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# Leptogenesis from a Phase Transition in a Dynamical Vacuum

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Based on :

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# Introduction

- Our universe is matter dominated universe.
  - This asymmetry is defined as :

$$\eta_B = \frac{n_B - n_{\bar{B}}}{s} \quad \text{or} \quad \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

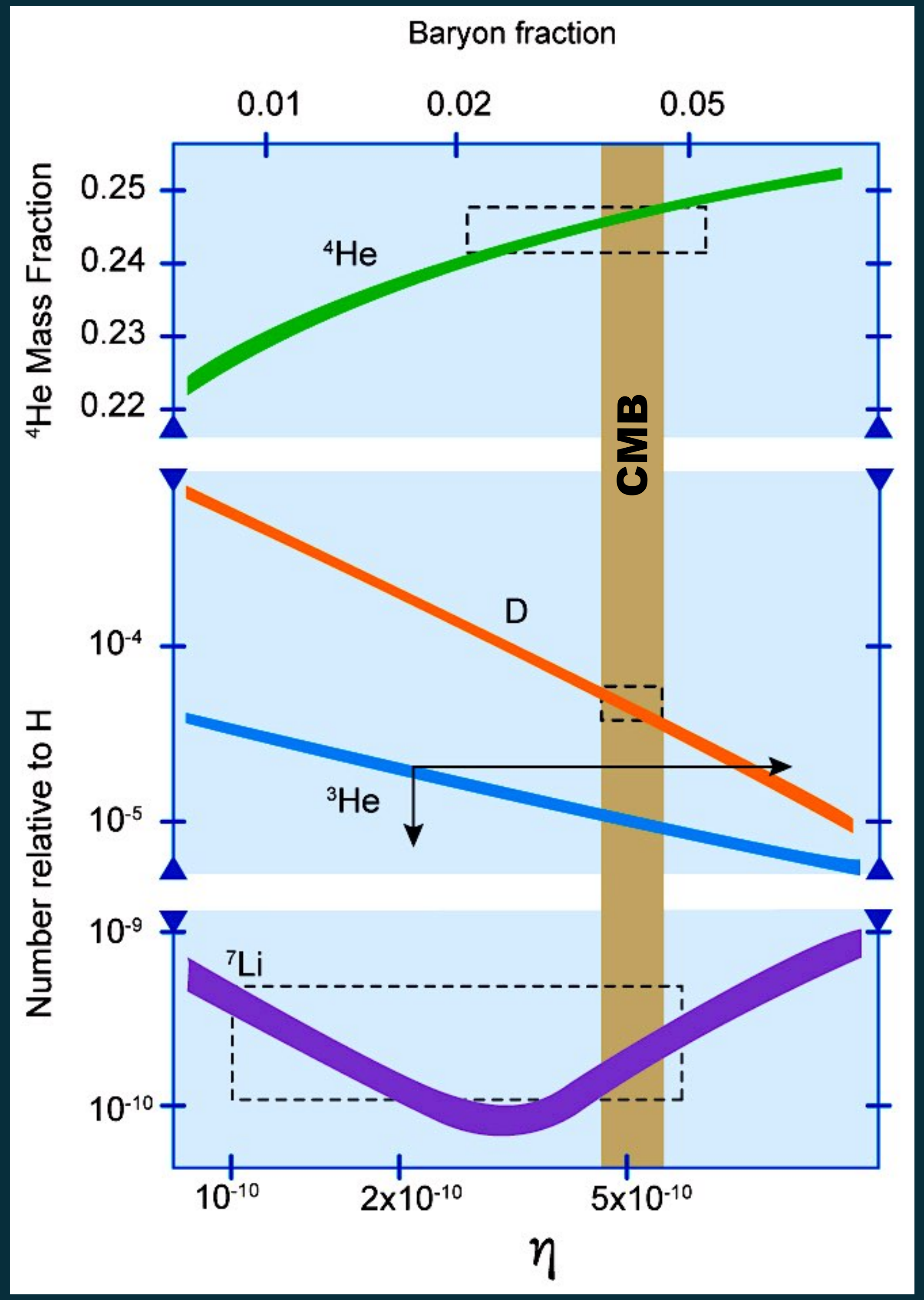



Photo credits: Libretexts Physics

- Measurement of $\eta$ from deuterium abundance ( D/H ) :
  $\eta = (6.28 \pm 0.35) \times 10^{-10}$

- From WMAP data :
  $\eta = (6.14 \pm 0.25) \times 10^{-10}$

**Need dynamical asymmetry generation**

Sakharov's Conditions:

- B violation → Sphaleron process — B+L violating & B-L conserving
- C & CP violation → CKM matrix element — ~~CP~~ amount is not sufficient — Need BSM sector
- Non-equilibrium

## Motivation

One of promising mechanism is Thermal Leptogenesis.

Type-I seesaw Lagrangian $-\mathscr{L}_{\rm I} = \bar{\ell}_{L_\alpha} (Y_\nu)_{\alpha i} \tilde{H} N_i + \frac{1}{2} \overline{N_i^c} M_i N_i + h.c.$ → Solves smallness of neutrino mass problem

$\not{CP}$ & Lepton number violating decay: $N_i \to \bar{\ell}_{L_\alpha} + H$ → B-L asymmetry → Sphaleron Process → Baryon asymmetry

To satisfy the observed baryon asymmetry ($\mathscr{O}(10^{-10})$) → $M_1 > 10^9$ GeV ( Davidson-Ibarra bound ) [Phys. Lett. B 535, 25 (2002)]

**To enhance the detection possibility, RHN mass should be lowered**

A possible way out is Resonant Leptogenesis → RHN mass can be lowered at TeV scale while satisfying the observed correct baryon asymmetry

↓ But

For, $M_1 < T_{EW}$ ( 100 GeV ) creates a problem → Sphaleron processess decouple below $T_{EW}$ → B-L asymmetry can not be converted to Baryon asymmetry through Sphaleron

What is the way out now ?

# Leptogenesis using a dynamical vacuum

RHN mass can be generated through the coupling : $\frac{1}{2}\alpha_i \phi \overline{N_i^c} N_i$

→ $U(1)_{B-L}$ symmetric term

→ $\phi$ is a BSM singlet scalar

A $U(1)_{B-L}$ symmetry breaking phase transition occurs at $T_*$ ⟶ $\phi$ acquires a *vev* ⟶ RHNs become massive

We construct a toy model of the potential so that the *vev* of $\phi$ ( $v_\phi$ ) evolves dynamically over a period of time with temperature and settles down to a constant value at zero temperature.

The *vev* structure of the $\phi$ field can be parametrised as:

$$v_\phi(T) \simeq \begin{cases} 0 & ; \quad T > T_* \\ AT^2 & ; \quad T_c < T \leq T_* \\ AT^2 + B\, v^2(T) & ; \quad T \leq T_c \end{cases}$$

&

Higgs *vev*: $v(T) = \sqrt{(\mu^2 - c_h T^2)/\lambda}$

Due to an effective $\phi H^\dagger H$ coupling, the term $Bv^2(T)$ is activated below $T_c$ ( EWSB temperature ) which helps to settle down $v_\phi$ to a constant value at zero temperature

# Toy model of Potential & Phase Transition details

The Tree-level of potential :

$$V_0(H,\phi,S,\eta) \supset -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + m_\phi^2 |\phi|^2 + (A_1\,\phi\,S\,H^\dagger H + A_2\,\phi\,S\,\eta^2 + \text{ h.c.})$$

Here, the singlet scalar field $\phi$ and $S$ have opposite $U(1)_{B-L}$ charge.

The singlet scalar field $\eta$ has no $U(1)_{B-L}$ charge.

The Finite temperature one-loop potential :

$$V_T(h,\phi,S,\eta;T) \supset \frac{T^4}{2\pi^2} J_B\left(\frac{m_h^2(h,\phi,S,T)}{T^2}\right) + \frac{3T^4}{2\pi^2} J_B\left(\frac{m_\chi^2(h,\phi,S,T)}{T^2}\right) + \sum_i g_i \frac{T^4}{2\pi^2} J_{B,F}\left(\frac{m_i^2(h,T)}{T^2}\right) + \frac{T^4}{2\pi^2} J_B\left(\frac{m_\eta^2(\phi,S,T)}{T^2}\right)$$

Where $J_{B,F}(z^2) = \int_0^\infty dx\, x^2 \ln[1 \mp exp(-\sqrt{x^2+z^2})$ is the thermal function for bosons and fermions.

$m_i$ $(g_i)$ denotes the field-dependent masses ( degrees of freedom ) for particles $i = [W_{T,L},\ Z_{T,L},\ A_L;\ \ t]$

In our setup, the $S$ field obtains a $vev$ at temperature $T_*$ so as to express as:

$$\langle S \rangle = v_s = \begin{cases} 0 & \text{for} \quad T > T_* \\ v_1 & \text{for} \quad T \le T_* \end{cases}$$

**While the $\eta$ field does not get $vev$ .**

The Higgs $vev$ structure is : $$\langle h \rangle \equiv v(T) = \begin{cases} 0 & \text{for} \quad T > T_c \\ \sqrt{\dfrac{\mu^2 - c_h T^2}{\lambda}} & \text{for} \quad T \le T_c \end{cases}$$

where $$c_h = \left( \frac{\lambda}{2} + \frac{3}{16} g_{\rm w}^2 + \frac{1}{16} g_{\rm y}^2 + \frac{y_t^2}{4} \right)$$

By suitable choice of parameters $A_1$ and $v_s$ , we can make $|A_1| v_\phi(T)\, v_s \ll \mu^2$ so as the Higgs vacuum remains unaffected.

The $vev$ structure of the $\phi$ field can be written as :

$$|\langle \phi \rangle| \equiv v_\phi(T)$$

$$= -\frac{v_s}{m_\phi^2} \left[ \frac{A_1 T^2}{2\pi^2} \left\{ J_B' \left( \frac{m_h^2(h,\phi,S,T)}{T^2} \right) + 3 J_B' \left( \frac{m_\chi^2(h,\phi,S,T)}{T^2} \right) \right\} + \frac{A_2 T^2}{\pi^2} J_B' \left( \frac{m_\eta^2(\phi,S,T)}{T^2} \right) + \frac{A_1}{2} v^2(T) \right]$$

$$= A T^2 + B\, v^2(T)$$

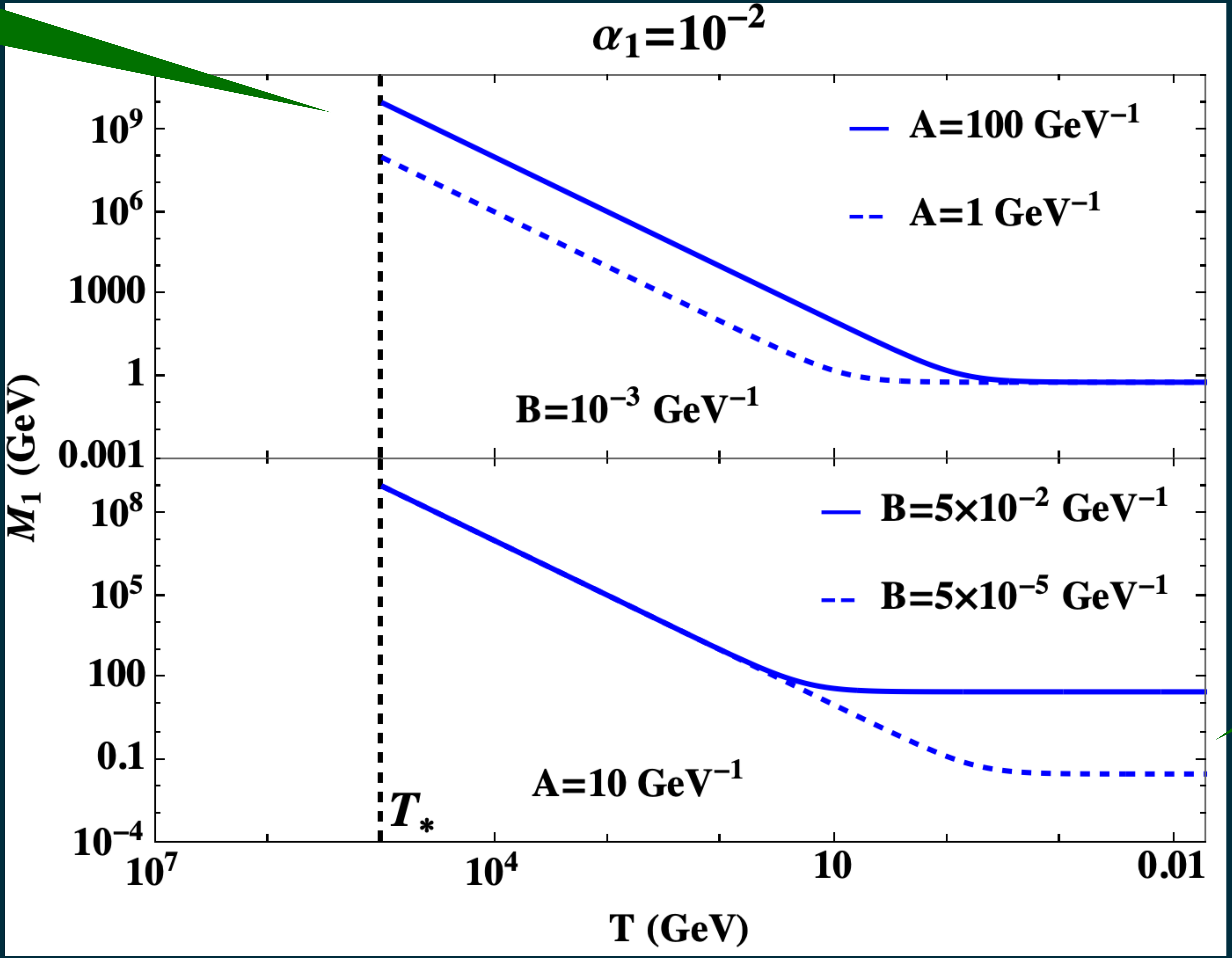
$$A = -\frac{v_s}{m_\phi^2} \left[ \frac{A_1}{2\pi^2} \left\{ J_B' \left( \frac{m_h^2(h,\phi,S,T)}{T^2} \right) + 3 J_B' \left( \frac{m_\chi^2(h,\phi,S,T)}{T^2} \right) \right\} + \frac{A_2}{\pi^2} J_B' \left( \frac{m_\eta^2(\phi,S,T)}{T^2} \right) \right]; \qquad B = -\frac{A_1 v_s}{2 m_\phi^2}$$

RHN mass evolves dynamically with temperature and can be written as :

$$M_i(T) = \alpha_i v_\phi(T) = \begin{cases} 0 & ; \quad T > T_* \\ \alpha_i A T^2 & ; \quad T_c < T \leq T_* \\ \alpha_i (A T^2 + B v^2(T)) & ; \quad T \leq T_c \end{cases}$$

$A$, $B$ and $T_*$ are three independent parameters

At $T_*$ , RHN mass depends on the parameter $A$



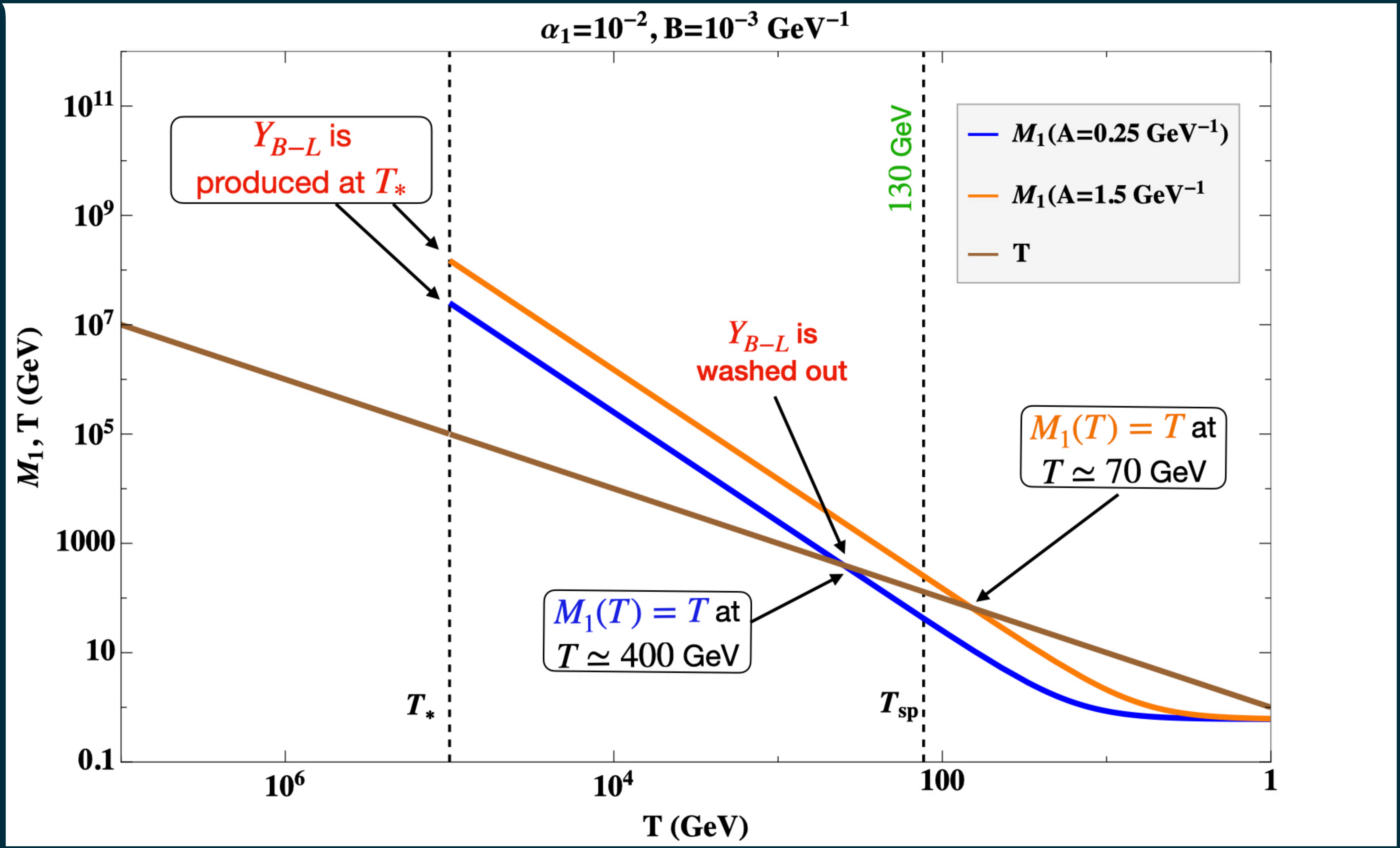

At zero temperature , RHN mass depends on the parameter $B$

# Case I: Leptogenesis with two hierarchical RHNs

Temperature decreases

- RHNs possess Relativistic Equilibrium number density $n_{N_i}^{eq}$
- RHNs are massless
- $U(1)_{B-L}$ symmetry breaks → $T_*$
- $\phi$ acquires temperature dependent $vev$, $v_\phi(T)$
- RHNs become suddenly massive $M_i(T)$
- If $M_i(T_*) > T_*$
- RHNs decay to SM leptons and Higgs doublets
- Electroweak symmetry breaks → $T_c$

Depending on $A$ values, the $Y_{B-L}$ is completely washed out, resulting zero baryon asymmetry




$$M_i(T_{sp}) = \alpha_i A_{min} T_{sp}^2 = T_{sp}$$ → We get the minimum value of $A$ parameter

RHNs immediately decay to the SM leptons and Higgs contributing to $\varepsilon_l^i$

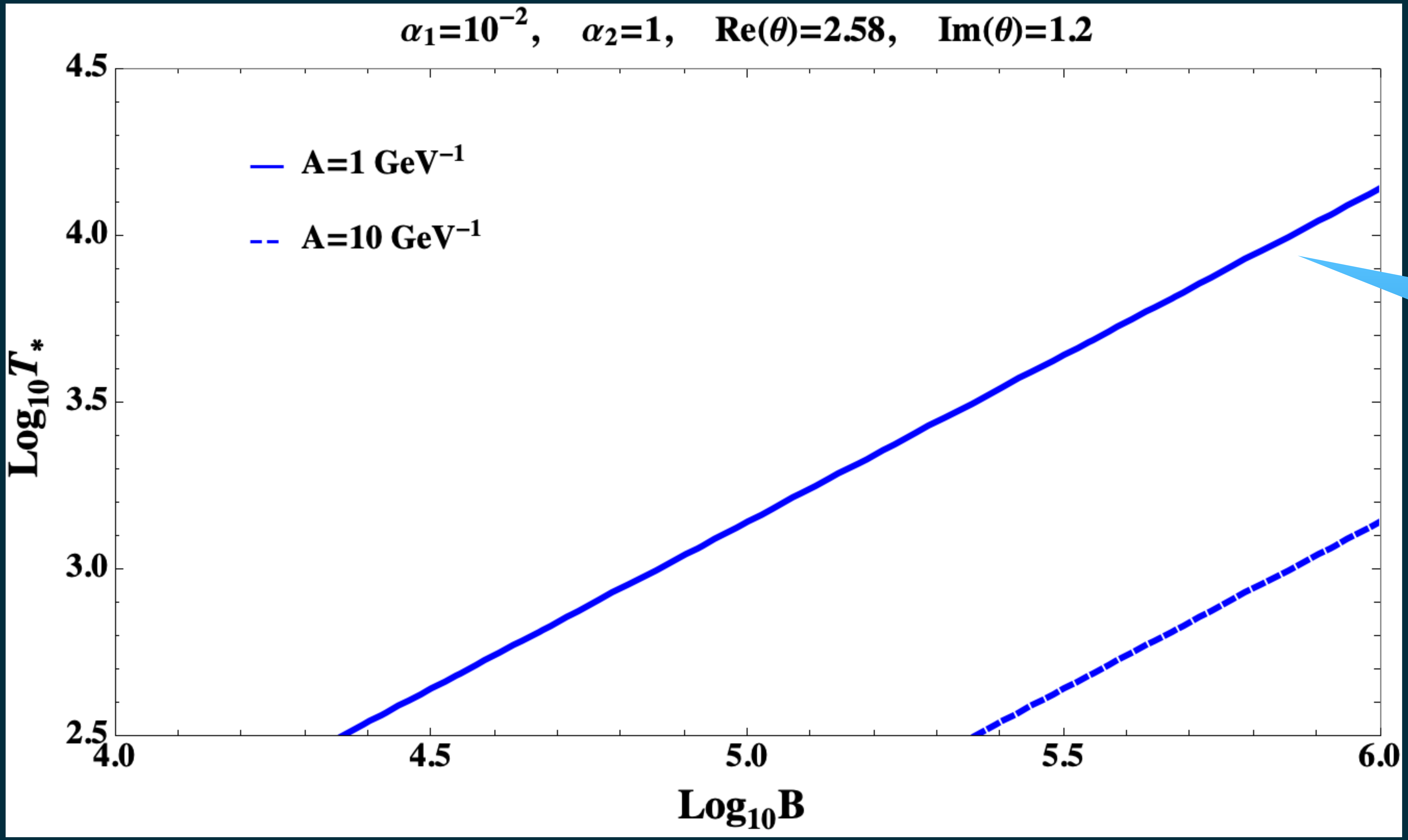
$$\varepsilon_\ell^i = \frac{1}{8\pi (Y_\nu^\dagger Y_\nu)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[ (Y_\nu^\dagger Y_\nu)_{ij}^2 \right] \mathbf{F}\left[ \frac{M_j^2(T)}{M_i^2(T)} \right]$$

$$\mathbf{F}[x] = \sqrt{x}\left[ 1 + \frac{1}{1-x} + (1+x)\ln\left( \frac{x}{1+x} \right) \right]$$

$Y_\nu$ can be extracted using Casas-Ibarra parametrization: $Y_\nu = -i\frac{\sqrt{2}}{v} U D_{\sqrt{m}} \mathbf{R} D_{\sqrt{M^0}}$

[Nucl. Phys. B 618, 171 (2001)]

The CP asymmetry then results in $Y_{B-L}$ asymmetry at $T_*$, and the sphaleron converts this $Y_{B-L}$ into $Y_B$ .




$$Y_B = \frac{28}{79} Y_{B-L} \simeq -\frac{28}{79} \sum_i \varepsilon_\ell^i \frac{n_{N_i}(T_*)}{s} = -\frac{28}{79}\frac{3}{4} \sum_i \varepsilon_\ell^i \frac{T_*}{M_i(T_*)}$$

[Phys. Rev. D 42, 3344 (1990)]

The observed baryon asymmetry ($\mathcal{O}(10^{-10})$) is produced in this case with the lightest zero temperature RHN mass of $M_1^0 \simeq \mathcal{O}(10^7)$ GeV

$$M_1^0 = \alpha_i B v^2$$

# Case II: Leptogenesis with two quasi degenerate RHNs (Resonant Leptogenesis)

The mass splitting between the two RHNs at $T > T_{sp}$ : $\Delta M(T) = \frac{1}{16}\text{Re}\left[(Y_\nu^\dagger Y_\nu)_{21}\right]\frac{T^2}{M(T)} + \alpha_{21} A T^2$

Thermally induced Mass splitting

$\alpha_{21} = \alpha_2 - \alpha_1$

The dominant contribution to the CP asymmetry comes from the interference between the tree level amplitude and the one loop self energy correction, expressed as :

$$\varepsilon_\ell^i = \sum_{j \neq i} \frac{\text{Im}(Y_\nu^\dagger Y_\nu)_{ij}^2}{(Y_\nu^\dagger Y_\nu)_{ii}(Y_\nu^\dagger Y_\nu)_{jj}} \frac{\left[M_i^2(T) - M_j^2(T)\right] M_i(T)\Gamma_{N_j}}{\left[M_i^2(T) - M_j^2(T)\right]^2 + M_i^2(T)\Gamma_{N_j}^2}$$

[Phys. Rev. D 56, 5431 (1997), Nucl. Phys. B 692, 303 (2004)]

The resonant enhancement of the CP asymmetry $\sim \mathcal{O}(1)$ may occur at $T > T_{sp}$ if the resonant condition $\Delta M(T) = M_2(T) - M_1(T) \sim \Gamma_{N_1}(T)/2$ is satisfied

[Nucl. Phys. B 692, 303 (2004)]

- For $M_i^0$ below the EW scale, a smaller value of $B$ is required, though the condition $M_i(T_*) > T_*$ is easily satisfied with suitable value of $A$ parameter and both RHNs decay at $T_*$ .

- The required mass splitting at $T_*$ can be obtained by appropriately choosing $\alpha_{21}$ while parameter $A$ is so chosen not to have $M_i(T) < T$ above $T_{sp}$ .

- Due to instant decay of RHNs at $T_*$ , radiation density may increase and the $B-L$ asymmetry can be diluted to some extent due to entropy injection.

Incorporating all such effects, we study the evolution of $B-L$ asymmetry by solving the coupled Boltzmann equations which reads as:

$$\frac{dN_i}{d\mathscr{A}} = -(N_i - N_i^{eq})\frac{\mathscr{K}_i}{\mathscr{A}}, \quad \text{with} \quad \mathscr{K}_i = \frac{\langle \Gamma_{N_i} \rangle}{\mathscr{H}}$$

$$\frac{dR}{d\mathscr{A}} = \sum_{i=1}^{2} \mathscr{K}_i \left[ M_i^{\mathrm{T}}(N_i - N_i^{eq}) \right]$$

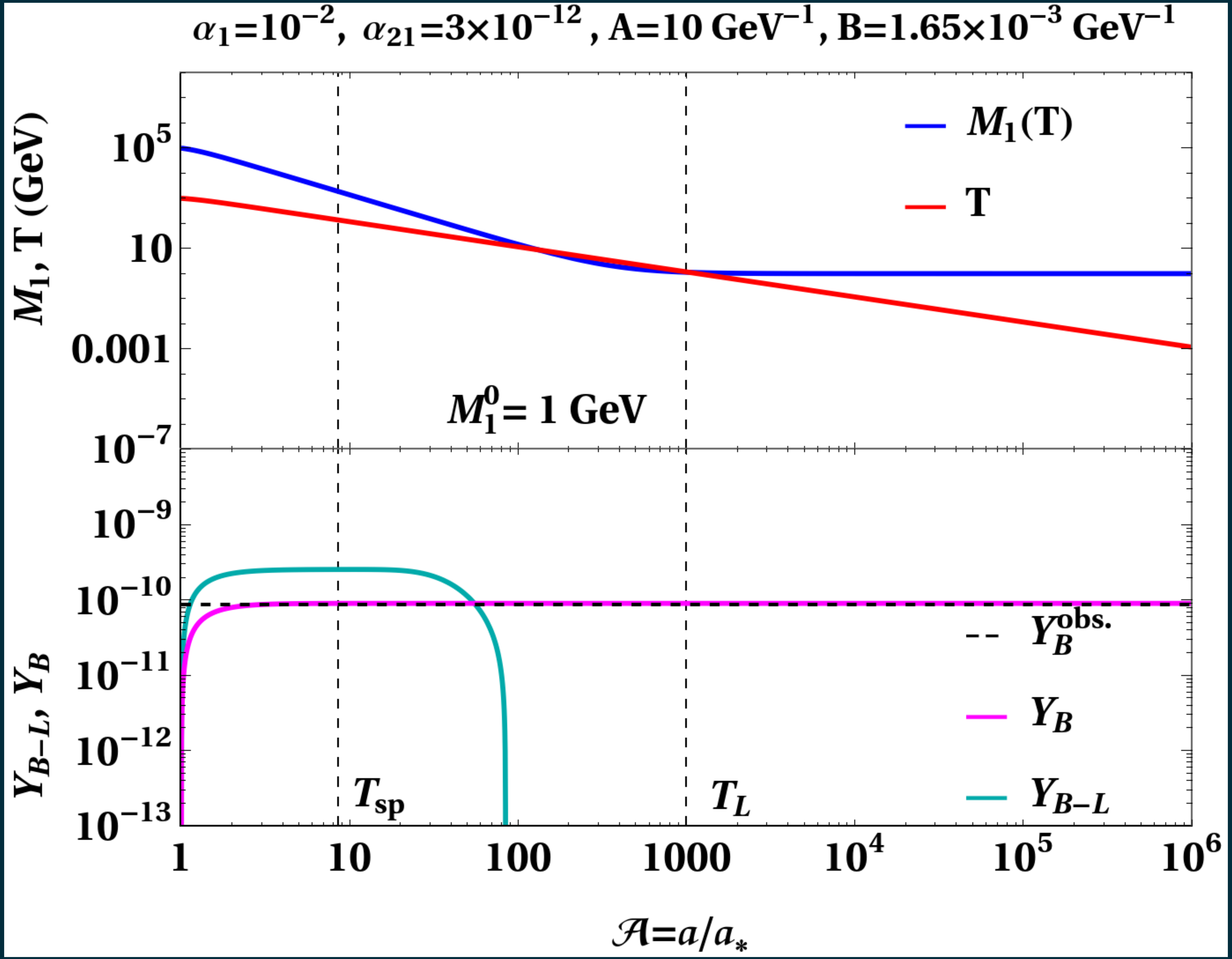
$$\frac{dN_{B-L}}{d\mathscr{A}} = -\sum_{i=1}^{2} \frac{\mathscr{K}_i}{\mathscr{A}} \left[ \varepsilon_\ell^i (N_i - N_i^{eq}) + \frac{n_{N_i}^{eq}}{2n_l^{eq}} N_{B-L} \right]$$

Where, $\mathscr{A} = a/a_*$ , $N_{i,(B-L)} = n_{N_i,(B-L)}\ \mathscr{A}^3$, $R = \rho_R\ \mathscr{A}^4$

$$\langle \Gamma_{N_i} \rangle = \frac{K_1(\mathscr{A})}{K_2(\mathscr{A})} \Gamma_{N_i}$$

Hubble Parameter, $\mathscr{H} = \sqrt{\dfrac{\rho_R + \sum_i M_i(T) n_{N_i}}{3M_P^2}}$

Here, $T_* = 1$ TeV is taken




We plot the evolution of the RHN mass, the temperature, $Y_{B-L}$ and $Y_B$ with the scale factor.

We have showed that the observed amount of baryon asymmetry can be produced with the zero temperature RHN mass of $M_1^0 = 1$ GeV.

# Late Leptogenesis & Helium Anomaly

Such amount of late lepton asymmetry may alter the primordial helium abundance ( $Y_P$ ) as compared to the prediction of Standard BBN ( $Y_P^{BBN}$ ) .

[PTEP 2022, 083C01 (2022), Astrophys. J. 941, 167 (2022)]

$$Y_P \simeq Y_P^{\mathrm{BBN}} e^{-0.96\xi_{\nu_e}}$$

where $\xi_{\nu_e}$ is the electron neutrino chemical potential

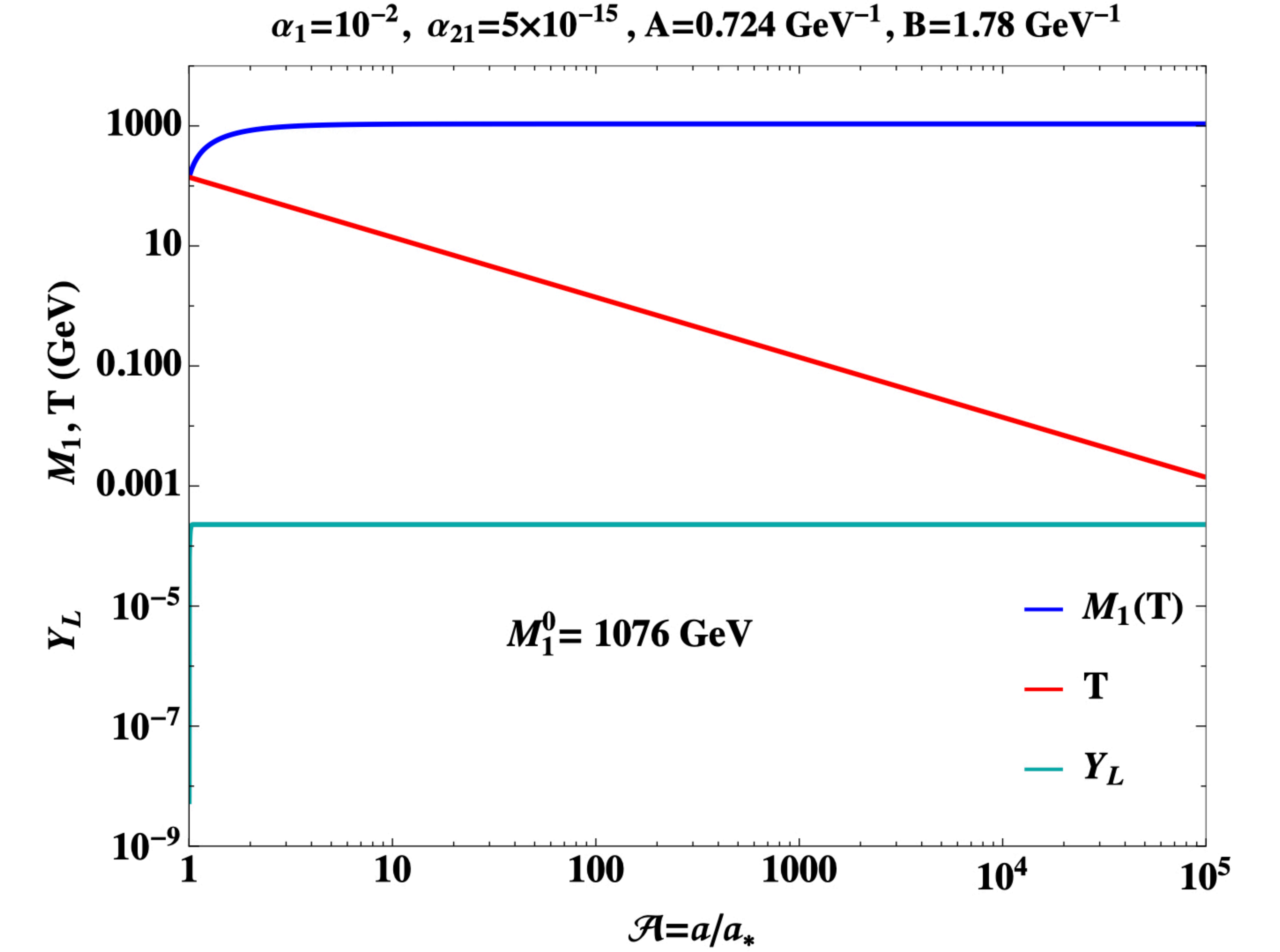
[JCAP 08 (08), 041, Phys. Rev. D 107, 035024 (2023)]

The lepton asymmetry is connected to the $\xi_{\nu_e}$ via the relation: $Y_L = 3Y_{\nu_e} \simeq 0.105\ \xi_{\nu_e}$

[PTEP 2022, 083C01 (2022)]

In our scenario, due to the temperature independent nature of the CP asymmetry parameter $\varepsilon_l$ , there is a direct correlation between the late lepton asymmetry and the baryon asymmetry via early leptogenesis at high temperature ( $T_*$ ).

# Late Leptogenesis & Helium Anomaly




Here, $M_i^0 > m_h + m_\ell$ is satisfied below the EW symmetry breaking temperature so RHNs will decay and produce a Late lepton asymmetry $\mathcal{O}(10^{-4})$ .

*Thank You*

Backup

$$|\phi|^4,\ \left(A_{10}\phi S|\phi|^2+h.c\right),\ A_3|\phi|^2H^\dagger H,\ A_4|\phi|^2|S|^2,\ \frac{A_5}{2}|\phi|^2\eta^2,\ \left(\frac{A_9}{2}\phi^2S^2+A_{11}\phi S|S|^2+h.c\right)$$

$$A_6|S|^2H^\dagger H,\ \frac{A_7}{2}|S|^2\eta^2,\ \frac{A_8}{2}\eta^2H^\dagger H,\ A_{12}\eta H^\dagger H,\ A_{13}\eta|\phi|^2,\ A_{14}\eta|S|^2$$

$$c_hT^2=\left(\frac{\lambda}{2}+\frac{3g_w^2}{16}+\frac{g_y^2}{16}+\frac{y_t^2}{4}+\frac{A_3}{12}+\frac{A_6}{12}+\frac{A_8}{24}\right)T^2$$

$$c_{\phi_r}T^2=\left(\frac{A_3}{6}+\frac{A_4}{12}+\frac{A_5}{24}+\frac{\alpha_1^2}{24}+\frac{\alpha_2^2}{24}\right)T^2$$

Higgs vev structure:

$$v(T)=\begin{cases}0 & \text{if}\quad T>T_c\\ \sqrt{\dfrac{\mu_h^2-A_1v_\phi v_s-\frac{A_3}{2}v_\phi^2-\frac{A_6}{2}v_s^2-c_hT^2}{\lambda}} & \text{if}\quad T<T_c\end{cases}$$

$\phi$ vev structure:

$$|v_\phi|=\frac{v_s\left[\frac{A_1T^2}{2\pi^2}\left\{J_B'\left(\frac{m_h^2}{T^2}\right)+3J_B'\left(\frac{m_\chi^2}{T^2}\right)\right\}+\frac{A_2T^2}{\pi^2}J_B'\left(\frac{m_\eta^2}{T^2}\right)+\frac{A_{11}T^2}{2\pi^2}\left\{3J_B'\left(\frac{m_{s_r}^2}{T^2}\right)+J_B'\left(\frac{m_{s_{im}}^2}{T^2}\right)\right\}+\frac{A_1}{2}v^2(T)+\frac{A_{11}}{2}v_s^3\right]}{m_\phi^2+\frac{A_3}{2}v^2(T)+\frac{1}{2}(A_4+A_9)v_s^2+\frac{T^2}{2\pi^2}\left\{A_3\left(J_B'\left(\frac{m_h^2}{T^2}\right)+3J_B'\left(\frac{m_\chi^2}{T^2}\right)\right)+(A_4+A_9)J_B'\left(\frac{m_{s_r}^2}{T^2}\right)\right\}+\frac{T^2}{2\pi^2}\left\{(A_4-A_9)J_B'\left(\frac{m_{s_{im}}^2}{T^2}\right)+A_5J_B'\left(\frac{m_\eta^2}{T^2}\right)-2\alpha_1^2J_F'\left(\frac{m_{N_1}^2}{T^2}\right)-2\alpha_2^2J_F'\left(\frac{m_{N_2}^2}{T^2}\right)\right\}}$$

Necessary conditions to be satisfied

↓

$A_1,\ A_3,\ A_6,\ A_{11}$ should be chosen small

$A_4=-A_9$

$2A_4+A_5=-(\alpha_1^2+\alpha_2^2)$