Title: Baryogenesis from L-violating Higgs doublet decay

Date: May 09, 2017 01:00 PM

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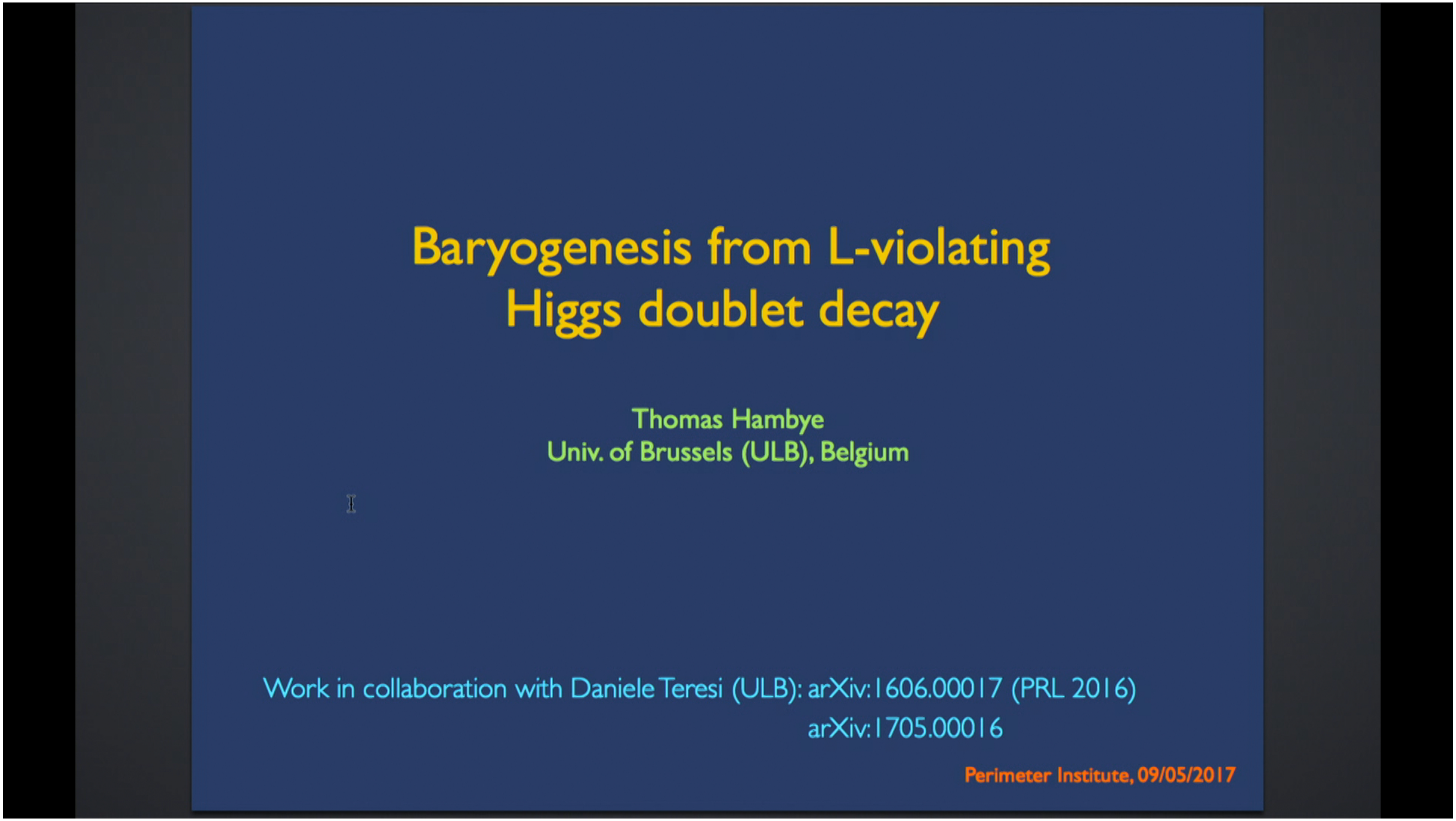
Abstract: <p>In the framework of the ordinary seesaw model with right-handed neutrinos (and nothing else) we show that the total lepton number violating decay of the Higgs doublet into a right-handed neutrino and a standard model lepton can successfully account for the baryon asymmetry of the Universe. This is possible thanks to thermal effects shortly before the sphalerons decouple.</p>



Baryogenesis from L-violating
Higgs doublet decay
Thomas Hambye
Univ. of Brussels (ULB), Belgium
Work in collaboration with Daniele Teresi (ULB): arXiv:1606.00017 (PRL 2016)
arXiv:1705.00016
Perimeter Institute, 09/05/2017

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

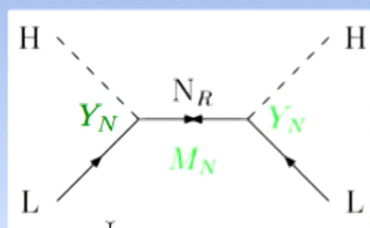
+ a series of numerical coincidences which makes it particularly effective

The 3 seesaw models

Fermion singlets: (type-I seesaw)

N_{R_i}

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



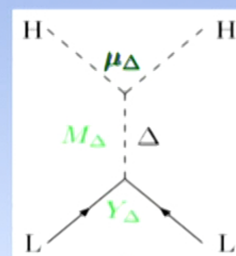
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

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

Scalar triplet: (type-II seesaw)

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

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



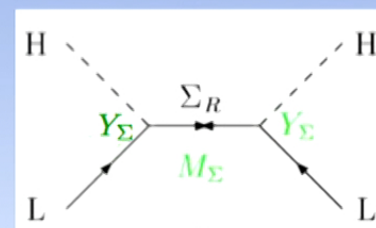
$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

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

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

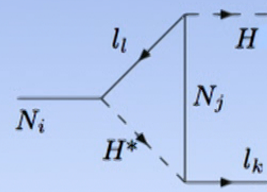
The 3 leptogenesis ingredients

first in type-I

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

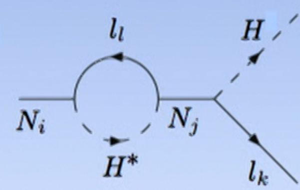
$$\varepsilon_{N_i} = \sum_k \frac{\Gamma(N_i \to L_k H) - \Gamma(N_i \to \bar{L}_k H^*)}{\Gamma^{TOT}_{N_i}}$$

⇒ 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

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

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

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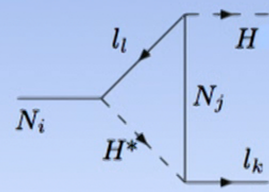

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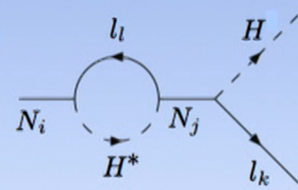

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⇒ $$Y_L \equiv \frac{n_L}{s} = \varepsilon_{N_i} \cdot \frac{n_{N_i}}{s}\Big|_{T>>M_{N_i}}$$

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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:

$$Y_N = n_N/s$$
$$Y_L = (n_l - n_{\bar{l}})/s$$
$$z \equiv \frac{M_N}{T}$$
$$\frac{\gamma_D}{H(T=M_N)} \equiv \frac{\Gamma_N^{TOT}}{H(T=M_N))}\frac{K_1(z)}{K_2(z)} n_N^{EQ}(z)$$

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

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

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 $\bar{l}\,H^* \to N \to l\,H$

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

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:

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

$$\Downarrow$$

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

$$\updownarrow$$

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

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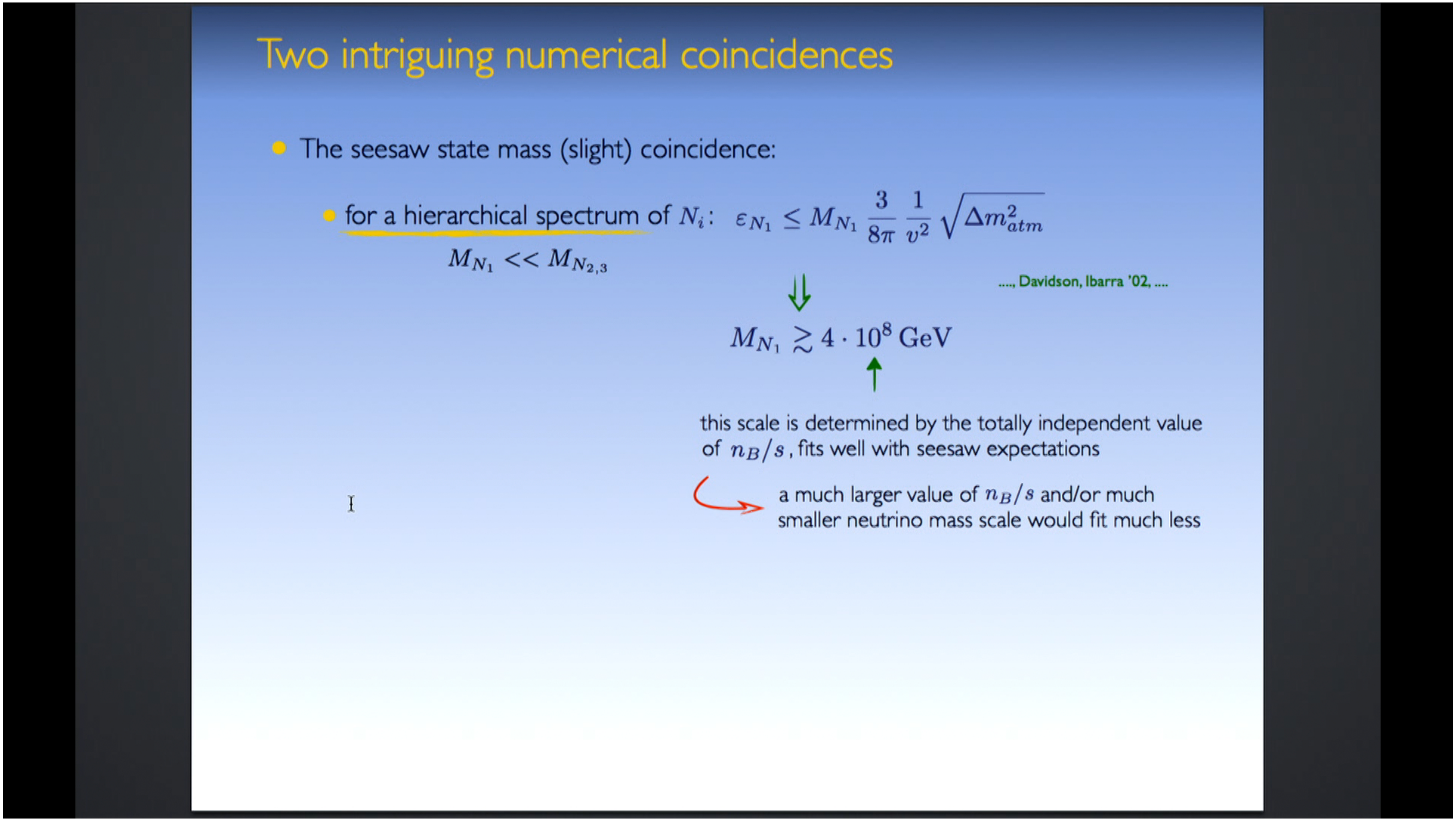
High scale leptogenesis (briefly)

↪ $m_N >>> v_{EW}$


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

Two intriguing numerical coincidences

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

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

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

..., Buchmuller, Di Bari, Plumacher, 96-2003, ...

→ 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

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

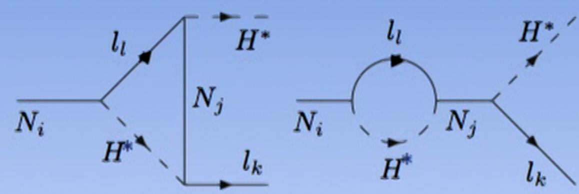
  same gauge interactions — SM charged Yukawa interactions out of equil.

⇒ 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: 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 $\varepsilon_\tau^{\not{F}} = -\varepsilon_{e+\mu}^{\not{F}} \neq 0$

- $\varepsilon_\tau^{\not{F}}$: can be not washed out
- $\varepsilon_{e+\mu}^{\not{F}}$: 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
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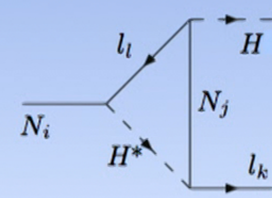

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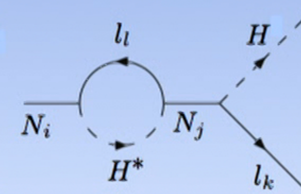

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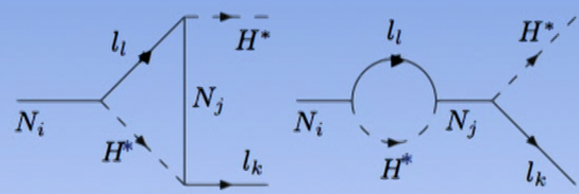

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Low scale leptogenesis

$\hookrightarrow m_N \gtrsim v_{EW}$

Going below the high scale lower bound on m_N

below $m_N > 4 \cdot 10^8\,\mathrm{GeV}$???

- in order to be able to produce the N
- not to be in tension with gravitino upper bound on reheating T $\quad T_{reh.} \lesssim 10^{8-9}\,\mathrm{GeV}$
- in order not to be in tension with naturalness

$$\delta m_h^2 \simeq \frac{1}{2\pi}\frac{m_\nu m_N^3}{v^2} \Rightarrow m_N < 3 \cdot 10^7\,\mathrm{GeV} \cdot \left(\frac{v}{246\,\mathrm{GeV}}\right)^{2/3}$$

$\delta m_H^2 < 1\,\mathrm{TeV}^2$

$\Rightarrow$ to lift up the naturalness problem:

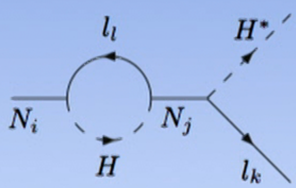
- regularize the radiative corrections: Susy, ... but gravitino problem
- to reduce the effective electroweak vev entering neutrino masses
- to consider a quasi-degenerate m_N spectrum

Going to lower m_N : resonance from quasi-degenerate spectrum

Covi, Roulet, Vissani 96'
Flanz, Paschos, Sarkar 96'

for a quasi-degenerate spectrum of N_i instead: resonance occurs:

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



$$\varepsilon_{CP} = \frac{\text{Im}[(Y_N Y_N^\dagger)^2_{12}]}{(Y_N Y_N^\dagger)_{11}(Y_N Y_N^\dagger)_{22}} \cdot \frac{2\,\Delta m_N\,\Gamma_N}{4\,(\Delta m_N)^2 + \Gamma_N^2}$$

- ε_{N_1} not bounded by value of M_{N_1} or m_ν
- M_{N_1} bounded from below only by sphaleron decoupling scale and m_h
- $M_{N_1} \sim \text{TeV}$ perfectly possible

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

a precise treatment of the resonant case requires inclusion of a series of extra effects, in particular quantum Boltzmann equations

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, '15
....

also relevant for weak washout regime $\frac{\Gamma_N}{H}\Big|_{T=M_N} << 1$

Testing low scale leptogenesis at colliders?

→ by producing low scale seesaw states at colliders?

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

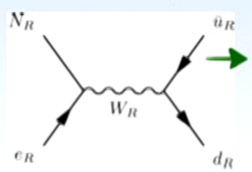
- type-I: very difficult:
  - → Yukawa couplings are expected far too small to allow N production
    - Dev, Millington, Pilaftsis, Teresi '14
    - in special cases larger Y_N are allowed,
    - → allowing N production + observable charged lepton flavor violation: $\mu \to e\gamma$, $\mu \to eee$, $R^{Al}_{\mu\to e}$, ...
  - → 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: $m_{\Delta,\Sigma} > 1.6\,\text{TeV}$ → 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 ⇒ $m_{W_R} \gtrsim 18\,\text{TeV}$

Dev, Lee, Mohapatra '14, '15

→ L-violating signal observation at LHC would lead to lower bound on washout

Very low scale leptogenesis

$\hookrightarrow m_N \sim \text{GeV} < v_{EW}$

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Leptogenesis from L-violating decay: relevant scales for low m_N

$T_{Sphaler.} \sim 135\,\mathrm{GeV}$

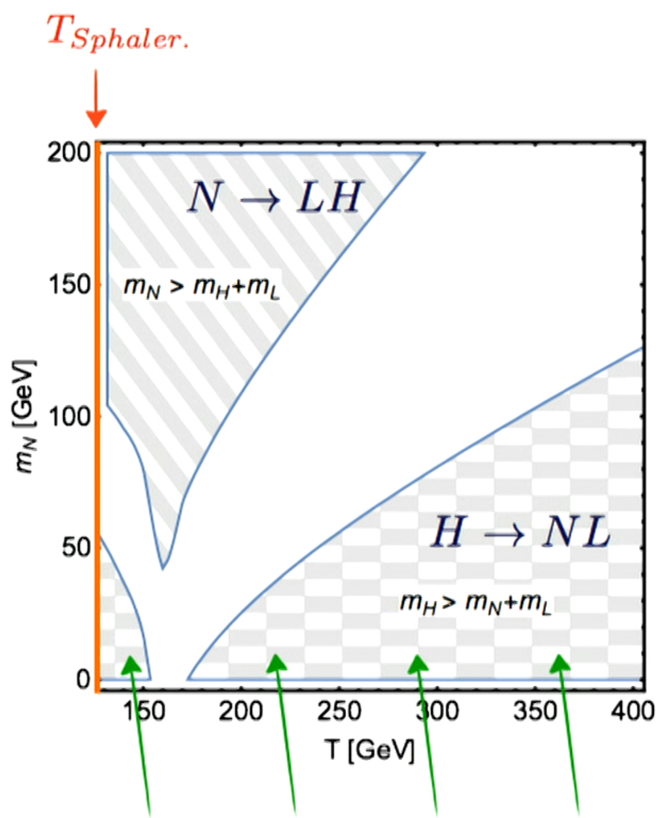
very low scale leptogenesis: $T_{Sphaler.} > m_H >> m_{N,L}$

- creation of L asymmetry at $T > T_{Sphaler.} >> m_N$ $\Rightarrow$ $\neq$ regime
- thermal effects are fully relevant: $T > T_{Sphaler.} > m_H >> m_{N,L}$

  $m_H^2(T) = m_H^2 + c_H \cdot T^2 \qquad m_L^2(T) = m_L^2 + c_L \cdot T^2 \qquad m_N^2(T) = m_N^2 + c_N \cdot T^2$

- $N \rightarrow LH$ forbidden but $H \rightarrow NL$ allowed

Temperatures allowing the $N \to LH$ and $H \to NL$ decays



T.H., Teresi 16'

$H \to NL$ leptogenesis from this region?

L asymmetry production from $H \to NL$ decay

T.H., Teresi 16'

2 issues at first sight:

1) out-of-equilibrium decay? ← 3rd Sakharov condition

H decaying particle is in deep thermal equilibrium at $T > T_{Sphaler.}$

but N in decay product is not necessarily in thermal equilibr.

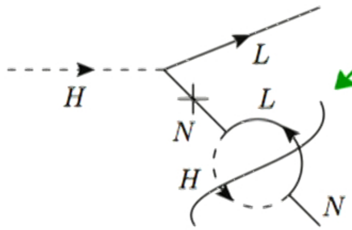
$$\frac{dn_N}{dt} \propto (n_N^{eq} - n_N) \cdot \Gamma_{H \to NL}$$

n_N^{eq} ↑ $H \to NL$ $\qquad$ n_N ↑ $NL \to H$

L asymmetry production from $H \to NL$ decay

2) Absorptive part for CP violation?

T.H., Teresi 16'



$m_H + m_L > m_N$ ⇒ no absorptive part?

↪ but only for $T = 0$!

finite T corrections: thermal cut: if H or L comes from the thermal bath the cut is kinematically allowed

Giudice, Notari, Raidal, Riotto, Strumia 03'

Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 12'

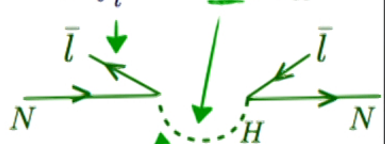
⇒ absorptive part $\Gamma_N(T)$ (calculated in Kadanoff Baym formalism)

Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 12'

$$\Pi^{\alpha\beta}(q_N) = \Pi_>^{\alpha\beta}(q_N) + \Pi_<^{\alpha\beta}(q_N)$$

$$\hookrightarrow \ni -2\int \frac{d^4p_l}{(2\pi)^4}\frac{d^4p_H}{(2\pi)^4}(2\pi)^4\delta^4(q_N - p_l - p_H)\,(Y_N^\dagger Y_N)_{\alpha\beta}\,[P_L S_>^l(t,p_l) P_R \Delta_>^H(t,p_H)]$$

$$\propto f_l^{FD} \quad \propto 1 + f_H^{BE}$$



$$\Rightarrow \Gamma_N(T) = \frac{1}{8\pi} m_{N_2}(Y_N Y_N^\dagger)_{22} \cdot \frac{p.L_N}{q_N.p_l}$$

$$\hookrightarrow L_N = 16\pi \int \frac{d^3p_l}{(2\pi)^3 2E_l}\frac{d^3p_H}{(2\pi)^3 2E_H}(2\pi)^4\delta^4(q_N - p_l - p_H)\,(f_l^{FD} + f_H^{BE})\,p_l$$

Total L number violating CP asymmetry

$$\varepsilon_{CP} = \frac{\mathrm{Im}[(Y_N Y_N^\dagger)_{12}^2]}{(Y_N Y_N^\dagger)_{11}(Y_N Y_N^\dagger)_{22}} \cdot \frac{2\,\Delta m_N^0\,\Gamma_N(T)}{4\,\Delta m_N(T)^2 + \Gamma_N(T)^2}$$

with thermal mass splitting: $\Delta m_N(T) \simeq \Delta m_N^0 + \frac{\pi\, T^2}{4\, m_N^2}\,\Gamma_{22}\sqrt{(1 - \frac{\Gamma_{11}}{\Gamma_{22}})^2 + 4\,\frac{|\Gamma_{12}|^2}{\Gamma_{22}^2}}$

$$\Gamma_{ij} \equiv m_N (Y_N Y_N^\dagger)_{ij}/(8\pi)$$

Boltzmann equations:

$$\frac{n_\gamma H_N}{z}\,\frac{d\eta_N}{dz} = \left(1 - \frac{\eta^N}{\eta_N^{\mathrm{eq}}}\right)\Big[\gamma_D + 2(\gamma_{Hs} + \gamma_{As}) + 4(\gamma_{Ht} + \gamma_{At})\Big]\,,$$

$$\frac{n_\gamma H_N}{z}\,\frac{d\eta_L}{dz} = \gamma_D\left[\left(\frac{\eta^N}{\eta_N^{\mathrm{eq}}} - 1\right)\epsilon_{CP}(z) - \frac{2}{3}\eta_L\right] - \frac{4}{3}\eta_L\left[2(\gamma_{Ht} + \gamma_{At}) + \frac{\eta^N}{\eta_N^{\mathrm{eq}}}(\gamma_{Hs} + \gamma_{As})\right]$$

$$\eta_N \equiv n_N/n_\gamma$$

$$z \equiv m_N/T$$

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$$\eta_N \equiv n_N/n_\gamma$$

$$z \equiv m_N/T$$

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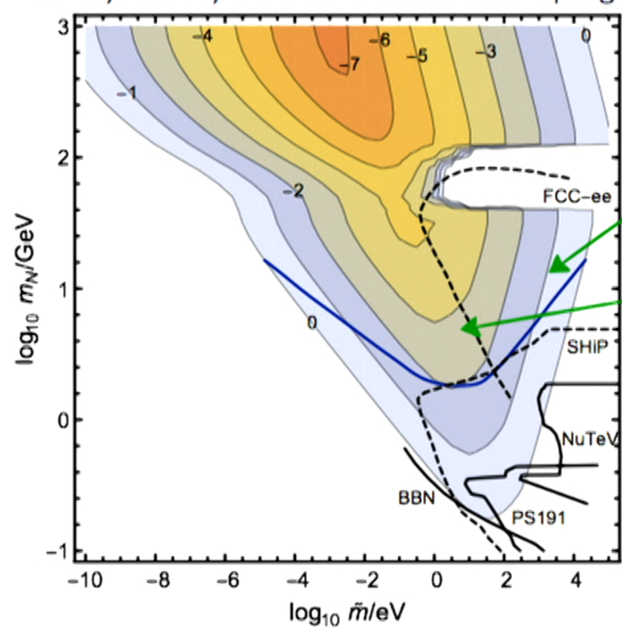
Results for the case where the N have thermalized

if N thermalized by large Y_N Yukawas or other interaction (e.g. a W_R) before an asymmetry is produced

CP-asymmetry needed for successful leptog.



T.H., Teresi 16'

the lower is m_N, the later it goes out-of-equilibrium, the more it will be in equilibr. at $T > T_{Sphaler.}$

⇓

lower bound on m_N

$m_N > 2.2\,\mathrm{GeV}$

if only $N \to LH$ decay we get: $m_N > 50\,\mathrm{GeV}$

$$\tilde{m} \equiv \frac{Y_N Y_N^\dagger v^2}{2 m_N}$$

requires that at least 2 of the N have quasi-degenerate masses

Results for the case where the N have not thermalized

- if no extra interaction thermalizing N, no thermalization is much more natural than in ordinary leptogenesis: thermalization at $T > T_{Sphaler.} >> m_N$ requires much larger Y_N Yukawas than in ordinary leptogenesis at $T \sim m_N$

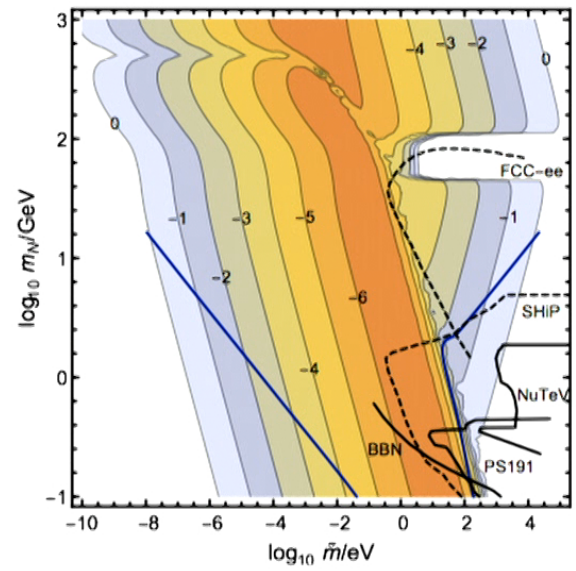
$$\tilde{m} \equiv \frac{Y_N Y_N^\dagger v^2}{2 m_N} \qquad \tilde{m} >> 10^{-3}\,\mathrm{eV} \qquad \tilde{m} \gtrsim 10^{-3}\,\mathrm{eV}$$

- for $H \to NL$ decay, to start from no N in the thermal bath boosts the asymmetry production, unlike for ordinary $N \to LH$ leptogenesis

  $H \to NL$: many H to decay and produce the asymmetry but few N to $NL \to H$ inverse decay

$$n_N^{eq} - n_N \sim n_N^{eq} >> n_N$$

Results for the case where the N have not thermalized

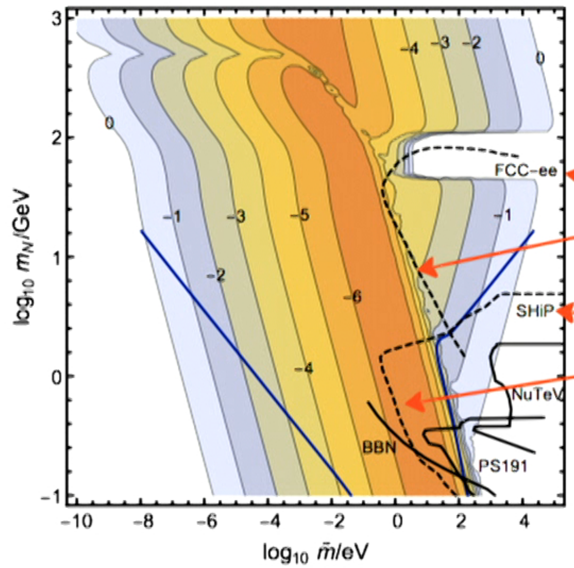


T.H., Teresi 16'

- for example for $m_N \sim 10\,\mathrm{GeV}$ and $\tilde{m} \sim 0.1\,\mathrm{eV}$ one needs $\Delta m_N^0 / m_N \lesssim 10^{-5}$
- leptogenesis for m_N as low as $\sim 20\,\mathrm{MeV}$ is possible (but BBN concerns)
- in all cases: asymmetry production at T just above $T_{Sphaler.}$ $\Rightarrow$ no dependence on UV physics!

Testability!

T.H., Teresi 16'



region that FCC should probe if constructed

region that SHIP should probe

Two important comparisons to do

- for $m_N \sim \mathrm{GeV}$: well-known baryogenesis mechanism in seesaw model: baryogenesis from right-handed neutrino oscillations: ``ARS'' mechanism

Akhmedov, Rubakov, Smirnov 98'
Asaka, Shaposhnikov 05'; Shaposhnikov 08'
Drewes, Garbrecht 11'
Canetti, Drewes, Frossard, Shaposhnikov 13'
Hernandez, Kekic, Lopez-Pavon, Racker, Rius 15'
.....

→ comparison of ARS with L-violating Higgs decay setup???

- to compute evolution of asymmetries with thermal effects: another well-known formalism: density matrix formalism

→ comparison of results in decay formalism above and in density density matrix formalism???

Density matrix formalism

N_{R_α} quantum system is described by density matrix : $n^N_{\alpha\beta} \equiv \langle a^{+\dagger}_\beta a^+_\alpha \rangle = Tr(\rho\, a^{+\dagger}_\beta\, a^+_\alpha)$

$\overline{N_{R_\alpha}}$ quantum system is described by density matrix : $n^{\bar{N}}_{\alpha\beta} \equiv \langle a^{-\dagger}_\beta a^-_\alpha \rangle = Tr(\rho\, a^{-\dagger}_\beta\, a^-_\alpha)$

$$n^N_{\alpha\alpha} = n^N_\alpha = \text{number density of } N_\alpha \text{ states}$$

$$n^N_{\alpha\beta} = \text{ coherence between } N_\alpha \text{ and } N_\beta \text{ states}$$

⇒ evolution of density matrix:

$$\frac{d}{dt} n^N_{\alpha\beta}(\mathbf{k}, t) \;=\; i\,\langle [H^N_0, n^N_{\alpha\beta}(\mathbf{k}, t)] \rangle \;-\; \frac{1}{2}\int_{-\infty}^{\infty} dt' \langle [H_{\rm int}(t'), [H_{\rm int}(t), n^N_{\alpha\beta}(\mathbf{k}, t)]] \rangle_t$$

oscillation term — interaction term

$$H_{int} = h_{l\alpha} \bar{L}_l \tilde{H} P_R N_\alpha + h.c.$$

$H_{int} \cdot H_{int}$ →
- terms in $a^{+\dagger}_\beta a^+_\alpha \to n^N_{\alpha\beta}$
- terms in $a^-_\alpha a^{-\dagger}_\beta \to 1 - n^N_{\alpha\beta}$

Density matrix formalism

$$\Rightarrow \quad \frac{d}{dt} n^N_{\alpha\beta}(\mathbf{k}) = -i \left[E_N, n^N(\mathbf{k})\right]_{\alpha\beta} - \frac{1}{2E_N}\left(\frac{1}{2}\{\Gamma^>(\mathbf{k}), n^N(\mathbf{k})\} - \frac{1}{2}\{\Gamma^<(\mathbf{k}), \mathrm{I} - n^N(\mathbf{k})\}\right)_{\alpha\beta},$$

$N + \bar{L} \to H$ $\qquad$ $H \to N + \bar{L}$

with:

$$\Gamma^{\lessgtr}_{\alpha\beta}(\mathbf{k}) = -i\,\mathrm{tr}\left\{\mathrm{P_R} u_+(\mathbf{k})\bar{u}_+(\mathbf{k})\mathrm{P_L}\,\Sigma^{\lessgtr}_{\alpha\beta}(k)\right\}$$

ARS scenario

keeping only the transitions where there is no m_N mass insertions because the asymmetry is produced at $T >> T_{sphaler.} >> m_N$

if mass insertion: m_N^2/T^2 suppression

with:

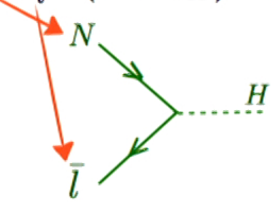
$$-i\Sigma^{\lessgtr}_{\alpha\beta}(k) = \int \frac{d^4p}{(2\pi)^4} \int \frac{d^4q}{(2\pi)^4} (2\pi)^4 \delta^{(4)}(q-k-p)\; iS_l^{\lessgtr}(-p)\, i\Delta^{\gtrless}(-q)\, h^*_{l\alpha} h_{l\beta}$$

Wightman propagator of L

Wightman propagator of H

for example:

$$n_N\,\Gamma^> \sim n_N\,\Sigma^> \propto n_N \cdot S_l^> \cdot \Delta^< \cdot h^*_{l\alpha}h_{l\beta} \propto n_N \cdot n_{\bar{l}} \cdot (1 + n_H) \cdot h^*_{l\alpha}h_{l\beta}$$



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Density matrix formalism

$$\Rightarrow \quad \frac{d}{dt} n^N_{\alpha\beta}(\mathbf{k}) = -i\left[E_N, n^N(\mathbf{k})\right]_{\alpha\beta} - \frac{1}{2E_N}\left(\frac{1}{2}\{\Gamma^>(\mathbf{k}), n^N(\mathbf{k})\} - \frac{1}{2}\{\Gamma^<(\mathbf{k}), \mathrm{I} - n^N(\mathbf{k})\}\right)_{\alpha\beta},$$

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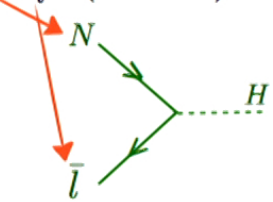

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Density matrix formalism: final evolution equations for N and $\bar{N}$

with no Majorana mass insertion
= ARS scenario

writing $$n_l = n_l^{Eq} + \frac{\delta n_l}{2} \qquad n_{\bar{l}} = n_l^{Eq} - \frac{\delta n_l}{2}$$ a term proportional to δn_l shows up: washout term: W

$$\frac{dn^N_{\alpha\beta}}{dt} = -i\left[\mathcal{E}_N, n^N(k)\right]_{\alpha\beta} - \frac{1}{2}\left\{\gamma^{LC}, \frac{n^N}{n^N_{eq}} - \mathrm{I}\right\}_{\alpha\beta} + \frac{\delta n^L_l}{2n^L_{eq}}\left((\gamma^{LC}_{WQ,l}) + \frac{1}{2}\left\{\gamma^{LC}_{WC,l}, \frac{n^N}{n^N_{eq}}\right\}\right)_{\alpha\beta}$$

$$\gamma^{LC}_{\alpha\beta} \equiv \int d\Pi_{\rm PS}\, n^N_{eq}(\mathbf{k})\left(n^L_{eq}(\mathbf{p}) + n^H_{eq}(\mathbf{q})\right) \times \ \mathrm{tr}\left\{\mathrm{P_R} u_+(\mathbf{k})\bar{u}_+(\mathbf{k})\mathrm{P_L}\, \not{p}\right\} h^*_{l\alpha} h_{l\beta}$$

$$\pm \frac{g_{iso}}{4\pi^2}\int_0^\infty dk\, \frac{k}{e^{k/T}+1}\frac{M_H^2 - M_L^2}{8\pi k} \times \int_{E^*}^\infty dE\left(\frac{1}{e^{\frac{E}{T}}+1} + \frac{1}{e^{\frac{E+k}{T}}-1}\right) h^*_{l\alpha}\, h_{l\beta}$$

$$\simeq 3.26 \times 10^{-4}\, T^4\, h^*_{l\alpha}\, h_{l\beta}$$

$$\gamma^{LC}_{WQ} = \frac{g_{iso}}{4\pi^2}\int_0^\infty dk\, k\, \frac{M_H^2 - M_L^2}{8\pi k} \times \int_{E^*}^\infty dE\, \frac{1}{e^{\frac{E}{T}}+1}\frac{1}{e^{\frac{E+k}{T}}-1}\ h^*_{l\alpha}\, h_{l\beta} \ \simeq 1.05 \times 10^{-4}\, T^4\, h^*_{l\alpha}\, h_{l\beta}$$

$$\gamma^{LC}_{WC} = \frac{g_{iso}}{4\pi^2}\int_0^\infty dk\, \frac{k}{e^{k/T}+1}\frac{M_H^2 - M_L^2}{8\pi k}\int_{E^*}^\infty dE\, \frac{1}{e^{\frac{E}{T}}+1}\ h^*_{l\alpha}\, h_{l\beta} \ \simeq 1.86 \times 10^{-4}\, T^4\ h^*_{l\alpha}\, h_{l\beta}$$

and similarly for $\bar{N}$

Density matrix formalism: final evolution equation for δn_l

with no Majorana mass insertion
= ARS scenario

$$\frac{d\,\delta n_l^L}{dt} = \frac{1}{n_{eq}^N}\mathrm{tr}\{(\gamma_l^{LC})\,n^N\} - \frac{1}{n_{eq}^N}\mathrm{tr}\{(\gamma_l^{LC\,*})\,\bar{n}^N\}$$

$$-\frac{\delta n_l^L}{n_{eq}^L}\mathrm{tr}\{\gamma_{WQ,l}^{LC}\} - \frac{\delta n_l^L}{2n_{eq}^L}\frac{1}{n_{eq}^N}\mathrm{tr}\{n^N(\gamma_{WC,l}^{LC})\} - \frac{\delta n_l^L}{2n_{eq}^L}\frac{1}{n_{eq}^N}\mathrm{tr}\{\bar{n}^N(\gamma_{WC,l}^{LC\,*})\}$$

for not too large Yukawa coupling these equations can be analytically solved order by order in the Yukawa couplings

⇒ at $\mathcal{O}(h^4)$:

$$Y_l(z) \simeq 4(\kappa^{LC})^2\rho_{eq}\,(h^\dagger h)_{11}(h^\dagger h)_{22}\,\delta_l^{LC}\int_0^z \mathrm{Im} f(z')dz' \qquad f(z) \equiv \int_0^z dz' e^{i\frac{\Delta m_N^2}{3\mu_{osc}^2}(z^3-z'^3)}$$

$$\delta_l^{LC} = \frac{\mathrm{Im}[h_{l1}^* h_{l2}(h^\dagger h)_{21}]}{(h^\dagger h)_{11}(h^\dagger h)_{22}}$$

CP-violating Yukawa combination which leaves the SM total lepton number unchanged:

$$\delta n_{l_i} \equiv n_{L_i} - n_{\bar{L}_i} \neq 0 \quad \text{but} \quad \sum_{i=e,\mu,\tau} \delta n_{l_i} = 0 \;\Rightarrow\; \sum_{i=e,\mu,\tau} Y_l = 0$$

⇒ no contribution at $\mathcal{O}(h^4)$!

Density matrix formalism: final result with no Majorana mass insertion

$$Y_{LC} \simeq -18.5 \times (\alpha^{LC})^2 \, \alpha_W^{LC} \, \frac{M_0^{7/3}}{T_c(\Delta m_N^2)^{2/3}} \times (h^\dagger h)_{11}(h^\dagger h)_{22} \sum_l \delta_l^{LC} (hh^\dagger)_{ll}$$

→ what happen's is that since there is no m_N mass insertions in the processes nowhere, all processes conserve total lepton number: assigning $L=1$ to N_R and $L=-1$ to $\overline{N_R}$, all processes conserve L

⇒ at $\mathcal{O}(h^4)$: SM lepton number and N lepton number are separately conserved:

$$\sum_{i=e,\mu,\tau} (n_{L_i} - n_{\bar{L}_i}) = 0 \qquad \sum_\alpha (n_{N_\alpha} - n_{\bar{N}_\alpha}) = 0$$

but flavour lepton number is not conserved: $\delta n_{l_i} \equiv n_{L_i} - n_{\bar{L}_i} \neq 0$

⇒ at $\mathcal{O}(h^6)$: if Yukawa for electron much smaller than for muon:

$n_{L_\mu} - n_{\bar{L}_\mu}$ strongly washed-out

$n_{L_e} - n_{\bar{L}_e}$ much less washed-out

$$\Rightarrow \sum_{i=e,\mu,\tau} (n_{L_i} - n_{\bar{L}_i}) = -\sum_\alpha (n_{N_\alpha} - n_{\bar{N}_\alpha}) \neq 0$$

↓ converted to B asym by sphalerons

↓ not converted to B asym by sphalerons

⇒ baryon asymmetry!

Density matrix formalism: final evolution equation for δn_l

with no Majorana mass insertion
= ARS scenario

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↑

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⇒ no contribution at $\mathcal{O}(h^4)$!

Total lepton number violating density matrix contribution

T.H., Teresi 17'

→ the L-violating Higgs decay contribution to baryogenesis is clearly $\neq$ from the ARS one since it is a $\mathcal{O}(h^4)$ contribution based on processes which do involve a Majorana mass insertion, i.e. which do violate total lepton number, unlike ARS

→ where to find this contribution in density matrix formalism??

⇓

the density matrix commutators lead also to contributions $\propto m_N^2$ which corresponds to processes with a Majorana mass insertion

↑

N to $\bar{L}$ transition instead of N to L transition

$$\Gamma^{\lessgtr}_{\alpha\beta}(\mathbf{k}) \ni +i\,\mathrm{tr}\left\{\mathrm{P_R} v_+(\mathbf{k})\bar{v}_+(\mathbf{k})\mathrm{P_L}\,\Sigma^{\lessgtr}_{\beta\alpha}(-k)\right\}$$

Full set of density matrix equation with LC and LV contributions

T.H., Teresi 17'

$$\frac{d\,n^N_{\alpha\beta}}{dt} = -i\left[\mathcal{E}_N, n^N(\mathbf{k})\right]_{\alpha\beta} - \frac{1}{2}\left\{\gamma^{LC}+\gamma^{LV}, \frac{n^N}{n^N_{eq}} - \mathrm{I}\right\}_{\alpha\beta}$$
$$+ \frac{\delta n^L_l}{2n^L_{eq}}\left(\left(\gamma^{LC}_{WQ,l} - \gamma^{LV}_{WQ,l}\right) + \frac{1}{2}\left\{\gamma^{LC}_{WC,l} - \gamma^{LV}_{WC,l}, \frac{n^N}{n^N_{eq}}\right\}\right)_{\alpha\beta},$$

$$\frac{d\,\bar{n}^N_{\alpha\beta}}{dt} = -i\left[\mathcal{E}_N, \bar{n}^N(\mathbf{k})\right]_{\alpha\beta}$$
$$- \frac{1}{2}\left\{\gamma^{LC\,*} + \gamma^{LV\,*}, \frac{\bar{n}^N}{n^N_{eq}} - \mathrm{I}\right\}_{\alpha\beta}$$
$$- \frac{\delta n^L_l}{2n^L_{eq}}\left(\left(\gamma^{LC\,*}_{WQ,l} - \gamma^{LV\,*}_{WQ,l}\right) + \frac{1}{2}\left\{\gamma^{LC\,*}_{WC,l} - \gamma^{LV\,*}_{WC,l}, \frac{\bar{n}^N}{n^N_{eq}}\right\}\right)$$

$$\frac{d\,\delta n^L_l}{dt} = \frac{1}{n^N_{eq}}\,\mathrm{tr}\left\{\left(\gamma^{LC}_l - \gamma^{LV}_l\right) n^N\right\}$$
$$- \frac{1}{n^N_{eq}}\,\mathrm{tr}\left\{\left(\gamma^{LC\,*}_l - \gamma^{LV\,*}_l\right) \bar{n}^N\right\}$$
$$- \frac{\delta n^L_l}{n^L_{eq}}\,\mathrm{tr}\left\{\gamma^{LC}_{WQ,l} + \gamma^{LV}_{WQ,l}\right\}$$
$$- \frac{\delta n^L_l}{2n^L_{eq}}\frac{1}{n^N_{eq}}\,\mathrm{tr}\left\{n^N\left(\gamma^{LC}_{WC,l} + \gamma^{LV}_{WC,l}\right)\right\}$$
$$- \frac{\delta n^L_l}{2n^L_{eq}}\frac{1}{n^N_{eq}}\,\mathrm{tr}\left\{\bar{n}^N\left(\gamma^{LC\,*}_{WC,l} + \gamma^{LV\,*}_{WC,l}\right)\right\}$$

$$\gamma^{LV} = \frac{g_{iso}}{4\pi^2}\int_0^\infty dk\,\frac{k}{e^{k/T}+1}\,\frac{m_N^2}{32\pi k^3} \times \int_{E^*}^\infty dE\,(4Ek + M_L^2 - M_H^2)\left(\frac{1}{e^{\frac{E}{T}}+1} + \frac{1}{e^{\frac{E+k}{T}}-1}\right) h^*_{l\alpha}\,h_{l\beta}$$
$$\simeq 3.35\times10^{-3}\,m_N^2\,T^2\,h^*_{l\alpha}\,h_{l\beta}$$

$$\gamma^{LV}_{WQ} = \frac{g_{iso}}{4\pi^2}\int_0^\infty dk\,k\,\frac{m_N^2}{32\pi k^3} \times \int_{E^*}^\infty dE\,(4Ek + M_L^2 - M_H^2)\left(\frac{1}{e^{\frac{E}{T}}+1} + \frac{1}{e^{\frac{E+k}{T}}-1}\right) h^*_{l\alpha}\,h_{l\beta} \simeq 5.49\times10^{-4}\,m_N^2\,T^2\,h^*_{l\alpha}\,h_{l\beta}$$

$$\gamma^{LV}_{WC} = \frac{g_{iso}}{4\pi^2}\int_0^\infty dk\,\frac{k}{e^{k/T}+1}\,\frac{m_N^2}{32\pi k^3} \times \int_{E^*}^\infty dE\,(4Ek + M_L^2 - M_H^2)\,\frac{1}{e^{\frac{E}{T}}+1}\,h^*_{l\alpha}\,h_{l\beta} \simeq 1.79\times10^{-3}\,m_N^2\,T^2\,h^*_{l\alpha}\,h_{l\beta}$$

Analytical solution for the LV contribution

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$$Y_{LV} \simeq 7.9 \times \alpha^{LC}\,\alpha^{LV}\,\frac{M_0}{T_c}\,\frac{m_N^2}{\Delta m_N^2}\,(h^\dagger h)_{11}(h^\dagger h)_{22}\,\delta^{LV}$$

$$\delta^{LV} \equiv \sum_l \delta_l^{LV} \neq 0$$

$$\delta_l^{LV} = \frac{\mathrm{Im}\left[h_{l1}^* h_{l2}(h^\dagger h)_{12}\right]}{(h^\dagger h)_{11}(h^\dagger h)_{22}}$$

CP-violating Yukawa combination which break total lepton number

⇒ already non vanishing at $\mathcal{O}(h^4)$ instead of $\mathcal{O}(h^6)$ for the LC contribution

suppressed by 2 rates instead of 3 rates for the LC contribution

$\alpha^{LC}\alpha^{LV}$ $\qquad$ $(\alpha^{LC})^2\alpha_W^{LC}$

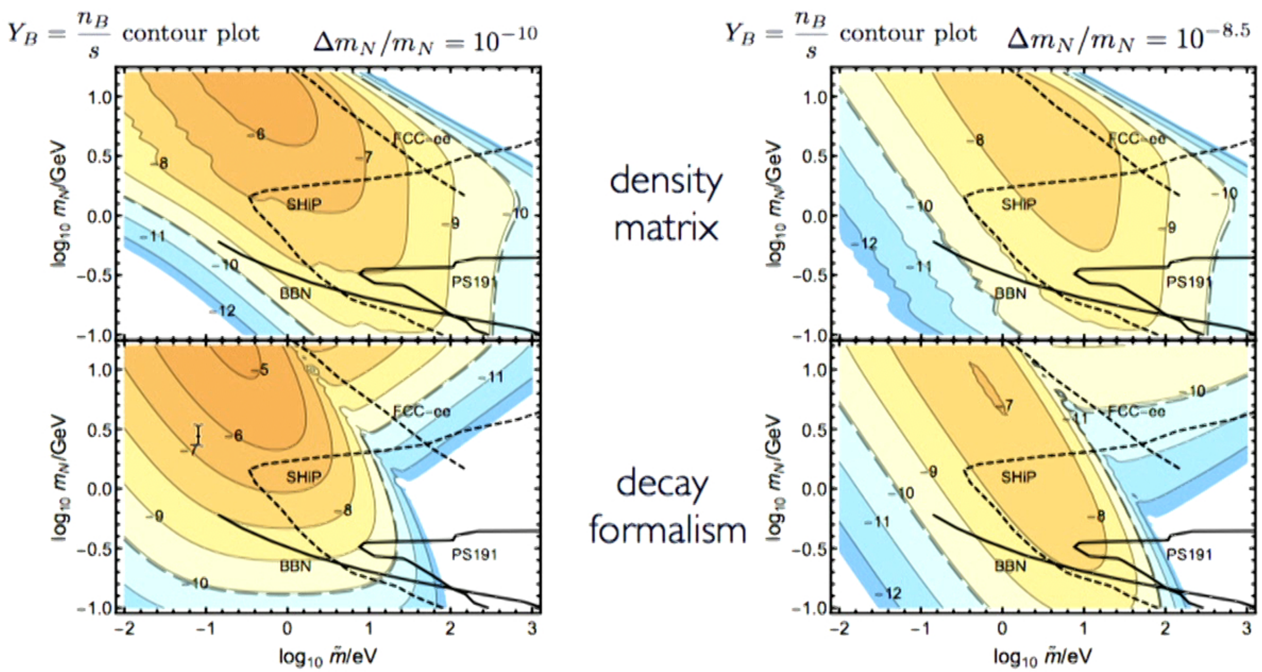
but m_N^2 suppression with different Δm_N^2 and M_{Planck} dependence

⇒ all in all the various factors more or less compensate each other with dominance of one or the other contribution depending on the parameters

Numerical results: comparison of decay and density matrix formalisms for the LV contribution

T.H., Teresi 17'

↪ with only one lepton flavour: no ARS, only LV contribution



⇒ qualitative or even quantitative agreement:

- except for small m_N: different thermal masses taken
- except for large $\tilde{m}$: washout suppression too big in decay formalism because doesn't take into account formation of $N-\bar{N}$ asymmetries

Numerical results: comparison of LC and LV contributions in matrix density formalism

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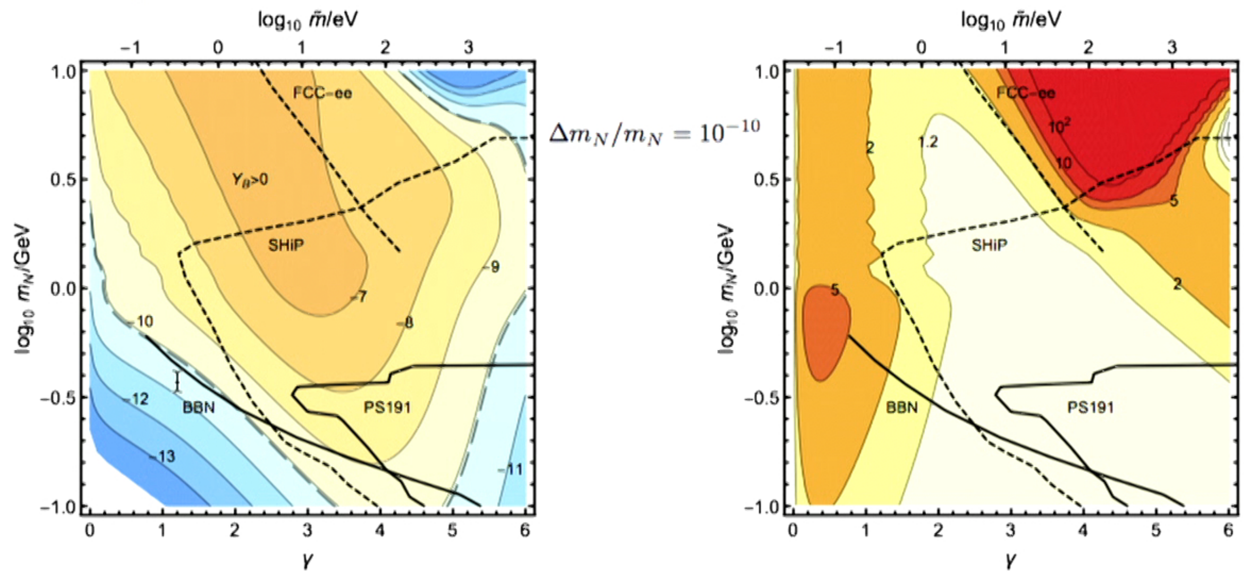
$Y_B = \frac{n_B}{s}$ contour plot: full LC+LV result

ratio of LV+LC over LC



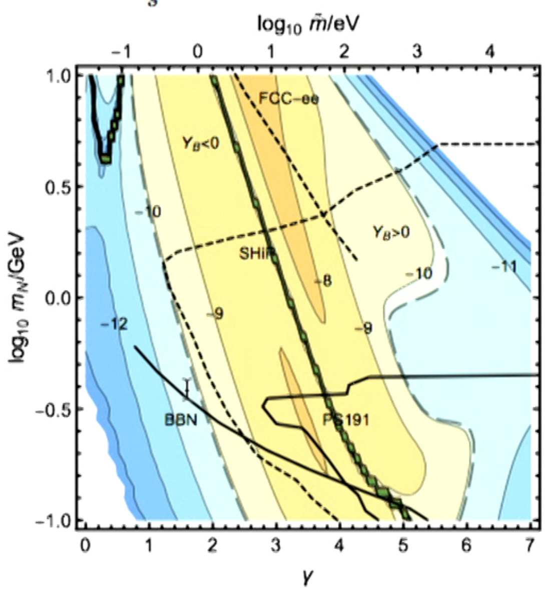
dominance of LV= - for small ``seesaw'' expected Yukawa couplings

- for very large Yukawas: less washout for LV than for LC
- the smaller $\Delta m_N/m_N$ the more LV dominates
- the larger m_N the more LV dominates

Numerical results: comparison of LC and LV contributions in matrix density formalism

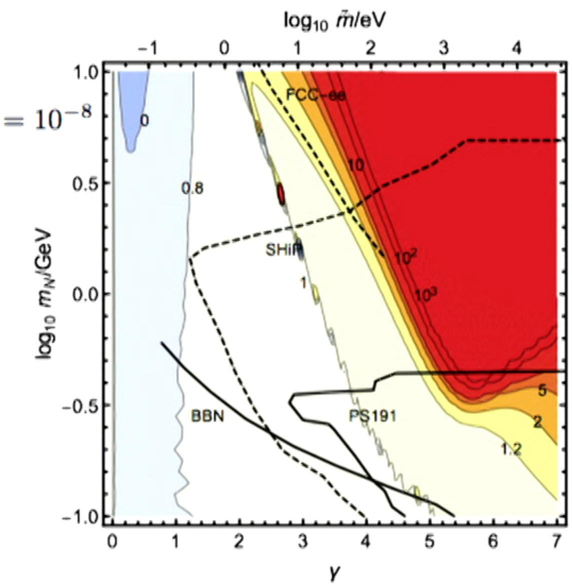
T.H., Teresi 17'

$Y_B = \frac{n_B}{s}$ contour plot: full LC+LV result



$\Delta m_N / m_N = 10^{-8}$

ratio of LV+LC over LC



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- the larger m_N the more LV dominates

Dominance of the LV contribution for low reheating temperatures

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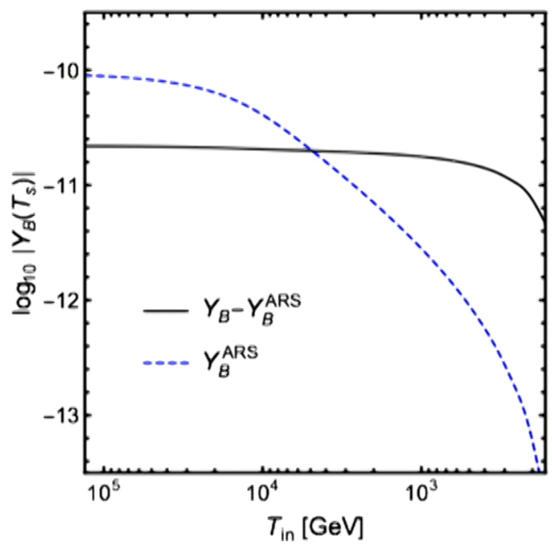
LV contribution produced at lower temperature than the ARS-LC contribution due to the m_N^2/T^2 relative factor



Summary

In usual leptogenesis decay formalism the L violating $H \to NL$ decay can easily lead to enough baryon asymmetry for $m_N < m_H$

- in type-I seesaw model with nothing else
- thanks to thermal effect leading to N self-energy thermal cut
- from total L number violating CP asymmetries: no need for flavour interplay
- at electroweak scale temperatures: $T \gtrsim T_{Sphaler.}$
- with boosted production if no N to begin with
- in a testable way (SHIP,...) for part of the parameter space

We have confirmed these results in density matrix formalism...

- both ARS-LC and LV contributions can dominate baryogenesis depending on parameters