7 Baryogenesis [Mukhanov 4.6.2]

BBN and CMB fluctuations give

$$\eta_B = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$$

One can simply assume some non-vanishing value of n_B as initial condition.
Cosmic inflation (which we will treat soon): phase of accelerated expansion by about e^{60} which would extremely dilute any charges.
Assuming inflation, the baryon asymmetry must have been created afterwards.

7.1 Sakharov conditions (1967)

To generate an asymmetry between particles and antiparticles three cond's have to be met:

1. Baryon number violation
2. C and CP violation
3. Non-equilibrium

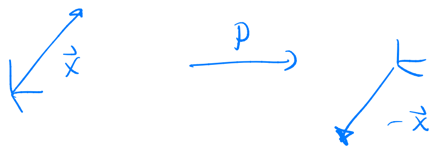
Cond. 1 is evident.

C: charge conjugation. It replaces each particle by antiparticle.

example: quantum state of an electron with momentum $\vec{p}$ and spin up $|e^- \, \vec{p} \uparrow\rangle$

$$C \, |e^- \, \vec{p} \uparrow\rangle = |e^+ \, \vec{p} \uparrow\rangle$$

P: parity point reflection



$$P \, |e^- \, \vec{p} \uparrow\rangle = |e^- \, -\vec{p} \uparrow\rangle$$

CP is the combination of C and P

$$CP \, |e^- \, \vec{p} \uparrow\rangle = |e^+ \, -\vec{p} \uparrow\rangle$$

A Universe with equal number of particles and antiparticles for each momentum direction is invariant under C and CP, while one with an asymmetry is not.

If C and CP were symmetries they would commute with the time evolution. Thus, to create an asymmetry, both C and CP have to be violated.

Third condition: In thermal equilibrium with zero charges all chemical potentials vanish. Then particles & antiparticles always have equal number densities.

In the SM of particle physics C and, much less so, CP are violated by weak interactions. However, since there is no first-order phase transition, there is no deviation from equilibrium.

7.2 Leptogenesis

To generate an asymmetry one has to extend the SM. But we already know that the SM is not correct: it predicts zero masses for neutrinos, while the experimental observation of neutrino oscillations imply nonzero differences between neutrino masses. Therefore at least two of the known neutrino species must have mass.

In the SM there are only left-handed neutrinos, while all other fermions also have right-handed (RH) partners. Their mass thus couple left- and right-handed fields like

$$\mathcal{L}_{mass} = -m\, \overline{\psi}_L \psi_R + cc$$

To get neutrino masses one can introduce also RH neutrinos ν_{R_j}, and the Yukawa interaction

$$\mathcal{L}_{int} = -y^{\nu}_{ij}\, \overline{L}_i \nu_{R_j}\, \tilde{\varphi} + cc \quad , \quad \tilde{\varphi} = \begin{pmatrix} \varphi_2^* \\ -\varphi_1^* \end{pmatrix}$$

L_i = left-handed lepton dublets

$$L_1 = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \quad L_2 = \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \quad L_3 = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$\bar{L} = L^\dagger \gamma^0$ with the Dirac matrix γ^0

When $\tilde{\varphi}$ gets a vacuum value,

$$\langle \tilde{\varphi} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$$

then neutrinos get a mass, just like the other fermions. This is called a <u>Dirac mass</u>.

[from particle physics w/o proof]:

$\bar{L}_i \tilde{\varphi}$ is gauge invariant $\Rightarrow$

The ν_{Rj} have no gauge charge. Thus they are also called <u>sterile neutrinos</u>.

Then one can also include a so-called <u>Majorana mass</u> term

$$\mathcal{L}_M = -\frac{1}{2} \overline{\nu^c_{R}}_i M_{ij} \nu_{Rj} + cc$$

where $\nu_R^c = \mathcal{C} (\bar{\Psi})^T$ charge conjugate field,

$$\mathcal{C} = -i \gamma^2 \gamma^0$$

$\mathcal{L}_M$ is not invariant under the $U(1)$ transformation

$\nu_R \to e^{i\varepsilon} \nu_R$ because then $\overline{\nu_R^c} \to e^{i\varepsilon} \overline{\nu_R^c}$

Thus the Majorana mass term violates lepton number conservation.

We have two mass terms for the neutrinos.

For $M_{ij} = 0$ we would have lepton number conservation, and neutrinos would come in particle-antiparticle pairs of equal mass, just like electrons and positrons. They would be called <u>Dirac neutrinos</u>.

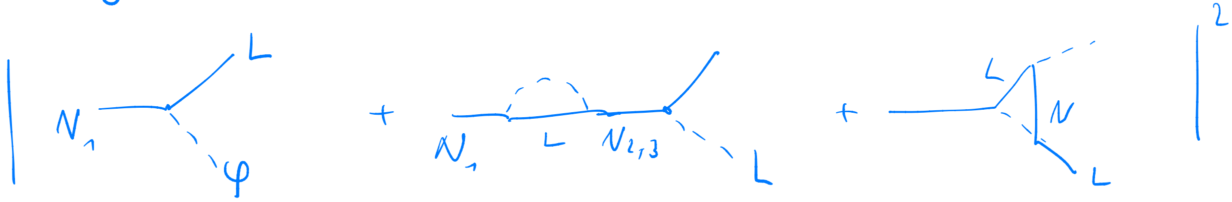
For $M_{ij} \neq 0$, lepton number is not conserved, and the masses of the neutrinos are split, and we would have two <u>Majorana neutrinos</u> ν, N with different masses.

The value of M_{ij} is unrelated to the vacuum value of the Higgs field. Therefore it could be much heavier than the other SM particles.

Let's assume that the masses M_i of the heavy neutrinos N_i are much larger than the EW scale (~ 100 GeV)

Then the N_i will decay around $T \sim M_i$.

Decay rate of the lightest ($= N_1$) determined by



The y^{ν}_{ij} can have complex phases $\Rightarrow$ decay rates into leptons and antileptons can be different.

Fig: $n_{N_1} > n^{eq}_{N_1}$ $\rightsquigarrow$ non equilibrium, more decays than inverse decays

$\rightsquigarrow$ lepton asymmetry $L \neq 0$

$\rightsquigarrow$ nonzero value of $B-L$

electroweak sphaleron redistribute $B-L$ among leptons and quarks $\rightarrow$ non-zero value of B

N.B. This way B and L are of the same order of magnitude