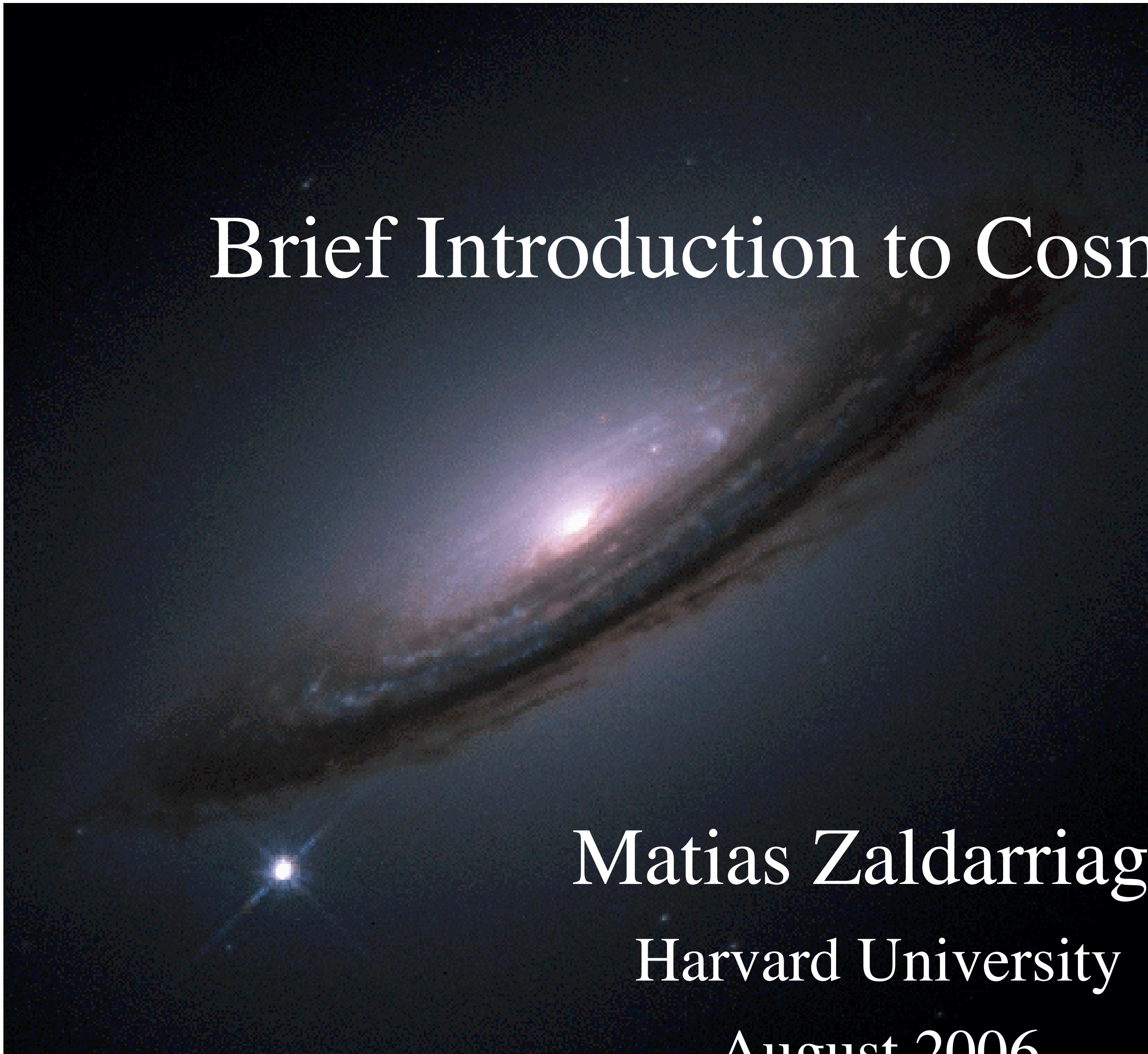
Brief Introduction to Cosmology



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August 2006

Basic Questions in Cosmology:

Connection to physics

- How does the Universe evolve?
- What is the universe made off?

Dark matter
Dark energy
Gravity

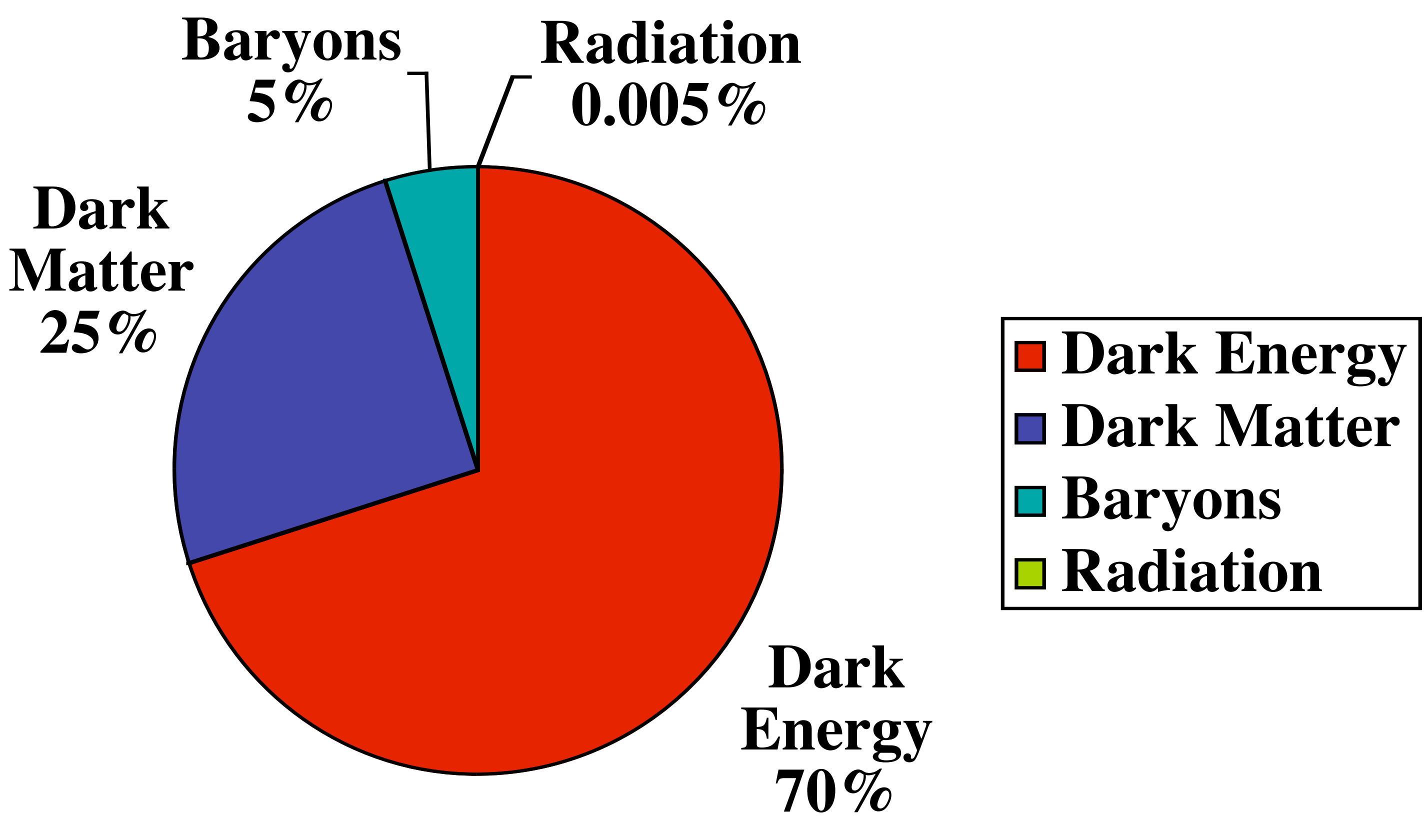
- How is matter distributed?
- How did structure form?

Initial conditions
"Inflation"

Of course many interesting astrophysics/astronomy issues. Piecing together the history of the Universe. Finding out what phenomena occur in it.

Difference with physics: observations vs experiments

Matter content 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,

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

H^2

Square of the Hubble constant

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

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

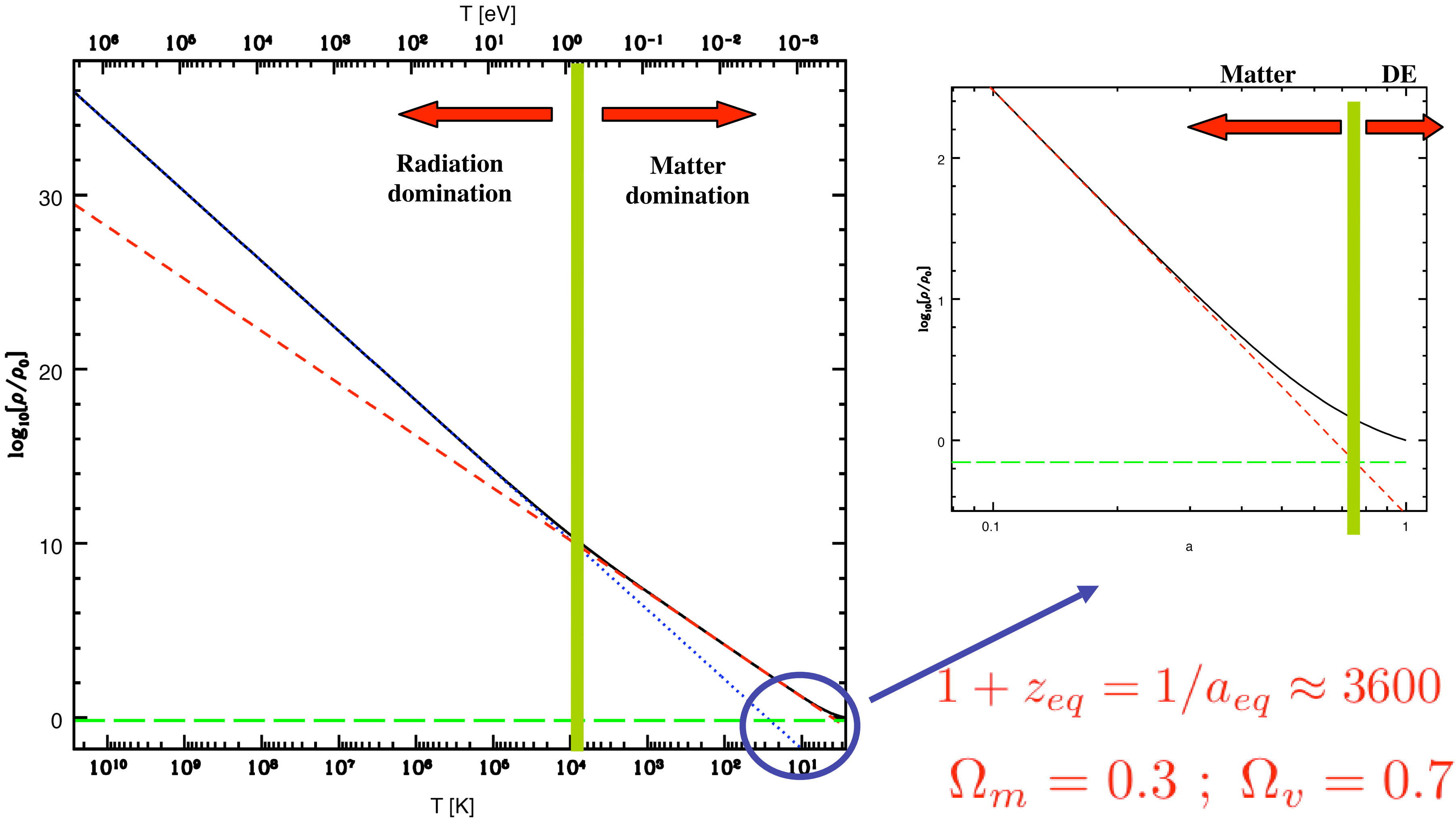
$$H^2 = \frac{\rho}{M_{pl}^2}$$

Matter equal radiation when $a \sim 2 \times 10^{-4}$

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

Acceleration if $w < -1/3$

Evolution of the density



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

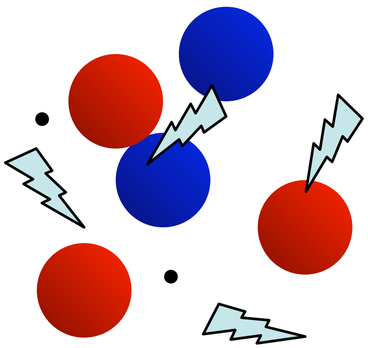
$$\Omega_m = 0.3\ ;\ \Omega_v = 0.7$$

Consequences of the Expansion

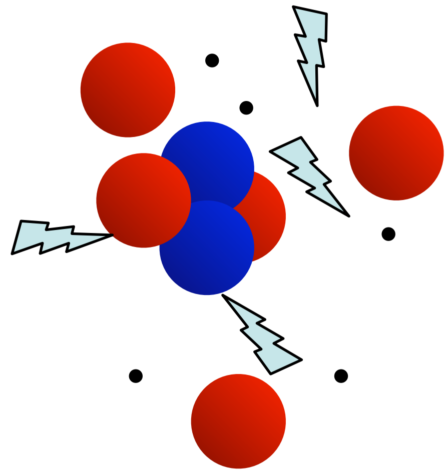
The Universe is not always the same.

The Universe was denser and hotter in the past.

The changing conditions allow us to explore physics in different energy regimes at different epochs.



Expansion

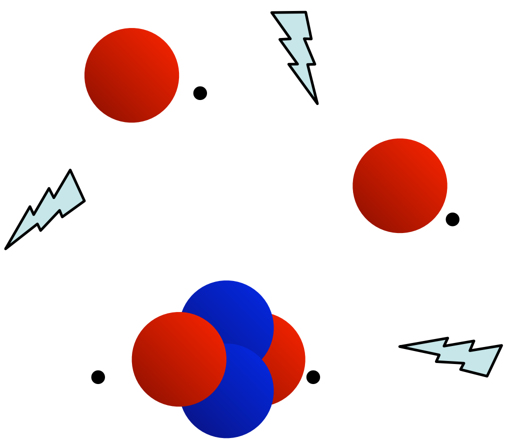


Expansion

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

Nucleosynthesis

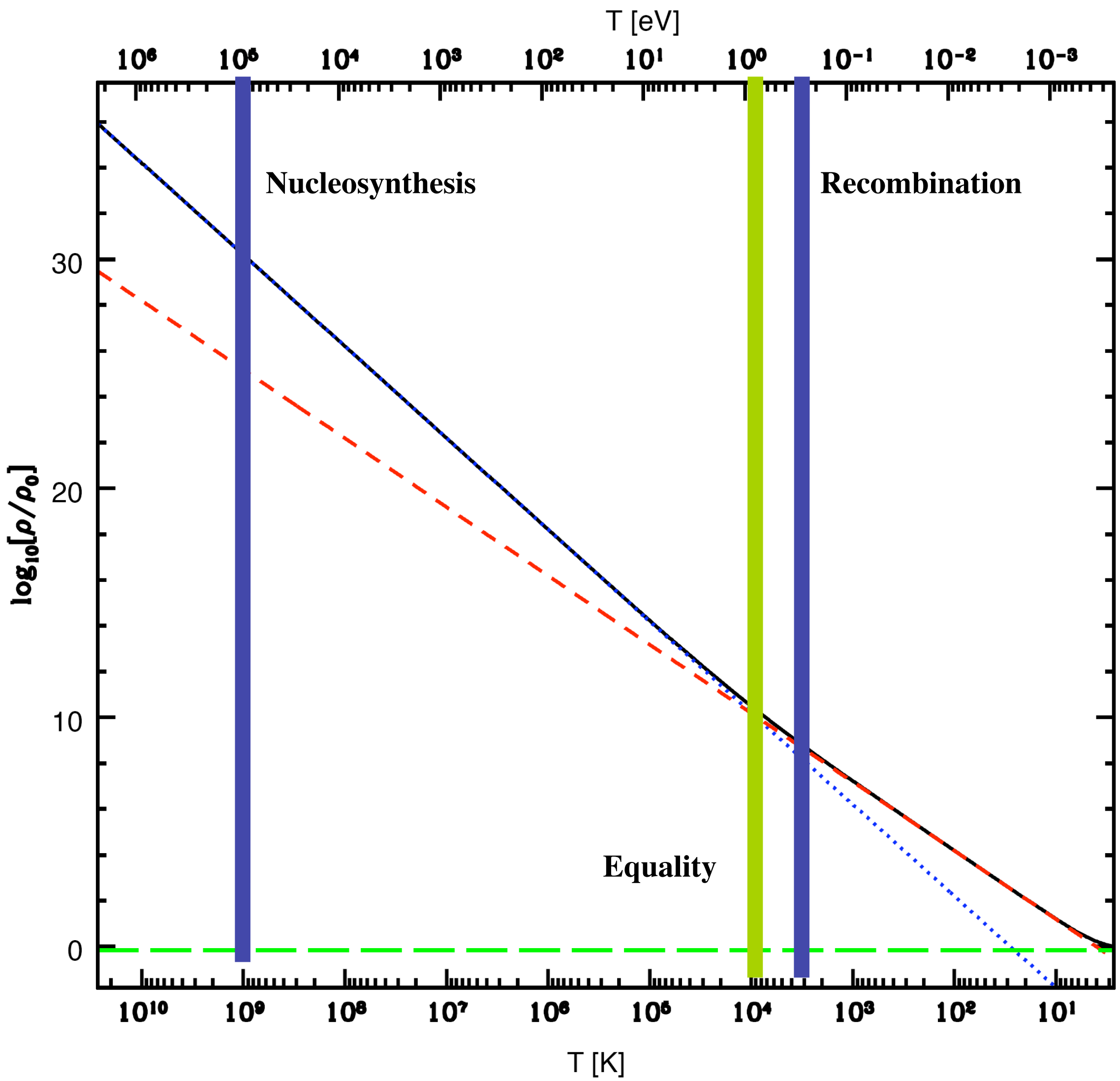
First minutes after the Big Bang: formation of Helium, Deuterium and Lithium.



Recombination

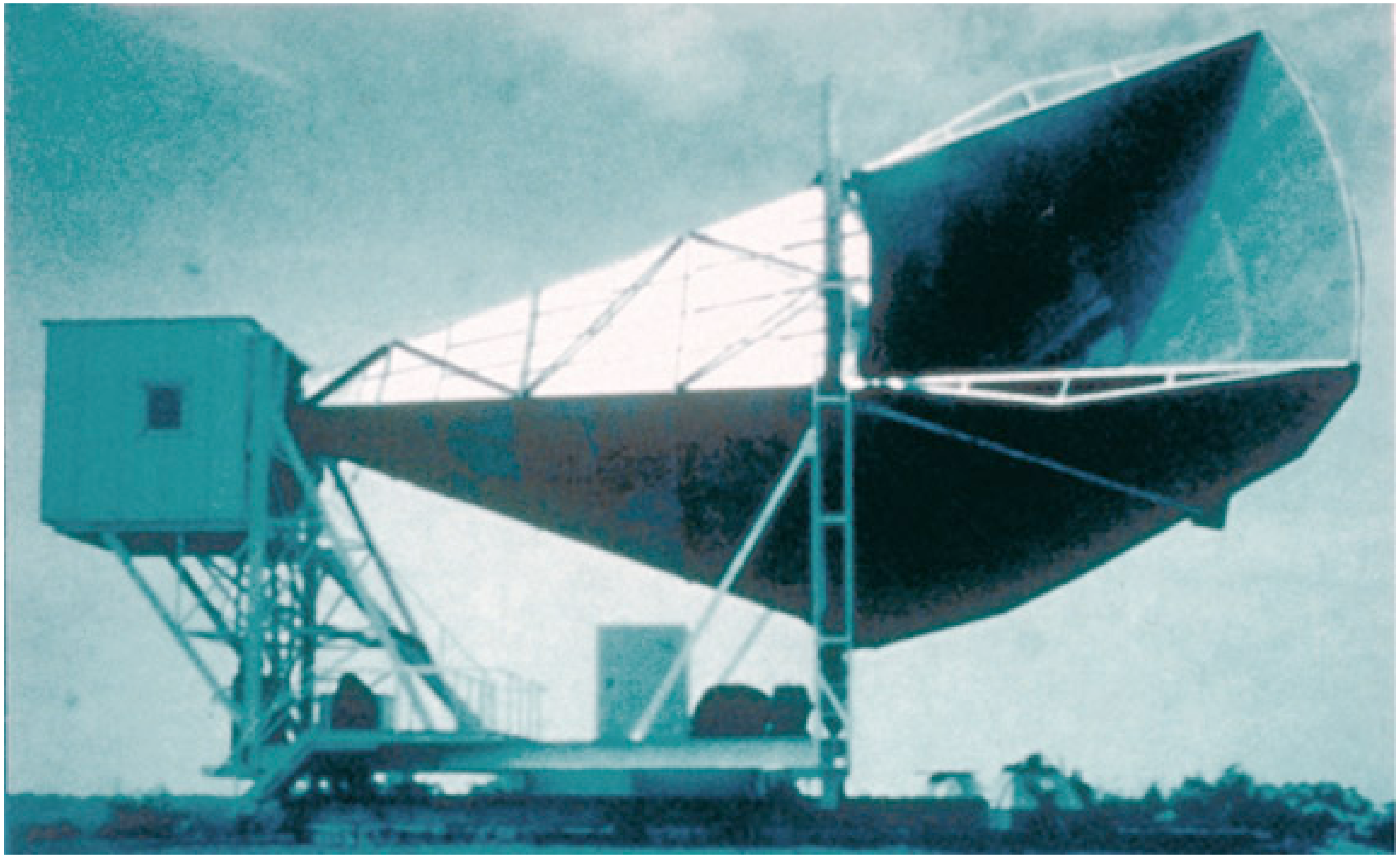
300,000 after the Big Bang. Universe cools enough to form neutral hydrogen. The universe becomes transparent to photons.

Thermal History



What is the Universe made off?

Photons: The Cosmic Microwave Background



Penzias & Wilson 1965

The Spectrum of the CMB

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

$\Omega_\gamma \approx 5\ 10^{-5}$

$T_\gamma \approx 2.7$ K

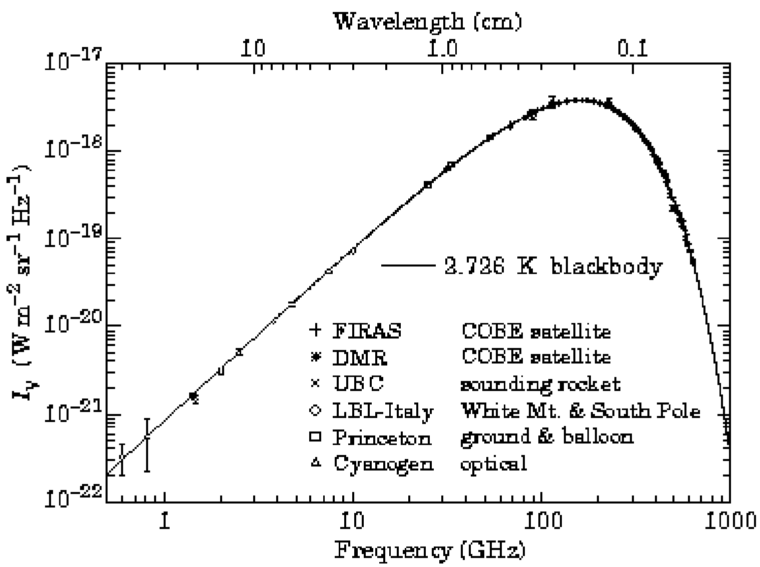


Figure 1. Precise measurements of the CMB spectrum. The line represents a 2.73 K blackbody, which describes the spectrum very well, especially around the peak of intensity. The spectrum is less well constrained at frequencies of 3 GHz and below (10 cm and longer wavelengths). (References for this figure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

Smoot & Scott '98

There is also a background of neutrinos with $T_\nu \approx 2$ K and $n_\nu \approx 115\ cm^{-3}$.

They are detected indirectly through their effect in the expansion at BBN.

Thermal Equilibrium

- Equilibrium thermodynamics
- Is this assumption valid?

Thermal Equilibrium

$$n = \frac{g}{2\pi^2}\int_m^\infty \frac{(E^2 - m^2)^{1/2}}{\exp[(E-\mu)/T] \pm 1} E\,dE$$

$$\rho = \frac{g}{2\pi^2}\int_m^\infty \frac{(E^2 - m^2)^{1/2}}{\exp[(E-\mu)/T] \pm 1} E^2\,dE$$

$$p = \frac{g}{6\pi^2}\int_m^\infty \frac{(E^2 - m^2)^{3/2}}{\exp[(E-\mu)/T] \pm 1} E\,dE$$

$$s = \frac{\rho + p}{T}$$

Number of degrees of freedom

Temperature	New Particles	$4N(T)$
$T < m_e$	γ's + ν's	29
$m_e < T < m_\mu$	$e^\pm$	43
$m_\mu < T < m_\pi$	$\mu^\pm$	57
$m_\pi < T < T_c{}^\dagger$	π's	69
$T_c < T < m_{\text{strange}}$	π's + $u, \bar{u}, d, \bar{d}$ + gluons	205
$m_s < T < m_{\text{charm}}$	$s, \bar{s}$	247
$m_c < T < m_\tau$	$c, \bar{c}$	289
$m_\tau < T < m_{\text{bottom}}$	$\tau^\pm$	303
$m_b < T < m_{\text{W,Z}}$	$b, \bar{b}$	345
$m_{W,Z} < T < m_{\text{Higgs}}$	$W^\pm, Z$	381
$m_H < T < m_{\text{top}}$	H^0	385
$m_t < T$	$t, \bar{t}$	427

$^\dagger T_c$ corresponds to the confinement-deconfinement transition between quarks and hadrons.

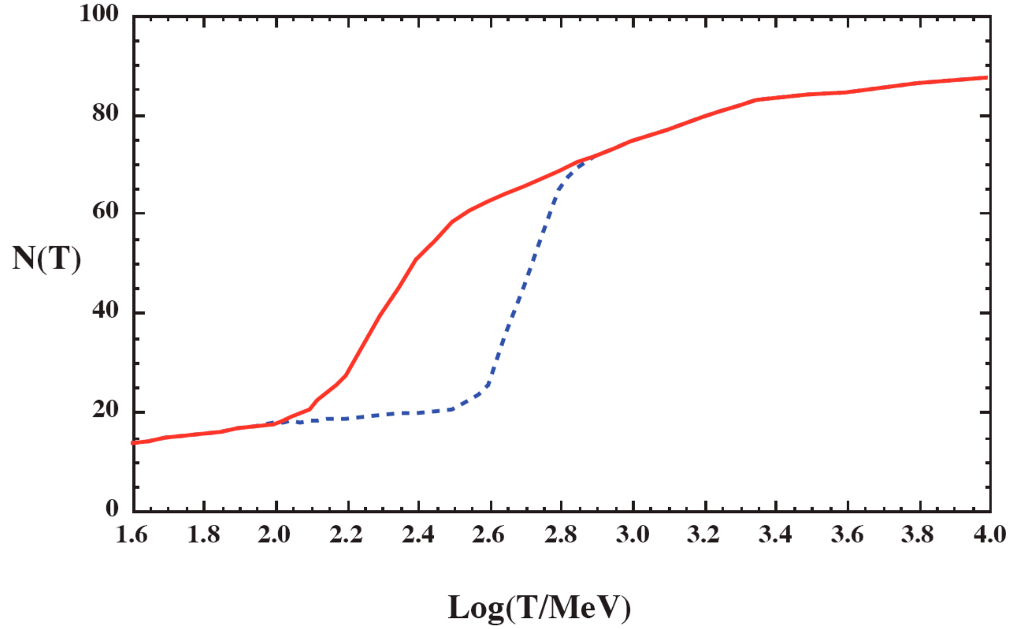
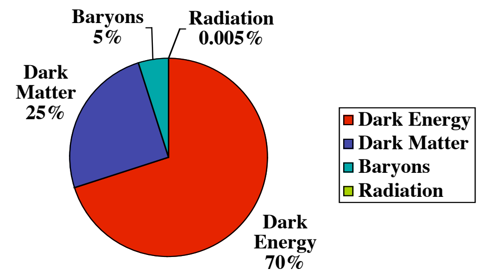


Figure 19.3: The effective numbers of relativistic degrees of freedom as a function of temperature. The sharp drop corresponds to the quark-hadron transition. The solid curve assume a QCD scale of 150 MeV, while the dashed curve assumes 450 MeV.

Equilibrium cannot be maintained forever

- Neutrino decoupling
- Photon Decoupling
- BBN
- Dark matter relic

Baryons:

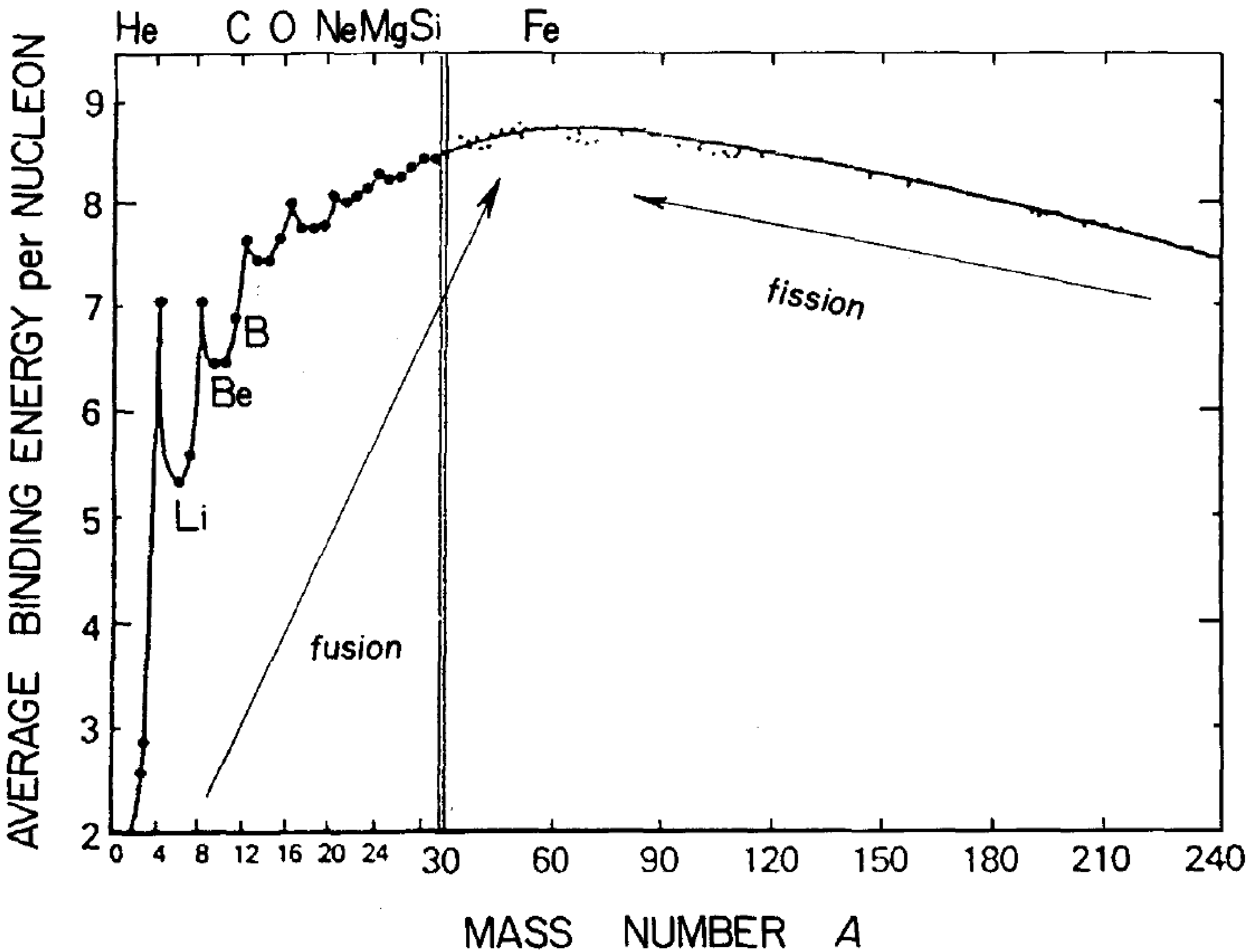


Stars, gas, etc. Seen by their emission and absorption of light

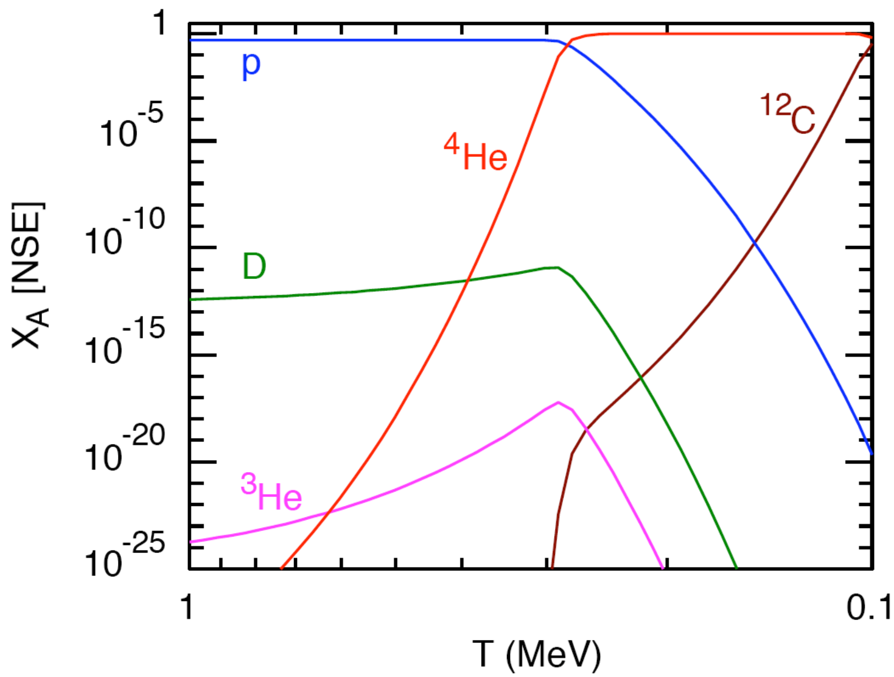
The best ways to count baryons are BBN and the CMB anisotropies.

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

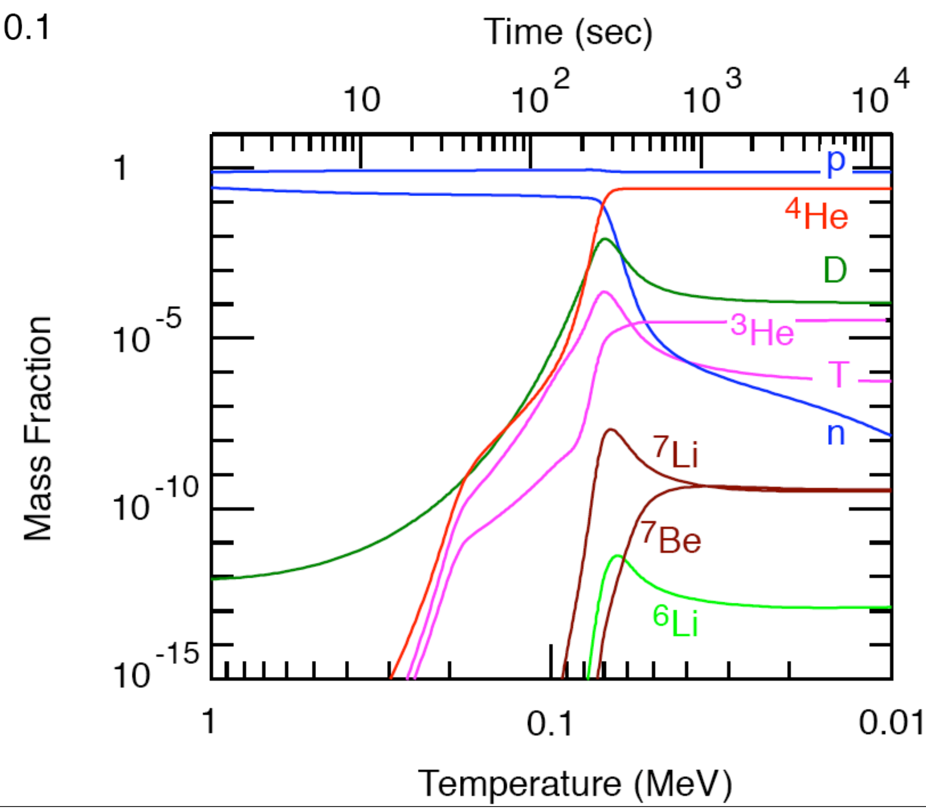
Binding energy per nucleon:



Equilibrium abundances

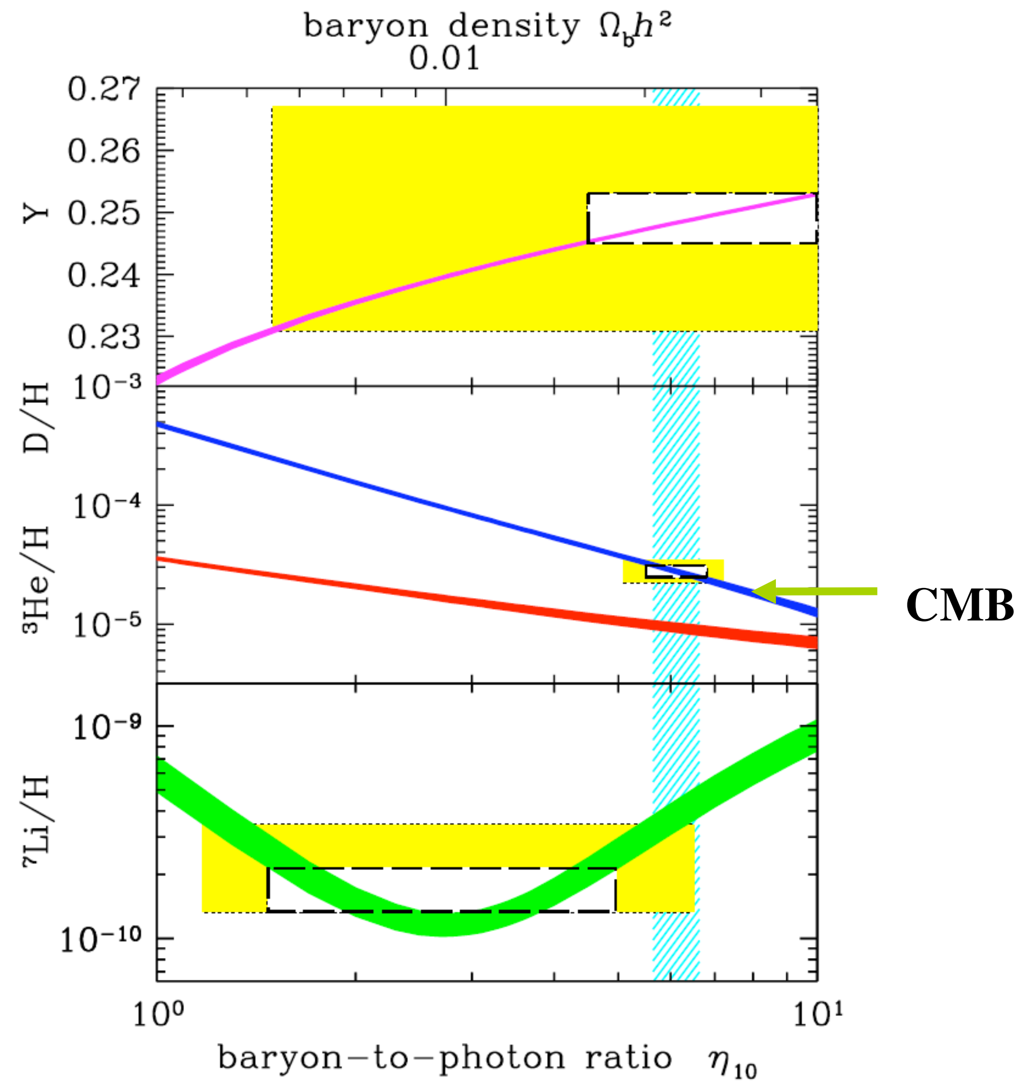


BBN Calculation



Nucleosynthesis

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



PDG review

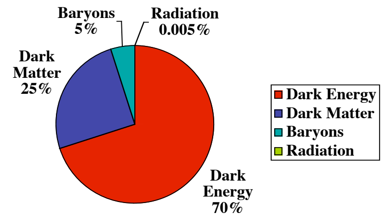
Figure 20.1: The abundances of ^{4}He, D, ^{3}He and ^{7}Li as predicted by the standard model of big-bang nucleosynthesis. Boxes indicate the observed light element abundances (smaller boxes: 2σ statistical errors; larger boxes: $\pm 2\sigma$ statistical and systematic errors). The narrow vertical band indicates the CMB measure of the cosmic baryon density. See full-color version on color pages at end of book.

Baryogenesis

Why is our Universe made of matter and not antimatter?

Do we know that this is the case?

Dark matter:



Only indirectly detected through its gravitational effect on 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 produced thermally

Dark Matter in Galaxies

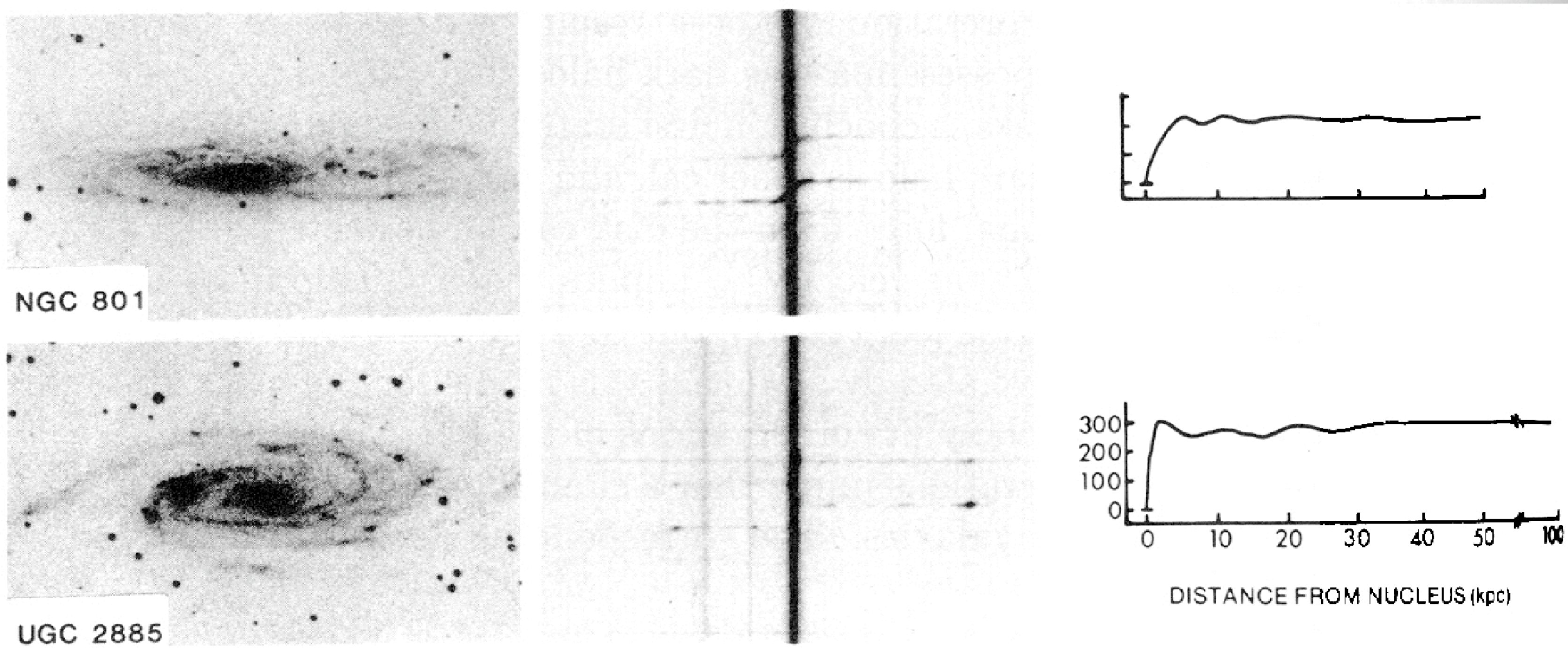
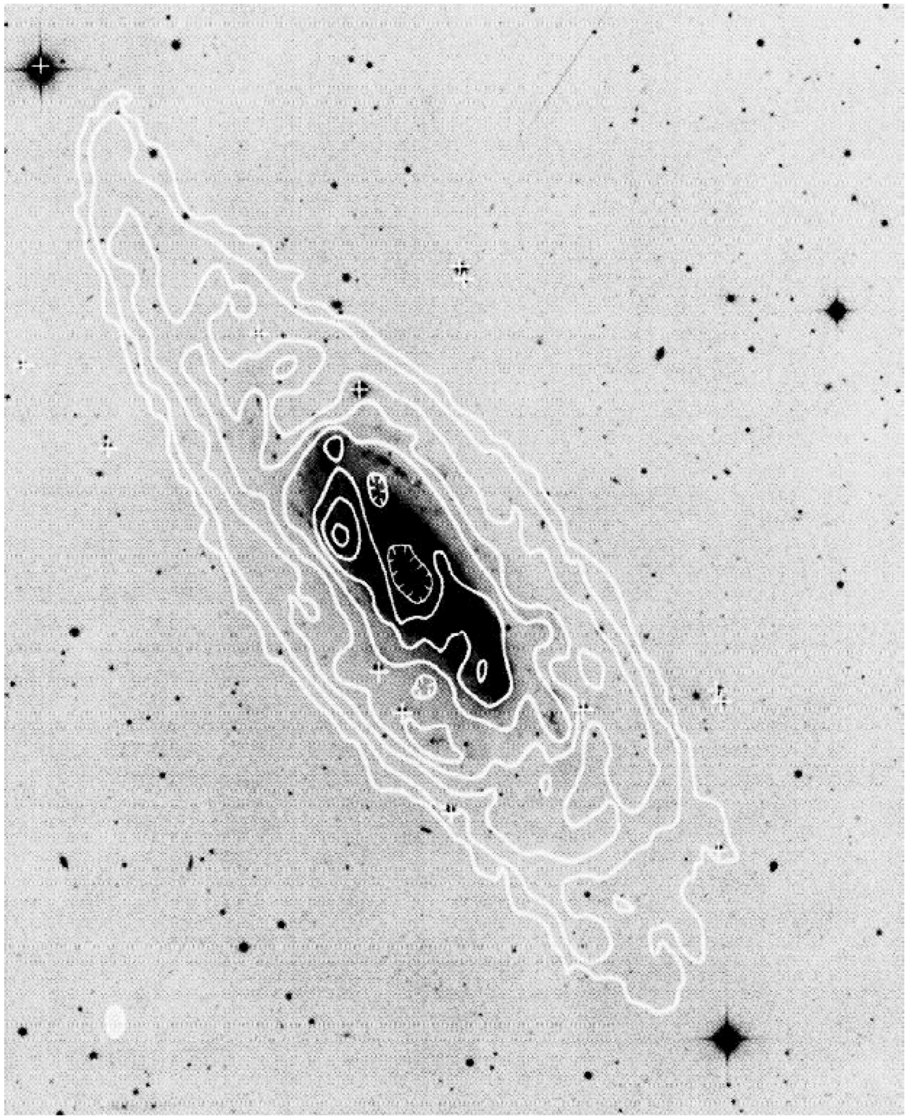


Figure 10-1. Photographs, spectra, and rotation curves for five Sc galaxies, arranged in order of increasing luminosity from top to bottom. The top three images are television pictures, in which the spectrograph slit appears as a dark line crossing the center of the galaxy. The vertical line in each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

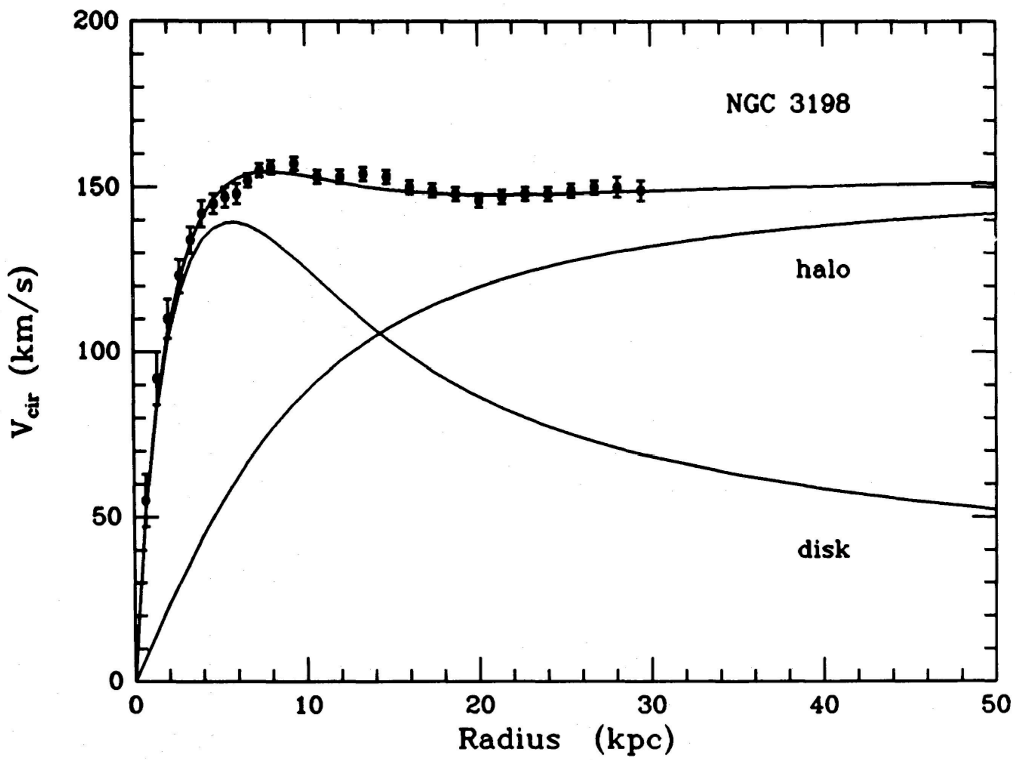


FIG. 4.—Fit of exponential disk with maximum mass and halo to observed rotation curve (*dots with error bars*). The scale length of the disk has been taken equal to that of the light distribution (60″, corresponding to 2.68 kpc). The halo curve is based on eq. (1), $a = 8.5$ kpc, $\gamma = 2.1$, $\rho(R_0)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

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

Failure to maintain equilibrium: Cold relic

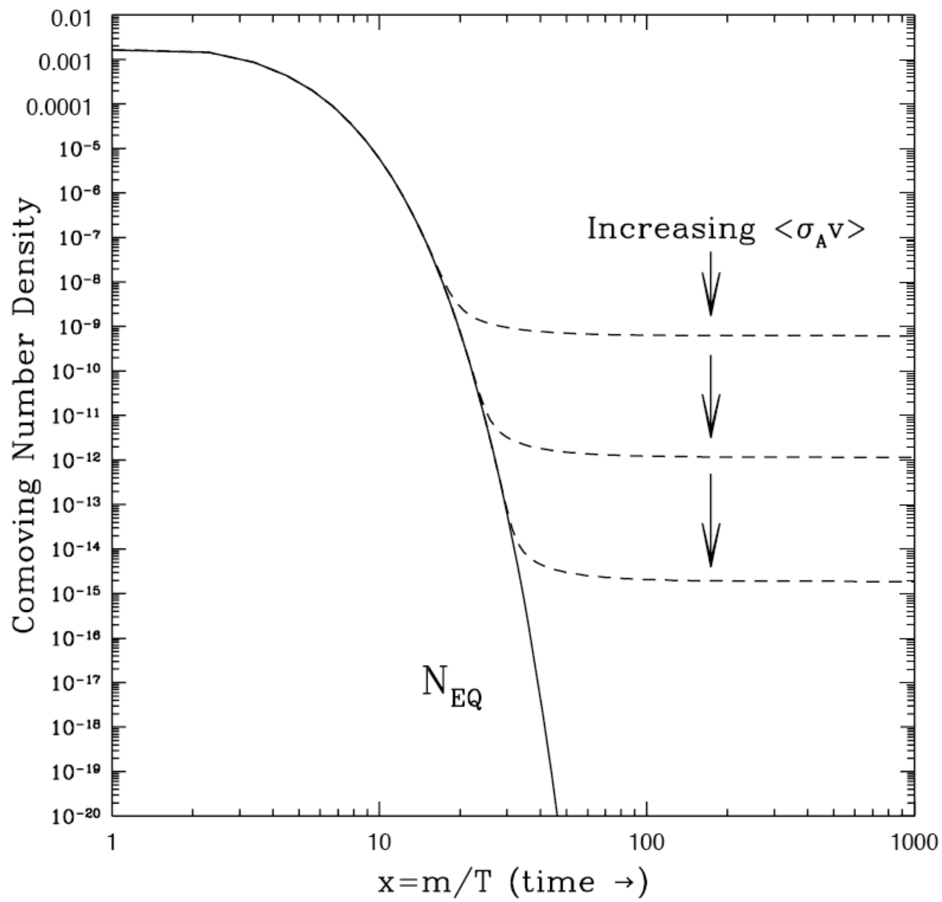
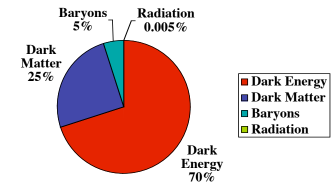


Figure 2: Comoving number density of a WIMP in the early Universe. The dashed curves are the actual abundance, and the solid curve is the equilibrium abundance.

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 large scale structure studies (CMB, galaxy surveys, etc)

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

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

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

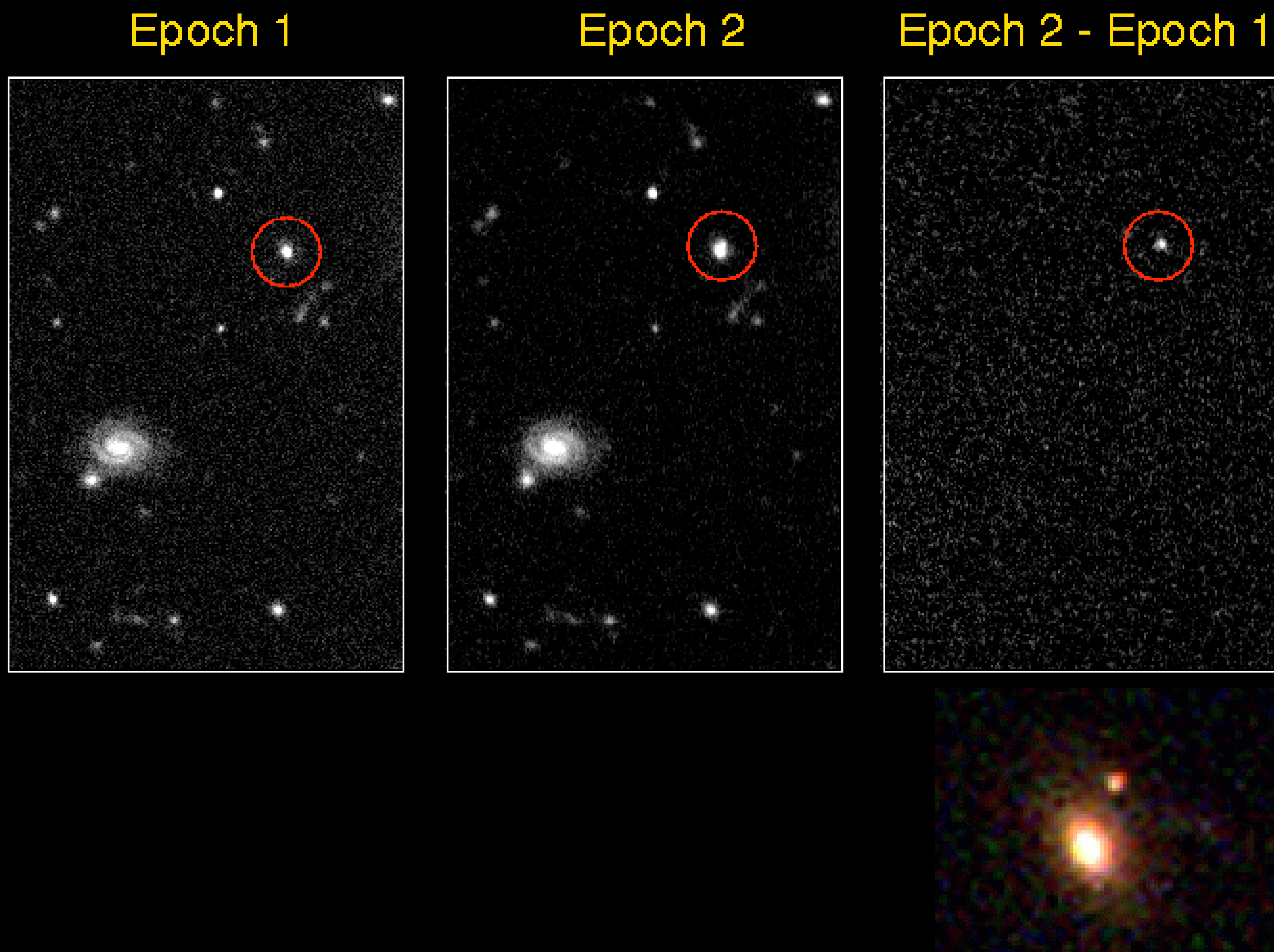
$$1 = \Omega_m + \Omega_r + \Omega_v + \Omega_K.$$

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

Astier et al.

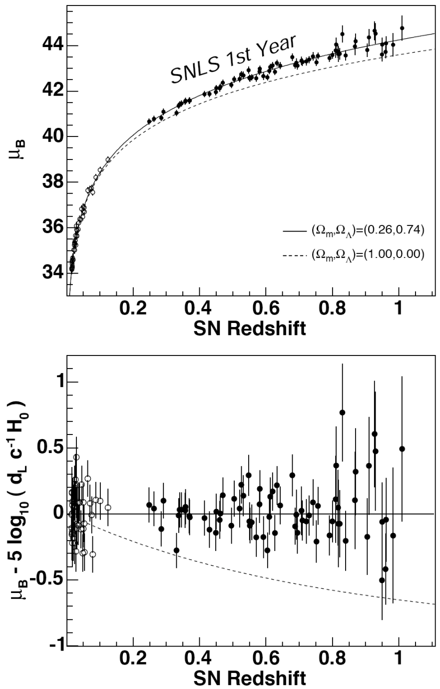


Fig. 4 Hubble diagram of SNLS and nearby SNe Ia, with various cosmologies superimposed. The bottom plot shows the residuals for the best fit to a flat Λ cosmology.

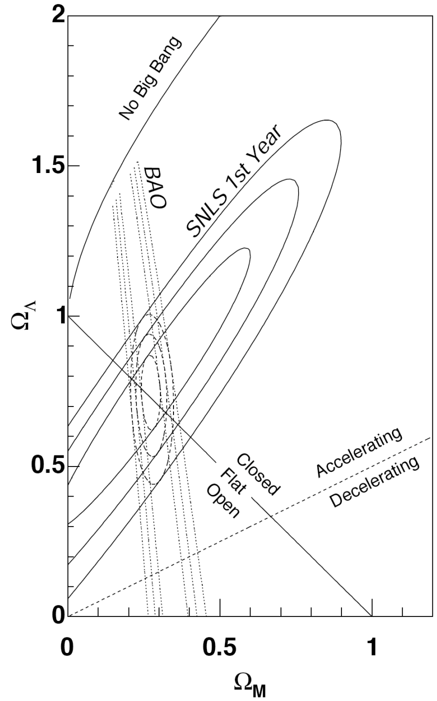


Fig. 5 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to an $(\Omega_M, \Omega_\Lambda)$ cosmology from the SNLS Hubble diagram (solid contours), the SDSS baryon acoustic oscillations (Eisenstein et al. 2005, dotted lines), and the joint confidence contours (dashed lines).

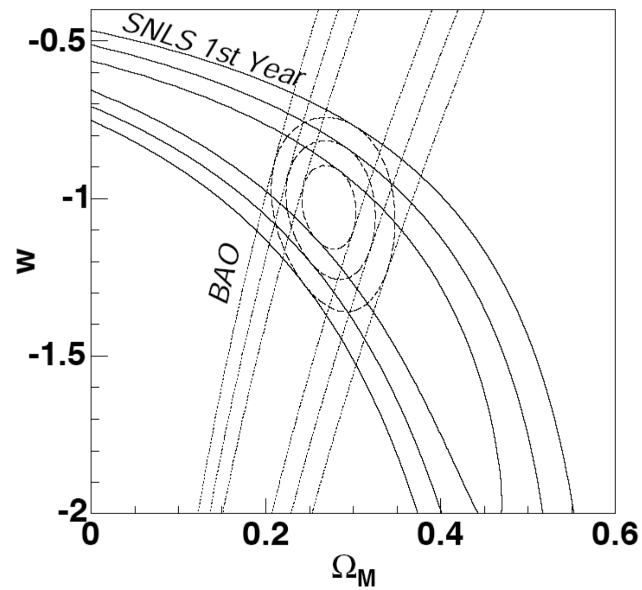
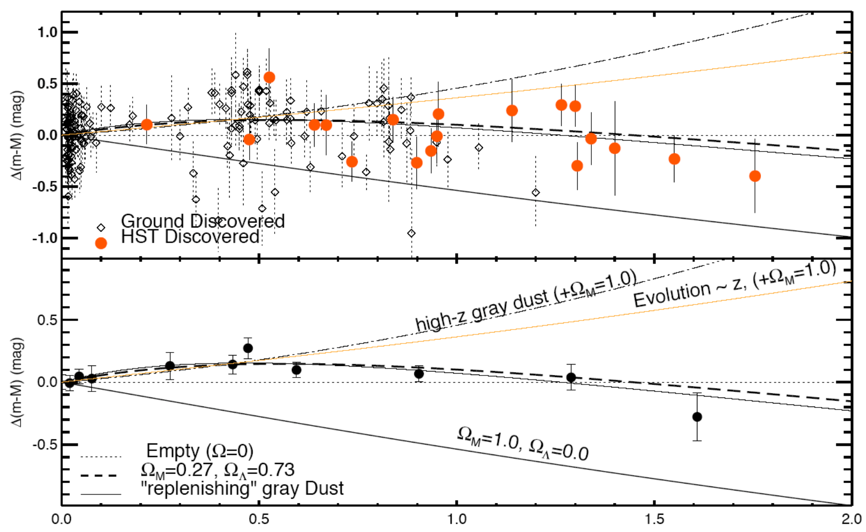


Fig. 6 Contours at 68.3%, 95.5% and 99.7% confidence levels for the fit to a flat (Ω_M, w) cosmology, from the SNLS Hubble diagram alone, from the SDSS baryon acoustic oscillations alone (Eisenstein et al. 2005), and the joint confidence contours.



Riesset al.

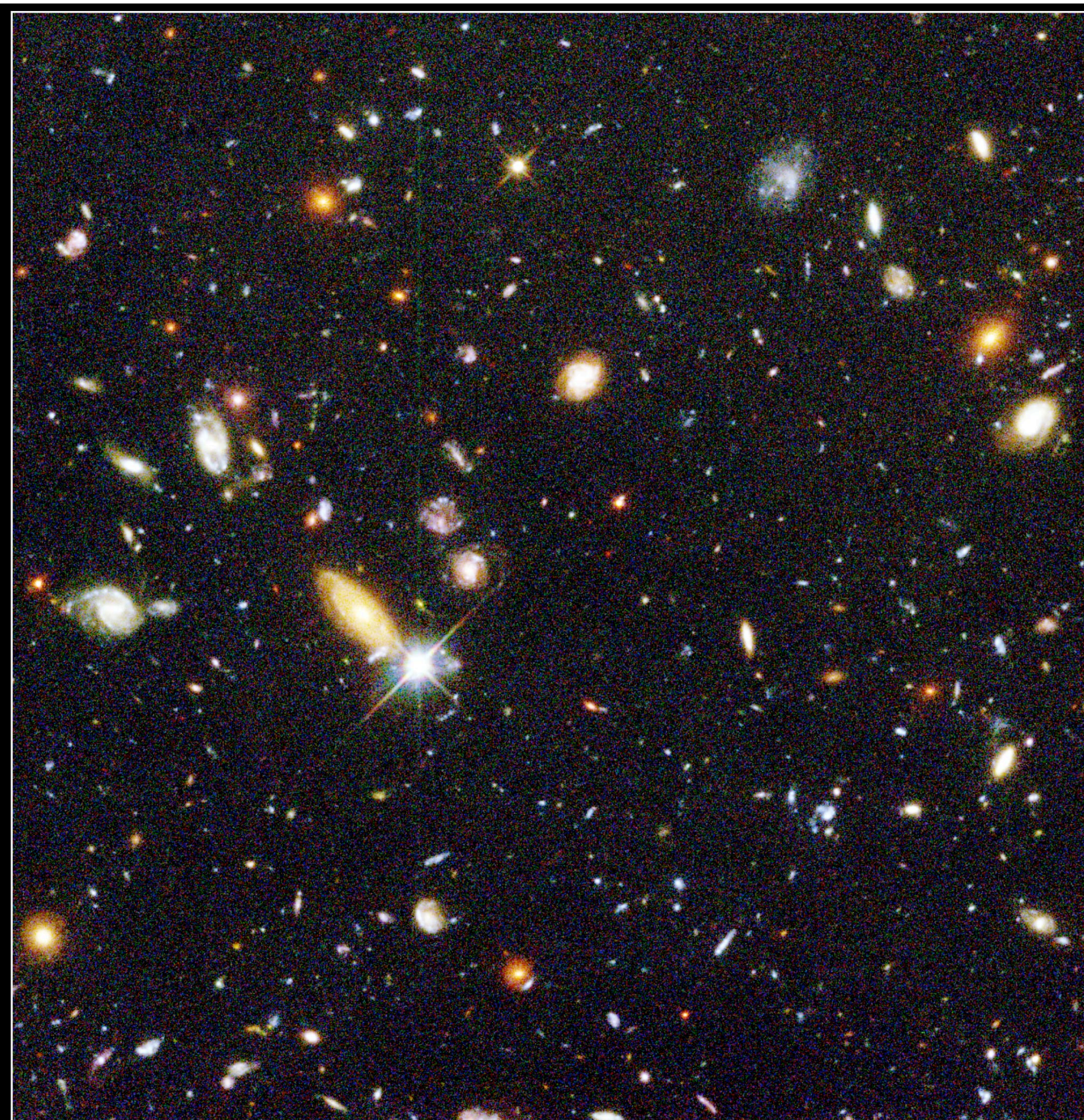
Could GR be wrong ?

How is matter distributed?

<u>Matter is not distributed uniformly</u>

It forms structure on many scales

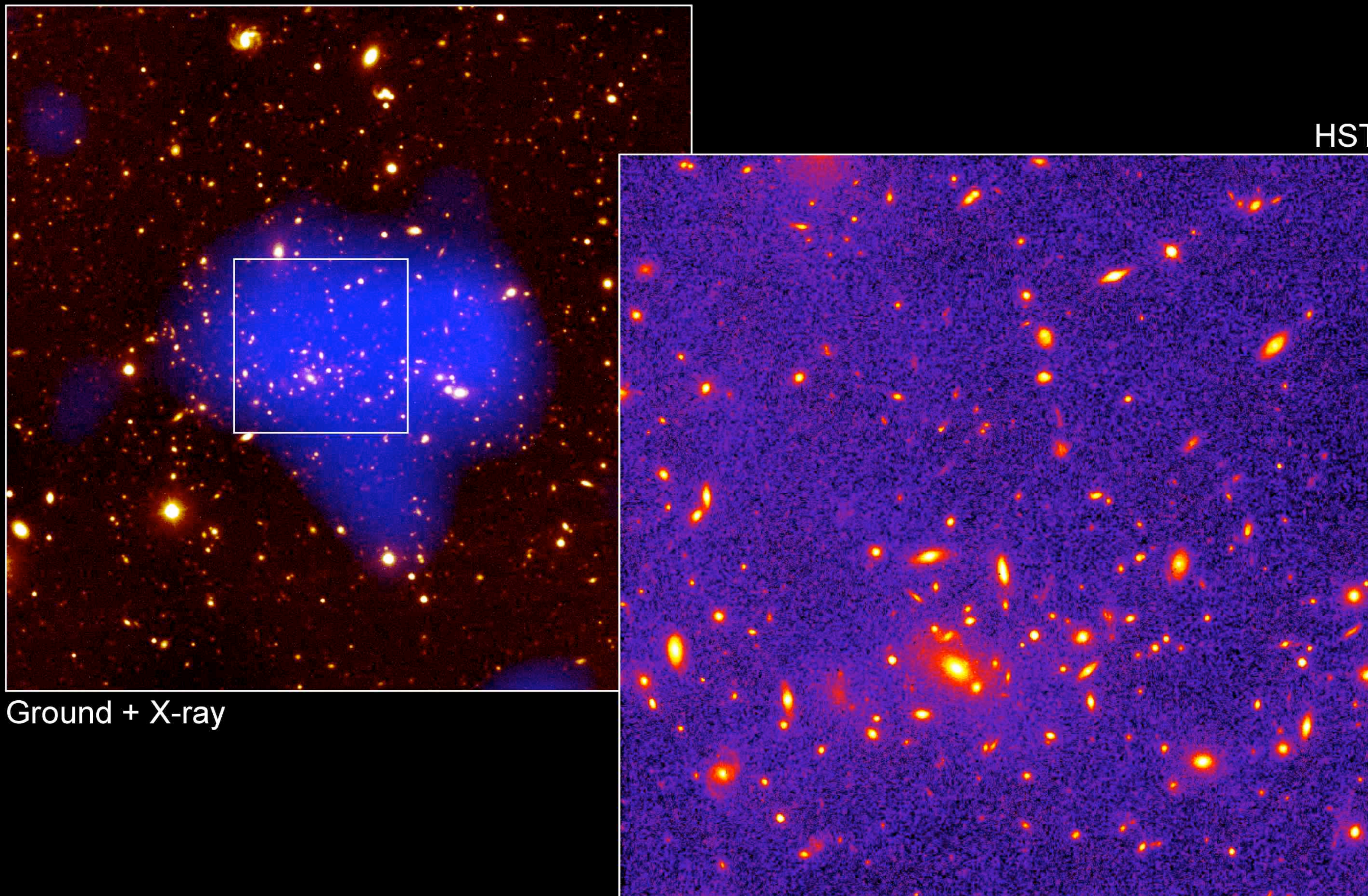
The level of structure evolves with time



Hubble Deep Field

Hubble Space Telescope • WFPC2

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

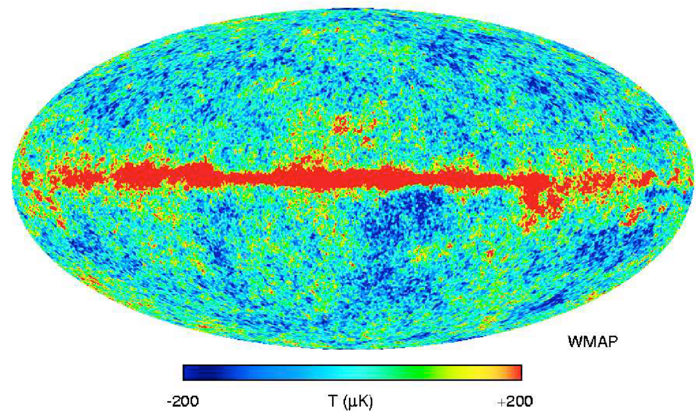


Distant Galaxy Cluster MS1054-0321

Hubble Space Telescope • Wide Field Planetary Camera 2

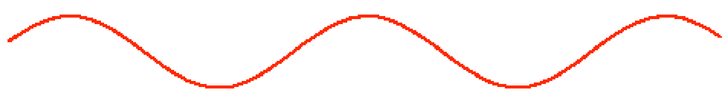
PRC98-26 • August 19, 1998 • STScI OPO • M. Donahue (STScI) and NASA

Gravitational Instability

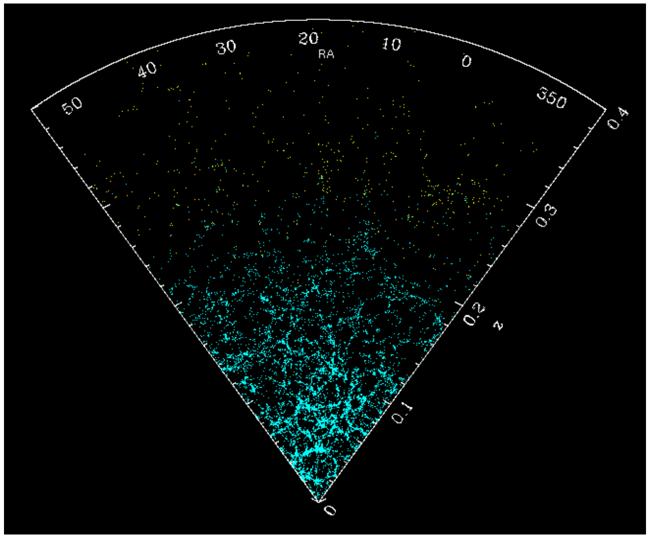


t_1

$t_2 > t_1$



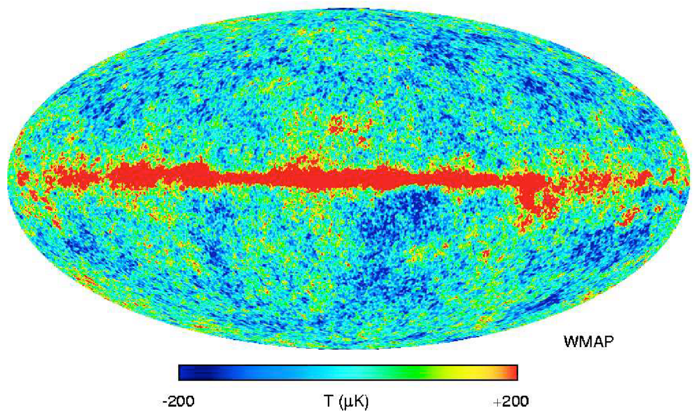
$$t_g \sim (G\rho)^{-1/2}$$

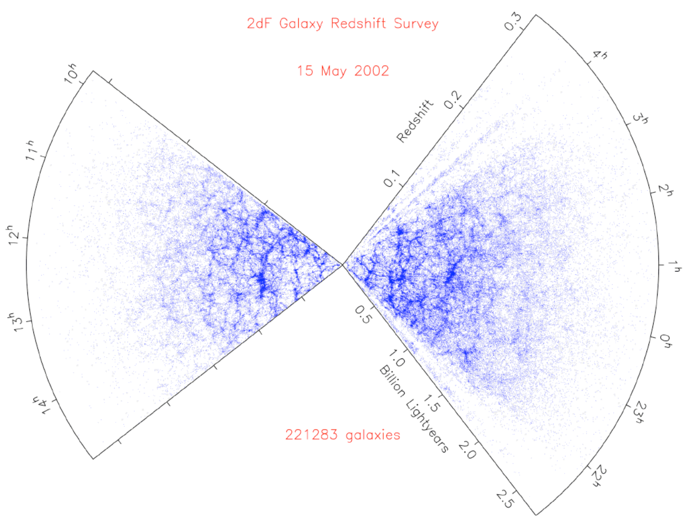


Probes of Large Scale Structure

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

The Era of Precision Cosmology



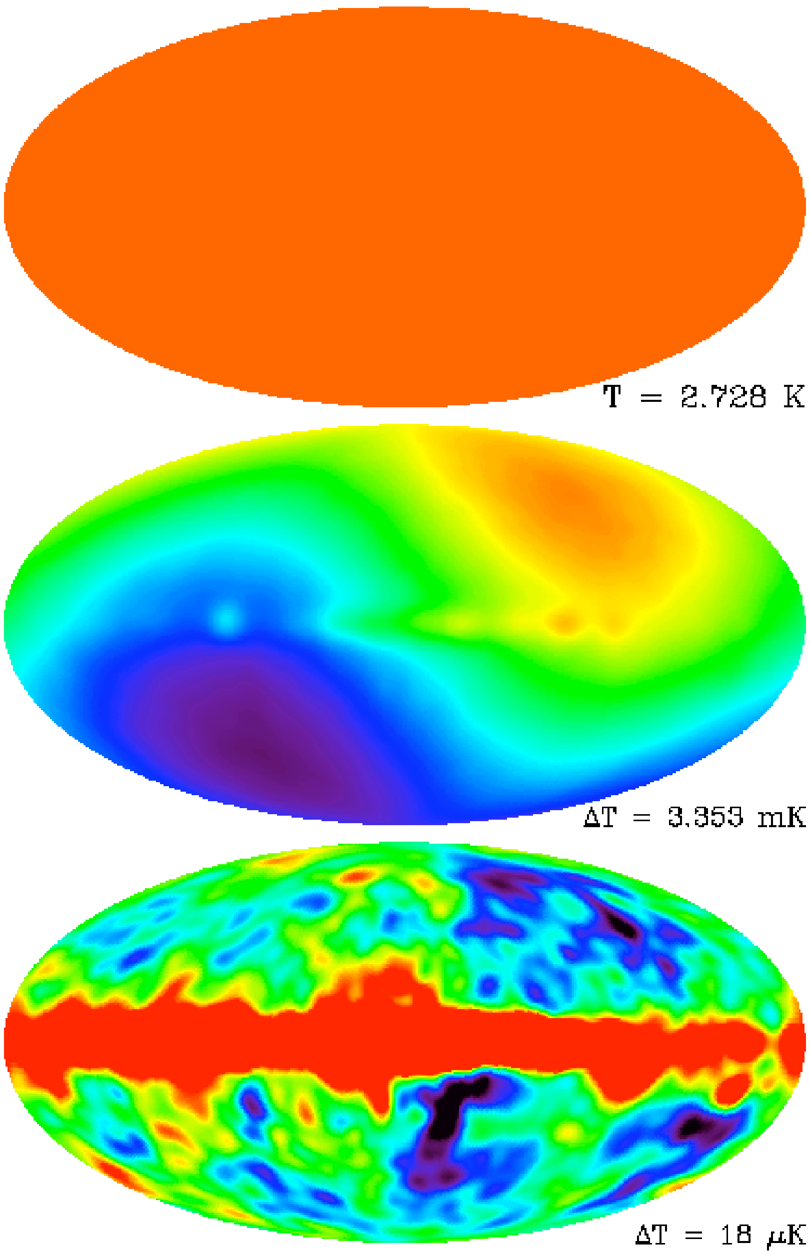


WMAP Cosmological Parameters Model: lcdm Data: all		
$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
A	=	$0.67^{+0.04}_{-0.05}$
$A_{0.002}$	=	$0.81^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \pm 1) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	=	$(24^{+1}_{-2}) \times 10^{-10}$
h	=	$0.71^{+0.01}_{-0.02}$
H_0	=	71^{+1}_{-2} km/s/Mpc
ℓ_A	=	$303.0^{+0.9}_{-1.3}$
n_s	=	$0.938^{+0.013}_{-0.018}$
$n_s(0.002)$	=	$0.938^{+0.012}_{-0.023}$
Ω_b	=	$0.044^{+0.002}_{-0.003}$
$\Omega_b h^2$	=	$0.0220^{+0.0006}_{-0.0008}$
Ω_c	=	$0.22^{+0.01}_{-0.02}$
$\Omega_c h^2$	=	$0.109^{+0.003}_{-0.006}$
Ω_Λ	=	0.74 ± 0.02
Ω_m	=	$0.26^{+0.01}_{-0.03}$
$\Omega_m h^2$	=	$0.131^{+0.004}_{-0.010}$
r_s	=	148^{+1}_{-2} Mpc
b_{SDSS}	=	$0.95^{+0.05}_{-0.06}$
σ_8	=	$0.75^{+0.03}_{-0.04}$
$\sigma_8\Omega_m^{0.6}$	=	$0.34^{+0.02}_{-0.03}$
A_{SZ}	=	$0.78^{+0.23}_{-0.78}$
t_0	=	$13.8^{+0.1}_{-0.2}$ Gyr
τ	=	$0.069^{+0.026}_{-0.029}$
θ_A	=	0.594 ± 0.002 °
z_{eq}	=	3135^{+85}_{-159}
z_r	=	$9.3^{+2.8}_{-2.0}$

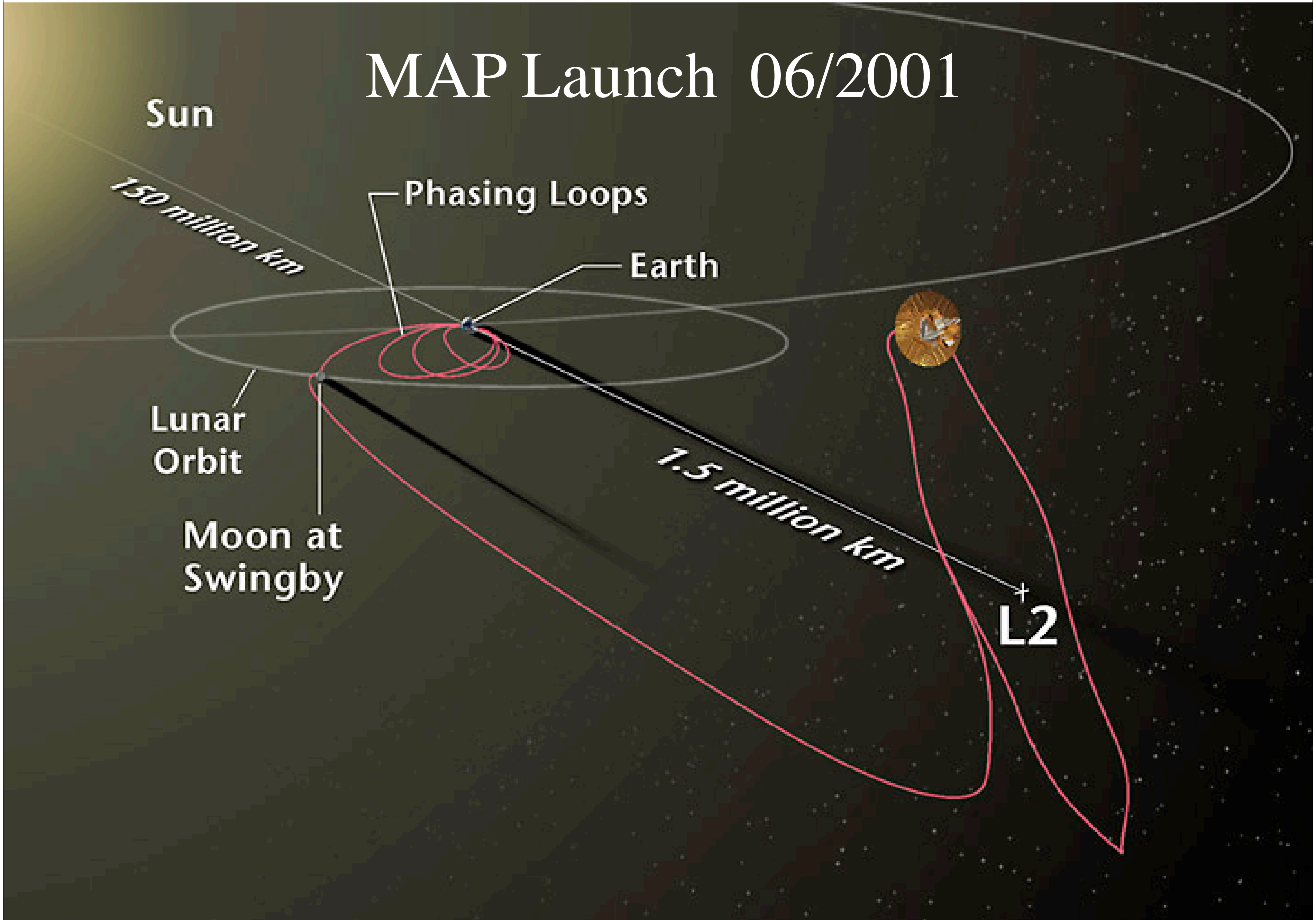
"Cosmologists are often in error, though never in doubt." -- Lev Landau

Anisotropies in the CMB temperature

COBE 1992



MAP Launch 06/2001



WMAP vs COBE

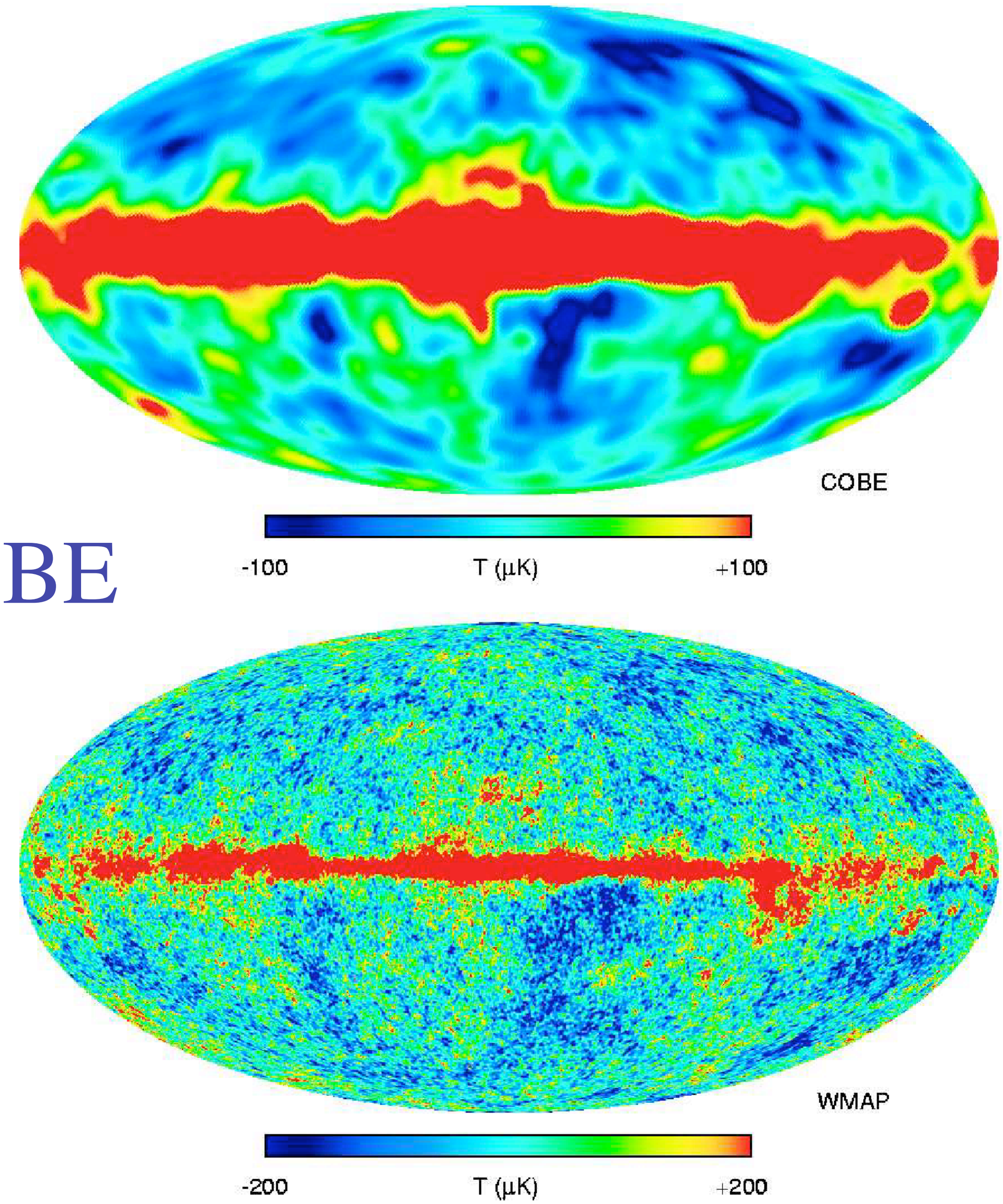
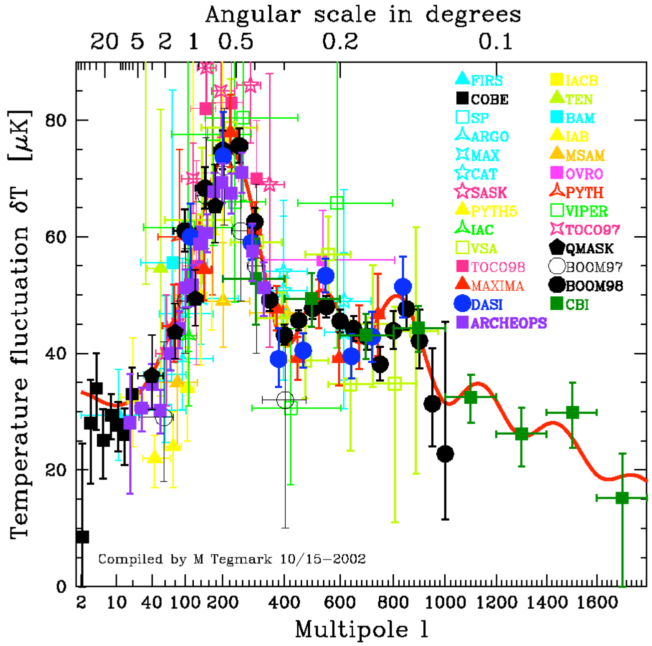
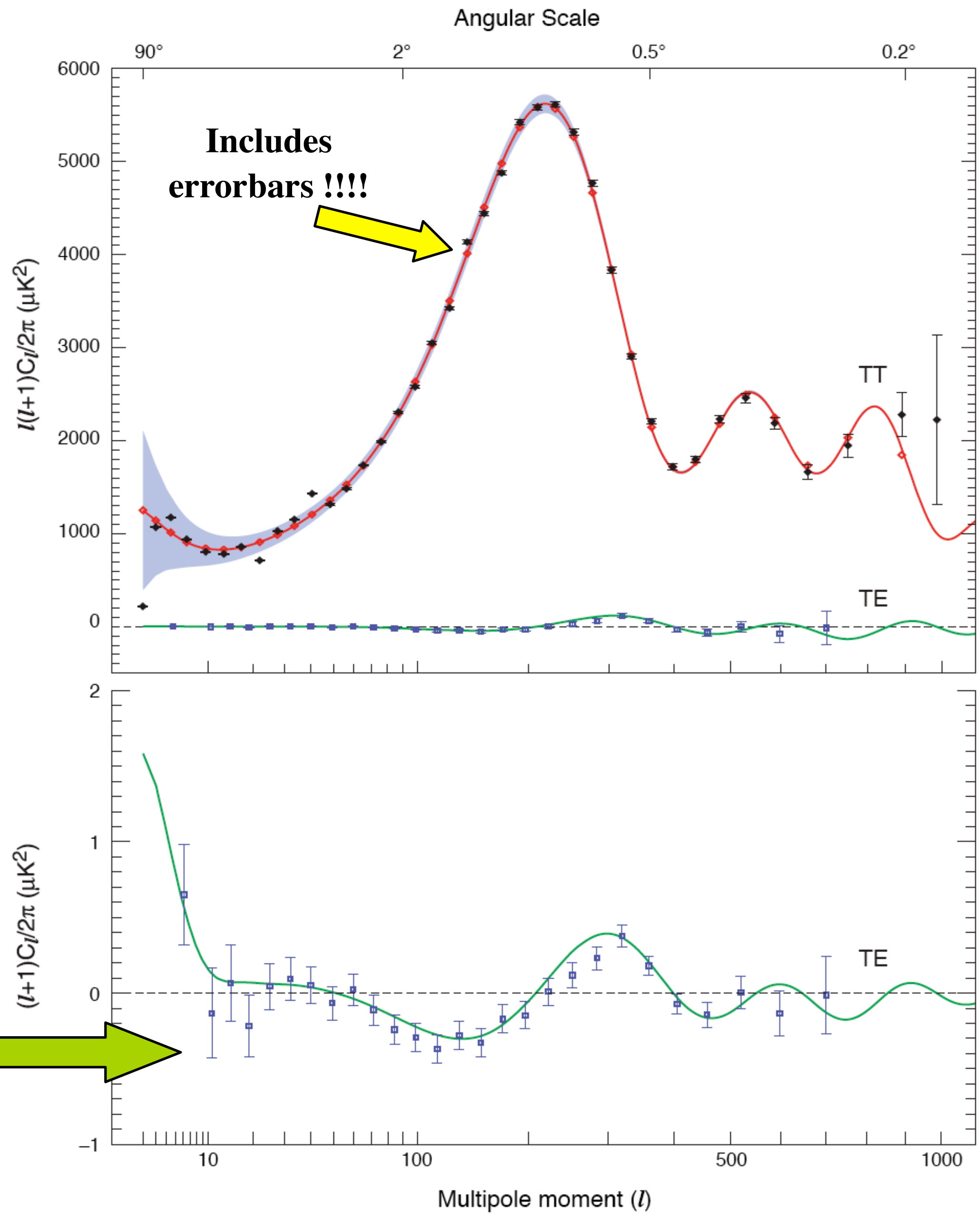


Fig. 7.— A comparison of the *COBE* 90 GHz map (Bennett et al. 1996) with the W-band *WMAP* map. The *WMAP* map has 30 times finer resolution than the *COBE* map.

WMAP Spectra

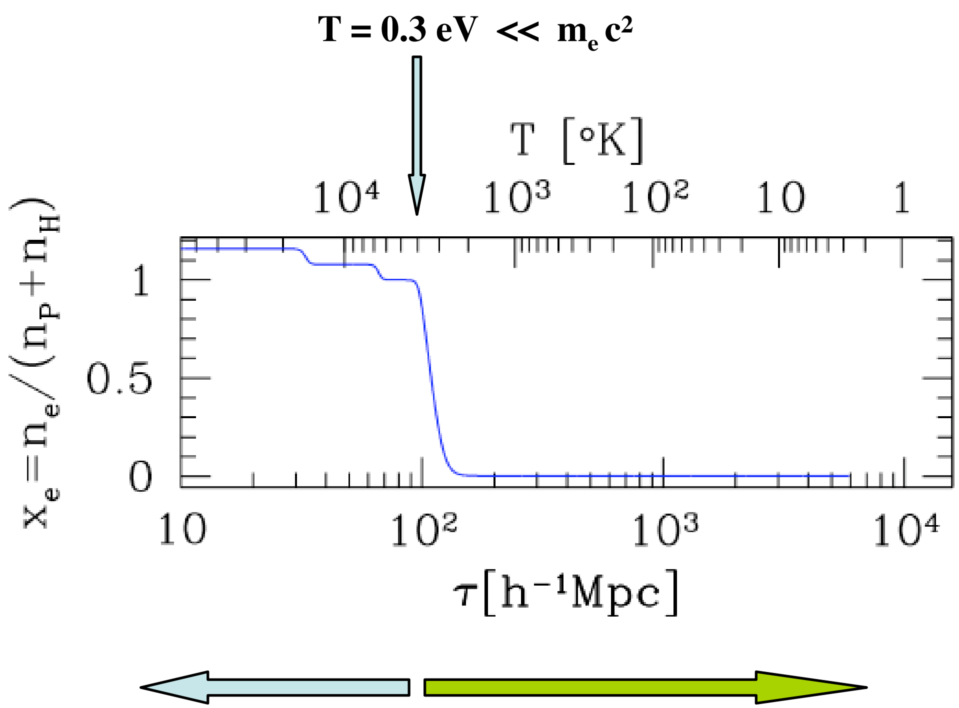




Temperature and polarization patterns are <u>correlated</u>

What creates the anisotropies?

Recombination



Hydrogen is ionized

Hydrogen is neutral

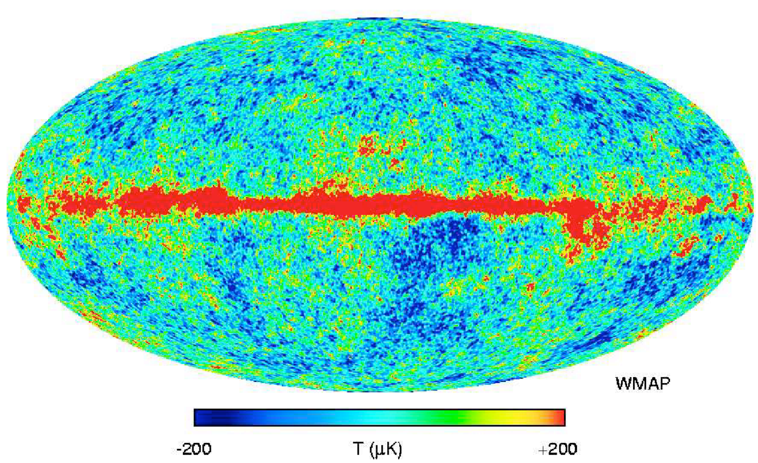
Thomson Scattering

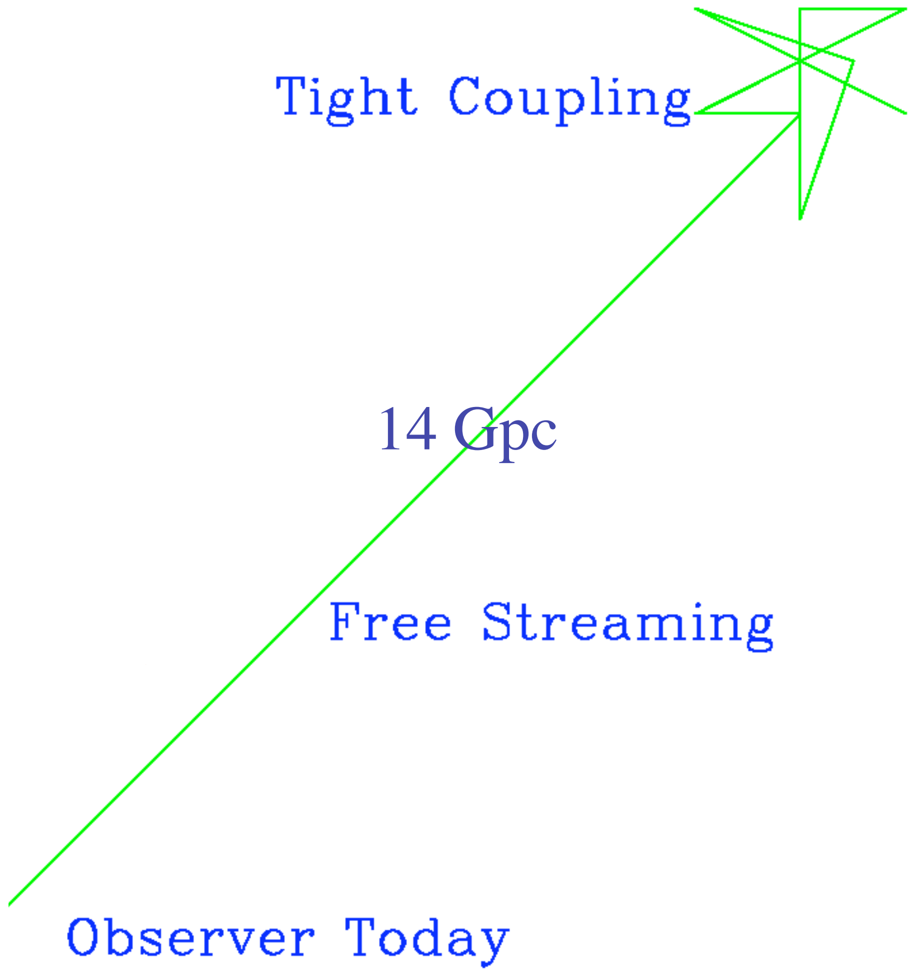
The basics of CMB Anisotropies

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

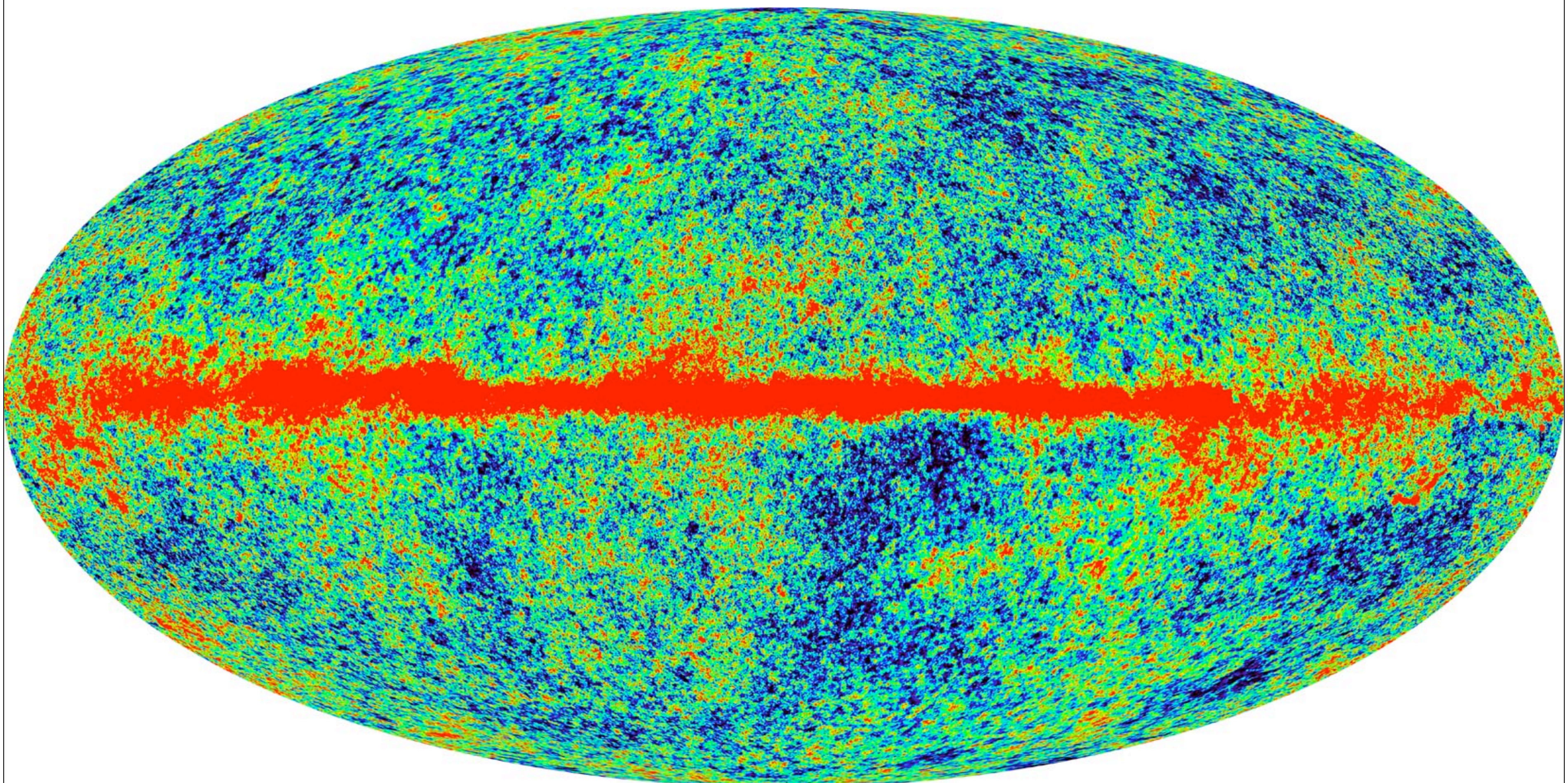
All 3 effects have the same origin

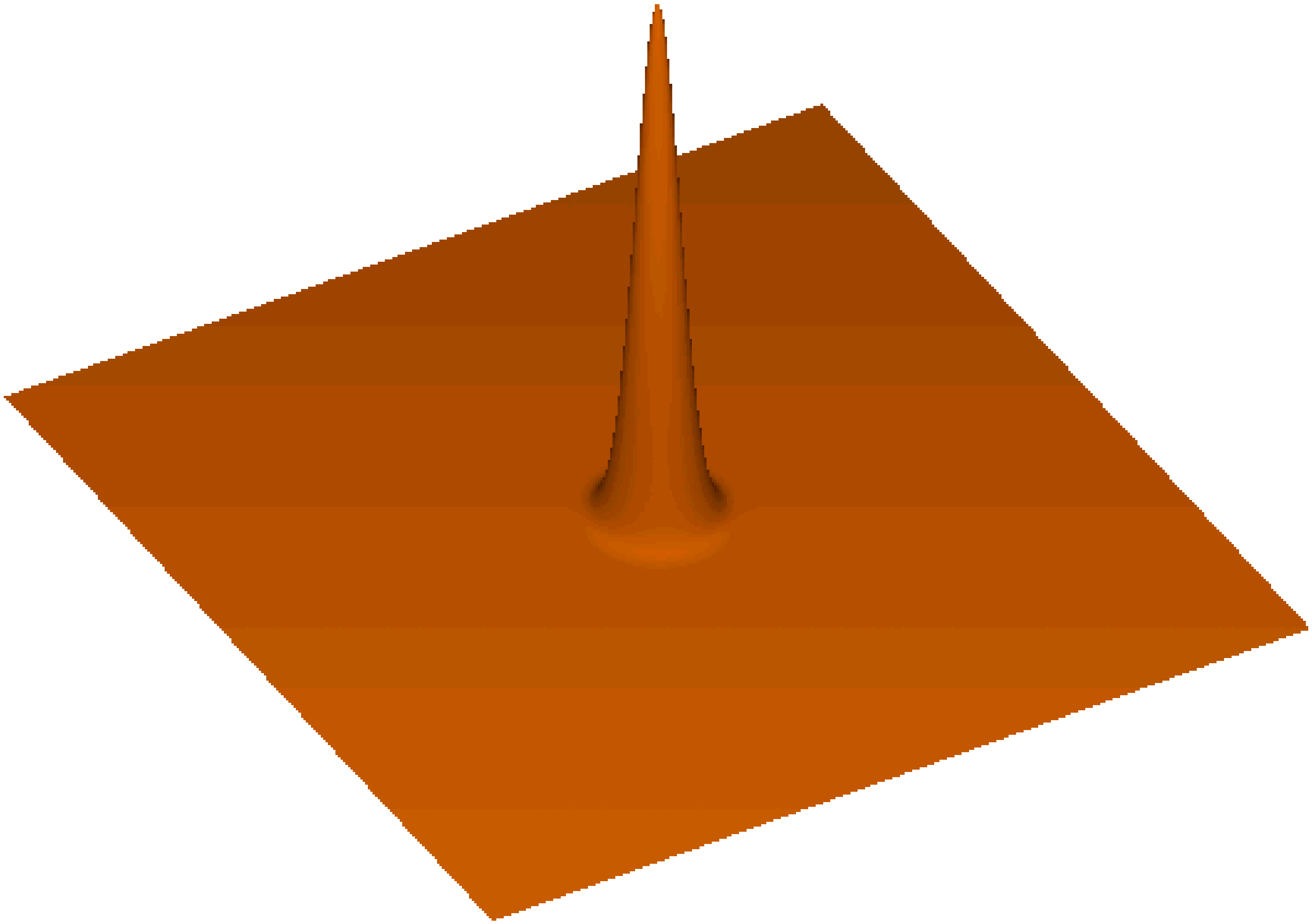
$$P \sim \lambda_T \nabla v$$





WMAP: level of structure at recombination





http://cmb.as.arizona.edu/~eisenste/acousticpeak/

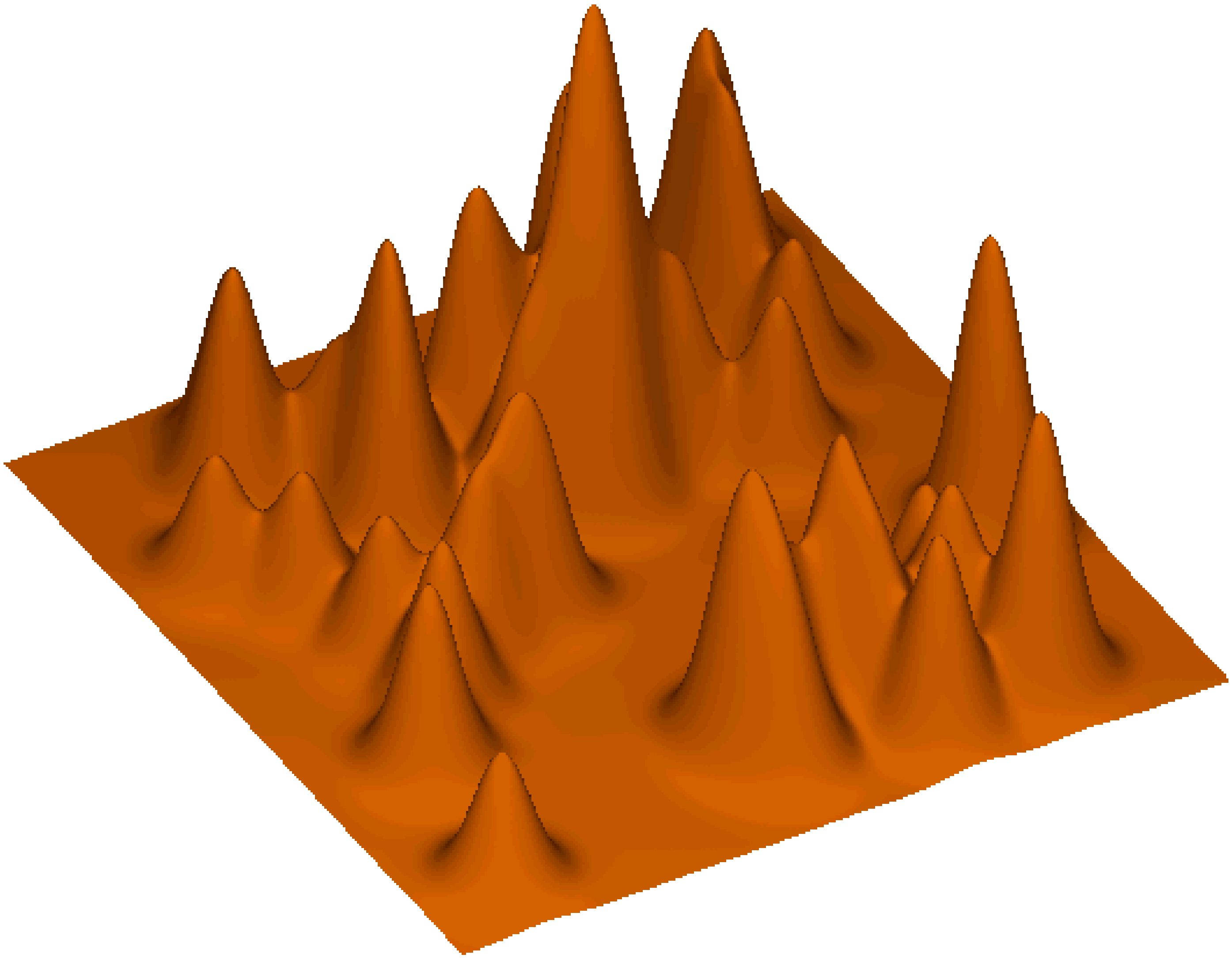
Observable

Initial conditions

$$O(n) = \int d^3x G(n, x, t)\zeta(x)$$

Greens function: depends on both time and the observable

In fourier space the observable is the “product” of the Fourier transforms of the initial conditions and the Green’s function. The features of the power spectrum come from the shape of the Green’s function.



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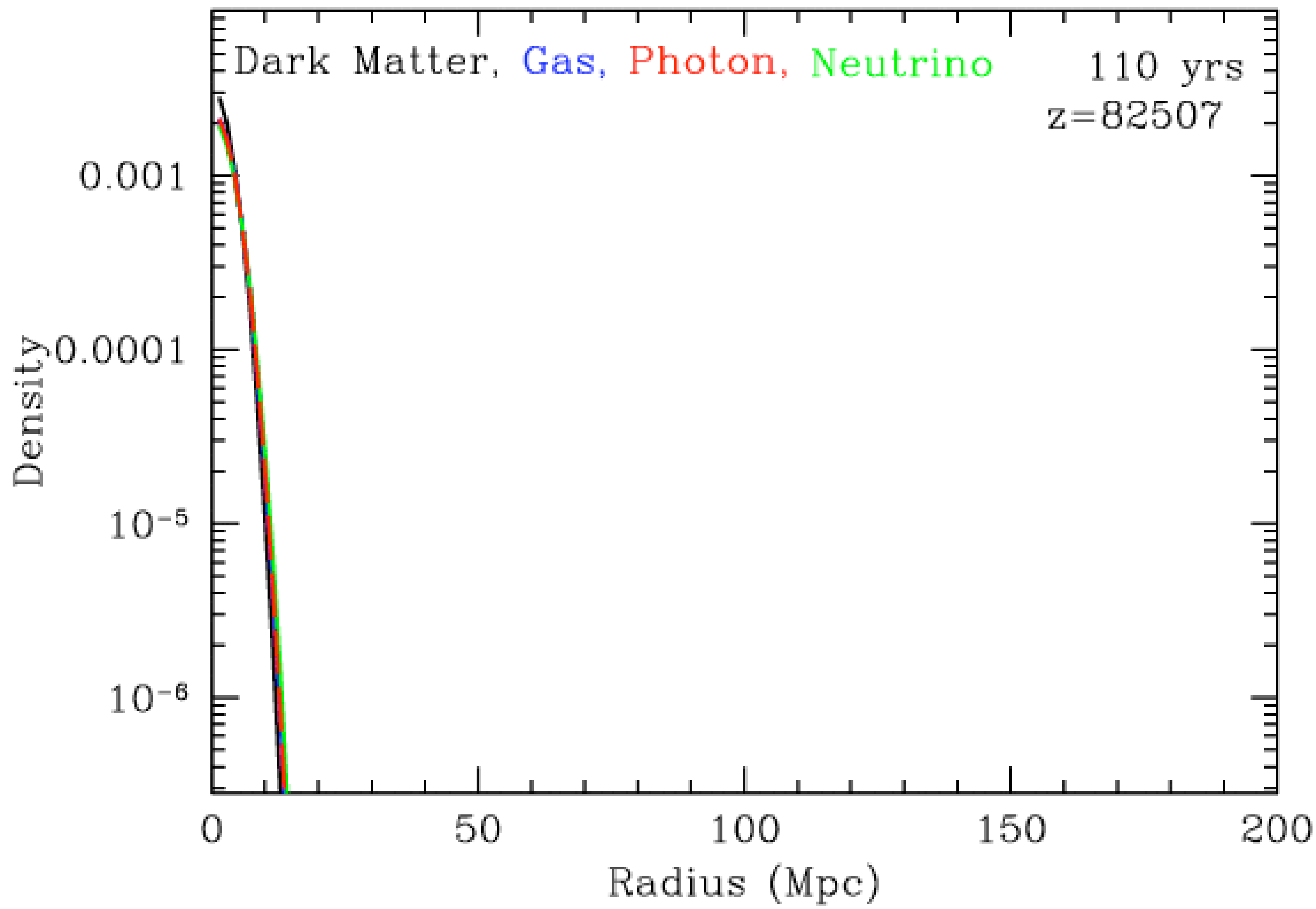
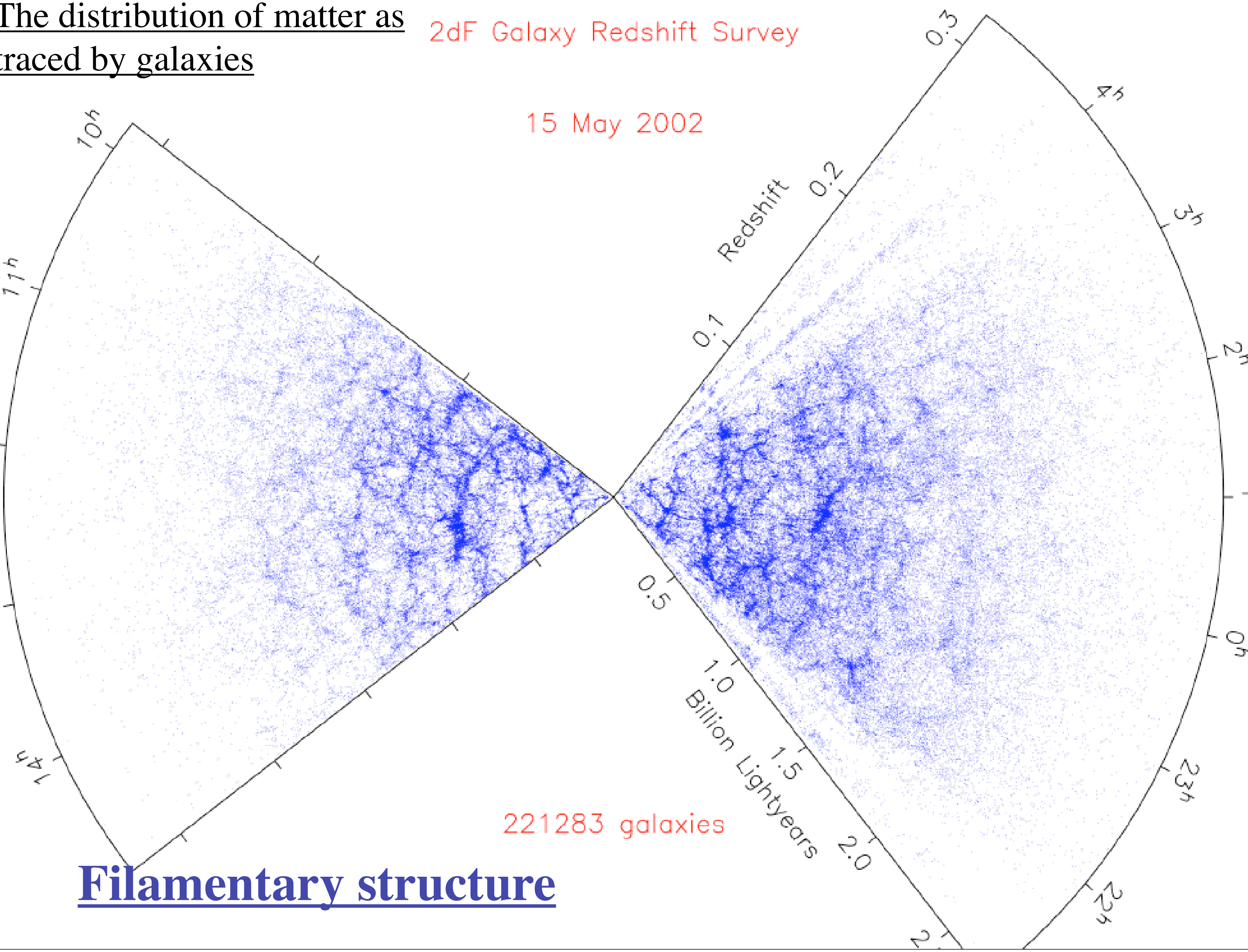
Daniel Eisenstein

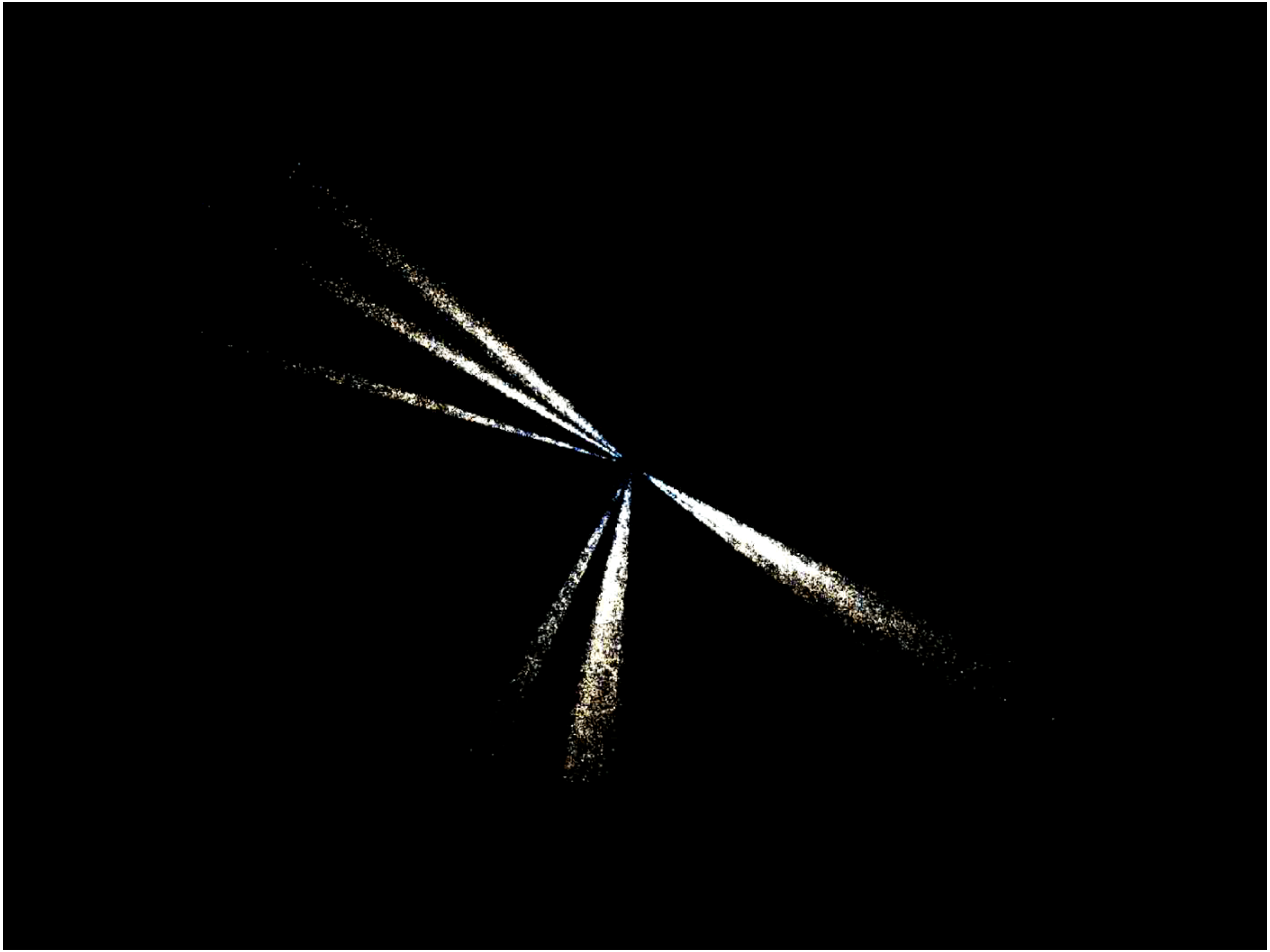


http://cmb.as.arizona.edu/~eisenste/acousticpeak/

The distribution of matter as traced by galaxies



Filamentary structure



DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

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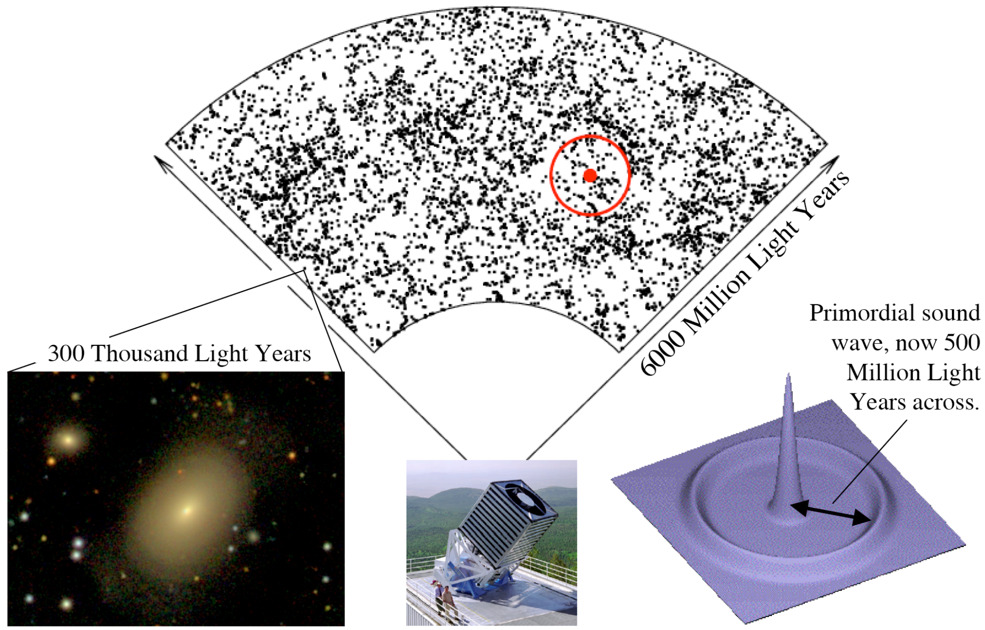
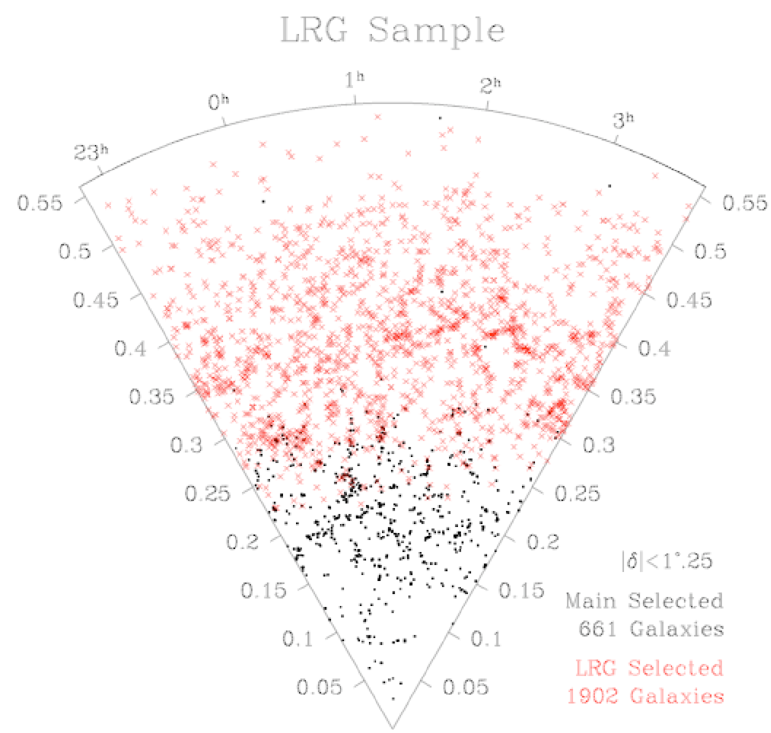
Submitted to The Astrophysical Journal 12/31/2004

ABSTRACT

We present the large-scale correlation function measured from a spectroscopic sample of 46,748 luminous red galaxies from the Sloan Digital Sky Survey. The survey region covers $0.72h^{-3}\,\mathrm{Gpc}^3$ over 3816 square degrees and $0.16 < z < 0.47$, making it the best sample yet for the study of large-scale structure. We find a well-detected peak in the correlation function at $100h^{-1}\,\mathrm{Mpc}$ separation that is an excellent match to the predicted shape and location of the imprint of the recombination-epoch acoustic oscillations on the low-redshift clustering of matter. This detection demonstrates the linear growth of structure by gravitational instability between $z \approx 1000$ and the present and confirms a firm prediction of the standard cosmological theory. The acoustic peak provides a standard ruler by which we can measure the ratio of the distances to $z = 0.35$ and $z = 1089$ to 4% fractional accuracy and the absolute distance to $z = 0.35$ to 5% accuracy. From the overall shape of the correlation function, we measure the matter density $\Omega_m h^2$ to 8% and find agreement with the value from cosmic microwave background (CMB) anisotropies. Independent of the constraints provided by the CMB acoustic scale, we find $\Omega_m = 0.273 \pm 0.025 + 0.123(1 + w_0) + 0.137\Omega_K$. Including the CMB acoustic scale, we find that the spatial curvature is $\Omega_K = -0.010 \pm 0.009$ if the dark energy is a cosmological constant. More generally, our results provide a measurement of cosmological distance, and hence an argument for dark energy, based on a geometric method with the same simple physics as the microwave background anisotropies. The standard cosmological model convincingly passes these new and robust tests of its fundamental properties.


6000 Million Light Years
300 Thousand Light Years
Primordial sound wave, now 500 Million Light Years across.


LRG Sample
0h
1h
2h
3h
23h
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
|δ|<1°.25
Main Selected
661 Galaxies
LRG Selected
1902 Galaxies

LRGs SDSS

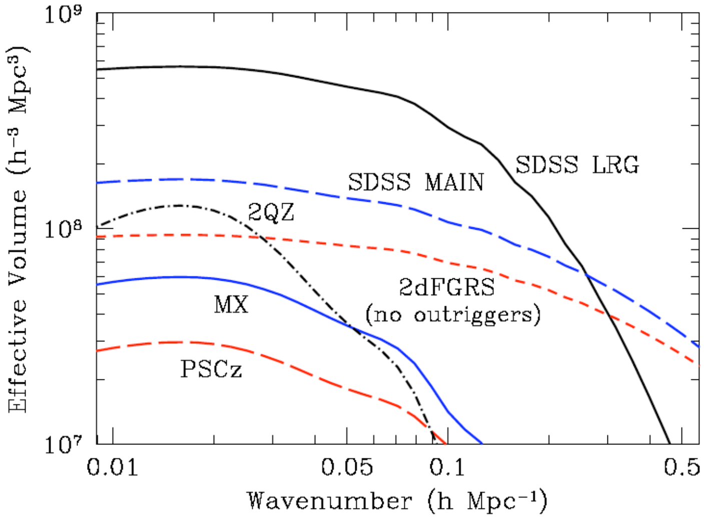


FIG. 1.— The effective volume (eq. [1]) as a function of wavenumber for various large redshift surveys. The effective volume is a rough guide to the performance of a survey (errors scaling as $V_{\rm eff}^{-1/2}$) but should not be trusted to better than 30%. To facilitate comparison, we have assumed 3816 square degrees for the SDSS Main sample, the same area as the SDSS LRG sample presented in this paper and similar to the area in Data Release 3. This is about 50% larger than the sample analyzed in Tegmark et al. (2004a), which would be similar to the curve for the full 2dF Galaxy Redshift Survey (Colless et al. 2003). We have neglected the potential gains on very large scales from the 99 outrigger fields of the 2dFGRS. The other surveys are the MX survey of clusters (Miller & Batuski 2001), the PSCz survey of galaxies (Sutherland et al. 1999), and the 2QZ survey of quasars (Croom et al. 2004a). The SDSS DR3 quasar survey (Schneider et al. 2005) is similar in effective volume to the 2QZ. For the amplitude of $P(k)$, we have used $\sigma_8 = 1$ for 2QZ and PSCz and 3.6 for the MX survey. We used $\sigma_8 = 1.8$ for SDSS LRG, SDSS Main, and the 2dFGRS; For the latter two, this value represents the amplitude of clustering of the luminous galaxies at the surveys' edge; at lower redshift, the number density is so high that the choice of σ_8 is irrelevant. Reducing SDSS Main or 2dFGRS to $\sigma_8 = 1$, the value typical of normal galaxies, decreases their $V_{\rm eff}$ by 30%.

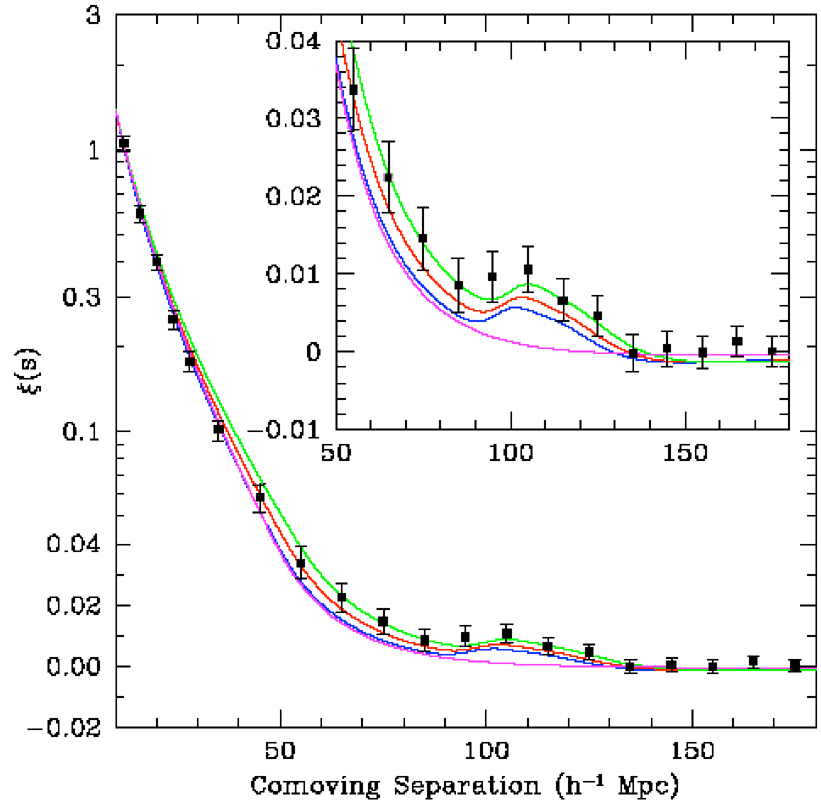


FIG. 2.— The large-scale redshift-space correlation function of the SDSS LRG sample. The error bars are from the diagonal elements of the mock-catalog covariance matrix; however, the points are correlated. Note that the vertical axis mixes logarithmic and linear scalings. The inset shows an expanded view with a linear vertical axis. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. It is interesting to note that although the data appears higher than the models, the covariance between the points is soft as regards overall shifts in $\xi(s)$. Subtracting 0.002 from $\xi(s)$ at all scales makes the plot look cosmetically perfect, but changes the best-fit χ^2 by only 1.3. The bump at $100h^{-1}$ Mpc scale, on the other hand, is statistically significant.

Eisenstein et al (SDSS)

Results

Summary of Parameter Constraints from LRGs

$\Omega_m h^2$	$0.130(n/0.98)^{1.2} \pm 0.011$
$D_V(0.35)$	1370 ± 64 Mpc (4.7%)
$R_{0.35} \equiv D_V(0.35)/D_M(1089)$	0.0979 ± 0.0036 (3.7%)
$A \equiv D_V(0.35)\sqrt{\Omega_m H_0^2}/0.35c$	$0.469(n/0.98)^{-0.35} \pm 0.017$ (3.6%)

NOTES.—We assume $\Omega_b h^2 = 0.024$ throughout, but variations permitted by WMAP create negligible changes here. We use $n = 0.98$, but where variations by 0.1 would create 1 σ changes, we include an approximate dependence. The quantity A is discussed in § 4.5. All constraints are 1 σ.

This distance ratio is consistent with the familiar cosmological constant cosmology. It is grossly inconsistent with the Einstein-de Sitter ($\Omega_m = 1$) model, which predicts $R_{0.35} = 0.133$ (nominally 10 σ). A model lacking dark energy would require $\Omega_m = 0.70$ with $\Omega_K = 0.30$ to match the distance ratio. This would require $h = 0.90$ and $\Omega_m h^2 = 0.57$ to match the CMB peak location, implying an age of 8 Gyr. This is in complete disagreement with the observed shape of the CMB anisotropy spectrum, the galaxy correlation function (including these LRG data), the cluster baryon fraction (White et al. 1993), the observed value of H_0 (Freedman et al. 2001), and the age of old stars (Krauss & Chaboyer 2003, and references therein), as well as other cosmological measurements. Hence, our measurement provides geometric evidence for dark energy.

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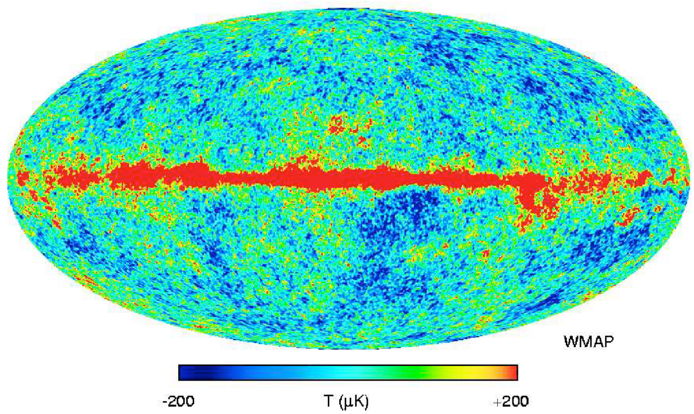
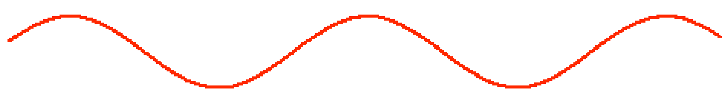
Gravitational Instability

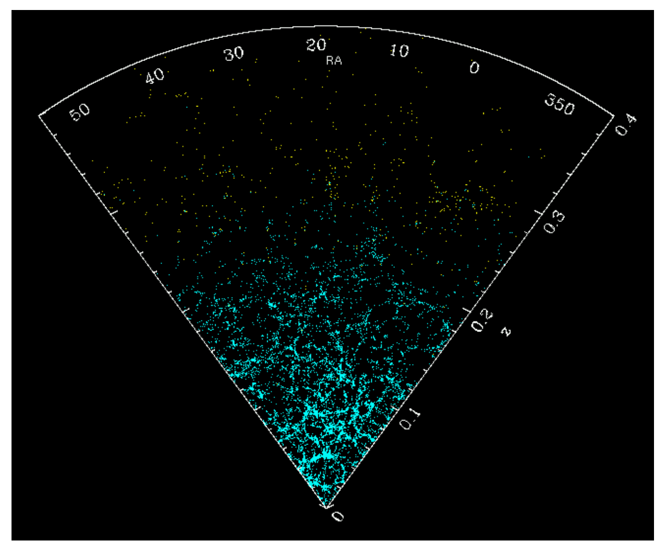
t_1



$t_2 > t_1$



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



Gravitational instability amplifies fluctuations but it does not create them.

We need some “seeds”

↓

Inflation