Models of Leptogenesis

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Leptogenesis motivation

Two fundamental questions beyond the Standard Model

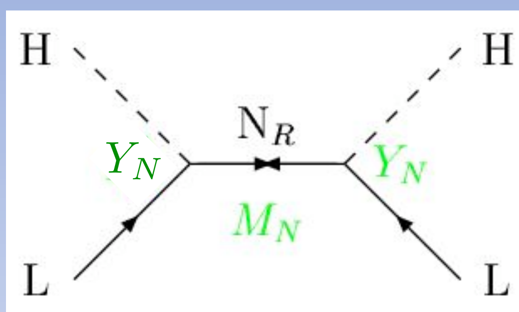
origin of neutrino masses ⟺ origin of the baryon asymmetry of the Universe

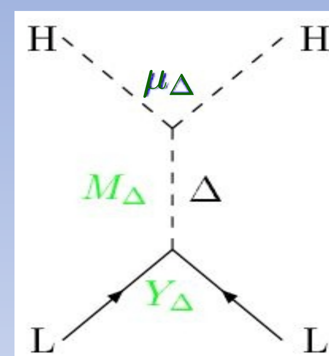
Leptogenesis:
both origins are the same

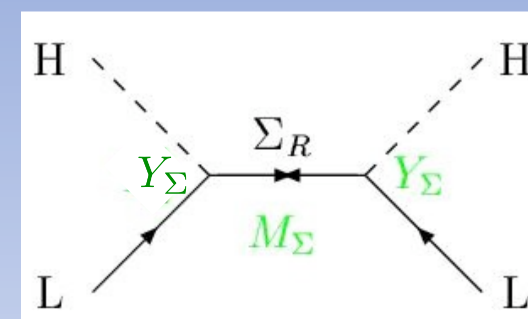
+ a series of numerical coincidences which makes it particularly effective

The 3 seesaw models

Fermion singlets: (type-I seesaw)	Scalar triplet: (type-II seesaw)	Fermion triplets: (type-III seesaw)
N_{R_i}	$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$	$\Sigma_i \equiv (\Sigma_i^{+}, \Sigma_i^{0}, \Sigma_i^{-})$
$\mathcal{L} \ni -Y_{N_{ij}} \bar{N}_i L_j H - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + h.c.$	$\mathcal{L} \ni -Y_\Delta \Delta L_i L_j - \mu_\Delta \Delta H H + h.c.$	$\mathcal{L} \ni -Y_{\Sigma_{ij}} \bar{\Sigma}_i L_j H - \frac{m_{\Sigma_i}}{2} \overline{\Sigma_i^c} \Sigma_i + h.c.$







$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

Minkowski; Gellman, Ramon, Slansky; Yanagida;Glashow; Mohapatra, Senjanovic

Magg, Wetterich; Lazarides, Shafi; Mohapatra, Senjanovic; Schechter, Valle

Foot, Lew, He, Joshi; Ma; Ma, Roy;T.H., Lin, Notari, Papucci, Strumia; Bajc, Nemevsek, Senjanovic; Dorsner, Fileviez-Perez;....

for example with $Y_N \sim 1$, $m_\nu \sim 0.1$ eV requires $M_N \sim 10^{15}$ GeV

with $Y_N \sim 10^{-6}$, $m_\nu \sim 0.1$ eV requires $M_N \sim$ TeV

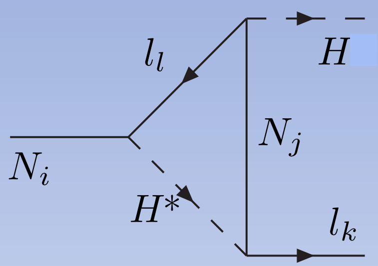
The 3 leptogenesis ingredients

first in type-I

- 1) The CP-asymmetry (averaged ΔL produced per N_i decay)

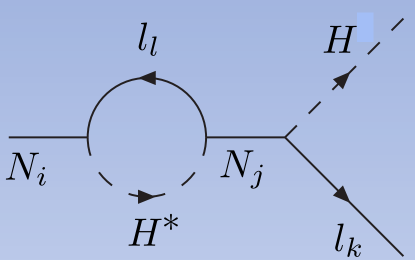
$$\varepsilon_{N_i} = \sum_k \frac{\Gamma(N_i \to L_k H) - \Gamma(N_i \to \bar{L}_k H^*)}{\Gamma^{\rm TOT}_{N_i}}$$

⇒ CP-violation from 2 one-loop diagrams:



vertex diagram

Fukugida, Yanagida '86



self-energy diagram

Liu, Segré '93; Flanz et al '94; Covi, Roulet, Vissani '94, Pilaftsis '97

$$\Rightarrow \varepsilon_{N_i} = \frac{1}{8\pi} \sum_j \frac{\sum_{jl} {\rm Im}[Y_{Nik} Y^\dagger_{Nkj} Y_{Nil} Y^\dagger_{Nlj}]}{\sum_k |Y_{Nik}|^2} \frac{M_{Nj}}{M_{Ni}} \cdot \left[1 - (1 + \frac{M^2_{Nj}}{M^2_{N_i}}) \log(1 + \frac{M^2_{Ni}}{M^2_{N_j}}) + \frac{M^2_{N_i}(M^2_{N_i} - M^2_{Nj})}{(M^2_{N_i} - M^2_{Nj})^2 + \Gamma^2_{N_j} M^2_{N_i}}\right]$$

$$\Rightarrow Y_L \equiv \frac{n_L}{s} = \varepsilon_{N_i} \cdot \frac{n_{N_i}}{s}\Big|_{T>>M_{N_i}}$$

The 3 leptogenesis ingredients

- 2) The efficiency η : $\frac{n_L}{s} = \varepsilon_{N_i} \cdot \frac{n_{N_i}}{s}\Big|_{T>>M_{N_i}} \cdot \eta$

$\eta \sim 1 \quad \leftarrow \quad$ out-of-equilibrium

$\eta << 1 \quad \leftarrow \quad$ N decays partly in thermal equil. and/or washout of L asym.

can be obtained integrating the Boltzmann equations:

$Y_N = n_N/s$

$Y_L = (n_l - n_{\bar{l}})/s$

$z \equiv \frac{M_N}{T}$

$\frac{\gamma_D}{H(T=M_N)} \equiv \frac{\Gamma_N^{\rm TOT}}{H(T=M_N))} \frac{K_1(z)}{K_2(z)} n_N^{EQ}(z)$

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

$$\frac{s}{z}\frac{dY_L}{dz} = \varepsilon_N \cdot \left(\frac{Y_N}{Y_N^{EQ}} - 1\right) \cdot \frac{\gamma_D}{H(T=M_N)} - 2\,\frac{Y_L}{Y_l^{EQ}} \cdot \frac{\gamma_{\Delta L=2}}{H(T=M_N)}$$

each decay produces a $\Delta L = \varepsilon_N$

each inverse decay produces a $\Delta L = -\varepsilon_N$

if more l than $\bar{l}$: more $l\,H \to N \to \bar{l}\,H^*$ processes than $\bar{l}\,H^* \to N \to l\,H$

$\Rightarrow$ main condition to avoid an efficiency suppression: $\Gamma_N^{\rm TOT} < H(T=M_N)$

The 3 leptogenesis ingredients

- 3) The L to B conversion from SM sphalerons:

  ⤷ above the EW scale B+L violating but B-L conserving

  SM sphalerons are in thermal equilibrium $T^{Sphal.}_{Decoupl.} \sim 140\,\mathrm{GeV}$

⇒ put B+L to ~ 0 but conserving B-L:

$$\left.\begin{array}{rcl} (B+L)_{Fin} & \sim & 0 \\ (B-L)_{Fin} & = & (B-L)_{In} \\ B_{In} & = & 0 \end{array}\right\} \Rightarrow B_{Fin} \sim -L_{Fin} \sim -\frac{L_{In}}{2}$$

⇓

$$\frac{n_B}{s} = -\frac{28}{79}\frac{n_L}{s} = -\frac{28}{79}\,\eta\,\epsilon_{N_i}\,\frac{n_{N_i}}{s}\Big|_{T>>M_{N_i}}$$

↕

$$\frac{n_B}{s} = (8.82 \pm 0.23)\cdot 10^{-11}$$

WMAP
Planck

Two intriguing numerical coincidences

- The seesaw state mass (slight) coincidence:

  - for a hierarchical spectrum of N_i : $\varepsilon_{N_1} \leq M_{N_1} \frac{3}{8\pi} \frac{1}{v^2} \sqrt{\Delta m^2_{atm}}$

    $M_{N_1} << M_{N_{2,3}}$

    Davidson, Ibarra '02,....

    $$\Downarrow$$

    $$M_{N_1} \gtrsim 4 \cdot 10^8 \, \mathrm{GeV}$$

    $$\uparrow$$

    this scale is determined by the totally independent value of n_B/s , fits well with seesaw expectations

    → a much larger value of n_B/s and/or much smaller neutrino mass scale would fit much less

  - for a quasi-degenerate spectrum of N_i instead: resonance occurs: ε_{N_1} not bounded by value of M_{N_1} or m_ν

    $M_{N_1} \sim M_{N_2}$

    → M_{N_1} bounded from below only by sphaleron decoupling scale

    → $M_{N_1} \sim \mathrm{TeV}$ perfectly possible

    Pilaftsis '97; '99; Pilaftsis, Underwood '05; ...; Dev, Millington, Pilaftsis, Teresi '14

see D. Teresi's and P. Millington talks

Two intriguing numerical coincidences

- The neutrino mass scale value versus electroweak and Planck scales coincidence

→ in full generality: $\Gamma_{N_1}/H(T=M_{N_1}) \geq m_\nu^{Min}/10^{-3}\,\mathrm{eV}$

$$\propto |Y_{N_{1i}}|^2 M_{N1} \qquad \propto M_{N1}^2 \qquad \propto \frac{Y_{N_{1i}}^2}{M_{N1}}$$

→ given the $m_\nu^{Min} < 2.2\,\mathrm{eV}$ direct bound or the $m_\nu^{Min} \lesssim 0.2\,\mathrm{eV}$ cosmology bound

the washout from inverse decays is naturally limited ← $\Gamma_{N_1}/H(T=M_{N_1}) \leq 1$ is not much violated

real coincidence because $10^{-3}\,\mathrm{eV}$ scale is determined by independent e-w scale and Planck scale

$$10^{-3}\,\mathrm{eV} \simeq 17 \cdot 8\pi \cdot v^2/M_{Planck}$$

for example $m_\nu \sim \mathrm{KeV}$ would have given quite large washout

N.B.: no much relevant at all upper bound on m_ν from successful leptogenesis condition

→ TH, Lin, Notari, Papucci, Strumia '04
Abada, Davidson, Josse-Michaux, Losada, Riotto '06

→ Buchmuller, Di Bari, Plumacher '02,'03

Flavor effects in leptogenesis

so far all results were obtained by just counting the number of lepton created and destroyed independently of whether the lepton is of e, μ or τ type

a single Boltzmann equation for total lepton number

justified for $T \gtrsim 10^{12}\,\mathrm{GeV}$: e^-, μ^-, τ^- indistinguishable in the thermal bath

same gauge interactions

SM charged Yukawa interactions out of equil.

⇒ the N_1 which couples to a single $\tilde{l} \propto Y_{N_{1e}} e + Y_{N_{1\mu}} \mu + Y_{N_{1\tau}} \tau$ flavour combination creates leptons in this combination which remains coherent afterwards

⇒ one has just to count the number of $\tilde{l}$ created and destroyed ⇒ a single Boltzmann equation!

Flavor leptogenesis: flavor discrimination by thermal bath

However: for $T \lesssim 10^{12}\,\mathrm{GeV}$: $\Gamma_\tau^{SM} > H$ ⟵ SM τ Yukawa interaction enters into thermal equilibr.

⇒ if $\Gamma_\tau^{SM} > \Gamma_{N-decay}$, SM τ Yukawa interactions do occur

↓

the thermal bath distinguishes
τ flavor from $e+\mu$ flavor

↓

2 Boltzmann equat.: one for number
of τ and one for number of e and μ
each one with its flavour asym.

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

Abada, Davidson, Josse-Michaux, Losada, Riotto '06
Nardi, Nir, Roulet, Racker '06
Abada et al. '06; Blanchet, Di Bari, Raffelt '06
De Simone, Riotto '06,
....

Similarly for $T \lesssim 10^{9}\,\mathrm{GeV}$: $\Gamma_\mu^{SM} > H$ ⇒ .... 3 Boltzmann equations, for τ, for μ and for e

(i.e. via its τ component of the $\tilde{l} \propto Y_{N_{1e}} e + Y_{N_{1\mu}} \mu + Y_{N_{1\tau}} \tau$ can undergo a SM Yukawa interaction: breaks the coherence of $\tilde{l}$ state, but this is really effective only once N inverse decay rate becomes slower than τ Yukawa rate, so that decoherence has time to occur before an inverse decay occurs)

Blanchet, Di Bari, Raffelt '06

Flavor leptogenesis typical effects

- Flavor hierarchy effect: example: if N decays much faster than H: $\frac{\Gamma_N}{H(T=m_N)} >> 1$

  - in one flavor approx.: strong washout

  - in two flavor case: possibility of less washout

  Barbieri, Creminelli, Strumia, Tetradis '99; Pilaftsis '05,;Pilaftsis, Underwood '05; Abada, Davidson, Josse-Michaux, Riotto '06; Nardi, Nir, Roulet, Racker '06 Abada et al. '06; Blanchet Di Bari, Raffelt '06 Pascoli, Petcov, Riotto '07; Aristizabal, Munoz, Nardi '09; Garbrecht et al '09,'11 ....

  ↪ e.g. if $\Gamma(N \to L_{e+\mu}H) >> \Gamma(N \to L_\tau H)$ the Y_τ asymmetry is not washed out even if $\frac{\Gamma_N}{H(T=m_N)} >> 1$

  ⇒ large flavor effects if strong washout regime $\frac{\Gamma_N}{H(T=m_N)} >> 1$

  ↪ as a result essentially no effect on $M_{N_1} \gtrsim 4 \cdot 10^8$ GeV bound

- "$N_{2,3}$-leptogenesis": in one flavor approxim. leptogenesis dominated by N_1 decays

  Vives '05; Engelhard, Grossman, Nardi, Nir '06; Blanchet, Di Bari '08

  ↪ L asym. created by $N_{2,3}$ washed-out by N_1 Yukawa interactions

  not true anymore with flavor if the $N_i's$ mostly couple to different flavors

- Initial condition dependence: in one flavor approx. any preexisting L asym would be very easily erased by $N_i's$ Yukawa interactions, not true anymore with flavor ⇒ initial cond. dependence!

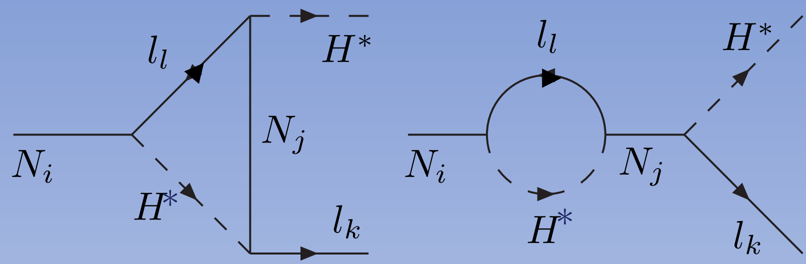
  Bertuzzo, Di Bari, Marzola '11

- CP-violating phase dependence: in one flavor approx. only 3 high-energy seesaw phases count with flavor: extra dependence on 3 low energy seesaw phases

  ↪ including δ_{PMNS} measurable in ν-oscillations

Flavor Leptogenesis: new flavor breaking L conserving CP asymmetries

L conserving (pure flavor) asymmetries



$\Rightarrow$ $$\varepsilon_\alpha^{\not F} \equiv \frac{\Gamma(N \to L_\alpha H) - \Gamma(N \to \bar{L}_\alpha \bar{H})}{\Gamma_N^{Tot}}$$

gives no contribution in one-flavor approx: $\sum_k \varepsilon_{N_k}^{\not F} = 0$

but has in reality a non-zero contribution: if $\varepsilon_\tau^{\not F} = -\varepsilon_{e+\mu}^{\not F} \neq 0$

can be not washed out | can be largely washed out $\Rightarrow$ a net L asym. remains

generically subleading because suppressed by a $\frac{m_{N_1}^2}{m_{N_{2,3}}^2}$ factor

except in setups with approximate lepton number violation where it can give the dominant contribution and lead to successful leptogenesis

"Purely flavored leptogenesis"

(not so easy to cook in type-I but possible)

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

A series of additional ingredients

- Finite temperature corrections ← mostly important for $T >> M_N$: weak washout regime $\left.\frac{\Gamma_N}{H}\right|_{T=M_N} << 1$

  Covi, Vissani '97
  Giudice et al '03
  Garbrecht, Prokopec, Schmidt '04
  Kiessig, Plumacher '11, ...

- "Spectator effects": through SM Yukawa interact. a part of left-handed lepton asym. created is transferred to right-handed asym.

  Barbieri, Creminelli, Strumia, Tetradis '98; Buchmuller, Plumacher '01; Nardi, Nir, Racker, Roulet '06; Abada, Josse-Michaux '07

  ↓ has Yukawa interact. with $N's$, has sphaleron interact.

  ↓ has no Yukawa interact. with $N's$, has no sphaleron interact.

- CP-violating contribution of scattering processes ← mostly relevant for $T >> M_N$:

  $l\,N \leftrightarrow b\,\bar{t}, \ldots$

  Abada, Davidson, Ibarra, Josse-Michaux, Riotto '06; Fong, Gonzalez-Garcia, Racker '11

- Deviation from Maxwell-Boltzmann momentum distribution effect ← mostly (mildly) relevant for weak washout regime where kinetic equilib. is not reached

  Basboll, Hannestad '07; Hahn-Woernle, Plumacher, Wong '09; Garayoa, pastor, Pinto, Rius, Vives '09

- Quantum Boltzmann equation treatment:

  mostly relevant: - for weak washout regime $\left.\frac{\Gamma_N}{H}\right|_{T=M_N} << 1$

  - for quasi-degenerate case: $M_{N_1} - M_{N_2} \lesssim \Gamma_{N_{1,2}}$

  takes into account memory effects, off-shell effects, finite density effects, flavor oscillations, decoherence

  Buchmüller, Fredenhagen '00
  De Simone, Riotto '07
  Cirigliano, Isidori, Masina, Riotto, '08
  Anisimov, Buchmüller, Drewes, Mendizabal '08
  Garny, Hohenegger, Kartavtsev, Lindner '09
  Garny, Hohenegger, Kartavtsev, '11
  Garbrecht, Herranen '11
  Cirigliano, Lee, Ramsey-Musolf, Tulin '13,
  Bhupal Dev, Millington, Pilaftsis, Teresi '14
  ....

  see D. Teresi and P. Millington talks

An alternative scenario: leptogenesis from N oscillations

3 step scenario:

Akhmedov, Rubakov, Smirnov '98

1) Creation of right-handed neutrinos after reheating:

$$n_{N_A} = n_{\bar{N}_A},\ n_{N_B} = n_{\bar{N}_B},\ n_{N_C} = n_{\bar{N}_C},$$

↓

no L asymmetry at this stage

$$\mathcal{L} \ni Y_{Na}\,\bar{l}_a N_{Ra} H + \frac{1}{2} M_{N_{ab}} N^c_{Ra} N_{Rb}$$

diagonal Yukawa matrix basis

2) N oscillations: $N_A \leftrightarrow N_B,\ N_A \leftrightarrow N_C,\ N_B \leftrightarrow N_C,$ $\quad \bar{N}_A \leftrightarrow \bar{N}_B,\ \bar{N}_A \leftrightarrow \bar{N}_C,\ \bar{N}_B \leftrightarrow \bar{N}_C,$

CP-violation in $M_{N_{ab}}$

⇓

$$n_{N_A} \neq n_{\bar{N}_A},\ n_{N_B} \neq n_{\bar{N}_B},\ n_{N_C} \neq n_{\bar{N}_C},$$

but still with L approximately conserved:

$$n_{N_A} + n_{N_B} + n_{N_C} = n_{\bar{N}_A} + n_{\bar{N}_B} + n_{\bar{N}_C}$$

An alternative scenario: leptogenesis from N oscillations

Akhmedov, Rubakov, Smirnov '98

3) Assume: - on the one hand: $Y_{N_{A,B}}$ large enough for $\Gamma^{Yuk.}_{N_{A,B}} > H$ before sphaleron decoupling:

$T_{sphaleron} \simeq 140$ GeV

$n_{N_{A,B}} - n_{\bar{N}_{A,B}}$ asymmetries

⇓ Yukawa interact.

$n_l - n_{\bar{l}}$ lepton asymmetry

⇓ sphalerons

$n_b - n_{\bar{b}}$ baryon asymmetry

- on the other hand: Y_{N_C} small enough for $\Gamma^{Yuk.}_{N_C} < H$ before sphaleron decoupling:

$n_{N_C} - n_{\bar{N}_C}$ asymmetry $= -(n_{N_A} - n_{\bar{N}_A}) - (n_{N_B} - n_{\bar{N}_B})$

⇓ Yukawa interact. but only at $T < T_{sphaleron}$ when N_C disappear by decaying to leptons

$n_l - n_{\bar{l}}$ lepton asymmetry

~~⇓~~ sphalerons

$n_b - n_{\bar{b}}$ baryon asymmetry

⇒ final net baryon asymmetry

An alternative scenario: leptogenesis from N oscillations

In practice: requires:

- N masses small: $1\,\mathrm{GeV} \lesssim m_{N_{A,B,C}} \lesssim 100\,\mathrm{GeV}$

  to avoid $N's$ are decaying during BBN

  to avoid too fast $N_i \leftrightarrow \bar{N}_i$ processes putting $n_{N_i} - n_{\bar{N}_i}$ asym. to 0

- Yukawa couplings in agreement with neutrino mass constraints

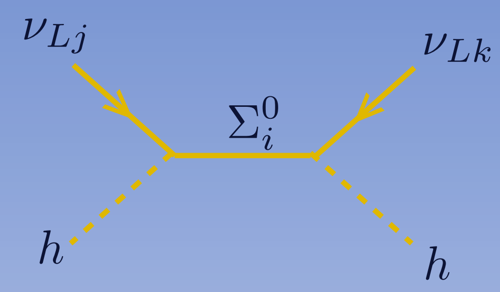
⇒ recently reconsidered in details with flavor effects included,.... Drewes, Garbrecht '13

↪ works very well in multi GeV range

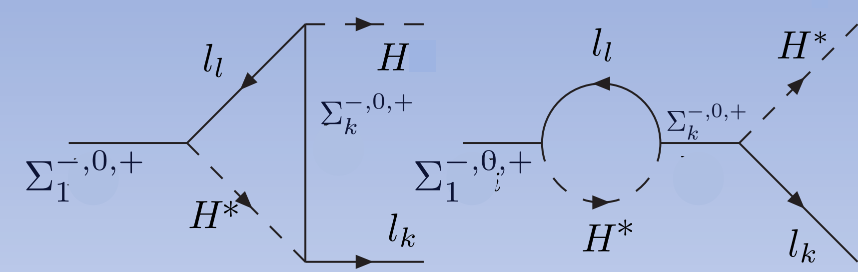
Type-III leptogenesis: decays of fermion triplets: $\Sigma_i \equiv (\Sigma_i^+, \Sigma_i^0, \Sigma_i^-)$

TH,Lin,Notari,Papucci,Strumia '03

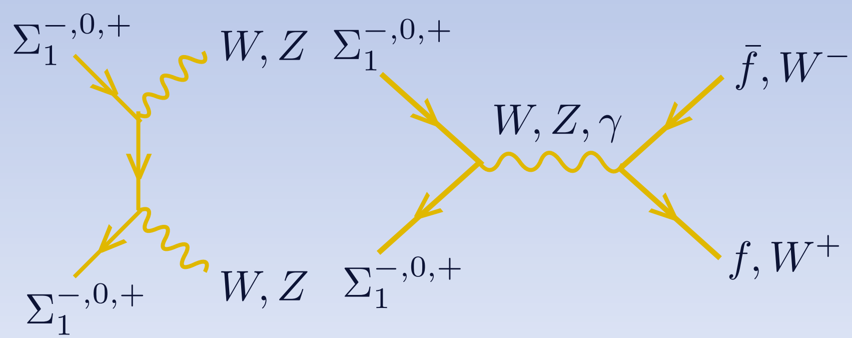
- generation of ν masses unchanged: $\Sigma_i^0 \leftrightarrow N_i$



- leptogenesis diagrams involve both neutral and charged seesaw states:



- important difference: gauge scatterings:



are in thermal equilibr. for $T \lesssim 10^{13,14}\,\mathrm{GeV}$

number of gauge scatter. per time per unit volume: γ_A

number of decay per time per unit volume: γ_D

$\Rightarrow$ asymmetry produced suppressed by γ_D/γ_A factor

Type-III seesaw bounds

Hierarchical Σ mass spectrum:

$$m_\Sigma > 1.5 \cdot 10^{10}\,\mathrm{GeV}$$

TH,Lin,Notari,Papucci,Strumia '03

Quasi-degenerate Σ mass spectrum:

$$m_\Sigma > 1.6\,\mathrm{TeV}$$

← is above LHC reach: $m_\Sigma \lesssim 1\,\mathrm{TeV}$

TH,Raidal,Strumia '06

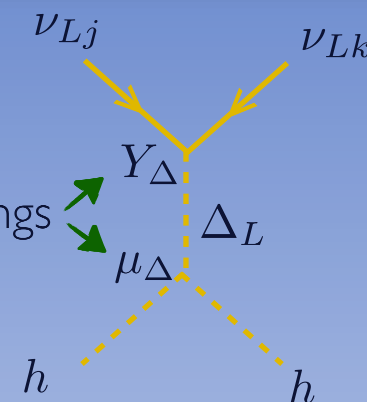
Strumia '09

Franceschini, TH, Strumia '07, ...

PS: flavor effects work the same way as in type-I except that when $\gamma_A > \gamma_D$ they are totally irrelevant (gauge scattering are flavor blind)

Aristizabal, Kamenek, Nemvesek, '10
TH '12

Type-II leptogenesis: decays of a scalar triplet: $\Delta_L = (\Delta_L^{++}, \Delta_L^{+}, \Delta_L^{0})$



→ different from type-I leptogenesis in quite many respects:

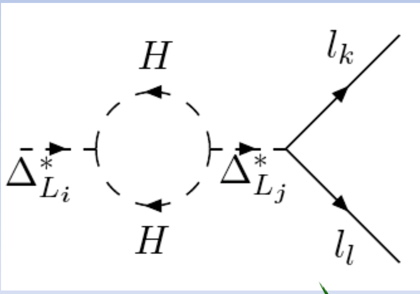
- a single seesaw state Δ_L can account for all ν masses from 2 types of couplings (unlike type-I and III)

- a single seesaw state Δ_L cannot account for leptogenesis (like type-I and III)

→ need for another (heavier) seesaw state

a second Δ_L : Δ_{L1}, Δ_{L2}

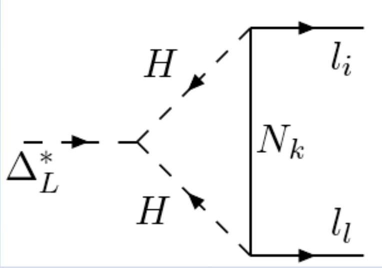
fermion singlet(s): $\Delta_L + N_i$ ← L-R and SO(10) models



Ma, Sarkar '98

TH, Ma, Sarkar '02

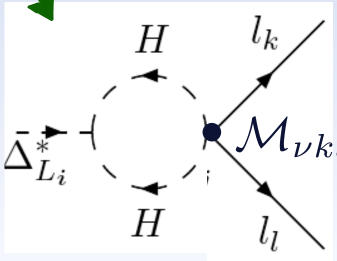
TH, Raidal, Strumia '06



TH, Senjanovic '03

TH, Raidal, Strumia '06

in the hierarchical limit $m_{\Delta_{L1}} << m_{\Delta_{L2}}, m_{N_i}$



← from any heavier source of m_ν : $\Delta_{L_2}, N_i, \ldots$

Antusch, King '04

Type-II leptogenesis: decays of a scalar triplet: $\Delta_L = (\Delta_L^{++}, \Delta_L^{+}, \Delta_L^{0})$

TH, Raidal, Strumia '06

- a Δ_L is not a self-conjugate particle multiplet

(unlike type-I and III)

↓

one more Boltzmann equation: for $n_\Delta - n_{\bar{\Delta}}$ asymmetry

⇒ doesn't change the typical leptogenesis scale:

Hierarchical mass spectrum: $m_{\Delta_{L1}} << m_{\Delta_{L2}}, m_{N_i}$: $m_\Delta > 3 \cdot 10^{10}\,\mathrm{GeV}$

Quasi-degenerate mass spectrum: $m_{\Delta_{L1}} \sim m_{\Delta_{L2}}$: $m_\Delta > 1.6\,\mathrm{TeV}$

TH,Raidal,Strumia '06

Strumia '09

⇒ but does change a lot the asym. creation dynamics!

↪ creation of a $\Delta - \bar{\Delta}$ asym. first, reprocessed in a L asym. later on

↪ allows to avoid any efficiency suppression: if $Br(\Delta_L \to LL) >> Br(\Delta_L \to HH)$

Type-II leptogenesis: flavor effects

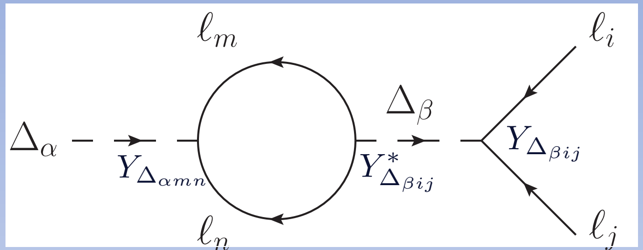
Aristizabal, Dhen, TH 14

Felipe, Joachim, Serodio 13

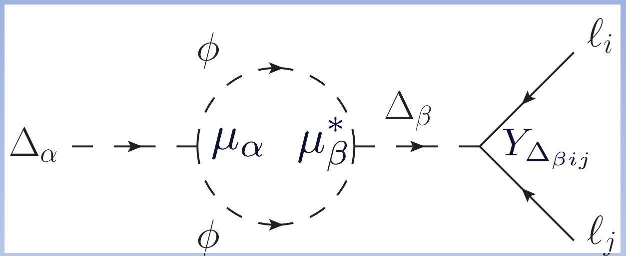
highly complex interplay of Boltzmann equations

→ one example of interesting flavour feature for the case with a second scalar triplet:

L conserving, flavour violating CP asym.



L violating, flavour violating CP asym.



$$\varepsilon^{\not F}_{ij} \equiv \frac{\Gamma(\Delta \to L_i L_j) - \Gamma(\bar{\Delta} \to \bar{L}_i \bar{L}_j)}{\Gamma^{Tot}_{\Delta} + \Gamma^{Tot}_{\bar{\Delta}}} \propto Y^4_\Delta \quad >> \quad \varepsilon^{\not L}_{ij} \equiv \frac{\Gamma(\Delta \to L_i L_j) - \Gamma(\bar{\Delta} \to \bar{L}_i \bar{L}_j)}{\Gamma^{Tot}_{\Delta} + \Gamma^{Tot}_{\bar{\Delta}}} \propto Y^2_\Delta \frac{\mu^2}{m^2_\Delta}$$

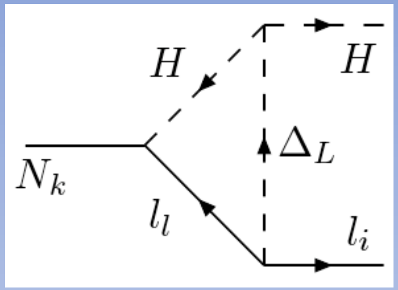
as soon as the Δ couple more to leptons than to scalars

⇒ Purely Flavoured Leptogenesis generically dominant for a very large part of parameter space

Type-I+ Type-II: contribution of Δ_L to N CP-asymmetry

L-R and SO(10) models

if $M_N << m_\Delta$ the N decays dominate naturally leptogenesis
but still there is a triplet contribution to the CP-asymmetry



TH, Senjanovic '03

can easily be dominant (e.g. if m_ν dominated by type-II contribution)
and lead to successful leptogenesis

see also Antusch, King '04

What about SUSY for leptogenesis?

SUSY seesaw leptogenesis works the same way as non-SUSY case up to factors of O(1)

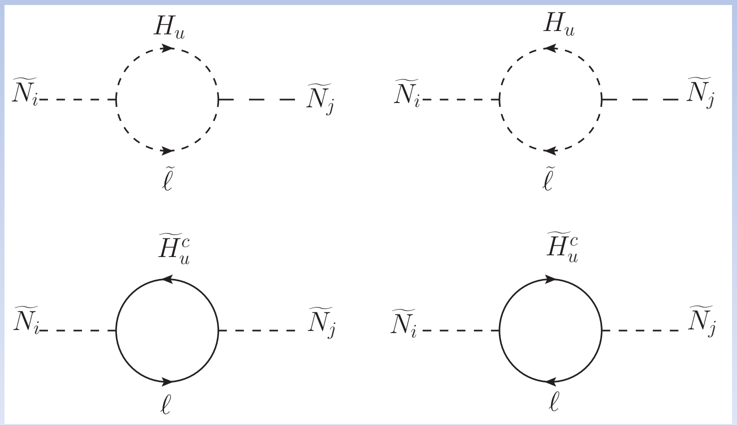
in addition it allows new scenarios: "Soft leptogenesis"

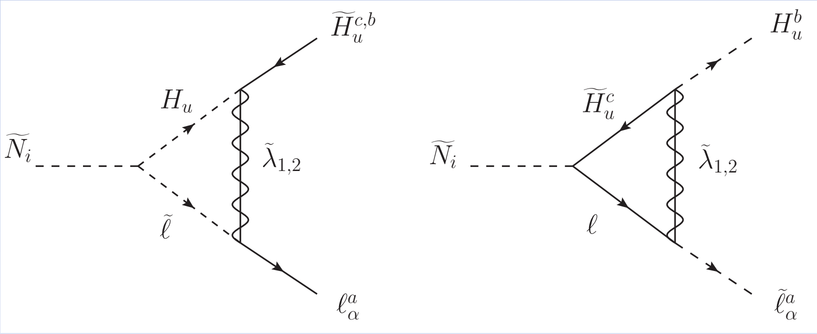
right-handed sneutrinos soft terms bring new source of L violation and CP violation

Boubekeur '02;
D'Ambrosio, Giudice, Raidal '03;
Grossman, Kashti, Nir, Roulet '03;

$$\mathcal{L}_{soft} \ni (-AY_{N_{i\alpha}}\tilde{N}_i\tilde{l}_\alpha H_u - \frac{1}{2}BM_i\tilde{N}_i\tilde{N}_i + h.c.) - \tilde{M}^2_{ij}\tilde{N}^*_i\tilde{N}_j$$

⇒ CP asymmetry from 1-loop self energy and vertex diagrams





D'Ambrosio, Giudice, Raidal '03;
Grossman, Kashti, Nir, Roulet '03;
D'Ambrosio, TH, Hektor, Rossi, Raidal '04;

can work typically within the range: $10^3\ \mathrm{GeV} \lesssim m_{\tilde{N}} \lesssim 10^9\ \mathrm{GeV}$

see recent review: Fong, Gonzalez-Garcia, Nardi '12

Testing low scale leptogenesis at colliders?

↪ by producing low scale seesaw states at colliders?

$Y_N \sim 10^{-6}$ for $M_N \sim 1\,\mathrm{TeV}$

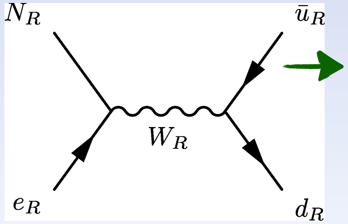
- type-I: very difficult:
  - → Yukawa couplings are expected far too small to allow N production
  - in special cases larger Y_N are allowed, (Dev, Millington, Pilaftsis, Teresi '14)
    - ↪ allowing N production + observable charged lepton flavor violation: $\mu \to e\gamma$, $\mu \to eee$, $R^{Al}_{\mu\to e}$, ...
  - → production mechanisms other than Yukawa
- type-II and type-III: Drell-Yan pair production mechanisms

problem: production interactions tend to thermalize the seesaw state ⇒ leptogenesis suppressions!

↪ SM gauge interact, for type-II and III: $m_{\Delta,\Sigma} > 1.6\,\mathrm{TeV}$ → too large for LHC

↪ N production via Z': similar bounds as for type-II/III (see Plumacher et al, Frère et al, Babu et al, Fileviez-Perez et al,...)

↪ N production via W_R : much more dramatic thermalization effect!



→ involves only one heavy external state instead of two (Frère, TH, Vertongen '07)

⇒ only one Boltzm. suppression power instead of 2

scattering is never slower than the decay ⇒ $m_{W_R} \gtrsim 18\,\mathrm{TeV}$

↪ L-violating signal observation at LHC would lead to lower bound on washout (see J. Harz talk)

High scale leptogenesis tests?

- in SUSY neutrino mass matrix knowledge and rare lepton flavour violating processes allows to reconstruct in principle the full seesaw lagrangian

Davidson, Ibarra '03

  the model can be overconstrained by the baryon asymmetry constraint

  but basically impossible to do in practice and based on the difficult to test assumption of universality of soft terms

- in specific GUT models one can have a closer relation between neutrino data and leptogenesis: we miss a successful example of one-to-one correspondance

  e.g. normalization factors as overall seesaw scale are left free and leptogenesis crucially depends on them

see for example Frigerio, Hosteins, Lavignac, Romanino '08

- or as well known if neutrinos are proven to have inverted hierarchy or quasi-degenerate with no corresponding $0\nu2\beta$ signal, usual seesaw falsified

Leptogenesis at TeV scale with non seesaw neutrino mass sources

several mechanisms: - resonance

- hierarchy of L -violating couplings with radiative neutrino masses TH '02
- 3-body decays with radiative neutrino masses TH '02
- radiative seesaw neutrino masses Ma '07; TH, Ling, Lopez-Honorez, Rocher '08; Gu, Sarkar '08
- ....

many possibilities: - $N_i + S^+$: - 3-body decays TH '02

- hierarchy of couplings Frigerio, TH, Ma '02

- 4th generation of leptons: hierarchy of couplings Abada, Losada '03

- soft leptogenesis: - resonance Boubekeur '02; Giudice et al. '03; Grossman et al '04; TH, March-Russel, West '04

- hierarchy of couplings with radiative m_ν Boubekeur, TH, Senjanovic '04
- ε' type CP-violation Grossman, Kashti, Nir, Roulet '04

- N_i + Dark Matter inert Higgs doublet: hierarchical couplings

Ma '07; TH, Ling, Lopez-Honorez, Rocher '08; Gu, Sarkar '08

- scalar singlet + scalar triplet Gu, He, Sarkar, Zhang '09
- scalar singlet + extra fermion triplet Patra '09
- N_i + various scalars Fong, Gonzalez-Garcia, Nardi, Peinado '13
- .....

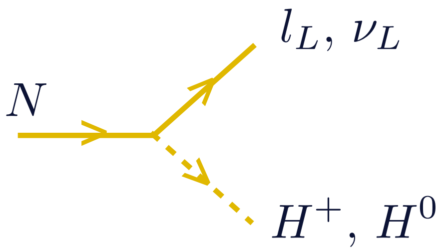
Some of these models are testable to a large extend at the price of giving up the seesaw and/or adding new fields

Very short conclusion

Despite of the fact that to test leptogenesis remains a really tough problem, even more difficult than to test the seesaw, leptogenesis remains very well motivated and the most straightforward explanation we have for the baryon asymmetry of the Universe

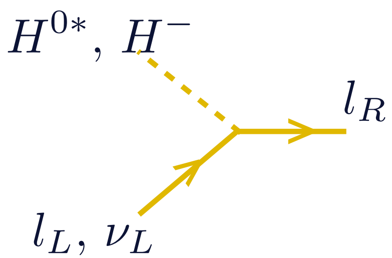
→ could have been very well realized in Nature!

Flavour leptogenesis: spectator process effects



⇒ L asymmetry created in left-handed lepton sector

Nardi, Nir, Racker, Roulet '06

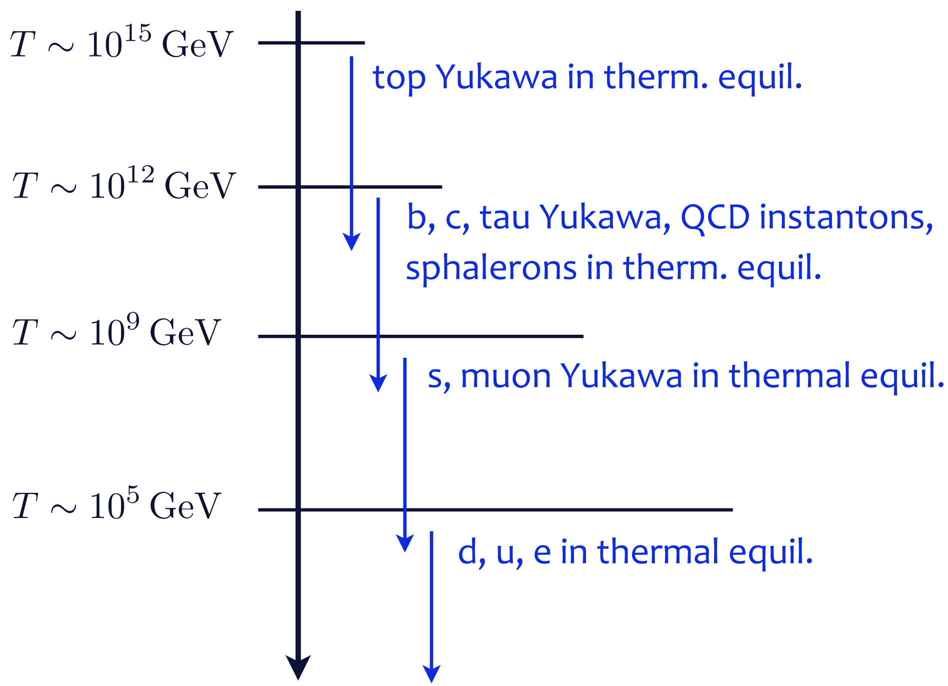


⇒ part of L asymmetry transferred to right-handed leptons

↓

- do not inverse decay to N
- do not undergo sphaleron transitions

→ only a part of L asym. is active in Boltzm. equat.



even quark Yukawa interact. have an effect when in thermal equilibrium through asym. redistribution

→ quite moderate effect

"spectator processes"

Given the neutrino data: no relevant bound on m_ν from leptogenesis

If for example $m_\nu = 2.2\,\mathrm{eV}$ the m_{ν_i} are highly degenerate

↓

to get such a m_{ν_i} spectrum it is much easier to assume $M_{N_1} \simeq M_{N_2} \simeq M_{N_3}$

$$m_\nu \sim Y_N^T \frac{1}{M_N} Y_N \, v^2$$

↓

a resonance occurs in the asymmetry

↓

leptogenesis easily successful

TH, Lin, Notari, Papucci, Strumia '03

An upper bound only if the N_i have hierarchical spectrum: $m_\nu \leq 0.12\,\mathrm{eV}$

↓

Buchmüller, Di Bari, Plumacher '02, '03
Giudice, Notari, Raidal, Strumia '03
TH, Lin, Notari, Papucci, Strumia '03

2 suppression effects in this case

↙ ↘

washout $\nearrow$ when $m_\nu \nearrow$

$$\Gamma_{N_1}/H(T = M_{N_1}) \geq m_\nu^{Min}/10^{-3}\,\mathrm{eV}$$

$\varepsilon_N \searrow$ when $m_\nu \nearrow$

$$\varepsilon_{N_1} \leq M_{N_1} \frac{3}{8\pi} \frac{1}{v^2} \frac{\Delta m^2_{atm}}{m_{\nu_3} + m_{\nu_1}}$$

Davidson, Ibarra '02

the $m_\nu \lesssim 0.12\,\mathrm{eV}$ one-flavor bound for N_i hierarchical spectrum can be largely relaxed (but was for an unlikely situation anyway)

Riotto et al. '06

Flavour leptogenesis: mass bounds with flavour

- the $M_{N_1} \gtrsim 4 \cdot 10^8\,\mathrm{GeV}$ bound essentially unaffected — see Antusch, Blanchet, Blennow, Fermandez-Martinez '10; Racker, Pena, Rius '12

- the $m_\nu \lesssim 0.12\,\mathrm{eV}$ one-flavor bound for N_i hierarchical spectrum can be largely relaxed (but was for an unlikely situation anyway) — Riotto et al. '06

Flavour leptogenesis: effect of low energy PMNS phase

effect of low energy phases: in one flavor approx. leptogenesis depends only on the 3 high energy phases

→ with several flavours it depends in addition on the 3 low energy phases (in PMNS matrix)

Pascoli, Petcov, Riotto '06

→ with flavour the PMNS Dirac phase alone can lead to successful leptogenesis

→ without flavour such a non zero phase would also basically imply leptogenesis because no reason from the UV physics point of view to have only the low-energy phases: UV doesn't care about low energy phenomenological phase values

Flavour leptogenesis: N_2 leptogenesis

Vives '05; Engelhard, Grossman, Nardi, Nir '06; Blanchet, Di Bari '08

"N_2 leptogenesis": in one flavour approx: asym. created by $N_{2,3}$ very easily washed out by N_1

→ not true anymore with several flavours for special cases with different flavour hierarchies between various N_i

→ interesting for SO(10) models which in simplest version give

$$m_{N_1} << m_{N_2} << m_{N_3} \Rightarrow m_{N_1} < 10^8 \, \mathrm{GeV}$$

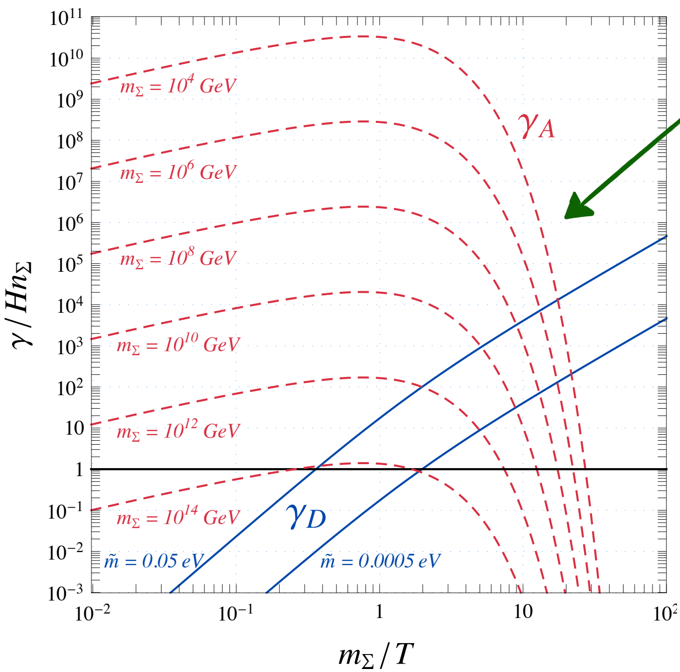
Gauge scattering thermalization effect

$\Delta\bar{\Delta} \leftrightarrow W^+W^-, ZZ, f\bar{f}, \ldots$

$\Sigma\bar{\Sigma} \leftrightarrow W^+W^-, ZZ, f\bar{f}, \ldots$

→ put the $\Delta,\ \Sigma$ into thermal equilibrium

suppression effect as long as $\Delta,\ \Sigma$ gauge scatter before it decays, i.e. as long as: $\dfrac{\gamma_A}{n^{Eq}_{\Delta,\Sigma}} \gtrsim \dfrac{\gamma_D}{n^{Eq}_{\Delta,\Sigma}}$



at $z = m_{\Delta,\Sigma}/T > 1$, γ_A gets more Boltzmann suppressed than γ_D

before $z \lesssim z_A$ (where $\gamma_A = \gamma_D$), Y_L suppressed by γ_D/γ_A factor

after $z \gtrsim z_A$, Y_L Boltzm. suppressed by little amount of $\Delta,\ \Sigma$ remaining $Y^{eq}_{\Delta,\Sigma}$

⇒ model and flavor independent bound on lepton asymmetry produced — TH '12

$$Y_L \lesssim \varepsilon_{\Delta,\Sigma} \int_{z_{in}}^{z_A} \frac{dY^{Eq}_{\Delta,\Sigma}}{dz} \frac{\gamma_D}{4\gamma_A} dz + \varepsilon_{\Delta,\Sigma} Y^{Eq}_{\Delta,\Sigma} \simeq \varepsilon_{\Delta,\Sigma}\, Y^{Eq}_{\Delta,\Sigma}(z_A)\,(z_A/4+1)$$