Leptogenesis and rescattering in susy models

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with Lotfi Boubekeur, Sacha Davidson, and Lorenzo Sorbo, to appear.

Plan of the talk

- Leptogenesis: bound on the CP asymmetry favors a nonthermal production of right handed neutrinos

- R.h. neutrinos can be efficiently produced at preheating; in SUSY models, production of quanta of sneutrinos is more efficient than the one of neutrinos since it is not limited by Puli blocking. A sufficient leptogenesis is easily achieved.

- Rescattering of these quanta can excite light MSSM degrees of freedom, coupled to the r.h. neutrinos; these (nonthermal) distributions can in some cases lead to an excessive production of gravitinos through perturbative scatterings

Leptogenesis is a mechanism for generating the observed baryon asymmetry $\eta_B \equiv n_B/s \sim (2-9) \times 10^{-11}$. First, η_L is generated by the decay of r. h. neutrinos; then, it is partially converted to η_B by $(B+L$ violating) sphaleron processes.

R.h. neutrinos are required in GUT like $SO(10)$, and in the see-saw mechanism to explain the lightness of the l.h. neutrinos

$$\mathcal{L} \supset -\bar{N} h_\nu H L - \frac{1}{2} \bar{N}^c M N + \text{h.c.}$$

$$m_\nu = -h_\nu^T M^{-1} h_\nu \langle H \rangle^2.$$

In the following, it is assumed that N are hierarchical ($M_1 < M_2 < M_3$; M diagonal), and that the asymmetry is generated by the decays of N_1 (an enhanced η_L can be produced by nearly degenerate r.h. neutrinos)

At the decay, $N_L = \epsilon_1 \, N_{N_1}$ is generated, where ϵ_1 arises from the interference between the tree level and the one loop diagrams

$$\epsilon_1 \equiv \frac{\Gamma\,(N \to \bar{H}\,L) - \Gamma\,(N \to \bar{L}\,H)}{\Gamma\,(N \to \bar{H}\,L) + \Gamma\,(N \to \bar{L}\,H)}$$

$$\simeq -\frac{3}{16\,\pi\,\left(h\,h^\dagger\right)_{11}} \sum_{i=2,3} \mathrm{Im}\left[\left(h\,h^\dagger\right)^2_{1i}\right] \frac{M_1}{M_i}$$

The CP asymmetry is bounded by

$$\epsilon_1 = \frac{3\,M_1\,m_{\nu_3}}{16\,\pi\,\langle H\rangle^2}\,\delta_{\mathrm{CP}} \simeq 10^{-6}\,M_{10}\,\left(\frac{m_{\nu_3}}{0.05\,\mathrm{eV}}\right)\delta_{\mathrm{CP}}$$

Hamaguchi, Murayama, and Yanagida, 01

m_{ν_3} is the mass of the heaviest l.h. neutrino,

$M_{10} \equiv \frac{M_1}{10^{10}\,\mathrm{GeV}}$, $\delta_{\mathrm{CP}} < 1$

Consequences for thermal production

The lepton asymmetry can be reduced by lepton violating scattering, which are active if N_1 decays when relativistic. This occurs for

$$K \equiv \frac{\Gamma_{N_1}}{2\,H}\Big|_{T=M_1} \simeq \frac{\tilde{m}_1}{2\times 10^{-3}\,\mathrm{eV}} \geq 1$$

where

$$\tilde{m}_1 \equiv \frac{\left(h_\nu\, h_\nu^\dagger\right)_{11}\,\langle H\rangle^2}{M_1}$$

parameterizes the relevant interactions of N_1 (it coincides with the light neutrino mass m_{ν_1} only in the limit of small mixing angles)

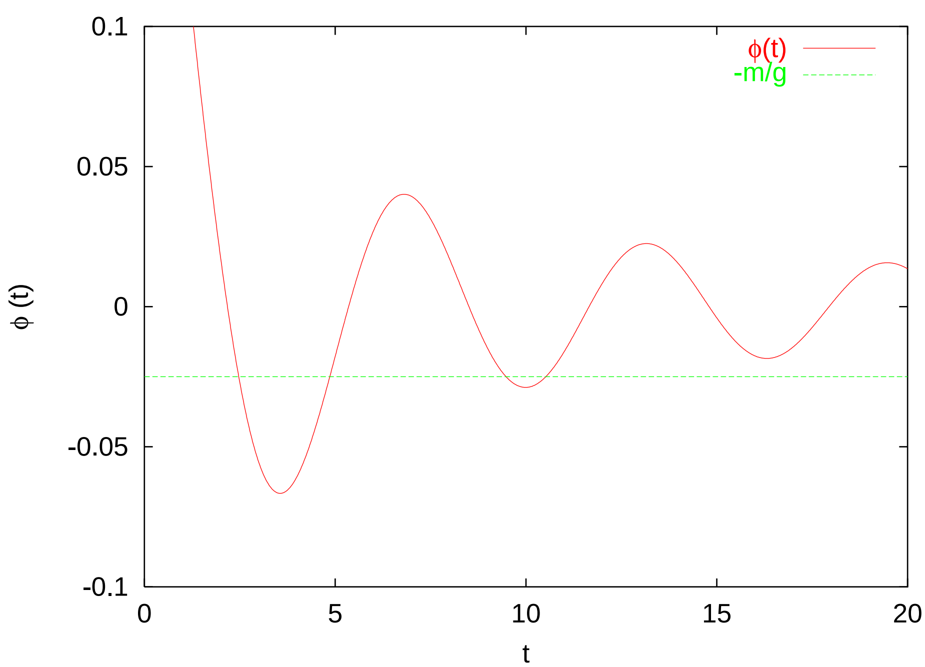
Requiring SM (MSSM) interactions to bring the N_1 in thermal equilibrium before they decay imposes $K \gtrsim 1$. From the limit on ϵ_1,

$$\eta_B \sim 10^{-10}\,M_{10}\left(\frac{m_{\nu_3}}{0.05\,\mathrm{eV}}\right)\left(\frac{\delta_{\mathrm{LVS}}}{0.1}\right)\delta_{CP}$$

Thus, $T > M_1 \gtrsim 10^9$ GeV is required; marginally compatible with the bound from thermal overproduction of gravitinos.

For such high masses, nonperturbative production has been proposed (Giudice, M.P., Riotto, Tkachev, 99), not to conflict with the thermal bound.

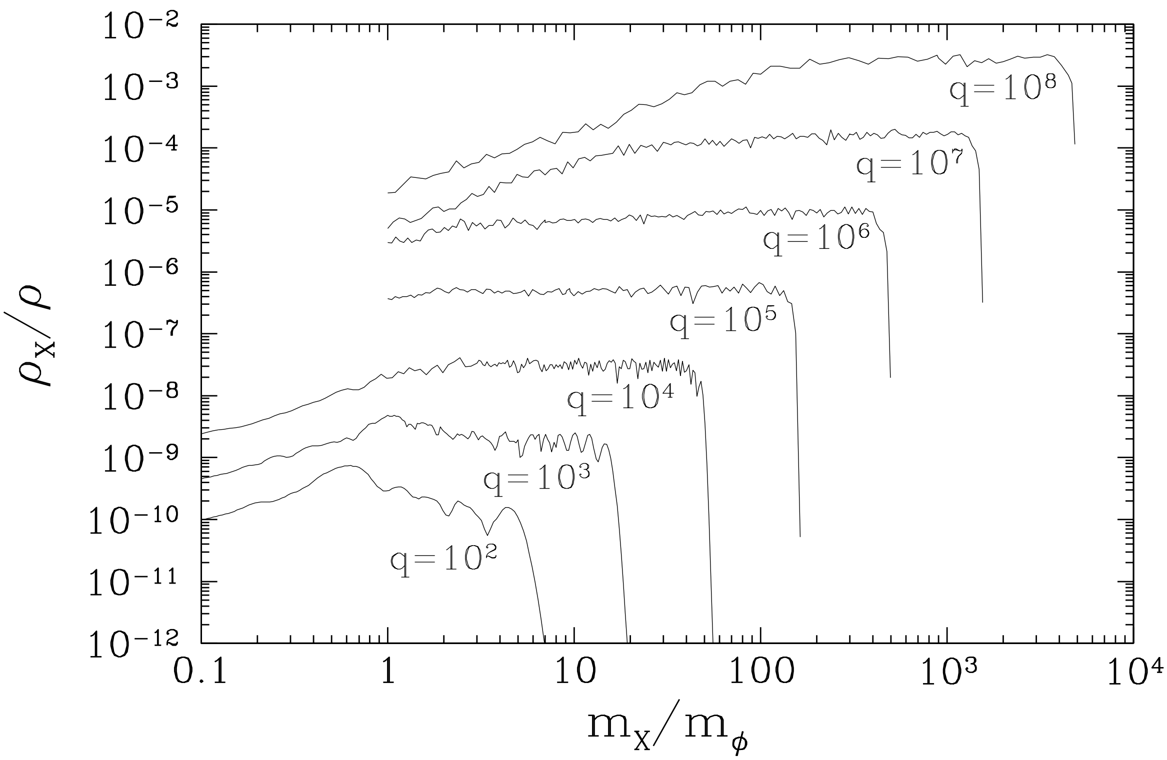
$$\mathcal{L} \supset (M_N + g\,\phi)\,\bar{N}\,N$$



The nonthermal production is effective if the total mass vanishes at least once, that is if

$$M_{10} < 5 \cdot 10^7 \left(\frac{q}{10^{10}}\right)^{1/2} \;, \quad q \equiv \frac{g^2\,\phi_0^2}{4\,m_\phi^2} \simeq 3\,g^2\,10^{10}$$

The sharp cut-off is evident



The production has been computed analytically M.P., Sorbo, 00

$$\frac{N_N}{\rho_\phi} = \frac{1.4\,\left(q/10^{10}\right)}{10^{14}\,\text{GeV}\,M_{10}^{1/2}}\left[\text{Log}\left(1.66\cdot 10^3\,\frac{q^{1/2}}{M_{10}}\right)\right]^{3/2}$$

For a massive inflaton, this ratio is constant until the inflaton decays.

If

$$\left(\frac{\tilde{m}_1}{0.05 eV}\right)^{1/2} > \frac{2\cdot 10^{-16}\, q}{M_{10}^{1/2}} \frac{T_{\rm RH}}{10^9\,\text{GeV}} \left[\text{Log}\left(1.66\cdot 10^3\, \frac{q^{1/2}}{M_{10}}\right)\right]^{3/2}$$

the final η_B is given by

$$\eta_B = 4\cdot 10^{-12}\, \frac{q\, M_{10}^{1/2}}{10^{10}} \frac{T_{\rm RH}}{10^9\,\text{GeV}}\, \frac{m_{\nu_3}}{0.05\,\text{eV}}\, \delta_{CP}\, \delta_{LVS}\, []^{3/2}$$

In the opposite case, the neutrinos live long enough to dominate over the thermal bath formed at the decay of the inflaton, and one recovers the maximal possible asymmetry

$$\begin{aligned}\eta_B &= \frac{6}{23}\epsilon_1\, N_1\, \frac{T}{N_1\, M_1} \\ &\simeq 1.8\cdot 10^{-6} \left(\frac{m_{\nu_3}}{0.05\,\text{eV}}\right) \left(\frac{\tilde{m}_1}{0.05\,\text{eV}}\right)^{1/2} M_{10}\, \delta_{CP}\end{aligned}$$

(N_1 cancels; i.e. the details of what happened before N dominance are irrelevant)

• In supersymmetric models, quanta of r.h. sneutrinos are more efficiently produced than the r.h. neutrinos. Although (because of SUSY) we expect a comparable coupling to the inflaton, the occupation number of sneutrinos is not limited to $n_k < 1$ by Pauli blocking, as it is the case for the neutrinos. A specific example

$$W = \frac{\sqrt{\lambda}}{3} \Phi^3 + \frac{1}{2} \left(\sqrt{2}\, g\, \Phi + M \right) N\, N + \ldots$$

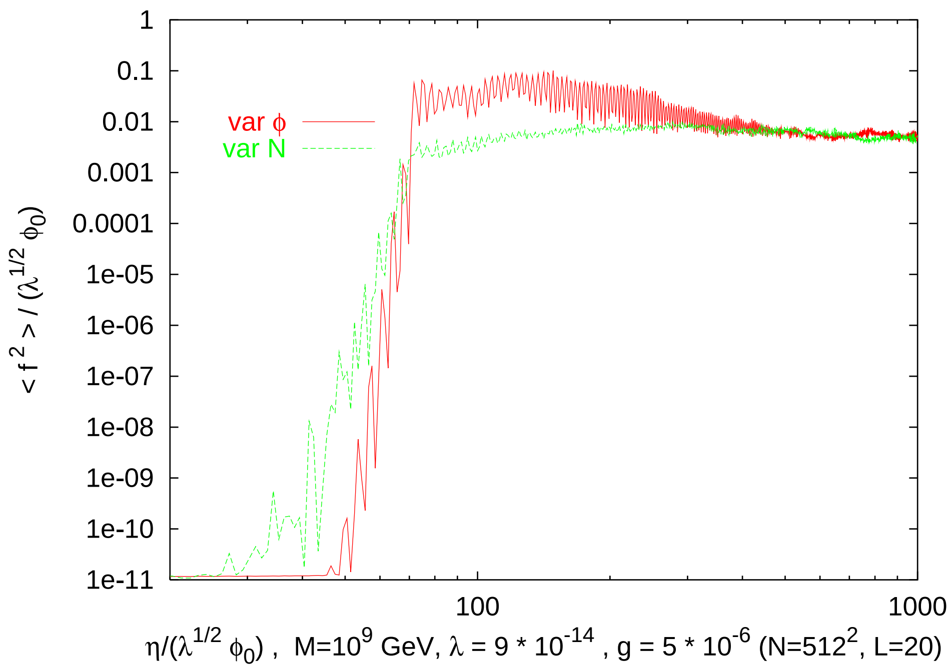
leading to the fermionic term $(M + g\,\phi)\,\bar{\psi}_N\,\psi_N$ discussed above

• Consider, for simplicity, only the real components of the scalar fields $\tilde{\Phi} = \phi/\sqrt{2}$, $\tilde{N} = N/\sqrt{2}$, and focus on the potential terms

$$V \supset \frac{\lambda}{4} \phi^4 + \frac{1}{2} (g\,\phi + M)^2\, N^2$$

• This can be embedded in sugra provided the Kähler potential $\mathcal{K}$ is invariant under $\Phi \to -\Phi^*$. Thus, $\mathcal{K} \neq \mathcal{K}\,(\mathrm{Re}\,\Phi)$

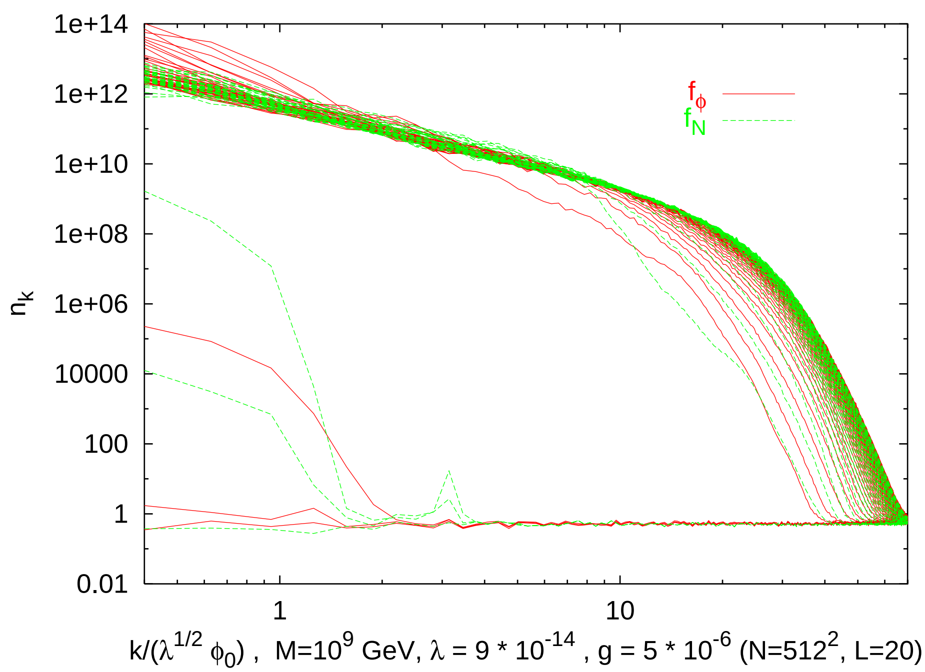
Kawasaki, Yamaguchi, and Yanagida, 01



1) Initial stage of preheating, with resonant particle production. The excited quanta scatter against the zero mode of the inflaton, destroying its coherence. In the present model, $\rho_{\delta\phi} \sim \rho_{\delta N} \sim \rho_{\phi_{\rm cl}}$ at $\eta \simeq 90/\left(\sqrt{\lambda}\,\phi_0\right)$

2) Rescattering: turbulent phase characterized by highly nonlinear interactions. Typically, also scalar fields non directly coupled to the inflaton are excited. Analytical approximations break down. Here, numerical results from lattice simulations, using the (publicly available) code "LATTICEEASY" by Felder and Tkachev, hep-ph/0011159

3) Prolonged phase after which thermal equilibrium is achieved. The spectra are much more populated in the IR w.r.t. a thermal distribution, and their evolution is characterized by an adiabatic decrease of the occupation numbers (through particle fusion).



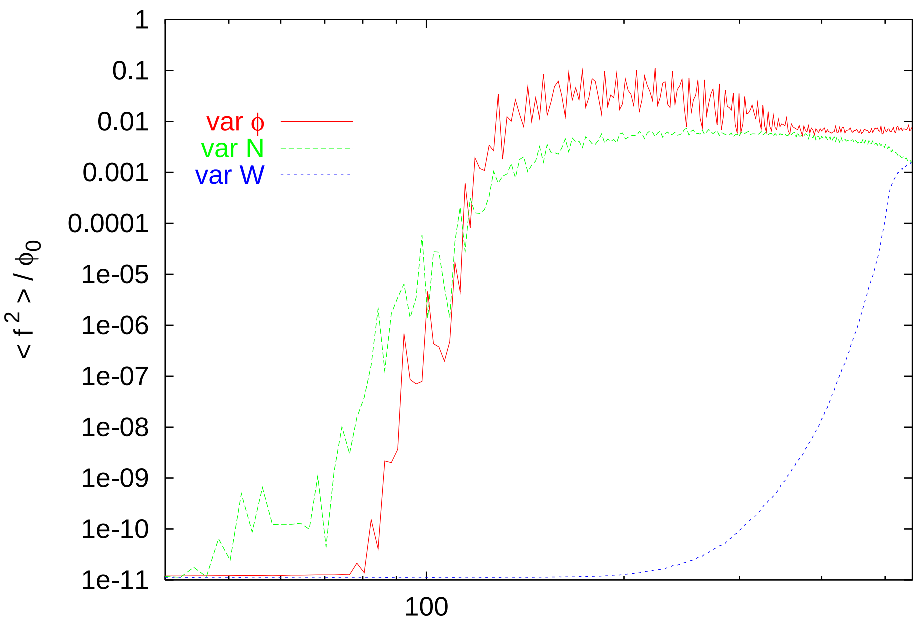
Detailed discussion, in the case of $M = 0$, given by Felder, Kofman, 01

R.h. neutrinos are coupled to MSSM degrees of freedom through the interaction term

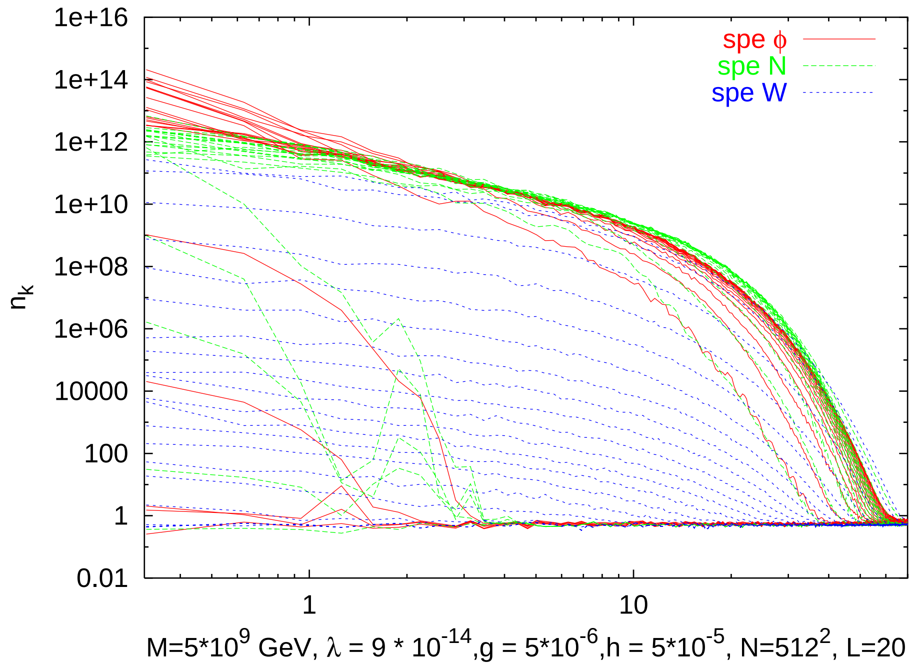
$$\Delta W = h\, N\, L\, H \quad \Rightarrow \quad \Delta V \supset h^2 N^2 \left(L^2 + H^2\right)$$

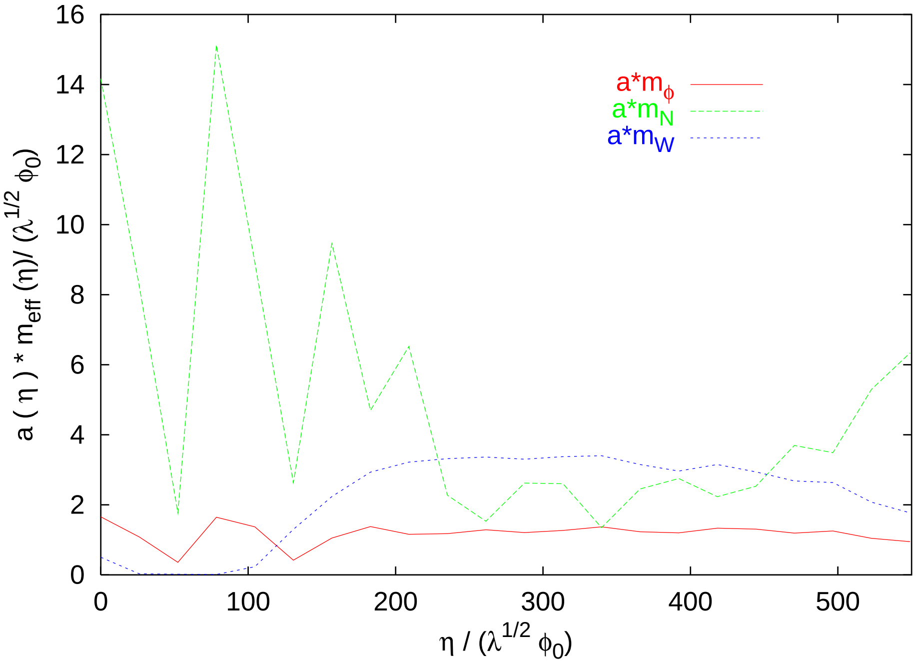
As a prototype, consider the potential

$$V = \frac{\lambda}{4}\phi^4 + (M + g\,\phi)^2\; N^2 + \frac{h^2}{2}\phi^2 W^2$$



M=5*10^9 GeV, λ = 9 * 10^{-14},g = 5*10^{-6},h = 5*10^{-5}, N=512^2, L=20





Notice that most of the quanta of W are relativistic ($k_{\text{comoving}} > a\, m_{\text{eff}}$)

- It is useful to compare the asymmetry produced by the N with the gravitinos produced (perturbatively) by the (nonthermal) distribution of quanta of light scalars. BBN requires $\eta_{3/2} \lesssim 10^{-14}$, $\eta_{\rm lep} \gtrsim 10^{-10}$. This poses a significant constraint on the ratio

$$\zeta \equiv \frac{\eta_{3/2}\,(t)}{\eta_{\rm lep}\,(t)} = \frac{N_{3/2}\,(t)}{N_{\rm lep}\,(t)} =$$

$$= \frac{N_{3/2}\,(t)}{N_N\,(t)\,/\,(\epsilon_1\,\delta_{\rm LVS})} < 10^{-4}$$

ζ can be computed prior the decay of the r.h. neutrinos. It is constant after the two distributions have saturated, and it is unaffected by late time entropy release

• Denote by t_0 the time at which inflation ends, and by t_1 the time at which the distribution of W saturates. At t_1 the two distributions have a characteristic momentum $p = \bar{p}\, H_0\,(a_0/a)$ (that is, their typical momentum at the end of inflation is $\bar{p}$ times the Hubble parameter after inflation), and typical occupation numbers $n_N, n_L \gg 1$, From this, one can estimate

$$\zeta \sim \frac{10^{-2}\,\bar{p}}{\delta_{\rm LVS}\,\epsilon_1}\,\frac{n_L^2}{n_N}\,\left(\frac{H_0}{M_p}\right)^2\,\left(\frac{a_0}{a_1}\right)^{3-1/\alpha}$$

where $\alpha = 2/3\,(1/2)$ for MD (RD) between t_0 and t_1 .

The parameters are very model dependent. In the example shown, $\bar{p} \sim 10\,, n_L \sim n_N \geq 10^9, a_1/a_0 \sim 500$, giving

$$\zeta \sim \frac{10^{-6}}{\epsilon_1\,\delta_{\rm LVS}} = \frac{1}{M_{10}}\,\left(\frac{0.05\,{\rm eV}}{m_{\nu_3}}\right)\,\frac{1}{\delta_{\rm LVS}\,\delta_{\rm CP}} > 10^{-4}$$

Work in progress

- Ideally, one would like to explore the parameter space (M_N, g, h). While this is easy for $M_N \geq 10^{10}$GeV , things get more complicated for higher masses.

- (Preliminary) numerical results indicate that the production of quanta of W is inefficient when the quanta of N are non relativistic. Since the typical momentum of the distribution scales as $q^{1/4}$ (Kofman, Linde, and Starobinsky, 97) this may indicate that, at any fixed M_N, if $q \sim g^2$ is not too large, the MSSM quanta are not excited and we do not have to worry about the production of gravitinos.

- We are presently trying to make this last statement more quantitative.

Conclusions

- Bound on the CP asymmetry favors a non-thermal production of right handed neutrinos

- R.h. neutrinos can be efficiently produced at preheating; in SUSY models, the production is overcome by the one of quanta of sneutrinos. A sufficient leptogenesis is easily achieved.

- Depending of the relative size of the sneutrino mass and their coupling to the inflaton, the quanta of sneutrino can excite quanta of light MSSM degrees of freedom, with a potential gravitino problem. This should result in a lower bound on the mass of the sneutrinos.