Flavor Leptogenesis During Reheating Era

Arunansu Sil

Dept. of Physics

Indian Institute of Technology Guwahati

Based on:

Arghyajit Datta, Rishav Roshan and AS: arXiv:2206.10650

Arghyajit Datta, Rishav Roshan **and** AS: **Phys. Rev. D 108 (2023) 3, 035029**

SCALARS 2023, University of Warsaw, Poland

Plan of the talk

- Matter antimatter asymmetry
- Thermal leptogenesis and flavor effect
- Post inflationary reheating and effect on flavor leptogenesis
- Conclusion

Leptogenesis

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

Neutrino Mass ⟷ Lepton asymmetry

Type-I Seesaw mechanism

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

(SM + 3 Right-Handed Neutrinos)

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

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

CP Violation

Lepton number Violation

Out-of equilibrium dynamics

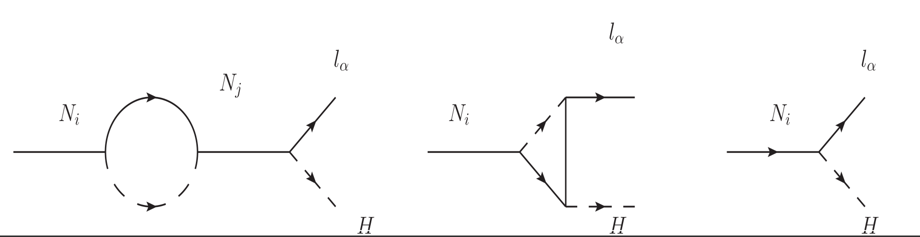
↓

Decay of RHN at T < M_N

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

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

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]

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

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

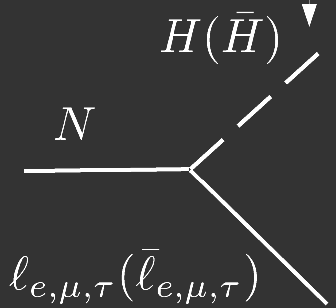
Neutrino mass, mixing and Leptogenesis are related

Lepton & Baryon asymmetry

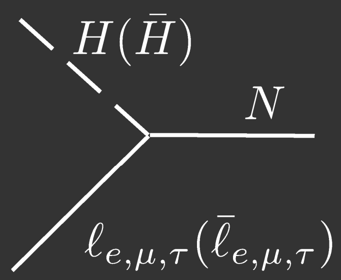
$$s\mathcal{H}z\frac{dY_{N_1}}{dz} = \left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)(\gamma_D + 2\gamma_{S_s} + 4\gamma_{S_t})$$

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

$[M_1 << M_2, M_3]$



Production



Washout

2-2 scattering Washout

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

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

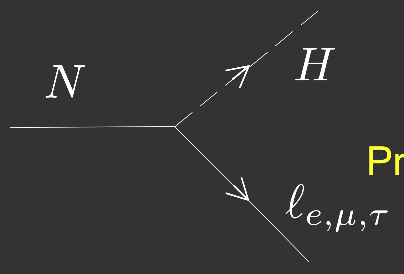
* $z = \frac{M_1}{T}$
* $Y_x = \frac{n_x}{s}$
* $\gamma_D = \gamma(N \to \ell H) + \gamma(N \to \bar{\ell}\bar{H})$

Flavor effect in Leptogenesis

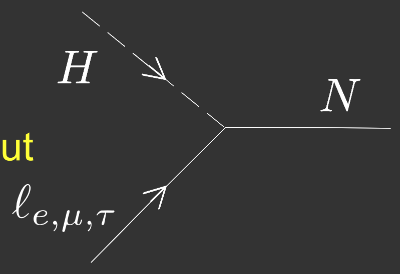
$$\mathcal{L} = Y^{\nu}_{\alpha i} \bar{\ell}_{L_\alpha} \tilde{H} N_i + Y_\alpha (\bar{\ell}_L)_\alpha H (\ell_R)_\alpha + h.c$$

[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

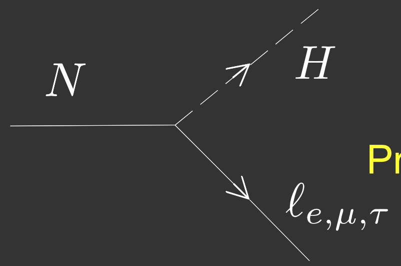


Flavor effect in Leptogenesis

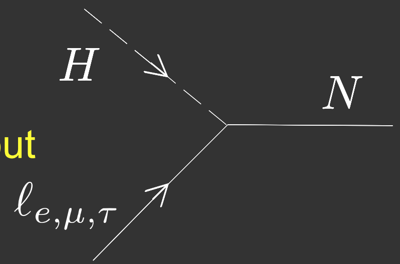
$$\mathcal{L} = Y^{\nu}_{\alpha i}\bar{\ell}_{L\alpha}\tilde{H}N_i + Y_\alpha(\bar{\ell}_L)_\alpha H(\ell_R)_\alpha + h.c$$

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

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

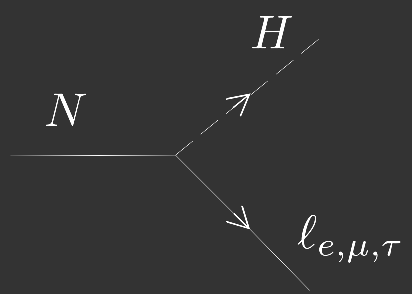


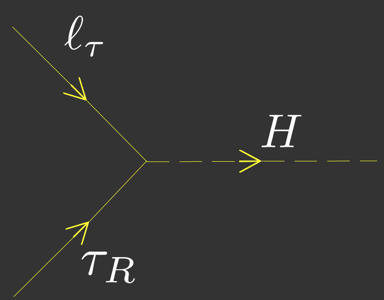
Production**[Flavor blind]**Washout

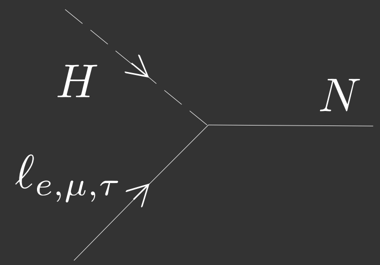


$$\Gamma_\tau(\propto m_h^2(T)/T) > \mathcal{H}$$

[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: $|\ell_1\rangle = \langle \ell_\alpha|\ell_1\rangle|\ell_\alpha\rangle$

$T^0_{\tau_R} \sim [5\times 10^{11}\ \mathrm{GeV}]$ — $\Gamma_\tau = \mathcal{H}$

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

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

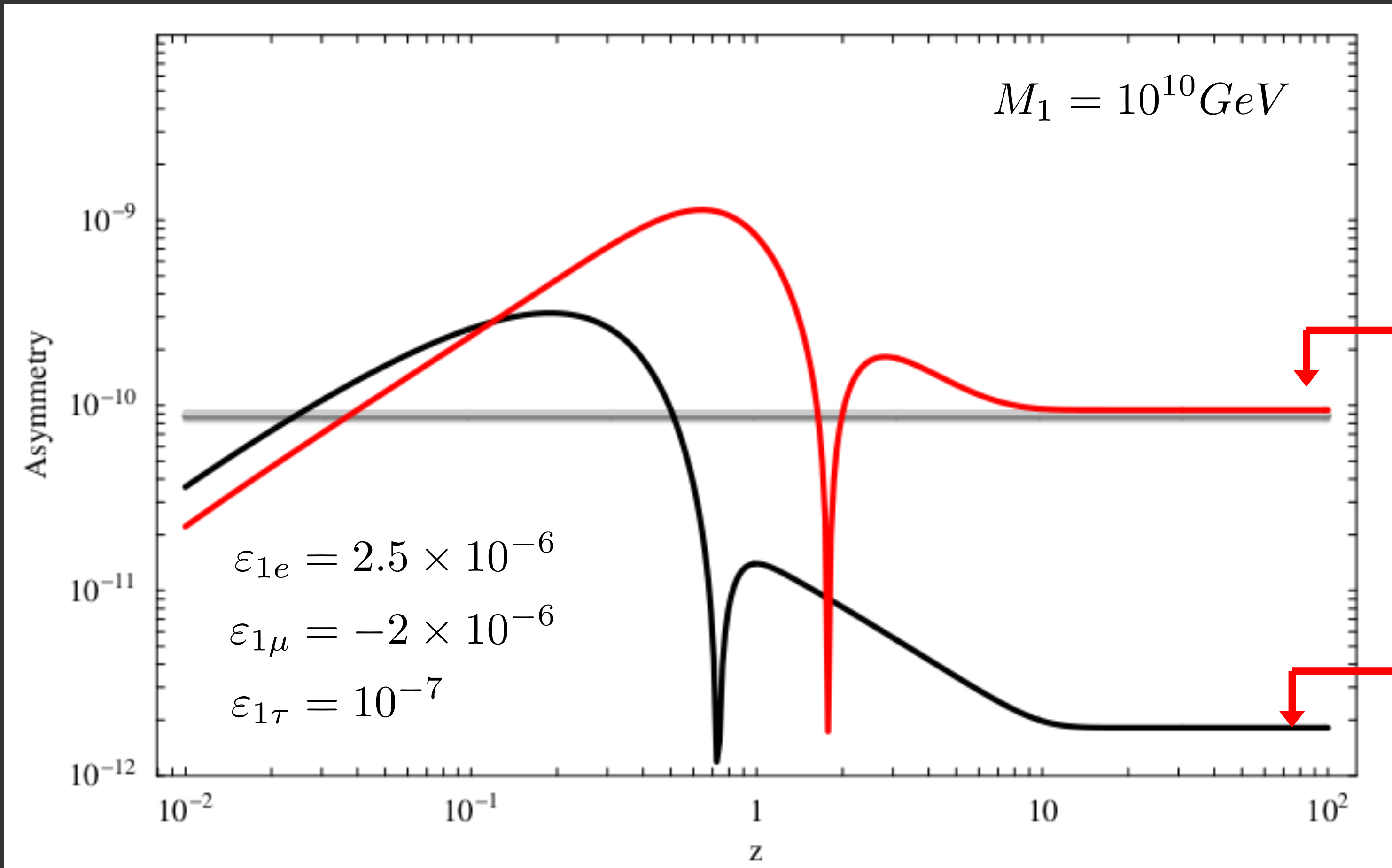
$T^0_{\mu_R} \sim [10^9\ \mathrm{GeV}]$ — $\Gamma_\mu = \mathcal{H}$

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

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

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

Importance of flavor effect



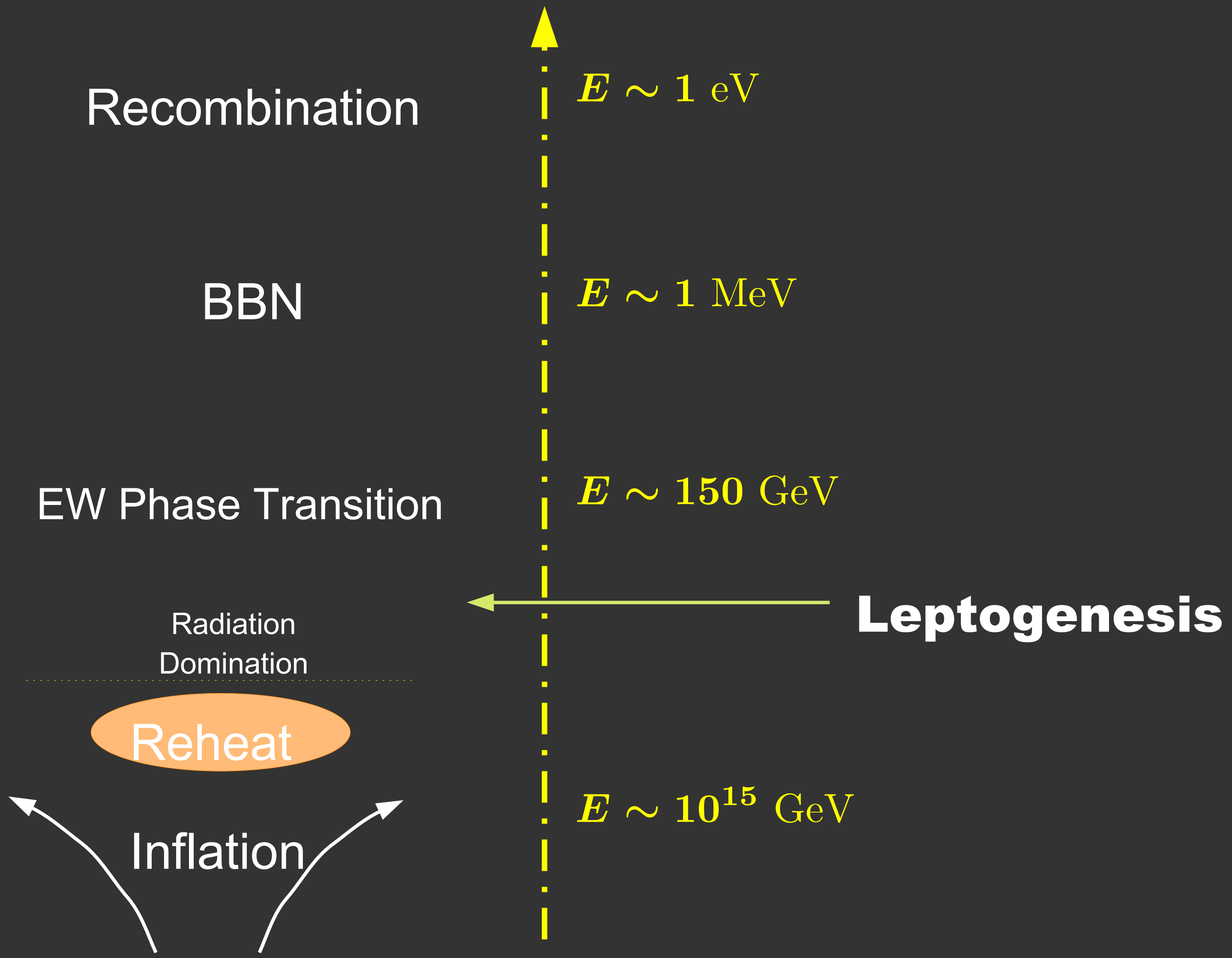
[Credit to A. Abada, S. Davidson, A. Ibarra, F.-X. Josse-Michaux, M. Losada and A. Riotto, JHEP0609:010,2006]

Two flavor

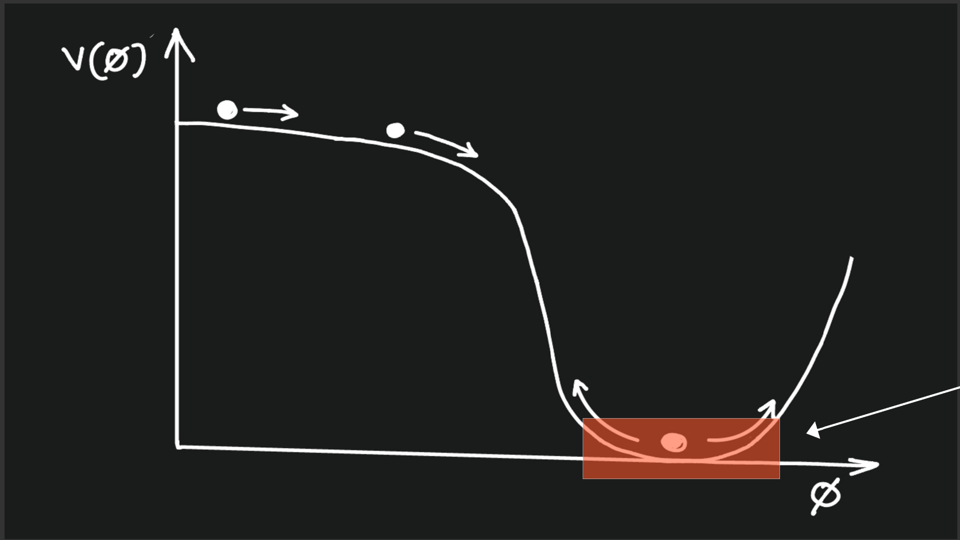
unflavor

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

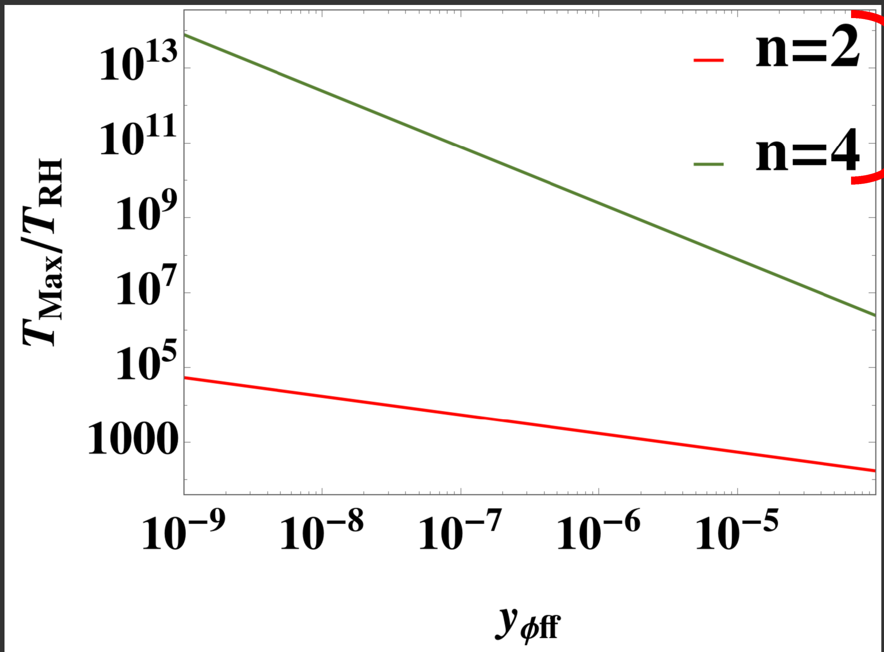
- Beginning of the thermal history.
- All elamantary particles (of SM) are generated

Era of rehating can be very rich.

Coupling between inflaton and SM

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

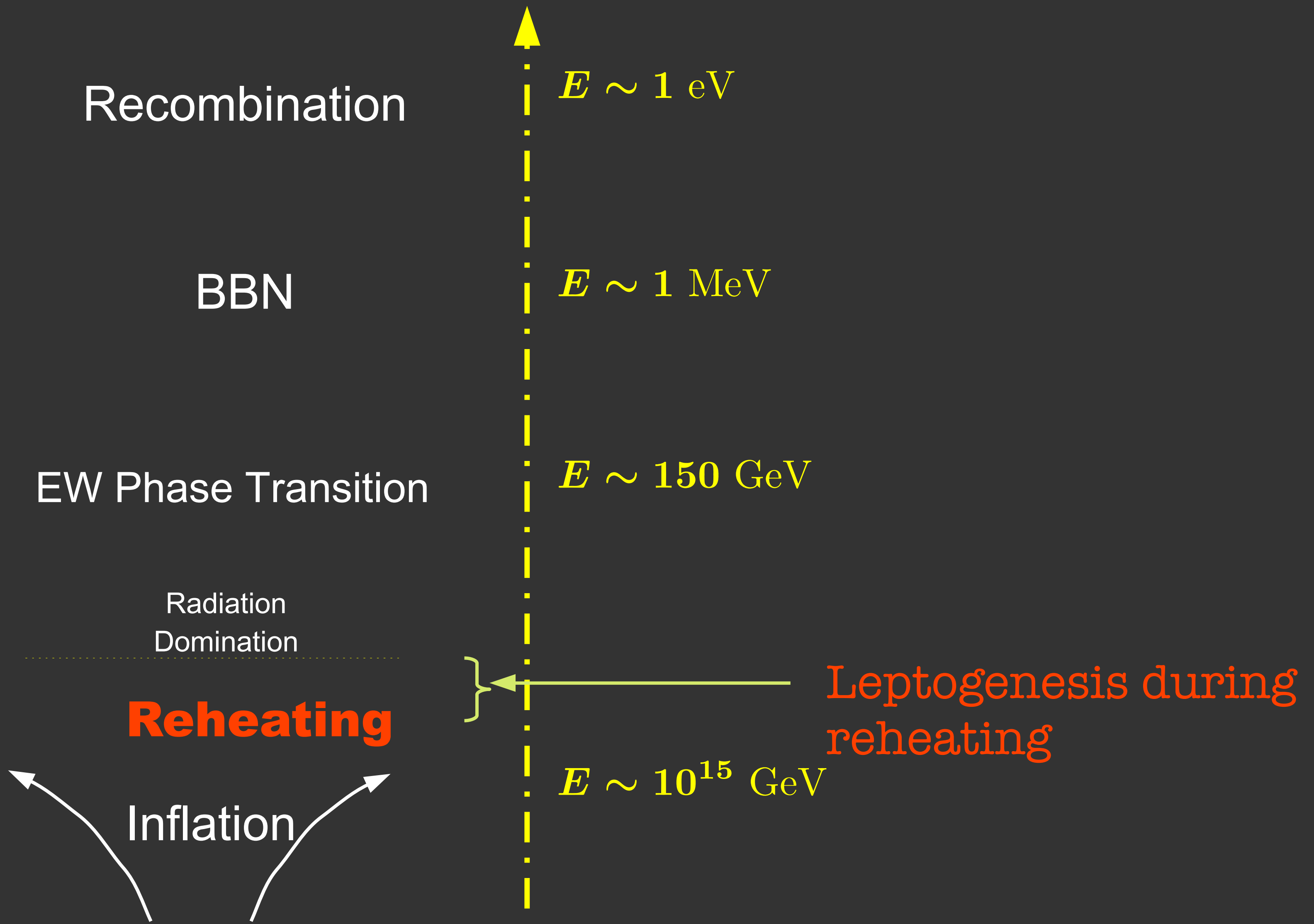
Produces radiation component ρ_R



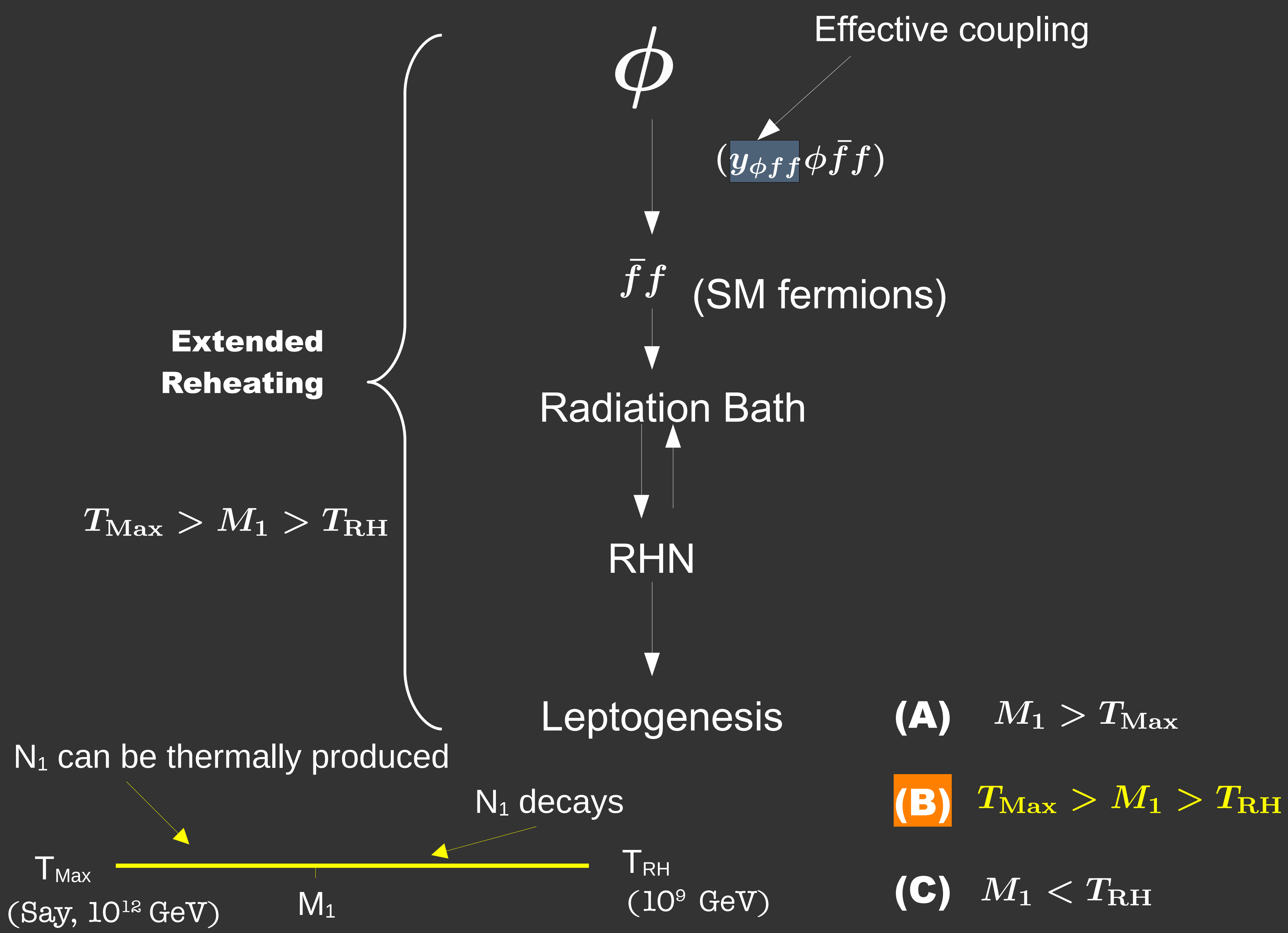
Power in inflaton potential

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

Timeline of Leptogenesis:



Setup:



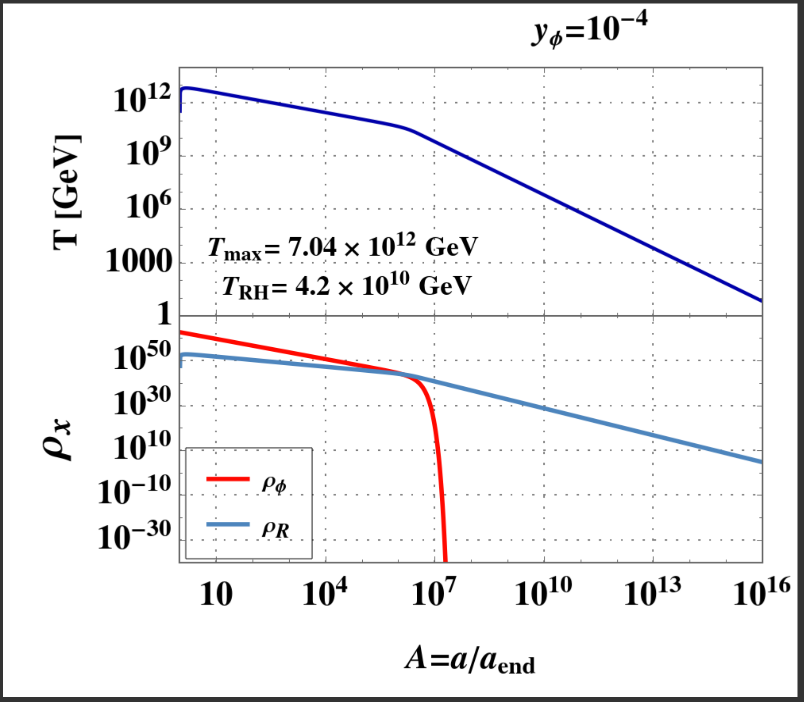
Effective coupling
ϕ
$(y_{\phi f f}\phi \bar{f} f)$
$\bar{f} f$ (SM fermions)
Extended Reheating
Radiation Bath
$T_{\rm Max} > M_1 > T_{\rm RH}$
RHN
Leptogenesis
N_1 can be thermally produced
N_1 decays
$T_{\rm Max}$
(Say, 10^{12} GeV)
M_1
$T_{\rm RH}$
(10^9 GeV)
(A) $M_1 > T_{\rm Max}$
(B) $T_{\rm Max} > M_1 > T_{\rm RH}$
(C) $M_1 < T_{\rm RH}$

Equilibration of Charged lepton Yukawa:

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

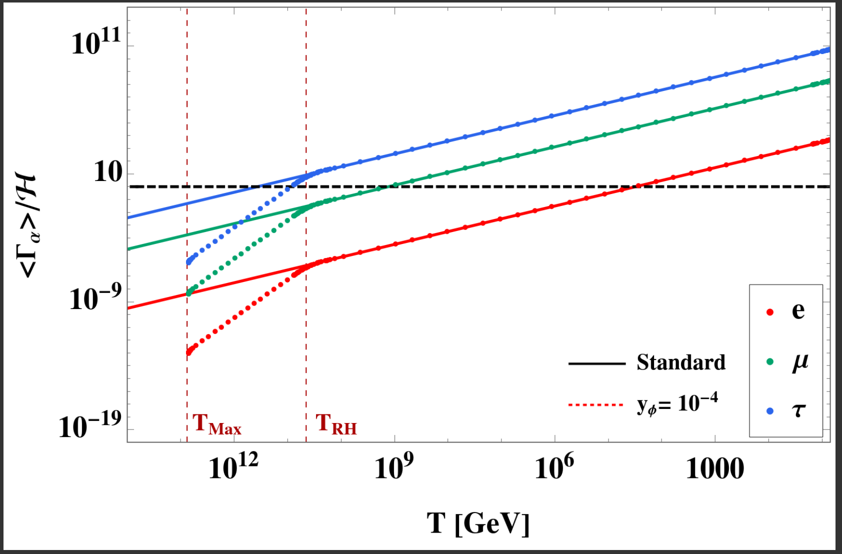
$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi$$

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



Thermal Mass of Higgs

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

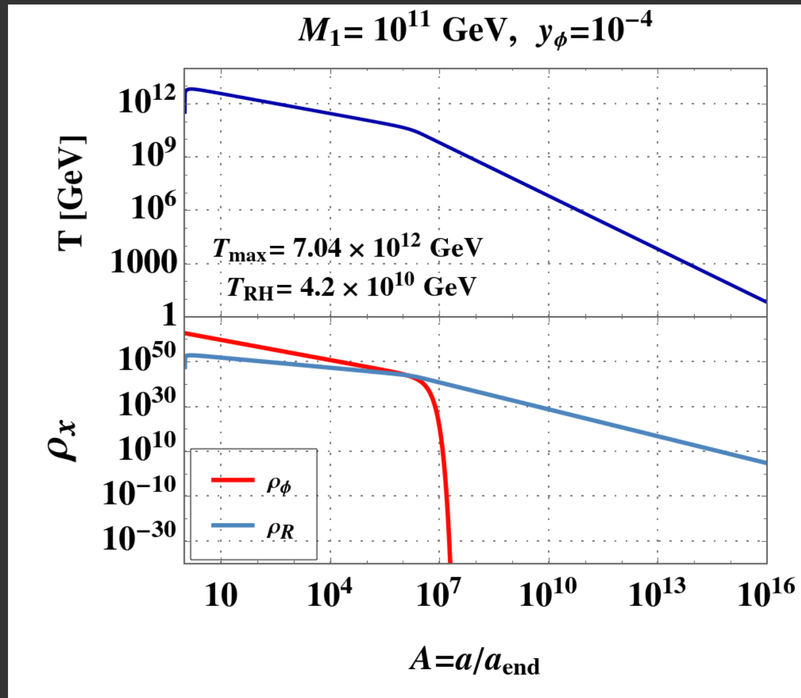


Equilibration of Charged lepton Yukawa:

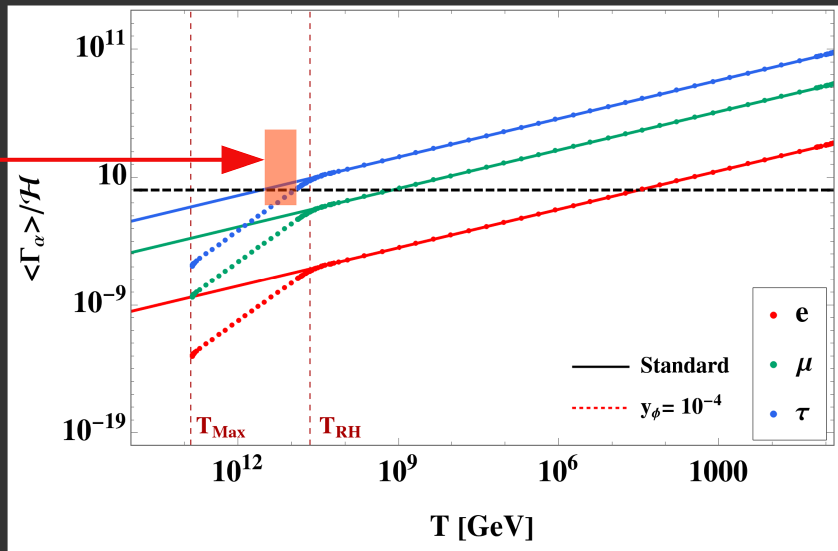
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

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

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



- 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

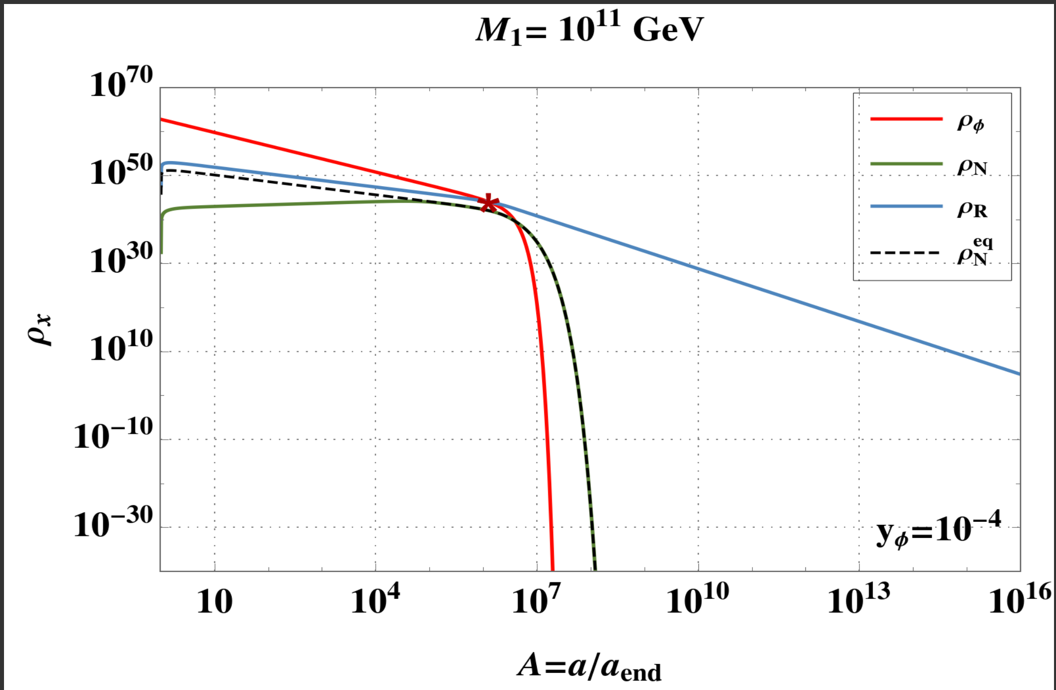
Bolzmann Equation and Temperature:

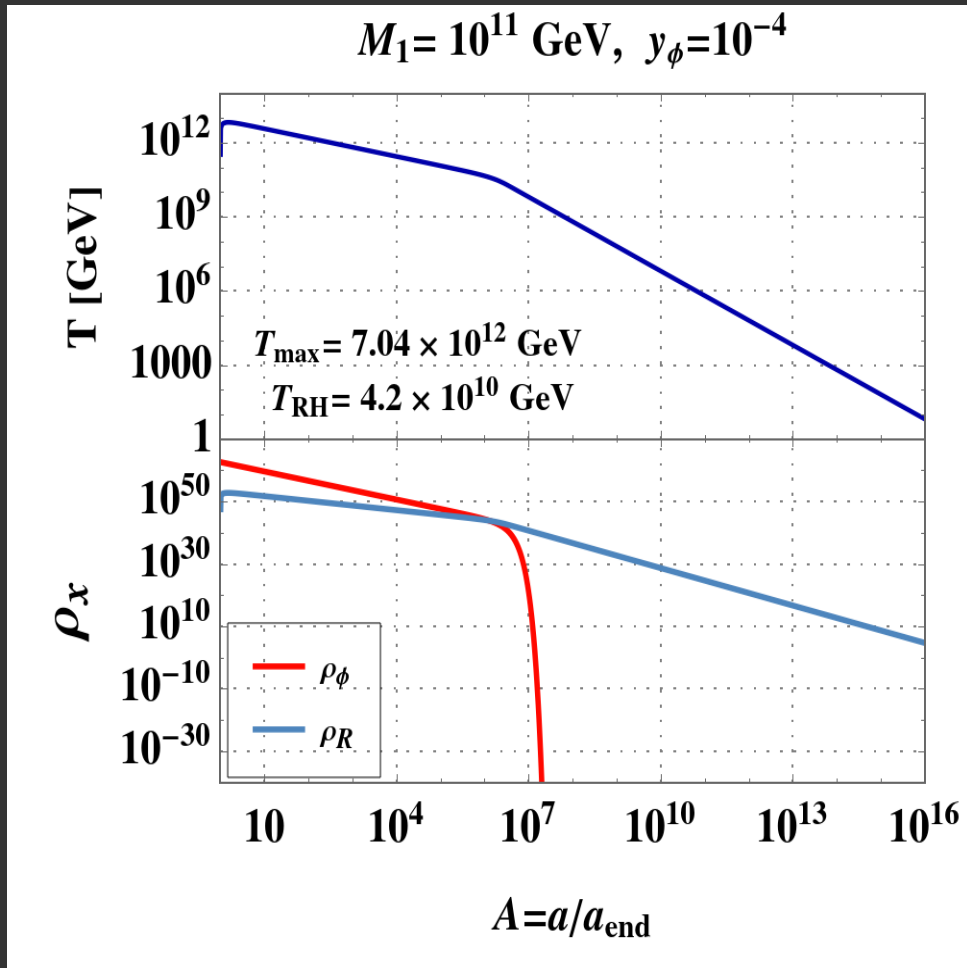
$$\frac{d(\rho_\phi a^3)}{da} = -\frac{\Gamma_\phi}{\mathcal{H}}\rho_\phi a^2$$

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

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

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





Modification of Flavor effect

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

$y_\phi = 10^{-4}$

T [GeV]

No Flavor effect:

$|\ell_1\rangle = \langle\ell_\alpha|\ell_1\rangle|\ell_\alpha\rangle$

$T^0_{\tau_R} \sim [5\times 10^{11}]$

$T_{\tau_R} \sim [7.5\times 10^{10}]$

$\Gamma_\tau = \mathcal{H}$

Leptogenesis

Two Flavor:

$|\ell_a\rangle,\ |\ell_\tau\rangle$

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

No Flavor effect

$T^0_{\mu_R} \sim [10^9]$

$\Gamma_\mu = \mathcal{H}$

Three Flavor:

$|\ell_e\rangle,\ |\ell_\mu\rangle,\ |\ell_\tau\rangle$

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

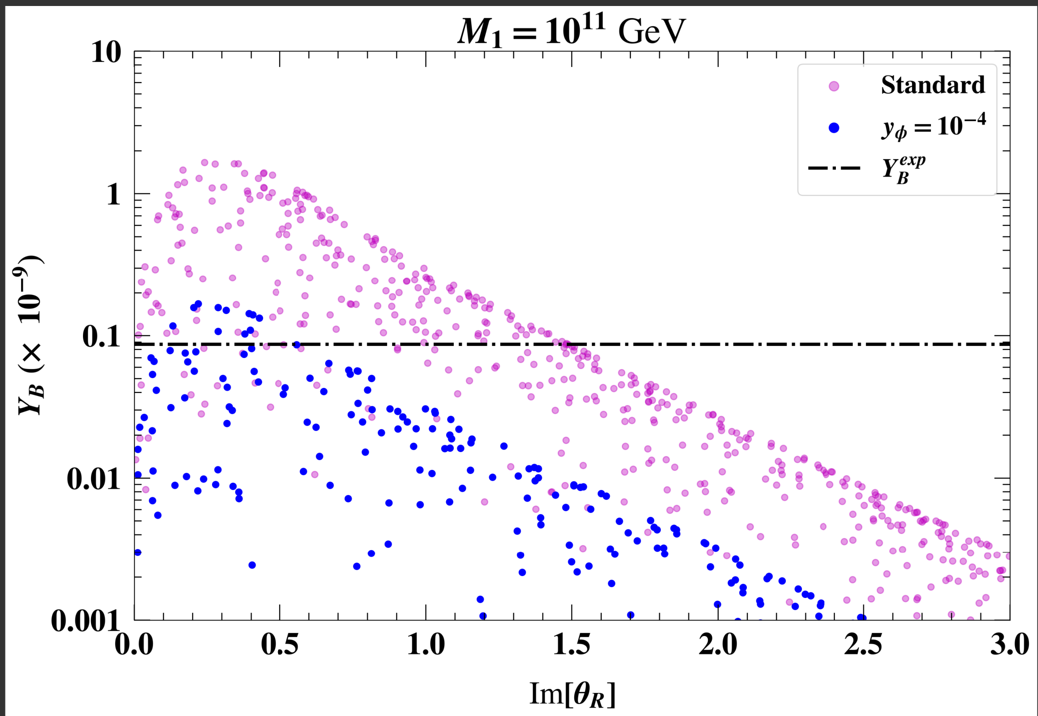
Modification of Baryon asymmetry

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

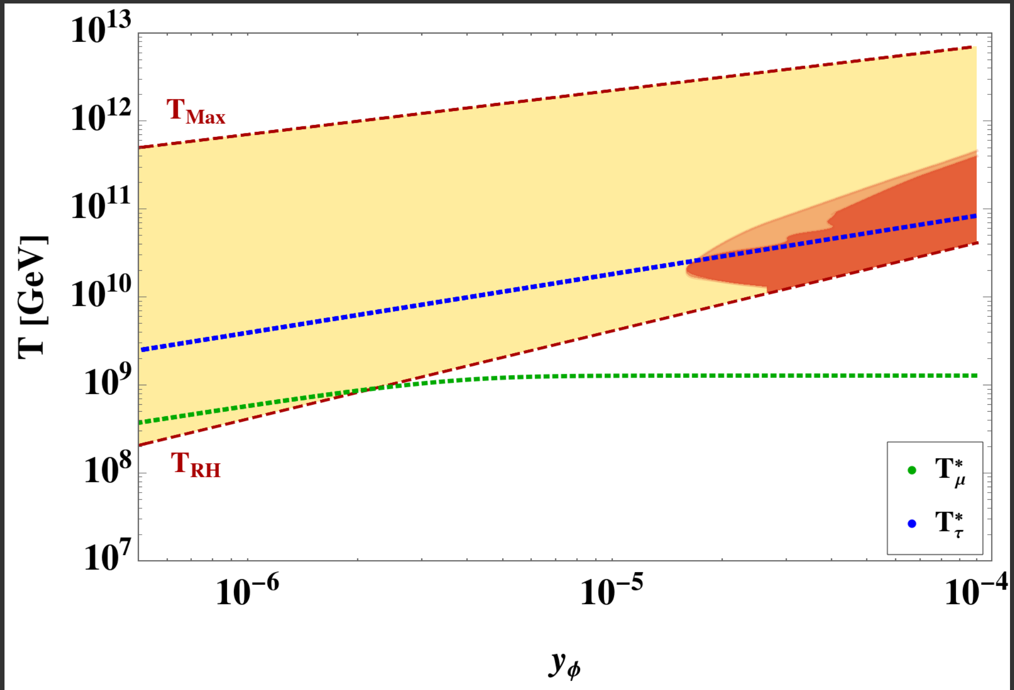
$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi + \frac{a^3}{H}\langle\Gamma_{N_1}\rangle(\rho_{N_1} - \rho_{N_1}^{\text{eq}})$$

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

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



Modification of Baryon asymmetry



- **Prolonged Reheating** was achieved 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 **modified flavor effect** as well as **dilution of baryon asymmetry** due to **entropy injection** from inflaton decay.

CONCLUSION

Leptogenesis takes place during an extended era of reheating

- Shift of Charged Lepton Yukawa Equilibrium Temperature
- Flavor Leptogenesis regime gets modified

Thank You