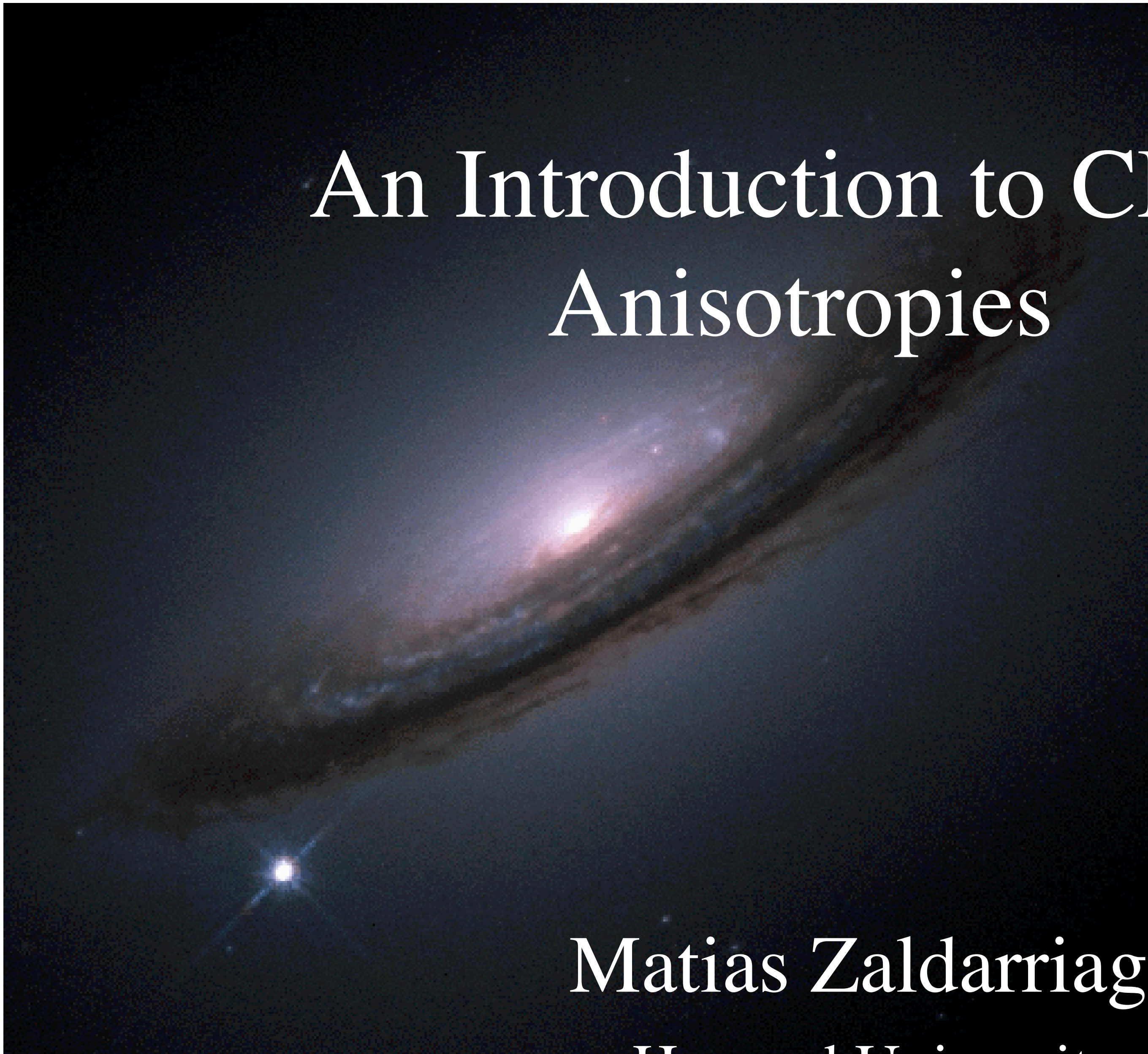
# An Introduction to CMB Anisotropies

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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

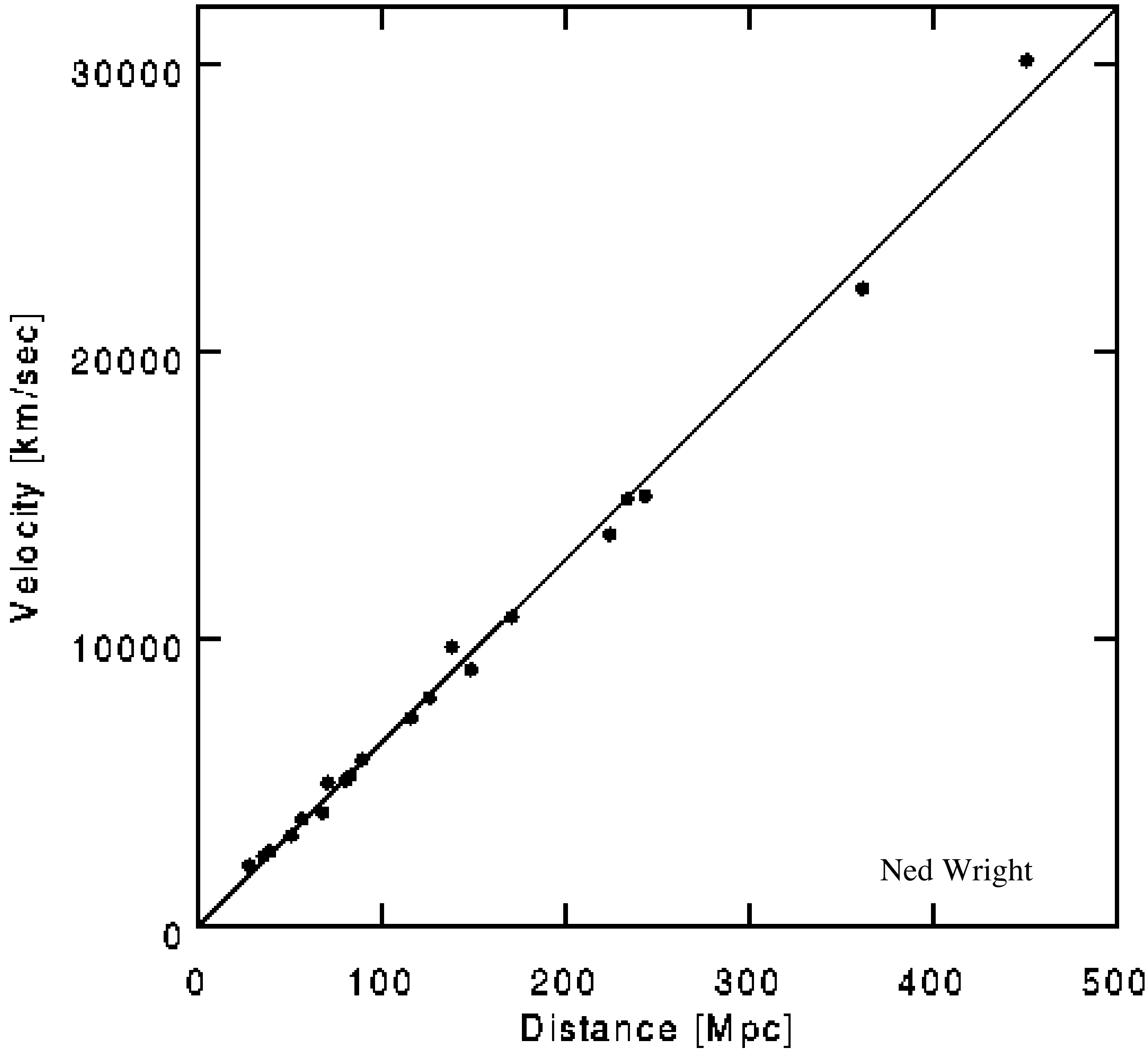
# Cosmology: Background

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

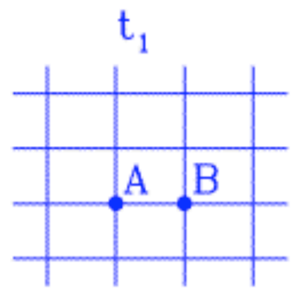
# The Expansion of the Universe

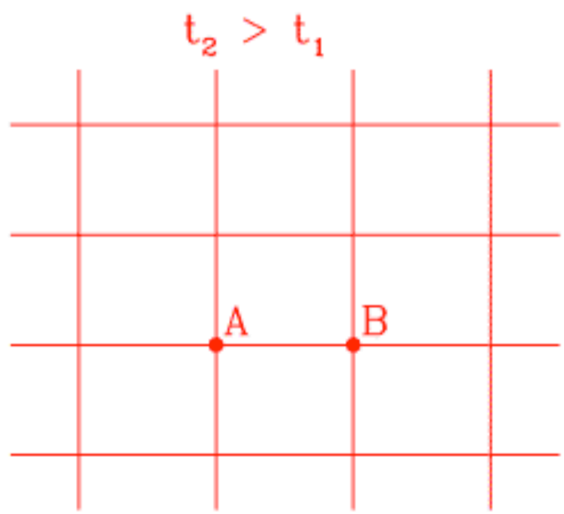
Type Ia SNe
Riess, Press &
Kirshner '96

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

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

# 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

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

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

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

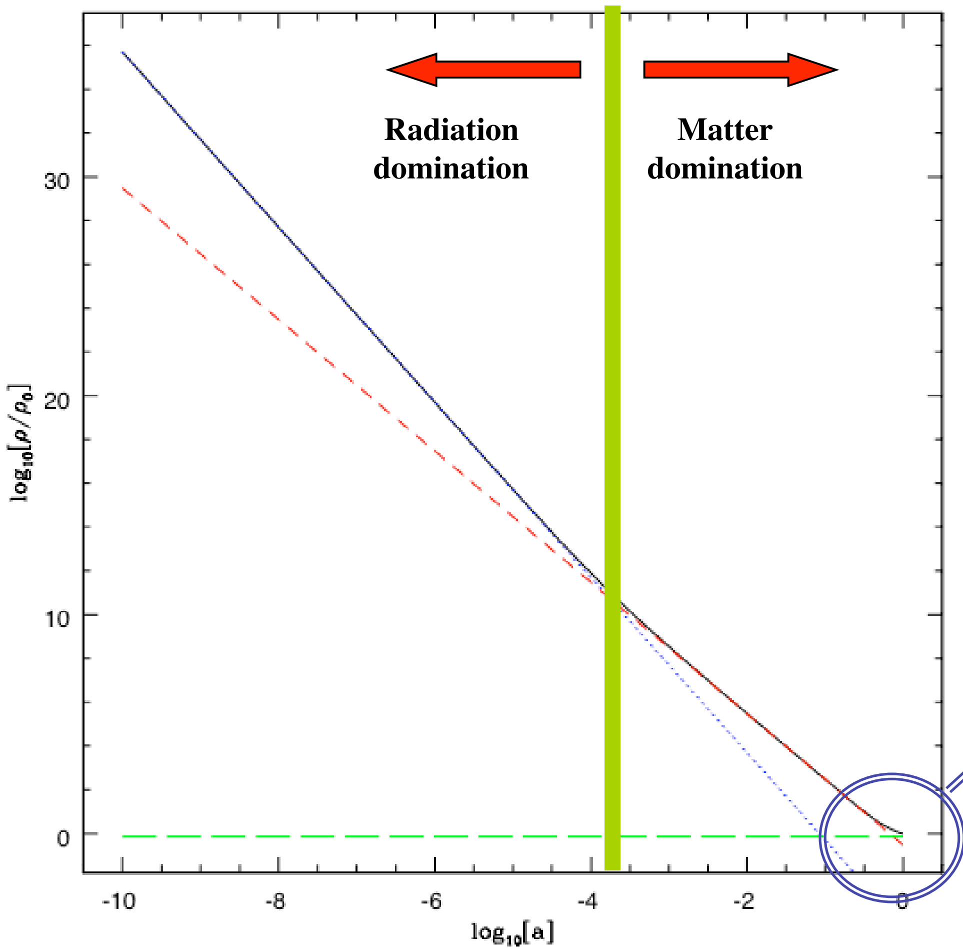
We can rewrite (2) in terms of the different densities at the present epoch measured in terms of the critical density ($\Omega_i = \rho_{i0}/\rho_{\rm crit}$),

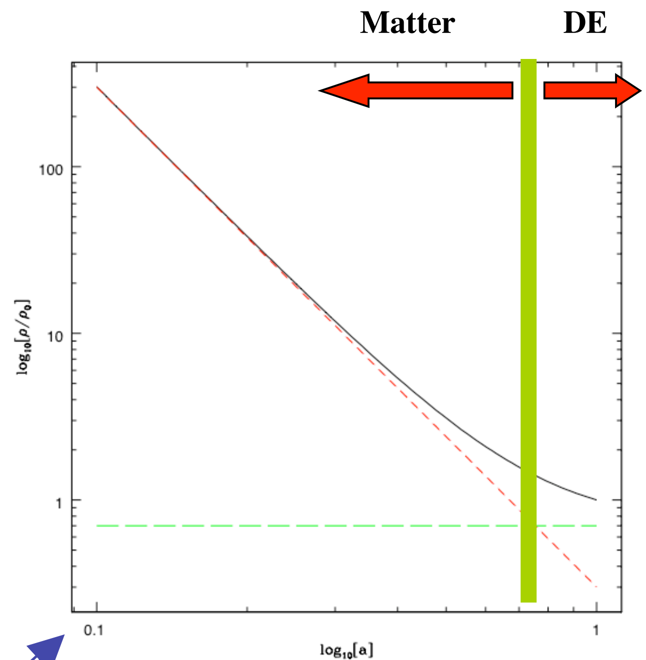
$$\begin{aligned} \left(\frac{1}{a}\frac{da}{dt}\right)^2 &= H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_v + \Omega_K a^{-2}] \\ 1 &= \Omega_m + \Omega_r + \Omega_v + \Omega_K. \end{aligned} \tag{4}$$

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.

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

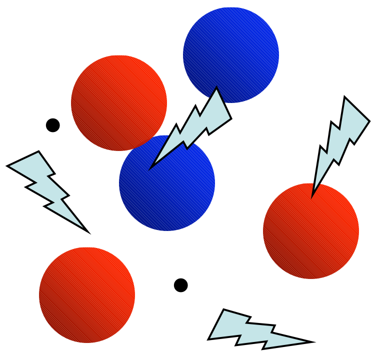
# Evolution of the density



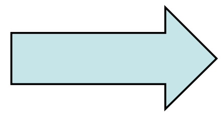



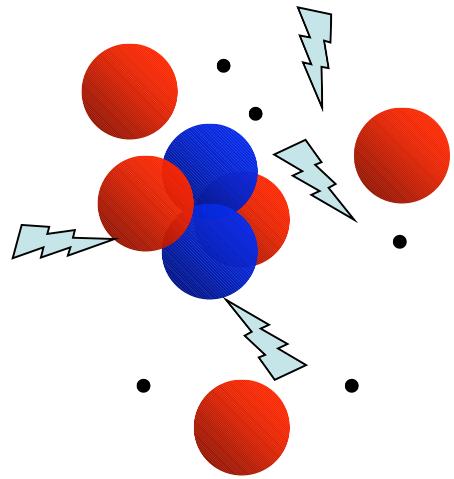

$$1 + z_{eq} = 1/a_{eq} \approx 3600$$

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



Expansion



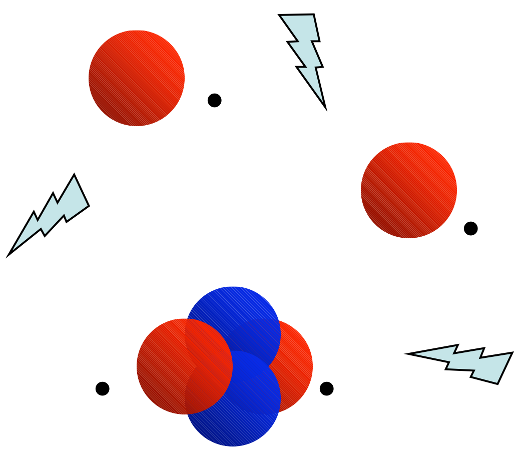


Expansion

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

Nucleosynthesis

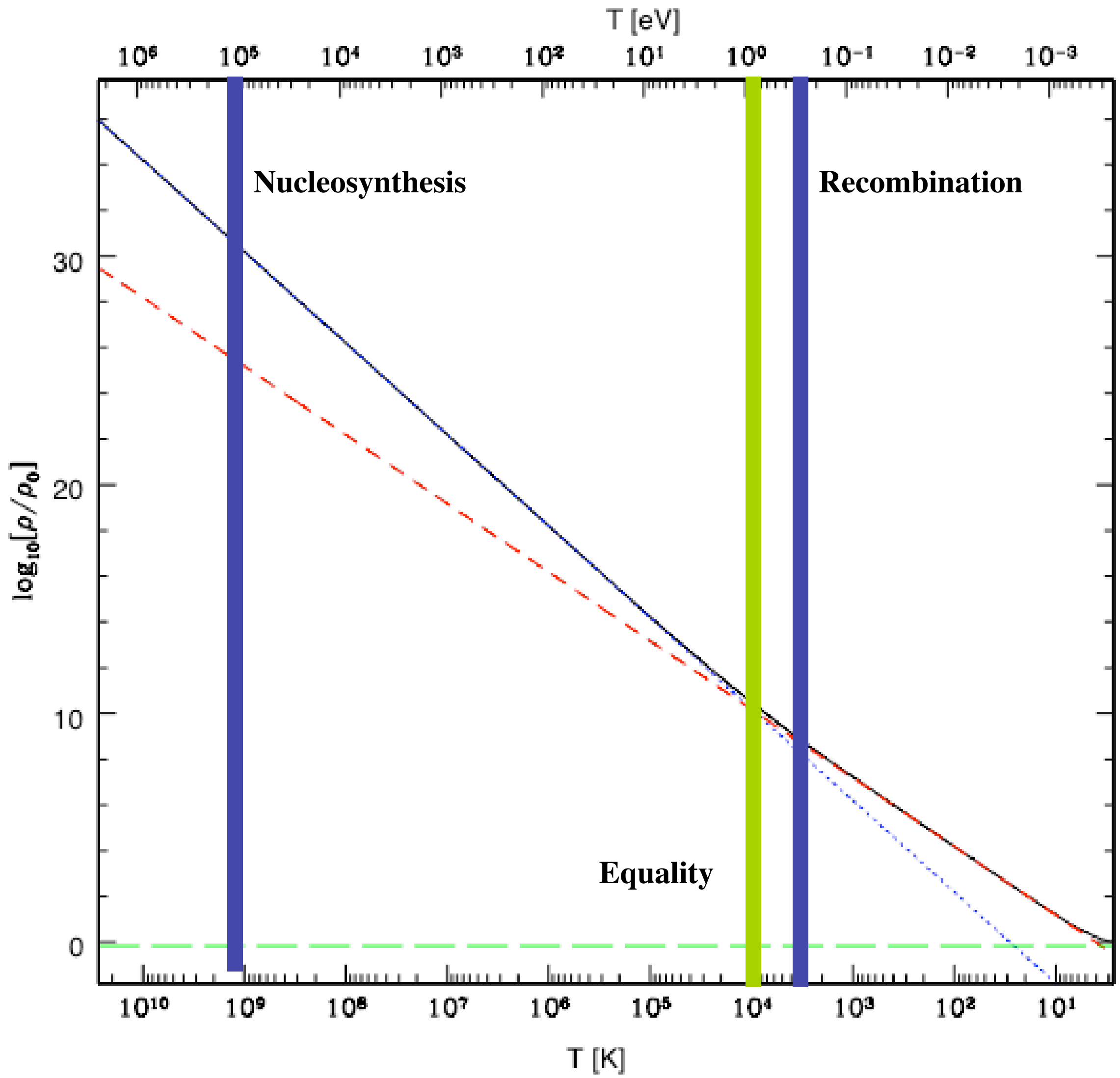
First minutes after the Big Bang: formation of Helium, Deuterium and Lithium.



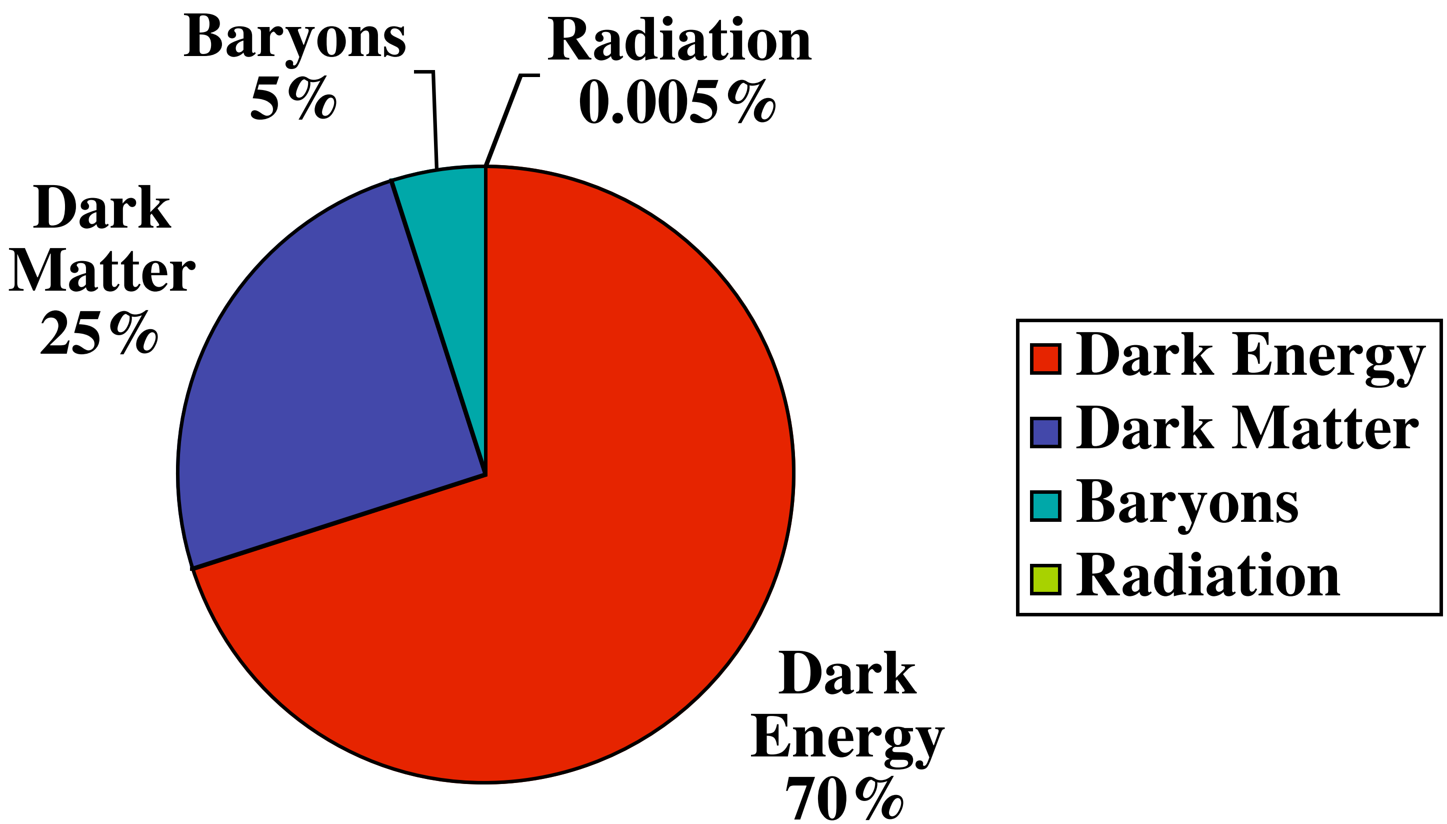
Recombination

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

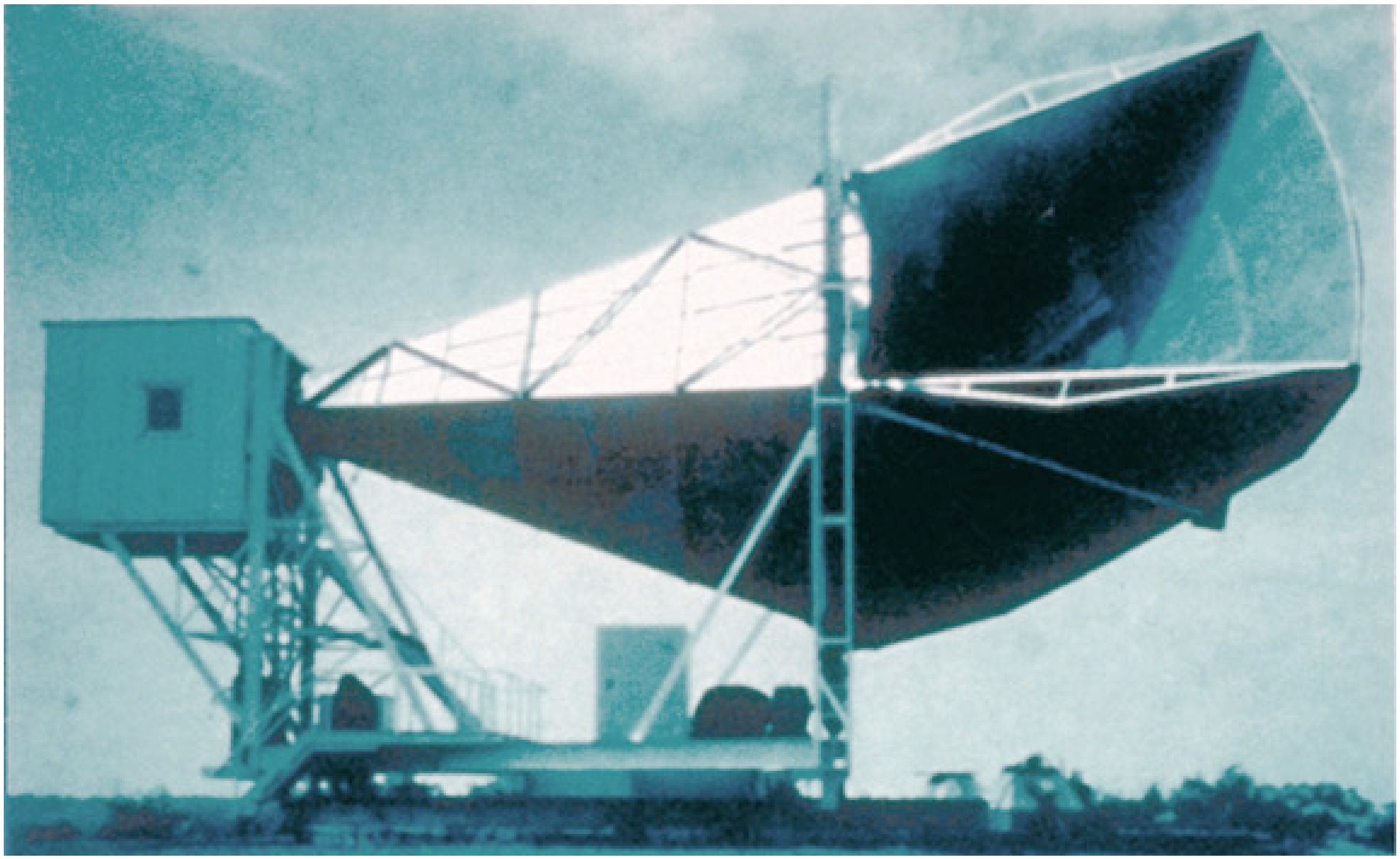
# Thermal History



# Matter content of the Universe



# <u>**Photons**</u>: The Cosmic Microwave Background



Penzias & Wilson 1965

# The Spectrum of the CMB

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

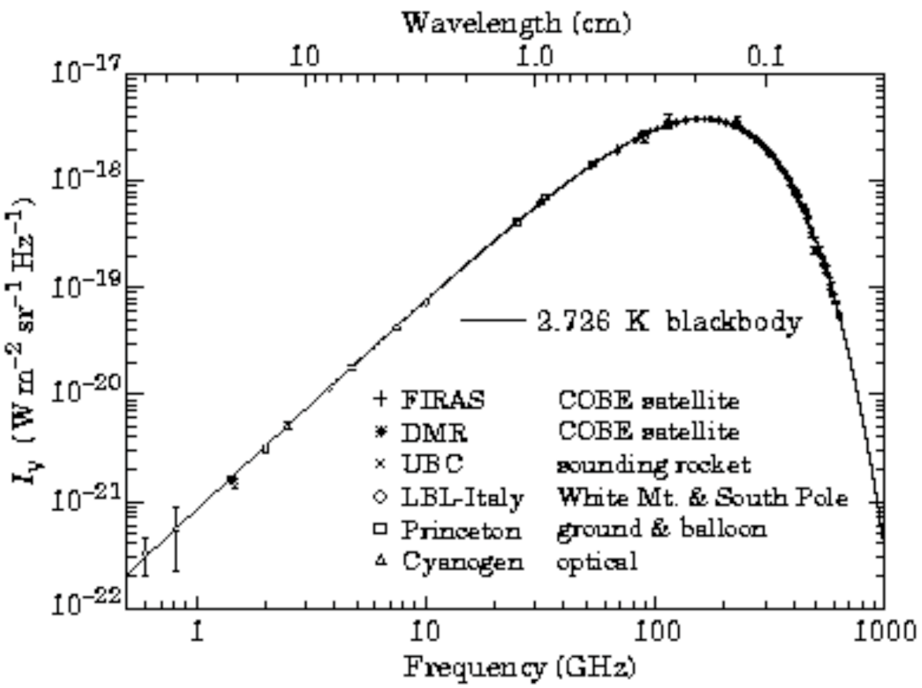
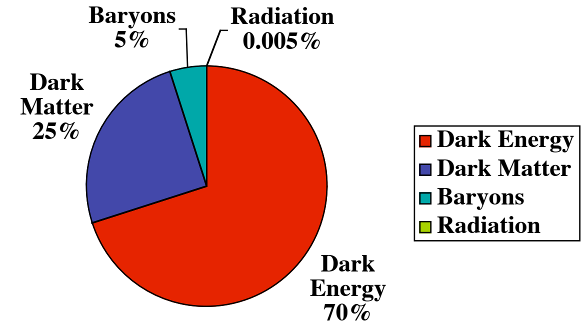



*Figure 1.* Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at frequencies of 3 GHz and below (10 cm and longer wavelengths). (References for this figure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

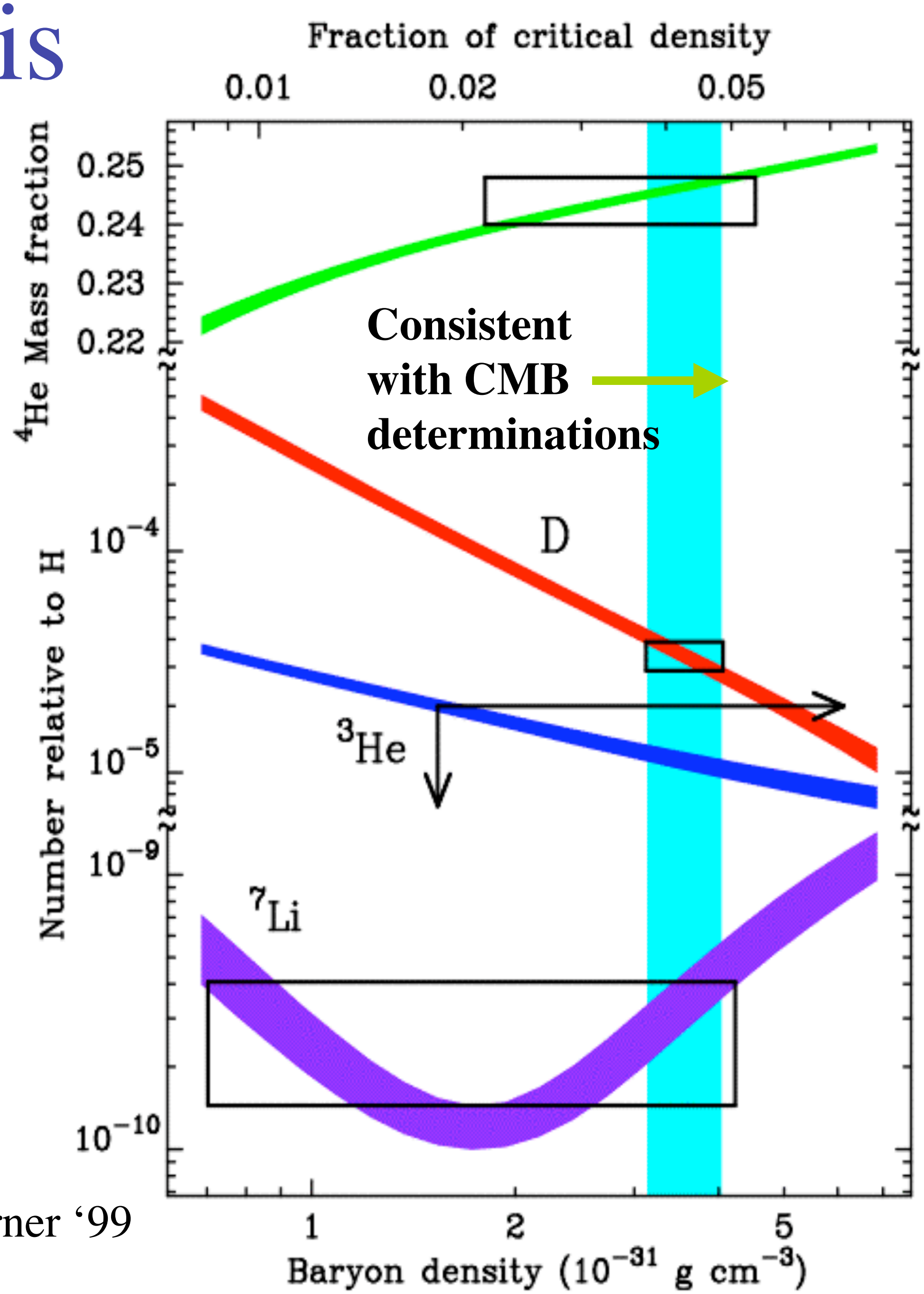
The best ways to count baryons are BBN and the CMB anisotropies.

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

# Nucleosynthesis

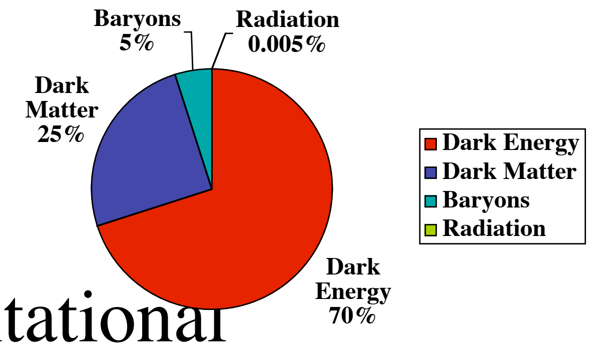
Light elements were created when the temperature of the CMB was in the MeV range, roughly a minute after the Big Bang.






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

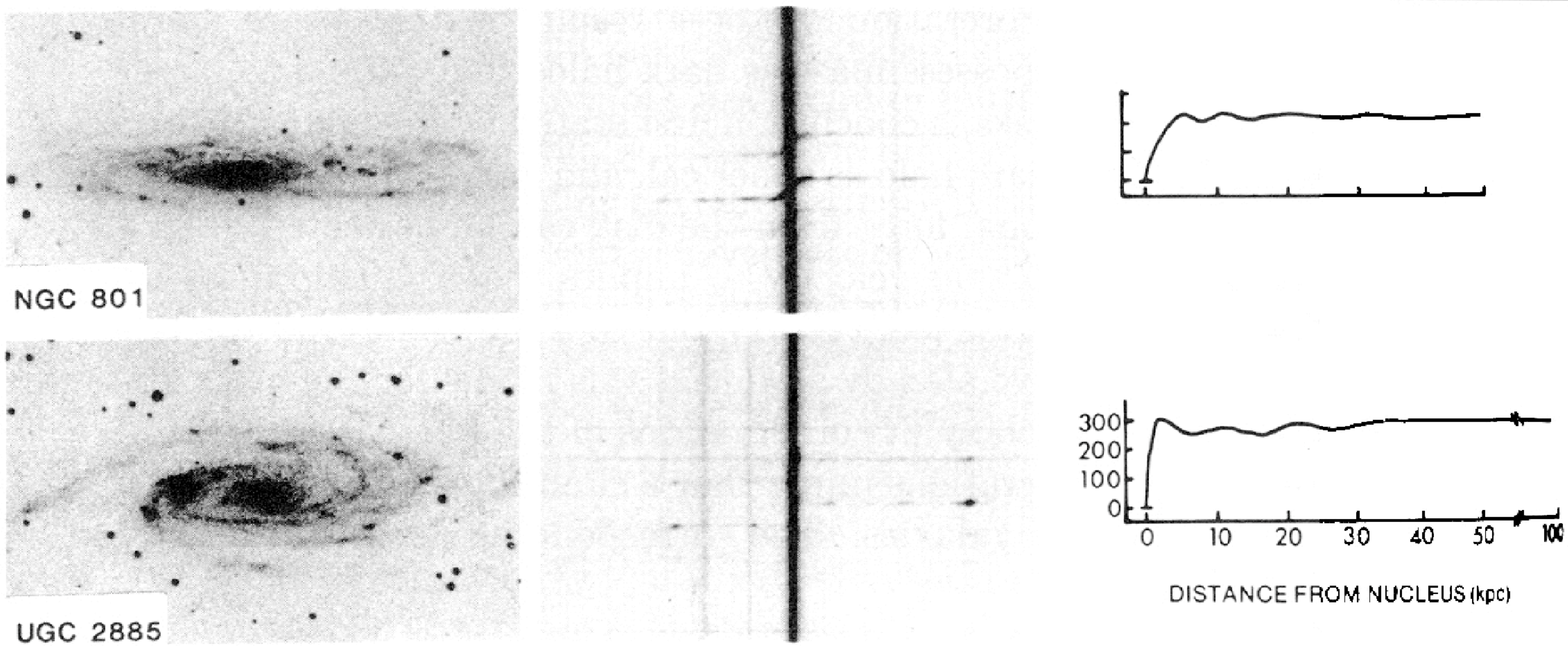
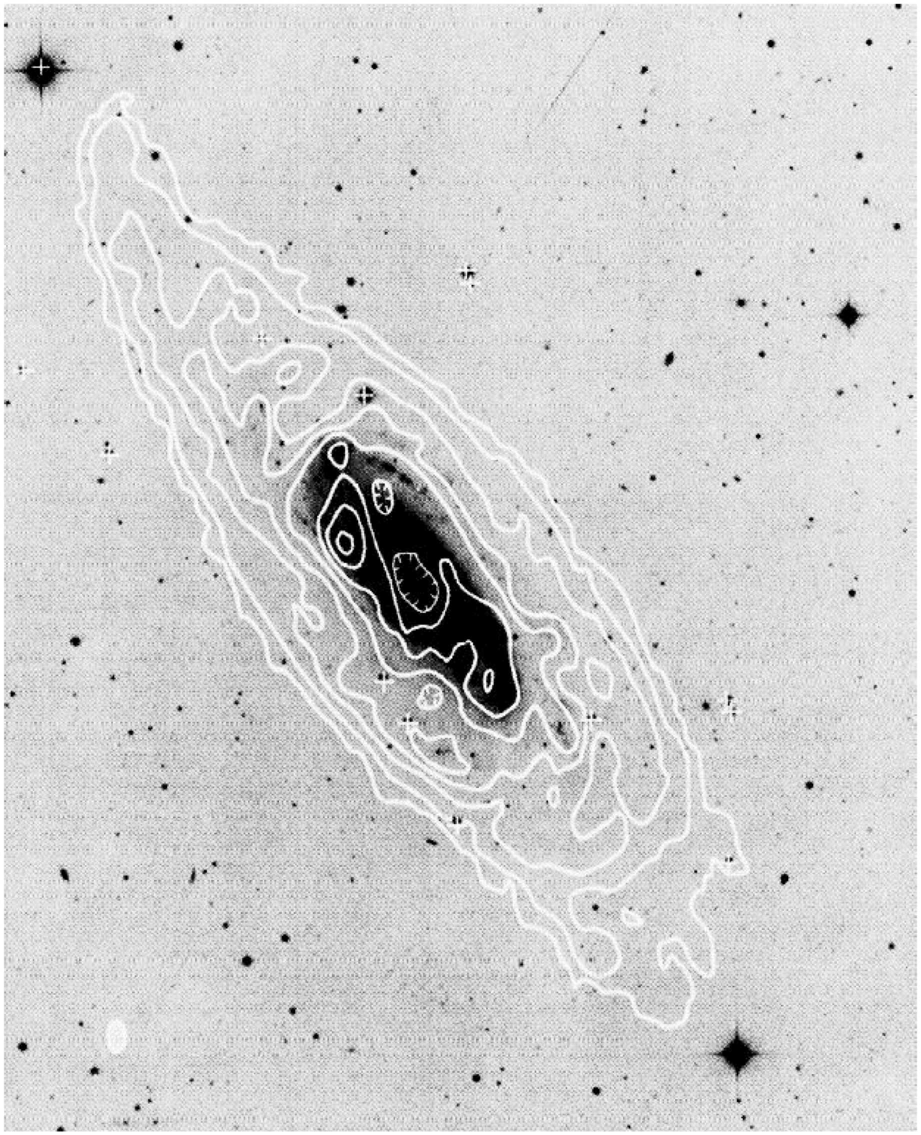



**Figure 10-1.** Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each 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

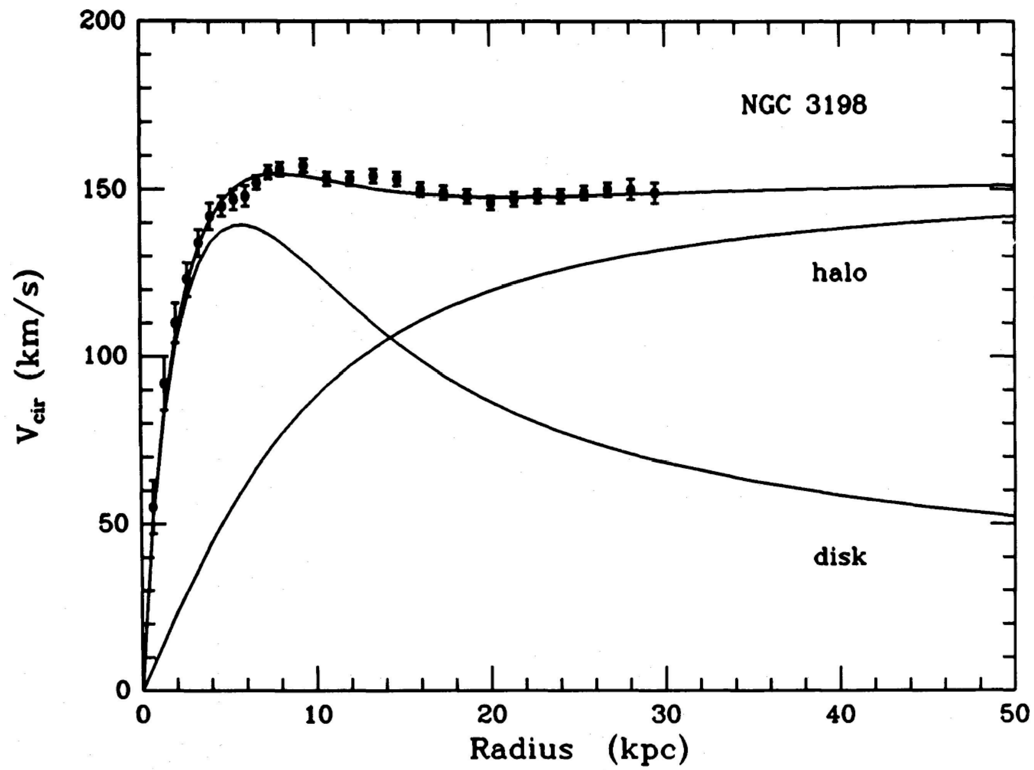


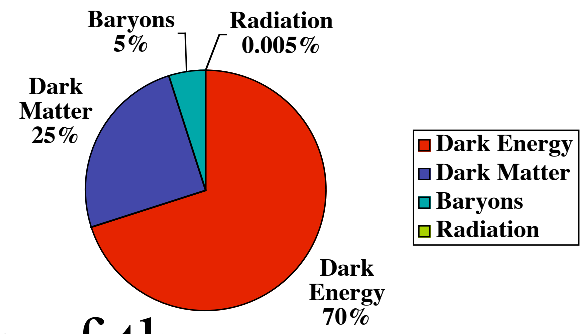

FIG. 4.—Fit of exponential disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the disk has been taken equal to that of the light distribution (60″, corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0)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

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

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

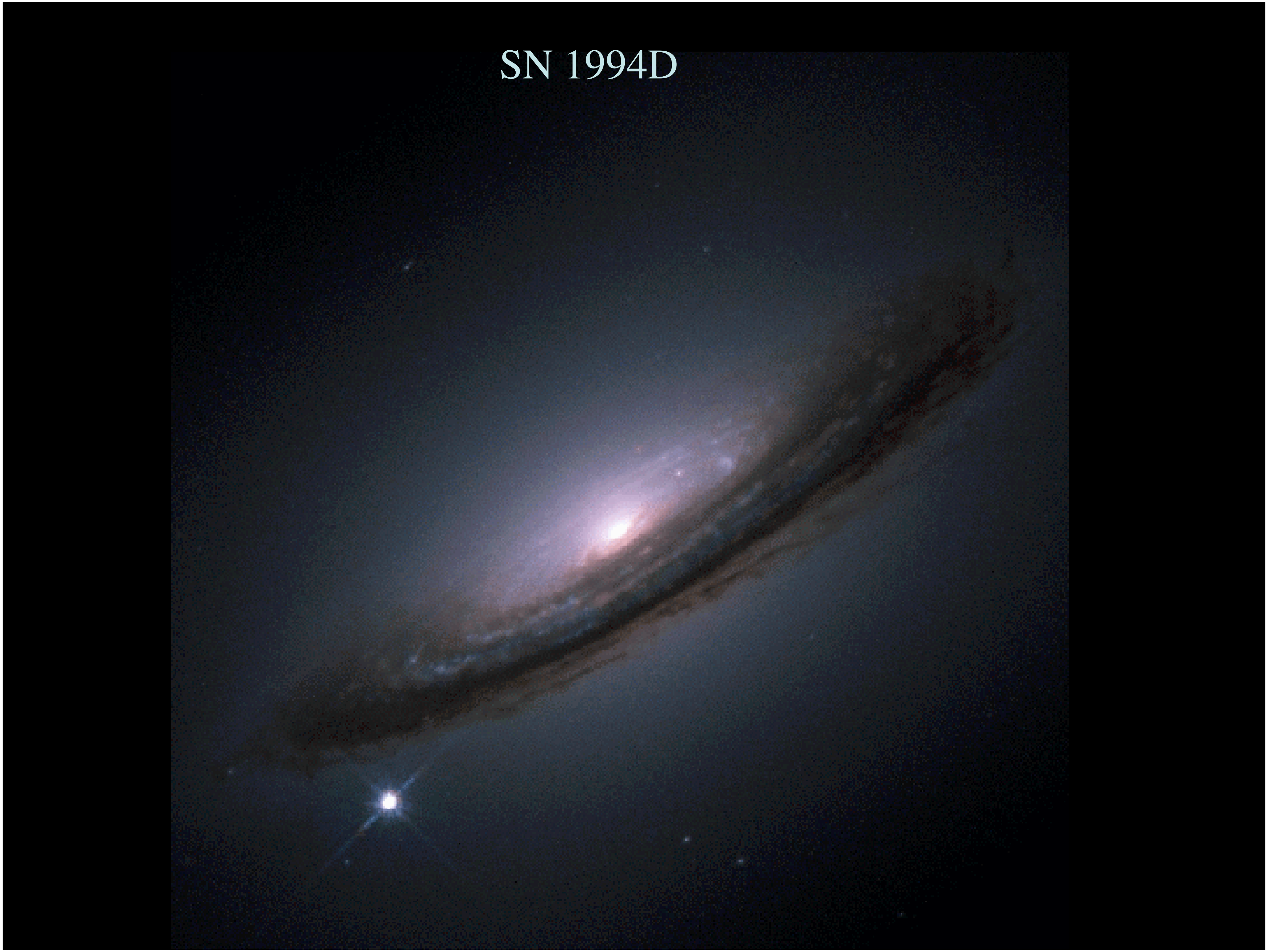
$$(\frac{1}{a}\frac{da}{dt})^2 = H_0^2[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_v + \Omega_K a^{-2}]$$

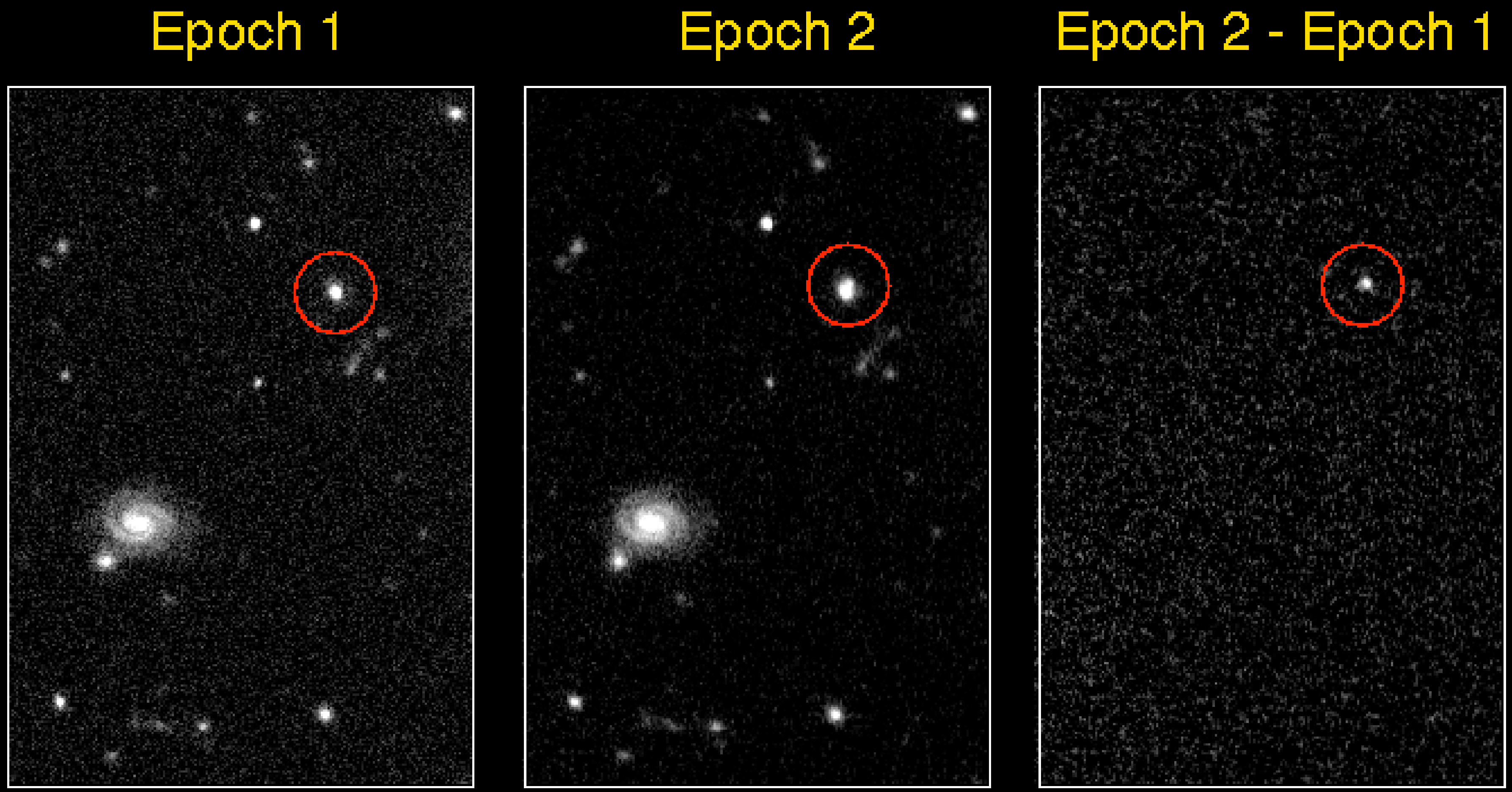
$$1 = \Omega_m + \Omega_r + \Omega_v + \Omega_K.$$

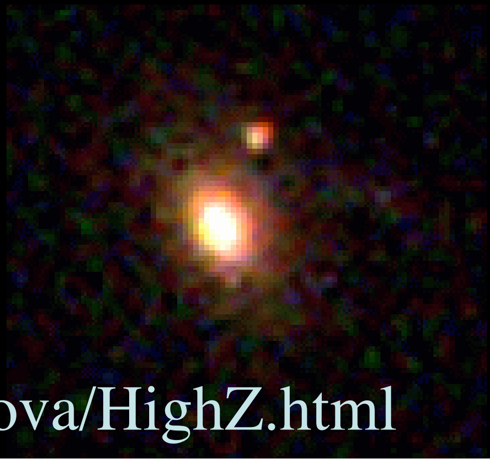
The time it takes the universe to expand by a certain factor depends on its matter content.

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.

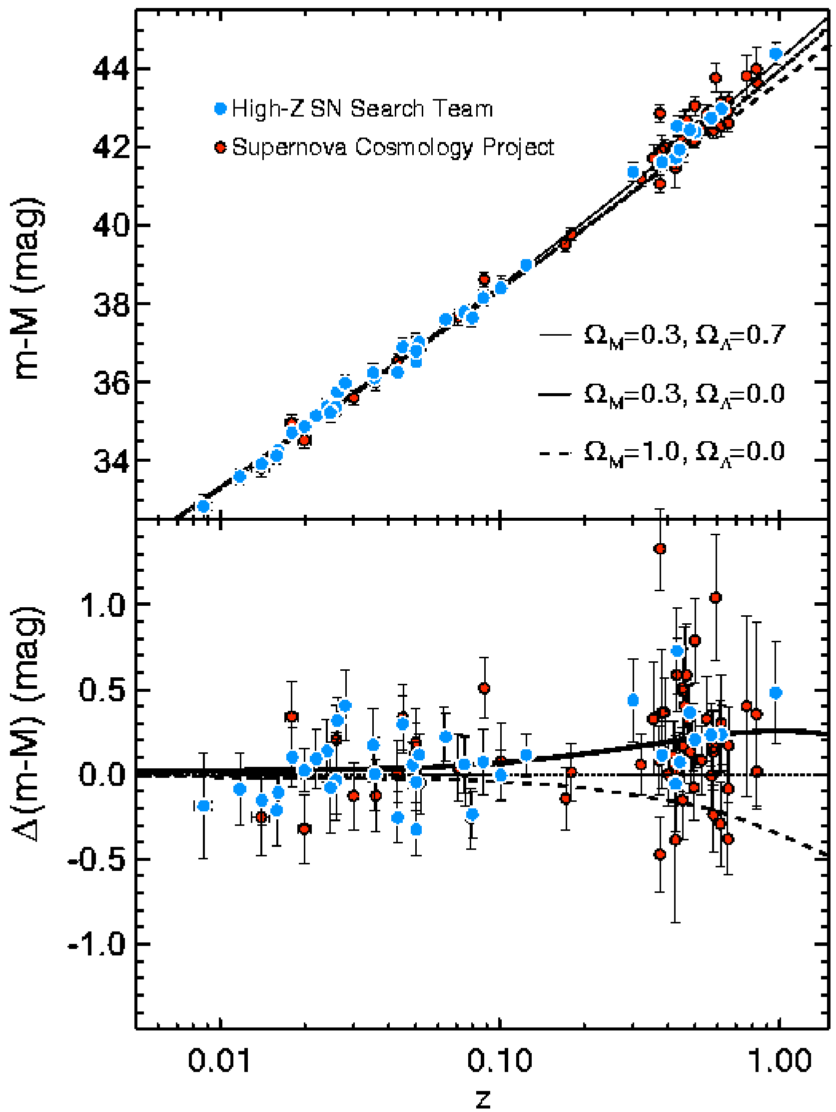

SN 1994D

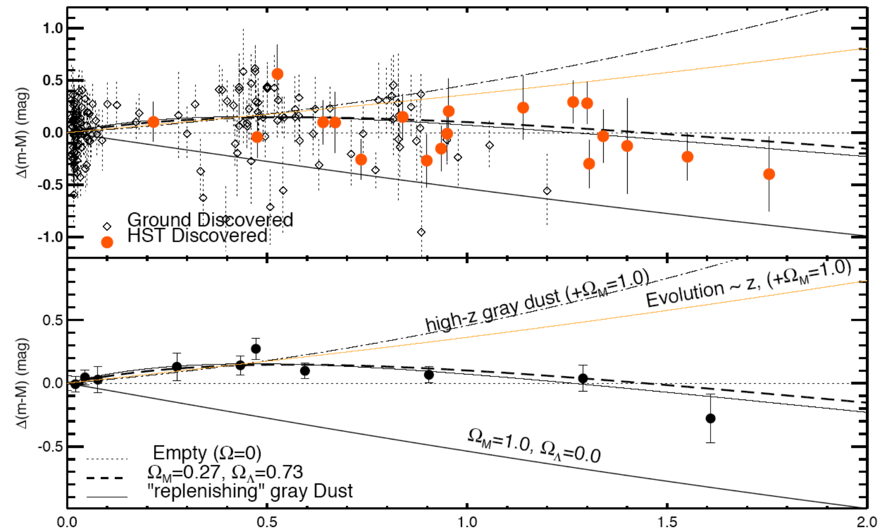


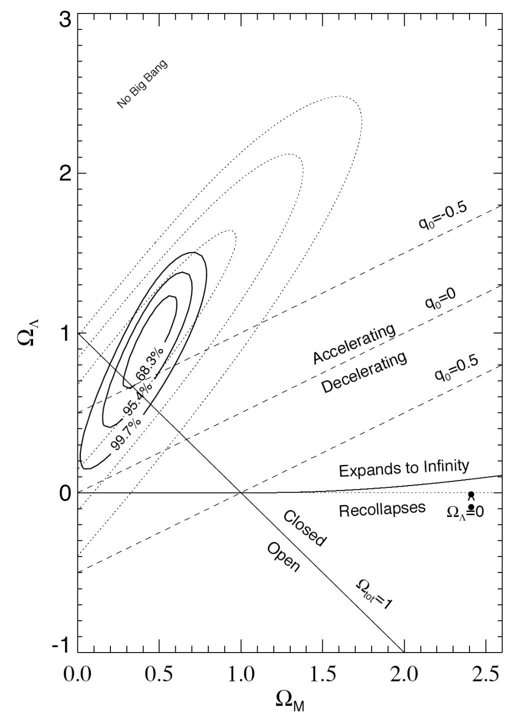



http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html

# Supernovae results



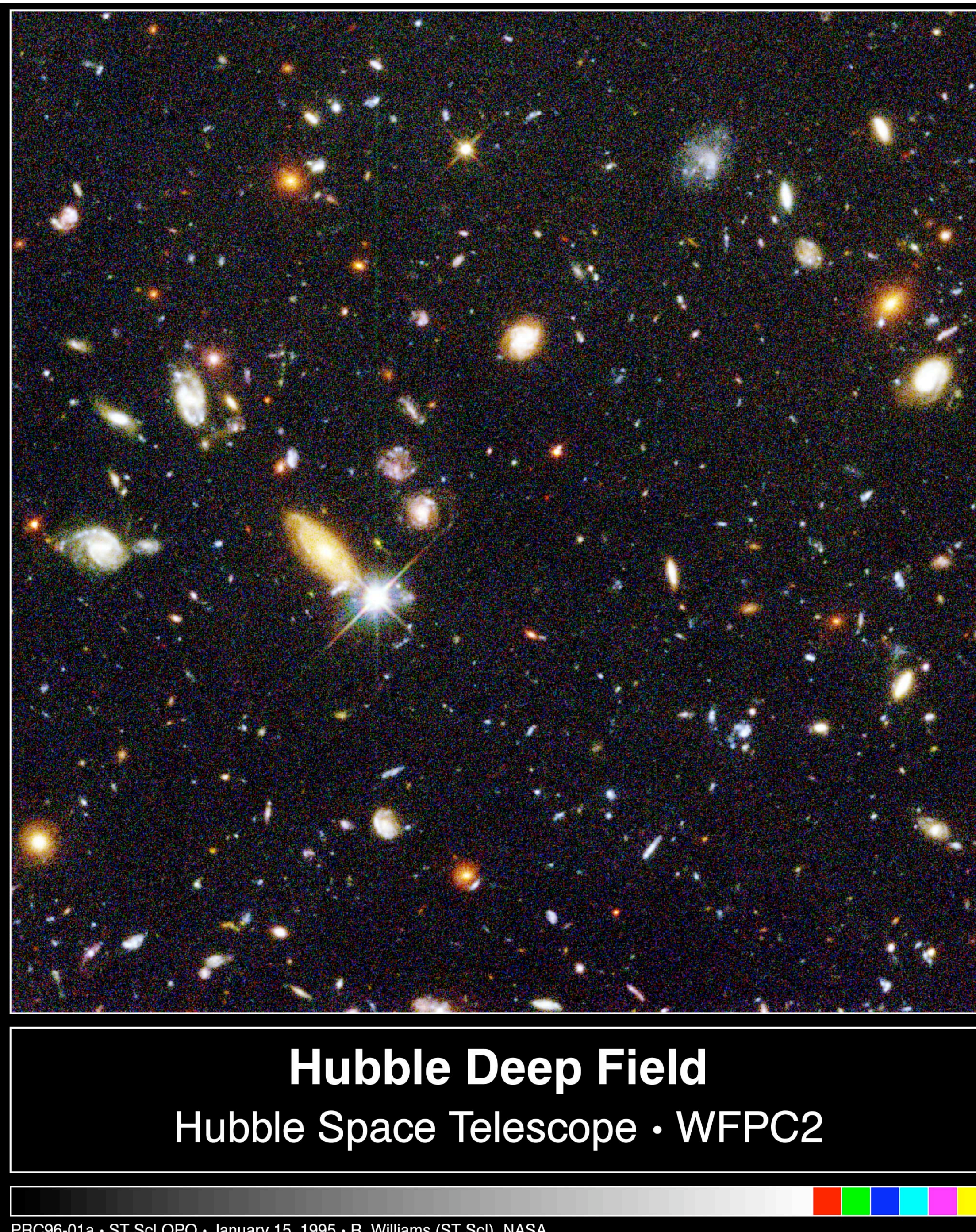
# Could GR be wrong ?

# How is matter distributed?

# Matter is not distributed uniformly

It forms structure on many scales

The level of structure evolves with time

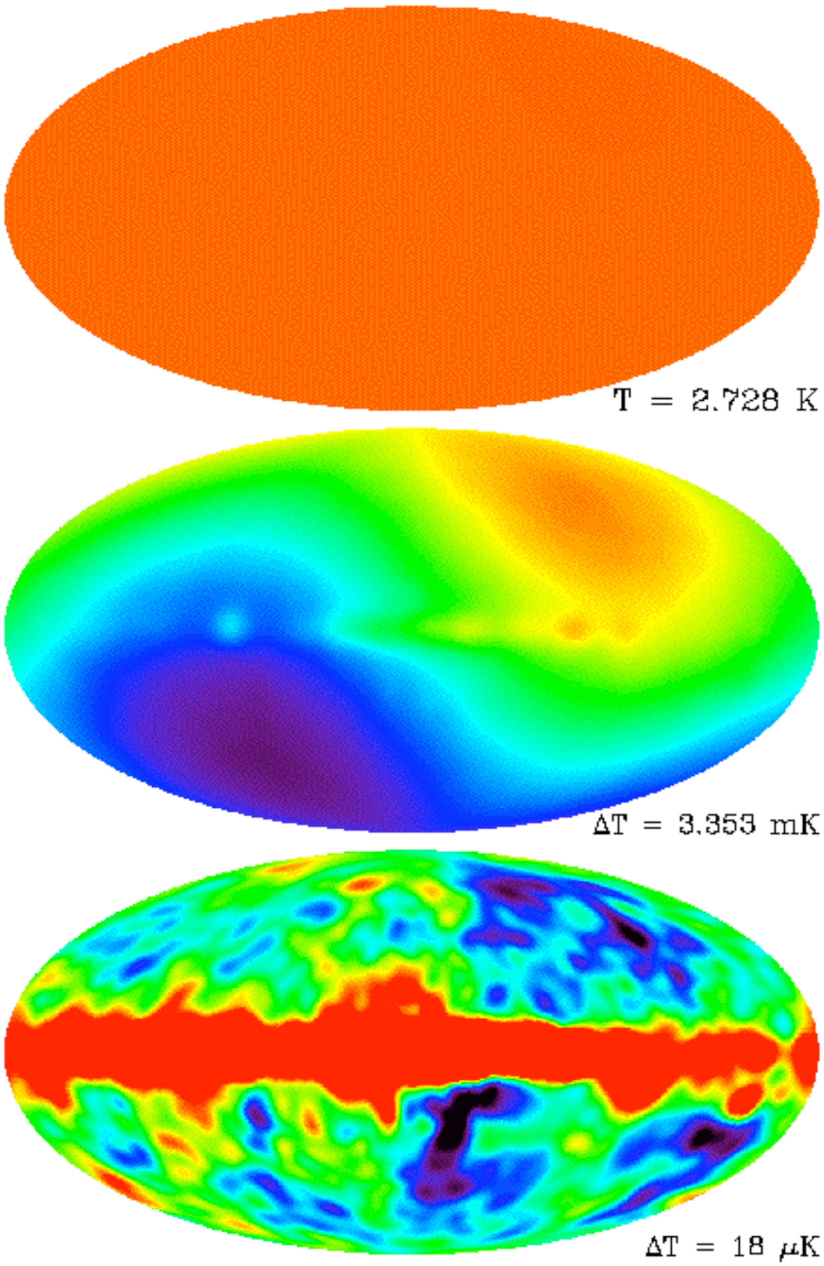


# Probes of Large Scale Structure

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

# Anisotropies in the CMB temperature

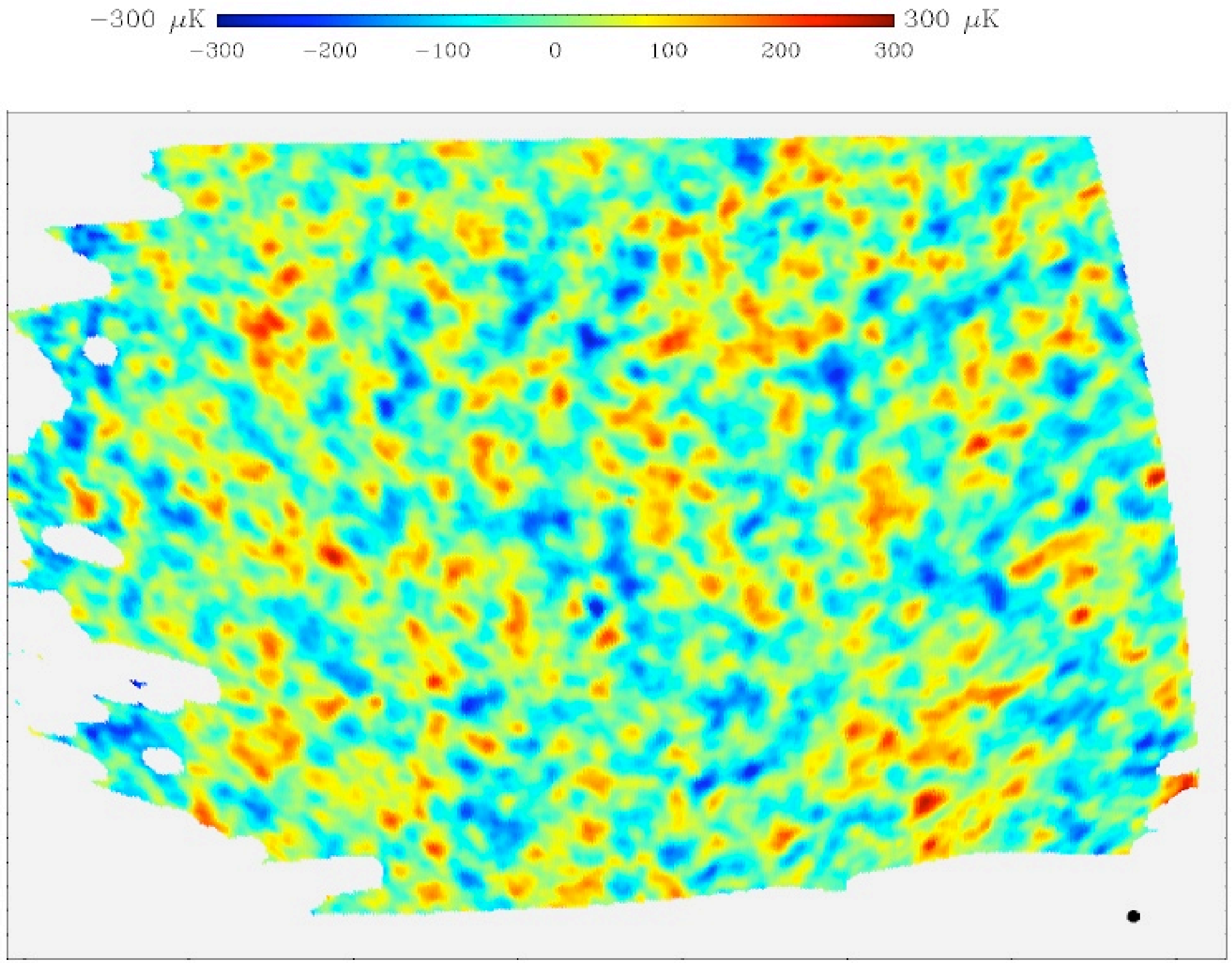
# COBE 1992



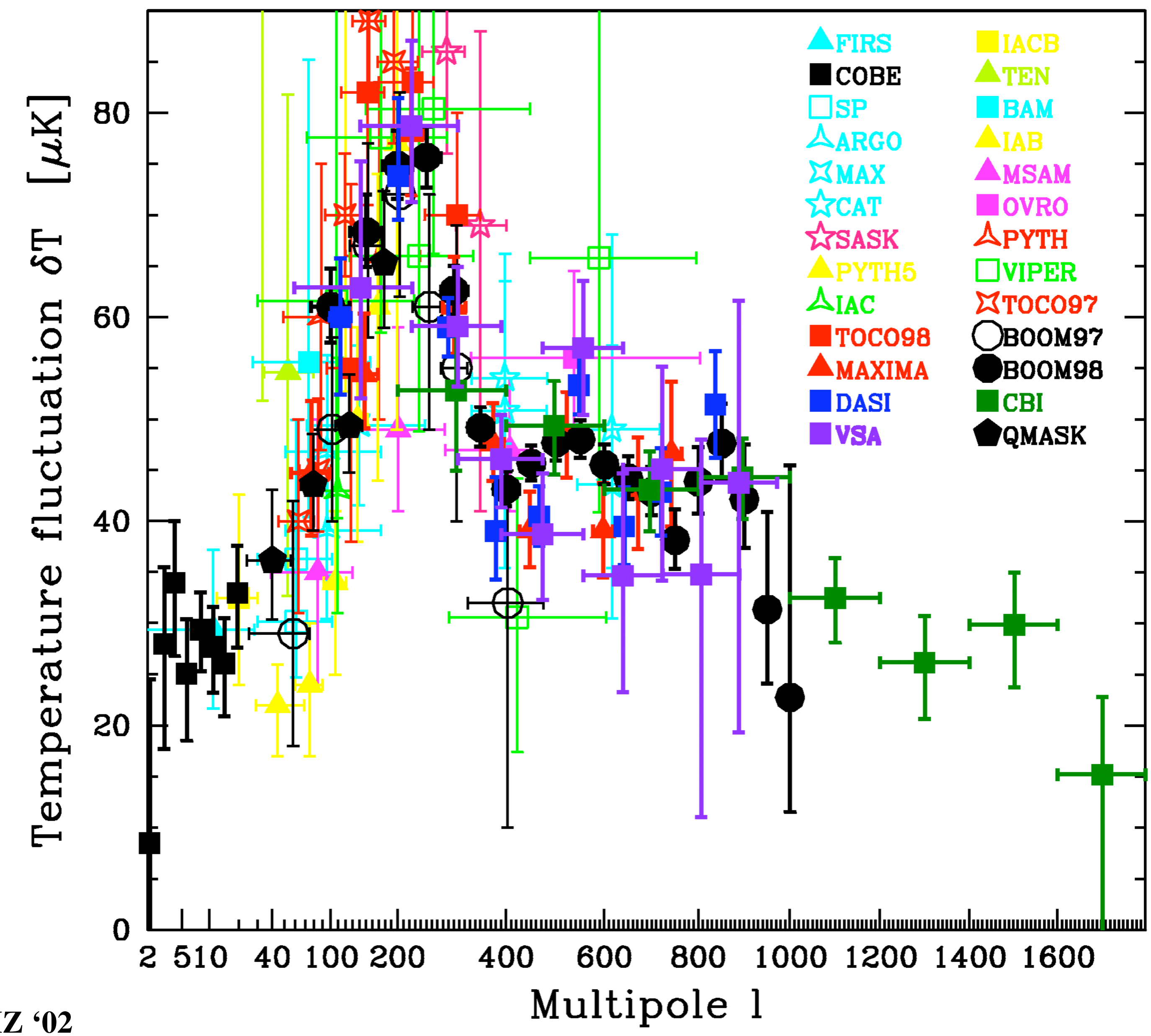
# Boomerang Launch 12/98

# Anisotropies as seen by Boomerang

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

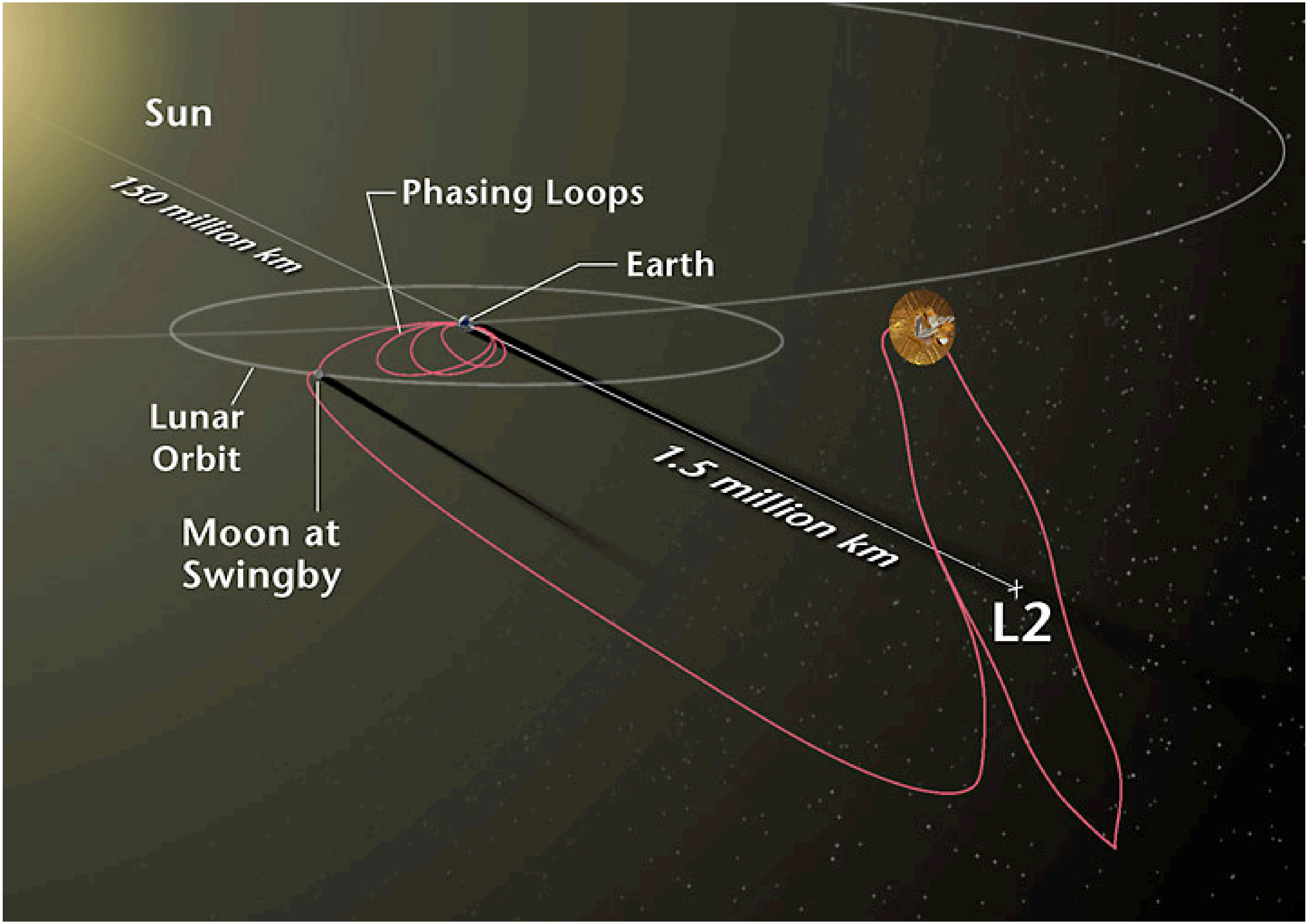


# Temperature Power Spectrum




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

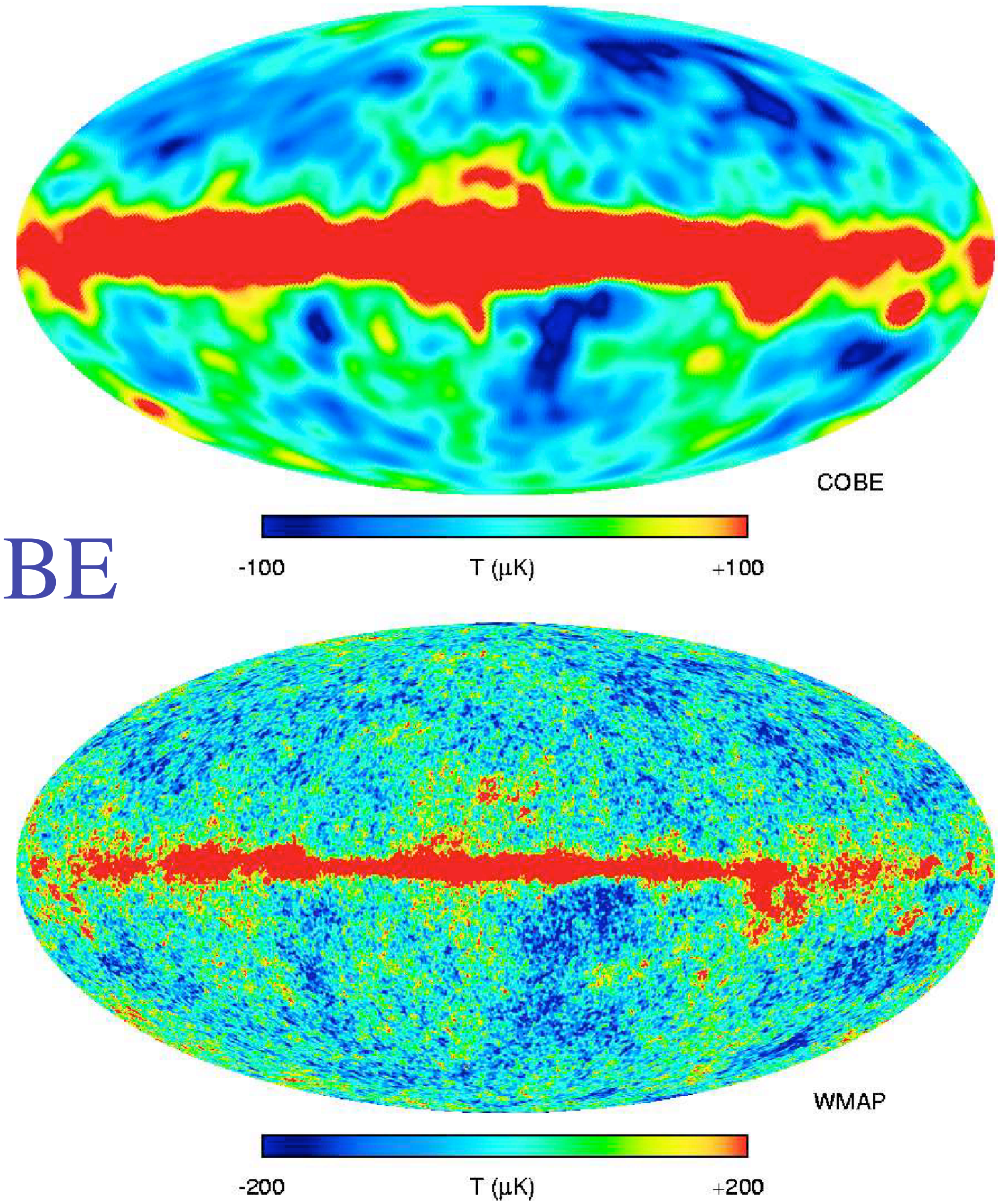
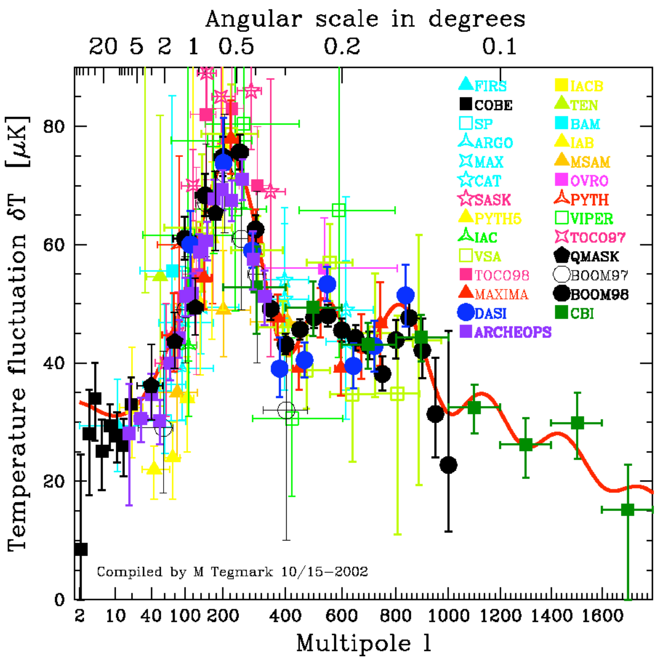
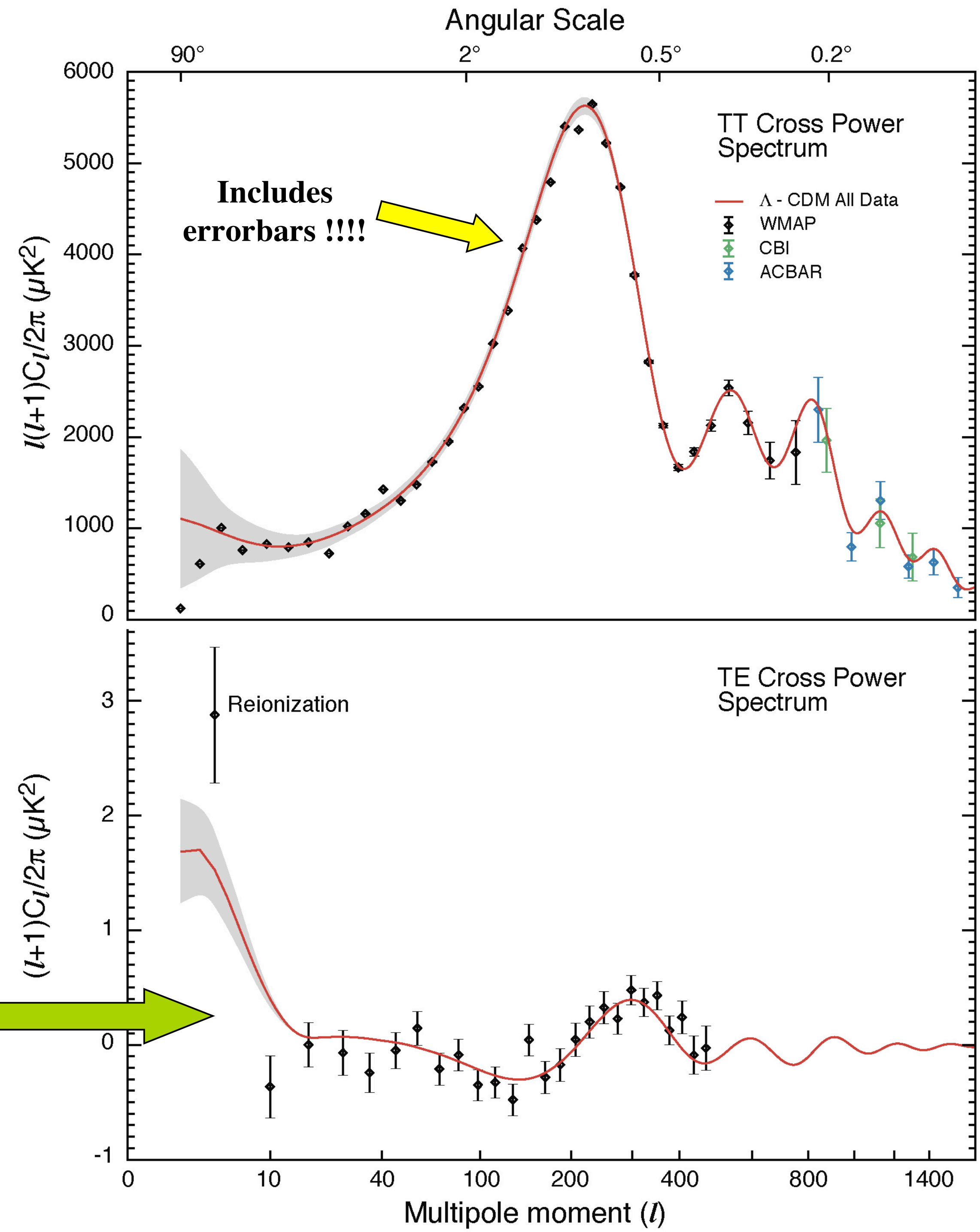



Fig. 7.— A comparison of the *COBE* 90 GHz map (Bennett et al. 1996) with the W-band *WMAP* map. The *WMAP* map has 30 times finer resolution than the *COBE* map.

# WMAP Spectra




**Includes errorbars !!!!**

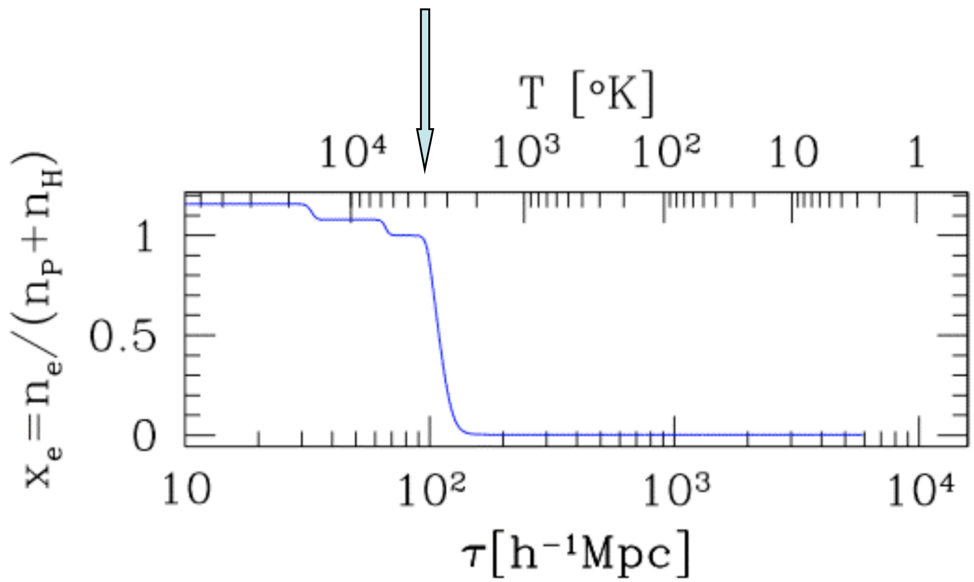



**Temperature and polarization patterns are correlated**

# What creates the anisotropies?

# Recombination

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




**Hydrogen is ionized**

**Hydrogen is neutral**

**Thomson Scattering**

# Orders of Magnitude:

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

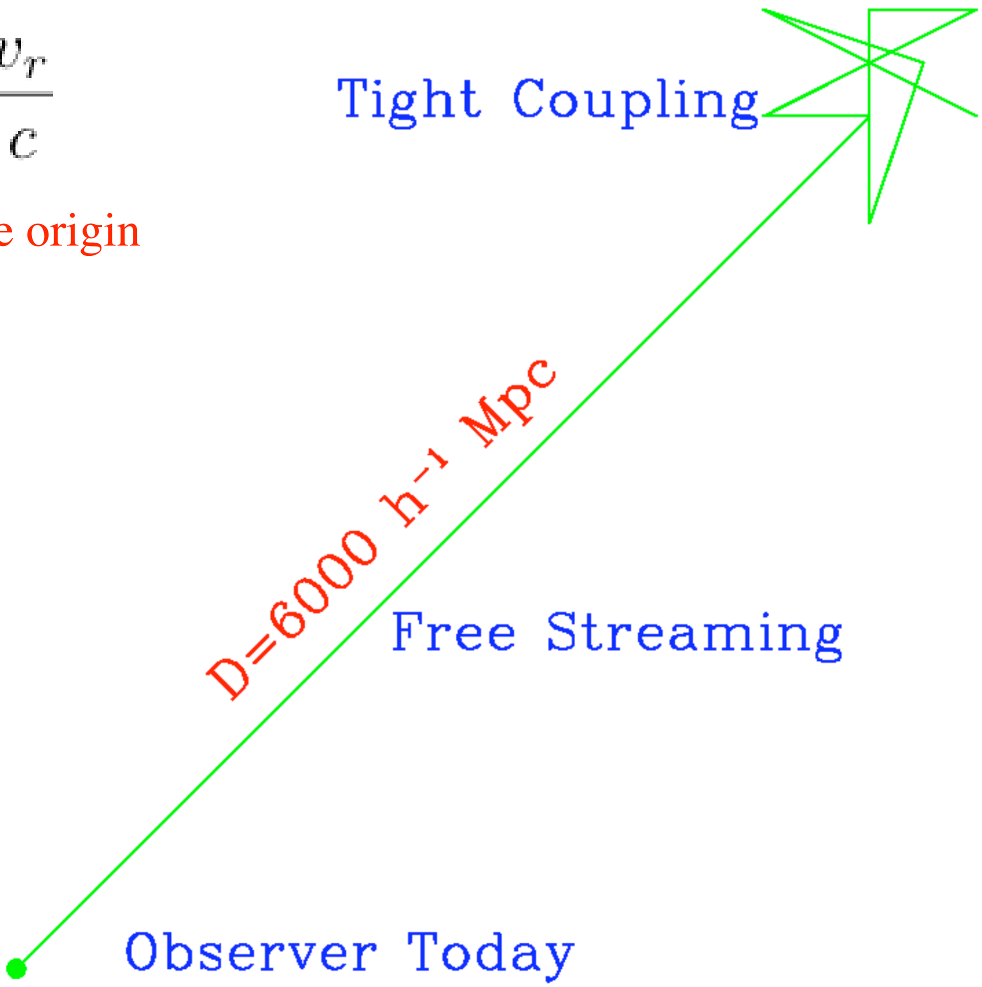
$$= 2\ \mathrm{Mpc}\ x_e^{-1}\ \ [(1+z)/1000]^{-2}$$

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

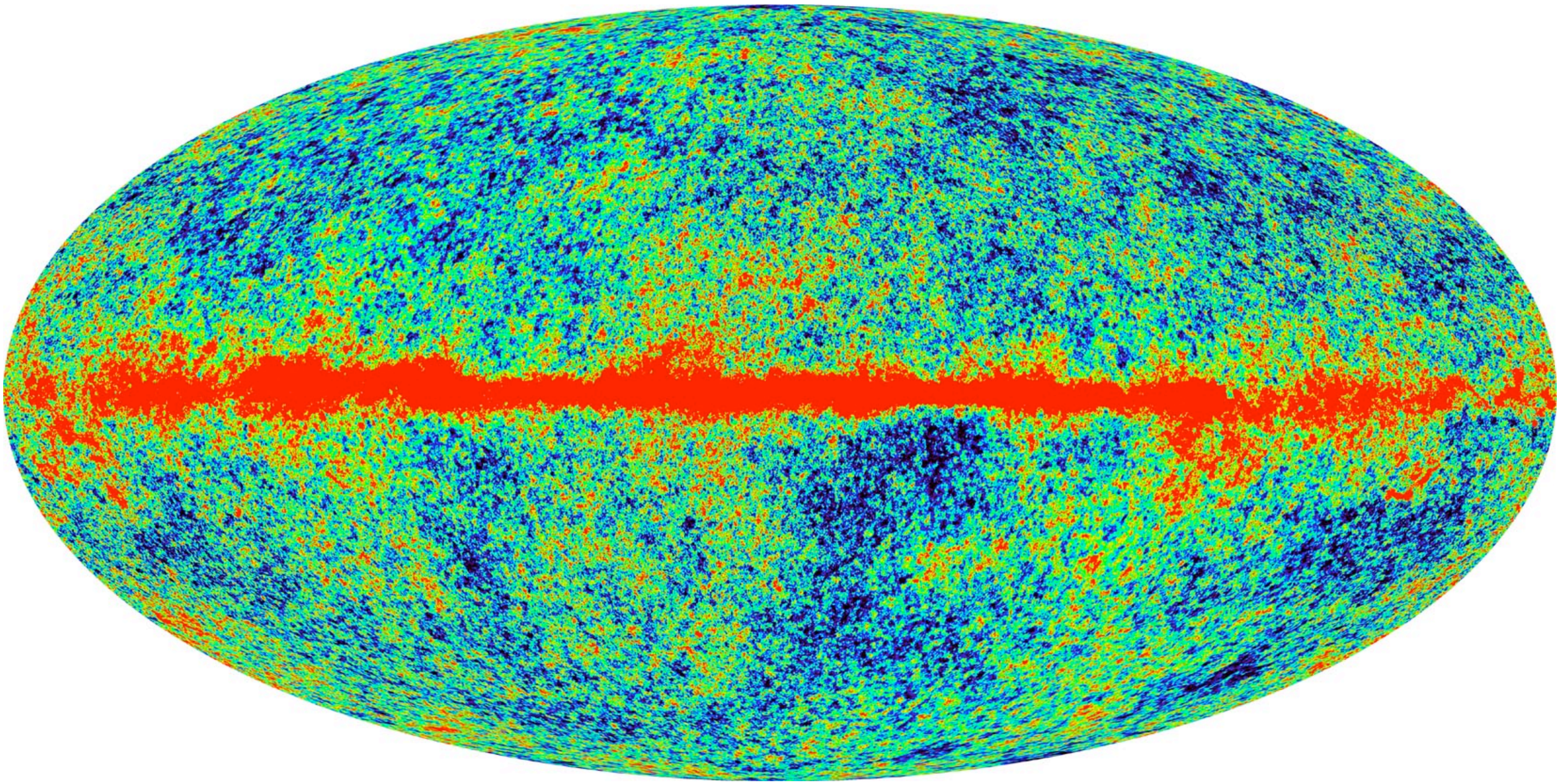
$$D = \tau_0 - \tau_R \approx 6000\ [\Omega h^2]^{-1/2}\ \mathrm{Mpc}$$

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

All 3 effects have the same origin

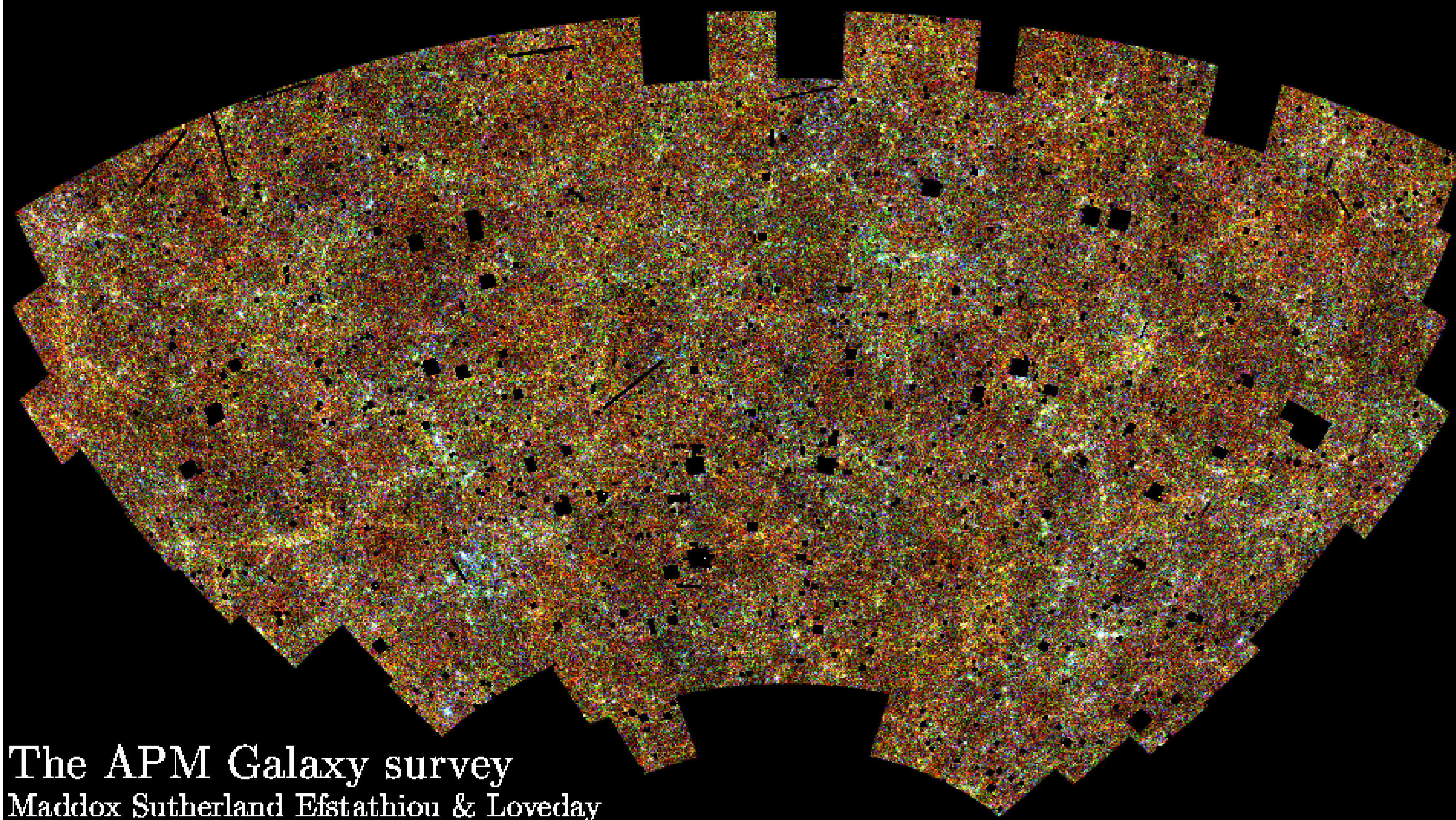


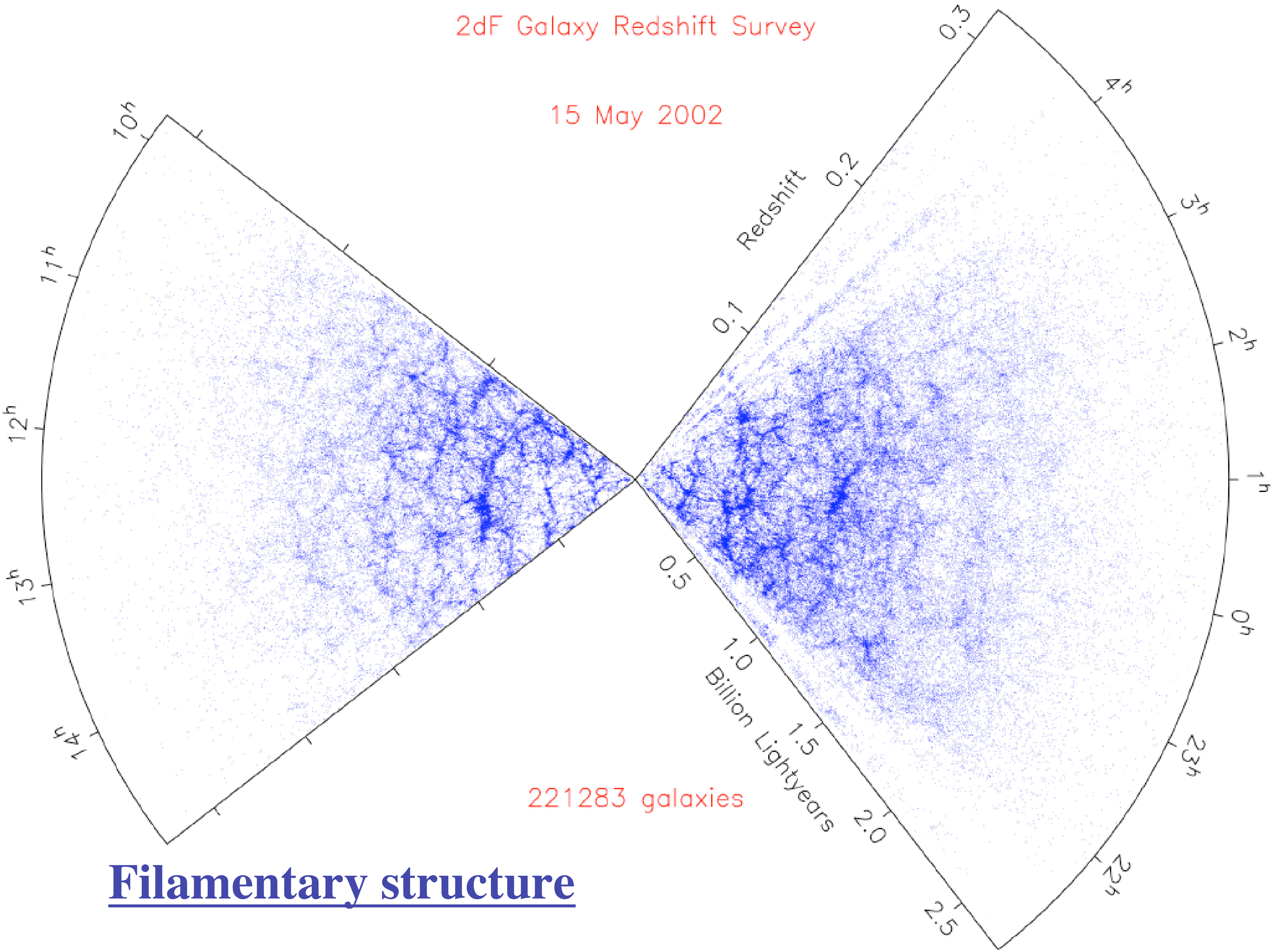
# WMAP: level of structure at recombination



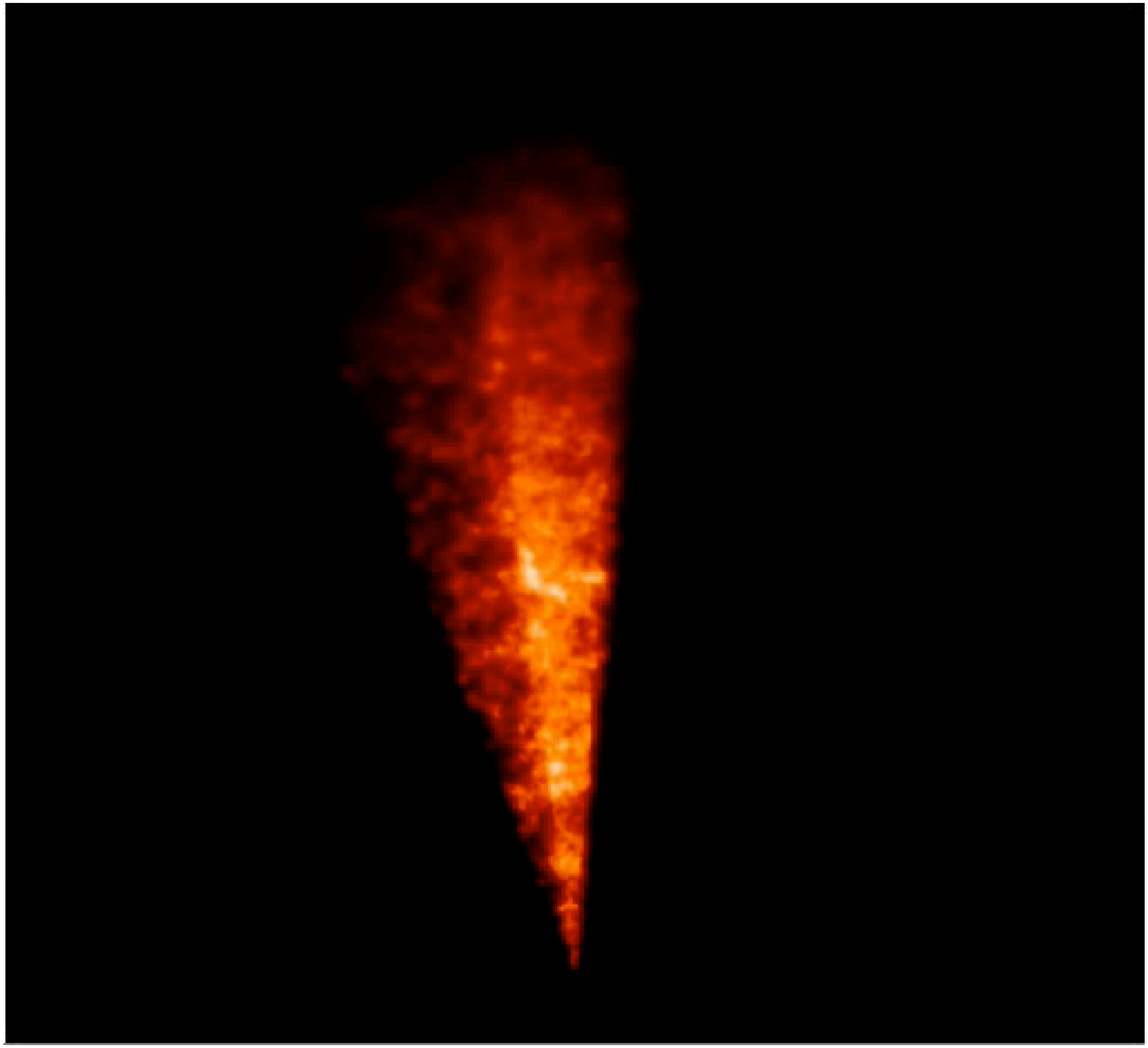
# Present day structure: the distribution of galaxies

# The distribution of matter as traced by galaxies





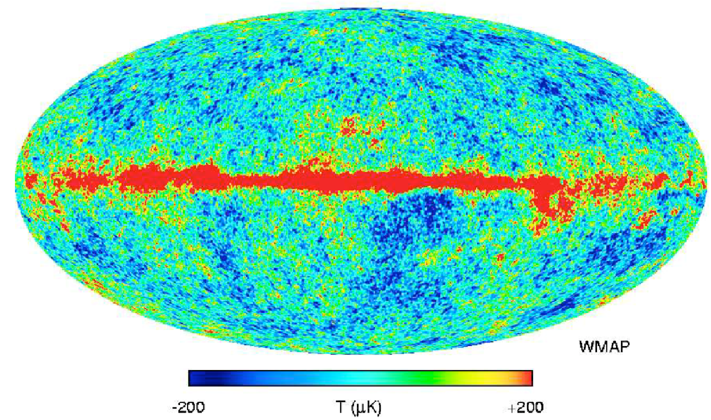

# Filamentary structure



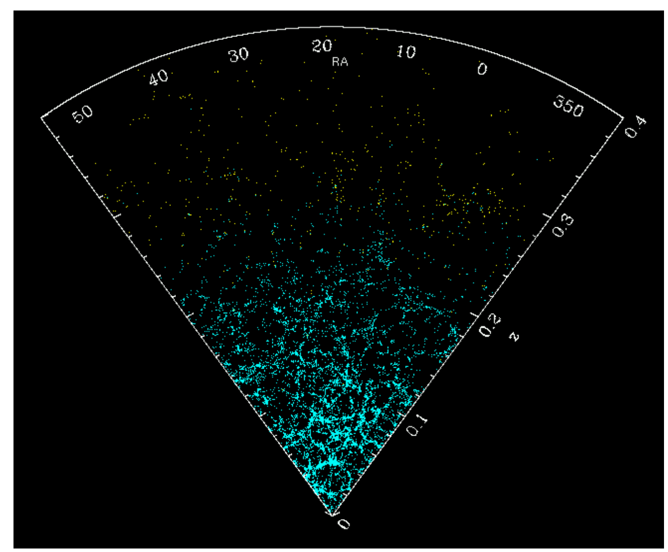
http://www.mso.anu.edu.au/2dFGRS/

# 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.

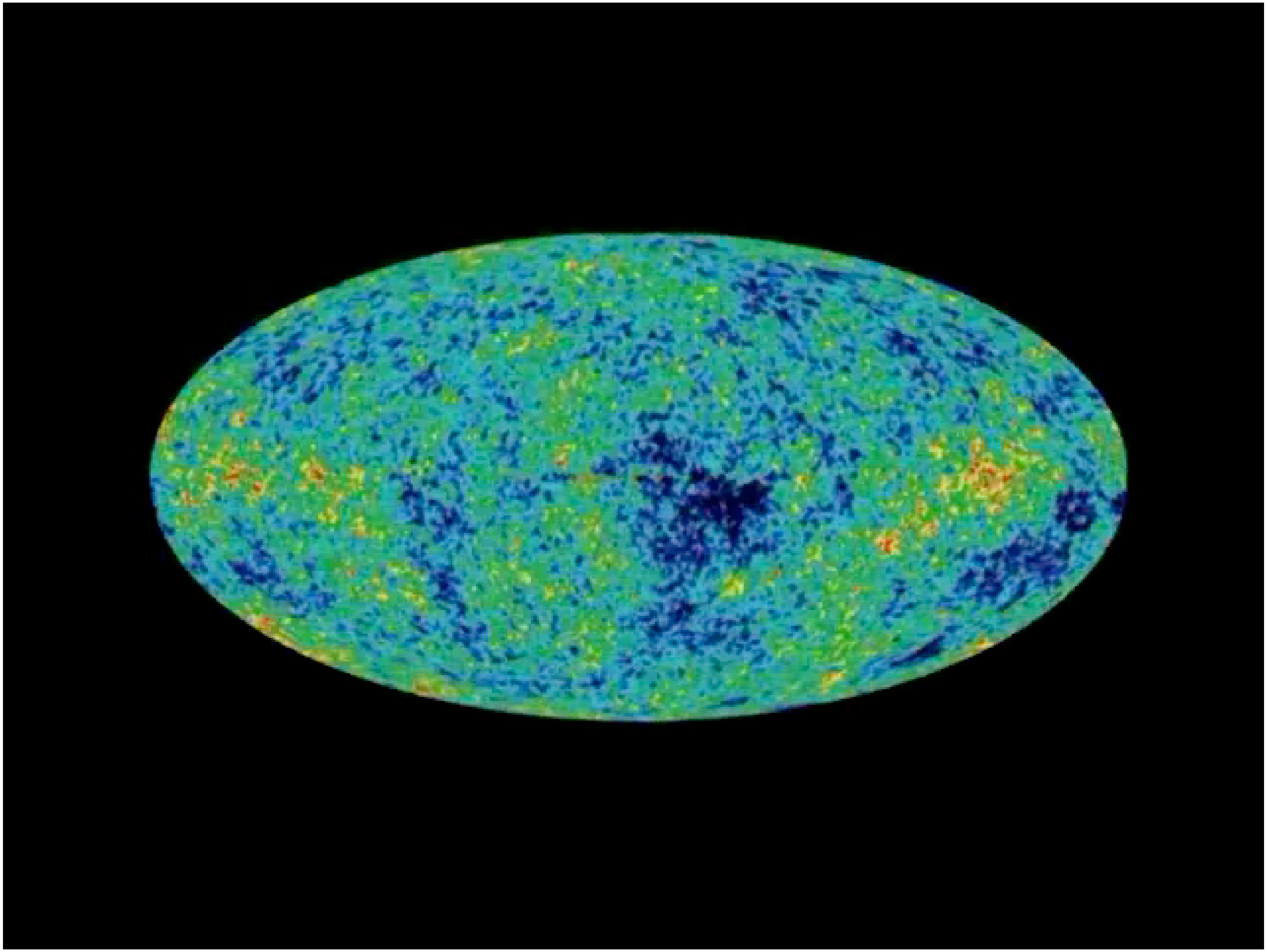
"Best" Cosmological Parameters:

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 | $\Omega_{tot}$ | 1.02 | 0.02 | 0.02 |
| Equation of state of quintessence | $w$ | $< -0.78$ | 95% CL | — |
| Dark energy density | $\Omega_\Lambda$ | 0.73 | 0.04 | 0.04 |
| Baryon density | $\Omega_b h^2$ | 0.0224 | 0.0009 | 0.0009 |
| Baryon density | $\Omega_b$ | 0.044 | 0.004 | 0.004 |
| Baryon density ($\mathrm{cm}^{-3}$) | $n_b$ | $2.5 \times 10^{-7}$ | $0.1 \times 10^{-7}$ | $0.1 \times 10^{-7}$ |
| Matter density | $\Omega_m h^2$ | 0.135 | 0.008 | 0.009 |
| Matter density | $\Omega_m$ | 0.27 | 0.04 | 0.04 |
| Light neutrino density | $\Omega_\nu h^2$ | $< 0.0076$ | 95% CL | — |
| CMB temperature (K)[a] | $T_{\mathrm{cmb}}$ | 2.725 | 0.002 | 0.002 |
| CMB photon density ($\mathrm{cm}^{-3}$)[b] | $n_\gamma$ | 410.4 | 0.9 | 0.9 |
| Baryon-to-photon ratio | $\eta$ | $6.1 \times 10^{-10}$ | $0.3 \times 10^{-10}$ | $0.2 \times 10^{-10}$ |
| Baryon-to-matter ratio | $\Omega_b \Omega_m^{-1}$ | 0.17 | 0.01 | 0.01 |
| Fluctuation amplitude in $8h^{-1}$ Mpc spheres | $\sigma_8$ | 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