Imprint of non-thermal leptogenesis in CMB

arXiv: 2210.14176

In collaboration with
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TeV Particle Astrophysics (TeVPA) @2023

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- Introduction and Motivation
- Connecting Inflation and Leptogenesis

  i) Inflaton directly couples to radiation

  ii) No direct inflaton-radiation coupling
- Results
- Conclusions

Introduction

- **Why do all the structures of the universe consist of ordinary matter?**

Matter-antimatter asymmetry $$\eta = \frac{n_B}{n_\gamma} = (6.02 - 6.18) \times 10^{-10}$$

- **Observations from BBN ($T \sim 1MeV$) and CMB ($T \sim 1eV$) agree with each other.**

- **What is the theoretical origin of the matter-antimatter asymmetry?**

Leptogenesis

- **What are the experimental or observational aspects?**

• Motivation

We are trying to find possible imprints of non-thermal leptogenesis in cosmic microwave background.

Requirements of leptogenesis?

Leptogenesis $\longrightarrow$ **Type-I seesaw**

SM+3 RHNs

Type-I seesaw and Leptogenesis

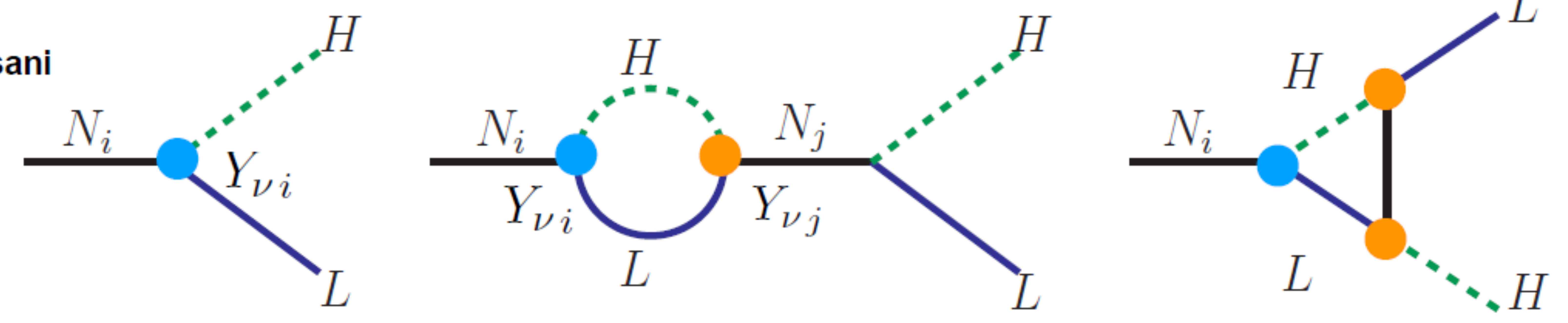
$$\mathscr{L} = -Y_\nu \bar{L}\tilde{H}N - \frac{1}{2}\overline{N^C}M_N N$$

Fukugita and Yanagida 1986

$$\begin{bmatrix} 0 & m_D \\ m_D^T & M_N \end{bmatrix}$$

$$m_\nu = \frac{Y_\nu^2 v^2}{M_N} \approx 0.1 eV$$

Covi, Roulet, Vissani



Generates neutrino mass, also explains matter-antimatter asymmetry: Elegant!!!

Type-I seesaw and Leptogenesis

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For $Y_\nu \approx \mathcal{O}(1)$, M_N have to be $10^{13} - 10^{14}$ GeV

Leptogenesis

$T_{Max} > M_N$

Thermal Leptogenesis

$T_{Max} < M_N$

Non-thermal Leptogenesis

Type-I seesaw and Leptogenesis

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Leptogenesis

How can we produce such heavy RHNs in the early universe?

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Thermal Leptogenesis

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Type-I seesaw and Leptogenesis

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Leptogenesis

How can we produce such heavy RHNs in the early universe?

$T_{Max} > M_N$

$T_{Max} < M_N$

Thermal Leptogenesis

Non-thermal Leptogenesis

Can be produced from the decay of the inflaton!

Type-I seesaw and Leptogenesis

$$\mathscr{L} = -Y_\nu \bar{L}\tilde{H}N - \frac{1}{2}\overline{N^C}M_N N$$ **Fukugita and Yanagida 1986**

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- **For successful thermal leptogenesis $M_N \geq 10^9 GeV$**

Davidson, Ibarra, hep-ph:0202239
Buchmuller, Bari, Plumacher, hep-ph:0401240

These scenarios are inaccessible to the conventional laboratory experiments!!

- **It's possible to have low scale leptogenesis for some particular scenarios.**

Pilaftsis, Underwood, hep-ph:0309342
Moffat, Pascoli, Petcov, Schulz, and Turner,1804.05066

Type-I seesaw and Leptogenesis

$$\mathcal{L} = -Y_\nu \bar{L}\tilde{H}N - \frac{1}{2}\overline{N^C}M_N N$$

Fukugita and Yanagida 1986

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For $Y_\nu \approx \mathcal{O}(1)$, M_N have to be $10^{13} - 10^{14}$ GeV

Leptogenesis

Why?

$T_{Max} > M_N$

Thermal Leptogenesis

$T_{Max} < M_N$

Non-thermal Leptogenesis

Why Non-thermal Leptogenesis?

It remembers its history!

Inflation and Reheating and CMB observables

Inflaton-dominated universe

Reheating

Radiation-dominated universe

Reheat temperature (T_{RH}): the maximum temperature of the radiation dominated universe.

ρ_{re}**: depends on interaction between inflaton and bath particles.**

ρ_{end}**: depends on the model of inflation.**

Number of e-folds:

$$N_{re} = \ln\left(\frac{a_{\rm re}}{a_{\rm end}}\right) = -\frac{1}{3(1+\overline{\omega}_{re})}\ln\left(\frac{\rho_{\rm re}}{\rho_{\rm end}}\right)$$

Inflation and Reheating

α-attractor model:

$$V(\phi) = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{Pl}}}\right)^{2n}$$

Independent parameters:

$$\boxed{\alpha, n}$$

Dependent parameters:

$$\boxed{\Lambda, M_\phi}$$

CMB Observables

Spectral index:

$$n_s = 1 - 6\epsilon_k + 2\eta_k$$

Tensor to scalar ratio:

$$r = 16\epsilon_k$$

$$\epsilon = \frac{M_{Pl}^2}{2}\left(\frac{\partial_\phi^2 V}{V}\right)^2 \qquad \eta = M_{Pl}^2 \frac{\partial_\phi^2 V}{V}$$

α-attractor model:

$$V(\phi) = \Lambda^4 \left(1 - e^{-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{Pl}}}\right)^{2n}$$

$$r = \frac{192\alpha n^2 \left(1 - n_s\right)^2}{\left[4n + \sqrt{16n^2 + 24\alpha n(1 - n_s)(1 + n)}\right]}$$

Can we relate n_s and r with the parameter of leptogenesis?

At horizon exit:

$$\ln\left(\frac{k}{a_k H_k}\right) = \ln\left(\frac{a_{\rm end}}{a_k}\frac{a_{\rm re}}{a_{\rm end}}\frac{a_0}{a_{\rm re}}\frac{k}{a_0 H_k}\right) = 0$$

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$$N_{\rm re} = \frac{4}{3\omega_{\rm re} - 1}\left[N_k + \ln\left(\frac{k}{a_0 T_0}\right) + \frac{1}{4}\ln\left(\frac{40}{\pi^2 g_*}\right) + \frac{1}{3}\ln\left(\frac{11 g_{s*}}{43}\right) - \frac{1}{2}\ln\left(\frac{\pi^2 M_P^2\, r\, A_s}{2V_{\rm end}^{1/2}}\right)\right]$$

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$$N_k = \frac{3\alpha}{4n}\left[e^{\sqrt{\frac{2}{3\alpha}}\frac{\phi_k}{M_P}} - e^{\sqrt{\frac{2}{3\alpha}}\frac{\phi_{\mathrm{end}}}{M_P}} - \sqrt{\frac{2}{3\alpha}}\frac{(\phi_k - \phi_{\mathrm{end}})}{M_P}\right]$$

$$\phi_k = \sqrt{\frac{3\alpha}{2}} M_{Pl} \ln\left(1 + \frac{4n + \sqrt{16n^2 + 24\alpha n(1-n_s)(1+n)}}{3\alpha(1-n_s)}\right)$$

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$N_{\rm re}$ depends on α, n

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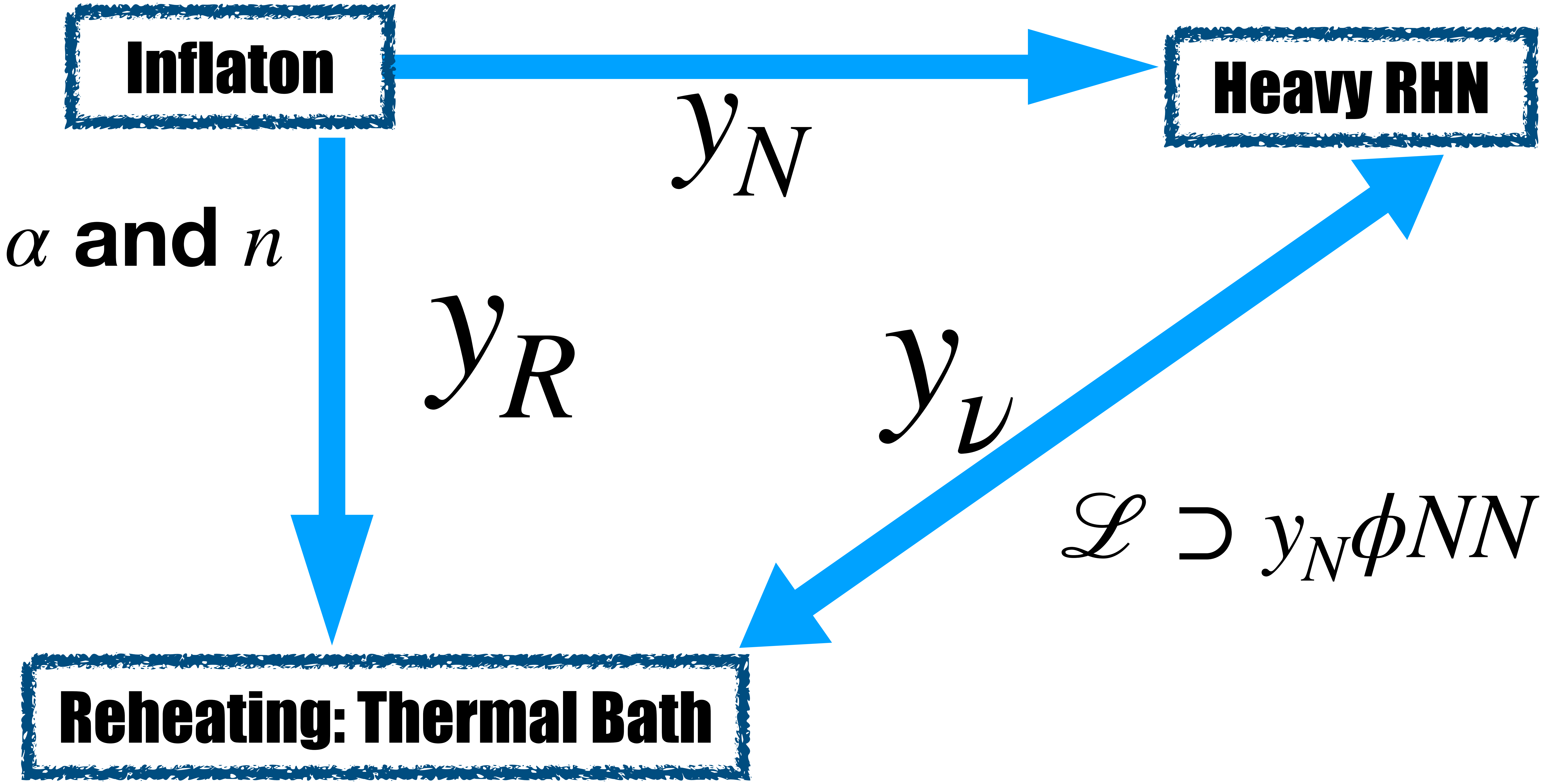
$$N_{\rm re} = -\frac{1}{3(1+\overline{\omega}_{re})}\ln\left(\frac{\rho_{\rm re}}{\rho_{\rm end}}\right)$$

Will depend on history of reheating.

$$\rho_{\rm end} = \frac{4}{3}\Lambda^4\left(\frac{2n}{2n+\sqrt{3\alpha}}\right)^{2n}$$

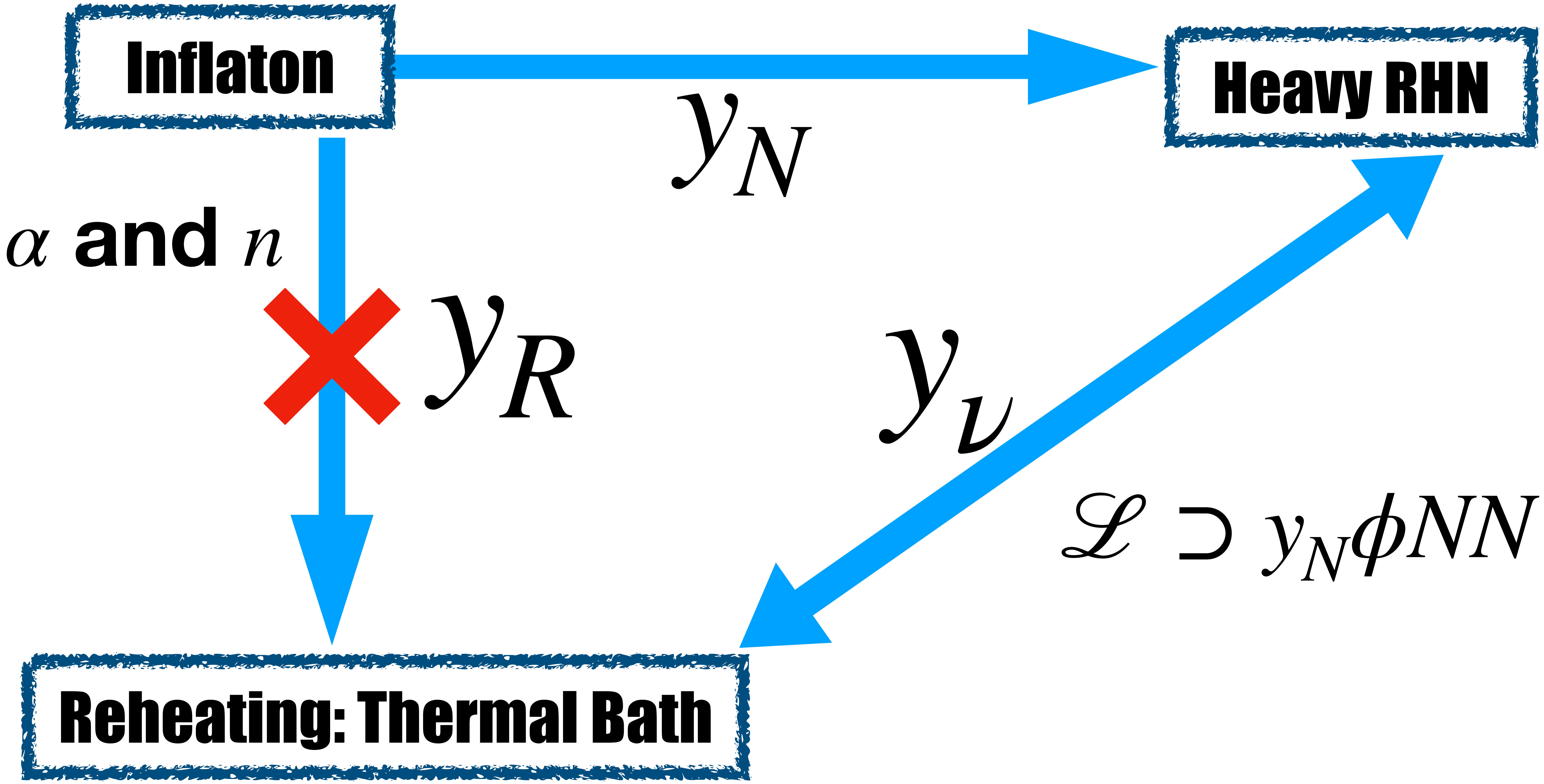
- We restrict ourselves to n=1. For n > 1, the effective potential exhibits zero mass at its minimum. Marco Drewes et al JHEP2017
- Which also sets, $\overline{\omega}_{re} = \dfrac{n-1}{n+1} = 0$
- Important parameters are α and the parameters responsible for producing ρ_{re}.

Parameters involved so far



$$\mathscr{L} \supset y_N \phi NN + y_R \phi XX + y_\nu \overline{\ell_L} \tilde{H} N$$

Parameters involved so far



$$\mathscr{L} \supset y_N \phi N N + \cancel{y_R \phi X X} + y_\nu \overline{\ell_L} \tilde{H} N$$

Results

Boltzmann Equations: case I

$$\frac{d\rho_\phi}{dt} + 3H(\rho_\phi + p_\phi) = -\Gamma^N_\phi \rho_\phi - \Gamma^R_\phi \rho_\phi$$

$$\frac{d\rho_R}{dt} + 3H(\rho_R + p_R) = \Gamma^R_\phi \rho_\phi + \Gamma_N \rho_N$$

$$\frac{d\rho_N}{dt} + 3H(\rho_N + p_N) = \Gamma^N_\phi \rho_\phi - \Gamma_N \rho_{\rho_N}$$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = -\frac{\epsilon \rho_N \Gamma_N}{M_N}$$

- y_N and y_R will decide the amount of energy going into non-thermal RHN sector or thermal bath.
- The L asymmetry can be converted to B asymmetry as,

$$\frac{n_B}{s} \sim -\left(\frac{8}{23}\right) \times \frac{n_L}{s}$$

- The parameters involved so far are, y_N, y_R and M_N.
- The additional parameters will come from the neutrino mass diagonalization conditions.
- We used the well known Casas-Ibara parameterizations for nu-mass diagonalization which introduces the complex mixing angles in the theory.

Boltzmann Equations: case I

$$\frac{d\rho_\phi}{dt} + 3H(\rho_\phi + p_\phi) = -\Gamma_\phi^N \rho_\phi - \Gamma_\phi^R \rho_\phi$$

$$\frac{d\rho_R}{dt} + 3H(\rho_R + p_R) = \Gamma_\phi^R \rho_\phi + \Gamma_N \rho_N$$

$$\frac{d\rho_N}{dt} + 3H(\rho_N + p_N) = \Gamma_\phi^N \rho_\phi - \Gamma_N \rho_{\rho_N}$$

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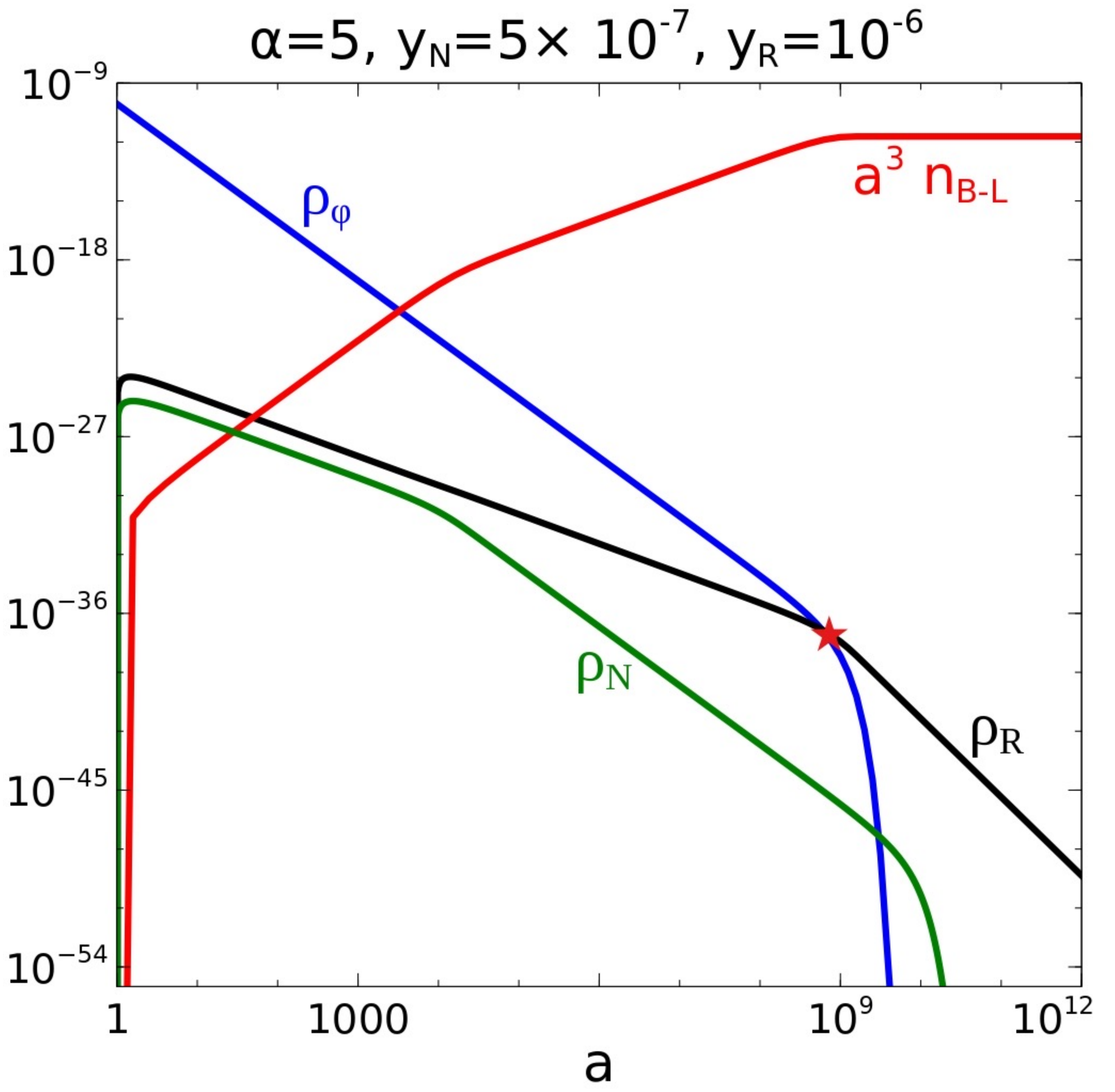


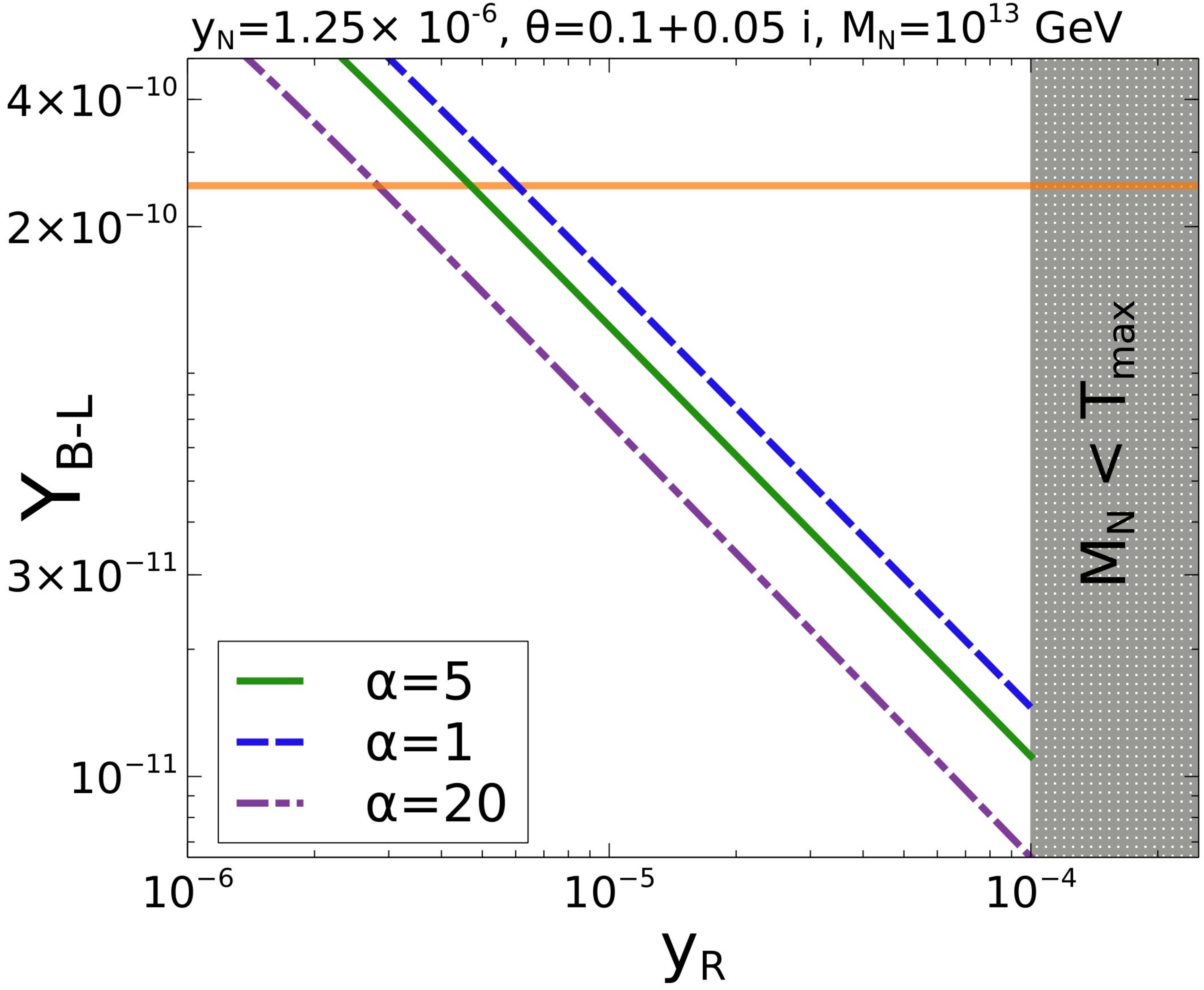
Case-1: Results

- In case of non-thermal leptogenesis: $Y_{B-L} \propto \mathrm{Br}_{\phi\to NN} \times T_{RH}$

- For a fixed y_N, $Y_{B-L} \propto \frac{1}{y_R}$

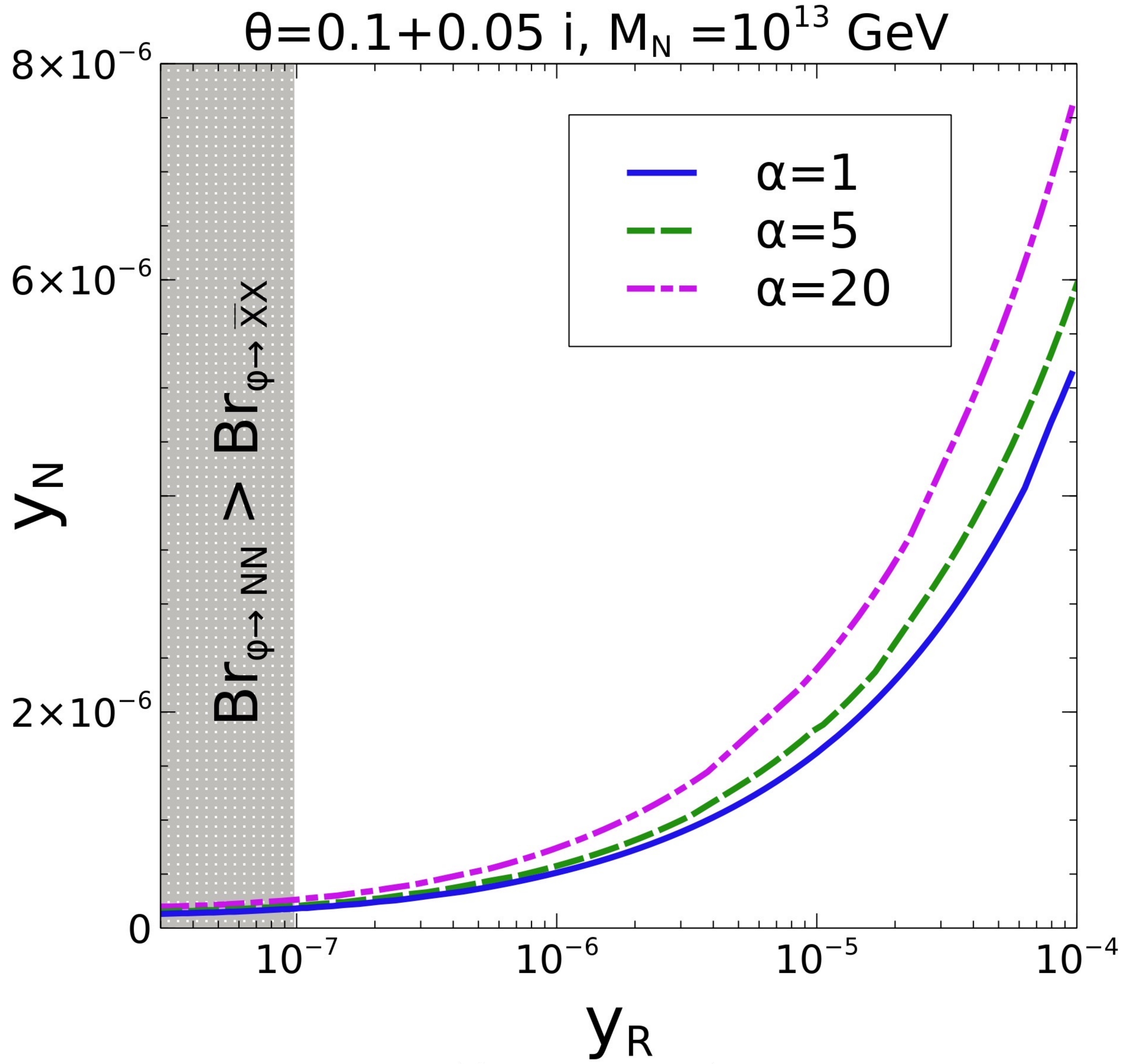
$$M_\Phi = \frac{2\Lambda^2}{\sqrt{3\alpha}M_{Pl}}$$

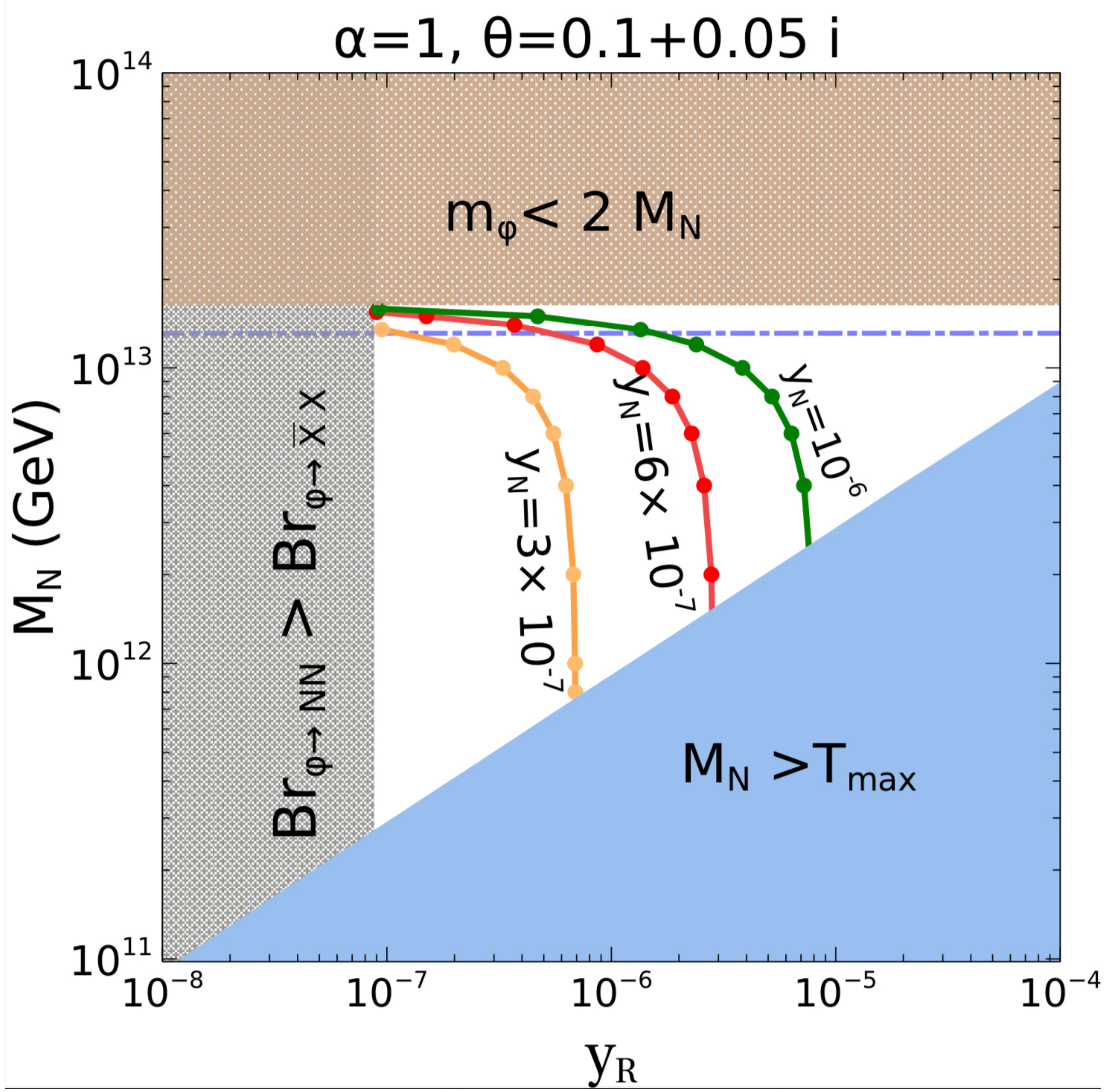
- Increasing α, will increase which will reduce $Br_{\phi\to NN}$.



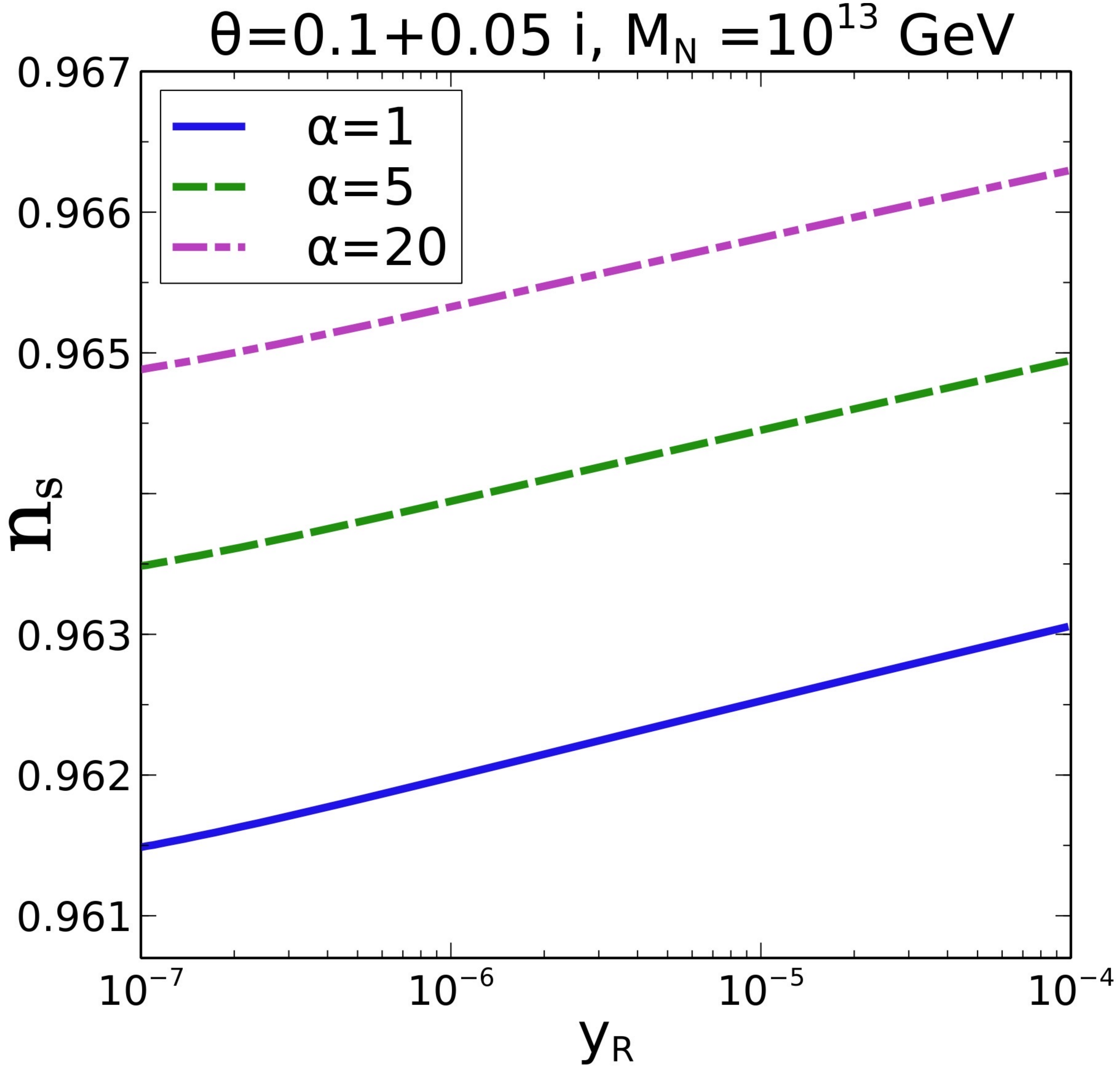
Case-1: Results

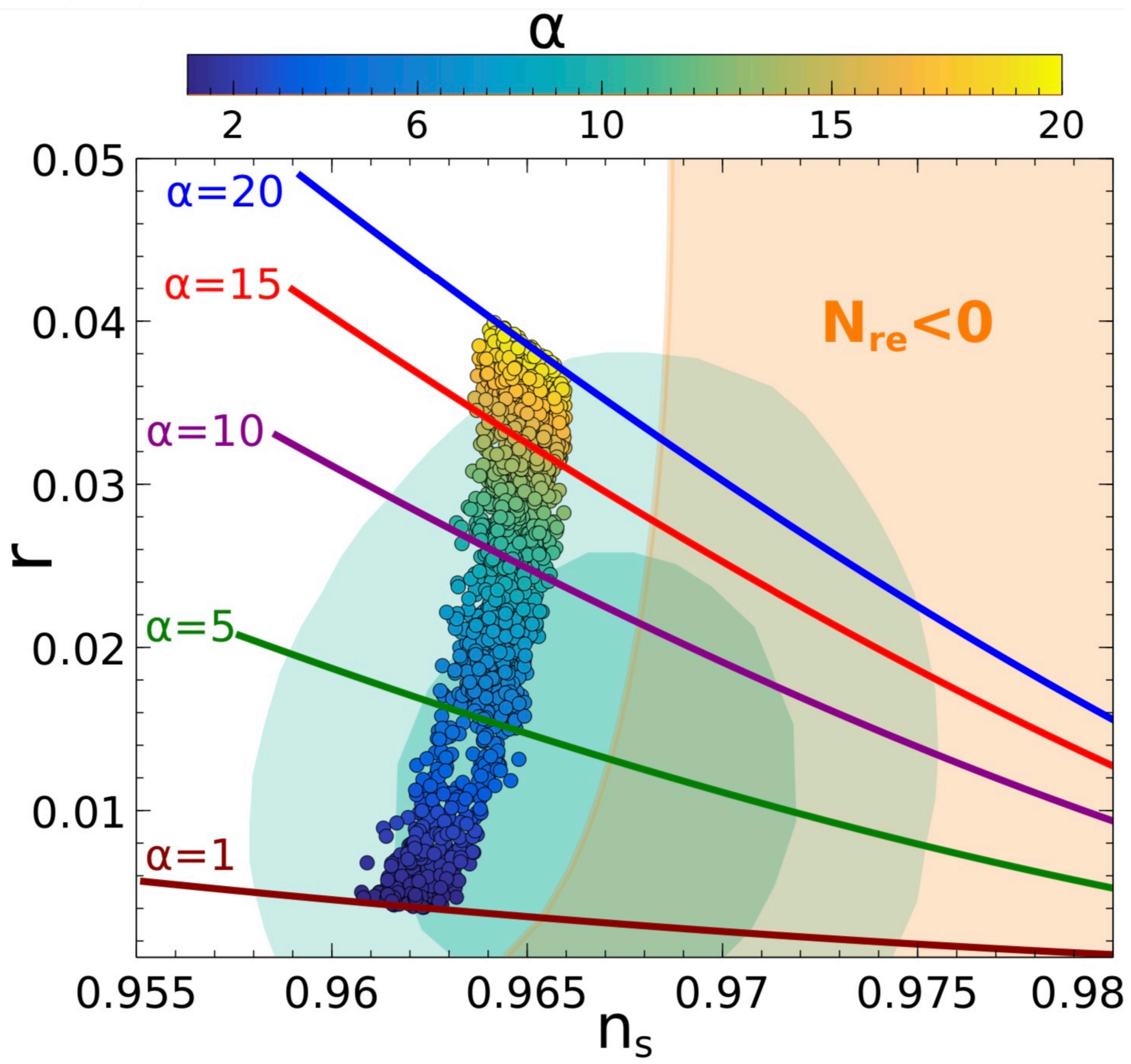
- y_N and y_R are correlated by the requirement of the correct order of baryon asymmetry.





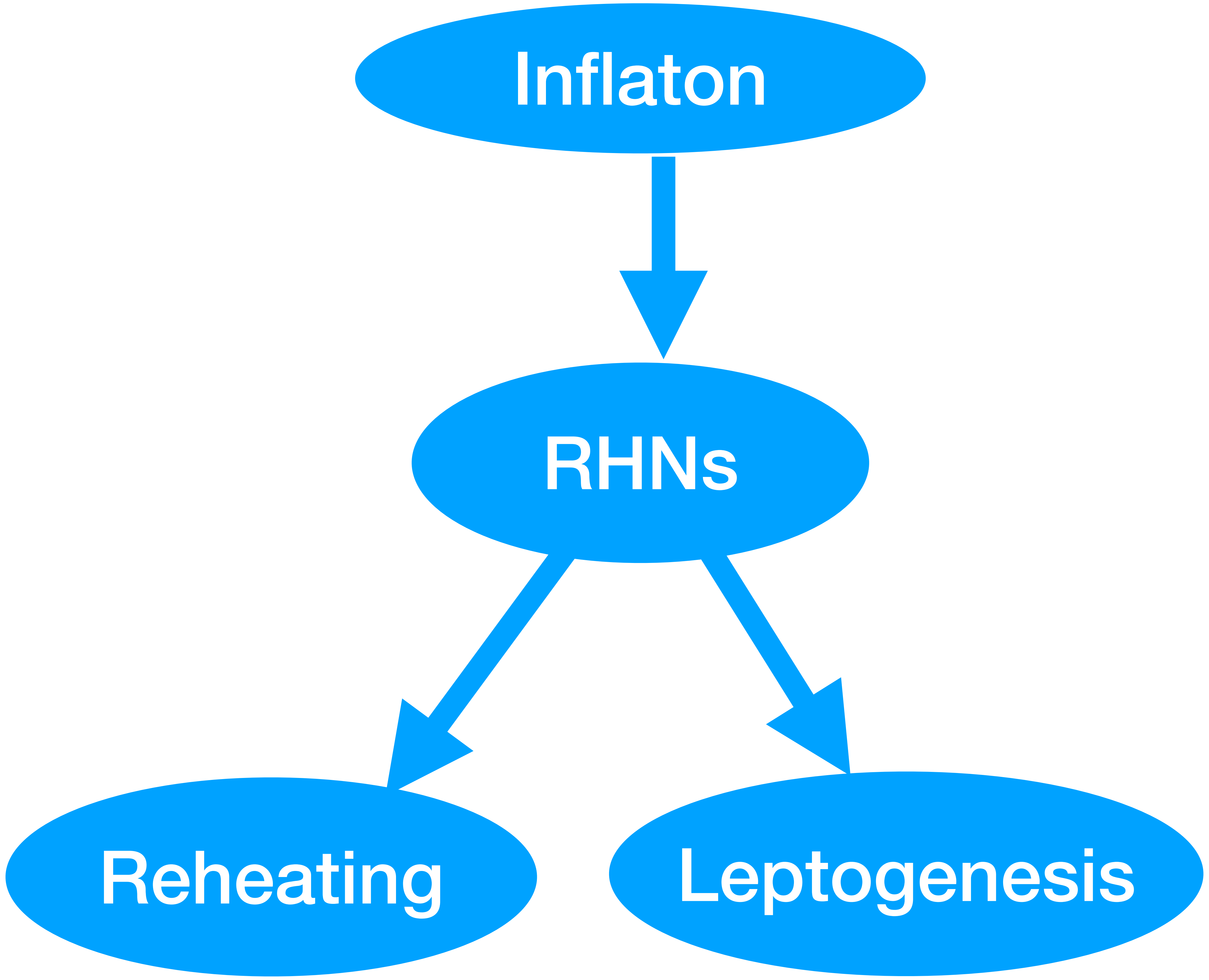
Case-I: Results





- For a constant α, the predicted range of r, the scalar to tensor ratio is highly restricted.

Boltzmann Equations: Case II



$$\frac{d\rho_\phi}{dt} + 3H(\rho_\phi + p_\phi) = -\Gamma^N_\phi \rho_\phi \cancel{- \Gamma^R_\phi \rho_\phi}$$

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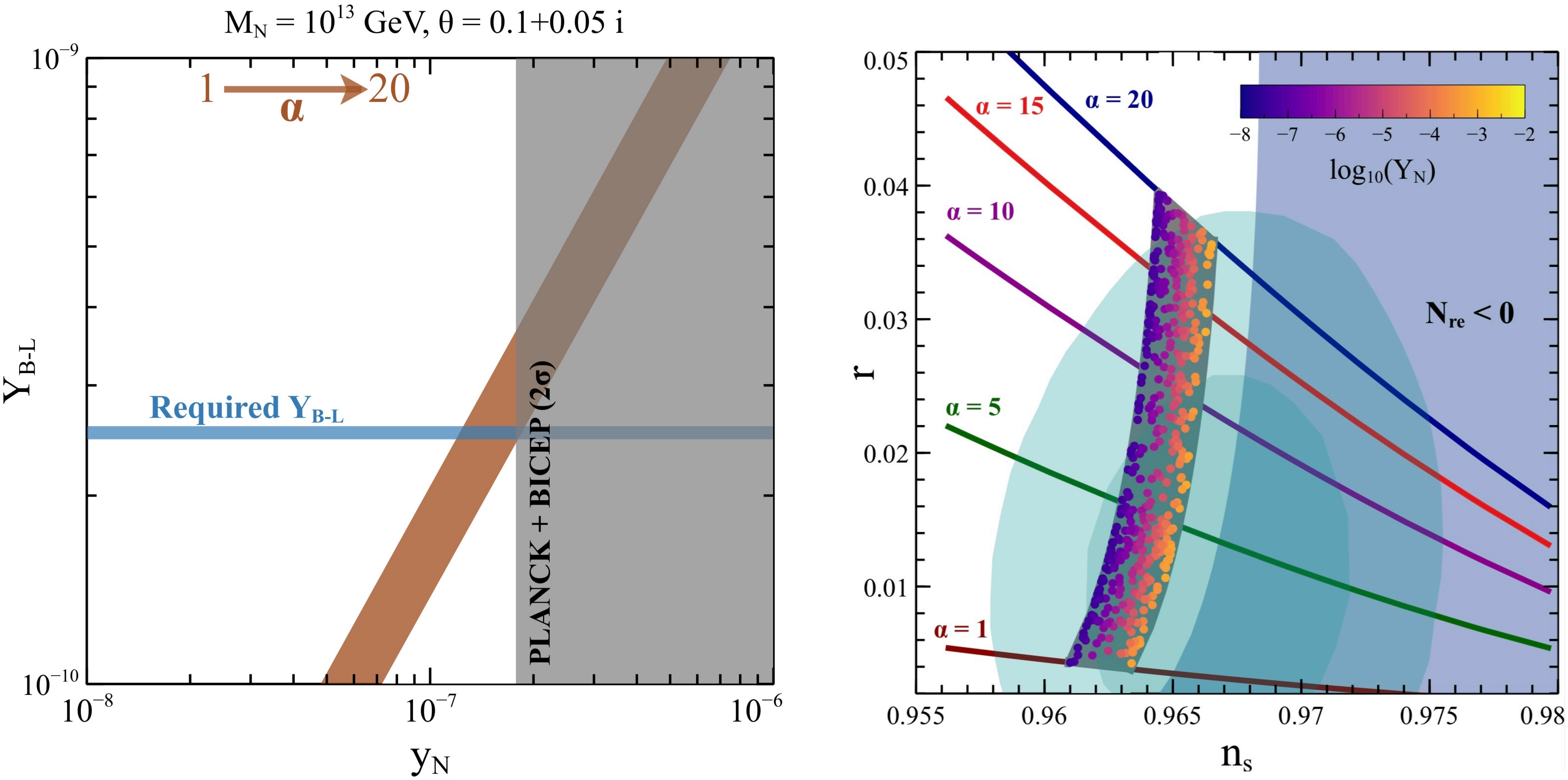
$$\frac{d\rho_N}{dt} + 3H(\rho_N + p_N) = \Gamma^N_\phi \rho_\phi - \Gamma_N \rho_{\rho_N}$$

$$\frac{dn_{B-L}}{dt} + 3Hn_{B-L} = -\frac{\epsilon \rho_N \Gamma_N}{M_N}$$

$$\mathscr{L} \supset y_N \phi NN + \cancel{y_X \phi XX} + y_\nu \overline{\ell_L} \tilde{H} N$$

Case-II: Results



Conclusions

- Here, we have discussed the impact of non-thermal leptogenesis on inflationary observables, n_s and r.
- The high scale RHN have been considered to create the required matter antimatter asymmetry.
- The source of those non-thermal heavy RHNs can be the inflatons itself and may have a direct correlation with the inflationary observables.
- We argue that such correlation can lead to distinct predictions for inflationary observables, n_s and r.
- For illustrations, we have considered the general form of α-attractor inflation model.

Thank you.

Comments and Questions?

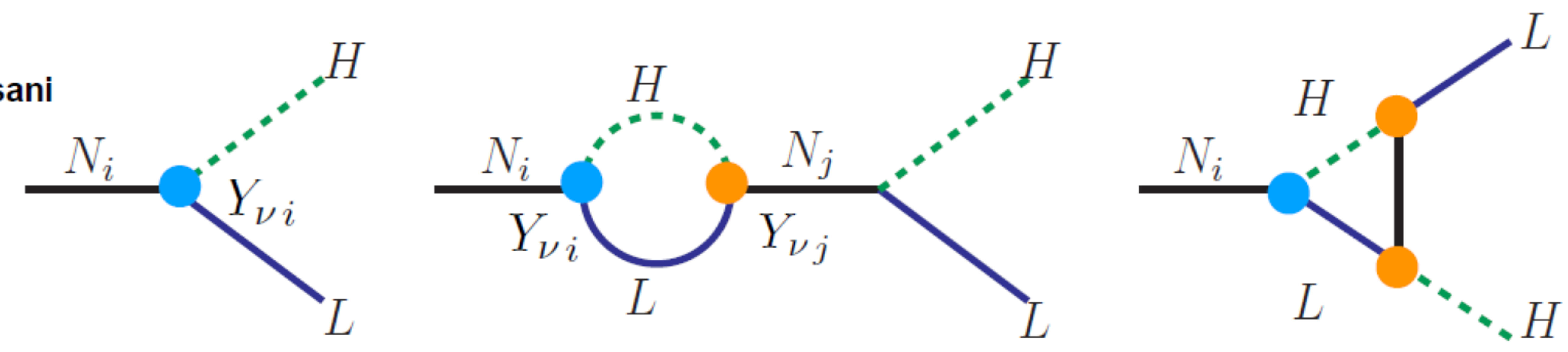
Backup Slides

Decay widths of inflaton and RHN:

$$\Gamma_\phi^N = \frac{y_N^2 m_\phi}{8\pi}\left(1 - \frac{4M_N^2}{m_\phi^2}\right) \qquad \Gamma_\phi^R \approx \frac{y_R^2 m_\phi}{8\pi} \qquad \Gamma_N \approx \frac{y_\nu^2 m_N}{16\pi}$$

$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma}_i}{\Gamma_i + \overline{\Gamma}_i}$$

Covi, Roulet, Vissani



Sakharov's Conditions

- <u>Baryon number violation:</u> required to evolve from $Y_{\Delta B} = 0$ to $Y_{\Delta B} \neq 0$.
- <u>C and CP violation:</u> interactions have to treat matter and anti-matter differently.
- <u>Out of equilibrium dynamics:</u> Otherwise asymmetries will be washed out.

Leptogenesis $\longrightarrow$ **Type-I seesaw**

SM+3 RHNs

How?

The slow roll parameters:

$$\epsilon = \frac{M_{Pl}^2}{2}\left(\frac{\partial_\psi^2 V}{V}\right)^2$$

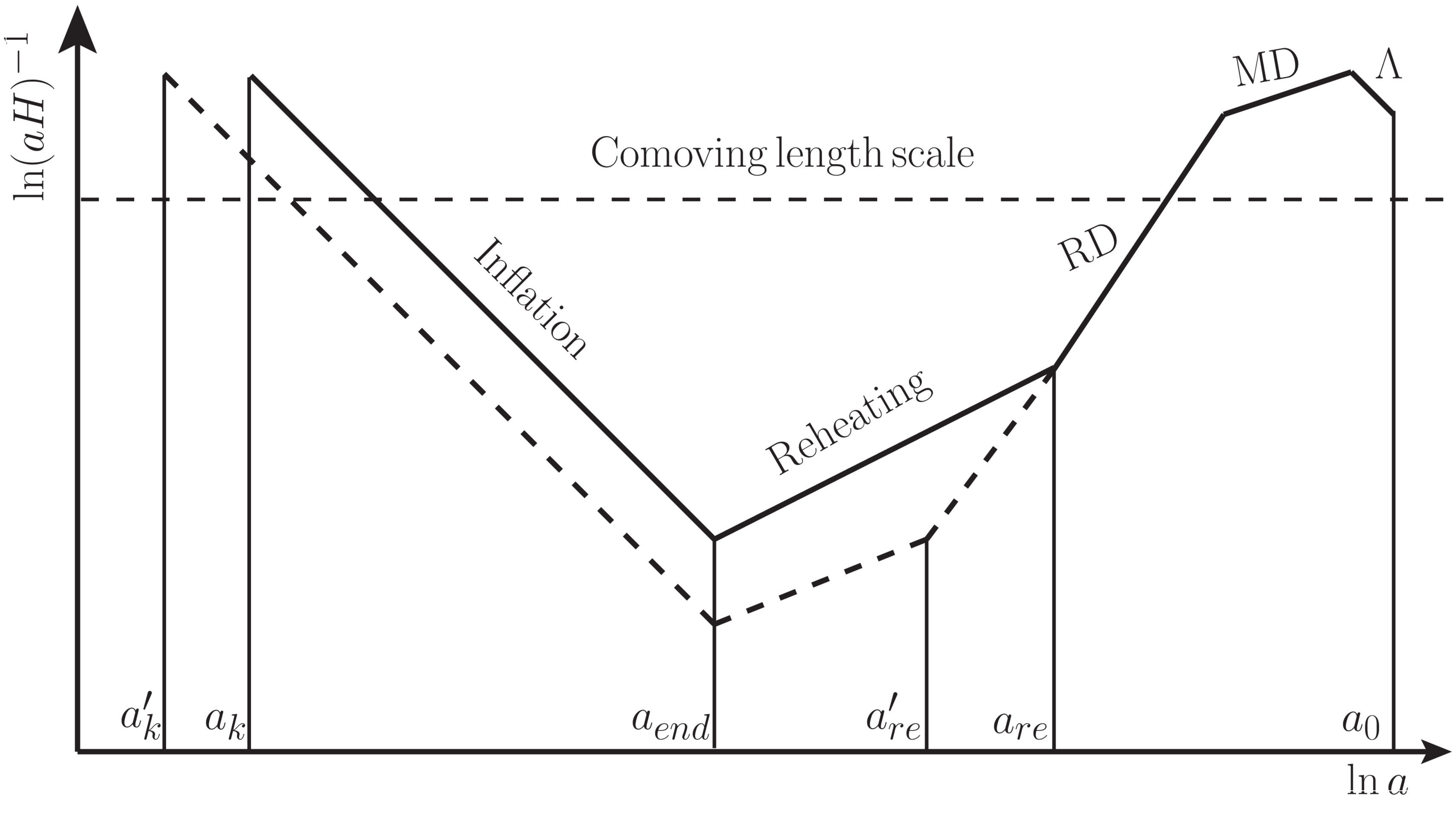
$$\eta = M_{Pl}^2 \frac{\partial^2 V}{V}$$

CMB observables:

$$n_s = 1 - 6\epsilon_k + 2\eta_k$$

$$r = 16\epsilon_k$$

$$H_k = \frac{\pi M_{Pl}\sqrt{rA_s}}{\sqrt{2}} = \sqrt{\frac{V(\phi_k)}{3M_{Pl}^2}}$$



$\ln(aH)^{-1}$
Comoving length scale
Inflation
Reheating
RD
MD
Λ
a'_k
a_k
a_{end}
a'_{re}
a_{re}
a_0
$\ln a$

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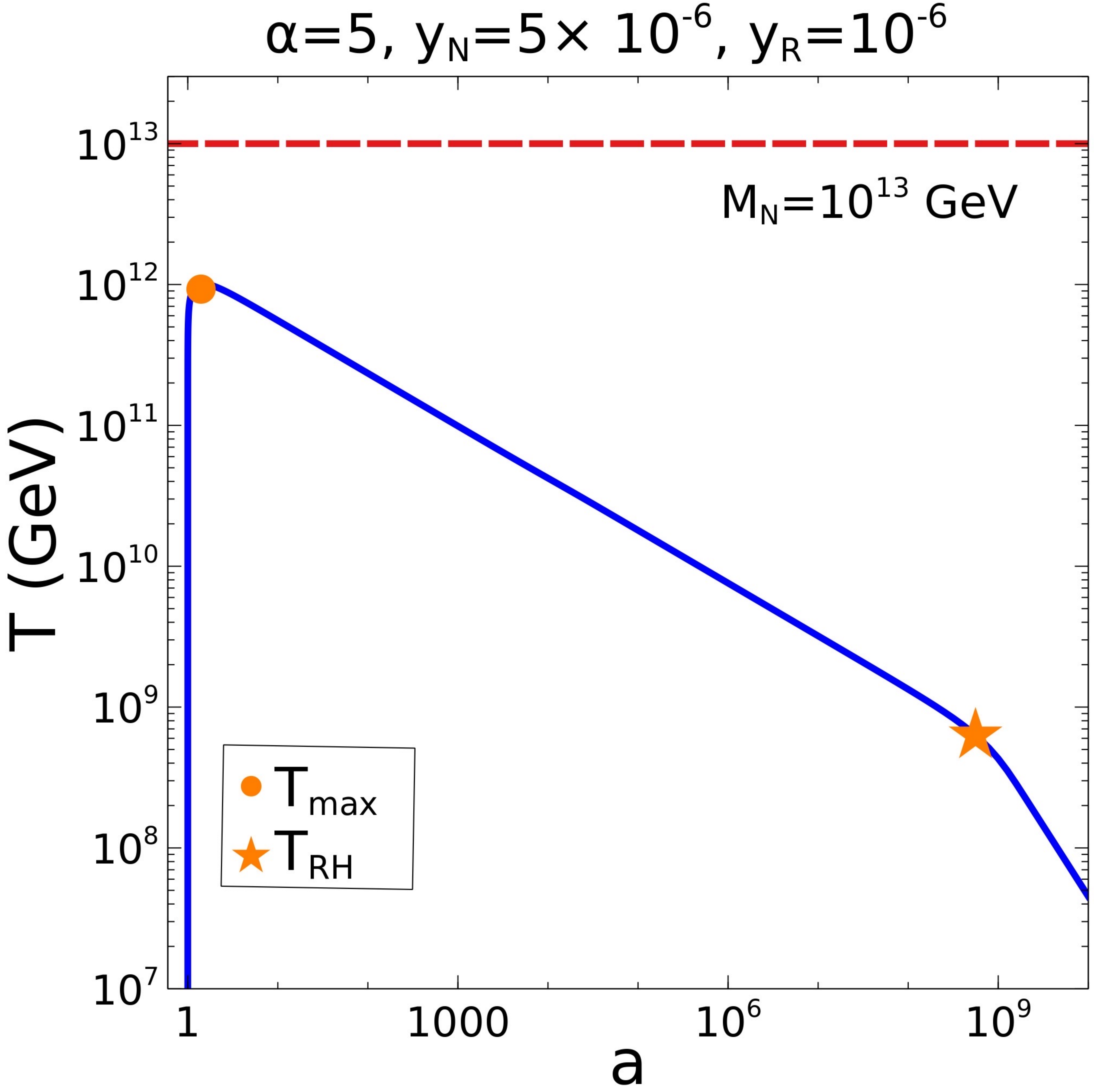

Case-II: Results