第五届粒子物理前沿研讨会

Non-thermal leptogenesis from inflaton decays

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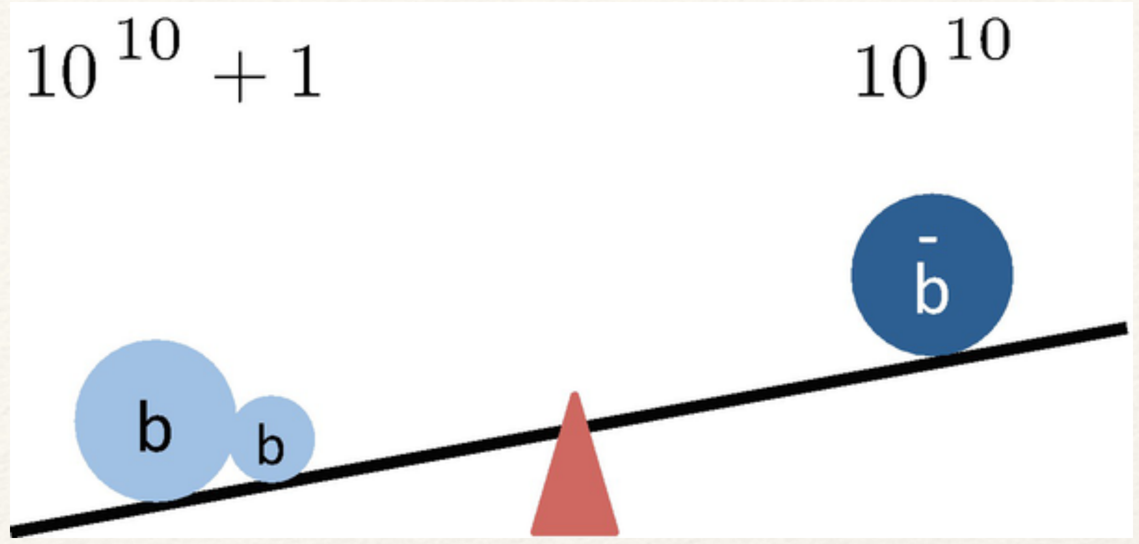
2024年4月15日，深圳

Baryon-antibaryon Asymmetry of the Universe (BAU)

The observed baryon-antibaryon asymmetry (Planck 2018)

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



K. Fuyuto, 2018

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

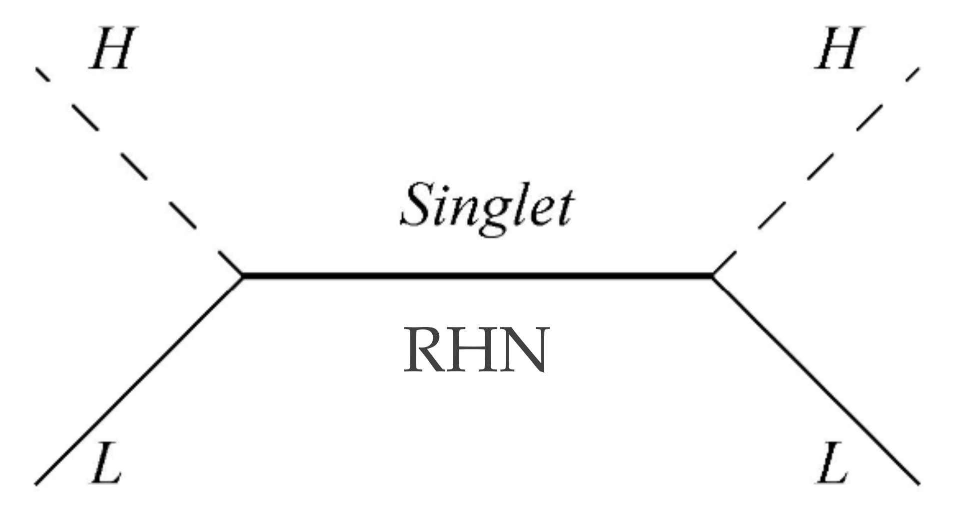
P. Minkowski 1977; T. Yanagida, 1979; S.L. Glashow, 1980; M. Gell-Mann et al, 1979; R. N. Mohapatra, G. Senjanovic, 1981…

- **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:

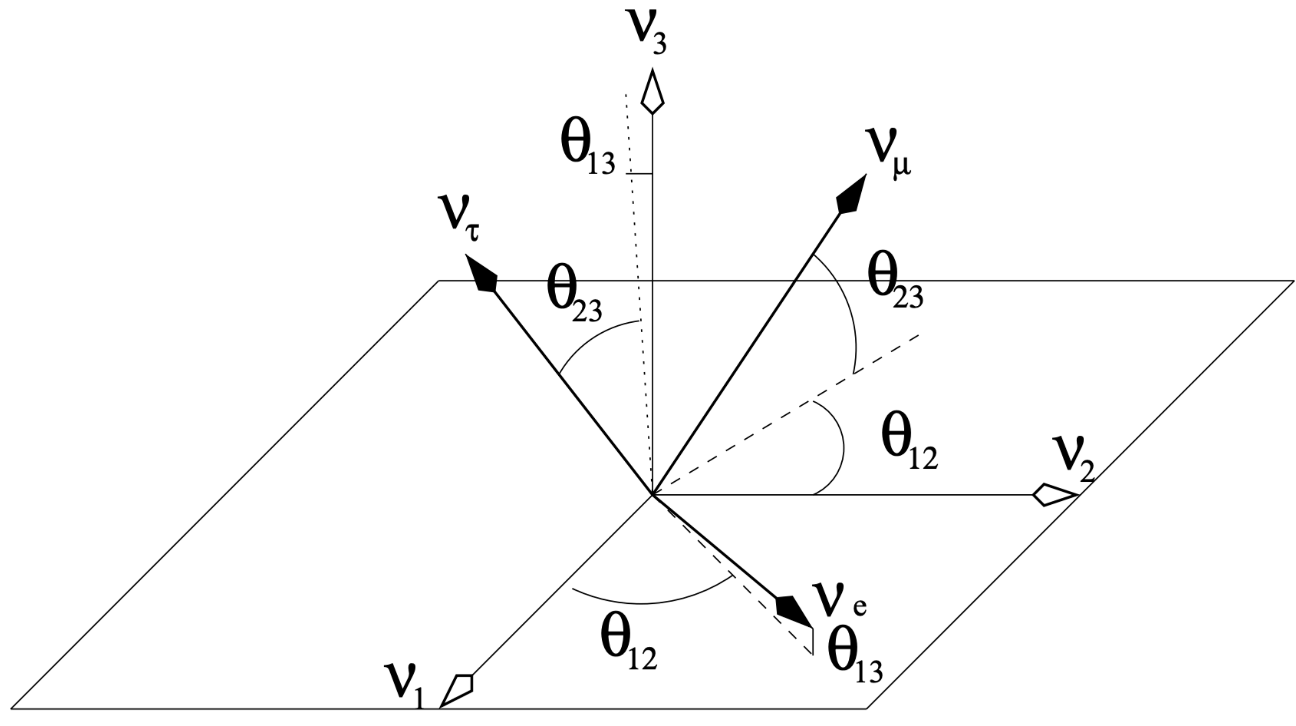
- Baryon number violation
- C and CP violation
- Deviation from equilibrium

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

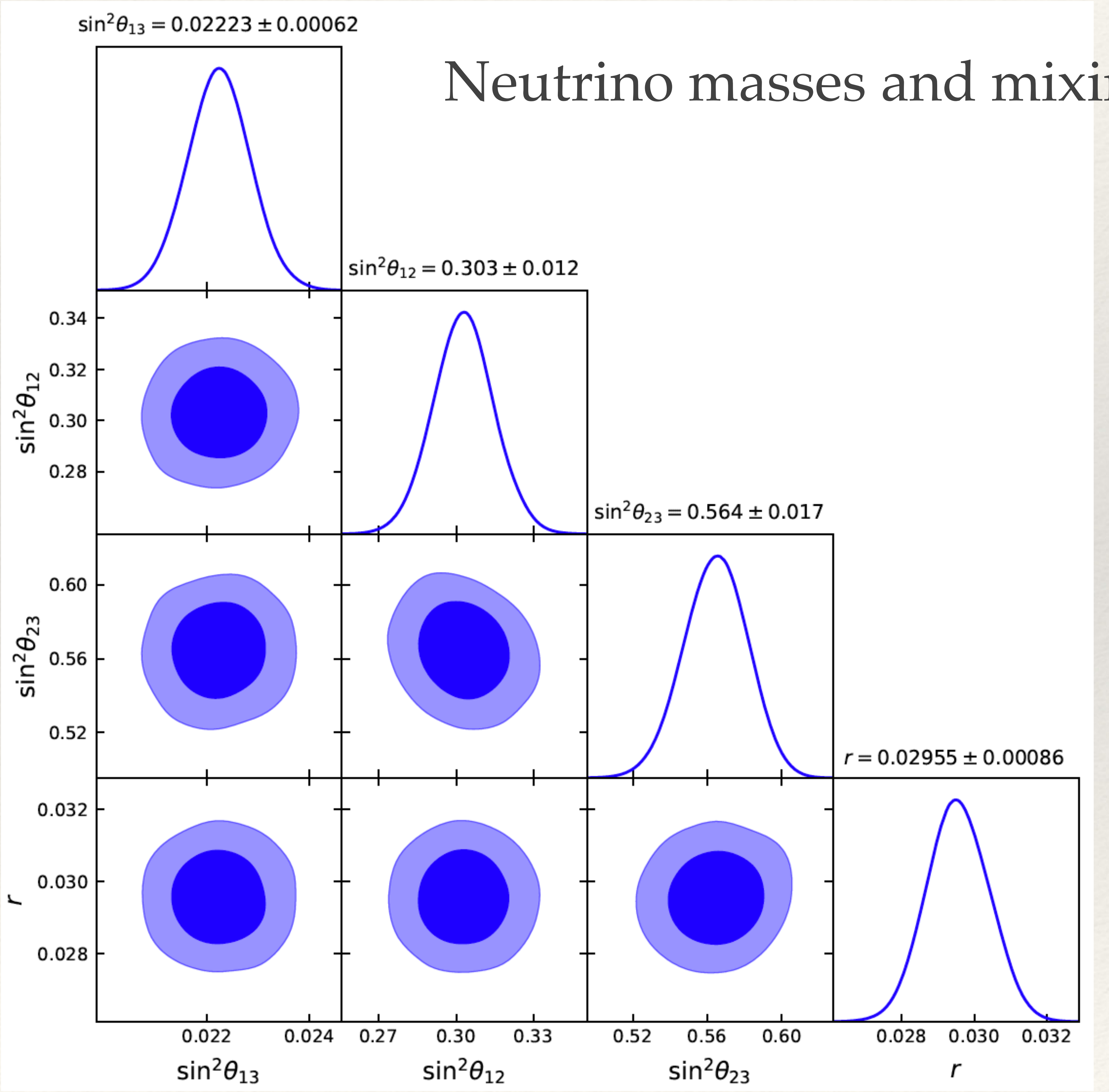
Adding mixing to the play



King, 0310204

With add-on flavor symmetry (either modular or discrete)

	L	H_u	H_d	E_1^C	E_2^C	E_3^C	N^C	S
SU(2)	2	2	2	1	1	1	1	1
S_4	**3**	**1**	**1**	**1′**	**1**	**1′**	**2**	**3**



Neutrino masses and mixing can be well-fitted

XYZ, Zhou, 2106.03433

ν mass models work perfectly with flavor models

Leptogenesis work with ν mass & mixing

Face constraints from

BAU (Y_B)

ν mass (m_0, Δm^2_{21}, $\Delta m^2_{31(2)}$)

ν mixing (θ_{ij}, δ)

Thermal leptogenesis:

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

Non-thermal leptogenesis:

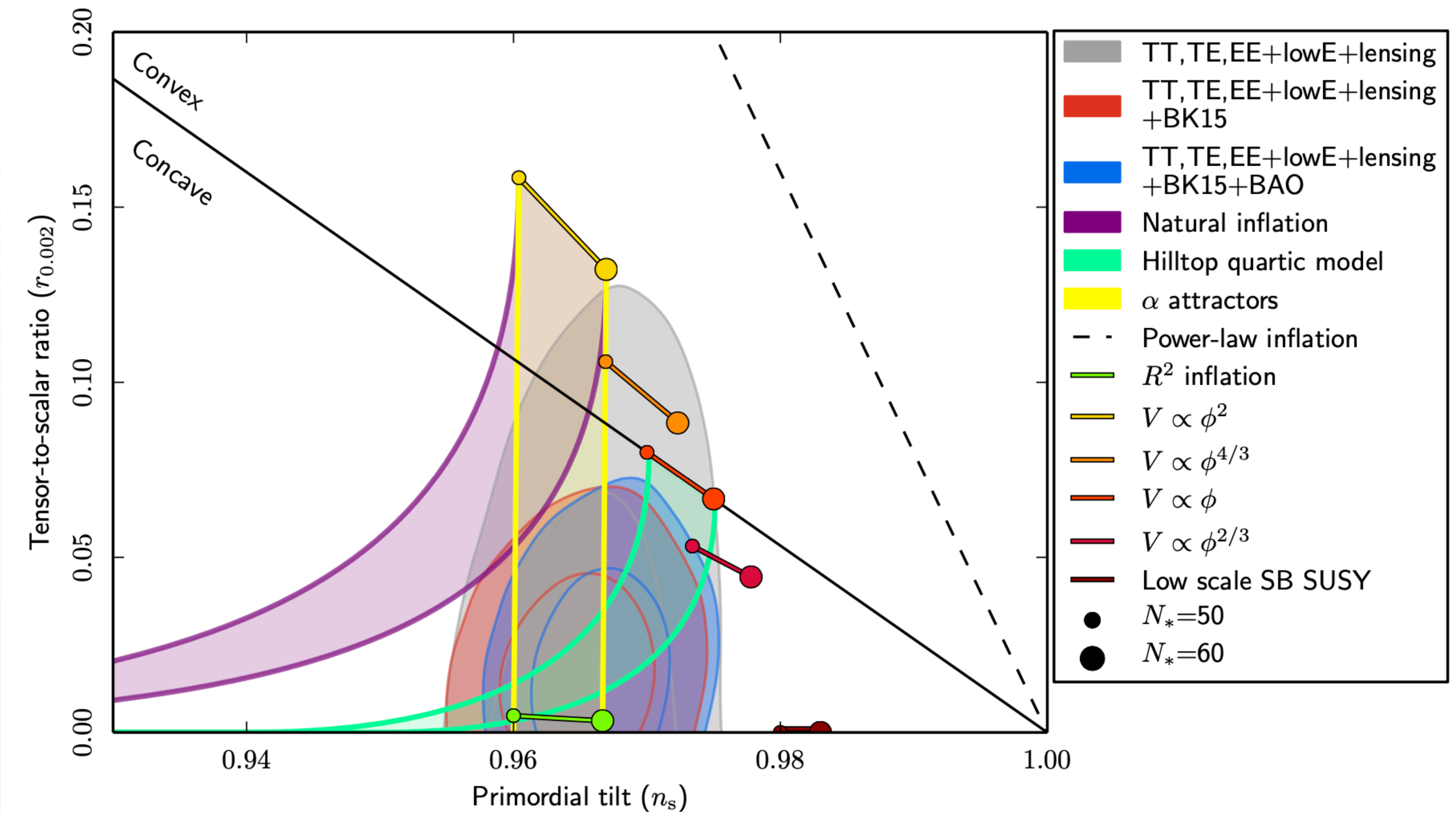
RHNs are produced non-thermally (e.g., via heavy particle decay)

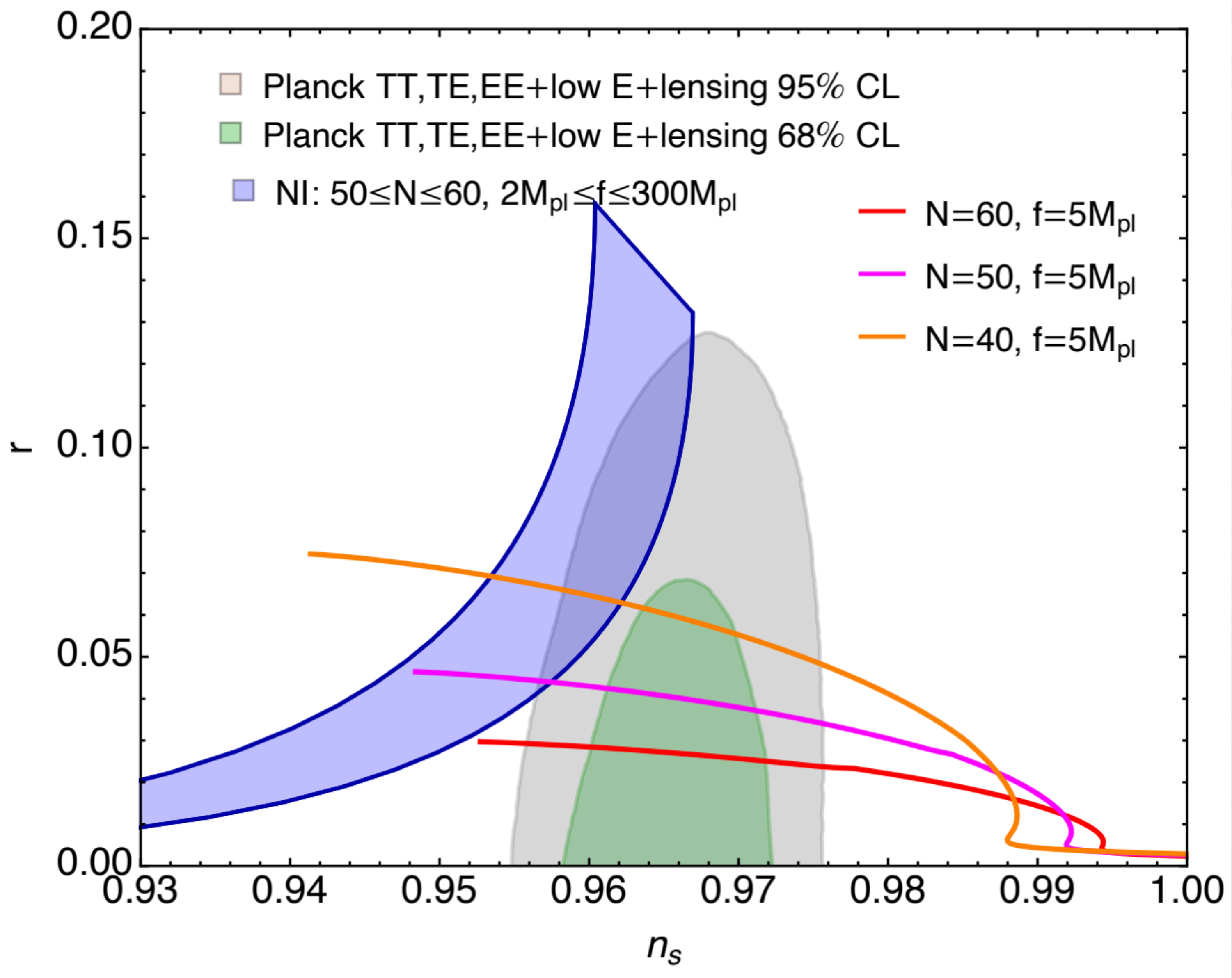
Why thermal leptogenesis?

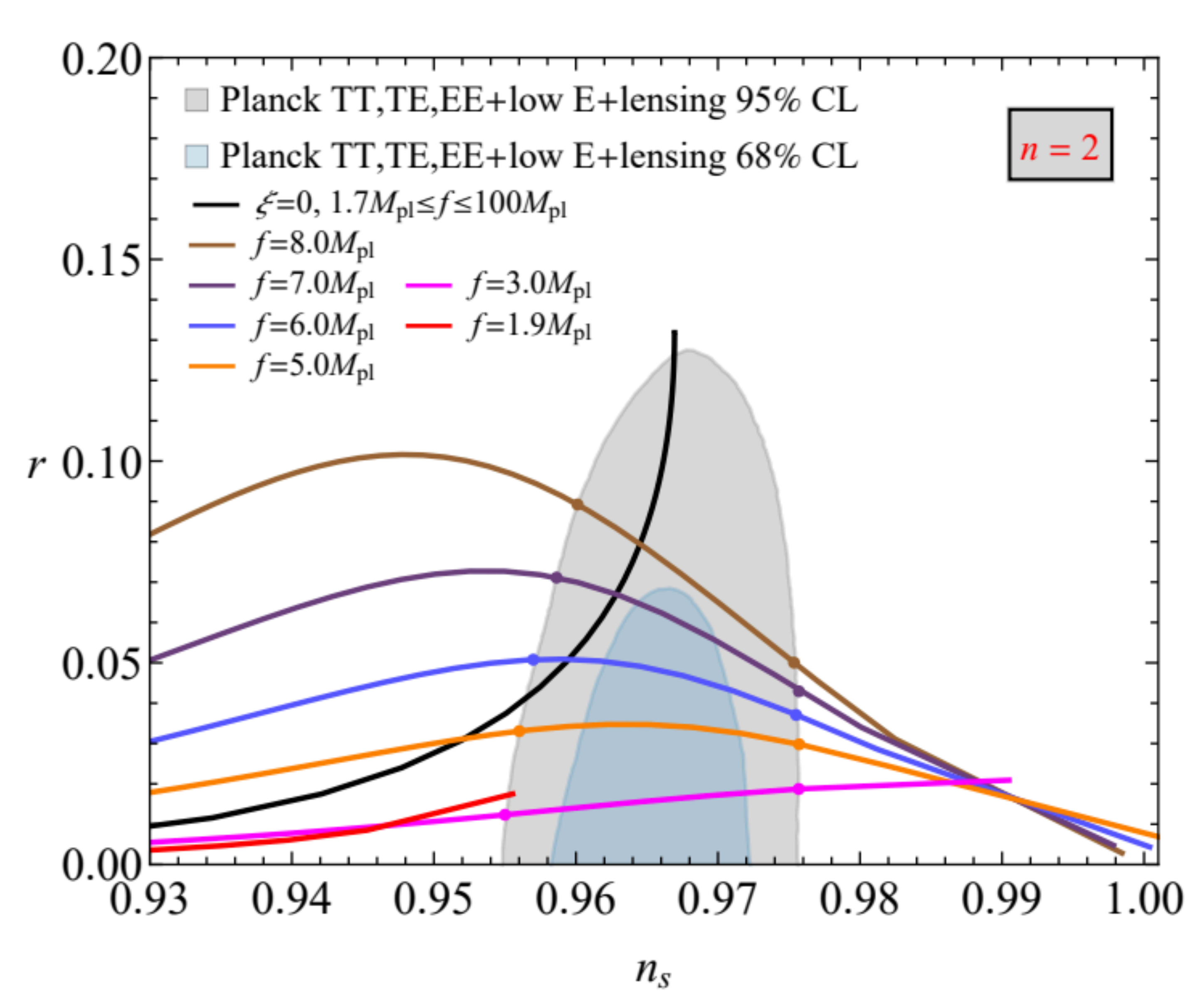
- Natural
- No memory of the initial state

What about non-thermal leptogenesis?

A detour to inflation

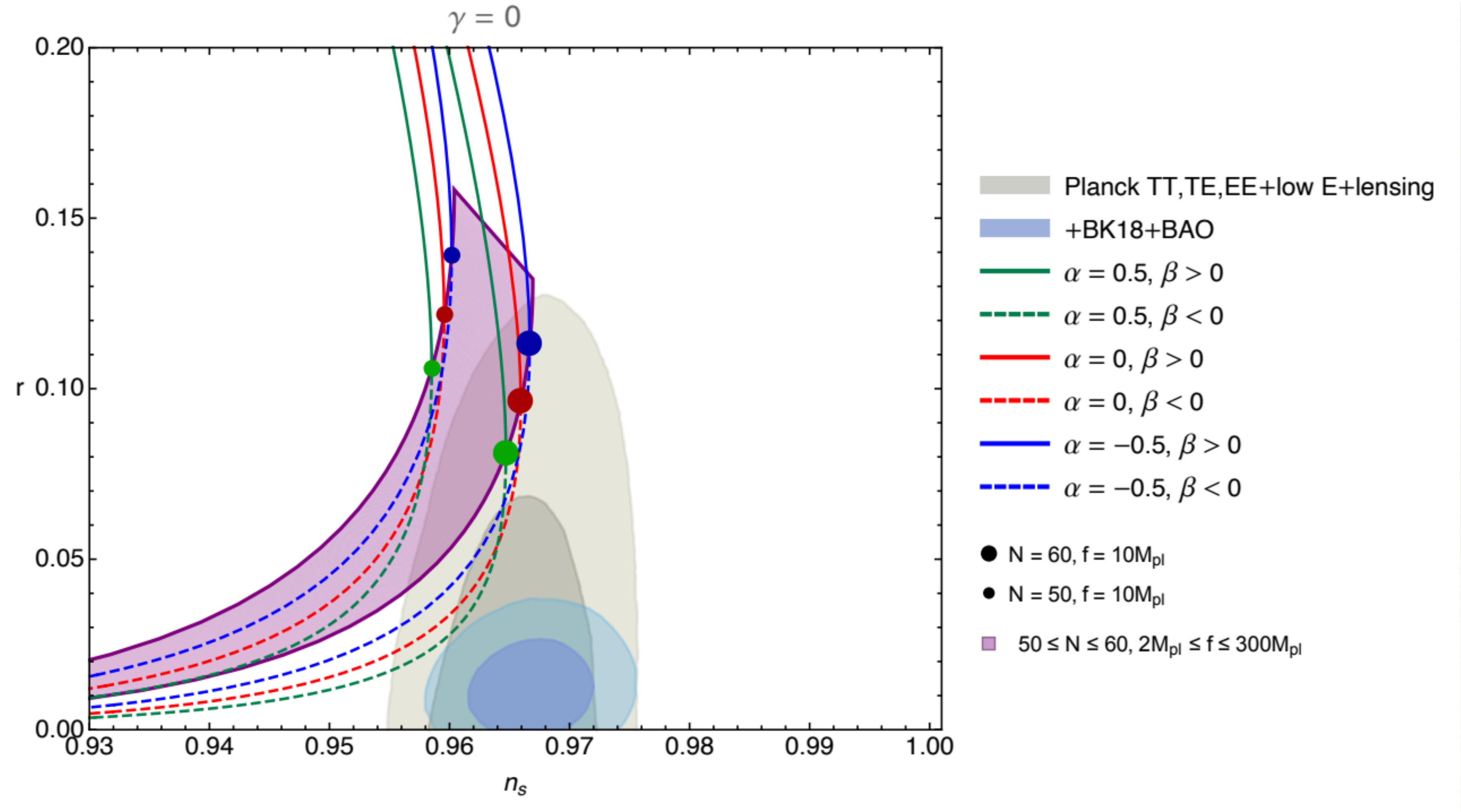






Reyimuaji, XYZ, 2012.07329

Reyimuaji, XYZ, 2012.14248

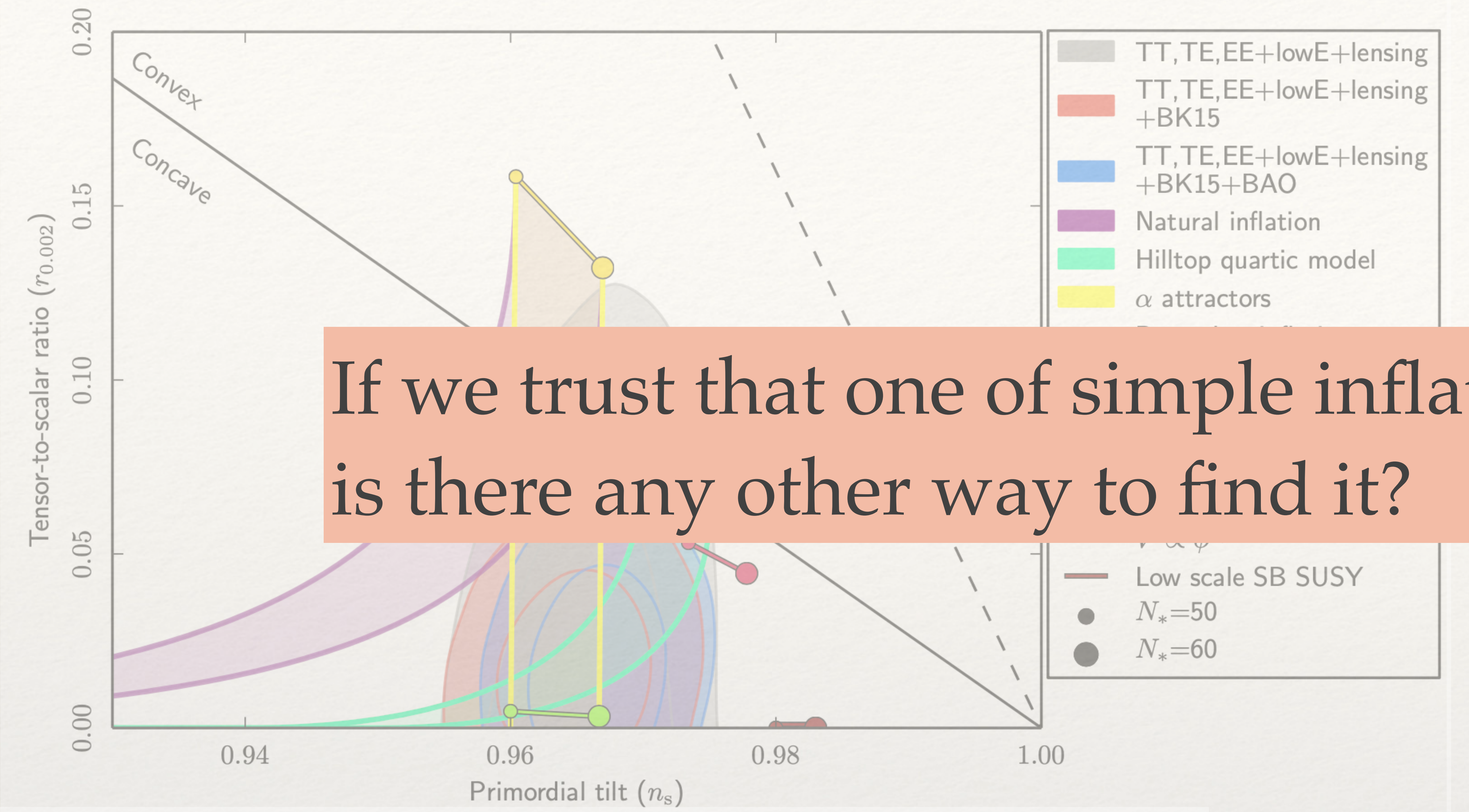


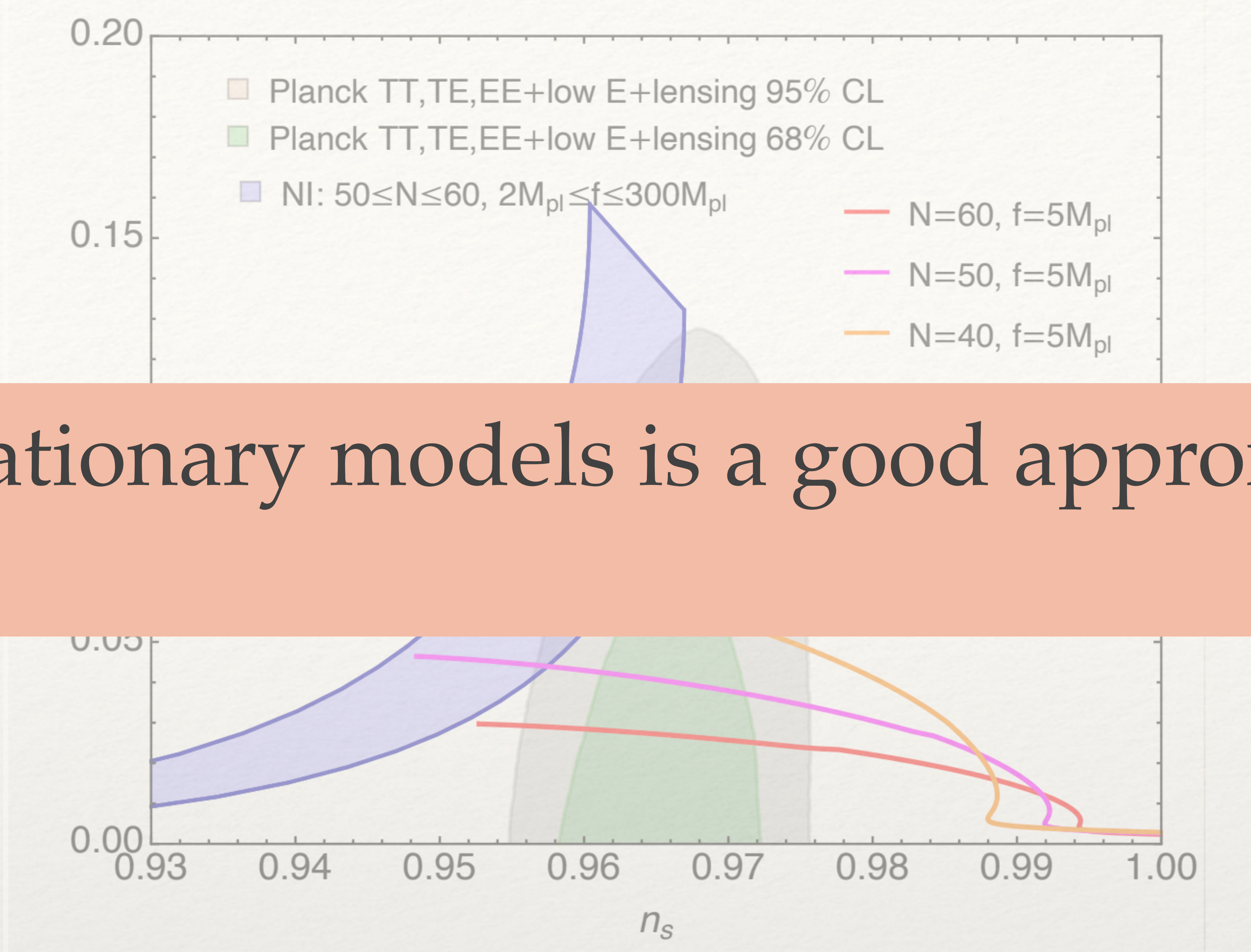
- CMB data starts ruling out simple inflationary models
- Simple inflationary models are "easily disguised" to "escape"

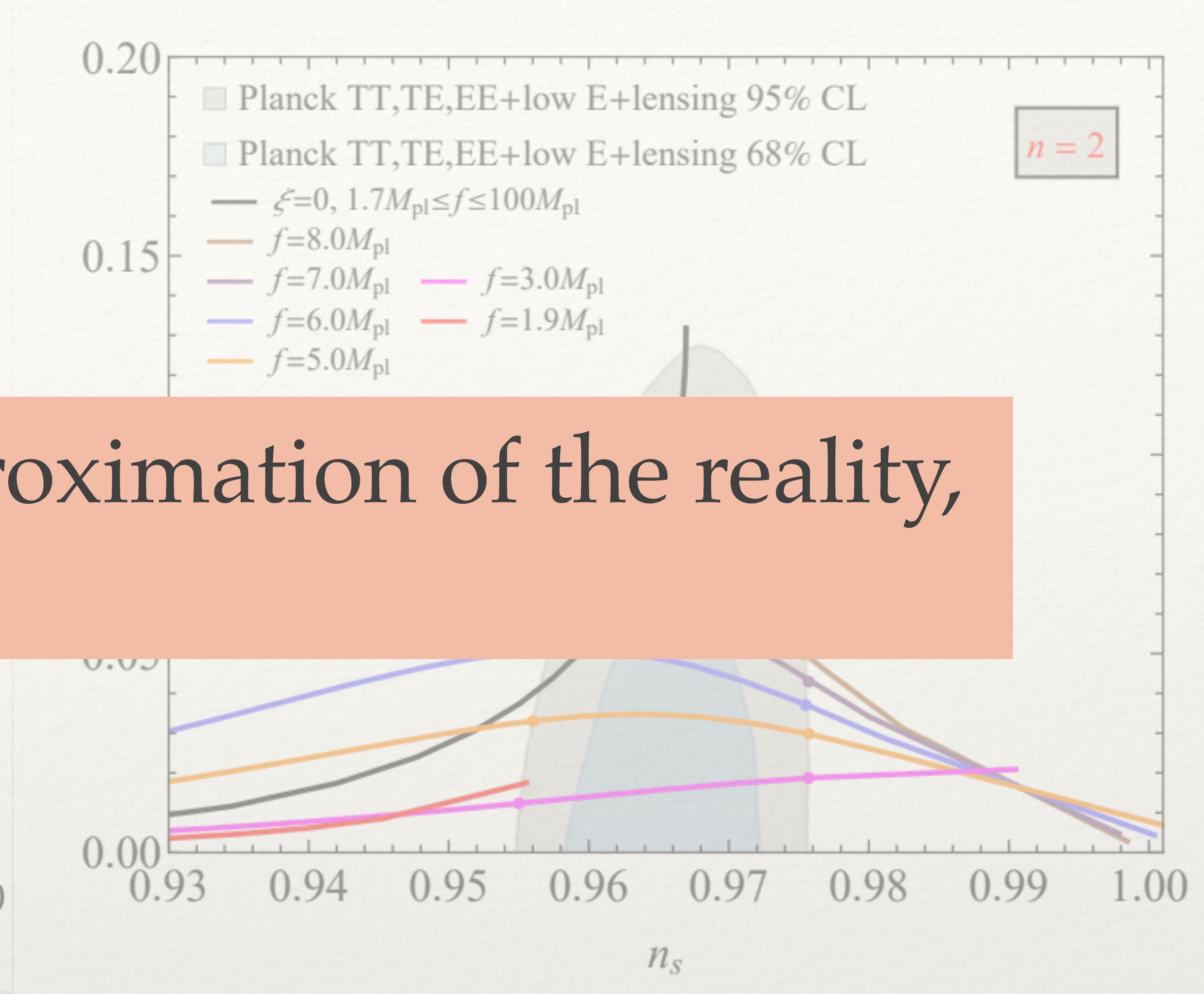
Chen, Reyimuaji, XYZ, 2203.15035

XYZ, Chen, Reyimuaji, 2108.07546

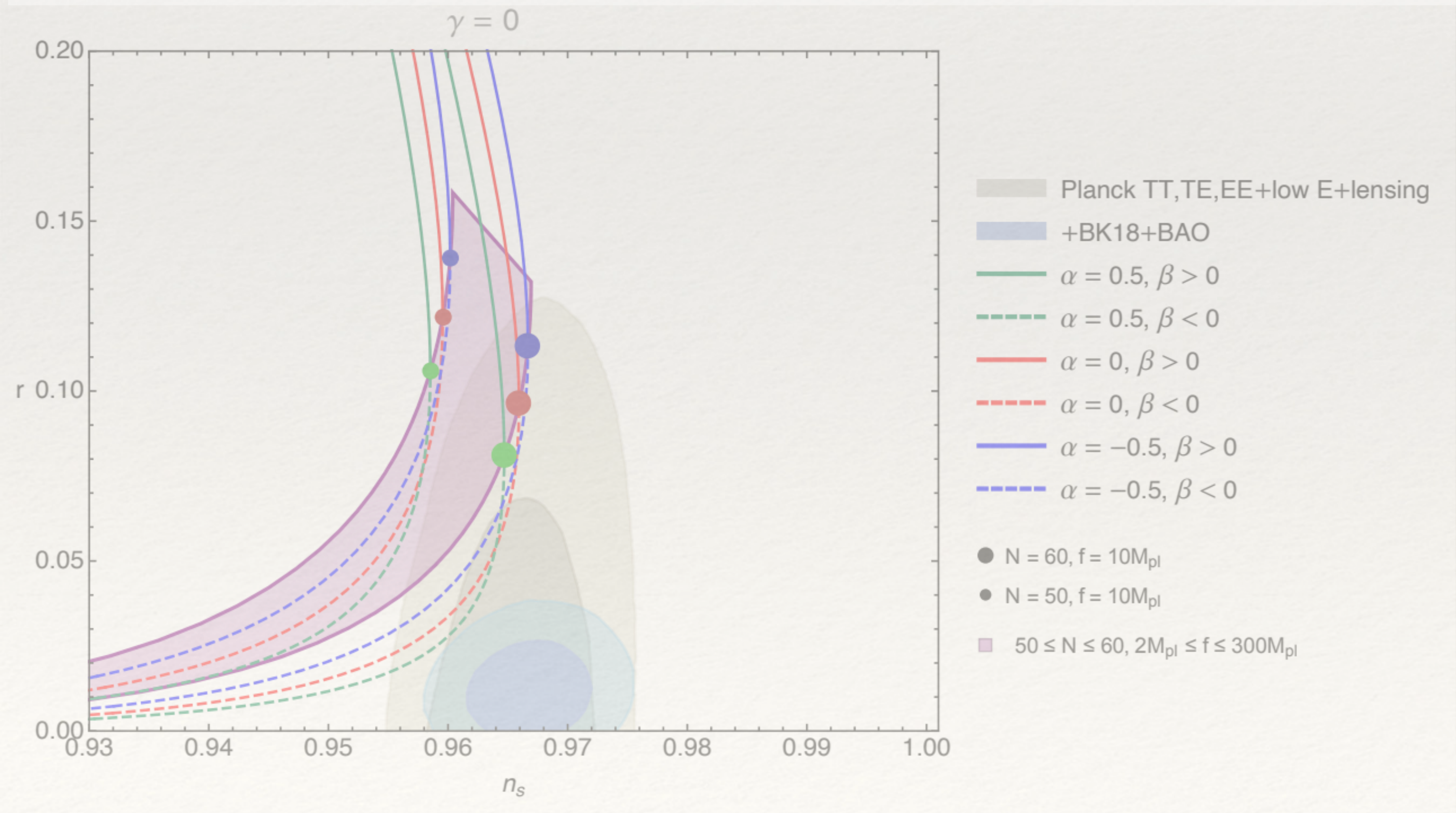
A detour to inflation







If we trust that one of simple inflationary models is a good approximation of the reality, is there any other way to find it?



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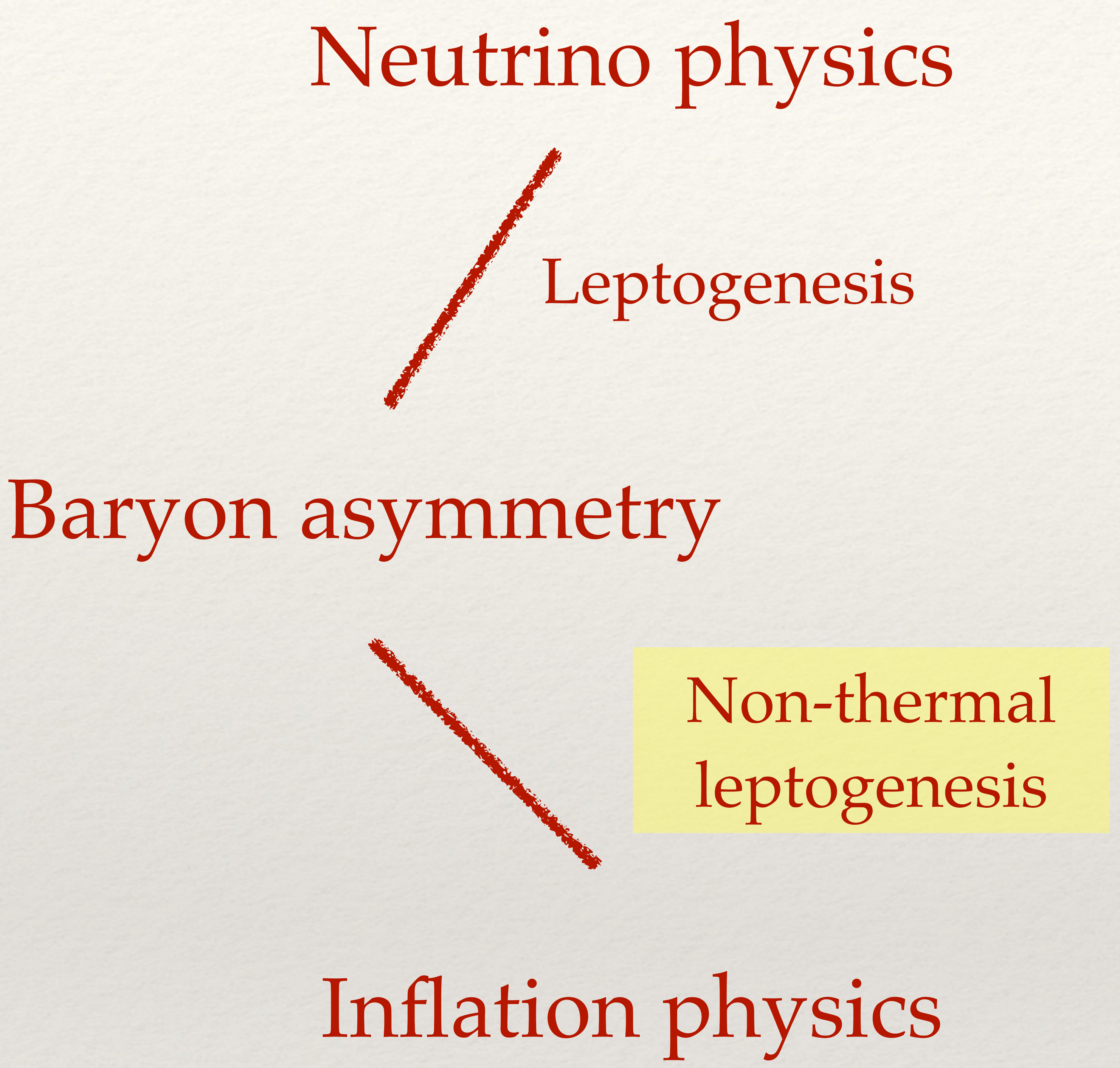


An incomplete list for non-thermal leptogenesis

- K. Kumekawa, T. Moroi and T. Yanagida, , Prog. Theor. Phys. 92 (1994) 437
- D.J.H. Chung, E.W. Kolb and A. Riotto, Phys. Rev. D 60 (1999) 063504
- T. Asaka, K. Hamaguchi, M. Kawasaki and T. Yanagida, Phys. Lett. B 464 (1999) 12
- G. Lazarides, Springer Tracts Mod. Phys. 163 (2000) 227
- R. Jeannerot, S. Khalil and G. Lazarides, Phys. Lett. B 506 (2001) 344
- V.N. Senoguz and Q. Shafi, Phys. Lett. B 582 (2004) 6
- T. Dent, G. Lazarides and R. Ruiz de Austri, Phys. Rev. D 69 (2004) 075012
- M. Endo, F. Takahashi and T.T. Yanagida, Phys. Rev. D 74 (2006) 123523
- F. Hahn-Woernle and M. Plumacher, Nucl. Phys. B 806 (2009) 68
- S. Antusch, J.P. Baumann, V.F. Domcke and P.M. Kostka, JCAP 10 (2010) 006
- S. Khalil, Q. Shafi and A. Sil, Phys. Rev. D 86 (2012) 073004
- C. Pallis and N. Toumbas, Non-Minimal Sneutrino Inflation, JCAP 02 (2011) 019
- S. Antusch and K. Marschall, JCAP 05 (2018) 015
- G. Panotopoulos, Astropart. Phys. 128 (2021) 102559
- A. Ghoshal, D. Nanda and A.K. Saha, 2210.14176

Mostly rely on a simple assumption

A systematic study on non-thermal leptogenesis needed

Basic idea

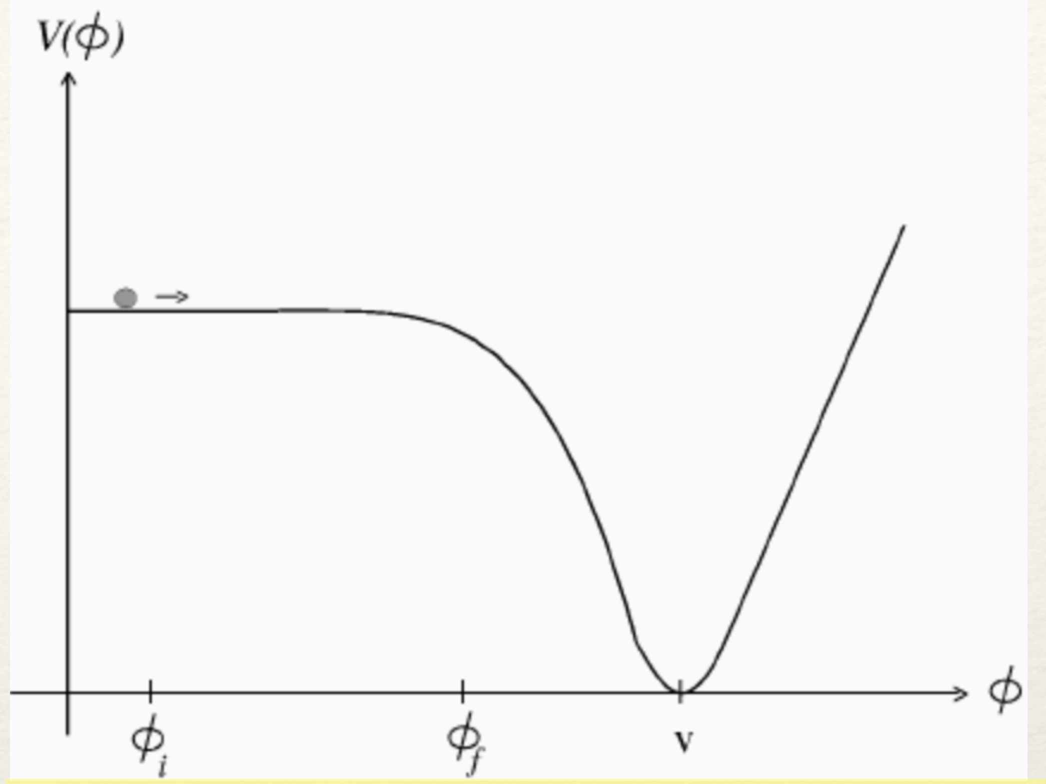
Introduce right-handed neutrinos (RHNs) to SM,

✓ Neutrino mass via type-I seesaw

✓ Leptogenesis

? more

Both leptogensis and inflation happen at high scale,
could connect more directly

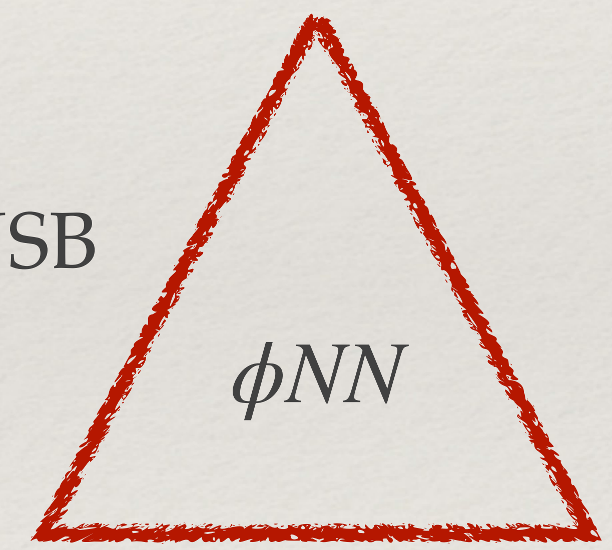


Simplest inflationary scenario
Single-field slow-roll

Let ϕNN be the key!

ϕ inflaton

N RHN



When ϕ acquires a vev,
a Majorana mass for RHN is generated

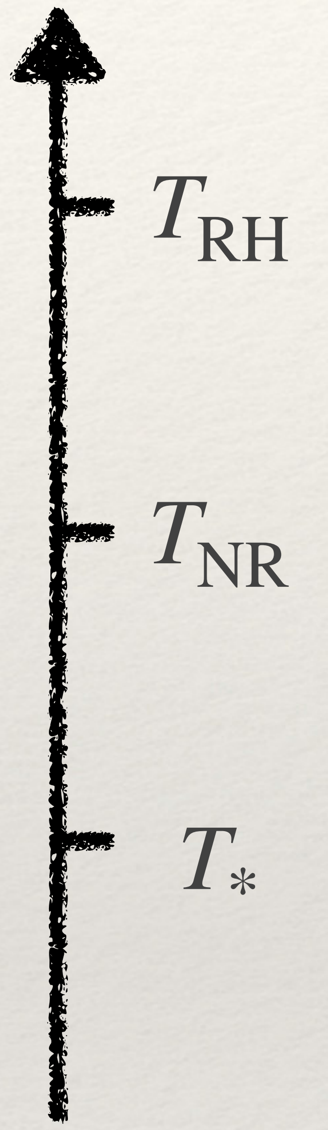
Extra bonus: lepton number spontaneously broken (LNSB)

Given only ϕNN, characteristic processes? quantities?

$K \ll 1$ limit

Weak Yukawa → Cannot thermalize RHN

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



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

Strong Yukawa → Cannot thermalize RHN

RHN decay too fast

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

$\Gamma_N \gg \Gamma_\phi$

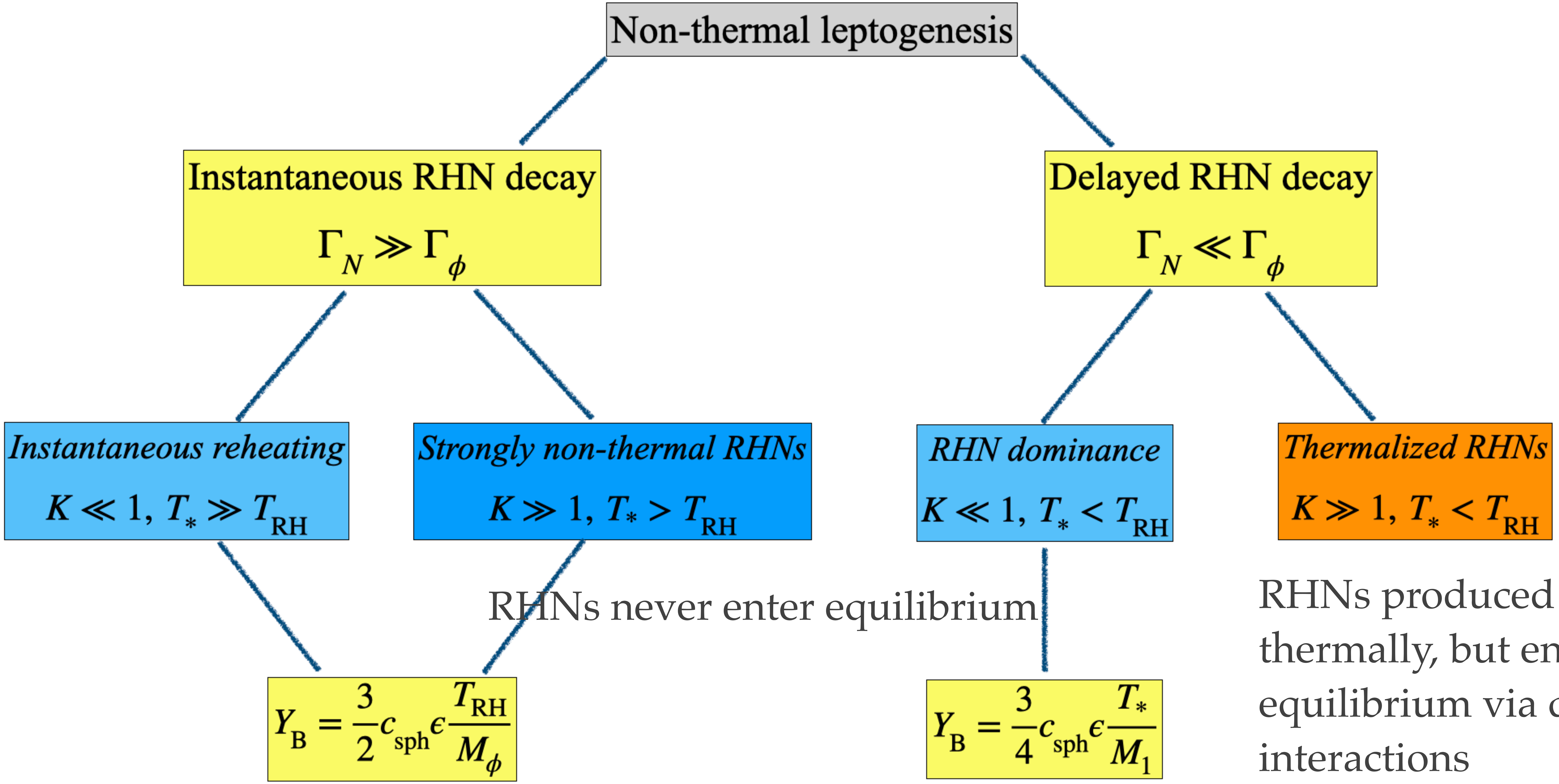
↓ Approx.

$T_* > T_{RH}$

↓ Stronger, quick assessment

$M_1 > T_{RH}$

Four limits



RHNs never enter equilibrium

RHNs produced non-thermally, but enter equilibrium via quick interactions

Boltzmann equations

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

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

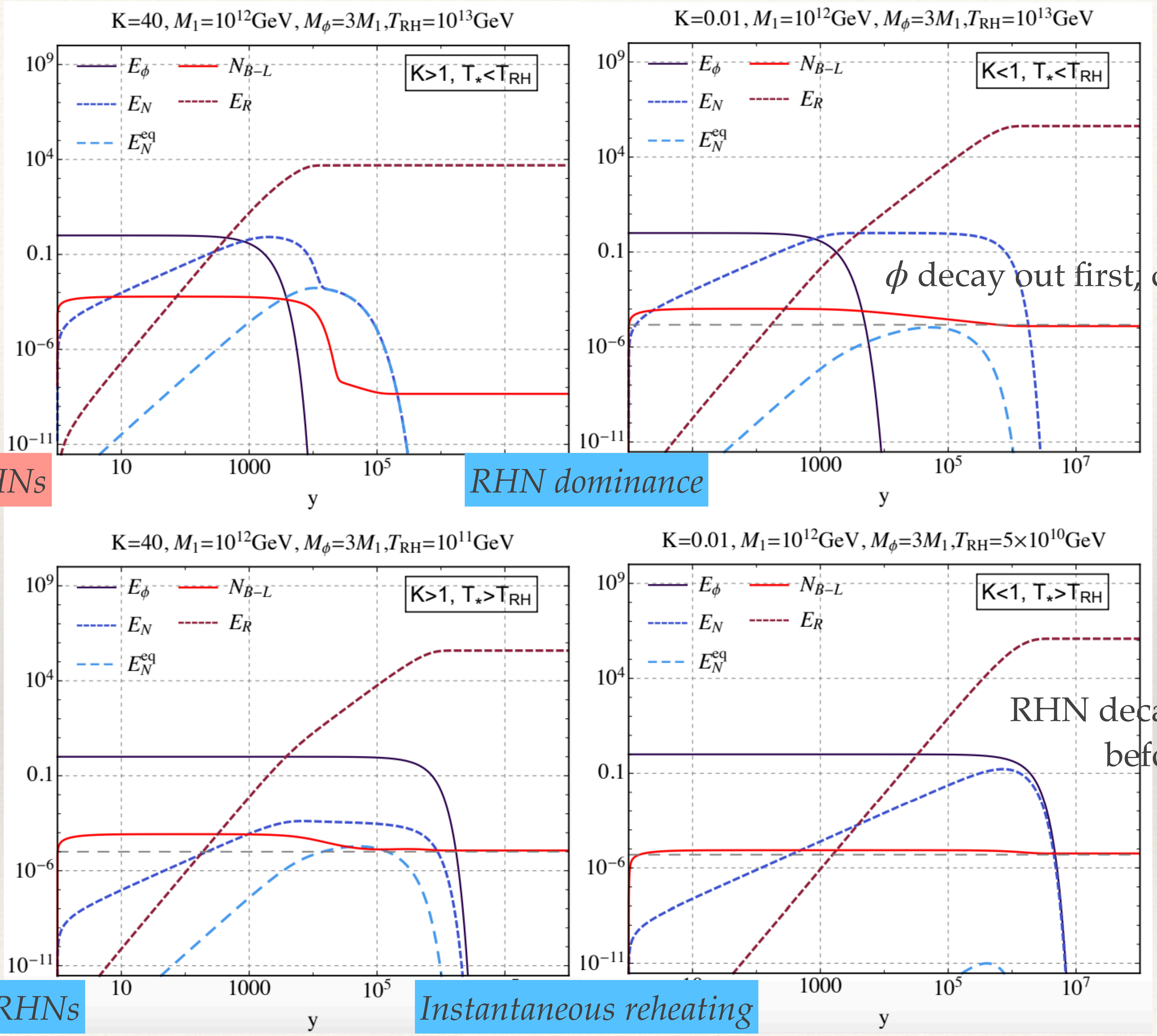
Scale out expansion $E_\phi = \rho_\phi a^3, E_N = \rho_N a^3, N_{B-L} = n_{B-L}a^3, E_R = \rho_R a^4$

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

Numeric results

Enter equilibrium

Yukawa strong, but RHNs decay before entering equilibrium



Thermalized RHNs

RHN dominance

ϕ decay out first, decayed RHN decay

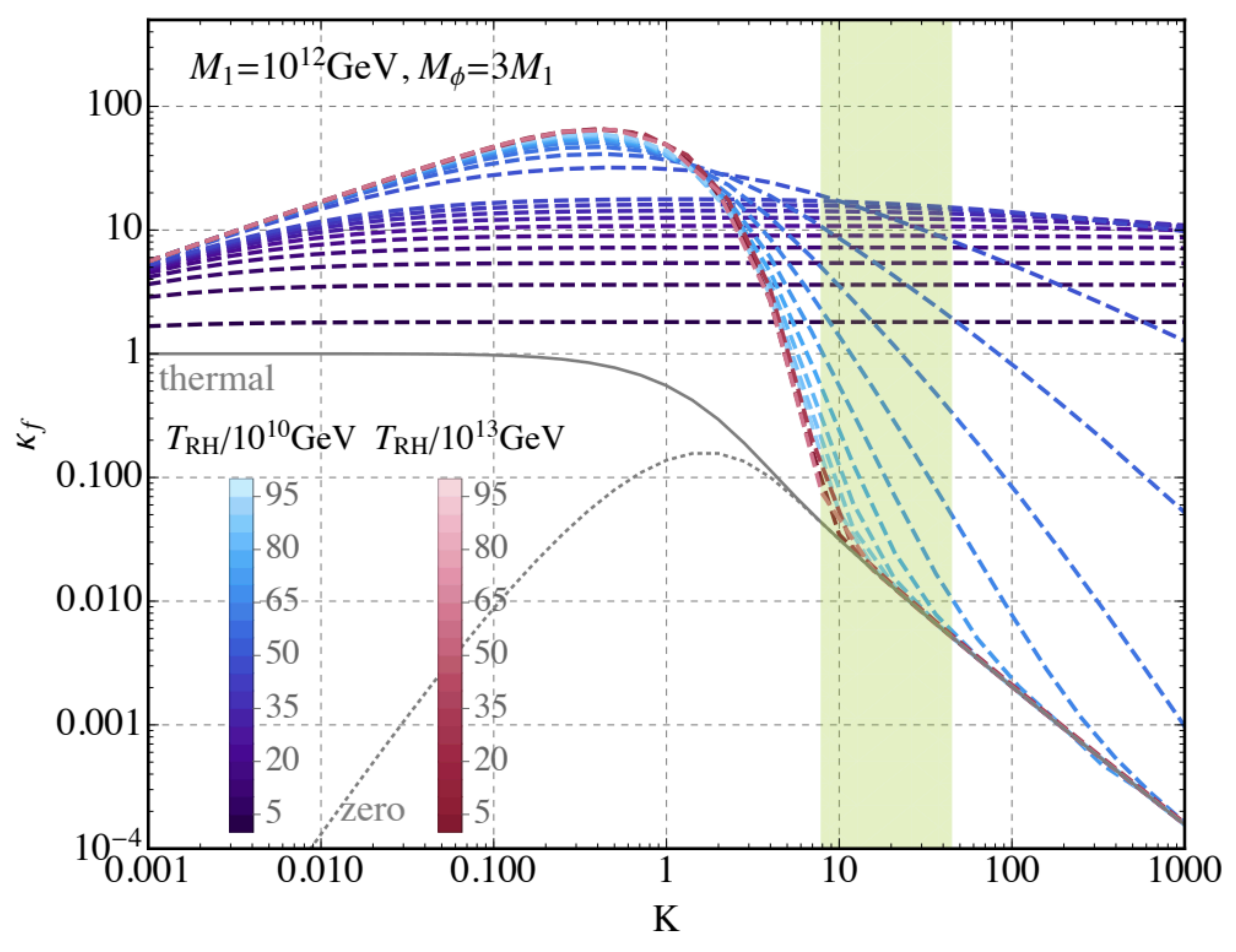
Strongly non-thermal RHNs

Instantaneous reheating

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

XYZ, 2311.05824

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

All three truly non-thermal cases have κ_f larger than thermal leptogenesis

XYZ, 2311.05824

Flavor effects

Take τ as an example

$\Gamma_\tau > \Gamma_{\rm ID}^\tau > H$ Same as the thermal

$\Gamma_\tau > H > \Gamma_{\rm ID}^\tau$ Unique in non-thermal

XYZ, 2311.05824

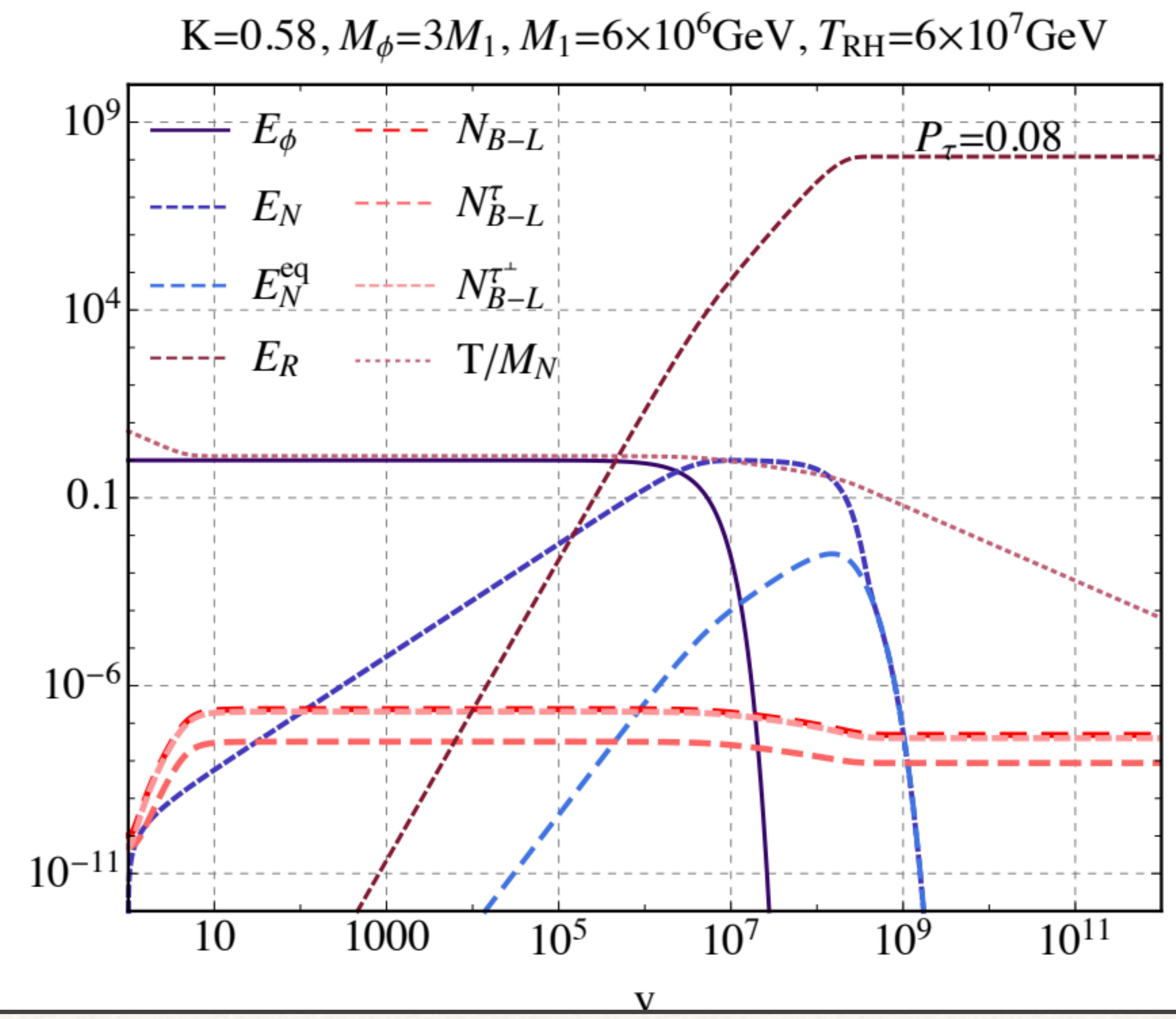
$$\frac{\mathrm{d}E_\phi}{\mathrm{d}y} = -\frac{\Gamma_\phi}{Hy}\left(E_\phi - E_\phi^{\rm eq}\right) \ ,$$

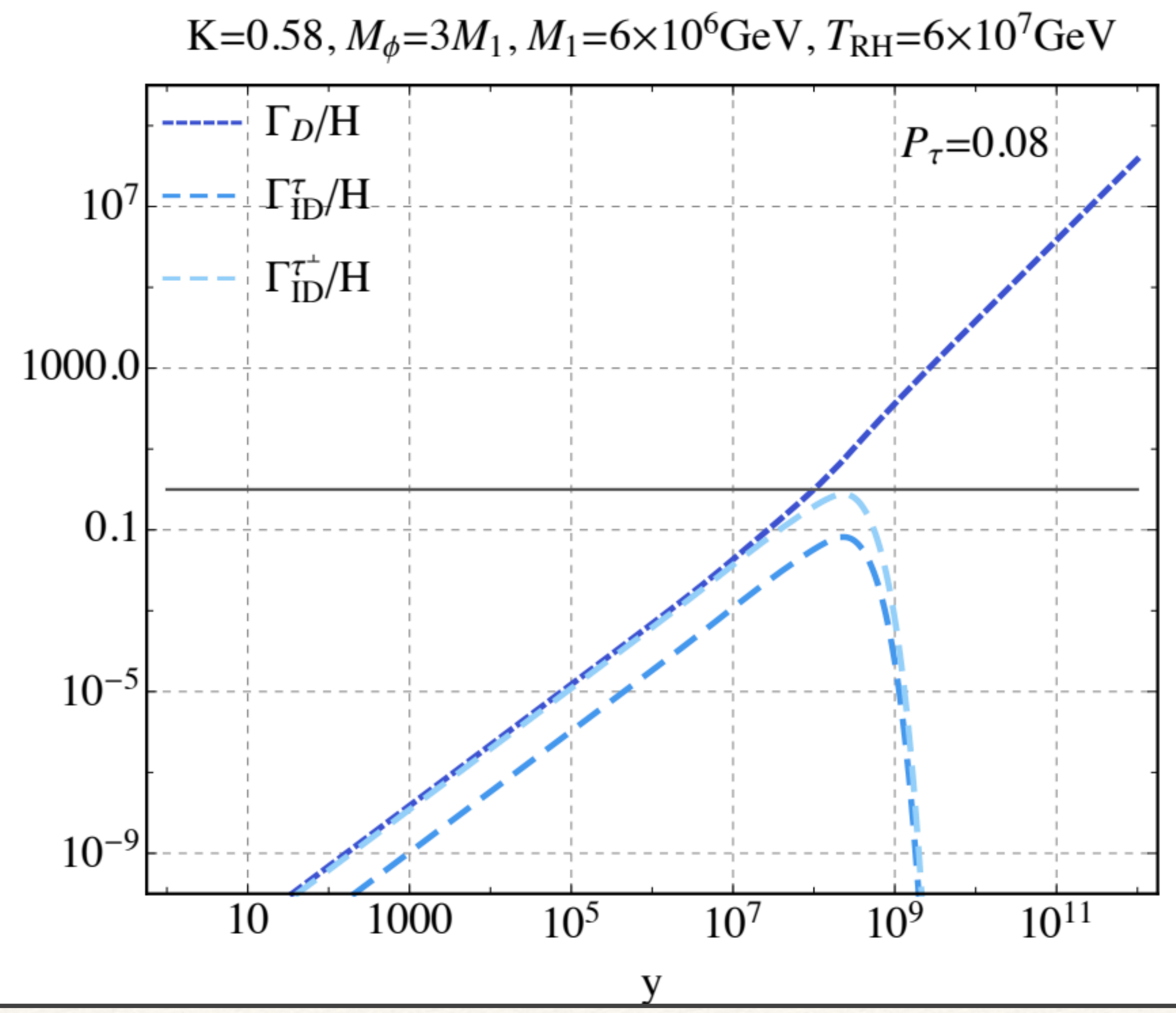
$$\frac{\mathrm{d}E_N}{\mathrm{d}y} = \frac{\Gamma_\phi}{Hy}\left(E_\phi - E_\phi^{\rm eq}\right) - \frac{\Gamma_N}{Hy}\left(E_N - E_N^{\rm eq}\right) \ ,$$

$$\frac{\mathrm{d}E_R}{\mathrm{d}y} = \frac{\Gamma_N}{H}\left(E_N - E_N^{\rm eq}\right) \ ,$$

$$\frac{\mathrm{d}N_{\Delta_\tau}}{\mathrm{d}y} = -\frac{\epsilon_\tau\Gamma_N}{Hy}\left(N - N^{\rm eq}\right) - \frac{P_\tau W_{\rm ID}}{Hy}\sum_{\alpha=\tau,\tau^\perp} C_{\tau\alpha}N_{\Delta_\alpha} \ ,$$

$$\frac{\mathrm{d}N_{\Delta_{\tau^\perp}}}{\mathrm{d}y} = -\frac{\epsilon_{\tau^\perp}\Gamma_N}{Hy}\left(N - N^{\rm eq}\right) - \frac{P_{\tau^\perp} W_{\rm ID}}{Hy}\sum_{\alpha=\tau,\tau^\perp} C_{\tau^\perp\alpha}N_{\Delta_\alpha} \ ,$$





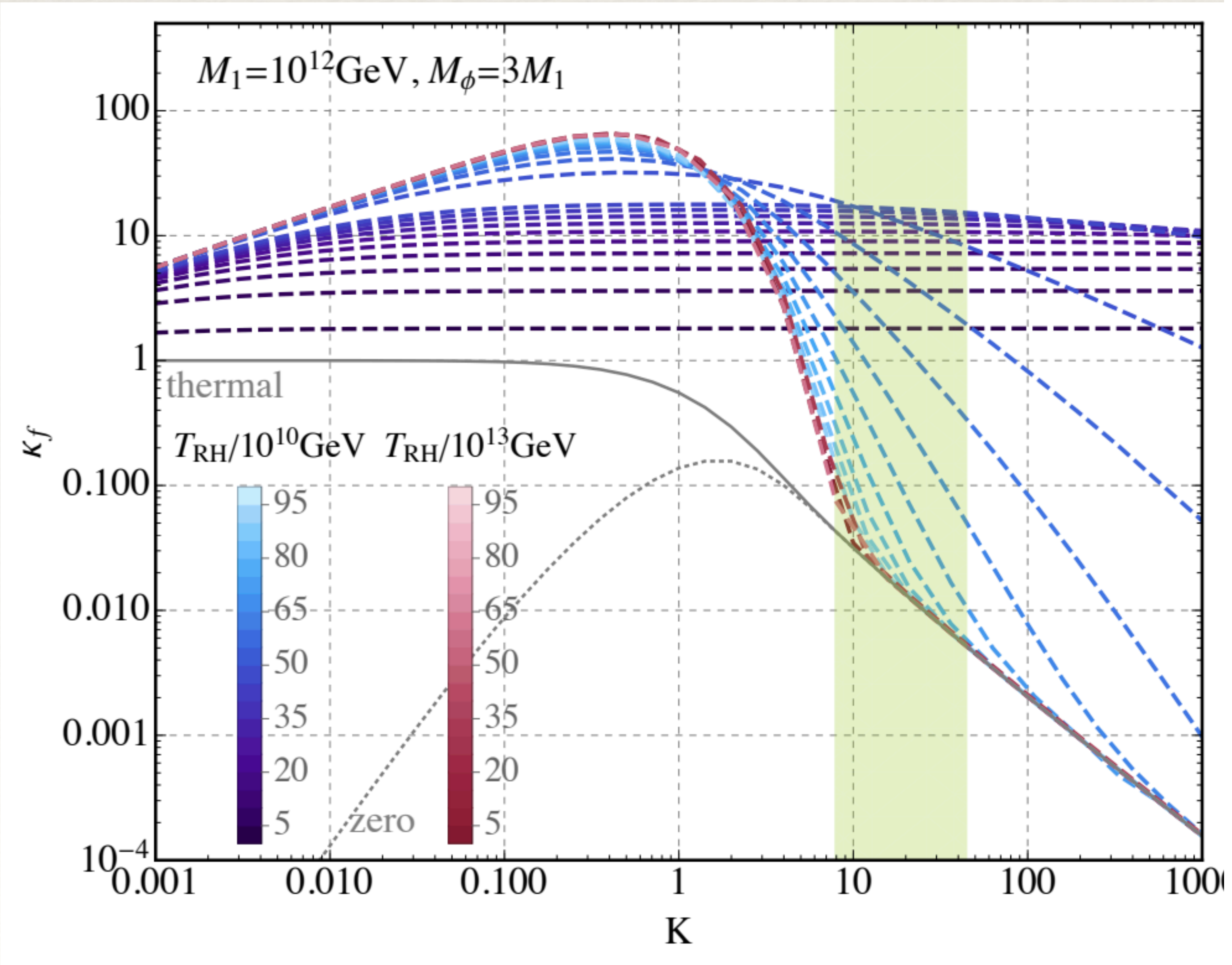
Neutrino mass bound

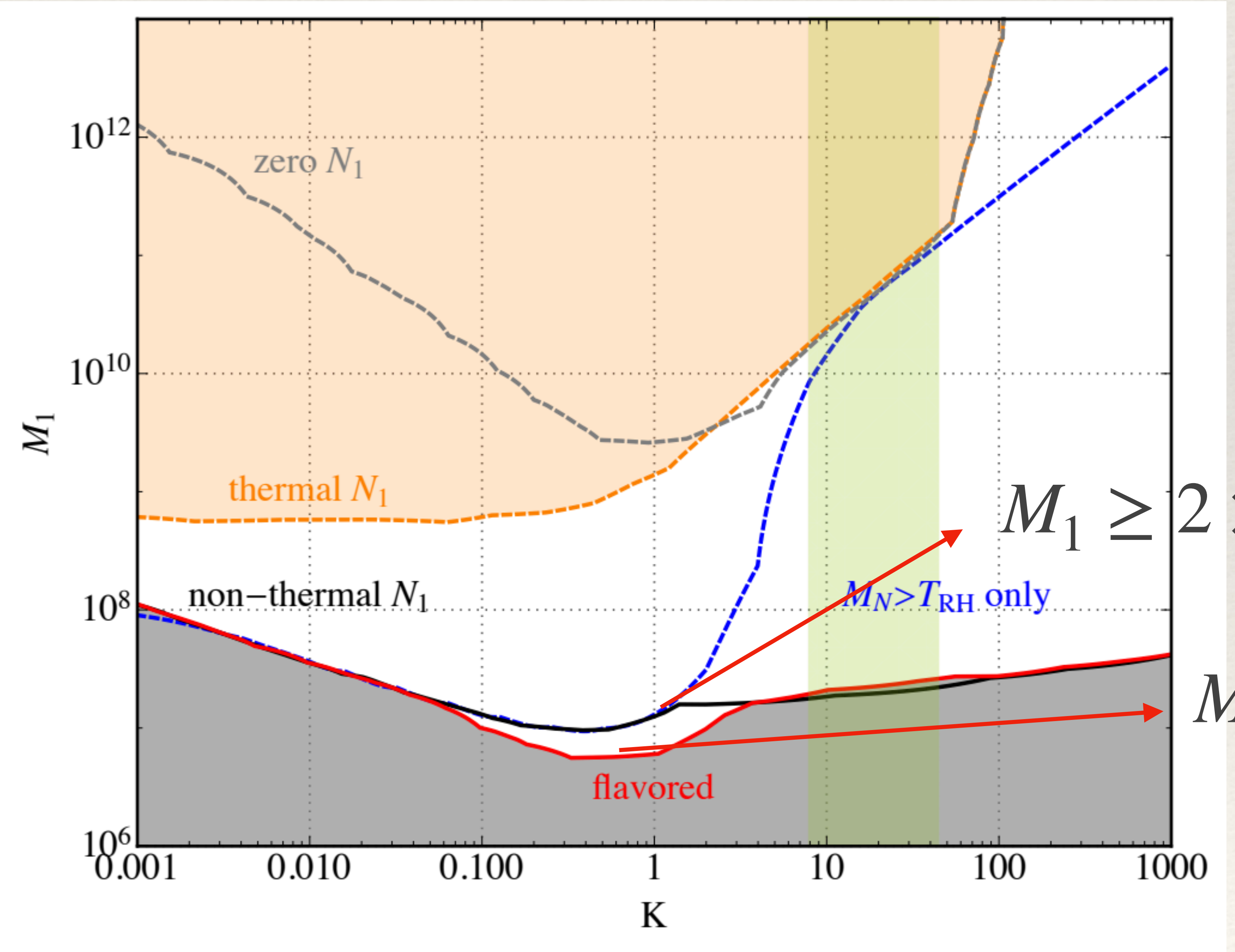
From the Dividson-Ibarra bound $|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1 m_{\rm atm}}{v^2}$

Davidson and Ibarra, 2022

We found a lower bound on the RHN mass

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





$M_1 \geq 2\times 10^7$ 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

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

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

Inflationary constraints:

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

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

Coleman-Weinberg potential

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

Inflation-observation-compatible benchmark values

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

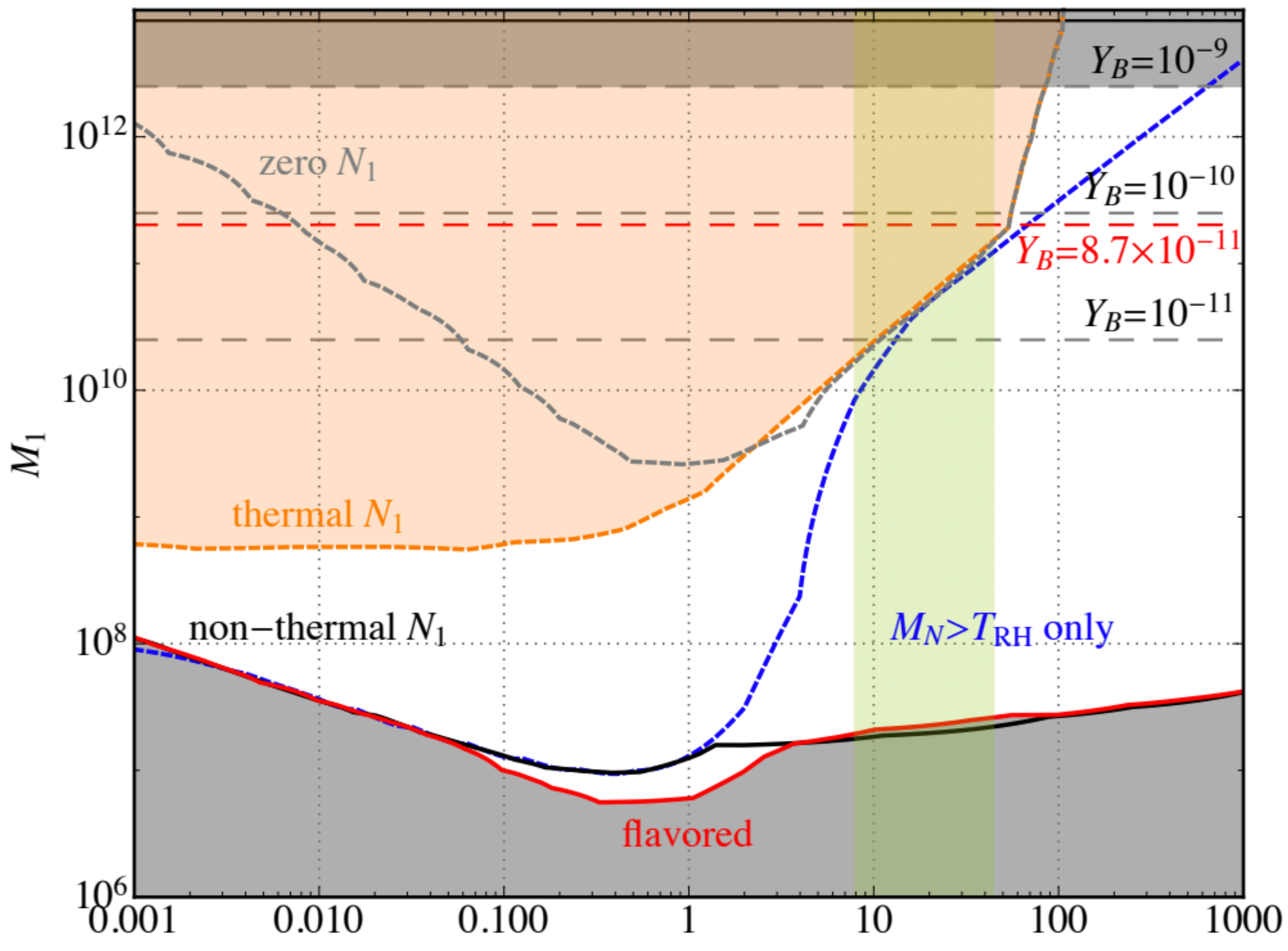
$$\rightarrow \quad M_\phi = 1.65 \times 10^{13}\ \text{GeV}$$

$$M_N = y_N v_\phi$$

Viable parameter space satisfy

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

Strongly non-thermal RHNs preferred



XYZ, 2311.05824

Natural inflation potential

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

Inflation-observation-compatible benchmark values

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

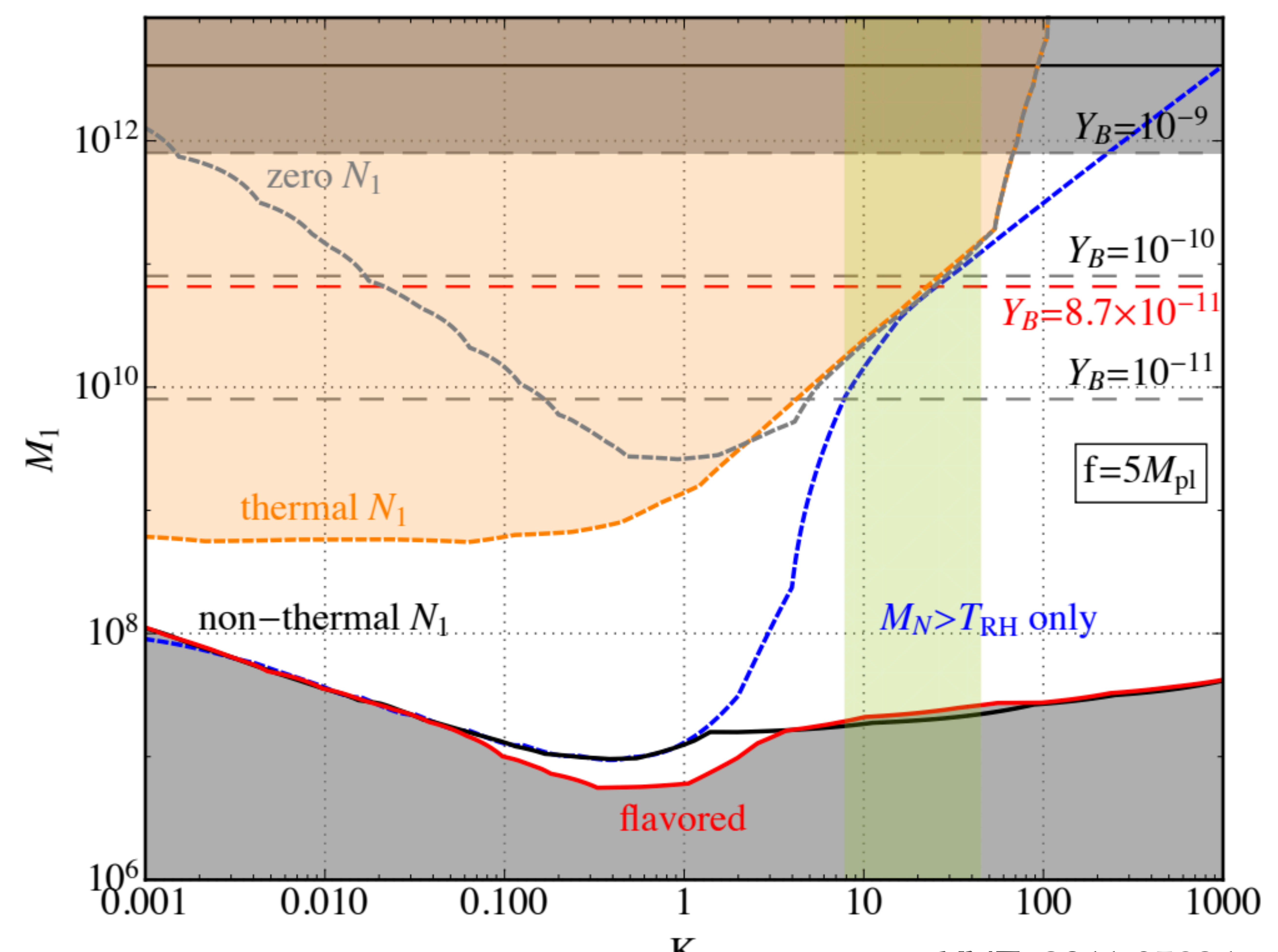
$$\rightarrow \quad M_\phi \leq 10^{13}\ \text{GeV}$$

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

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

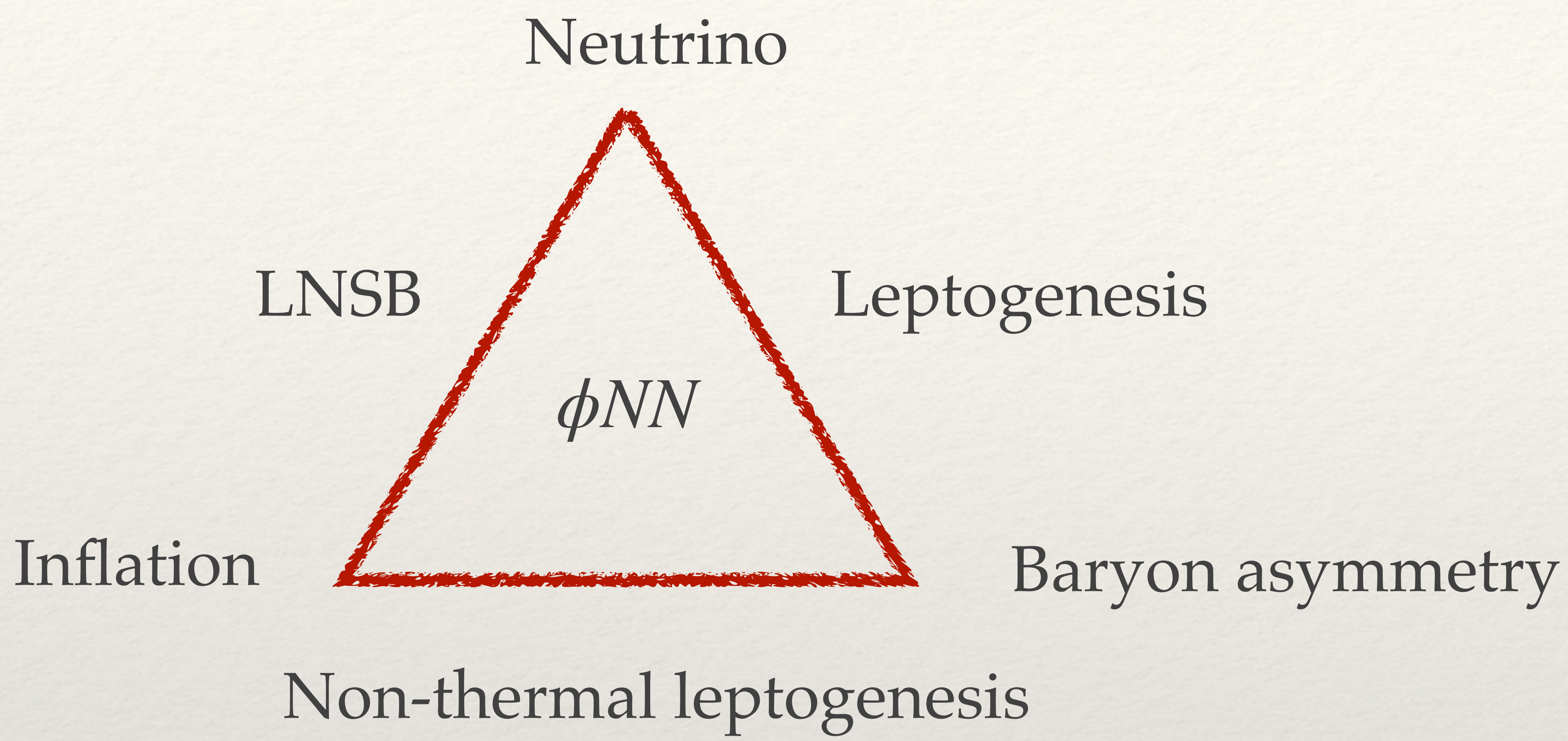
$$M_N = y_N f \ \rightarrow\ T_{\rm RH} \simeq 6\times 10^{-5} M_1$$

Strongly non-thermal RHNs preferred

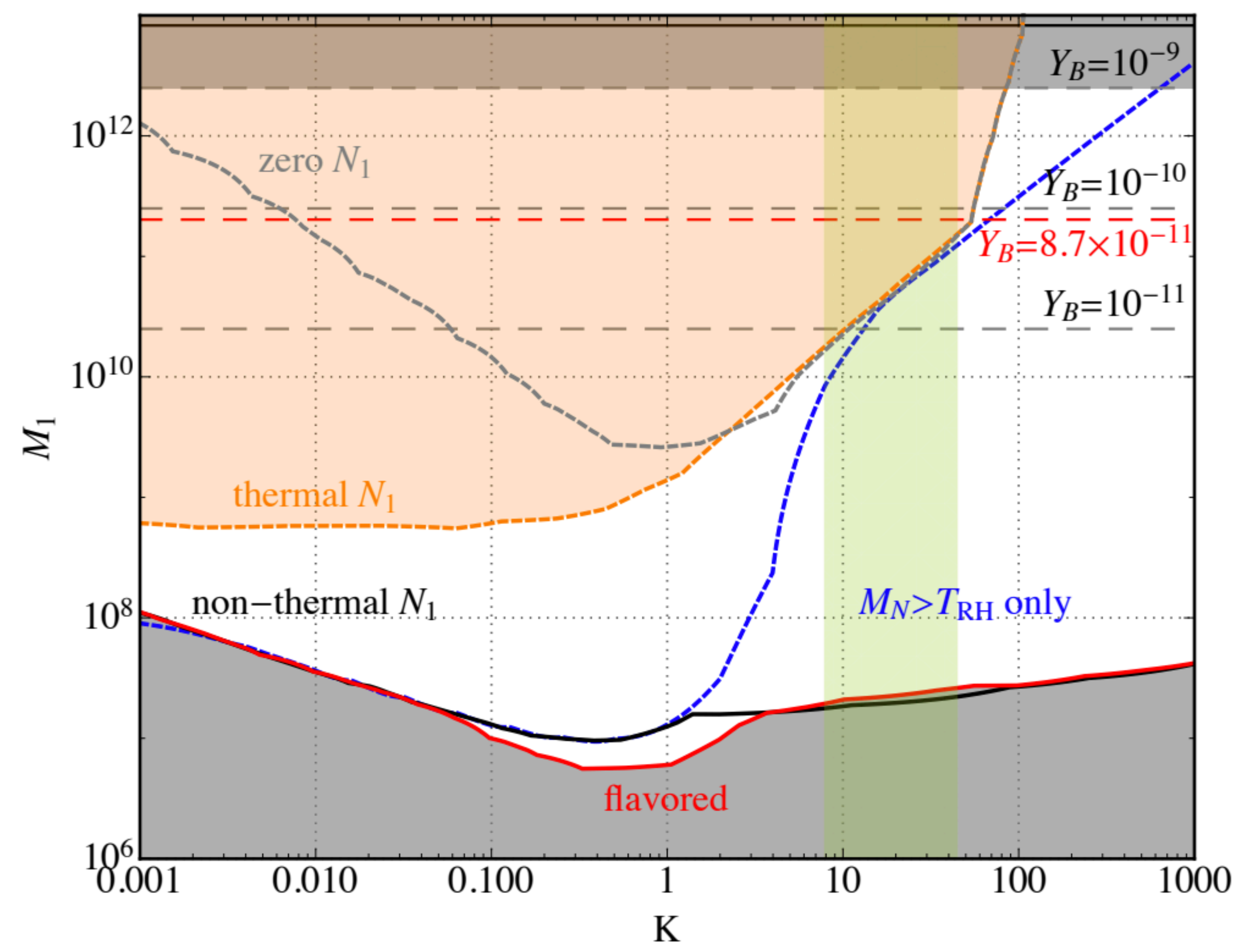


XYZ, 2311.05824

Conclusions



LNSB → strongly non-thermal RHNs



Things to explore:

- Detailed reheating
- Include ν flavor
- keV sterile ν
- Generalized inflation
- ……

Thanks and stay tuned!

Backup

Important quantities

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

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

Effectively parametrize y_N

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

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

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

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

Effectively the Yukawa strength

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

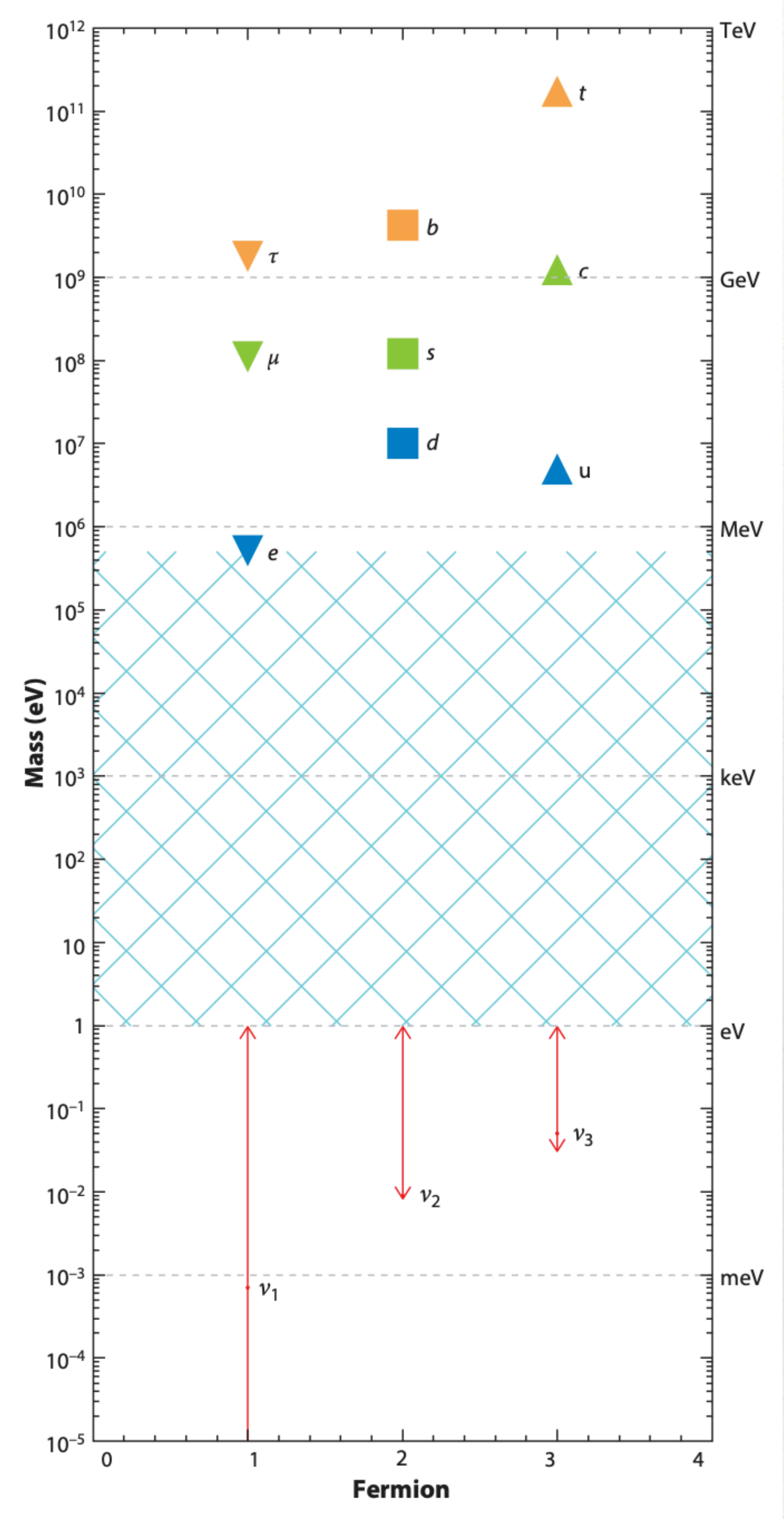
$$Y_{\mathrm{B}} = \frac{n_{\mathrm{B}}}{s} = \frac{c_{\mathrm{sph}} \epsilon}{s} n_N$$

Open questions concerning ν

- What is the nature of neutrinos? Are they Dirac particles or Majorana particles?
- What is the absolute mass of neutrinos?
- Why are neutrino masses so small?
- Why are neutrino mixings so large?
- Are there any sterile neutrinos? Are they at eV scale or keV scale, or even heavier?

Neutrinos' role in astrophysics and cosmology

Connection to other beyond standard model physics



Annu. Rev. Nucl. Part. Sci. 2016.66:197-217.

Neutrino mass generation mechanism

With only SM fields,

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

unique dimension 5 operator
Lepton-number violating

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

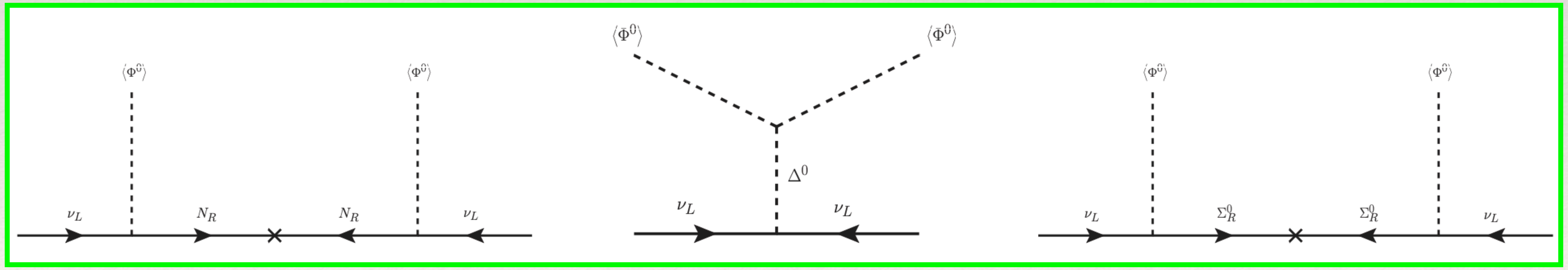
Consider different contracting,

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

Chulia, Srivastava and Valle, 1802.05722

Add new fields to make renormalizable operators

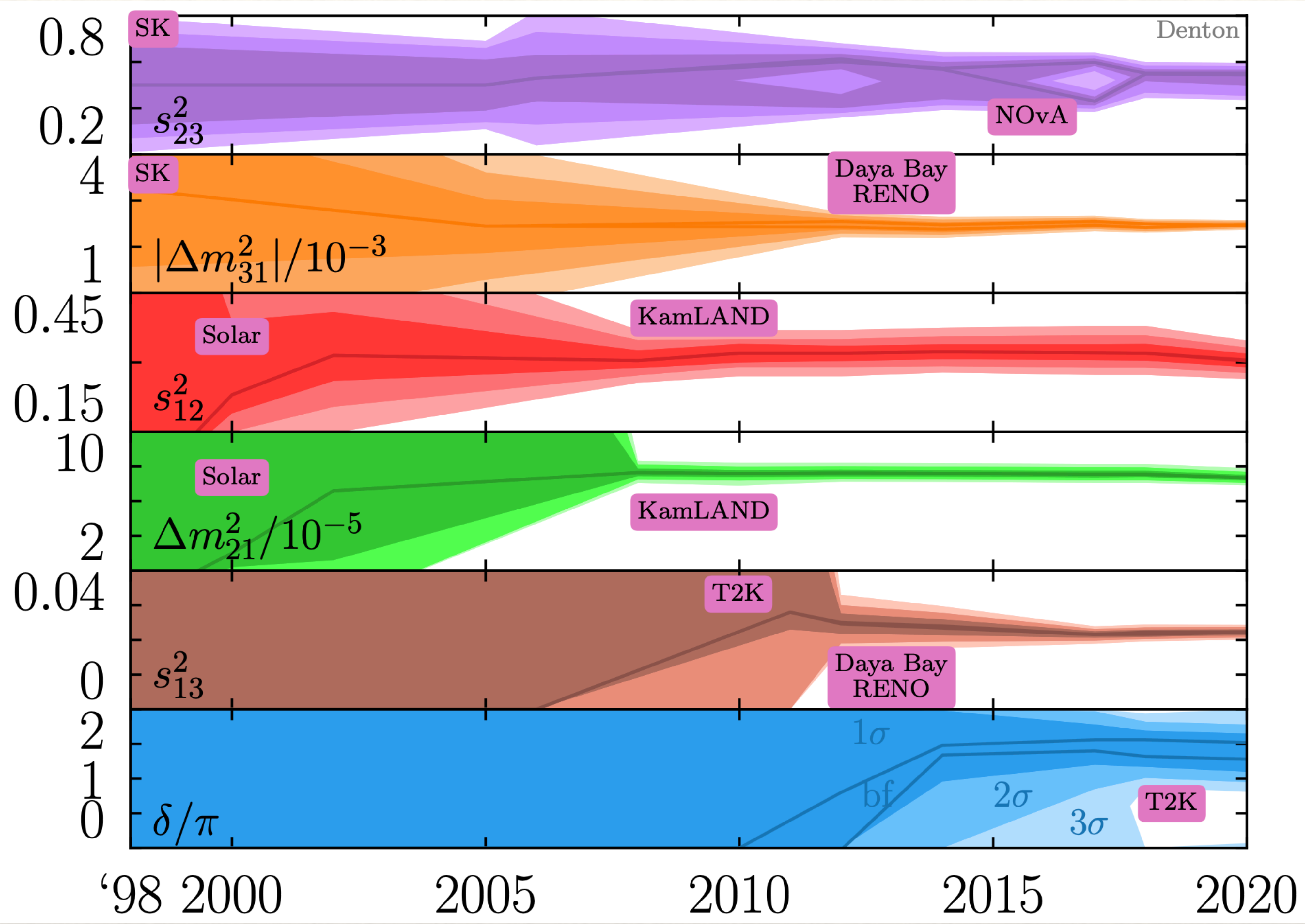
Tree-level realization of Weinberg operator



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

Experimental progress



Peter Denton, Neutrino 2022

- In ~10 years from now, oscillation will mostly be understood: mass hierarchy and CP phase will be known
- Neutrino absolute masses may be measured in ~20 years, through cosmology, beta decays and double beta decays
- Majorana neutrino nature maybe determined in ~30 years

Yifang Wang, Neutrino 2022

Single-field slow-roll inflation

Guth 1981
Kazanas 1980
Starobinsky 1980
Sato 1981

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

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

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

The dynamics is governed by

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

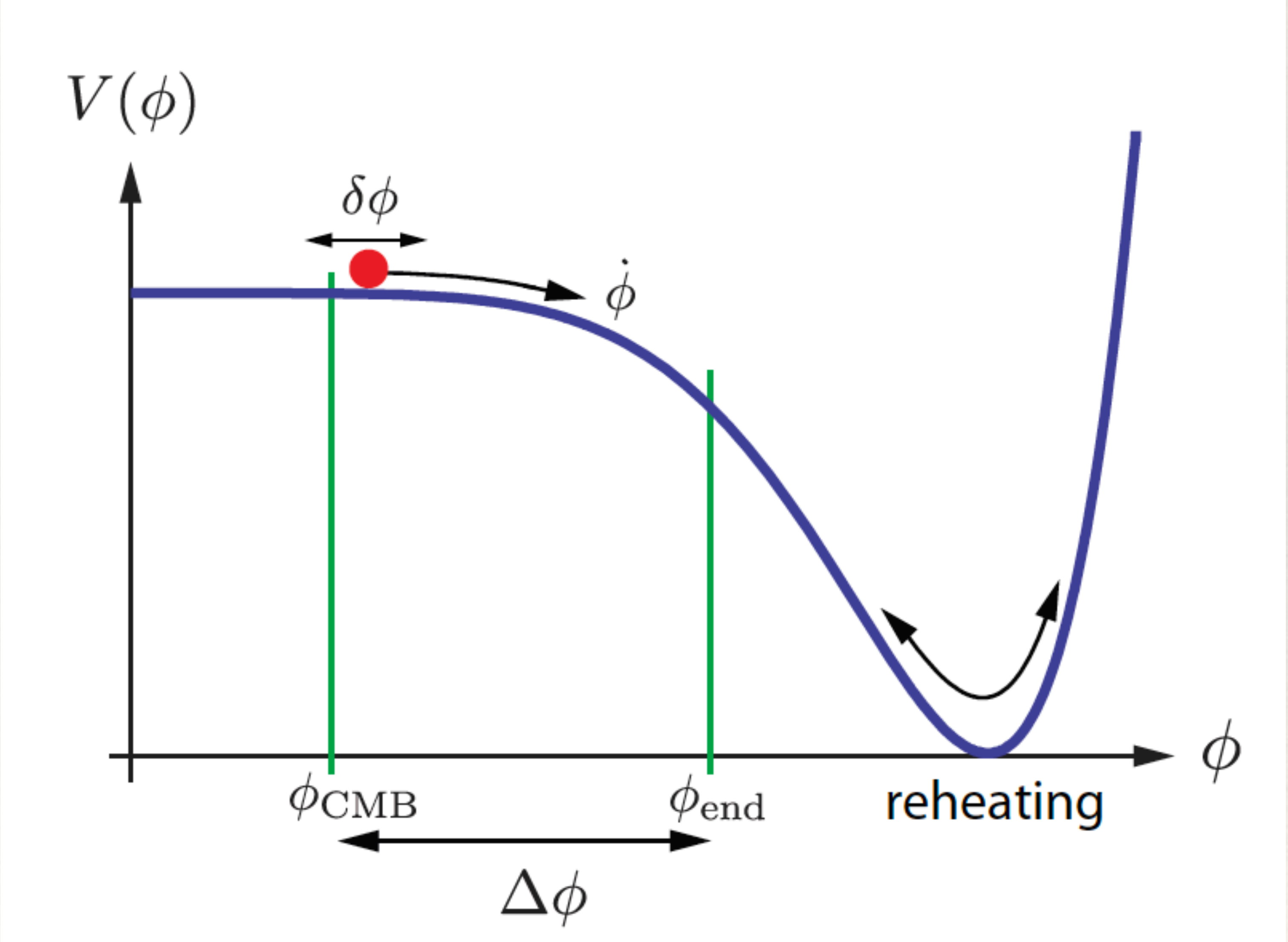
$$H^2 = \frac{1}{3}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right)$$

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

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

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

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

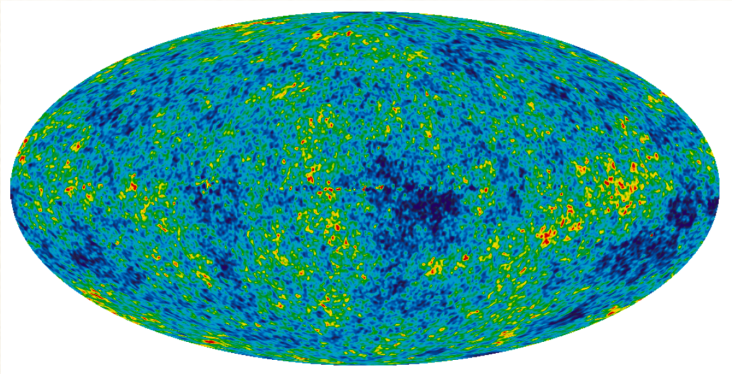
Slow-roll condition

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

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

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

Inflation confronts observation



The inflaton perturbations backreact on the spacetime geometry

Matter perturbations and metric perturbations are coupled

The power spectrum $P_{\rm s}(k) = \frac{H^2}{2k^3}\frac{H^2}{\dot\phi^2}\Big|_{k=aH}$ $P_{\rm t}(k) = \frac{4}{k^3}\frac{H^2}{M_{\rm pl}^2}\Big|_{k=aH}$

The dimensionless power spectrum $\Delta^2(k) \equiv \frac{k^3}{2\pi^2}P(k)$

The spectral tilt

$$n_{\rm s} - 1 \equiv \frac{d\ln\Delta_{\rm s}^2}{d\ln k} = 2\eta_{\rm v} - 6\epsilon_{\rm v}\,,$$
$$n_{\rm t} \equiv \frac{d\ln\Delta_{\rm t}^2}{d\ln k} = -2\epsilon_{\rm v}\,.$$

Tensor-to-scalar ratio $r \equiv \frac{\Delta_{\rm t}^2}{\Delta_{\rm s}^2} = 16\epsilon_{\rm v}$