

2ND BETHE CENTER WORKSHOP
PHYSIKZENTRUM - BAD HONNEF

MATTER AND DARK MATTER FROM FALSE VACUUM DECAY

BASED ON PLB 693 (2010) 421
IN COLLABORATION WITH W.BUCHMULLER & K.SCHMITZ



G.VERTONGEN
(DESY HAMBURG)

MOTIVATION

Obs: $\exists$ B Asymmetry of the Universe

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

Q? How generating B dynamically ?

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

$$\eta_B \propto n_N^{\text{eq}} \epsilon_{\text{CP}} \kappa C_{\text{sph}}$$

Hierarchical $N_R \rightarrow M_1 \gtrsim 10^{10} \text{ GeV}$

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

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Virtue: stable gravitinos as DM

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

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

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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

$$\tilde{m}_1 \equiv \frac{(m_D^\dagger m_D)_{11}}{M_1} \sim 10^{-2} \text{ eV}$$

→ Heavy Majorana neutrino has a width of

$$\Gamma_{N_1}^0 = \frac{\tilde{m}_1}{8\pi} \left(\frac{M_1}{v_{\text{EW}}} \right)^2 \sim 10^3 \text{ GeV}$$

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

FLAVOUR MODEL

Superpotential:

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

- 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

$$\langle H_u \rangle = v_u, \quad \langle H_d \rangle = v_d, \quad \langle S \rangle = v_{B-L}$$

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Yukawa couplings: Froggatt-Nielsen U(1) flavour symmetry [Buchmuller & Yanagida 97]

Yukawas from non-renorm. $U(1)_{FN}$ -inv. higher-dim. operators

$$h_{ij} \propto \eta^{Q_i + Q_j} \quad \eta \equiv v_{FN}/\Lambda \simeq 1/\sqrt{300}$$

with Q_i charges and η determined by quark & lepton mass hierarchies

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Specific Example: $a=1, d=1$

► Requirement : $M_1 \ll M_{2,3} = m_S \rightarrow b = c = d-1 = 0$

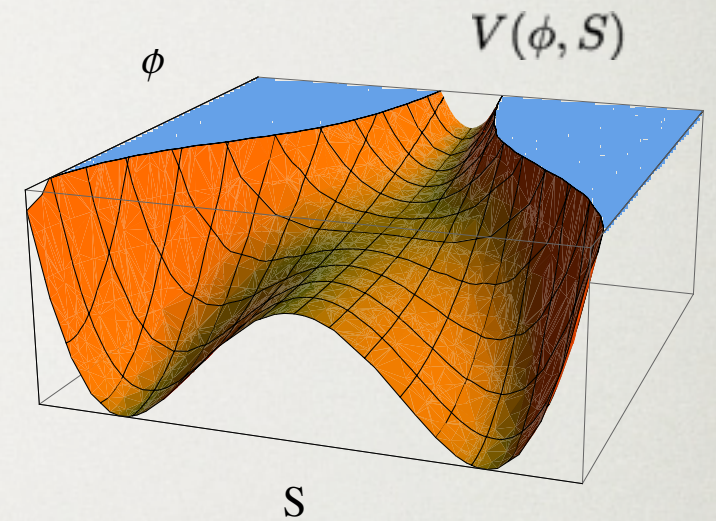
► $v_{B-L} \sim 3 \times 10^{12} \text{ GeV}$ $M_1 \sim 10^{10} \text{ GeV}$ $M_{2,3} = m_S \sim v_{B-L}$

COSMOLOGICAL SCENARIO

False vacuum decay after Hybrid inflation:

If $B-L$ symmetry breaking field couple to the inflaton, Then

1. responsible for SSB and generation of Neutrino masses
2. responsible for the sudden end of the inflationary era

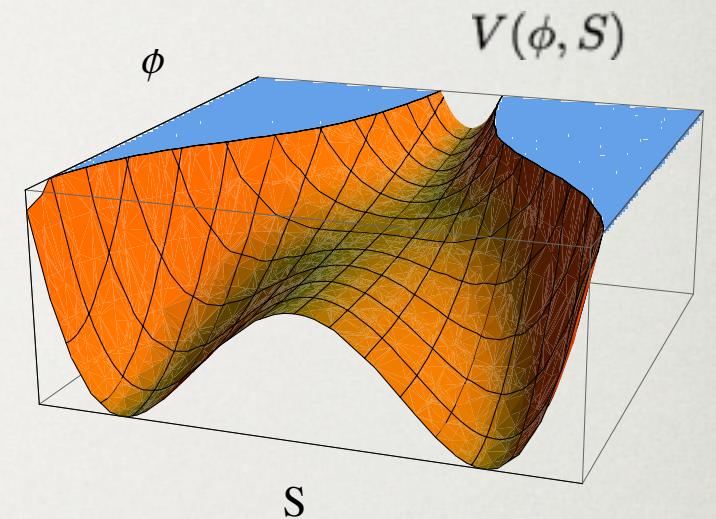


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Dynamics of symmetry breaking:

Tachyonic instability in the S potential for $\phi < \phi_{crit.}$ causes spinodial growth of long-wavelength S modes : *Tachyonic preheating* [Felder et al. 2001]

False vacuum energy $\rho_0 = \frac{1}{4}\lambda v_{B-L}^4$ rapidly transferred to [Garcia-Bellido & Ruiz Morales, 2002]

- nonrelativistic gas of S bosons
- heavy neutrinos N_i

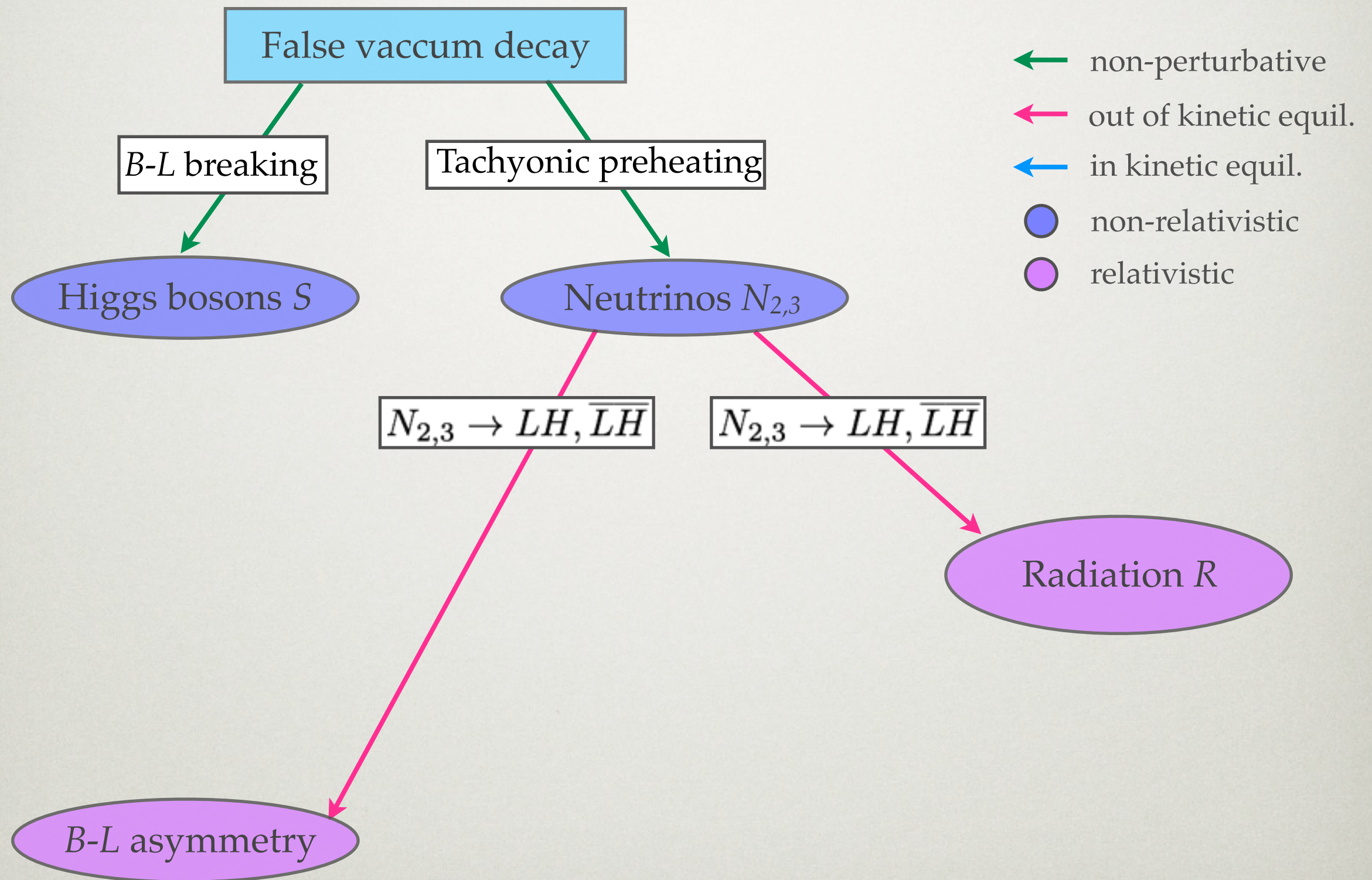
$$\rho_S \simeq \rho_0$$

$$\rho_{N_i}/\rho_0 \simeq 1.5 \times 10^{-3} g_N f(h_i^n/\sqrt{\lambda}, 0.8)$$

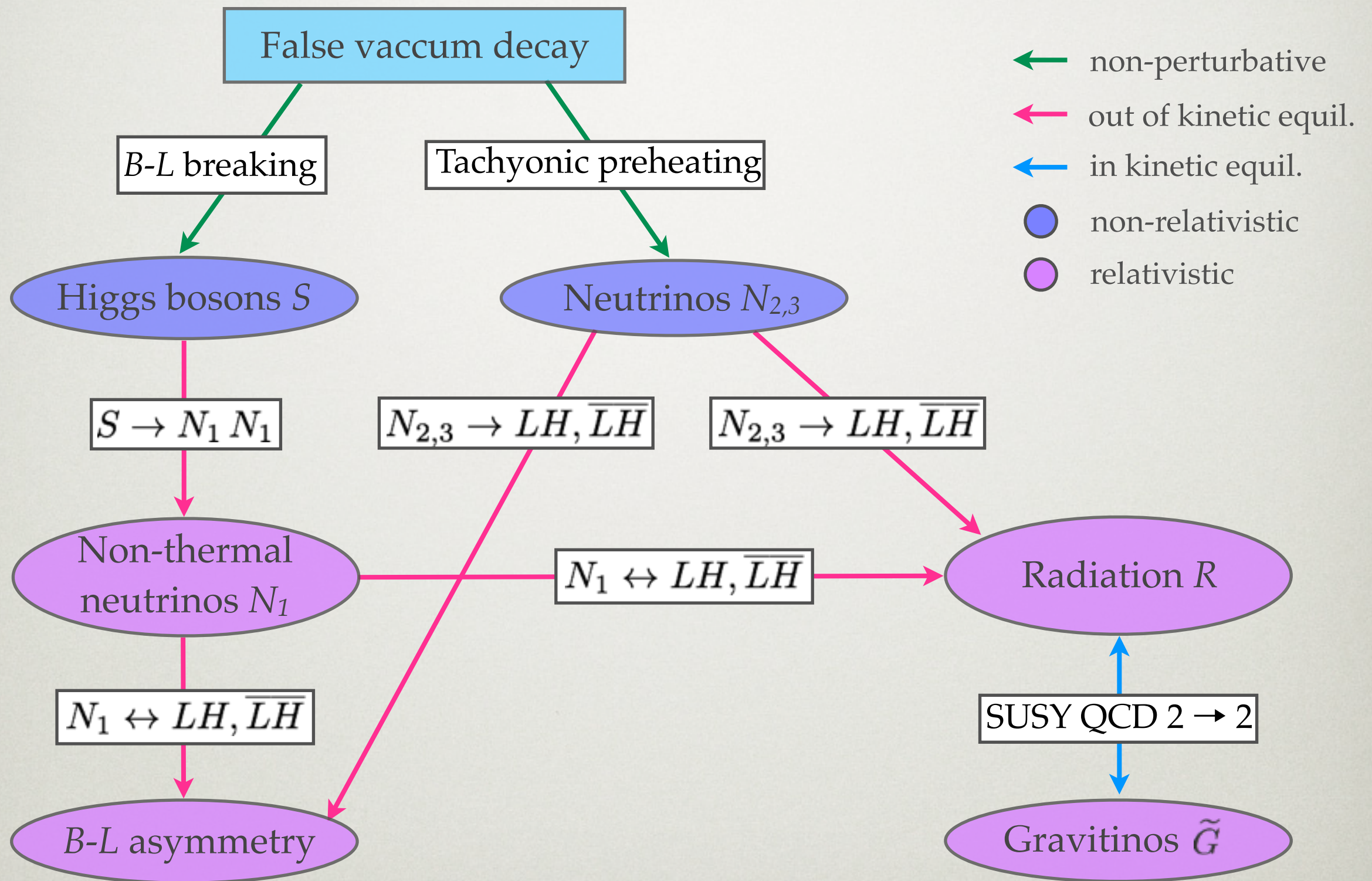
For the considered flavour model :

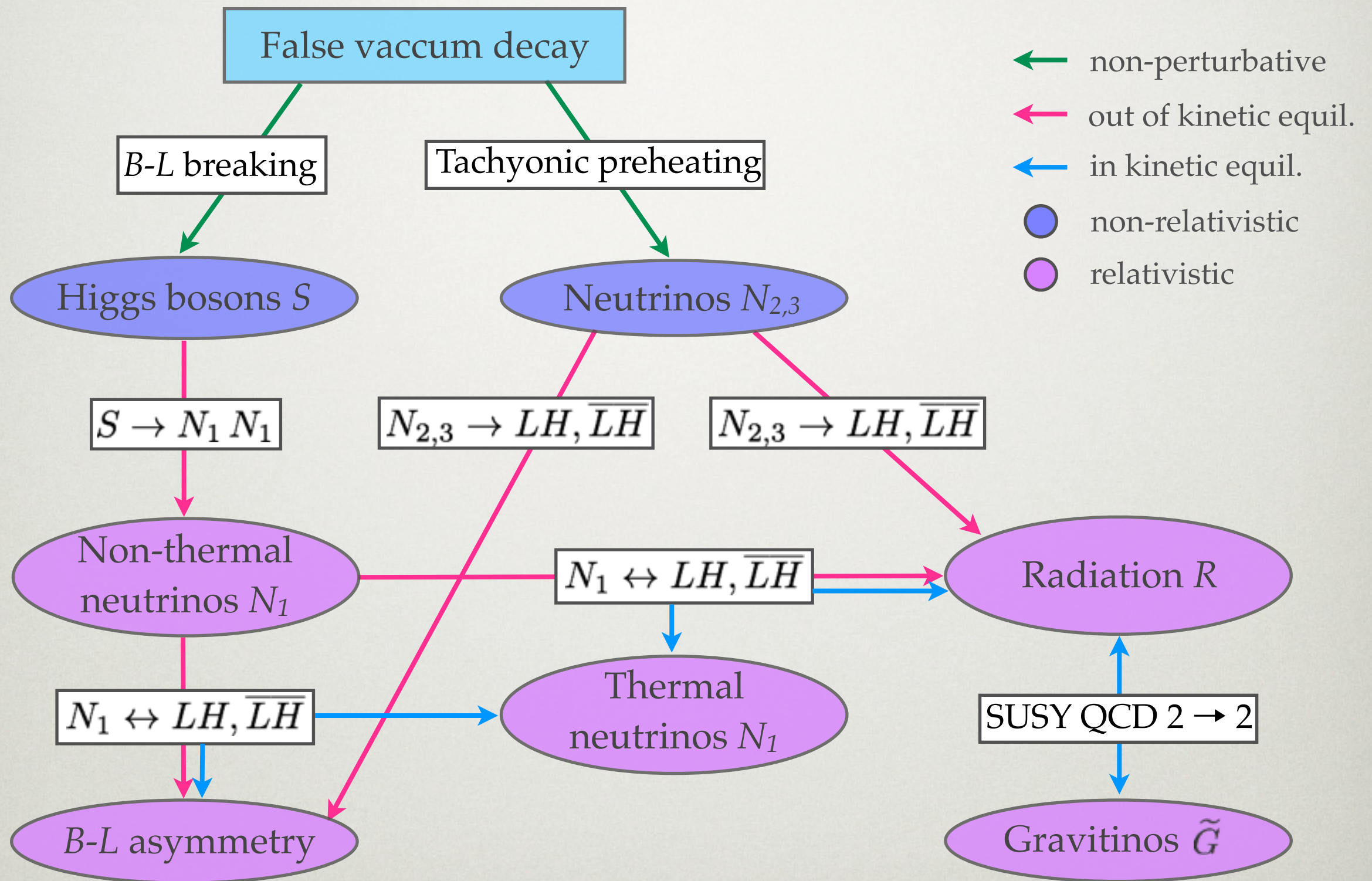
$$\rho_{N_1}/\rho_0 = \mathcal{O}(\eta^4), \quad \rho_{N_{2,3}}/\rho_0 \simeq 10^{-3}$$

COSMOLOGICAL SCENARIO: INITIAL STATE



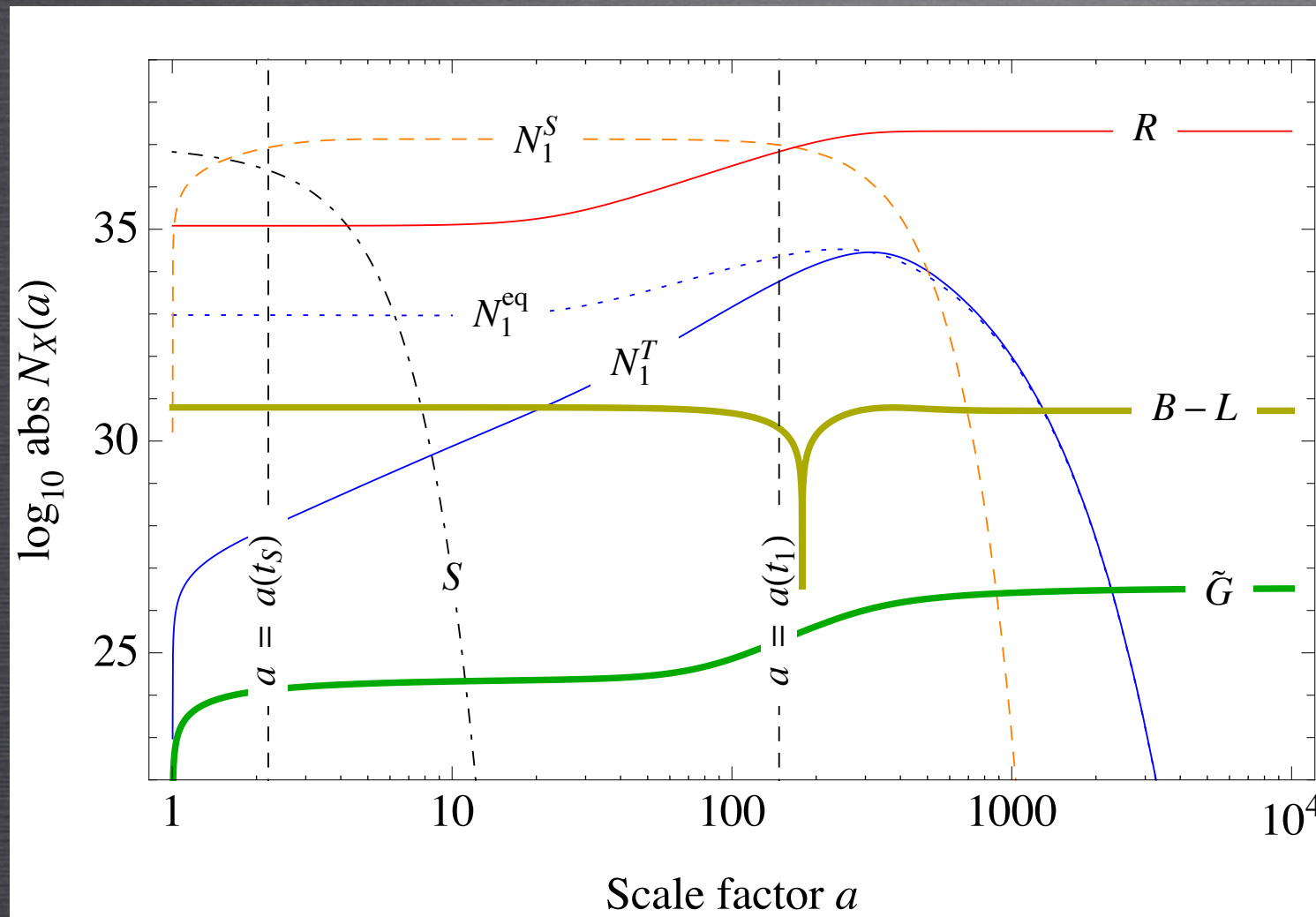
COSMOLOGICAL SCENARIO: NON THERMAL N_1





COSMOLOGICAL EVOLUTION

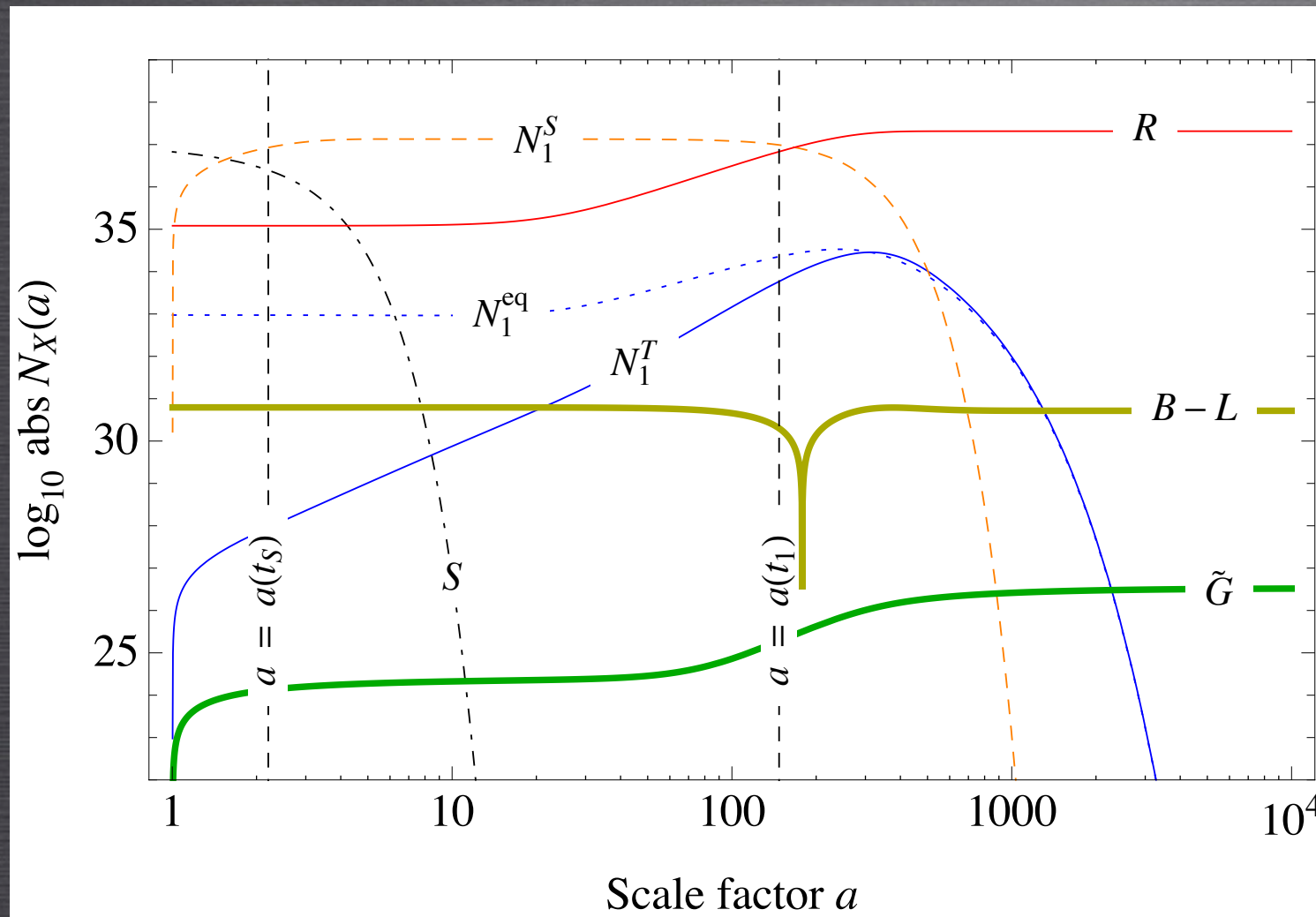
Evolution of the comobile densities $N_i \equiv a^3 n_i$ with the scale factor a



$$\begin{aligned}
 M_1 &= 10^{10} \text{ GeV} \\
 M_{2,3} &= 3 \times 10^{12} \text{ GeV} \\
 \tilde{m}_1 &= 10^{-3} \text{ eV} \\
 \epsilon_1 &= 10^{-6} \\
 \epsilon_{2,3} &= -3 \times 10^{-4} \\
 M_{\tilde{G}} &= 100 \text{ GeV} \\
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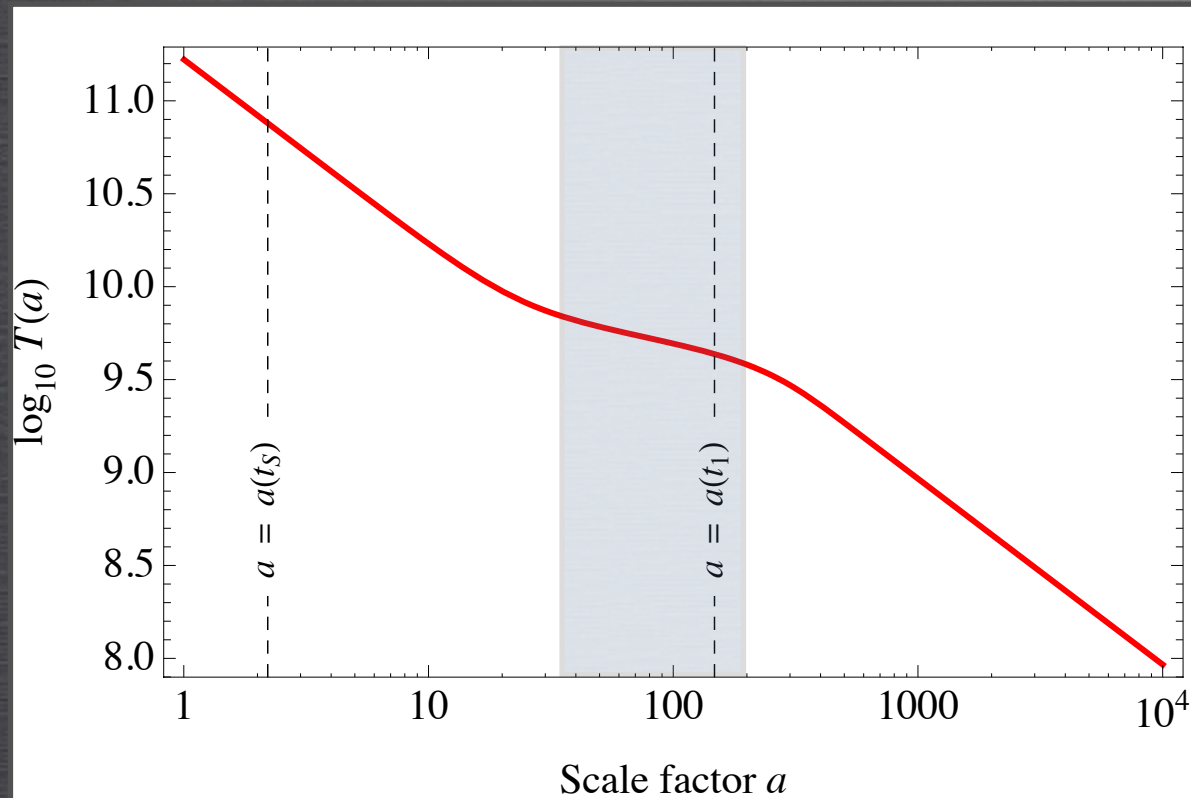


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$$\eta_B = 1.6 \times 10^{-7} > \eta_B^{\text{obs}} = 6.2 \times 10^{-10} \quad \checkmark$$

$$\Omega_{\tilde{G}} h^2 = 0.11 = \Omega_{\text{DM}} h^2 \quad \checkmark$$

COSMOLOGICAL EVOLUTION

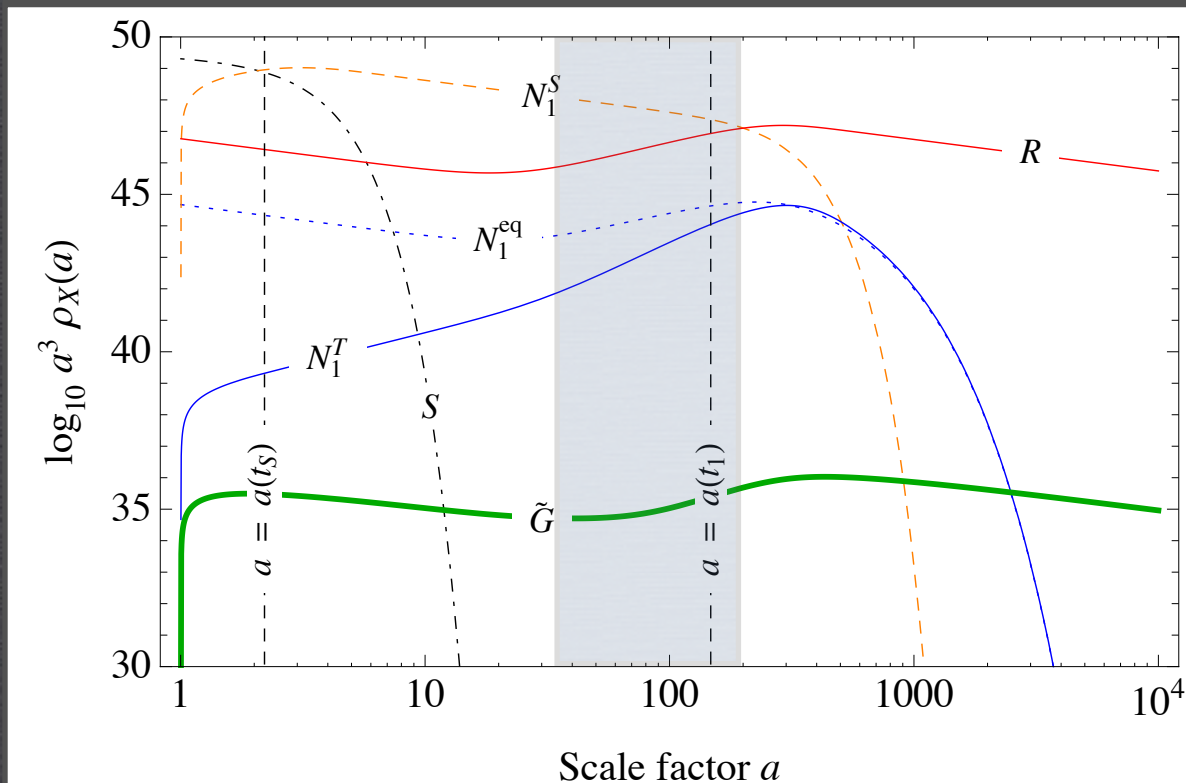


Reheating temperature:

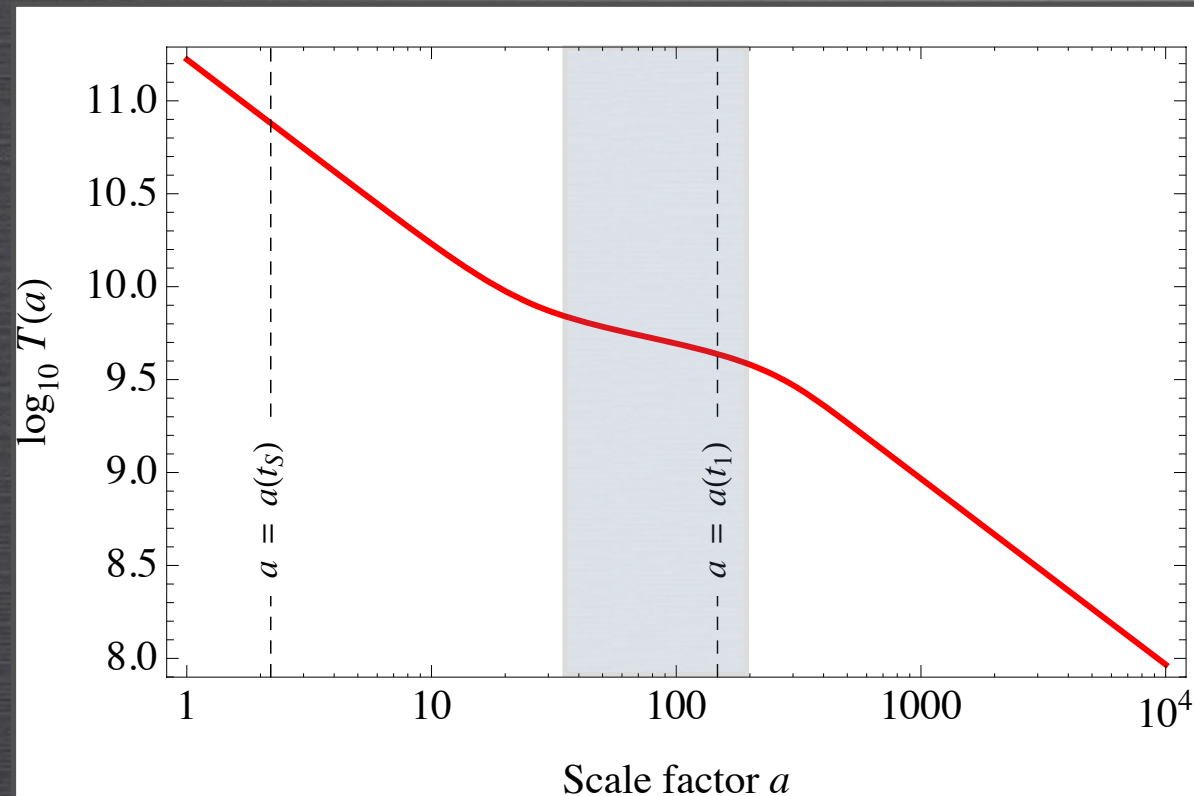
$$T_R \simeq 5 \times 10^9 \text{ GeV}$$

in agreement with the estimate

$$T_R = \left(\frac{90}{8\pi^3 g_*} \right)^{1/4} \sqrt{\Gamma M_P} \simeq 8 \times 10^9 \text{ GeV}$$



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Extreme cases:

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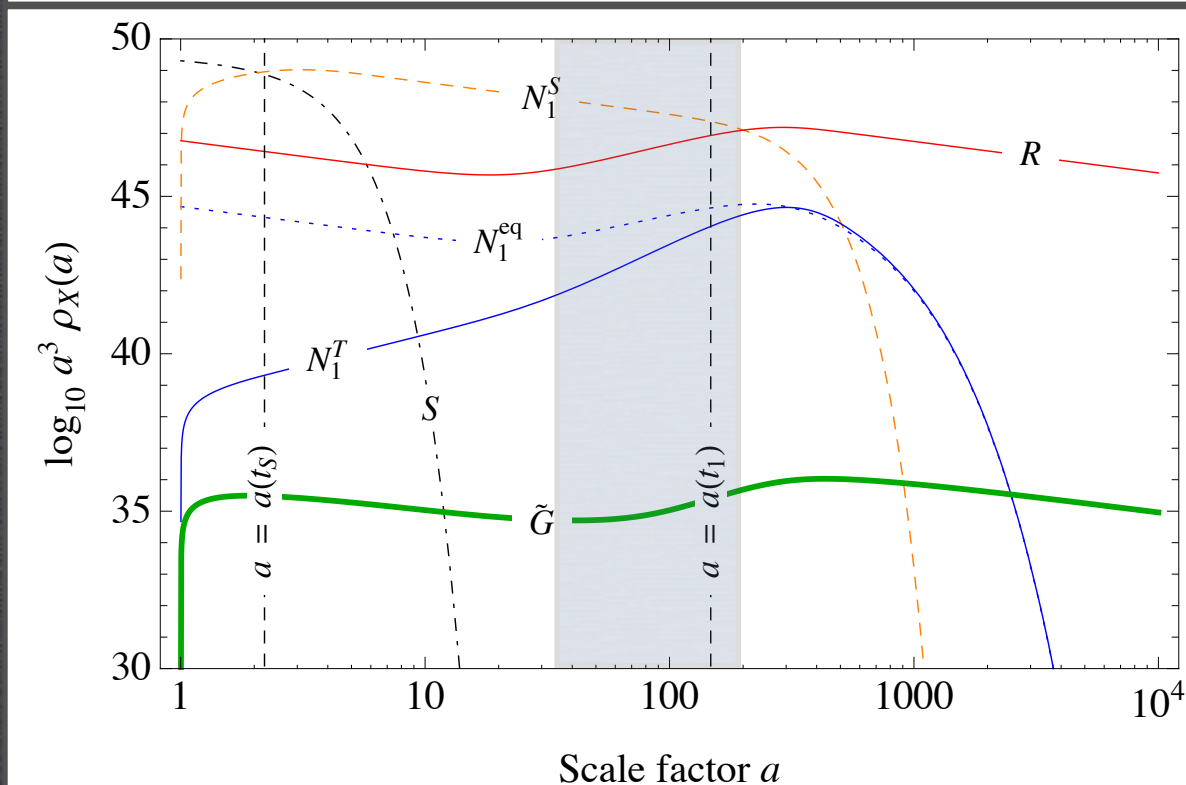
- thermal leptogenesis :

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

- rapid nonrelativistic N_1 conversion

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

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



SUMMARY

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- ▶ Heavy Majorana neutrinos N_i
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In the end: Matter and Dark Matter at Once

- ▶ Combination of thermal and non-thermal leptogenesis
- ▶ Thermal production of gravitinos
- ▶ Link between SUGRA and neutrino mass: $\tilde{m}_1 \leftrightarrow m_{\tilde{G}}$

BACKUP

BOLTZMANN EQUATIONS

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

$$\hat{L}[f_{N_1}^S(t, p)] = -\frac{M_1}{E_{N_1}} \Gamma_{N_1}^0 f_{N_1}^S(t, p) + \frac{2\pi^2 n_S \Gamma_S^0}{E_{N_1}^2} \left[1 - (2M_1/m_S)^2\right]^{-1/2} \delta(E_{N_1} - m_S/2)$$

$$aH \frac{d}{da} N_{N_1}^T = -\Gamma_{N_1} (N_{N_1}^T - N_{N_1}^{\text{eq}})$$

$$aH \frac{d}{da} N_{B-L} = \epsilon_1 \Gamma_{N_1} (N_{N_1}^T - N_{N_1}^{\text{eq}}) - \frac{N_{N_1}^{\text{eq}}}{2N_L^{\text{eq}}} \Gamma_{N_1} N_{B-L} + \epsilon_1 \Gamma_{N_1}^0 \tilde{N}_{N_1}^S$$

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

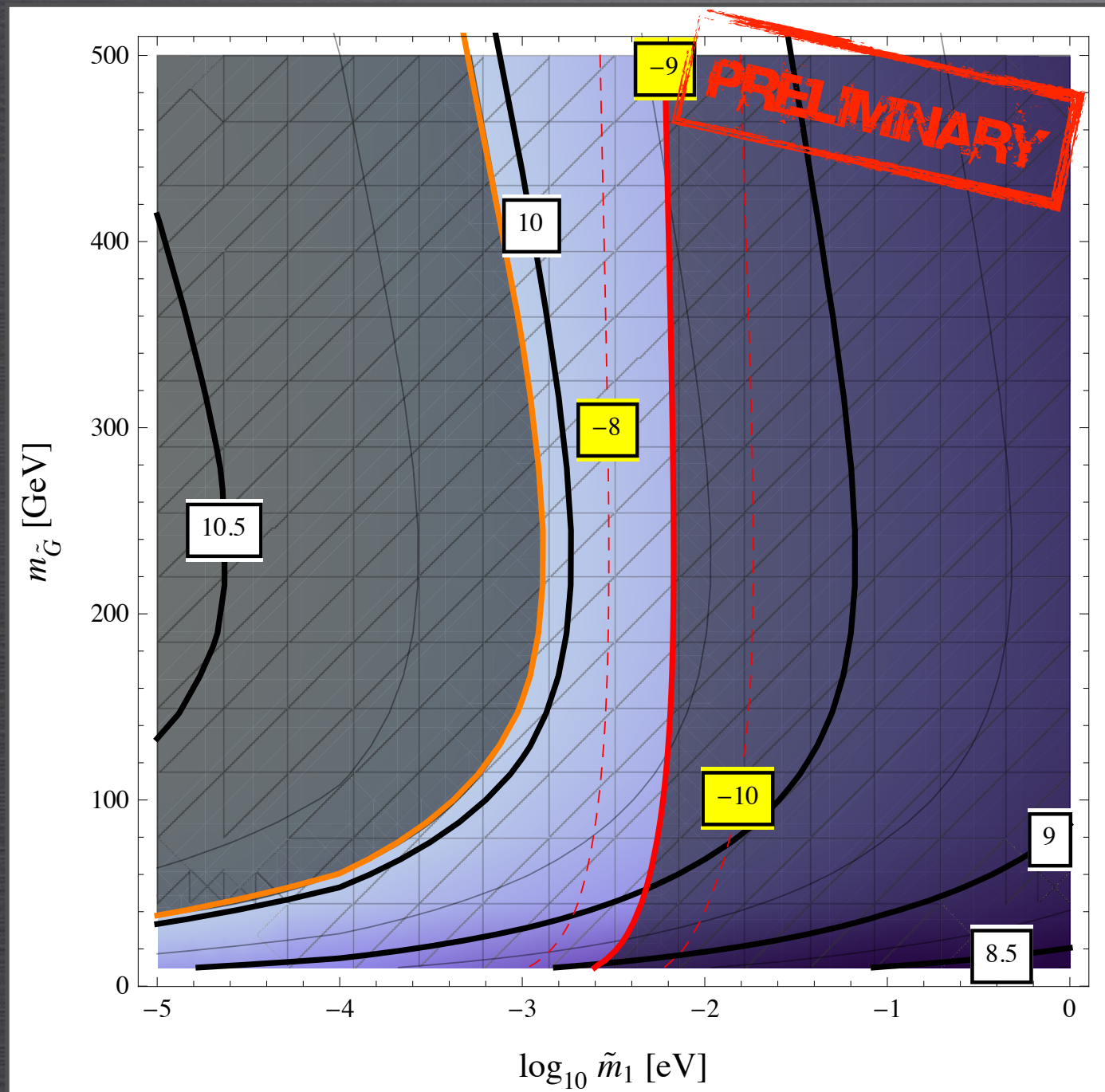
$$0 = \frac{d}{dt} (\rho_R + \rho_{N_1}^T + \rho_S + \rho_{N_1}^S) + 3H (\rho_R + \rho_{N_1}^T + \rho_S + \rho_{N_1}^S + p_R + p_{N_1}^T + p_{N_1}^S)$$

with

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

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

SUSY DEPENDANCE



$$v_{B-L} = 3.4 \times 10^{12} \text{ GeV}$$

$$m_{\tilde{g}} = 800 \text{ GeV}$$

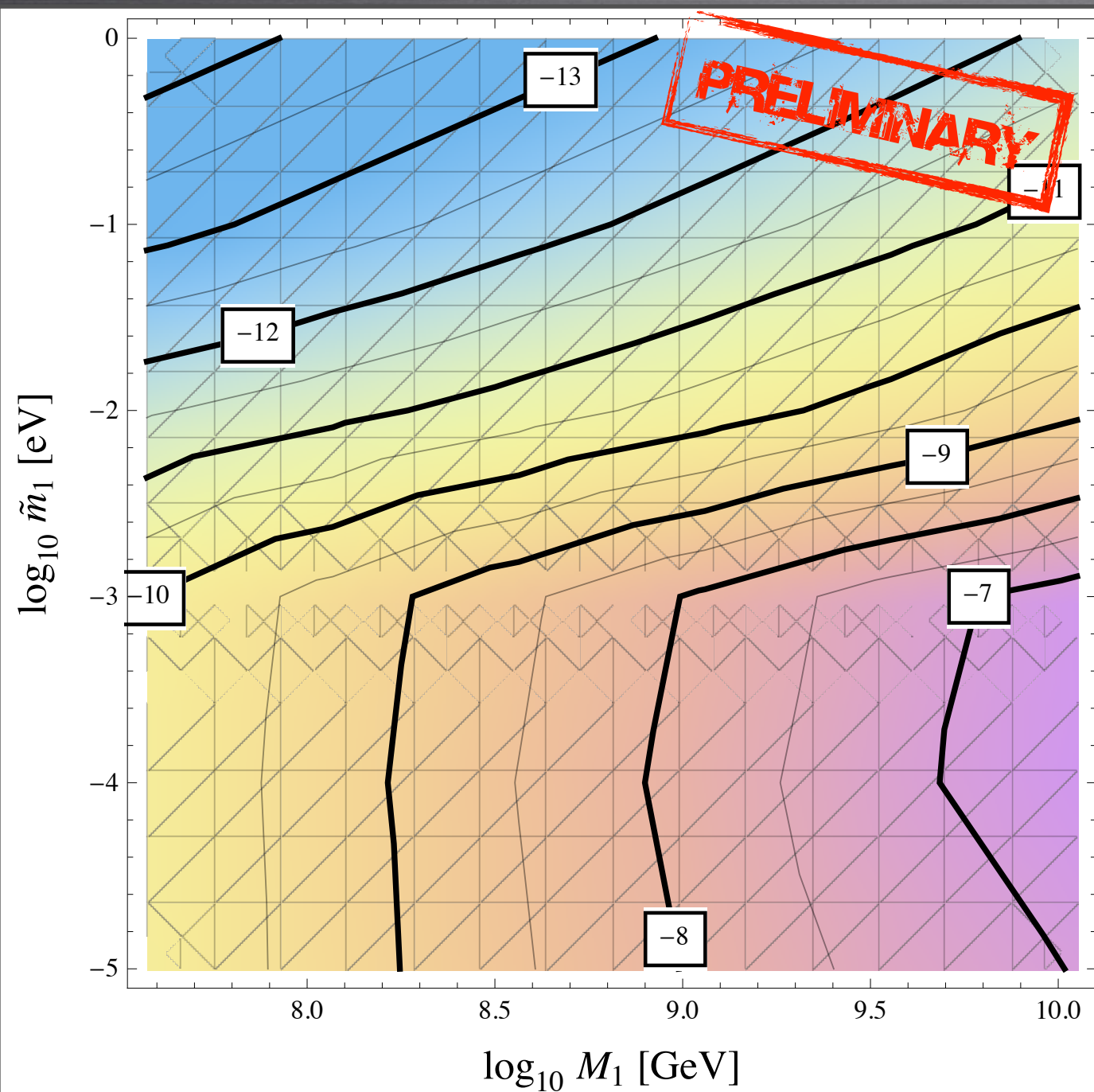
$$\log_{10}(M_1) = f(\tilde{m}, m_{\tilde{G}})$$

each M_1 being chosen such that

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

- Flavour Model Limit
- Obs. Baryon Asymmetry

BARYON ASYMMETRY



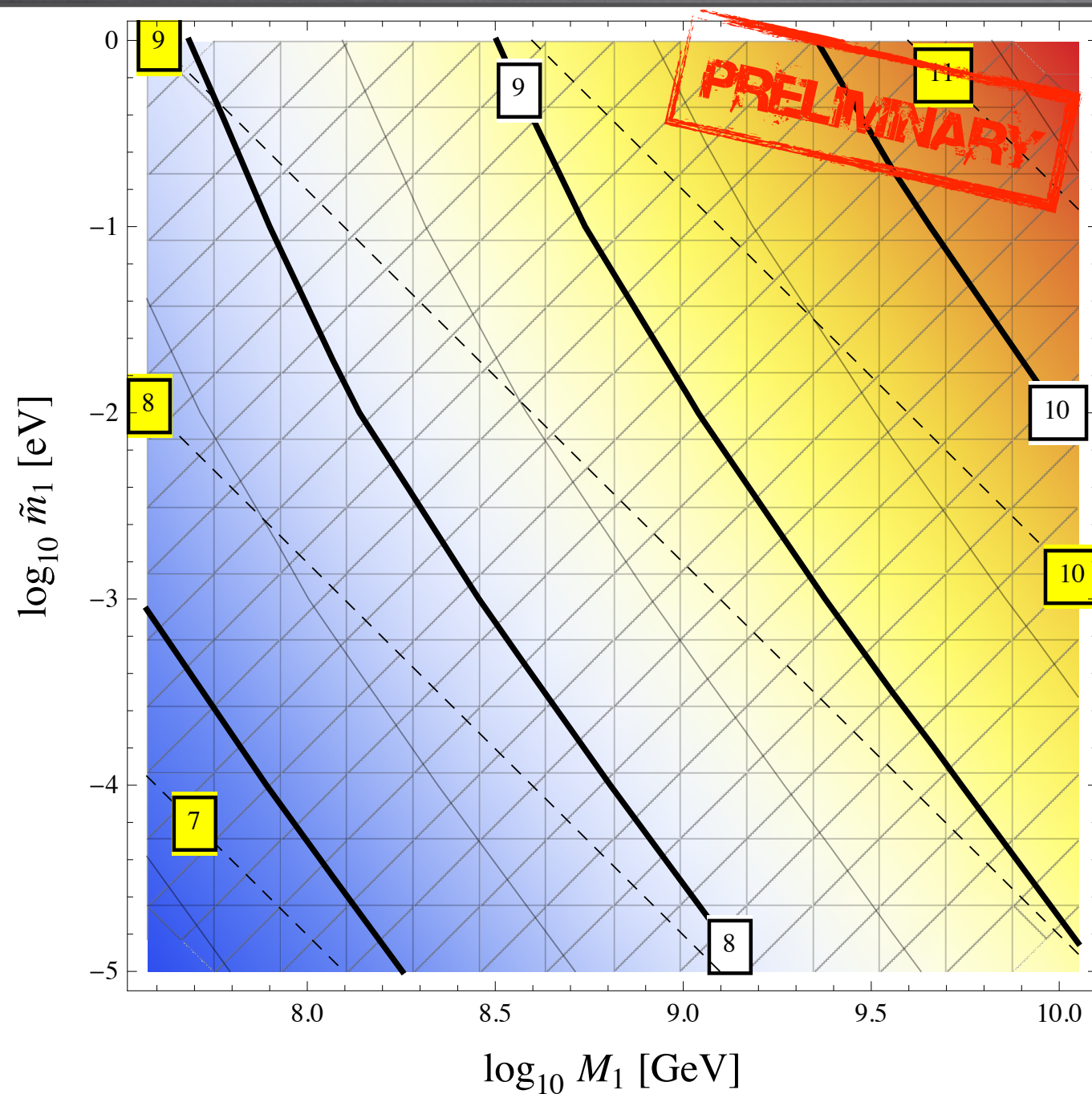
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REHEATING TEMPERATURE



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