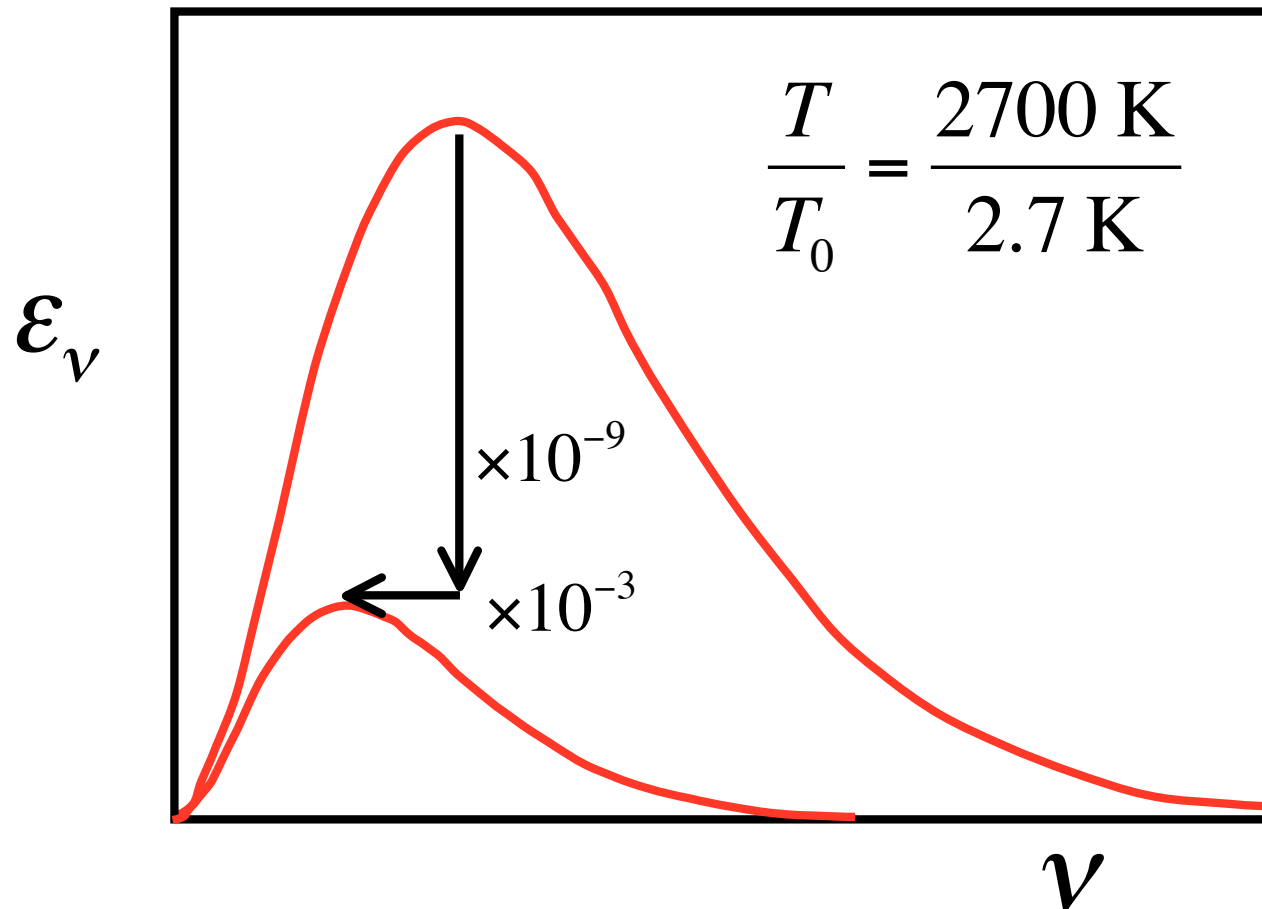


## *Lecture 2: The First Second origin of neutrons and protons*

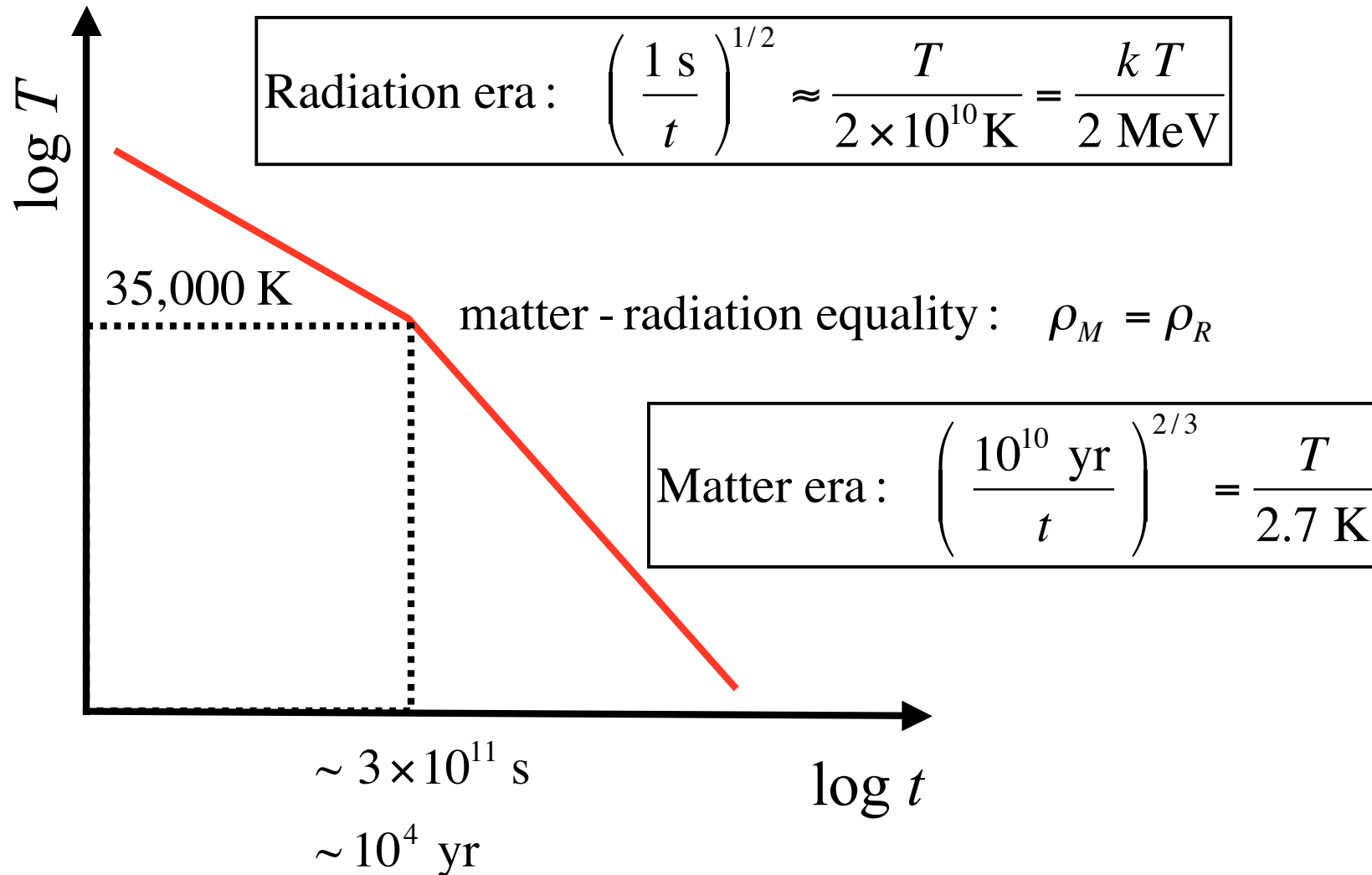
- Hot Big Bang
- Expanding and cooling
- Soup of free particles + anti-particles
- Symmetry breaking
- Soup of free quarks
- Quarks confined into neutrons and protons
- The neutron-proton ratio

*Adiabatic Expansion  
preserves the Blackbody spectrum*

$$h\nu \sim kT \propto \frac{1}{R} \quad \varepsilon \propto T^4 \propto R^{-4}$$



# Cooling History: $T(t)$



In the early Universe

(  $kT > E$  ) photons break up atomic nuclei

binding energies:

Deuterium  $\sim 2$  MeV       $T \sim 10^9$  K       $t \sim 100$  s

Iron  $\sim 7$  MeV       $T \sim 10^{10}$  K       $t \sim 1$  s

Earlier still, neutrons and protons break into quarks

mass energies (  $E=mc^2$  ):

neutron  $\sim 939.6$  MeV       $T \sim 10^{12}$  K       $t \sim 10^{-4}$  s

proton  $\sim 938.3$  MeV

This takes us back to the quark soup!

*Now run the clock forward!*

# Fundamental Particles

Early Universe:  $t < 10^{-4}$  s  $T > 10^{12}$  K

Grand Unified Theories (GUTs) predict  
all fundamental particles exist in roughly equal numbers.

**quarks**  
(6 flavours, 3 colours)

$\hat{mass}$   $\dashrightarrow$

Top ...	Bottom ...
Charm ...	Strange ...
Up ...	Down ...

*Immune to strong force*

**leptons**      **neutrinos**

$\hat{mass}$   $\dashrightarrow$

$\tau$	$\nu_{\tau}$
$\mu$	$\nu_{\mu}$
e	$\nu_e$

**gluons**  
(exchanged by quarks)

(others ?)

**bosons**

Higgs (X)
$W^{\pm}$ , $Z^0$
Photon $\gamma$

Plus antiparticles in equal numbers

Because  $kT \gg mc^2$ ,

enough energy to create particle / anti-particle pairs,  
pairs annihilate creating photons, collisions / decays create  
new particles, change one type to another.

(different forms of energy)



Expect: equal numbers of  
all particles and anti-  
particles.

net charge = 0

net colour = 0

net spin = 0

## *The Photon-Baryon ratio*

Expect:  $N_\gamma \sim N_X \sim N_{\bar{X}} \sim N_q \sim N_{\bar{q}}$

Because: over-abundant species undergo more collisions, transforming to other species, until *roughly* equal numbers.

Later, 3 quarks  $\Rightarrow$  1 baryon, expect  $N_{\text{photon}} \sim N_{\text{baryon}}$ .

But today, we observe  $N_{\text{photon}} / N_{\text{baryon}} \sim 10^9$ . Why?

## Why more particles than anti-particles ?

If equal numbers, annihilation when  $kT < mc^2$  eliminates all, leaving only photons.

Symmetry breaking:  $T \sim 10^{27}$  K  $t \sim 10^{-33}$  s.

$X$  &  $\bar{X}$  bosons decay in two possible ways:

$$X \Rightarrow a (q \bar{q}) + (1-a) (\bar{q} \bar{l})$$

$$\bar{X} \Rightarrow b (\bar{q} q) + (1-b) (q l)$$

If  $a > b$ , more quarks than anti-quarks.

From particle accelerators:  $a - b \sim 10^{-9} a$

quarks	$10^9 + 1$	$\longrightarrow$	1	quark
anti-quarks	$10^9$		$\sim 10^9$	photons

# *Quark soup*

When  $kT < mc^2$ , high-mass particles no longer created, decay to low-mass particles plus photons.

quark	U	D	S	C	T	B
$m$ (GeV)	0.35		0.53	1.8	4.5	40

X, W, Z bosons “freeze out”, decay to quarks.

Heavy quarks ( S, C, T, B ) “freeze out”, transmute into U and D.

Leaves a soup of free U and D quarks, leptons, photons, gluons and some residual heavy quarks and bosons.

## *Quark confinement -> Hadron Era*

$$t \sim 10^{-2} \text{ s} \quad T \sim 10^{13} \text{ K (1 GeV)}$$

U and D quarks confined to form colourless hadrons.

***Baryons*** ( 3 quarks ) :

UUD  $\rightarrow$  proton (938.3 MeV)

DDU  $\rightarrow$  neutron (939.6 MeV)

***Mesons*** ( quark + anti-quark )

pions: (  $U\bar{U}$ ,  $U\bar{D}$ ,  $D\bar{U}$ ,  $D\bar{D}$  )

Others, e.g. UDS, are rare.

Produced in labs but rapidly decay.

Only protons and neutrons are relatively stable.

# *Hadron Formation*

## Formation of Hadrons

Time Code Duration: (seconds: frames)  
animation = 0:00:00

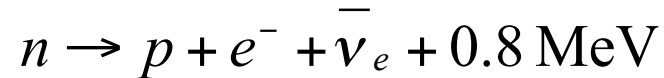
## Formation of Hadrons (detail)

Time Code Duration: (seconds: frames)  
animation = 1:00:00

# *The neutron-proton ratio*

Quark charges U:  $+2/3$  D:  $-1/3$

Neutron decay: (DDU)  $\rightarrow$  (UUD)



When  $kT \gg 0.8 \text{ MeV}$ , the reaction is reversible  
and  $N_n \sim N_p$ .

Thermal equilibrium

Maxwell-Boltzmann distribution:

$$N \propto m^{3/2} e^{(-m c^2 / kT)}$$

$$\frac{N_n}{N_p} = \left( \frac{m_n}{m_p} \right)^{3/2} e^{\left[ -\frac{(m_n - m_p) c^2}{kT} \right]}$$

At  $kT \sim 0.8$  MeV,  $n \rightarrow p + e^- + \bar{\nu}_e$  no longer reversible.

$$\frac{N_n}{N_p} = \left( \frac{939.6}{938.3} \right)^{\frac{3}{2}} e^{\left[ -\frac{(939.6-938.3)}{0.8} \right]} \cong \frac{1}{5}$$

5 protons per neutron

At  $t \sim 100$  s and  $T \sim 10^9$  K (0.1 MeV),  
protons and neutrons confined into nuclei  
→ NUCLEOSYNTHESIS

First step:      Deuterium       $p + n \rightarrow {}^2\text{D}$

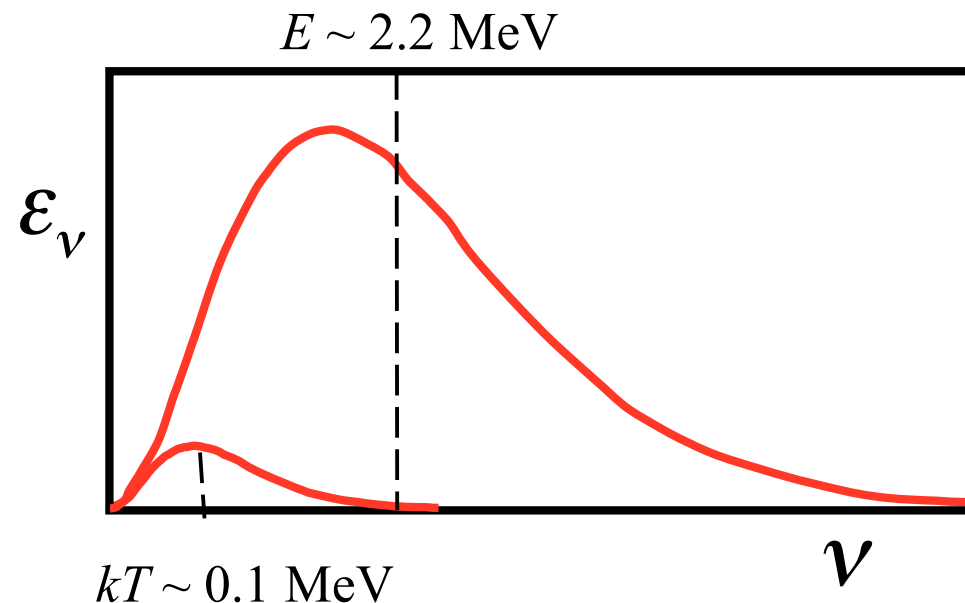
Nucleosynthesis starts at  $kT \sim 0.1$  MeV.

But,  ${}^2\text{D}$  binding energy  $E \sim 2.2$  MeV.

Shouldn't nucleosynthesis start at 2.2 MeV?

No! Because  $N_{\text{photon}} / N_{\text{baryon}} \sim 10^9$ .

Photons in the high-energy tail of the blackbody break up  ${}^2\text{D}$  until  $kT \sim 0.1$  MeV.



Photons in the blackbody tail:

$$N_\gamma(h\nu > E) = \int_{E/h}^{\infty} \frac{\epsilon_\nu d\nu}{h\nu} \approx N_\gamma \exp(-E/kT)$$

Set  $T$  to get 1 photon with  $h\nu > E = 2.2 \text{ MeV}$  per baryon:

$$N_\gamma \exp(-E/kT) \approx N_b$$

$$\frac{E}{kT} \approx \ln\left(\frac{N_\gamma}{N_b}\right) \approx \ln(10^9) \approx 20$$

With  $E = 2.2 \text{ MeV}$  need  $kT \sim 0.1 \text{ MeV}$ .

# *Neutron decay*

Free neutron decay time  $\tau \sim 940$  s

Cooling time 0.8 MeV to 0.1 MeV:  $t \sim 300$  s.

From radioactive decay:

$$N_n(t) = N_n(0) e^{-t/\tau} = 0.73 N_n(0)$$

$$N_p(t) = N_p(0) + 0.27 N_n(0)$$

$$\frac{N_p(t)}{N_n(t)} = \frac{N_p(0) + 0.27 N_n(0)}{0.73 N_n(0)} \approx \frac{5 + 0.27}{0.73} \approx 7$$

7 protons per neutron

## *Summary*

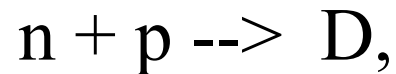
The universe expands and cools  
from a sea of particles and anti-particles ( $kT > mc^2$ ),  
to a soup of quarks

( symmetry breaking  $\rightarrow 10^9$  photons per quark)

to a soup of neutrons and protons

(quarks confined ).

At  $T \sim 0.1$  MeV, there are 7 protons per neutron,



leaving 6 protons per Deuterium nucleus.

Next time: *Nucleosynthesis*