Class 16 : The thermal history of the Universe

- This class
  - Evolution of radiation and matter
  - Timeline of the hot big bang
  - Particle physics in the early Universe

I : Thermal history of the Universe

- Recall from last class the following two facts:
  - If there is no source or sink of photons, the temperature is $T \propto 1/a \propto (1+z)$
  - The Universe is radiation pressure dominated until the epoch of equality, after which it becomes matter dominated.
- Thus, provided that there are no sources or sinks of photons, we can map out the full temperature evolution of the radiation…

$$T = 2.725 \left(\frac{t}{t_0}\right)^{-2/3} \mathrm{K} \qquad t > t_{\mathrm{eq}}$$

(not strictly correct – why?)

$$T = T_{\mathrm{eq}} \left(\frac{t}{t_{\mathrm{eq}}}\right)^{-1/2} \qquad t < t_{\mathrm{eq}}$$

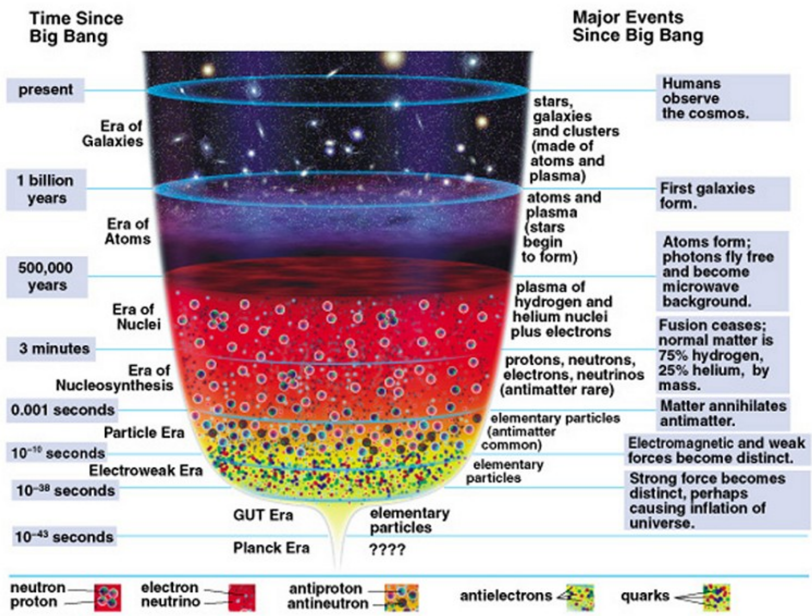
- What about matter? This has a more complex temperature evolution…
  - Before decoupling (z>1090), matter and radiation are in thermal equilibrium hence $T_{mat}=T_{rad}$
  - For a while after decouping (z=100-1000), the matter is still locked to the radiation temperature (why?)
  - Well after decoupling but before first stars form (z=20-100), we can assume that the matter is evolving adiabatically… this gives $T_{\rm mat} \propto a^{-2} \propto t^{-4/3}$
  - Once first stars and black holes form (z<20-30), the temperature of the intergalactic matter is forever affected and determined by complex astrophysical processes

II : Timeline of the hot big bang

- Going back in time, temperature increases.

$$T_{rad} = 10^{10}\left(t/1s\right)^{-1/2} K$$

- More and more energetic processes are enabled…
- Main discussion will be on the board.
  Important milestone/events in the Universe's history are:
  - t~100-200 Myrs : First stars form
  - t≈0.38 Myrs : decoupling of radiation from matter
  - t~60,000 yrs : matter-radiation equality
  - t~200s : Primordial nucleosynthesis
  - t~10^{-10}-1s : The "particle" era
  - t~10^{-35}s : Inflationary era



III : Particle physics in the early Universe

- When photons have energy comparable to rest-mass of particles, the creation/destruction of particle/anti-particle pairs becomes important.
- On board, we begin this with a discussion of electron/anti-electrons. Main findings:
  - We define a threshold temperature $T_{th}=2m_e c^2/3k_B$
  - For $T>T_{th}$, photons, electrons and positrons in thermal equilibrium

$$\gamma + \gamma \rightleftharpoons e^- + e^+$$

  - For $T<T_{th}$, electron-positron annihilation strongly preferred over production… extra energy "dumped" into photon field. Radiation temperature jumps up!