II LEPTOGENESIS IN TYPE-I SEESAW: BASIC PICTURE

$h = 0.67$

PLANCK data: $\Omega_B h^2 = 0.0224 \pm 0.0001$ ← impressive

BBN : $0.019 < \Omega_B h^2 < 0.024$ ↙ agreement from physics at 2 completely ≠ early universe epochs!

↳ <=> $\left.\frac{n_B}{n_\gamma}\right|_{today} \sim 6 \cdot 10^{-10}$

$\left.\frac{n_B}{s}\right|_{today} \sim 9 \cdot 10^{-11}$

↳ this value of Ω_B is:

- large : if $n_b = n_{\bar{b}}$ => annihilat° catastrophy at $T \lesssim m_p$ ($p\bar{p} \to \pi\pi$, $\gamma\gamma$, ...) very efficient: $\frac{n_b}{n_\gamma} = \frac{n_{\bar{b}}}{n_\gamma} \sim 10^{-18} \gg 10^{-10}$
- small : at $T \gg m_p$: $n_q \sim n_{\bar{q}} \sim n_\gamma$ ($q\bar{q} \Leftrightarrow \gamma\gamma \dots$) => if during annih. catastrophy B number is conserved (as expected): $\left.\frac{n_q - n_{\bar{q}}}{n_q}\right|_{T \gg m_p} \sim \left.\frac{n_q - n_{\bar{q}}}{n_\gamma}\right|_{T \gg m_p} \sim \left.\frac{n_q - n_{\bar{q}}}{n_\gamma}\right|_{T \ll m_p} \sim 10^{-10}$

  ↳ need to create a very small asym. at $T > m_p$ (N.B: at end of inflation (before reheating) one expects $n_q = n_{\bar{q}} = 0$).

=> Leptogenesis motivation:

- baryogenesis requires BSM physics
- leptogenesis provides a straigthforward explamation for baryogenesis from same BSM physics as the one one invokes to account for ν masses ...

A] TYPE-I SEESAW LEPTOGENESIS: THE 3 BASIC INGREDIENTS

1) The CP-asymmetry:

type-I seesaw: $\mathcal{L} \ni -(Y_{\nu ij}\, \overline{N_{Ri}}\, \tilde{H}^{\dagger} L_{\alpha} + h.c.)$
$\qquad\qquad\qquad -\frac{1}{2}(m_{N_i}\, \overline{N^c_{Ri}}\, N_{Ri} + h.c.)$

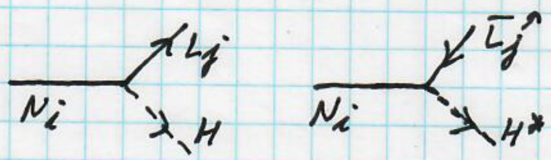
early universe thermal bath:

- at $T \gg m_{N_i}$: N_{Ri} in thermal equilibrium

$$n_{N_i}(T) = \underbrace{g_{N_i}}_{2} \cdot \frac{3}{4}\frac{\zeta(3)}{\pi^2}T^3 \sim n_\gamma = \underbrace{g_\gamma}_{2}\frac{\zeta(3)}{\pi^2}T^3$$

↳ thermalization from Y_ν interact°s or other interact°s

- at $T \leq m_{N_i}$: N_i disappears by decaying:



↳ we work in physical N_i state basis: $N_i = N_{Ri} + N^c_{Ri}$

⇒ the averaged ΔL produced each time a N_i decays:

$$\varepsilon_{N_i} = \frac{\Gamma(N_i \to L_j H) - \Gamma(N_i \to \bar{L}_j H^*)}{\Gamma^{TOT}_{N_i}}$$

↳ "CP asymmetry":

1st Sakharov cond. → - requires L violation: $N_{Ri} \xrightarrow{m_{N_i}} N^c_{Ri}$: $\Delta L = 2$

- " CP " : if not: $\Gamma(i \to f) = \Gamma(i_{CP} \to f_{CP})$
$\qquad N_i \to L_j H \qquad N_i \to \bar{L}_j H^*$

2nd Sakharov cond.

- " C " : if not $\Gamma(i \to f) = \Gamma(i_C \to f_C)$
↳ V-A structure of Y_ν: no R doublet

$\Rightarrow$ expectation: $$\frac{n_L}{s} = \underbrace{\varepsilon_{N_i}}_{\Delta L} \Big(\underbrace{\frac{n_{N_i}}{s}}_{\#\text{ of decays.}}\Big)\Big|_{\text{before decay } (T \gg m_{N_i})} \quad (*)$$

$\uparrow$

after the N_i decays

↳ $n_L = n_\ell - n_{\bar{\ell}}$ number density

$n_{N_i} = N_i$ number density

s = entropy density $= \frac{2\pi^2}{45} g_{*s} T^3$

↳ $g_{*s} = \sum_{i=\text{bos}} g_i \left(\frac{T_i}{T}\right)^3 + \sum_{i=\text{ferm}} g_i \cdot \frac{7}{8}\left(\frac{T_i}{T}\right)^3$

↳ comoving quantity: $\propto 1/\text{Volume}$

2) The efficiency factor: $(*)$ true only if N_i decays occur perfectly out-of-equilibrium.

3rd Sakharov condition

↳ if not: $$\frac{n_L}{s} = \eta_i \, \varepsilon_{N_i} \left(\frac{n_{N_i}}{s}\right)\Big|_{T \gg m_{N_i}} \quad (**)$$

$\uparrow$

efficiency suppression factor: $\eta_i \leq 1$

3) The L asym. to B asym. sphaleron conversion factor:

↳ breaks B+L but not B−L

↳ are in thermal equilib. for $T \gtrsim 150$ GeV

$$\Rightarrow \frac{n_B}{s} = \underbrace{\frac{n_L}{s}\Big|_{\text{init}}}_{=(**)} \cdot \frac{28}{79} \quad \Rightarrow \text{baryogenesis!}$$

↳ $\Rightarrow$ if $\eta_i \sim 1$ one needs $\varepsilon_{N_i} \sim 10^{-7}$ to get $\frac{n_B}{s} \sim 10^{-10}$ $\leftarrow \left(\frac{n_{N_i}}{s}\right)\Big|_{T \gg M_{N_i}} \sim 10^{-3}$

B] CP-ASYMMETRY CALCULATION

$$\mathcal{L} = -Y_{\nu ij}\, \tilde{H}^* \overline{N_i} P_L L_j - Y^*_{\nu ij}\, \overline{L_j} P_R N_i \tilde{H}^T$$
$$-\frac{1}{2} M_{N_i} \underbrace{(\overline{N_i} N_i)}_{\to\, \overline{N^c_{Ri}} N_{Ri} + \overline{N_{Ri}} N^c_{Ri}}$$

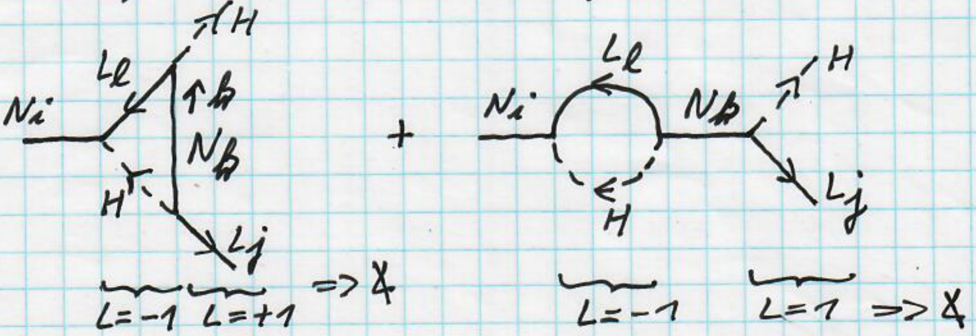
$$N_i = \begin{pmatrix} N_{Ri} \\ N^c_{Ri} \end{pmatrix} \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \quad L = \begin{pmatrix} \nu_L \\ e^-_L \end{pmatrix}$$

Tree level:

$$\left.\begin{aligned} \Gamma(N_i \to l^-_j H^+) &= \frac{1}{32\pi} |Y_{\nu ij}|^2 M_{N_i} \\ \Gamma(N_i \to \nu_{Lj} H^0) &= \quad '' \\ \Gamma(N_i \to l^+_j H^-) &= \quad '' \\ \Gamma(N_i \to \overline{\nu_{jL}} H^{0*}) &= \quad '' \end{aligned}\right\} \Gamma^{TOT}_{N_i} = \frac{1}{8\pi} \underset{\substack{\uparrow \\ \text{sum over } j \\ = e,\mu,\tau}}{|Y_{\nu ij}|^2} M_{N_i}$$

$\Rightarrow \varepsilon_{N_i} = 0$ at tree level (no $\not{CP}$ at tree level)

One-loop-tree level interference:

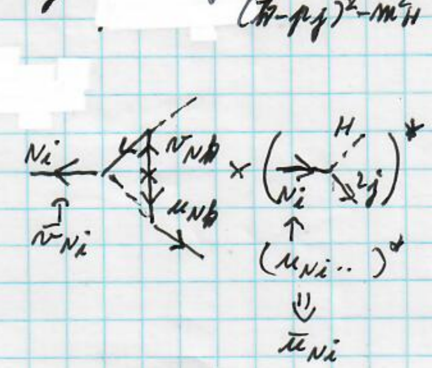


$\Rightarrow$ vertex diagram amplitude $M^{(1)}$ x tree level $M^{(0)*}$

$$M^{(1)} M^{(0)*} = \int \frac{d^4k}{(2\pi)^4} (iY_{\nu il})(iY^*_{\nu kl})(iY^*_{\nu kj})(-iY_{\nu ij}) \frac{i}{(k-p_j)^2 - m^2_H}$$

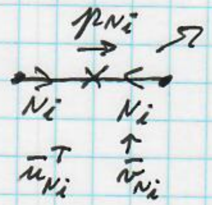
$$\cdot \underbrace{(\overline{N_i}\, l_l\, \overline{l_l}\, N_k \cdot \underbrace{\overline{l_j} N_k}_{= N_k^T \overline{l_j}^T} \cdot \underbrace{\overline{N_i}\, l_{jL}}_{= l^T_{jL} \overline{N_i}^T})}_{= Tr[\overline{N_i}^T \overline{N_i}\, l_l \overline{l_l}\, N_k N_k^T\, \overline{l_j}^T l^T_{jL}]}$$

with $\overline{N_i}^T \leftarrow \overline{u}^T_{Ni}$, $\overline{N_i} \leftarrow \overline{v}_{Ni}$, $N_k N_k^T \leftarrow v_{Nk} u^T_{Nk}$



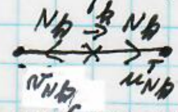
$\Rightarrow l_l \bar{l}_l$: usual propag. of a fermion l_l : $i \sum_s \frac{\overbrace{u_{l_l} \bar{u}_{l_l}}^{p\!\!\!/_{l_l}+m_{l_l}}}{p^2_{l_l}-m^2_{l_l}} = \frac{i}{p\!\!\!/_{l_l}-m_{l_l}}$ $\overset{!!}{0}$

$\bar{l}_j^T l_j^T : (l_j \bar{l}_j)^T$ = transpose of usual external fermion line : $(\sum_s u_{l_j} \bar{u}_{l_j})^T = (p\!\!\!/_{l_j} + m_{l_j})^T$



$\bar{N}_i^T \bar{N}_i$: external N_i line : $\sum_s \bar{u}^T_{N_i} \bar{v}_{N_i} = C^{-1}(p\!\!\!/_{N_i} - M_{N_i})$

$N_k N_k^T$: propag. of N_k : $i \sum \frac{v_{N_k} u^T_{N_k}}{p^2_{N_k} - M^2_{N_k}} = \frac{-i(k\!\!\!/ - M_{N_k})C^T}{p^2 - M^2_{N_k}}$



$\Rightarrow$ commuting C and γ matrices and performing the trace

$$M^{(1)} M^{(0)*} = i \int \frac{d^4 k}{(2\pi)^4} \frac{1}{(k+p_j)^2} \frac{1}{(k-p_H)^2} \frac{1}{(k^2 - M^2_{N_k})} (M^2_{N_i} + 2 k p_j)$$

$$\cdot M_{N_i} M_{N_k} \cdot C_{ik} \qquad C_{ik} = Y_{\nu il} Y^*_{\nu kl} Y_{\nu kj}^* Y_{\nu ij}$$

$$\Rightarrow \Gamma(N_i \to L_j H^-) = \frac{1}{16\pi} \frac{1}{M_{N_i}} \frac{1}{2} \underbrace{(M^{(1)} M^{(0)*} + M^{(0)} M^{(1)*})}_{I_{ik} C_{ik} + I^*_{ik} C^*_{ik}} \cdot \underset{l_j H^+ + \nu_j H^0}{2}$$

I_{ik} = loop integral

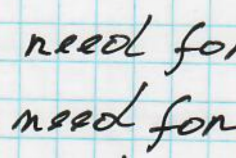
$$\Gamma(N_i \to \bar{L}_j H^*) = \ldots \, (I_{ik} C^*_{ik} + I^*_{ik} C_{ik}) \ldots \cdot 2$$

$$\Rightarrow \varepsilon_{N_i} = \frac{1}{16\pi} \frac{1}{M_{N_i}} \frac{(I_{ik} C_{ik} + I^*_{ik} C^*_{ik} - I_{ik} C^*_{ik} - I^*_{ik} C_{ik})}{\frac{1}{8\pi} |Y_{\nu im}|^2 M_{N_i}}$$

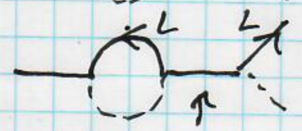
$$= -\frac{1}{2} \frac{1}{M^2_{N_i}} \cdot \frac{4 \, \mathrm{Im}\, I_{N_i k} \, \mathrm{Im}\, C_{ik}}{|Y_{im}|^2}$$

$\Rightarrow$ non trivial requirements for a CP asym. :

- 1) $\mathrm{Im}\, C_{ik} \neq 0 \Rightarrow$ need for CP phases in C_{ik}
- 2) $\mathrm{Im}\, I_{ik} \neq 0 \Rightarrow$ need for an absorptive part

 $\Rightarrow M^2_{N_i} > (m_H + m_e)^2$

-3) explicit $\not{L}$ in the loop :  $\Rightarrow Im\, C_{ik} = 0$

 $\Rightarrow Im\, C_{ik} \neq 0$

$= \xleftarrow{N_{Ri}} \times \xrightarrow{N_{Ri}}$ M_{Ni}

-4) if $i = k \Rightarrow Im\, C_{ii} = 0 \Rightarrow$ need for at least 2 heavy states.

$$\Rightarrow \varepsilon_{Ni} = \frac{1}{8\pi} \frac{M_{Nk}}{M_{Ni}} \frac{Im\left[Y_{\nu il} Y^*_{\nu kl} Y^*_{\nu kj} Y_{\nu ij} \right]}{|Y_{im}|^2}$$

$$\cdot \left\{ \underbrace{\left[1 - \left(1 + \frac{M^2_{Nk}}{M^2_{Ni}}\right) \log\left(1 + \frac{M^2_{Ni}}{M^2_{Nk}}\right) \right]}_{\text{vertex}} + \underbrace{\left[\frac{M^2_{Ni}}{M^2_{Ni} - M^2_{Nk}} \right]}_{\text{self-energy}} \right\}$$

c] Efficiency factor : Boltzmann equations

↳ requires to compare reaction rate with Hubble expansion rate H

reaction rate → # of reacts. a single particle i undergoes per second $= (1/\Delta t)$

↳ time between 2 reacts.

$\Rightarrow$ no thermal equilibr. if : $\Delta t > \underbrace{\frac{1}{H}}_{\sim \text{age of the universe}} \iff \Gamma < H$

↳ with $H = \left(\frac{8\pi \rho_{TOT}}{3 M_p^2}\right)^{1/2} \sim 17 \frac{T^2}{M_{pl}}$

$$\rho_{TOT} = \frac{\pi^2}{30} T^4 \underbrace{\left[\sum_{bos} g_i \left(\frac{T_i^4}{T^4}\right) + \frac{7}{8} \sum_{ferm.} g_i \left(\frac{T_i^4}{T^4}\right)\right]}_{\equiv g_*^{eff} : \text{ \# of relativistic degrees of freedom in universe thermal bath}}$$

$\Rightarrow$ Boltzmann equations : allow to compute the # density of each particle specie as a function of T.

for DM

\# of inverse scattering = γ^{EQ} because xx are assumed to be in thermal equil.

$$s\,z\,H(z)\,\frac{dY_{DM}}{dz} = 2\gamma^{EQ}\left(1-\frac{Y_{DM}^2}{Y_{DM}^{EQ\,2}}\right)$$

Δn_N per inverse scatt

$$= \underbrace{-2}_{\Delta n_{DM} \text{ per scattering}}\gamma^{EQ}\frac{Y_{DM}^2}{Y_{DM}^{EQ2}} \qquad + \overbrace{2}\gamma^{EQ}$$

↳ takes into account that Y_{DM} is not necessarily in thermal equil.

$$\gamma^{EQ} = n_{DM}^{EQ^2}\langle \sigma_{DM\,DM\to xx}\, v\rangle$$

↳ = # of scattering if DM is in thermal equil.

⇒ for Y_N : same logic:

= # of inverse decays = γ_D^{EQ} because L and H in thermal equil.

$$s\,z\,H(z)\,\frac{dY_N}{dz} = 1\,\gamma_D^{EQ}\left(1-\frac{Y_N}{Y_N^{EQ}}\right)$$

$$= \underbrace{-1}_{\Delta n_N \text{ per } N\to LH \text{ decay}}\;\underbrace{\gamma_D^{EQ}}\;\frac{Y_N}{Y_N^{EQ}} \qquad +\overbrace{1\gamma_D^{EQ}}$$

Δn_N per $LH\to N$ inver decay

$$\gamma_D^{EQ} = n_N^{EQ}\underbrace{\langle \Gamma_N^{TOT}\rangle}_{=\Gamma_N^{TOT}\langle \frac{E}{m_N}\rangle}$$

boost of the lifetime

↳ = # of decays if N is in thermal equilibrium

• If N_i has no interact$^\circ$: $n_N \sim \text{const} \cdot a^{-3}$

$\uparrow$ scale factor $\frac{1}{a^3} = \frac{1}{\text{volume}}$

$$\Rightarrow \frac{d n_N}{dt} \equiv \dot{n}_N = -3\frac{\dot{a}}{a}\frac{\text{const}}{a^3} = -3H n_N$$

• If N_i decays: $N \to \ell H$

$$d\pi_X = \frac{d^3 p_X}{2E_X(2\pi)^3}$$

$$\dot{n}_N + 3Hn_N = \int d\pi_N\, d\pi_\ell\, d\pi_H (2\pi)^4 \delta^4(p_N - p_\ell - p_H)$$

$$\cdot \Big[\underbrace{f_N(p_N)}_{\substack{\text{momentum}\\ \text{distribution}\\ \text{of } N}} \underbrace{|\mathcal{M}(N\to \ell H)|^2}_{\substack{\sim\text{transit}^\circ\\ \text{probability}}} \cdot \underbrace{(-1)}_{\Delta n_N} + f_\ell(p_\ell) f_H(p_H) \cdot |\mathcal{M}(\ell H \to N)|^2 \cdot \text{-}1$$

$\Rightarrow$ 7 steps:

(1) $f_\ell(p_\ell) f_H(p_H) = f_\ell^{EQ}(p_\ell) f_H^{EQ}(p_H)$ $\Leftarrow$ L, H in thermal equilib.

(2) we take Maxwell-Boltzmann mom. distribut$^\circ$ (good approxim.) $\Rightarrow$ $f_\ell^{EQ}(p_\ell) f_H^{EQ}(p_H)$

$$= e^{-E_\ell/T} \cdot e^{-E_H/T} = e^{-\overbrace{(E_\ell+E_H)}^{E_N}/T}$$

$$= f_N^{EQ}(p_N)$$

(3) $|\mathcal{M}(\ell H\to N)|^2 = |\mathcal{M}(N\to \ell H)|^2$

$\uparrow$ at tree level which dominates

$$\Rightarrow \dot{n}_N + 3Hn_N = -\int \frac{d^3 p_N}{(2\pi)^3} \left(f_N(p_N) - f_N^{EQ}(p_N)\right) \cdot \frac{M}{E}$$

$$\cdot \underbrace{\frac{1}{2M_N} \int d\pi_\ell\, d\pi_H\, (2\pi)^4 \cdot \delta^4(p_N - p_\ell - p_H)\, |\mathcal{M}(N\to \ell H)|^2}_{= \Gamma(N\to \ell H)\ (4)}$$

$$\int \frac{d^3 p_N}{(2\pi)^3} f_N^{EQ}(p_N) = n_N^{EQ}$$

(5)

$$= (n_N - n_N^{EQ}) \underbrace{\left\langle \frac{M}{E} \right\rangle}_{} \cdot \Gamma(N\to \ell H)$$

~ 1 for $T \ll M$

(6) $n_N \to Y_N \equiv \frac{n_N}{s}$: comoving # density => no more $3Hn_N$

(7) $t \to z \equiv m_N / T$ with $t = \frac{1}{2}\frac{1}{H(z)} = \frac{1}{2}\frac{z^2}{H(M_N)}$

$\hookrightarrow H(M_N)\, dt = z\, dz$

$$\Rightarrow \frac{dY_N}{dz} = -z \underbrace{\frac{\Gamma_N^{TOT}}{H(M_N)}}_{\equiv K(M_1)} \left\langle \frac{M}{E} \right\rangle (Y_N - Y_N^{EQ})$$

$\langle \frac{M}{E} \rangle$: boost factor of Γ; Y_N: decay; Y_N^{EQ}: inverse decay

defining $\gamma_D^{EQ} \equiv n_N^{EQ} \Gamma_N^{TOT} \cdot \langle \frac{\Gamma}{E} \rangle$ = "reaction density"
= # of N decay per unit time per unit volume if N is in thermal equil.
= # of inverse decays because ℓ and H are in thermal equilibr.

$$\Rightarrow s\, z\, H(z) \frac{dY_N}{dz} = \underbrace{-1}_{\Delta n_N \text{ per decay}} \cdot \underbrace{\gamma_D^{EQ} \frac{Y_N}{Y_N^{EQ}}}_{} + \gamma_D^{EQ} \cdot 1$$

1: Δn_N per inv. decay

γ_D^{EQ}: # of inverse decays per time per volume

$\gamma_D^{EQ} \frac{Y_N}{Y_N^{EQ}}$: # of decays per time per volume taking into account that N is not necessarily in thermal equil.: Y_N / Y_N^{EQ} factor

=> to see if N is in thermal equilibrium one has to compare $\frac{\gamma_D^{EQ}}{n_N^{EQ}} = \underbrace{\Gamma_N^{TOT} \langle \frac{\Gamma}{E} \rangle}_{\text{reaction rate}}$ = # of decay a

single N undergo per unit time, with Hubble rate

• Similarly for the lepton # density the Boltzm. equation is:

$$s z H(z) \frac{dY_L}{dz} = \gamma_D^{EQ}\left(\frac{Y_N}{Y_N^{EQ}} - 1\right) \underset{\uparrow}{\varepsilon_N} - \frac{Y_L}{Y_\ell^{EQ}}\gamma_D^{EQ}$$

↑ # of decays ↑ # of inverse decay ↑ ΔL per decay = −ΔL per inverse dec.

⇒ what is new here is the $-\frac{Y_L}{Y_\ell^{EQ}} \cdot \gamma_D^{EQ}$: crucial! ↙ "wash-out" term

↳ if $n_\ell > n_{\bar{\ell}}$ with $n_\ell - n_{\bar{\ell}} \ll n_\ell + n_{\bar{\ell}}$
↑ small asym.

$$\Rightarrow n_\ell = n_\ell^{EQ} + \frac{\Delta n_\ell}{2}$$
$$n_{\bar{\ell}} = n_\ell^{EQ} - \frac{\Delta n_\ell}{2}$$

⇒ # of $\ell H \to N$ processes $= \gamma_D^{EQ}\left(1 + \frac{\Delta n_\ell}{2 n_\ell^{EQ}}\right)$

of $\bar{\ell} H^* \to N$ " $= \gamma_D^{EQ}\left(1 - \text{"}\right)$

$$\Rightarrow \text{change of } \frac{n_L}{s} = \gamma_D^{EQ}\left[\left(-1 - \frac{\Delta n_\ell}{2 n_\ell^{EQ}}\right) + \left(1 - \frac{\Delta n_\ell}{2 n_\ell^{EQ}}\right)\right]$$
$$= \gamma_D^{EQ} \frac{\Delta n_\ell}{n_\ell^{EQ}} = \frac{Y_L}{Y_\ell^{EQ}} \gamma_D^{EQ}$$

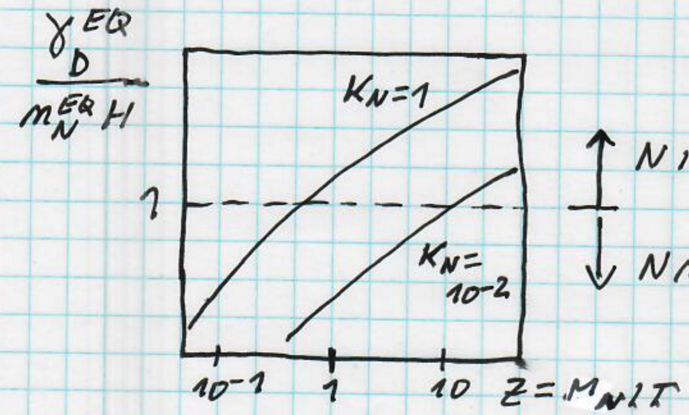
↳ nothing to do with $\not{C}\not{P}$

↳ pure statistical effect occuring even if no $\not{C}\not{P}$: if $n_\ell > n_{\bar{\ell}}$: more $\ell \to \ldots$ than $\bar{\ell} \to \ldots$

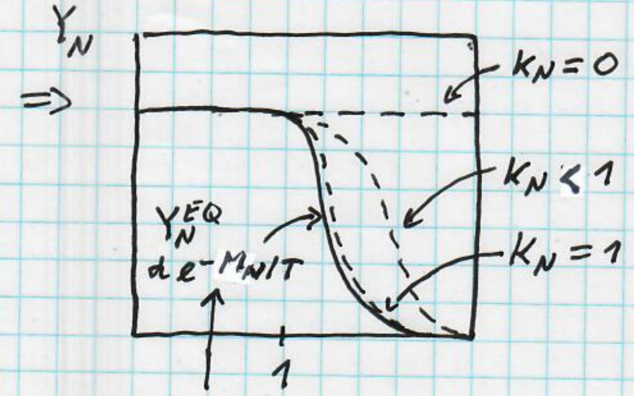
$\Rightarrow$ in summary:

$\hookrightarrow$ 1st Boltzm. eq.: if $\frac{\gamma_D^{EQ}}{n_N^{EQ} H}(z) > 1 \Rightarrow N$ in thermal equilibrium: many decays and inverse decays

$\hookrightarrow \Rightarrow Y_N - Y_N^{EQ}$ suppressed



$\Rightarrow$



$\hookrightarrow$ in 2nd Boltzm. eq.:

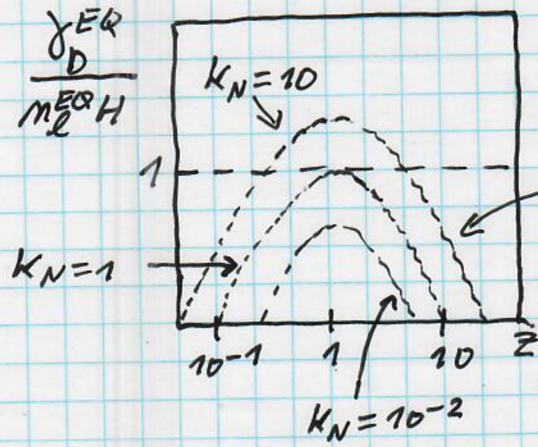
- if no wash-out term: no efficiency suppression even if $Y_N - Y_N^{EQ}$ suppressed from 1st Boltzm. eq.: γ_D^{EQ} large in this case $\Rightarrow \gamma_D^{EQ}(Y_N - Y_N^{EQ})$ not suppressed $\Rightarrow \gamma_D^{EQ}(Y_N/Y_N^{EQ} - 1)\varepsilon_N$ term unsuppressed in 2nd Boltz. eq $\Rightarrow \eta = 1$

- however if γ_D^{EQ} big, wash-out term in 2nd Boltz. equ. big $\Rightarrow$ washout whenever:

$$\frac{\gamma_D^{EQ}}{n_\ell^{EQ} H} > 1 \Rightarrow$$ 3rd Sakharov cond.: is the decay/inverse decay in equil. from the Λ of ℓ, not of N!

\# of inverse decays a ℓ will undergo per unit time % Hubble constant.

$\Rightarrow$



$$\frac{\gamma_D^{EQ}}{n_\ell^{EQ} H} \propto \frac{n_N^{EQ} \cdot \Gamma}{n_\ell^{EQ}}$$

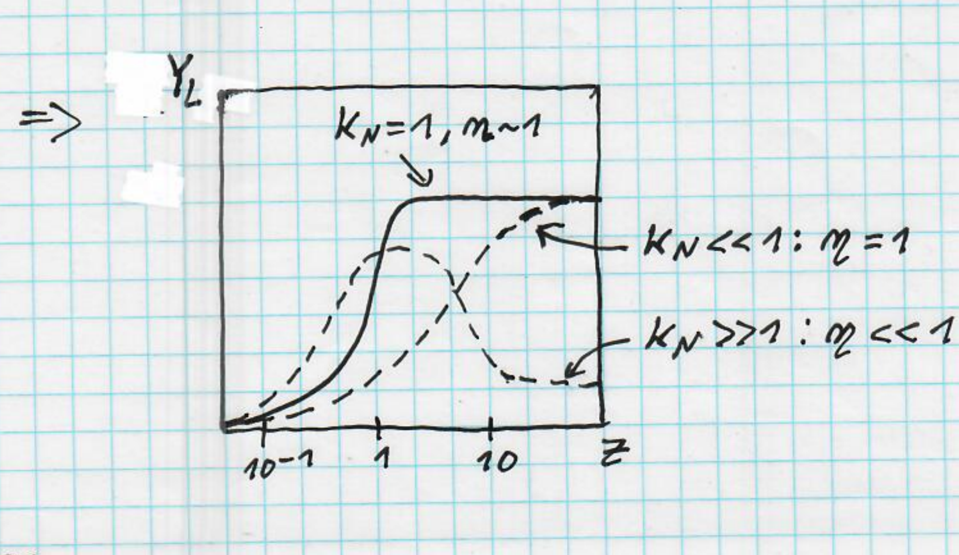
$n_N^{EQ} \propto e^{-M_N/T}$ for $M_N < T$ $\hookrightarrow$ Boltz. suppres.

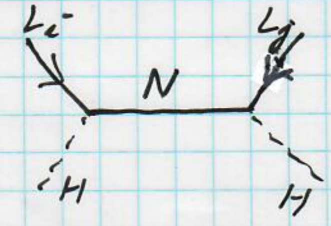
n_ℓ^{EQ} not Boltzm. suppres. for $M_N < T$

$\hookrightarrow$ this is this Boltz. suppres which makes leptogenesis possible, so that we are here to talk about.

$\hookrightarrow$ $\frac{\gamma_D^{EQ}}{n_N^{EQ} H} \propto \frac{n_N^{EQ} \cdot \Gamma}{n_N^{EQ}}$ is instead not Boltz suppres. $\Rightarrow$ but that's no problem.

$\Rightarrow$



• $\Delta L = 2$ scatterings: 

$\Rightarrow$ extra $-\frac{Y_L}{Y_\ell^{EQ}} \gamma^{EQ}_{scatt.} \cdot 2$ term in 2^{nd} Boltz. eq.

\# of scatter per unit time and vol.

$$\gamma^{EQ}_{scatt} = \langle \sigma v \rangle n_\ell^{EQ} n_h^{EQ}$$

↳ gives washout if $\frac{\gamma_{scatt}}{n_\ell^{EQ} H} > 1$

↳ N.B: the on-shell N part of $\Delta L = 2$ scatter is nothing but the inverse decays $\Rightarrow$ need to substract it to avoid double counting.

• erasure of asym. produced by heavier N: N_2, N_3

↳ if $K_{N_1} > 1$: inverse decay washout term will put back to ~ 0 L asym produced by N_2, N_3 decays, but less L asym produced by N_1 because for the later the creation/washout are occuring at same time while for the former creation occurs before N_1 washout.