GDR Terascale

Université Libre de Bruxelles

Matter and Dark Matter from False Vaccum Decay

PLB 693 (2010) 421

In Collaboration with W.Buchmuller and K.Schmitz

G.Vertongen

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 generate B dynamically ?

Motivation

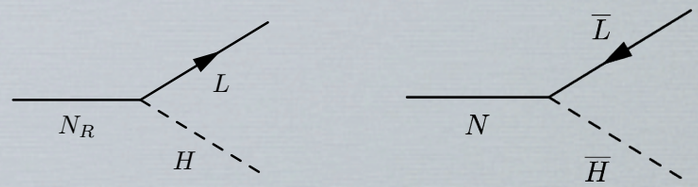
Obs: **∃ B Asymmetry of the Universe**

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

Q? How to generate B dynamically ?

Prop: Use the seesaw N_R : (Baryogenesis through leptogenesis) [Fukugida, Yanagida 97] :

- decay to LH pairs : generation of L asymmetry
- no SM gauge interaction : out-of-equilibrium
- generation of CP asymmetry
- L asymmetry converted to B through sphalerons



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

Baryon Asymmetry : $\eta_B \equiv \dfrac{n_B - n_{\bar{B}}}{n_\gamma} = n_N^{eq}\, \epsilon_{CP}\, \kappa\, c_{sph}$

Motivation

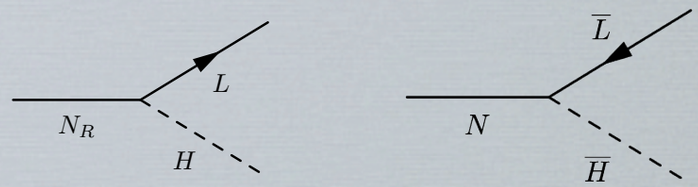
Obs: ∃ B Asymmetry of the Universe

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

Q? How to generate B dynamically ?

Prop: Use the seesaw N_R : (Baryogenesis through leptogenesis) [Fukugida, Yanagida 97] :

- decay to LH pairs : generation of L asymmetry
- no SM gauge interaction : out-of-equilibrium
- generation of CP asymmetry
- L asymmetry converted to B through sphalerons

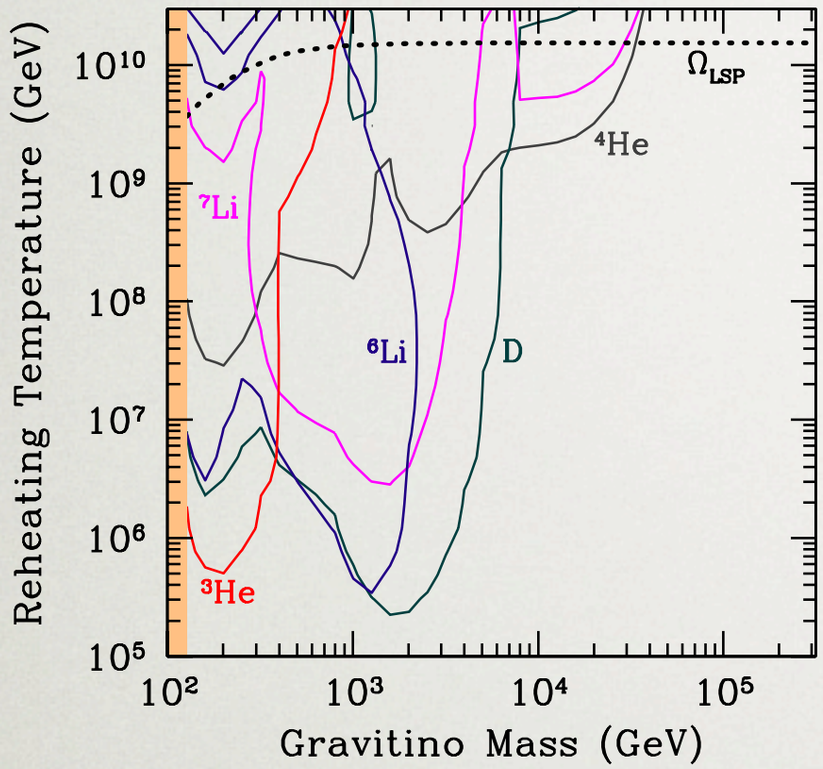


$$\epsilon_N \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \bar{L}\bar{H})}{\Gamma(N \to LH) + \Gamma(N \to \bar{L}\bar{H})}$$

Baryon Asymmetry : $\eta_B \equiv \dfrac{n_B - n_{\bar{B}}}{n_\gamma} = n_N^{eq}\, \epsilon_{CP}\, \kappa\, c_{sph}$

Hierarchical N_R → $M_1 \gtrsim 10^{10}\,\text{GeV}$ Thermal N_R production → $T_L \gtrsim 10^{10}\,\text{GeV}$

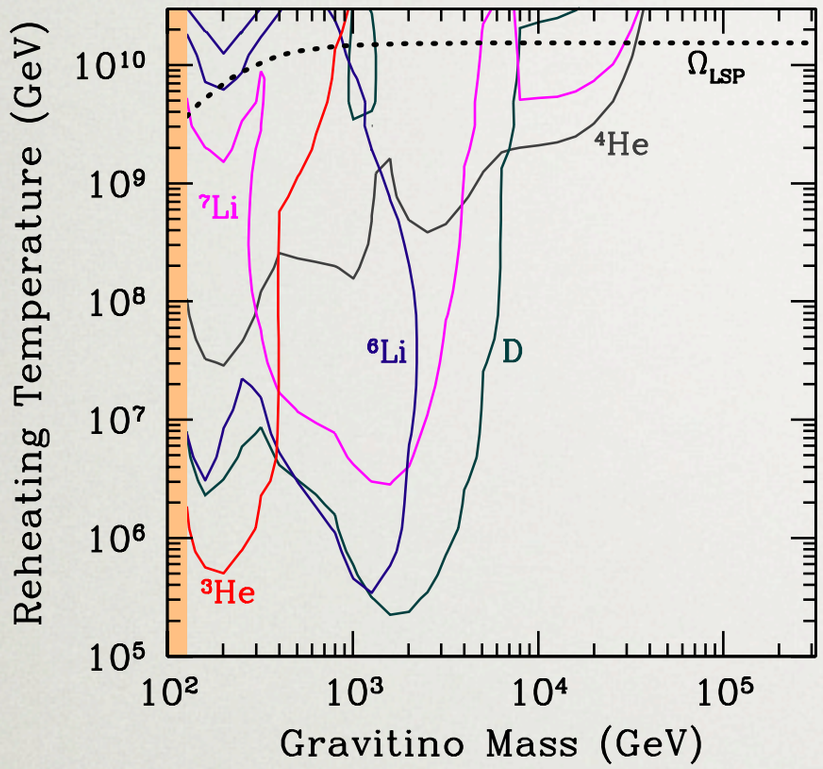
Leptogenesis vs. SUSY



Tension: unstable gravitinos:
BBN constraint [Kawasaki, Kohri, Moroi 05]

$$T_R \leq 10^5\,\mathrm{GeV}$$

Leptogenesis vs. SUSY



Tension: unstable gravitinos:
BBN constraint [Kawasaki, Kohri, Moroi 05]

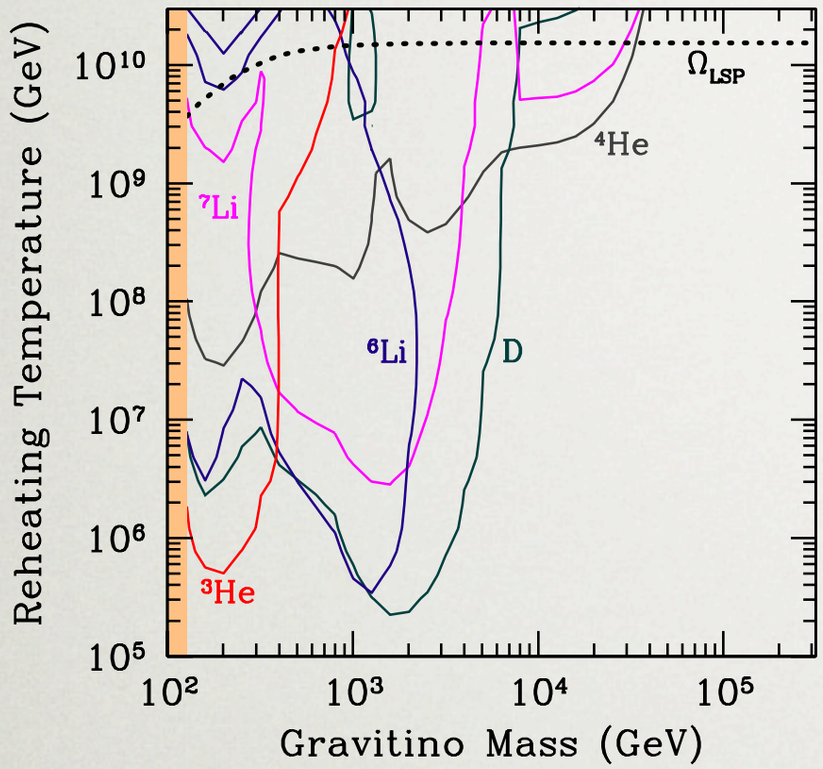
$$T_R \leq 10^5\,\mathrm{GeV}$$

Virtue: stable gravitinos as DM : Thermal production [Bolz et al. 01 ; Pradler & Steffen 06] :

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

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

Leptogenesis vs. SUSY



Tension: unstable gravitinos:
BBN constraint [Kawasaki, Kohri, Moroi 05]

$$T_R \leq 10^5\,\mathrm{GeV}$$

Virtue: stable gravitinos as DM : Thermal production [Bolz et al. 01 ; Pradler & Steffen 06] :

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

→ $\Omega_{\tilde{G}} h^2 \simeq \Omega_{\mathrm{DM}}^{\mathrm{obs}} h^2$ 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 $M_1 \sim 10^{10}\,\mathrm{GeV}$

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

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

Observation

Thermal leptogenesis: typical parameters

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

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

→ Heavy Majorana neutrino has a width of $\Gamma_{N_1}^0 = \dfrac{\tilde{m}_1}{8\pi}\left(\dfrac{M_1}{v_{\mathrm{EW}}}\right)^2 \sim 10^3\,\mathrm{GeV}$

Reheating: through particle decays with Γ width

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

Observation

Thermal leptogenesis: typical parameters

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

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

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

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 $\tilde{G}$ Dark Matter !

Observation

Thermal leptogenesis: typical parameters

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

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

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

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 $\tilde{G}$ Dark Matter !

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

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

Flavour Model

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

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

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

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

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

Flavour Model

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

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

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

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

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

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}^*_3$	$\mathbf{5}^*_2$	$\mathbf{5}^*_1$	n^c_3	n^c_2	n^c_1
Q_i	0	1	2	a	a	a+1	b	c	d

Flavour Model

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

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

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

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

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

ψ_i	$\mathbf{10}_3$	$\mathbf{10}_2$	$\mathbf{10}_1$	$\mathbf{5}^*_3$	$\mathbf{5}^*_2$	$\mathbf{5}^*_1$	n^c_3	n^c_2	n^c_1
Q_i	0	1	2	a	a	a+1	b	c	d

Specific Example: a=1, d=1

- Requirement : $M_1 << M_{2,3} = m_S$ → $b = c = d\text{-}1 = 0$
- $v_{B\text{-}L} \sim 3 \times 10^{12}$ GeV $\quad M_1 \sim 10^{10}$ GeV $\quad M_{2,3} = m_S \sim v_{B\text{-}L}$

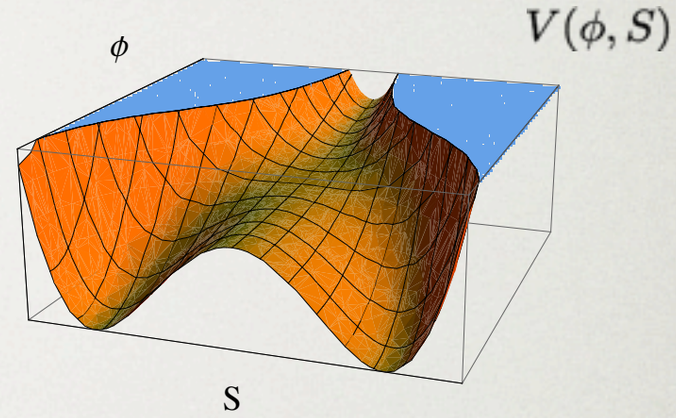
Cosmological Scenario

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



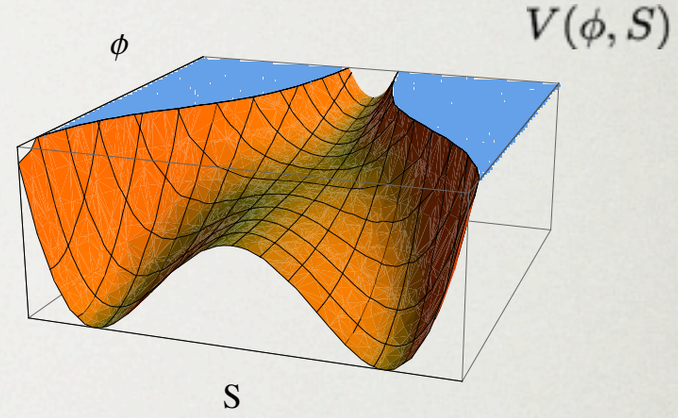
Cosmological Scenario

False vacuum decay after Hybrid inflation:

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

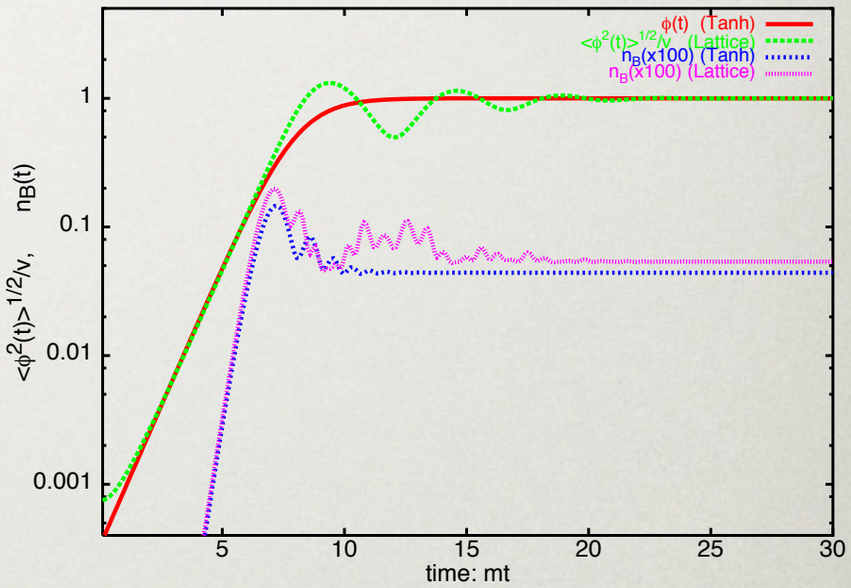
1. responsible for SSB and generation of Neutrino masses

2. responsible for the sudden end of the inflationary era



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]



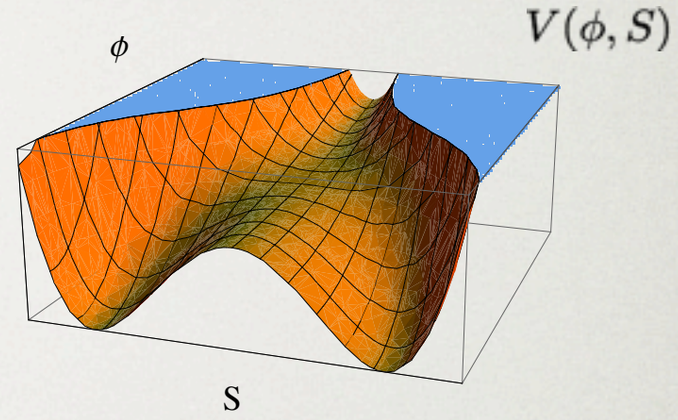
Cosmological Scenario

False vacuum decay after Hybrid inflation:

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

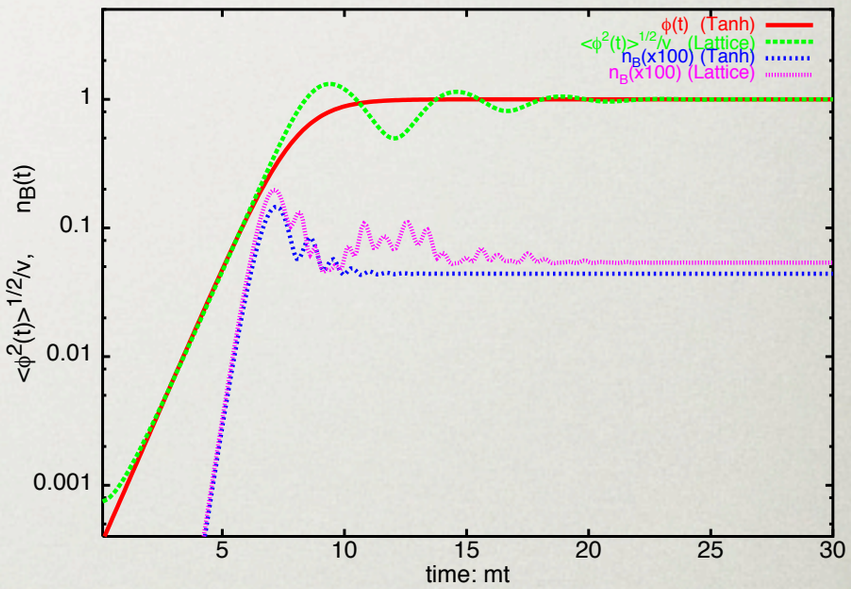
1. responsible for SSB and generation of Neutrino masses

2. responsible for the sudden end of the inflationary era



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]

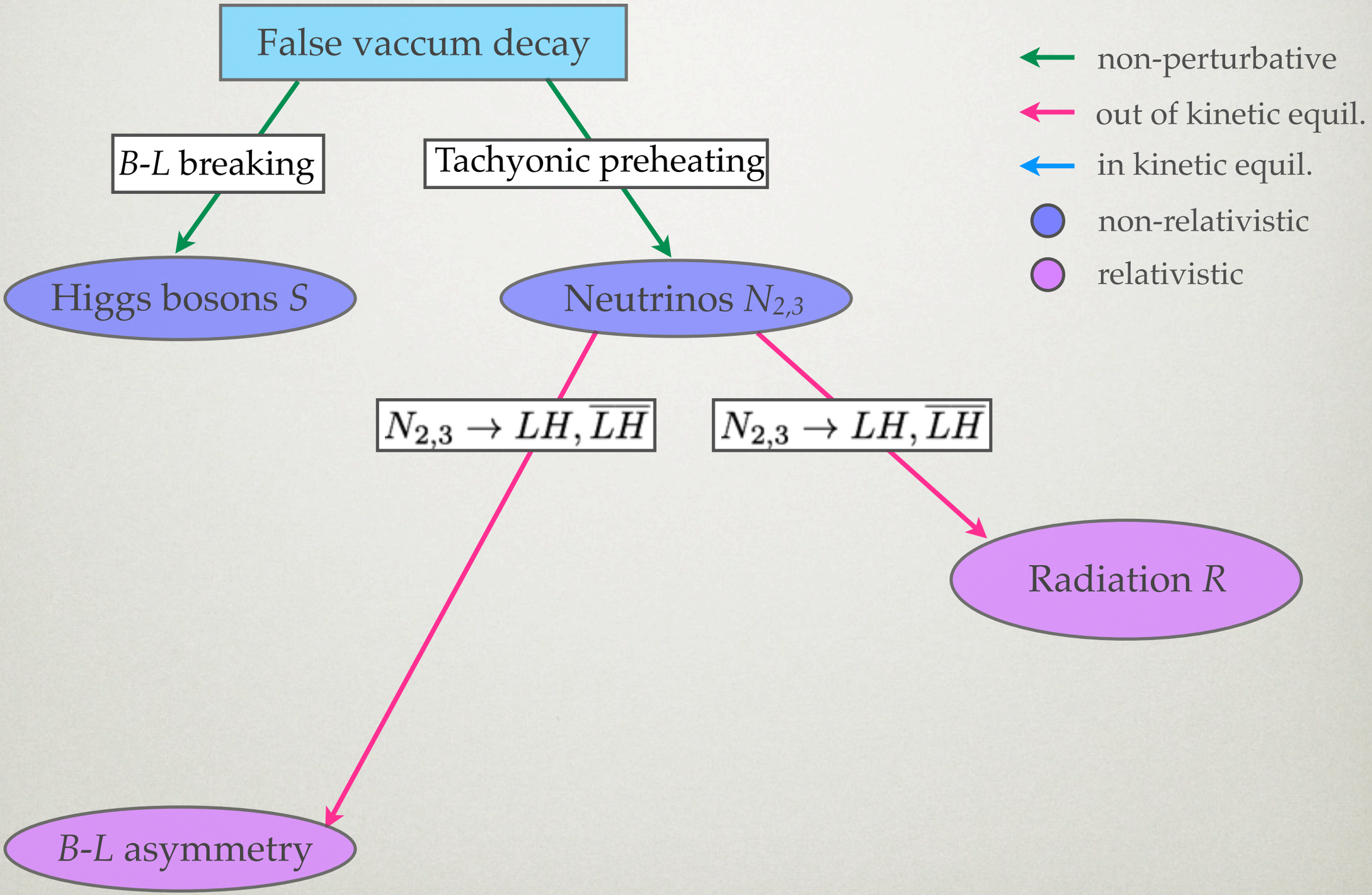


False vacuum energy $\rho_0 = \frac{1}{4}\lambda v_{B-L}^4$ rapidly transferred to [Garcia-Bellido & Ruiz Morales, 2002]

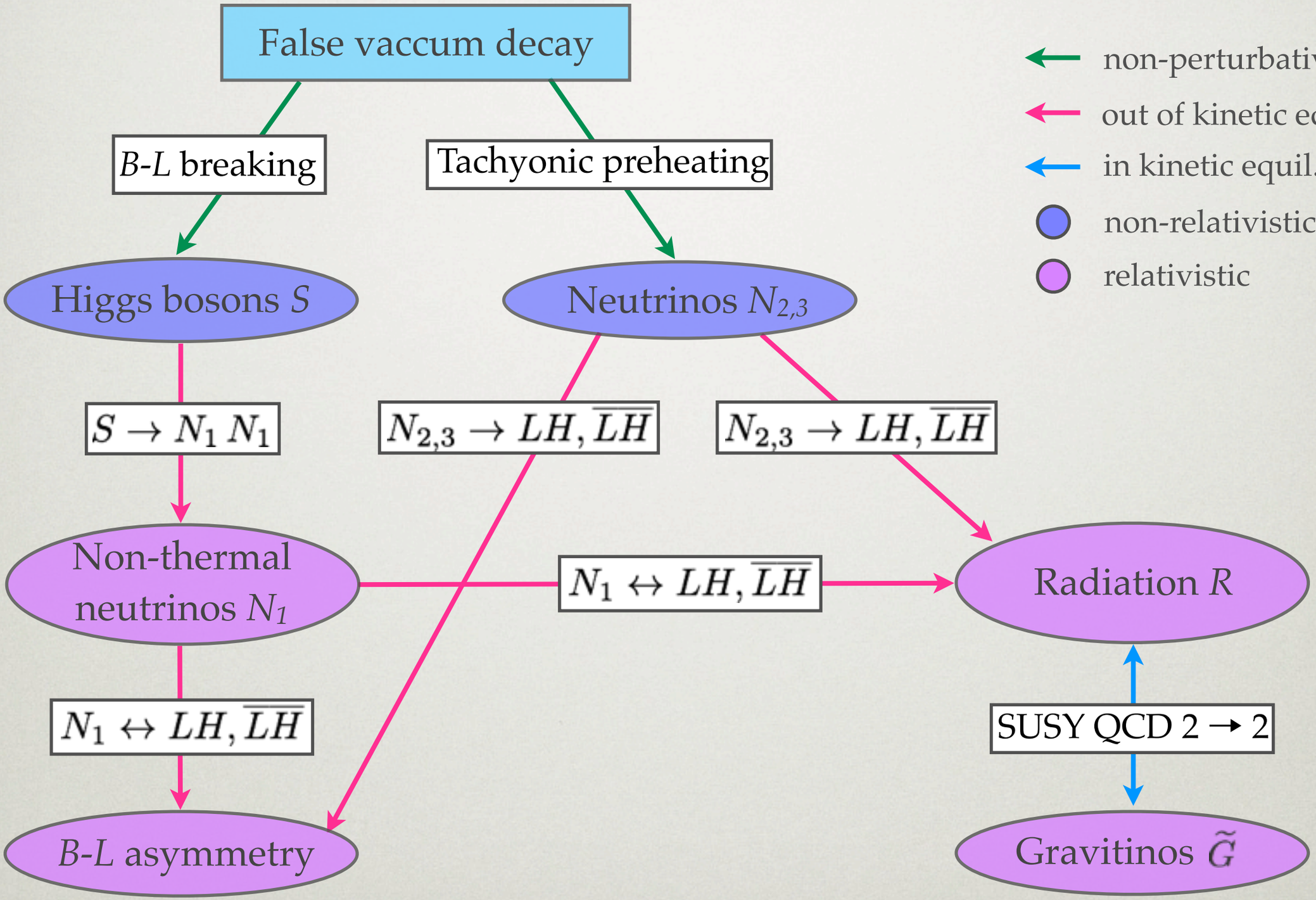
- nonrelativistic gas of *S* bosons $\rho_S \simeq \rho_0$
- heavy neutrinos N_i $\rho_{N_i}/\rho_0 \simeq 1.5 \times 10^{-3} g_N \, f(h_i^n/\sqrt{\lambda}, 0.8)$

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

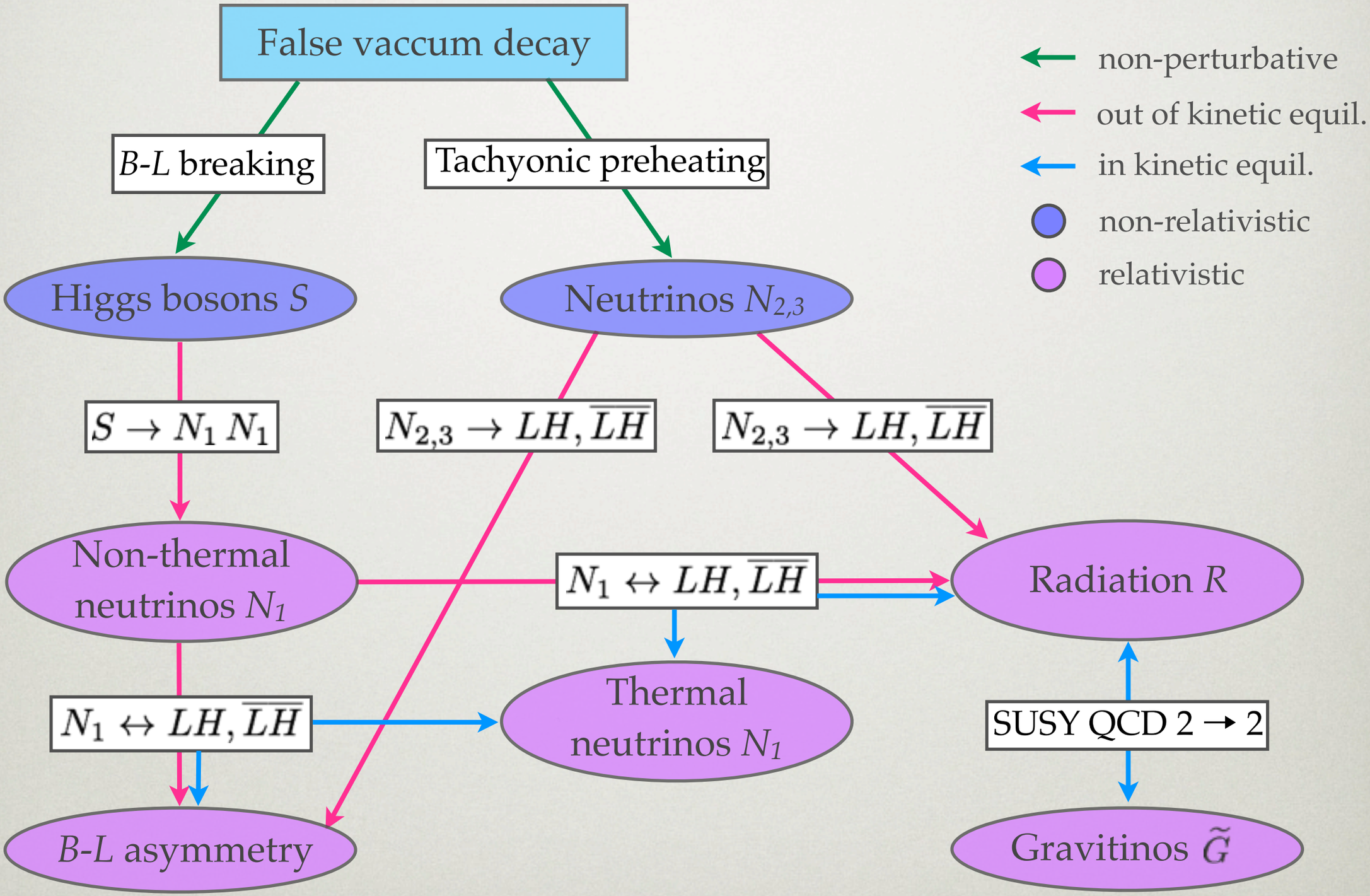
Cosmological Scenario: Initial State



Cosmological Scenario: Non Thermal N_1

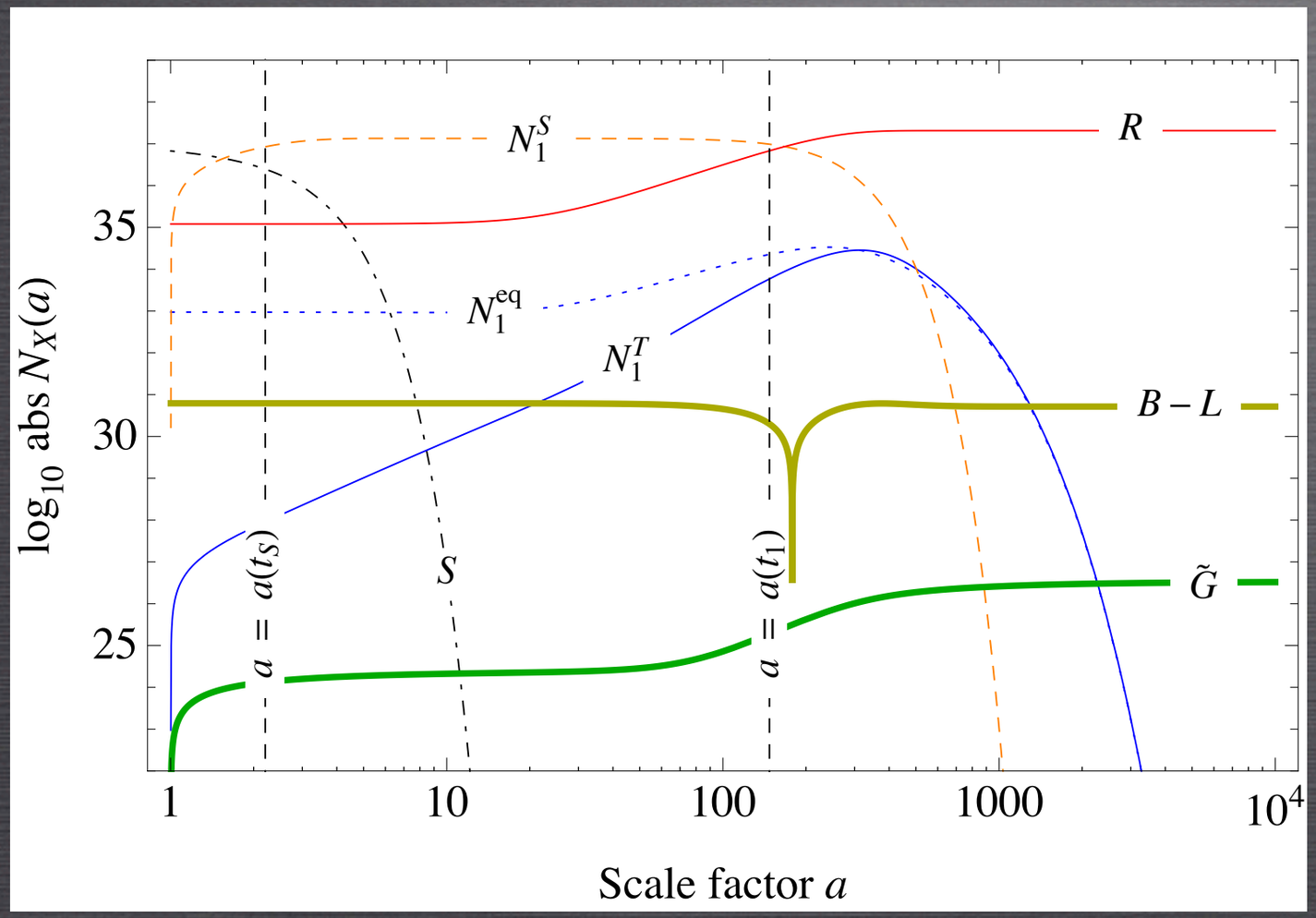


Cosmological Scenario: Thermal N_1



Cosmological Evolution

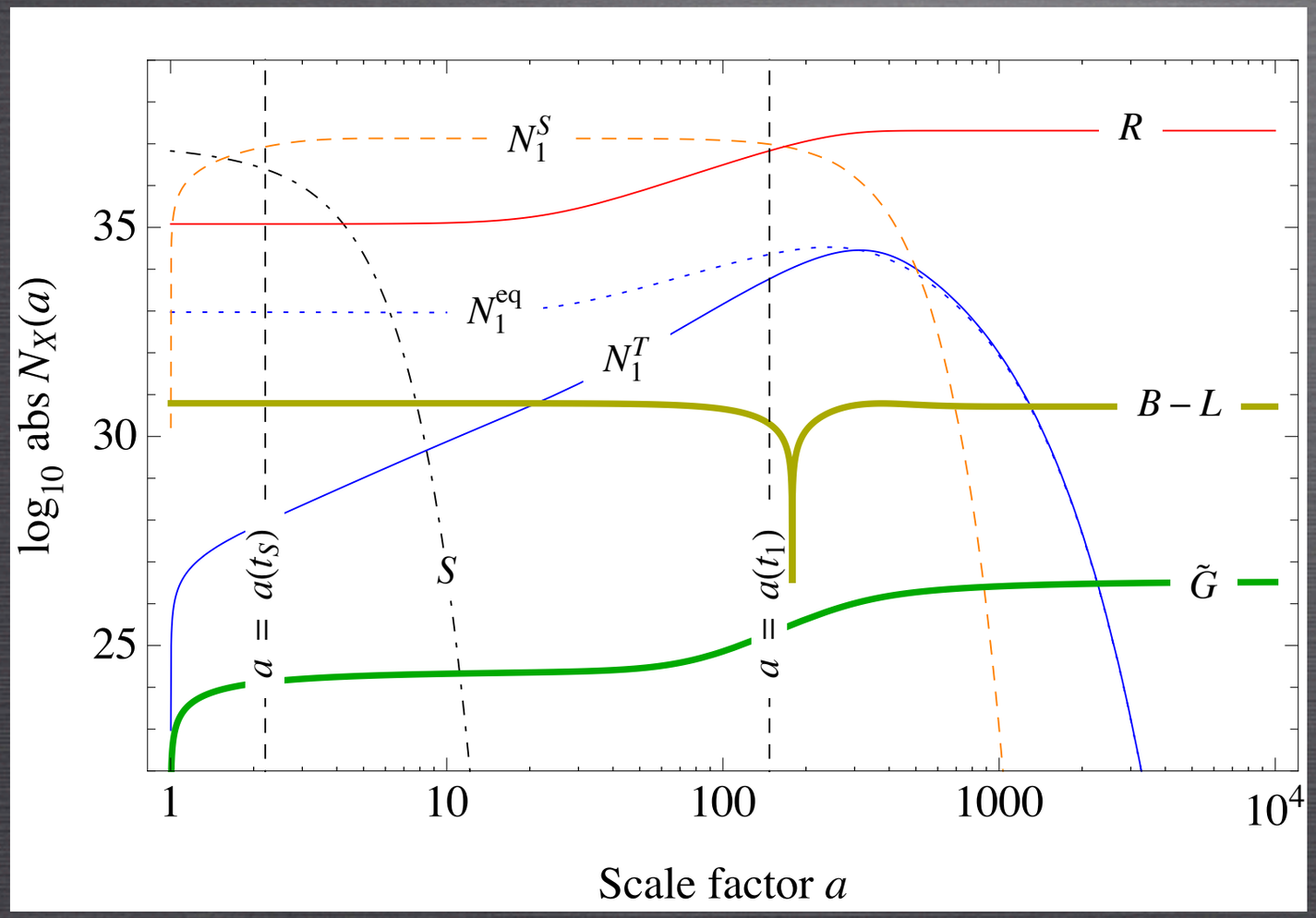
Evolution of the comobile densities $N_i \equiv a^3\, n_i$ with the scale factor a



$$M_1 = 10^{10}\,\text{GeV}$$
$$M_{2,3} = 3 \times 10^{12}\,\text{GeV}$$
$$\tilde{m}_1 = 10^{-3}\,\text{eV}$$
$$\epsilon_1 = 10^{-6}$$
$$\epsilon_{2,3} = -3 \times 10^{-4}$$
$$M_{\tilde{G}} = 100\,\text{GeV}$$
$$M_{\tilde{g}} = 800\,\text{GeV}$$

Cosmological Evolution

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

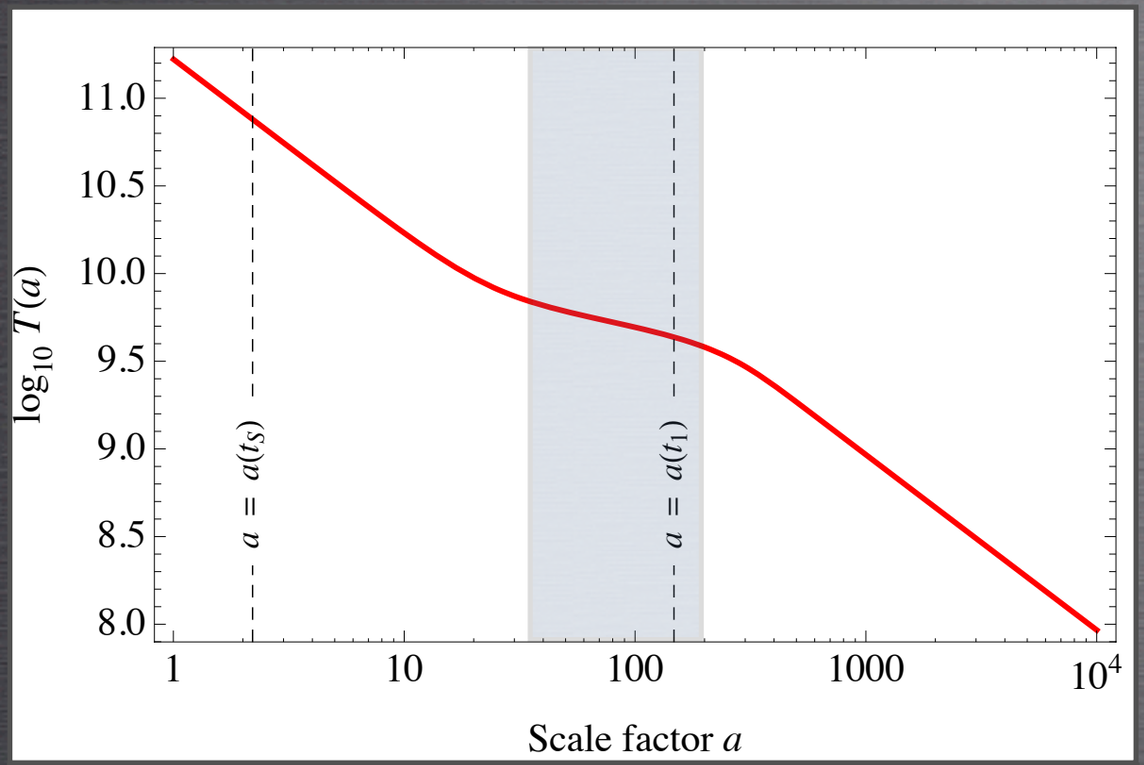


$$M_1 = 10^{10}\,\text{GeV}$$
$$M_{2,3} = 3 \times 10^{12}\,\text{GeV}$$
$$\tilde{m}_1 = 10^{-3}\,\text{eV}$$
$$\epsilon_1 = 10^{-6}$$
$$\epsilon_{2,3} = -3 \times 10^{-4}$$
$$M_{\tilde{G}} = 100\,\text{GeV}$$
$$M_{\tilde{g}} = 800\,\text{GeV}$$

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

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

Cosmological Evolution

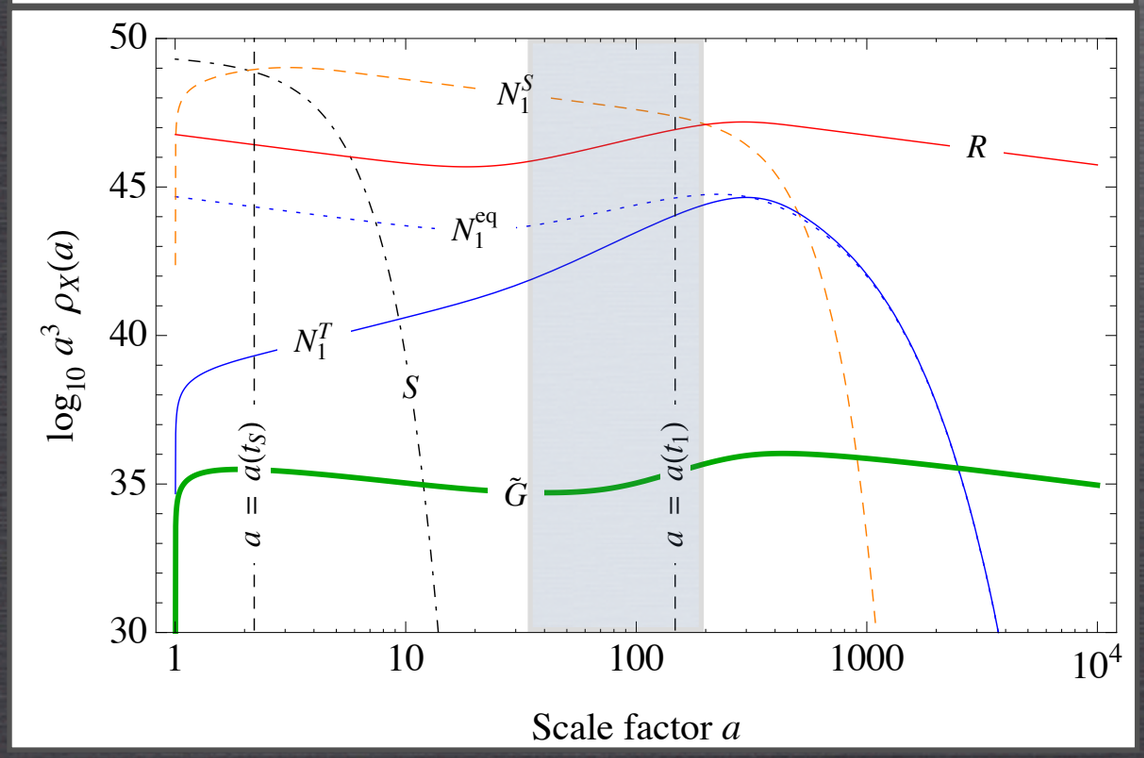


Reheating temperature:

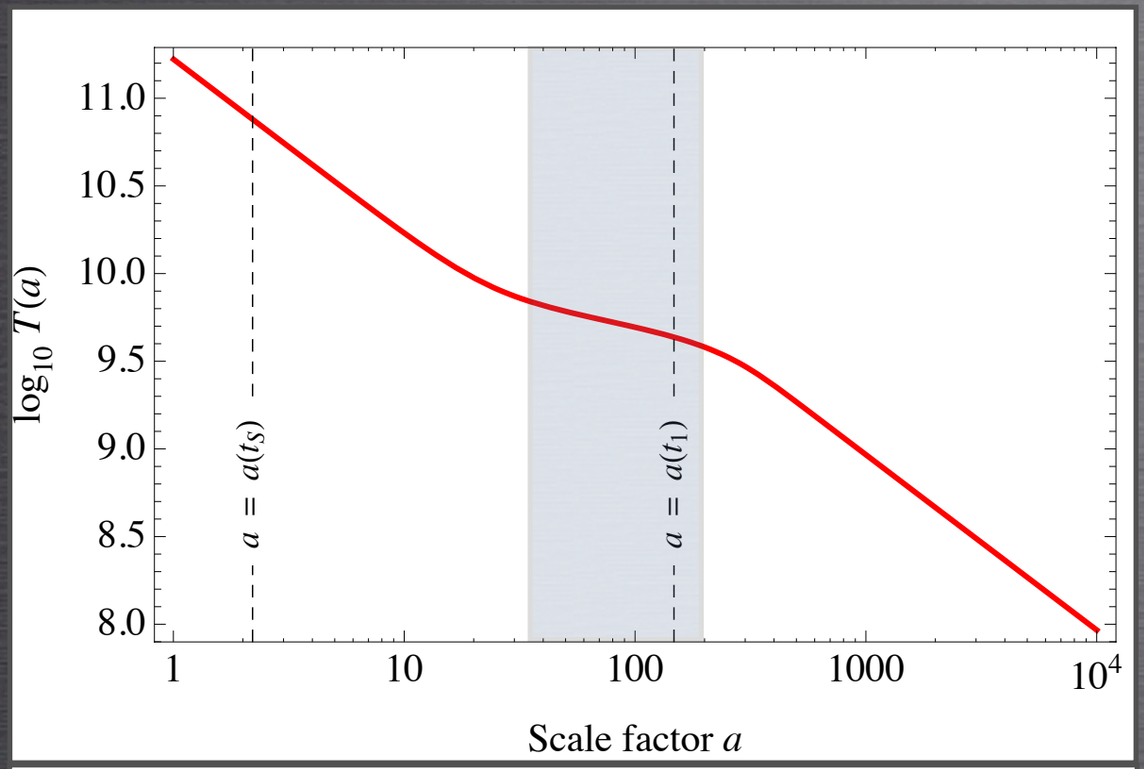
$$T_R \simeq 5 \times 10^9 \mathrm{GeV}$$

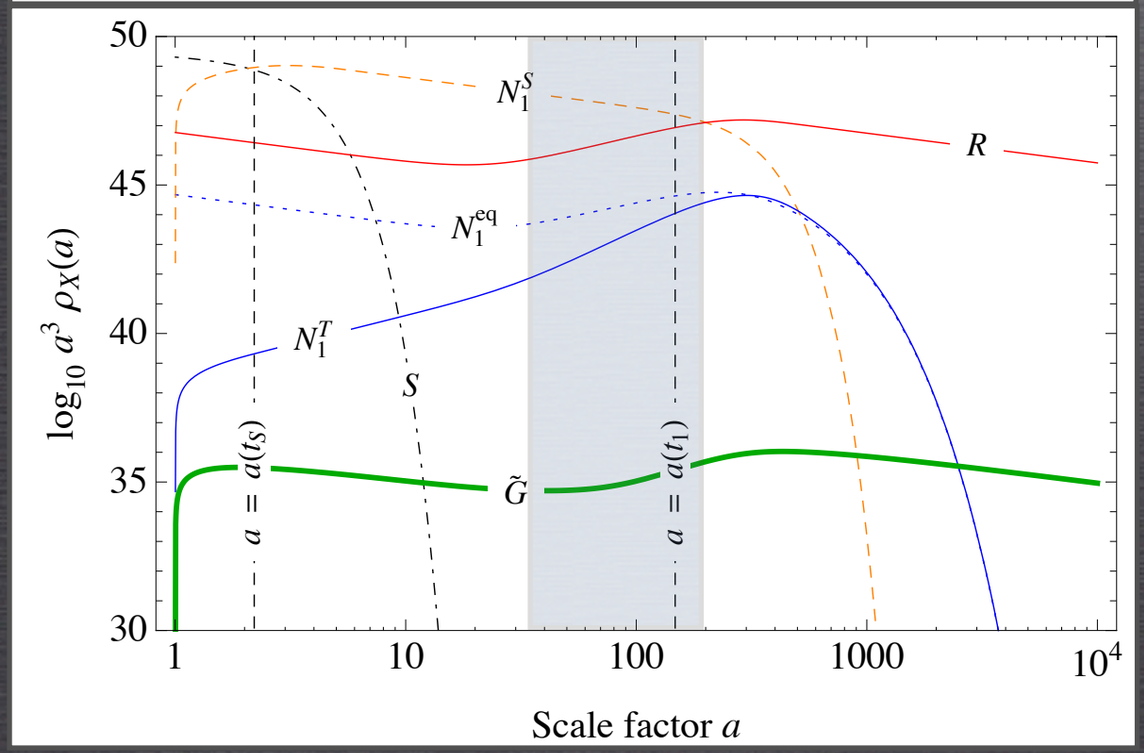
in agreement with the estimate

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



Cosmological Evolution





Reheating temperature:

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

in agreement with the estimate

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

Extreme cases:

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

- thermal leptogenesis :

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

- rapid nonrelativistic N_1 conversion

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

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

Summary

Ingredient: Seesaw extension of the SM

- Heavy Majorana neutrinos N_i
- B-L symmetry breaking field S

Recipe: Reheating of universe through N_1 decays

- Non-thermal N_1 production from S decays after false vacuum decay
- Tachyonic preheating after hybrid inflation

In the end: A common origin of Matter and Dark Matter

- 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

Matter & DM Backup

- Boltzmann equations
- SUSY Dependance
- Baryon Asymmetry
- Reheating Temperature

Boltzmann equations

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

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

$$aH\frac{d}{da}N_{N_1}^T = -\,\Gamma_{N_1}\left(N_{N_1}^T - N_{N_1}^{\rm eq}\right)$$

$$aH\frac{d}{da}N_{B-L} = \;\epsilon_1\Gamma_{N_1}\left(N_{N_1}^T - N_{N_1}^{\rm eq}\right) - \frac{N_{N_1}^{\rm eq}}{2N_L^{\rm eq}}\,\Gamma_{N_1}N_{B-L} + \epsilon_1\,\Gamma_{N_1}^0\,\widetilde{N}_{N_1}^S$$

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

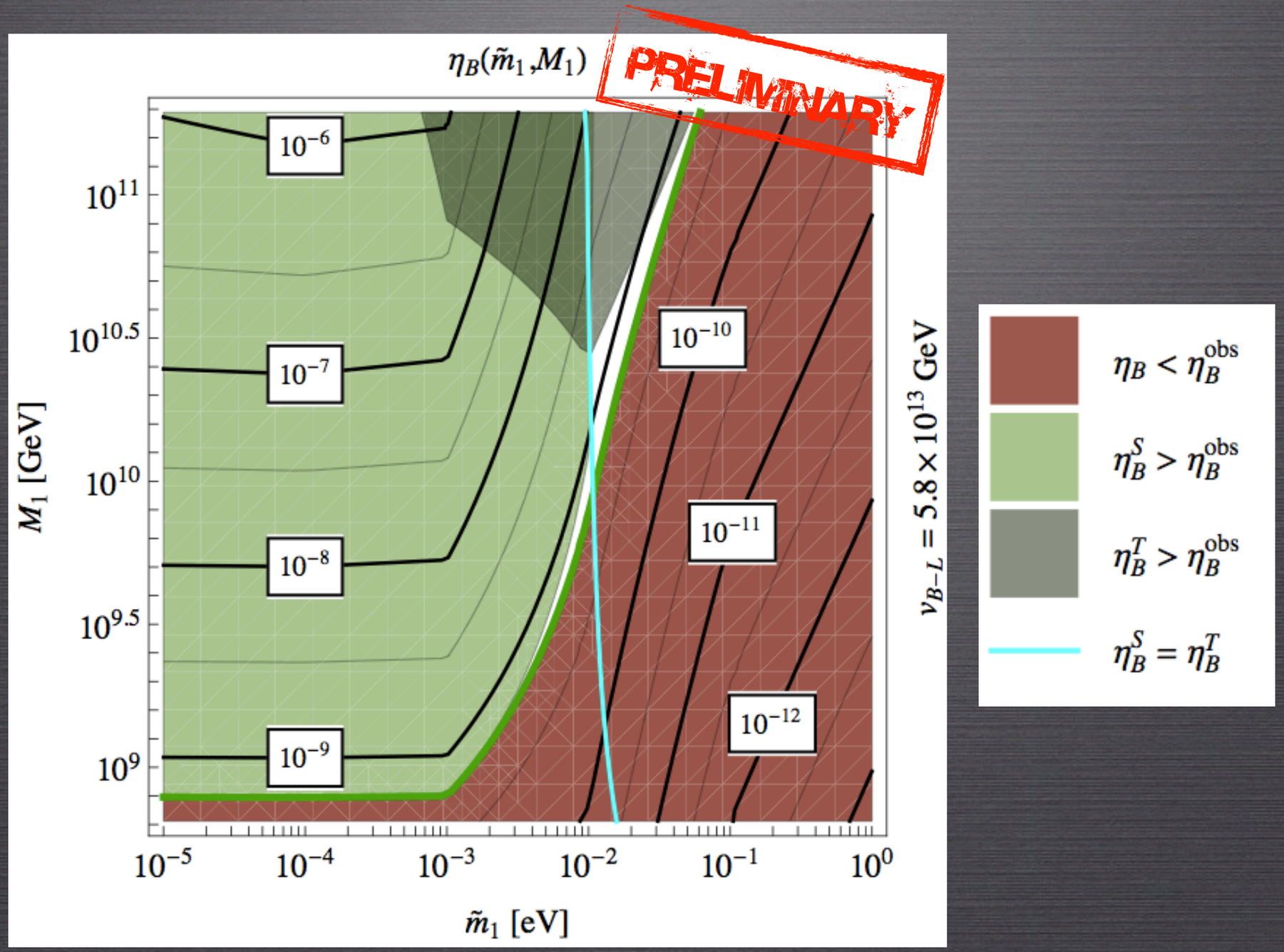
$$0 = \;\frac{d}{dt}\left(\rho_R+\rho_{N_1}^T+\rho_S+\rho_{N_1}^S\right)+3H\left(\rho_R+\rho_{N_1}^T+\rho_S+\rho_{N_1}^S+p_R+p_{N_1}^T+p_{N_1}^S\right)$$

with

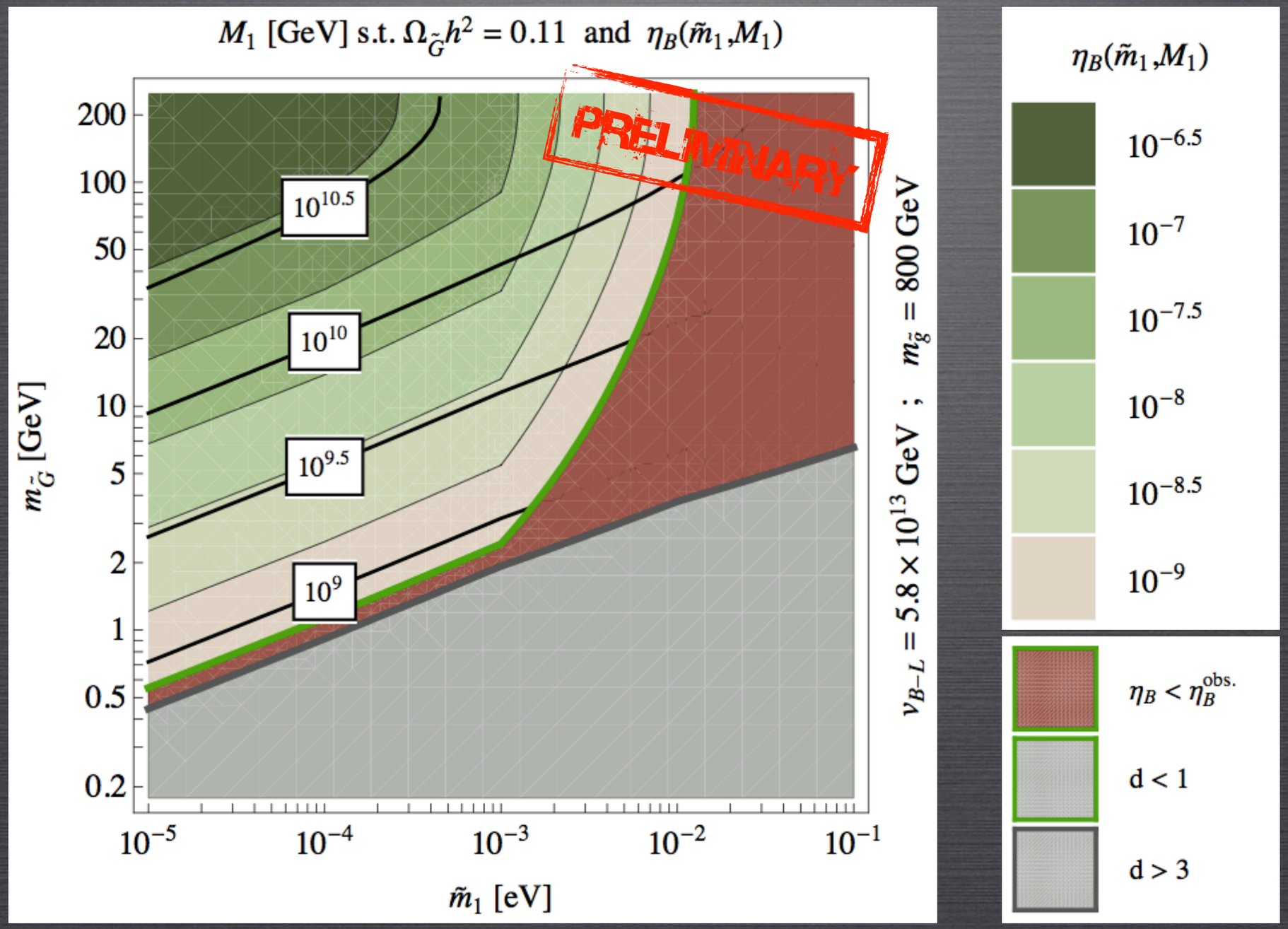
$$N_X(t) = \;a^3\frac{g_X}{(2\pi)^3}\int d^3p\, f_X(t,p)$$

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

Baryon Asymmetry



SUSY Dependance



Reheating Temperature