Outline

- Go over problem 9.2
- Cosmological recombination
- Cosmic Microwave Background

Equation of State of the Universe

- Radiation dominated: $P = (1/3)u = (1/3)\,\rho c^2$
  - Use energy conservation to show $\rho \sim R^{-4}$

- Matter dominated: $\rho c^2 >> P$
  - Use energy conservation to show $\rho \sim R^{-3}$

- Λ dominated: $P_\Lambda = -\varepsilon_\Lambda$
  - $\rho \sim \varepsilon_\Lambda/c^2$ = constant

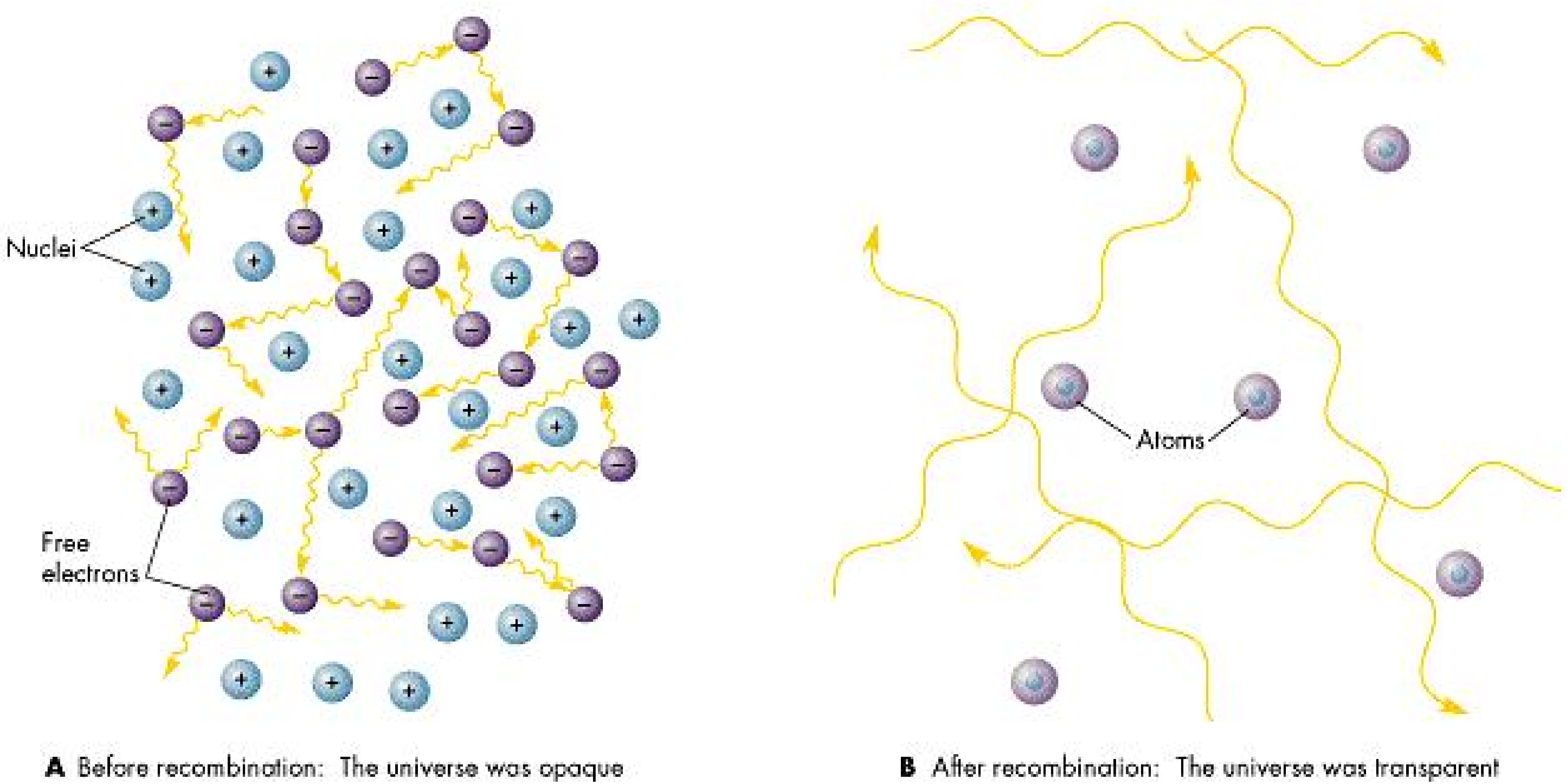
- Which dominated at early times?

Radiation Dominated Era

- Mass/energy density $\rho \sim R^{-4}$
- Mass/energy density in radiation $\rho c^2 = aT^4$
- Solve for T, find $T \sim 1/R$

- Early universe was hot
- Atoms were ionized
  - Universe was opaque due to electron scattering
- When universe cooled, $T \sim 3000$ K, atoms recombined
  - Universe became transparent to light λ < Lyman-α
  - Was universe transparent for $\lambda(T \sim 3000 \text{ K})$?

Recombination



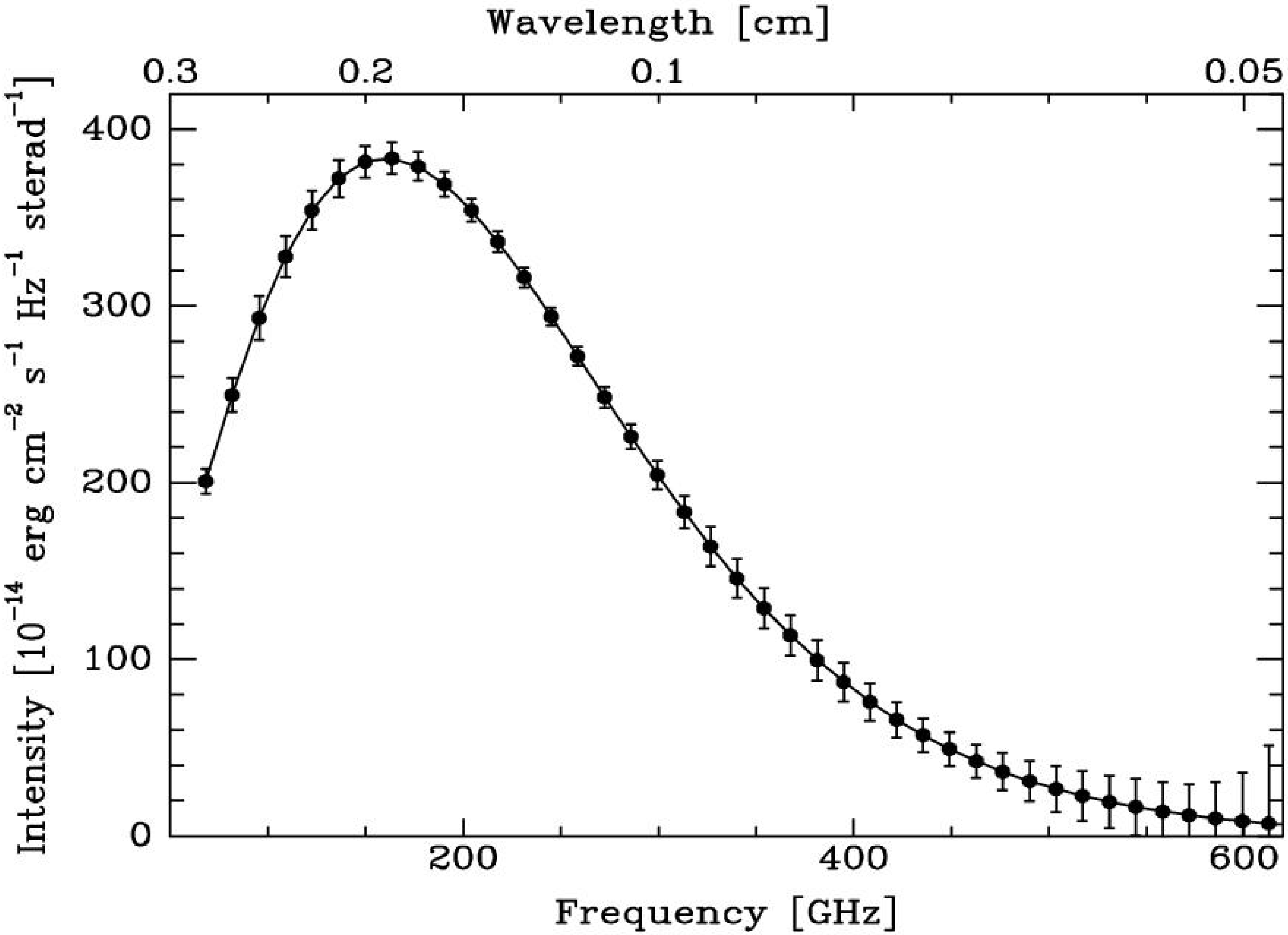
Transition occurs at around T = 30000-4000 K.

Recombination

- Before recombination, atoms and radiation were in equilibrium.
  - Atoms and radiation at the same temperature
  - Radiation had a black body spectrum

- Recombination decoupled radiation from matter
  - Radiation still had a black body spectrum
  - Radiation continued to evolve
    - Number density $n \sim R^{-3}$
    - Photon energy $E \sim R^{-1}$
    - Energy density $\rho \sim R^{-4}$
  - Show on board that radiation maintains blackbody spectrum

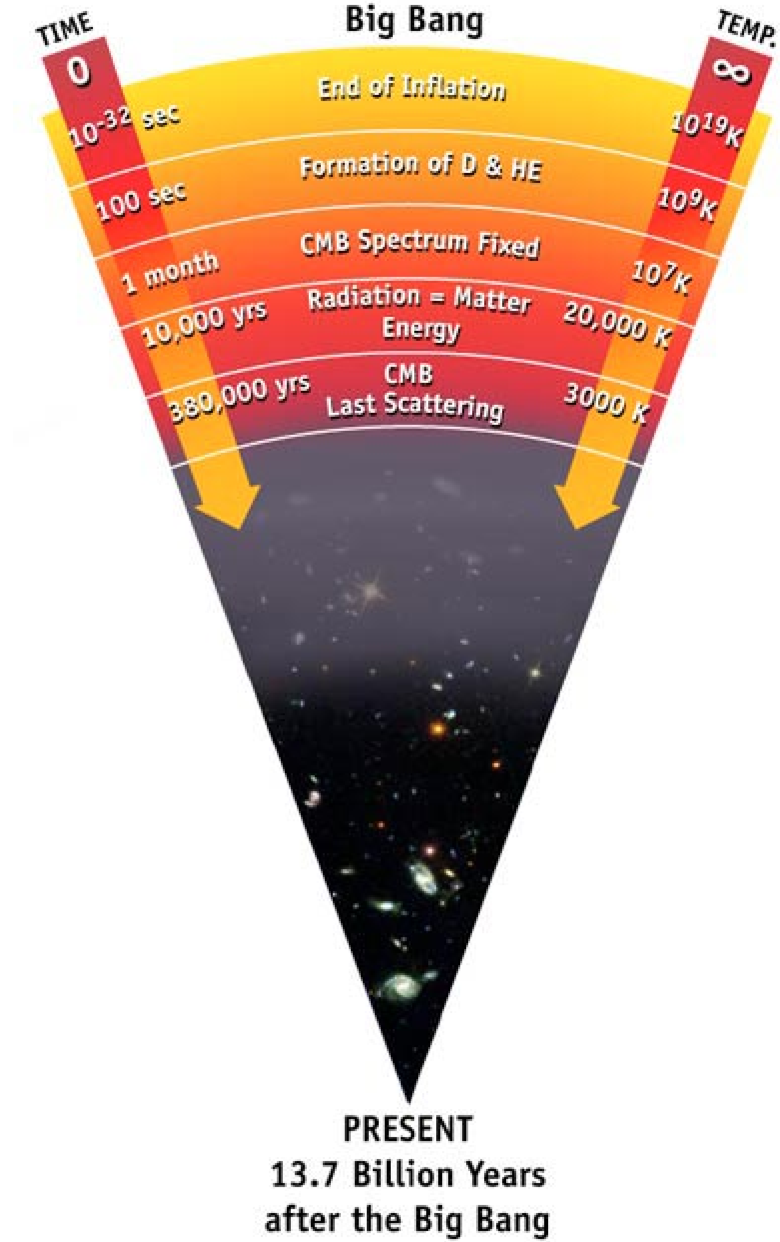
Cosmic Microwave Background



- Blackbody spectrum
- Temperature $T_{cmb} = T_{rec}/(1+z_{rec}) = 2.725$ K

Cosmic Microwave Background

- CMB photons have travelled from reionization to us – we actually see back to the surface of last scatter.
- CMB covers the whole sky. Instrument with larger field of view will measure more flux. One measures intensity = energy flux per unit solid angle
- If on Rayleigh-Jeans side of peak, can translate intensity to “brightness temperature”,
- $B_\nu = (2\nu^2/c^2)\, kT$



The cosmic microwave background Radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.

Cosmic Microwave Background

- Number density of photons in CMB
  - = energy density/average photon energy
  - = $aT^4/(2.8\,kT) = 400\ \mathrm{cm}^{-3}$

- Number density of photons in star light ~ $0.004\ \mathrm{cm}^{-3}$

- Number density of baryons
  - = $0.04\,\rho_c/m_p = 2\times10^{-7}\ \mathrm{cm}^{-3}$
  - Baryon to photon ratio ~ 5×10^{-10}

Homework

For next class: problem 9.3