A biased review of Leptogenesis

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Baryogenesis: Basics

Observation

Our Universe is baryon asymmetric.

$$\frac{n_B}{s} \equiv \frac{n_b - n_{\bar{b}}}{s} \simeq 10^{-11}$$

BAU is measured in CMB and BBN. Perfect agreement with each other.

Theory

Sakharov Conditions for successful baryogenesis

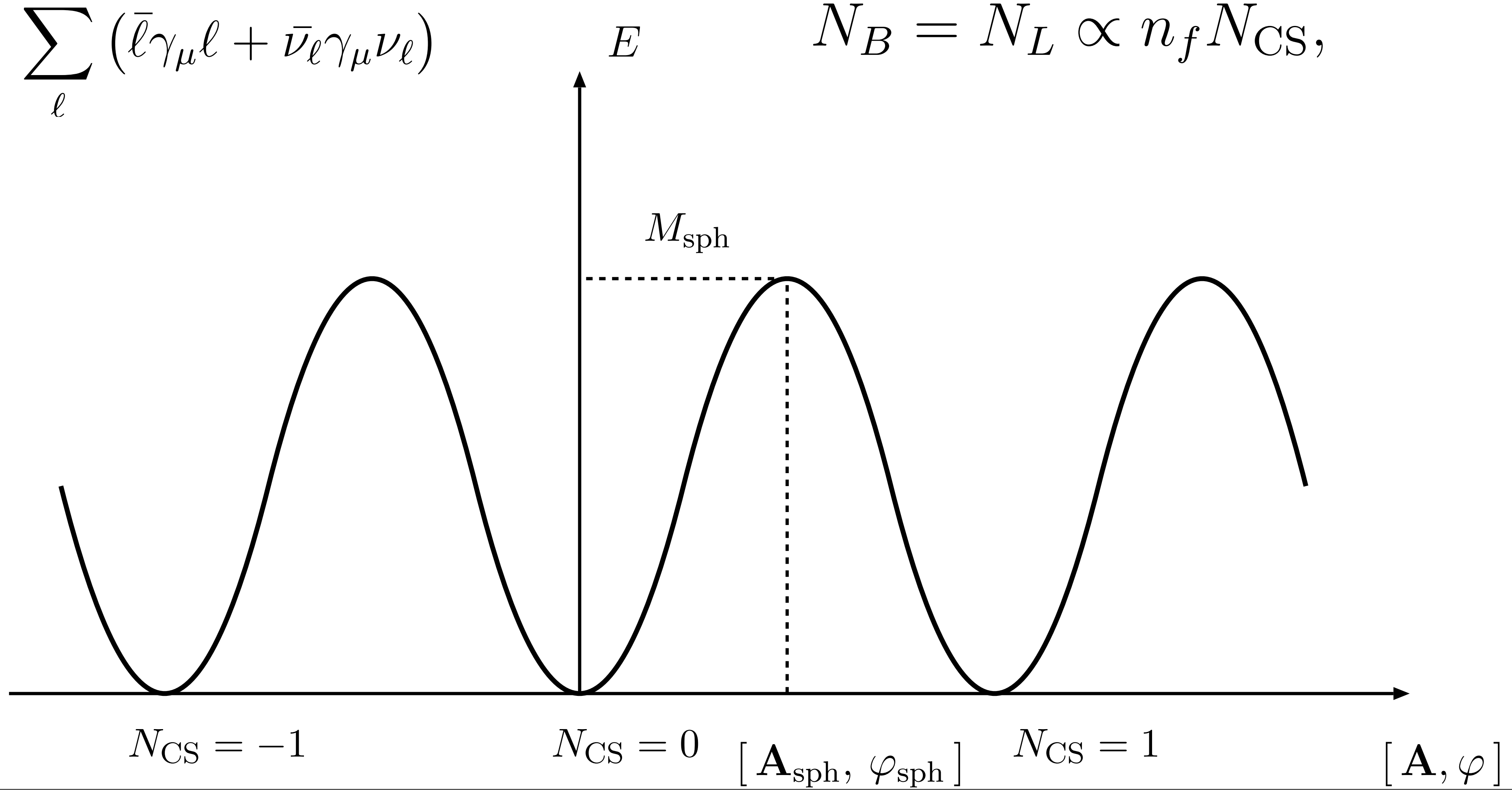
- B violation $\qquad \tau_p \gtrsim 10^{32}\ \mathrm{yrs}$
- C & CP violation
- Departure from thermal equilibrium

EW Sphalerons

One of the great successes of SM is to explain why Baryon and Lepton numbers are conserved perturbatively.

But at the non perturbative level, B and L are no more conserved due to EW anomaly.

$$\begin{aligned} J^B_\mu &= \frac{1}{3}\sum_{\substack{\text{colors}\\ \text{generations}}} \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right) \\ J^L_\mu &= \sum_{\ell}\left(\bar{\ell}\gamma_\mu \ell + \bar{\nu}_\ell \gamma_\mu \nu_\ell\right) \end{aligned} \quad \Rightarrow \quad \begin{aligned} \partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{n_f}{32\pi^2}\mathrm{Tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right)\,, \\ N_B = N_L \propto n_f N_{\mathrm{CS}}, \end{aligned}$$

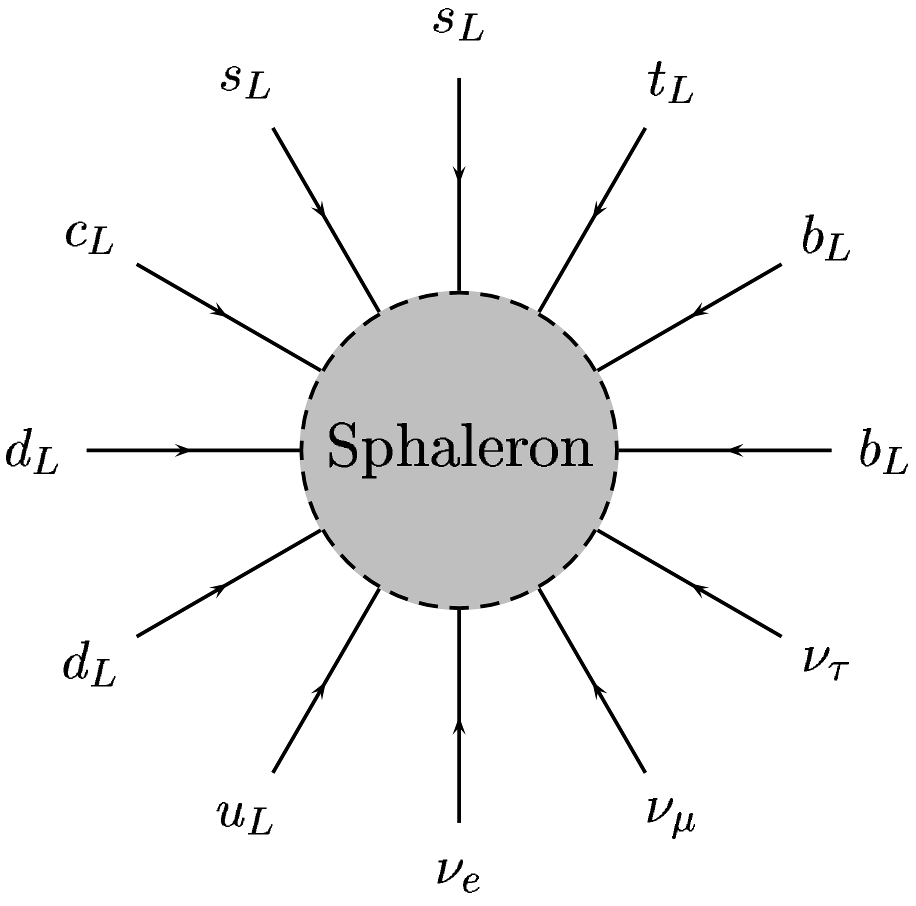


Rate of B+L violation is given by

$$\Gamma \sim \begin{cases} \exp\left(\frac{-4\pi}{\alpha_W}\right) \sim 10^{-160}, & T = 0 \\ (\alpha_W T)^4 \left(\frac{m_{sph}}{T}\right)^7 \exp\left(-\frac{m_{\rm sph}}{T}\right), & T < T_C \\ \alpha_W^5 T^4 & T > T_C \end{cases}$$

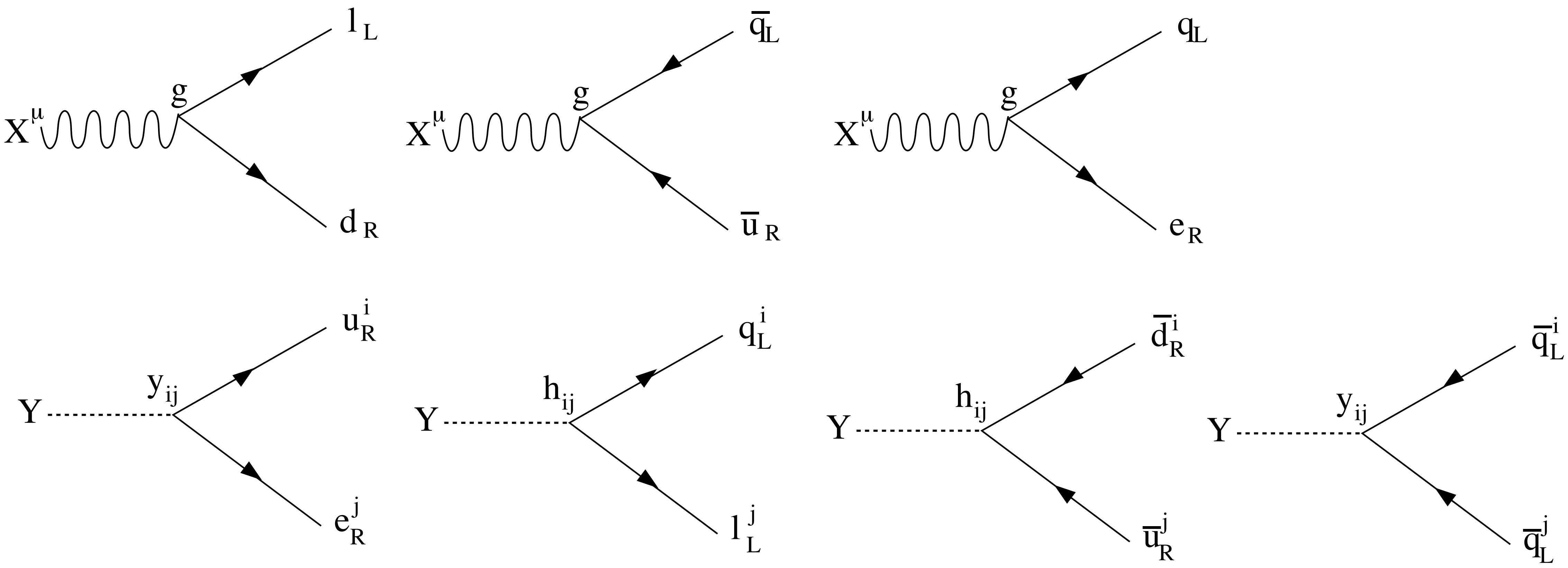
=> Sphalerons are in equilibrium for $10^2\mathrm{GeV} < T < 10^{12}\mathrm{GeV}$

$$B = \left(\frac{8n_g + 4n_H}{22n_g + 13n_H}\right) L$$



GUT Baryogenesis

B violation mediated by X and Y bosons present in GUTs



The scenario works however it is disfavoured because of the required high reheat temperature to produce X and Y => gravitinos, monopoles, ...

Affleck-Dine Baryogenesis

-In SUSY, there exists plenty of flat directions (F=D=0).

-Their flatness is only lifted by ~~SUSY~~ or non-renormalizable operators.

-Furthermore during inflation, SUSY is broken since V≠0.

Example

$$W = \lambda \frac{(LH_u)^2}{M} \qquad L_i = \frac{1}{\sqrt{2}} \begin{pmatrix} \varphi \\ 0 \end{pmatrix}, \quad H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}$$

This flat direction carries lepton number $n_L = \frac{i}{2}(\varphi^* \dot{\varphi} - \varphi \dot{\varphi}^*)$,

$$V(\varphi) \;=\; (m_{3/2}^2 - c_H H^2)|\varphi|^2 + a_H H \frac{\varphi^4}{4M} + a_m m_{3/2} \frac{\varphi^4}{4M} + \text{h.c.} + \frac{|\lambda|^2}{M^2}|\varphi|^6 .$$

During inflation $H \gg m_{3/2}$ => $|\varphi_0| \simeq \left(\frac{c_H M^2 H^2}{|\lambda|^2} \right)^{1/4}$.

$$\dot{n}_L + 3Hn_L = \mathrm{Im}\left[\varphi \frac{\partial V(\varphi)}{\partial \varphi} \right] \quad \Rightarrow \quad n_L \approx \frac{m_{3/2}}{2M} \mathrm{Im}(a_m \varphi^4) t$$

Spontaneous Baryo/Leptogenesis

Important Caveat: CPT is assumed to be conserved.

If ~~CPT~~, then Baryogenesis can proceed in equilibrium.

Baryon or lepton number can couple through

$$\mathcal{L} \supset J_B^\mu \partial_\mu \phi \rightarrow n_B \, \dot{\phi}$$

If $\dot{\phi} \neq 0$ Poincare' is broken => ~~CPT~~ (Greenberg Theorem).

The evolution of baryon number will follow:

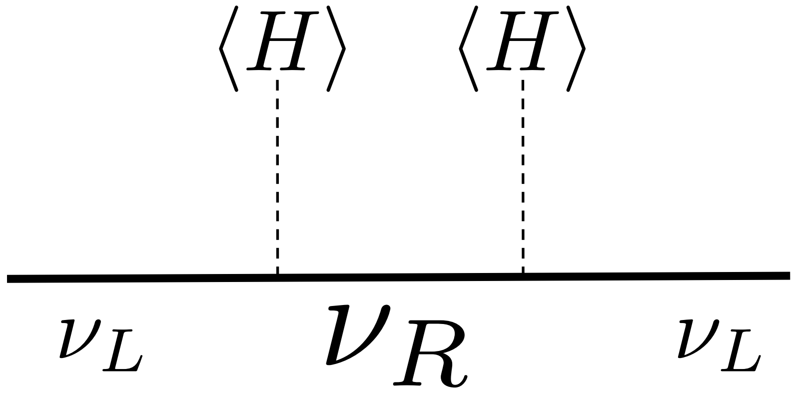
$$\partial_\mu J_B^\mu \propto \partial^2 \phi \rightarrow \dot{n}_B + 3 H n_B \propto \ddot{\phi}$$

E.g. coupling with Ricci $\partial^\mu R \partial_\mu \phi$, ...

=> model dependent predictions

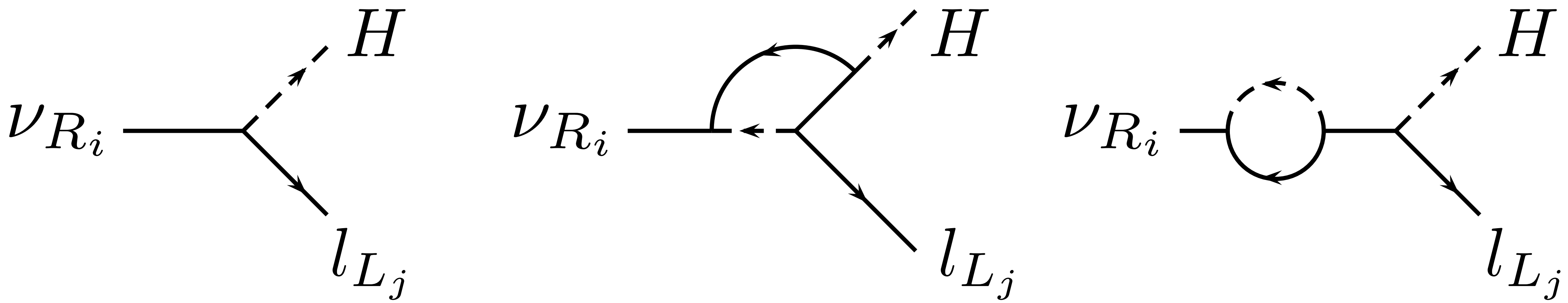
Type I See-saw & leptogenesis

- The existence of a heavy right handed (RH) explains the smallness of neutrino masses



$$\Rightarrow m_\nu \simeq -\frac{Y^T Y}{M_{\nu_R}} \langle H \rangle^2 \ll m_{q,\ell} = Y_{q,\ell} \langle H \rangle$$

- The decay of RH neutrinos leads to a L asymmetry which is converted to a baryon asymmetry through SM sphalerons.



$$\frac{n_B}{s} = -\frac{28}{79} \epsilon_{\nu_{R_1}} \eta(\tilde{m}_1) \frac{n_{\nu_{R_1}}}{s} (T \gg M_{\nu_{R_1}})$$

CP violation

washout factor

Baryogenesis through leptogenesis

- Lepton number produced through $\not{L}$ decay of Right handed neutrino

- Exploits EW sphalerons to transform L to B.

$$Y_B \equiv \frac{n_B}{s} = \left(\frac{8n_g + 4n_H}{22n_g + 13n_H}\right) \frac{n_L}{s} \, ,$$

- CP violation: interference of tree + 1-loop (vertex and self energy)

$$\begin{aligned} \varepsilon_i \quad &\equiv \quad \frac{\sum_j \Gamma(N_i \to \ell_j h_u) - \sum_j \Gamma(N_i \to \bar{\ell}_j \bar{h}_u)}{\sum_j \Gamma(N_i \to \ell_j h_u) + \sum_j \Gamma(N_i \to \bar{\ell}_j \bar{h}_u)} \\ &= \quad -\frac{1}{8\pi} \frac{1}{(YY^\dagger)_{ii}} \sum_{k \neq i} \mathrm{Im}\left[\{(YY^\dagger)_{ik}\}^2\right] \left[F_V\left(\frac{M_k^2}{M_i^2}\right) + F_S\left(\frac{M_k^2}{M_i^2}\right)\right] \end{aligned}$$

with $$F_V(x) = \sqrt{x} \ln\left(1 + \frac{1}{x}\right) , \quad F_S(x) = \frac{2\sqrt{x}}{x - 1}$$

Departure from thermal equilibrium vs. thermal production

Consider hierarchical RH neutrino masses => B is created through decay of N_1

Departure from thermal equilibrium => $\Gamma_{\rm Decay} < H$

$$\frac{\Gamma(T=0)}{H(T=M)} = \frac{(Y^\dagger Y)_{11}\cdot M}{8\pi} \Big/ \left(g_*^{1/2} \frac{M^2}{M_P} \frac{2\pi^{3/2}}{\sqrt{45}} \right) \equiv \frac{\widetilde{m}_1}{1.1\times 10^{-3}{\rm eV}} < 1,$$

On the other hand, thermal production of RH neutrinos => $\Gamma_{\rm Prod} > H$

$$\Gamma_{\rm Prod} = \langle n\sigma v\rangle \simeq g_*(Y^\dagger Y)_{11} T > g_*^{1/2} T^2/M_P \Big|_{T=M} \Rightarrow \widetilde{m}_1 > 10^{-5}\ {\rm eV}$$

$$\Downarrow$$

$$10^{-5}\ {\rm eV} \lesssim \widetilde{m}_1 \lesssim 10^{-3}\ {\rm eV}$$

In general, one invokes the presence of B-L gauge bosons, which are in equilibrium for

$$M_{Z'} < \left(\frac{T_{RH}}{10^{10}\ {\rm GeV}}\right)^{3/4} 4\times 10^{11}\ {\rm GeV}.$$

The gravitino problem in leptogenesis

Thermal production of N_1 => $T_{RH} > M_{N_1} \simeq 10^9\,\mathrm{GeV}$

On the other hand, in the SUSY version of leptogenesis

$$\Omega_{3/2}\,h^2 \quad = 0.21 \left(\frac{T_{\rm RH}}{10^{10}\ \mathrm{GeV}}\right) \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right) \left(\frac{m_{\tilde{g}}}{1\ \mathrm{TeV}}\right)^2$$

No overproduction of gravitinos => $T_{RH} < 10^9\,\mathrm{GeV}$.

Possible solutions

- Either the gravitino is very heavy or very light.
- Gravitino is dark matter.
- Non-thermal production (preheating, inflaton decay, ...)
- Low reheat temperature.

Low Scale Leptogenesis

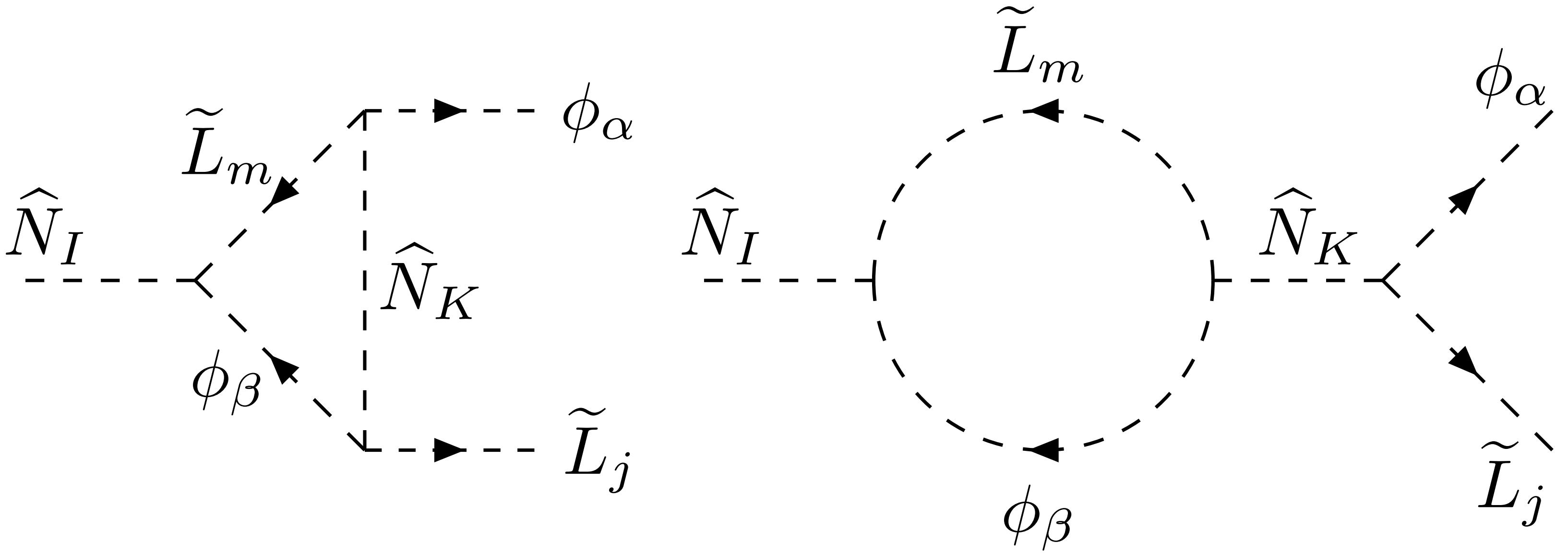
LB, hep-ph/0208003

LB, T. Hambye & G. Senjanović, PRL ’04.

- Thermal production $T_{RH} > 10^9\ \mathrm{GeV}$ $\cancel{\longleftrightarrow}$ Gravitinos $T_{RH} < 10^9\ \mathrm{GeV}$
- Proposed solution: RH neutrinos could have masses ~ TeV. Then T_{RH} ~TeV.

➡New sources de CP and L violation.

$$\mathcal{L}_{\widetilde{N}} = (m^2_{\widetilde{N}})_{ij}\widetilde{N}^*_i\widetilde{N}_j + B_{ij}\widetilde{N}_i\widetilde{N}_j + A^U_{ij}\widetilde{L}_iH_U\widetilde{N}_j$$
$$+ A'^U_{ij}\widetilde{L}_iH_U\widetilde{N}^*_j + A^D_{ij}\widetilde{L}_iH^*_D\widetilde{N}_j + A'^D_{ij}\widetilde{L}_iH^*_D\widetilde{N}^*_j + \mathrm{h.c.}$$



Going to the diagonal basis

$$\mathcal{L}_{\widetilde{N}} = M^2_{\widehat{N}_I}\widehat{N}_I^2 + \mu^{\alpha}_{Ij}\widehat{N}_I\widetilde{L}_j\phi_\alpha + \mu^{\alpha*}_{Ij}\widehat{N}_I\widetilde{L}^*_j\phi^*_\alpha\,,$$

The CP asymmetry reads

$$\varepsilon^V_I = \frac{-1}{8\pi M^2_{\widehat{N}_I}}\frac{1}{|\mu^\alpha_{Ij}|^2}\sum_{K\neq I}\mathrm{Im}\big[\mu^\beta_{Im}\mu^{\beta*}_{Kj}\mu^{\alpha*}_{Km}\mu^\alpha_{Ij}\big]\,F_V(x_K),$$

$$\varepsilon^S_I = \frac{-1}{4\pi M^2_{\widehat{N}_I}}\frac{1}{|\mu^\alpha_{Ij}|^2}\sum_{K\neq I}\mathrm{Im}\big[\mu^\beta_{Im}\mu^{\beta*}_{Km}\mu^{\alpha*}_{Kj}\mu^\alpha_{Ij}\big]\,F_S(x_K),$$

With $x_K = M^2_{\widehat{N}_I}/M^2_{\widehat{N}_K}$ and $F_V(x) = \ln(1+x), \qquad F_S(x) = x/(1-x).$

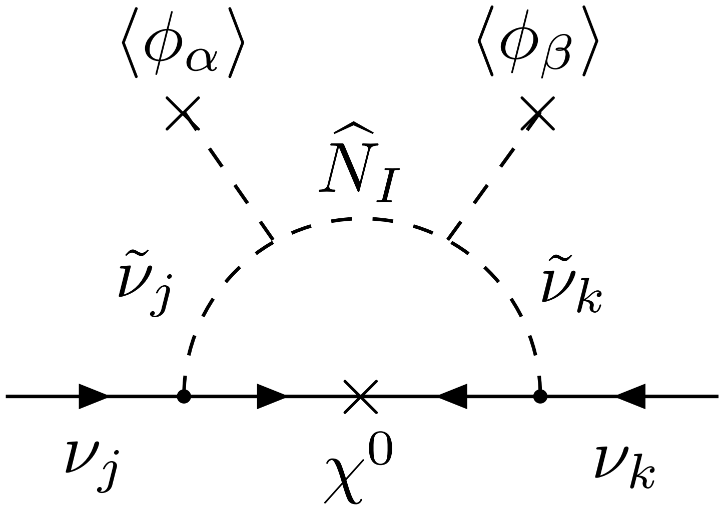
Numerical example:

$$M_{\widehat{N}_1} \sim 2\,\mathrm{TeV},\; M_{\widehat{N}_2} \sim 6\mathrm{TeV}$$

$$(\mu^\alpha_{1j})^{\max} \sim 5\cdot 10^{-8}\,M_{\widehat{N}_1},\; (\mu^\alpha_{2j})^{\max} \sim 10^{-3}\,M_{\widehat{N}_2}$$

gives $\varepsilon_1 \sim 10^{-7}$ and $n_B/n_\gamma \sim 6\cdot 10^{-10}$

➡ New contributions to light neutrino masses



$$(m_\nu^{\rm rad})_{jk} \simeq \frac{\alpha}{4\pi}\,\frac{\mu^\alpha_{Ij}\;\mu^\beta_{Ik}}{M^2_{\widehat{N}_I}}\,\frac{m_\chi}{m^2_{\tilde{\nu}_j}-m^2_{\tilde{\nu}_k}}\langle\phi_\alpha\rangle\langle\phi_\beta\rangle \\ \times\left[\frac{m^2_{\tilde{\nu}_j}}{m^2_{\tilde{\nu}_j}-m^2_\chi}\ln\frac{{m_{\tilde{\nu}_j}}^2}{m^2_\chi}-j\to k\right].$$

For our numerical example with $m_{\tilde{\nu}_i}\approx 500\ \mathrm{GeV}$ and $m_\chi\approx 100\ \mathrm{GeV}$ gives

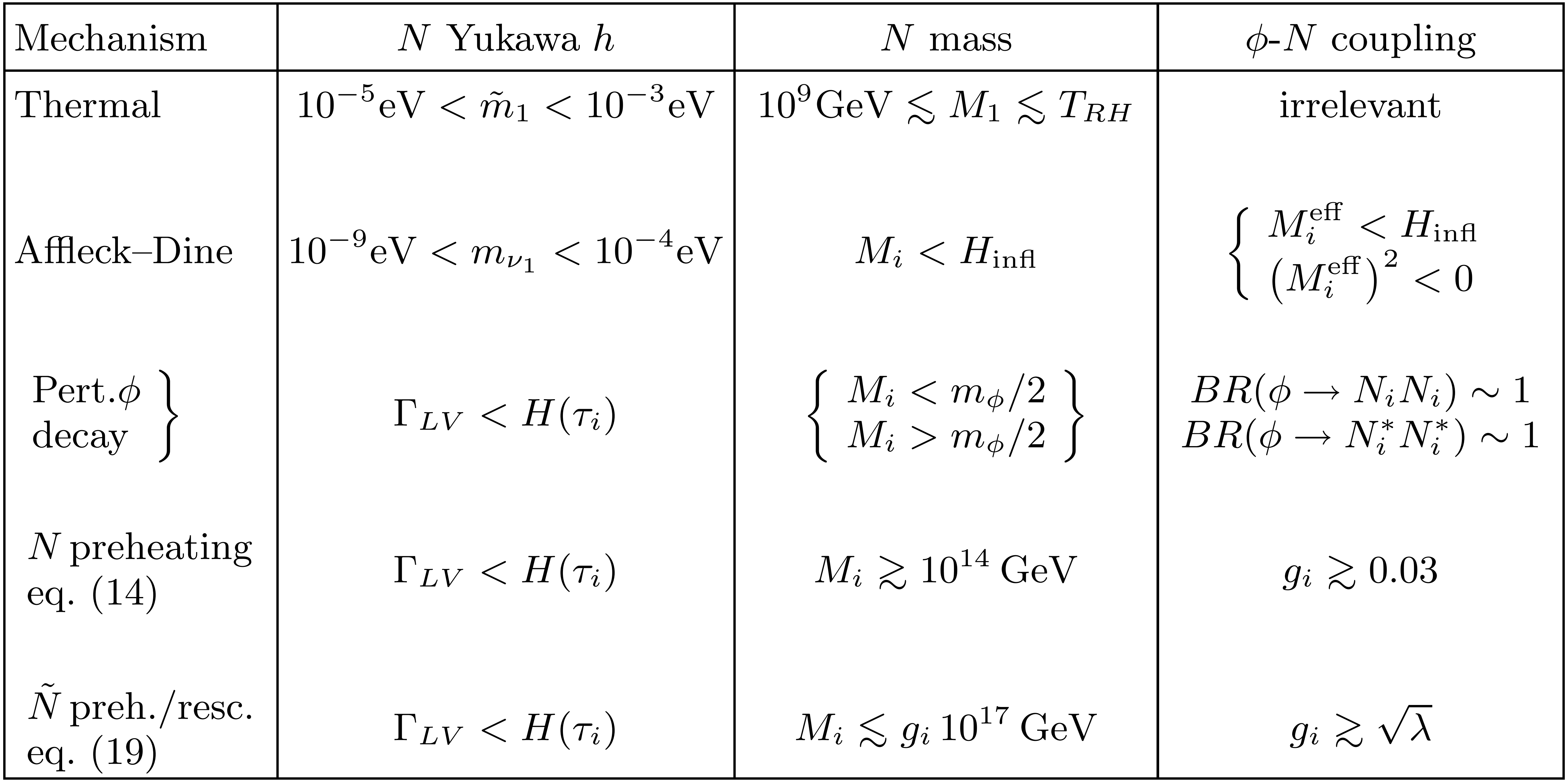
$$m_\nu^{\rm rad}\approx 1\ \mathrm{eV}!$$

$$\Downarrow$$

Degenerate spectrum for light neutrinos

Non thermal production of RH neutrinos

LB & Davidson, Peloso, Sorbo, PRD '02



Mechanism	N Yukawa h	N mass	ϕ-N coupling
Thermal	$10^{-5}\text{eV} < \tilde{m}_1 < 10^{-3}\text{eV}$	$10^9\text{GeV} \lesssim M_1 \lesssim T_{RH}$	irrelevant
Affleck–Dine	$10^{-9}\text{eV} < m_{\nu_1} < 10^{-4}\text{eV}$	$M_i < H_{\text{infl}}$	$\left\{ \begin{array}{l} M_i^{\text{eff}} < H_{\text{infl}} \\ \left(M_i^{\text{eff}}\right)^2 < 0 \end{array} \right.$
$\left. \begin{array}{l} \text{Pert.}\phi \\ \text{decay} \end{array} \right\}$	$\Gamma_{LV} < H(\tau_i)$	$\left\{ \begin{array}{l} M_i < m_\phi/2 \\ M_i > m_\phi/2 \end{array} \right\}$	$BR(\phi \to N_i N_i) \sim 1$ $BR(\phi \to N_i^* N_i^*) \sim 1$
N preheating eq. (14)	$\Gamma_{LV} < H(\tau_i)$	$M_i \gtrsim 10^{14}$ GeV	$g_i \gtrsim 0.03$
$\tilde{N}$ preh./resc. eq. (19)	$\Gamma_{LV} < H(\tau_i)$	$M_i \lesssim g_i\, 10^{17}$ GeV	$g_i \gtrsim \sqrt{\lambda}$

- RH neutrinos are produced through the coupling

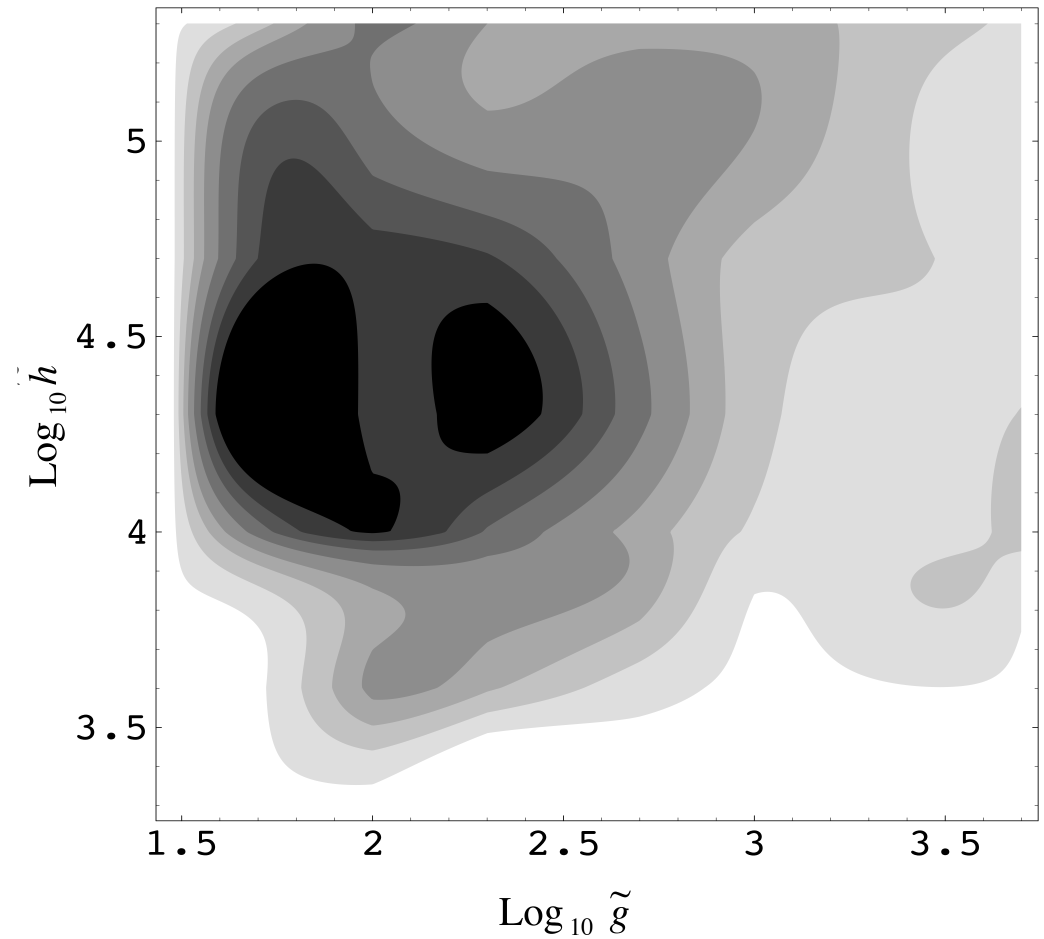
$$\mathcal{L}_{N,\,\phi} = \bar{N}\,\left(M + g\,\phi\right)\,N$$

- Rescattering is important

Rescattering term

$$\frac{dN_{3/2}}{dt} + 3\,H\,N_{3/2} \simeq \langle\sigma|v|\rangle N_X N_N$$

- Eventough RHN are produced at lower temperture, also gravitinos could be produced.



Inhomogeneous Leptogenesis

LB & P. Creminelli, PRD '06

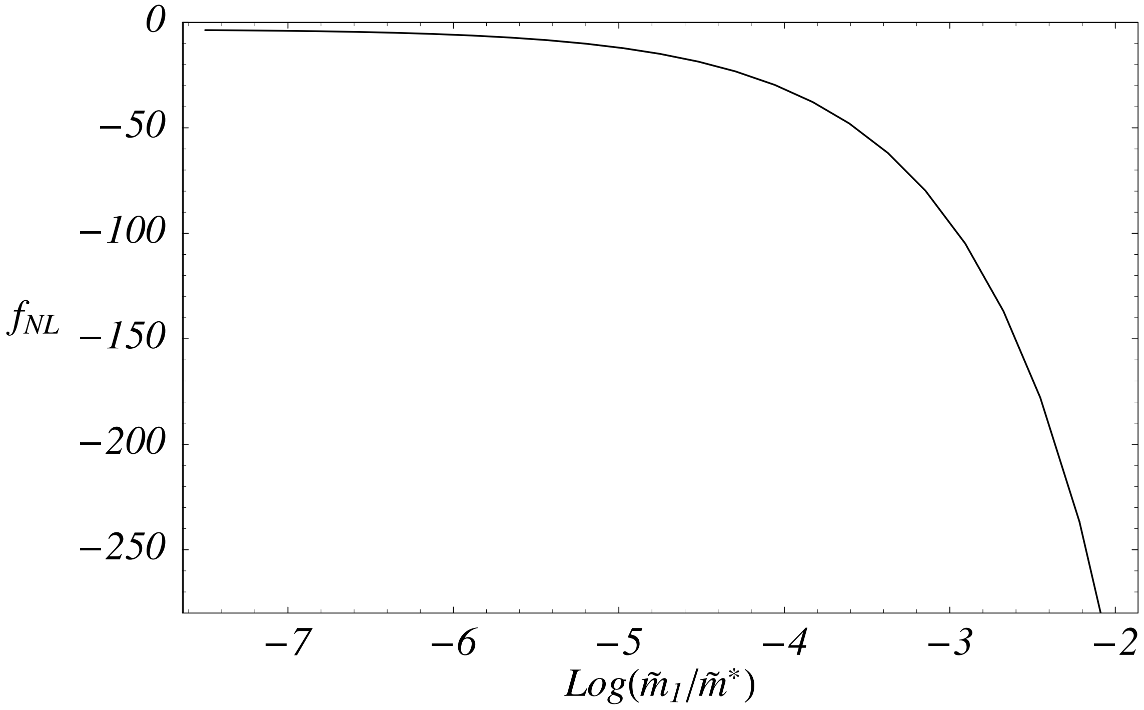
- See-saw with couplings depending on a light field χ

$$\mathcal{L} = \mathcal{L}_{\rm SM} + Y_{ij}\left(\frac{\chi}{M_P}\right) L_i H N_j + M_i\left(\frac{\chi}{M_P}\right) N_i N_i + (\partial\chi)^2$$

- RH neutrinos will decay differently in different places => curvature fluctuations.

$$ds^2 = -dt^2 + e^{2\zeta(\vec{x})}a(t)^2 d\vec{x}^2$$

- Non-Gaussianity due to χ.



➡Constraints on $f_{\rm NL}$ => Light neutrinos have hierarchical or inverse hierarchical spectrum.

➡Constraints on the dynamics of χ => $\cancel{M(\chi/M_P)}, Y(\chi/M_P)$ ✓

Conclusions

- In general baryogenesis probes physics beyond the standard model.
- Leptogenesis is a typical working example. Links neutrinos to BAU.
- Gravitino overproduction => low scale models.
- Gravitino overproduction => preheating and rescattering.
- Inhomogeneous leptogenesis could be responsible for CMB temperature anisotropies.
- Good opportunity to test ideas.