Lecture 4: Matter-Radiation Decoupling and the Cosmic Microwave Background

- Annihilation (with symmetry breaking)
  - quark soup
- Baryogenesis (quark confinement)
  - neutrons and protons
- Nucleosynthesis
  - Plasma of charged nuclei (75% H 25% He)

    + electrons, photons, neutrinos, traces of Li, Be.
- Recombination
  - Neutral atoms
  - Matter and radiation decouple (Universe transparent)
- Origin of the Cosmic Microwave Background

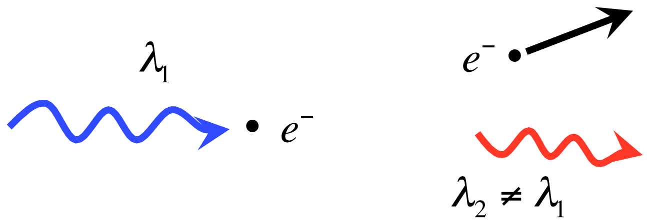
The Plasma Era

After Nucleosynthesis: charge-neutral plasma.

$12\ H^{+} + He^{++} + 14\ e^{-} + 10^{9}$ photons

Thompson scattering of photons by electrons:

$$e + \gamma \rightarrow e + \gamma$$



Electrons and photons exchange energy.

Maintains thermal equilibrium and

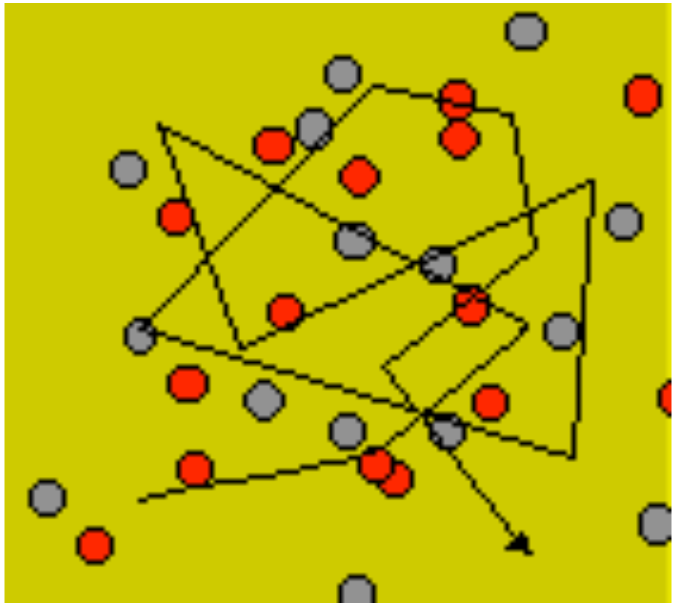
coupling (same *T*) between radiation and matter.

The Universe is opaque.

Photons cannot travel far without scattering on electrons.

Photons "random walk".

Like "looking thru fog".



1. matter-radiation equality ($T \sim 30{,}000$ K $t \sim 10^4$ yr)

energy density of photons drops below that of matter

Before: $T \propto \frac{1}{R} \propto \frac{1}{t^{1/2}}$ After: $T \propto \frac{1}{R} \propto \frac{1}{t^{2/3}}$

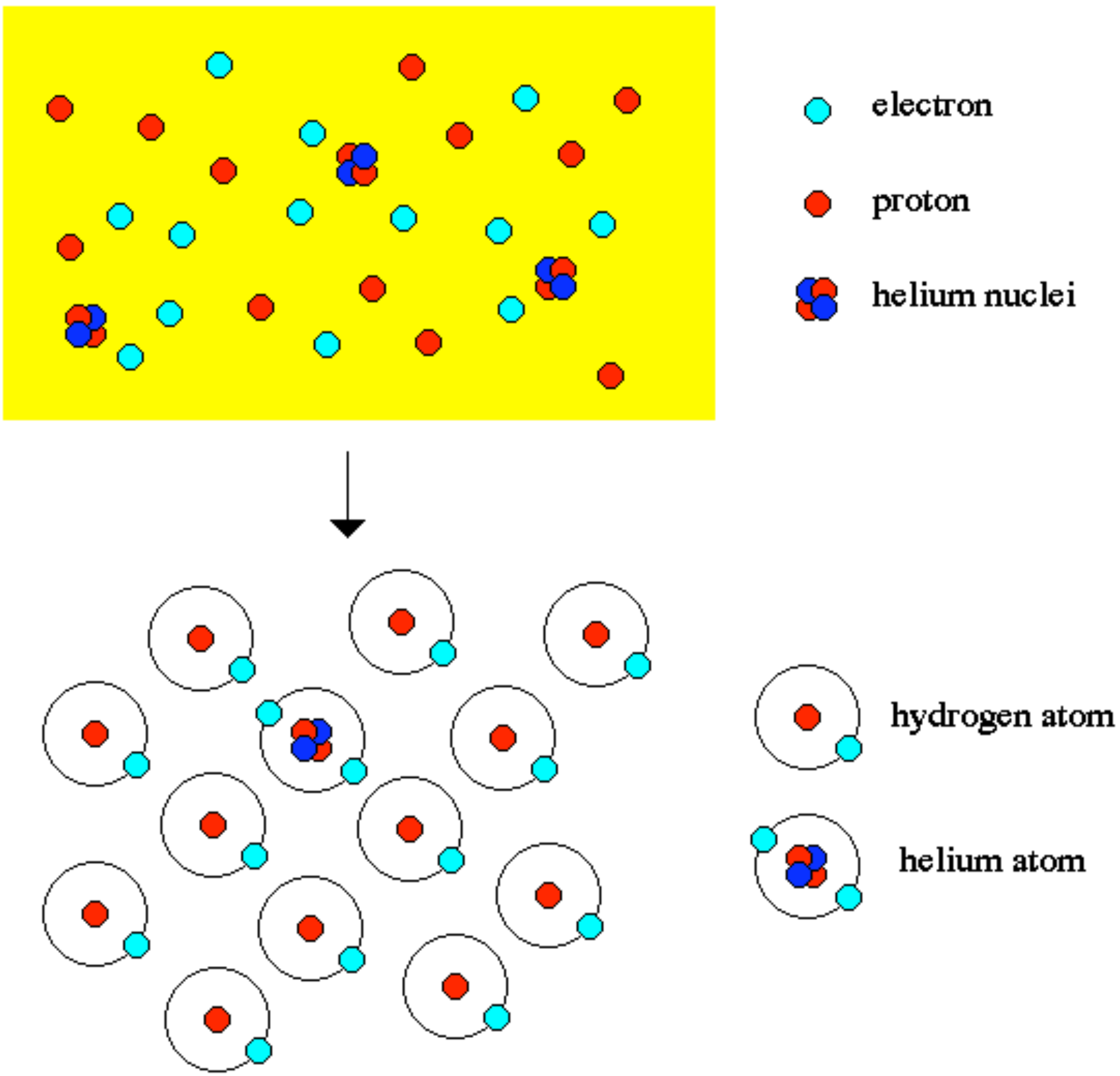
2. "recombination" ($T \sim 3000$ K $t \sim 3x10^5$ yr)

electrons + nuclei --> neutral atoms

Recombination

Plasma

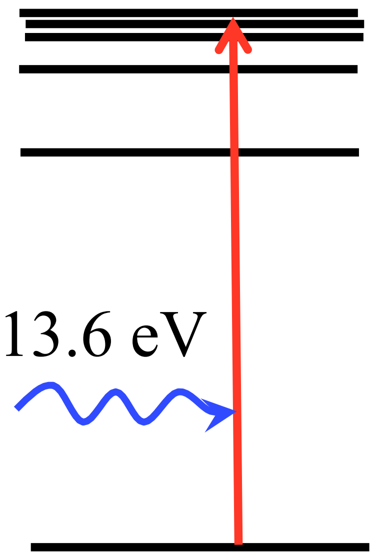
Neutral gas



Recombination Temperature

H ionisation potential $I = 13.6$ eV.

Photons with $h\nu > I$ can ionise H.



Mean energy of blackbody photons: $\overline{h\nu} = 3\,k\,T$

Recombination temperature: $3\,k\,T \sim I$

$$T \sim \frac{I}{3\,k} = \frac{(13.6 \text{ eV})(11600 \text{ K eV}^{-1})}{3} \approx 52{,}000\text{K}$$

$1/k = 11{,}600$ K/eV

Too crude, because:

1) $\sim 10^9$ photons per H atom
   (photons in blackbody tail can ionise H)

2) H has bound states (excited electrons)

Refined Calculation

Energy levels: $E_n = - I / n^2$.
Excitation to $n = 1 \text{-->} 2$ needs
$$E = E_2 - E_1 = 13.6 \times (1 - 1/2^2) = 10.2 \text{ eV}.$$

Photon/proton ratio: $\dfrac{N_\gamma}{N_p} \approx 10^9$

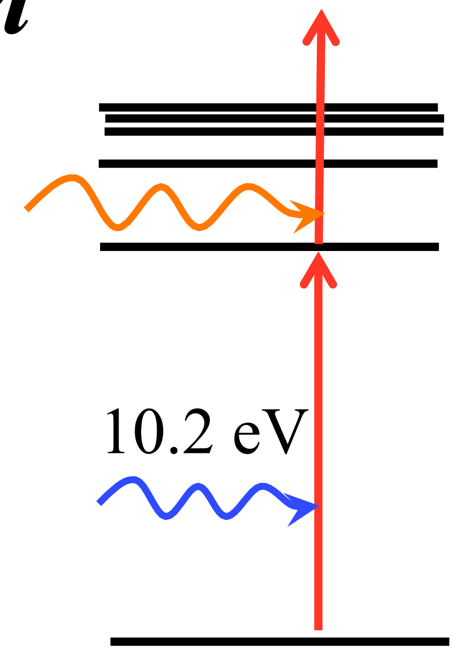
To get ~ 1 photon (with $h\nu > 10.2$ eV) per proton.

$$N_p = N_\gamma(h\nu > E) \approx N_\gamma \exp(-E / k\,T)$$

$$\frac{E}{k\,T} = \ln\left(\frac{N_\gamma}{N_p}\right) \approx \ln(10^9) \approx 20$$

$$k\,T \approx \frac{10.2 \text{ eV}}{\ln(10^9)} \approx 0.5 \text{ eV}$$

$$T \approx 5700 \text{ K}$$



Ionisation from bound states keeps gas ionised until T drops further.

Detailed calculation gives 3000 K.

<u>At T < 3000 K, electrons and nuclei form neutral atoms</u>, not immediately re-ionised by photons.

Photons interact strongly with free charges (i.e. mainly free electrons), but not with neutral atoms.

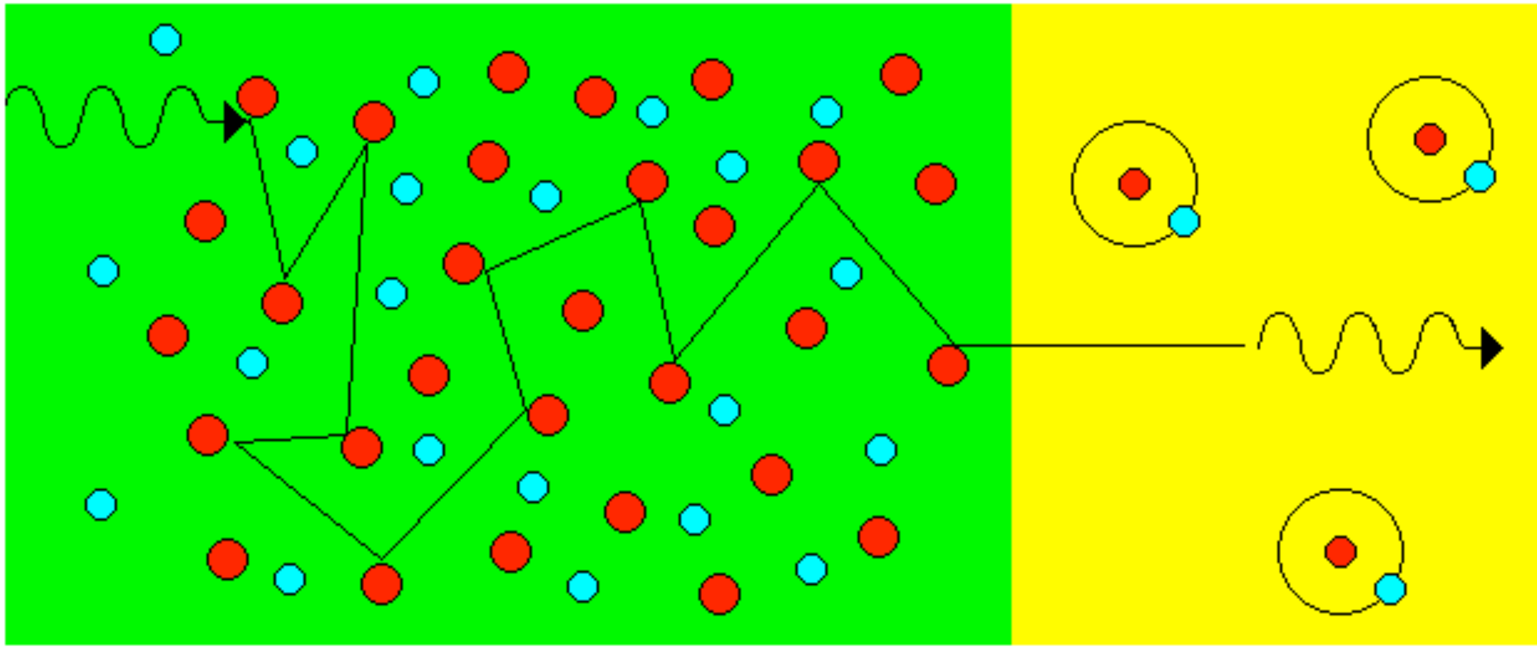
<u>Photons & matter decouple and no longer interact!</u>

<u>Universe becomes transparent.</u>

Photons now fly uninterrupted across the Universe.

(this is the Cosmic Microwave Background)

Last Scattering Epoch



$T > 3000K$ $\quad$ $T < 3000K$

Redshift of Last Scattering

Photons, now free of matter, fly freely in all directions.

Their temperature decreases as the Universe expands.

Today we see these photons from all directions with

$T = 3000$ K / expansion factor = 2.7 K.

expansion factor = (1 + z) = (3000 / 2.7) = 1100.

1948. Gamow predicts $T \sim 5$ K.

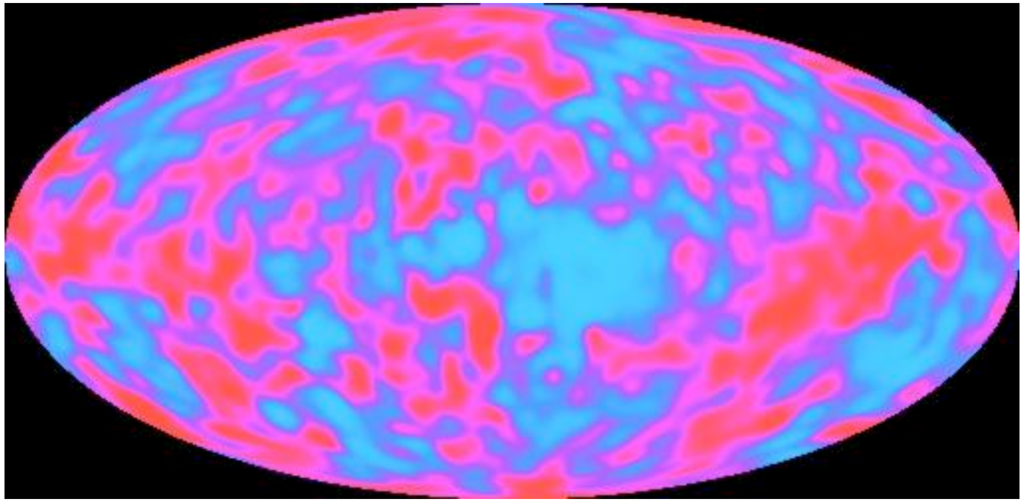
1965. Penzias & Wilson discover the CMB. $T \sim 2.7$ K.

1995. COBE measures perfect blackbody spectrum. $T = 2.728$ K

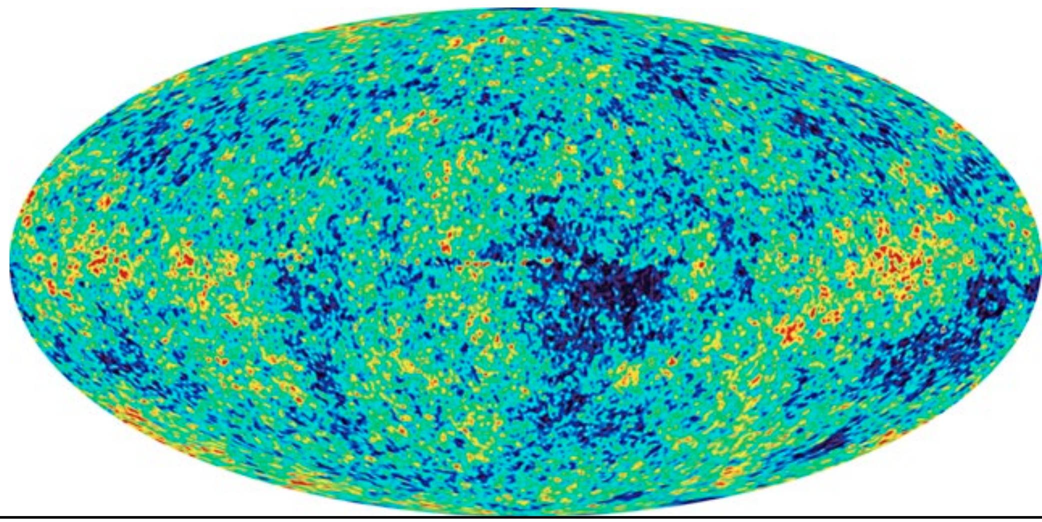
2004. WMAP resolves the ripples. $\Delta\theta \sim 1^{\circ}$ $\frac{\Delta T}{T} \sim 10^{-5}$

All-sky maps

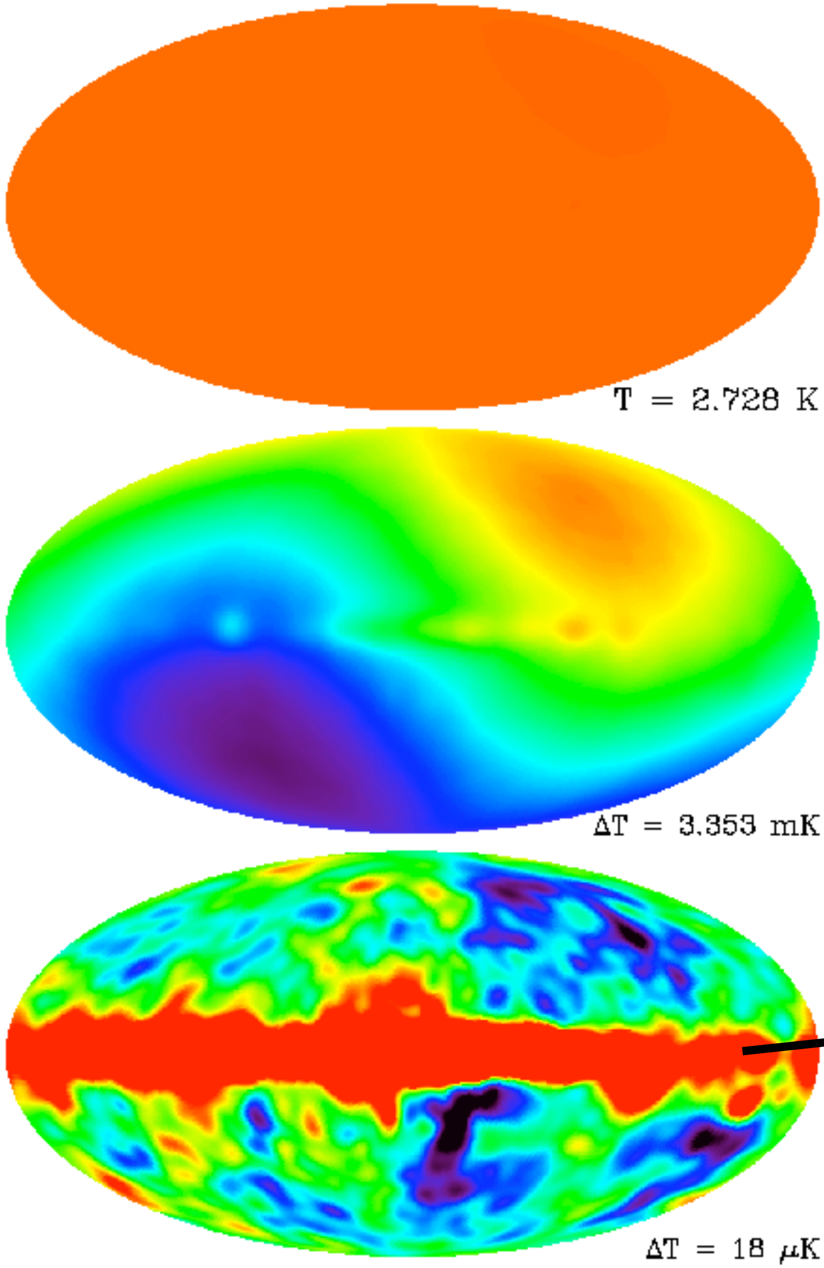
COBE :



WMAP :



CMB



Almost isotropic

$T = 2.728$ K

Dipole anisotropy

$$\frac{V}{c} = \frac{\Delta\lambda}{\lambda} = \frac{\Delta T}{T} \approx 10^{-3}$$

Our velocity:

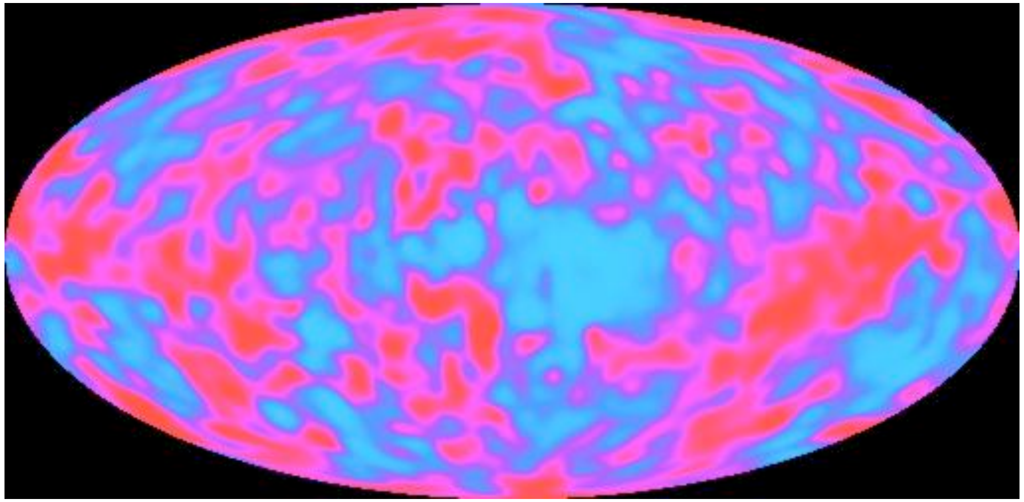
$V \approx 400$ km/s

Milky Way sources

$+$ anisotropies $\dfrac{\Delta T}{T} \sim 10^{-5}$

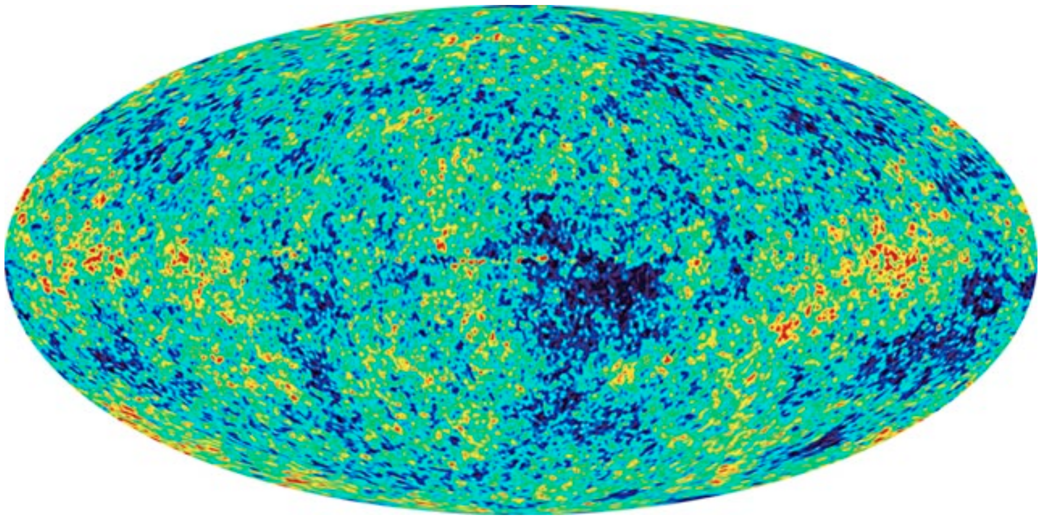
CMB Anisotropies

COBE
1994



$$\frac{\Delta T}{T} \sim 10^{-5}$$

WMAP
2004



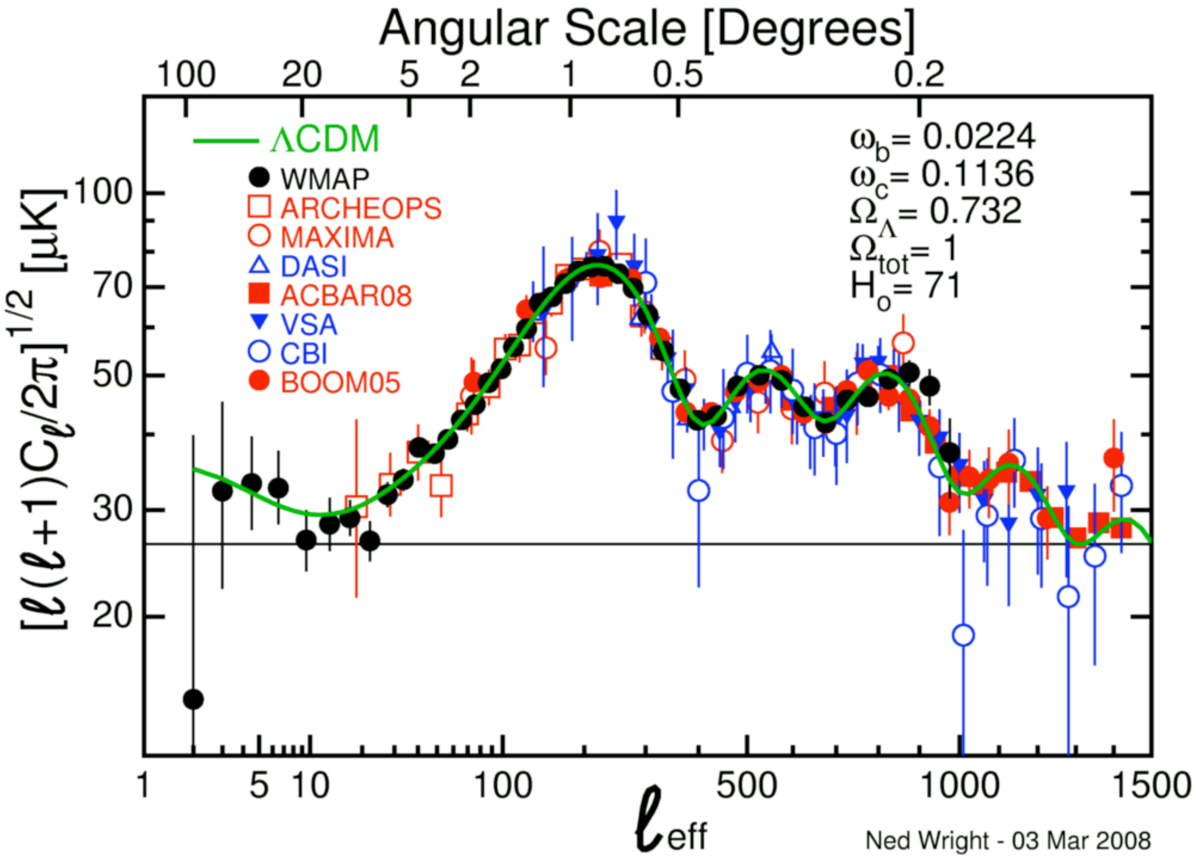
$$\Delta\theta \sim 1^{o}$$

Snapshot of Universe at z = 1100
Seeds of galaxy formation.

Power Spectrum of CMB anisotropies

Temperature ripple ΔT
vs angular scale
$\theta = 180^o / \ell$

Peak at 1^o scale
=> Flat geometry,
$\Omega_{tot}=1$



"Acoustic Peaks" arise from sound waves in the plasma era. Sound speed is $c/\sqrt{3}$. Peak when the duration of plasma era matches a multiple of half a sound wave oscillation period.

Recap of key physics

Matter: $\varepsilon_{\mathrm{M}} = \rho_M c^2 \propto R^{-3}$

Radiation: $\varepsilon_{\mathrm{R}} = \rho_R c^2 = \alpha T^4 \propto R^{-4}$

Observations: $T_{CMB} = 2.7\ \mathrm{K} \quad \Rightarrow \quad \rho_R \approx 10^{-31}\ \mathrm{kg\ m^{-3}}$

$$\rho_M \approx 10^{-28}\ \mathrm{kg\ m^{-3}} \quad \Rightarrow \quad \frac{\text{photons}}{\text{baryons}} = \frac{N_\gamma}{N_b} \sim 10^9$$

Mean energy of blackbody photons: $\overline{h\nu} = 3kT$

For <1 photon in the blackbody tail per baryon:

$$N_\gamma(h\nu > E) \approx N_\gamma \exp\left(-E/kT\right) < N_b$$

$$\Rightarrow \quad k\,T < \frac{E}{\ln\left(N_\gamma/N_b\right)} = \frac{E}{\ln\left(10^9\right)} \approx \frac{E}{20}$$

Sets p/n ratio, hence H/He ratio and T=3000K at recombination.

Key stages in the history of our Universe:

~ 1 TeV — matter-antimatter annihilation

quark soup

~ 1 GeV — baryogenesis (quark confinement)

neutron proton soup

~ 0.8 MeV — neutron – proton freeze-out

neutrons decay

~ 0.1 MeV — nucleosynthesis

H+He+e Thomson scattering plasma

~ 1 eV — Recombination / decoupling

neutral atoms + CMB photons

Galaxy Formation

~ 10^{-3} eV — Today

Recollapse or Eternal expansion ?

Radiation era (~ 1 TeV to ~ 0.1 MeV)

Matter era (~ 1 eV to today)