B-L Breaking as the Origin of the Hot Early Universe

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I. Inflation, B-L Breaking & Leptogenesis

- Light neutrino masses can be explained by mixing with Majorana neutrinos with GUT scale masses from $B - L$ breaking (seesaw mechanism)

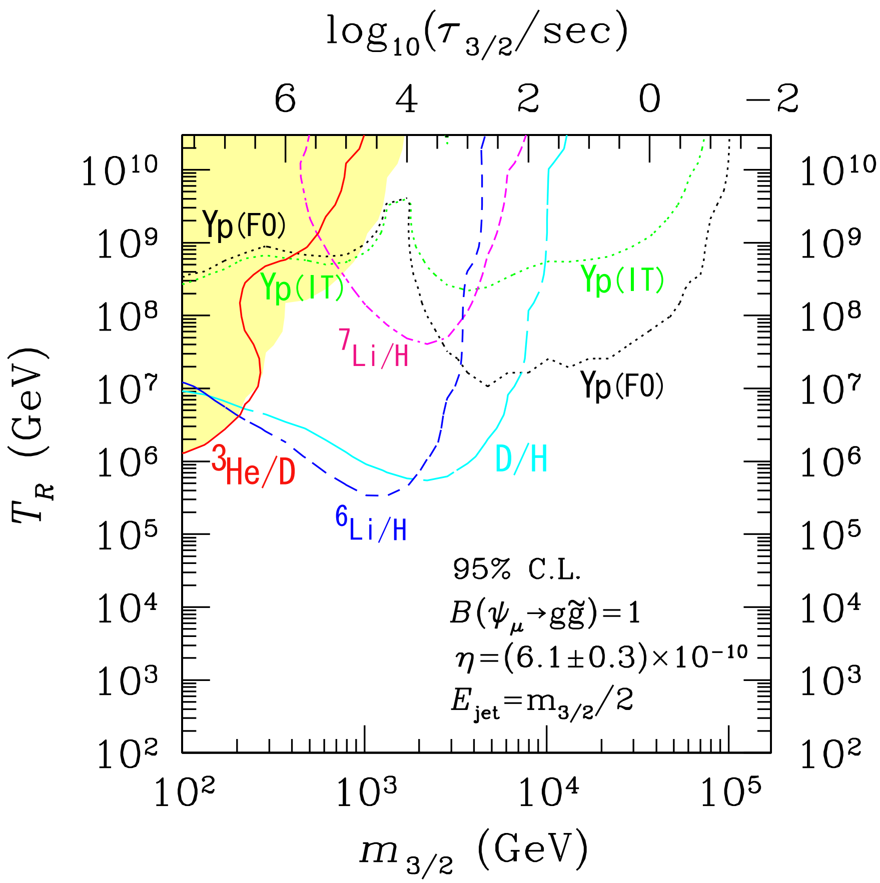
- Decays of heavy Majorana neutrinos natural source of baryon asymmetry (leptogenesis)

- Heavy neutrinos can be produced thermally of non-thermally (inflaton decays, low reheating temperature wanted)

- In supersymmetric models simple connection with hybrid inflation; scalar neutrino as inflaton?

Considerable literature: Lazarides, Shafi '91; Asaka, Hamaguchi, Kawasaki, Yanagida '99; Murayama, Suzuki, Yanagida, Yokoyama'93; Ellis, Raidal, Yanagida '03; Allaverdi, Drees '04; Antusch, Baumann, Domcke, Kostka, '10; ...

Leptogenesis and the ‘gravitino problem’



Thermal LG requires temperature $T_L \sim 10^{10}$ GeV

Most stringent upper bound on T_R (Kawasaki, Kohri, Moroi ’05):

$$T_R < \mathcal{O}(1) \times 10^5 \text{ GeV},$$

hence standard mSUGRA with neutralino LSP incompatible with thermal leptogenesis !!

Possible way out: Gravitino LSP & DM, various options for NLSP ...

'Gravitino virtue': for typical leptogenesis temperatures and superparticle masses, thermal gravitino production yields observed amount of DM,

$$\Omega_{\tilde{G}} h^2 = C \left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right) \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2 , \quad C \sim 0.5 \; ;$$

$\Omega_{\mathrm{DM}} h^2 \sim 0.1$ is natural value; but why $T_R \sim T_L$?

Heavy neutrino decay width is determined by neutrino masses,

$$\Gamma^0_{N_1} = \frac{\tilde{m}_1}{8\pi} \left(\frac{M_1}{v_{\mathrm{EW}}}\right)^2 \sim 10^3 \text{ GeV} , \quad \widetilde{m}_1 = 0.01 \text{ eV} , \quad M_1 \sim 10^{10} \text{ GeV} .$$

Reheating temperature for decaying gas of heavy neutrinos

$$T_R \sim 0.2 \cdot \sqrt{\Gamma^0_{N_1} M_P} \sim 10^{10} \text{ GeV} ,$$

wanted temperature for gravitino dark matter, misleading coincidence?

II. B-L breaking and false vacuum decay

Supersymmetric SM with right-handed neutrinos ($SU(5)$ notation),

$$W_M = h_{ij}^u \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^d \mathbf{5}_i^* \mathbf{10}_j H_d + h_{ij}^\nu \mathbf{5}_i^* n_j^c H_u + h_i^n n_i^c n_i^c S_1 \ ,$$

with electroweak breaking, $\langle H_{u,d} \rangle = v_{u,d}$, and $B - L$ breaking,

$$W_{B-L} = \frac{\sqrt{\lambda}}{2} T \left(v_{B-L}^2 - 2 S_1 S_2 \right) \ ,$$

$\langle S_{1,2} \rangle = v_{B-L}/\sqrt{2}$; Yukawa's from FN flavour symmetry (cf. WB, Yanagida '98),

$$h_{ij} \propto \eta^{Q_i + Q_j} \ , \quad \eta \simeq 1/\sqrt{300} \ .$$

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}_3^*$	$\mathbf{5}_2^*$	$\mathbf{5}_1^*$	n_3^c	n_2^c	n_1^c	$H_{u,d}$	$S_{1,2}$	T
Q_i	0	1	2	a	a	$a+1$	b	c	d	0	0	e

Lagrangian is motivated by low energy physics: quark, lepton, neutrino masses etc, but it contains all ingredients wanted in cosmology: inflation, leptogenesis, gravitino dark matter,..., all related!

Restrict analysis to special case (for purpuse of illustration): $b = c = d-1 = e/2$, then

$$
\begin{aligned}
M_1 &\simeq \eta^{2d}\, v_{B-L}\ , \\
M_{2,3} &\simeq \eta^{2(d-1)}\, v_{B-L} \simeq m_S \gg M_1\ .
\end{aligned}
$$

Light neutrino masses from seesaw,

$$
m_D = h^\nu v_u \quad M = h^n v_{B-L}, \quad m = -m_D \frac{1}{M} m_D^T\ ,
$$

$$
m_1 \simeq \eta^{2a+2} \frac{v_{\rm EW}^2}{v_{B-L}}\ , \quad m_{2,3} \simeq \eta^{2a} \frac{v_{\rm EW}^2}{v_{B-L}}\ .
$$

With $\overline{m}_\nu = \sqrt{m_2 m_3} \simeq 3 \times 10^{-2}$ eV, scale of $B-L$ breaking,

$$v_{B-L} \simeq \eta^{2a} \, \frac{v_{\rm EW}^2}{\overline{m}_\nu} \simeq \eta^{2a} \; 10^{15} \text{ GeV} \; .$$

Range of parameters ($0 \leq a \leq 1$, $\tan\beta > \mathcal{O}(1)$; $1 \leq d < 3$, leptogenesis):

$$3 \times 10^{12} \text{ GeV} \leq v_{B-L} \leq 1 \times 10^{15} \text{ GeV} \; ,$$
$$1 \times 10^{5} \text{ GeV} \leq M_1 \leq 3 \times 10^{12} \text{ GeV} \; ;$$

unknown $\mathcal{O}(1)$ parameters strongly affect lightest neutrino mass, choose range

$$10^{-5} \text{ eV} \leq \widetilde{m}_1 \leq 0.1 \text{ eV} \; , \quad \widetilde{m}_i = \frac{(m_D^\dagger m_D)_{ii}}{M_i} \; ;$$

finally analysis with 3 parameters: v_{B-L}, M_1, $\widetilde{m}_1$.

Further leptogenesis parameters: decay widths,

$$\Gamma^0_{N_i} \simeq \frac{\widetilde{m}_i}{8\pi}\frac{M_i^2}{v_{\rm EW}^2} \ , \quad \widetilde{m}_i \simeq \eta^{2a} \ \frac{v_{\rm EW}^2}{v_{B-L}} \simeq \overline{m}_\nu \ ,$$

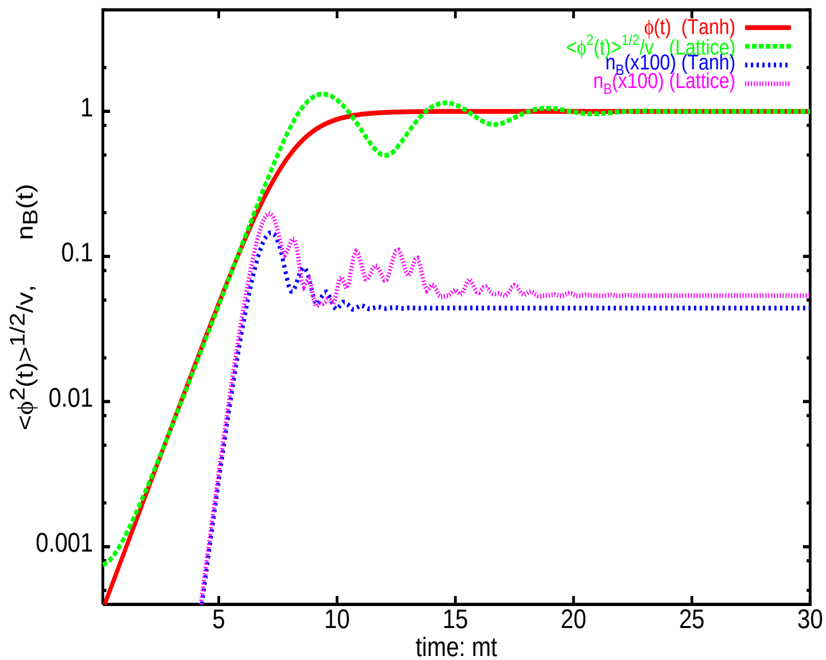
and CP asymmetries,

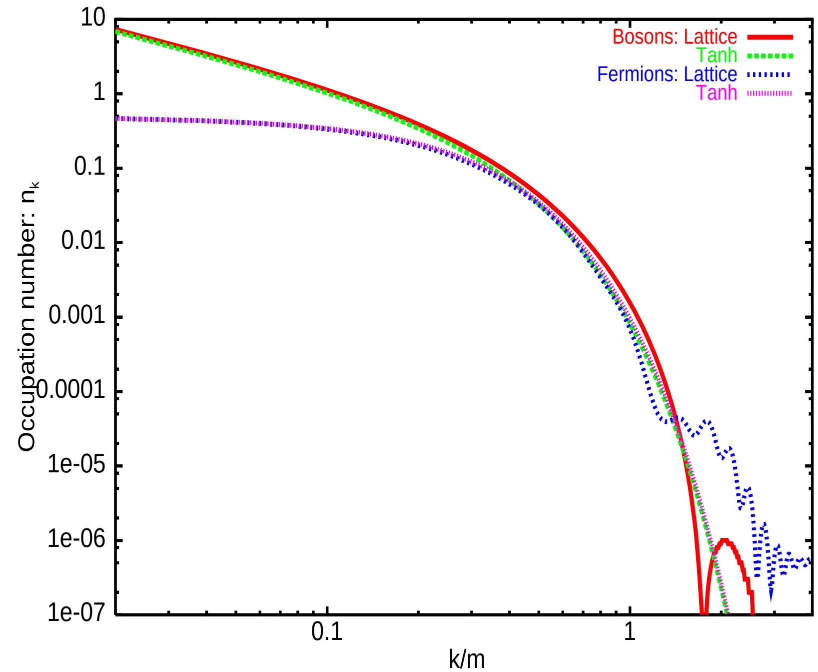
$$\begin{aligned} \epsilon_i &= \frac{1}{8\pi (h^{\nu\dagger}h^\nu)_{ii}} \sum_{j\neq i} \mathrm{Im}\left\{\left[\left(h^{\nu\dagger}h^\nu\right)_{ij}\right]^2\right\} \ F\left(\frac{M_j}{M_i}\right) \ , \\ \epsilon_1 &\simeq 0.1 \frac{\overline{m}_\nu \ M_1}{v_{\rm EW}^2} \sim 10^{-6} \ \frac{M_1}{10^{10} \ \mathrm{GeV}} \ , \\ \epsilon_{2,3} &\simeq \epsilon_1 \, \eta^{-2} \ ; \end{aligned}$$

$N_{2,3}$ decay much faster than N_1, and generate larger asymmetries.

Tachyonic Preheating

Hybrid inflation ends at critical value T_c of inflaton field T by rapid growth of fluctuations of $B-L$ Higgs field S ('spinodal decomposition'):





in addition, particles which couple to S are produced by rapid increase of 'waterfall field' (Garcia-Bellido, Morales '02); no coherent oscillations!

Decay of false vacuum produces long wave-length S-modes, true vacuum reached at time $t_{\rm PH}$ (even faster decay with inflaton dynamics),

$$\langle S^\dagger S\rangle\big|_{t=t_{\rm PH}} = v_{B-L}^2 \;, \qquad t_{\rm PH} \simeq \frac{1}{2m_S}\ln\left(\frac{32\pi^2}{\lambda}\right) \;.$$

Initial state: nonrelativistic gas of S-bosons, $N_{2,3}$ and N_1 heavy neutrinos; energy fractions:

$$r_{N_1} \ll r_{N_{2,3}} \sim 10^{-3} \ll r_S \simeq 1 \;.$$

Time evolution: rapid $N_{2,3}$ decays, yields initial radiation, thermal N_1's and gravitinos; S decays produce nonthermal N_1's; N_1 decays produce most of radiation and baryon asymmetry; details of evolution described by Boltzmann equations.

Energy densities of radiation and Higgs bosons at $t_2 = t_{\rm PH} + 1/\Gamma^0_{N_{2,3}}$:

$$\begin{aligned} \rho_R(t_2) &= 2r_{N_2}\frac{\rho_0}{a^3(t_2)}\ , \quad \rho_0 = \frac{1}{4}\lambda v^4_{B-L}\ , \\ \rho_S(t_2) &= \frac{1}{a^3(t_2)}\left(1-2r_{N_2}\right)\rho_0\ . \end{aligned}$$

Temperature and asymmetry of small initial thermal bath,

$$\begin{aligned} T(t_2) &= \left(\frac{30}{\pi^2 g_{\star,\rho}}\frac{2r_{N_2}\rho_0}{a^3(t_2)}\right)^{1/4}\ , \\ N_{B-L}(t_2) &= \epsilon_2\, N_{N_2}(t_2) + \epsilon_3\, N_{N_3}(t_2)\ , \\ &\simeq 0.2\ \eta^{-2}\frac{\overline{m}_\nu M_1}{v^2_{\rm EW}} N_{N_2}(t_{\rm PH})\ ; \end{aligned}$$

initial temperature higher than ‘reheating temperature’, possibly important for gravitino production!

Nonthermal initial distribution of $B-L$ Higgs bosons,

$$N_S(t_2) = a^3(t_2)\,\frac{\rho_S(t_2)}{m_S}\ , \quad \rho_S(t_2) = \frac{1}{a^3(t_2)}\,(1-2r_{N_2})\,\rho_0\ ,$$
$$f_S(t_2,p) = 2\pi^2 N_S(t_2)\frac{\delta(k)}{k^2}\ , \quad k = a(t_2)\,p(t_2) = a(t)\ p(t)\ ;$$

initial N_1 and gravitino number densities,

$$N_{N_1}(t_2) = 0\ , \quad N_{\widetilde{G}}(t_2) = 0\ .$$

Time-dependence of scale factor and temperature from Friedmann equation,

$$a(t) = a\,(t_2)\left[1+\frac{3}{2}(1+\omega)\left(\frac{8\pi}{3M_p^2}\,\rho_{\rm tot}\,(t_2)\right)^{1/2}(t-t_2)\right]^{\frac{2}{3(1+\omega)}}\ ,$$

with effective equation of state ω, covariant energy conservation ... (decays of S and N_1 !!)

Boltzmann Equations

S bosons just decay; dinstinguish between nonthermal and thermal contributions to N_1 densities,

$$
\begin{aligned}
N_S(t) &= N_S(t_2)e^{-\Gamma_S^0(t-t_2)} \; , \\
n_{N_1}^S &= g_{N_1} \int \frac{d^3p}{(2\pi)^3}\, f_{N_1}^S \\
&= \frac{2\Gamma_S^0}{a^3} \int\limits_{t_2}^{t} dt' \left[N_S(t') \exp\left(-M_1 \Gamma_{N_1}^0 \int\limits_{t'}^{t} dt'' \mathcal{E}_{N_1}^{-1}(t',t'') \right) \right] , \\
aH\frac{d}{da} N_{N_1}^T &= -\left(N_{N_1}^T - N_{N_1}^{\rm eq} \right) \Gamma_{N_1}^T \; ,
\end{aligned}
$$

and nonthermal and thermal contributions to $B-L$ asymmetry,

$$aH\frac{d}{da}N^S_{B-L} \;=\; \epsilon_1 N^S_{N_1}\Gamma^S_{N_1} - \frac{N^{\mathrm{eq}}_{N_1}}{2N^{\mathrm{eq}}_\ell}\,\Gamma^T_{N_1}N^S_{B-L}\ ,$$

$$aH\frac{d}{da}N^T_{B-L} \;=\; \epsilon_1\left(N^T_{N_1} - N^{\mathrm{eq}}_{N_1}\right)\Gamma^T_{N_1} - \frac{N^{\mathrm{eq}}_{N_1}}{2N^{\mathrm{eq}}_\ell}\,\Gamma^T_{N_1}N^T_{B-L}\ ;$$

gravitinos are produced from the thermal bath,

$$aH\frac{d}{da}N_{\widetilde{G}} \;=\; a^3\,\gamma_{\widetilde{G}}(T)\ ,$$

$$\gamma_{\widetilde{G}}(T) \;=\; \left(1+\frac{m^2_{\tilde{g}}(T)}{3m^2_{\widetilde{G}}}\right)\frac{54\zeta(3)g^2_s(T)}{\pi^2M^2_p}\,T^6\left[\ln\left(\frac{T^2}{m^2_g(T)}\right)+0.8846\right]\ ;$$

nonthermal gravitino production is negligable (see Nakayama, Takahashi, Yanagida '10)

An Illustrative Example

Choose the input parameters:

$$v_{B-L} = 5.8 \times 10^{13}\ \text{GeV}\ ,\ M_1 = 1.4 \times 10^{10}\ \text{GeV}\ ,\ \widetilde{m}_1 = 3 \times 10^{-3}\ \text{eV}\ ,$$
$$m_{\widetilde{G}} = 100\ \text{GeV}\ , \quad m_{\widetilde{g}} = 800\ \text{GeV}\ ,$$

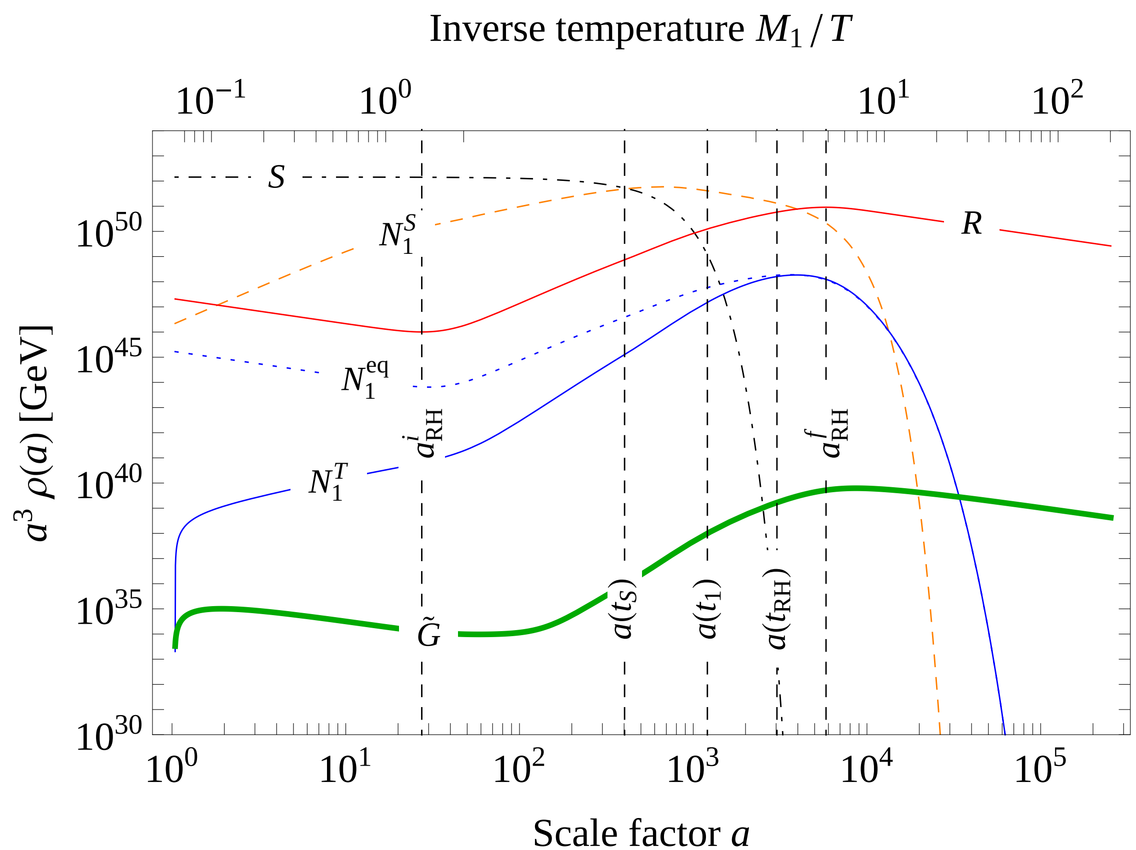
fixes related parameters:

$$m_s, M_{2,3} = 4.1 \times 10^{12}\ \text{GeV}\ , \quad \lambda = 5.0 \times 10^{-3}\ ,$$
$$\epsilon_1 = 1.4 \times 10^{-6}\ , \quad \epsilon_{2,3} = -4.1 \times 10^{-4}\ .$$

Predicted baryon asymmetry and gravitino dark matter:

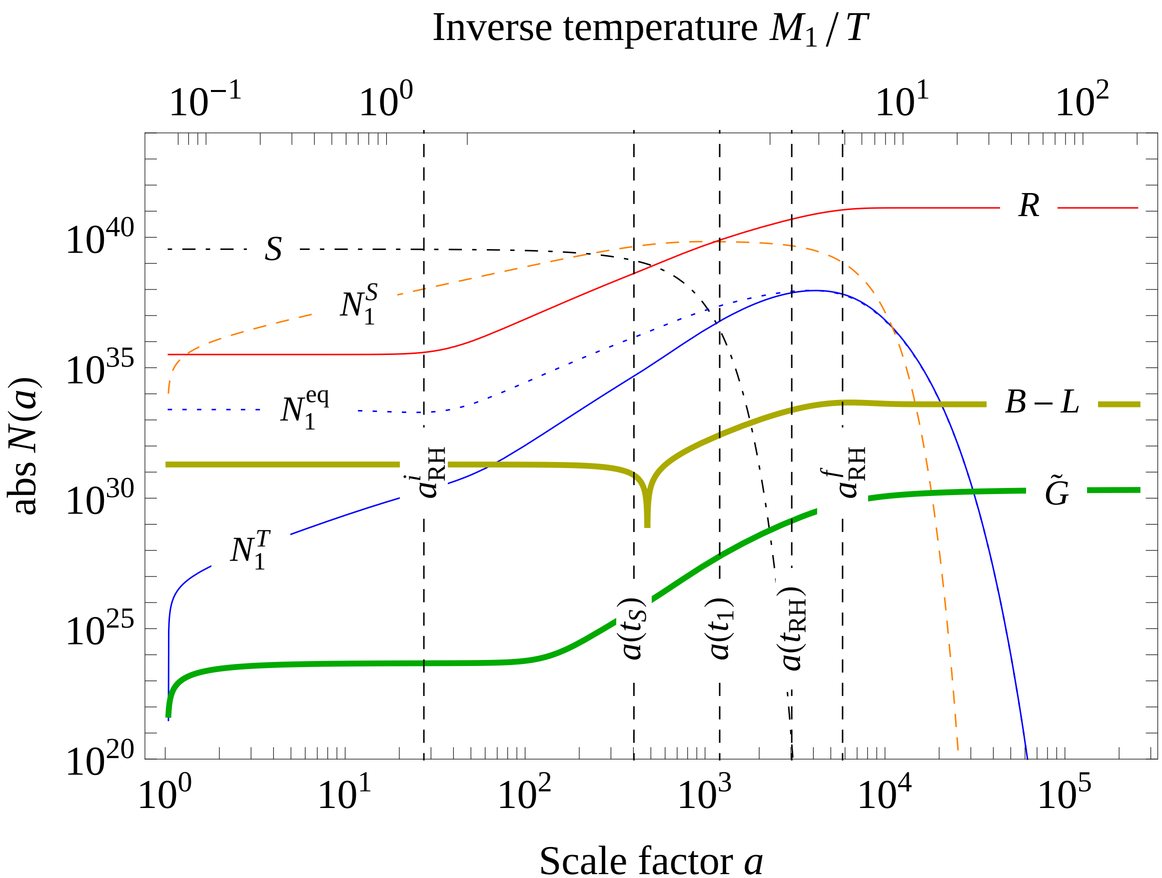
$$\eta_B \simeq 1.9 \times 10^{-8} > \eta_B^{\text{obs}} \simeq 6.2 \times 10^{-10}\ ,$$
$$\Omega_{\widetilde{G}} h^2 \simeq 0.11\ .$$

Thermal and nonthermal energy densities



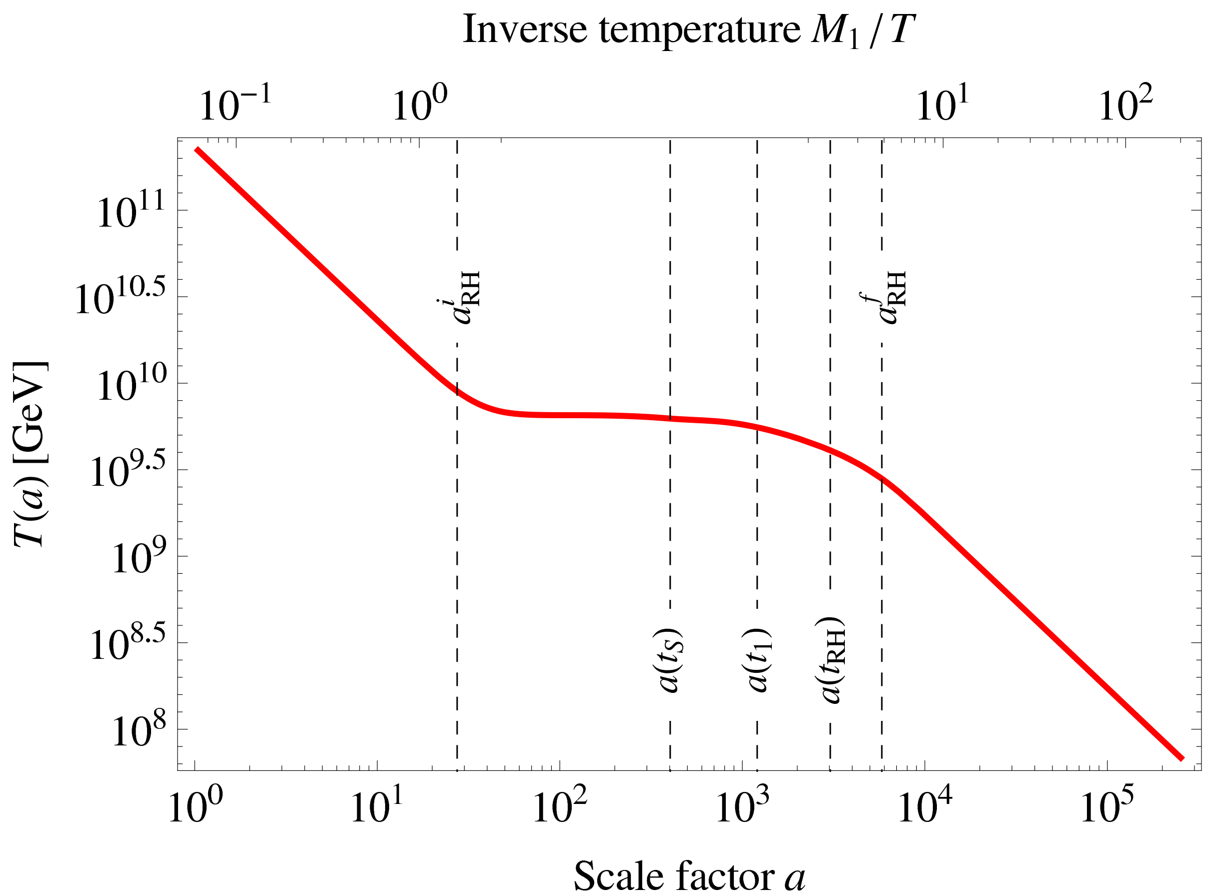
Comoving energy densities of thermal and nonthermal $N_1's$, gravitinos and radiation as functions of scale factor a.

Thermal and nonthermal number densities



Comoving number densites of thermal and nonthermla $N_1's$, $B-L$, gravitinos and radiation as functions of scale factor a.

Time evolution of temperature



Gravitino abundance can be understood from effective 'reheating temperature'.

III. Leptogenesis & Gravitino Dark Matter

- In 'neutrino reheating' baryogenesis is a mixture of thermal and nonthermal leptogenesis

- The allowed range for 'successful leptogenesis' in the $M_1 - \widetilde{m}_1$ plane is considerably extended compared to thermal leptogenesis

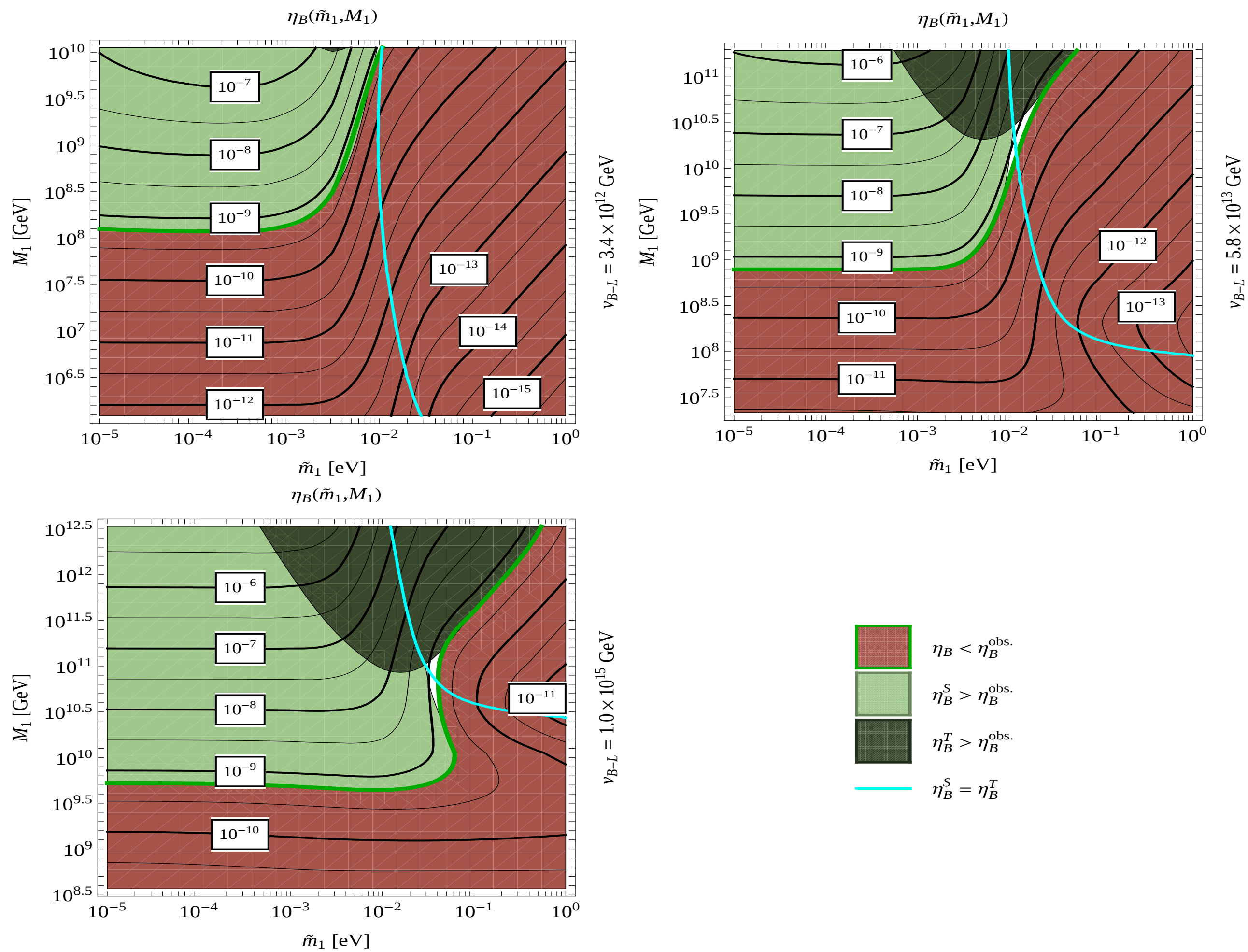
- Gravitino production is dominated by thermal processes

- For a wide range of parameters gravitino dark matter is consistent with baryogenesis via leptogenesis

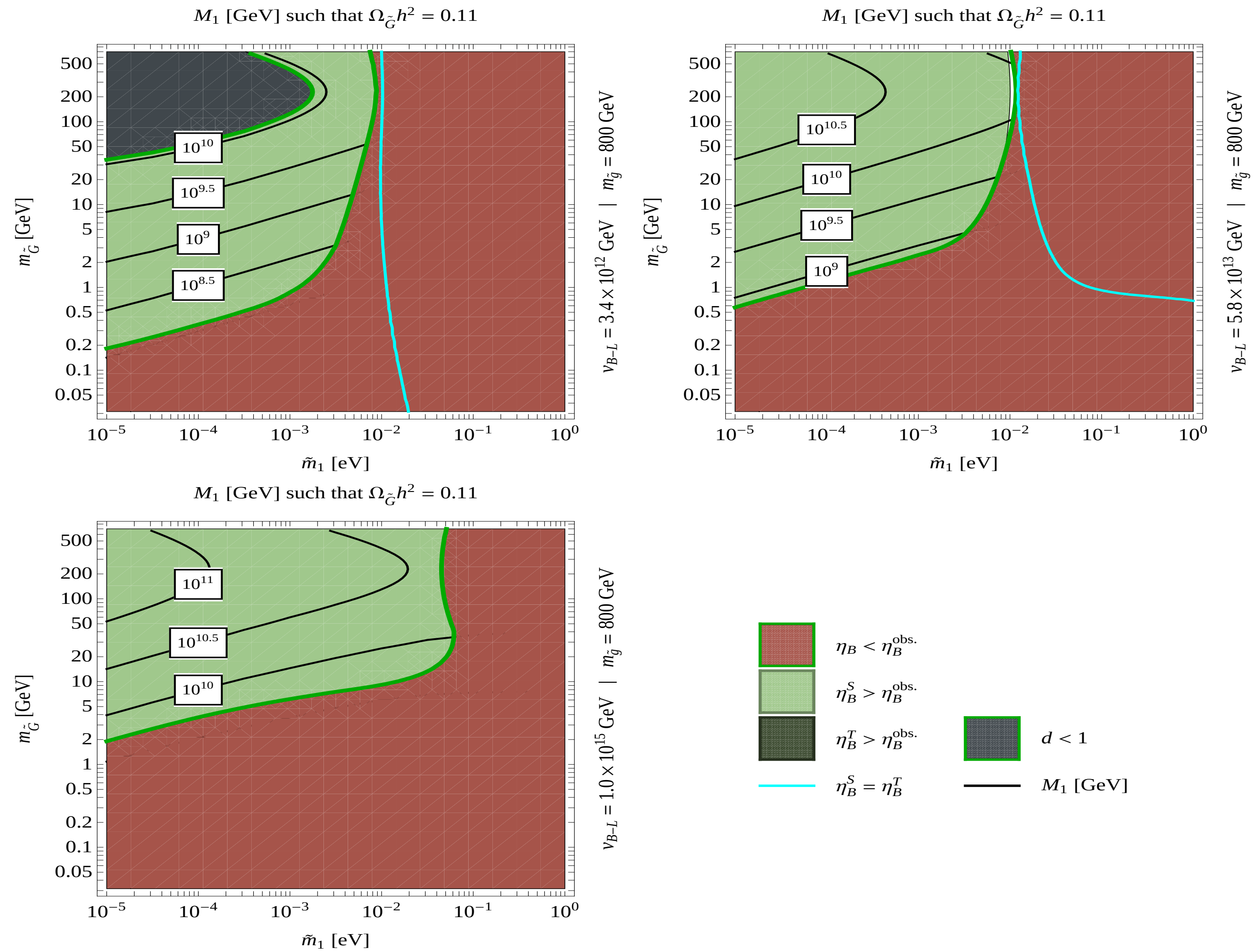
- A lower bound on the neutrino masses implies a lower bound on the gravitino mass, for instance: $m_{\widetilde{G}} \gtrsim 200\ \mathrm{MeV}$ for $m_1 \gtrsim 10^{-5}\ \mathrm{eV}$, or $m_{\widetilde{G}} \gtrsim 9\ \mathrm{GeV}$ for $m_1 \gtrsim 0.01\ \mathrm{eV}$

- For $m_1 \gtrsim 0.1\ \mathrm{eV}$ 'neutrino reheating' is excluded

(Non)Thermal Leptogenesis in $M_1 - \tilde{m}_1$ Plane



Gravitino Dark Matter vs Leptogenesis



Summary and Outlook

Result: Decay of false vacuum of unbroken B-L symmetry leads to reheating through heavy neutrino decays; byproducts are baryon asymmetry and gravitino dark matter; connection between neutrino mass scale and gravitino mass

Work in progress:

- Full supersymmetric calculation
- Production of cosmic strings in hybrid inflation
- Effect of inflaton dynamics on tachyonic preheating
- Quantitative connection to inflation