Is leptogenesis during gravitational reheating flavorful?

Arghyajit Datta
LSSU, Jeonbuk National University

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Evidence of matter-antimatter asymmetry

Baryon to photon ratio:

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

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]

Leptogenesis

Dynamically generates the baryon asymmetry by generating a lepton asymmetry first

Advantages: Neutrino Mass $\longleftrightarrow$ Lepton asymmetry

Type-I Seesaw mechanism
(SM + 3 Right-Handed Neutrinos)

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

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

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

Leptogenesis

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

Advantages: 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]

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

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CP Violation

Lepton number Violation

Out-of equilibrium dynamics

[Sakharov, 1967]

Decay of RHN at T < M_N

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

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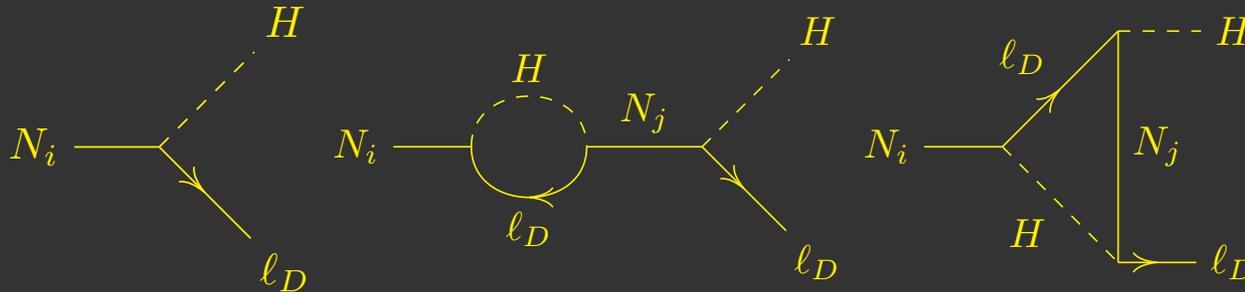
Leptogenesis

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

Assumptions:

1) Hierarchical RHNs : only lightest RHN will generate the asymmetry.

2) $\ell_D = \dfrac{Y^{\nu}_{\alpha 1}}{\sqrt{(Y^{\nu\dagger}Y^{\nu})_{11}}} \ell_{\alpha}$ **: asymmetry is generated along this direction**

$$\epsilon_i = \frac{\Gamma(N_i \to \ell_D + H) - \Gamma(N_i \to \bar{\ell}_D + H^{\dagger})}{\Gamma(N_i \to \ell_D + H) + \Gamma(N_i \to \bar{\ell}_D + H^{\dagger})} = \frac{1}{8\pi(Y^{\nu\dagger}Y^{\nu})_{ii}} \sum_{j \neq i} \text{Im}\left[(Y^{\nu\dagger}Y^{\nu})^2_{ij}\right] \mathcal{F}\left(\frac{M_j^2}{M_i^2}\right)$$
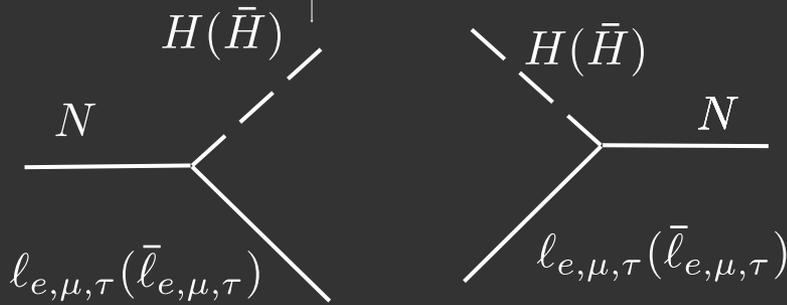
$$\mathcal{F}(x) = \sqrt{x}\left[1 + \frac{1}{1-x} + (1+x)\ln\left(\frac{x}{1+x}\right)\right]$$

Lepton & Baryon asymmetry

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

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

$$[M_1 << M_2, M_3]$$

$H(\bar{H})$

$H(\bar{H})$

2-2 scattering Washout

N

N

$\ell_{e,\mu,\tau}(\bar{\ell}_{e,\mu,\tau})$

$\ell_{e,\mu,\tau}(\bar{\ell}_{e,\mu,\tau})$

Production

Washout

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

(At sphaleron decoupling limit)

$T \sim 150 \text{ GeV}$

$* \quad z = \dfrac{M_1}{T}$

$* \quad Y_x = \dfrac{n_x}{s}$

$* \quad \gamma_D = \gamma(N \to \ell H) + \gamma(N \to \bar{\ell}\bar{H})$

$$\mathcal{L} = Y_{\alpha i}^{\nu} \bar{\ell}_{L_{\alpha}} \tilde{H} N_i + Y_{\alpha} (\bar{\ell}_L)_{\alpha} H (\ell_R)_{\alpha} + h.c$$
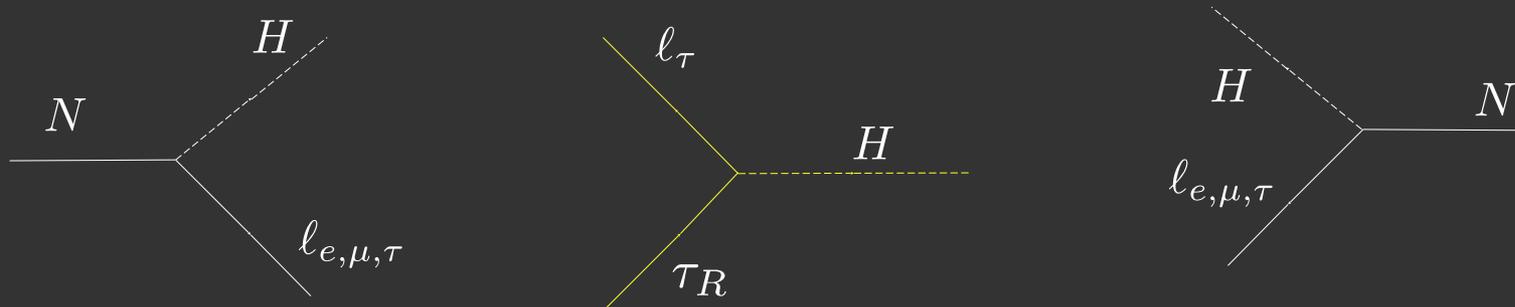
[Credit to
**Barbieria et. al.,2000; Nardi et. al., 2005, 2006;
Blanchet, Bari, 2006, 2007; A. Abada et.al.,2007;**
,and many more...]

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

N

H

$\ell_{e,\mu,\tau}$

Production **[Flavor blind]** Washout

H

N

$\ell_{e,\mu,\tau}$

Flavor effect in Leptogenesis

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

[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

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

T [GeV]

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

$T_\tau^0 \sim 5 \times 10^{11}$ GeV

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

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

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

$T_\mu^0 \sim 10^9$ GeV

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

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

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

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

Importance of flavor effect

$M_1 = 10^{10} GeV$

$\varepsilon_{1e} = 2.5 \times 10^{-6}$

$\varepsilon_{1\mu} = -2 \times 10^{-6}$
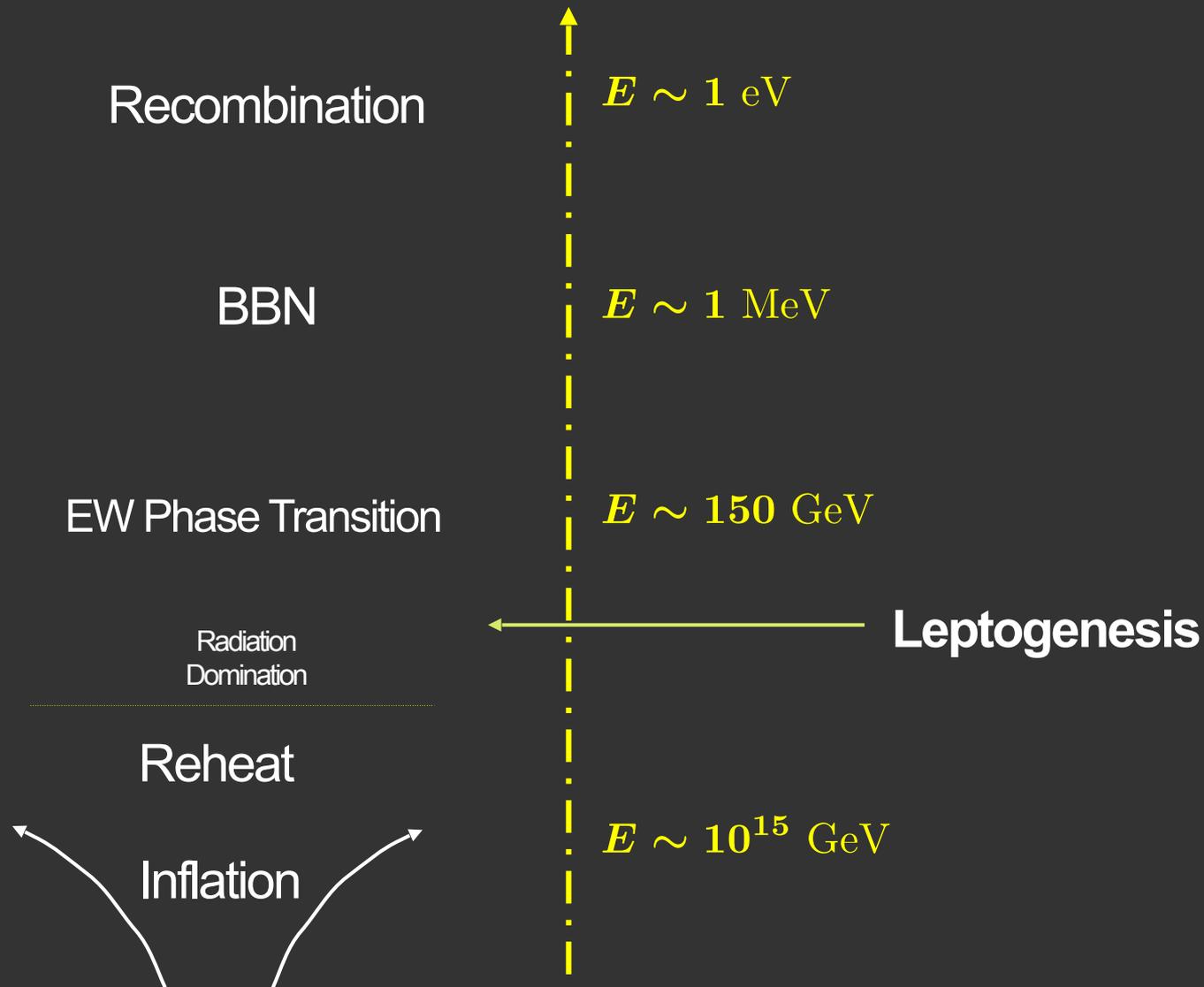
$\varepsilon_{1\tau} = 10^{-7}$

Two flavor
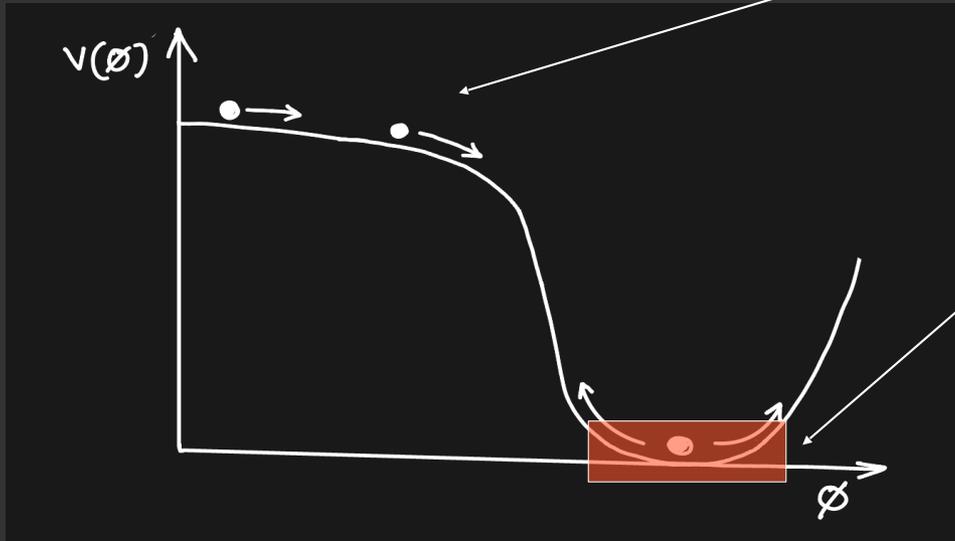
unflavor / one flavor

Almost one order shift in produced baryon asymmetry can be achieved

Timeline of Leptogenesis:

Recombination $E \sim 1 \; \mathrm{eV}$

BBN $E \sim 1 \; \mathrm{MeV}$

EW Phase Transition $E \sim 150 \; \mathrm{GeV}$

Radiation
Domination

   $\longleftarrow$ **Leptogenesis**

Reheat

$E \sim 10^{15} \; \mathrm{GeV}$

Inflation

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

Transfer of energy of inflaton

V($\varnothing$)

$\varnothing$

Reheating

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

$$V(\phi) = \lambda M_p^4 \left[\sqrt{6} \tanh\left(\frac{\phi}{\sqrt{6} M_p} \right) \right]^k \longrightarrow \lambda M_p^4 \left(\frac{\phi}{M_p} \right)^k$$

[See Marcos Garcia, Yann Mambrini's Talk]

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

V(∅)

∅

Transfer of energy of inflaton

Reheating

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

Most Minimal way
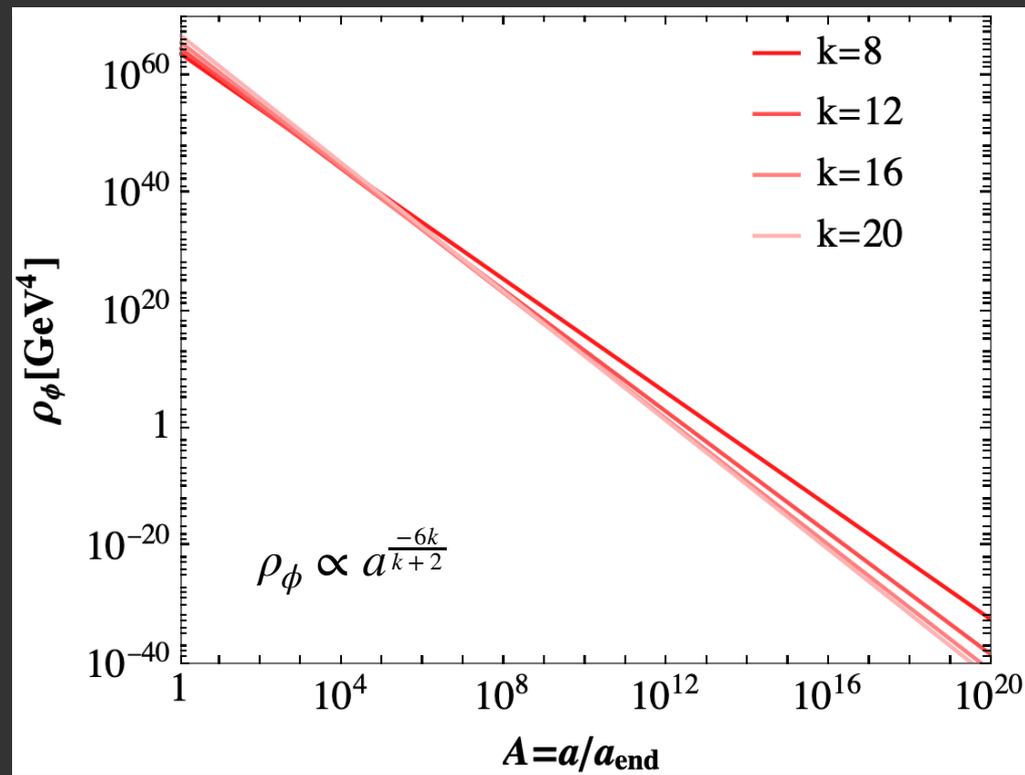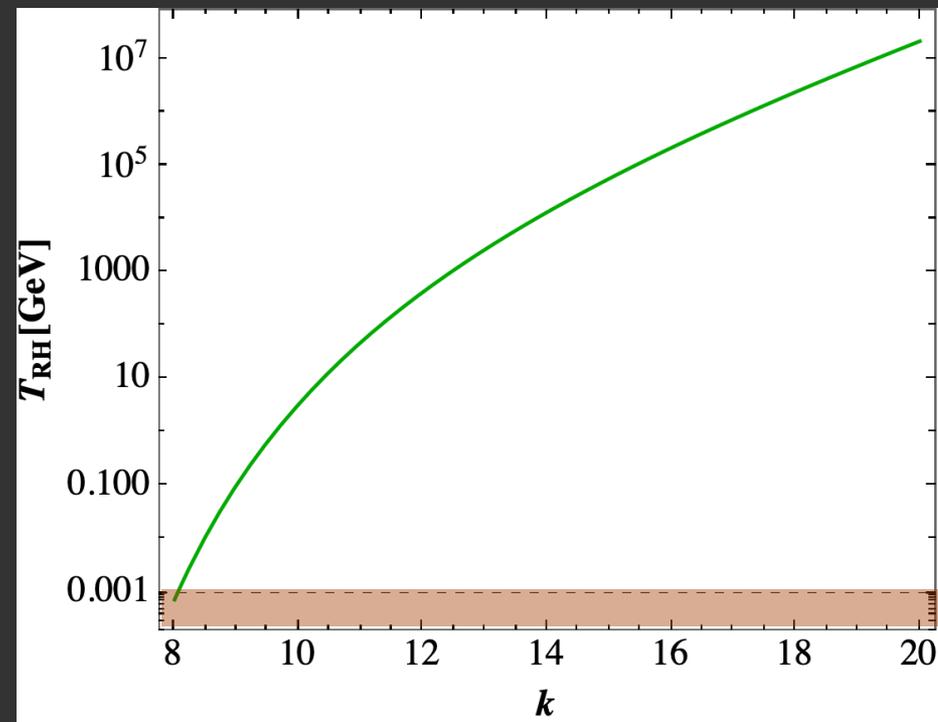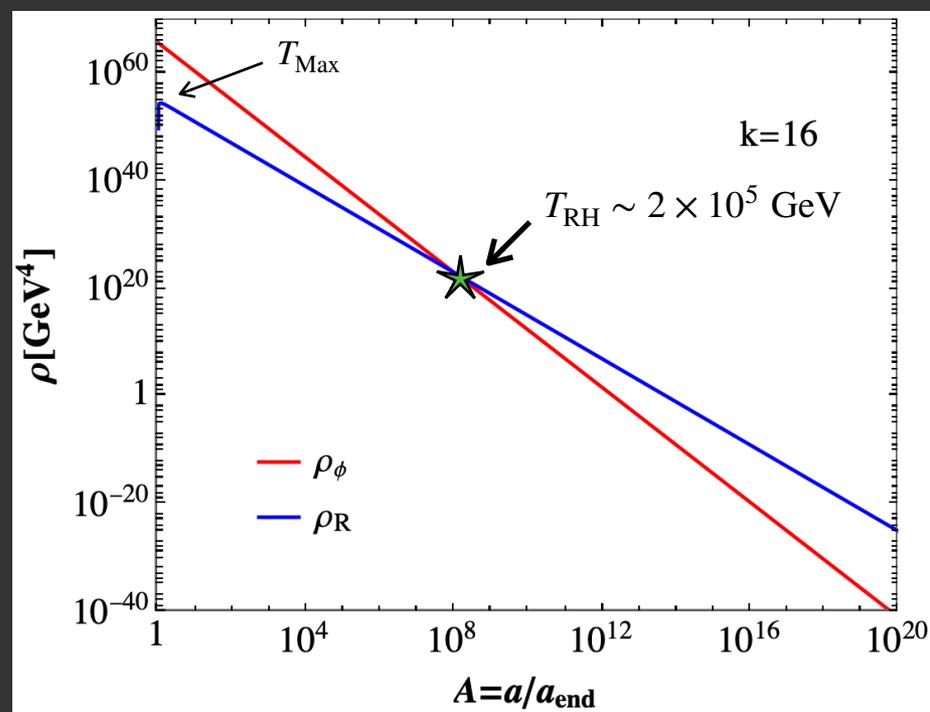
Universal Gravitational Coupling

$$V(\phi) = \lambda M_p^4 \left[\sqrt{6} \tanh\left(\frac{\phi}{\sqrt{6}M_p} \right) \right]^k \longrightarrow \lambda M_p^4 \left(\frac{\phi}{M_p} \right)^k$$

$$S = \int d^4 x \sqrt{-g} \left[\frac{M_p^2}{2} R + \mathcal{L}_\phi + \mathcal{L}_{\mathrm{SM}} \right]$$

$$g_{\mu\nu} \simeq \eta_{\mu\nu} + \frac{2}{M_p} h_{\mu\nu}$$

$$\sqrt{-g}\mathcal{L} = -\frac{1}{M_p} h_{\mu\nu} T_{s/f}^{\mu\nu}$$

ϕ

ϕ

s/f

s/f

$h_{\mu\nu}$

$$\rho_\phi \propto a^{\frac{-6k}{k+2}}$$
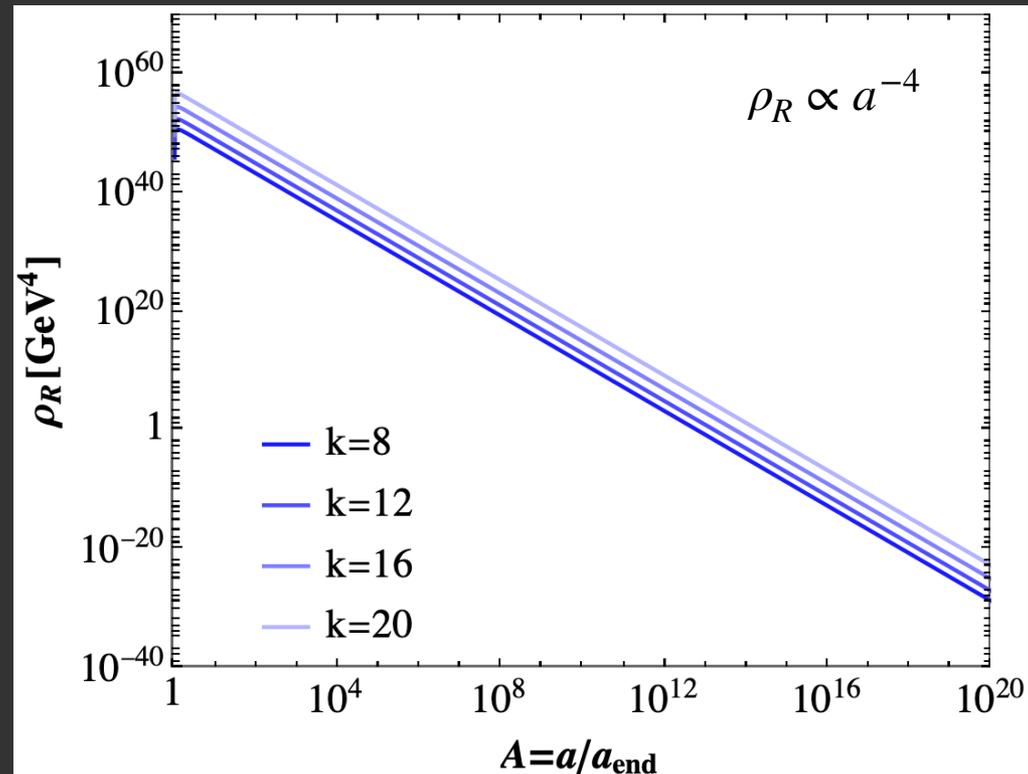
$$\rho_R \propto a^{-4}$$

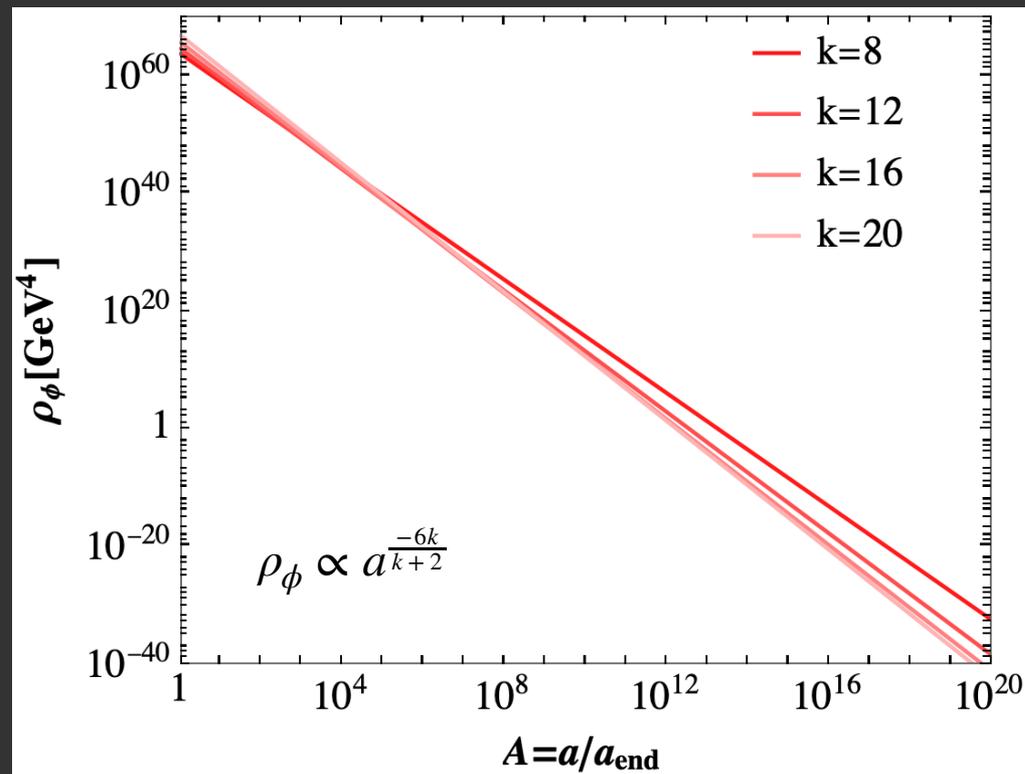$$V(\phi) = \lambda M_p^4 \left[\sqrt{6} \tanh\left(\frac{\phi}{\sqrt{6} M_p} \right) \right]^k \longrightarrow \lambda M_p^4 \left(\frac{\phi}{M_p} \right)^k$$
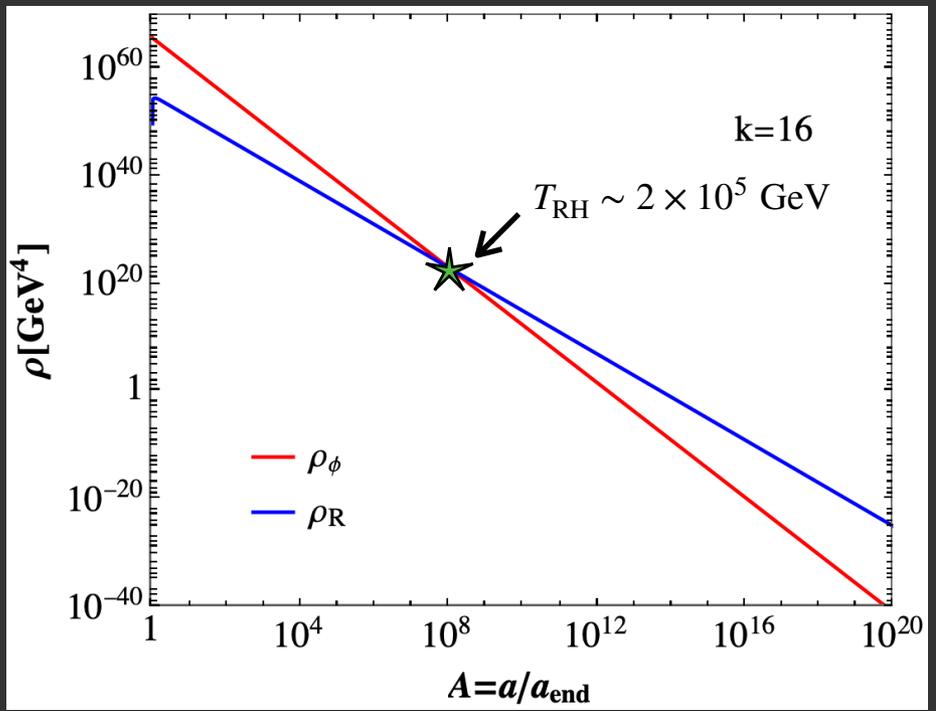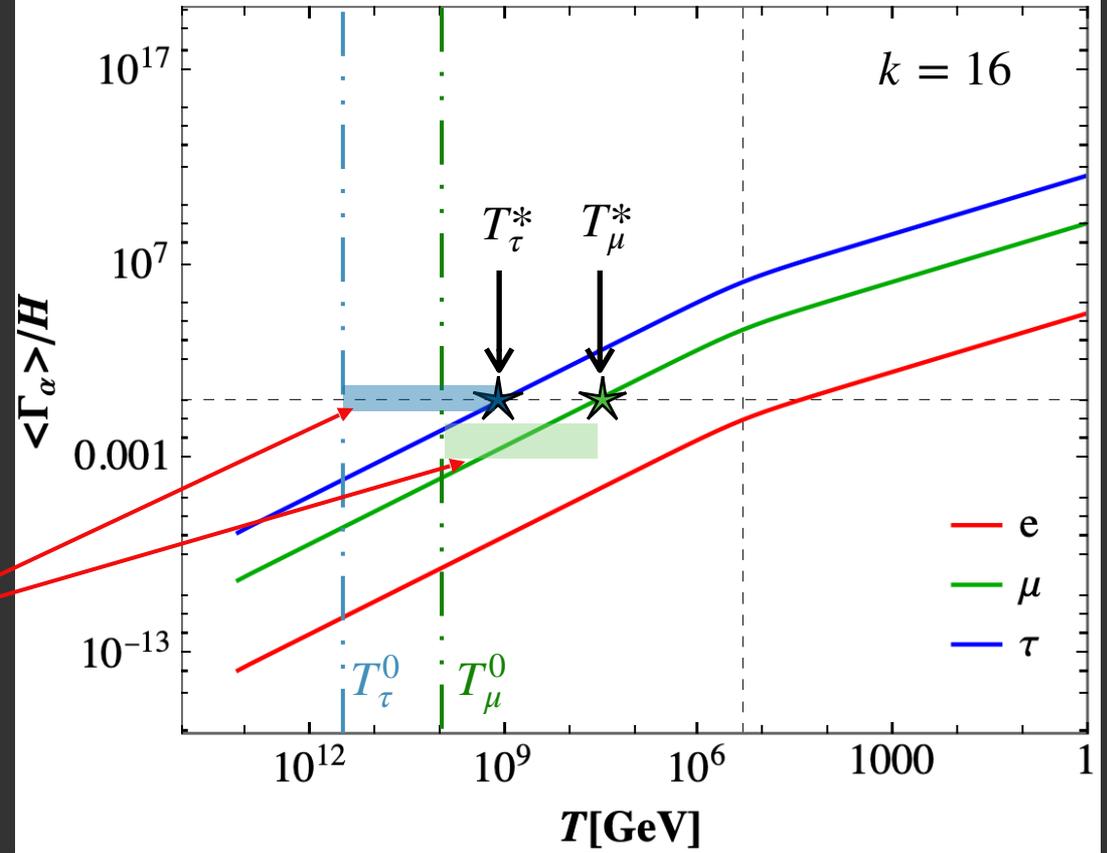
$$\frac{d\rho_\phi}{dt} + 3\mathscr{H}(1 + \omega_\phi)\rho_\phi = -(1 + \omega_\phi)\rho_\phi \Gamma_\phi$$

$$\frac{d\rho_R}{dt} + 4\mathscr{H}\rho_R = (1 + \omega_\phi)\rho_\phi \Gamma_\phi$$

$\rho_\phi \propto a^{\frac{-6k}{k+2}}$

$\rho_R \propto a^{-4}$

T_{Max}

$T_{\mathrm{RH}} \sim 2 \times 10^5 \text{ GeV}$

k=16

ρ_ϕ

ρ_R

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

Delayed equilibration of charged lepton Yukawa interactions

Modification of Flavor effect

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

T [GeV]

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

$T^0_\tau \sim 5 \times 10^{11}$ GeV $\qquad \Gamma_\tau = \mathscr{H}$

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

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

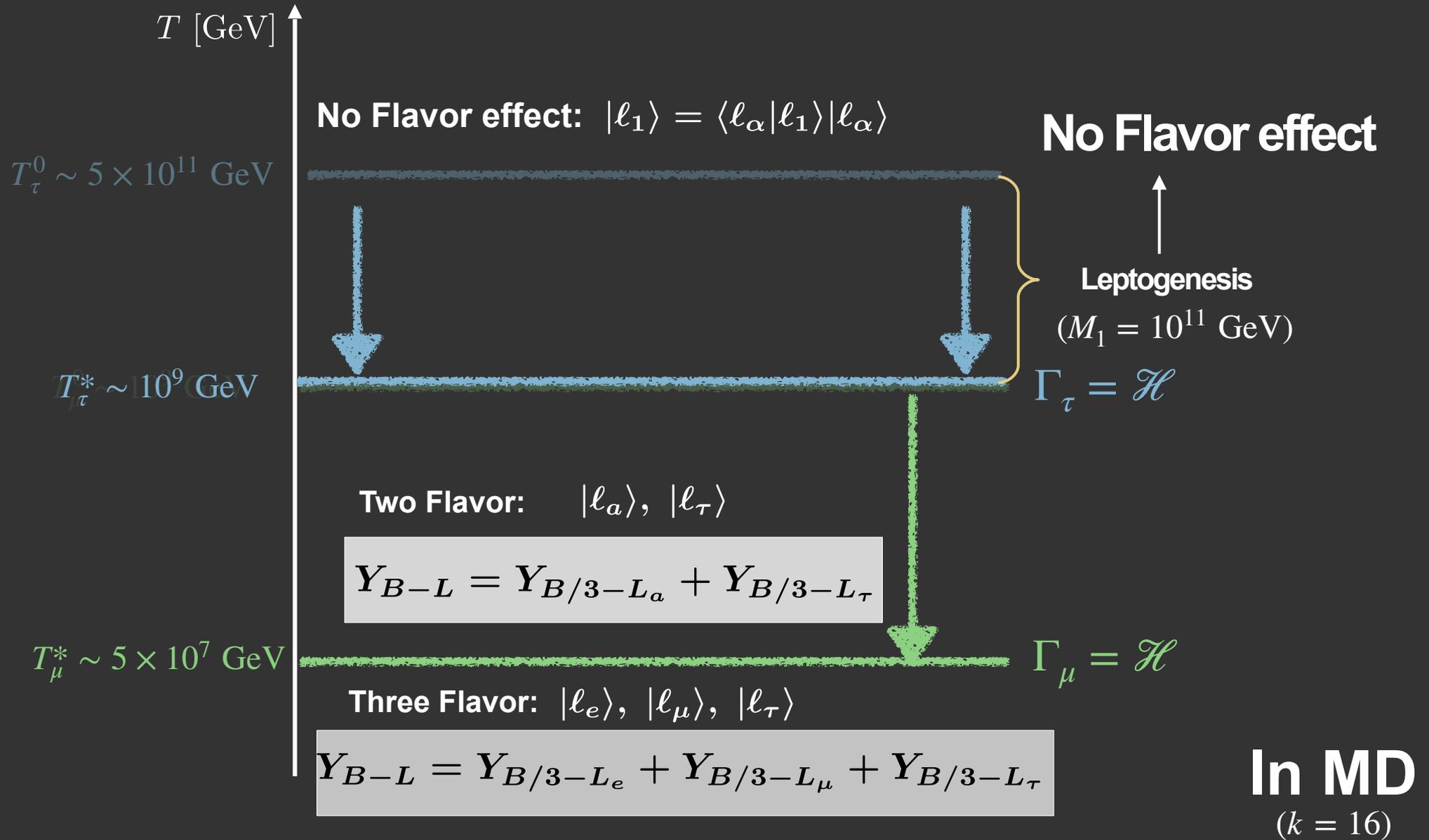$T^0_\mu \sim 10^9$ GeV $\qquad \Gamma_\mu = \mathscr{H}$

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

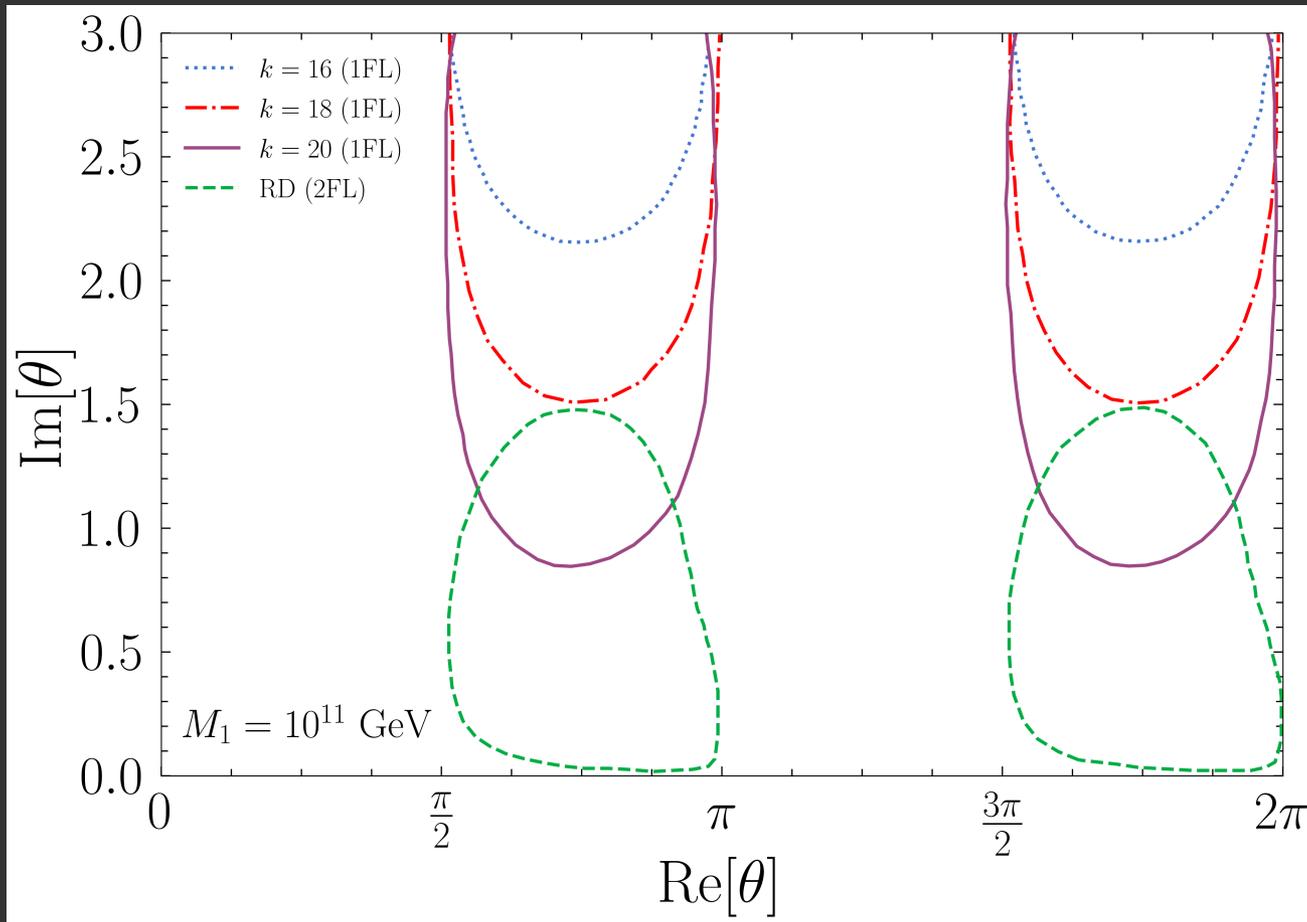$$Y_{B-L} = Y_{B/3 - L_e} + Y_{B/3 - L_\mu} + Y_{B/3 - L_\tau}$$

In RD

Modification of Flavor effect

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

T [GeV]

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

No Flavor effect

$T^0_\tau \sim 5\times10^{11}$ GeV

Leptogenesis

$(M_1 = 10^{11}$ GeV$)$

$T^*_\tau \sim 10^9$ GeV

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

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

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

$T^*_\mu \sim 5\times10^7$ GeV

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

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

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

In MD

$(k = 16)$

Modification of Baryon asymmetry

$$Y^\nu = -i\frac{\sqrt{2}}{v}UD_{\sqrt{m}}RD_{\sqrt{M}}$$
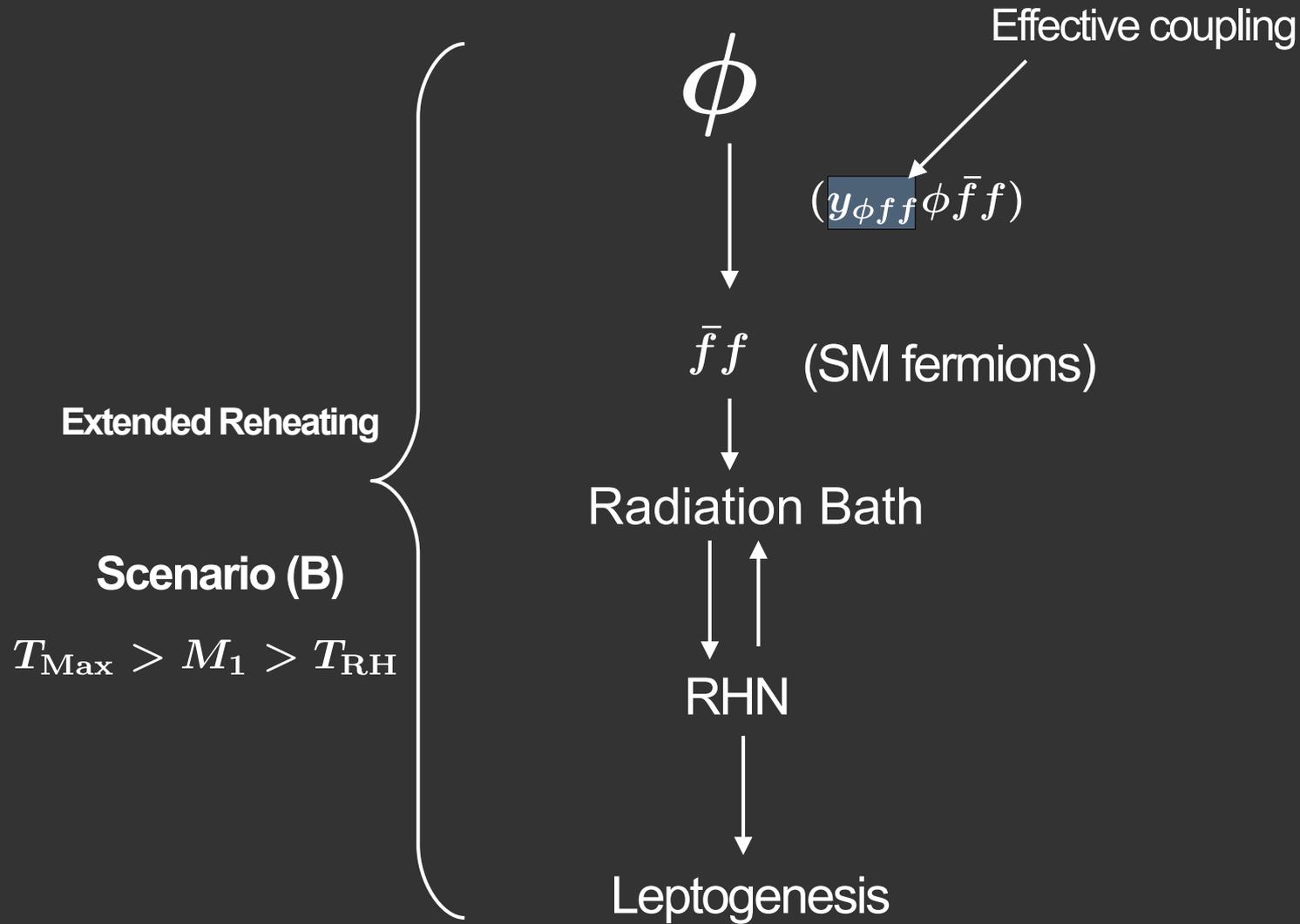
[Casas, Ibarra, 2001]

$$R = R(\theta)$$

Complex Angle

- **One needs larger Neutrino Yukawa coupling to produce the correct baryon asymmetry.**

- **Smaller k(>8) values, although reheat the Universe, will not always generate the observed baryon asymmetry.**
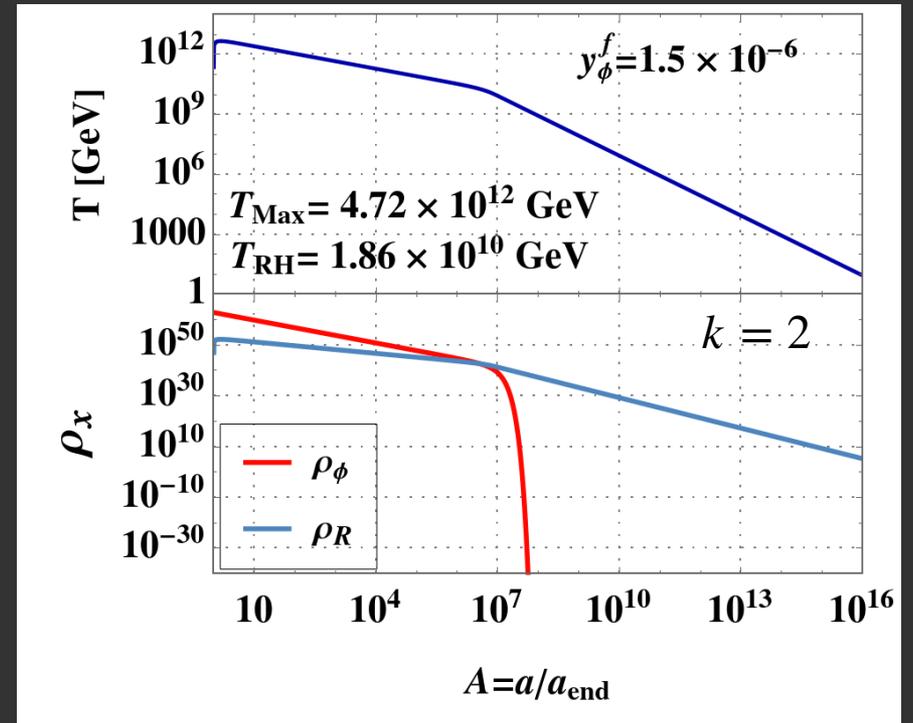
Effective coupling

$$\phi$$

$$(y_{\phi ff}\,\phi\bar{f}f)$$

$$\bar{f}f$$ (SM fermions)

Radiation Bath

RHN

Leptogenesis

Extended Reheating

Scenario (B)

$$T_{\mathrm{Max}} > M_1 > T_{\mathrm{RH}}$$

Boltzmann Equation and Temperature:

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

$$\frac{d\left(\rho_R a^4\right)}{da} = \frac{a^3}{\mathcal{H}}\Gamma_\phi\rho_\phi$$
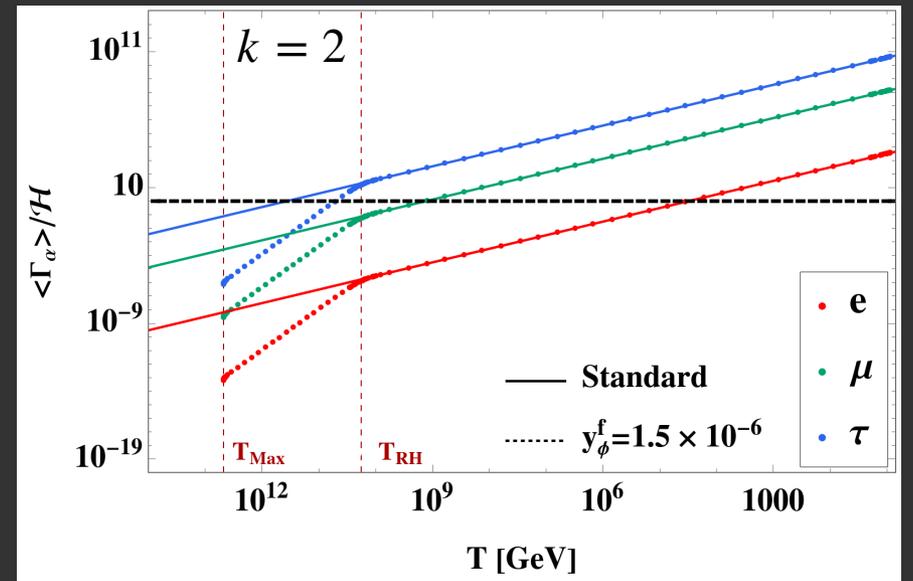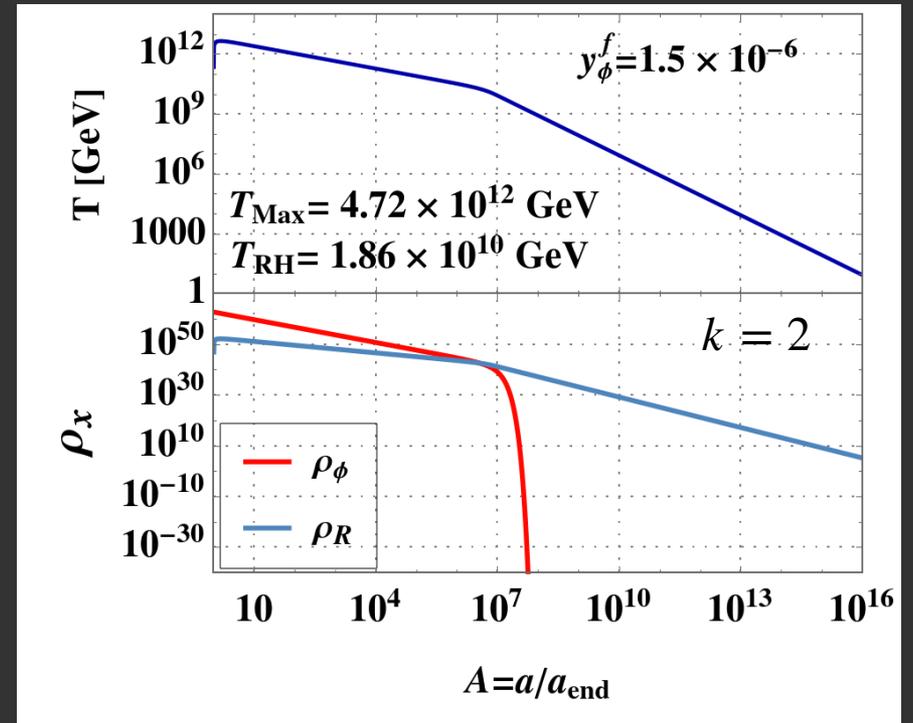
$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$

Equilibration of Charged lepton Yukawa:

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

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

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

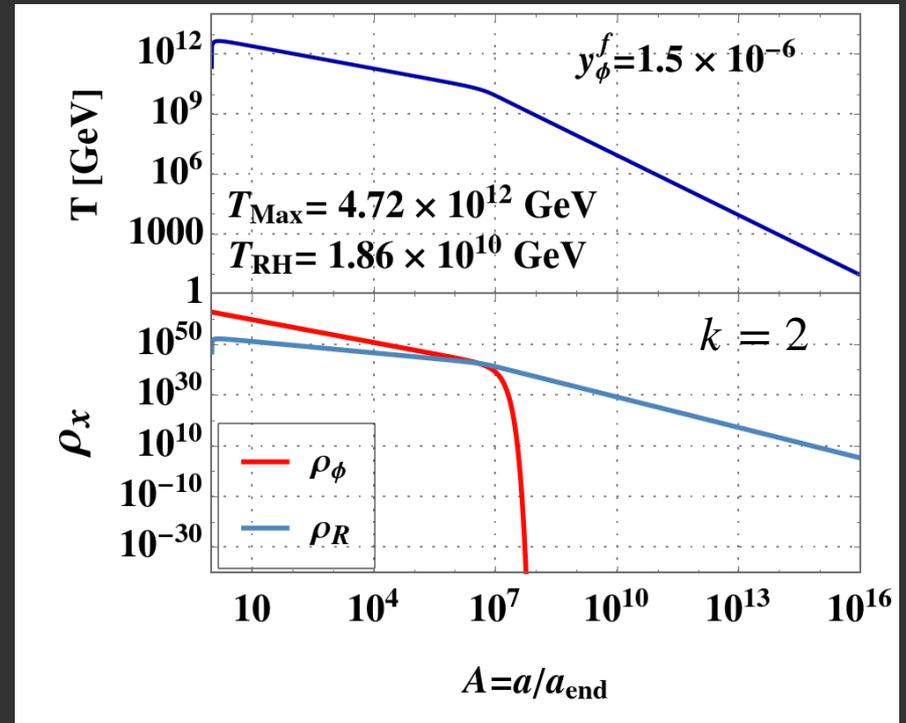$$\langle \Gamma_\alpha \rangle = \frac{\pi Y_\alpha^2}{192\zeta(3)}\frac{m_h^2(T)}{T} = \mathcal{H}$$

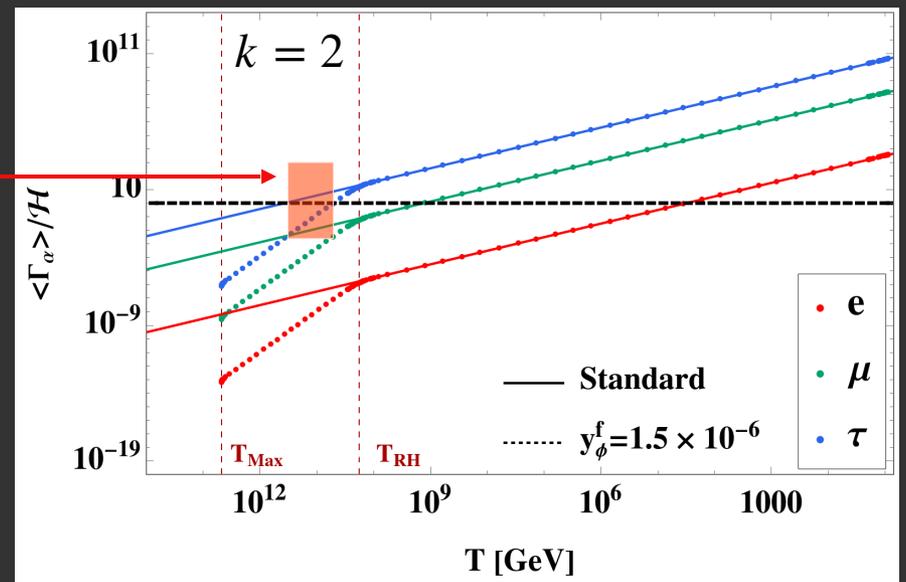# Equilibration of Charged lepton Yukawa:

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

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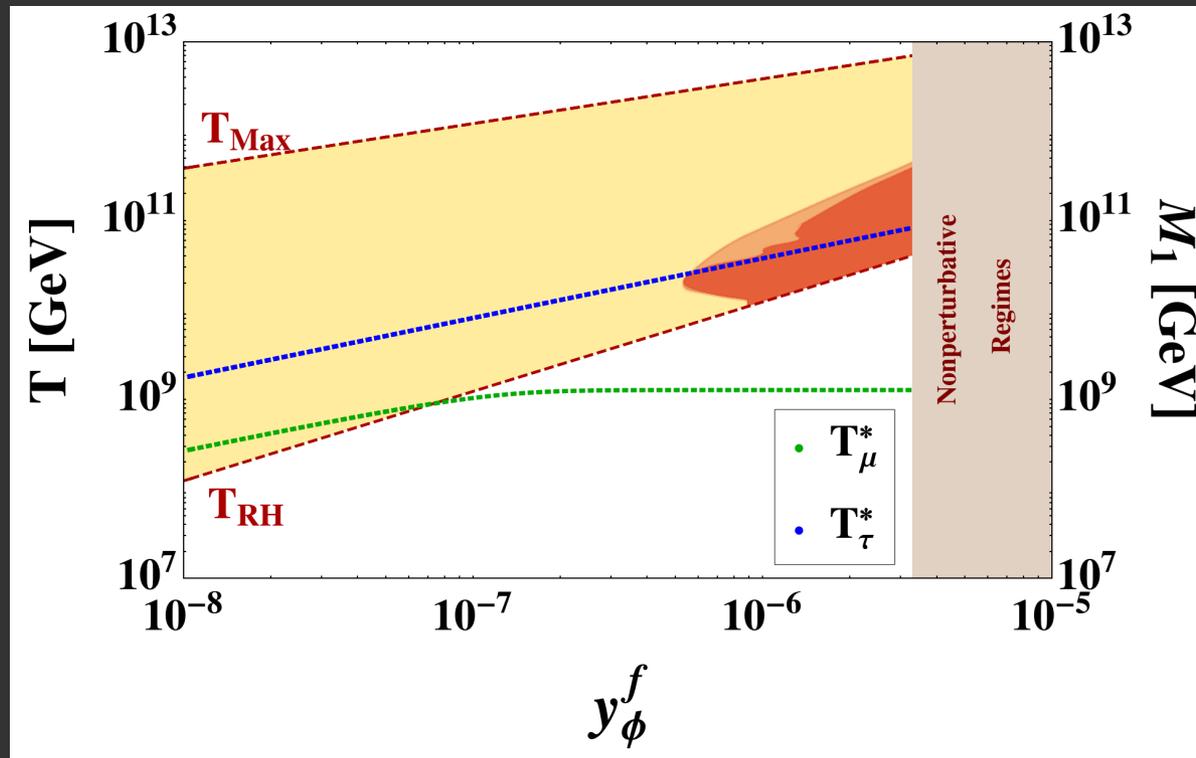
$$\mathcal{H}^2 = \frac{\rho_\phi + \rho_R}{3M_P^2}$$

$y_\phi^f = 1.5 \times 10^{-6}$

$T_{\text{Max}} = 4.72 \times 10^{12} \text{ GeV}$
$T_{\text{RH}} = 1.86 \times 10^{10} \text{ GeV}$

$k = 2$

ρ_ϕ
ρ_R

$A = a/a_{\text{end}}$

Delayed equilibration of charged lepton Yukawa interactions

$k = 2$

Standard
$y_\phi^f = 1.5 \times 10^{-6}$

e
μ
τ

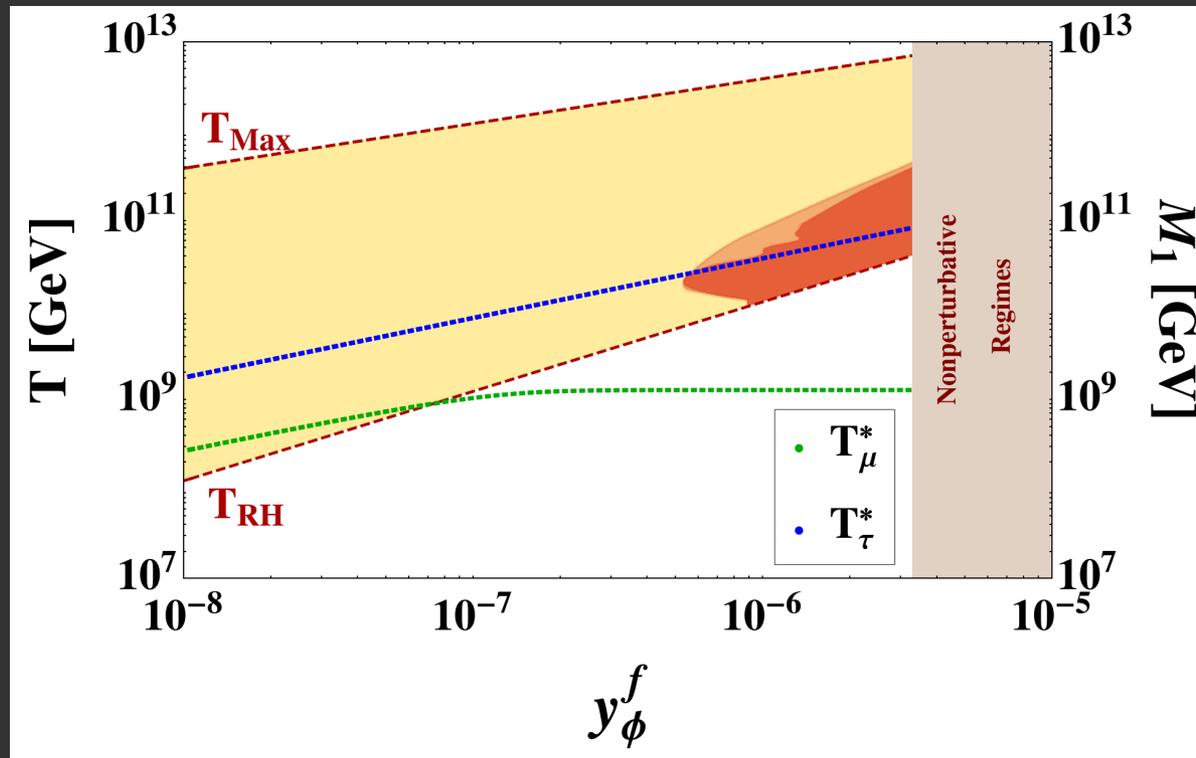T_{Max} T_{RH}

T [GeV]

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.
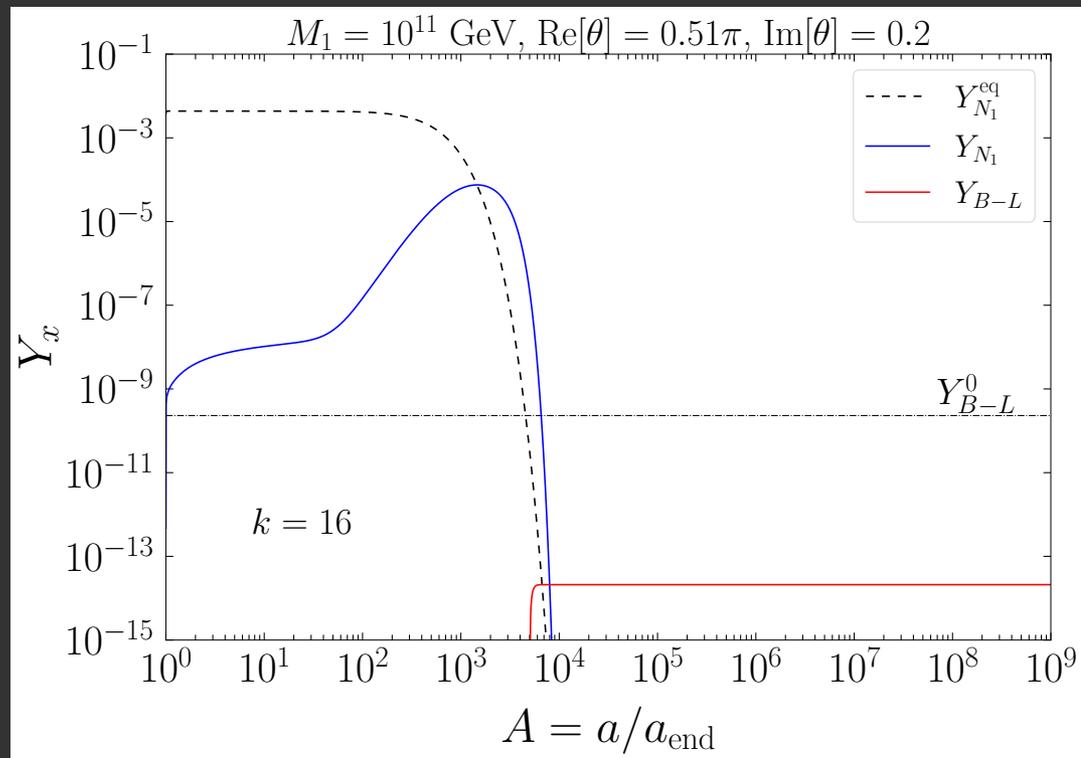
Modification of Baryon asymmetry

- **Leptogenesis during reheating phase may not sometimes be flavorful.**
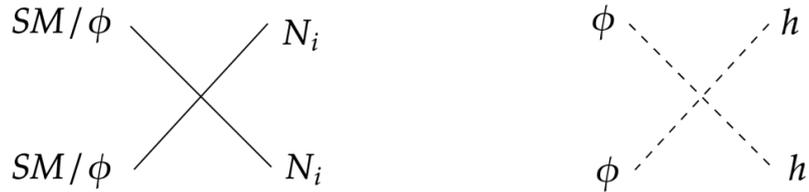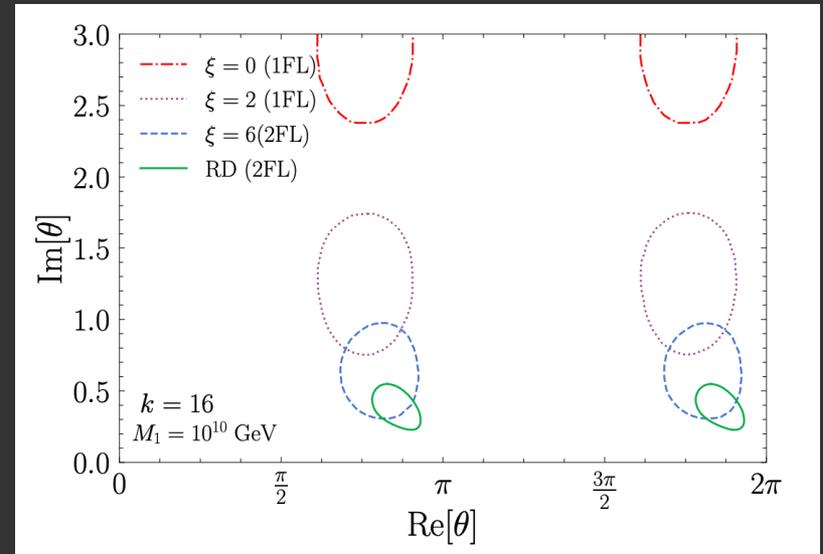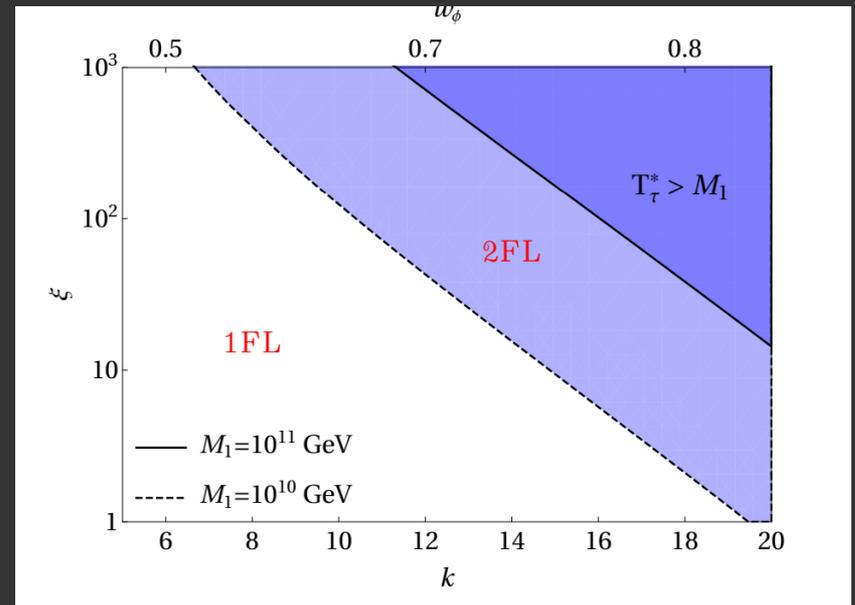
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Thank You

-

-

BACK UP

Jordan Frame + Unitary gauge

$$\mathcal{L} \sim (\xi_\phi \phi^2 + \xi_h h^2) R$$

Einstein Frame

negligible effects in RHN production for small ξ.
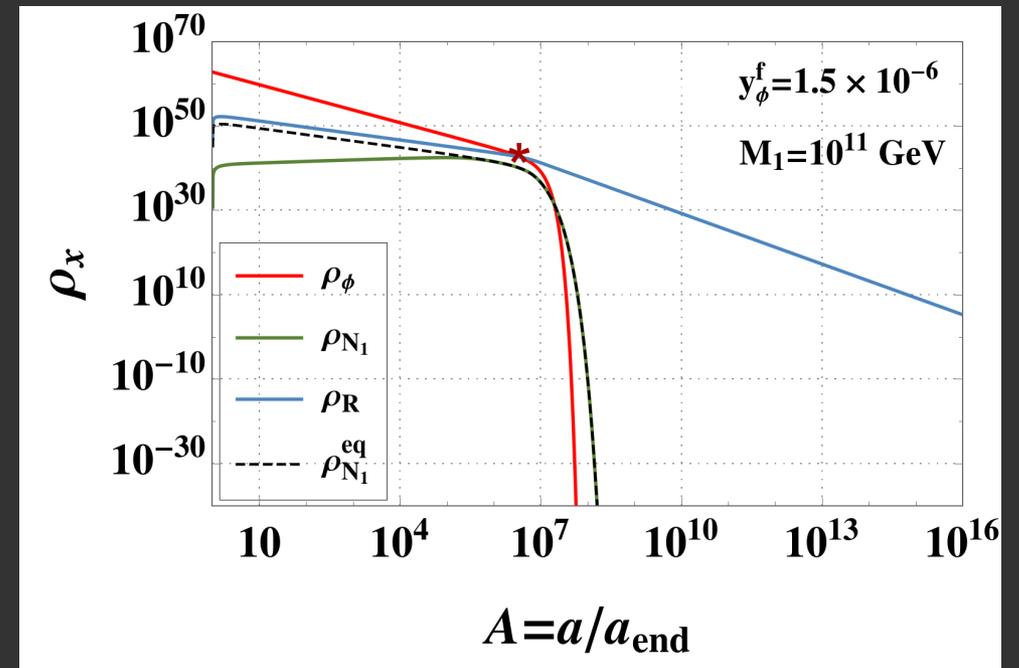
Bolzmann Equation and Temperature:

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

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

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

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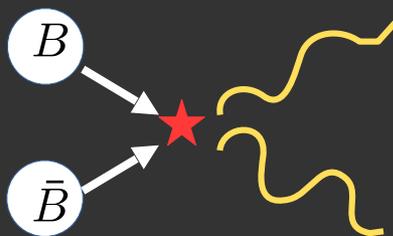
Evidence of Anti-matter

From Solar System

To Cluster of Galaxy

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

Upto ~ 10^3 Mpc using EGRET

[Steigman, JCAP 0810:001,2008]

From Cosmic Ray

Cosmic Ray anti-proton search by PAMELA, AMS
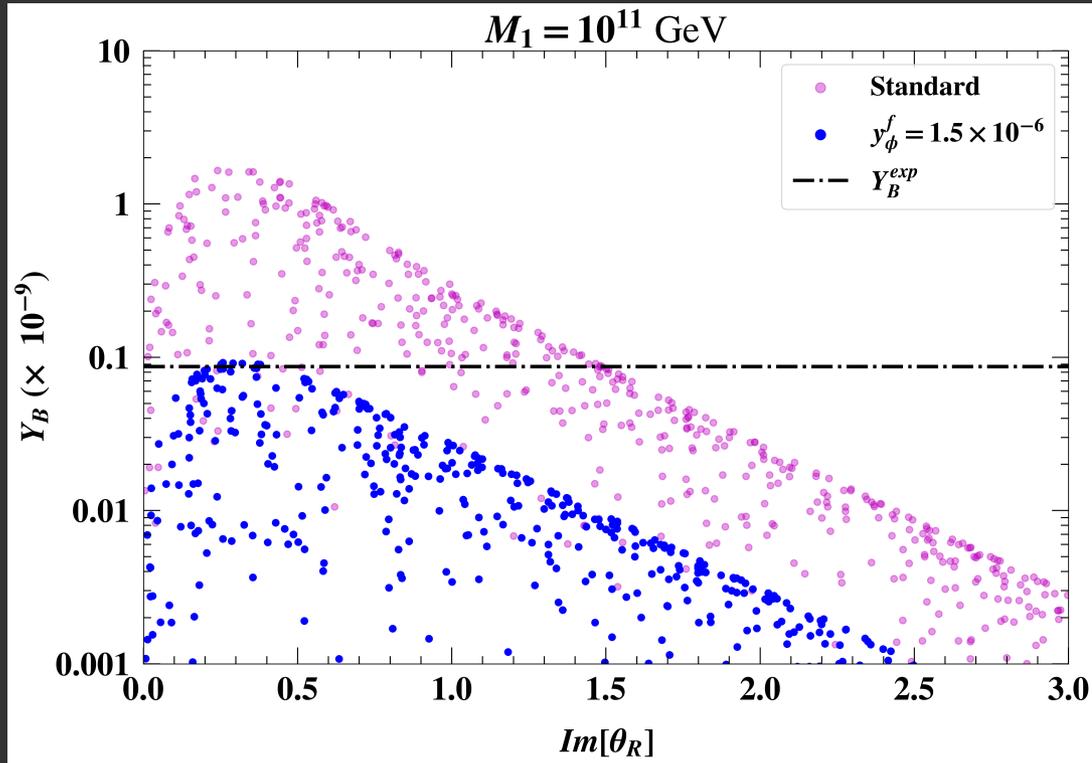
$$\frac{\bar{\Phi}_P}{\Phi_P} \lesssim 10^{-5}$$

Explained by other astrophysical processes

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

No evidence of anti-matter structure

Modification of Baryon asymmetry

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

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

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

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

Matter-Antimatter asymmetry

[Leptogenesis $\longleftrightarrow$ 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**

$$T^0_{\tau_R} \sim 5 \times 10^{11}\,\text{GeV}$$
$$T^0_{\mu_R} \sim 10^9\,\text{GeV}$$
$$T^0_{e_R} \sim 5 \times 10^4\,\text{GeV}$$

Prolonged Reheating

If M_1 satisfy: $T_{max} > M_1 > T_{RH}$

1) Effect on equilibration temperature of charged lepton Yukawa

2) Effect on flavor Leptogenesis

Should be generated after inflation

[Post inflationary epoch]

Perturbative Reheating: instantaneous/ extended

Universe reaches a maximum temperature T_{max}

Reheating temperature T_{RH}

(onset of radiation domination)

$T_{Max} - T_{RH}$: May differ by several orders of magnitude