7.) BARYOGENESIS

i) Basics

ii) GUT-genesis

iii) Lepto-genesis

•) The aim of various baryogenesis scenarios is to provide a dynamical explanation for the measured value of : $\eta = \frac{n_B}{n_\gamma} \approx 6 \times 10^{-10}$.

This implies there are more baryons ~~an~~ than $\bar{B}$ = anti-baryons in the early universe. We do not observe local patches of anti-matter and the rate of anti-matter from cosmic rays is consistent with secondary production of $f\bar{f}$ pairs.

CMB, LSS & BBN require : $\Omega_b h^2 = \frac{m_p n_B}{\rho_{cr}} = 0.0223 \pm 0.0002$

precise!

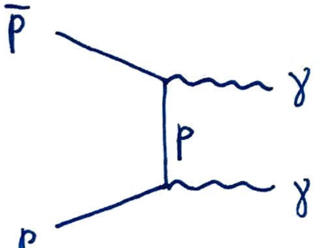
From $T_\gamma \cong 3K$, we get : $\eta = \frac{n_B}{n_\gamma} = 6.1 \times 10^{-10}$

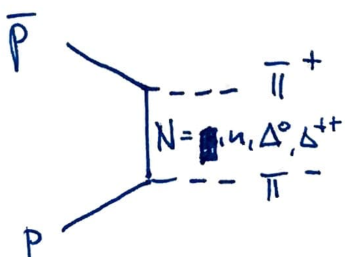
•) The aim of baryogenesis is to derive this number η, starting from a baryon-symmetric universe $B^{tot}=0$. This may be motivated by inflation, which dilutes any pre-exiting charges.

•) Note that if we start from a B-symmetric universe with $B=0$, we will have $n_B \neq 0$.

At high $T \gg$ GeV we have q, ℓ, W, but below $\Lambda_{QCD} \lesssim$ GeV, we have $p, n, \pi^{\pm}, \pi^{0}$, K's, ... and their antiparticles. Let's focus on the stable protons.

Similarly to e^+e^-, they would annihilate via





QED

$$\langle \sigma v \rangle_\gamma \sim \frac{\alpha^2}{m_p^2} \sim 10^{-4}\,\text{GeV}^{-2}$$

STRONG

$$\langle \sigma v \rangle_\pi \sim \frac{1}{m_\pi^2} \sim 10^{2}\,\text{GeV}^{-2}$$

in eq.: $\left[\frac{n_p n_{\bar{p}}}{n_p^{0\,2}} - 1 \right] = 0$

•) They both freeze-out, and give a remaining n_B

$$\Gamma = n_p^0 \langle \sigma v \rangle_\pi = \underbrace{\frac{1}{m_\pi^2}}_{\langle \sigma v \rangle_\pi} \underbrace{2 \left(\frac{m_p T}{2\pi} \right)^{3/2} e^{-m_p/T}}_{n_p^0} = H = \frac{1.7 \overbrace{\sqrt{g_*}}^{\sim 10}}{M_{Pl}} T^2$$

•) $x = \frac{m_p}{T}$, $T = \frac{m_p}{x}$

$$\frac{2}{m_\pi^2} \frac{m_p^{\cancel{3}}}{(2\pi)^{3/2}} \cdot \cancel{x^{-3/2}} e^{-x} = \frac{10}{M_{Pe}} \cancel{m_p^2} x^{-2+3/2 = -1/2}$$

$$\Rightarrow \quad x^{1/2} e^{-x} = \frac{5 m_\pi^2 (2\pi)^{3/2}}{[redacted]\, m_p M_{Pe}} = 10^{-19}.$$

$$x_f \simeq 45.7$$

$$Y_{B\infty} \cong \frac{x_f m_\pi^2}{M_{Pe} m_p} \sim \underline{\underline{90 \cdot 10^{-20}}} \sim \underline{\underline{10^{-18}}}.$$

(remember from DM freeze-out: $\lambda = \frac{m_x^3 \langle \sigma v \rangle}{H(m_x)}$

here: $\lambda_p = \frac{\cancel{m_p} M_{Pe}}{10\, m_p^{\cancel{2}} m_\pi^2}$)

•) This [redacted] gives us the abundance

$$Y_B = \frac{n_B}{s} = 10^{-18}$$

while the measured value is

$$Y_B^{obs} = \frac{\eta n_\gamma}{s} = \frac{\eta}{7.04} \cong 10^{-10}.$$

So, we're missing 8 orders of magnitude. Not to mention that we would have to "hide" the $\bar{p}$'s somewhere in the B-symmetric scenario.

•) To get to the observed value of $\eta \sim 10^{-10}$, we have to start from a baryon-asymmetric universe with $n_p > n_{\bar{p}}$, or more generally $n_B > n_{\bar{B}}$. The baryons annihilate with $\bar{B}$ until the anti-matter gets depleted and we are left with n_B only. This number density then scales as usual with a^{-3} until today.

•) How do we create a baryon-asymmetric universe? There are three general guidelines, usually called the SAKHAROV conditions.

1) <u>B violation</u> : Interactions have to violate B, otherwise if we start from $B = 0$, equilibrium would simply redistribute n_B & $n_{\bar{B}}$ to set them equal.

There are two usual examples, where B is broken.

a) Grand Unified Theories = GUTs

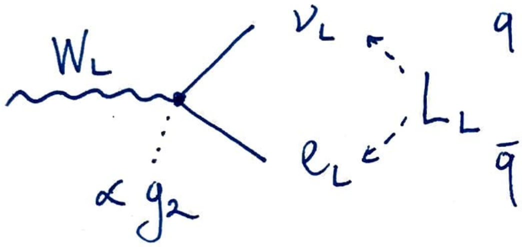
b) Sphaleron field configurations in the SM.

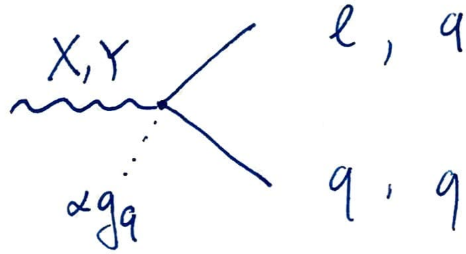
a) $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L , \; L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L , \quad \begin{matrix} u_R \\ d_R \end{matrix} , \; e_R \quad \times \overset{\overset{3}{\shortparallel}}{n_g}$$

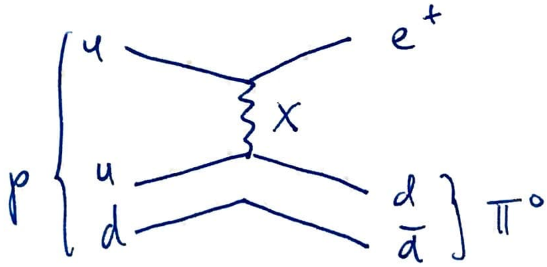
$G_{GUT} = SU(5)$ or $SO(10)$

in $SU(5)$: $$5_{\bar{F}} = \begin{pmatrix} L_L \\ \bar{d} \end{pmatrix} = \begin{pmatrix} \nu \\ e \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \end{pmatrix} \quad \& \quad 10_F = \begin{pmatrix} 0 & \bar{u} & \bar{u} & \multicolumn{2}{c}{\overbrace{\begin{pmatrix} u & d \end{pmatrix}}^{Q_L \times N_c}} \\ & 0 & \bar{u} & & \\ & & 0 & & \\ \text{Asymm.} & & & 0 & e_R \\ & & & & 0 \end{pmatrix}$$





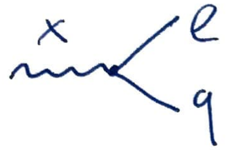
·) When we have both couplings to l, q and q, q, we cannot assign baryon number to X anymore and both B an L get broken. This leads e.g. to p-decay



$p \to \pi^0 e^+$

$$\Gamma_p \sim \frac{m_p^5}{M_X^4} g_{GUT}^4 \qquad \tau_{p\to\pi^0 e^+} \gtrsim 10^{32}\,\text{yrs} \sim 10^{39}\,\text{s}$$

$$\Rightarrow \; M_X \gtrsim (10^{15} - 10^{16})\,\text{GeV}$$

·) When $T \gtrsim M_X$, we will excite these states in the plasma  and $n_X = n_X^0$ will be in equilibrium. When T drops, X can go out of equilibrium and decay to produce η. = GUT-genesis.

b) B-violation in the SM

==== ADVANCED TOPIC, NEEDS QFT ===

The way B is broken in the SM is highly non-trivial. It doesn't happen perturbatively, so it cannot be seen by Feynman diagrams. Instead it comes by realizing

i) that vacuum states in gauge theories are non-trivial.

ii) symmetries (or conserved charges) get broken at the quantum level.

It turns out that both B and L number are conserved only classically, but get broken at a one loop level. Such symmetries are called <u>anomalous</u>.

•) Symmetries and conserved charges.

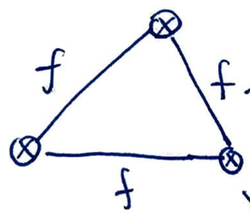
<u>QED</u> : $\frac{dQ_e}{dt} = 0$ is conserved

$\Downarrow$ QFT

$$\partial_\mu j_a^\mu = 0 \,, \quad \mu = 0 : \quad \frac{d}{dt} j_a^0 = 0$$

$$j_a^\mu = \sum Q_f \bar{f}\gamma^\mu f = -\bar{e}\gamma^\mu e + \frac{2}{3}\bar{u}\gamma^\mu u - \frac{1}{3}\bar{d}\gamma^\mu d$$

QED is not anomalous and Q is conserved at all loops (Ward-Takahashi identities). For baryon and lepton number this is not the case; they get broken @ 1 loop level through the triangle anomalous diagrams



BARYON # : $j_B^\mu = \frac{1}{3}\bar{q}\gamma^\mu q + \phi\, \bar{l}\gamma^\mu l$

LEPTON # : $j_L^\mu = 1\, \bar{l}_L\gamma^\mu l_L + 1\, \bar{\nu}_L\gamma^\mu \nu_L + \phi\, \bar{q}\gamma^\mu q$

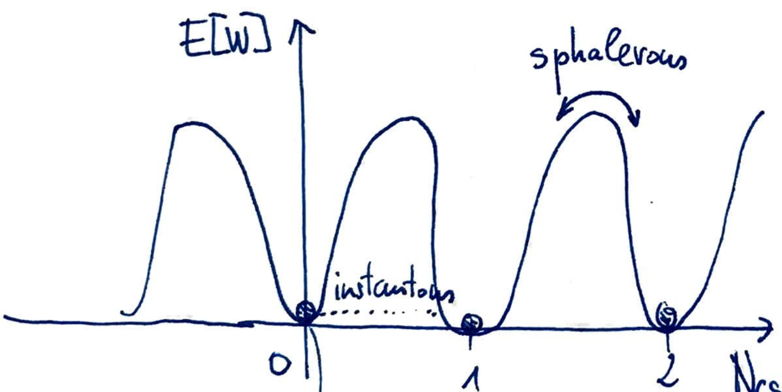
$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = \frac{n_g \alpha_2}{8\pi} W\tilde{W} \,, \quad W\tilde{W} = \frac{1}{2}\varepsilon^{\mu\nu\alpha\beta} W^a_{\mu\nu} W^a_{\alpha\beta}$$

$$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + i\varepsilon_{abc} W^b_\mu W^c_\nu$$

•) The $W\tilde{W}$ is a non-trivial ($W \neq 0$) vacuum field configuration. Note that both currents are proportional to the same $W\tilde{W}$. Therefore, the B-L current is not anomalous and remains conserved (just like Q, except it's a global symmetry). The B+L is the "broken" direction and gets broken by: $\underbrace{\partial_\mu (j^\mu_B + j^\mu_L)}$ $= \frac{n_g}{4\pi} \underbrace{W\tilde{W}}$.

Ok, we have a direct connection between B+L violation and non-trivial gauge vacuum.

The $W_{\mu\nu}^{vac}$ vacuum configurations correspond to minima of the classical energy E (in QED that would be $\frac{1}{2}(\vec{E}^2 + \vec{B}^2)$)



N_{cs} ... topological # that

$W_{\mu\nu}^{N_{cs}=0}$ $W_{\mu\nu}^{N_{cs}=1}$ ... classifies all the vacua.

On top of W^{vac}, there are configurations that interpolate between the minima and describe tunnelling between distinct vacua.

•) The tunnelling between different vacua are described by $W_{\mu\nu}^{inst.}$ at $\underline{\underline{T=0}}$, the instanton configurations, [’t Hooft] such that

$$\Delta N_{cs} = N_{cs}(t\to\infty) - N_{cs}(t\to-\infty) = \frac{\alpha_2^2}{8\pi}\int d^4x\,\tilde{W}W$$

•) Using the anomaly triangles, the change of N_{cs} is directly connected to ΔB, such that

$$\Delta B = \int_{-\infty}^{\infty} dt\; \partial_0 \int j_B^{0}\, d^3x = \underbrace{\int j^{B0} d^3x}_{B(\infty)} - \underbrace{\int j^{B0} d^3x}_{B(-\infty)} = \Delta B$$

$$= n_g \int d^4x \frac{\alpha_2^2}{8\pi} W\tilde{W} = \underset{\overset{\shortparallel}{3}}{n_g}\, \Delta N_{cs}.$$

•) This implies that the SM breaks B by $\Delta B = 3N_{cs}$, so by 3 units. The rate for such processes is given by the semi-classical approximation

$$\frac{1}{V}\Gamma_{inst.}^{\Delta B=3} \sim v^4 e^{-\frac{2\pi}{\alpha_2}\Delta N_{cs}} \sim 10^{-160}\, v^4$$

$\Downarrow$

UNOBSERVABLY SMALL

•) There are also gauge field configurations, which operate at finite temperatures, called sphalerons.

•) The sphaleron W^{sph} configurations describe the tunnelling between vacua and are given by

@ lower T :

very suppressed below $v \sim 246$ GeV

$$\gamma_{sph} \sim (\alpha_2 T)^4 \left(\frac{E_{sph}}{T}\right)^7 e^{-E_{sph}/T}, \quad E_{sph} \sim \frac{8\pi v}{g_2} \underbrace{f\left(\frac{m_h}{M_W}\right)}_{\mathcal{O}(1)}$$

@ high T :

$$\gamma_{sph} \sim 18\, \alpha_2^5\, T^4 = \text{very fast.}$$

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2) CP VIOLATION

The 2nd ingredient for a dynamical generation of baryon dominance over anti-baryons, is CP violation.

This implies that interactions of particles f are different from anti-particles. If they were equal and since $B(\bar{f}) = -B(f)$, then the total B would equilibrate to zero in equilibrium.

While CP must be broken, CPT needs to be conserved under very general assumptions.

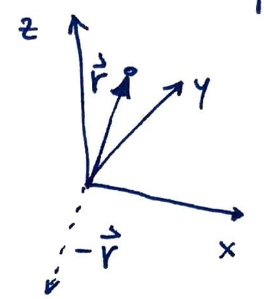
•) Quantifying ~~CP~~ and requirements on models.

CP transformations on scalars, fermions & gauge bosons

<u>SCALARS</u> $\phi(t,\vec{x}) \in \mathbb{C}$

$$P: \phi(t,x) \longrightarrow \phi(t,-x)$$
$$C: \phi(t,x) \longrightarrow \phi^*(t,x)$$

<u>Parity</u> = inversion in space



$$\vec{r} \to -\vec{r} \; ; \; x_\mu = (t,\vec{x}) \xrightarrow{P} (t,-\vec{x})$$

• <u>FERMIONS</u> $\psi(t,x) = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$

$$P: \psi \to \gamma_0 \psi(t,-x) = \begin{pmatrix} \psi_R(t,-x) \\ \psi_L(t,-x) \end{pmatrix}$$

$$C: \psi \to i\gamma_2 \psi^* = \psi^c = \begin{pmatrix} i\sigma_2 \psi_R^* \\ -i\sigma_2 \psi_L^* \end{pmatrix}$$

• <u>GAUGE BOSONS</u> $A_\mu(t,x)$ ... is also a vector

$$P: \quad A_0 \to A_0(t,-x)$$
$$\quad\;\; A_i \to -A_i(t,-x)$$

$$C: \quad A_\mu \to -A_\mu$$ (remember $j^\mu A_\mu$ is the interaction

•) With all these assignments, we can check when CP is conserved (or violated) in $\mathcal{L}$ terms.

•) In gauge interactions CP is usually conserved in the starting interaction (or gauge) basis.

Yukawa terms are in general complex matrices y_{ij}.

$$\mathcal{L}_Y = \boxed{y_{ij}}\, \bar{\Psi}_{Li}\, \phi\, \Psi_{Rj} + \underbrace{y_{ij}^*\, \bar{\Psi}_{Rj}\, \phi^+ \Psi_{Li}}_{h.c.}$$

$$\Big\Downarrow \text{CP}$$

$$y_{ij}\, \bar{\Psi}_{Rj}\, \phi^+ \Psi_{Li} + \boxed{y_{ij}^*}\, \bar{\Psi}_{Li}\, \phi\, \Psi_{Rj}$$

CP is violated when $y_{ij} \neq y_{ij}^*$.

•) This is a required, not a necessary conditions. In order to really establis $\cancel{CP}$, one has to check that coupling remain $\mathbb{C}$ even after all the phase rotations on the fields are performed.

<u>EXAMPLE</u> in the SM $\quad y_u, y_d \in \mathbb{C}_{3\times3}$

•) Rotate to the mass basis $\Rightarrow$ $M_q \in \mathbb{R}$ & diagonal

$$\left.\begin{array}{l} u_L^f \to U_L u_L^m \\ d_L^f \to D_L d_L^m \end{array}\right\} \quad V_{CKM} = U_L^+ D_L$$

contains only <u>one</u> phase.

3) Out of equilibrium

•) The out-of-equilibrium condition is somewhat obvious. If we are in full thermal & chemical equilibrium, any potential creation of $B \neq 0$ that goes in one time direction, will also take place in reverse. The reverse process will thus undo the creation of asymmetry and set it back to zero. Another way of stating the same is note that $\langle \sigma \rangle$ will always be time independent, $\frac{d}{dt}\langle B \rangle = 0$ as well. More pictorially, there is no time arrow in full equilibrium.

•) There are different ways to go out-of-eq. One is provided by the expansion of the universe, the $H(T)$. Another option is to have a cosmological phase transition of a 1^{st} order. This completely changes the vacuum, eq. ground states of scalar fields.

Such 1st order transitions are irreversible and thus out of equilibrium.

CHEMICAL POTENTIALS

- note that $\mu_{\bar f} = -\mu_f$, which implies that

$$n_f - n_{\bar f} = g \int_p \frac{1}{e^{(E-\mu_f)/T}+1} - \frac{1}{e^{(E+\mu_f)/T}+1}$$

$$\simeq g \begin{cases} \frac{T^2}{6}\mu_f & , T \gg m \\ 2\,\mathrm{sh}\left(\frac{\mu_f}{T}\right)\left(\frac{mT}{2\pi}\right)e^{-m/T} & , T \ll m \end{cases}$$

$$\wr \quad \frac{\mu_f}{T} \text{ for } \mu_f \ll T.$$

- in any case, μ measures the difference of number densities in particles vs. antiparticles: $\mu_f > 0$ = ASYMMETRY

- In full equilibrium : $\sum_i \mu_i = \text{const.}$

With sphalerons active: $\sum_i (\mu_{Bi} + \mu_{Li}) = \sum_i (3\mu_{qi} + \mu_{ei}) = \underline{\underline{0}}.$

In equilibrium : $\gamma_{sph} \sim \alpha_2^5 T^4 \Rightarrow \Gamma_{sph} \sim \alpha_2^5 T = H \sim \frac{T^2}{M_{Pe}}$

$$\gamma_{sph} = \frac{\Gamma}{V \propto T^3}$$

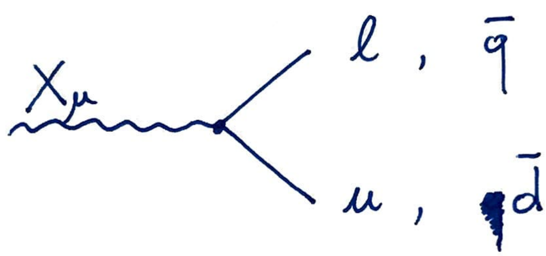
$$\Rightarrow \; T^{\mathrm{IN}}_{\mathrm{sph}} = \alpha_2^5 M_{\mathrm{Pl}} \sim 10^{-8} M_{\mathrm{Pl}} \sim 10^{11}\,\mathrm{GeV}$$

out of eq. happens very sharply due to $e^{-v/T}$

$$T^{\mathrm{OUT}}_{\mathrm{sph}} \cong 133\,\mathrm{GeV}.$$

Between these two T's : $\sum_{i=1}^{3} (3\mu_{qi} + \mu_{ei}) = 0$.

- GOT - genesis $\qquad X_\mu (3, 2, -5/6)$ with respect to $SU(3)_c \times SU(2)_L \times U(1)_Y$



We need : $\Gamma(X \to \ell u) \neq \Gamma(\bar{X} \to \bar{\ell}\bar{u})$

- $$\underbrace{\varepsilon}_{\text{asymmetry parameter}} = \frac{\frac{1}{3}\left(\Gamma_{X\to \ell u} - \Gamma_{\bar{X}\to\bar{\ell}\bar{u}}\right) - \frac{2}{3}\left(\Gamma_{X\to\bar{q}\bar{d}} - \Gamma_{\bar{X}\to q d}\right)}{\Gamma_X^{tot}}$$

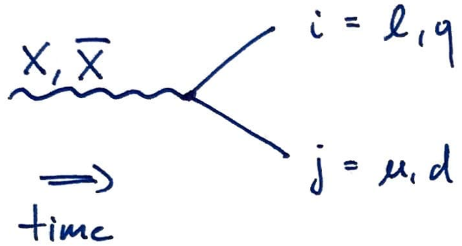
$\rightsquigarrow$ by CPT : $\Gamma_X^{tot} = \Gamma_{\bar{X}}^{tot}$

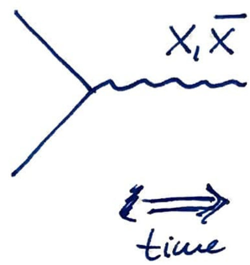
from a microscopic theory

-) Moving on to the Boltzmann equation for the baryon asymmetry.

•) Baryon asymmetry Boltzmann equation:

$$a^{-3}\frac{d}{dt}\left(a^3 n_B\right) = \underbrace{(n_X + n_{\bar X})\Gamma_X \varepsilon}_{\substack{\text{production of baryon}\\ \text{asymmetry by } X, \bar X \text{ decays}}} - \underbrace{\sum_{i,j} n_i n_j \langle \sigma v \rangle_{ij\to X\bar X} Br_{X\to ij}}_{\substack{\text{inverse decays, fusing}\\ \text{of } i \,\&\, j \text{ into } X, \bar X}}$$





CREATION WASH-OUT

•) When T drops below M_X, the $\langle E \rangle \sim T$ of $i \,\&\, j$ particles is not sufficient to wash out the asymmetry. In this case, the wash-out can be neglected and out-of-equilibrium is achieved.

•) for $T \gtrsim M_X$ we can estimate $n_X^0 \sim \overbrace{g\frac{\zeta(3)}{\pi^2}T^3}^{n_X^0} e^{-\Gamma_X t}$.

$$Y_B = \frac{n_B}{s} \Rightarrow \frac{dY_B}{dt} \simeq 2 Y_X^0 e^{-\Gamma_X t}\,\Gamma_X \varepsilon - \overset{\simeq 0}{\text{washout}}$$

$$Y_B\Big|_{t\to\infty} - \underset{0}{\underset{\shortparallel}{Y_B\Big|_{t\to 0}}} = 2 Y_X^0 e^{-\Gamma_X t}\Big|_0^\infty \frac{\cancel{\Gamma_X}\varepsilon}{-\cancel{\Gamma_X}}$$

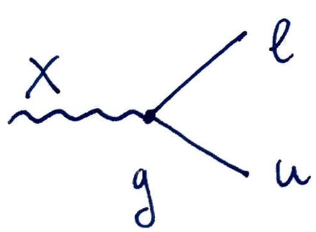
We finally arrived at

$$Y_{B\infty} = 2 Y_X^0 \varepsilon .$$

•) That's it for the (naive) Boltzmann estimate. In practice one solves the entire set of interactions, including $ij \to X$ inverse decays, as well as other scattering $ij \leftrightarrow kl$ terms.

In principle this is enough for the heuristic understanding. But to make a precise connection to the microscopic model parameters, one has to consider how ε comes about.

TREE LEVEL DECAYS

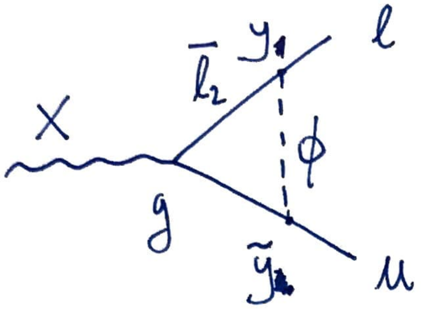


$$\mathcal{A}_{X \to lu} \propto g \;, \quad \Gamma_{X \to lu} \propto |g|^2 \quad \Big\} \text{ NO ASYMMETRY}$$

$$\mathcal{A}_{\bar{X} \to \bar{l}\bar{u}} \propto g^* \;, \quad \Gamma_{\bar{X} \to \bar{l}\bar{u}} \propto |g|^2$$

•) No asymmetry gets created at tree level. The same is true for $X \to \bar{q}\bar{d}$ and $\bar{X} \to qd$.

LOOP CORRECTIONS, STRONG and WEAK CP phases



STRONG CP phases

$$\mathcal{A}_{X\to e\mu} = g_1 + g_2^* g^* \tilde{y}^* (A+iB)$$

$$\mathcal{A}_{\bar{X}\to \bar{e}\bar{\mu}} = g_1^* + \underbrace{g_2 g \tilde{y}}_{\text{WEAK CP phases}} (\underbrace{A+iB}_{F})$$

·) Weak phases change signs upon conjugation

$$g_i, y_i \xrightarrow{CP} g_i^*, y_i^*$$

·) Strong phases remain the same. In this case they come about because of light particles running in the loop. When $m_{loop} \ll M_X$, these can be on-shell and the OPTICAL theorem states that there must be an imaginary part of the loop ~~amplitude~~ function $\text{Im}\, F \neq 0$. In fact it has to be equal to the forward scattering σ. The point is that this effect is kinematical & therefore the same for X and $\bar{X}$. $\Rightarrow$ STRONG CP phase.

•) The final result is then $\varepsilon = \frac{2B}{|g_1|^2} \operatorname{Im}(g_1 g_2^* y^* \tilde{y}^*)$

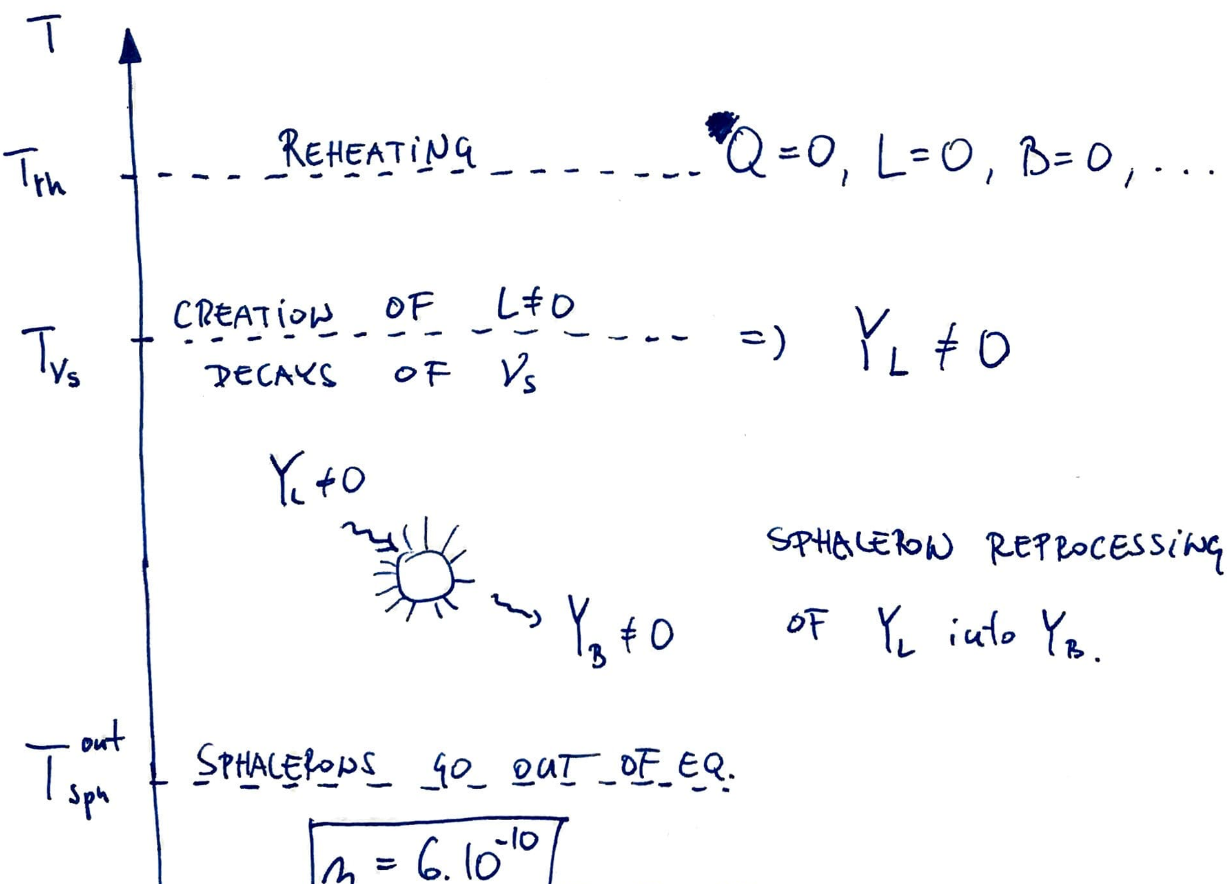
and $$\eta \cong 7\, Y_{B\infty} \sim \underline{\underline{14\, \varepsilon\, Y_X^0}}.$$

LEPTOGENESIS

•) The basic idea: $m_\nu \neq 0 \iff \eta \neq 0$

In 2 steps. 1) Create $L \neq 0$ from ν_s decays.

2) Reprocess $L \to B \neq 0$ via sphalerons.



•) We saw how the introduction of ν_s provides the masses to ν_L via the see-saw mechanism.

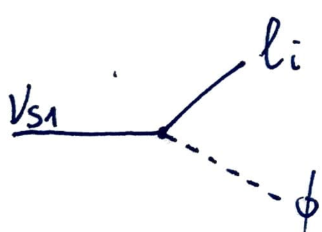
$$\mathcal{L}_{\nu_s} \ni \underbrace{y_{ij}}_{} \, \bar{L}_i \phi \, \nu_{s_j} + \underbrace{M_{s_{ij}}}_{} \, \nu_{si}^T \nu_{s_j}$$

Dirac Yukawa couples ν_s to the SM $\Rightarrow$ ν_s^0 in EQ.

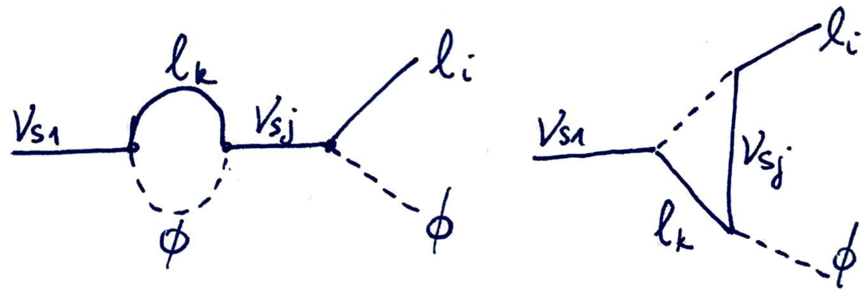
Majorana mass matrix breaks lepton number $\nu_s \to e^{i\alpha}\nu_s$.

•) ν_s is a Majorana fermion and decays 50%-50% into l^+ and l^- : $\nu_s \longrightarrow l^\pm \phi^\mp$

Let's focus on ν_{s1}, the lightest sterile neutrino



$\propto y_{1i}$



TREE LEVEL

LOOP LEVEL, with STRONG phases from loop

$$\mathcal{A}_{\nu_s \to l\phi} \sim c_0 + c_1 F$$

$$\mathcal{A}_{\nu_s \to \bar{l}\bar{\phi}} \sim c_0^* + c_1^* F$$

•) We get the lepton number asymmetry parameter

LNV : $\varepsilon_L = \dfrac{\mathrm{Im}\left(y_{ik}^{*} \, (y^{\dagger} y^{*})_{kj} \, y_{ij} \right)}{8\pi \quad (y^{\dagger} y)_{11}} \underbrace{g\left(\left(\frac{M_j}{M_i} \right)^2 \right)}$

lepton number violation

this is the loop function that gives the strong CP phase $g = \sqrt{x} \left(\frac{2}{x-1} + \ln \left(1 - \frac{1}{x} \right) \right)$

•) Following the same steps in the Boltzmann equations as we did for the decay of X, we get:

$$Y_{B-L} \cong - \varepsilon_L \, Y^{0}_{\nu_{s1}} \qquad (\text{we have } Y_B = 0)$$

•) This is naive, one also has to worry about the inverse decays washout, scatterings, flavour effects and coupled Boltzmann equations.

•) The main point is, we got $Y_{BL} \neq 0$ at $T \gg T_{sph}^{in}$.

This asymmetry yield will be redistributed from B-L into B and L by sphalerons, as we will derive now.

A note on chemical potentials : Sphaleron redistribution

•) SM @ $T \gg v$ in equilibrium

$$\underbrace{Q, u, d, L, e}_{\times 3 \text{ generations}}, \phi$$ ... Higgs

$$n_i - \bar{n}_i = g \mu_i \frac{T^2}{6} \begin{cases} 1 & , \text{fermions} \\ \times 2 & , \text{bosons} \end{cases}$$

•) For gauge bosons : $\mu_Y = \mu_W = \mu_g = 0$ but $\mu_\phi \neq 0$.

$\sim\!\!<^{u_L, \nu_L}_{d_L, e_L}$ $\mu_{u_L} = \mu_{d_L} = \mu_Q$, $\mu_{e_L} = \mu_{\nu_L} = \mu_{\ell_L}$

all generations thermalized together : $\mu_{Q_i} = \mu_Q$

$\mu_{\ell_{L_i}} = \mu_{\ell_L}$

•) Yukawa terms : $\mathcal{L}_Y = y_u \bar{Q} \phi u + y_d \bar{Q} \tilde{\phi} d + y_e \bar{L} \tilde{\phi} e$

$\Rightarrow$ $\mu_Q + \mu_\phi = \mu_u$, $\mu_Q - \mu_\phi = \mu_d$, $\mu_{\ell_L} - \mu_\phi = \mu_e$

•) Hypercharge neutrality

$$\left(6 \tfrac{1}{6} \mu_Q + 3 \tfrac{2}{3} \mu_u + 3 \left(-\tfrac{1}{3}\right) \mu_d + 2 \left(-\tfrac{1}{2}\right) \mu_{\ell_L} - \mu_e \right) \overset{3}{\overset{\shortparallel}{n_g}} + 2 \cdot 2 \tfrac{1}{2} \mu_\phi \underset{=0}{}$$

•) Plugging $\mu_{u,d,e}$ from Yukawa equilibration into Y

$$3\times\left(\mu_Q + 2(\mu_Q+\mu_\phi) - (\mu_Q-\mu_\phi) - \mu_{\ell_L} - (\mu_{\ell_L}-\mu_\phi)\right) + 2\mu_\phi = 0$$

•) The sphaleron rate equilibrates 3 q_L's and one ℓ_L per generation.

$$\hookrightarrow\ 3\mu_q + \mu_{\ell_L} = 0 \Rightarrow \mu_Q = -\frac{1}{3}\mu_{\ell_L}$$

Solving for $\mu_\phi = \frac{4}{7}\mu_{\ell_L}$

Finally we have the chemical potentials for the total Baryon μ_B and Lepton μ_L number.

$$\mu_L = n_g(2\mu_{\ell_L} + \mu_e) = 3(2\mu_{\ell_L} + \mu_{\ell_L} - \mu_\phi)$$

$$= \frac{51}{7}\mu_{\ell_L}$$

$$\mu_B = n_g(2\mu_Q + \mu_u + \mu_d) = -4\mu_{\ell_L}$$

$$\Rightarrow\quad \mu_B = C_s(\mu_B - \mu_L),\quad \mu_L = (C_s - 1)(\mu_B - \mu_L)$$

$$C_s = \frac{8n_g + 4}{22n_g + 13} = \frac{28}{79}\ \text{for } n_g = 3$$

•) SM interactions conserve B-L interactions (like Q_e), therefore $\mu_B - \mu_L = $ const.

•) However, if we only have Y_L initially, then

$$Y_B = -c_s Y_L^{in} = -\frac{28}{79} Y_L^{in}$$

$$\eta \cong 7 Y_B \sim 7 \frac{28}{79} \varepsilon_L Y^0_{\nu_{S1}}.$$

What does this imply for the mass of ν_S?

$$m_\nu \sim \frac{m_D^2}{m_{\nu S}} \sim \frac{(y v)^2}{m_{\nu S}} \Rightarrow y \sim \frac{\sqrt{m_\nu m_{\nu S}}}{v}$$

$$\varepsilon_1 \lesssim \frac{3}{16\pi} \frac{m_{\nu S1}}{v^2} \Delta m_\nu$$

$$\Downarrow$$

$m_{\nu_{S1}} \lesssim 10^8$ GeV = very high scales, beyond the reach of LHC.

SUMMARY

•) Baryogenesis is a cosmological process of dynamical generation of matter over anti-matter. It takes place at high T in the early universe and requires the interactions in the plasma to:

i) violate B, [GUT models, SM sphalerons]

ii) violate CP, [weak & strong CP phases]

iii) go out of equilibrium. [Hubble, phase trans.]

<u>GUT Baryogenesis</u> is the creation of η through late decays of $X \to \ell q, qq$ gauge bosons. The resulting η is connected to the complex CP parameters of GUT models. Moreover, the presence of strong CP phases requires an interference between tree-level and one loop diagrams.

Leptogenesis relates the η parameter to the existence of massive sterile neutrinos ν_s, which provide mass to light SM ν_L.

The out-of equilibrium decays of ν_s create a lepton number (or better B-L) asymmetry. This then gets reprocessed by spholerons from the initial Y_L into Y_B giving $\eta \sim 10^{-10}$. For generic $\mathcal{O}(1)$ phases this happens only for very heavy sterile neutrinos with $m_{\nu_{s1}} \gtrsim 10^8$ GeV.