

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

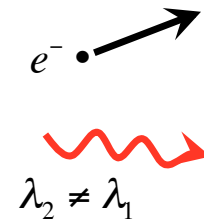
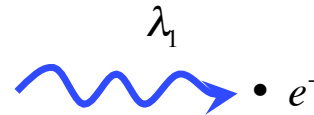
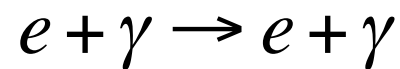
- Annihilation (with symmetry breaking)
 - quark soup
- Baryogenesis (quark confinement)
 - neutrons and protons
- Nucleosynthesis
 - Plasma of charged nuclei (75% H 25% He)
 - + electrons, photons, neutrinos, traces of Li, Be.
- Recombination
 - Neutral atoms
 - Matter and radiation decouple (Universe transparent)
- Origin of the Cosmic Microwave Background

The Plasma Era

After Nucleosynthesis: charge-neutral plasma.



Thompson scattering of photons by electrons:



Electrons and photons exchange energy.

Maintains thermal equilibrium and

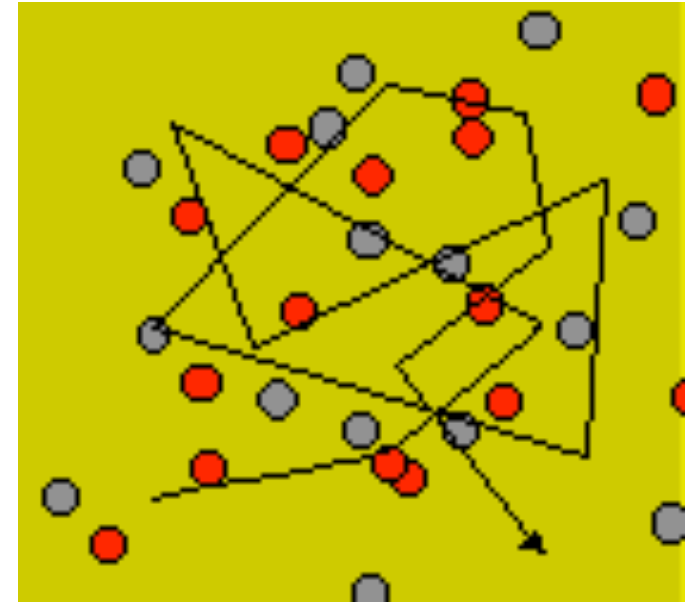
coupling (same T) between radiation and matter.

The Universe is opaque.

Photons cannot travel far
without scattering on electrons.

Photons “random walk”.

Like “looking thru fog”.



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

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” ($T \sim 3000 \text{ K}$ $t \sim 3 \times 10^5 \text{ yr}$)

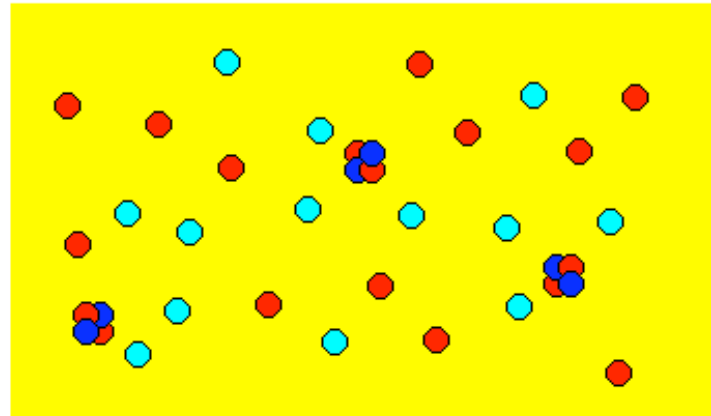
electrons + nuclei \rightarrow neutral atoms




Recombination

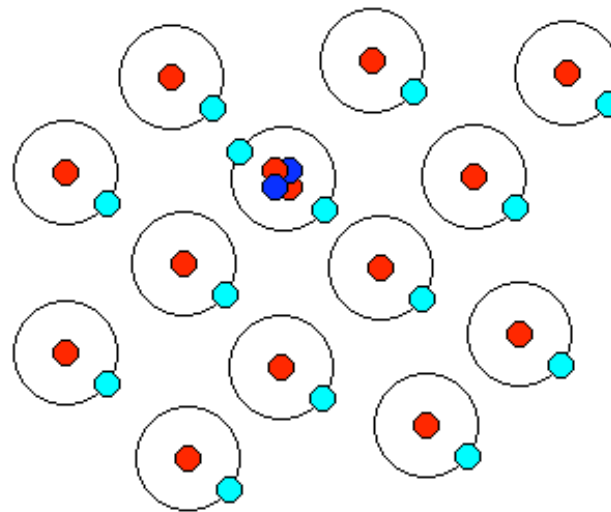
Plasma





Neutral gas



-  electron
-  proton
-  helium nuclei



-  hydrogen atom
-  helium atom

Recombination Temperature

H ionisation potential $I = 13.6 \text{ eV}$.

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

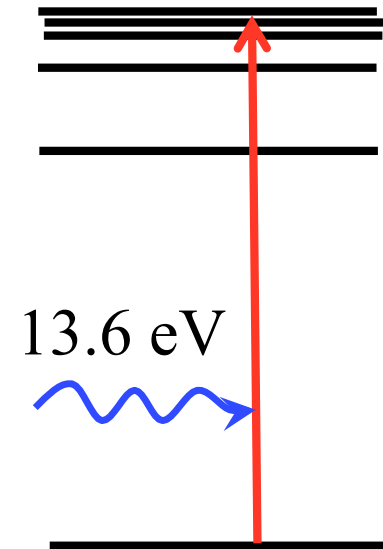
Mean energy of blackbody photons: $\overline{h\nu} = 3kT$

Recombination temperature: $3kT \sim I$

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

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)



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

Refined Calculation

Energy levels: $E_n = -I / n^2$.

Excitation to $n = 1 \rightarrow 2$ needs

$$E = E_2 - E_1 = 13.6 \times (1 - 1/2^2) = 10.2 \text{ eV.}$$

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

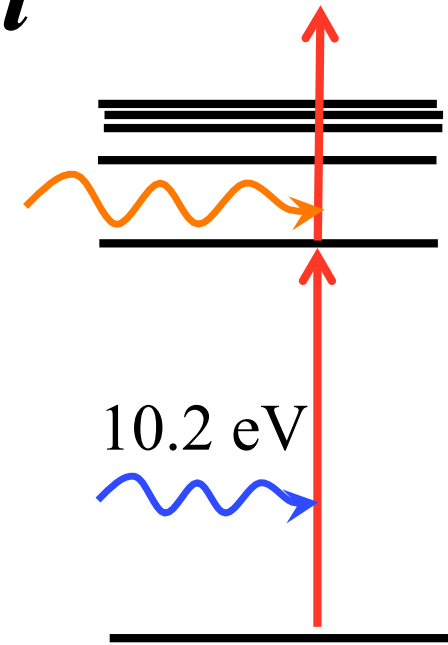
To get ~ 1 photon (with $h\nu > 10.2 \text{ eV}$) per proton.

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

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

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

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



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

Detailed calculation gives 3000 K.

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

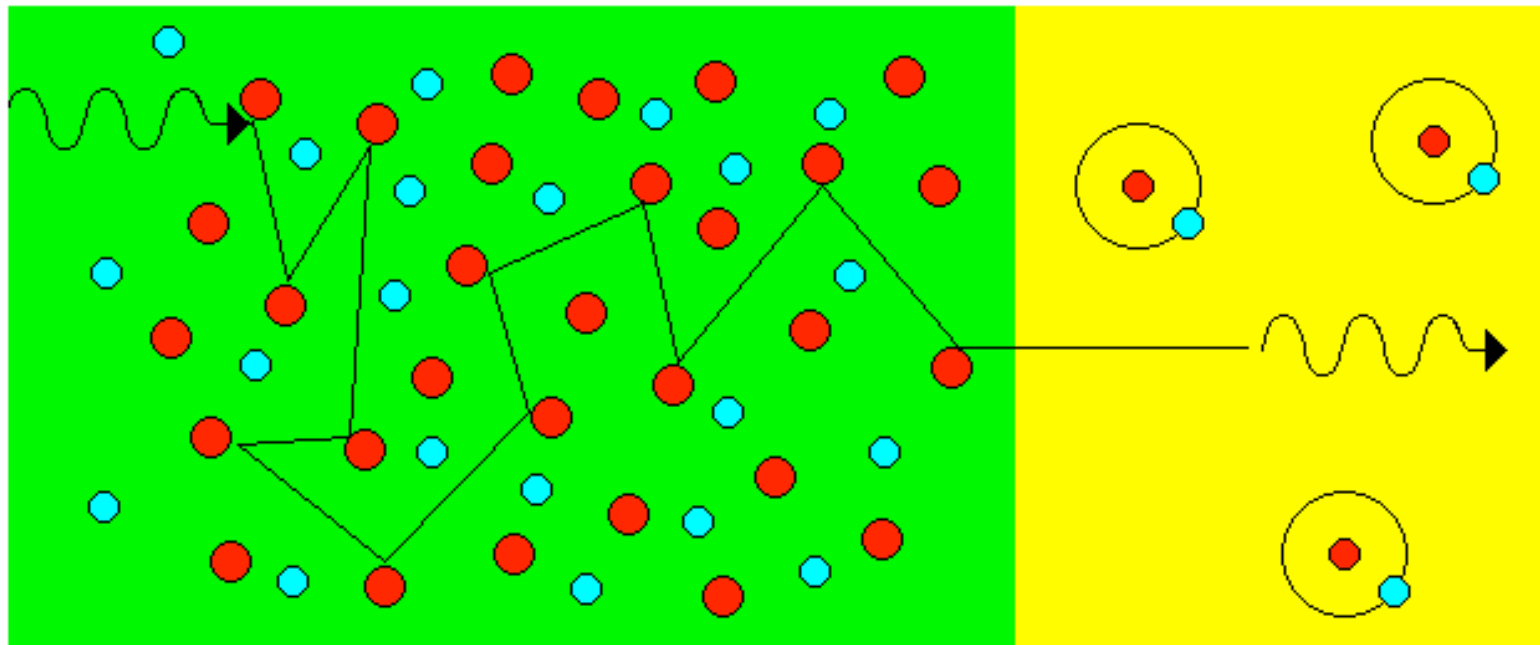
Photons interact strongly with free charges (i.e. mainly free electrons), but not with neutral atoms.

Photons & matter decouple and no longer interact!

Universe becomes transparent.

Photons now fly uninterrupted across the Universe.
(this is the Cosmic Microwave Background)

Last Scattering Epoch



hydrogen plasma

atomic hydrogen

$T > 3000K$

$T < 3000K$

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

$T = 3000 \text{ K} / \text{expansion factor} = 2.7 \text{ K}.$

$\text{expansion factor} = (1 + z) = (3000 / 2.7) = 1100.$



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

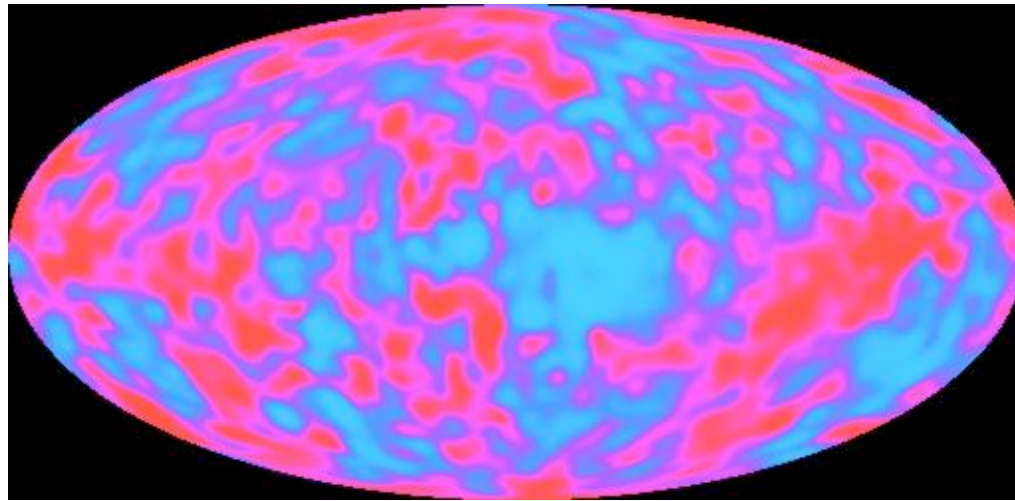
1965. Penzias & Wilson discover the CMB. $T \sim 2.7$ K.

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

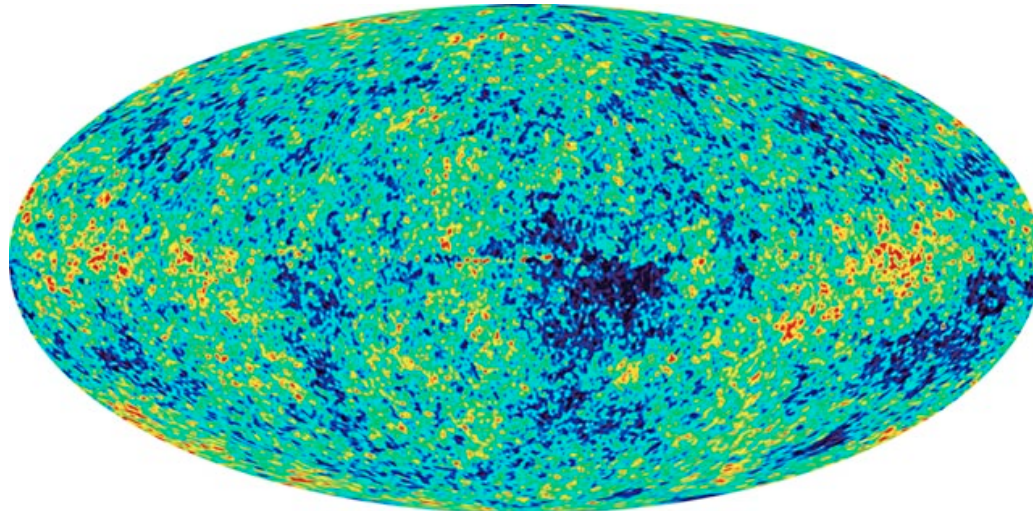
2004. WMAP resolves the ripples. $\Delta\theta \sim 1^\circ$ $\frac{\Delta T}{T} \sim 10^{-5}$

All-sky maps

COBE :



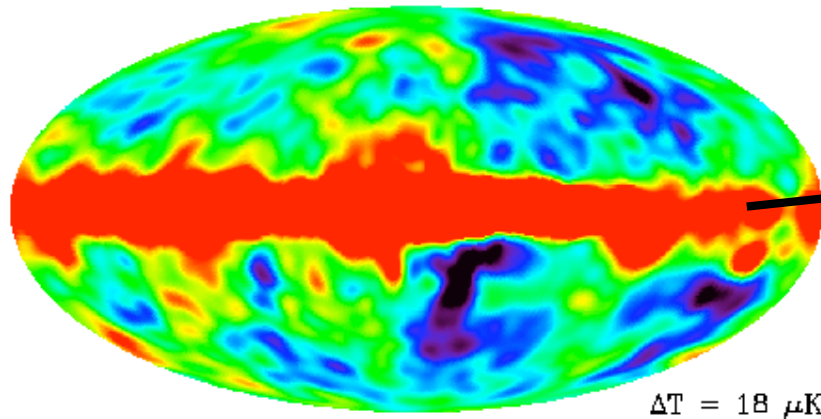
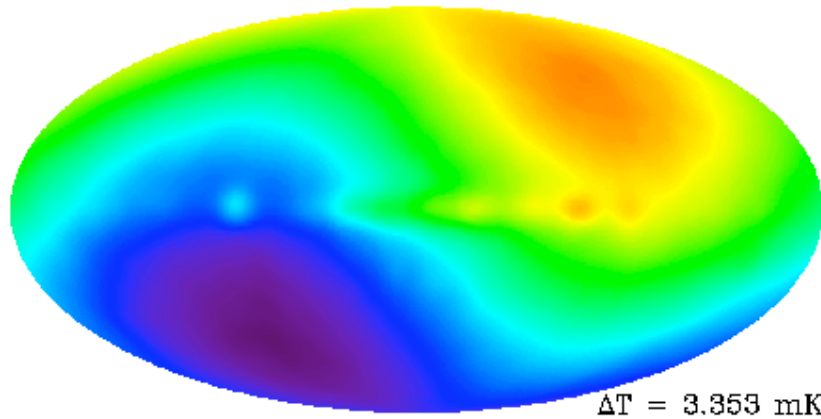
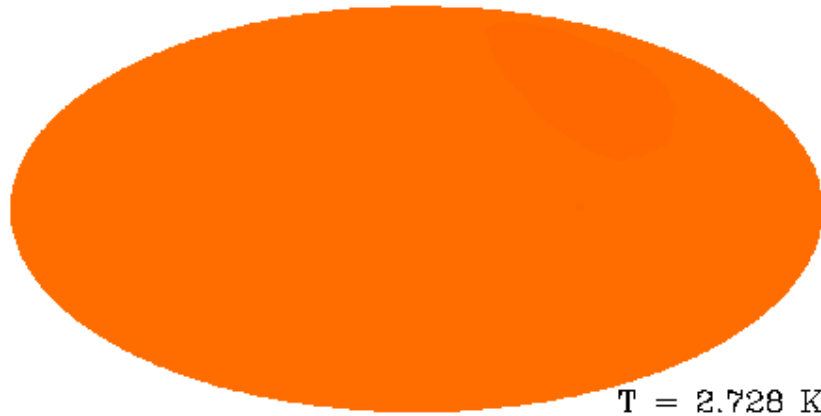
WMAP :



CMB

Almost isotropic

$$T = 2.728 \text{ K}$$



Dipole anisotropy

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

Our velocity:

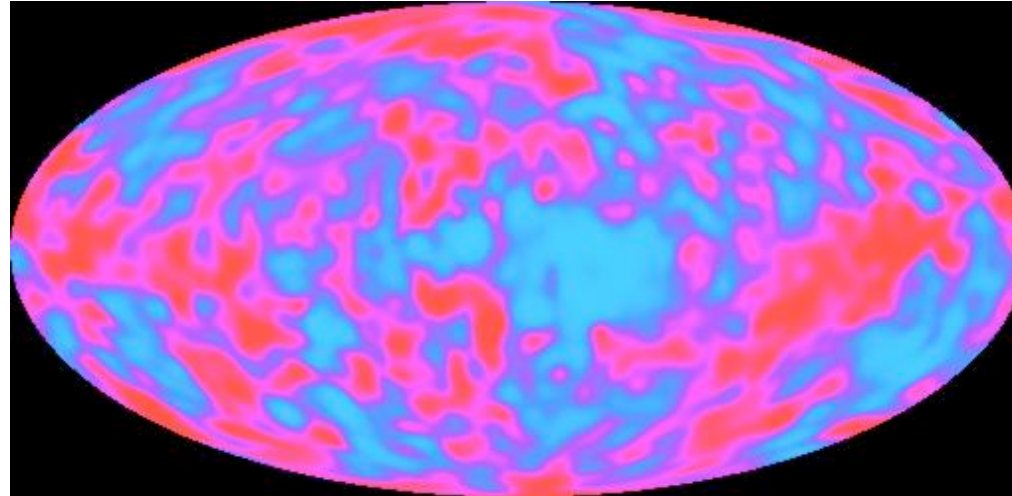
$$V \approx 400 \text{ km/s}$$

Milky Way sources

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

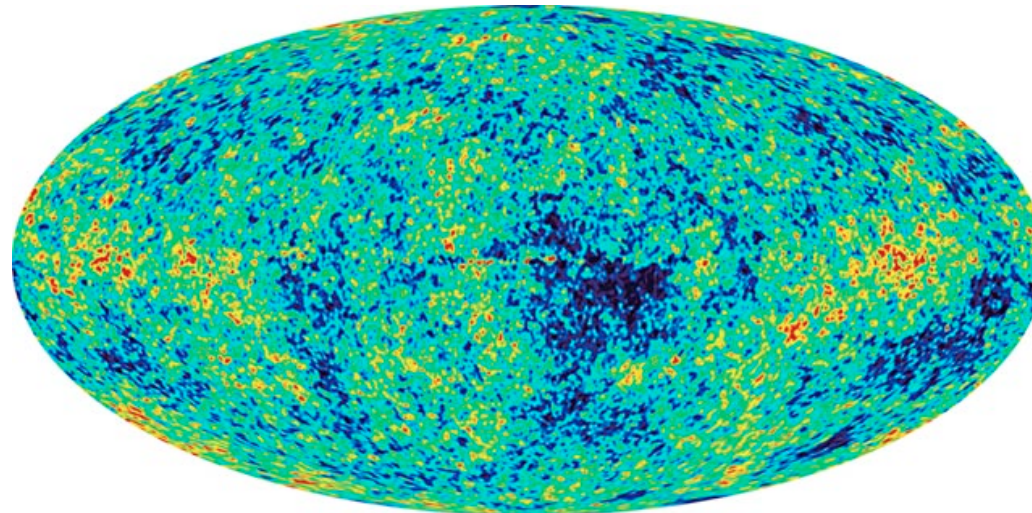
CMB Anisotropies

COBE
1994



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

WMAP
2004



$$\Delta\theta \sim 1^\circ$$

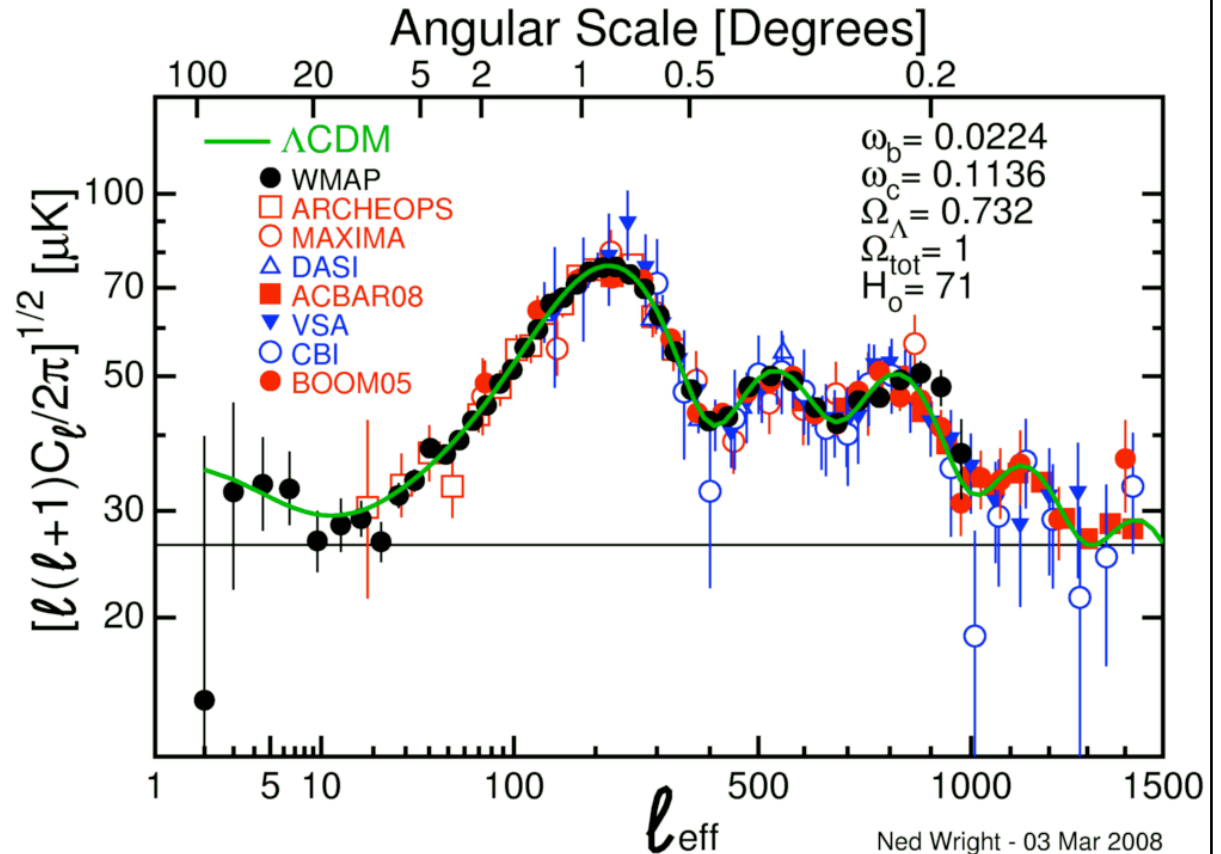
Snapshot of Universe at $z = 1100$
Seeds of galaxy formation.

Power Spectrum of CMB anisotropies

Temperature ripple ΔT
vs angular scale

$$\theta = 180^\circ / \ell$$

Peak at 1° scale
 \Rightarrow Flat geometry,
 $\Omega_{\text{tot}} = 1$



“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: $\varepsilon_M = \rho_M c^2 \propto R^{-3}$

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

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

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

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

For <1 photon in the blackbody tail per baryon:

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

$$\Rightarrow kT < \frac{E}{\ln(N_\gamma/N_b)} = \frac{E}{\ln(10^9)} \approx \frac{E}{20}$$

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

Key stages in the history of our Universe:

