D] TWO INTRIGUING COINCIDENCES

- The seesaw scales needed for leptogenesis versus the seesaw scales needed for ν masses.

↳ for a hierarchical spectrum of N_i : $M_{N_1} \ll M_{N_{2,3}}$

$$\varepsilon_{N_1} = -\frac{3}{16\pi} \sum_{b=2,3} \frac{M_{N_1}}{M_{N_b}} \frac{\mathrm{Im}\left[(Y_\nu Y_\nu^\dagger)^2_{1b}\right]}{|Y_\nu Y_\nu^\dagger|_{11}}$$

$$\Big\} \; \mathcal{M}_\nu = -\frac{v^2}{2} Y_\nu^T (M_N)^{-1} Y_\nu$$

$$= -\frac{3}{8\pi} \frac{M_{N_1}}{v^2} \frac{\mathrm{Im}\left[(Y_\nu \mathcal{M}_\nu^* Y_\nu)_{11}\right]}{|Y_\nu Y_\nu^\dagger|_{11}}$$

$$\Big\} \; Y_\nu = \frac{\sqrt{2}}{v} (M_N)^{1/2} R (\mathcal{M}_\nu^{DIAG})^{1/2} \cdot U^\dagger_{PMNS}$$

$$= -\frac{3}{16\pi} \frac{M_{N_1}}{v^2} \frac{\sum m_{\nu_j}^2 \, \mathrm{Im}(R_{1j}^2)}{\sum m_{\nu_i} |R_{1i}|^2}$$

$$\Rightarrow \varepsilon_{N_1} \leq \frac{3}{16\pi} \frac{M_{N_1}}{v^2} (m_{\nu_3} - m_{\nu_1}) \lesssim \frac{3}{16\pi} \frac{M_{N_1}}{v^2} \underbrace{\sqrt{\Delta m^2_{13}}}_{0.05\,eV}$$

$\Rightarrow$ requiring $\frac{n_B}{s} = \frac{28}{79} \cdot \varepsilon_{N_i} \left(\frac{n_{N_i}}{s}\right)_{T \gg m_{N_1}} \cdot \underbrace{\eta}_{\lesssim 1} \simeq 9 \cdot 10^{-11}$

$\Rightarrow \underline{M_{N_1} > 4 \cdot 10^8\,GeV}$ Davidson-Ibarra 02.

↳ this value (obtained for $\mathrm{Im}(R_{1j}^2) \sim |R_{1i}|^2 \sim 1$ or higher values of M_{N_1} (for smaller R_{ij}) fit very well with seesaw scales needed for ν masses (in particular scales where seesaw mass suppression of $\mathcal{M}_\nu$ is fully operative)

↳ N.B.: for $M_{N_{2,3}} \sim 10\, M_{N_1}$ for example one can have successful leptogenesis for much smaller values of M_{N_1} (for large entries of R)

T.H. et al 03

- The ν mass scale value versus v and m_{planck} scales coincidence:

$$K_{N_1} \equiv \frac{\Gamma_{N_1}^{TOT}}{H(T=M_{N_1})} \geq \frac{m_\nu^{MIN}}{10^{-3}eV} \qquad \Leftarrow 10^{-3}eV = \frac{17.8\pi\, v^2}{m_{planck}}$$

$$\uparrow \qquad\qquad \uparrow$$

$$\propto \frac{\Sigma\, |Y_{N_1i}|^2 \cdot M_{N_1}}{M_{N_1}^2 / m_{planck}} \quad \propto \Sigma\, Y_N^T \cdot M_{N_{ij}}^{-1} Y_\nu .$$

$\Rightarrow$ given the $m_\nu \leq 1.1eV$ bound from KATRIN this means the washout is naturally limited:
$\Gamma_{N_1} / H(T=M_{N_1}) \leq 1$ cannot be much violated
↳ real coincidence because $10^{-3}eV$ scale is determined by $v = 246\,GeV$ and $m_{planck} = 10^{19}GeV$
↳ $m_\nu \sim keV$ for example would kill Leptogenesis

- In fact for $M_{N_1} <<< M_{N_{2,3}}$ successful leptogenesis requires $m_\nu \leq 0.12\,eV \Leftarrow$ in this case $m_{\nu_1} \sim m_{\nu_2} \sim m_{\nu_3} \sim m_\nu$

↳ due to 2 effects:

  - $\varepsilon_{N_1} < \frac{3}{4\pi} \frac{M_{N_1}}{v^2} (m_{\nu_3} - m_{\nu_1}) \downarrow$ when $m_\nu \uparrow$
    ↳ $m_{\nu_3} - m_{\nu_1} = \frac{2.5 \cdot 10^{-3} eV^2}{2 m_\nu}$
  - $K_{N_1} \geq \frac{m_\nu^{MIN}}{10^{-3}eV} \uparrow$ when $m_\nu \uparrow \Leftarrow m_\nu^{MIN} \sim m_\nu$ for $m_\nu > 0.05eV$

↳ however: - to get a quasi-degenerate m_ν spectrum from hierarchical M_{N_i} spectrum implies tuning (cancellation in $\mathcal{M}_\nu \propto Y_\nu^T M_N^{-1} Y_\nu$)
↳ more natural is to get it from quasi-

degenerate spectrum of M_{N_i} => in this case no more relevant upper bound on m_ν T.H. et al 03

↳ resonance in ε_N: see below

- flavor effect also relax this bound (see below)

=> to sum up so far: the scales (m_ν, v, m_{Planck}) and the $\frac{n_B}{s}$ observed value match very well!!

↳ it is nevertheless difficult to make any precise prediction:

$$\varepsilon_{N_1} = -\frac{3}{16\pi} \frac{M_{N_1}}{v^2} \frac{\sum m_{\nu_j}^2 \, Im(R_{1j}^2)}{\sum m_{\nu_i} |R_{1i}|^2}$$

↳ depends on low energy m_ν value but the phases leading to leptogenesis are the 3 "high-energy" ones

+ dependence on 3 real parameters in R which are also "high-energy"

+ dependence in unknown M_{N_1}

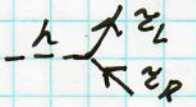
E] FLAVOR LEPTOGENESIS

↳ so far all results: counting the # of lepton created and destroyed independently of their e, μ or τ flavor

↳ justified for $T \gtrsim 10^{12}$ GeV: e^-, μ^-, τ^- indistinguishable in the thermal bath: same gauge inter. and SM charged inter. out of equilibr.

↳ $\Rightarrow$ the N_1 couples to a single $\tilde{\ell} \propto Y_{N_1 e}\, e + Y_{N_1 \mu}\, \mu + Y_{N_1 \tau}\, \tau$ and this combinat° remains coherent afterwards: one counts # of $\tilde{\ell}$ created/destroyed $\Rightarrow$ a single Boltzmann equ.

↳ However: for $T \lesssim 10^{12}$ GeV: $\Gamma_\tau^{SM} > H$ $\Leftarrow$ SM τ Yukawa



↳ $\Rightarrow$ thermal bath distinguishes τ flavor from $e+\mu$ flavor

Abada, Davidson, Josse-Michaux, Losada Riotto '06; Nardi, Nir, Roulet, Racker 06 ...

$\Rightarrow$ 2 Botzm. equat°: $\rightarrow$ for # of τ

$\rightarrow$ for # of $e+\mu$

↳ each one with its flavor asym.:

$$\varepsilon_{N\alpha} \equiv \frac{\Gamma(N \to L_\alpha H) - \Gamma(N \to \bar{L}_\alpha \bar{H})}{\Gamma_N^{TOT}} \qquad \alpha = \tau, e+\mu$$

for $T \leq 10^{9}$ GeV: $\Gamma_\mu^{SM} > H$

↳ 3 Boltzm equat°: $\rightarrow$ for # of e, $\rightarrow$ for # of μ, $\rightarrow$ for # of τ

N.B.: in fact more precisely the Y_τ Yukawa interact. breaks the $\tilde{\ell}$ coherence if a τ undergoes a Y_τ interact° on average before it goes in an inverse decay $\tau + h \to N_1$

Blanchet, DiBari, Raffelt 06

Flavor typical effects:

- Reduction of washout effect: in strong washout case: $K_{N_1} \gg 1$
  - ↳ in one flavor approx: strong washout
  - ↳ in several flavor case: possibility of less washout: e.g. if $\Gamma(N_1 \to L_{e+\mu} H) \gg \Gamma(N \to L_\tau H)$: τ asym. less washed-out
    - ↳ change result by factor of a few (typically)
    - ↳ does not change on $M_{N_1} \gtrsim 4 \cdot 10^8$ GeV bound obtained anyway in no washout case.

Barbieri et al 99
Pilaftsis et al 05
Abada et al 06
Nardi et al 06
...

- $N_{2,3}$ leptogenesis:
  - ↳ in one flavor approx.: Y created by N_2, N_3 decays washed out by N_1 interact°.
  - ↳ in several flavor case: not so true anymore if N_i's couple to $\neq$ flavors

Vives 05,
Engelhard et al 06
Blanchet, Di Bari 08

- Initial condition dependence:
  - ↳ in one flavor approx.: any preexisting L asym would be easily washed out by N_i's interactions
  - ↳ in several flavor case: not so true anymore

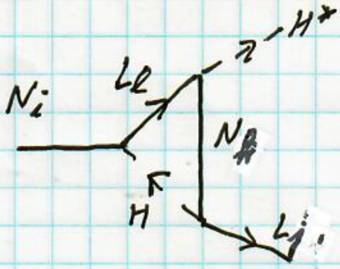
Bertuzzo,
Di Bari,
Marzola 11'

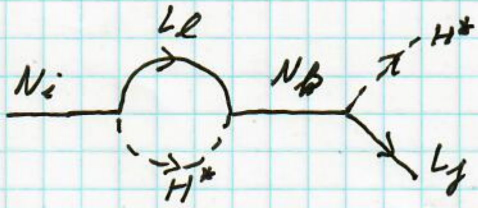
- CP phases contributing to leptogenesis
  - ↳ in one flavor approx: only the 3 high energy phases
  - ↳ in several flavor case: the 3 low energy phases in $\mathcal{M}_\nu$ can also contribute $\Rightarrow$ in general less predictive. Possibility to have leptogenesis with only Dirac phase in $\mathcal{M}_\nu$, δ_{CP}, but no reason to have only it at all!

δ_{CP} = complicated low energy combination of 6 high energy phases in Y_ν.

• Purely flavored leptogenesis:

Aristizabal-Sierra, Losada, Nardi 08
Gonzalez-Garcia, Racker, Rius 09
...





$\Rightarrow$ for each L_j flavor: $\varepsilon_j^* \equiv \frac{\Gamma(N\to L_j H^*) - \Gamma(N\to \bar{L}_j H)}{\Gamma_N^{TOT}}$

↳ in one flavor case: $\sum_j \varepsilon_j^* = 0 \Rightarrow$ no leptogenesis

↳ in several flavor case: $\varepsilon_\tau^* = -\varepsilon_{e+\mu}^* \neq 0$

can be not washed out — can be washed out $\Rightarrow$ leptogenesis

↳ generically subleading because suppressed by $\frac{m^2_{N_1}}{m^2_{N_{2,3}}}$ factors but possible

E] QUASI-DEGENERATE M_{N_i} SPECTRUM CASE: LOW SCALE LEPTOGENESIS

If at least 2 N_i have similar masses $\Rightarrow$ resonance effect!

$\hookrightarrow$ for $M_{N_1} \sim M_{N_2}$:

Covi, Roulet, Vissani 93
Flanz et al 93

$$\Rightarrow \varepsilon_{N_1} = \frac{1}{8\pi} \frac{\mathrm{Im}\left[(Y_\nu Y_\nu^\dagger)^2_{12} \right]}{(Y_\nu Y_\nu^\dagger)_{11}} \cdot \frac{M_{N_1}}{M_{N_2}} \cdot S_{12}$$

$$S_{12} = \frac{M^2_{N_2}}{M^2_{N_1} - M^2_{N_2}}$$

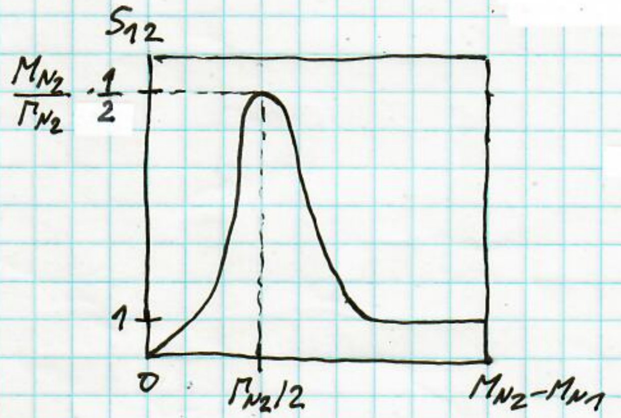
$\Rightarrow$ need to include decay width:

$$\left.\begin{aligned} M^{(1)} M^{(0)*} &\propto \frac{1}{M^2_{N_1} - M^2_{N_2} + i\Gamma_{N_2} M_{N_1}} \\ M^{(0)} M^{(1)*} &\propto \frac{1}{\quad '' \quad - i \quad '' \quad} \end{aligned}\right\} \Rightarrow S_{12} = \frac{M^2_{N_2}(M^2_{N_1} - M^2_{N_2})}{(M^2_{N_2} - M^2_{N_1})^2 + \Gamma^2_{N_2} M^2_{N_1}}$$

$\Rightarrow$ if $M_{N_2} \gg M_{N_1}$: $S_{12} = 1$

if $M_{N_2} - M_{N_1} = \frac{\Gamma_{N_2}}{2} \Rightarrow S_{12} = \frac{M_{N_2}}{\Gamma_{N_2}} \cdot \frac{1}{2} \gg 1 \Rightarrow$ huge resonant enhancem.

if $M_{N_2} = M_{N_1} \Rightarrow S_{12} = 0$



$\Rightarrow$ • ε_{N_1} not bounded any more by $M_{N_1}\frac{(m_{\nu_3}-m_{\nu_1})}{v^2}$

↳ $\varepsilon_{N_1} \leq \frac{1}{2}$ $\varepsilon_{N_1}+\varepsilon_{N_2} \leq 1$

at the peak

Pilaftsis 97, ...

$\Rightarrow$ no more bound on M_{N_1} from ε_{N_1}

$\Rightarrow$ "low scale leptogenesis"

↳ $M_{N_1} \sim M_{N_2} \sim v_{EW}$ perfectly possible

↳ N decay to LH only requires

$M_{N_1} > m_L + m_H \sim 100\,\text{GeV}$

• No more relevant upper bound on m_ν: $m_\nu \sim 1\,\text{eV}$ perfectly possible

↳ if $m_{\nu_1} \sim m_{\nu_2} \sim m_{\nu_3} \sim 1\,\text{eV}$: $\frac{m_{\nu_3}-m_{\nu_1}}{m_{\nu_3}} \sim 10^{-3}$

↳ easier to explain if $\frac{M_{N_i}-M_{N_j}}{M_{N_1}} \lesssim 10^{-3}$ too $\Rightarrow$ resonance!

• A proper treatment of resonant case: quantum Boltzm. equat^{s} bring corrections

Buchmuller et al. 00
De Simone, Riotto 07
Garny et al 09

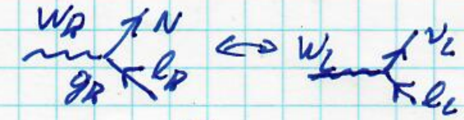
• Tests of low scale leptogenesis:

↳ if $M_{N_1} \sim$ TeV one could naively expect a production of N's at colliders

↳ however $m_\nu \sim Y_\nu^2 v^2/M_N \sim 0.1\,\text{eV}$ requires typically $Y_\nu \sim 10^{-7} \Rightarrow$ too small to produce N's at colliders (N is $SU(2)_L \times U(1)_Y$: no gauge interact^{s}).

↳ 2 ways out one could think of:

- production of N's from other interactions

↳ for example: L-R models: 

$\Rightarrow$ N's can be produced at LHC via W_R 

↳ however: any large interact° of N such as g_R ones will deeply thermalize TeV scale N's:

$$\ldots \frac{dY_N}{dz} = \ldots \gamma_D \left(1 - \frac{Y_N}{Y_N^{EQ}}\right) + \ldots \gamma_{W_R} \left(1 - \frac{Y_N}{Y_N^{EQ}}\right) + \ldots$$

e.g. $q\bar{q} \leftrightarrow W_R \leftrightarrow N\bar{l}_R$ ...

$\Rightarrow$ since $\gamma_{W_R} \gg \gamma_D \Rightarrow Y_N - Y_N^{EQ}$ much more suppressed than with γ_D term only

$$\Rightarrow \ldots \frac{dY_L}{dz} = \ldots \gamma_D \underbrace{\left(1 - \frac{Y_N}{Y_N^{EQ}}\right)}_{\text{very suppressed}} \varepsilon_N + \ldots$$

↳ $\Rightarrow$ not much product° of Y_L

↳ this is not a washout effect but a N thermalizat° effect

↳ $\Rightarrow$ successful leptogenesis requires $m_{W_R} > 18$ TeV $\Rightarrow$ N production at LHC through W_R hopeless in this case

Frère, T.H., Vanlangen 08'

- approximate L conservation frameworks: if one assumes (just so for the sake of testability) that there exists an extra $U(1)_L$ global symmetry that is broken only by a small amount, one can get small ν masses even though some of the Yukawa's are large.

example: 2N's framework with $L(N_1) = 1$, $L(N_2) = -1$

$$\Rightarrow \mathcal{M} = \begin{array}{c} \begin{array}{ccc} \nu_L & N_1^c & N_2^c \end{array} \\ \begin{pmatrix} 0 & Y_N v & 0 \\ Y_N v & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix} \end{array} \Rightarrow \underset{\substack{\uparrow \\ L \text{ conserved}}}{\mathcal{M}_\nu = 0}$$

$\Rightarrow$ adding & perturbations:

$$\mathcal{M} = \begin{pmatrix} 0 & Y_N v & Y_N' v \\ Y_N v & \mu' & M_N \\ Y_N' v & M_N & \mu \end{pmatrix}$$

$$\Rightarrow \mathcal{M}_\nu \sim Y_N' \frac{1}{M_N} Y_N v^2 - Y_N^T \frac{1}{M_N} \mu \frac{1}{M_N} Y_N v^2$$

$\Rightarrow$ testable at LHC for $M_N \sim$ TeV, $Y_N \sim 10^{-n}$ $n \sim 0-2$

testable by experiments searching for rare charged lepton flavor violating processes such as $\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ conversion in atomic nuclei $\leftarrow$ rates are $\propto \frac{1}{M_N^4}$ $\leftarrow$ dim-6 operat.

Drewes et al
P. Hernandez et al
Garbrecht et al
$\uparrow$ ...

for leptogenesis such frameworks e.g. imply a suppression of ε_N CP-asymmetries which requires L violation $\Rightarrow \propto$ to small Y_N', μ ... which can be $\pm$ compensated by large quasi-degeneracy of $M_{N_{1,2}}$: $M_{N_1} \sim M_{N_2}$ predicted here: $M_{N_1} - M_{N_2} \sim \mu, \mu'$

Leptogenesis testable to some extend $\Leftarrow$ pushing all parameters in right direction.

G] LEPTOGENESIS WITH VERY SMALL VALUES OF M_N

↳ if $M_N < m_h, m_W, m_Z \Rightarrow$ no more 2 body N decays

↳ but $N_i \leftrightarrow N_j$ $\cancel{CP}$ transitions can still be operative together with **NLH** Yukawa interactions **inducing** various processes, $H \leftrightarrow NL$ + scatterings...

↳ leptogenesis from N oscillations: Akmedhov, Rubakov, Smirnov

Asaka, Shaposhnikov
Drewes et al
Garbrecht, et al
P. Hernandez et al

↳ purely flavored framework occuring at T typically 10^5 GeV $\Rightarrow T \gg m_{N_i}$: finite temperature effect important.

↳ generation of $L_i - \bar{L}_i$ asym and $N_i - \bar{N}_i$ asym with $\sum_i (L_i - \bar{L}_i) = 0 = \sum (N_i - \bar{N}_i)$ until a flavor asym is more washed out than another one $\Rightarrow \sum (L_i - \bar{L}_i) = -\sum (N_i - \bar{N}_i) \neq 0$: total lepton asym $= 0$ but total SM lepton asym $\neq 0$

Since this later one is transfered into B via sphalerons (at $T > 150$ GeV) unlike the N asym $\Rightarrow$ baryogenesis.

no time to give details for this mechanism in these lectures

↳ doesn't require huge quasi-degeneracy of N_i's but some degeneracy is still needed.

testable partly: N productᵒ compatible with successful leptogen.

↳ there is also a $\cancel{L}$ contribution which is suppressed by $\frac{M_N^2}{T^2}$ but involves 2 powers less of $Y_\nu \Rightarrow$ can dominate easily for larger quasi-degeneracy of N and occurs just before sphaleron decoupling: $T \sim 200$ GeV

T.H., Teresi 15, 17

T.H., Teresi 17
Klaric, Shaposhnikov 19

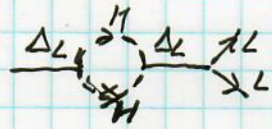
↳ both pure flavor ARS and $\cancel{L}$ contributions can be considered in a density matrix formalism as well as decay/scattering Boltzmann formalism

III. LEPTOGENESIS IN ALTERNATIVE SCENARIOS

↳ here will talk mainly about frameworks involving type-II and type-III seesaw

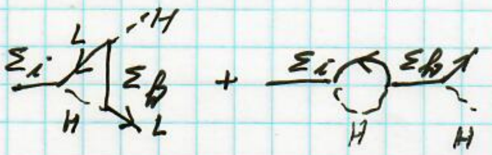
Type-II leptogenesis:

↳ type-II requires only one Δ_L ⇒ no CP-asymmetry:



⇒ $Im[\ldots] = 0$

Type-III leptogenesis: T.H., Lin, Notari, Papucci, Strumia 03

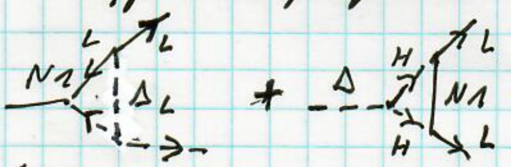


$\Rightarrow M_{\Sigma_1} > 1.5\ 10^{10}\,GeV \quad (M_{\Sigma_1} \ll M_{\Sigma_{2,3}})$

$M_{\Sigma_1} > 1.6\,TeV \quad (M_{\Sigma_2} \sim M_{\Sigma_1})$

Strumia 09

Type-I + Type II leptogenesis: T.H., G. Senjanovic, 03'



$\rightarrow M_\Delta > 3 \cdot 10^{9}\,GeV$

T.H., Raidal, Strumia 07

↳ $M_{N_1} > 4 \cdot 10^{8}\,GeV \quad (M_{N_1} \ll M_{N_2, N_3})$

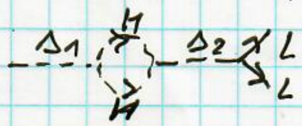
↳ T.H., Senjanovic 03
Antusch, King 04

↳ this framework is very well motivated in SO(10) GUT: all fermion SM generat° in a single SO(10) representation: 16 representat°

↳ contains also a N ⇒ type-I seesaw!

↳ M_N Majorana mass if generated from renormalizable coupling requires a 126 scalar representat°: this 126 scalar repres. contains a Δ_L ⇒ type-II seesaw!

Type-II + Type-II



Ma, Sarkar 98

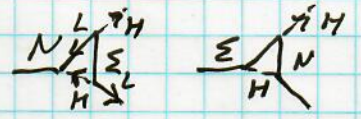
TH., Raidal, Strumia 07

$\Rightarrow M_{\Delta_1} > 3\cdot 10^{10}$ GeV ($M_{\Delta_1} \ll M_{\Delta_2}$)

$M_{\Delta_1} > 1.6$ TeV ($M_{\Delta_1} \sim M_{\Delta_2}$)

Strumia 08

Type-III + Type III



: pure vertex

$M_{N_1} > 4\cdot 10^8$ GeV ($M_{N_1} < M_\Sigma$)

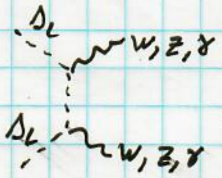
$M_\Sigma > 1.5\cdot 10^{10}$ GeV ($M_\Sigma < M_N$)

Bajc et al 07'
Fileviez-perez et al 07'

↳ natural in SU(5) GUT
with a single 24 fermion
repres. which contains a N and a Σ

- From decay of a triplet (Δ_L or Σ): lower bounds on decaying triplet mass above are somewhat higher than on M_{N_1} in type-I seesaw

↳ triplets unlike N's have $SU(2)_L$ gauge interactions:



: fast interactions : $g \sim 1$

$\Rightarrow$ suppresses $Y_\Delta - Y_\Delta^{EQ}$ in $\frac{dY_\Delta}{dz}$ Boltzm. equ.

$\Rightarrow$ suppresses Y_L asymmetry producti°

in $\frac{dY_L}{dz} = \gamma_D \underbrace{\left(1 - \frac{Y_\Delta}{Y_\Delta^{EQ}}\right)}_{\text{suppressed}} \varepsilon_\Delta + \ldots$

↳ such a suppression occurs if gauge interact. are in thermal equil. $\frac{\gamma_W}{n_\Delta^{EQ} H} > 1$ ($\Leftrightarrow T \lesssim 10^{14}$ GeV) and if $\gamma_W > \gamma_D \Leftrightarrow$ if a Δ_L undergo on average a gauge inter. before undergoing a decay. $\Rightarrow$ even on the resonance peak one still needs $M_\Delta, M_\Sigma > 1.6$ TeV

45.