第四届高能物理理论与实验融合发展研讨会

Connecting inflation and baryon asymmetry via neutrino reheating

Xinyi Zhang 张忻怿 (河北大学)
zhangxy@hbu.edu.cn

Based on: JHEP 05 (2024) 147 （arXiv:2311.05824)
JHEP 07 (2025) 099 (arXiv:2501.16114)

2025年9月21日，大连

Connecting inflation and baryon asymmetry via neutrino reheating

1. Why connect inflation with BAU?

2. What is neutrino reheating

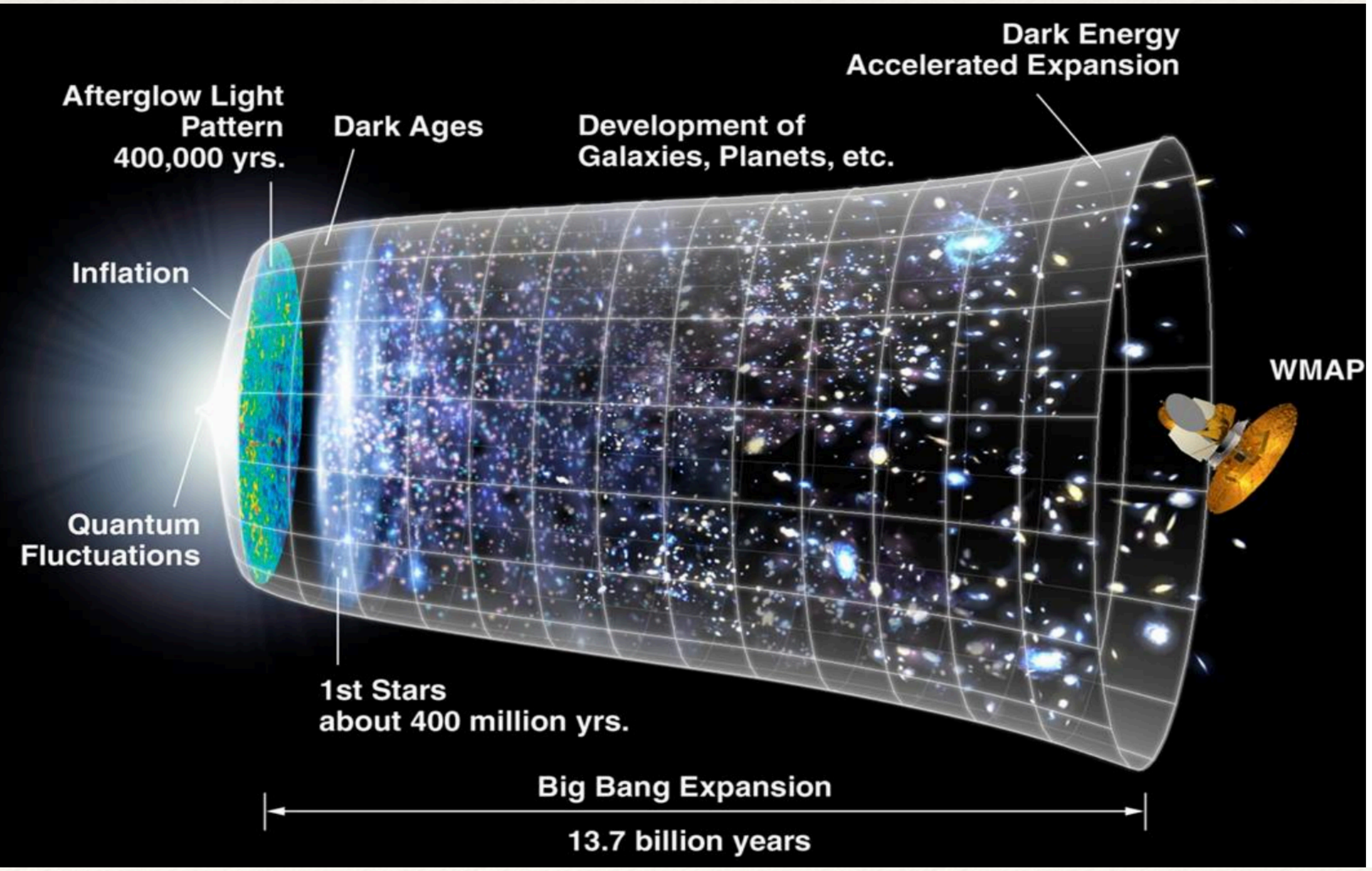
3. How neutrino reheating helps in connecting?

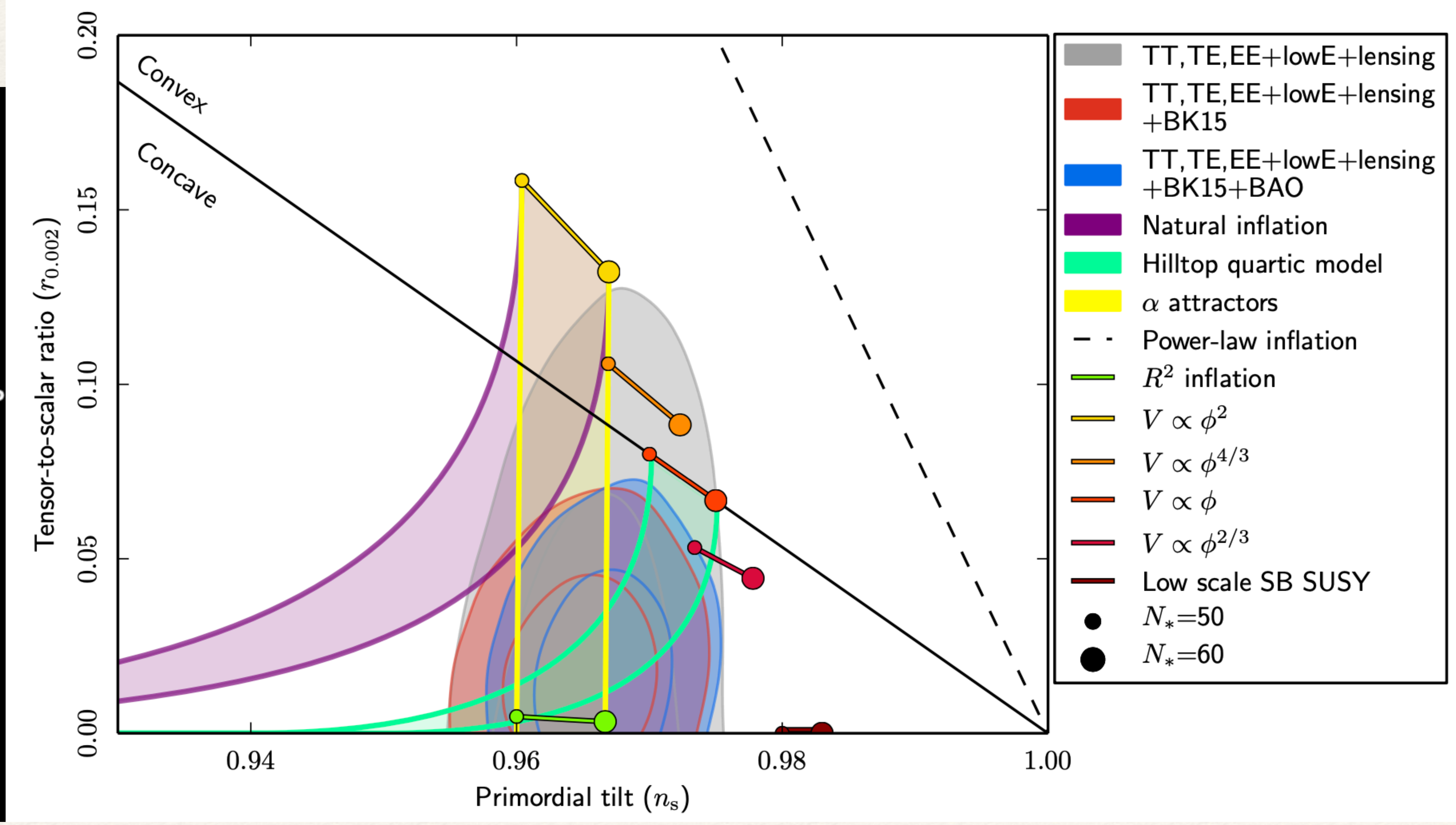
Inflation

- Theoretical support: flatness & horizon problem, quantum fluc -> LSS
- Observational support: near scale invariant power spectrum by CMB

Limited info

Model degeneracy





1.2 Baryon-antibaryon Asymmetry of the Universe (BAU)

The observed baryon-antibaryon asymmetry (Planck 2018)

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.72 \pm 0.08) \times 10^{-11}$$

To generate the BAU dynamically (baryogenesis), Sakharov (1967) proposes three conditions:

- Baryon number violation
- C and CP violation
- Deviation from equilibrium

Standard model confronts the Sakharov conditions

- Sphaleron process
- KM mechanism
- Electroweak phase transition (EWPT)

Existing baryongenesis mechanisms (incomplete list!):

- **GUT baryogenesis**: heavy boson out-of-equilibrium decay

A.Y. Ignatiev et al, 1978; M. Yoshimura, 1978; D. Toussaint et al, 1979; S.Dimopoulos, L. Susskind, 1978…

- **Leptogenesis:** heavy neutrino out-of-equilibrium decay

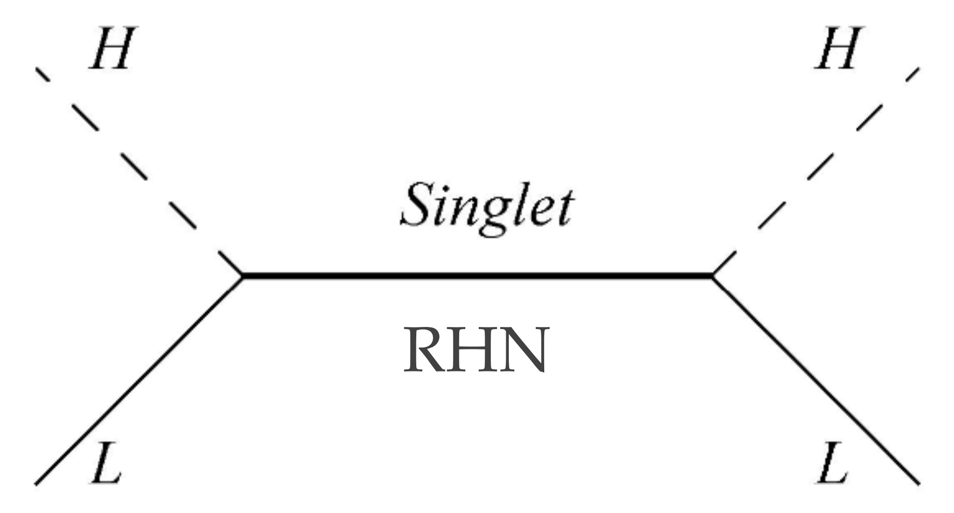
P. Minkowski 1977; T. Yanagida, 1979; S.L. Glashow, 1980; M. Gell-Mann et al, 1979; R. N. Mohapatra, G. Senjanovic, 1981…

- **Electroweak baryogengesis**: EWPT V. A. Rubakov and M. E. Shaposhnikov, 1996; A. Riotto and M. Trodden, 1999; J. M. Cline, 2006…
- **The Affleck-Dine mechanism:** I. Affleck and M. Dine, 1985; M. Dine, L. Randall, and S. D. Thomas, 1996…

Leptogenesis

Introduce right-handed neutrinos (RHNs) to SM

Light neutrino mass is explained through type-I seesaw



P. Minkowski,1977; T. Yanagida, ,1979;
J. Schechter and J. W. F. Valle, 1980

To generate the BAU dynamically (baryongenesis), Sakharov (1967) proposes three conditions:

- Baryon number violation
- C and CP violation
- Deviation from equilibrium

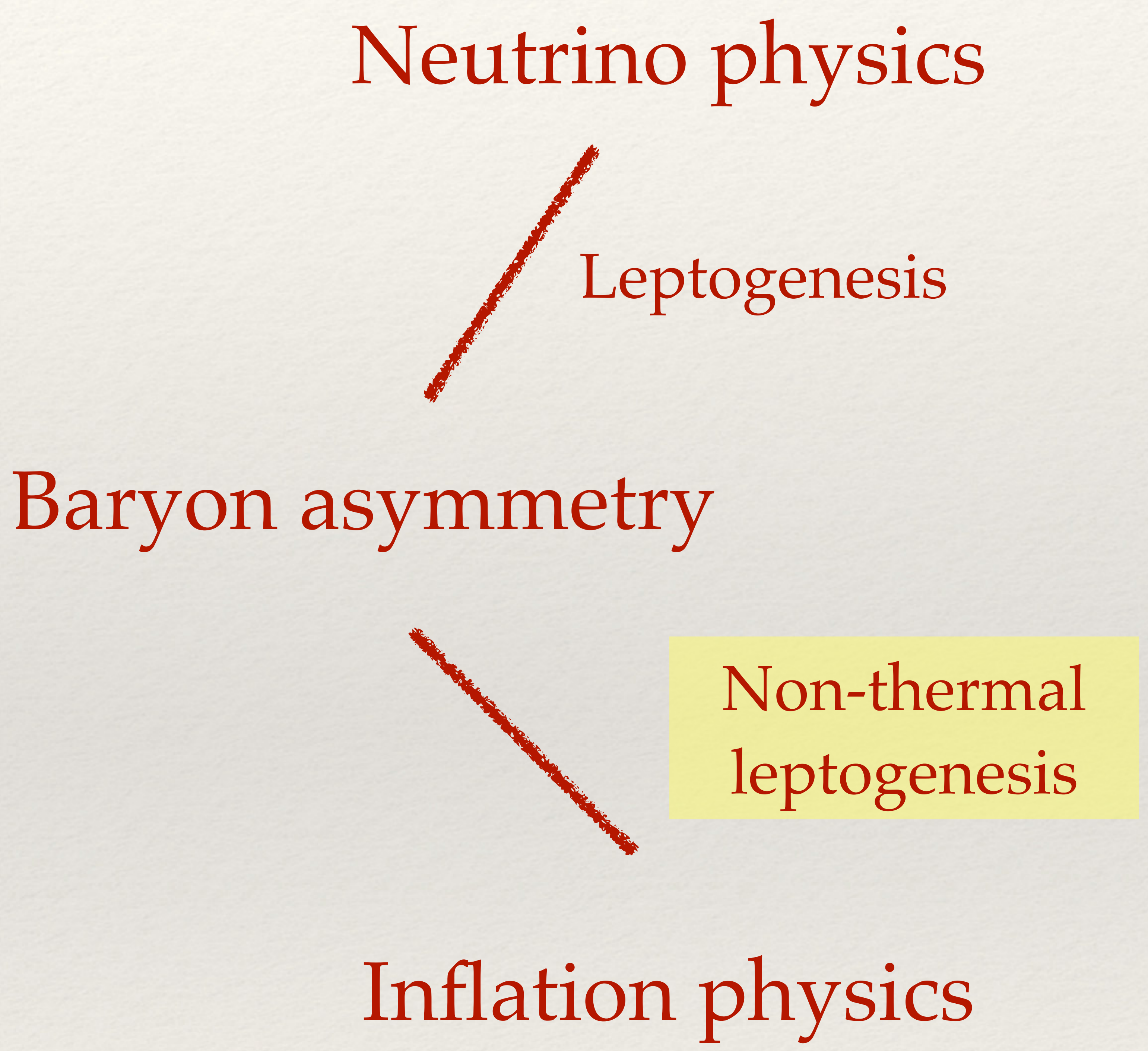
In (type-I seesaw) leptogenesis,
RHNs decay out-of-equilibrium,
generating a CP asymmetry (also a L asymmetry),
which converts to a B asymmetry via SM sphalerons

Address light neutrino mass and BAU at the same time

- Realization in ν models: e.g. Gehrlein, Petcov, Spinrath, and **XYZ** 1502.00110, 1508.07930; Xing, Zhao, 2008.12090; Zhao, 2205.01021; Zhao, Shi, Shao, 2402.14441; Zhao, Zhang, Wu, 2403.18630
- Connection to low energy CPV: e.g. Xing, Zhang, 2003.06312, 2003.00480; **XYZ**, Yu and Ma, 2008.06433
- Testability: e.g. Granelli, Moffat, Petcov, 2009.03166; Fong, Rahat, Saad, 2103.14691; Liu, Xie, Yi, 2109.15087

1. Why connect inflation with BAU?

- Both happens at high energy scale
- BAU reconcile with m_ν via RHNs
- Well motivated RHNs could do more



1.3

Thermal leptogenesis:

RHNs are produced in thermal bath (zero initial abundance/thermal distribution)

Non-thermal leptogenesis:

RHNs are produced non-thermally (e.g., via heavy particle decay)

Why thermal leptogenesis?

- Natural
- No memory of the initial state

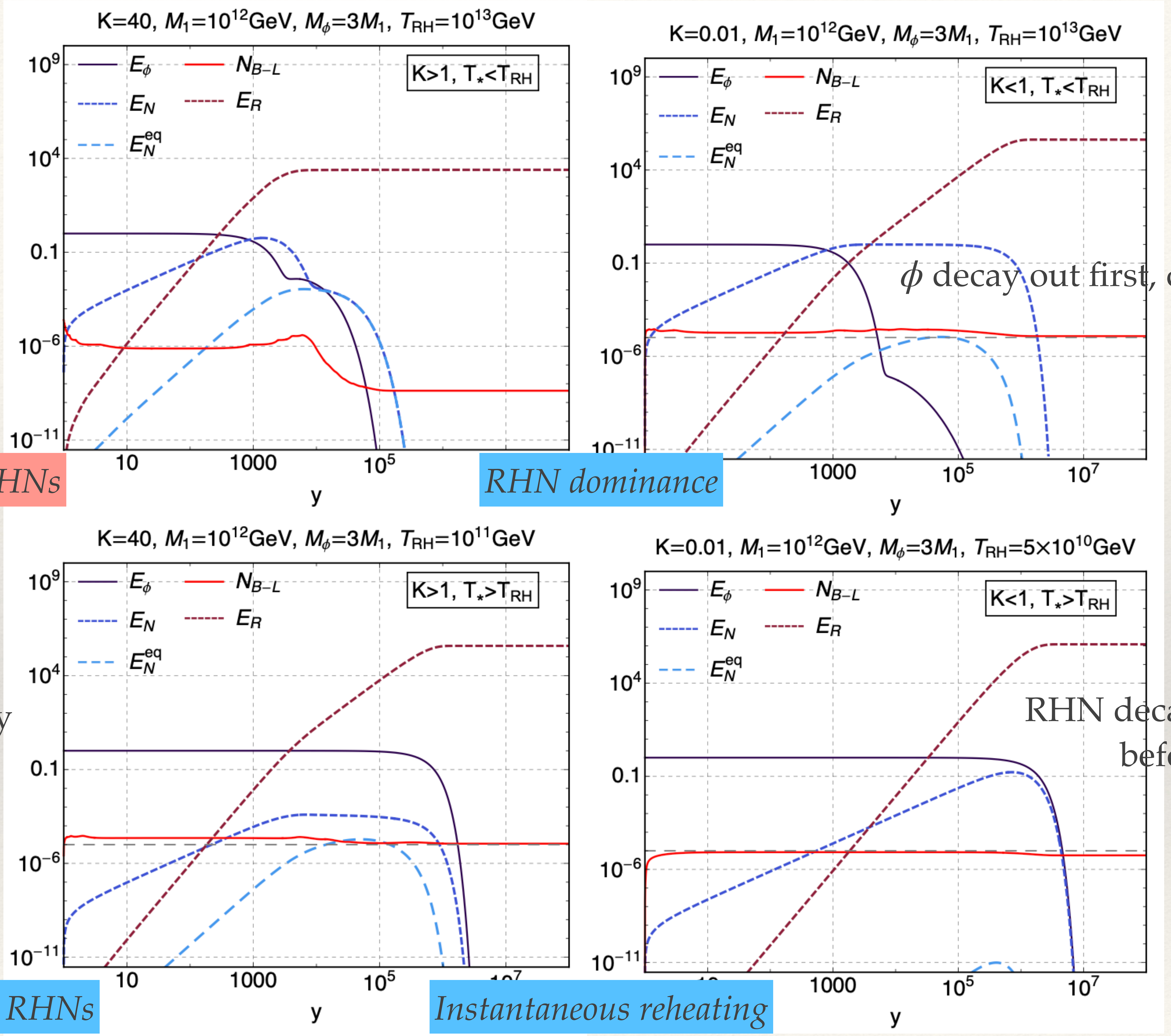
What about non-thermal leptogenesis?

- Natural in early Universe
- With memory of the initial state, we can infer info about the early Universe

1.4

Non-thermal leptogenesis
Instantaneous RHN decay
$\Gamma_N \gg \Gamma_\phi$
Delayed RHN decay
$\Gamma_N \ll \Gamma_\phi$
Instantaneous reheating
$K \ll 1,\ T_* \gg T_{\rm RH}$
Strongly non-thermal RHNs
$K \gg 1,\ T_* > T_{\rm RH}$
RHN dominance
$K \ll 1,\ T_* < T_{\rm RH}$
Thermalized RHNs
$K \gg 1,\ T_* < T_{\rm RH}$
RHNs never enter equilibrium
RHNs produced non-thermally, but enter equilibrium via quick interactions
$Y_{\rm B} = \frac{3}{2} c_{\rm sph} \epsilon \frac{T_{\rm RH}}{M_\phi}$
$Y_{\rm B} = \frac{3}{4} c_{\rm sph} \epsilon \frac{T_*}{M_1}$

Numeric results



Enter equilibrium

Thermalized RHNs

RHN dominance

ϕ decay out first, decayed RHN decay

Yukawa strong, but RHNs decay before entering equilibrium

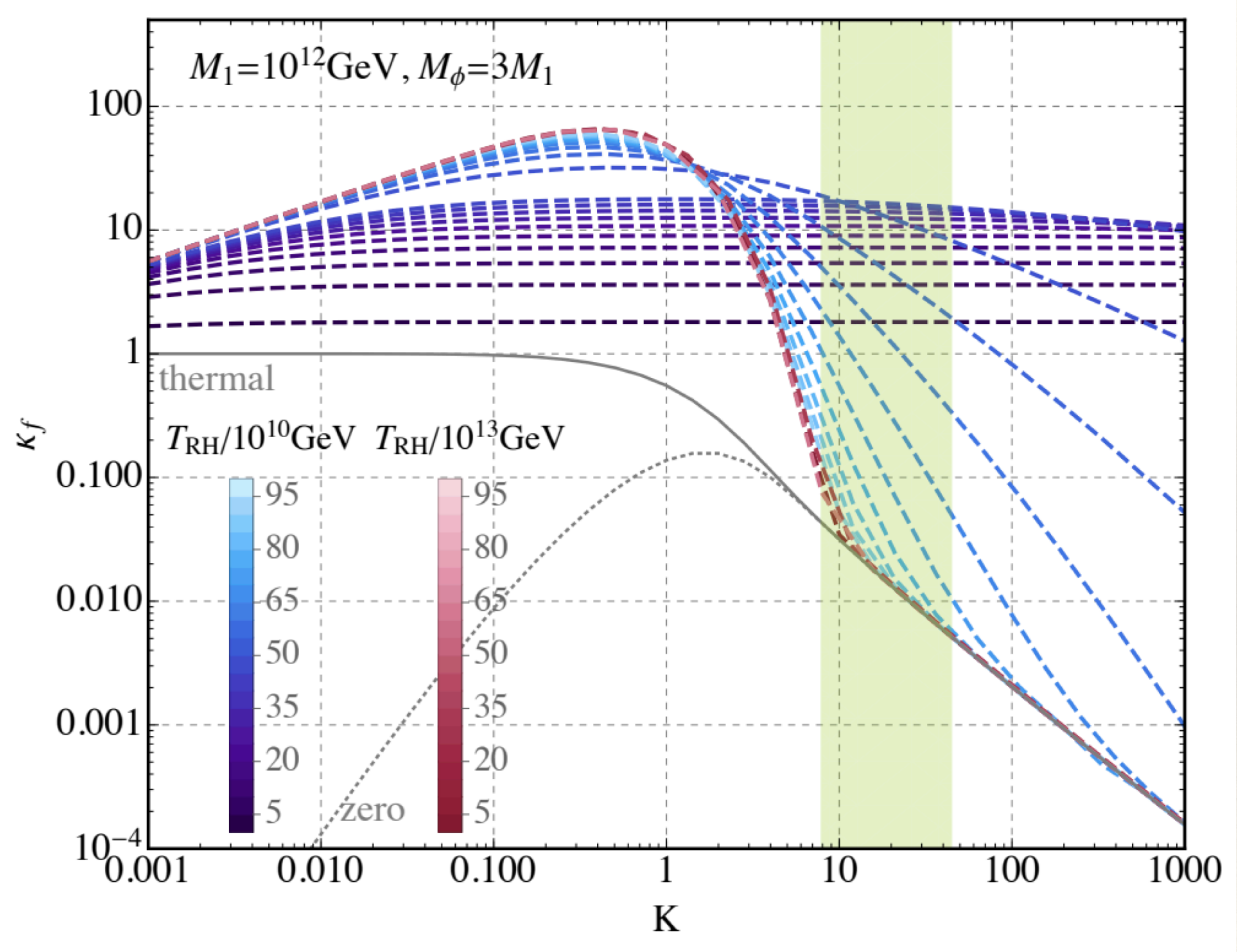
Strongly non-thermal RHNs

Instantaneous reheating

RHN decay once it's produced, before ϕ decay out

1.4

Final efficiency



$\{K, M_1, M_\phi, T_{RH}\}$

$$\eta_{B-L} = \frac{n_{B-L}}{n_\gamma^{eq}} = -\frac{3}{4}\epsilon\kappa_f$$

final efficiency factor κ_f

Have larger efficiency than thermal leptogenesis

Expand parameter space compared with thermal leptogenesis

1.4

Coleman-Weinberg potential

Connects to inflation limits parameter space in (M_1, K)

$$V(\phi) = A\phi^4 \left[\ln\left(\frac{\phi}{v_\phi}\right) - \frac{1}{4}\right] + \frac{1}{4}Av_\phi^4$$

Inflation-observation-compatible benchmark values

$$A = 2.41 \times 10^{-14}, v_\phi = 22.1 M_{\rm pl}$$

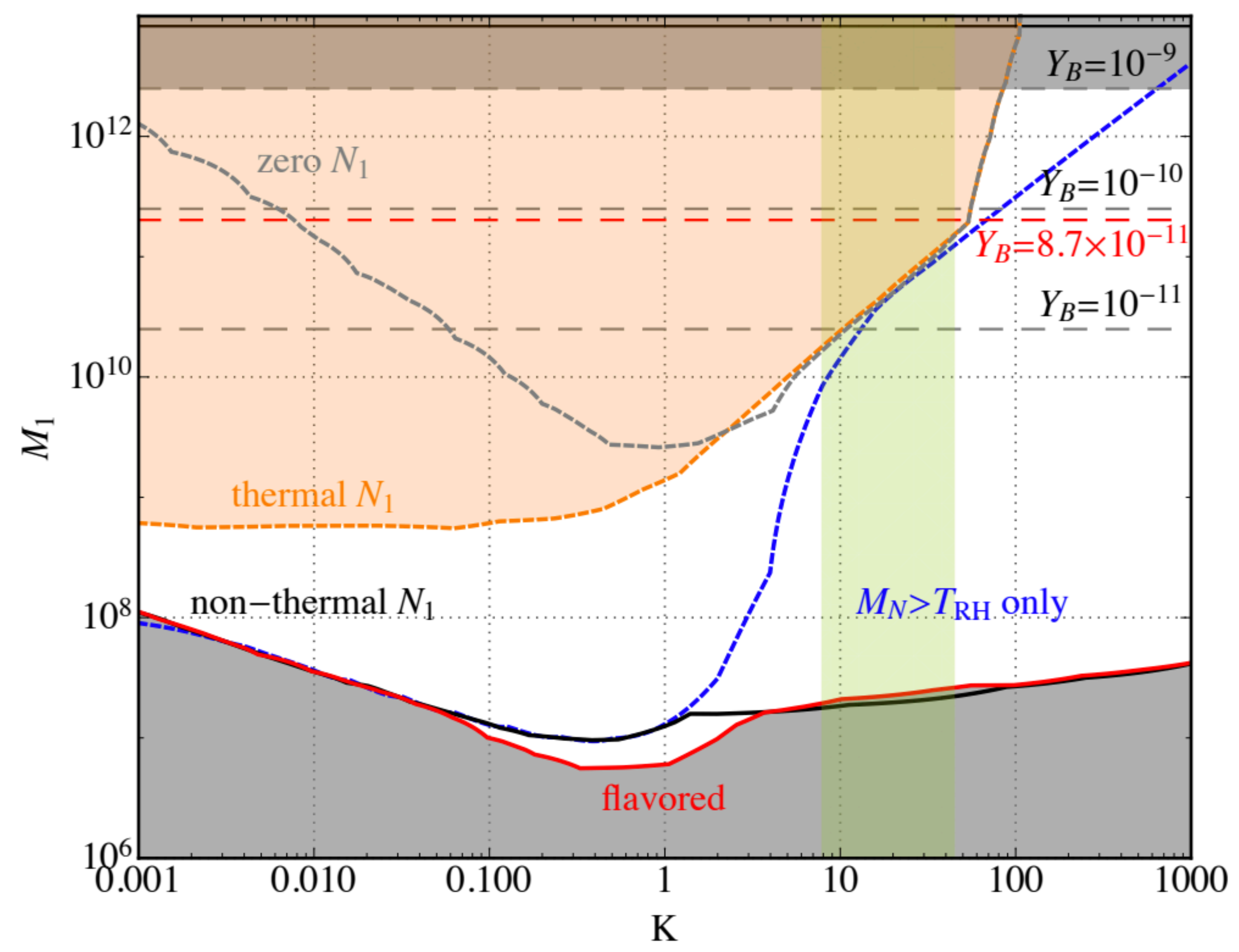
$$\rightarrow \quad M_\phi = 1.65 \times 10^{13}\ \text{GeV}$$

$$M_N = y_N v_\phi$$

Viable parameter space satisfy

$$T_{\rm RH} \simeq 10^{-5} M_1$$

Strongly non-thermal RHNs preferred



Natural inflation potential

$$V(\phi) = \Lambda\,(1 + \cos\phi/f)$$

Inflation-observation-compatible benchmark values

$$\Lambda \leq 10^{16}\text{GeV} \quad f \geq 10^{19}\ \text{GeV}$$

$$\rightarrow \quad M_\phi \leq 10^{13}\ \text{GeV}$$

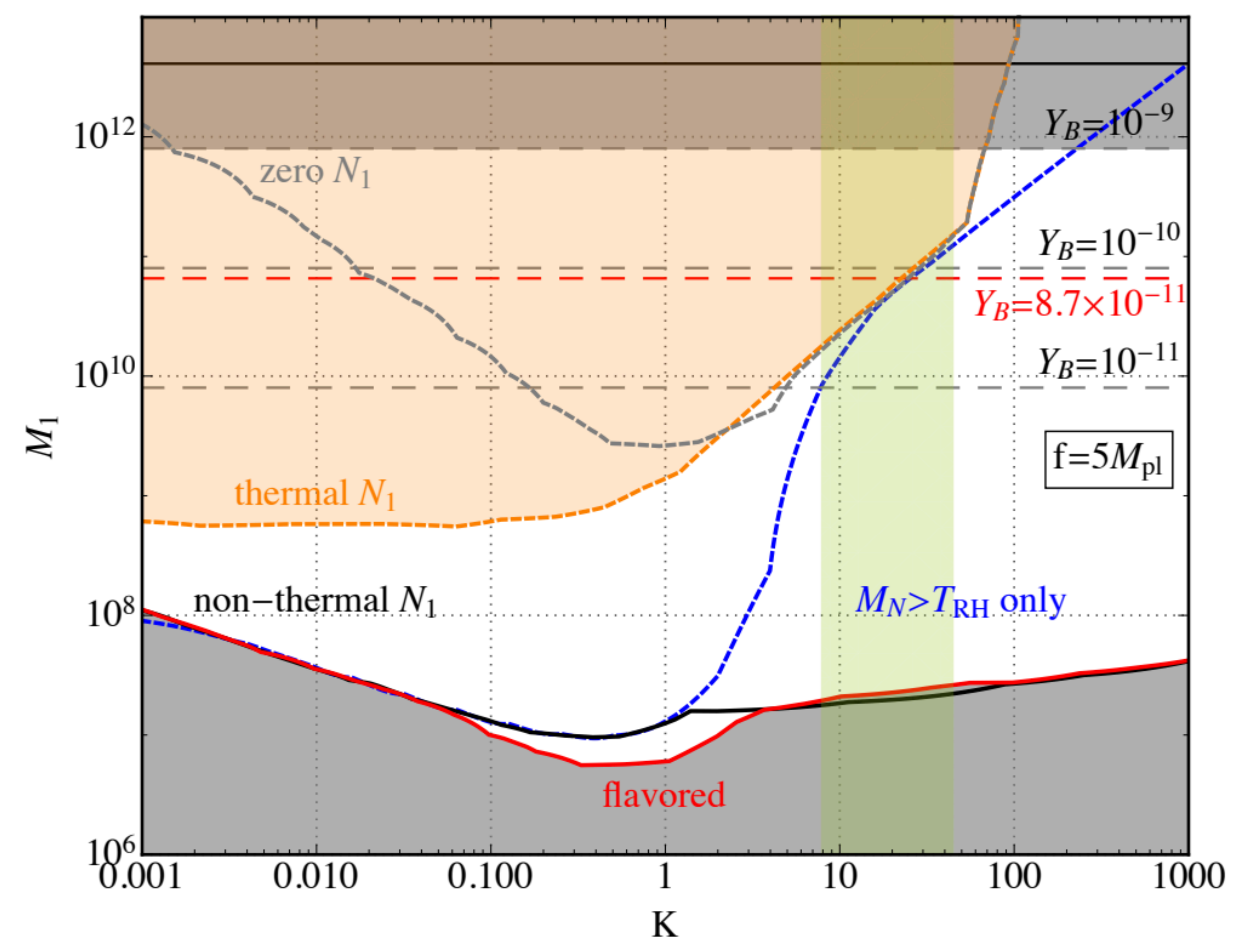
$$M_\phi^2 = \frac{\mathrm{d}^2 V}{\mathrm{d}\phi^2}\Big|_{\min} = \frac{\Lambda^4}{f^2}$$

Take $M_\phi = 10^{13}$ GeV $\quad f = 5M_{\rm pl}$

$$M_N = y_N f \ \rightarrow \ T_{\rm RH} \simeq 6 \times 10^{-5} M_1$$

Strongly non-thermal RHNs preferred

Connects to inflation limits parameter space in (M_1, K)



2

Reheating

Supercool state

at the end of inflation

→

Hot, radiation dominated state

L. Abbott, E. Farm, M.B. Wise, PLB, 1982, *Particle production in the new inflationary cosmology*

For reviews, see:
R. Allahverdi, R. Brandenberger, F. Cyr-Racine, A. Mazumdar, 1001.2600
K. Lozano, 1907.04402

2

Neutrino reheating

Assume direct inflaton RHN coupling

RHNs decay reheats the universe through their subsequent decays to SM particles

RHN responsible for reheating also in:

C. Cosme, F. Costa and O. Lebedev, 2402.04743

M.R. Haque, D. Maity and R. Mondal, 2311.07684, 2408.12450, *gravitational neutrino reheating*

3.1

The $N_{\rm RH} - N_k$ relation

$$N_{\rm RH} \equiv \ln\frac{a_{\rm RH}}{a_{\rm end}} = \frac{1}{3(1+\omega_{\rm RH})}\ln\left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)$$

$$N_{\rm RH} = \frac{4}{3(1+\omega_{\rm RH})}\left[\ln\frac{V_{\rm end}^{1/4}}{H_k} + \frac{1}{4}\ln\frac{45}{\pi^2 g_*} - \frac{1}{3}\ln\frac{43}{11 g_{*s,\rm RH}} + \ln\frac{k}{a_0 T_0} + N_k + N_{\rm RH}\right]$$

$$\omega_{\rm RH} \neq 1/3 \qquad N_{\rm RH} = \frac{4}{(1-3\omega_{\rm RH})}\left[-\ln\frac{V_{\rm end}^{1/4}}{H_k} - \frac{1}{4}\ln\frac{45}{\pi^2 g_*} + \frac{1}{3}\ln\frac{43}{11 g_{*s,\rm RH}} - \ln\frac{k}{a_0 T_0} - N_k\right]$$

$$\omega_{\rm RH} = 1/3 \qquad 0 = \ln\frac{V_{\rm end}^{1/4}}{H_k} + \frac{1}{4}\ln\frac{45}{\pi^2 g_*} - \frac{1}{3}\ln\frac{43}{11 g_{*s,\rm RH}} + \ln\frac{k}{a_0 T_0} + N_k$$

This relation decodes how reheating affects inflationary observations

3.2

Neutrino reheating and non-thermal leptogenesis

(1) Instantaneous RHN decay $\Gamma_N \gg \Gamma_\phi$

$N_{\rm RH} = 0$

$$0 = \ln\frac{V_{\rm end}^{1/4}}{H_k} + \frac{1}{4}\ln\frac{45}{\pi^2 g_*} - \frac{1}{3}\ln\frac{43}{11 g_{*s,{\rm RH}}} + \ln\frac{k}{a_0 T_0} + N_k$$

Definite prediction of $N_k \to (n_s, r)$

$$N_{\rm RH} \equiv \ln\frac{a_{\rm RH}}{a_{\rm end}} = \frac{1}{3(1+\omega_{\rm RH})}\ln\left(\frac{\rho_{\rm end}}{\rho_{\rm RH}}\right)$$

$\rho_{\rm RH} \to T_{\rm RH}$ *{inflationary parameters}*

$$Y_B = \frac{3}{2} c_{\rm sph}\epsilon\frac{T_{\rm RH}}{M_\phi}$$

3.2

Neutrino reheating and non-thermal leptogenesis

（2） Delayed RHN decay $\Gamma_N < \Gamma_\phi$

T_ϕ — Inflaton effectively decay

$$\rho_N|_{T_\phi} = \rho_\phi|_{T_\phi} = E_N n_N$$

$T_{\rm NR}$ — RHNs become non-relativistic

$$\rho_N|_{T_{\rm NR}} = M_N n_N$$

$T_{\rm RH}$ — RHNs effectively decay

$$\rho_N|_{T_{\rm RH}} = \rho_{\rm R}|_{T_{\rm RH}}$$

$$Y_{\rm B} = \frac{3}{4} c_{\rm sph} \epsilon \frac{T_{\rm RH}}{M_1}$$

$$N_{\rm I} = \frac{1}{3(1+\omega_{\rm I})} \ln \frac{\rho_N|_{T_\phi}}{\rho_N|_{T_{\rm NR}}}$$

$$N_{\rm RH} = N_{\rm I} + N_{\rm II}$$

$$N_{\rm II} = \frac{1}{3(1+\omega_{\rm II})} \ln \frac{\rho_N|_{T_{\rm NR}}}{\rho_N|_{T_{\rm RH}}}$$

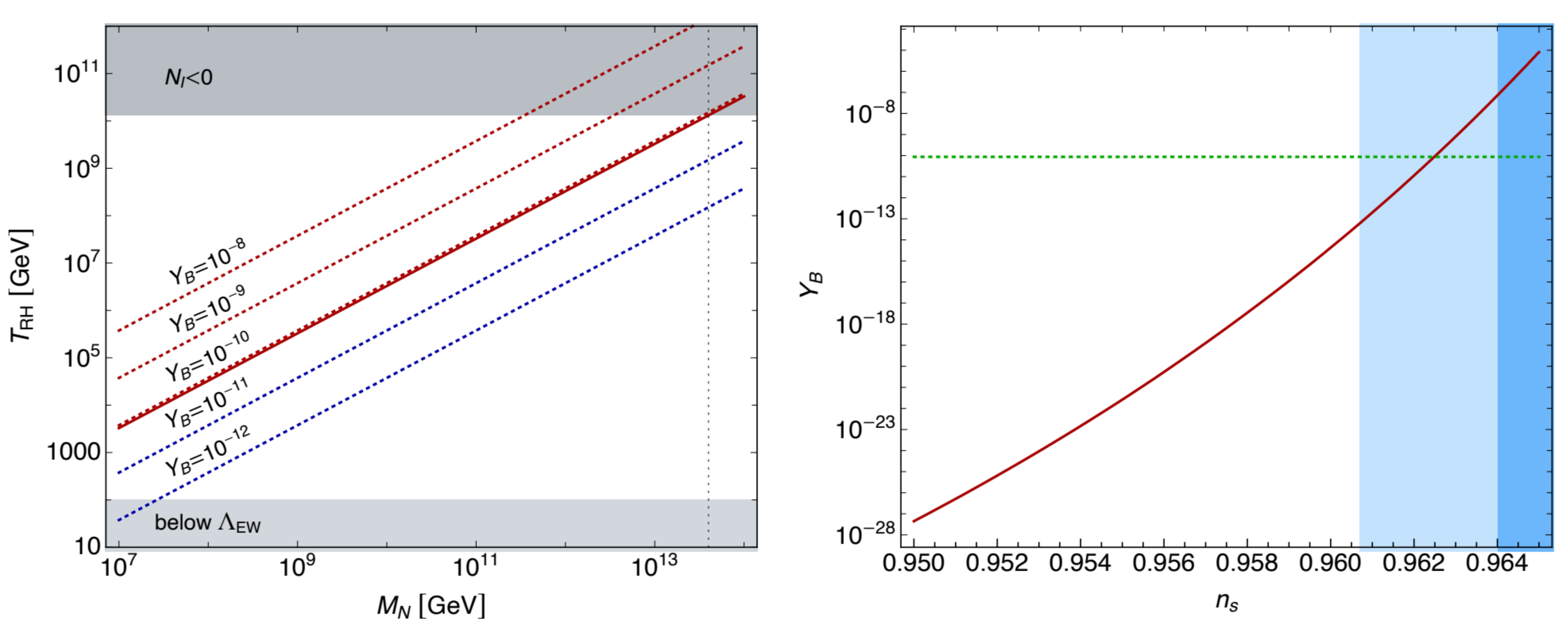
A polynomial type potential

$$V = \frac{1}{2} m^{4-\alpha} \phi^{\alpha}$$

(1) $\Gamma_N \gg \Gamma_\phi$:

$n_s = 0.9652,\ r = 0.139,\ T_{\rm RH} = 2.19 \times 10^{15}\text{GeV},\ Y_{\rm B} = 1.85 \times 10^{-5}$

(2) $\Gamma_N < \Gamma_\phi$:



3.3

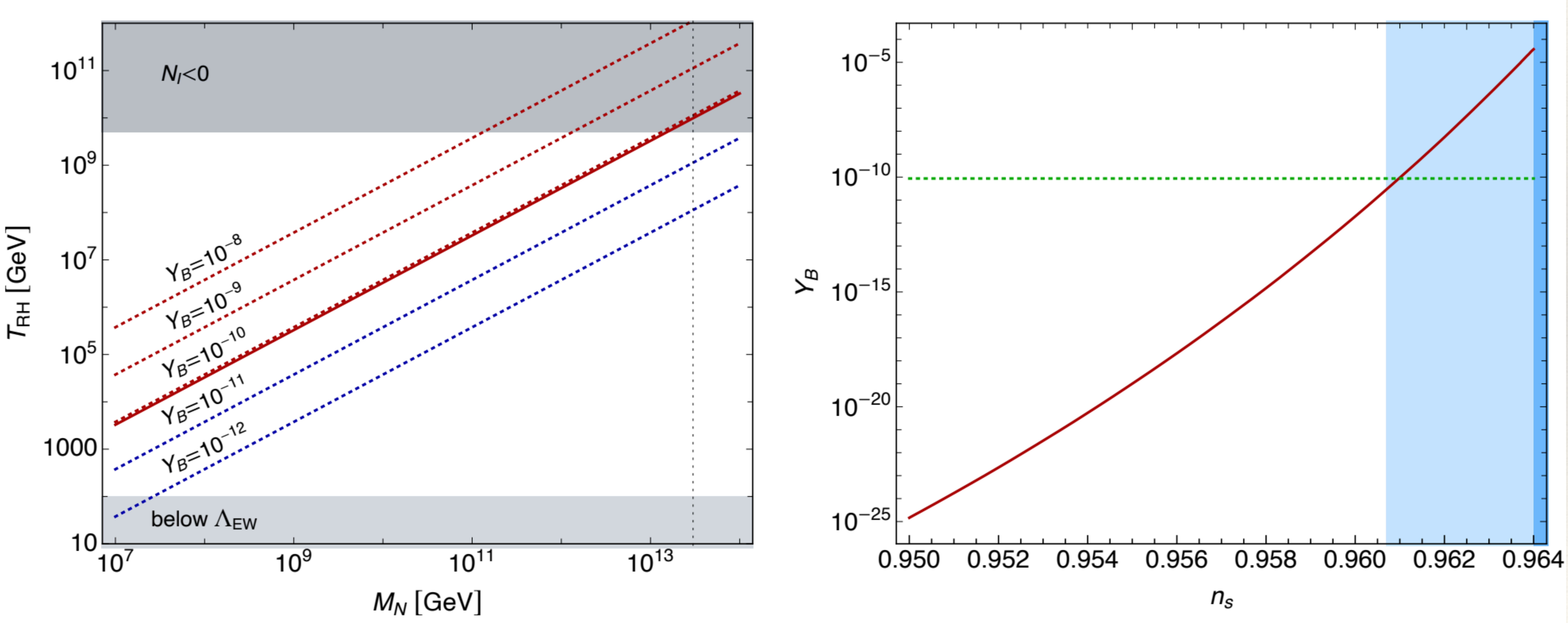
Starobinsky model

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

(1) $\Gamma_N \gg \Gamma_\phi$:

$n_s = 0.964,\ r = 0.0039,\ T_{RH} = 2.75 \times 10^{15}\text{GeV},\ Y_B = 4.67 \times 10^{-5}$

(2) $\Gamma_N < \Gamma_\phi$:



3.3

Coleman-Weinberg inflation

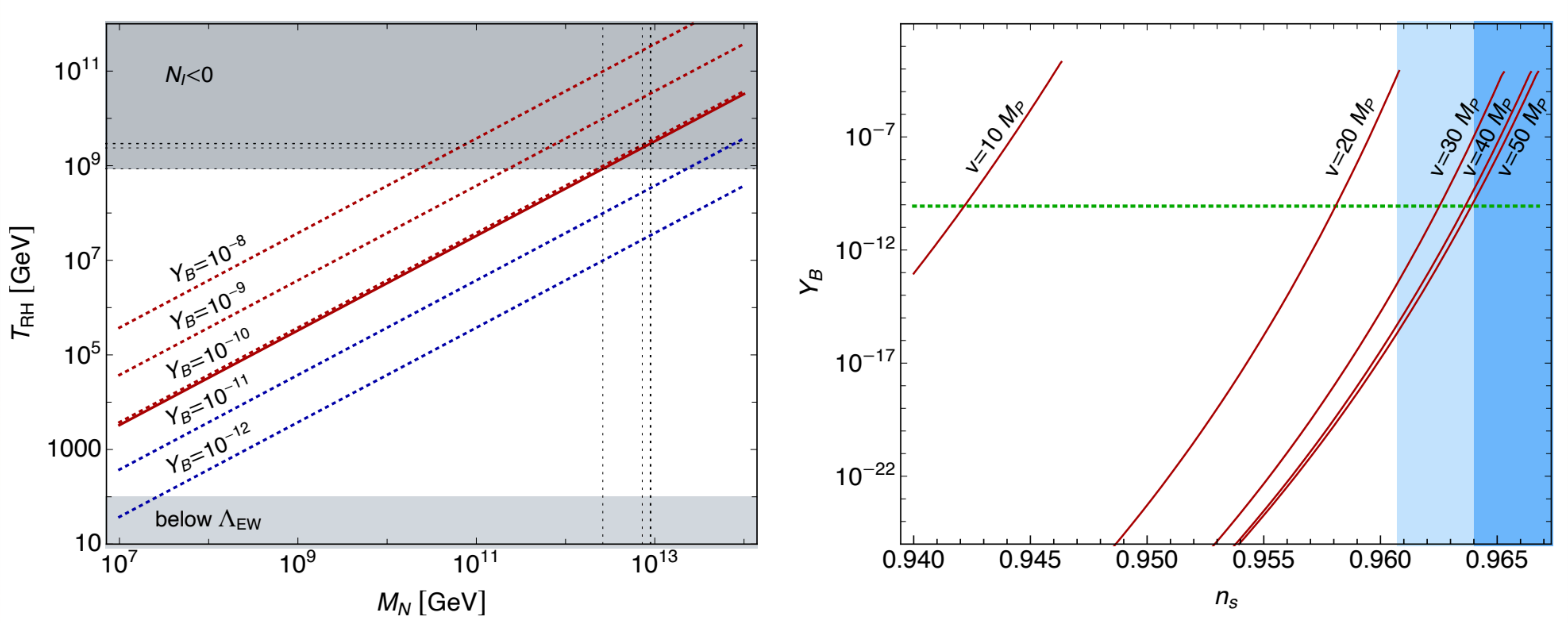
$$V = A\phi^4\left[\ln\left(\frac{\phi}{v}\right) - \frac{1}{4}\right] + \frac{1}{4}Av^4$$

(1) $\Gamma_N \gg \Gamma_\phi$:

$v \in [13,47]M_{\rm P}$, $T_{\rm RH} \in [2.47,2.91] \times 10^{15}$GeV, $M_\phi \in [1.40,1.71] \times 10^{13}$GeV

$Y_{\rm B} \in [9.05,9.39] \times 10^{-5}$

(2) $\Gamma_N < \Gamma_\phi$:



Natural inflation

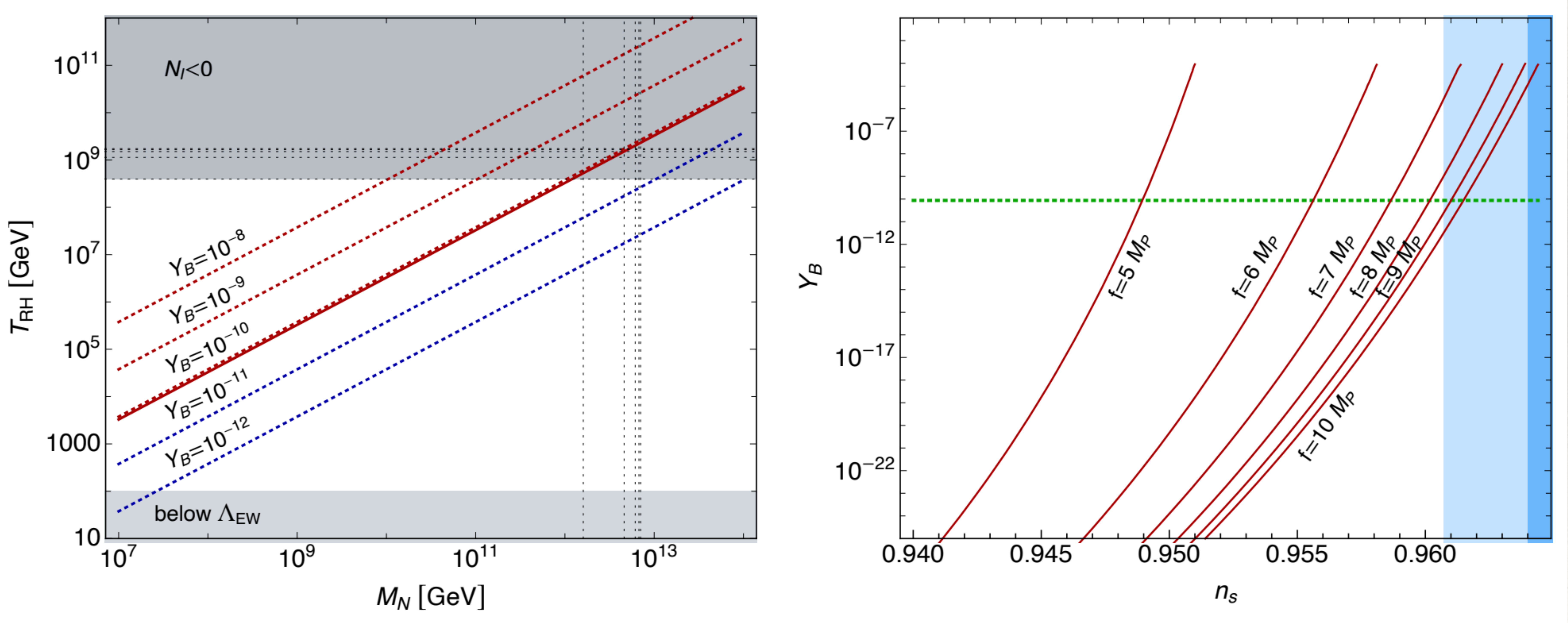
$$V = \Lambda^4 \left(1 + \cos\frac{\phi}{f}\right)$$

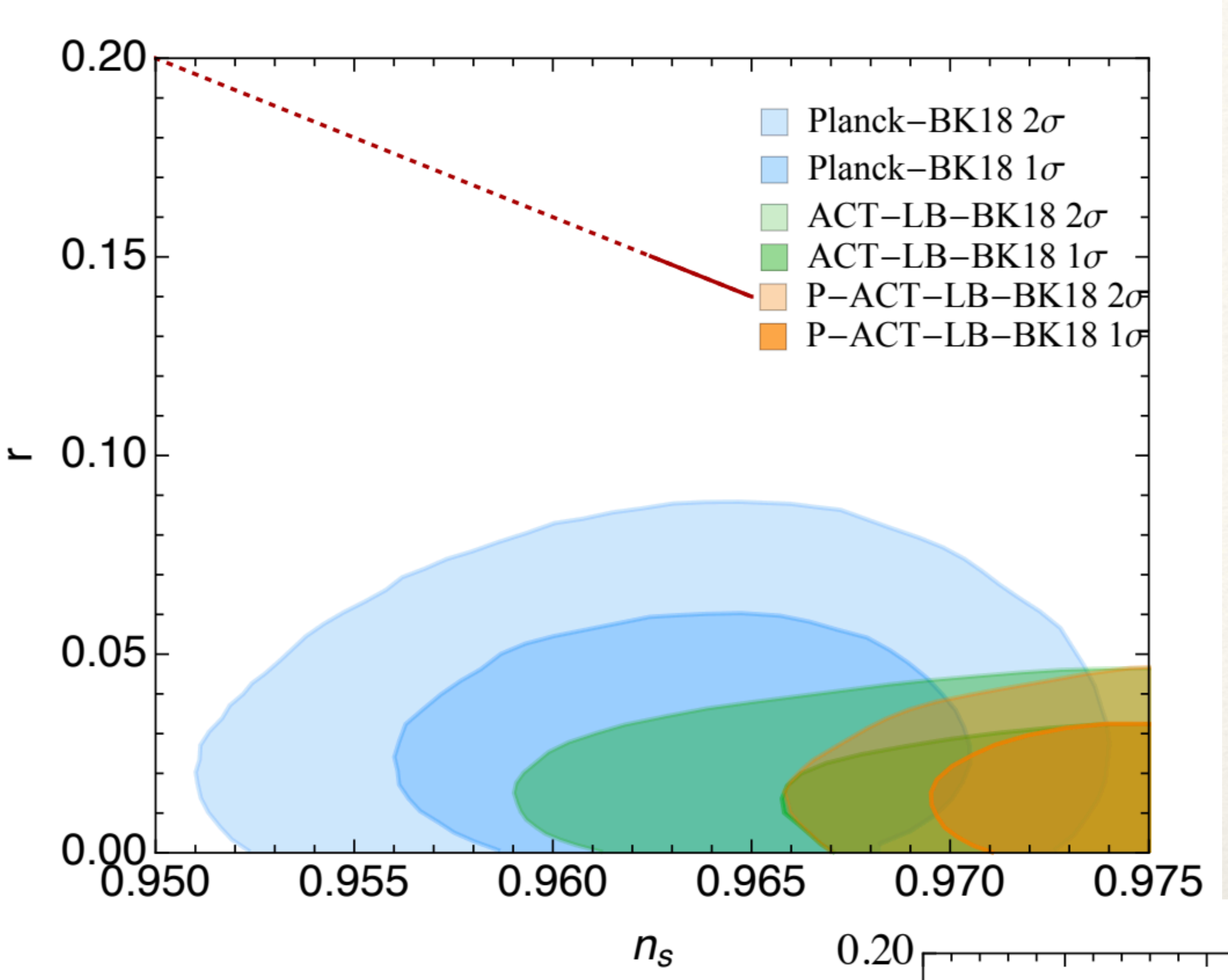
(1) $\Gamma_N \gg \Gamma_\phi$:

$f \in [5.09, 8.26] M_\mathrm{P}$, $T_\mathrm{RH} \in [2.52, 2.74] \times 10^{15}\mathrm{GeV}$, $M_\phi \in [1.23, 1.44] \times 10^{13}\mathrm{GeV}$

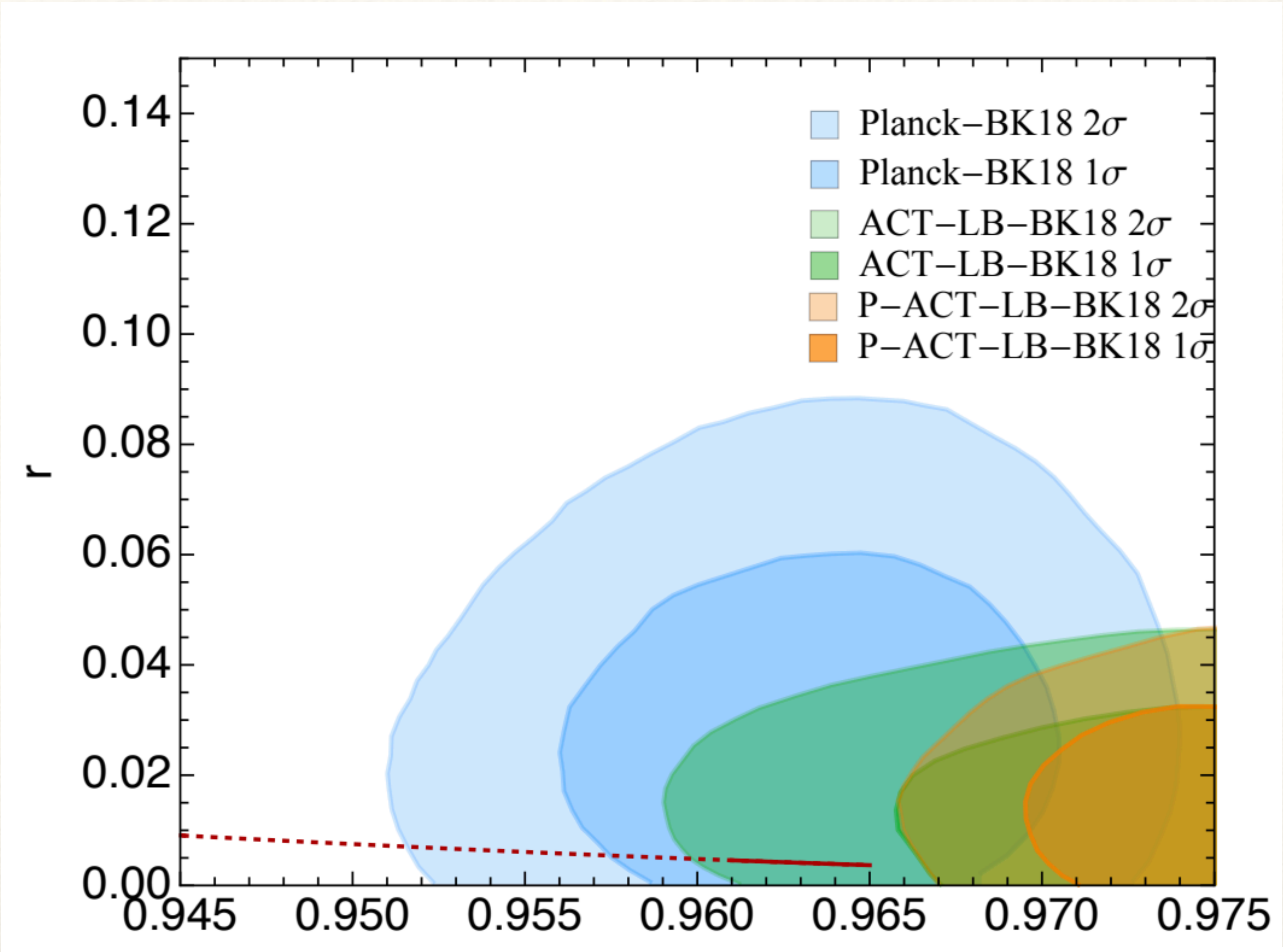
$Y_\mathrm{B} \in [1.00, 1.09] \times 10^{-4}$

(2) $\Gamma_N < \Gamma_\phi$:

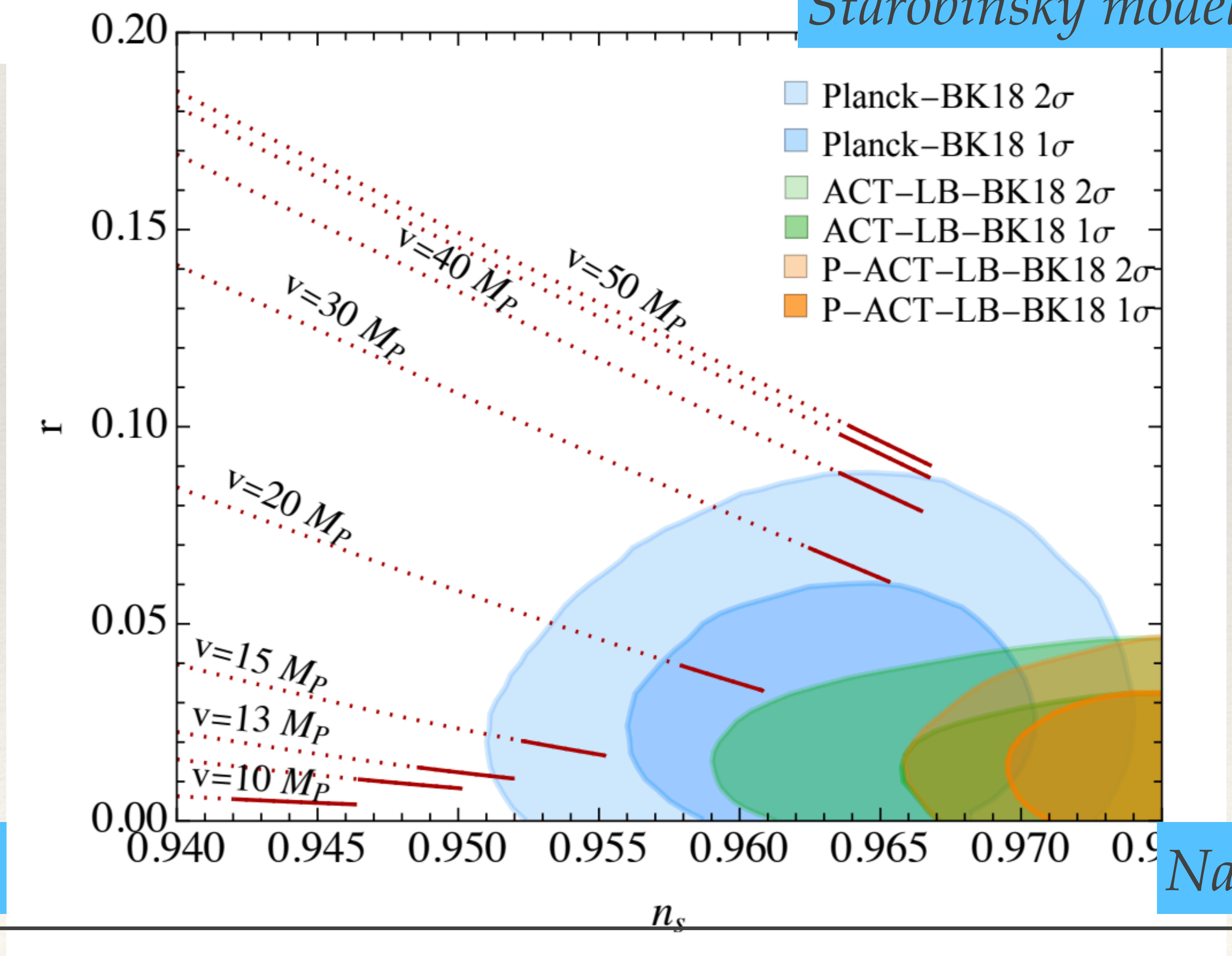




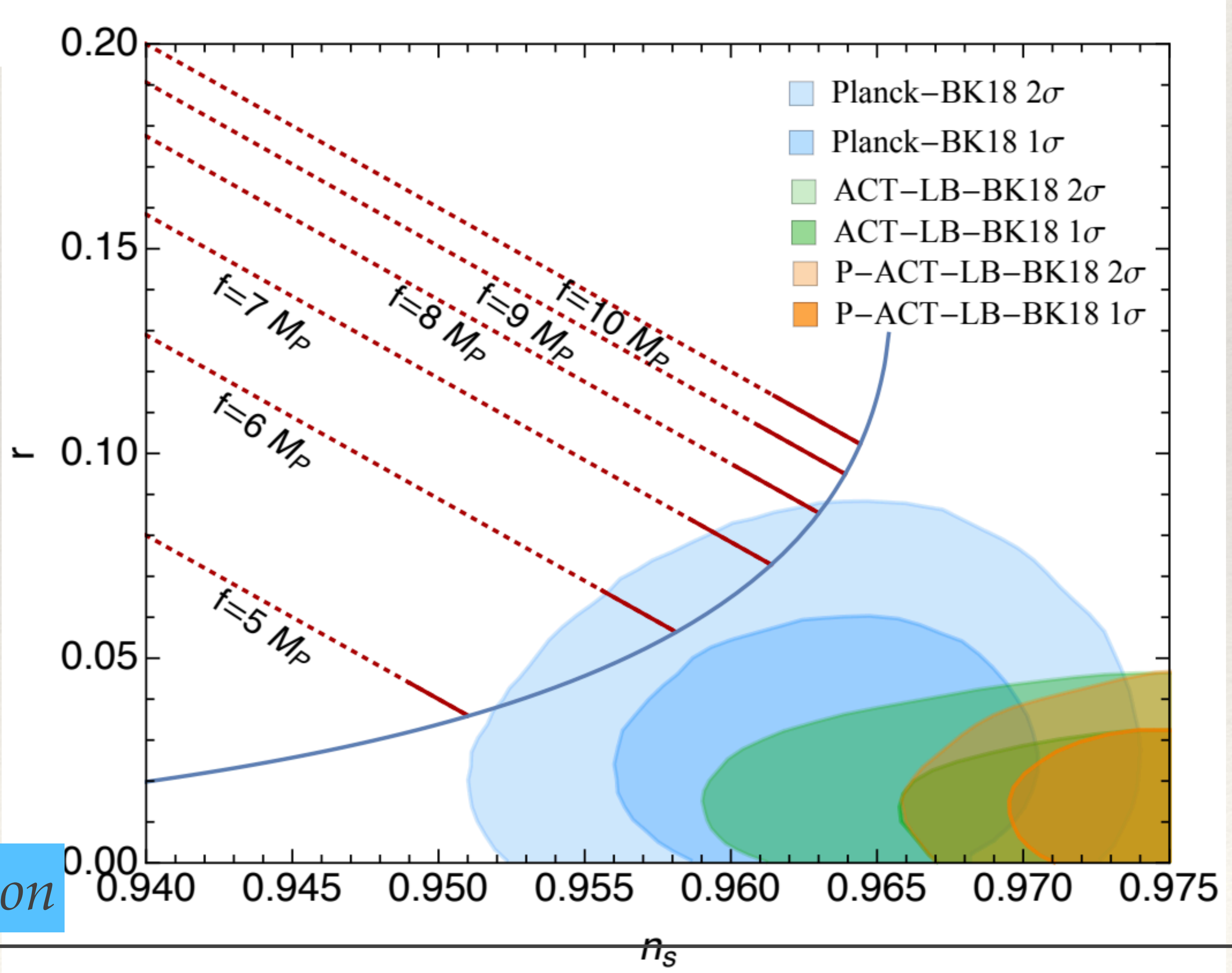
Polynomial type potential



Starobinsky model



Coleman-Weinberg inflation



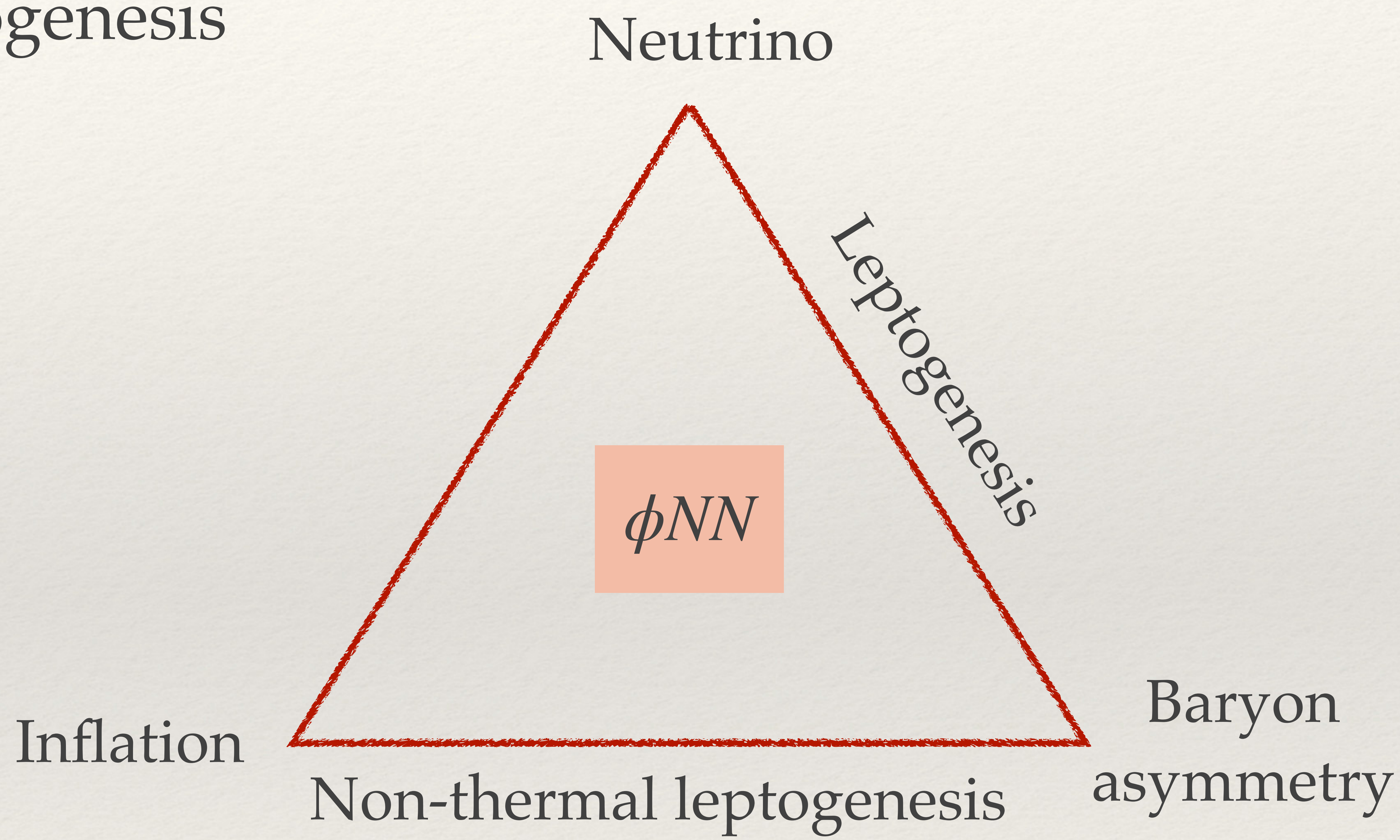
Natural inflation

Conclusions

With neutrino reheating + non-thermal leptogenesis

Y_B grows with n_s

- In right trend considering ACT
- ✓ Helps break model degeneracy
- ☐ Still model dependent



Thanks and stay tuned!

Backup

$K \ll 1$ limit

Weak Yukawa → Cannot thermalize RHN

$$Y_{\rm B} = \frac{n_{\rm B}}{s} = \frac{c_{\rm sph}\epsilon}{s} n_N$$

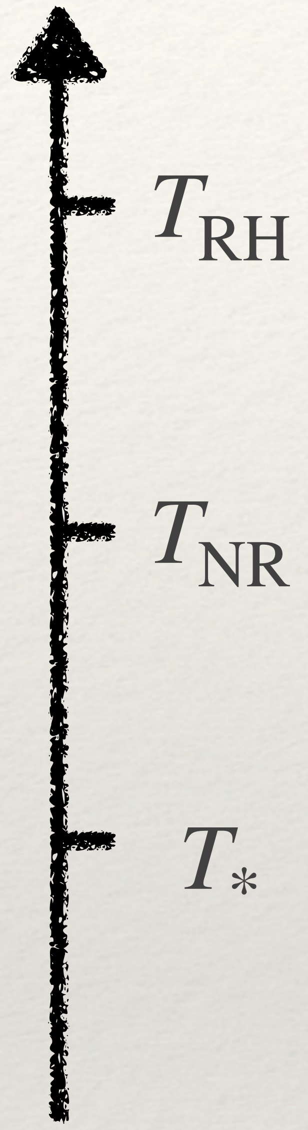
When the RHNs decay

Decay parameter

$$K = \tilde{m}_1 / m_*$$

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11}\, v^2}{M_1} = \frac{8\pi v^2}{M_1^2} \tilde{\Gamma}_N$$

$$m_* = \frac{8\pi v^2}{M_1^2} H(M_1) \, ,$$



For RHNs produced relativistically,

$$T_{\rm NR} = T_{\rm RH} M_1 / E_N \qquad E_N \simeq M_\phi / 2$$

For RHNs produced non-relativistically,

RHN dominance

$$T_{\rm NR} \simeq T_{\rm RH} \qquad Y_{\rm B} = \frac{3}{4} c_{\rm sph} \epsilon \frac{T_*}{M_1}$$

If RHNs decay instantly when produced

Instantaneous reheating

$$Y_{\rm B} = \frac{3}{2} c_{\rm sph} \epsilon \frac{T_{\rm RH}}{M_\phi}$$

Chung, Kolb and Riotto 1999

$K \gg 1$ limit

Strong Yukawa → thermalize RHN — Thermal leptogenesis

Strong Yukawa → Cannot thermalize RHN

RHN decay too fast

$$Y_B = \frac{3}{2} c_{\rm sph} \epsilon \frac{T_{\rm RH}}{M_\phi}$$

$\Gamma_N \gg \Gamma_\phi$

↓ Approx.

$T_* > T_{\rm RH}$

↓ Stronger, quick assessment

$M_1 > T_{\rm RH}$

Boltzmann equations

Solve Boltzmann equations for the system $\{\phi, N, R\}$

Previous

$$\begin{aligned}
\dot{\rho}_\phi &= -3H\rho_\phi - \Gamma_\phi\left(\rho_\phi - \rho_\phi^{\rm eq}\right) \ , \\
\dot{\rho}_N &= -3H\rho_N + \Gamma_\phi\left(\rho_\phi - \rho_\phi^{\rm eq}\right) - \Gamma_N\left(\rho_N - \rho_N^{\rm eq}\right) \ , \\
\dot{\rho}_R &= -4H\rho_R + \Gamma_N\left(\rho_N - \rho_N^{\rm eq}\right) \ , \\
\dot{n}_{\rm B-L} &= -3Hn_{\rm B-L} - \epsilon\Gamma_N\left(n_N - n_N^{\rm eq}\right) - W_{\rm ID}n_{\rm B-L} \ ,
\end{aligned}$$

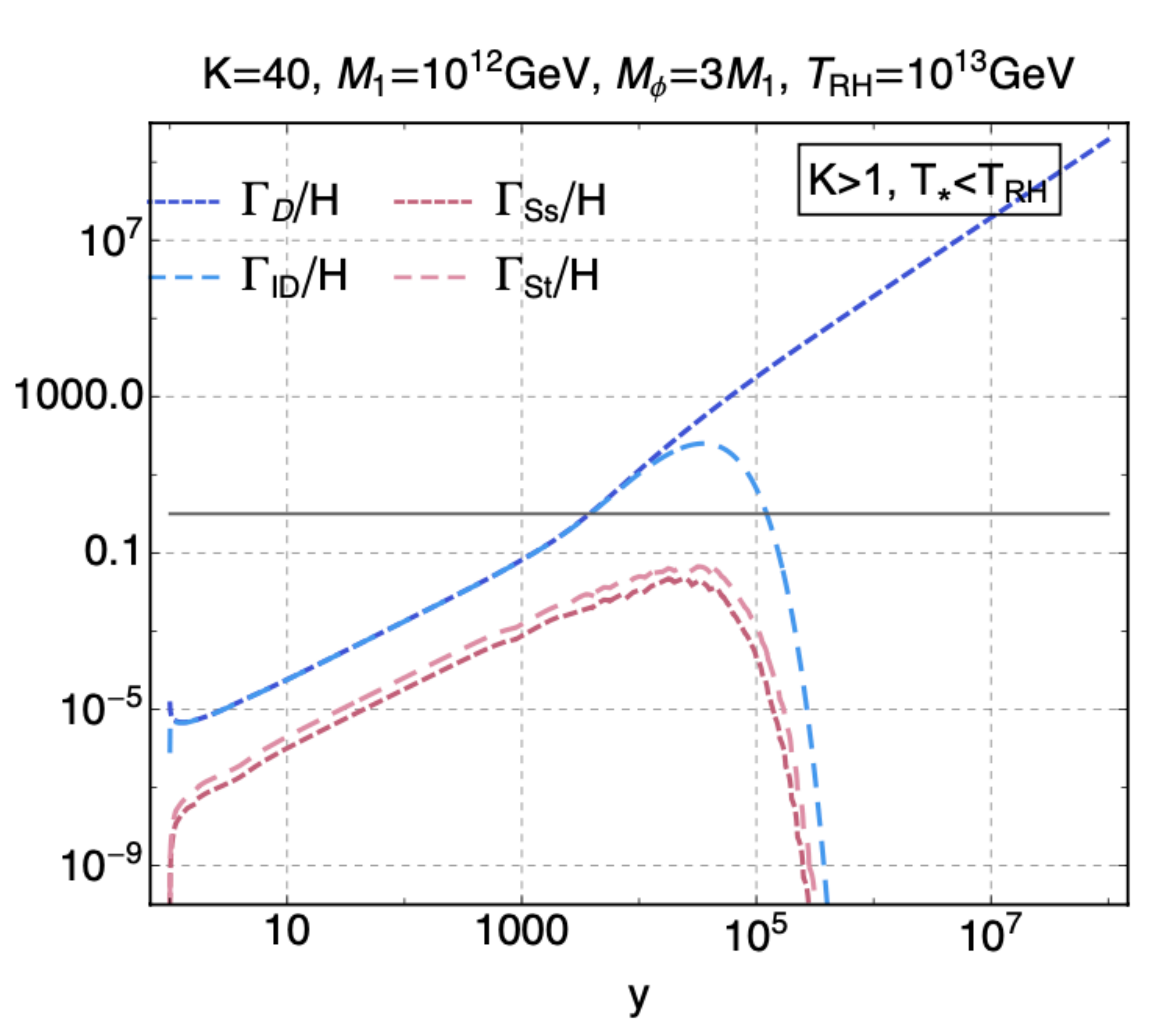
Now

$$\begin{aligned}
\dot{\rho}_\phi &= -3H\rho_\phi - \Gamma_\phi\left(\rho_\phi - \rho_\phi^{\rm eq}\right) , \\
\dot{\rho}_N &= -3H\rho_N + \Gamma_\phi\left(\rho_\phi - \rho_\phi^{\rm eq}\right) - \left(\Gamma_N + 2\Gamma_{Ss} + 4\Gamma_{St}\right)\left(\rho_N - \rho_N^{\rm eq}\right) , \\
\dot{\rho}_R &= -4H\rho_R + \left(\Gamma_N + 2\Gamma_{Ss} + 4\Gamma_{St}\right)\left(\rho_N - \rho_N^{\rm eq}\right) , \\
\dot{n}_{\rm B-L} &= -3Hn_{\rm B-L} - \epsilon\Gamma_N\left(n_N - n_N^{\rm eq}\right) - \left(W_{\rm ID} + \Gamma_{Ss}\frac{\rho_N}{\rho_N^{\rm eq}} + 2\Gamma_{St}\right)n_{\rm B-L},
\end{aligned}$$

Scale out expansion

$$E_\phi = \rho_\phi a^3, E_N = \rho_N a^3, N_{\rm B-L} = n_{\rm B-L}a^3, E_R = \rho_R a^4$$

$$\begin{aligned}
\frac{{\rm d}E_\phi}{{\rm d}y} &= -\frac{\Gamma_\phi}{Hy}\left(E_\phi - E_\phi^{\rm eq}\right) \ , \\
\frac{{\rm d}E_N}{{\rm d}y} &= \frac{\Gamma_\phi}{Hy}\left(E_\phi - E_\phi^{\rm eq}\right) - \frac{\Gamma_N}{Hy}\left(E_N - E_N^{\rm eq}\right) \ , \\
\frac{{\rm d}E_R}{{\rm d}y} &= \frac{\Gamma_N}{H}\left(E_N - E_N^{\rm eq}\right) \ , \\
\frac{{\rm d}N_{\rm B-L}}{{\rm d}y} &= -\frac{\epsilon\Gamma_N}{Hy}\left(N - N^{\rm eq}\right) - \frac{W_{\rm ID}}{Hy}N_{\rm B-L} \ .
\end{aligned}$$



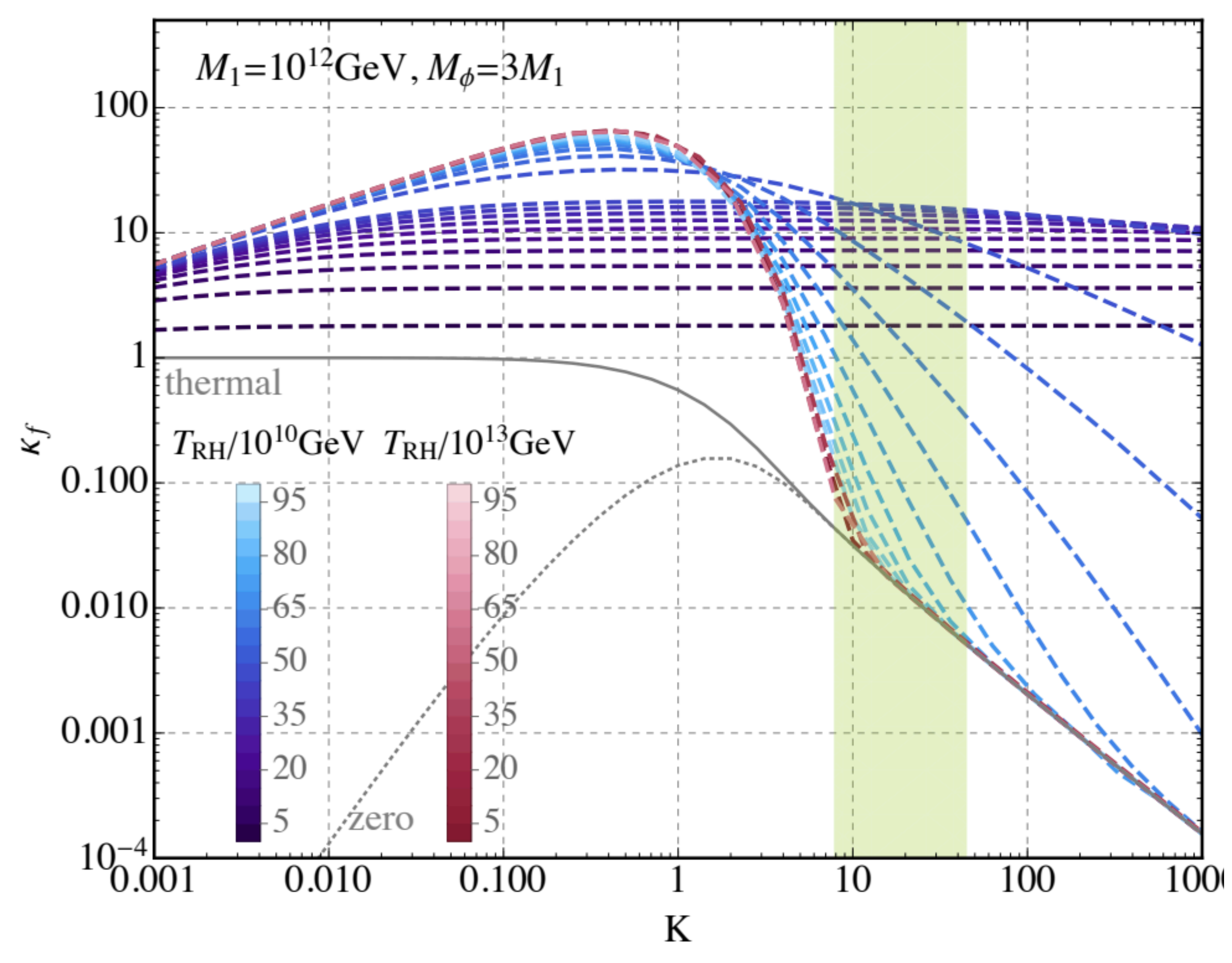
Neutrino mass bound

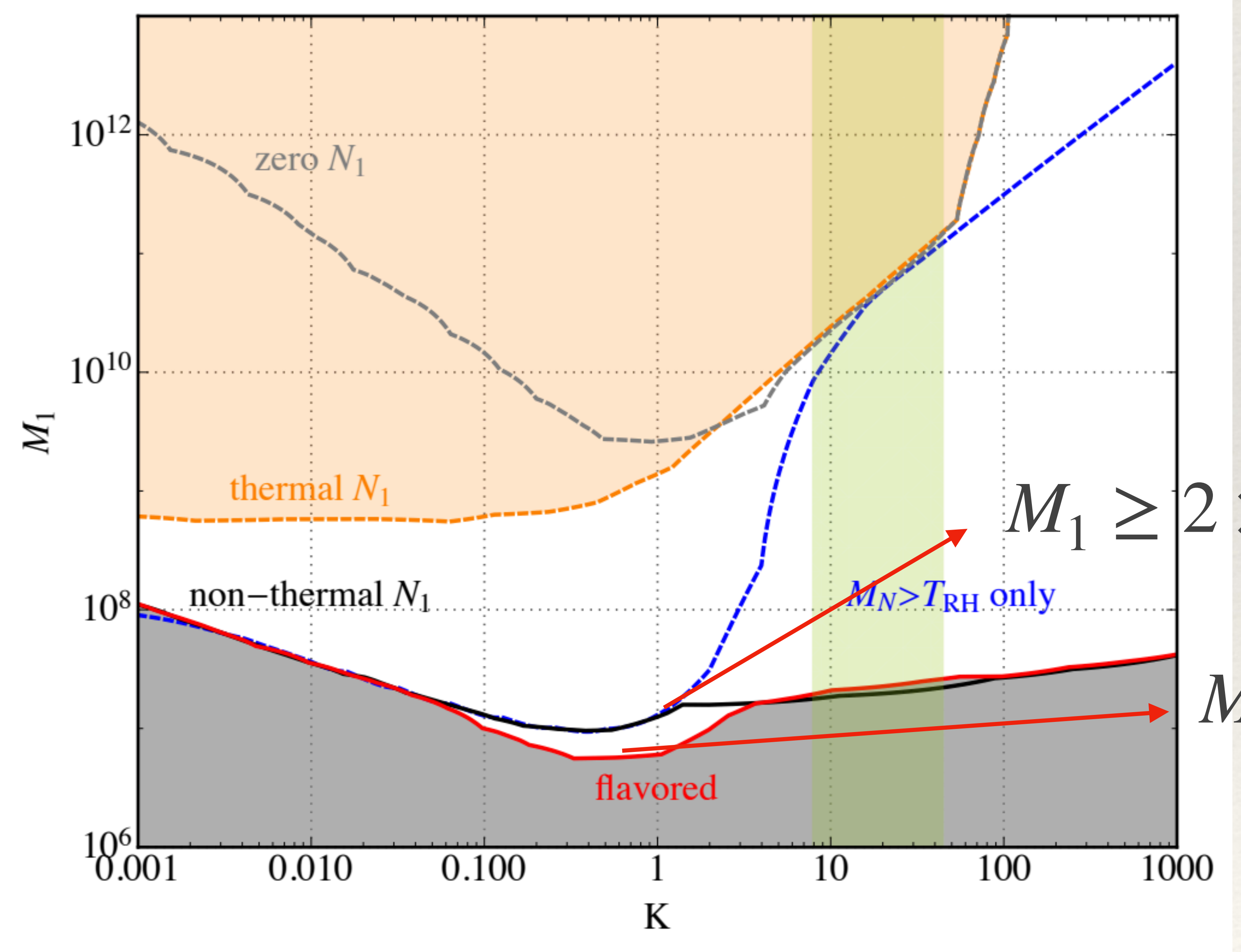
From the Dividson-Ibarra bound $|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1 m_{\rm atm}}{v^2}$

Davidson and Ibarra, 2022

We found a lower bound on the RHN mass

$$M_1 \geq 6\times 10^8\ \text{GeV}\left(\frac{Y_B}{8\times 10^{-11}}\right)\left(\frac{0.05\ \text{eV}}{m_{\rm atm}}\right)\kappa_f^{-1}(K)$$
$$\geq 6.28\times 10^8\ \text{GeV}\left(\frac{0.05\ \text{eV}}{m_{\rm atm}}\right)\kappa_f^{-1}(K)\,,$$





$M_1 \geq 2\times 10^7$ GeV

$M_1 \geq 10^7$ GeV

Connect to inflation

Scalar field charged under lepton number

$$\mathcal{L} \supset \overline{N} i \partial\!\!\!/ N + (\partial^\mu \sigma^\dagger)(\partial_\mu \sigma) - \bar{L} Y_\nu \widetilde{H} N - y_N \sigma \overline{N^c} N - V(H, \sigma) + \text{h.c.}$$

RHNs

RHNs get masses once lepton number spontaneously broken

$\phi = \mathrm{Re}(\sigma)$ Coleman-Weinberg potential

$\phi = \mathrm{Im}(\sigma)$ Natural inflation potential

Inflationary constraints:

$$n_s = 0.9649 \pm 0.0126, \quad r < 0.056, \ (95\% \text{ C.L.})$$

$$V_* = \frac{3\pi^2}{2} A_s r M_{\rm pl}^4 < \left(1.6 \times 10^{16} \text{ GeV}\right)^4$$

Important quantities

Inflaton decay rate $\Gamma_\phi = y_N^2 \frac{M_\phi}{4\pi}$

Reheating temperature $T_{\rm RH} = \left(\frac{45}{4\pi^3 g_*}\right)^{\frac{1}{4}} \sqrt{\Gamma_\phi m_{\rm pl}}$

Effectively parametrize y_N

RHN decay rate $\Gamma_N = H(M_1) K \frac{K_1(z)}{K_2(z)}$

Decay parameter $K = \tilde{m}_1 / m_*$

$$\tilde{m}_1 = \frac{(Y_\nu^\dagger Y_\nu)_{11} v^2}{M_1} = \frac{8\pi v^2}{M_1^2} \tilde{\Gamma}_N$$

$$m_* = \frac{8\pi v^2}{M_1^2} H(M_1) \, ,$$

Effectively the Yukawa strength

RHN decay temperature $T_* = \sqrt{K} M_1$

$$Y_{\rm B} = \frac{n_{\rm B}}{s} = \frac{c_{\rm sph}\epsilon}{s} n_N$$

The $N_{\rm RH} - N_k$ relation

$$\frac{a_0}{a_{\rm RH}} = \frac{a_k}{a_{\rm end}}\frac{a_{\rm end}}{a_{\rm RH}}\frac{a_0 H_k}{a_k H_k} = \frac{a_k}{a_{\rm end}}\frac{a_{\rm end}}{a_{\rm RH}}\frac{a_0 H_k}{k}$$

Entropy conservation

$$g_{*s,\rm RH} T_{\rm RH}^3 a_{\rm RH}^3 = \left(2T_0^3 + 6 \times \frac{7}{8} T_{\nu 0}^3\right) a_0^3$$

$$T_{\rm RH} = \left(\frac{43}{11 g_{*s,\rm RH}}\right)^{1/3} \frac{a_0}{a_{\rm RH}} T_0$$