2 The hot Universe

today: no thermal equilibrium between matter & radiation

hot Big Bang picture: thermal equilibrium of photons with matter for $t < t_{dec}$ when $T > T_{dec}$, $T_{dec} \sim 4000K \simeq 0.3\,eV$ in a plasma of photons, electrons and nuclei

[ionization energy of hydrogen $= 13.6\,eV$]

2.1 Conservation laws

A system in thermal equilibrium completely determined by the values of conserved quantities.

These are energy and the values of conserved "charges" Q_i

examples: (i) electric charge Q. Actually, this is a charge which has to be exactly zero in order to have equilibrium.

(ii) baryon number B

proton p, neutron n have $B = 1$

antiproton $\bar{p}$, antineutron $\bar{n}$ have $B = -1$

pions, photons, electrons, neutrinos $B = 0$

protons and neutrons consist of quarks

all quarks (antiquarks) have $B = \frac{1}{3}$ ($B = -\frac{1}{3}$)

up quarks u have $Q = \frac{2}{3}$
down quarks d have $Q = -\frac{1}{3}$

B is conserved, e.g., in neutron decay $n \to p\, e^- \bar{\nu}_e$

no B-nonconserving process ("B violating") process has ever been observed.

p is the lightest baryon (particle with $B \neq 0$) $\Rightarrow$

B conservation implies proton stability

Standard Model of particle physics predicts B-violation.

extremely rare at $T = 0$ $\rightsquigarrow$ proton lifetime $\gg$ age of Universe

rapid when $T \gtrsim 130$ GeV

(iii) lepton number L

$e^-, \nu_e, \mu^-, \nu_\mu, \tau^-, \nu_\tau$ have $L = 1$

$e^+, \bar{\nu}_e, \mu^+, \bar{\nu}_\mu, \tau^+, \bar{\nu}_\tau$ have $L = -1$

neutrinos have mass $\rightsquigarrow$ neutrino oscillations like

at high T, neutrino oscillations can be neglected

Then L_e, L_μ, L_τ are separately conserved

Like B, L is violated at $T > 130$ GeV