Leptogenesis in Higgs triplet model

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Introduction

- Non-zero neutrino masses and mixing angles provide a convincing evidence of physics beyond the Standard Model
- See-saw mechanism: a paradigm to understand neutrino masses
- The see-saw scenario involves a high-energy scale where lepton number L is not conserved → leptogenesis through out-of-equilibrium $\not{L}$ decay of heavy particle X in presence of $\not{CP}$ (Saharov conditions)
- sphaleron conversion to Baryon number
- if X is not so heavy: direct measurement of neutrino parameters at accelerators?

Some papers on the subject

- G. D'Ambrosio, T. Hambye, A. Hektor, M. Raidal, A. Rossi, PLB604 (2004) 199
- G.F. Giudice, A. Notari, M. Raidal, A. Riotto, A. Strumia, NPB685(2004)89
- T. Hambye, E. Ma, U. Sarkar, NPB602 (2001) 23
- A. Rossi, PRD66 (2002) 075003
- L. Covi, N. Rius, E.Roulet, F. Vissani, PRD57 (1998) 93
- T. Hambye, M. Raidal and A. Strumia, PLB632(2006)667.
- E.Ma and U. Sarkar, PRL80, (1998) 5716
- T. Hambye and G. Senjanović, PLB582 (2004) 73

S. Scopel. E. J. Chun, PLB636(2006)278

Different types of see-saw

Dimension-5 effective operator: $\frac{\mathcal{K}}{M} LLHH$

with M typical scale of lepton number violation.

- Type I: 3 singlet heavy fermions N:

$$W= \mathbf{Y}_N^{ij} N_i L_j H_2 + \frac{1}{2}\mathbf{M}_N^{ij} N_i N_j$$

$$\frac{\mathcal{K}}{M} = \frac{1}{M_L}\mathbf{Y}_\nu^{ij} = \mathbf{Y}_N^{Tik}\mathbf{M}_N^{-1kl}\mathbf{Y}_N^{lj} \longrightarrow \boxed{\mathbf{m}_\nu^{ij} = \frac{v_2^2}{M_L}\mathbf{Y}_\nu^{ij} = v_2^2\,\mathbf{Y}_N^{Tik}\mathbf{M}_N^{-1kl}\mathbf{Y}_N^{lj}}$$

- Type II: Higgs heavy triplet(s):

	non-SUSY	SUSY	~~SUSY~~
MINIMAL CONTENT compatible to ~~CP~~:	2 scalar triplets or 1 triplet+1 ν_R	4 (triplet+striplet)	2 (triplet+striplet)

Type I + Type II…

Type II see-saw, the simplest (?) case:

SM+1 scalar triplet Δ

1 doublet $H \equiv (H^+, H^0)$

1 triplet $\Delta \equiv (\Delta^{++}, \Delta^+, \Delta^0)$

$$f_{ij}\left[\Delta^0 \nu_i \nu_j + \Delta^+(\nu_i l_j + l_i \nu_j)/\sqrt{2} + \Delta^{++} l_i l_j\right] + \mathrm{h.c.}$$

$$< \Delta^0 > \neq 0$$ ⇒ neutrino mass

$$\begin{aligned} V &= m^2 H^\dagger H + M^2 \Delta^\dagger \Delta \\ &+ \frac{1}{2}\mu_1 \left(H^\dagger H\right)^2 + \frac{1}{2}\mu_1 \left(\Delta^\dagger \Delta\right)^2 + \mu_3 \left(H^\dagger H\right)\left(\Delta^\dagger \Delta\right) \\ &+ \lambda[\Delta_0 H_0 H_0 + \sqrt{2}\Delta_- H^+ H^0 + \Delta_{--} H^+ H^+] + \mathrm{h.c.} \end{aligned}$$

$$<H^0> \;\equiv\; v$$
$$<\Delta^0> \;\equiv\; u$$

minimization conditions:

$$m^2 + \mu_1 v^2 + \mu_3 u^2 + 2\mu u = 0$$
$$u(M^2 + \mu_2 u^2 + \mu_3 v^2) + \lambda v^2 = 0$$

$\lambda \neq 0 \longrightarrow$ lepton number explicitly broken

$$(\sqrt{2}\, Im\ H^0, \sqrt{2}\, Im\ \Delta^0) \begin{pmatrix} -4\lambda u & 2\lambda v \\ 2\lambda v & -\lambda v^2/u \end{pmatrix} \begin{pmatrix} \sqrt{2}\, Im\ H^0 \\ \sqrt{2}\, Im\ \Delta^0 \end{pmatrix}$$

1 massless eigenstate (longitudinal dof of Z boson)

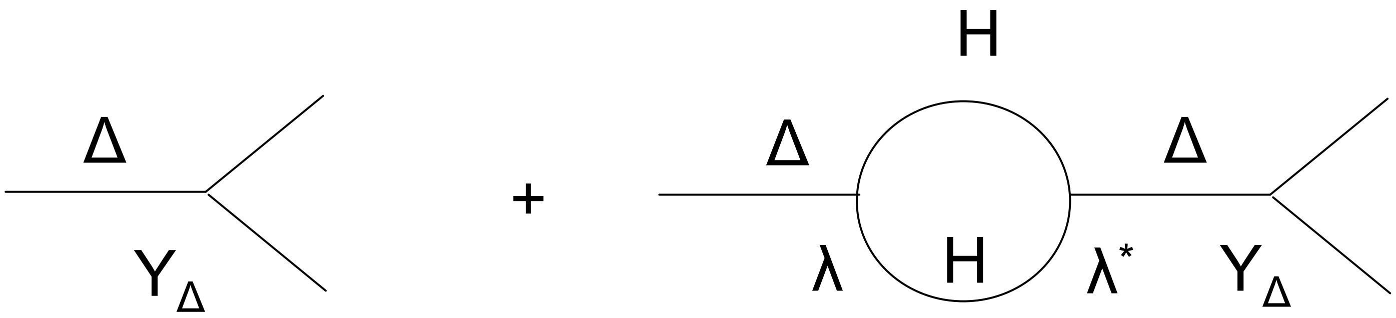
1 massive Majoron: $M^2_{Majoron} = -\frac{\lambda}{u}(v^2 + 4u^2) = M^2 + \mu_3 v^2 \gg M_Z$

$$u \simeq \frac{\lambda v^2}{M^2} \ll v = 174\,\mathrm{GeV}$$

$$\boxed{m_{\nu_{ij}} = Y_{ij}\frac{\lambda v^2}{M^2}}$$

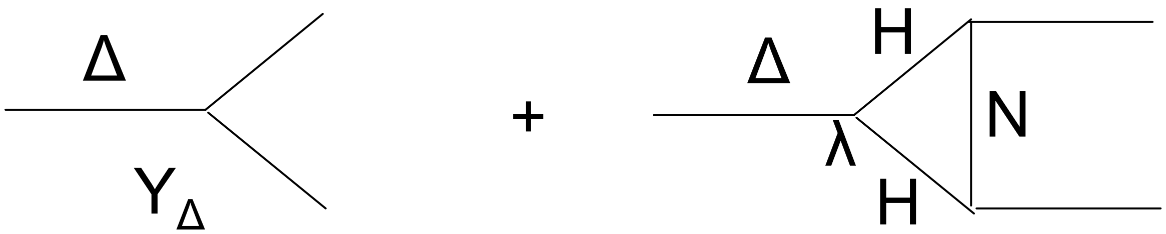
Type II see-saw, the simplest (?) case:

SM+1 scalar triplet Δ



$$\cancel{CP}\ \alpha\ \mathrm{Im}(\ \lambda\,\lambda^*\ Y_\Delta\ Y_\Delta^*\ ) = 0$$

1 triplet is not enough: type I + type II…



T. Hambye and G. Senjanović, PLB582 (2004) 73

…or one additional triplet

Type II see-saw, SUSY

Superpotential:

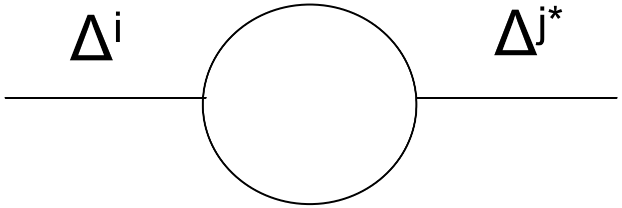
$$W = M\Delta_1\Delta_2 + Y_{ij}L_iL_j\Delta_1 + \lambda_1 H_1H_1\Delta_1 + \lambda_2 H_2H_2\Delta_2 + \mu H_1H_2$$

2 doublets & 2 triplets with opposite hypercharge:

$$H_1 \equiv (H_1^0, H_1^-) \qquad \Delta_1 \equiv (\Delta_1^{++}, \Delta_1^+, \Delta_1^0) \qquad Y=1$$

$$H_2 \equiv (H_2^+, H_2^0) \qquad \Delta_2 \equiv (\Delta_2^0, \Delta_2^-, \Delta_2^{--}) \qquad Y=-1$$

$$\left\{\begin{array}{l} \Delta_1 \to LL, H_2H_2, \tilde{H}_1\tilde{H}_1 \\ \Delta_2 \to \tilde{L}\tilde{L}, \tilde{H}_2\tilde{H}_2, H_1H_1 \end{array}\right. \Rightarrow$$



=0 for i≠j

no $\cancel{CP}$ through Δ_1 - Δ_2 mixing

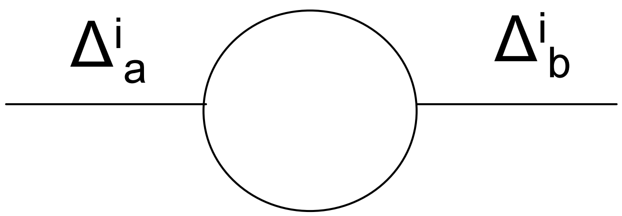
2 triplets are not enough. 2 possibilities…

first possibility (T. Hambye, E. Ma, U. Sarkar, NPB602 (2001) 23):

2 more triplets:

$$W = M_{ab}\Delta_1^a\Delta_2^b + Y_{ij}^a L_i L_j \Delta_1^a \lambda_1^a H_1 H_1 \Delta_1^a + \lambda_2^a H_2 H_2 \Delta_2^a + \mu H_1 H_2$$

$$\left\{\begin{array}{l} \Delta_1^a \to LL, H_2H_2, \tilde{H}_1\tilde{H}_1 \\ \Delta_2^a \to \tilde{L}\tilde{L}, \tilde{H}_2\tilde{H}_2, H_1H_1 \end{array}\right. \Rightarrow$$



a,b=1,2

≠0 for a≠b

second possibility ($\Delta_1 \to \Delta$, $\Delta_2 \to \Delta^c$) (G. D'Ambrosio at al. PLB604 (2004) 199)

$$W = hLL\Delta + \lambda_1 H_1 H_1 \Delta + \lambda_2 H_2 H_2 \Delta^c + M\Delta\Delta^c$$

Include the relevant soft ~~SUSY~~ terms:

$$\begin{aligned} -\mathcal{L}_{soft} &= \{hA_L LL\Delta + \lambda_1 A_1 H_1 H_1 \Delta \\ &+ \lambda_2 A_2 H_2 H_2 \Delta^c + BM\Delta\Delta^c + h.c.\} \\ &+ m_\Delta^2 |\Delta|^2 + m_{\Delta^c}^2 |\Delta^c|^2 \end{aligned}$$

where we assume: $A_L, A_1, A_2 \equiv A_0$ for trilinear terms and $m_\Delta = m_{\Delta^c} \equiv m_0$ for Δ's soft scalar masses

the mass matrix of Δ, Δ^c is diagonalized by:

$$\begin{aligned} \Delta &= \frac{1}{\sqrt{2}}(\Delta_+ + \Delta_-) \\ \bar{\Delta}^c &= \frac{1}{\sqrt{2}}(\Delta_+ - \Delta_-) \end{aligned}$$

$\Delta_\pm$=mass eigenstates with mass:

$$M_{\Delta_\pm} = M_\pm^2 = M^2 + m_0^2 \pm BM$$

2 consequences of SUSY breaking:

CP violation ($\mathrm{Im}(A_0) \neq 0$)

$\Delta - \overline{\Delta^c}$ mixing ($B \neq 0$)

Summarizing:

- Type II: Higgs heavy triplet(s):

	non-SUSY	SUSY	~~SUSY~~
MINIMAL CONTENT:	2 scalar triplets or 1 triplet+1 ν_R	4 (triplet+striplet)	2 (triplet+striplet)

type II see-saw + broken susy:

- reasonable
- simple (economical)
- predictive (falsifiable?)
- non trivial phenomenology

More about this model later

Phenomenological analysis

$$\epsilon_i \equiv \frac{\Gamma_D(T \to \bar{i}\,\bar{i}) - \Gamma_D(\bar{T} \to ii)}{\Gamma_D(\bar{T} \to ii) + \Gamma_D(T \to \bar{i}\,\bar{i})}$$

$$\sum_i \epsilon_i = 0 \quad (\text{unitarity})$$

ε_i=free parameters

scalar triplet langrangian:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + |D_\mu T|^2 - M_T^2 \left|T^a\right|^2 + \frac{1}{2}(\boldsymbol{\lambda}_L^{gg'} L_g^i \tau_{ij}^a \epsilon L_{g'}^j T^a + M_T \lambda_H \, H^i \tau_{ij}^a \epsilon H^j T^{a*} + \mathrm{h.c.})$$

(particle content: T,l,H)

supersymmetric version. introduce 2 chiral superfields T and $\bar{\mathrm{T}}$ with superpotential:

$$W = W_{\mathrm{MSSM}} + M_T T \bar{T} + \frac{1}{2}(\boldsymbol{\lambda}_L^{gg'} L_g L_{g'} T + \lambda_{H_{\mathrm{d}}} H_{\mathrm{d}} H_{\mathrm{d}} T + \lambda_{H_{\mathrm{u}}} H_{\mathrm{u}} H_{\mathrm{u}} \bar{T})$$

(particle content: T,$\bar{\mathrm{T}}$,t,$\bar{\mathrm{t}}$,l,L,$\mathrm{H_u}$,$\mathrm{h_u}$,$\mathrm{H_d}$,$\mathrm{h_d}$)

(upper case=scalars, lower case=leptons)

($\mathrm{H_{u(d)}}$ couples to u(d)-type quarks) in both cases:

$$m_\nu = \lambda_L \lambda_{H_{(u)}} \frac{v_{(u)}^2}{M}$$

$$\Rightarrow \quad K \equiv \frac{(\Gamma_D)_{T=0}}{(H)_{T=M}} \propto \frac{1}{\sqrt{B_L B_{H_{(u)}}}}$$

K<1 → “fast” inverse decay, out of equilibrium decay at early times (M/T<1) , mild or no washout effect

K>1 → fast inverse decay keeps triplets in thermal equilibrium preventing leptogenesis until M/T>1, when their equilibrium density is exponentially suppressed

minimal K if $B_L = B_H$: $m_\nu = 0.05 \rightarrow K \sim 40 >> 1$ need Boltzman eqns.

Inverse decay is NOT the only effect:

- (L-conserving) $\Delta\,\bar{\Delta}$ annihilations to gauge bosons and light particles ((s)leptons,Higgs(inos))are also important

This effect is well known, but may be often neglected, since for T<<M the Δ’s are non relativistic, and annihilations are proportional to the Δ density squared (Fry, Olive, Turner, PRD32(1980)2977).

However, in our case the above argument does not hold. This is due to the fact that, in order to explain neutrino masses, especially for low M, the Yukawa couplings that enter in decays are much smaller than the gauge couplings that enters in annihilations.

Decays vs. annihilations: a back-of-the-envelope estimation

Boltzmann equation for triplet density (z≡M/T) :

$$\boxed{\frac{1}{zK}\frac{dY_\Delta}{dz} = -\gamma_d\left(Y_\Delta - Y_\Delta^{eq}\right) - \gamma_a\left(Y_\Delta^2 - Y_\Delta^{eq\,2}\right) \simeq -\left(\underline{\gamma_d + 2\gamma_a Y_\Delta^{eq}}\right)\left(Y_\Delta - Y_\Delta^{eq}\right)}$$

$$Y_\Delta^{(eq)} \equiv \frac{n_\Delta^{(eq)}}{s}$$ (s=entropy of the Universe)

What matters is wether annihilations can keep Δ's in thermal equilibrium longer than decays →the ratio of the 2 contributions at the freeze-out temperature z_f for inverse decays:

$$z_f K Y_\Delta^{eq}(z_f) \simeq K z_f^{\frac{5}{2}} e^{-z_f} = 1 \longrightarrow$$ z_f≈9.2 for K≈40

$$\Gamma_d \simeq \alpha_x M \longrightarrow \alpha_x \simeq 5K\frac{M}{M_{Plank}}$$

$$\boxed{\epsilon \equiv \frac{<\Gamma_a(z_f)>}{<\Gamma_d(z_f)>} \simeq 2\frac{\alpha^2}{\alpha_x} z_f^{-\frac{3}{2}} e^{-z_f} \simeq 2\frac{\alpha^2}{\alpha_x}\frac{1}{K z_f^4} \simeq 2\left(\frac{10^8\mathrm{GeV}}{M}\right)}$$

So in the Bolzmann approximation, the 2 contributions are proportional to the following functions (z≡M/T) :

- Decay amplitude:

$$\gamma_D = \frac{K_1(z)}{K_2(z)}$$ (→1 for z>>1)

(K$_{1,2}$=modified Bessel functions)

- Annihilation amplitude:

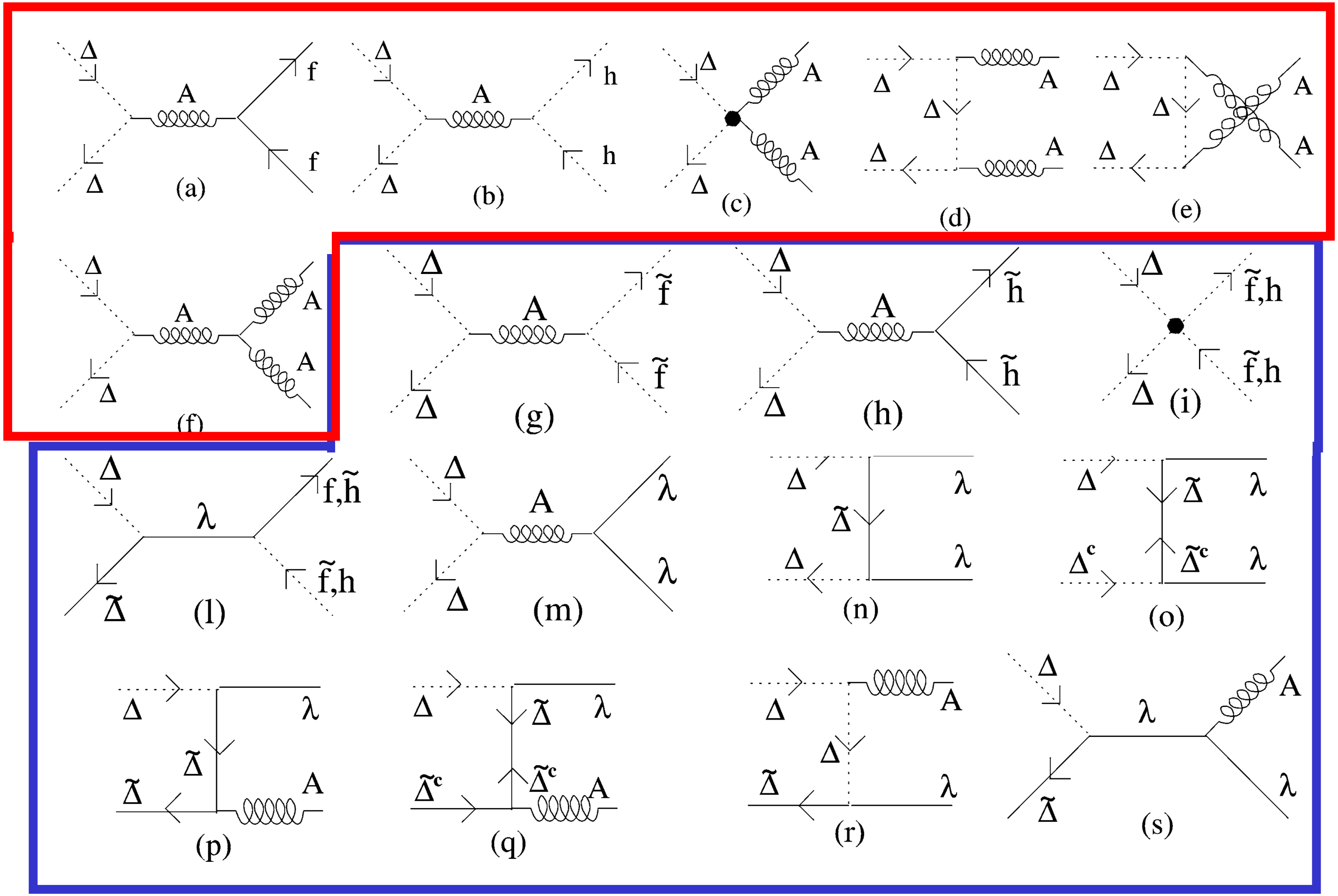
$$\gamma_A = \frac{\alpha_2^2 M}{\pi K H_1} \int_1^{\infty} dt \, \frac{K_1(2zt)}{K_2(z)} \, t^2 \beta(t) \, \sigma(t) \quad , \qquad \beta(t) \equiv \sqrt{1 - t^{-2}}$$

σ(t)=reduced annihilation cross section averaged over initial triplet states and summed over coannihilating particles

$\Delta \, \Delta \rightarrow$ fermions,higgs,gauge bosons

supersymmetric version: $\Delta \, \Delta + \Delta \, \Delta_c + \Delta \, \tilde{\Delta} + \Delta \, \tilde{\Delta}_c \rightarrow$(s)fermions, higgs(inos), gauge bosons,gauginos

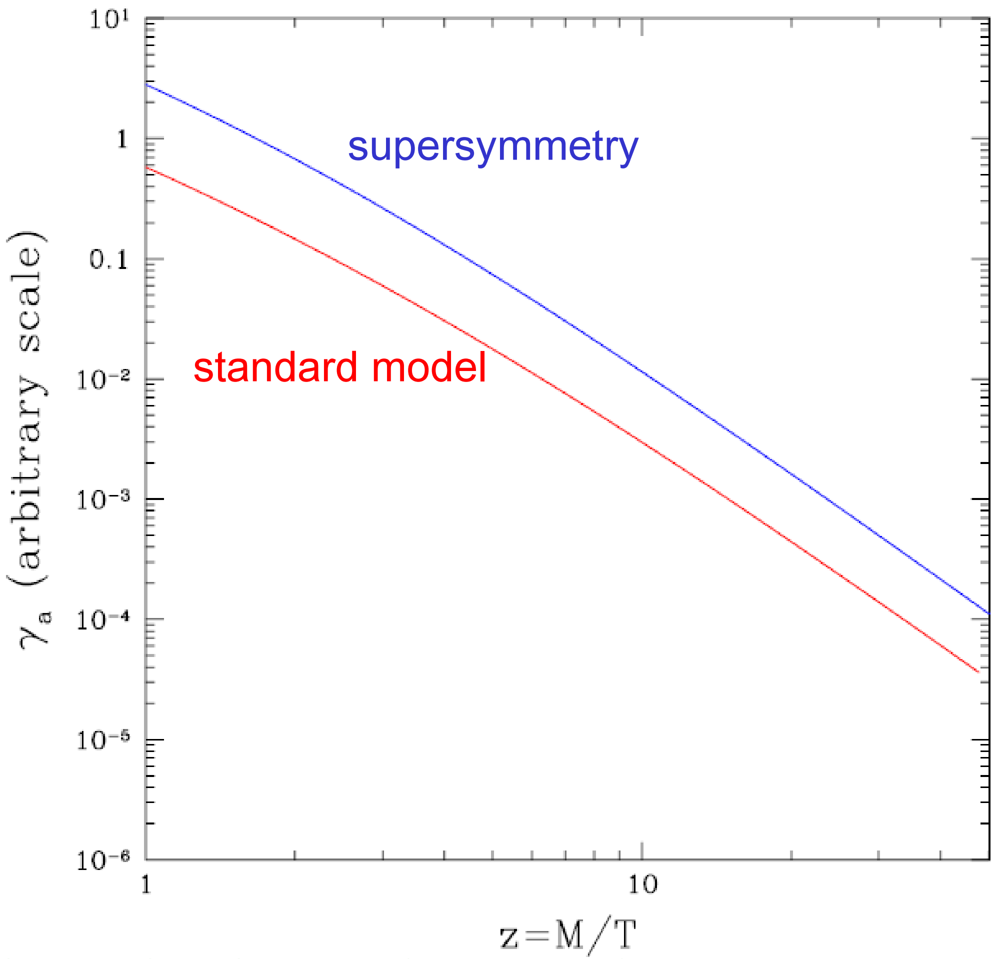
Diagrams contributing to the annihilation cross section:



non susy model

supersymmetry

Annihilation amplitude, arbitrary scale, no thermal masses



low temperature approx (z>>1):

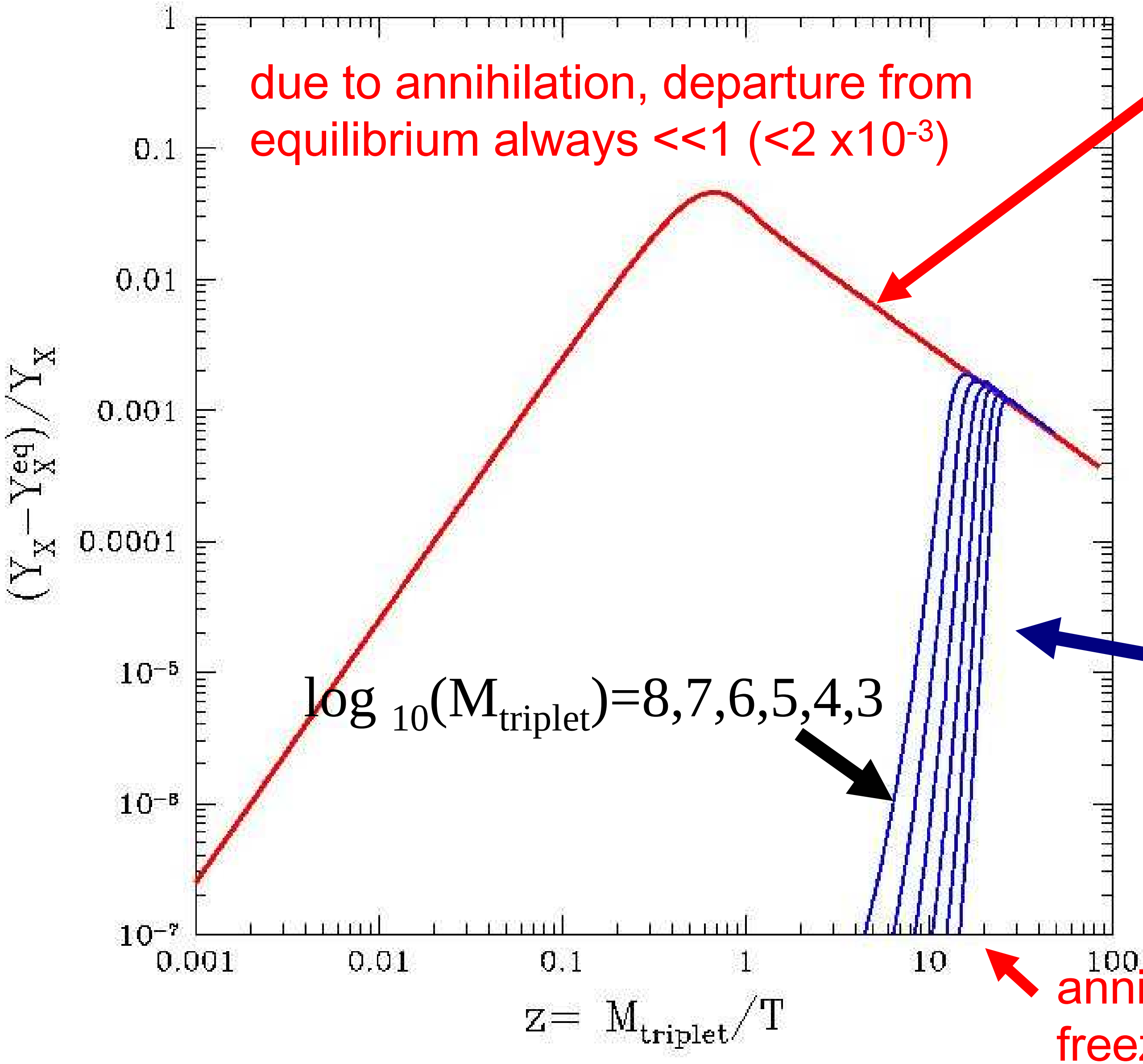
$$\int_1^\infty dt \, \frac{K_1(2zt)}{[zK_2(z)]^2} t^2 \beta(t) \sigma(t) \simeq \frac{1}{2z^3}\left[b_0 + \frac{b_1}{z} + \cdots \right]$$

$$b_0 = 47 + 32 t_w^2 + \frac{49}{2} t_w^4$$ (susy)

$$b_0 = 6 + 8 t_W^2 + 2 t_W^4$$ (non SUSY)

SM→SUSY: ~ factor of 8 increase, bigger than ~2 from naïve expectation (“contact term” for scalars + Δ Δ→gauginos+gauge bosons)

Thermal evolution of Y_Δ: departure of triplet density from equilibrium value (supersymmetric case)



due to annihilation, departure from equilibrium always <<1 (<2 x10^{-3})

Boltzmann approx, no annihilation

$\log_{10}(M_{triplet})$=8,7,6,5,4,3

annihilation included

annihilations freeze out at z≈20

Thermal evolution of Y_Δ: analytical approximation

In the limit $(Y_\Delta - Y_\Delta^{eq})/Y_\Delta \ll 1$ (small departure from equilibrium):

$$Y_\Delta - Y_\Delta^{eq} \simeq \frac{-\frac{dY_\Delta^{eq}}{dz}}{Kz(\gamma_d + 2\gamma_a Y_\Delta^{eq})}$$

Boltzman equations for asymmetries (T=triplet, P_i=light particles):

initial conditions: $T^-(0)=P^-_i(0)=0$, $T^+(0)=P^+_i(0)=2$

$$z \equiv \frac{M}{T}$$

$$\begin{cases} \dfrac{dT^-}{dz} = K z \gamma_d \left[-T^- - T^+_{eq} \left(\sum_i B_i P_i^-\right) \right] \\ \dfrac{dP_i^-}{dz} = 2 \dfrac{g_T}{g_i} K z \gamma_d \left[-B_i T^- - B_i T^+_{eq} P_i^- + \enclose{circle}{\epsilon_i \Delta_T^+ / 2} \right] \end{cases}$$

$$B_i \equiv \left(\frac{\Gamma_D(T \to \bar{i}\,\bar{i})}{\Gamma_D} \right)_{T=0}$$

$$\sum_i B_i = 1$$

$$Y_T^\pm \equiv \frac{n_T \pm \bar{n}_T}{s} = \frac{g_T}{g_*} \frac{45}{4\pi^4} T^\pm \qquad \left(T^+\right)_{eq} \simeq z^2 K_2(z)$$

$$Y_i^\pm \equiv \frac{n_i \pm \bar{n}_i}{s} = \frac{g_i}{g_*} \frac{45}{4\pi^4} P_i^\pm \qquad P_i^+ \simeq \left(P_i^+\right)_{eq} = 2 \quad \left(\frac{m_i}{T} << 1\right)$$

source term proportional to:

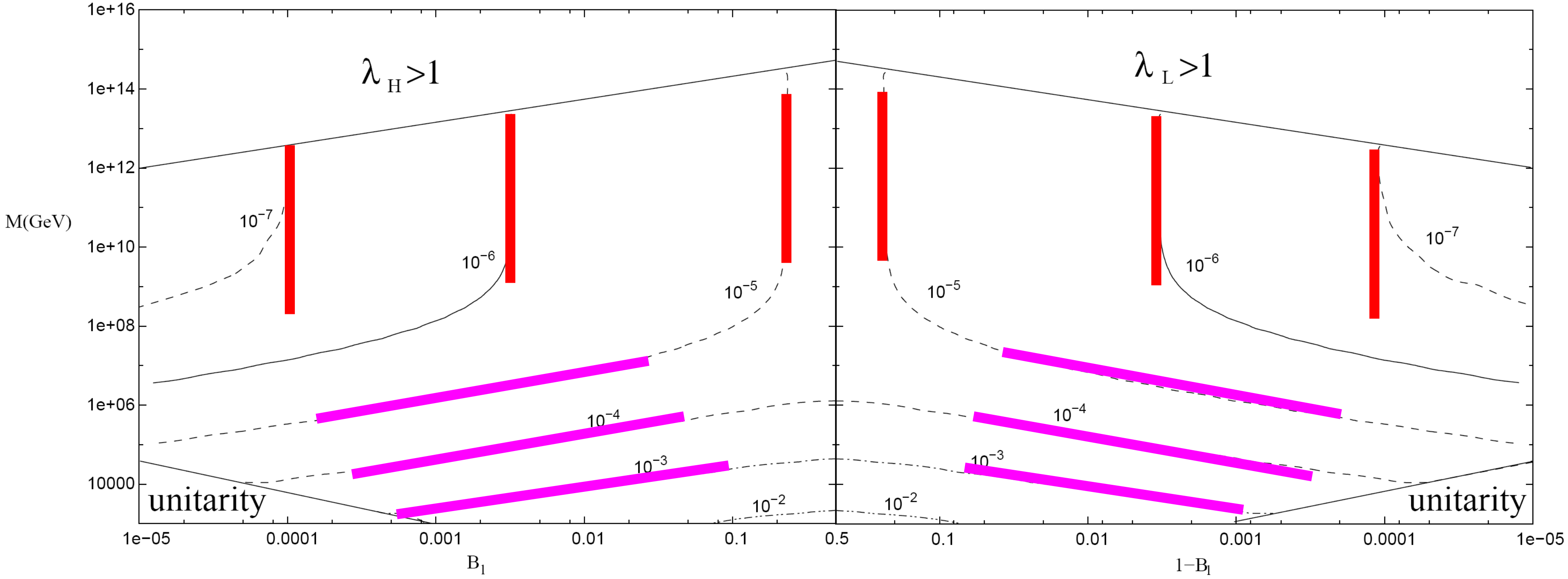
$$\Delta_T^+ \equiv T^+ - \left(T^+\right)_{eq}$$

$$\epsilon_i \equiv \frac{\Gamma_D(T \to \bar{i}\,\bar{i}) - \Gamma_D(\bar{T} \to i i)}{\Gamma_D(\bar{T} \to i i) + \Gamma_D(T \to \bar{i}\,\bar{i})}$$

$$\sum_i \epsilon_i = 0 \quad \text{(unitarity)}$$

$$\boxed{2T^- + \sum_i P_i^- = 0}$$

Contour plots for ε_L needed for successful leptogenesis non supersymmetric case



symmetry $B_l \to 1-B_l$

unitarity conditions: $\varepsilon_L+\varepsilon_H=0$, $|\varepsilon_L|=|\varepsilon_H|<2 \min (B_L,B_H)$

high mass: freeze out determined by inverse decay,strong dependence on B_L,B_H <u>small ε whenever $B_L,B_H<<1$</u>

low mass: freeze out determined by annihilation, mild dependence on B_L,B_H

small ε if B_L, B_H <<1 (i.e. high efficiency) since:

K>>1

but: $B_{L,H} \times K \propto B_{L,H} \times \frac{1}{\sqrt{B_L B_H}} = \sqrt{\frac{B_{L,H}}{B_{H,L}}}$ <1

one of the 2 channels is “slow” and decays out of equilibrium producing an asymmetry with high efficiency

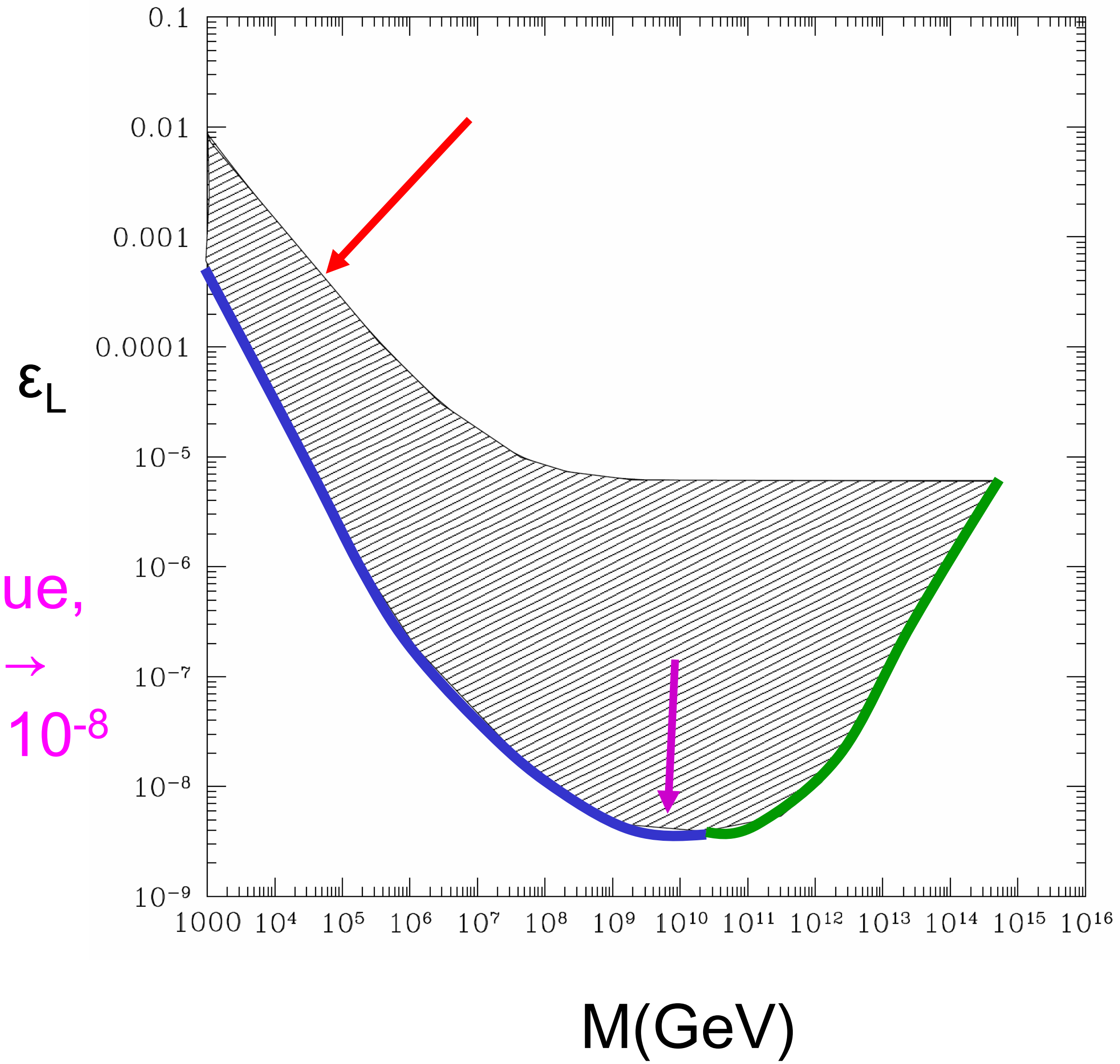
eventually the asymmetry of the other “fast” channel becomes the same as the “slow” one, since:

$2\,T^-(z)+L^-(z)+H^-(z)=0$

$T^-(\infty)=0 \rightarrow |L^-(\infty)|=|H^-(\infty)|$

(asymmetry of “fast” channel is stored in triplet asymmetry T^- which is released at late times when T’s decay)

ε_L needed for successful leptogenesis as a function of triplet mass M (non supersymmetric case)



unitarity constraint

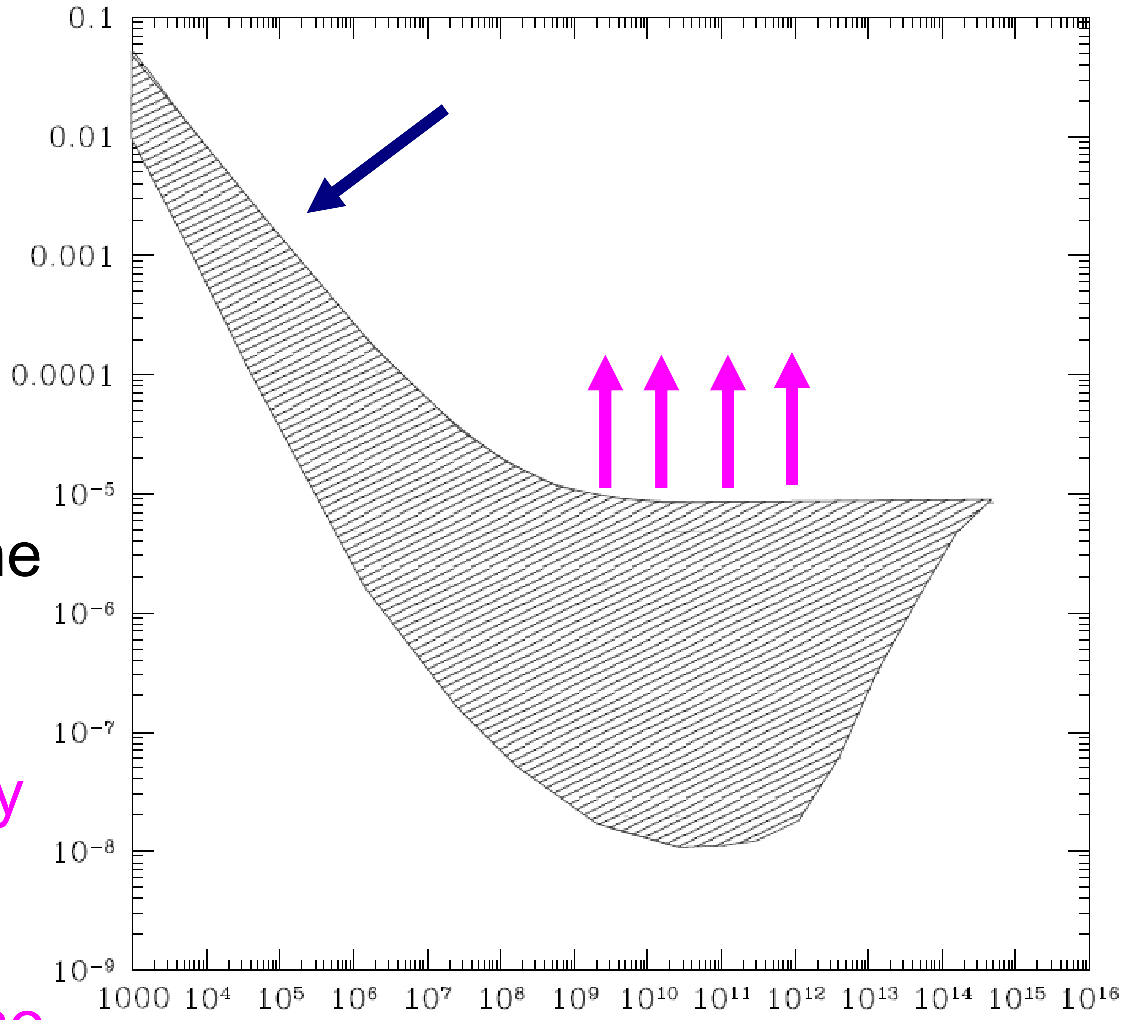
λ_L or $\lambda_H > 1$

efficiency drops due to annihilation

Out-of-equilibrium value, $Y_L = 10^{-10} = T_{eq}\ \varepsilon \sim 1/g_* \ \varepsilon \rightarrow$ $\varepsilon \sim g_* 10^{-10} = 10^2 * 10^{-10} = 10^{-8}$

$g_* \sim 10^2$=relativistic degrees of freedom

ε_L needed for successful leptogenesis as a function of triplet mass M (supersymmetric case, $\lambda_d=\varepsilon_d=0$)



at low mass one order of magnitude higher due to higher annihilation cross section

$\lambda_d=\varepsilon_d\neq 0$? (2 doublets in the game)

main effect: at higher masses lepton asymmetry may vanish due to cancellations among different asymmetries → no upper bound on ε

One specific model: type II see-saw + broken susy (soft leptogenesis)

(S. Scopel. E. J. Chun, PLB636(2006)278)

In terms of the mass eigenstates, the Lagrangian of the model is:

$$\begin{aligned} -\mathcal{L} \;=\; & \frac{1}{\sqrt{2}}\Delta_{\pm}\big[h\,LL + h(A_L \pm M)\,\tilde{L}\tilde{L} \\ & \lambda_1\,\tilde{H}_1\tilde{H}_1 + \lambda_1(A_1 \pm M)\,H_1H_1 \\ & \pm\lambda_2^*\,\bar{\tilde{H}}_2\bar{\tilde{H}}_2 \pm \lambda_2^*(A_2^* \pm M)\,\bar{H}_2\bar{H}_2\big] + h.c. \end{aligned}$$

N.B.: only scalars couple through A’s

The out-of-equilibrium decay $\Delta\to\tilde{L}\tilde{L}$,LL may lead to a lepton asymmetry in the Universe in presence of the CP violation:

$$\epsilon_{L,\tilde{L}} \equiv \frac{\Gamma(\bar{\Delta}_{\pm} \to LL, \tilde{L}\tilde{L}) - \Gamma(\Delta_{\pm} \to \bar{L}\bar{L}, \bar{\tilde{L}}\bar{\tilde{L}})}{\Gamma_{\pm}}$$

Sakarov conditions: $\cancel{L}$ + $\cancel{CP}$ + out-of-equilibrium decay

Wash-out effect

Equilibrium parameter $K \equiv \Gamma_{\pm}/H_1$ with:

$H_1 = 1.66\sqrt{g_*}M_{\tilde{N}}^2/m_{Pl}$ =Hubble parameter at T=M

In this model K>>1, i.e. inverse decays keep Δ's in thermal equilibrium for T<<M → lepton asymmetry suppression

- The minimum value of K is obtained for: $|h| = |\lambda_2| \gg |\lambda_1|$

In particular, for $\lambda_1=0$:

$$K = \frac{\Gamma_{\pm}}{H_1} = K = \enclose{circle}{32}\frac{|h|^2+|\lambda_2|^2}{2|h||\lambda_2|}\left(\frac{|m_\nu|}{0.05\ \mathrm{eV}}\right)$$

→ need to solve Bolzmann equations to evaluate L asymmetry

Boltzman equations for light particles

$$\frac{g_i}{g_\Delta}\frac{1}{zK}\frac{dY_i}{dz} = -2\gamma_i Y_\Delta^- - 4\gamma_i Y_\Delta^{eq} + 2\epsilon_i\gamma_i(Y_\Delta - Y_\Delta^{eq})$$

$$\boxed{|h| = |\lambda_2| \gg |\lambda_1|}$$

i=L,$\tilde{L}$,H_1, $\tilde{H}_1$,$H_{2,}$ $\tilde{H}_2$, g_i,g_Δ=dof

$$\gamma_i \equiv \frac{\Gamma_i^d}{\Gamma_\pm^d} = B_i c_{F,B}$$

,B_i=branching ratio to state i

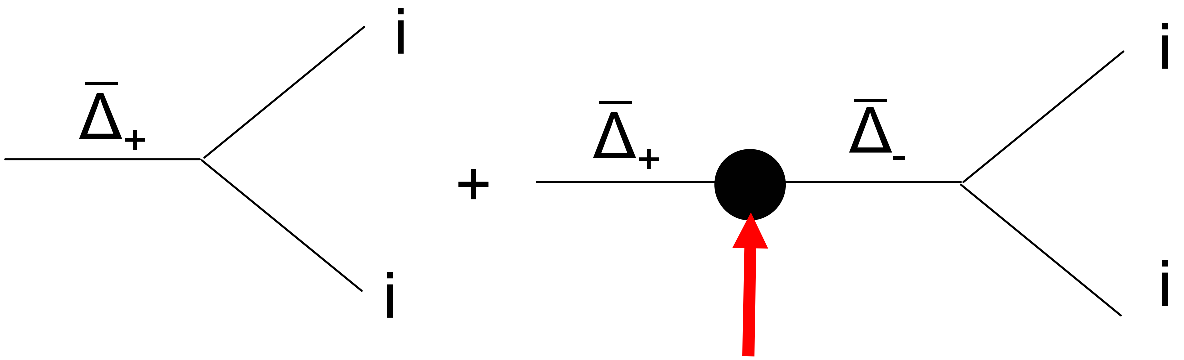
$c_{F,B}$= decay functions for fermions and bosons

$$Y_i \equiv \frac{n_i - n_{\bar{i}}}{s}$$

$$Y_\Delta^- \equiv \frac{n_\Delta - n_{\bar{\Delta}}}{s}$$

$$\epsilon_i \equiv \frac{\Gamma(\bar{\Delta}_\pm \to i) - \Gamma(\Delta_\pm \to \bar{i})}{\Gamma_\pm}$$

=CP violation



Π^{+-}=absorptive part of 2-point function

CP violation given by interference between tree-level and 1-loop contributions

$$\epsilon_i \gamma_i = \epsilon_0 \sum_k \hat{\epsilon}_{ik} c_i R_k$$

$$\Pi^{+-} = \frac{1}{32\pi} \sum_k S_k^{+*} S_k^{-} R_k$$

$$\epsilon_0 = \frac{M^2}{64\pi\Gamma_\pm} \frac{B}{4B^2 + \Gamma_\pm^2}$$

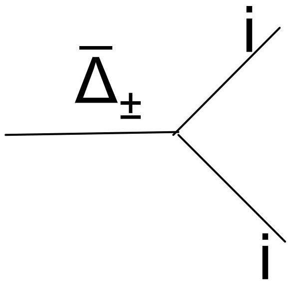
(Γ=2B→ “resonant” effect)

$$\hat{\epsilon}_{ij} \equiv \frac{1}{M^4} Im \left(S_-^{i*} S_+^{i} S_-^{j} S_+^{j*} \right)$$

(note that $\sum_{ij} \hat{\epsilon}_{ij} = 0$ due to unitarity)

$$\epsilon \propto \frac{4|h|^2|\lambda_2|^2}{(|h|^2 + |\lambda_1|^2 + |\lambda_2|^2)^2}$$

$S^i_\pm \equiv \bar{\Delta}_\pm ii$ tree-level coupling



Thermal masses

$$m^2_\Delta(T) = m^2_\Delta + \left(g_2^2 + \frac{1}{2} g_Y^2\right) T^2$$

$$m^2_{\tilde{L}} = 2m^2_L(T) = m^2_{H_1}(T) = \left(\frac{3}{8} g_2^2 + \frac{1}{8} g_Y^2\right) T^2$$

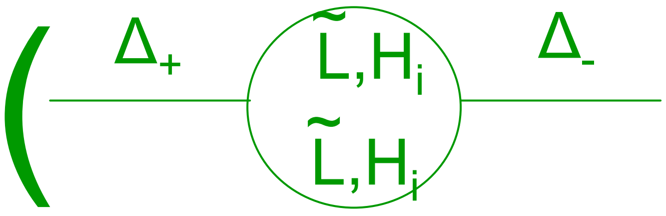
$$m^2_{H_2} = \left(\frac{3}{8} g_2^2 + \frac{1}{8} g_Y^2 + \frac{3}{4} y_t^2\right) T^2$$

$$z = \frac{m_\Delta}{T} \lesssim 0.4 \quad \rightarrow \quad M_\Delta(T) < 2m_{\tilde{L}}(T) = 2m_{H_1}(T) \simeq 2m_{H_2}(T)$$

$$\Gamma(\Delta \rightarrow \tilde{L}\tilde{L}) = 0$$

$\Rightarrow \varepsilon_i = 0$

Im (



) =0

only scalars couple through A's

no CP violation for z<0.4 (however due to annihilation thermal equilibrium lasts longer, no consequence for leptogenesis)

N.B. In the SUSY limit (M>>M_{SUSY}) and in the Boltzman approximation CP violation from decays to fermions and bosons cancel:

$$\epsilon_{L,\tilde{L}} \equiv \frac{\Gamma(\bar{\Delta}_{\pm} \to LL, \tilde{L}\tilde{L}) - \Gamma(\Delta_{\pm} \to \bar{L}\bar{L}, \bar{\tilde{L}}\bar{\tilde{L}})}{\Gamma_{\pm}}$$

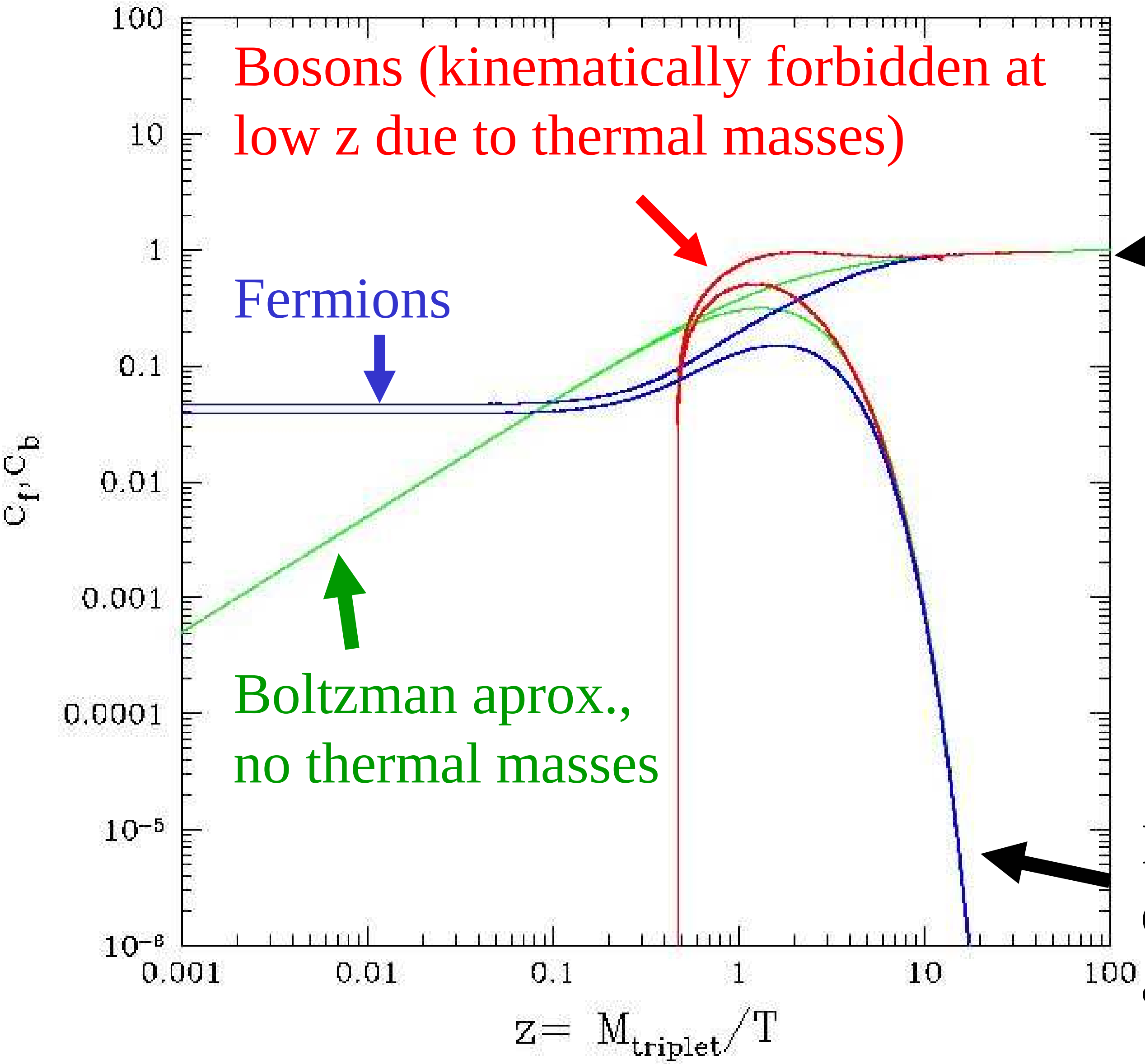
$$\epsilon_L + \epsilon_{\tilde{L}} \longrightarrow 0 \qquad T \to 0$$

A non-vanishing lepton asymmetry arises after taking into account the supersymmetry breaking effect at finite temperature, namely the difference between the bosonic and fermionic statistics given by the Bose-Einstein and Fermi-Dirac distributions

In the limit: $|h| = |\lambda_2| \gg |\lambda_1|$

$$\sum_k \hat{\epsilon}_{ik} c_i R_k \to 4M^3 |h|^2 |\lambda_2|^2 Im(A) \left(\overbrace{R_b(c_B - c_F)}^{\delta_{BF}} + \overbrace{\frac{|A|^2}{M^2} R_B c_B}^{\text{suppressed if } |A| \ll M} \right)$$

Decay and inverse-decay amplitudes



Bosons (kinematically forbidden at low z due to thermal masses)

Fermions

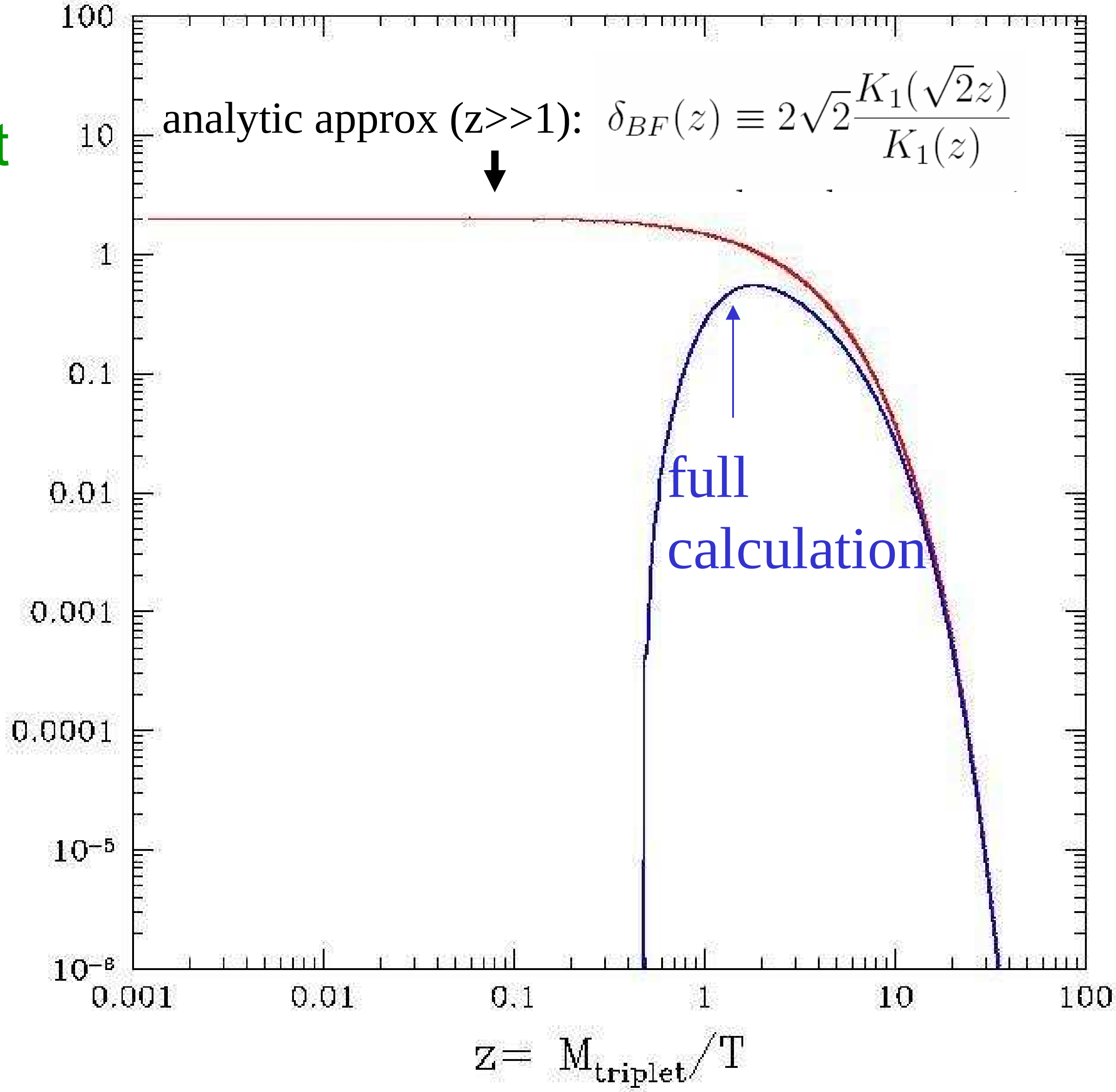
Boltzman aprox., no thermal masses

Decay→1

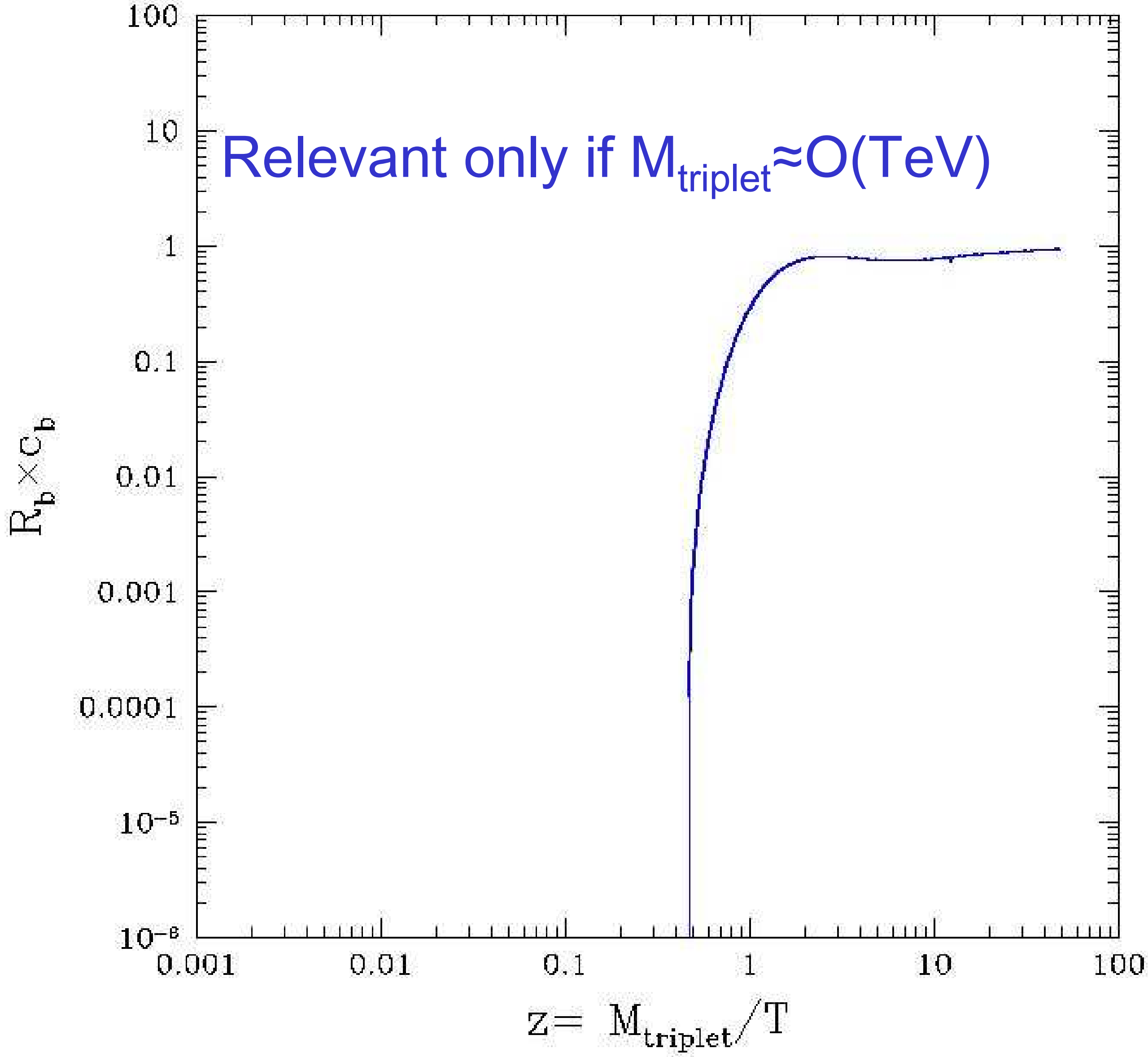
Inverse decay vanishes at low temp.

Bosons minus fermions: the CP violating term

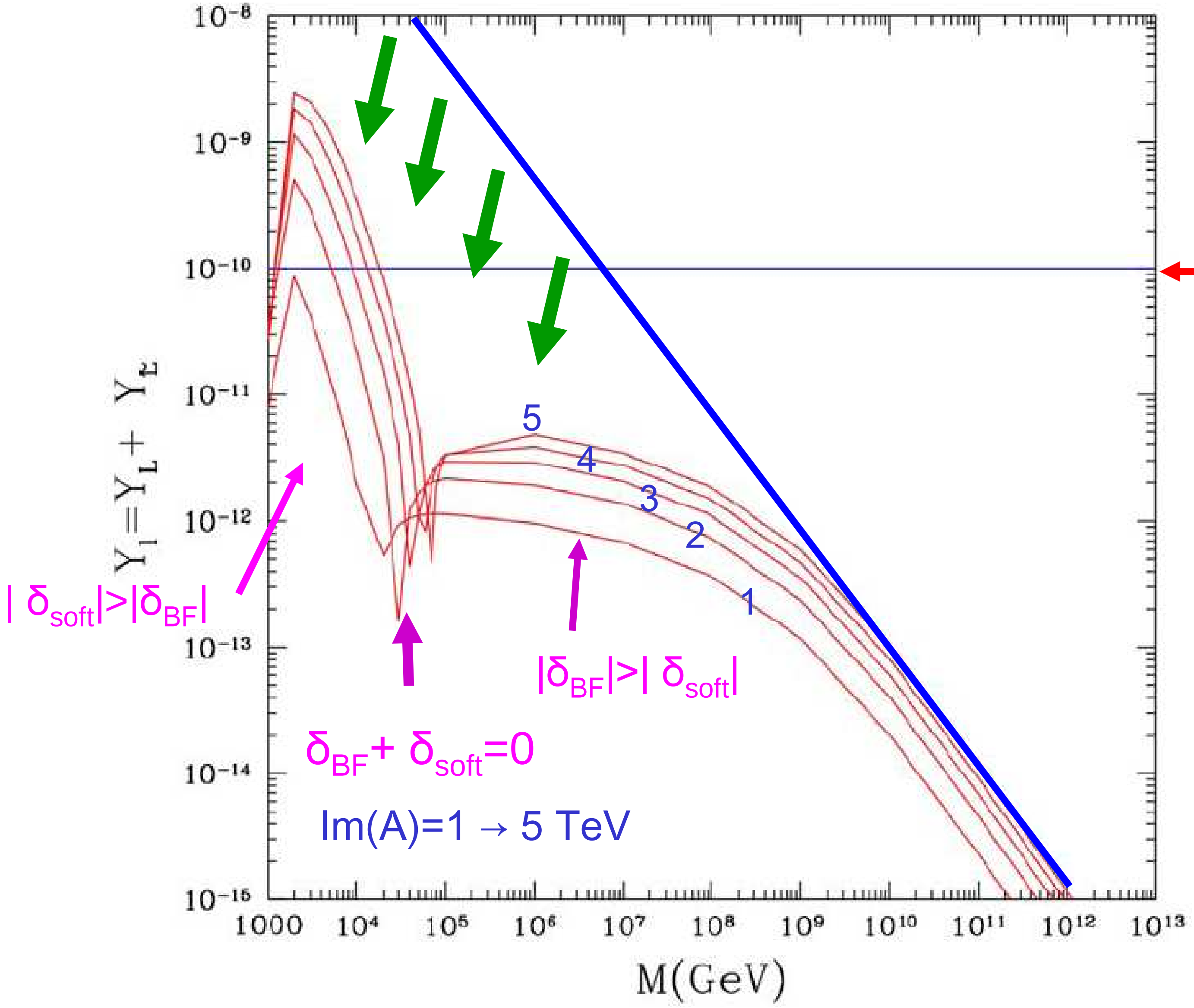
- Finite – temperature effect (0.4<z<30)
- High-temp: CP violating decay to scalars kinematically forbidden due to thermal masses
- Low temp: cancellation between CP asymmetries from fermionic and bosonic final states



CP violation due to SUSY-Breaking term: $R_b C_b$



Lepton asymmetry produced by triplet decay



$|\delta_{soft}| > |\delta_{BF}|$

$\delta_{BF} + \delta_{soft} = 0$

$|\delta_{BF}| > |\delta_{soft}|$

Im(A)=1 → 5 TeV

Required amount
for successful
baryogenesis

only decay
and inverse
decay

suppression due
to annihilation

Comment: Im(A)>M → SUSY BADLY broken

- K>>32 (mild effect since annihilation dominates)
- Striplet decoupling

- Resonant leptogenesis:

$$B = \frac{1}{2}\Gamma$$

$$M_\Delta = 10^8 \text{ GeV} \Rightarrow B = 1 \text{ GeV}$$
$$M_\Delta = 10^3 \text{ GeV} \Rightarrow B = 10^{-10} \text{ GeV}$$

Conclusions

- type-II seesaw with SUSY breaking induced CP violating terms can explain neutrino masses and baryogenesis with 1 pair of Higgs triplets (reasonable ,simple, predictive)

- when $M<10^{10}$ very small values of Yukawa couplings, CP-conserving $\bar{\Delta}$- Δ annihilations through electro-weak couplings dominate over decays for $z<10$-20

- →strong suppression of lepton asymmetry unless $M_{triplet}O(TeV)$

- detectable at LHC? (e.g. production and decay of $\Delta^{\pm\pm}$)