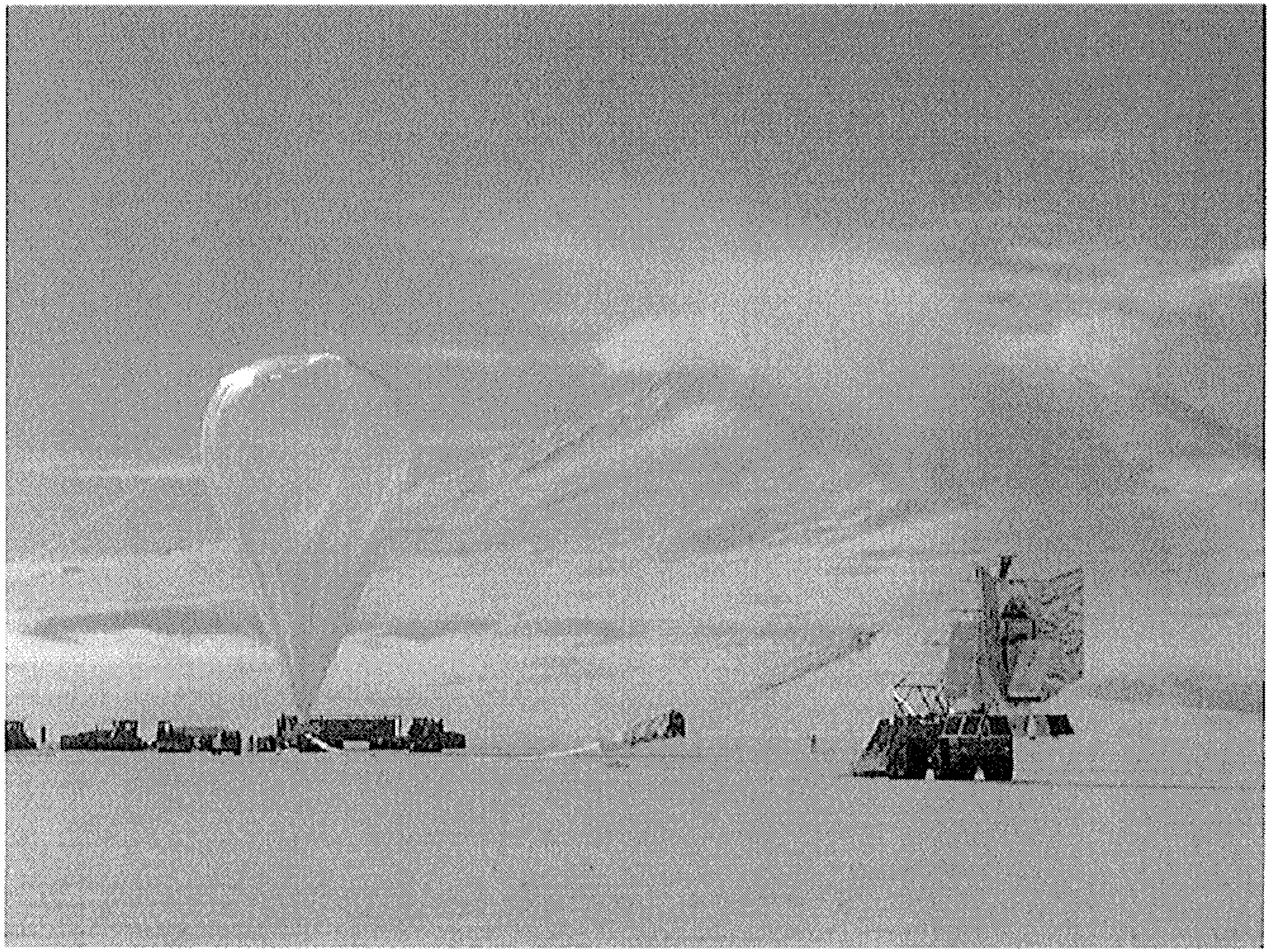
- The cosmic microwave background
- The distribution of Galaxies
- Weak gravitational lensing
- The Lyman alpha forest

Anisotropies in the CMB temperature

COBE 1992

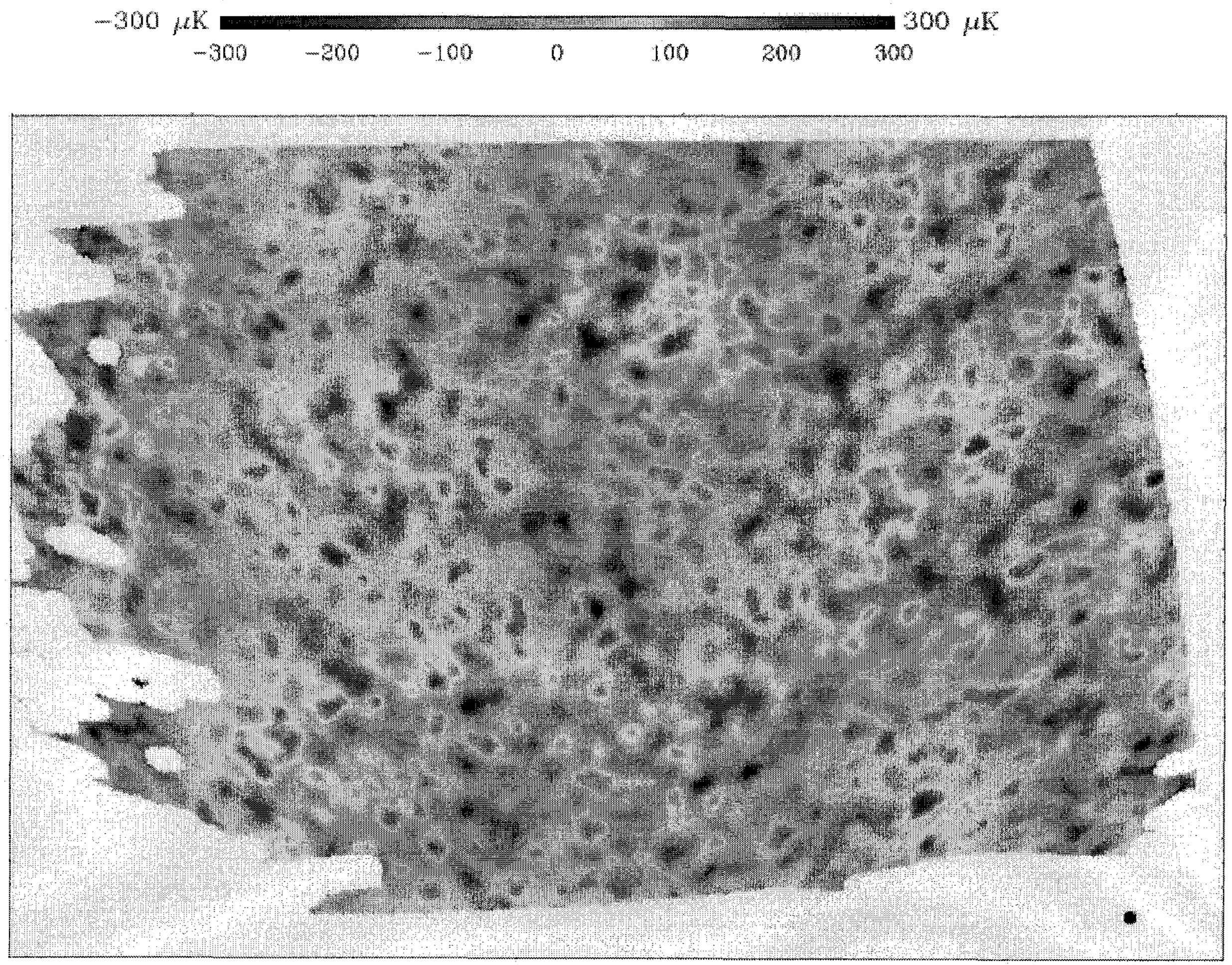


Boomerang Launch 12/98

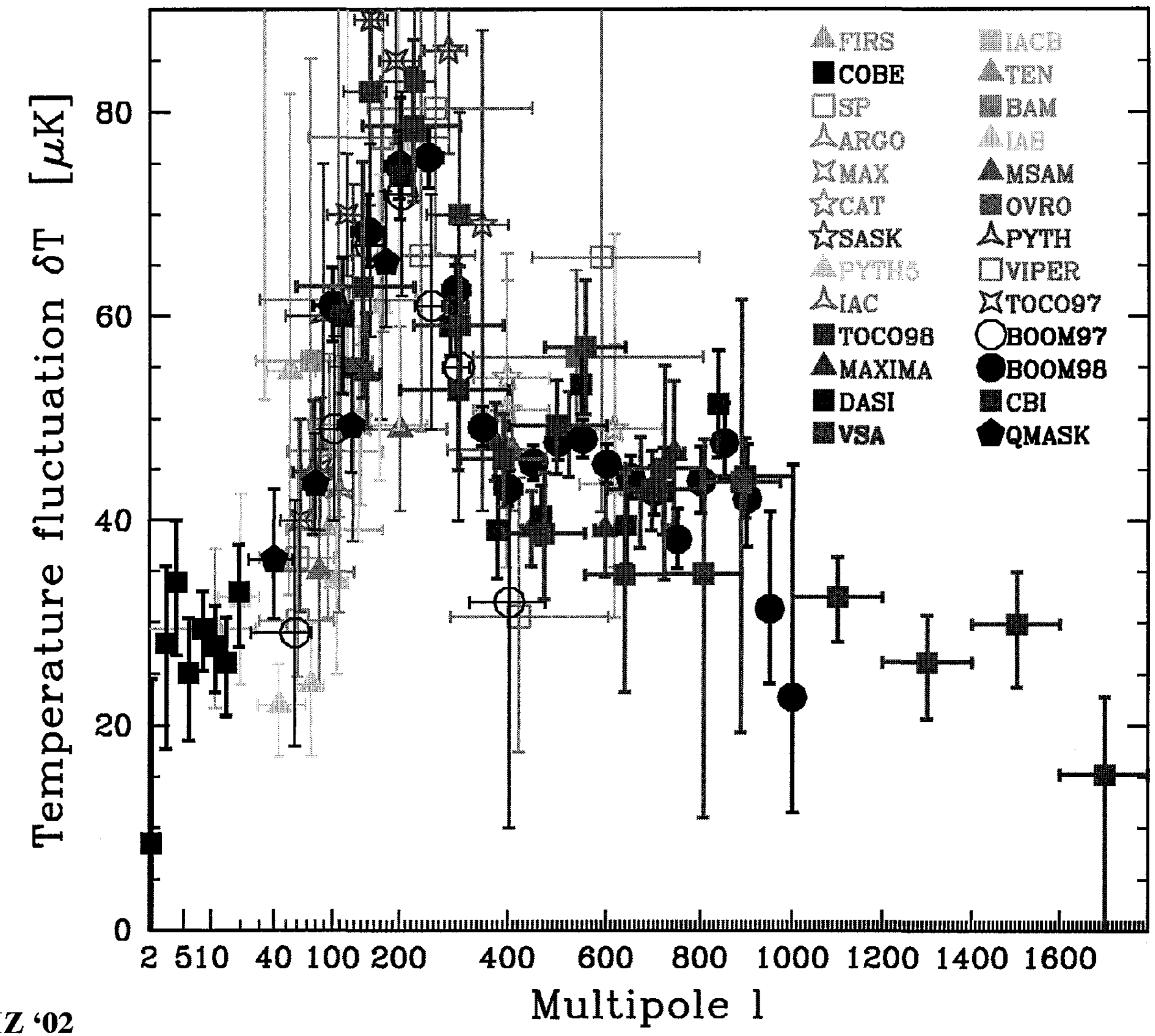


Anisotropies as seen by Boomerang

Flight: 10 days
1800 deg^2
3 % of the Sky
Resolution 0.2°

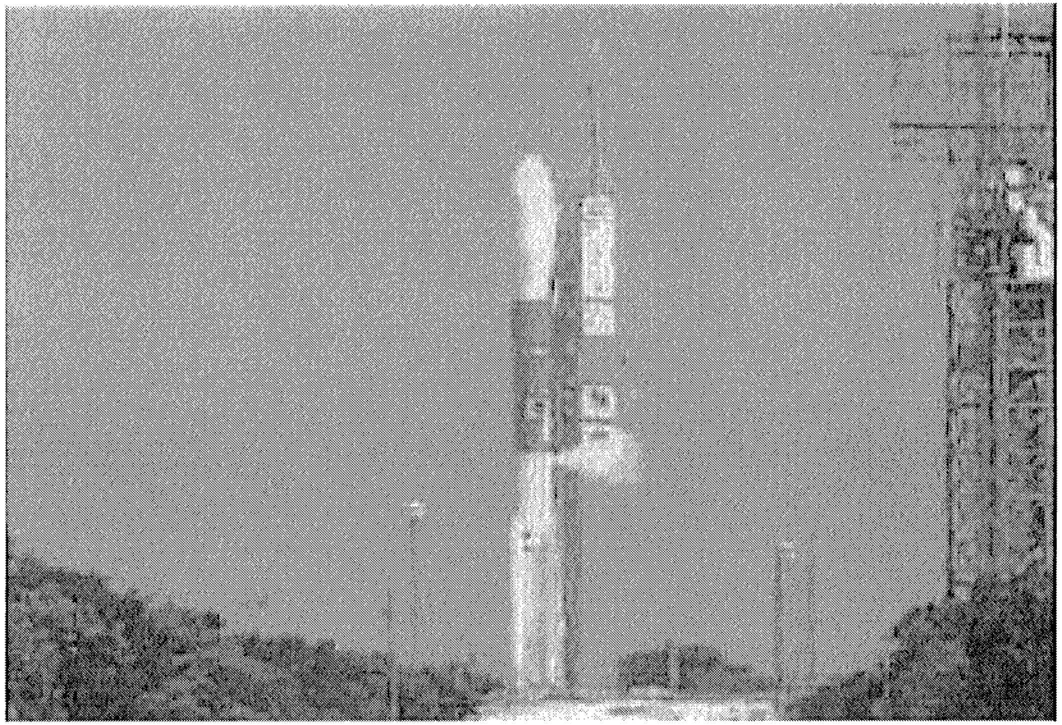


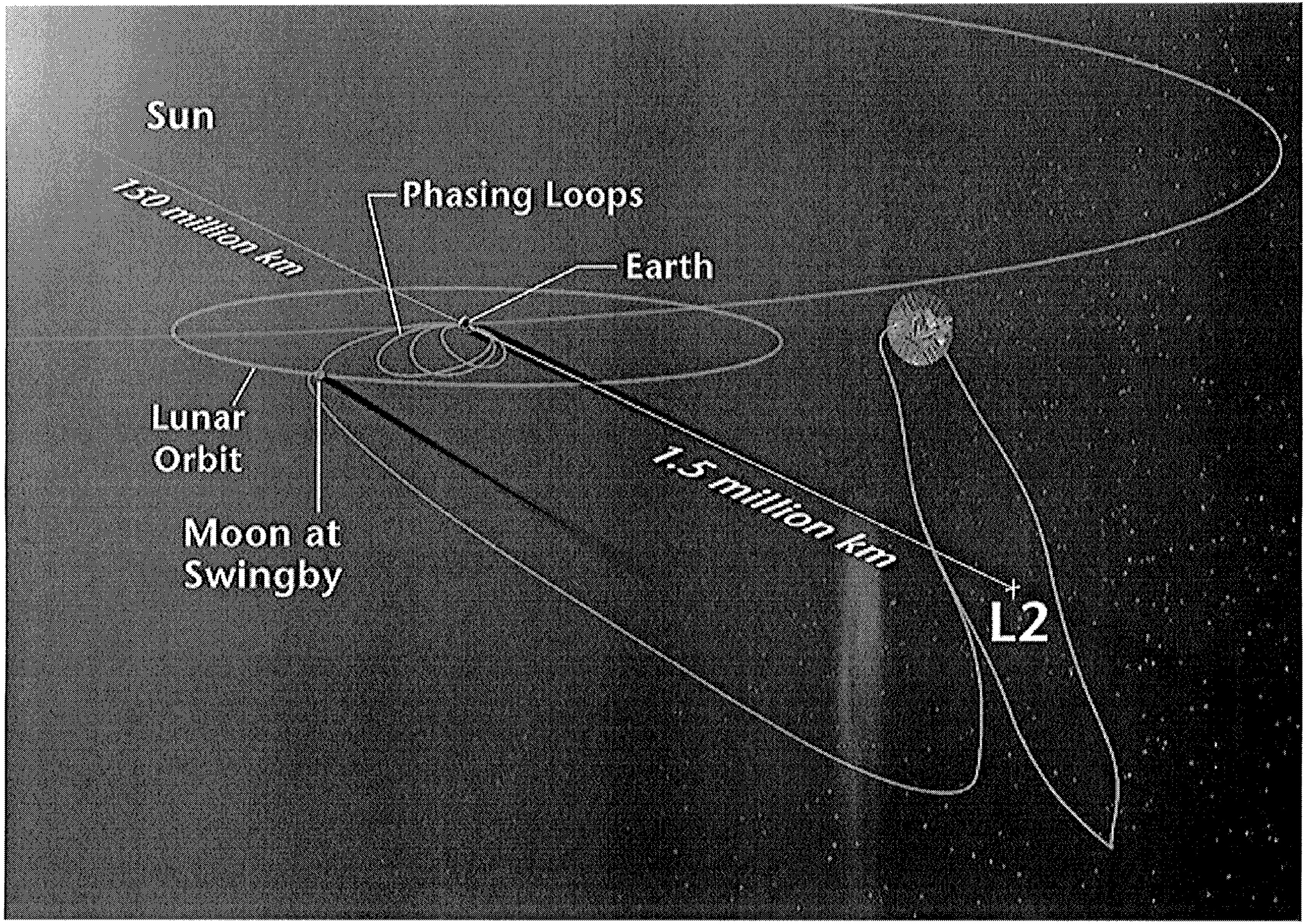
Temperature Power Spectrum



Tegmark & MZ '02

MAP Launch 06/2001




Sun
150 million km
Phasing Loops
Earth
Lunar
Orbit
Moon at
Swingby
1.5 million km
L2

WMAP vs COBE

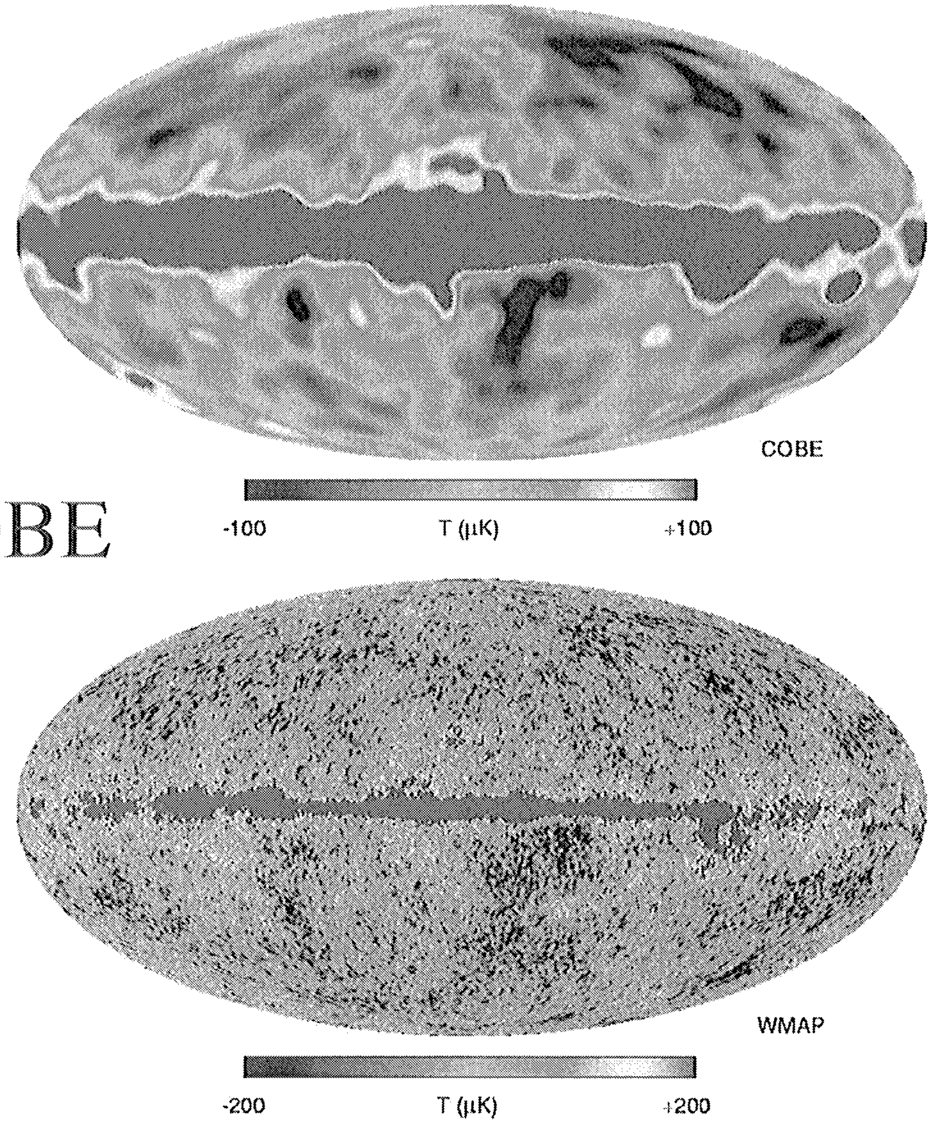
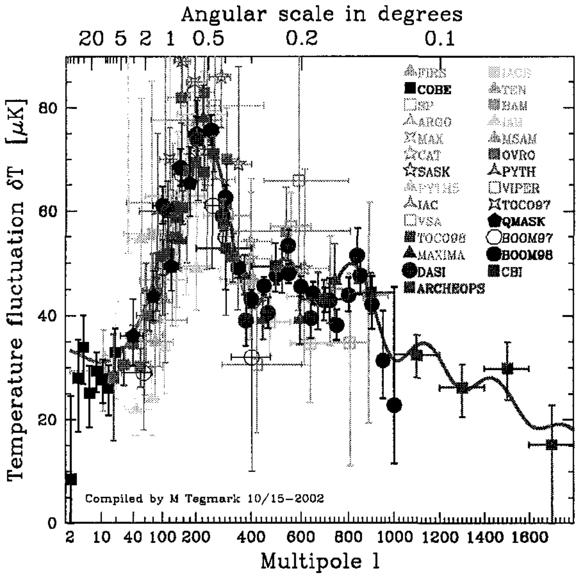
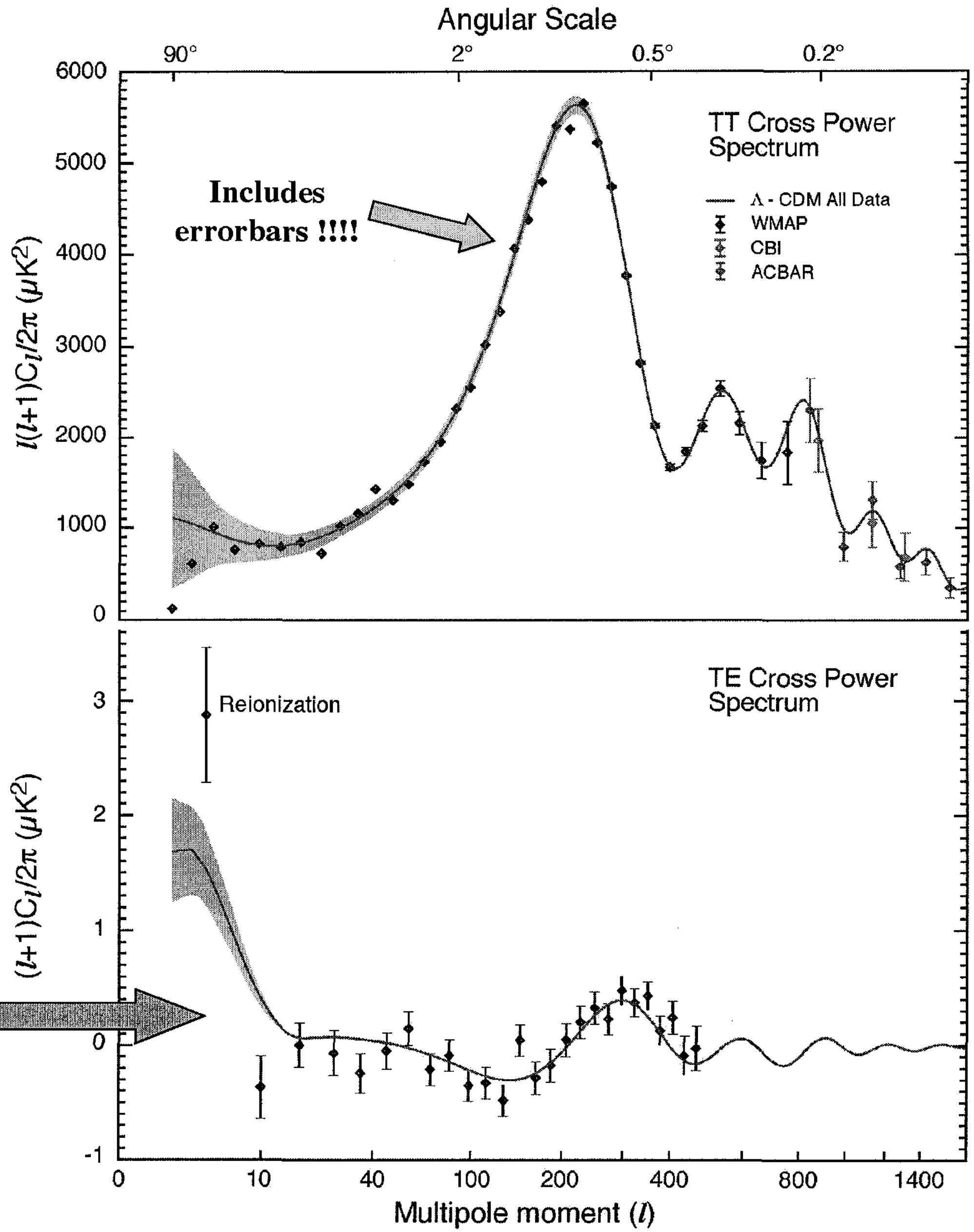


Fig. 7.— A comparison of the *COBE* 90 GHz map (Bennett et al. 1996) with the W-band *WMAP* map. The *WMAP* map has 30 times finer resolution than the *COBE* map.

WMAP Spectra





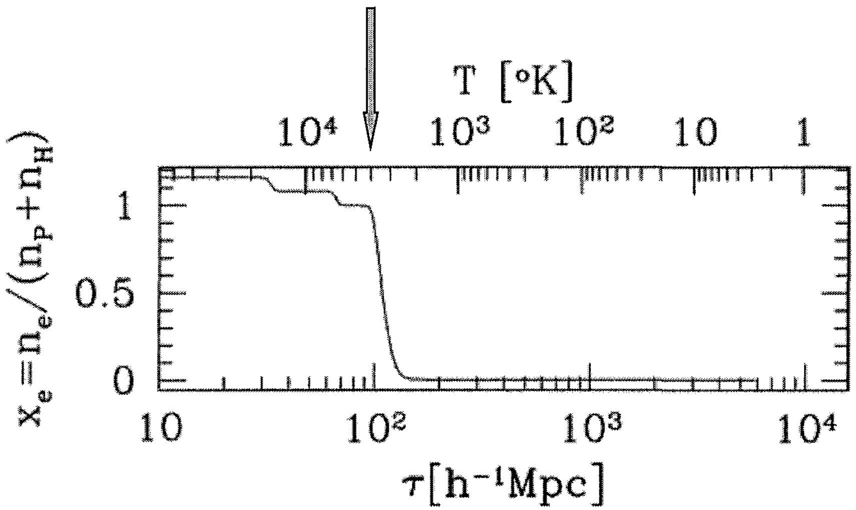
Includes errorbars !!!!

Temperature and polarization patterns are <u>correlated</u>

What creates the anisotropies?

Recombination

T = 0.3 eV << $m_e c^2$



Hydrogen is ionized **Hydrogen is neutral**

Thomson Scattering

Orders of Magnitude:

$$\lambda_T = (a\ n_e\ \sigma_T)^{-1}$$

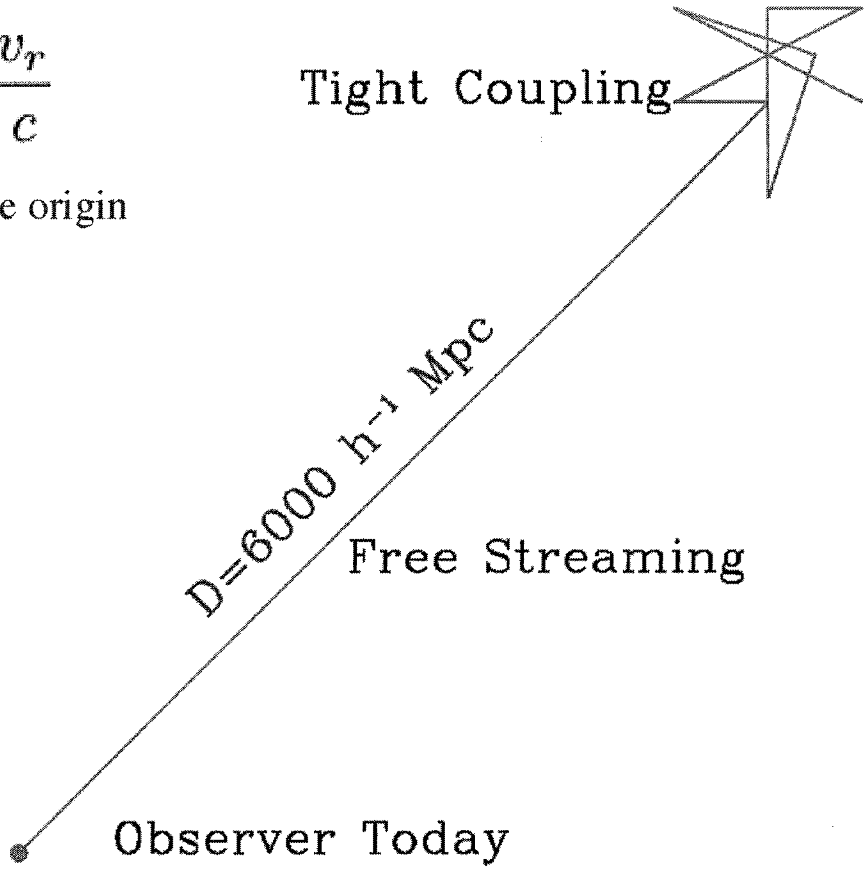
$$= 2\ \mathrm{Mpc}\ x_e^{-1}\ \ [(1+z)/1000]^{-2}$$

$$\tau_R \approx 100\ [\Omega h^2]^{-1/2}\ \mathrm{Mpc}$$

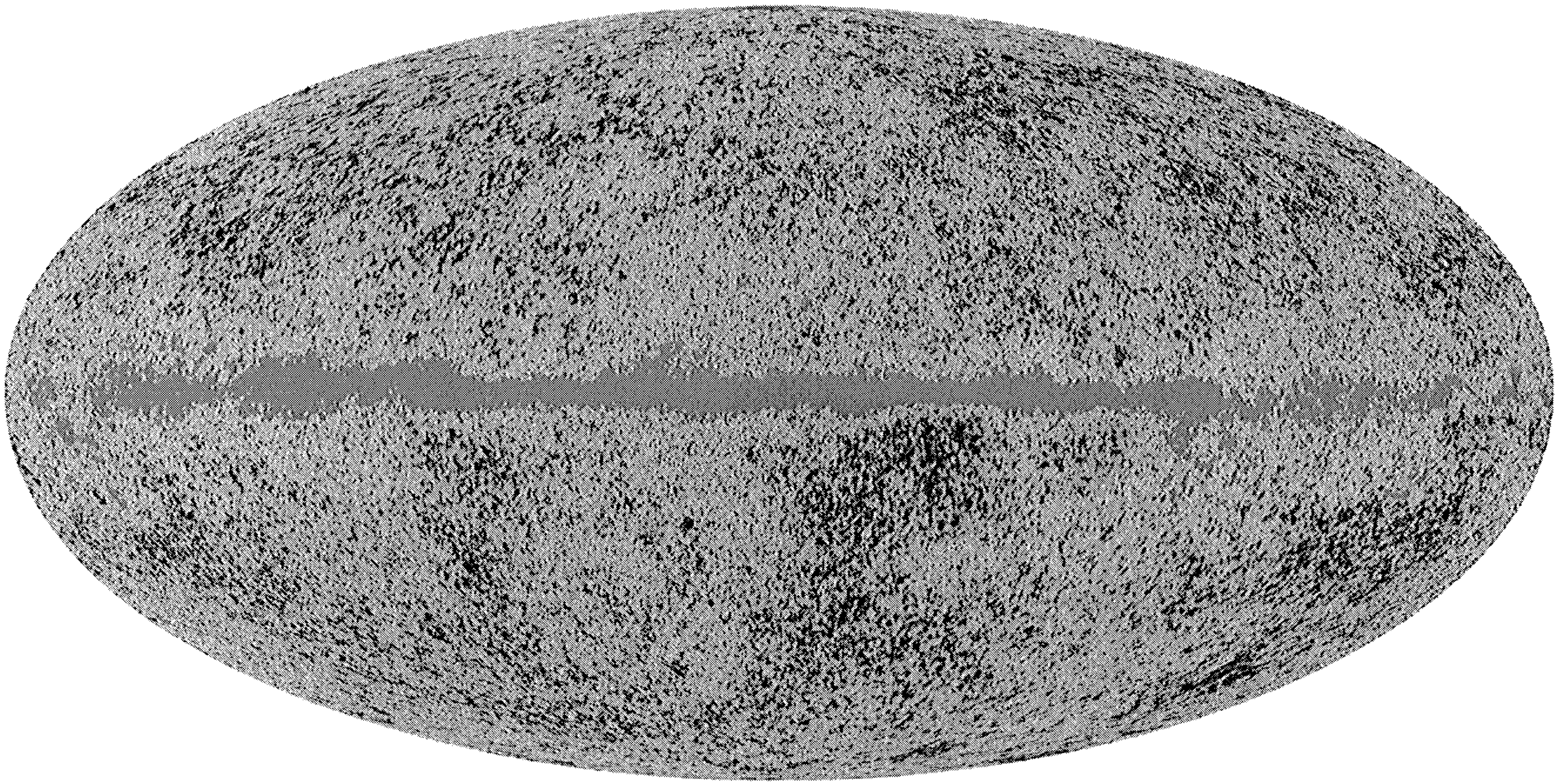
$$D = \tau_0 - \tau_R \approx 6000\ [\Omega h^2]^{-1/2}\ \mathrm{Mpc}$$

$$\frac{\delta T}{T} = \phi + \frac{\delta_\gamma}{4} + \frac{v_r}{c}$$

All 3 effects have the same origin

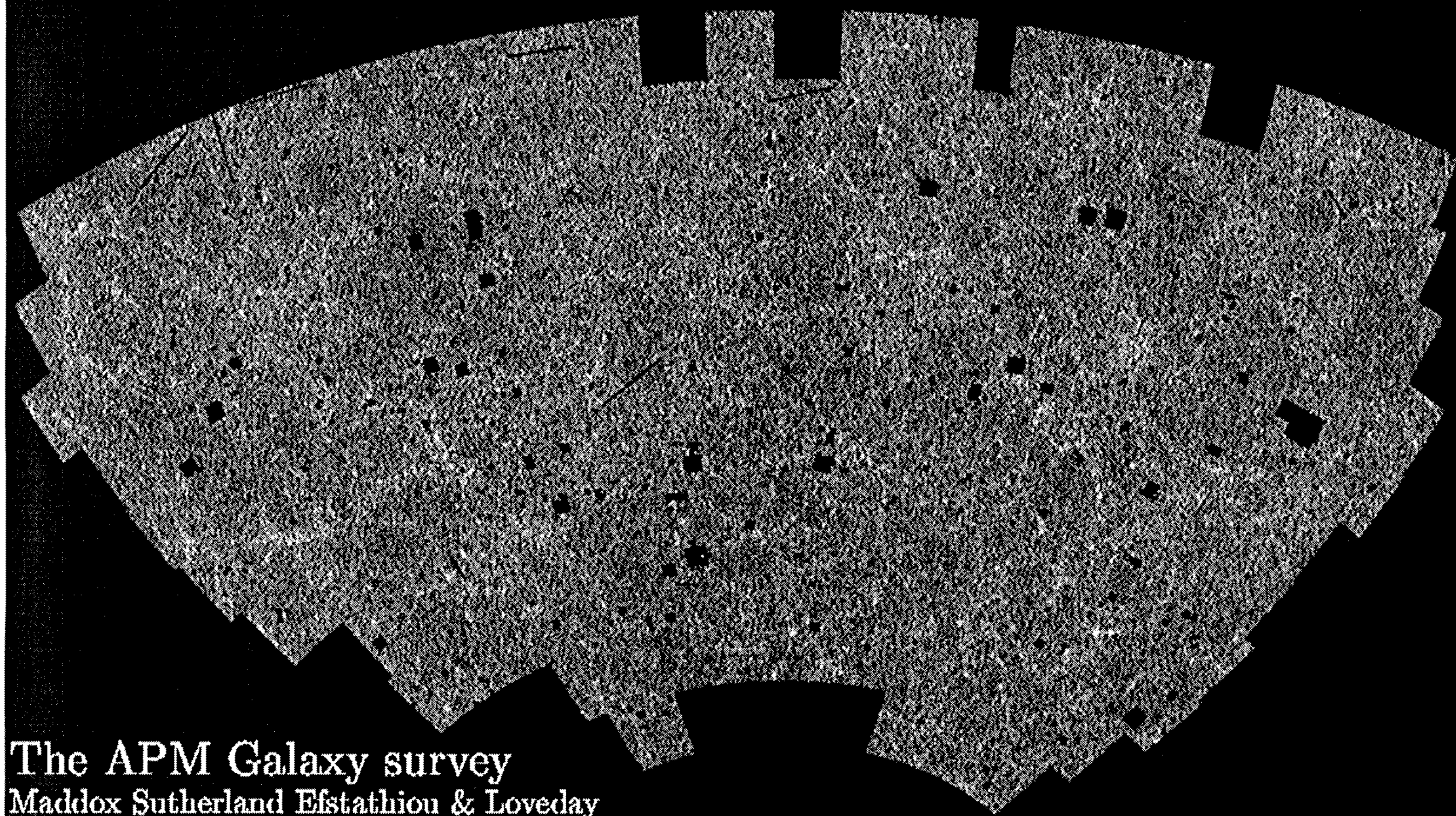


WMAP: level of structure at recombination

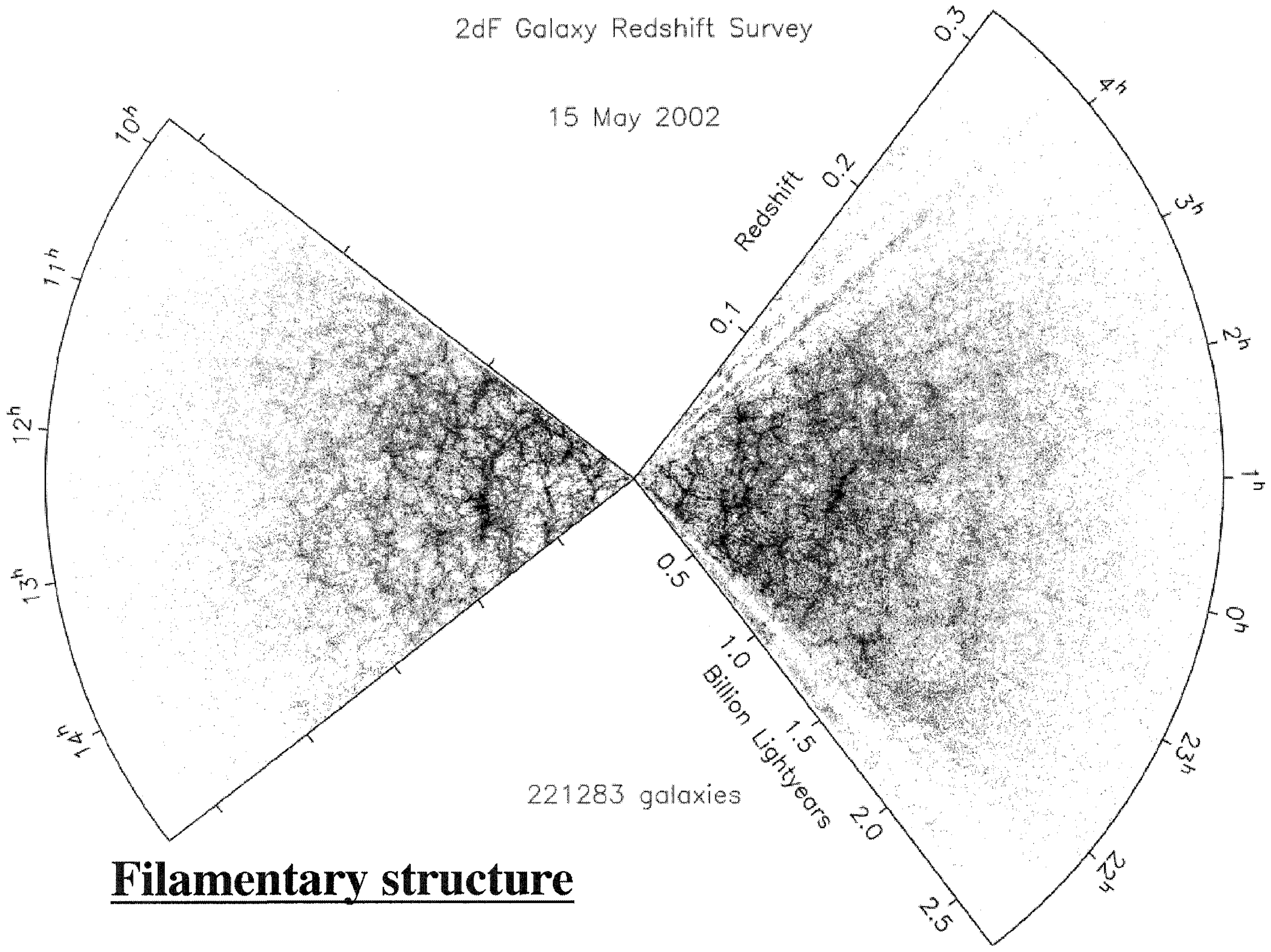


<u>Present day structure:</u> the distribution of galaxies

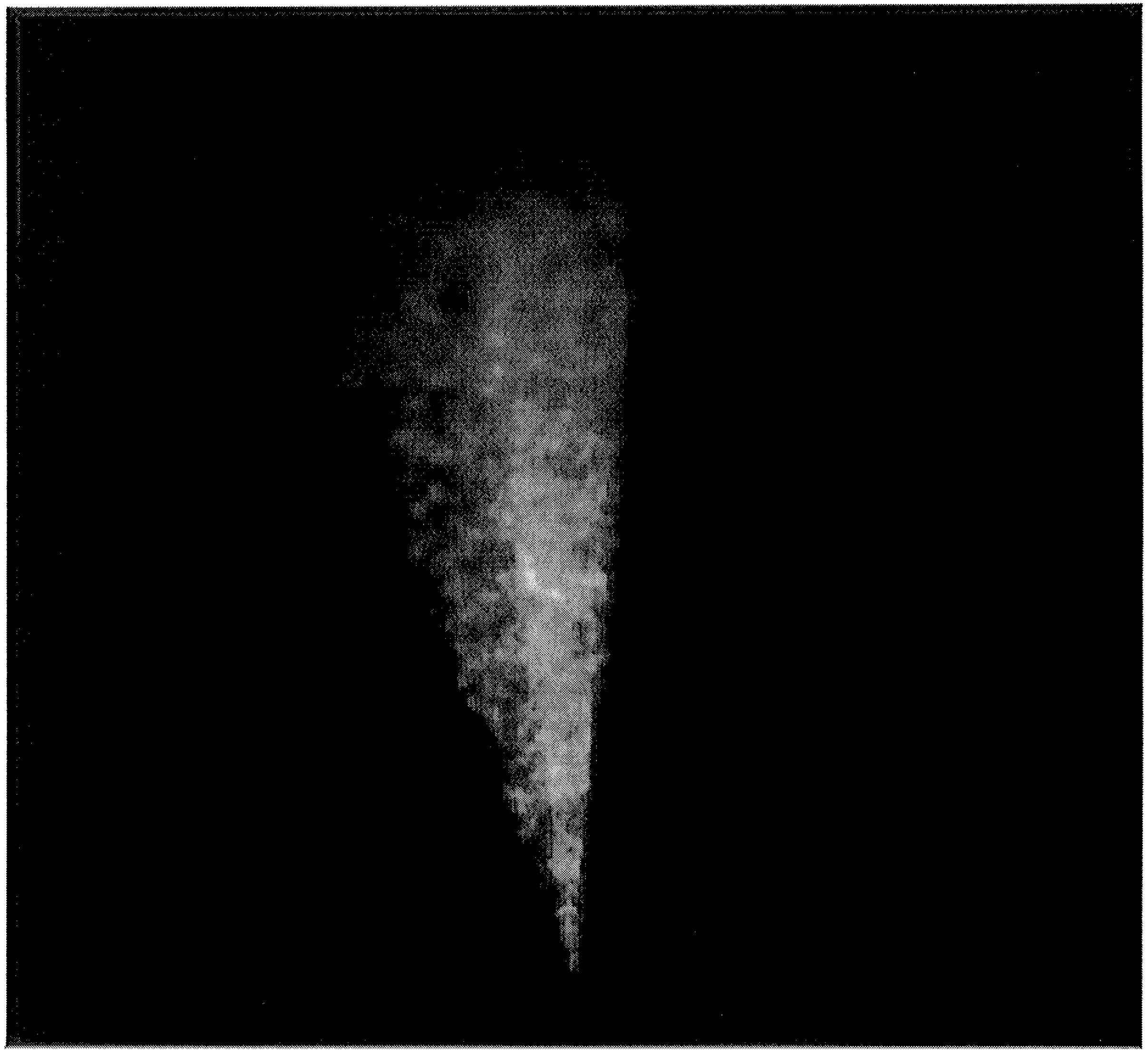
The distribution of matter as traced by galaxies



The APM Galaxy survey
Maddox Sutherland Efstathiou & Loveday

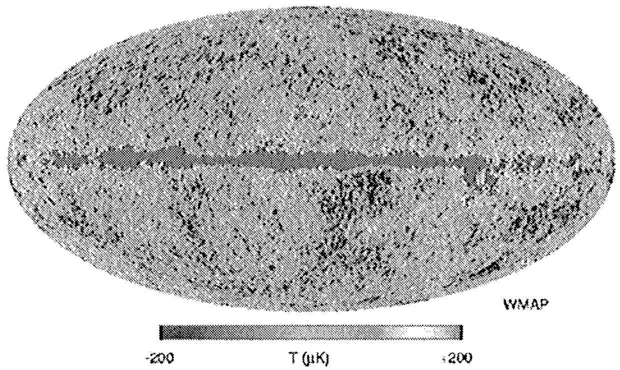


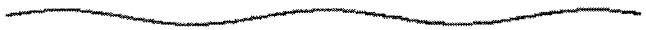
Filamentary structure



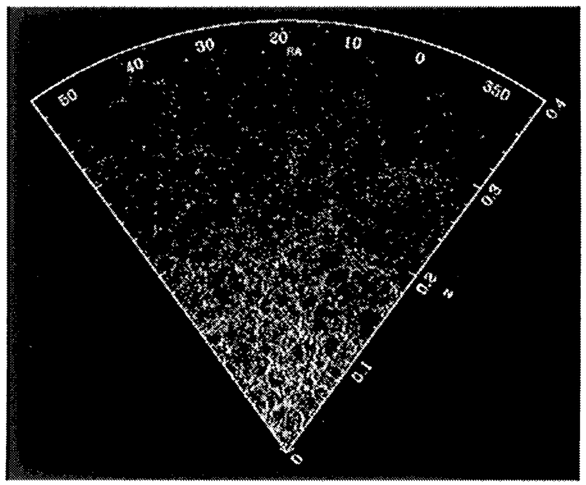
http://www.mso.anu.edu.au/2dFGRS/

Gravitational Instability



t_1 

$t_2 > t_1$ 



$$t_g \sim (G\rho)^{-1/2}$$

Different constituents can be distinguished when studying the evolution of perturbations because of their different interactions.

Baryons are coupled to the CMB before recombination.

CDM only interacts with the rest through gravity but can cluster.

A cosmological constant is spatially constant so it only affects the evolution of the expansion factor.

"Best" Cosmological Parameters:

Table 3 from ***Wilkinson Microwave Anisotropy Probe (WMAP) Observations:* Preliminary Maps and Basic Results**,

C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;

available at `http://lambda.gsfc.nasa.gov/`

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05\ \mathrm{Mpc}^{-1}$)[c]	$dn_s/d\ln k$	-0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002\ \mathrm{Mpc}^{-1}$)	r	< 0.90	95% CL	—

http://lambda.gsfc.nasa.gov/

Gravitational instability amplifies fluctuations but it does not create them.

We need some “seeds”

↓

Inflation

Summary of model parameters

1. Dark matter density
2. Baryon density
3. Radiation density
4. Neutrino fraction

Matter budget: affects the physics of perturbations

5. Curvature
6. Cosmological "constant"

Affect the evolution of a(t)

7. Initial spectrum of scalar perturbations
8. Initial spectrum of gravity waves

Properties of the initial seeds

Objective: Invert the physics of the perturbations to get at properties of the seeds and hopefully to the mechanism that created the seeds

Topics for future lectures

- Temperature anisotropies: what goes into making the predictions? Example of calculation of the spectrum under some simplifying assumptions
- CMB polarization: Origin and information it encodes
- Secondary anisotropies
- Other probes of structure formation. Summary about what they tell us about the parameters of the cosmological model.
- Origin of the perturbations: inflation