

## 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  $T > T_{dec}$ ,  $T_{dec} \sim 4000K \approx 0.3 eV$  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.

There 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  $n \rightarrow p e^- \bar{\nu}_e$

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  $T=0 \rightarrow$  proton lifetime  $\gg$  age of Universe

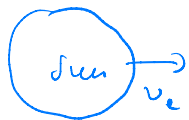
rapid when  $T \gtrsim 130 \text{ GeV}$

(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  $\rightarrow$  neutrino oscillations like



$\rightarrow \nu_\mu$  Earth

at high  $T$ , neutrino oscillations can be neglected

Then  $L_e, L_\mu, L_\tau$  are separately conserved

like  $B, L$  is violated at  $T > 130 \text{ GeV}$