The XIX International Conference on Topics in Astroparticle and Underground Physics (TAUP2025)

Connecting inflation and the baryon asymmetry with neutrino reheating

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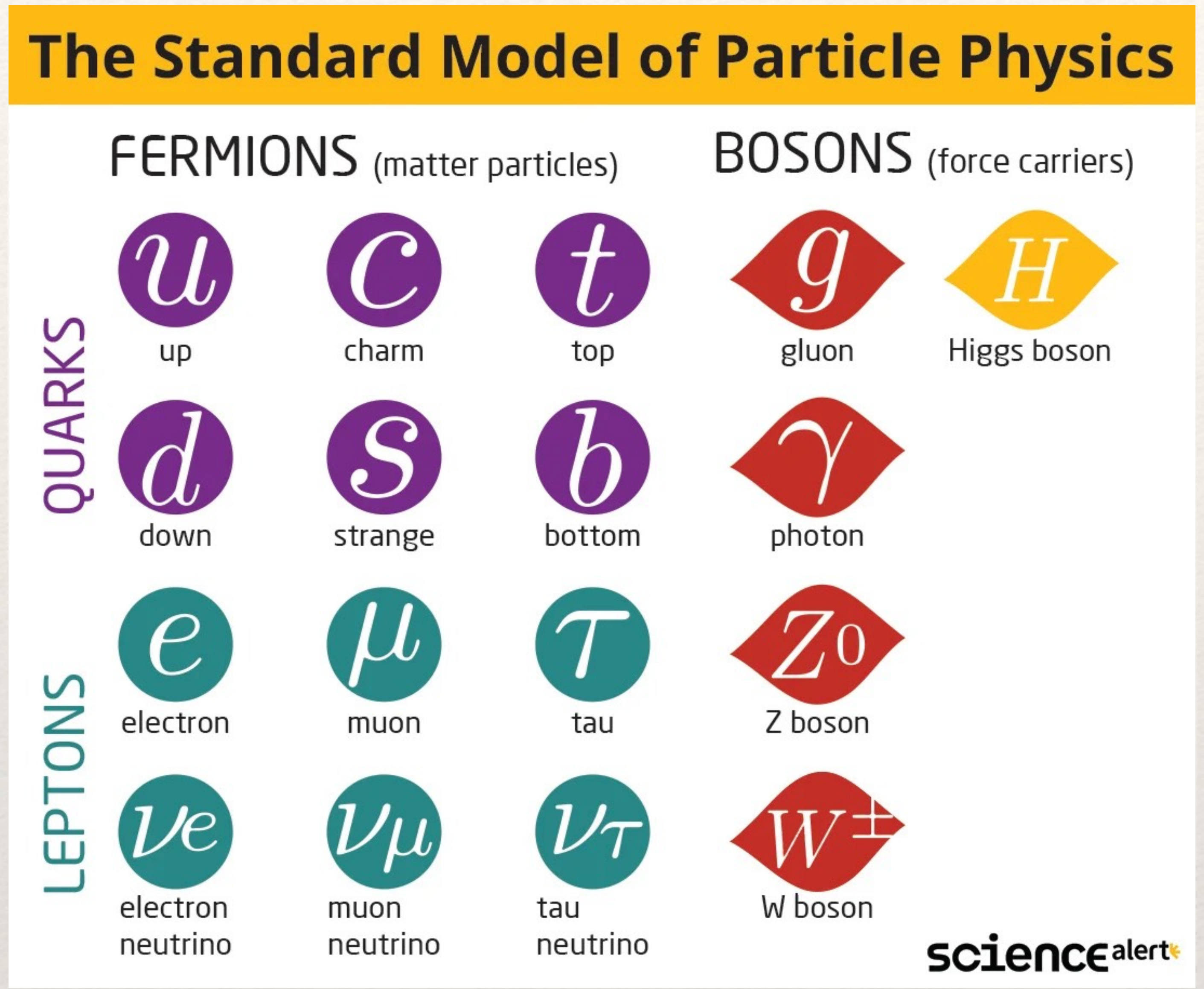
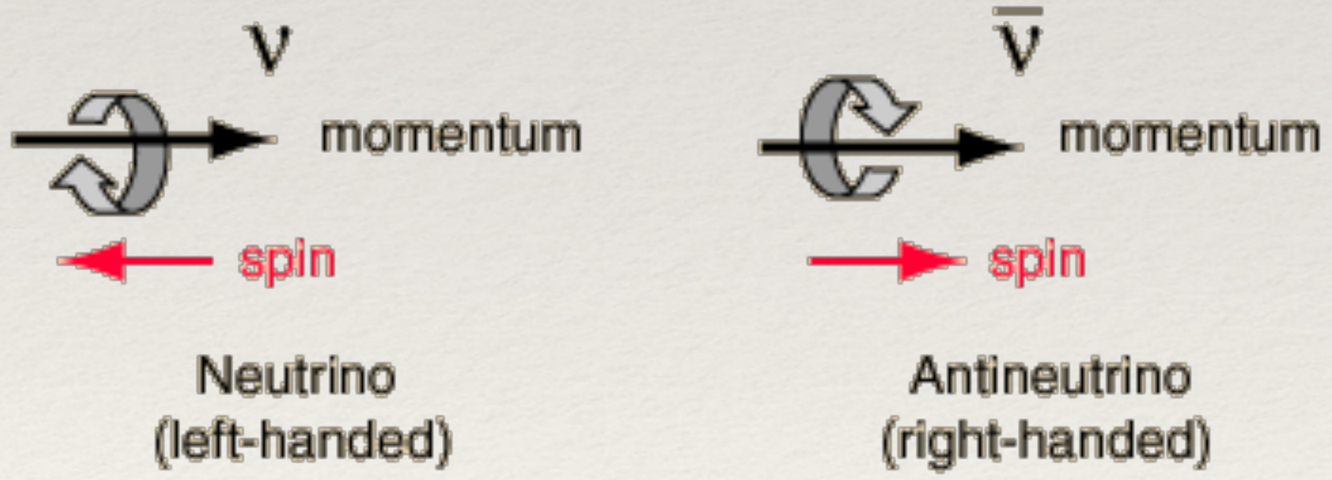
JHEP 07 (2025) 099 (arXiv:2501.16114)

2025年8月25日, Xichang

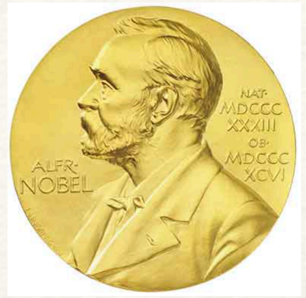
Massive neutrinos

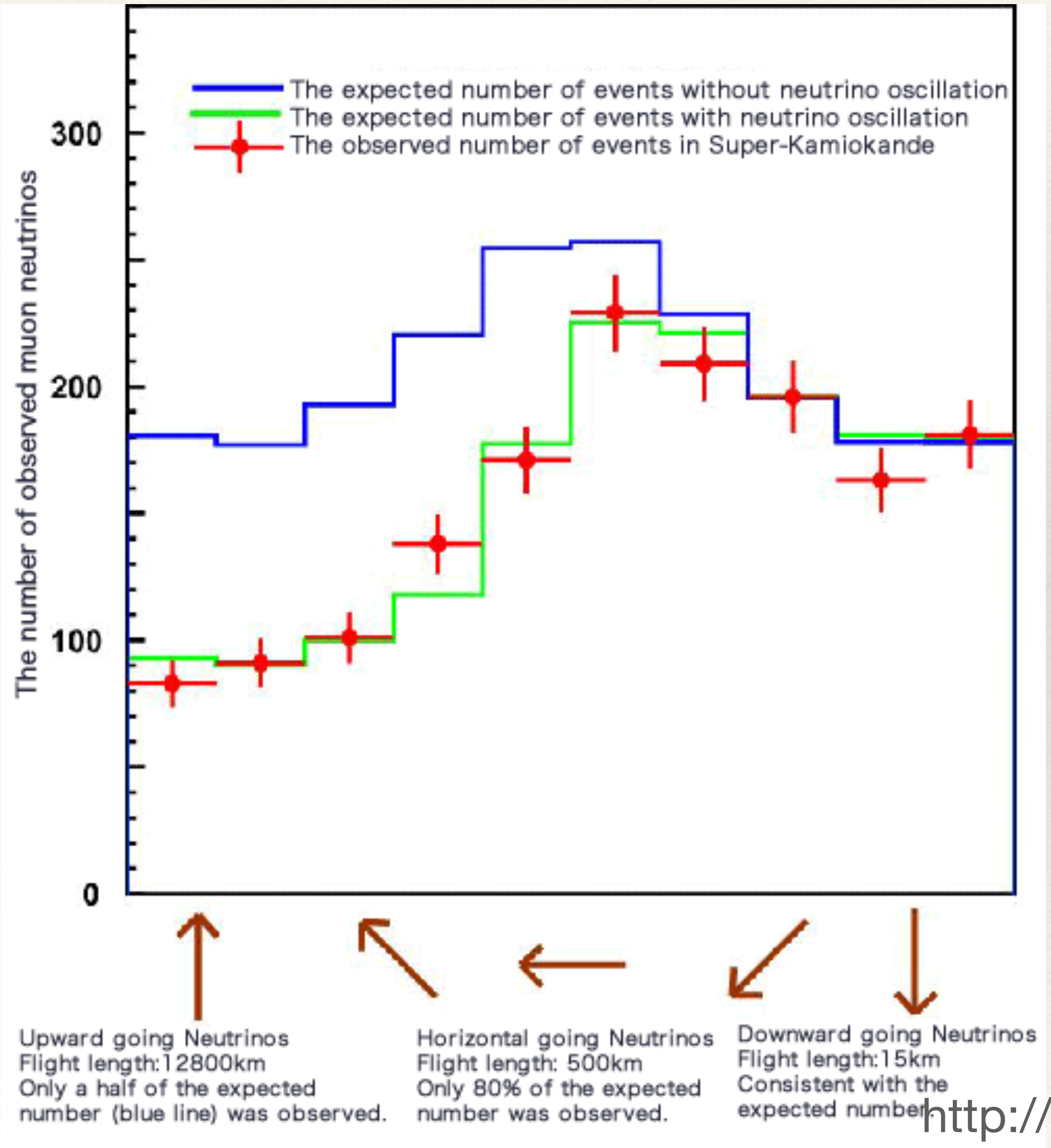




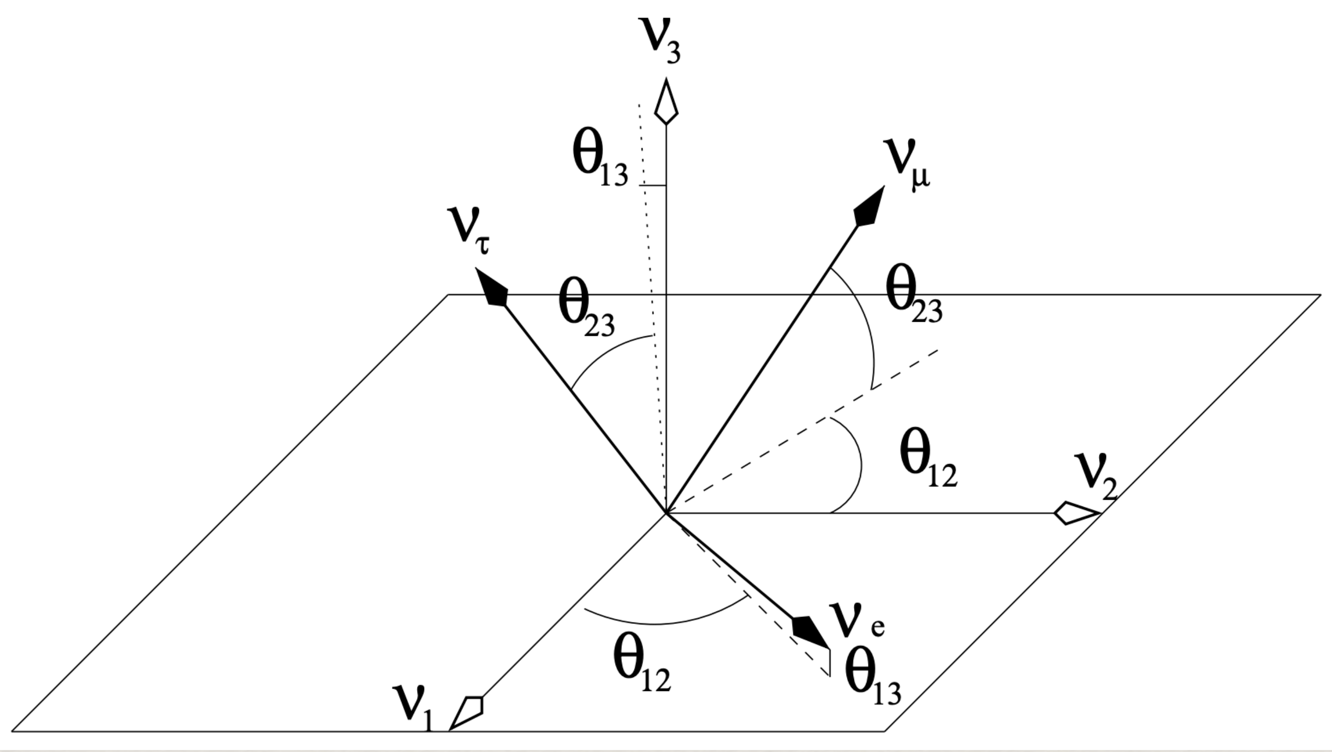
SM neutrinos are massless

2015 Nobel Prize in Physics: T. Kajita and A. B. McDonald, "for the discovery of neutrino oscillations, which shows that neutrinos have mass".





http://www.hyper-k.org/



S. F. King, 0310204

Neutrinos have masses and mixing

One of the most solid BSM evidence

Neutrino mass generation mechanism

With only SM fields,

S. Weinberg, 1980 $\frac{1}{\Lambda}\bar{L}^c \otimes \Phi \otimes \Phi \otimes L$

$\boxed{\text{unique dimension 5 operator} \\ \text{Lepton-number violating}}$

$$\frac{1}{\Lambda^{2n+1}}\bar{L}^c\Phi^2\left(\Phi^\dagger\Phi\right)^n L, \quad n \in \{0, 1, 2, 3...\}$$

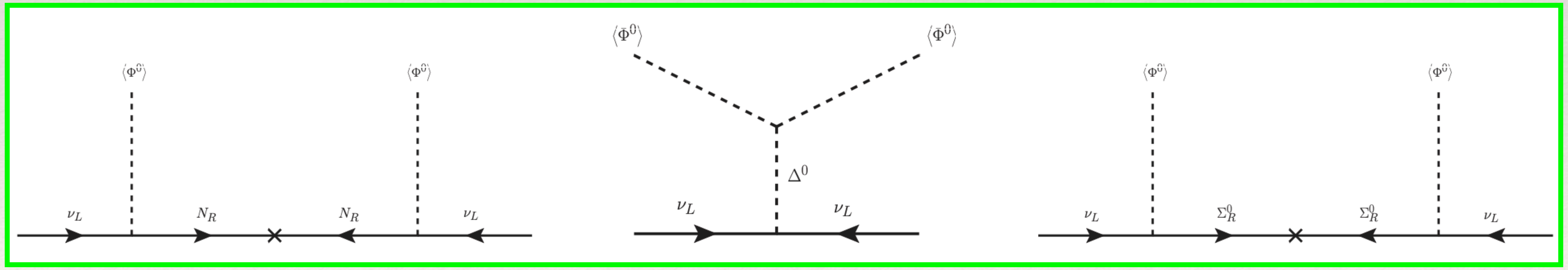
Consider different contracting,

$$\underbrace{\underbrace{\bar{L}^c \otimes \Phi}_{1} \otimes \underbrace{\Phi \otimes L}_{1}}_{\text{Type I}}, \quad \underbrace{\underbrace{\bar{L}^c \otimes L}_{3} \otimes \underbrace{\Phi \otimes \Phi}_{3}}_{\text{Type II}}, \quad \underbrace{\underbrace{\bar{L}^c \otimes \Phi}_{3} \otimes \underbrace{\Phi \otimes L}_{3}}_{\text{Type III}}$$

Chulia, Srivastava and Valle, 1802.05722

Add new fields to make renormalizable operators

Tree-level realization of Weinberg operator



Type I, II, III Seesaw mechanism:
Neutrino mass suppressed by the heavy mediator mass

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

Type-I seesaw mechanism

With only SM fields,

S. Weinberg, 1980 $\frac{1}{\Lambda}\bar{L}^c \otimes \Phi \otimes \Phi \otimes L$

Adding SM singlet fermion, right-handed neutrino (RHN)

$$\frac{1}{\Lambda^{2n+1}}\bar{L}^c\Phi^2\left(\Phi^\dagger\Phi\right)^n L, \quad n \in \{0,1,2,3...\}$$

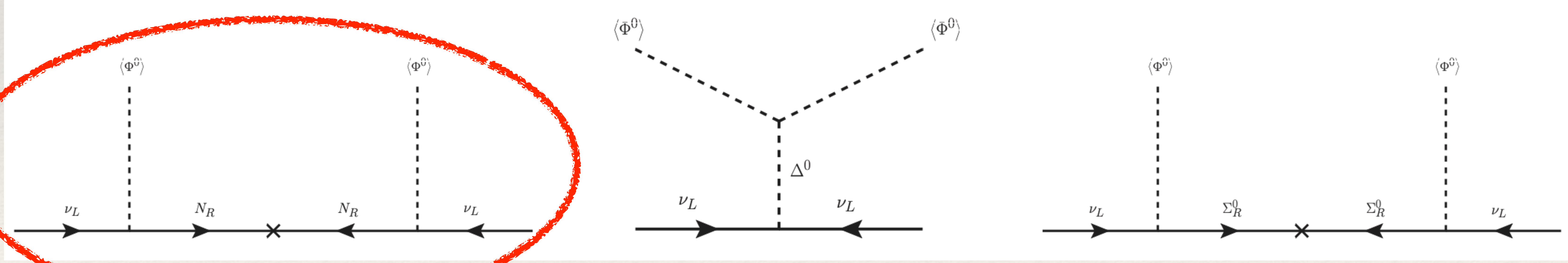
Consider different contracting,

$$\underbrace{\underbrace{\bar{L}^c \otimes \Phi}_{1} \otimes \underbrace{\Phi \otimes L}_{1}}_{\text{Type I}}, \quad \underbrace{\underbrace{\bar{L}^c \otimes L}_{3} \otimes \underbrace{\Phi \otimes \Phi}_{3}}_{\text{Type II}}, \quad \underbrace{\underbrace{\bar{L}^c \otimes \Phi}_{3} \otimes \underbrace{\Phi \otimes L}_{3}}_{\text{Type III}}$$

Chulia, Srivastava and Valle, 1802.05722

Add new fields to make renormalizable operators

Simplest SM extension to accomodate m_ν



Type I, II, III Seesaw mechanism:
Neutrino mass suppressed by the heavy mediator mass

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

Baryon-antibaryon Asymmetry of the Universe (BAU)

The observed baryon-antibaryon asymmetry (Planck 2018)

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

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

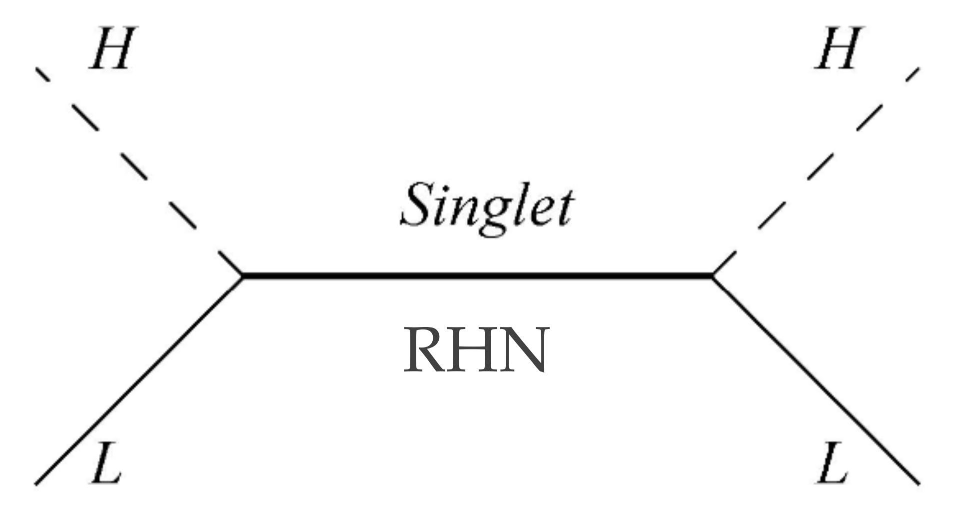
P. Minkowski 1977; T. Yanagida, 1979; S.L. Glashow, 1980; M. Gell-Mann et al, 1979; R. N. Mohapatra, G. Senjanovic, 1981…

- **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 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

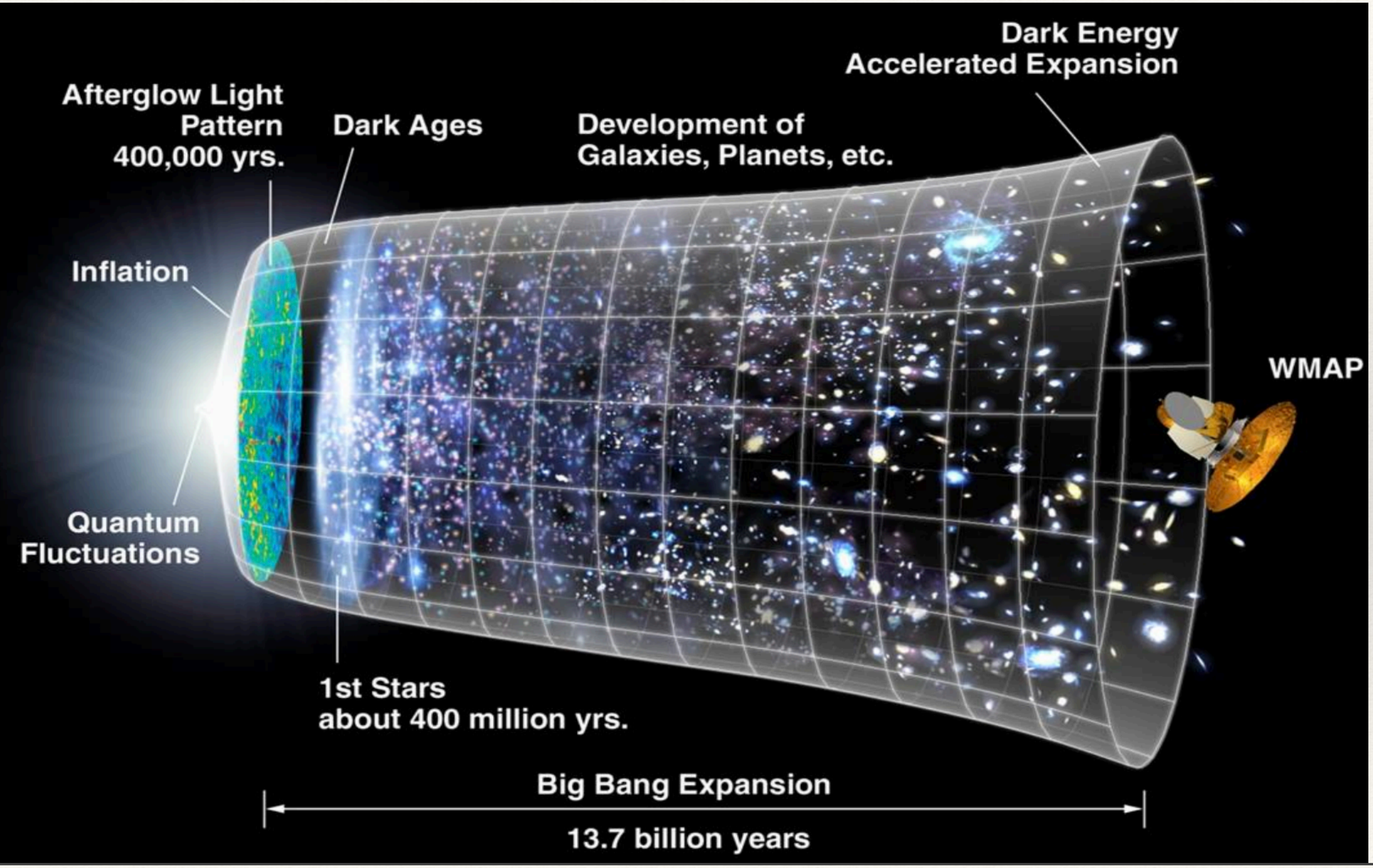
In (type-I seesaw) leptogenesis,
RHNs decay out-of-equilibrium,
generating a CP asymmetry (also a L asymmetry),
which converts to a B asymmetry via SM sphalerons

Address m_ν 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

Inflation

Standard model of cosmology / ΛCDM



Guth 1981
Kazanas 1980
Starobinsky 1980
Sato 1981

2014 Kavli Prize
for invention of inflation

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

For reviews, see e.g. Lyth & Riotto 1999, Bassett, Tsujikawa & Wands 2006, Martin, Ringeval & Vennin 2014

Single-field slow-roll inflation

For a homogenous scalar field minimally coupled to gravity, we have the EOS

$$\boxed{w_\phi \equiv \frac{p_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V}{\frac{1}{2}\dot{\phi}^2 + V}}$$

Negative pressure achieved if the potential energy V dominates over the kinetic energy

The dynamics is governed by

$$\ddot{\phi} + 3H\dot{\phi} + V_{,\phi} = 0$$

$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

$$\dot{\phi}^2 \ll V(\phi)$$

Accelerated expansion sustained for a sufficiently long time when

$$|\ddot{\phi}| \ll |3H\dot{\phi}|\,,\ |V_{,\phi}|$$

$$\eta = -\frac{\ddot{\phi}}{H\dot{\phi}} = \varepsilon - \frac{1}{2\varepsilon}\frac{d\varepsilon}{dN}$$

Slow-roll parameters

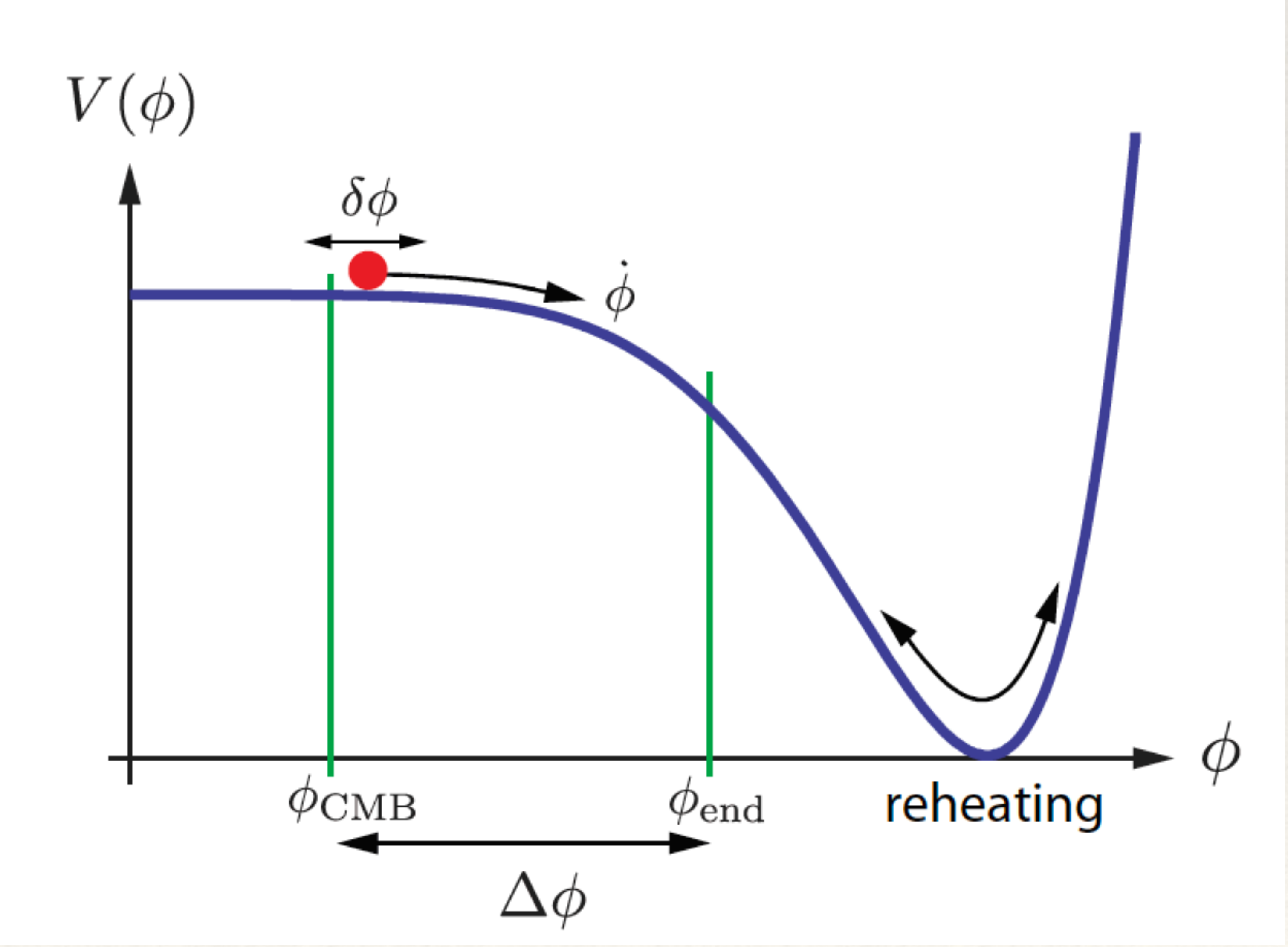
$$\boxed{\epsilon_{\rm v}(\phi) \equiv \frac{M_{\rm pl}^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2}$$

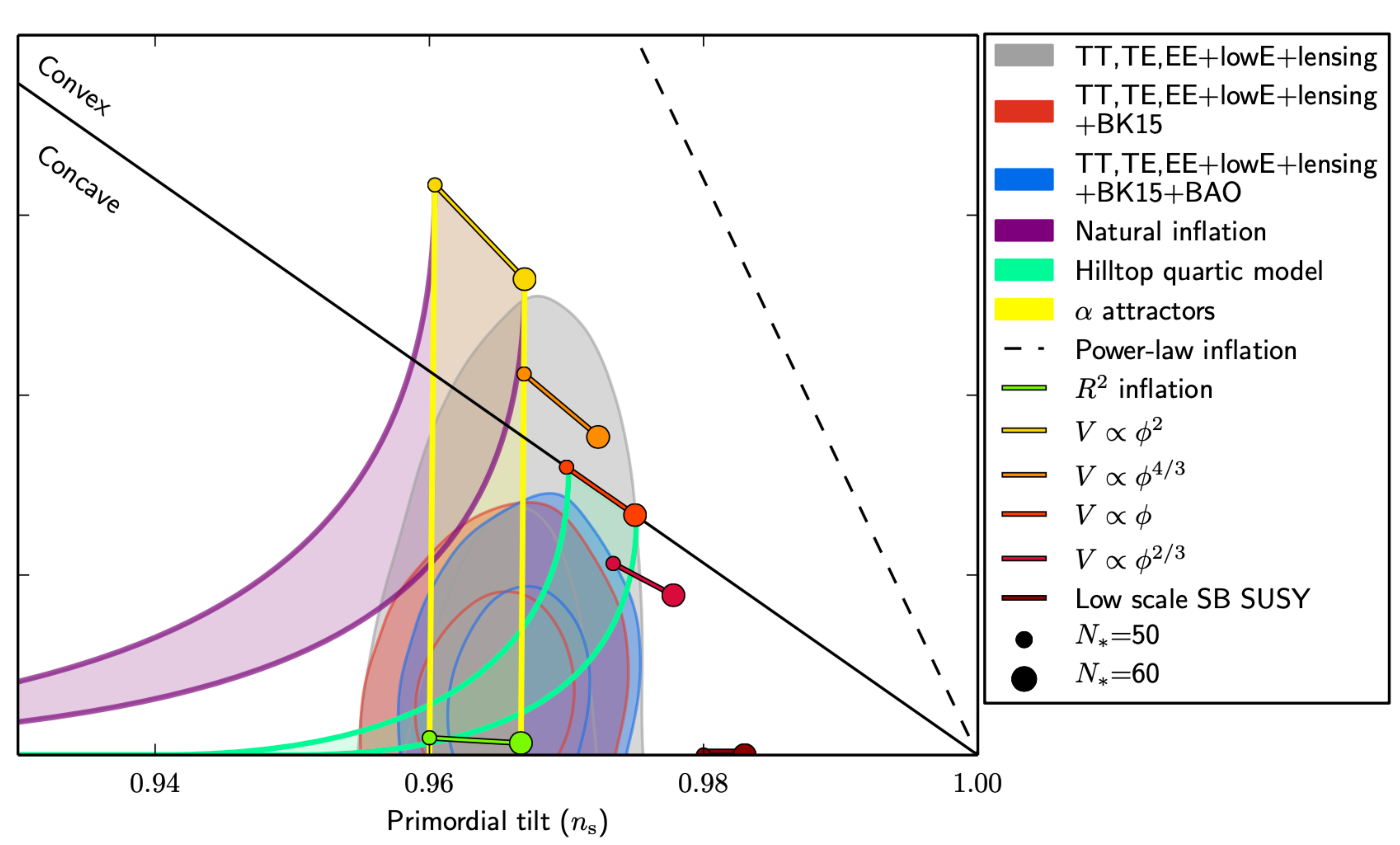
$$\boxed{\eta_{\rm v}(\phi) \equiv M_{\rm pl}^2\frac{V_{,\phi\phi}}{V}}$$

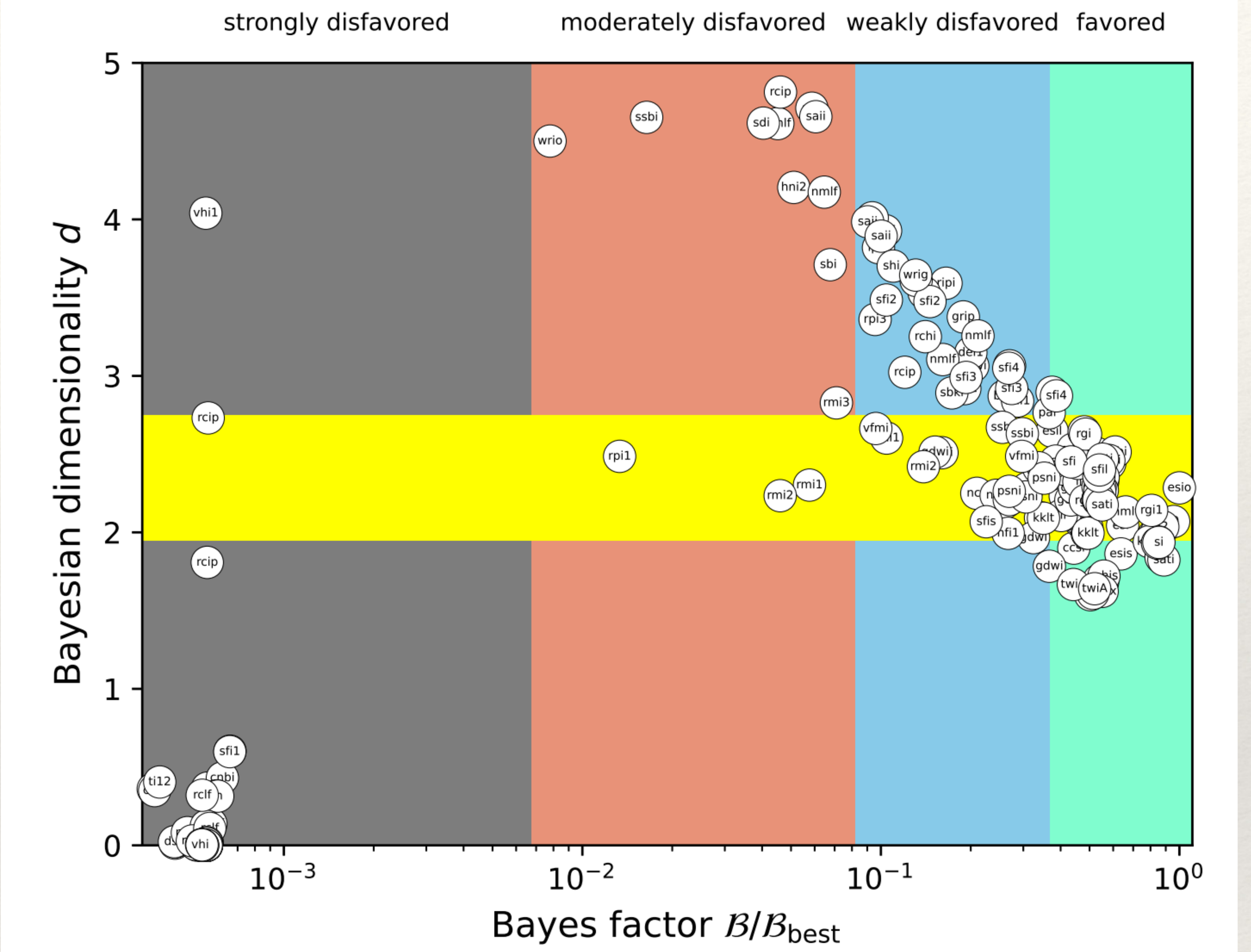
Slow-roll condition

$$\epsilon_{\rm v}, |\eta_{\rm v}| \ll 1$$

$$\varepsilon \approx \epsilon_{\rm v}\,, \qquad \eta \approx \eta_{\rm v} - \epsilon_{\rm v}\,.$$







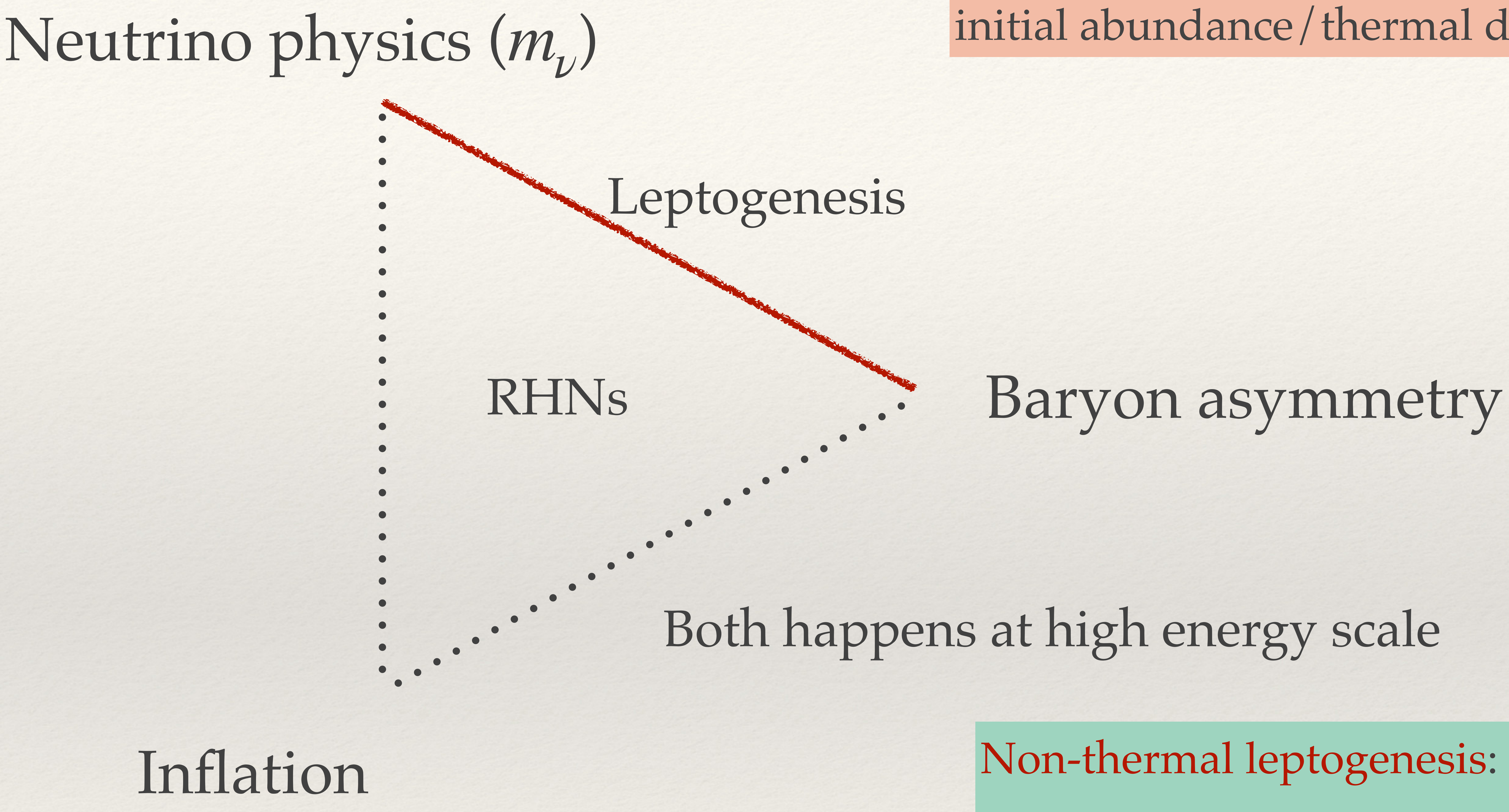
Martin, Ringeval, Vennin, 2404.10647

Limited info

Model degeneracy

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)

$K \ll 1$ limit

Weak Yukawa → Cannot thermalize RHN

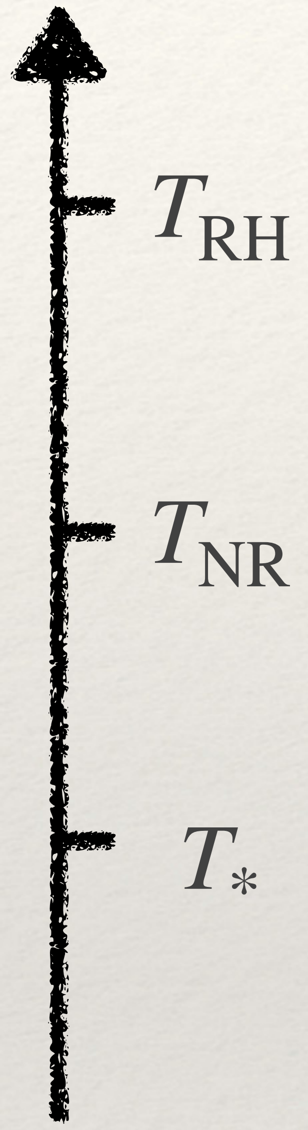
$$Y_B = \frac{n_B}{s} = \frac{c_{\rm sph}\epsilon}{s} n_N$$ When the RHNs decay

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*

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

If RHNs decay instantly when produced *Instantaneous reheating*

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

Chung, Kolb and Riotto 1999

$K \gg 1$ limit

Strong Yukawa

thermalize RHN

Thermal leptogenesis

Cannot thermalize RHN

RHN decay too fast

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

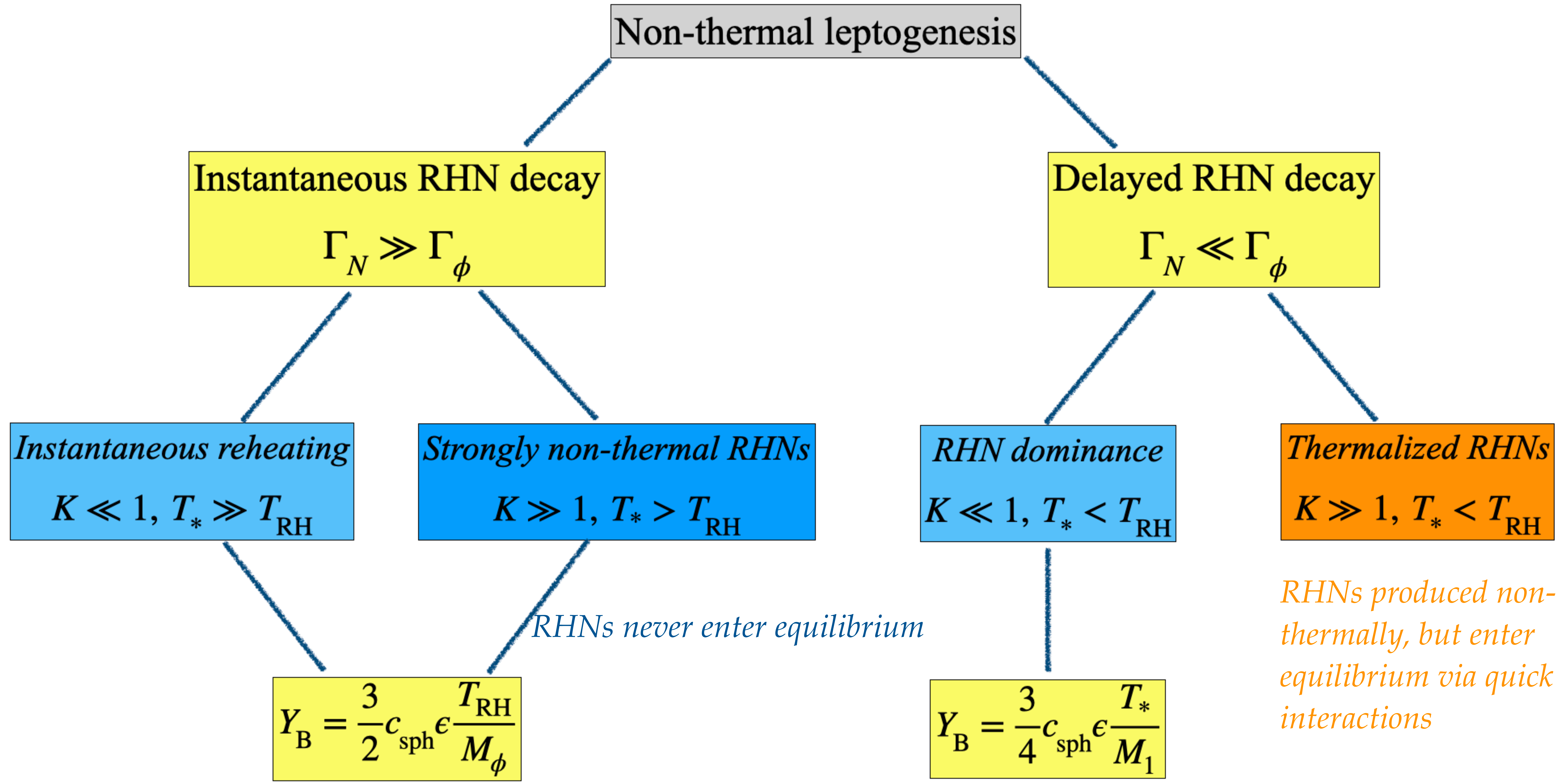
$\Gamma_N \gg \Gamma_\phi$

Approx.

$T_* > T_{\mathrm{RH}}$

Stronger, quick assessment

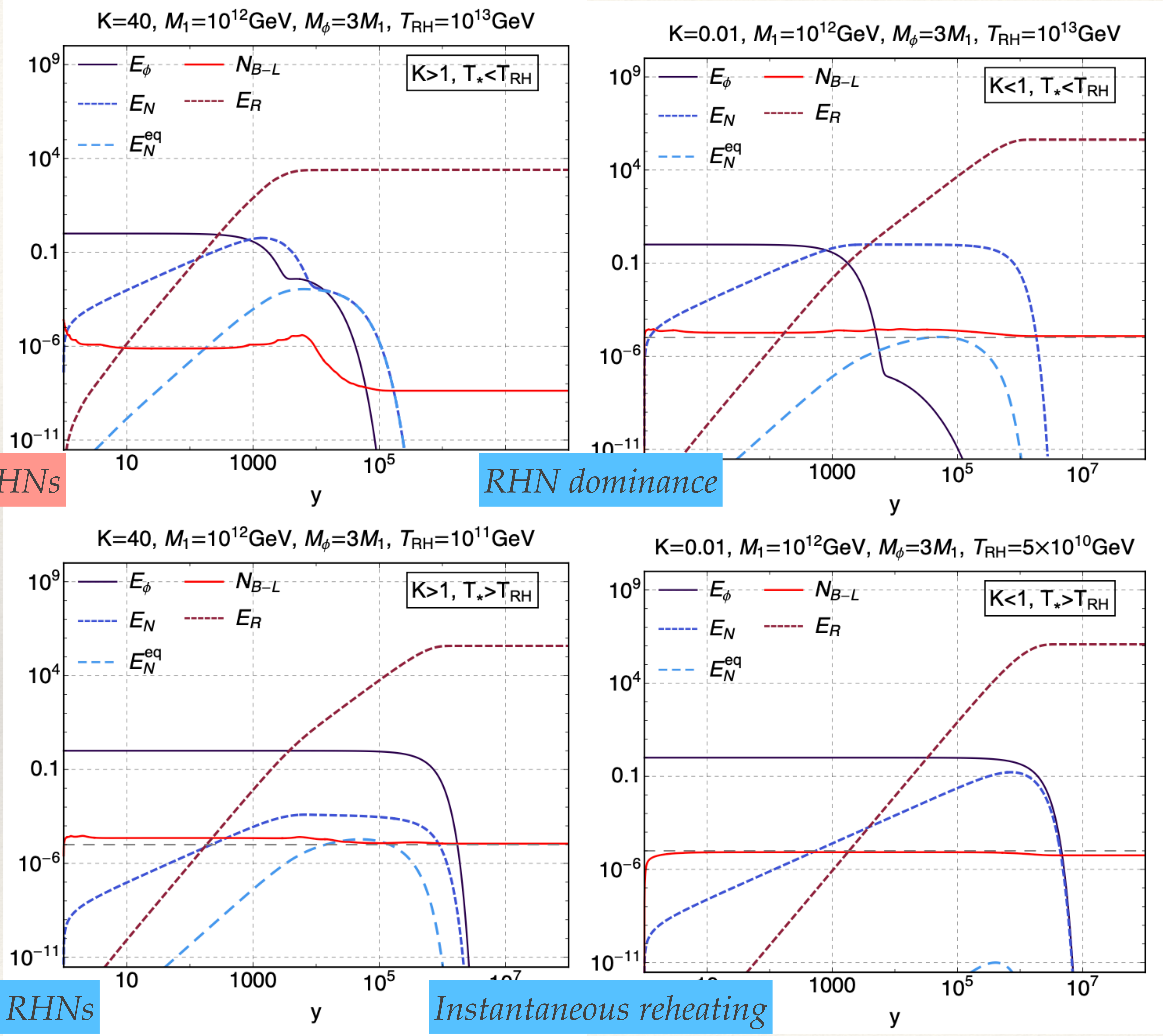
$M_1 > T_{\mathrm{RH}}$


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

Yukawa strong, but RHNs decay before entering equilibrium



Thermalized RHNs

RHN dominance

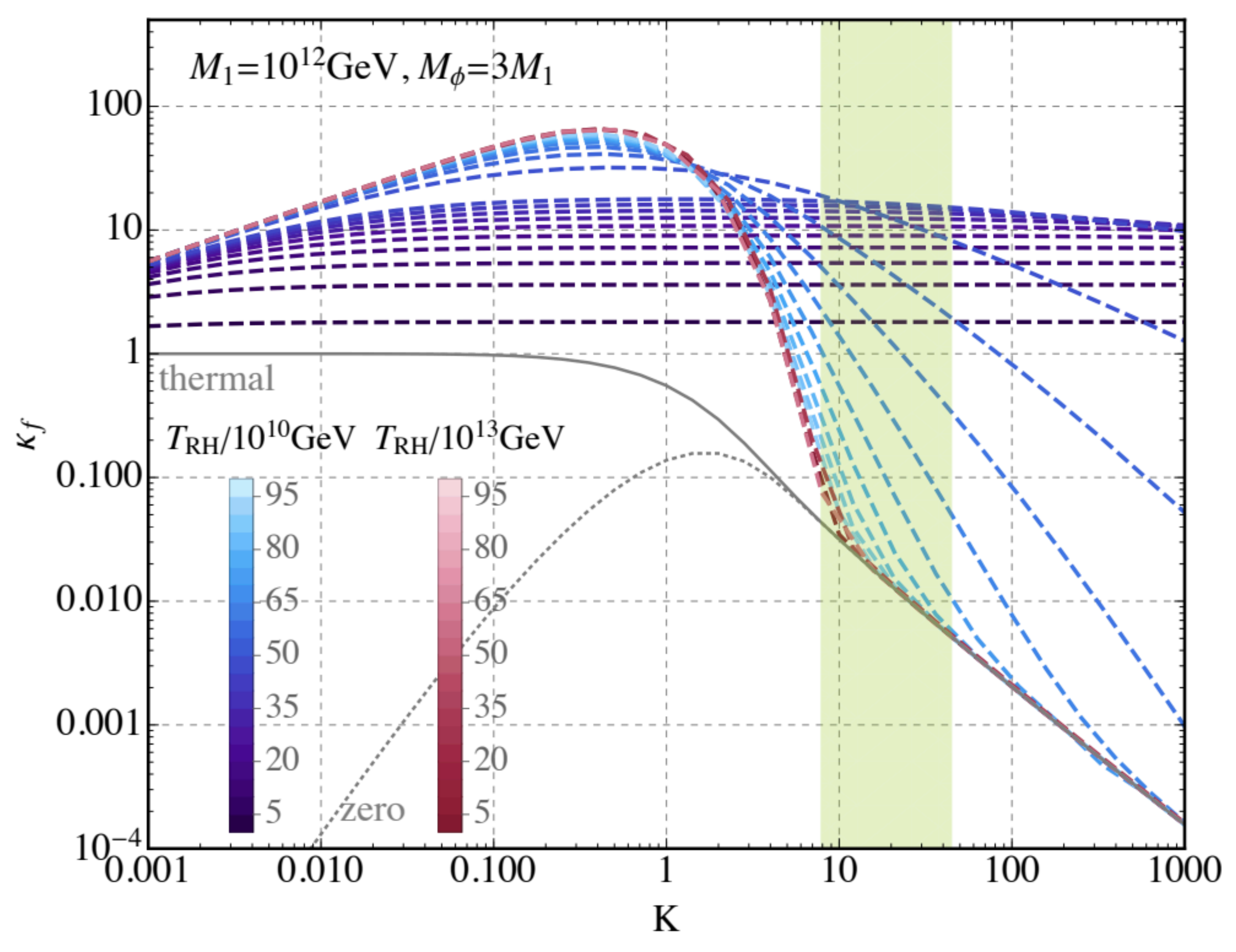
Strongly non-thermal RHNs

Instantaneous reheating

ϕ decay out first, decayed RHN decay

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

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

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

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

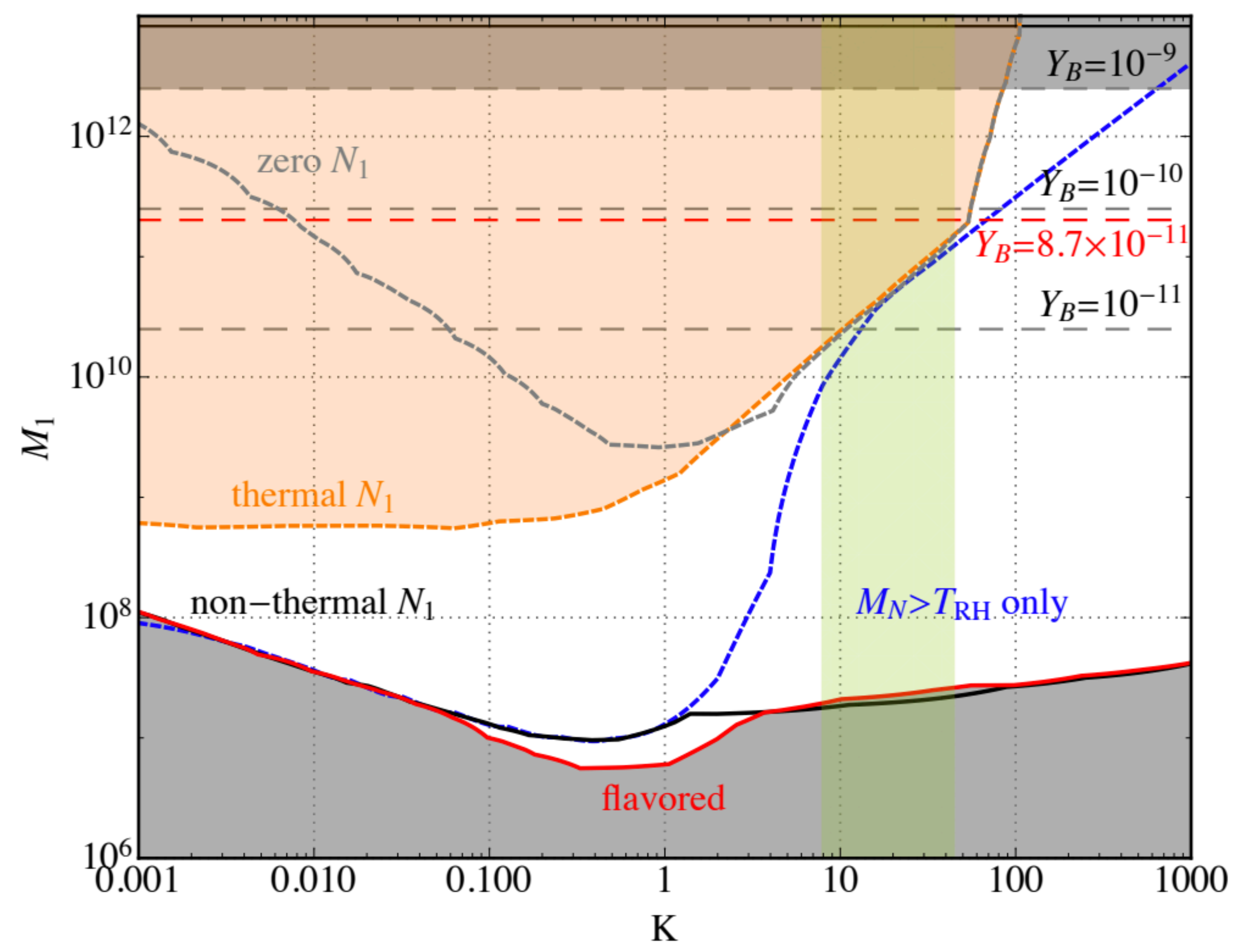
$$\rightarrow \quad M_\phi = 1.65 \times 10^{13}\ \text{GeV}$$

$$M_N = y_N v_\phi$$

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

$$\Lambda \le 10^{16}\text{GeV} \quad f \ge 10^{19}\ \text{GeV}$$

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

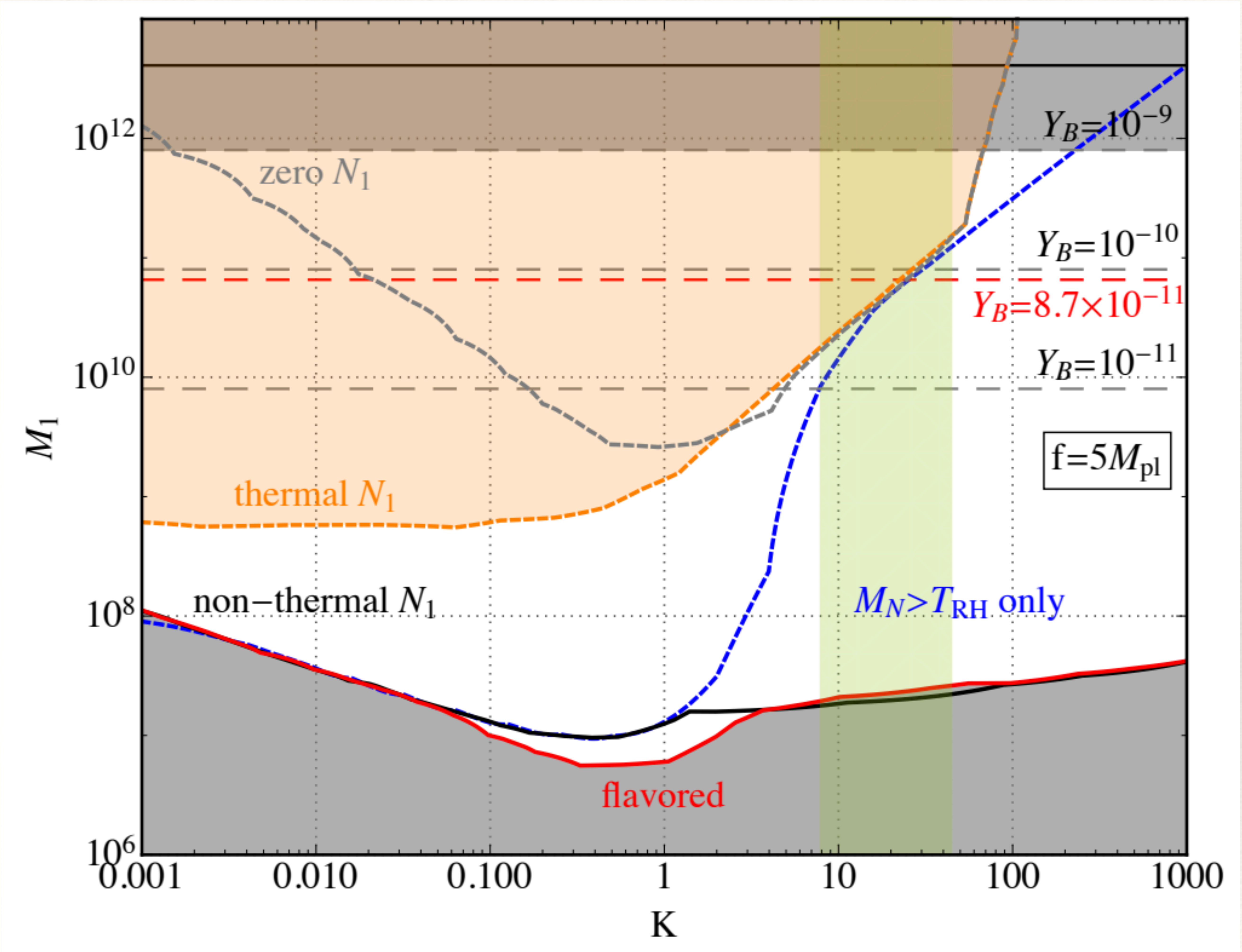
$$M_\phi^2 = \frac{d^2V}{d\phi^2}\Big|_{\min} = \frac{\Lambda^4}{f^2}$$

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

$$M_N = y_N f \ \rightarrow \ T_{\rm RH} \simeq 6\times10^{-5} M_1$$

Strongly non-thermal RHNs preferred

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



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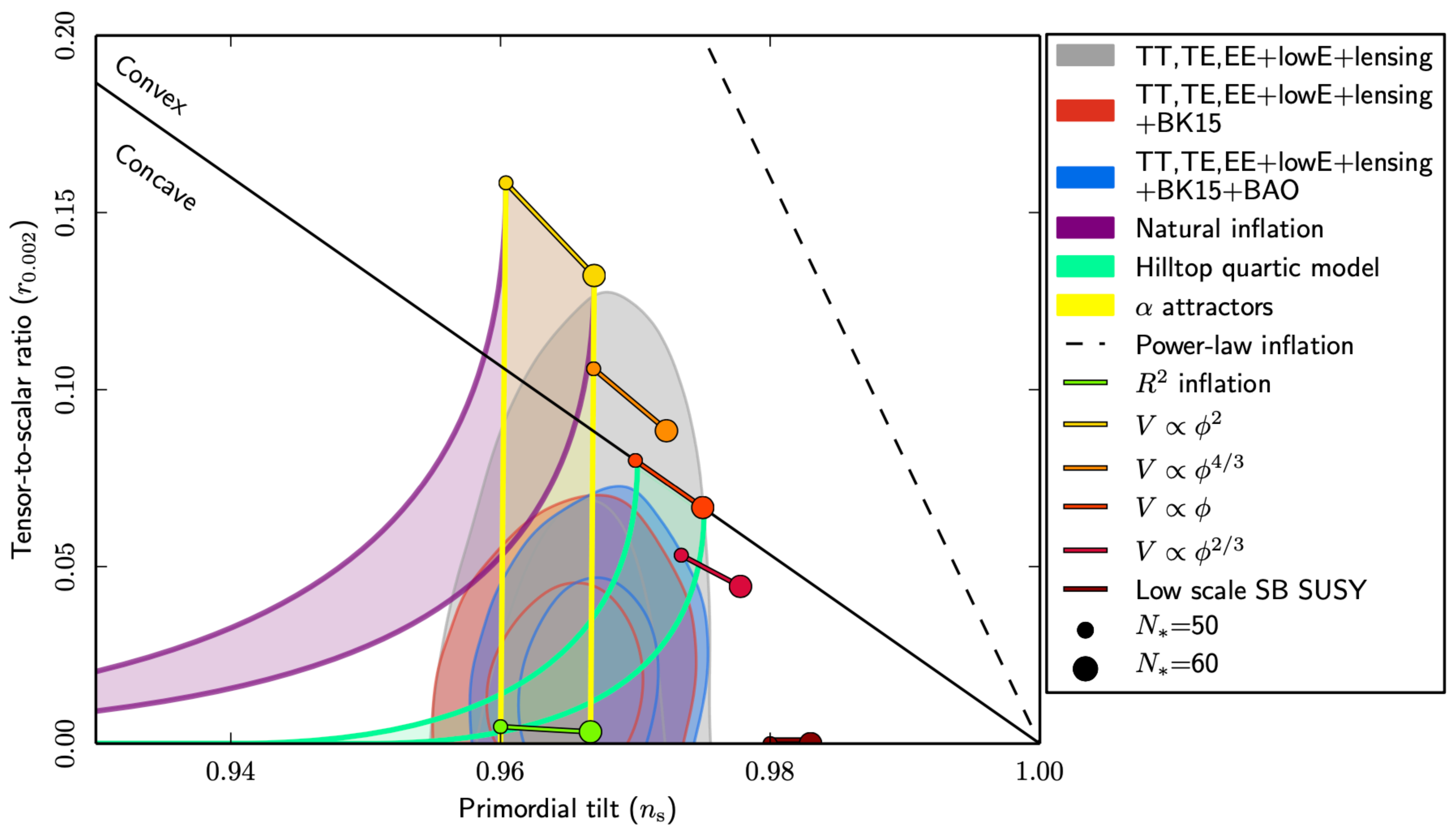
However, it is not the full story, something important is missing

$N_k(N_*) = 50?$



$$N_k \equiv \ln \frac{a_k}{a_{\text{end}}}$$

- Enough inflation for the horizon problem $\rightarrow N_k \in [50,70]$;
- Depends on expansion history after inflation

With specified after inflation expansion, N_k can be calculated

Reheating

Supercool state

at the end of inflation

$\longrightarrow$

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

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*

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

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

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

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

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

This relation decodes how reheating affects inflationary observations

Neutrino reheating and non-thermal leptogenesis

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

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

$N_{\rm RH} = 0$

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}*

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

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

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

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

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

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

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

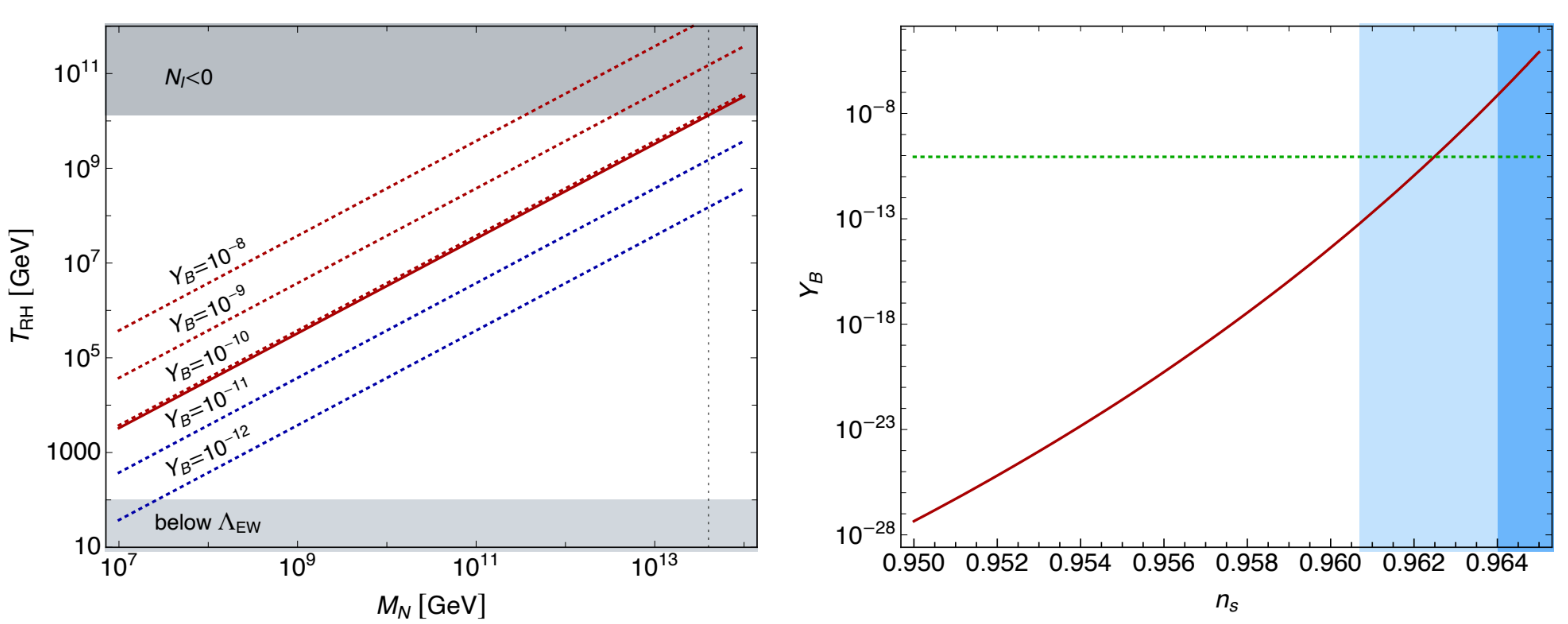
A polynomial type potential

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

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

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

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



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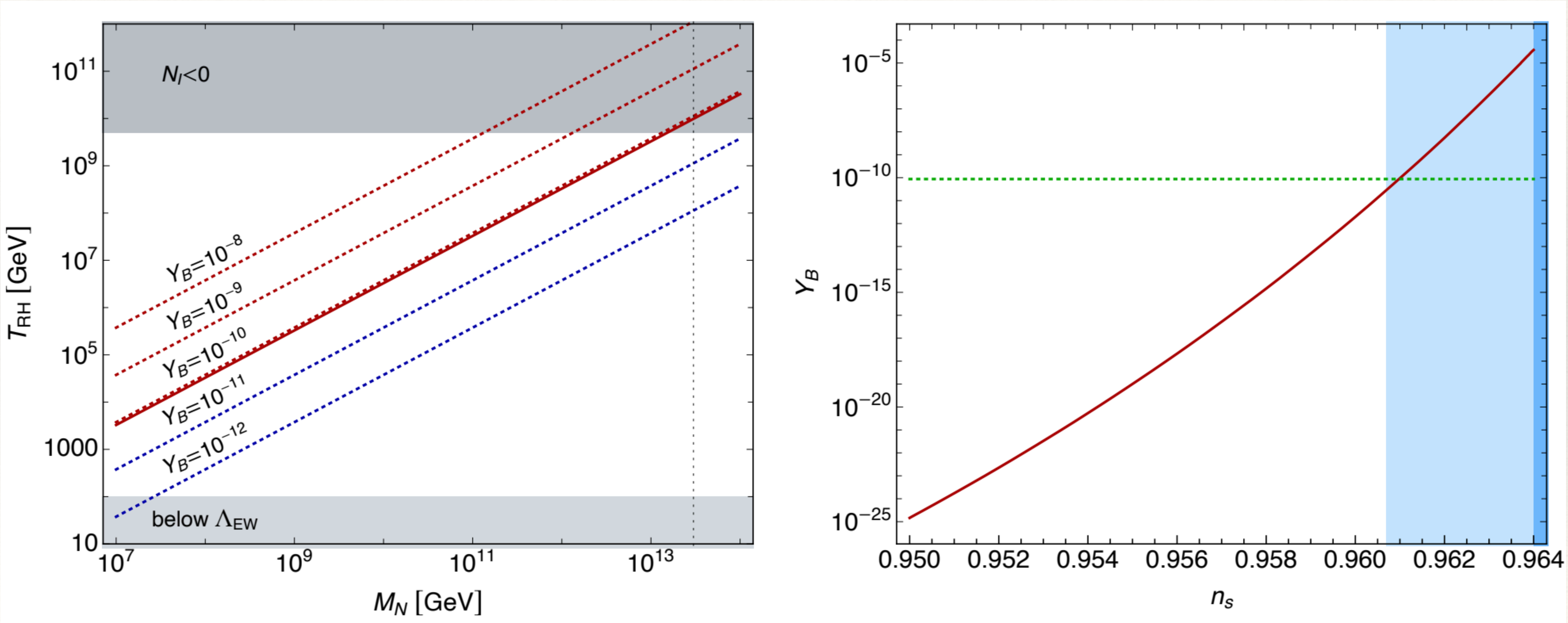
Starobinsky model

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

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

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

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



Coleman-Weinberg inflation

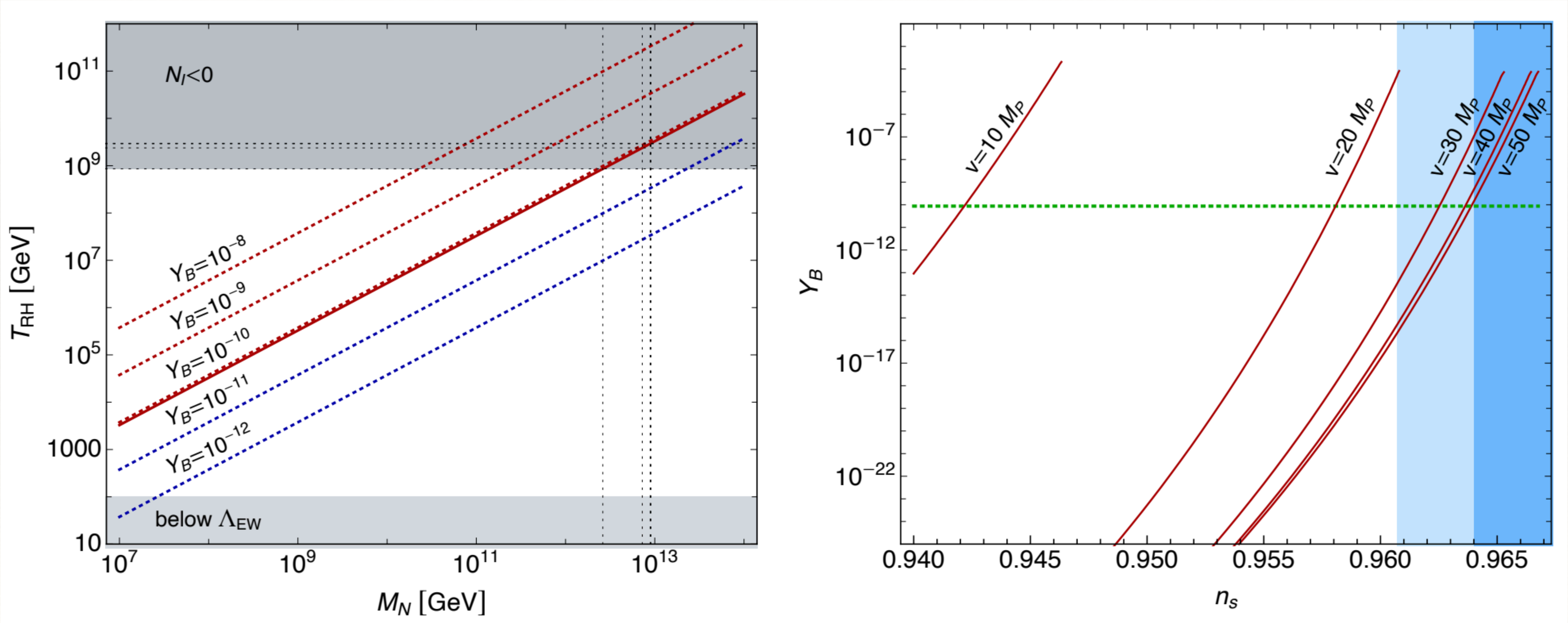
$$V = A\phi^4 \left[\ln\left(\frac{\phi}{v}\right) - \frac{1}{4} \right] + \frac{1}{4} A v^4$$

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



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Natural inflation

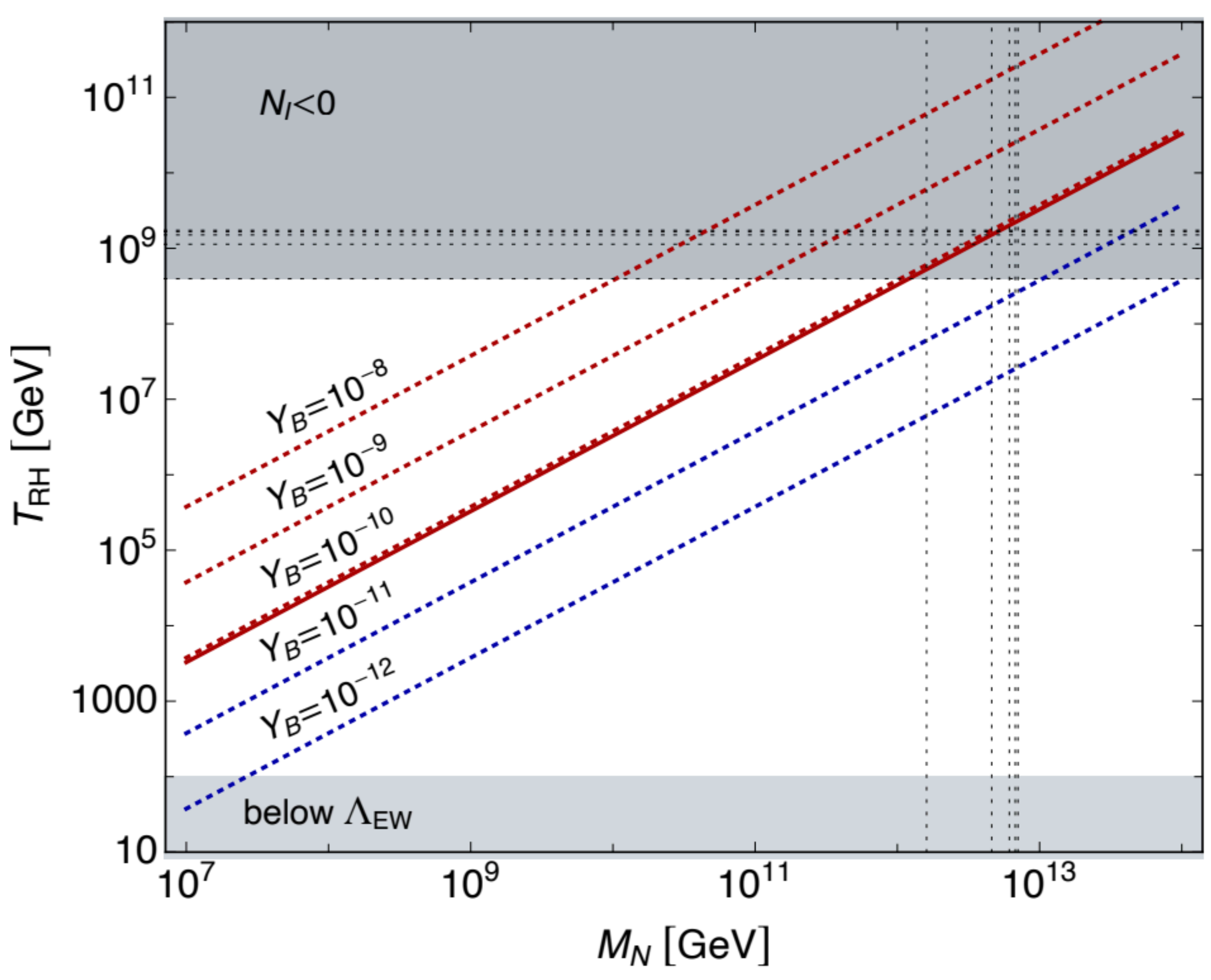
$$V = \Lambda^4\left(1+\cos\frac{\phi}{f}\right)$$

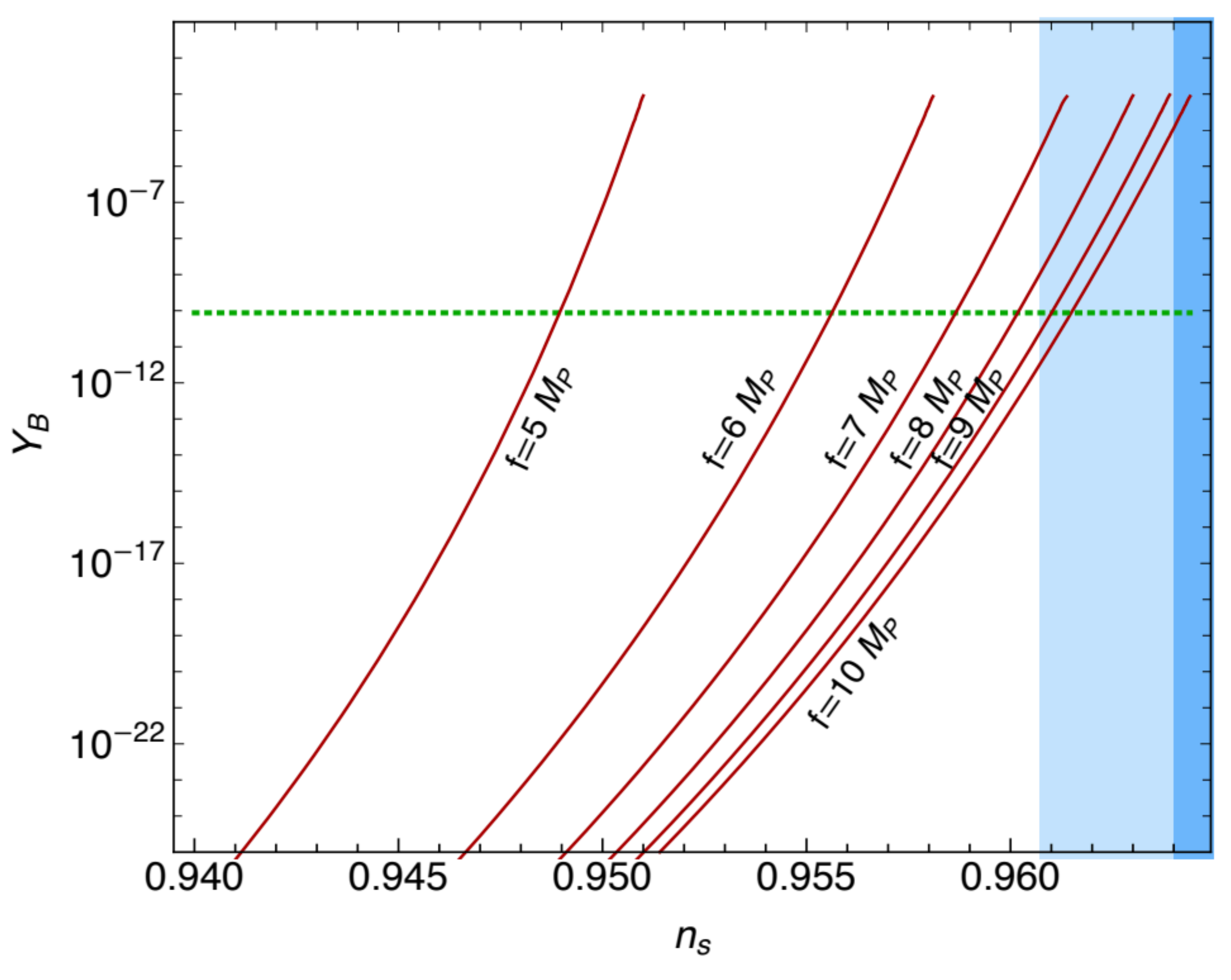
(1) $\Gamma_N \gg \Gamma_\phi$:

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

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

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





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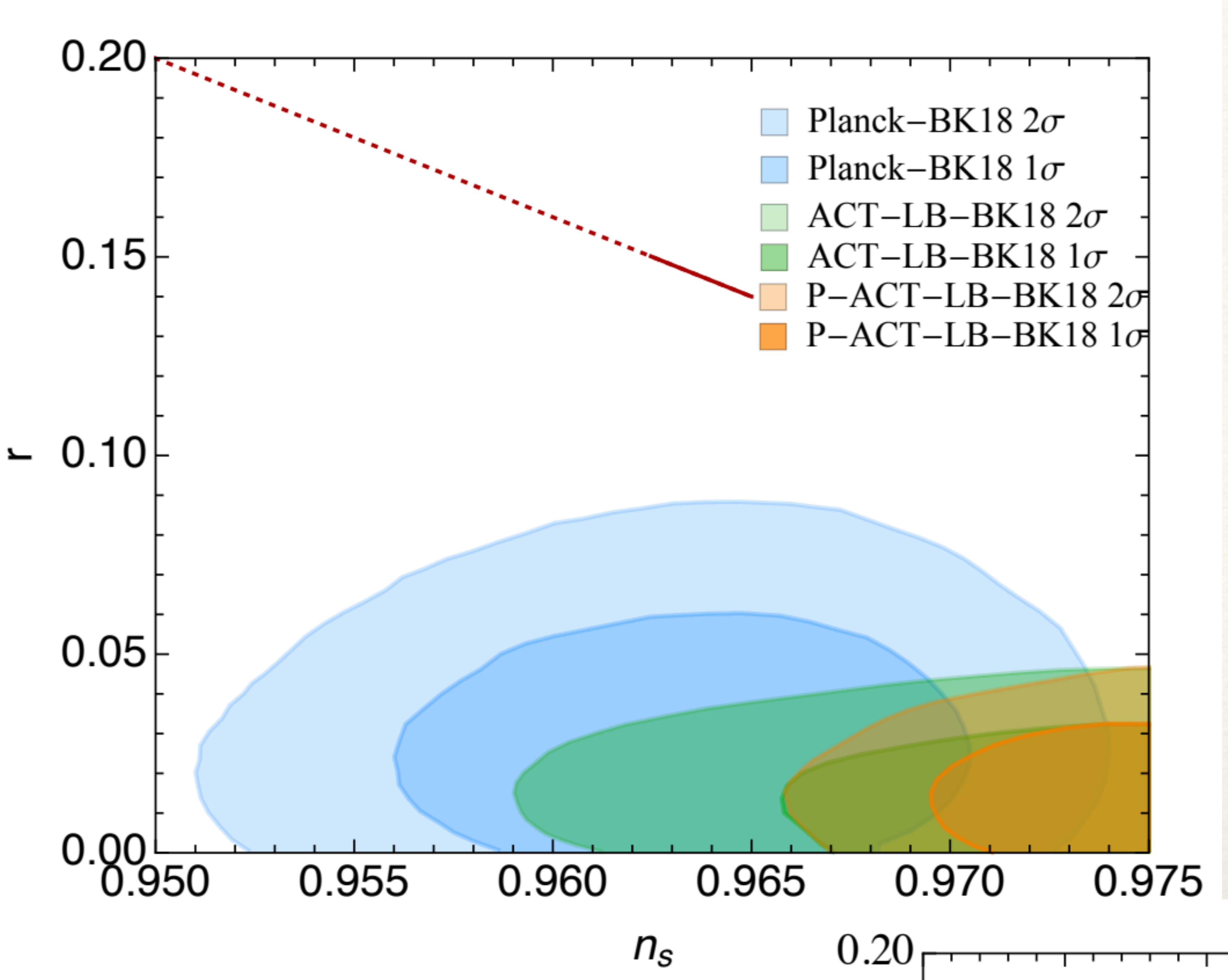
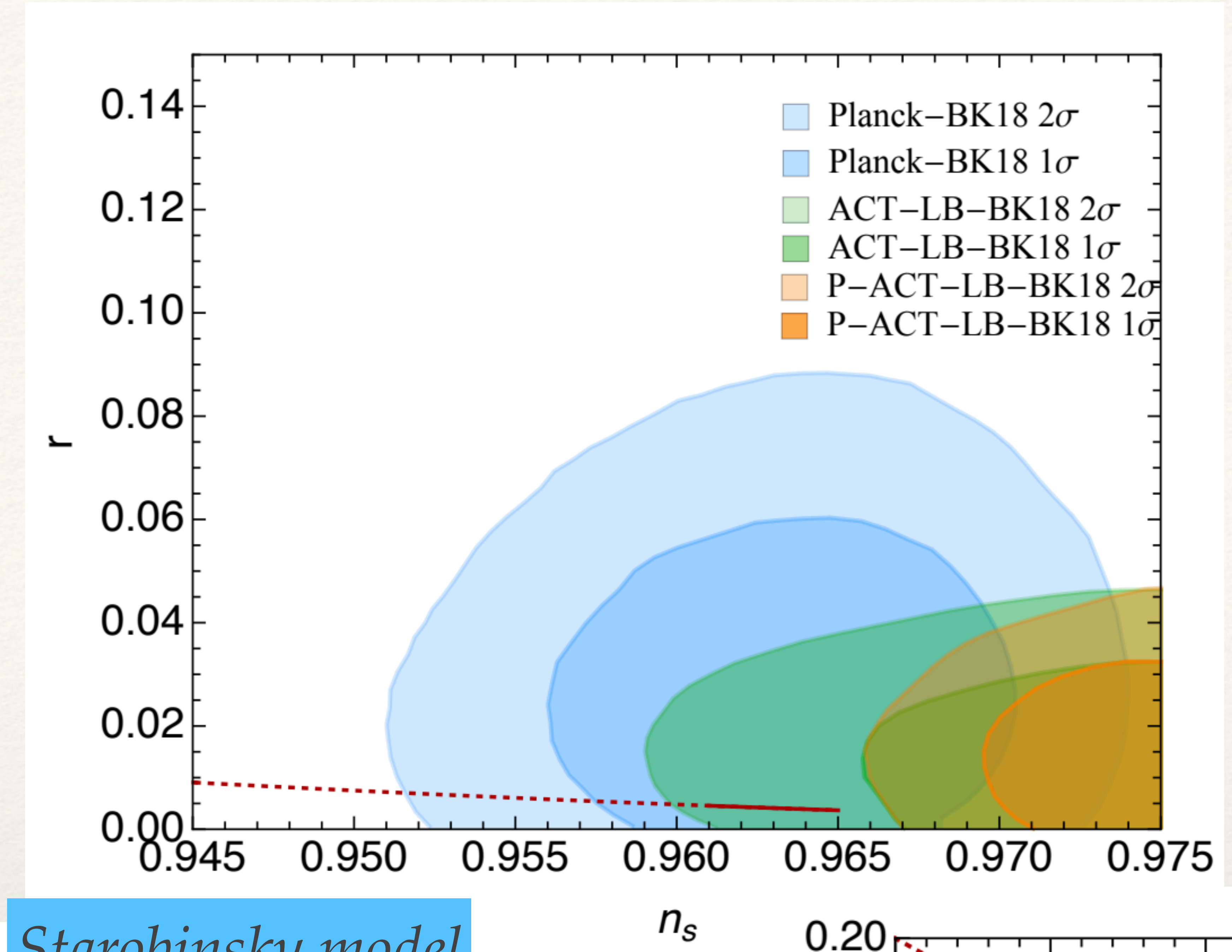
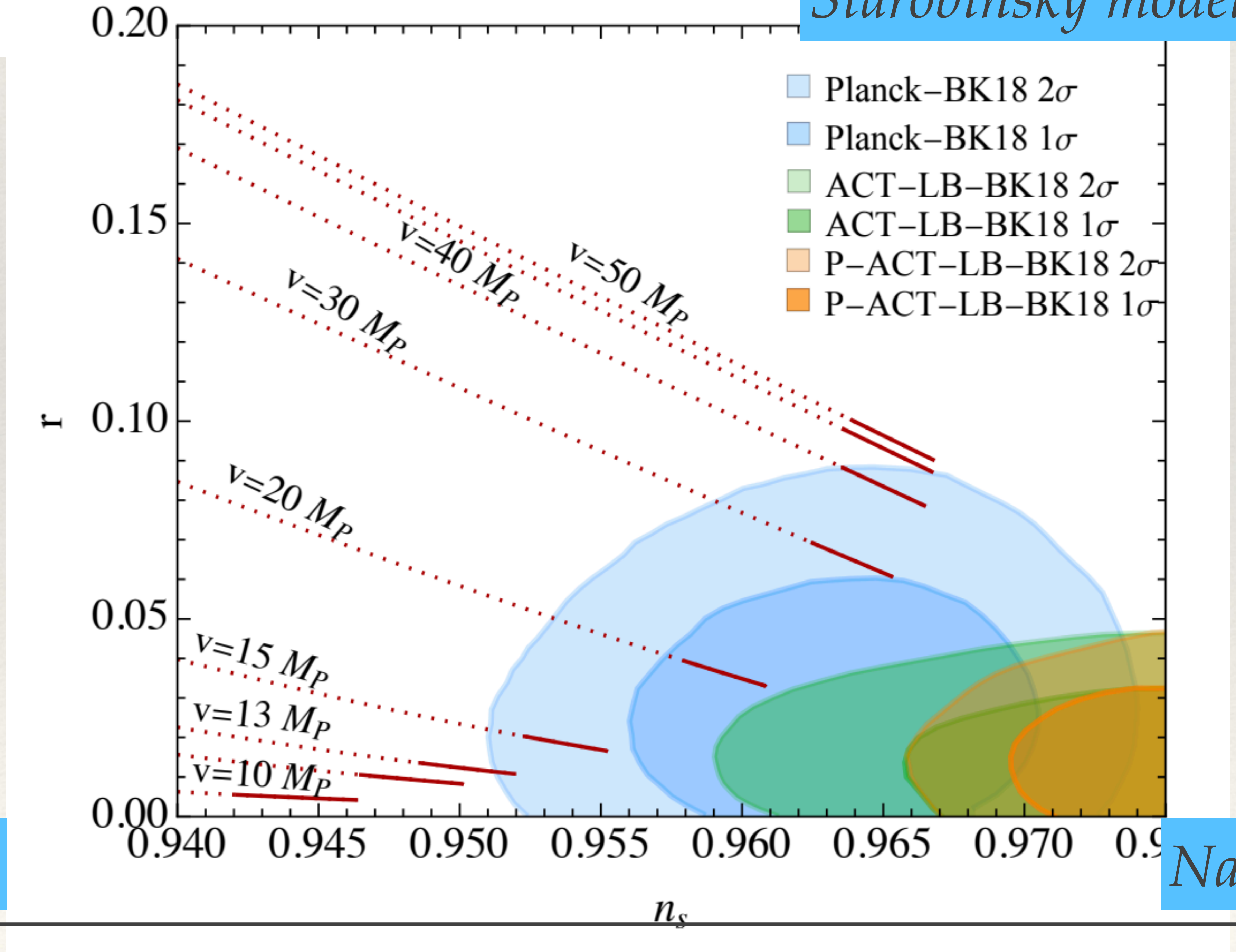


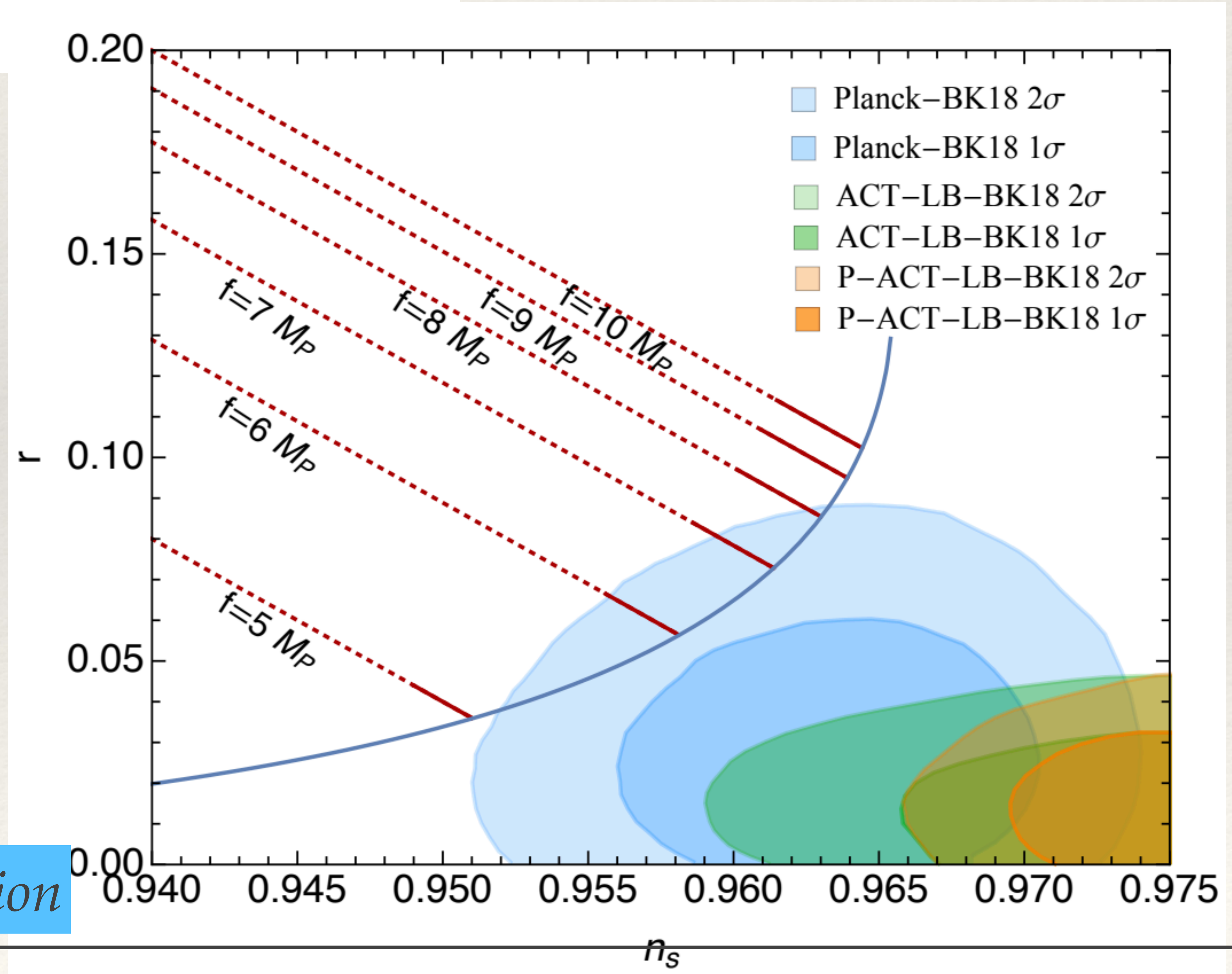
Polynomial type potential



Starobinsky model



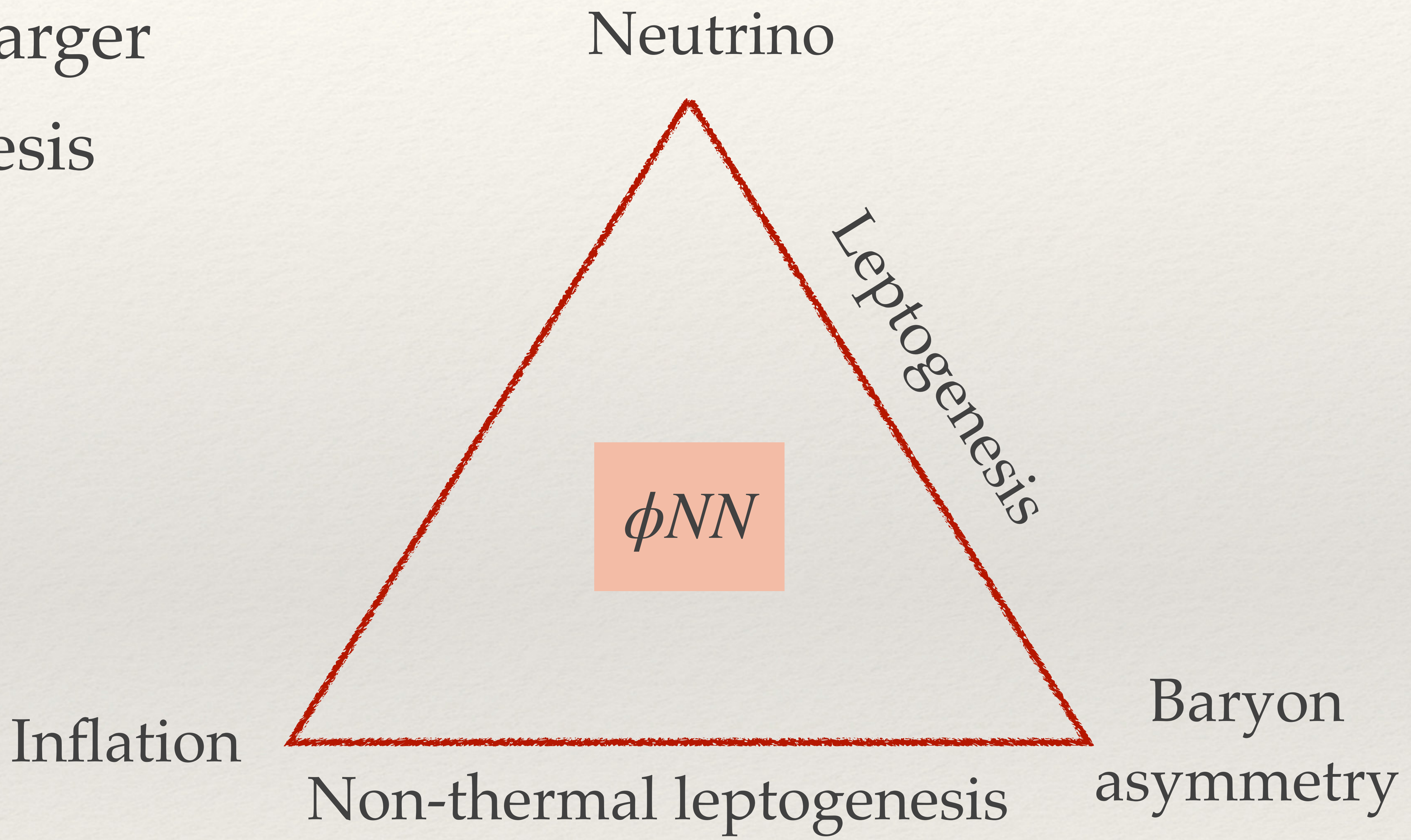
Coleman-Weinberg inflation



Natural inflation

Conclusions

- Non-thermal leptogenesis allows for a larger parameter space than thermal leptogenesis
- Neutrino reheating + non-thermal leptogenesis: Y_B grows with n_s
  - ✓ *Helps break model degeneracy*
  - ☐ *Still model dependent*
  - ☐ *Full parameter space*
  - ☐ *Preheating*



Thanks and stay tuned!