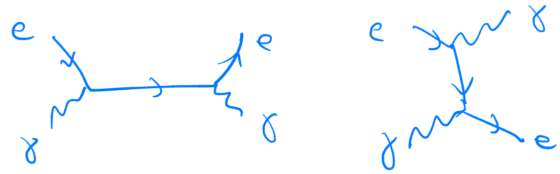
5.2 Photon decoupling

also called "photon last scattering".

$e\gamma$ scattering:



for energies $\ll m_e$ the cross section is given by the Thomson cross section

$$\sigma_T \simeq \frac{8\pi}{3}\frac{\alpha^2}{m_e^2} \simeq 6.7 \times 10^{-25}\ cm^2$$

N.B. The cross section for γp scattering is much smaller!
Thermal equilibrium is maintained by Coulomb interaction of e and p.

Boltzmann eq: $\partial_t f_\gamma = f_\gamma n_e \sigma_T$ $\Rightarrow$

mean free time of a photon

$$\tau_\gamma = \frac{1}{n_e \sigma_T}$$

At T_{rec}: $n_e = 0.67 \times 1.8 \times 10^{-11} \eta_{10} \, (0.31\,eV)^3$

$$\simeq 2.1 \times 10^{-12} (eV)^3$$

$$\sigma_T = 1.7 \times 10^{-15} (eV)^{-2}$$

$$\tau_\gamma = 2.7 \; 10^{26}\, eV^{-1}$$

$$\hbar = 6.7 \times 10^{-22}\, MeV\,s = 6.7 \times 10^{-16}\, eV\,s$$

$$\tau_\gamma = 1.8 \times 10^{11}\, s \ll H_{rec}^{-1}$$

So then the photons are still in kin. equilibrium with electrons.

Therefore photons decouple later than recombination.

Since n_e is then no longer in equilibrium, one needs to solve Boltzmann equations to determine the decoupling time.

result: $T_{dec} \simeq 0.26\, eV$ [Gorbunov Rubakov 6.2]

6 Electroweak epoch

6.1 Symmetry restoration

In the standard model of particle physics all fundamental constituents are quanta of some fields.
Historically, the first example was the quantum of the electromagnetic field.

matter (spin $1/2$) quarks, leptons

force carriers/gauge bosons (spin 1) γ, $\underbrace{W^{\pm}, Z}_{\text{weak interaction}}$, g

gluons, strong interactions

Higgs field (spin 0)

The quarks, charged leptons and weak gauge bosons get their masses from interaction with the Higgs field

Yukawa interaction for leptons

$$\mathcal{L}_{\text{Yukawa}} = - y \bar{L} \varphi e + \text{c.c.}$$

$\bar{L}$, e spin $\frac{1}{2}$ fields

For one fermion family (we have actually three)

$L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ left-handed doublet

$e = e_R$ right-handed electron

$\varphi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix}$

y: Yukawa coupling

In the vacuum the Higgs field has a non-zero constant value $\langle \varphi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$, $v \simeq 246$ GeV

This gives a mass term

$$\mathcal{L}_{mass} = -\frac{y}{\sqrt{2}} v \, \bar{e}_L e_R + c.c.$$

for the electron, while neutrinos remain massless.

This term is not invariant under the SM gauge transformations, $\bar{L} \to \bar{L} U^\dagger$, $e_R \to V e_R$ with $U \in SU(2) \times U(1)$, $V \in U(1)$. That's why it's called <u>electroweak symmetry breaking</u>.

N.B. Most of the mass of SM matter in our universe is due to binding effects of the strong interaction.

Example: the proton contains 3 quarks uud, held together by gluons

quark masses $m_u, m_d \lesssim 10$ MeV

gluons are massless

But: proton mass $m_p \simeq 930$ MeV

At $T \gg 250$ MeV the running coupling of QCD $\alpha_s(T)$ becomes small. Then quarks and gluons are no longer confined to hadrons and can be approximately viewed as weakly interacting particles, just like leptons and photons.

high temperatures

Suppose we are at temperatures T bigger than the mass of the heaviest SM particle, the top quark with

$$m_{top} \simeq 176 \text{ GeV}$$

Then the pressure is given by its massless limit plus some small correction due to the mass

$$P = g\, T^4 \begin{cases} \frac{\pi^2}{90} - \frac{m^2}{24 T^2} + \cdots & \text{bosons} \\ \frac{7}{8}\frac{\pi^2}{90} - \frac{m^2}{48 T^2} + \cdots & \text{fermions} \end{cases}$$

The m^2-correction is negative because the mass reduces the momentum of the particles for given energy, giving less pressure.

The Higgs field is a dynamical field, so that its value can change.

$$P = c_0 T^4 - c_2 T^2 |\langle\varphi\rangle|^2 + \cdots$$

with $c_0, c_2 > 0$

regions with smaller $|\langle\varphi\rangle|$ have larger pressure and are favored $\Rightarrow$

$$\langle\varphi\rangle = 0 \quad \text{at high } T$$

<u>electroweak symmetry restoration</u>

Thus all particles become massless at $T \gtrsim m_{top}$

A more precise computation shows that this happens for $T \gtrsim 130$ GeV