The cosmic microwave background radiation —18 Feb 2010

- Midterm exam
  - Key ideas. How to do better
- Cosmic microwave background radiation
  - Why is the existence of the CBR important for the history of the universe?
  - Important events
- Angular scale of fluctuations in the CBR
  - What is the physical length of the fluctuations?
    What is the density parameter of universe seen in the CBR?
    What is the age of the universe?

Midterm exam

- Statistics

Quartiles: 15.5, 18, 22.75
Top score: 33/35

- Key ideas, misconceptions
  - Q1, on finding $g^{\theta\theta}$
    a^μ is not the same as a_μ.
  - Q2a, on finding p^μ for a photon on a radial path
  - Q2b, on finding the energy measured by an observer.
  - Q3, on a clock on Earth
  - Q4,

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Penzias & Wilson, 1965, “A measurement of the excess antenna temperature at 4080Mc/s,” ApJ 142, 419.
“The excess temperature is … isotropic, unpolarized, and free from seasonal variation.”

Why is this radiation with a temperature of 3K important for the history of the universe? DPRW explained.

Dicke, Peebles, Roll, & Wilkinson, 1965, “Cosmic Black-body Radiation,” ApJ 142, 414.
“Could the universe have been filled with black-body radiation from this possible high-temperature state?

Black-body radiation

A wavelength characterizes black body radiation

$$\lambda = \frac{h\,c}{k\,T}.$$

Alternatively, Wien's Law. Peak of the spectrum in wavelength is

$$\lambda_{\text{peak}} = 2.9\,\text{mm}\,\frac{1\,K}{T}$$

Because wavelengths expand with the universe, the wavelength of the black-body radiation increases with time and the temperature decreases.

The temperature of the radiation changes as a^{-1}.

Q: Why is this significant for the history of the universe?

The mass-energy density changes

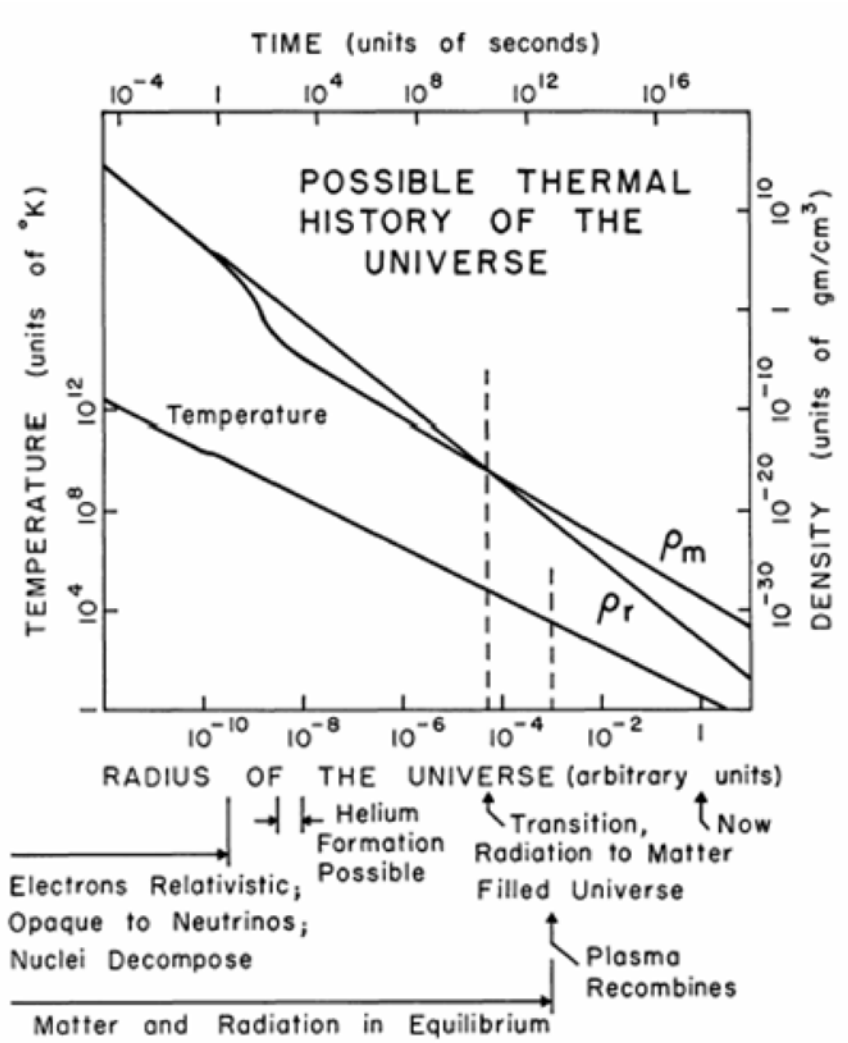
$$\rho_{\text{radiation}} \sim a^{-4}$$

whereas

$$\rho_{\text{pressureless matter}} \sim a^{-3}$$

a^{-4} always beats a^{-3} for small enough a. At early times, the radiation determines the history of the universe.

Dicke, Peebles, Roll, Wilkinson



Important events in the history of the universe

- "Recombination"
  Universe changes from ionized to neutral at T=3000K. $p + e^{-} \to H$
  - Q: What is the expansion parameter at recombination?
  - Q: The ionization energy of hydrogen is 13.6eV=13.6×11600K/eV=160,000K. Why does recombination occur at such a low temperature?
  - The cross section for scattering for free electrons is much higher than for bound electrons.
  - The universe was opaque before recombination.
    The cosmic microwave background is a snapshot of the universe at recombination at 400, 000 years.
- Helium forms. The early universe was too hot for nuclei (other than n and p) to exist.
  - At $a = 10^{-9}$, the universe became cool enough for $n + p \to {}^{2}H$. Then ${}^{4}He$ and trace amounts of ${}^{7}Li$ and ${}^{3}He$ form.

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2.7 / 11600 × 10*^9
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2.32759 × 10^6
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