Flavor Leptogenesis During Reheating Era

Based on:

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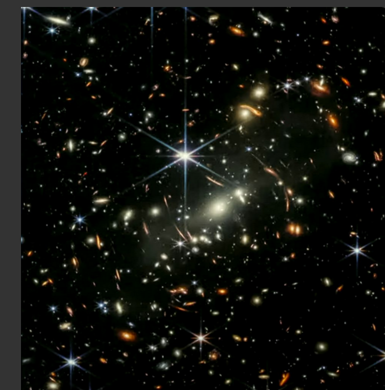
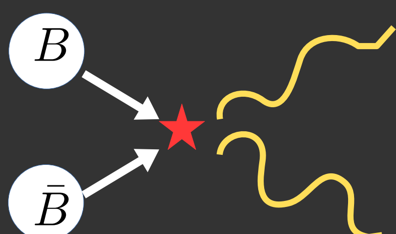
Evidance of Anti-matter

From Solar System

To Cluster of Galaxy





$$\frac{n_{\bar{M}}}{n_M + n_{\bar{M}}} \lesssim 10^{-6}$$

Upto ~10 Mpc using EGRET

[Steigman, JCAP 0810:001,2008]

From Cosmic Ray

Cosmic Ray anti-proton
scearch by PAMELA, AMS

$$\frac{\Phi_{\bar{P}}}{\Phi_P} \lesssim 10^{-5}$$

[O. Adriani et al., PRL 105, 121101 (2010)]

Explained by other astrophysical processes

No evidance of anti-matter structure

Quantifying the Asymmetry

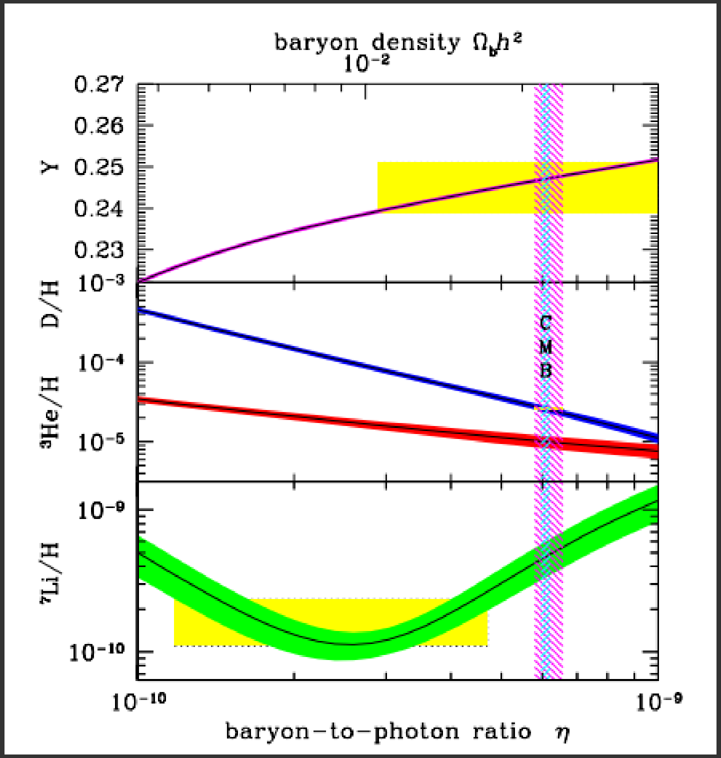
Baryon to photon ratio:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

Baryon to entropy density:

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s}$$

- Both CMB and BBN provide similar bounds on this Baryon asymmetry Parameter



[PDG, 2018]

$$\eta_B = (6.047 \pm 0.074) \times 10^{-10}$$

[PLANCK, 2015]

Generation of Baryon Asymmetry

Option 1: Start with a **baryon asymmatric** Universe

- At early Universe, Ten Billion baryon anti-baryon pair + one extra baryon
- Inflation can washout all asymmetry.

Option 2: **Dynamically generate** the required Baryon asymmetry

Sakharov's Condition

[Sakharov, 1967]

- C and CP violation
- Baryon number violation

} **Consistant** with **SM**

- Out-of-equilibrium dynamics → **Inconsistant**

↑

EW Phase Transition is of 2^{nd} order (due to Higgs mass)

Need to introduce BSM physics

Leptogenesis

Advantages: **connects the origin of neutrino mass**

Neutrino Mass ⟷ **Lepton asymmetry**

Type-I Seesaw mechanism

(SM + 3 Right-Handed Neutrinos)

[Minkowsky, 1977]
[Yanagida, 1979]
[Gell-Mann,Ramond,Slansky,1979]
[Mohapatra,Senjanovic,1980]

$$m_D = \frac{Y_\nu v}{\sqrt{2}}$$

$$\mathcal{L}_{BSM} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + \frac{M_N}{2}\bar{N_i}^c N_i + h.c \longleftrightarrow m_\nu = -m_D M_N^{-1} m_D^T$$

CP Violation

Lepton number Violation

Out-of equilibium dynamics

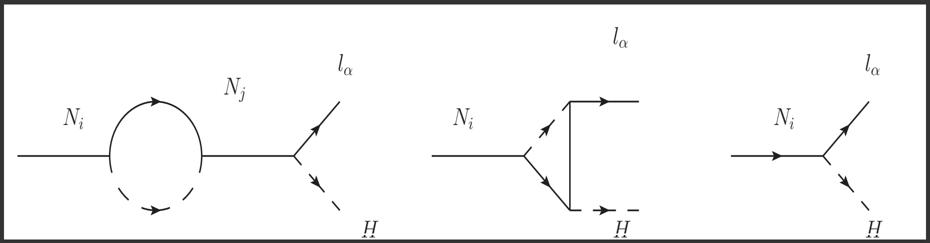
↓

Decay of RHN at T < M_N

$$[N \to \ell + H]$$
$$[N \to \bar{\ell} + \bar{H}]$$

$$\Delta L \neq 0 \xrightarrow{\text{Sphaleron Process}} \Delta B \neq 0$$

Quantifying CP asymmetry



$$\epsilon_{i\alpha} = \frac{[\Gamma(N_i \to \ell_\alpha + H) - \Gamma(N_i \to \bar{\ell_\alpha} + \bar{H})]}{\sum_\alpha [\Gamma(N_i \to \ell_\alpha + H) + \Gamma(N_i \to \bar{\ell_\alpha} + \bar{H})]}$$

$$\varepsilon_{i\alpha} = \frac{1}{8\pi (Y_\nu^\dagger Y_\nu)_{ii}} \sum_{j \neq i} \left[\mathrm{Im}\left\{(Y_\nu^\dagger)_{i\alpha}(Y_\nu)_{\alpha j}(Y_\nu^\dagger Y_\nu)_{ij}\right\} \mathbb{F}\left(\frac{M_j^2}{M_i^2}\right) + \mathrm{Im}\left\{(Y_\nu^\dagger)_{i\alpha}(Y_\nu)_{\alpha j}(Y_\nu^\dagger Y_\nu)_{ji}\right\} \mathbb{G}\left(\frac{M_j^2}{M_i^2}\right)\right],$$

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

$$Y_\nu = -i\frac{\sqrt{2}}{v} U D_{\sqrt{m}} \mathrm{R} D_{\sqrt{M}}$$

(Casas-Ibarra Parametrization)

[JA Casas, 2001]

$$U^\dagger m_\nu U^* = D_m$$

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & e^{-i\delta}s_{13} \\ -s12 s_{23} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e_{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s12 s_{23} - e^{i\delta}c_{12}s_{13}s_{23} & -c_{12}c_{23} - e_{i\delta}s_{12}s_{13}s_{23} & c_{13}c_{23} \end{pmatrix} U_m$$

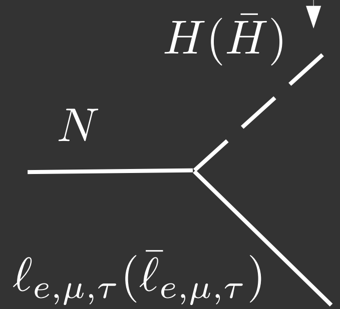
Neutrino mass, mixing and Leptogenesis are related

Lepton & Baryon asymmetry

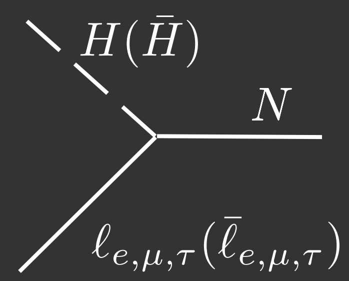
$$s\mathcal{H}z\frac{dY_{N_1}}{dz} = \left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)(\gamma_D + 2\gamma_{S_s} + 4\gamma_{S_t})$$

$$s\mathcal{H}z\frac{dY_{B-L}}{dz} = -\left\{\left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)\varepsilon_1\gamma_D - \frac{Y_{B-L}}{Y_\ell^{\rm eq}}\left(2\gamma_N + 2\gamma_{S_t} + \gamma_{S_s}\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}}\right)\right.$$

$[M_1 << M_2, M_3]$



Production



Washout

2-2 scattering Washout

$$Y_B = \frac{28}{79}Y_{B-L}$$

(At sphaleron decoupling limit) $T \sim 150$ GeV

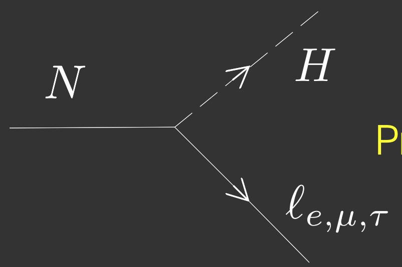
* $z = \frac{M_1}{T}$
* $Y_x = \frac{n_x}{s}$
* $\gamma_D = \gamma(N \to \ell H) + \gamma(N \to \bar{\ell}\bar{H})$

Flavor effect in Leptogenesis

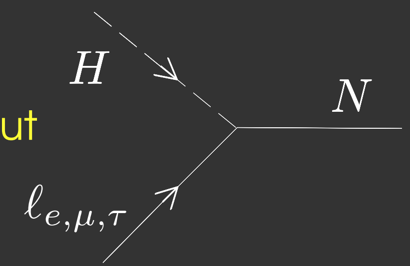
$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

[Credit to
Barbieria et. al.,2000; Nardi et. al., 2005, 2006; Blanchet, Bari, 2006, 2007; A. Abada et.al.,2007;
,and many more...]

$$\Gamma_\alpha < \mathcal{H} \quad (T >> 5 \times 10^{11}\ \text{GeV})$$

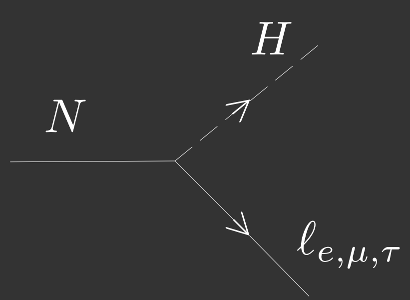


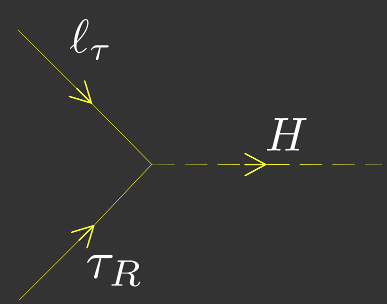
Production **[Flavor blind]** Washout

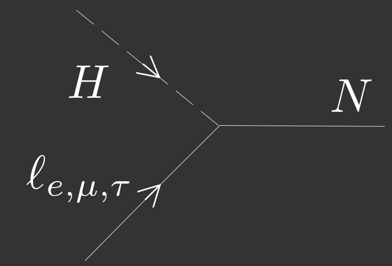


$$\Gamma_\tau(\propto m_h^2(T)/T) > \mathcal{H}$$

[right-handed tau enters equilibrium]







Washout along individual flavors become different

Flavor effect in Leptogenesis

$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

T [GeV]

No Flavor effect: $|\ell_1\rangle = \langle\ell_\alpha|\ell_1\rangle|\ell_\alpha\rangle$

$T \sim [5\times 10^{11}\ \text{GeV}]$ — $\Gamma_\tau = \mathcal{H}$

Two Flavor: $|\ell_a\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_a} + Y_{B/3-L_\tau}$$

$T \sim [10^9\ \text{GeV}]$ — $\Gamma_\mu = \mathcal{H}$

Three Flavor: $|\ell_e\rangle,\ |\ell_\mu\rangle,\ |\ell_\tau\rangle$

$$Y_{B-L} = Y_{B/3-L_e} + Y_{B/3-L_\mu} + Y_{B/3-L_\tau}$$

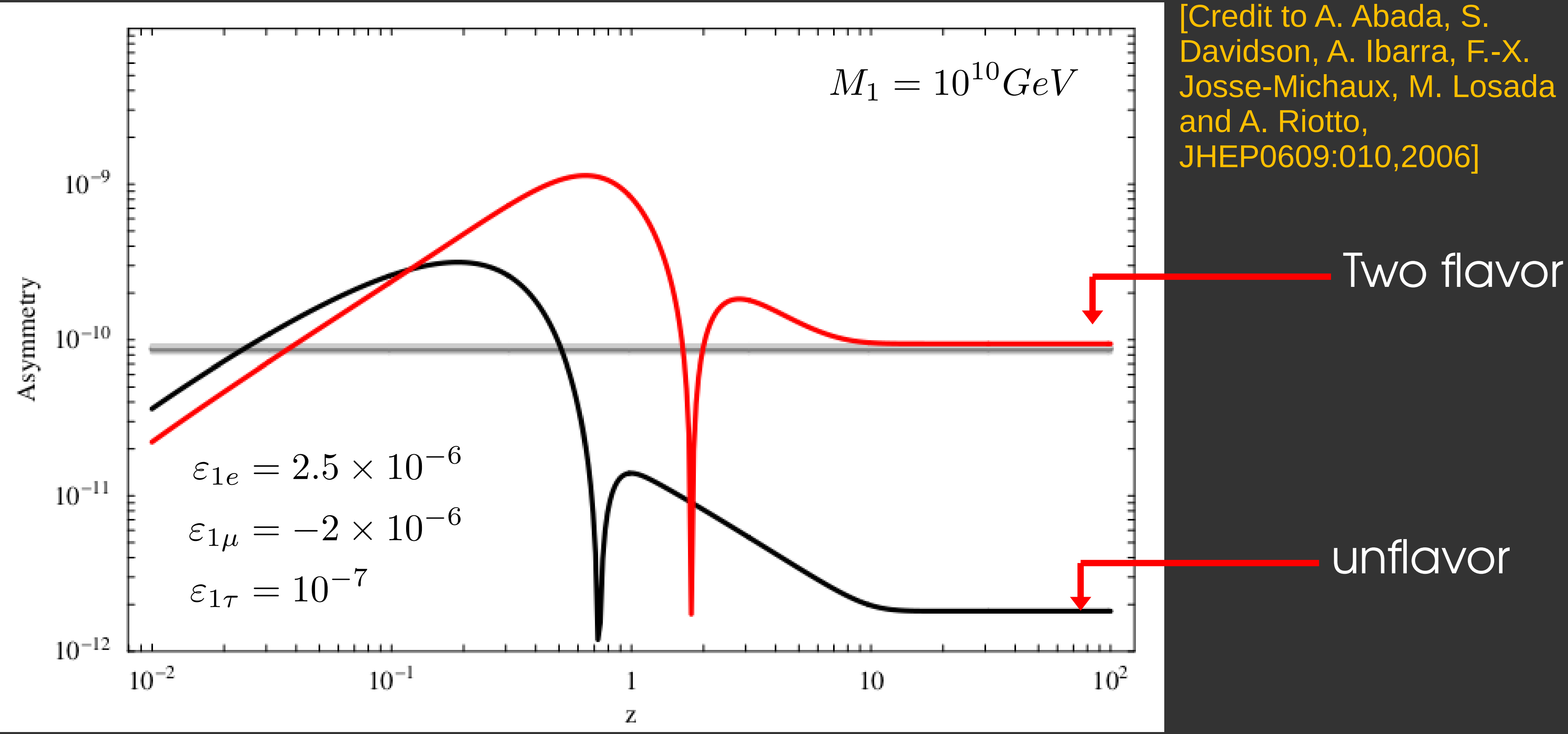
$$Y_B = \frac{28}{79}\sum_\alpha Y_{B/3-L_\alpha}$$

Flavor Projector: $|\langle\ell_\alpha|\ell_1\rangle|^2$

Asymmetry converter Matrix

$$s\mathcal{H}z\frac{dY_{B/3-L_\alpha}}{dz} = -\left\{\left(\frac{Y_{N_1}}{Y^{\rm eq}_{N_1}} - 1\right)\varepsilon_{\ell_\alpha} + \frac{1}{2}K^0_\alpha\sum_\beta(C^\ell_{\alpha\beta} + C^H_\beta)\frac{Y_{B/3-L_\beta}}{Y^{\rm eq}_\ell}\right\}\gamma_D$$

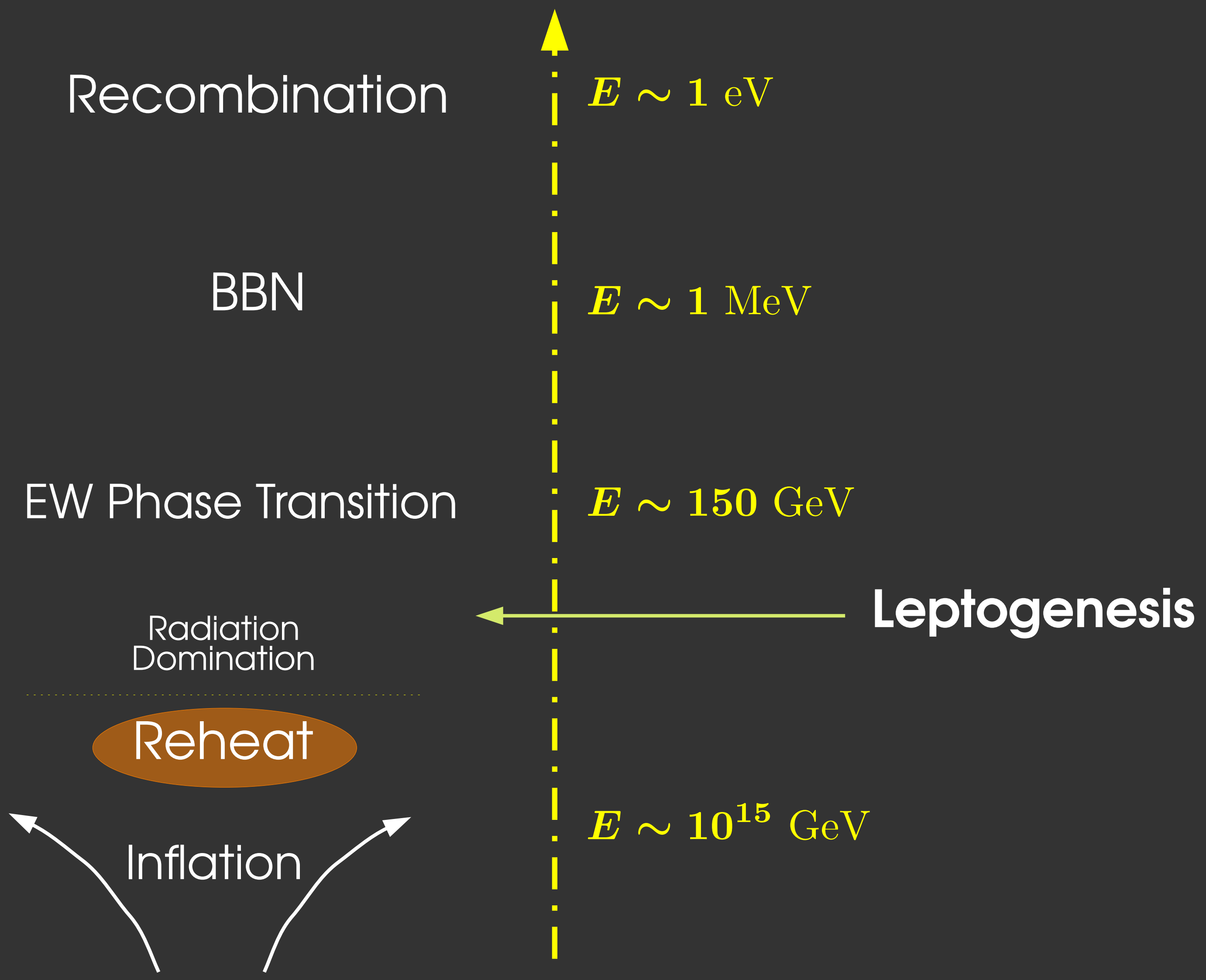
Importance of flavor effect



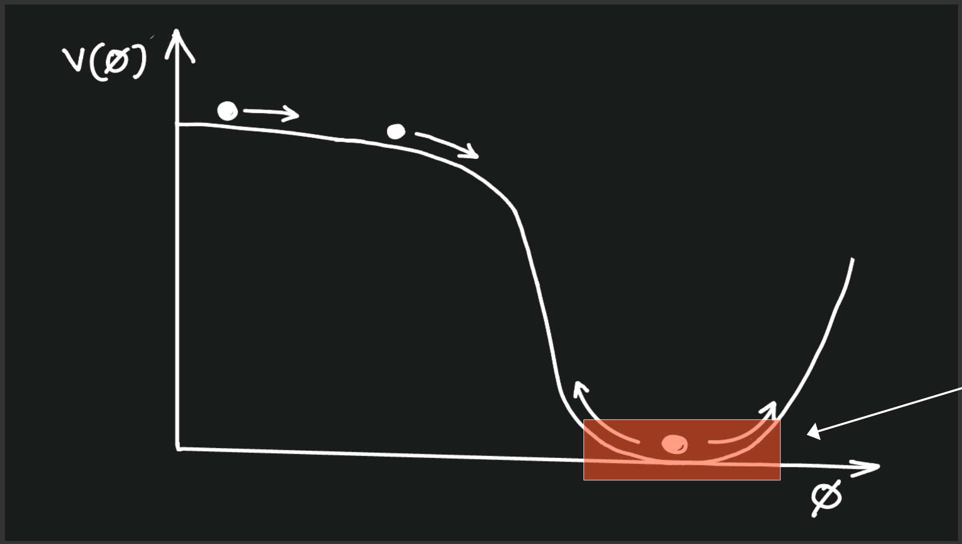
[Credit to A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, JHEP0609:010,2006]

Almost one order shift in produced baryon asymmetry can be achieved

Timeline of Leptogenesis:



Inflationary Universe [exponential expansion: $a \sim e^{Ht}$]



Inflaton must decay to radiation

Reheating

- Beginning of the thermal history.
- All elemantary particles (of SM) are generated

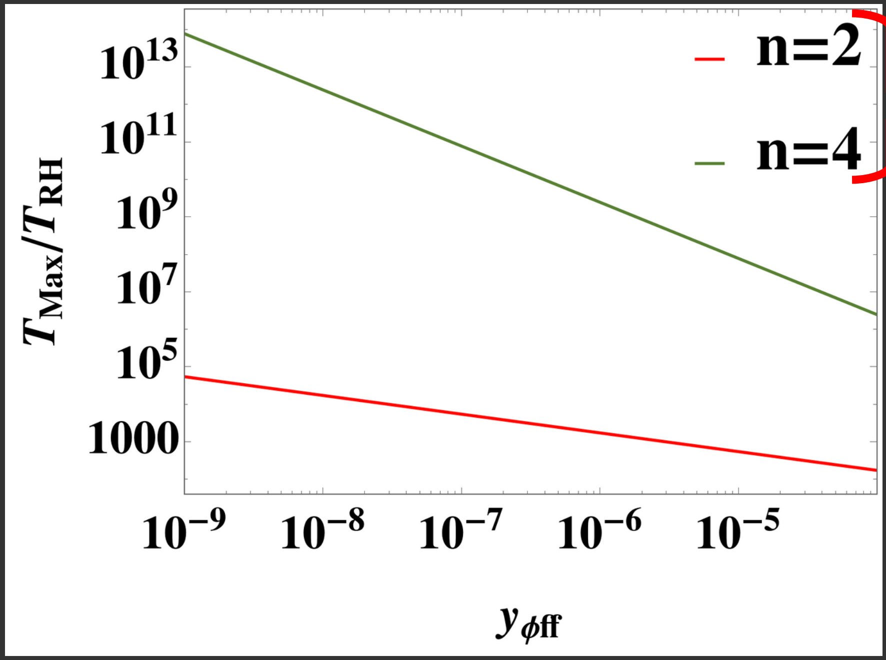
Era of rehating can be very rich.

Coupling between inflaton and SM

$\mathcal{L} = y_{\phi f f} \phi \bar{f} f$

Produces radiation component

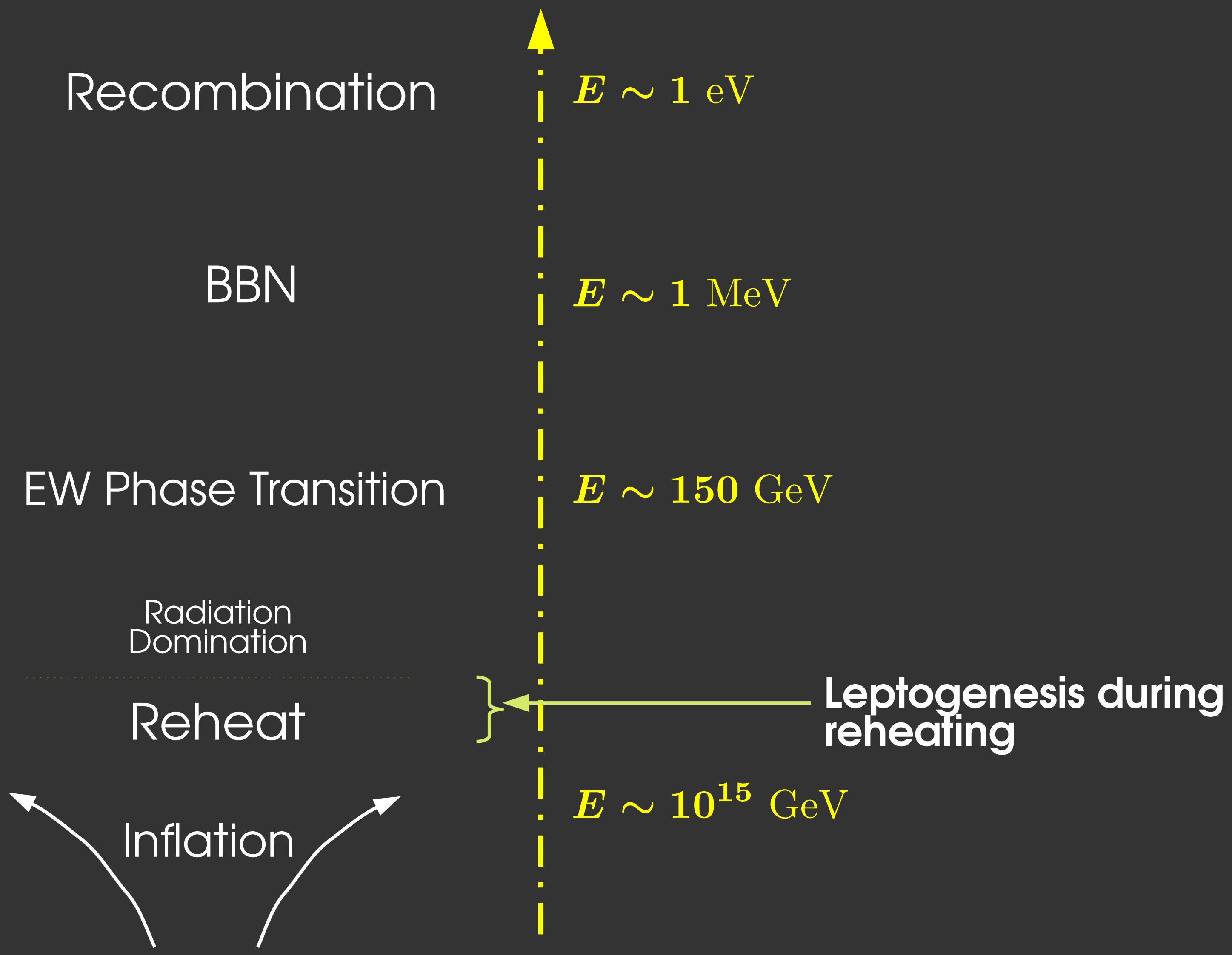
ρ_R



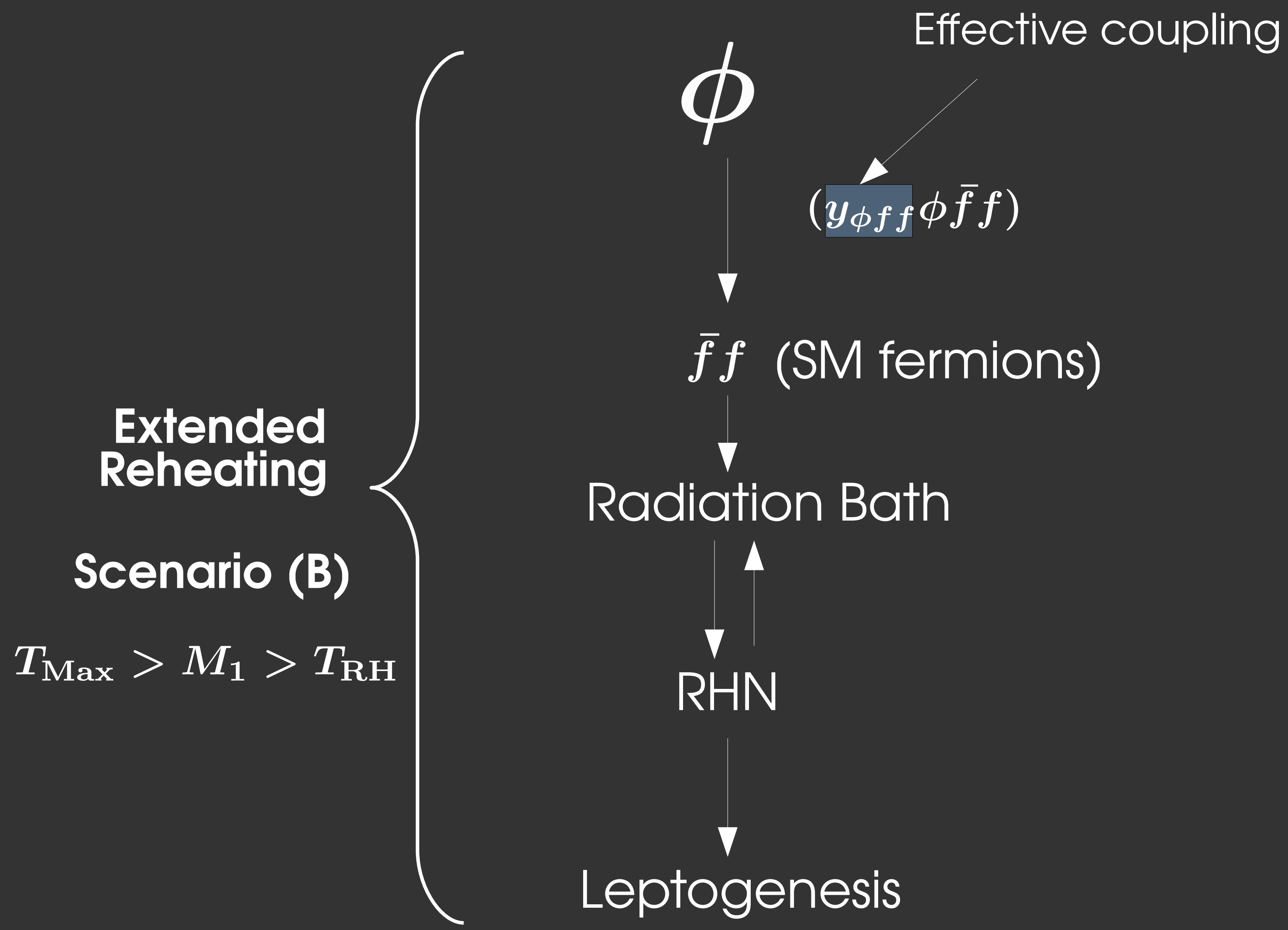
Power in inflaton potential

- **Temperature varies differently.**
- **T_{max} – T_{RH} : depends on effective coupling**

Timeline of Leptogenesis:



Setup:



(A) $M_1 > T_{\rm Max}$

(B) $T_{\rm Max} > M_1 > T_{\rm RH}$

(C) $M_1 < T_{\rm RH}$

Equilibration of Charged lepton Yukawa:

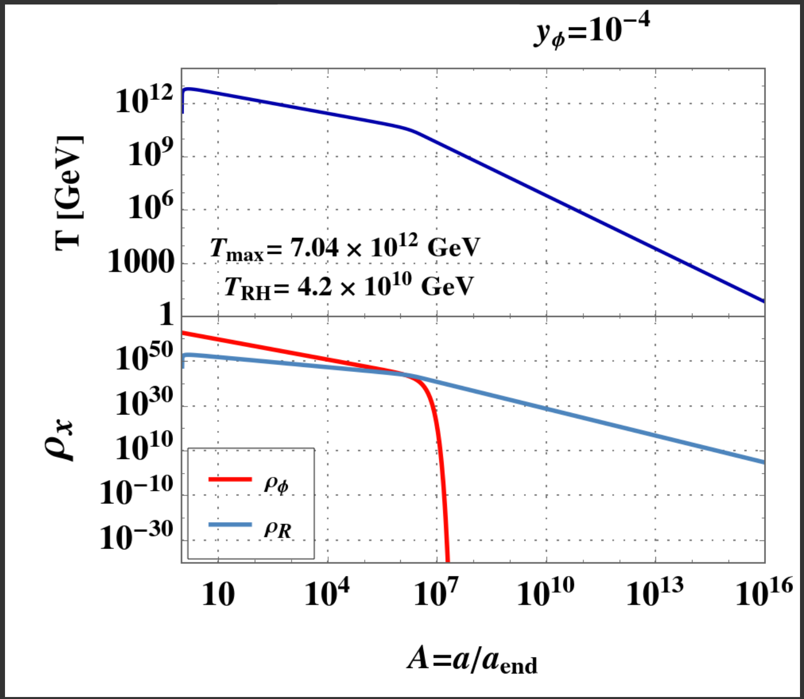
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}} \rho_\phi a^2$$

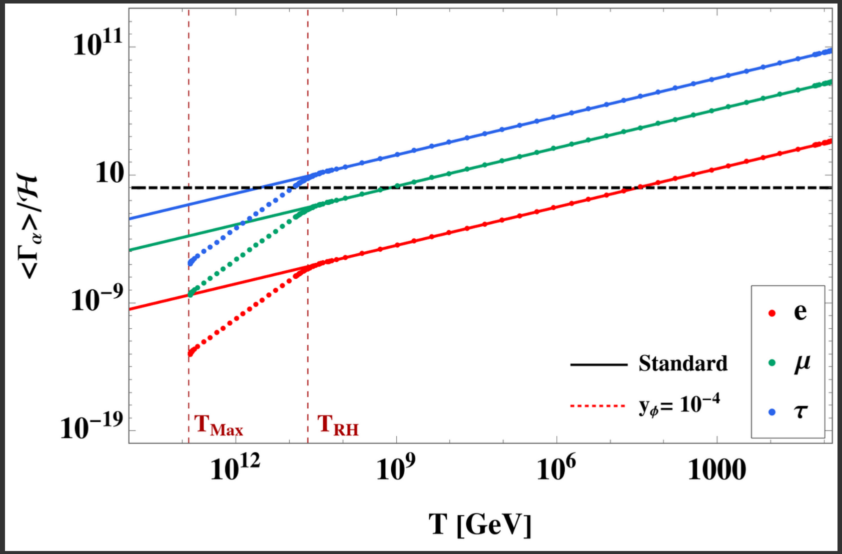
$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}} \Gamma_\phi \rho_\phi$$

$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$

Thermal Mass of Higgs

$$\langle \Gamma_\alpha \rangle = \frac{\pi Y_\alpha^2}{192\zeta(3)} \frac{m_h^2(T)}{T} = \mathcal{H}$$





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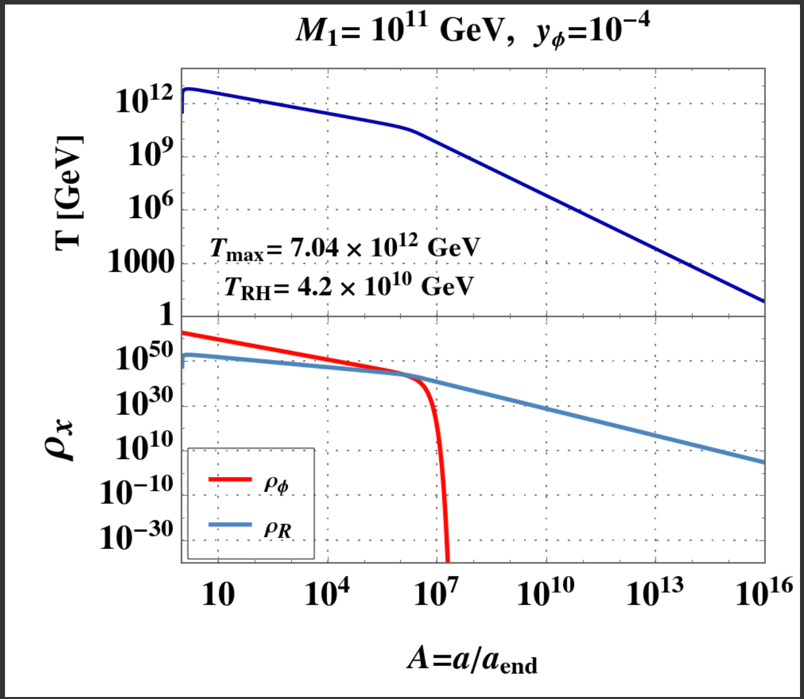
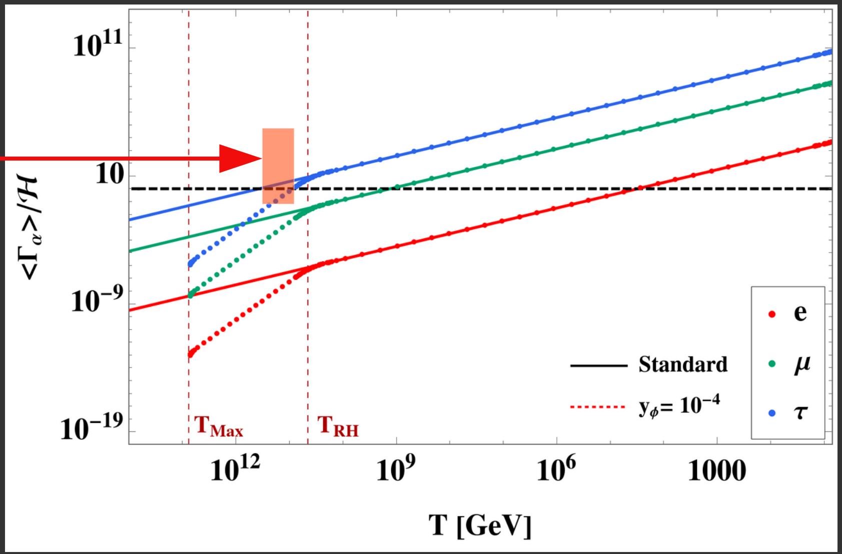


- **Delayed equilibration of charged lepton Yukawa interactions**



Shift in ET and effect on flavor leptogenesis

$$T_{max} > M_1 > T_{RH}$$

- Decay of N_1 would produce lepton asymmetry
  - However, flavor regimes are shifted

Need to relook into flavor leptogenesis

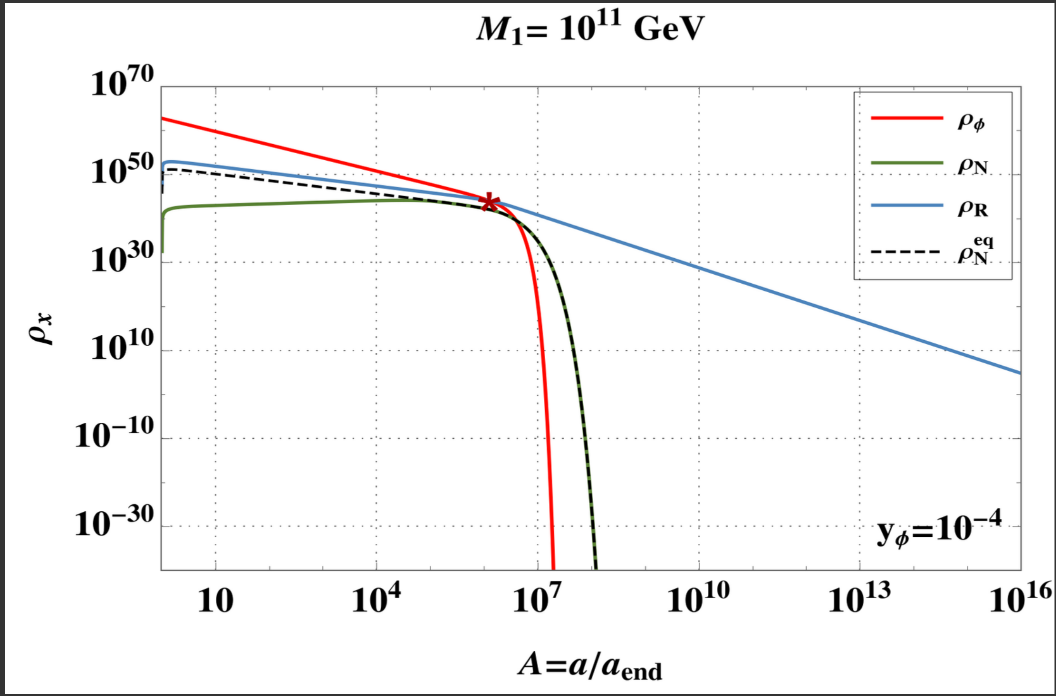
Bolzmann Equation and Temperature:

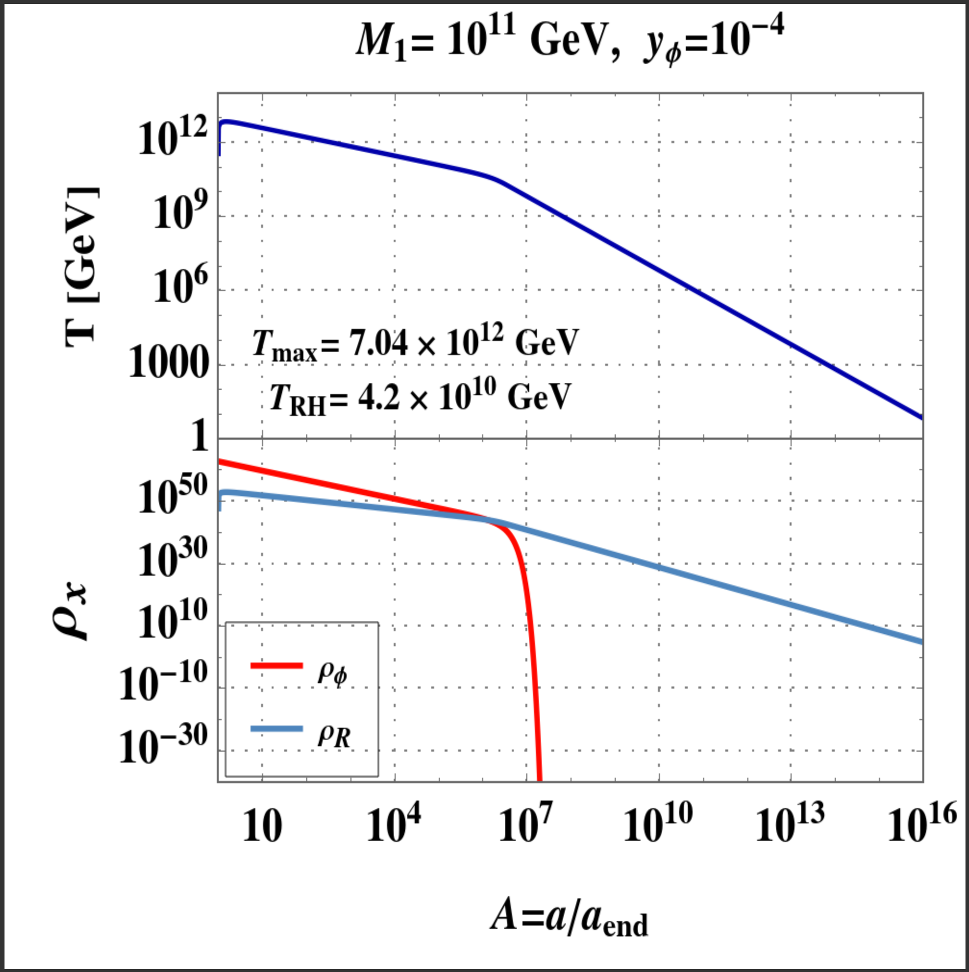
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi + \frac{a^3}{H}\langle\Gamma_{N_1}\rangle(\rho_{N_1} - \rho_{N_1}^{\rm eq})$$

$$\frac{d(\rho_{N_1} a^3)}{da} = -\frac{\langle\Gamma_{N_1}\rangle a^2}{\mathcal{H}}(\rho_{N_1} - \rho_{N_1}^{\rm eq})$$

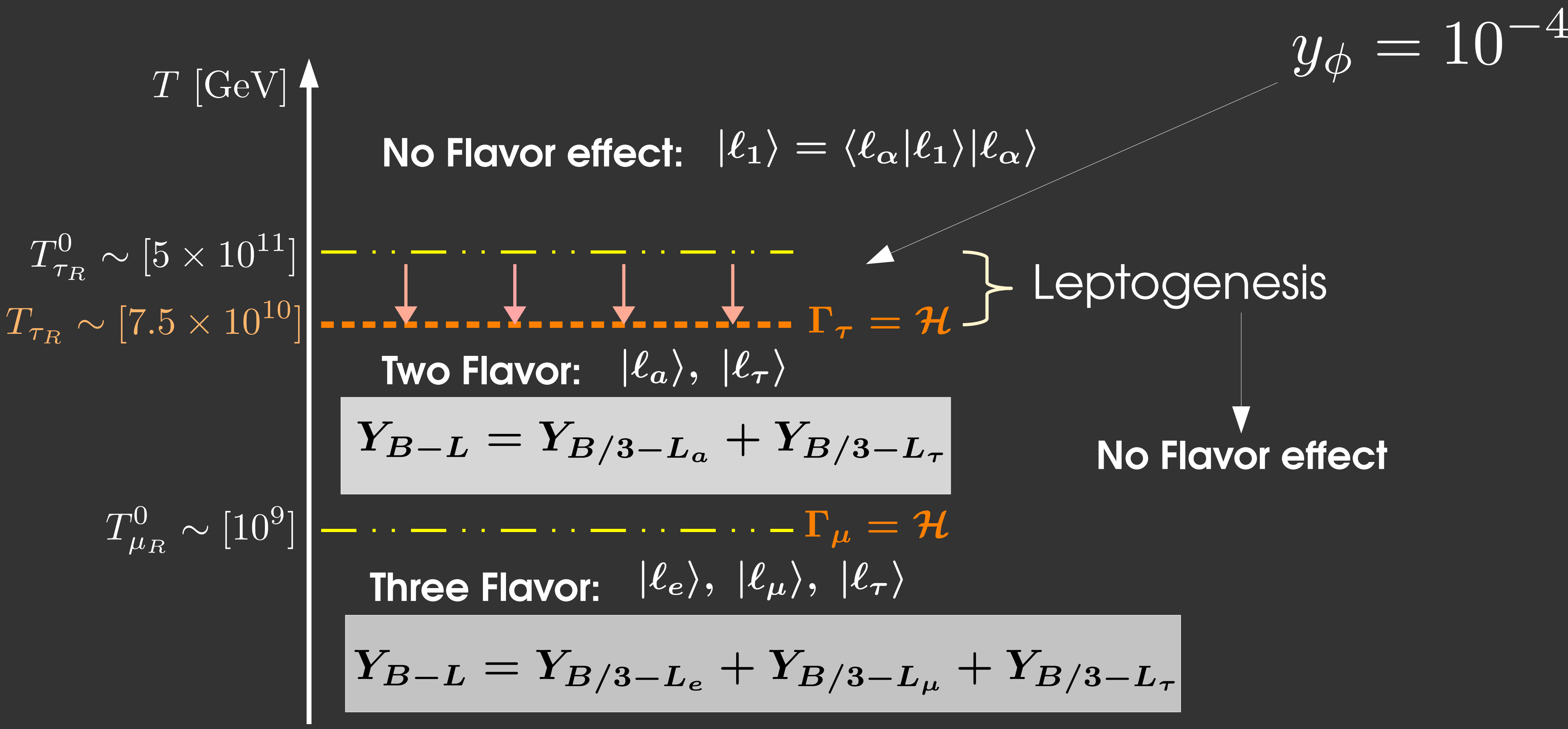
$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R + \rho_{N_1}}{3M_P^2}$$





Modification of Flavor effect

$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L_\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$



Modification of Baryon asymmetry

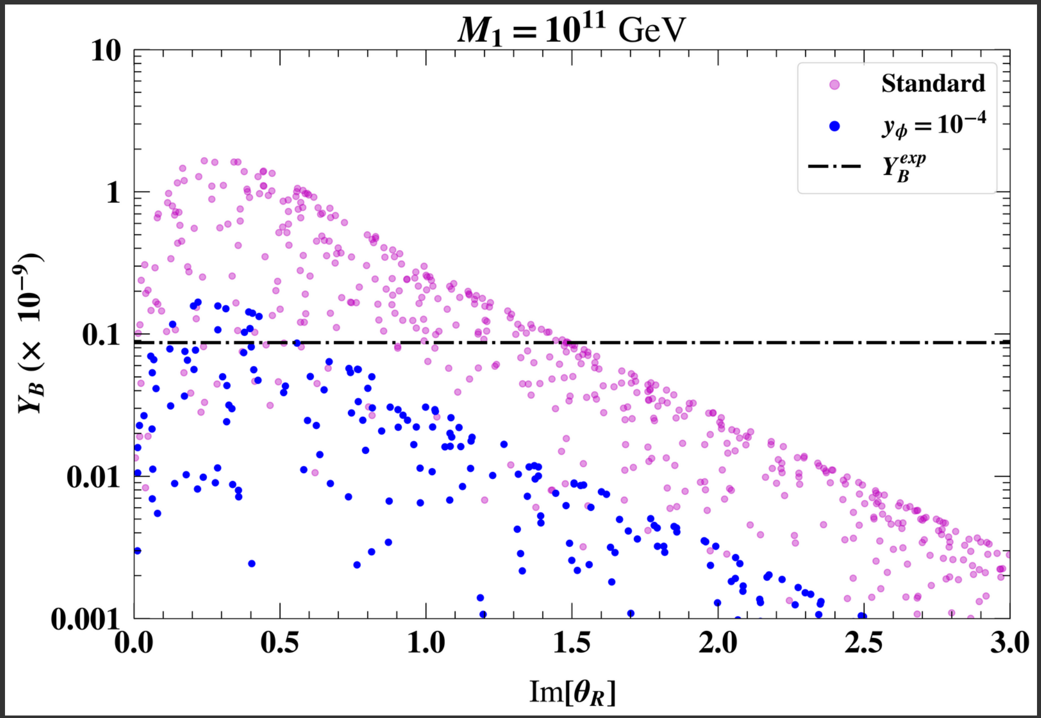
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi + \frac{a^3}{H}\langle\Gamma_{N_1}\rangle(\rho_{N_1} - \rho_{N_1}^{\text{eq}})$$

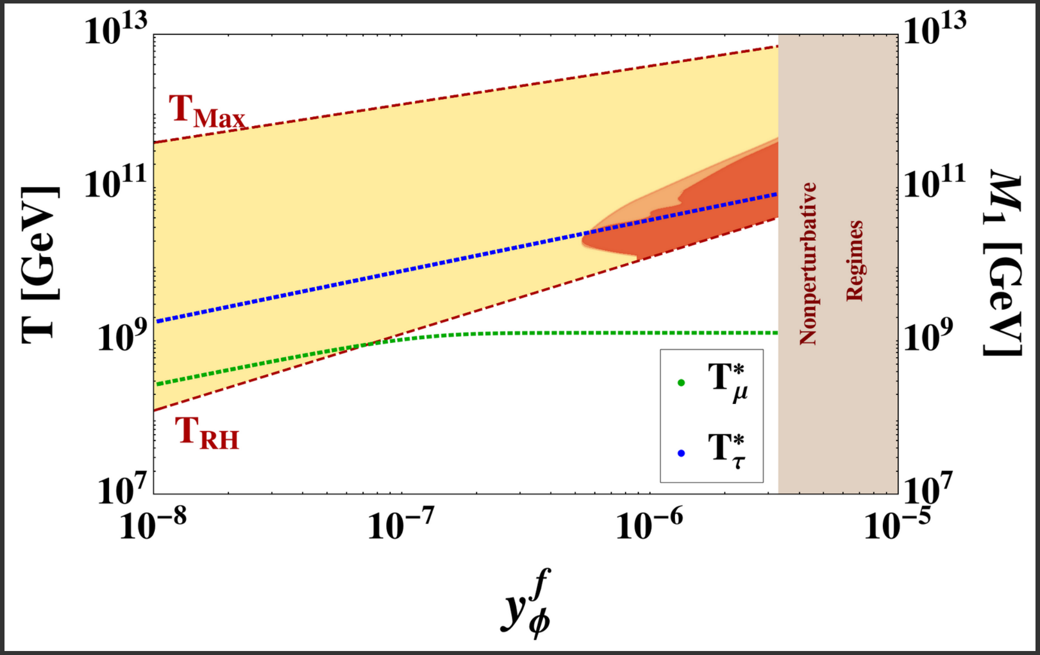
$$\frac{d(\rho_{N_1} a^3)}{da} = -\frac{\langle\Gamma_{N_1}\rangle a^2}{\mathcal{H}}(\rho_{N_1} - \rho_{N_1}^{\text{eq}})$$

$+$

$$\frac{d(n_{B-L}a^3)}{da} = -\frac{\langle\Gamma_{N_1}\rangle a^2}{\mathcal{H}}\left[\frac{\varepsilon_\ell}{M_1}(\rho_{N_1} - \rho_{N_1}^{\text{eq}}) + \frac{n_{N_1}^{\text{eq}}}{2n_\ell^{\text{eq}}}n_{B-L}\right]$$



Modification of Baryon asymmetry



- **Prolonged Reheating** was achived by varying the inflaton-SM fermion coupling.
- Due to the **nontrivial behaviour of Temperature** in between T_{max} and T_{RH}, **equilibration temperature of charged lepton Yukawa interactions shift** from their standard thermal value.
- **More stringent parameter space** satisfying correct baryon asymmetry is observed due to the **modifed flavor effect** as well as **dilution of baryon asymmetry** due to **entropy injection** from inflaton decay.

Thank You

Boltzmann Equations

$$sHz\frac{dY_{N_i}}{dz} = -\left\{ \left(\frac{Y_{N_I}}{Y^{\rm eq}_{N_I}} - 1\right)\left(\gamma_{D_i} + 2\gamma_{N^i_s} + 4\gamma_{N^i_t}\right) + \sum_{j\neq i}\left(\frac{Y_{N_i}}{Y^{\rm eq}_{N_i}}\frac{Y_{N_j}}{Y^{\rm eq}_{N_j}} - 1\right)\left(\gamma^{(1)}_{N_iN_j} + \gamma^{(2)}_{N_iN_j}\right)\right\}$$

$$sHz\frac{dY_{\Delta_\alpha}}{dz} = -\left\{\sum_i\left(\frac{Y_{N_i}}{Y^{\rm eq}_{N_i}} - 1\right)\epsilon_{i\alpha}\gamma_{D_i} - \sum_\beta\left[\sum_i K_{i\alpha}\left(\frac{1}{2}\left(C^\ell_{\alpha\beta} - C^H_\beta\right)\gamma_{D_i}\right.\right.\right.$$

$$+\left(C^\ell_{\alpha\beta}\frac{Y_{N_i}}{Y^{\rm eq}_{N_i}} - \frac{C^H_\beta}{2}\right)\gamma_{N^i_s} + \left(2C^\ell_{\alpha\beta} - \frac{C^H_\beta}{2}\left(1 + \frac{Y_{N_i}}{Y^{\rm eq}_{N_i}}\right)\right)\gamma_{N^i_t}\Bigg)$$

$$\left.\left.\left. + \sum_\gamma\left(\left(C^\ell_{\alpha\beta} + C^\ell_{\gamma\beta} - 2C^H_\beta\right)\left(\gamma^{(1)\alpha\gamma}_N + \gamma^{(2)\alpha\gamma}_N\right) + \sum_{i,j}\left(C^\ell_{\alpha\beta} - C^\ell_{\gamma\beta}\right)\gamma^{(1)\alpha\gamma}_{N_iN_j}\right)\right]\frac{Y_{\Delta_\beta}}{Y^{\rm eq}}\right\}$$

Matter-Antimatter asymmetry

[Leptogenesis ⟷ Origin of Neutrino Mass]

decay of RHN: $N \to \ell H \quad (Y_\nu \bar{\ell}\tilde{H}N)$

Flavor Leptogenesis

Depend on when **charged lepton Yukawa of different flavors comes to equilibrium**

$T^0_{\tau_R} \sim 5 \times 10^{11}\mathrm{GeV}$

$T^0_{\mu_R} \sim 10^{9}\mathrm{GeV}$

$T^0_{e_R} \sim 5 \times 10^{4}\mathrm{GeV}$

- Should be generated after inflation

[Post inflationary epoch]

Perturbative Reheating: instanteneus/extended

Matter-Antimatter asymmetry

[Leptogenesis ⟷ Origin of Neutrino Mass]

decay of RHN: $N \to \ell H \quad (Y_\nu \bar{\ell}\tilde{H}N)$

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[Post inflationary epoch]

Perturbative Reheating: instanteneus/extended

Universe reaches a maximum temperature $\mathbf{T_{max}}$

Reheating temperature $\mathbf{T_{RH}}$

(onset of radiation domination)

$\mathbf{T_{Max}}$ – $\mathbf{T_{RH}}$: May differ by several orders of magnitude

CP asymmetry and Lepton asymmetry

- **CP asymmetry generation**

- All the RHNs will generate CP asymmetry.
- Interference between tree level and one loop level diagram will generate CP asymmetry

$$\epsilon_{i\alpha} = \frac{[\Gamma(N_i \to \ell_\alpha + H) - \Gamma(N_i \to \bar{\ell_\alpha} + \bar{H})]}{[\Gamma(N_i \to \ell_\alpha + H) + \Gamma(N_i \to \bar{\ell_\alpha} + \bar{H})]}$$

- **Lepton asymmetry generation processes**

$$\Delta L = 1 : [N_i + \ell \leftrightharpoons Q + \bar{U}] \;,\; [N_i + \bar{Q} \leftrightharpoons \bar{\ell} + \bar{U}] + [N_i + U \leftrightharpoons \bar{\ell} + \bar{Q}]$$

$$\Delta L = 2 : [\ell + H \leftrightharpoons \bar{\ell} + \bar{H}], [\ell + \ell \leftrightharpoons \bar{H} + \bar{H}]$$

Due to flavor effect: $[N_i + N_j \leftrightharpoons \bar{\ell_\alpha} + \ell_\beta]$

- **RHN number changing processes**

$$N_i + \ell \leftrightharpoons Q + \bar{U}] \;,\; [N_i + \bar{Q} \leftrightharpoons \bar{\ell} + \bar{U}] + [N_i + U \leftrightharpoons \bar{\ell} + \bar{Q}]$$

Almost degenerate RHN: $[N_i + N_j \leftrightharpoons \bar{\ell} + \bar{\ell}], [N_i + N_j \leftrightharpoons \bar{H} + H]$