Higgs doublet decay as the origin of the baryon asymmetry

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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

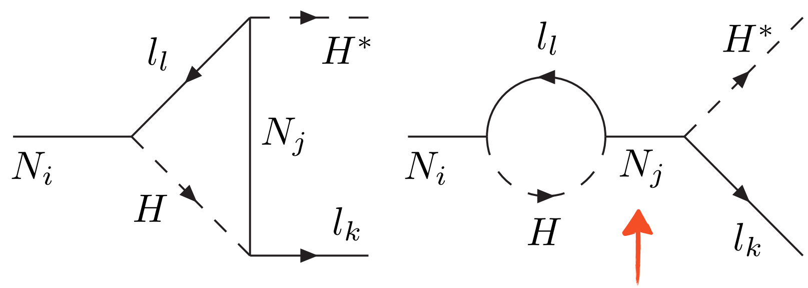
this talk: new way at low scale: total lepton number violating Higgs doublet decay into ~0.1-100 GeV right-handed neutrinos

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 $T \sim m_N >> T_{Sphaler.}$ ⇒ B asymmetry



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

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

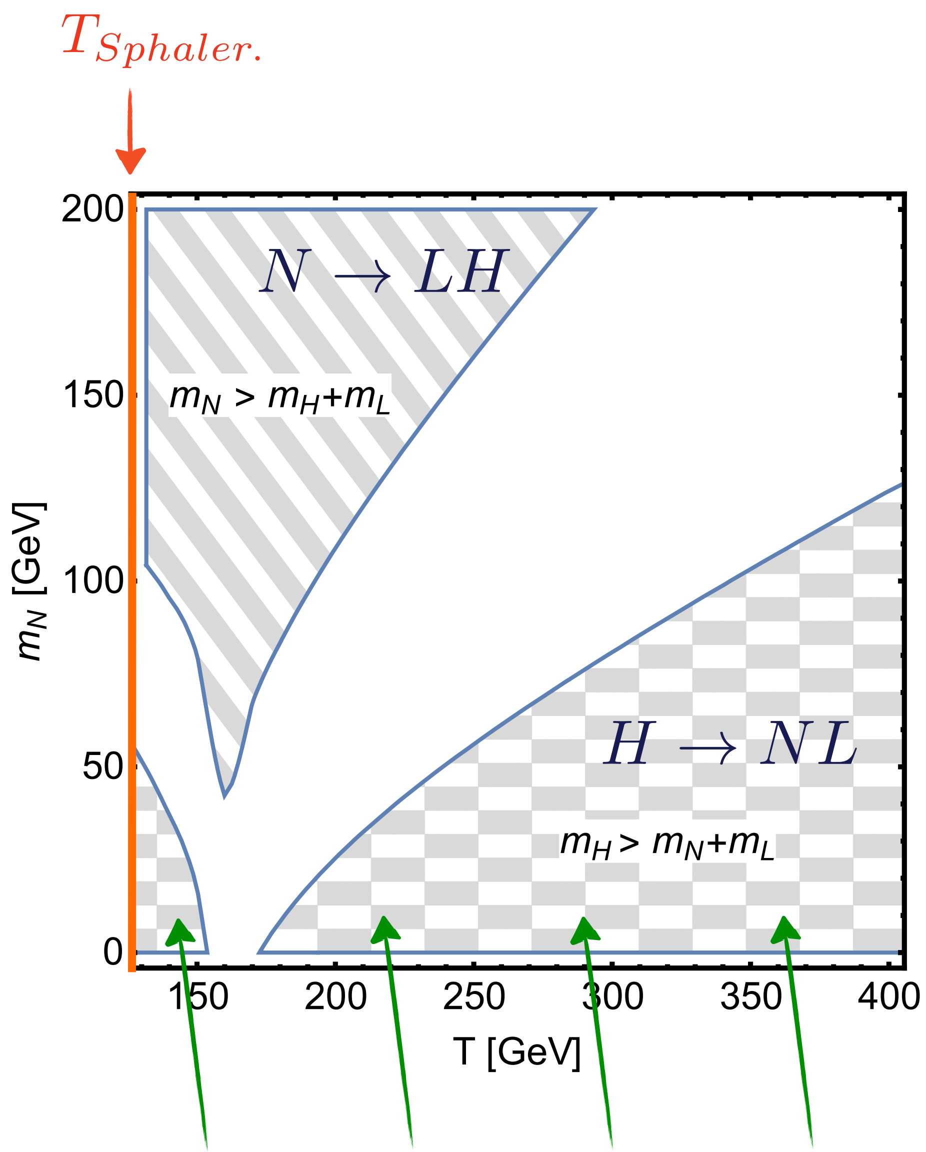
↪ creation of L asymmetry at $T > T_{Sphaler.} >> m_N$ ⇒ $\neq$ regime

↪ 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.

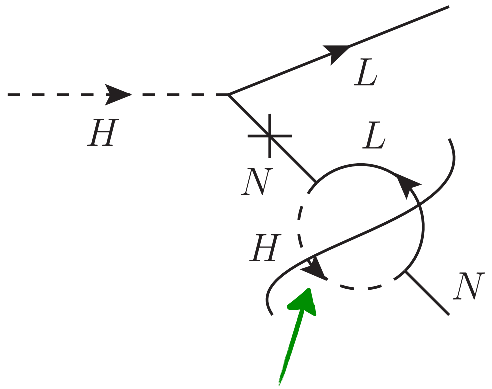
$$\frac{dn_N}{dt} \propto (n_N^{eq} - n_N) \cdot \Gamma_{H \to NL}$$

$H \to NL$ $\quad$ $NL \to H$

L asymmetry production from $H \to NL$ decay

2 issues at first sight:

2) Absorptive part for CP violation?



$m_H + m_L > m_N$ ⇒ 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)

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:

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

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

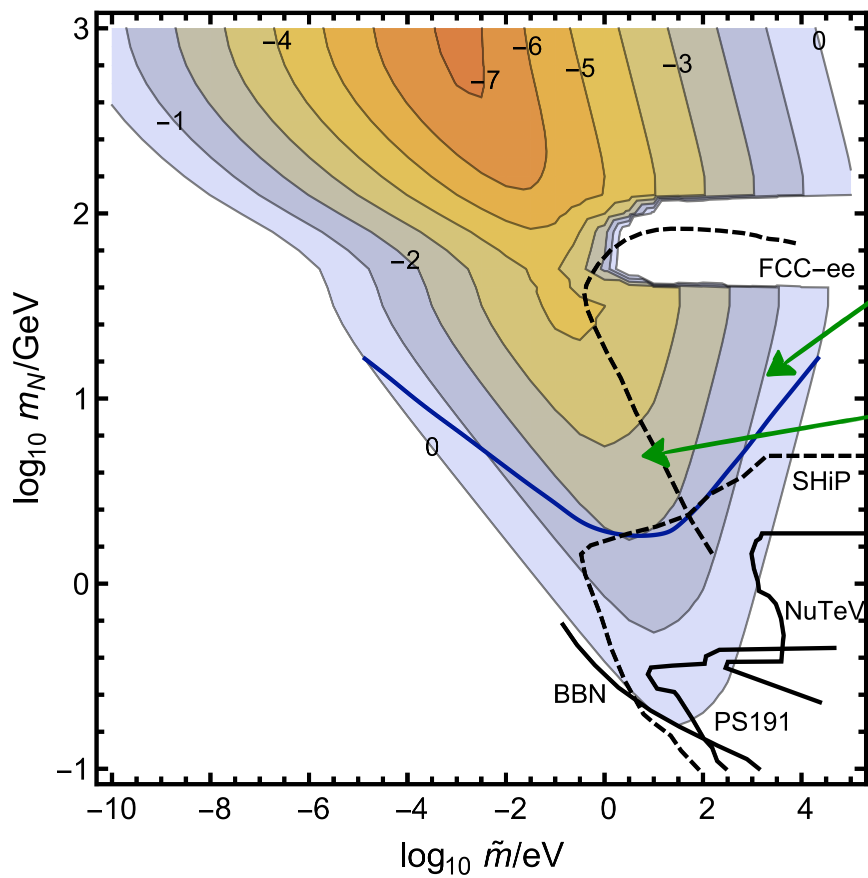
$$\eta_N \equiv n_N/n_\gamma$$

$$z \equiv m_N/T$$

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 $T > T_{Sphaler.}$

⇓

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 $T \sim m_N$

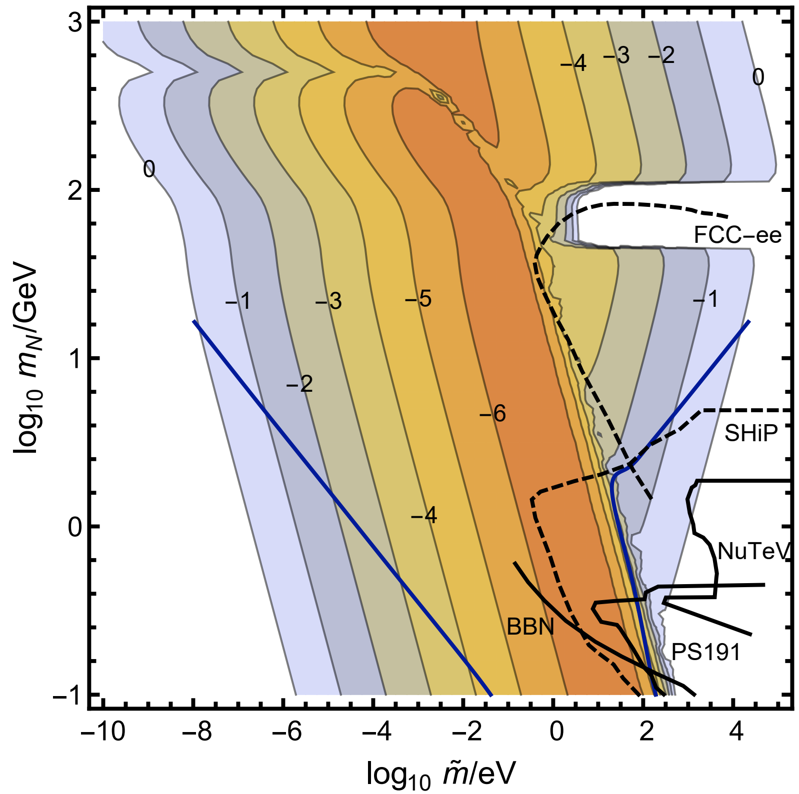
$$\tilde{m} \equiv \frac{Y_N Y_N^\dagger v^2}{2m_N} \qquad \tilde{m} >> 10^{-3}\,\mathrm{eV} \qquad \tilde{m} \gtrsim 10^{-3}\,\mathrm{eV}$$

- 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

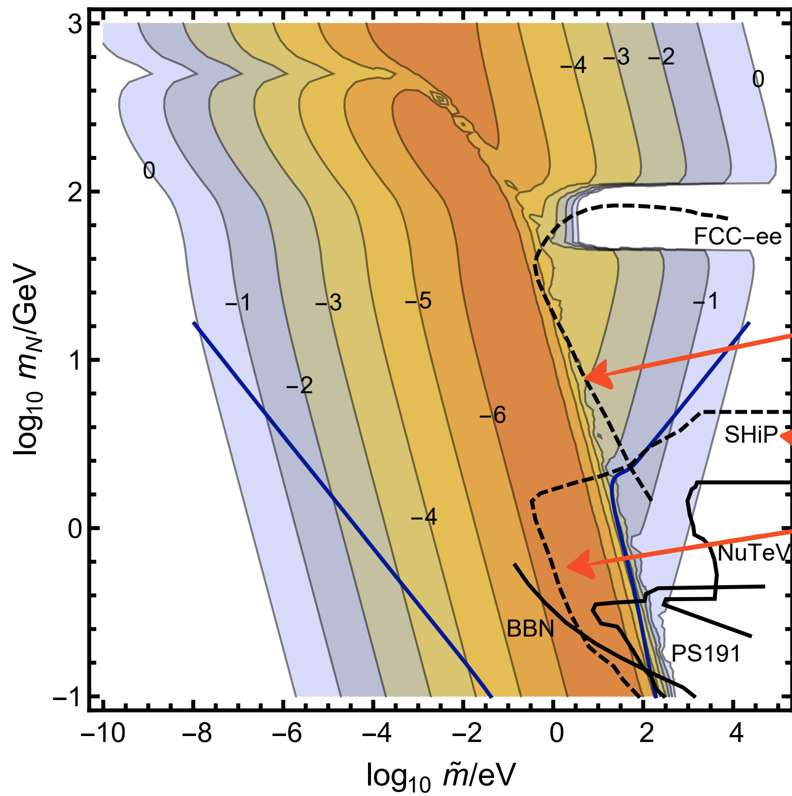
$$n_N^{eq} - n_N \sim n_N^{eq} >> n_N$$

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

Links with other very low scale frameworks

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

N oscillation frameworks

- based on density matrix formalism
- based on purely flavour asymmetries $><$ $H \to NL$ total L number violating framework which doesn't require flavour

  $$(Y_N Y_N^\dagger)_{ll} > (Y_N Y_N^\dagger)_{l'l'}$$ ← especially if large Δm_N

- has been considered in many $\neq$ regimes: large/small Δm_N, large/small $\tilde{m}$, 2 or 3 N, many/few oscillat., ...

flavour asym.

$\propto Y_N^2 T^2$

→ production at $T >>> T_{Sphaler.}$

$$\propto \frac{Y_N^6 M_{Planck}^{4/3}}{(\Delta m_N^2)^{2/3}}$$

L violating asym.

$\propto m_N^2$

→ production at $T \gtrsim T_{Sphaler.}$

$$\propto \frac{Y_N^4 m_N^2}{\Delta m_N^2}$$

$\Rightarrow$ e.g. dominance or L violating asym. for Δm_N not too large, especially if no big cancellations between the Y_N in m_ν or if flavour hierarchy is small or low reheating temperature

Links with other very low scale frameworks

↪ as a matter of principle the L violating decay contribution must also appear in density matrix formalism

↪ there is a L violating term showing up in density matrix Boltzmann equations: ``R_M" term, considered to be negligible for $T >> m_N$ and thus neglected for baryon asymmetry production

Shaposhnikov 08'

Canetti, Drewes, Frossard, Shaposhnikov 13'

we are computing and comparing the R_M contribution in N-oscillation formalism to our decay formalism contribution

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 are looking at same effect in density matrix formalism...

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