The Big Bang & the Early Universe

- Thermal History of the Big Bang, MWB & Co.

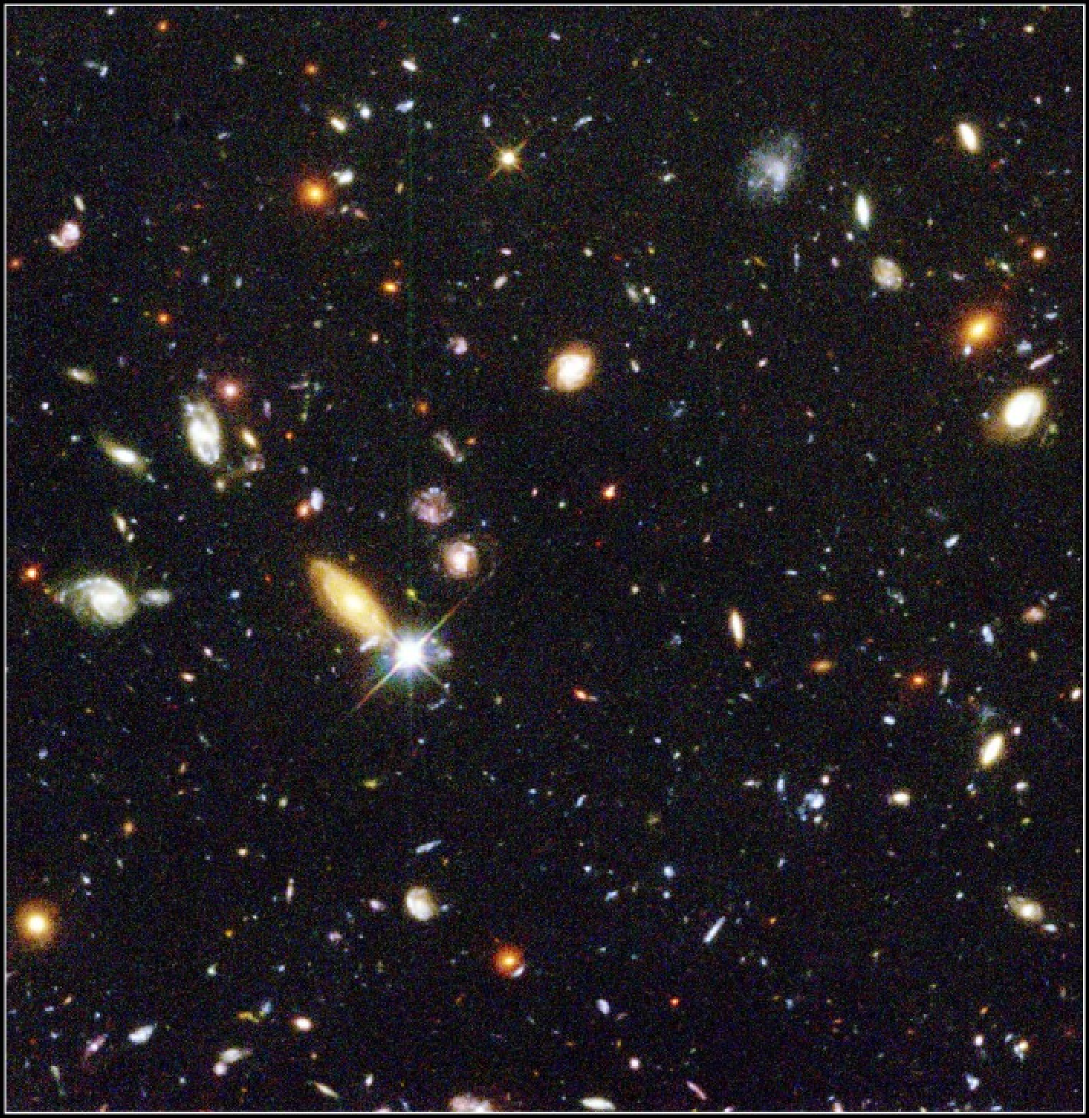
- Nucleosynthesis as Probe for the Early Universe

Source: Weinberg, 2008, in: Cosmology, Chap. 3.1 and 3.2, (and references therein)

The H II Region M8

- M8 is a cloud of hot gas.
- Its spectrum has emission lines of H, He, C, Fe, and other elements.
- The universe is made of the same material as the Earth.

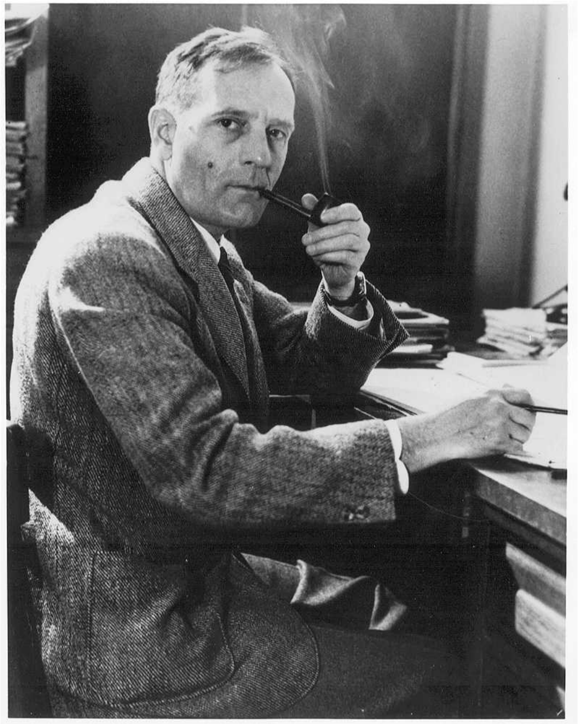
The Hubble Deep Field

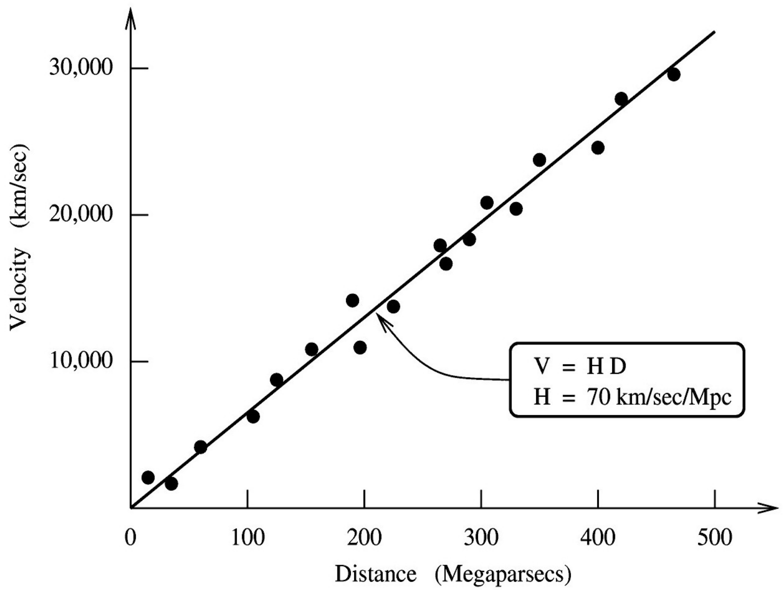


The universe is extremely large.

We observe QSOs more that 10 billion light years away.

The Hubble Expansion



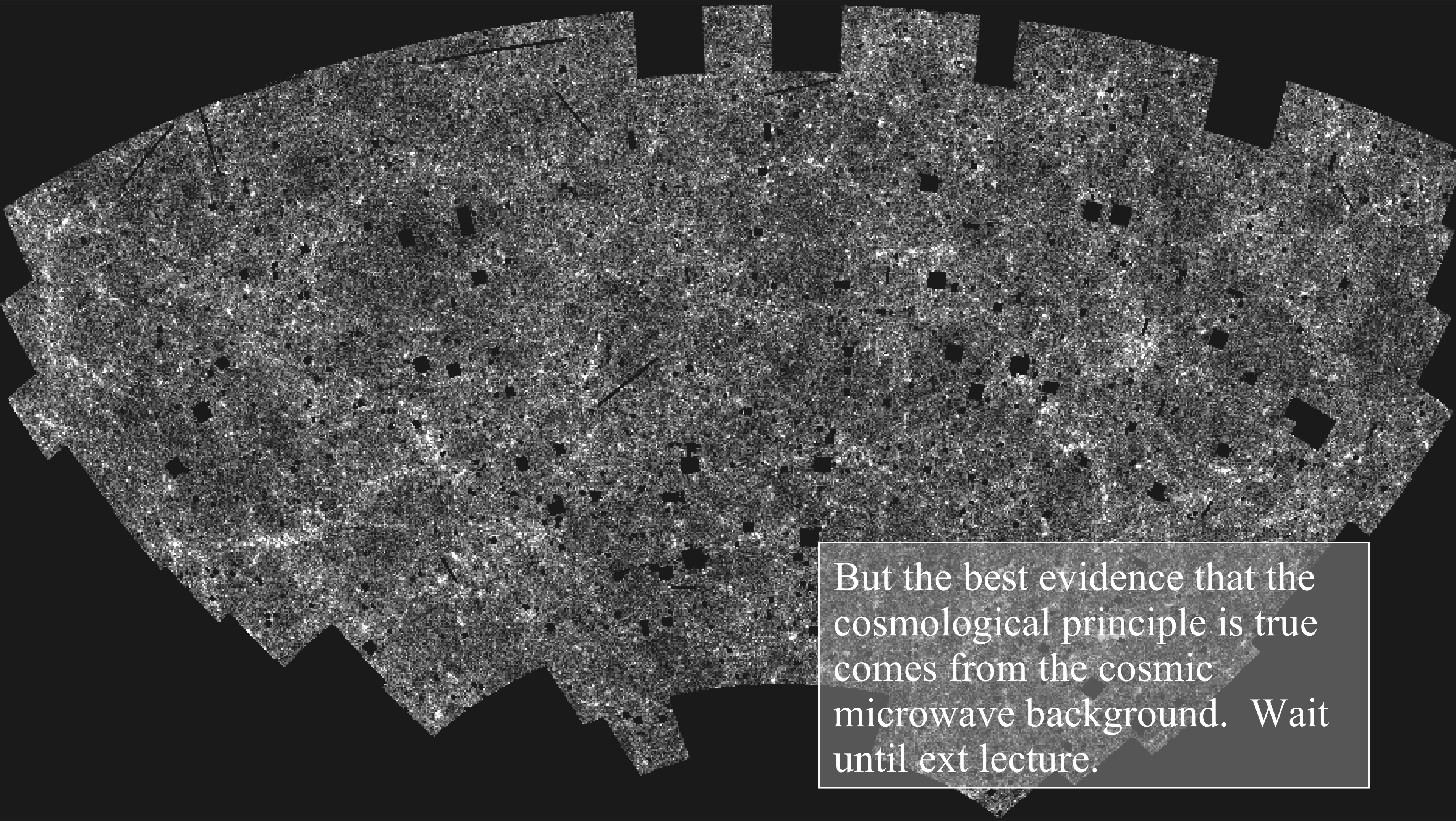


Galaxies are moving away with v = H d , v=vel. d:distance
H: Hubble constant

=> Universe has a beginning at about T=1/H

BIG BANG

The 2dF Survey: A Map of the Galaxies on the Sky



But the best evidence that the cosmological principle is true comes from the cosmic microwave background. Wait until ext lecture.

The Cosmological Principle

"When averaged over a large enough volume, the universe appears the same in all locations."

The significance of the Cosmological Principle:

- The universe has no boundaries (boundaries look different).
- The structure of the universe is not so special that the laws of physics are inapplicable.

The Cosmological Principle only holds for regions larger than 500 Mpc.

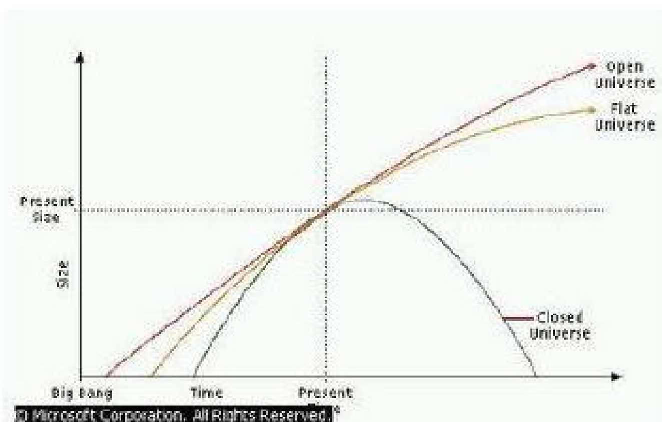
The Friedman Equation

The equation governing the expansion of an isotropic gas with scale parameter $R(t)$ is

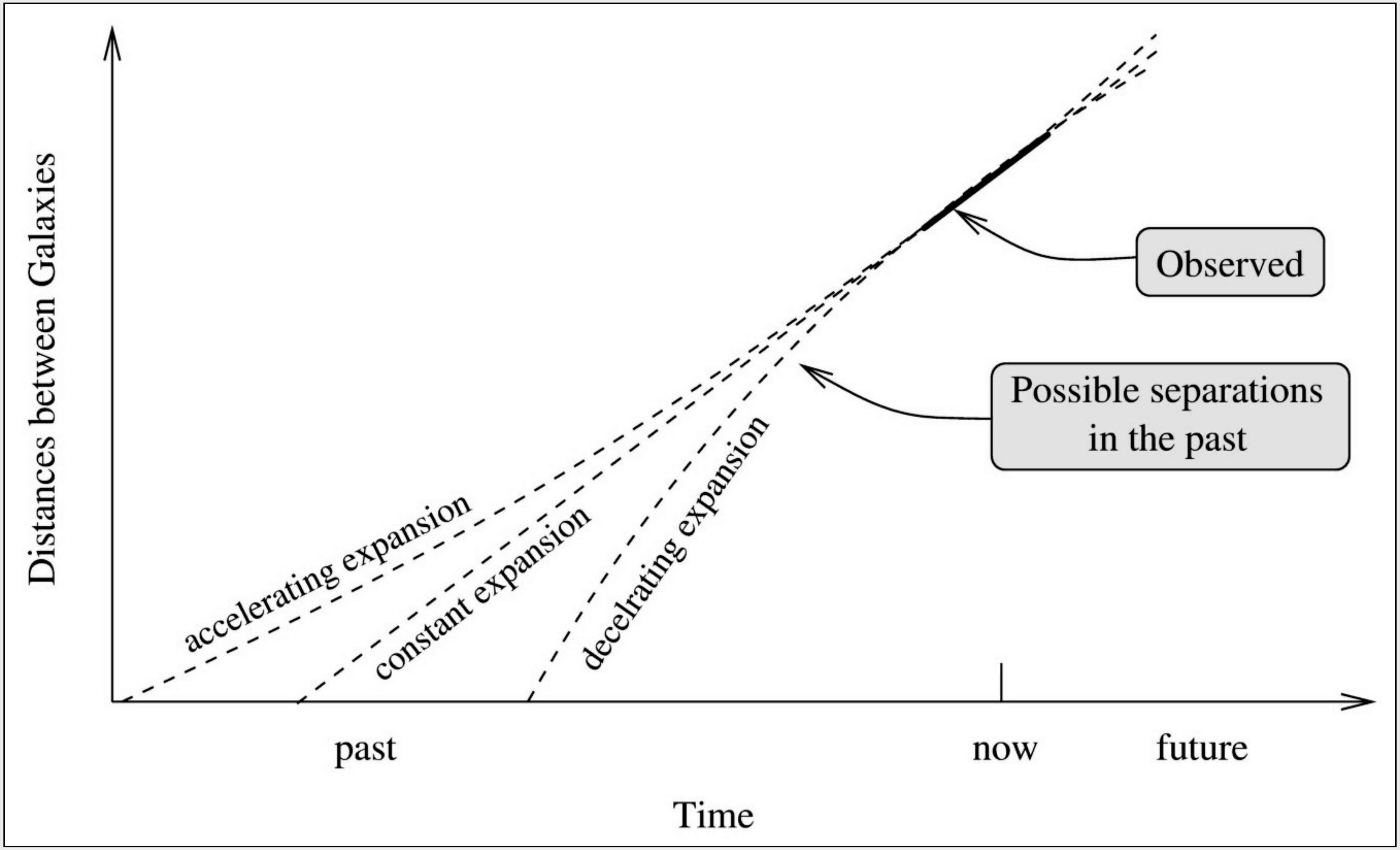
$$\left(\frac{\dot{R}}{R}\right)^2 = H^2(t) = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2},$$

where k determines the geometry of the Universe.

$k > 0$	closed Universe	Big Crunch
$k = 0$	flat Universe	expands forever
$k < 0$	open Universe	Big Chill



How the Distances between Galaxies (or Anything Else) Increase in an Expanding Universe



Solutions for the Friedman Equation

Friedmann equation for $k = 0$

$$(\frac{\dot{R}}{R})^2 = H^2(t) = \frac{8\pi G}{3}\rho$$

To solve one needs $\rho(R)$. There are two important cases:

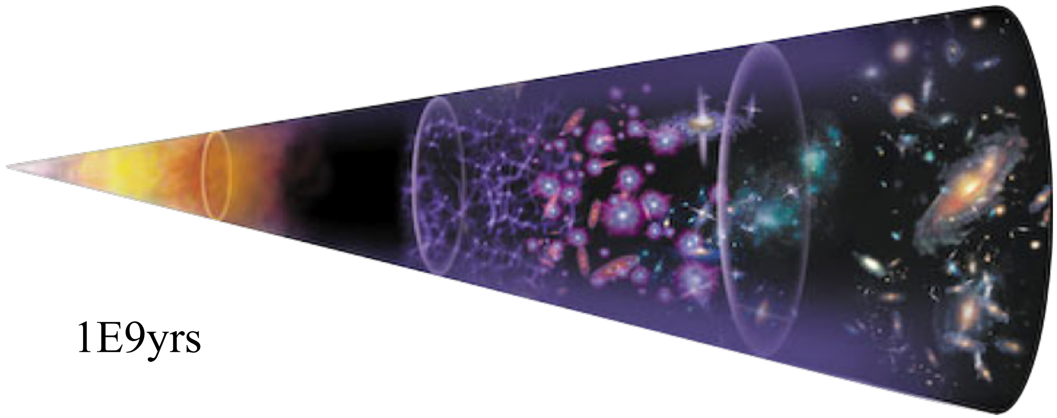
1. $\rho \sim R^{-4}$ (radiation-dominated Universe). Then

$$R(t) = (\frac{t}{t_0})^{1/2} \; ; \; \rho(t) = \frac{\rho_0}{R^4} = \frac{\rho_0 t_0^2}{t^2}$$

2. $\rho \sim R^{-3}$ (matter-dominated Universe). Then

$$R(t) = (\frac{t}{t_0})^{2/3} \; : \; \rho(t) = \frac{\rho_0}{R^3} = \frac{\rho_0 t_0^2}{t^2}$$

•Evolution of the Universe: Thermal Evolution of the Universe



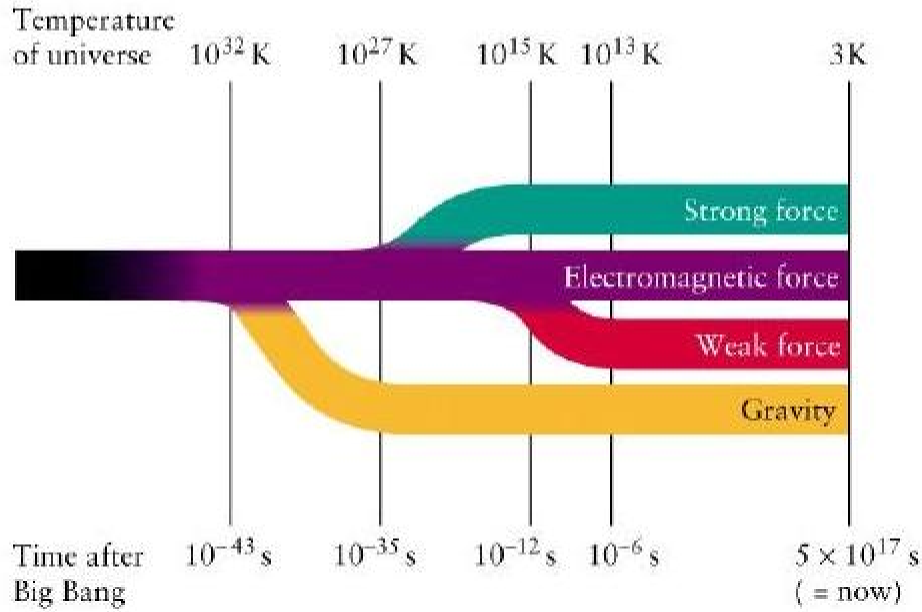
3E6yrs

1E9yrs

13.7E9yrs

- $T \sim 10^{15}\ K, t \sim 10^{-12}$ sec: Primordial soup of fundamental part
- $T \sim 10^{13}\ K, t \sim 10^{-6}$ sec: Protons and neutrons form.
- $T \sim 10^{10}\ K, t \sim 3$ min: Nucleosynthesis: nuclei form.
- $T \sim 3000\ K, t \sim 300,000$ years: Atoms form.
- $T \sim 10\ K, t \sim 10^{9}$ years: Galaxies form.
- $T \sim 3\ K, t \sim 10^{10}$ years: Today.

Thermal History in QCD Regime (<1E-6 sec)



kT	united forces	big bang time
$\sim 10^2$ GeV	electromagnetic + weak	
$\sim 10^{13}$ GeV	electromagnetic + weak + strong	$\approx 10^{-35}$ s
$\sim 10^{19}$ GeV	electromagnetic + weak + strong + gravity	$\approx 10^{-43}$ s Planck time

Thermal History after 1E-6 sec to 3 minutes

a) Basic Equations of the Standard Model:

Time scale for the expansion (Friedman equation)

$$\left(\frac{dR}{dt}\right)^2 = \left(\dot{R}\right)^2 = \frac{8\pi G\rho R^2(t)}{3}$$

Energy conservation

$$R^3\frac{dP}{dt} = \frac{d}{dt}\left[R^3(P+\rho)\right]$$

$R(t)$	:	length scale('radius')
ρ	:	energy density
G	:	gravitational constant
P	:	pressure

Basic Assumptions of the Standard Big Bang:

- thermodynamical equilibrium (of all components)

- neutral (net charge = 0)

- radiation dominated

=> particle distributions depend only on the temperature T (see thermodynamics)

Basic Equations:

Thermodynamical Equilibrium implies adiabatic expansion in comoving frame

$$S = S(R^3, T) = \frac{R^3}{T}[\rho_{eq}(T) + P_{eq}(T)] = \text{ const.}$$

Conservation of energy

$$\frac{dP_{eq}(T)}{dT} = \frac{1}{T}\{\rho_{eq}(T) + P_{eq}(T)\}$$

I) Equation of State for extreme Relativistic Particles (or massless)

energy density: $$\rho(T) = \int_0^\infty n(p,T)\, dp\, \sqrt{p^2+m^2}\ ,$$

pressure $$p(T) = \int_0^\infty n(p,T)\, dp\, \frac{p^2}{3\sqrt{p^2+m^2}}$$

entropy density $$s(T) = \frac{1}{T}\int_0^\infty n(p,T)\, dp \left[\sqrt{p^2+m^2} + \frac{p^2}{3\sqrt{p^2+m^2}}\right]$$

=> $$\rho(T) = g\int_0^\infty \frac{4\pi p^3 dp}{(2\pi\hbar)^3}\left(\frac{1}{\exp(p/k_{\mathcal{B}}T)\pm 1}\right)$$

$$= \begin{cases} g a_{\mathcal{B}} T^4/2 & \text{bosons} \\ 7 g a_{\mathcal{B}} T^4/16 & \text{fermions} \end{cases},$$

& $p(T) = \rho(T)/3$ and $s(T) = 4\rho(T)/3T$

The Time Evolution of the Temperature

Acceleration by GR

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G\rho(T)}{3} .$$

Combination with entropy conservation

$$t = -\int \frac{s'(T)\, dT}{s(T)\sqrt{24\pi G\rho(T)}} + \text{constant}$$

plus EOS for entropy S:

$$t = \sqrt{\frac{3}{16\pi G \mathcal{N} a_{\mathcal{B}}}} \frac{1}{T^2} + \text{constant} .$$

Thermal History:

Remark: Only Particles with m<kT are present in noticable numbers (thermodynamical equilibrium)

For $T \approx 1.5 \cdot 10^{12}$ K ($\approx m_\pi$) these are: $\mu^\pm$, $e^\pm$, ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, γ.
μ's, e's: Fermi distribution
photons: Planck distribution
neutrinos: Fermi distribution

When the temperature decreases, particles might fall out of equilibrium, depending on their masses. Thus their number densities are reduced by a Boltzmann factor $\exp -m/kT$. This affects first the muons with mass $m_\mu \sim 105$ MeV.

Concept: Particles fall out of equilibrium when reactions cannot keep up with the T decline!!

=> Weak freeze-out (slowest reactions).

Estimate for weak freeze-out:

Cross section for weak processes:
$\sigma_W \approx g_W^2 \hbar^{-4} (kT)^2$ ($g_W = 1.4 \cdot 10^{-49}$ erg cm^3)
Number densities for muons, electrons: $n_l \approx (\frac{kT}{\hbar})^3$

Reaction rate for weak processes per lepton $\sigma_W \cdot n_l \approx g_W^2 \hbar^{-7} (kT)^5$.

Total energy density: $\rho \approx E \cdot n_l \approx kT \cdot (\frac{kT}{\hbar})^3$

Expansion rate: $H = \frac{\dot{R}}{R} \approx \sqrt{G\rho} \approx \sqrt{G} \hbar^{-3/2} (kT)^2$.

Then $\frac{\sigma_W n_l}{H} \approx (\frac{T}{10^{10}\mathrm{K}})^3$.

For $T \approx 10^{12}$ K muon and electron neutrinos are still in equilibrium with matter.

For T = 1E11K, particles which only couple via weak interaction freeze out.

Electron-positron annihilation:

m(e) = 511 kEv = 4E9K

T > me,   e- + e+   <-> photons

T < me, e- + e+ -> photons

=> Neutrinos and photons have different temperatures thereafter

Ratio of T(nu)/T(el) after T < 4E9 K

Table 3.1: Ratio of electron-photon temperature T to neutrino temperature T_ν and the time t required for the temperature to drop from 10^{11} K to T, for various values of T.

T (K)	T/T_ν	t(sec)
10^{11}	1.000	0
6×10^{10}	1.000	0.0177
3×10^{10}	1.001	0.101
2×10^{10}	1.002	0.239
10^{10}	1.008	0.998
6×10^{9}	1.022	2.86
3×10^{9}	1.080	12.66
2×10^{9}	1.159	33.1
10^{9}	1.345	168
3×10^{8}	1.401	1980
10^{8}	1.401	1.78×10^{4}
10^{7}	1.401	1.78×10^{6}
10^{6}	1.401	1.78×10^{8}

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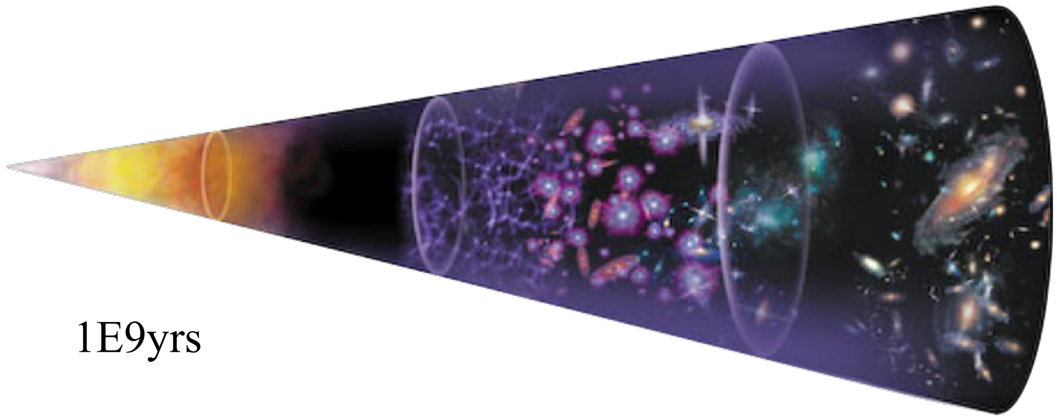

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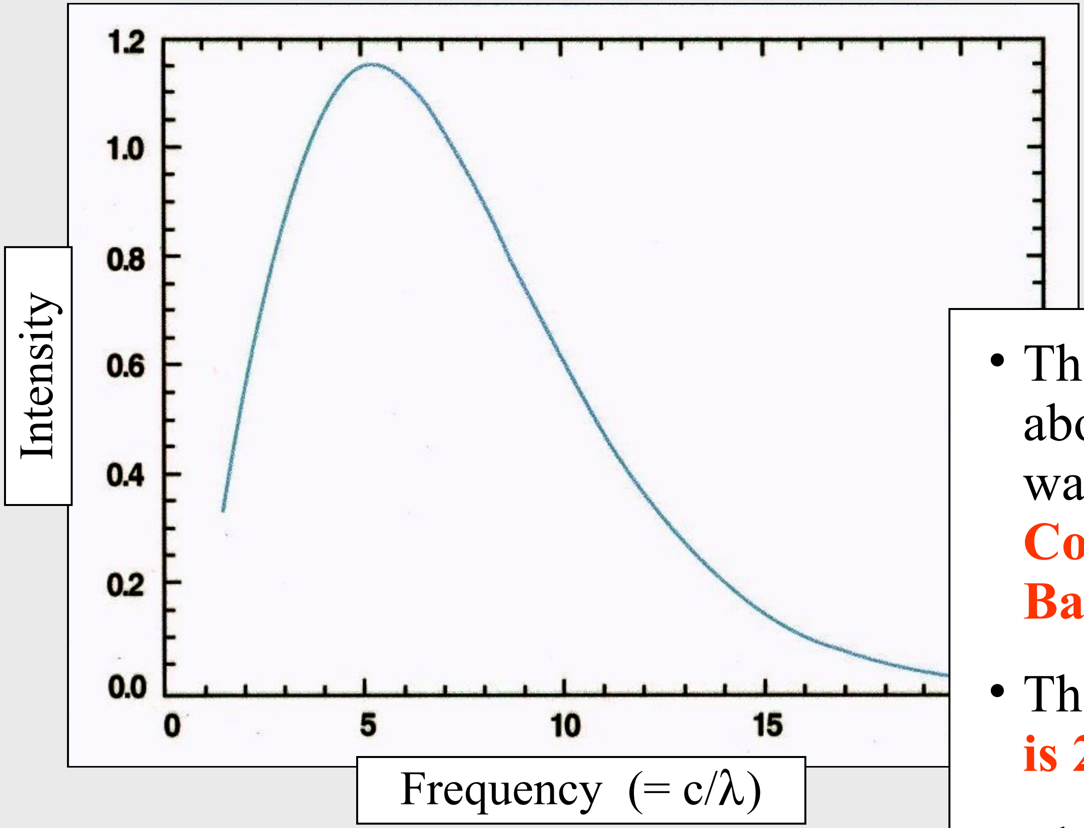
The Big Bang Light Was Discovered in 1965 by…

Arno Penzias

Robert Wilson

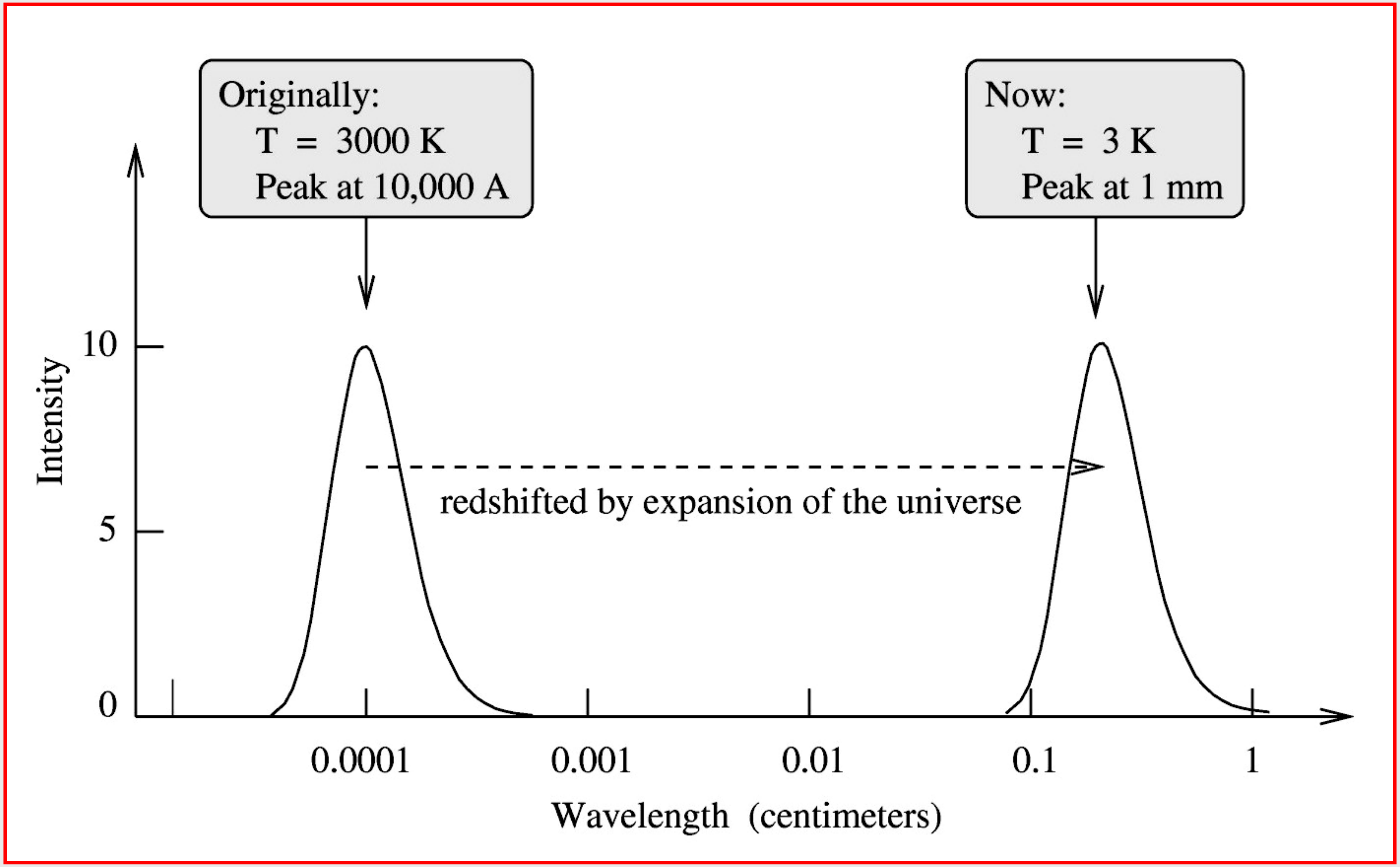
1978 Nobel Laureates in Physics

The Cosmic Microwave Background

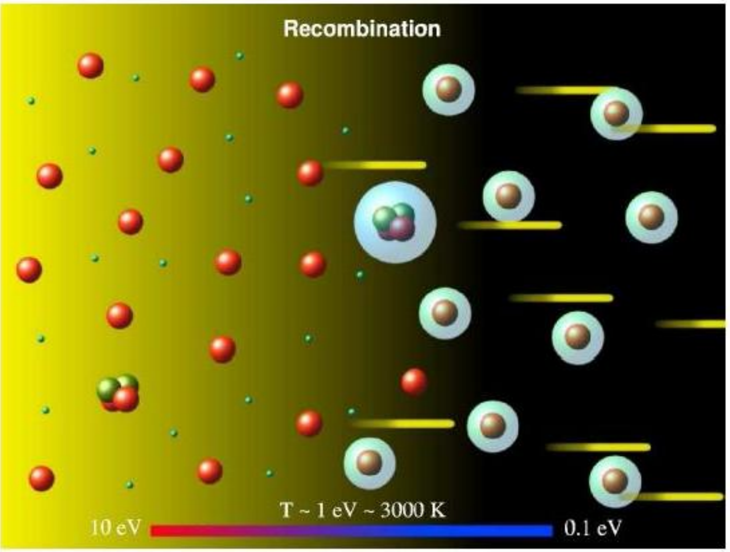


- The peak of the spectrum is at about 1 mm. These are micro-waves so the light is called the **Cosmic Microwave Background, or CMB**.
- The corresponding **temperature is 2.7**
- The spectrum is not measurably different from a **black body spectrum**.

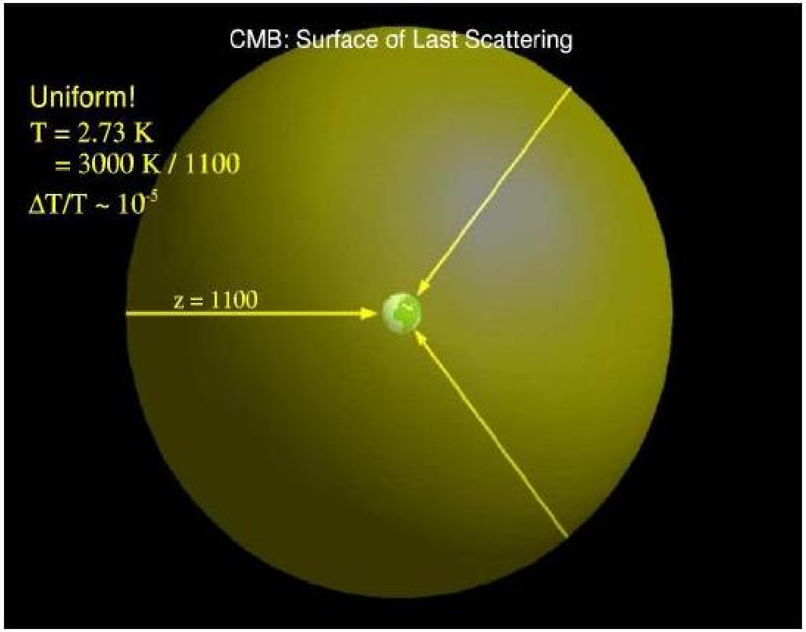
The Light from the Big Bang Now Looks Cool



•Recombination & the CMB



0-Order Expectation for MWB



Saha Eq. $$\frac{1-X_e}{X_e^2} = \frac{4\sqrt{2}\zeta(3)}{\sqrt{\pi}}\eta\left(\frac{T}{m_e}\right)^{3/2}\exp\left(\frac{13.6\text{ eV}}{T}\right).$$

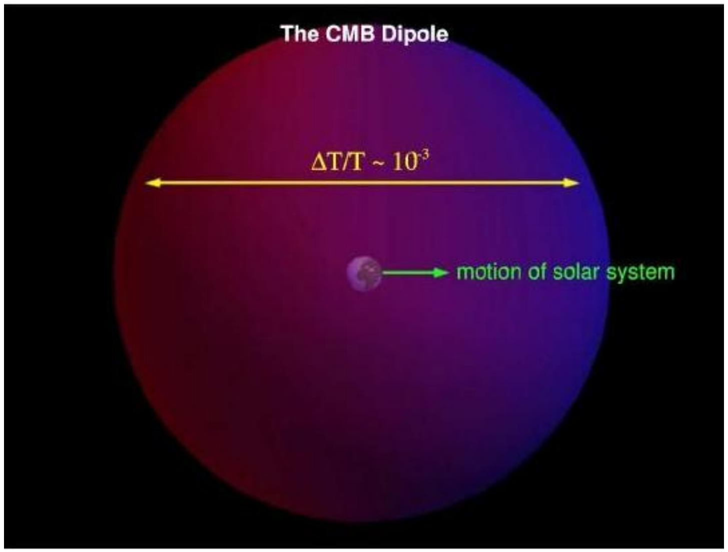
Baryon Frac. $$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} = 2.68\times10^{-8}\left(\Omega_b h^2\right).$$

H recombines at $$T = T_R = 3000\text{ K}$$

$$T \propto a(t)^{-1}$$

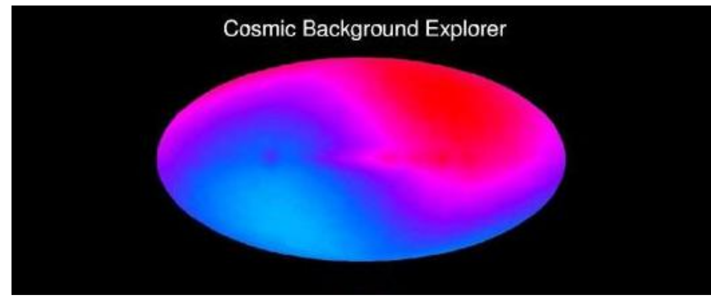
T is red-shifted
With scale a(t) $$1 + z_R = \frac{a(t_0)}{a(t_R)} = \frac{T_R}{T_0} \simeq 1100.$$

• Anisotropy: The motion of the Earth



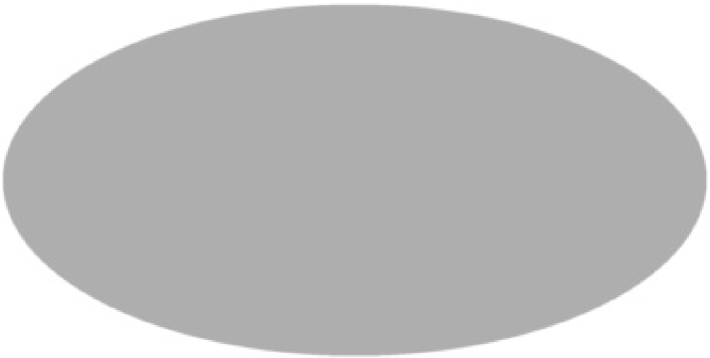
Doppler Shift

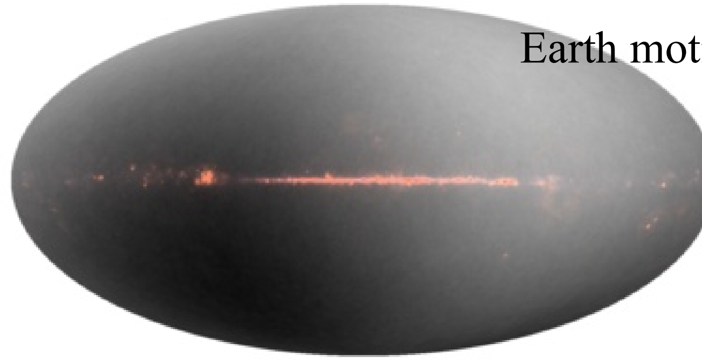
600 km/sec



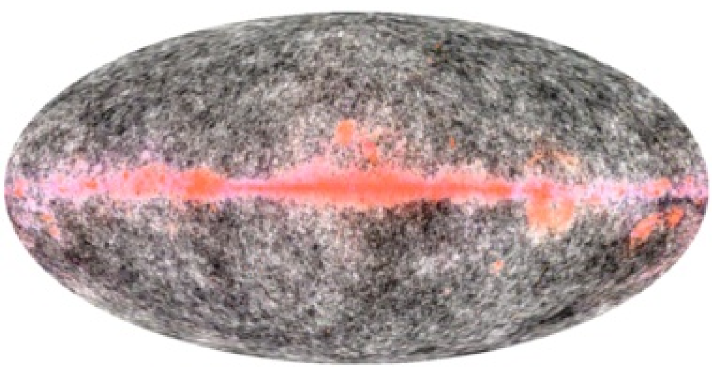
yrs

What the CMB really looks like

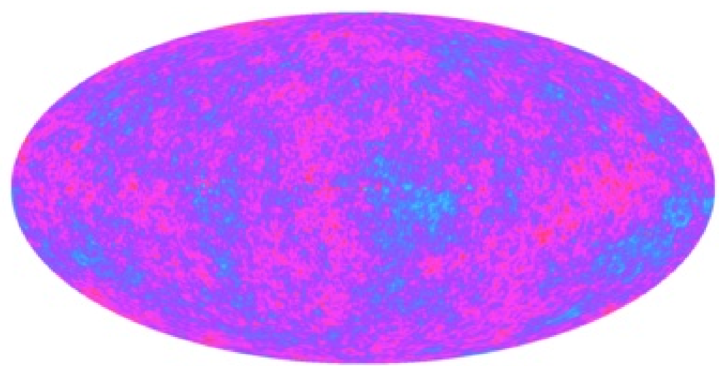




Earth motion & galaxy

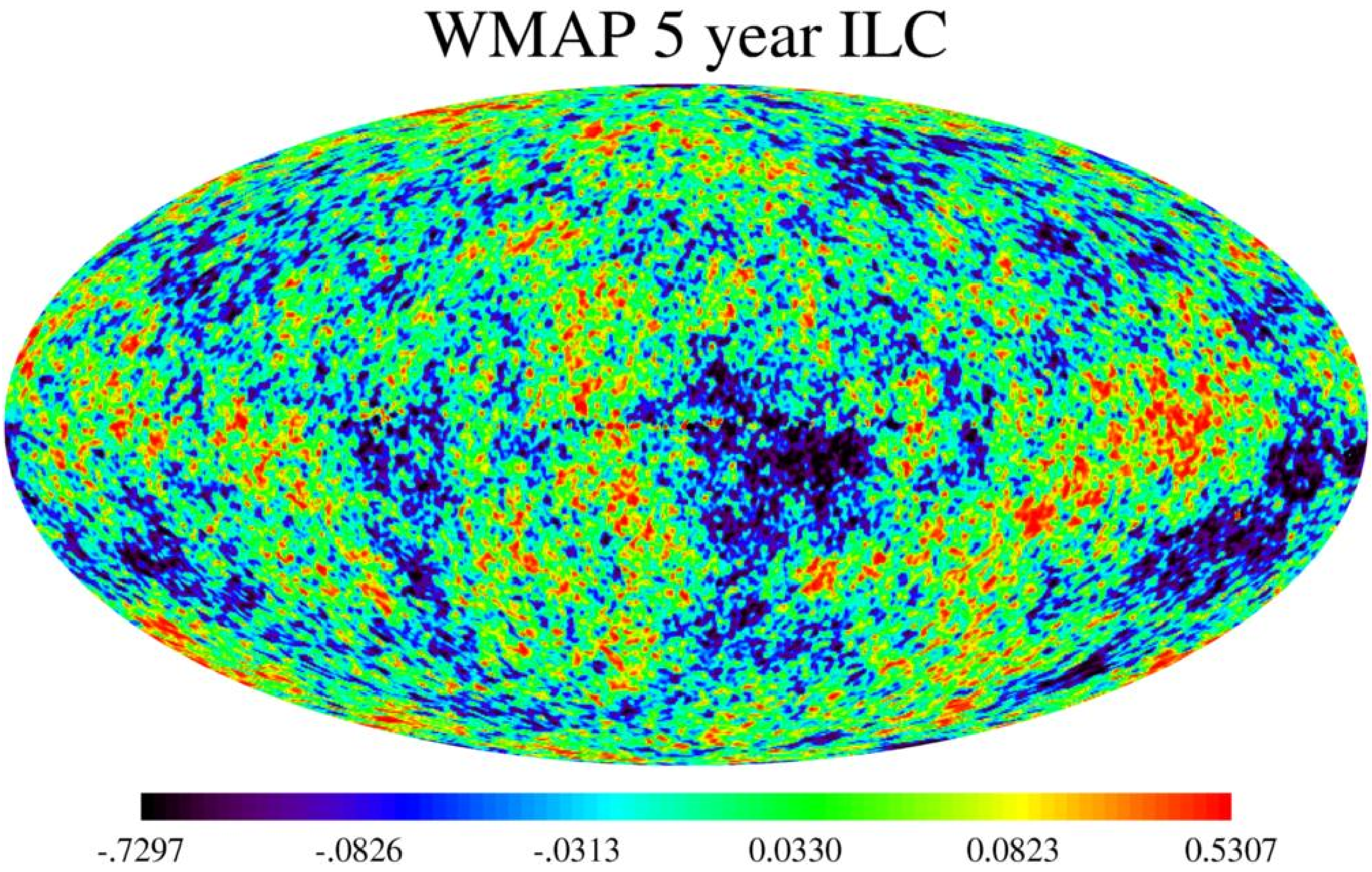


rgalactic electrons & clusters of Galaxies



Residual at the 1E-5

Does this look totally random to you?



Spherical Harmonics

l=0

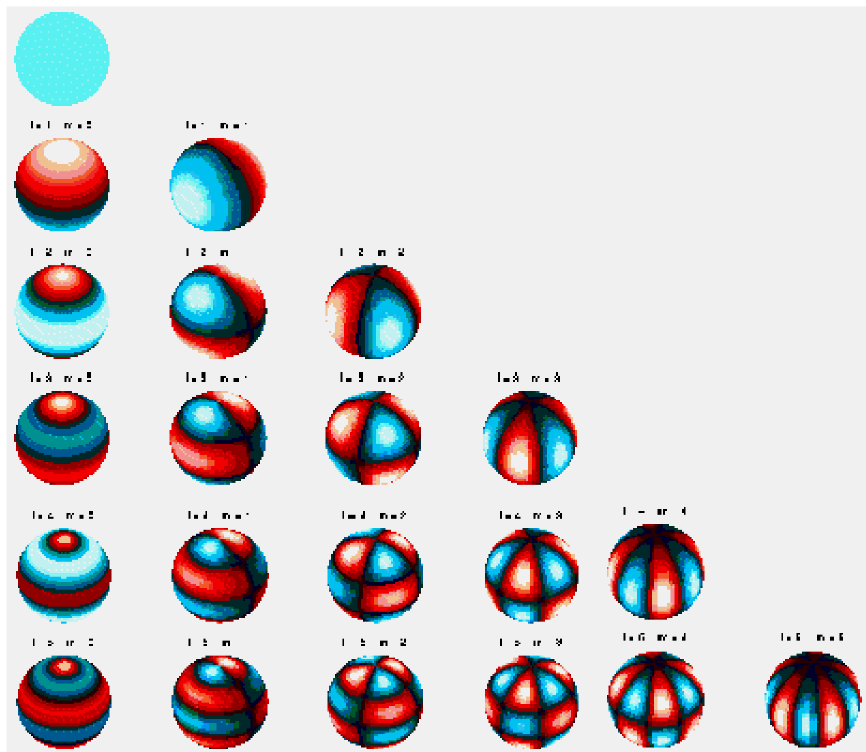
l=1

l=2

l=3

l=4

l=5

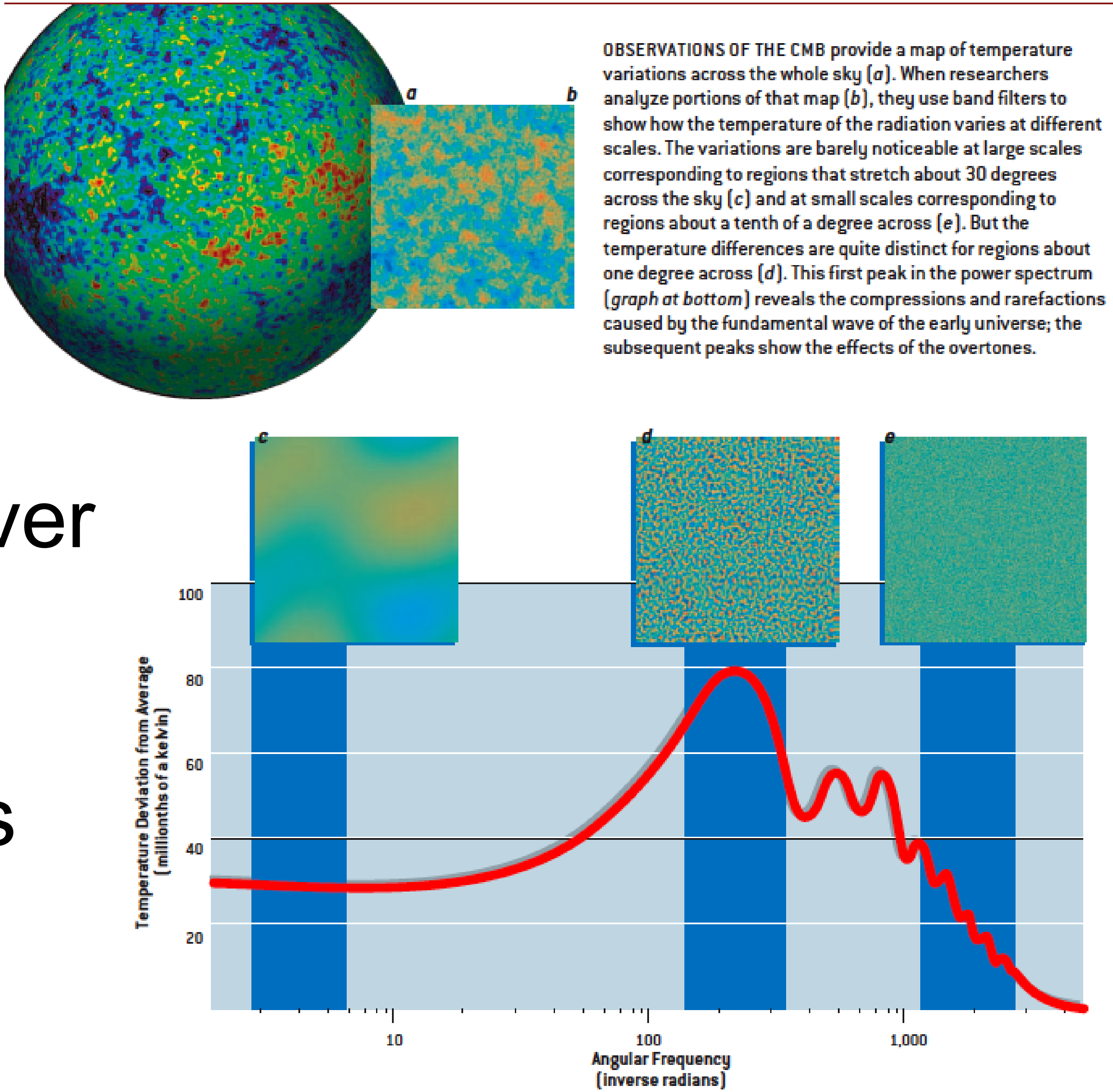


m=0 m=1 m=2 m=3 m=4 m=5

$$\frac{\Delta T}{T} = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi).$$

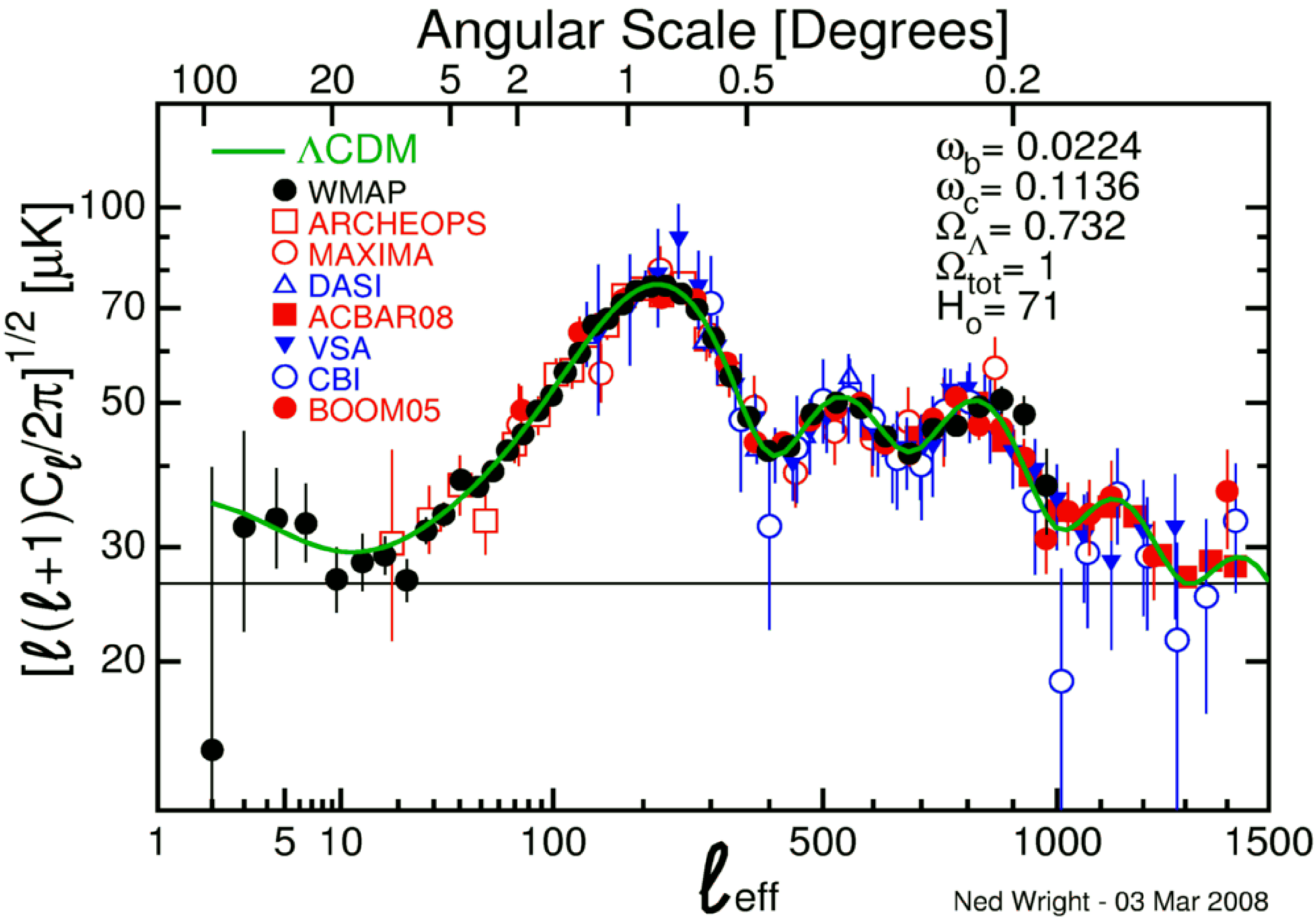
$$C_\ell \equiv \sum_m |a_{\ell m}|^2.$$

Build up a power spectrum by averaging over m-modes. (large uncertainties for low-l modes)



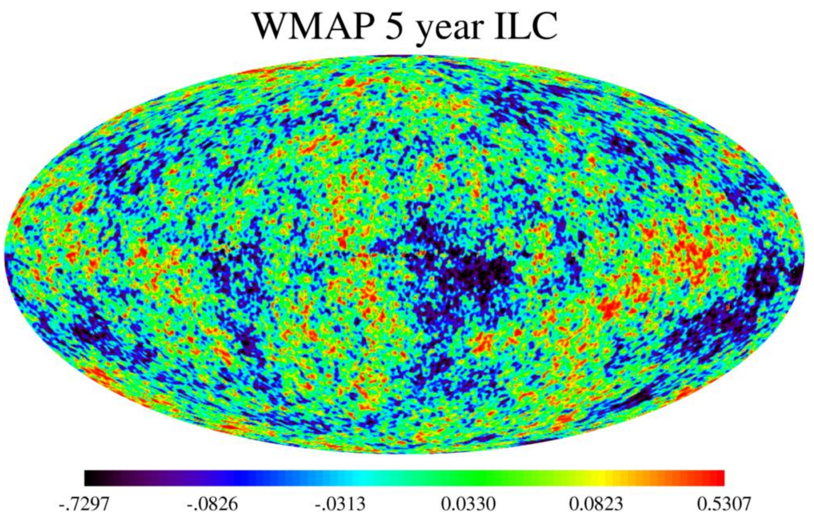
OBSERVATIONS OF THE CMB provide a map of temperature variations across the whole sky (*a*). When researchers analyze portions of that map (*b*), they use band filters to show how the temperature of the radiation varies at different scales. The variations are barely noticeable at large scales corresponding to regions that stretch about 30 degrees across the sky (*c*) and at small scales corresponding to regions about a tenth of a degree across (*e*). But the temperature differences are quite distinct for regions about one degree across (*d*). This first peak in the power spectrum (*graph at bottom*) reveals the compressions and rarefactions caused by the fundamental wave of the early universe; the subsequent peaks show the effects of the overtones.

CMB Power Spectrum



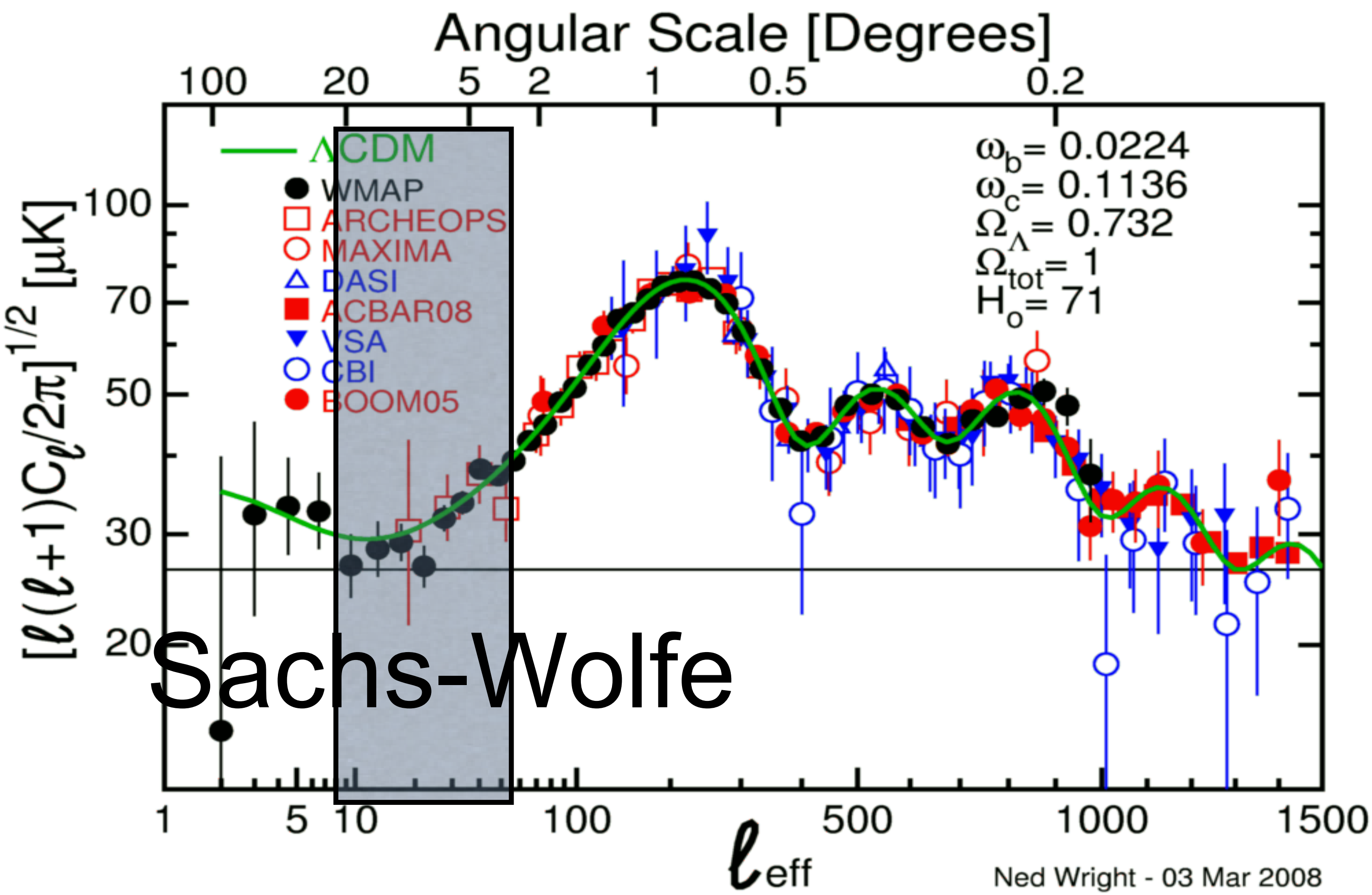
Why do we see spots?

- Actual thermal perturbations
- Doppler boosting due to velocity perturbations
- Gravitational redshift due to density perturbations

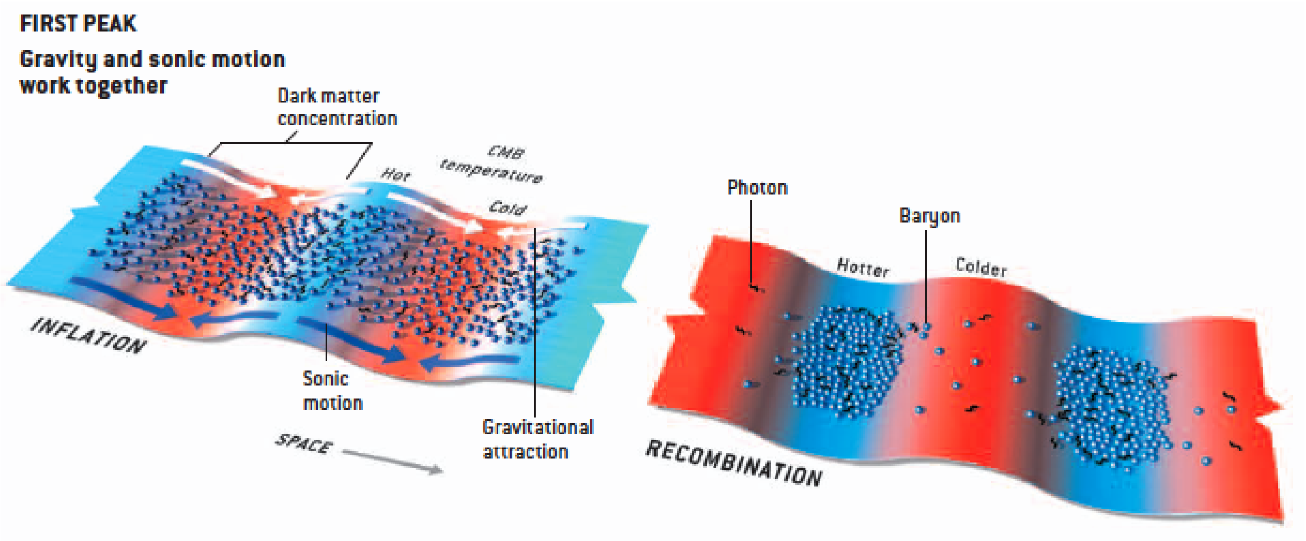


Results depend on the scale of perturbations relative to the acoustic horizon

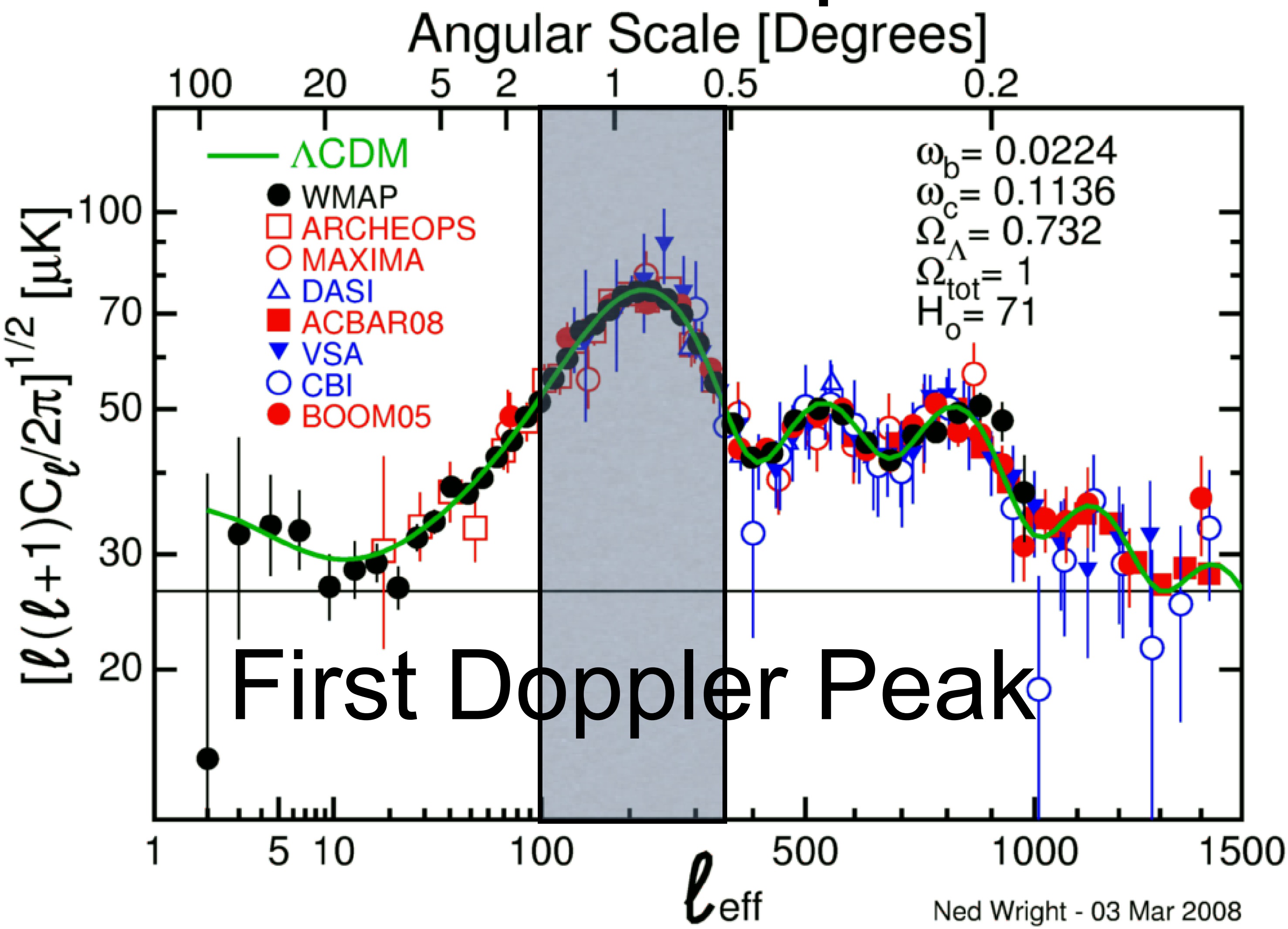
CMB Power Spectrum



Doppler Peak: Half an Oscillation

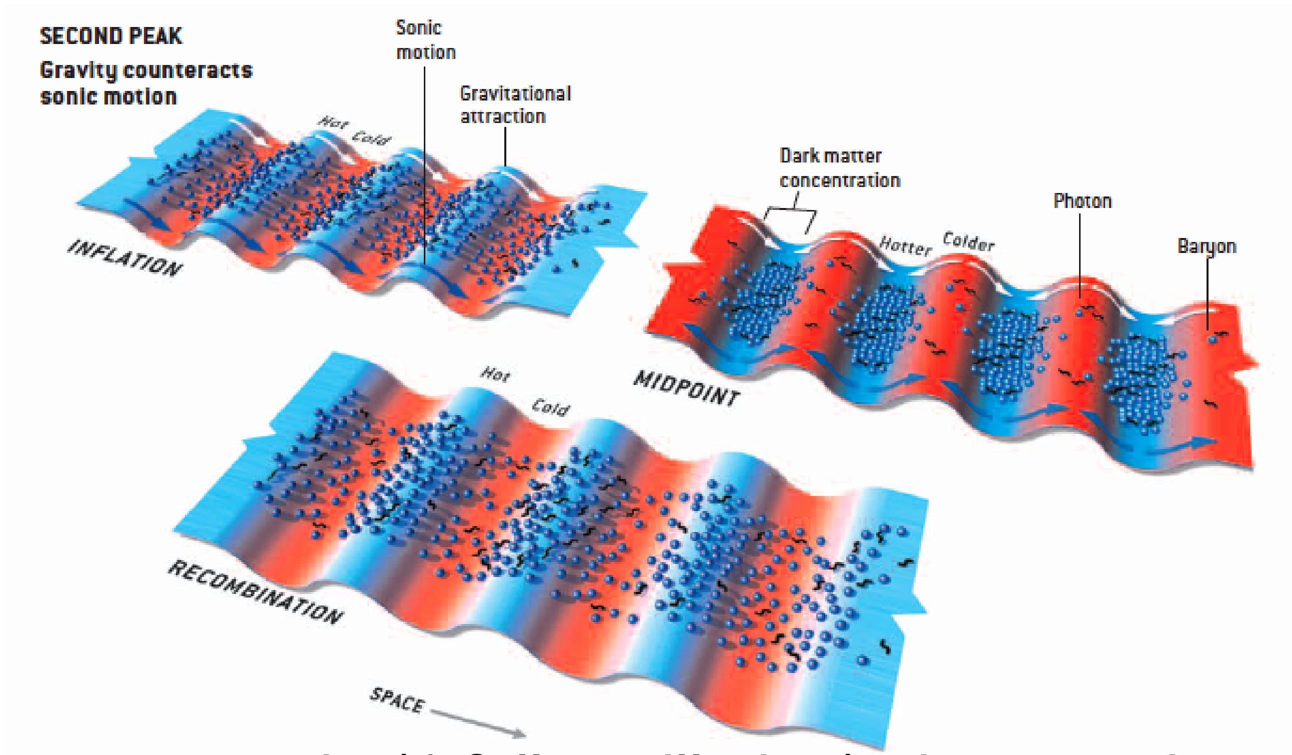


CMB Power Spectrum



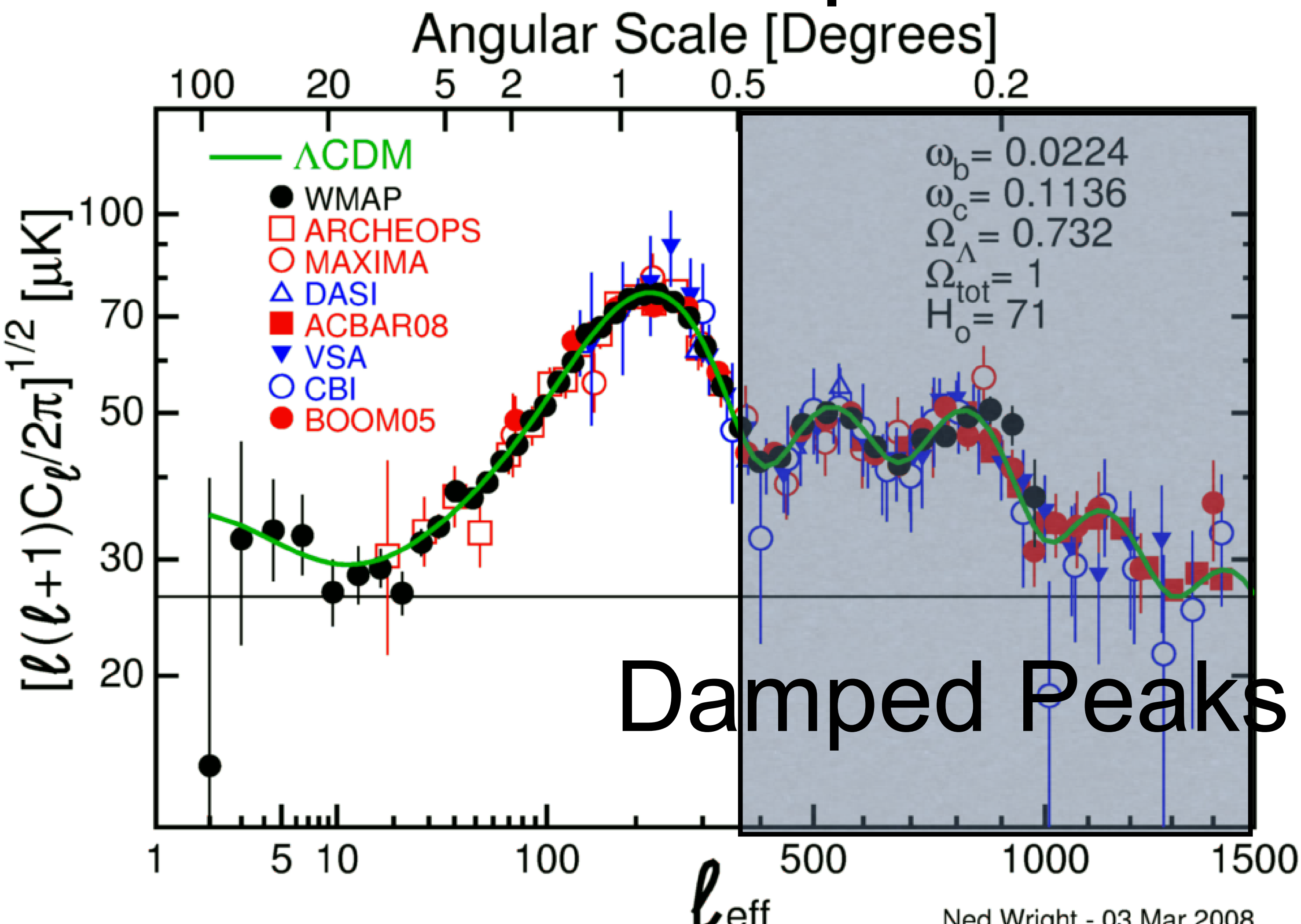
First Doppler Peak

Second Peak



For the next peak, (1 full oscillation), the sound waves are beginning to fight the dark-matter dominated gravitational perturbations

CMB Power Spectrum



Power Spectrum vs Cosmological

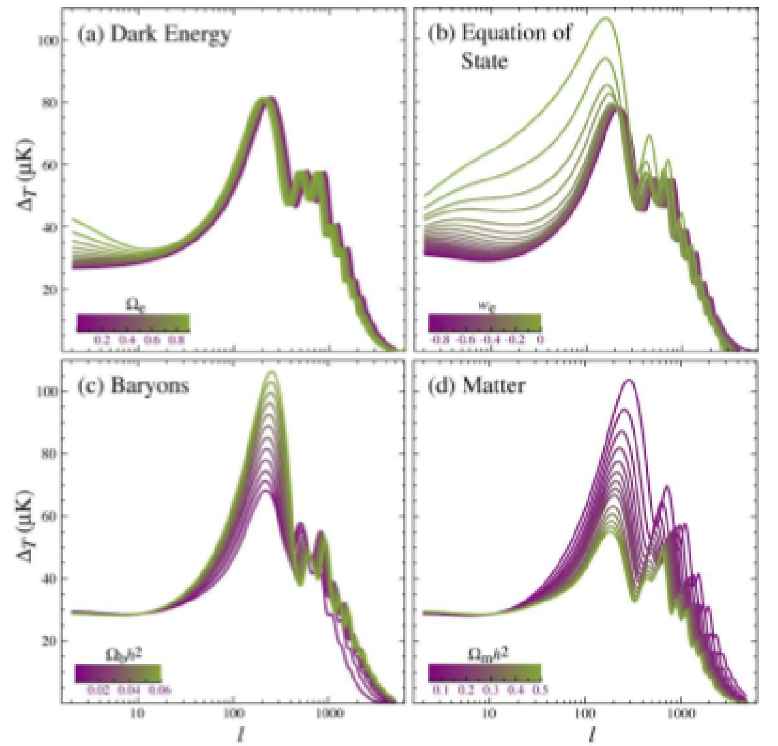
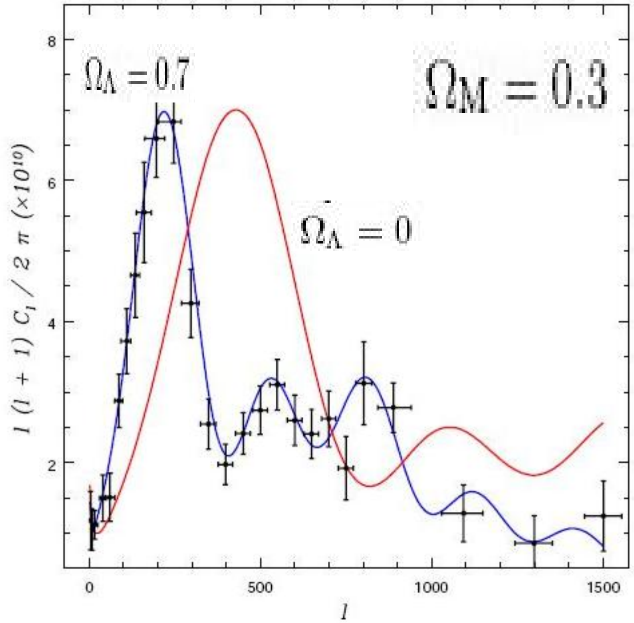


FIGURE 5. Sensitivity of the temperature power spectrum to four fundamental cosmological parameters: the energy density of the dark energy today Ω_e in units of the critical density, the equation of state parameter of the dark energy w_e, the physical baryon density $\Omega_b h^2$ and the physical matter density $\Omega_m h^2$. All are varied around a fiducial flat model of $\Omega_e = 0.65$, $w_e = -1$, $\Omega_b h^2 = 0.02$ and $\Omega_m h^2 = 0.15$ with $n = 1$.

The Flatness Problem

•



Definition of critical density:

$$\Omega \equiv \frac{8\pi G}{3}\left(\frac{\rho}{H^2}\right).$$

$1 + 3w > 0.$

$$p = w\rho$$

Equation of State EOS:

$$\rho \propto a^{-3(1+w)}$$

With

With Friedman equation => $\frac{d\Omega}{d\log a} = (1+3w)\Omega(\Omega - 1).$

For ordinary matter $1 + 3w > 0.$ **=>** $\frac{d\,|\Omega - 1|}{d\log a} > 0,\ 1 + 3w > 0.$

- Why is the CMB isotropic?