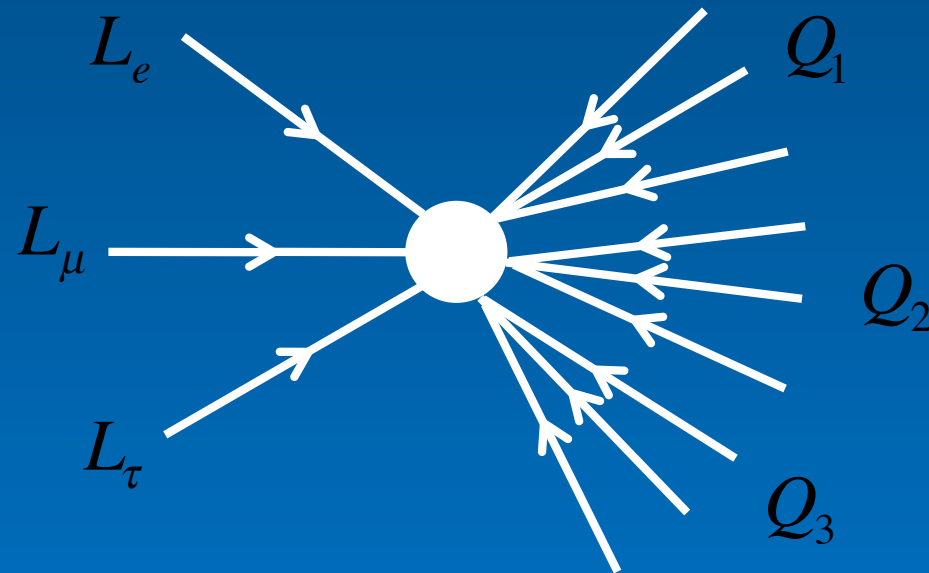


# Baryogenesis



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# Baryogenesis

- Observational evidence

Antimatter was predicted by Dirac (1928) and found (positrons) in cosmic rays by Anderson (1932). Since then we know that all particles have their antiparticles, with same mass and opposite charges (CPT invariance).

In every day's life there is more matter than antimatter by a large amount. The ratio of anti-proton-to-proton flux in cosmic rays is  $\sim 10^{-4}$  over a large range of energies. The anti-Helium-to-Helium flux is constrained to be less than  $\sim 10^{-6}$  by AMS. There is no evidence for antinuclei in the Universe.

Today we think all antimatter annihilated in the early universe with matter to produce photons.



Why is there a small remnant of matter left?

Why didn't it all annihilate into photons?

- Baryon-to-photon ratio

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 1.80 g_{*S} \frac{n_B - n_{\bar{B}}}{s} \approx \text{const.}$$

$$\text{where } s = \frac{2\pi^2}{45} g_{*S} T^3 = 7.04 \left( \frac{g_{*S}}{3.91} \right) n_\gamma$$

- Relation to present baryon content (exercise)

$$\eta_{10} = 10^{10} \eta = 273.7 \Omega_B h^2$$

$$\text{BBN (2014)} \quad \eta_{10} = 6.2 \pm 0.5$$

$$\text{Planck (2015)} \quad \eta_{10} = 6.103 \pm 0.038$$

- Origin of baryons

Even in a homogeneous baryon-symmetric universe, there would still be a few baryons and anti-baryons left since annihilation isn't perfectly efficient.

At freeze-out there is a small remnant:  
(exercise)

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-20}$$

Which is too small to account for BBN or CMB!

- Hot Big Bang Theory

In the old HBB theory, baryon asymmetry was considered as an initial condition. However, in the context of inflation this is not possible since inflation would dilute any primordial asymmetry and we would start again in a baryon-symmetric universe after reheating.

Therefore, **the baryon asymmetry of the universe must be generated after inflation.**

- Sakharov conditions for baryogenesis (1967)
  1. Baryon number violating interactions must exist
  2. C and CP violating interactions must exist
  3. The process must occur out of equilibrium

The Standard Model of particle physics has 25 fields (12 fermions, 12 gauge fields and 1 Higgs), with their masses and charges, with three gauge symmetries:  $U(1)_Y$   $SU(2)_L$   $SU(3)_C$  plus three discrete symmetries (C, P, T) and two accidental symmetries (B and L number).

We have already seen how the mass thresholds change the number of degrees of freedom that are relativistic at a given moment in the history of the universe and how that determines BBN, neutrino decoupling and CMB.

# 1. B-violating interactions

At tree level, the SM Lagrangian is invariant under Baryon number phase transformations. B-violating interactions today are extremely weak, otherwise we would have observed them, e.g. via the decay of the proton.

Current limits to the proton lifetime are from SuperKamiokande (2014)

$$\tau_p > 1.29 \times 10^{34} \text{ yrs} \quad (95\% \text{ c.l.})$$

The lowest-dimension (6) operators mediating proton decay are of the form

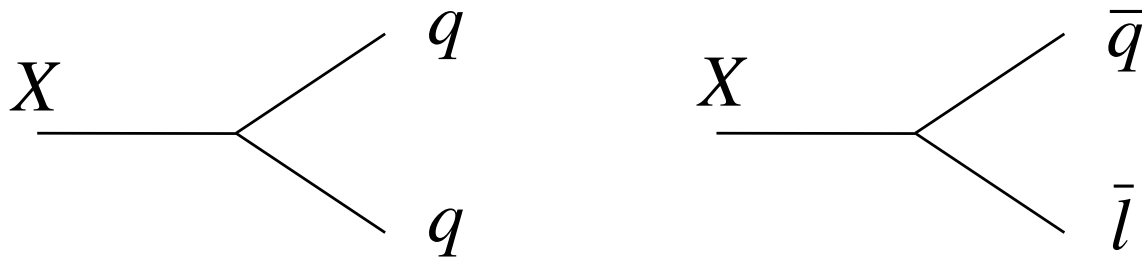
$$\frac{qqql}{\Lambda^2}, \quad \frac{d^c u^c u^c e^c}{\Lambda^2}, \quad \Delta B = \Delta L = 1; \quad \Delta(B - L) = 0$$

with typical decay process:  $p^+ \rightarrow e^+ + \pi^0 \rightarrow e^+ + 2\gamma$

$$\text{SM - EFT: } \tau_p > 1.29 \times 10^{34} \text{ yrs} \Rightarrow \Lambda > 10^{16} \text{ GeV (GUT)}$$

In GUT theories it is postulated that quarks ( $B=1/3$ ) and leptons ( $L=1$ ) are members of the same multiplet of a larger gauge group  $G=SU(5)$  or  $SO(10)$ . The breaking of  $G$  generates the difference between quarks and leptons. The gauge bosons  $X$  and  $Y$  are the mediator of GUT interactions.

B-violating GUT interactions go via operators:  $Xqq, X\bar{q}\bar{l}$



In GUT theories, the proton decay is mediated via  $X$  gauge bosons

$$\tau_p \sim \alpha_{GUT}^{-2} M_X^4 m_p^{-5} > 1.29 \times 10^{34} \text{ yrs} \Rightarrow M_X > 10^{16} \text{ GeV}$$

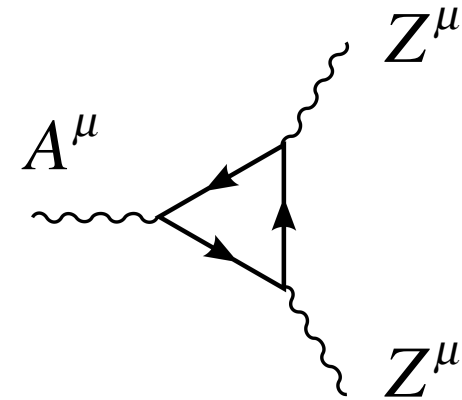
But the universe never reheated above such high energies after inflation. Present bounds (from absence of B-modes in CMB polarization) suggest that inflation reheated well below GUT energies, and thus thermal GUT baryogenesis is not viable.

# • Baryon-violation in the Standard Model

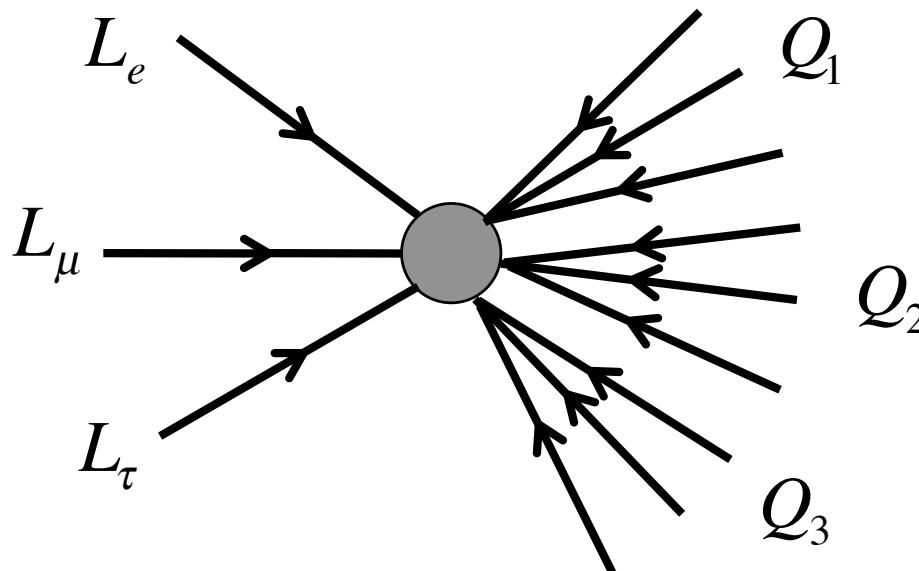
Even though B and L are accidental symmetries of the Lagrangian, at the quantum level, B+L is violated by the SU(2)-chiral anomaly, while B-L is conserved also at the quantum level.

$$\partial_\mu j_{B+L}^\mu = \frac{N_f g^2}{32\pi^2} \epsilon^{\alpha\beta\gamma\delta} F_{\alpha\beta}^a F_{\gamma\delta}^a$$

$$\partial_\mu j_{B-L}^\mu = 0$$



We can think of sphalerons as non-perturbative field configurations



$$\Delta B = \Delta L = N_f = 3$$



## 2. Out of equilibrium condition

Most of the history of the universe has occurred via adiabatic expansion, with fundamental interactions keeping particles in thermal and chemical equilibrium.

In order for baryogenesis to occur it is necessary that the B-violating interactions occur out of equilibrium, since otherwise all the produced baryons will be washed out.

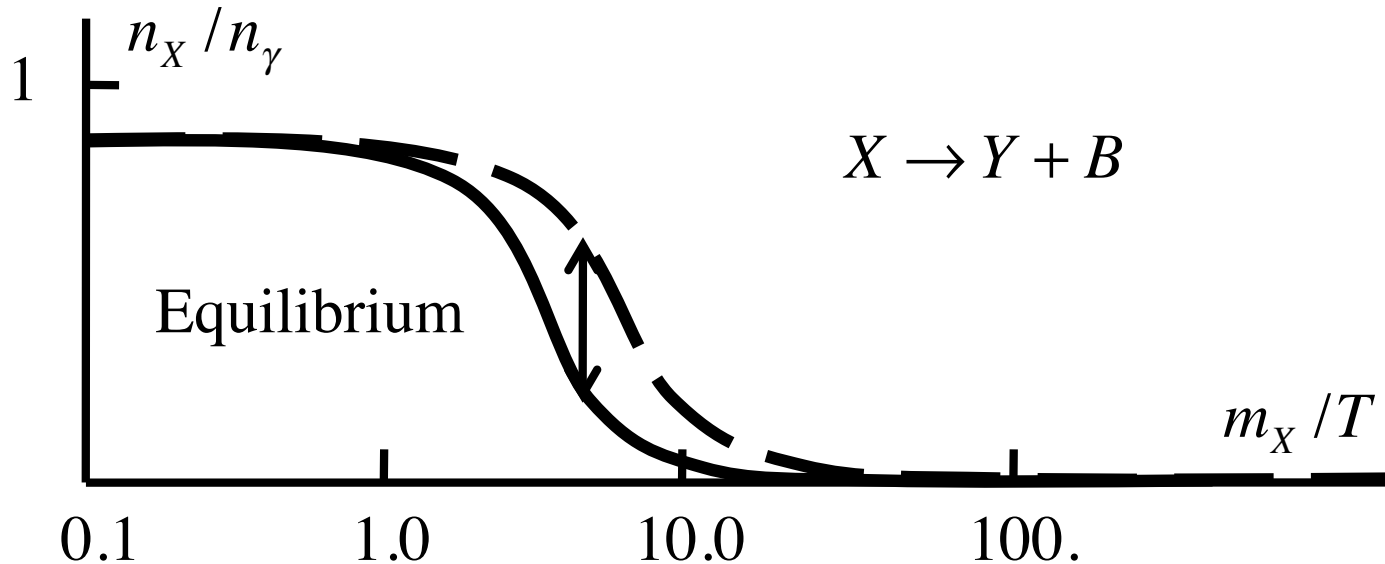
Suppose a process such as  $X \rightarrow Y + B$  with initial B=0 state decaying into a state Y also with B=0, plus a state B with non-zero baryon number. If the process occurs in thermal equilibrium, then the rate in one direction is identical to the rate in the opposite direction

$$\Gamma(X \rightarrow Y + B) = \Gamma(Y + B \rightarrow X)$$

So that no net baryon number is produced, since the inverse process destroys B as fast as the direct process generates it.

# Out of equilibrium decay of massive particles

A classic example is the decay of a massive particle  $X$  out of equilibrium, when  $m_X > T$  at the time of  $X$  decay,  $\tau \sim 1/\Gamma(X \rightarrow all)$



In this case, the energy of the final state  $Y + B$  is of order the temperature  $T$  and there is no phase space available for the inverse decay  $Y + B \rightarrow X$  since  $m_X > T$  and the rate is Boltzmann-suppressed

$$\Gamma(Y + B \rightarrow X) \sim e^{-\frac{M_X}{T}} \ll 1$$

and we thus generate an extra abundance of  $B$ .

### 3. C- and CP-violating interactions

Sakharov realized that it is not enough to have B-violating interactions out of equilibrium, one needed also C- and CP-violating interactions.

Consider the decay  $X \rightarrow Y + B$  and the (charge) C-conjugate process  $\bar{X} \rightarrow \bar{Y} + \bar{B}$ . If C is a symmetry of the Lagrangian, then the rates are the same:

$$\Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B}) = \Gamma(X \rightarrow Y + B)$$

If there are equal number of B=0 states  $X$  and C-conjugate  $\bar{X}$ , then the net baryon production grows like

$$\frac{dB}{dt} \propto \Gamma(X \rightarrow Y + B) - \Gamma(\bar{X} \rightarrow \bar{Y} + \bar{B})$$

and thus vanishes in the case of C-conserving interactions.

Sakharov also realized that one needed CP-violating interactions.

Consider the chiral decay  $X \rightarrow q_L + q_L$  and  $X \rightarrow q_R + q_R$

Under CP:  $q_L \rightarrow \bar{q}_R$

L, R keeps track of fermion in SU(2) doublet

Under C:  $q_L \rightarrow \bar{q}_L$

Even though C-violation implies  $\Gamma(X \rightarrow q_L + q_L) \neq \Gamma(\bar{X} \rightarrow \bar{q}_L + \bar{q}_L)$

CP-conservation would imply 
$$\begin{cases} \Gamma(X \rightarrow q_L + q_L) = \Gamma(\bar{X} \rightarrow \bar{q}_R + \bar{q}_R) \\ \Gamma(X \rightarrow q_R + q_R) = \Gamma(\bar{X} \rightarrow \bar{q}_L + \bar{q}_L) \end{cases}$$
 and therefore

$$\Gamma(X \rightarrow q_L + q_L) + \Gamma(X \rightarrow q_R + q_R) = \Gamma(\bar{X} \rightarrow \bar{q}_R + \bar{q}_R) + \Gamma(\bar{X} \rightarrow \bar{q}_L + \bar{q}_L)$$

Thus, as long as the initial state has equal numbers of  $X$  and  $\bar{X}$ , we end up with no net baryon asymmetry.

# Action of C, P and CP on SM fields

The Standard Model of particle physics has 12 fermions, 12 gauge fields and 1 scalar. Let us see how do they change under discrete symmetries.

## Scalars

$$C: \phi \rightarrow \phi^*$$

$$P: \phi(t, \vec{x}) \rightarrow \pm \phi(t, -\vec{x}) \quad (\text{pseudo})\text{scalar}$$

$$CP: \phi(t, \vec{x}) \rightarrow \pm \phi^*(t, -\vec{x})$$

## Fermions

$$C: \psi_L \rightarrow i\sigma_2\psi_R^*, \quad \psi_R \rightarrow -i\sigma_2\psi_L^*, \quad \psi \rightarrow i\gamma_2\psi^*$$

$$P: \psi_L \rightarrow \psi_R(t, -\vec{x}), \quad \psi_R \rightarrow \psi_L(t, -\vec{x}), \quad \psi \rightarrow \gamma^0\psi(t, -\vec{x})$$

$$CP: \psi_L \rightarrow i\sigma_2\psi_R^*(t, -\vec{x}), \quad \psi_R \rightarrow -i\sigma_2\psi_L^*(t, -\vec{x}), \quad \psi \rightarrow i\gamma^2\gamma^0\psi^*(t, -\vec{x})$$

## Vectors

$$C: A^\mu \rightarrow -A^\mu$$

$$P: A^\mu(t, \vec{x}) \rightarrow (A^0, -\vec{A})(t, -\vec{x})$$

$$CP: A^\mu(t, \vec{x}) \rightarrow (-A^0, \vec{A})(t, -\vec{x})$$

# Examples of CP-violating operators beyond SM

Generally, CP-violation exists whenever there are complex phases in the Lagrangian that cannot be removed by field redefinitions.

Scalars:

$$\begin{cases} L_{CP} = |\partial\phi|^2 - m^2 |\phi|^2 - \lambda |\phi|^4 \\ L_{CPV} = -(\mu^2 \phi^2 + g\phi^4 + \text{h.c.}) \end{cases}$$

under  $CP$ :  $L_{CPV} \rightarrow -(\mu^2 \phi^{*2} + g\phi^{*4} + \text{h.c.})$

in general complex:  $\mu^2 = |\mu|^2 e^{i\phi_\mu}$ ;  $g = |g| e^{i\phi_g}$

We can do field redefinitions to get rid of e.g. phase  $\phi_\mu$ :  $\phi \rightarrow e^{-\frac{i}{2}\phi_\mu} \phi$   
 Then, the CP-violating lagrangian becomes

$$L_{CPV} = -\left(|\mu|^2 \phi^2 + |g| e^{i(\phi_g - 2\phi_\mu)} \phi^4 + \text{h.c.}\right)$$

The only combination that violates CP (independent of field redefinitions) is

$$\phi_{inv} = \arg\left(\frac{g}{\mu^2}\right) = \phi_g - 2\phi_\mu \quad \text{such that if } \phi_{inv} = 0 \text{ CP is conserved.}$$

# B and CP violation in the Standard Model

In 1976 Gerard t'Hooft showed that the triangle (chiral) anomaly violates Baryon number through non-perturbative effects. We saw above that B+L is not conserved at the quantum level in the presence of external W-field strengths. However, this B-violation is never manifest in any perturbative process. It is associated with the vacuum structure of SU(2) with spontaneous broken symmetry.

We introduce the concept of Chern-Simons number  $N_{CS} = \int d^3x K^0$  where  $K^0$  is the zero component of a 4-current

$$K^\mu = \frac{g^2}{32\pi^2} \varepsilon^{\mu\nu\alpha\beta} \left( F_{\nu\alpha}^a A_\beta^a - \frac{g}{3} \varepsilon_{abc} A_\nu^a A_\alpha^b A_\beta^c \right)$$

Such that  $\partial_\mu K^\mu = \frac{g^2}{32\pi^2} \varepsilon^{\alpha\beta\gamma\delta} F_{\alpha\beta}^a F_{\gamma\delta}^a$

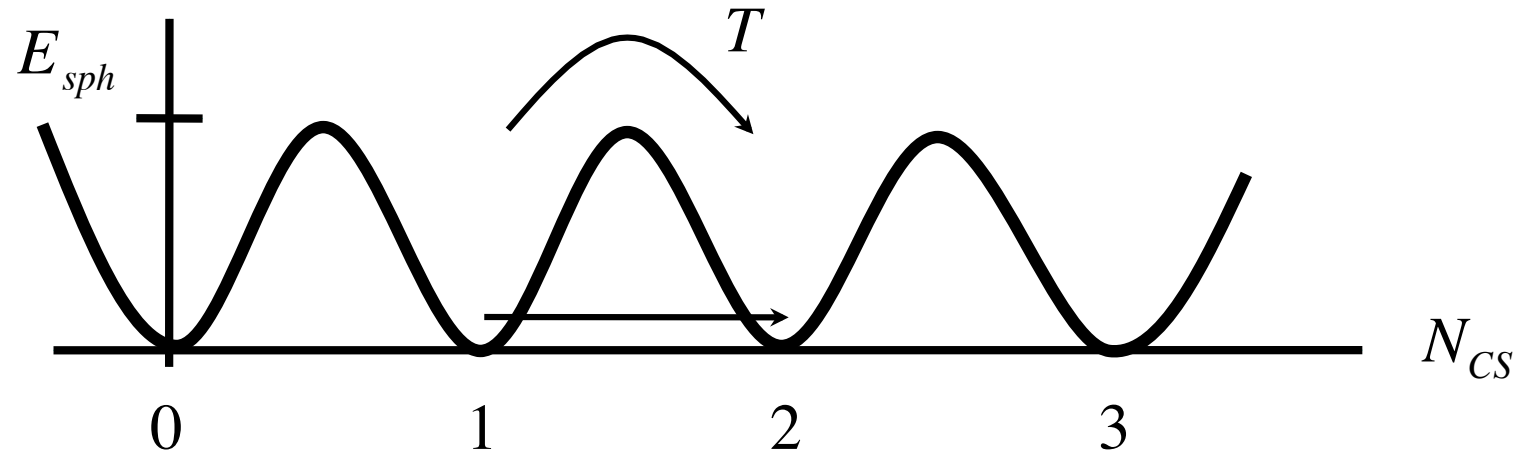
The topological nature of  $N_{CS}$  is seen between configurations that are pure gauge at some initial and final times

$$N_{CS}(t_1) - N_{CS}(t_0) = \int dt \int d^3x \partial_\mu K^\mu = n \in \mathbb{Z}$$

where n is the winding number of the mapping  $A^\mu : R^3 \rightarrow SU(2) \approx S^3$

# Vacuum structure of SU(2) gauge theory

Consider a family of static gauge field configurations with varying  $N_{CS}$ . Configurations with integer values are pure gauge everywhere ( $F_{\mu\nu} = 0$ ). To interpolate between them, one must go through configurations  $F_{\mu\nu} \neq 0$



$$E_{sph} \approx \frac{2m_W}{\alpha_w} f\left(\frac{\lambda}{g^2}\right) \sim 10 \text{ TeV} \quad \alpha_w = \frac{g^2}{4\pi} \cong \frac{1}{30}$$

Tunneling between the n-vacua occurs via instantons, with probability rate

$$\Gamma \sim e^{-4\pi/\alpha_w} \sim 10^{-160} \quad \text{so } B \text{ is a conserved quantum no. in SM}$$



## B violation and the vacuum structure of SU(2)

The relation between Baryon number and Chern-Simons is via  $\chi$ -anomaly:

$$\partial_\mu j_{B+L}^\mu = N_f \partial_\mu K^\mu \quad \text{with } N_f = 3 \text{ number fermion generations}$$

Integrating over 3-space:

$$3 \frac{d}{dt} N_{CS} = \frac{d}{dt} B = \frac{d}{dt} L$$

so that each instanton transition violates B and L:  $\Delta B = \Delta L = 3$ , which thus corresponds to a spontaneous production of 9 quarks and 3 leptons, one of each generation.

In 1985 Kuzmin, Rubakov and Shaposhnikov realized that at high temper. The transitions between vacua are not suppressed due to thermal energy available for over-the-barrier transitions.

Finite-T transitions are called “sphalerons” (ready to decay) and correspond to field configurations of Higgs and gauge fields which sit at the top of the barrier between vacua. A sphaleron is a static saddle point solution of the field equations, not an instanton.

# Sphaleron transitions at high temperatures

At temperatures below the top of the barrier one can compute the rate of sphaleron transitions per unit volume

$$\frac{\Gamma}{V} = O(1) \left( \frac{E_{sph}}{T} \right)^3 \left( \frac{m_W(T)}{T} \right)^4 T^4 e^{-\frac{E_{sph}}{T}}$$

At higher temperatures the EW symmetry is restored, the Higgs vev=0 and the barrier between vacua disappears. The sphaleron rate cannot be computed analytically – we need to use the lattice computations

$$\frac{\Gamma}{V} = (25.9 \pm 2.0) \alpha_w^5 T^4 = (1.06 \pm 0.08) 10^{-6} T^4$$

Comparing with the rate of expansion  $H = 1.66 g_*^{1/2} \frac{T^2}{M_P}$

we find that sphaleron transitions are efficient for

$$10^2 \text{ GeV} < T < 10^{13} \text{ GeV}$$

# B and L number exchange via sphaleron transitions

In chiral theories like the SM, topological transitions due to sphalerons lead to the non-conservation of total number of left-handed fermions. In the EW theory exist interactions that convert L-particles into R-particles. Hence the total fermion number is not conserved and some linear combination of baryon and lepton number ( $B + \mathbf{a} L$ ) should vanish in thermal equilibrium above the EW scale. The coefficient  $\mathbf{a}$  can be found by taking into account conservation laws (e.g. conservation of charge and hypercharge) and conditions of chemical equilibrium for all particles involved. The result is

$$a = \frac{8N_f + 4}{14N_f + 9} = \frac{28}{51} \quad \text{for } N_f = 3$$

which means that if we have an initial (B-L) value we could end up, through sphaleron transitions, with a final B value

$$B_f = \frac{8N_f + 4}{22N_f + 13} (B - L)_i = \frac{28}{79} (B - L)_i$$

On the other hand, if (B-L) is conserved and there is no production of (B+L), one cannot generate B. Furthermore, if B has been produced above the EW scale, sphalerons will wash out any primordial B asymmetry.

# Electroweak Baryogenesis

One possibility is to produce the Baryon asymmetry at the electroweak scale via a strongly first order phase transition which is sufficiently fast to keep the universe out of equilibrium and at the same time prevent the sphalerons from washing out the asymmetry.

The requirement of a strongly first order phase transition at the EW scale is now known to be impossible. The known degrees of freedom of the SM give rise to a crossover, not even a second order phase transition, and adding new degrees of freedom (like SUSY) at the EW scale (100 GeV – 1 TeV) is incompatible with present bounds from LHC at CERN.

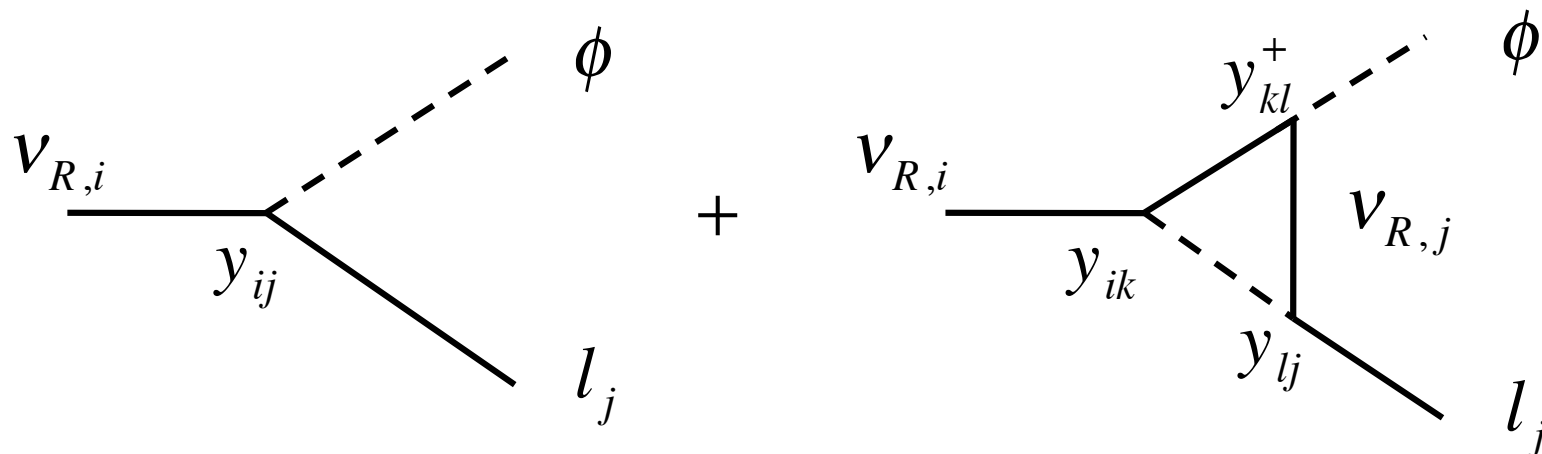
A possibility still not ruled out is to have preheating after inflation at the EW scale providing a strongly out of equilibrium environment for over the barrier quantum fluctuations giving sphaleron transitions to generate the baryon asymmetry and then reheating well below the EW scale so that no wash out occurs. The difficulty comes from the need for a sizeable CP violation which does not arise from the CKM quark matrix. Unfortunately, there is no evidence of CP violation beyond the SM in the LHC-B data.

# Baryogenesis from Leptogenesis

Another possibility is to produce a net Lepton asymmetry at high scales and use the sphalerons to convert the initial Lepton asymmetry into a Baryon asymmetry,  $B_f = -28/79 L_i$ . This solution is known as Leptogenesis and also requires physics beyond the SM. Proposed by Fukugita & Yanagida (1986).

It was assumed that the L asymmetry would appear in the neutrino sector, to preserve charge neutrality of the universe. The L asymmetry would be produced in the out of equilibrium decay of the heavy right handed neutrinos at scales close to GUT but somewhat smaller.

In this case, CP violation is produced via the interference of decay diagrams



which correspond to Lepton violating interactions with  $\Delta L = 1$

# Right-handed neutrinos (beyond the SM)

The terms beyond the SM Lagrangian responsible for Leptogenesis are

$$L_{N_R} = y_{ij} \bar{\nu}_{R,i} H l_j + h.c. \quad \text{Dirac}$$
$$- \frac{1}{2} \left( M_{ij} \bar{\nu}_{R,i}^c \nu_{R,j} + h.c. \right) \quad \text{Majorana}$$

When the Higgs gets an expectation value, the mass term becomes

$$L_{MN} = - \frac{1}{2} \left( \bar{\nu}_L \bar{\nu}_R^c \right)_i \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}_{ij} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}_j + h.c.$$

Where we have used  $\bar{\nu}_L \nu_R = \bar{\nu}_R^c \nu_L^c$  and  $(m_D)_{ij} = v y_{ij}$

Diagonalizing the mass term:

$$\rightarrow \begin{pmatrix} -m_D M^{-1} m_D^T & 0 \\ 0 & M \end{pmatrix}$$

# Right-handed neutrinos (beyond the SM)

The light neutrino states

$$V \approx V_L + V_L^c \quad \text{with mass} \quad m_\nu \approx \frac{m_D^2}{M}$$

The heavy neutrino states

$$N \approx V_R + V_R^c \quad \text{with mass} \quad m_N \approx M$$

We can estimate the masses of the right-handed neutrinos  $N$  from those of the light left-handed neutrinos

$$M \sim \frac{y^2 v^2}{m_\nu} \sim y^2 10^{14} \text{ GeV} \quad \text{where} \quad m_\nu \sim 0.05 \text{ eV}$$

Since typically  $y < 1$ , we can have  $M < T_{\text{rh}}$  after inflation.

Usually one assumes a hierarchy between the right-handed neutrinos,  $M_1 \ll M_2, M_3$ , so that  $N_1$  is the last heavy neutrino to decay out of equilibrium and generates the Lepton asymmetry. This leaves some space for model building even with low reheat temperatures after inflation.

# CP violation in the neutrino sector

To estimate the Lepton asymmetry we need a dimensionless measure of CP violation in the neutrino sector

$$\varepsilon_1 = \frac{\Gamma(N_1 \rightarrow lH) - \Gamma(N_1 \rightarrow \bar{l}\bar{H})}{\Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow \bar{l}\bar{H})} = \frac{1}{8\pi} \frac{1}{yy^+} \sum_{i=2,3} \text{Im}(yy^+)_{il}^2 f\left(\frac{M_i^2}{M_1^2}\right)$$

where  $f(x) = \sqrt{x} \left[ \frac{x-2}{x-1} + (x+1) \ln\left(1 + \frac{1}{x}\right) \right]$

It can be shown that  $\varepsilon_1 \leq \frac{3}{16\pi} \frac{M_1 m_3}{v^2}$

The final baryon asymmetry is then given by ( $m_3 \sim 0.01 m_1$ )

$$\eta = 10^{-2} \varepsilon_1 \kappa = 6 \times 10^{-10} \quad \text{for } M_1 = 3 \times 10^{13} \text{ GeV}$$

Where the efficiency factor  $\kappa$  takes into account the wash-out process

$$\kappa \cong 2 \times 10^{-2} \left( \frac{10^{-2} \text{ eV}}{\tilde{m}_1} \right) \quad \text{with } \tilde{m}_1 = \frac{(m_D^+ m_D)_{11}}{M_1}$$



# Conclusions on Baryogenesis

Baryogenesis in the early universe is required for explaining the observed baryon-to-photon ratio measured consistently in both BBN and CMB.

It requires the three Sakharov conditions (BV, CV+CPV & non-equilibrium). Most of the evolution of the universe occurs in adiabatic expansion, except at reheating after inflation. This is the natural place where baryogenesis or leptogenesis could have occurred. We are still many orders of magnitude away from the exploration of the physics of reheating, but there may be surprises via the detection of a GW background from that epoch.

EW baryogenesis seems very unlikely unless CP violation during preheating is better understood and CKM phases can be used to generate the baryon asymmetry.

The most natural scenario nowadays is baryogenesis through leptogenesis. It could occur right after inflation in the out-of-equilibrium decay of heavy right handed neutrinos. This opens the window to physics beyond the SM.