SUSY10

Physikalisches Institut - Bonn

Matter and Dark Matter from False Vacuum Decay

based on arXiv:1008.2355

In Collaboration with W.Buchmuller & K.Schmitz

G.Vertongen

(DESY Hamburg)

Motivation

Obs: ∃ B Asymmetry of the Universe

$$\eta_B^{\rm obs} \equiv \frac{n_B}{n_\gamma} \simeq 6 \times 10^{-10} \quad \gg \quad \eta_B^{\rm sym} \simeq 10^{-18}$$

Q? How to avoid the 'annihilation catastrophe' ? How to generate B dynamically ?

Sol: *Baryogenesis* through *leptogenesis* [Fukugida, Yanagida 97] : use the seesaw N_R

$$\eta_B \propto n_N^{\rm eq}\, \epsilon_{\rm CP}\, \kappa\, c_{\rm sph}$$

Hierarchical N_R $\rightarrow$ $M_1 \gtrsim 10^{10}$ GeV   Thermal N_R production $\rightarrow$ $T_L \gtrsim 10^{10}$ GeV

Tension: unstable gravitinos: BBN constraint [Kawasaki, Kohri, Moroi 05] $T_R \lesssim 10^5$ GeV

Virtue: stable gravitinos as DM

Thermal production from 2 → 2 QCD processes [Bolz et al. 01 ; Pradler & Steffen 06]

$$\Omega_{\tilde G} h^2 = 0.27 \left(\frac{T_R}{10^{10}\,\rm GeV}\right)\left(\frac{100\,\rm GeV}{m_{\tilde G}}\right)\left(\frac{m_{\tilde g}}{1\,\rm TeV}\right)^2$$

$\rightarrow$ $\Omega_{\tilde G} h^2 \simeq \Omega_{\rm DM}^{\rm obs} h^2$ for typical supergravity and leptogenesis parameters

Q? Why T_L and T_R have the same order of magnitude ?

Observation

Thermal leptogenesis: typical parameters

- Heavy Majorana neutrino mass $M_1 \sim 10^{10}\,\text{GeV}$

- Effective neutrino mass $\widetilde{m}_1 \equiv \frac{(m_D^\dagger m_D)_{11}}{M_1} \sim 10^{-2}\,\text{eV}$

→ Heavy Majorana neutrino has a width of $\Gamma^0_{N_1} = \frac{\widetilde{m}_1}{8\pi}\left(\frac{M_1}{v_{\text{EW}}}\right)^2 \sim 10^3\,\text{GeV}$

Reheating: through particle decays with Γ width

$$T_R = \left(\frac{90}{8\pi^3 g_*}\right)^{1/4} \sqrt{\Gamma M_P}$$

Assume: N_1 neutrino decays responsible for reheating

→ $\mathbf{T_R \sim 10^{10}}$ GeV i.e. temperature to produce $\widetilde{G}$ Dark Matter !

Q? Could B asymmetry and $\widetilde{G}$ Dark Matter be both generated out of the thermal bath produced by N_1 decays ?

Flavour Model

Superpotential: $W_M = h^u_{ij}\mathbf{10}_i\mathbf{10}_j H_u + h^d_{ij}\mathbf{5}^*\mathbf{10}_j H_d + h^\nu_{ij}\mathbf{5}^*_i n^c_j H_u + h^n_i n^c_i n^c_i S$

- SM fields $\mathbf{10} \equiv (q, u^c, e^c), \quad \mathbf{5}^* \equiv (d^c, l)$
- Heavy Majorana neutrinos $N_i \equiv n_i + n_i^c$
- Symmetry breaking fields $\langle H_u \rangle = v_u \;, \quad \langle H_d \rangle = v_d \;, \quad \langle S \rangle = v_{B-L}$

Yukawa couplings:

Representative model with Froggatt-Nielsen U(1) flavour symmetry [Buchmuller & Yanagida 97]

$$h_{ij} \propto \eta^{Q_i+Q_j}$$

with Q_i charges and $\eta \simeq 1/\sqrt{300}$ determined by quark & lepton mass hierarchies

N_R - Masses : $M_{1,} \simeq \eta^2 \, v_{B-L}$, $M_{2,3} \simeq v_{B-L}$ - Widths : $\Gamma^0_{N_{1,}} \propto \eta^4 \, M_1$, $\Gamma^0_{N_{2,3}} \propto \eta^2 \, M_{2,3}$

***B-L* Higgs potential:**

- Unbroken phase energy density : $\rho_0 = \frac{\lambda}{4} v^4_{B-L}$ - S mass : $m_S^2 = \lambda \, v^2_{B-L}$

Mass scale: Thermal leptogenesis : $M_1 = 10^{10}$ GeV → v_{B-L} fixed

→ $2M_{2,3} \gtrsim m_S \gtrsim 2M_1$ $\quad \epsilon_1 \sim 10^{-6}$ $\quad \epsilon_{2,3} \sim 3 \times 10^{-4}$

Cosmological Scenario

Note : *B-L* symmetry breaking field could be responsible for the sudden end of the inflationary era through a tachyonic preheating phase [Felder et al. 2001]

SSB : False vacuum energy ρ_0 rapidly transferred to [Garcia-Bellido & Ruiz Morales, 2002]

- nonrelativistic gas of *S* bosons $\rho_S \simeq \rho_0$
- heavy neutrinos N_i $\rho_{N_i}/\rho_0 \simeq 1.5 \times 10^{-3} g_N\, f(h_i^n/\sqrt{\lambda}, 0.8)$

For the considered flavour model : $\rho_{N_1}/\rho_0 = \mathcal{O}(\eta^4)\,,\qquad \rho_{N_{2,3}}/\rho_0 \simeq 10^{-3}$

Initial state :

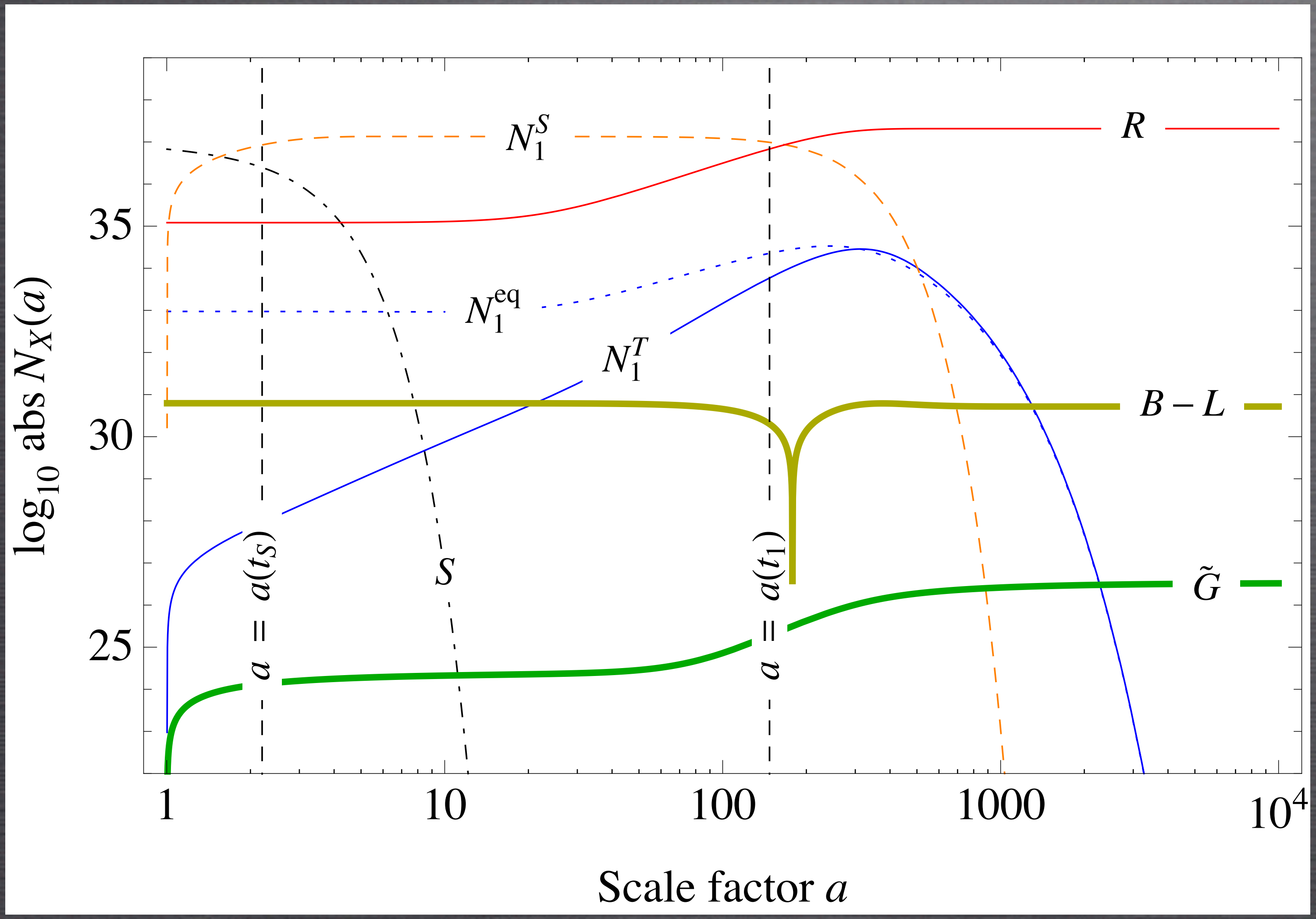
- $N_{2,3}$ decays : Radiation $N_R(t_2)$ + *B-L* asymmetry $N_{B-L}(t_2) \simeq 2\,\epsilon_2\, N_{N_2}(t_2)$
- nonrelativistic *S* boson gas

Processes in action :

- *S* decays → relativistic nonthermal N_1
- Radiation → gravitinos $\widetilde{G}$ + thermal N_1
- N_1 decays → radiation + *B-L* asymmetry

Cosmological Evolution

Evolution of the comobile densities $N_i \equiv a^3 n_i$ with the scale factor a



$M_1 = 10^{10}$ GeV

$M_{2,3} = 3 \times 10^{12}$ GeV

$\tilde{m}_1 = 10^{-3}$ eV

$\epsilon_1 = 10^{-6}$

$\epsilon_{2,3} = -3 \times 10^{-4}$

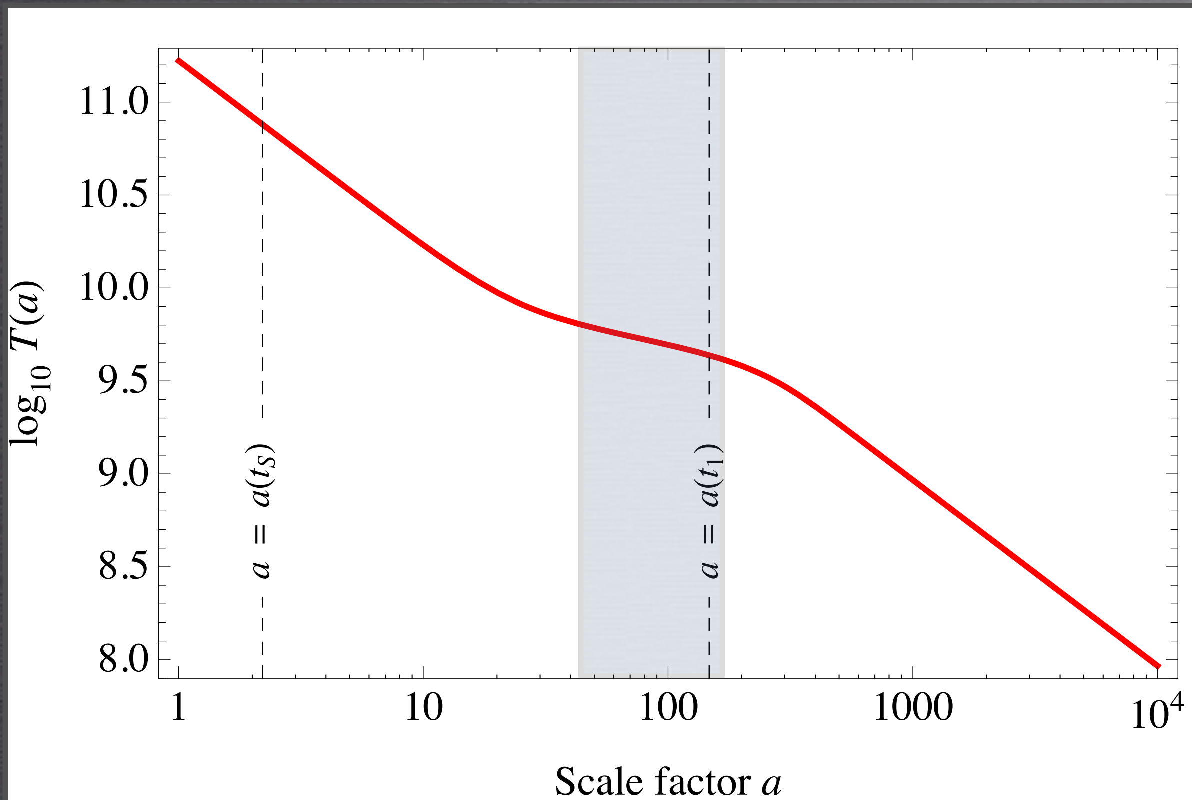
$M_{\tilde{G}} = 100$ GeV

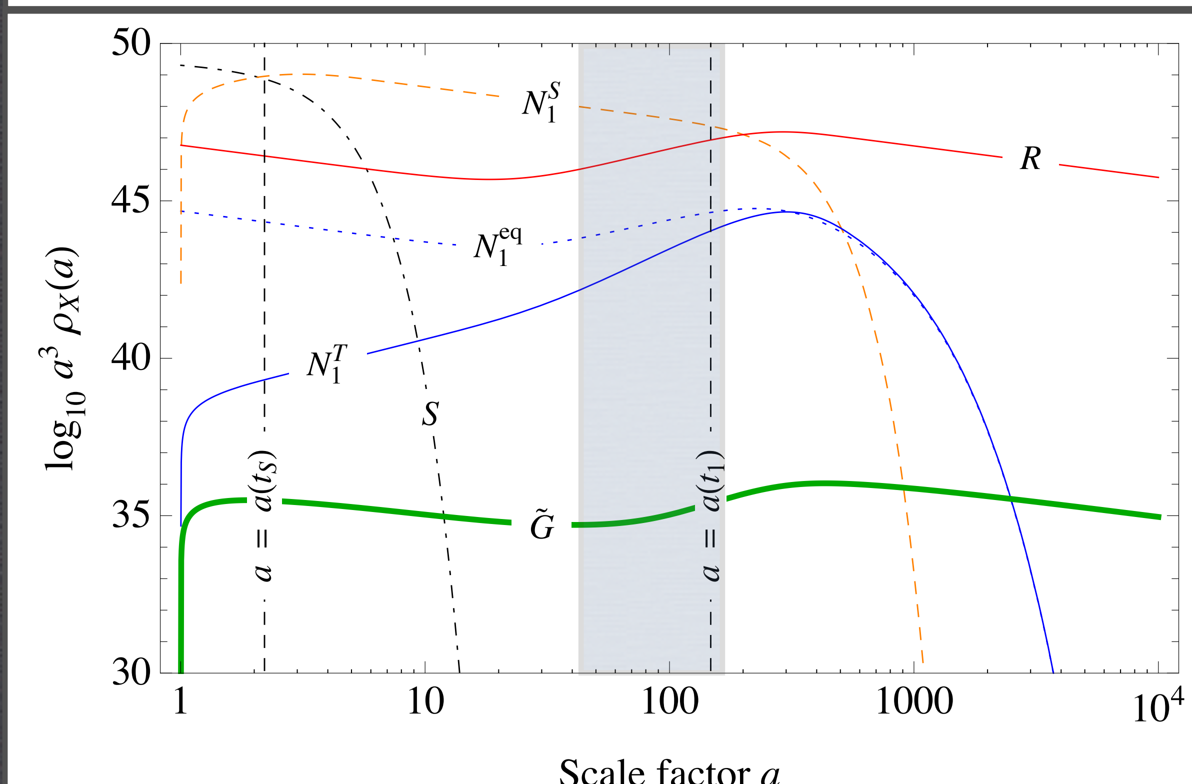
$M_{\tilde{g}} = 800$ GeV

$\eta_B = 1.6 \times 10^{-7} \quad > \quad \eta_B^{obs} = 6.2 \times 10^{-10}$ ✓

$\Omega_{\tilde{G}} h^2 = 0.11 = \Omega_{DM} h^2$ ✓

Cosmological Evolution





Reheating temperature:

$$\mathbf{T_R \simeq 5 \times 10^9\ GeV}$$

in agreement with the estimate

$$T_R = \left(\frac{90}{8\pi^3 g_*}\right)^{1/4} \sqrt{\Gamma^0_{N_1} M_P}$$

Extreme cases:

$\eta_B = 1.6 \times 10^{-7}$

- thermal leptogenesis :

$$\eta_B^{\text{thermal}} = \frac{3}{4}\frac{g_\star^0}{g_\star} c_{\text{sph}}\, \epsilon_1\, \kappa_f(\tilde{m}_1) \simeq 5 \times 10^{-10}$$

- rapid nonrelativistic N_1 conversion

$$\eta_B^{\text{rapid}} = 7\,\frac{3}{4}\, c_{\text{sph}}\, \epsilon_1\, \frac{T_L}{M_1} \simeq 9 \times 10^{-7}$$

→ $(\mathbf{M_1, \tilde{m}_1})$ drives the interpolation between thermal and nonthermal leptogenesis

Summary

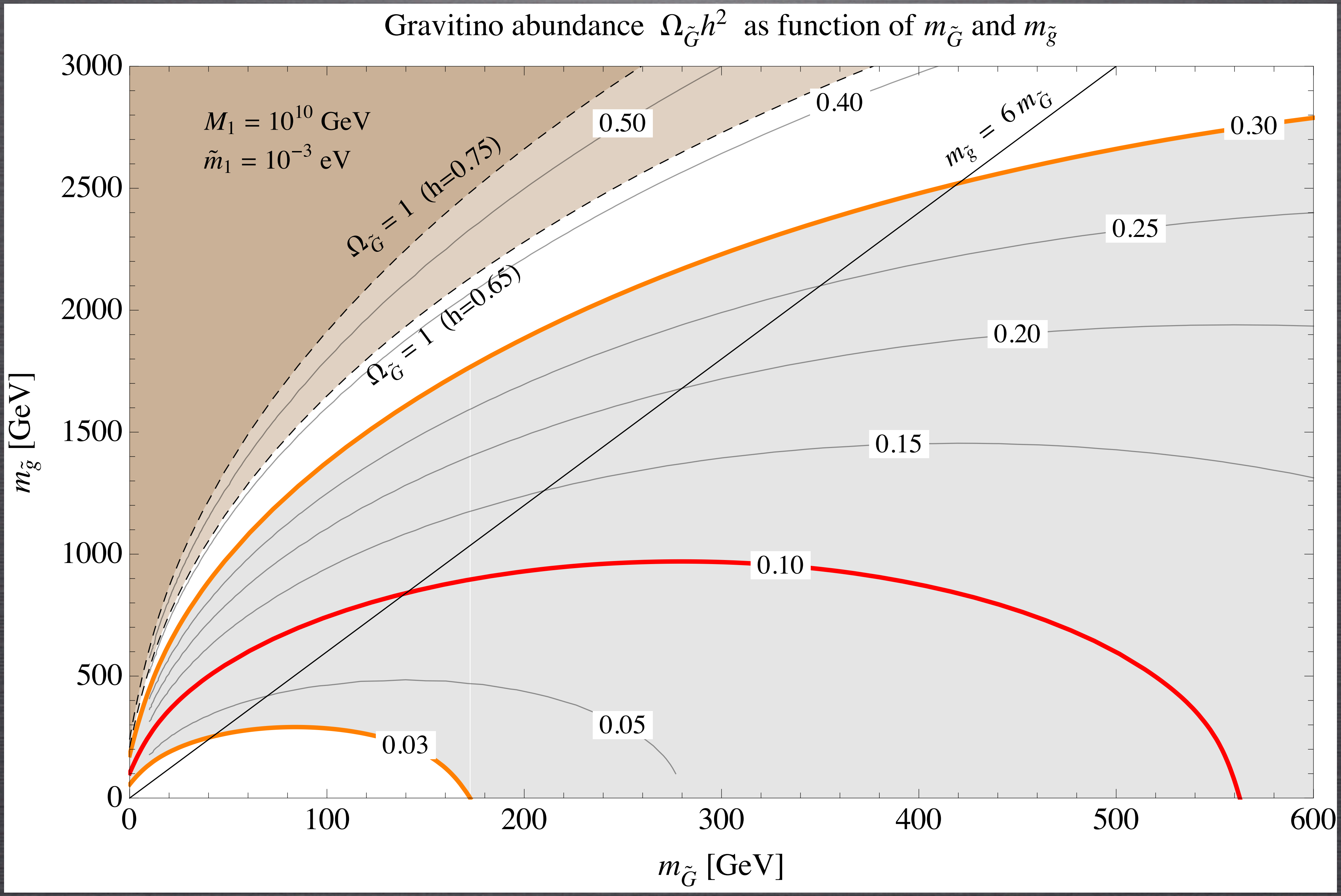
Reheating of the universe through N_1 decays generates both the BAU and DM (thermally produced gravitinos)

Tachyonic preheating leads to an interplay of thermal and non-thermal leptogenesis which is controlled by Γ_N

Link between the absolute neutrino mass scale m_1 the gravitino mass $m_{\widetilde{G}}$

Backup

SUSY Dependance



Boltzmann equations

$$\hat{L}[f_S(t,p)] = -\frac{m_S}{E_S}\Gamma^0_S f_S(t,p)$$

$$\hat{L}[f^S_{N_1}(t,p)] = -\frac{M_1}{E_{N_1}}\Gamma^0_{N_1} f^S_{N_1}(t,p) + \frac{2\pi^2\, n_S\,\Gamma^0_S}{E^2_{N_1}}\left[1-(2M_1/m_S)^2\right]^{-1/2}\delta\left(E_{N_1}-m_S/2\right)$$

$$aH\frac{d}{da}N^T_{N_1} = -\Gamma_{N_1}\left(N^T_{N_1}-N^{\rm eq}_{N_1}\right)$$

$$aH\frac{d}{da}N_{B-L} = \epsilon_1\Gamma_{N_1}\left(N^T_{N_1}-N^{\rm eq}_{N_1}\right) - \frac{N^{\rm eq}_{N_1}}{2N^{\rm eq}_L}\Gamma_{N_1}N_{B-L} + \epsilon_1\,\Gamma^0_{N_1}\widetilde{N}^S_{N_1}$$

$$aH\frac{d}{da}N_{\tilde{G}} = a^3\,\mathcal{C}_{\tilde{G}}(T)$$

$$0 = \frac{d}{dt}\left(\rho_R+\rho^T_{N_1}+\rho_S+\rho^S_{N_1}\right) + 3H\left(\rho_R+\rho^T_{N_1}+\rho_S+\rho^S_{N_1}+p_R+p^T_{N_1}+p^S_{N_1}\right)$$

with

$$N_X(t) = a^3\frac{g_X}{(2\pi)^3}\int d^3p\, f_X(t,p)$$

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