When Radiation Ruled—26 Oct

- At present, radiation from the Big Bang is weak
  - \( T = 2.7 \text{ K} \)
  - Has no affect on history of universe
- In past, radiation from the Big Bang was
  - Hot enough to change matter
  - Denser than matter
- Temperature and expansion
  \( T / T_{\text{now}} = 1/a \)
  \( a = \text{Dist} / \text{Dist}_{\text{now}} \)

Rad: 0.6kg  
\( T = 0.8 \times 10^9 \text{ K} \)

Matter: 0.1mg  
\( T = 0.8 \times 10^9 \text{ K} \)

Expansion stretches wavelength of light

- We see black-body radiation with \( T=2.7 \text{ K} \), and wavelength at the peak intensity \( \lambda_{\text{max}} = 1 \text{ mm} \).
  \( \lambda_{\text{max}} = 2.7 \text{ mm-K} / T \) (Wein’s Law)
- Wavelength of radiation stretches same as universe expands.
  1. When the U was half the present size, what was the wavelength at the peak intensity and what was the temperature of the radiation? Not graded: What principle did you use?

Book-burning Universe

- At one time, the universe was hot enough to burn paper
  - Occurs at 451 F = 500 K.
  - (In reality, there was no carbon and no paper at that time.)
- Hoag’s object is 300 Mpc from the Milky Way. How far was it when the U was just hot enough to burn paper?
  
- What other reactions might have occurred when the universe was smaller & hotter?
**Book-burning Universe**

- What other reactions might have occurred when the universe was smaller & hotter?
- Events in the universe’s life
- Recombination: U changed from opaque to transparent
  - Chemical reaction
  - Free p + e $\rightarrow$ hydrogen atom
- Production of helium
  - Nuclear reaction
  - Free protons + neutrons $\rightarrow$ helium nucleus

**How mass density changes**

- Fill a 2-L bottle with an average of the present universe
- Matter
  - Mass = $2 \times 10^{-27}$ kg
  - Same mass as 1 hydrogen atom
- Radiation (Light) has mass because radiation has energy
  - $E = mc^2$
- Radiation
  - 32 M photons in the bottle
  - Mass of each photon = $1.1 \times 10^{-39}$ kg
  - Mass of light = $3.6 \times 10^{-32}$ kg
  - Same mass as 1/50,000 hydrogen atom

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**How mass density changes**

- Mass of matter = $2 \times 10^{-27}$ kg
  - Same mass as 1 hydrogen atom
- Define expansion parameter
  - $a$ = distance between two galaxies / present distance
  - The expansion parameter $a$ changes from ___ at the Big Bang to ___ at the present.

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5. (2 pts.) The matter in the 2-L bottle used to occupy a smaller volume. When universe half the present size, how much volume did the matter in the 2-L bottle fill? The mass density at that time was ___ that of the present mass density.