Leptogenesis: where do we stand?

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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

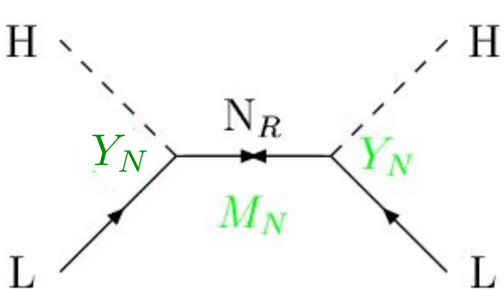
Leptogenesis:
both origins are the same

The 3 seesaw models

Right-handed singlet:
(type-I seesaw)

$$N_{R_i}$$

$$\mathcal{L} \ni -Y_{N_{ij}} \bar{N}_i L_j H - \frac{m_{N_i}}{2} \overline{N_i^c} N_i + h.c.$$



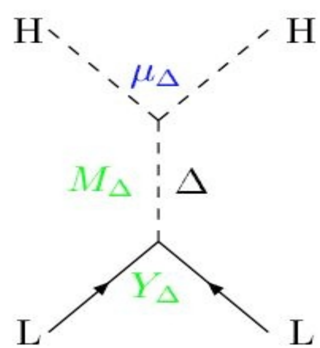
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

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

Scalar triplet:
(type-II seesaw)

$$\Delta \equiv (\Delta^{++}, \Delta^{+}, \Delta^{0})$$

$$\mathcal{L} \ni -Y_\Delta \Delta L_i L_j - \mu_\Delta \Delta H H + h.c.$$



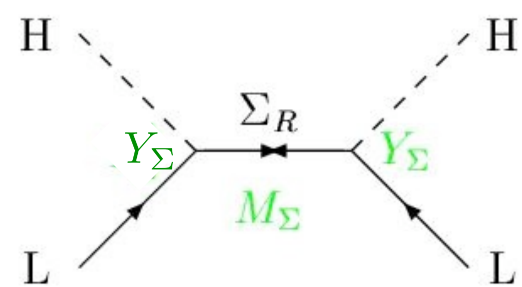
$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

Fermion triplet:
(type-III seesaw)

$$\Sigma_i \equiv (\Sigma_i^{+}, \Sigma_i^{0}, \Sigma_i^{-})$$

$$\mathcal{L} \ni -Y_{\Sigma_{ij}} \bar{\Sigma}_i L_j H - \frac{m_{\Sigma_i}}{2} \overline{\Sigma_i^c} \Sigma_i + h.c.$$



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

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

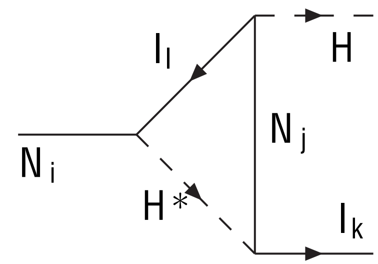
The 3 leptogenesis ingredients

first in type-I with one flavour approximation

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

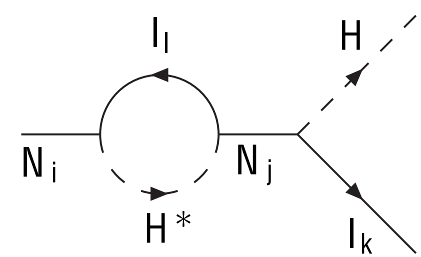
$$\varepsilon_{N_i} = \sum_k \frac{\Gamma(N_i \to L_k H) - \Gamma(N_i \to \bar{L}_k H^*)}{\Gamma^{\rm TOT}_{N_i}}$$

⇒ 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

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

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

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

$\eta << 1 \quad \leftarrow \quad$ thermal equilibrium

can be obtained integrating the Boltzmann equations:

$Y_N = n_N/s$

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

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

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

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

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

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

$$T^{Sphal.}_{Decoupl.} \sim 140\,\mathrm{GeV}$$

$\Rightarrow$ put B+L to ~ 0 but conserving B-L:

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

$\Downarrow$

$$\frac{n_B}{s} \simeq -\frac{1}{2}\frac{n_L}{s} = -\frac{1}{2}\,\eta\,\varepsilon_{N_i}\,\left.\frac{n_{N_i}}{s}\right|_{T>>M_{N_i}}$$

$\updownarrow$

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

WMAP
Planck

Two intriguing numerical coincidences

- The seesaw state mass (slight) coincidence:
  - for a hierarchical spectrum of N_i: $\varepsilon_{N_1} \leq M_{N_1} \frac{3}{8\pi} \frac{1}{v^2} \sqrt{\Delta m^2_{atm}}$

Barbieri et al '00,;T.H. '01; Davidson, Ibarra '02,....

$$\Downarrow$$

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

$$\uparrow$$

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 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} bounded from below only by shaleron decoupling scale: $M_{N_1} \gtrsim 2.6\,\text{GeV}$

Frère, TH, Vertongen '07

Two intriguing numerical coincidences

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

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

→ 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 give quite large washout

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_ν $\nearrow$

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

ε_N $\searrow$ when m_ν $\nearrow$

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

Davidson, Ibarra '02

Flavour issues in leptogenesis

so far all results were obtained by considering only the Boltzmann equation of total lepton number

- justified for $T \gtrsim 10^{12}\,\mathrm{GeV}$: e^-, μ^-, τ^- indistinguishable
  - same gauge interactions
  - 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 issues in leptogenesis

- however for $T \lesssim 10^{12}\,\mathrm{GeV}$: SM τ Yukawa interaction enters into thermal equilibr.

⇒ the 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:

the thermal bath distinguish the τ from $e + \mu$ ⇒ 2 Boltzmann equations each one with its flavour asym.

$$\varepsilon_{N_\alpha} \equiv \frac{\Gamma(N \to L_\alpha H) - \Gamma(N \to \bar{L}_\alpha \bar{H})}{\Gamma_N^{Tot}}$$

$$\alpha = \tau, e + \mu$$

⇒ various kinds of effects:

Barbieri, Creminelli, Strumia, Tetradis '99; Pilaftsis '05 (prelim.)
Abada, Davidson, Josse-Michaux, Losada, Riotto '06
Nardi, Nir, Roulet, Racker '06
Abada et al. '06; Blanchet et al '06
Pascoli, Petcov, Riotto '07; Aristizabal, Alfredo Munoz, Nardi '09; Garbrecht et al '09
....

- effects of flavour hierarchies:

  example: if N decays much faster than H :

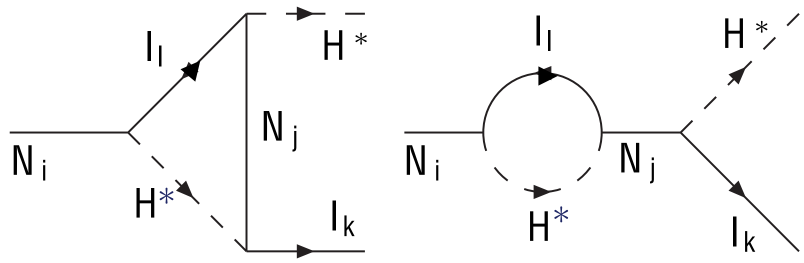
  in one flavour approx.: strong washout

  in two flavour case: possibility of less washout

  ↪ e.g. if $\Gamma(N \to L_{e+\mu} H) >> \Gamma(N \to L_\tau H)$ smaller Y_τ washout and large Y_τ asym. produced, especially if $\varepsilon_{N_\tau} > \varepsilon_{N_{e+\mu}}$

Flavour issues in leptogenesis

- effects of L conserving (pure flavour) asymmetries



$\Rightarrow \quad \varepsilon_{N_k}^{\not{F}}$

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

but has in reality a non-zero contribution, 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"

(possible even if no special need for that)

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

Flavour issues in leptogenesis

- in equilibrium SM Yukawa interaction: transfer of part of L-asymmetry to right-handed charged lepton "spectator processes"
  - → quite moderate effect — Nardi, Nir, Racker, Roulet '06

- "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

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

- 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

Mass bounds with flavor

- 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 a likely situation anyway)

Riotto et al. '06

Finite temperature, finite density and quantum Boltzmann equation studies

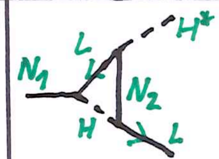
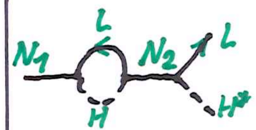
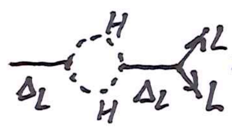
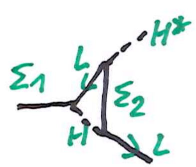
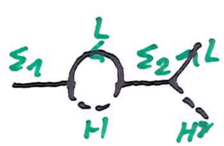
Covi, Vissani '97
Giudice et al '03
Garbrecht, Prokopec, Schmidt '04
......

Beneke, Garbrecht, Herannen, Schwaller '10
....

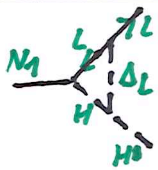
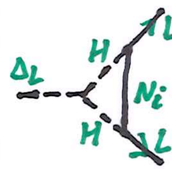
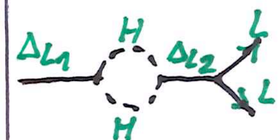
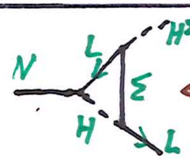
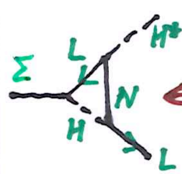
Buchmüller, Fredenhagen '00
De Simone, Riotto '07
Cirigliano, Isidori, Masina, Riotto, '08
Anisimov, Buchmüller, Drewes, Mendizabal '08
Garny, Hohenegger, Kartavtsev, Lindner '09
Cirigliano, Lee, Ramsey-Musolf, Tulin '13
Garbrecht et al '08-'13
....

quite interesting theoretically,
small effect on bounds,
numerically relevant in particular cases, e.g. for extreme quasi-degenerate N_i spectrum

Leptogenesis in Seesaw Models

Seesaw type	GUT embedding	Leptogenesis diagrams	Leptogenesis peculiarity	Seesaw state mass bounds	Leptog. for any values of $\theta_{ij}, \delta, \alpha, \beta$?
Type-I N_i	VERY NATURAL ⇓ NON-RENORMAL. SO(10) MODELS	 FUKUGIDA-YANAGIDA 86'  LIU, SEGRÉ 90' FLANZ, PASCHOS, SARKAR 94' COVI, ROULET, VISSANI 94'	VERTEX + SELF-ENERGY	$M_{N_1} > 4 \cdot 10^8$ GeV ($M_{N_1} \ll M_{N_{2,3}}$) $M_{N_1} > 2.6$ GeV ($M_{N_1} \sim M_{N_2}$)	YES!
Type-II Δ_L	NATURAL	NO DIAGRAM! ↳  : DOESN'T BREAK CP!	NO LEPTOGENESIS!	/	/
Type-III Σ_i	POSSIBLE	  TH, LIN, NOTARI, PAPUCCI, STRUMIA 03'	VERTEX + SELF-ENERGY; Σ_i ARE THERMALIZED BY GAUGE INTERACTIONS ⇓ EXTRA WASHOUT!	$M_{\Sigma_1} > 1.5 \cdot 10^{10}$ GeV ($M_{\Sigma_1} \ll M_{\Sigma_{2,3}}$) T.H., LIN, NOTARI, PAPUCCI STRUMIA 03' STRUMIA 07' $M_{\Sigma_1} > 1.6$ TeV ($M_{\Sigma_1} \sim M_{\Sigma_2}$)	YES!

LEPTOGENESIS IN COMBINED SEESAW MODELS

SEESAW TYPE	GUT EMBEDDING	LEPTOGENESIS DIAGRAMS	LEPTOGENESIS PECULIARITY	SEESAW STATE MASS BOUNDS	LEPTOG. FOR ANY VALUES OF $\theta_{ij}, \delta, \alpha, \beta$?
TYPE-I + TYPE-II $N_i + \Delta_L$	VERY NATURAL ⇓ RENORMALIZABLE SO(10) MODELS (WHERE TRIPLET GIVES MASSES TO N_i)	 ← IF $M_{N_1} < M_{\Delta_L}$ O'DONNELL, SARKAR 94' T.H., SENJANOVIC 03'  ← IF $M_{\Delta_L} < M_{N_1}$	PURE VERTEX ⇓ NO RESONANCE ⇓ ONLY HIGH SCALE	← $M_{N_1} > 4 \cdot 10^8$ GeV (m_ν HIERARC.) $M_{N_1} \gtrsim 4 \cdot 10^7$ GeV ($m_\nu \sim 0.6$ eV) TH, SENJANOVIC 03' ANTUSCH, KING 03' ← $M_\Delta > 3 \cdot 10^{10}$ GeV (m_ν HIERARC.) $M_\Delta \gtrsim 3 \cdot 10^9$ GeV ($m_\nu \sim 0.6$ eV) TH, RAIDAL, STRUMIA 05'	YES!
TYPE-II + TYPE-II $\Delta_{L1} + \Delta_{L2}$	POSSIBLE	 MA, SARKAR 98'	PURE SELF-ENERGY	$M_\Delta > 3 \cdot 10^{10}$ GeV ($M_{\Delta_1} \ll M_{\Delta_2}$) TH, RAIDAL, STRUMIA 05' STRUMIA 07' $M_\Delta > 1.6$ TeV ($M_{\Delta_1} \sim M_{\Delta_2}$)	YES!
TYPE-I + TYPE-III $N + \Sigma$	NATURAL ⇓ ADJOINT SU(5) ↳ N, Σ IN SAME 24 REPRESENTAT°	 ← IF $M_N < M_\Sigma$ BAJC ET AL 07' E.G. FILEVIEZ-PEREZ ET AL 07'  ← IF $M_\Sigma < M_N$	PURE VERTEX ⇓ NO RESONANCE ⇓ ONLY HIGH SCALE	← $M_N > 4 \cdot 10^8$ GeV ($M_{N_1} < M_\Sigma$) ← $M_\Sigma > 1.5 \cdot 10^{10}$ GeV ($M_\Sigma < M_N$)	YES!

NB: dynamics of a decaying scalar triplet very different from a decaying N or Σ: one more Boltz. eq.: for $\Delta - \bar{\Delta}$ asymmetry

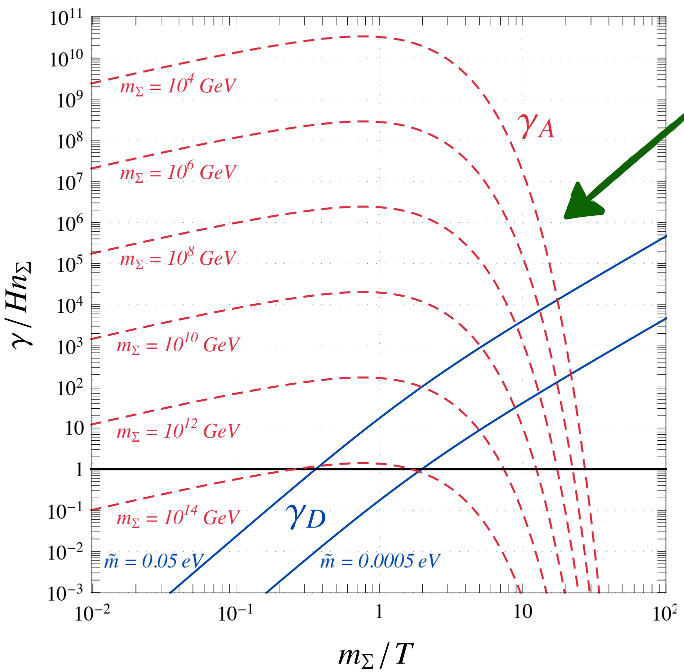
TH, Raidal, Strumia '07, TH '12

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 Δ, Σ into thermal equilibrium

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



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 Δ, Σ remaining $Y^{eq}_{\Delta,\Sigma}$

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

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

Testing low scale leptogenesis at colliders?

by producing low scale seesaw states at colliders?

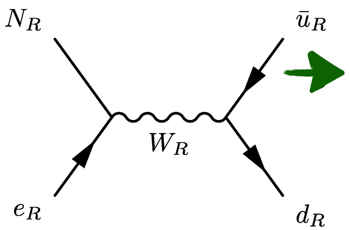
see F. del Aguila talk

- type-I: impossible unless:
  - Yukawa couplings are much larger than expected
  - production mechanims other than Yukawa

- type-II and type-III: Drell-Yan pair production mechanisms

problem: production interactions tend to thermalize the seesaw state $\Rightarrow$ 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
$\Rightarrow$ only one Boltzm. suppression power instead of 2
scattering is never slower than the decay $\Rightarrow$ $m_{W_R} \gtrsim 18\,\mathrm{TeV}$

Frère, TH, Vertongen '07

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 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
is the most straightforward and probably best motivated explanation
we have for the baryon asymmetry of the Universe

↪ could have been very well realized in Nature!