Baryogenesis from L-violating Higgs doublet decay

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Work in collaboration with Daniele Teresi (ULB): arXiv:1606.00017 (PRL 2016)
arXiv:1705.00016 (PRD 2017)

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Baryogenesis via leptogenesis

very highly motivated: same origin as neutrino masses

very natural at high scale: a series of numerical coincidences which make it particularly efficient but very difficult to test

clearly possible at low scale: if seesaw seesaw states have a quasi-degenerate mass spectrum and/or if large cancellation among Yukawa couplings

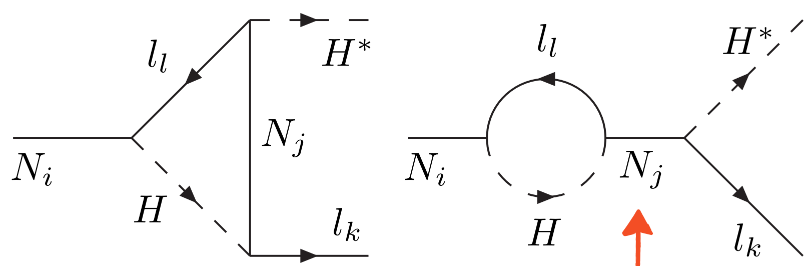
this talk: new way at low scale: total lepton number violating Higgs doublet decay into ~0.1-100 GeV right-handed neutrinos

Leptogenesis relevant scales for low m_N

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

usual leptogenesis: $m_N >> T_{Sphaler.} > m_{H,L}$: leptogenesis from $N \to LH$ decay

creation of L asymmetry at $T \sim m_N >> T_{Sphaler.}$ $\Rightarrow$ B asymmetry



resonant propagator if $m_{N_j} \sim m_{N_i}$ $\Rightarrow$ ~TeV scale leptogenesis

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

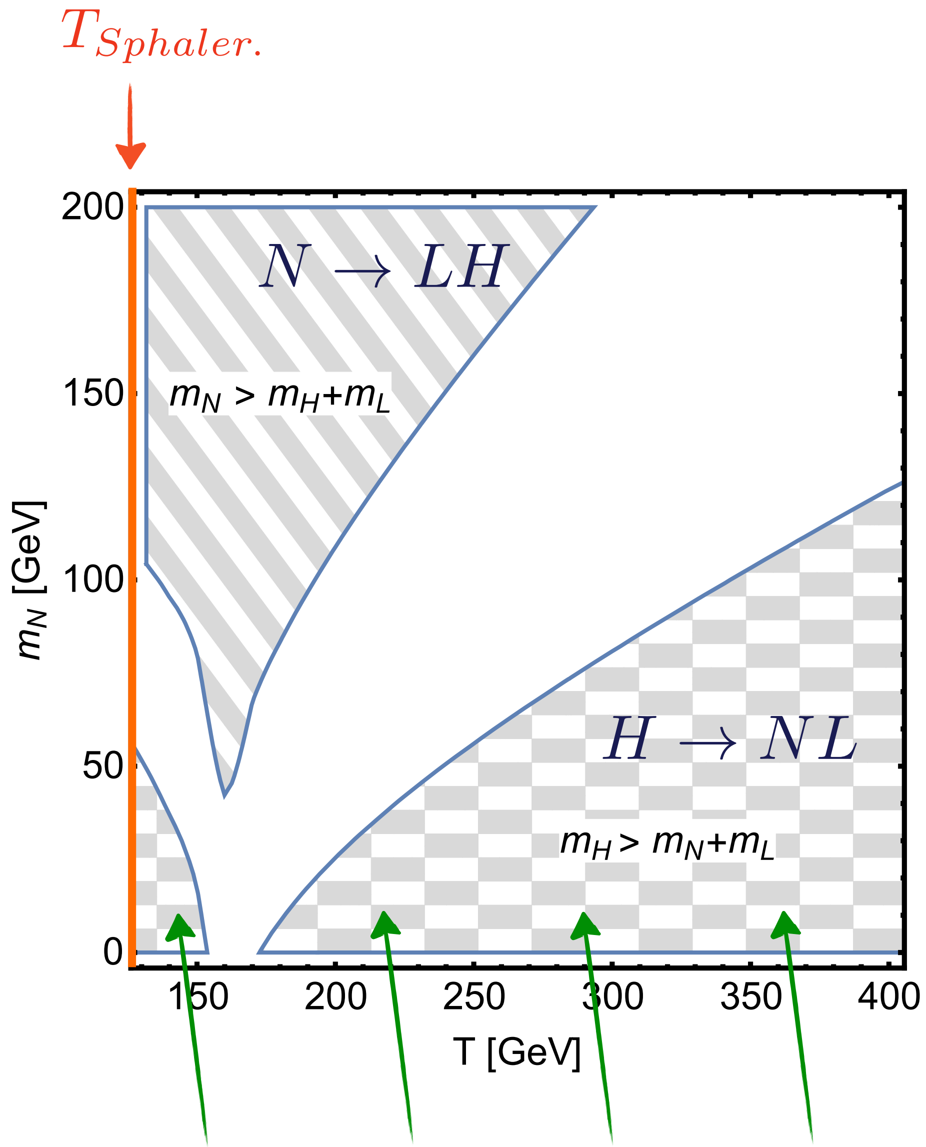
creation of L asymmetry at $T > T_{Sphaler.} >> m_N$ $\Rightarrow$ $\neq$ regime

thermal effects are fully relevant: $T > T_{Sphaler.} > m_H >> m_{N,L}$

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

$N \to LH$ forbidden but $H \to NL$ allowed

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



$H \to NL$ leptogenesis from this region?

L asymmetry production from $H \to NL$ decay

2 issues at first sight:

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

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

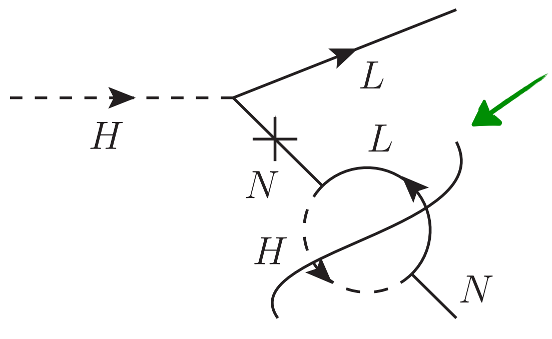
but N in decay product is not necessarily in thermal equilibr.

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

L asymmetry production from $H \to N L$ decay

2) Absorptive part for CP violation?

T.H., Teresi 16'



$m_H + m_L > m_N \Rightarrow$ 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'

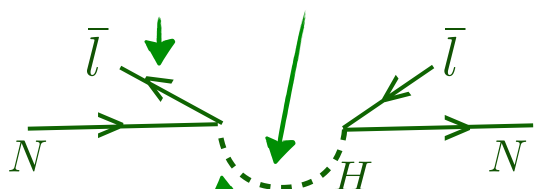
$\Rightarrow$ absorptive part $\Gamma_N(T)$ (calculated in Kadanoff Baym formalism)

Frossard, Garny, Hohenegger, Kartavtsev, Mitrouskas 12'

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

$$\ni -2\int \frac{d^4 p_l}{(2\pi)^4}\frac{d^4 p_H}{(2\pi)^4}(2\pi)^4\delta^4(q_N - p_l - p_H)\,(Y_N^\dagger Y_N)_{\alpha\beta}\left[P_L S^l_{>}(t,p_l) P_R \Delta^H_{>}(t,p_H)\right]$$

$$\propto f_{\bar{l}}^{FD} \quad \propto 1 + f_H^{BE}$$



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

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

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

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

Boltzmann equations:

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

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

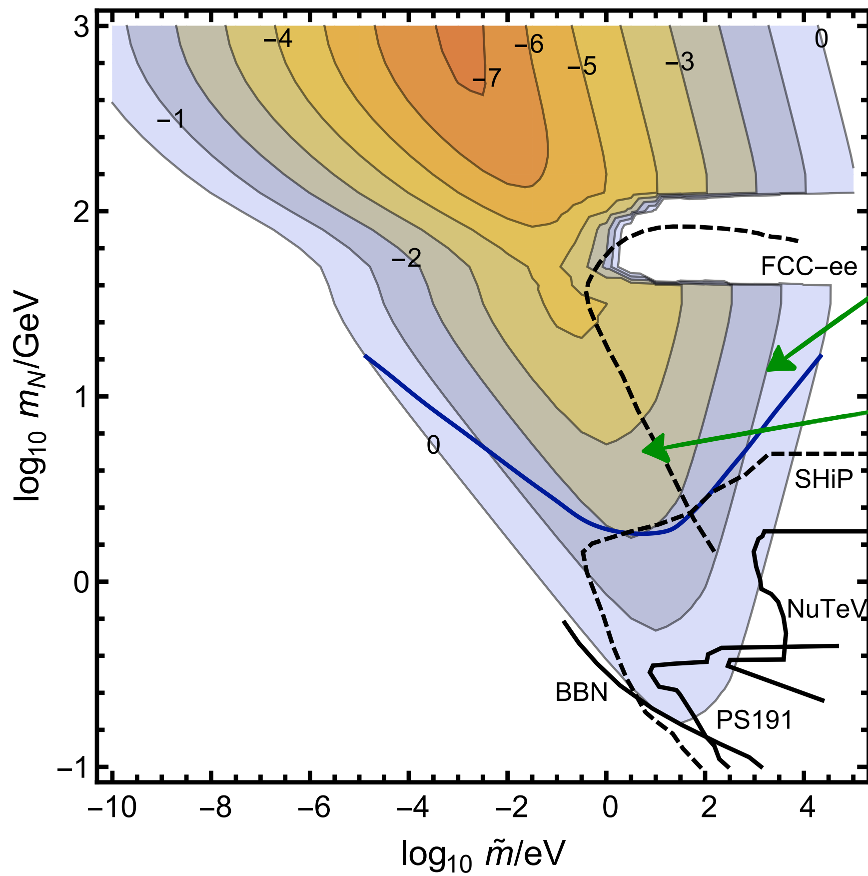
$\eta_N \equiv n_N/n_\gamma$

$z \equiv m_N/T$

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.



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

$\Downarrow$

lower bound on m_N

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

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

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

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 $T \sim m_N$

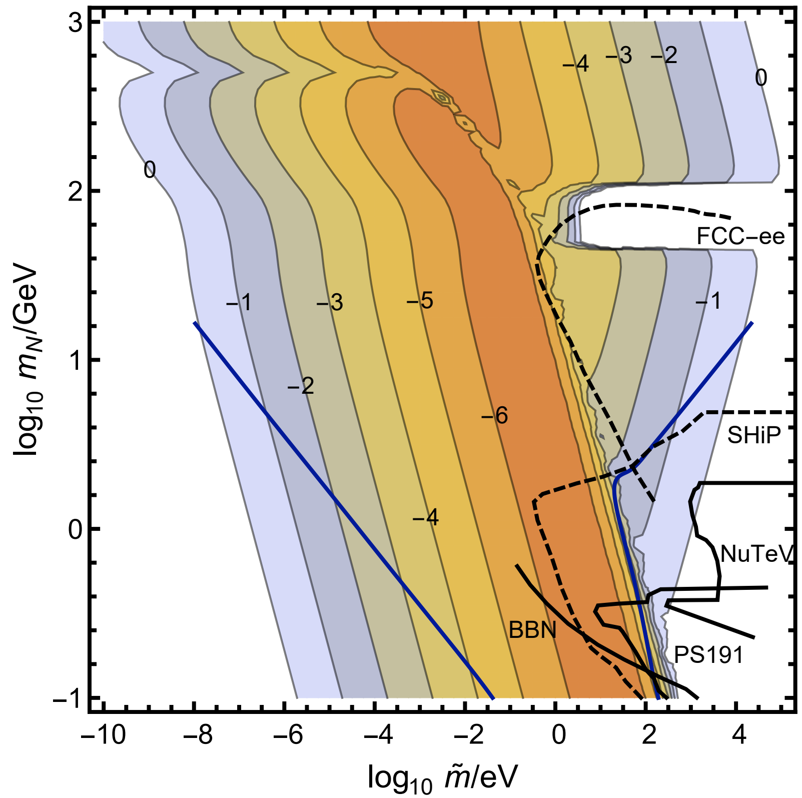
$\tilde{m} \equiv \frac{Y_N Y_N^\dagger v^2}{2m_N}$ $\qquad$ $\tilde{m} >> 10^{-3}\,\mathrm{eV}$ $\qquad$ $\tilde{m} \gtrsim 10^{-3}\,\mathrm{eV}$

- 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

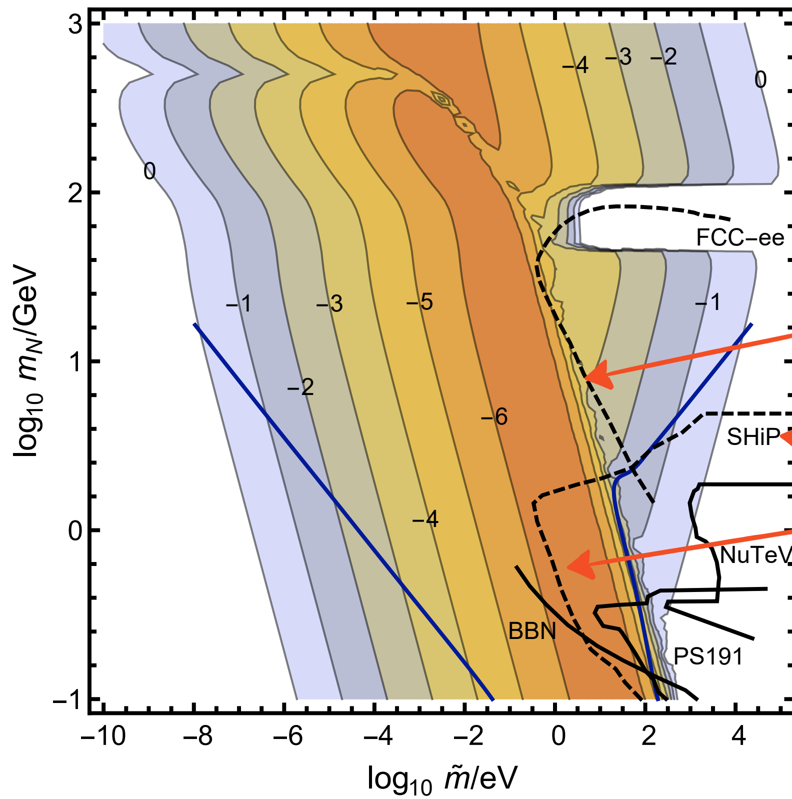
$$n_N^{eq} - n_N \sim n_N^{eq} >> n_N$$

Results for the case where the N have not thermalized



- 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!



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 of decay formalism and 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 : $n^{\bar N}_{\alpha\beta} \equiv \langle a^{-\dagger}_\beta a^-_\alpha \rangle = Tr(\rho\, a^{-\dagger}_\beta\, a^-_\alpha)$

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

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

$\Rightarrow$ 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

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

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

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

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

ARS contribution in density matrix formalism

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

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

with:

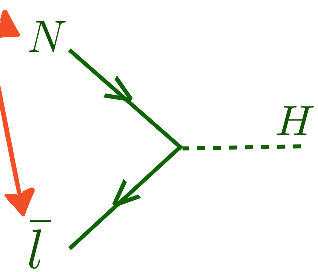
Wightman propagator of H

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

Wightman propagator of L

for example:

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



Density matrix formalism: evolution equations and rates

ARS scenario

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

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

and similarly for $\bar N$

$$\frac{d\,\delta n^L_l}{dt} = \frac{1}{n^N_{eq}}\mathrm{tr}\left\{\left(\gamma^{LC}_l\right) n^N\right\} - \frac{1}{n^N_{eq}}\mathrm{tr}\left\{\left(\gamma^{LC\,*}_l\right) \bar n^N\right\}$$

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

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

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

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

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

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

Density matrix formalism: ARS final result

first non-vanishing term in Yukawa coupling expansion

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

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

ARS is based on processes where there is no m_N mass insertions

only $N \to L$ and $\bar{N} \to \bar{L}$ transitions

no $N \to \bar{L}$

no $\bar{N} \to L$

assigning $L=1$ to N and $L=-1$ to $\bar{N}$, all processes conserve L:

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

$\Rightarrow$ 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 flavor lepton number is not conserved:

$$\delta n_{l_i} \equiv n_{L_i} - n_{\bar{L}_i} \neq 0$$

$\Rightarrow$ at $\mathcal{O}(h^6)$: if for example 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!

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??

$\Downarrow$

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'

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

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

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

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

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

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

Analytical solution for the LV contribution for weak washout

$$Y_{LV} \simeq 7.9 \times \alpha^{LC}\,\alpha^{LV}\,\frac{M_0}{T_c}\,\frac{m_N^2}{\Delta m_N^2}\,(h^\dagger h)_{11}(h^\dagger h)_{22}\,\delta^{LV} \leftarrow \delta^{LV} \equiv \sum_l \delta_l^{LV} \quad \neq 0$$

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CP-violating Yukawa combination which breaks total lepton number

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

$$Y_{LC} \simeq -18.5 \times (\alpha^{LC})^2\,\alpha_W^{LC}\,\frac{M_0^{7/3}}{T_c(\Delta m_N^2)^{2/3}} \times (h^\dagger h)_{11}(h^\dagger h)_{22} \sum_l \delta_l^{LC} (h h^\dagger)_{ll} \leftarrow \delta_l^{LC} = \frac{\mathrm{Im}\left[h_{l1}^* h_{l2} (h^\dagger h)_{21}\right]}{(h^\dagger h)_{11}(h^\dagger h)_{22}}$$

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

⇒ LV vs LC contributions:

- $\mathcal{O}(h^4)$ instead of $\mathcal{O}(h^6)$ for the LC contribution
- suppressed by 2 rates instead of 3 rates for the LC contribution

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

~ Planck mass

- but m_N^2 suppression with different Δm_N^2 and M_0 dependence

⇒ all in all the various factors compensate each other more or less 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

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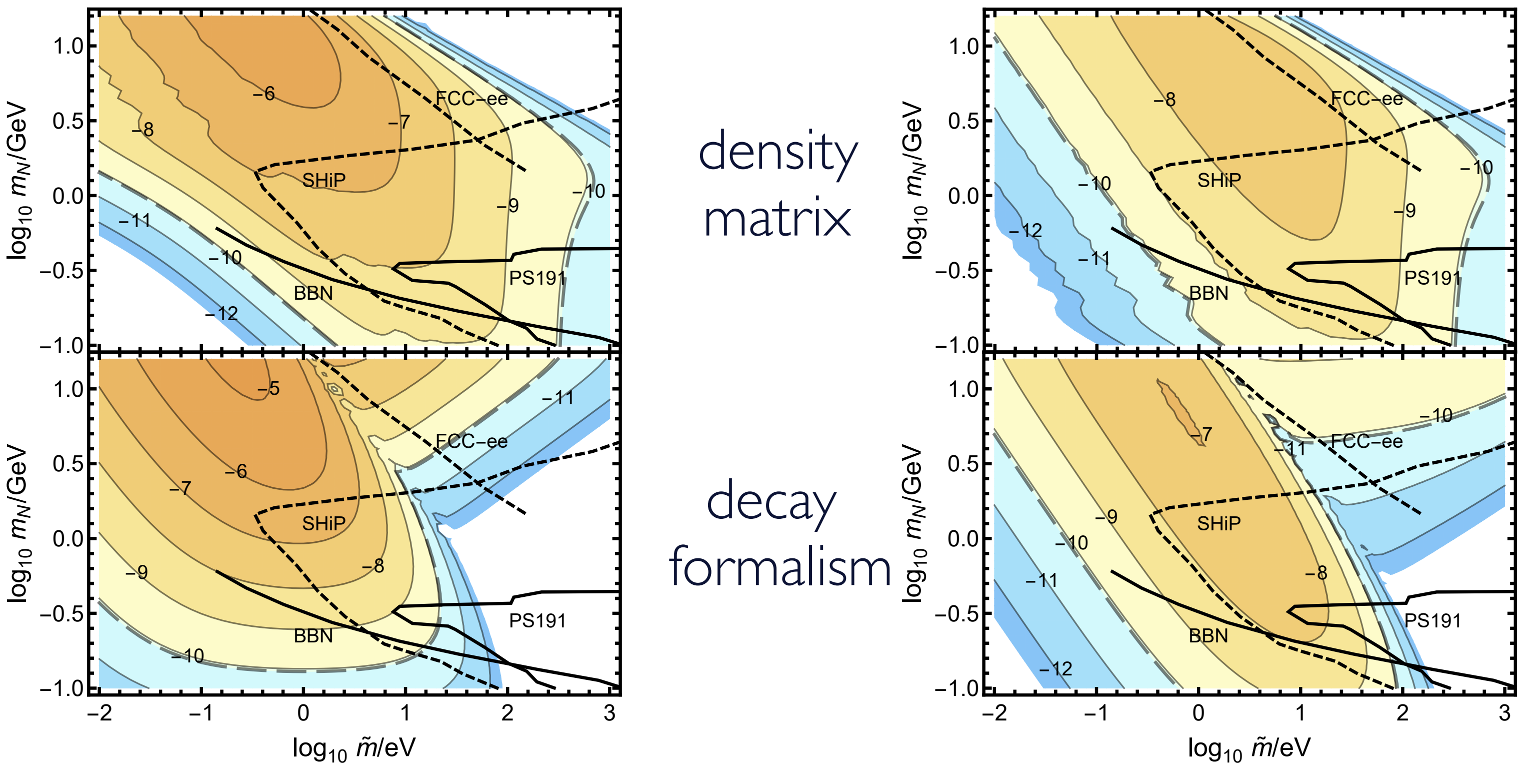
with only one lepton flavour: no ARS, only LV contribution

$Y_B = \frac{n_B}{s}$ contour plot $\quad \Delta m_N/m_N = 10^{-10}$ $\qquad$ $Y_B = \frac{n_B}{s}$ contour plot $\quad \Delta m_N/m_N = 10^{-8.5}$



$\Rightarrow$ 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
- in decay formalism the H is decaying "at rest" unlike in density matrix formalism

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

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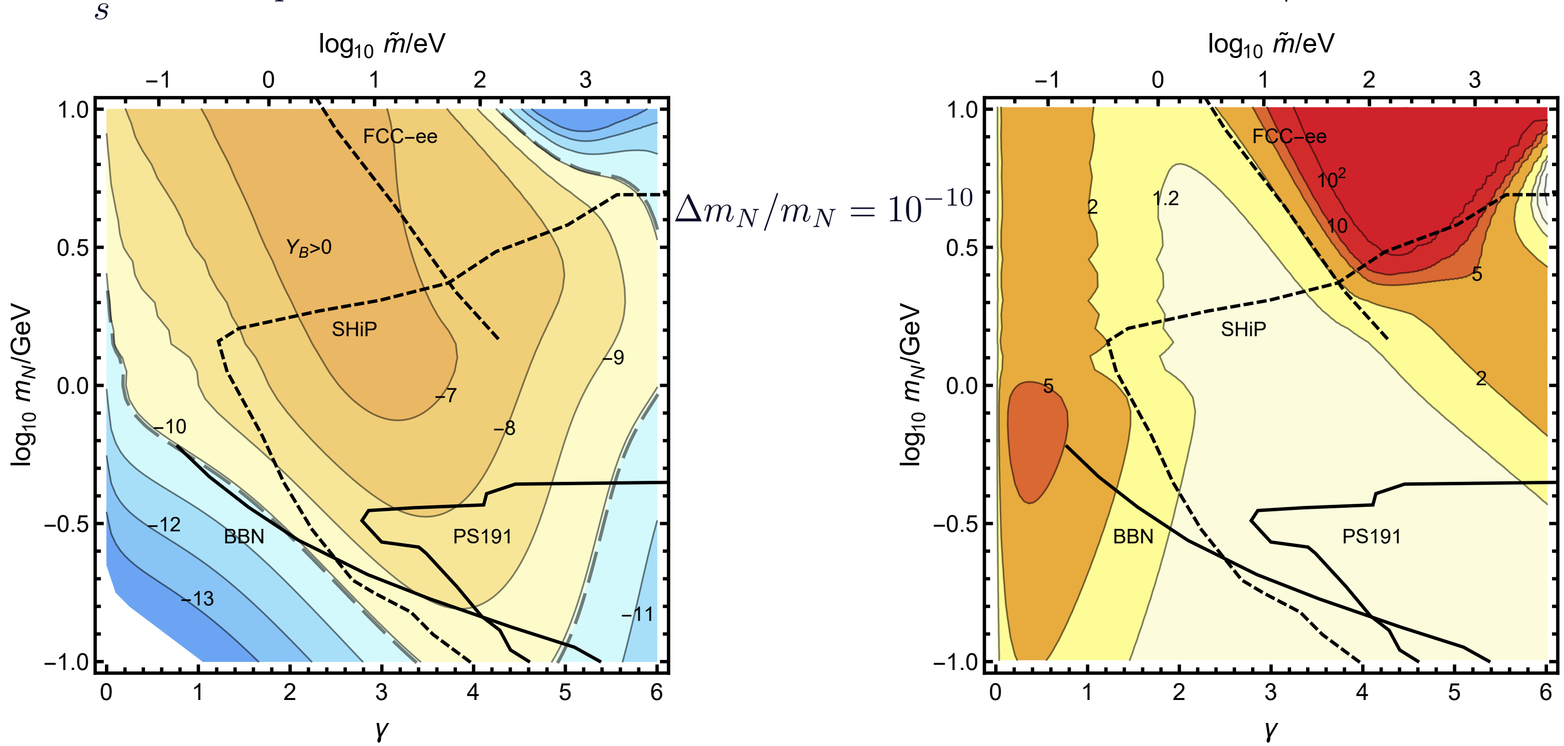
$Y_B = \frac{n_B}{s}$ contour plot: full LC+LV result

ratio of LV+LC over LC



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

- for very large Yukawas: less washout for LV than for LC !

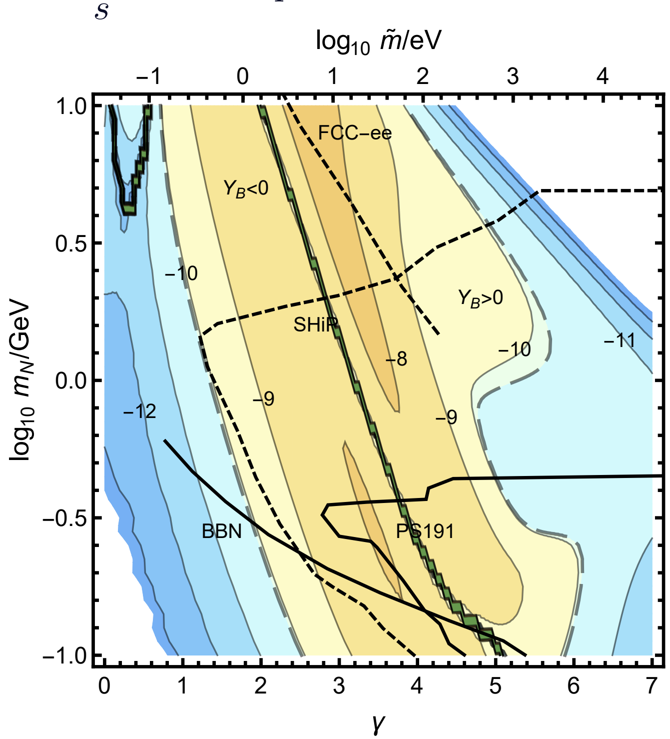
$$\propto m_N^2 T^2 \ << \ \propto T^4$$

- 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

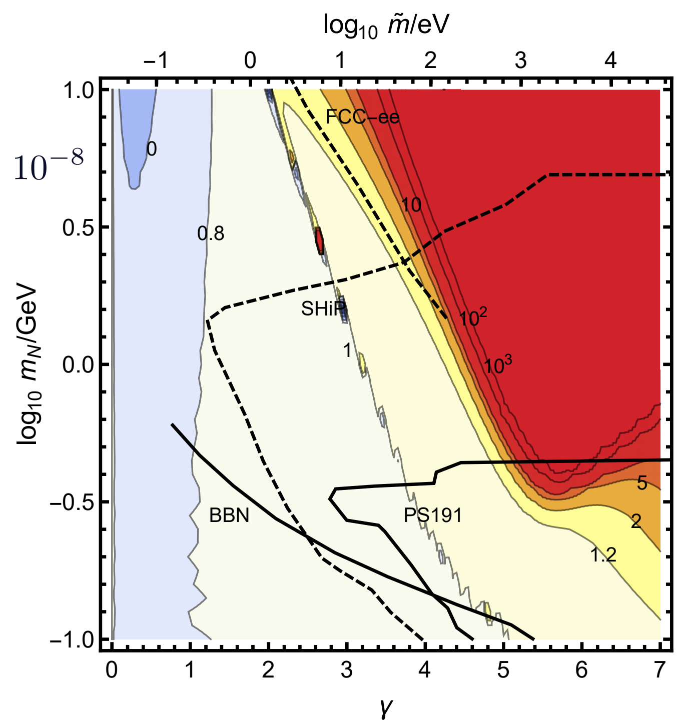
T.H., Teresi 17'

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



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

ratio of LV+LC over LC



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

- for very large Yukawas: less washout for LV than for LC !

$$\propto m_N^2 T^2 \;<<\; \propto T^4$$

- the smaller $\Delta m_N/m_N$ the more LV dominates
- the larger m_N the more LV dominates

Dominance of the LV contribution for low reheating temperatures

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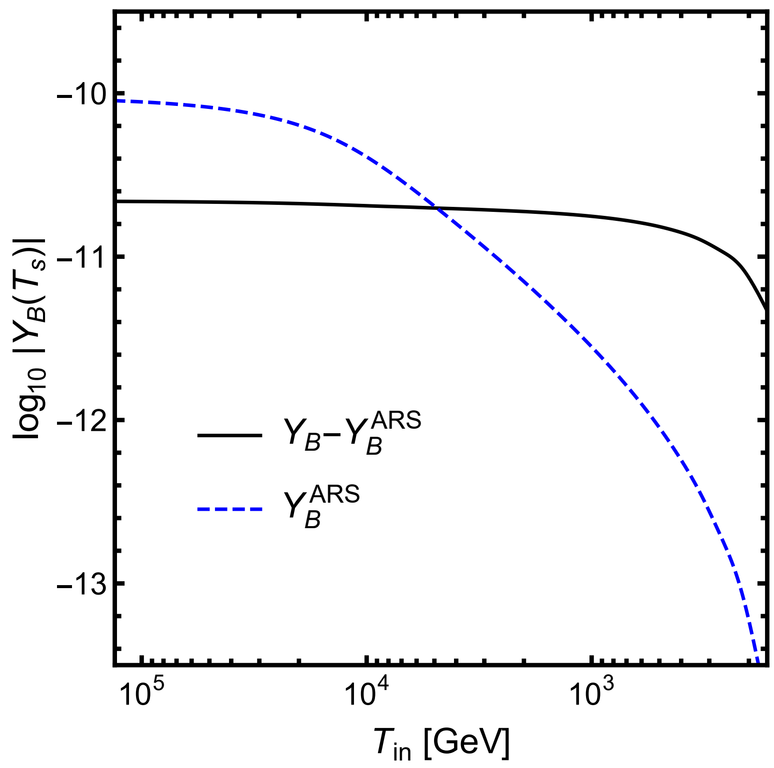
LV contribution produced at lower temperature than the ARS-LC contribution due to the m_N^2/T^2 relative factor



Need to incorporate other processes for a full quantitative asymmetry calculation

top quark scattering processes, gauge scattering processes, ...

Besak, Bodeker 12'
see also Ghiglieri, Laine 17'

have all a $H \to LN$ transition as building block $\Rightarrow$ same mechanism expected to be operative

additional effect found to be small

Drewes, Garbrecht, Güter, Klaric, 16'

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

baryon asymmetries obtained for 3 values of $\Delta m_N^0/m_N$