Phenomenology of superconformal subcritical hybrid inflation

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1. Introduction

Standard Model (SM)

SM describes well the phenomena of elementary particles below 1TeV

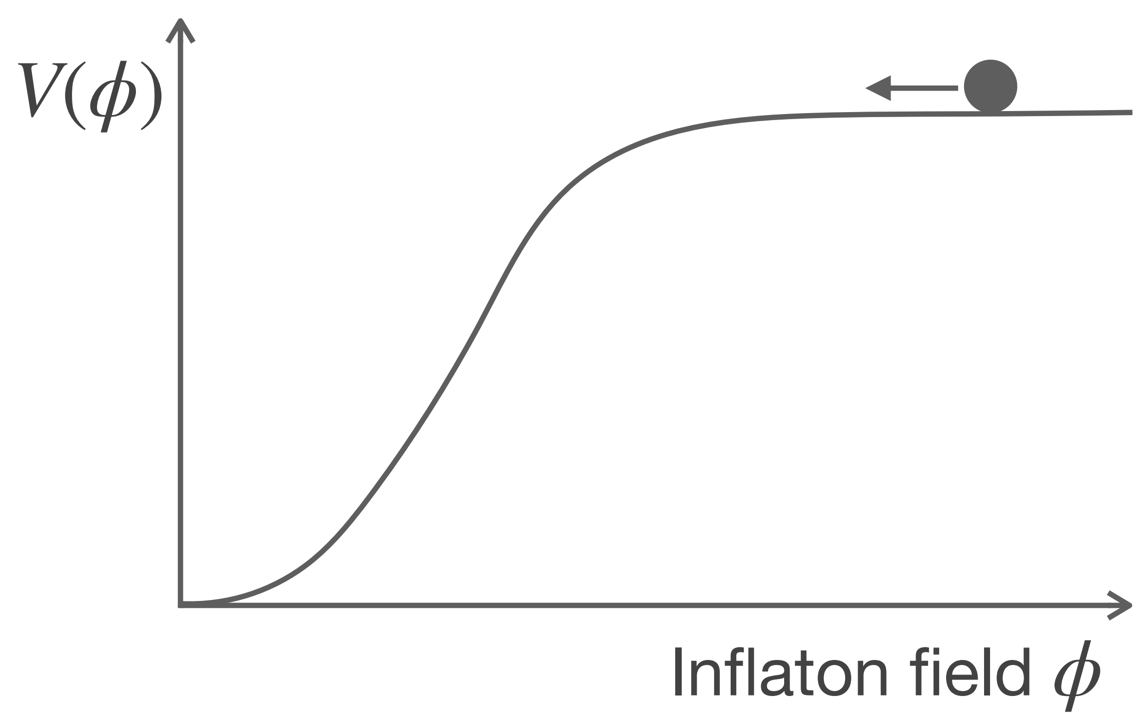
The phenomena unexplained in SM:

- Inflation
- Baryon asymmetry
- Light neutrino masses
- Dark matter

…

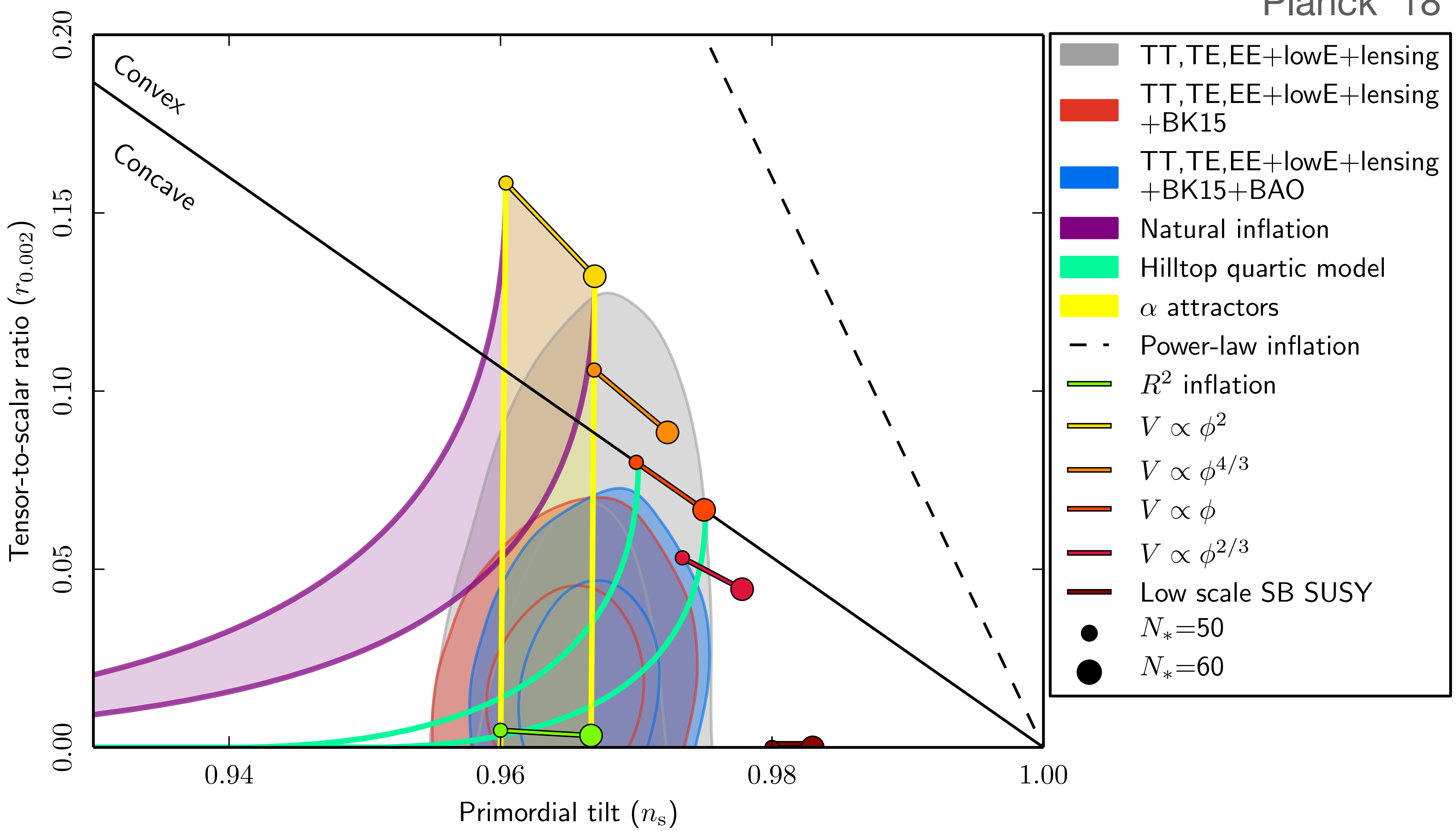
Inflation

- It is a paradigm of accelerated expansion of the early universe
- It is supported by cosmic microwave background (CMB) observations
- It is realized by the potential energy of a slow-rolling scalar field (inflaton)



Inflation

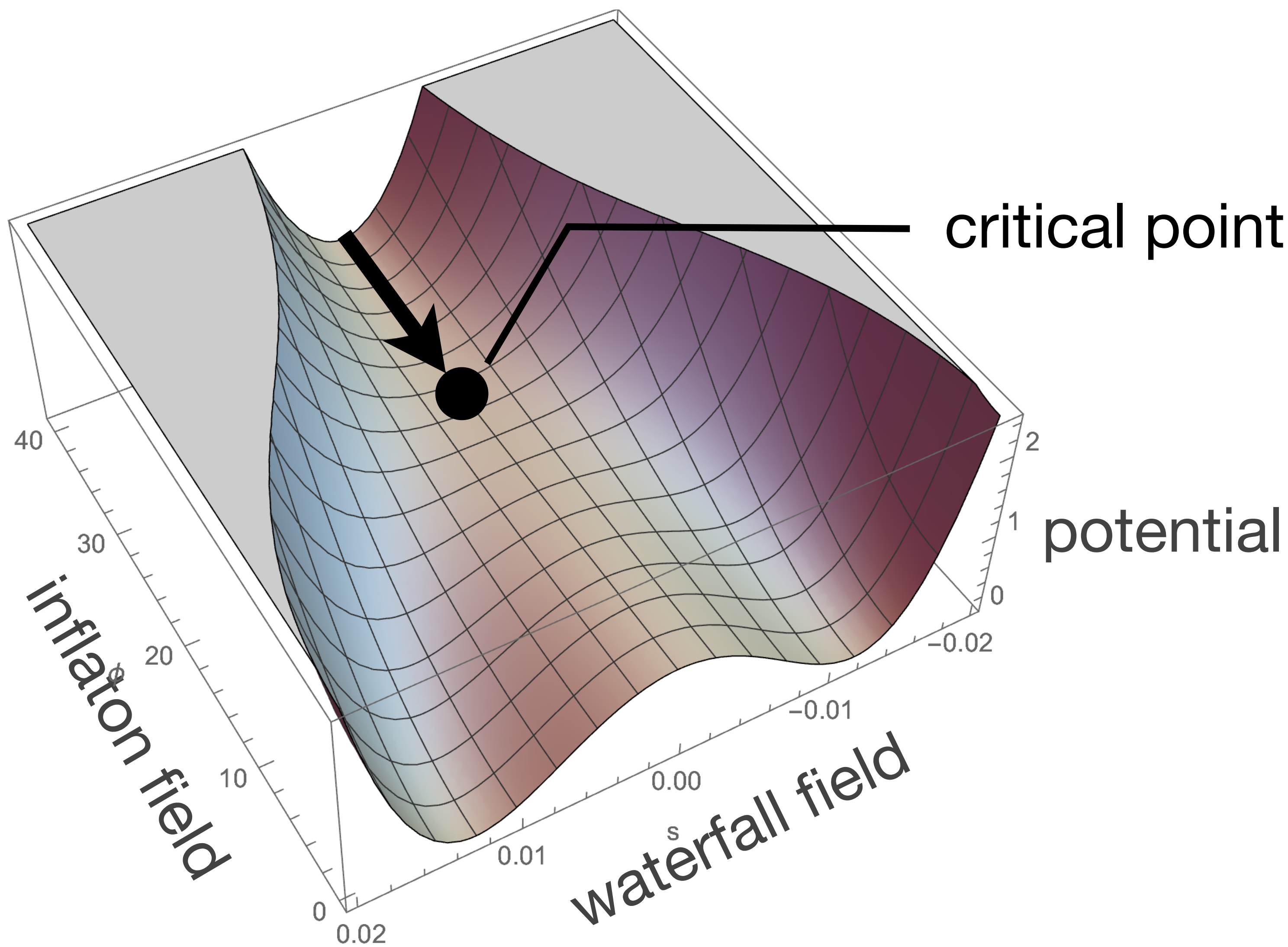
Planck '18



- Many inflation models have been proposed so far
- The CMB observations constrain the inflation models

Hybrid inflation Linde ’93

- Inflation occurs until slow-rolling inflaton reaches the critical point
- It is simple model but not consistent with current CMB observations



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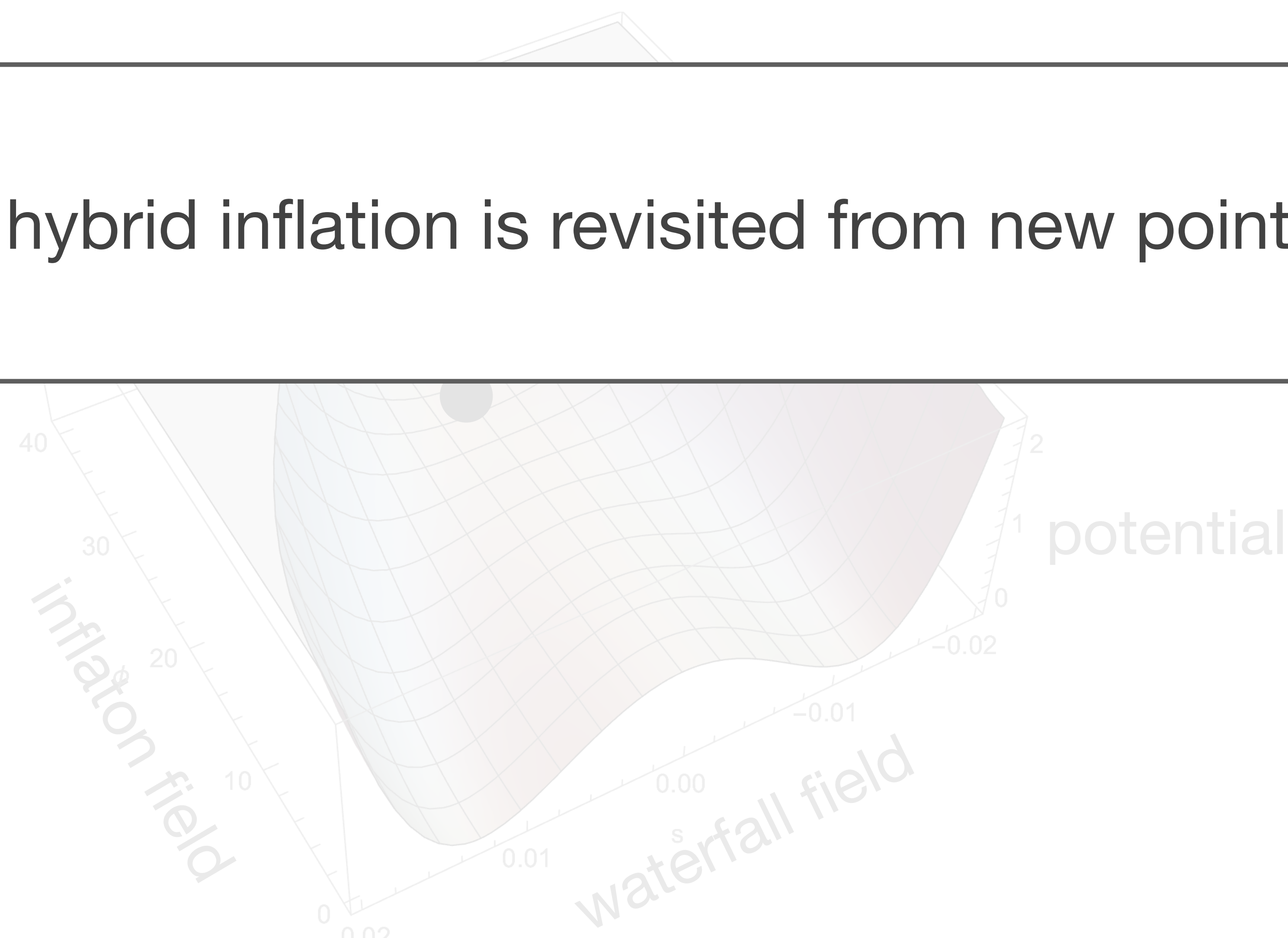
D-term hybrid inflation is revisited from new point of view



Various types of D-term hybrid inflation are realized depending on the symmetry of the Kähler potential

- Superconformal symmetry   Starobinsky type

Buchmuller, Domcke, Schmitz ’13
Buchmuller, Domcke, Kamada ’13

- Shift symmetry   Chaotic regime (below critical point)

Buchmuller, Domcke, Schmitz ’14
Buchmuller, Ishiwata ’13

- Superconformal
  + approx. shift symmetry α-attractor type (below critical point)

Ishiwata ’18

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Subcritical hybrid inflation

- Shift symmetry Chaotic regime (below critical point)

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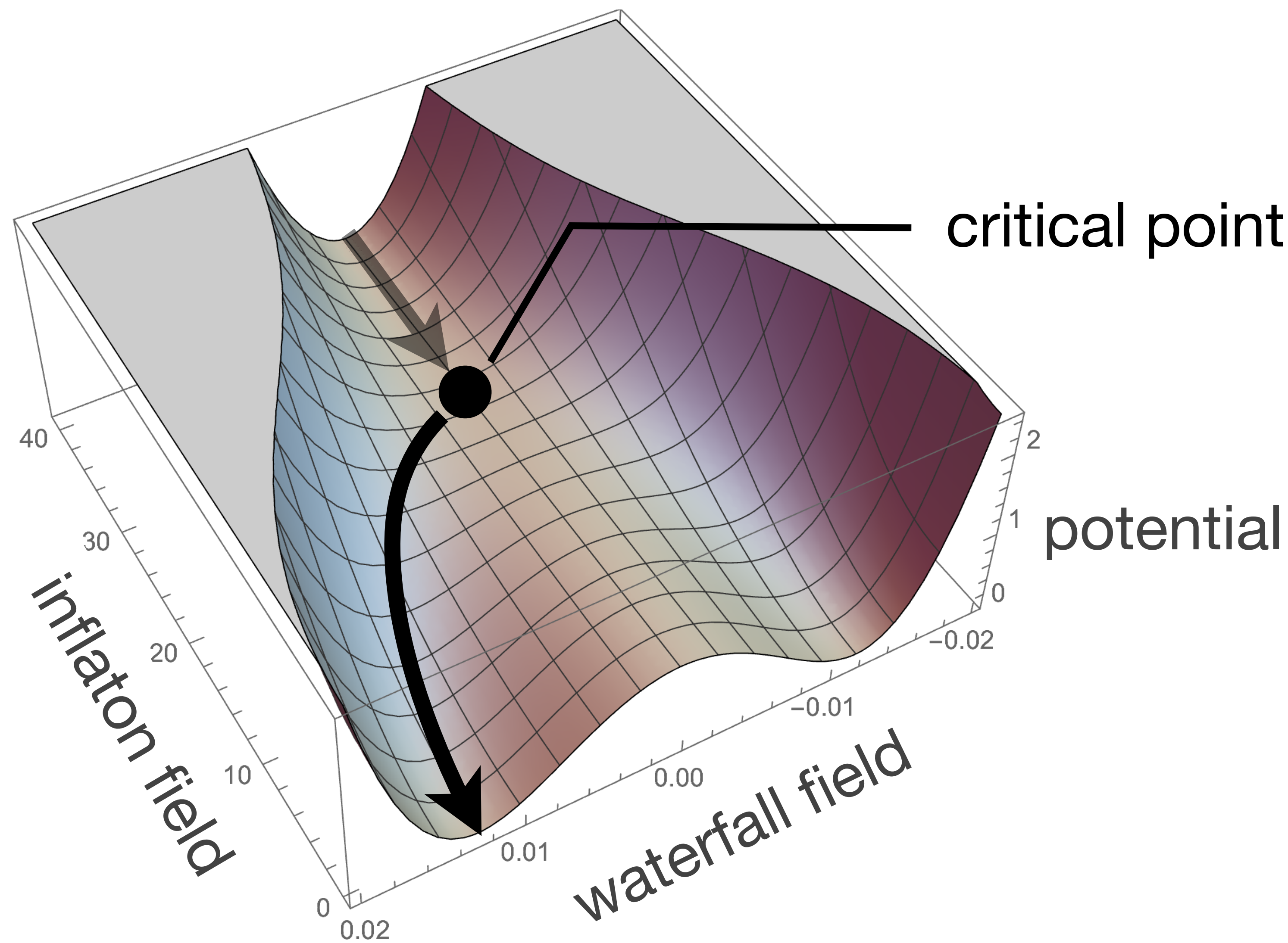
- Superconformal
  + approx. shift symmetry α-attractor type (below critical point)

Ishiwata ’18

Subcritical hybrid inflation

- Inflaton keeps slow-rolling after crossing the critical point
- Inflation continues in subcritical regime with growth of waterfall field



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Superconformal subcritical hybrid inflation

- Superconformal
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Ishiwata '18

Superconformal subcritical hybrid inflation

Ishiwata '18

- Superpotential

$$W = \lambda S_+ S_- N$$

	S_+	S_-	N
U(1)	q	$-q$	0

$q > 0$

- Kähler potential

$$K = -3\log\left(-\frac{\Phi}{3}\right)$$

with $\Phi = -3 + |S_+|^2 + |S_-|^2 + |N|^2 + \underline{\frac{\chi}{2}(N^2 + \bar{N}^2)}$

superconf. breaking term

$\lambda \ll 1 \;\&\; \chi \simeq -1$ ⋯ $\mathrm{Re}\,N$ has an approx. shift sym.

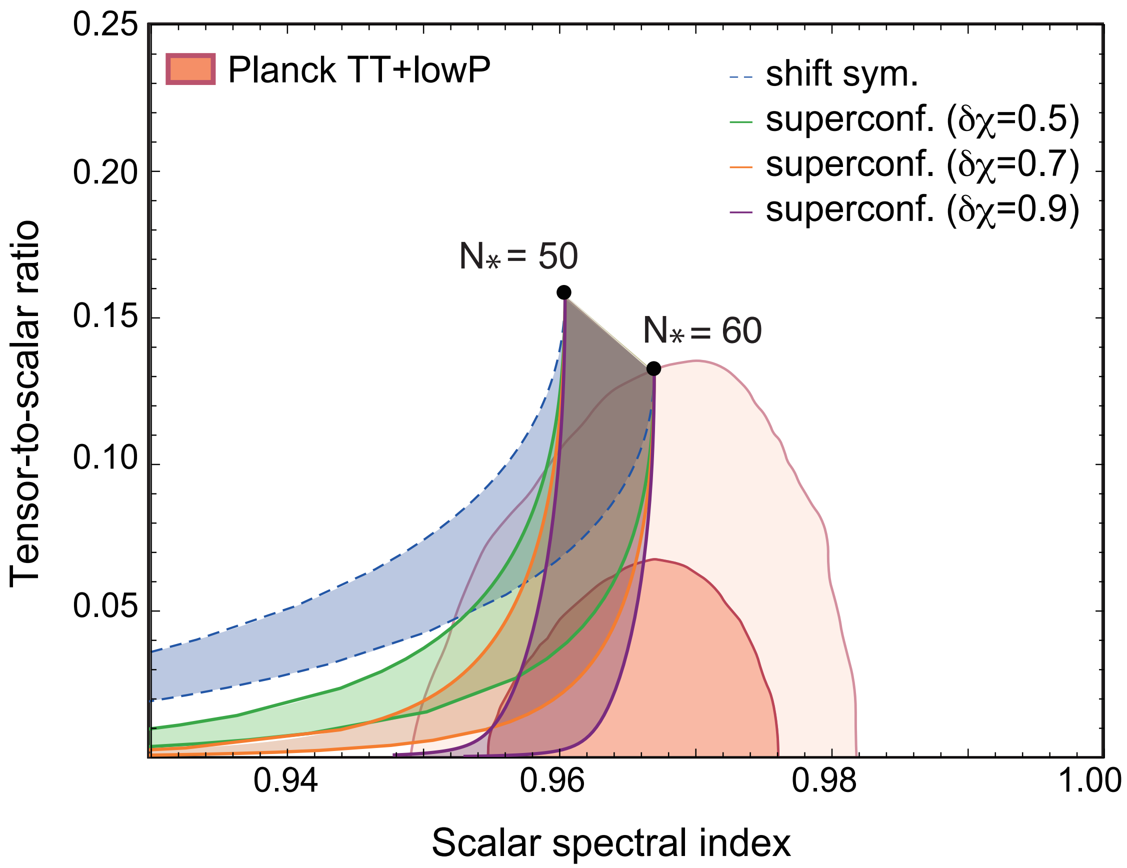
$\phi \equiv \sqrt{2}\,\mathrm{Re}\,N$: inflaton field

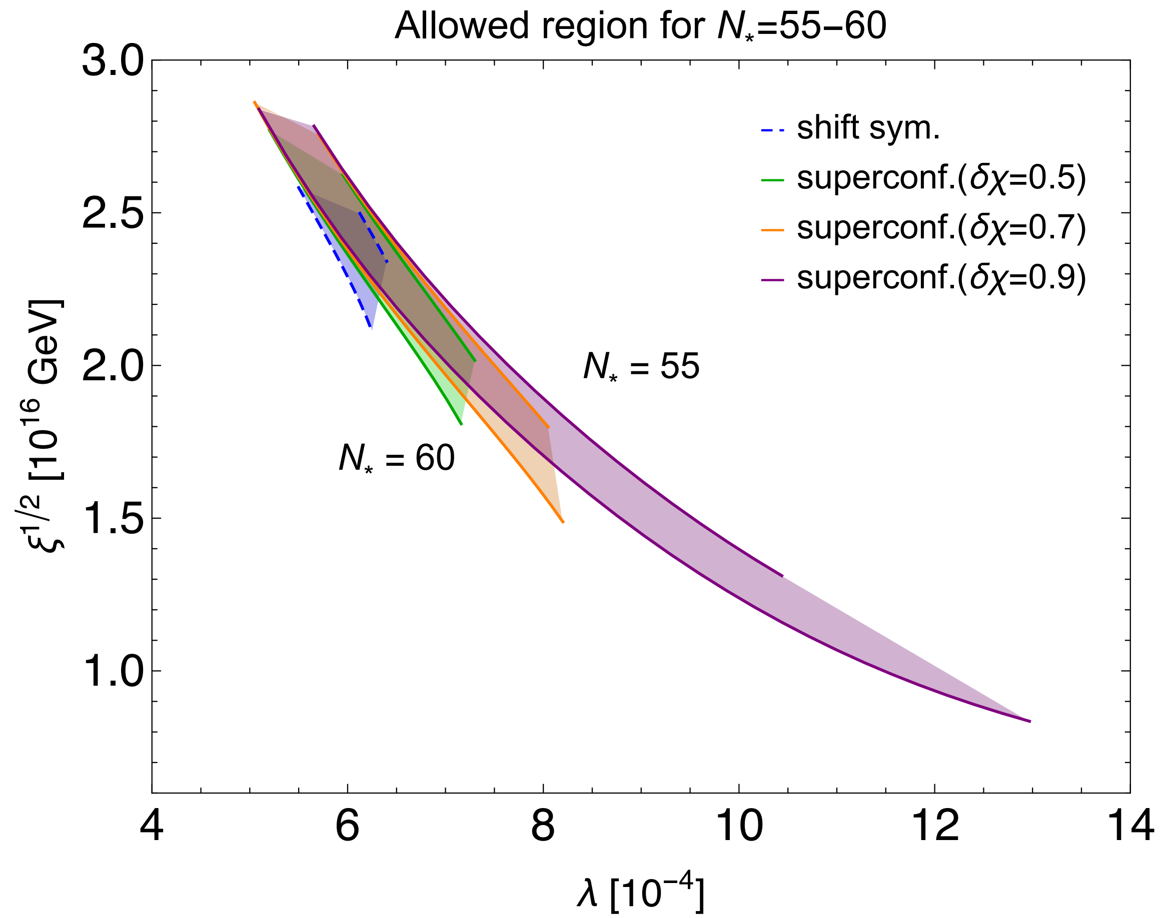
$s \equiv \sqrt{2}\,|S_+|$: waterfall field

$M_{\mathrm{pl}} = 1$

Superconformal subcritical hybrid inflation

Ishiwata '18





This model is consistent with the CMB observations:

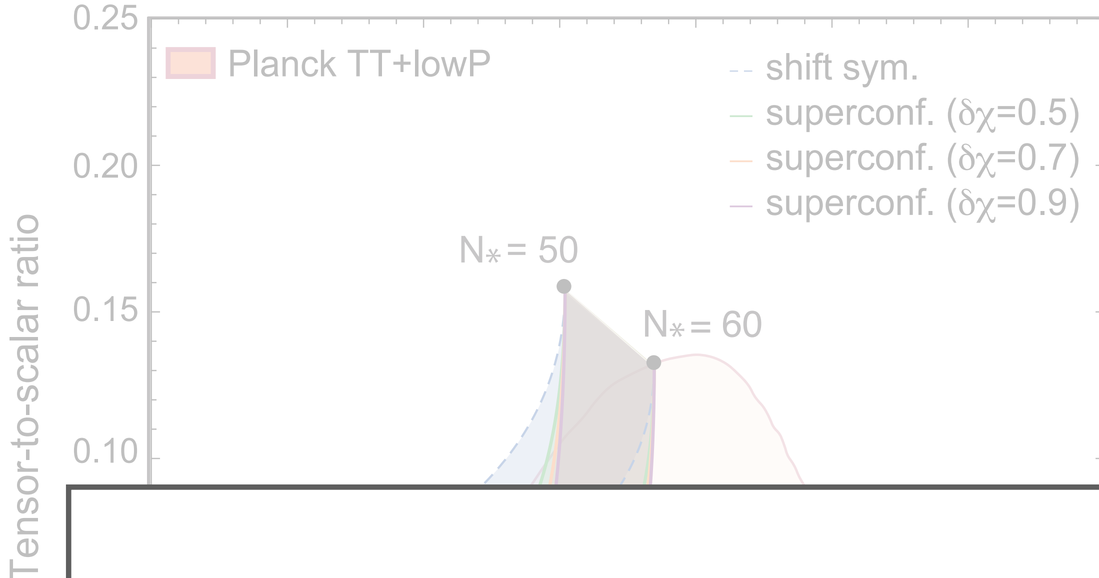
- Parameter values are $\lambda \simeq 10^{-3}, \sqrt{\xi} \simeq 10^{16}\,\mathrm{GeV}$
- Inflaton mass is $m_\phi \simeq \lambda\sqrt{\xi} \simeq 10^{13}\,\mathrm{GeV}$

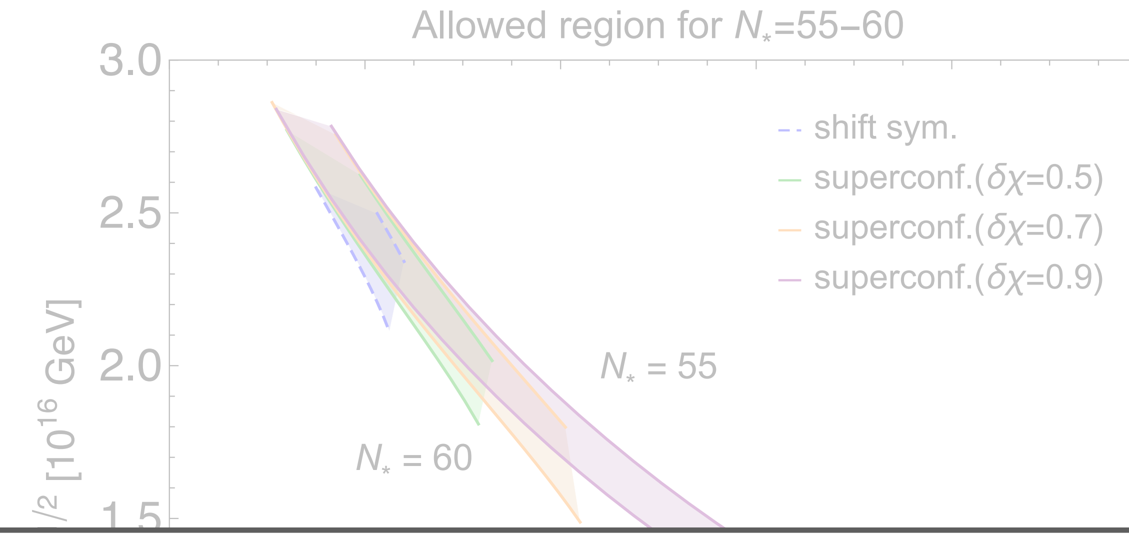
ξ: constant Fayet-Iliopoulos term

$(\xi > 0)$

Superconformal subcritical hybrid inflation

Ishiwata '18





We focus on this model & study about its phenomenology

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ξ: constant Fayet-Iliopoulos term
$(\xi > 0)$

Outline

1. Introduction

2. Leptogenesis after the inflation

3. Generalized superconformal subcritical hybrid inflation

4. Conclusions

2. Leptogenesis after the inflation

The extended model

YG & Ishiwata '19

Introduce three right-handed neutrinos N_i^c with the Majorana masses

- Superpotential

$$W_{\rm neu} = \lambda_i S_+ S_- N_i^c + \frac{1}{2} M_{ij} N_i^c N_j^c + y_{\nu ij} N_i^c L_j H_u$$

- Kähler potential

$$K = -3 \log\left(-\frac{\Phi}{3}\right)$$

$$\Phi = -3 + |S_+|^2 + |S_-|^2 + |N_i^c|^2 + \frac{\chi_i}{2}(N_i^{c2} + \bar{N}_i^{c2})$$

The extended model

YG & Ishiwata '19

Consider a minimal extension $\begin{cases} \lambda_3 \neq 0,\ \chi_3 \simeq -1,\ \text{The others} = 0 \\ M_{ij} = \mathrm{diag}(M_1, M_2, M_3) \end{cases}$

$$W_{\rm neu} = \lambda_3 S_+ S_- N_3^c + \frac{1}{2} M_i N_i^c N_i^c + y_{\nu ij} N_i^c L_j H_u$$

$$\Phi = -3 + |S_+|^2 + |S_-|^2 + |N_i^c|^2 + \frac{\chi_3}{2}(N_3^{c2} + \bar{N}_3^{c2})$$

$\phi \equiv \sqrt{2}\,\mathrm{Re}\,\tilde{N}_3^c$: inflaton field

$s \equiv \sqrt{2}\,|S_+|$: waterfall field

We study the thermal history after the inflation in this setup

The effect of M_3 on inflation

An additional term appears in the inflaton potential by the extension

$$V_{\rm inf} = V + \Delta V(M_3) \qquad W_{\rm inf} = \lambda_3 N_3^c S_+ S_- + \frac{1}{2} M_3 N_3^c N_3^c + \cdots$$

The condition to avoid the effect of ΔV on the inflationary trajectory

$$\Delta V(M_3)/V \ll 1$$

The upper bound on M_3

$$M_3 \lesssim 2 \times 10^{11}\ \text{GeV} \ll m_\phi \simeq 10^{13}\,\text{GeV}$$

m_ϕ : inflaton mass

The effect of $M_{1,2}$ on inflation

On the other hand, there are no restrictions on $M_{1,2}$

$\cdots$ $M_{1,2}$ are free parameters

We consider the thermal history in two cases:

$(\mathrm{I})\,.\quad M_1, M_2 < m_\phi$

$(\mathrm{II})\,.\ M_1, M_2 > m_\phi$

$m_\phi \simeq 10^{13}\,\mathrm{GeV}$: Inflaton mass

Light neutrino masses

Seesaw mechanism: $M_\nu = -\tilde{m}_\nu^T \tilde{M}^{-1} \tilde{m}_\nu$

$$\tilde{m}_\nu = \begin{pmatrix} & m_\nu & \\ 0 & 0 & 0 \end{pmatrix}$$

$$m_{\nu ij} = y_{\nu ij} \langle H_u^0 \rangle$$

4×3 matrix

$$\tilde{M} = \left(\begin{array}{ccc|c} M_1 & & & \\ & M_2 & & \\ & & M_3 & m_\phi \\ \hline & & m_\phi & 0 \end{array}\right)$$

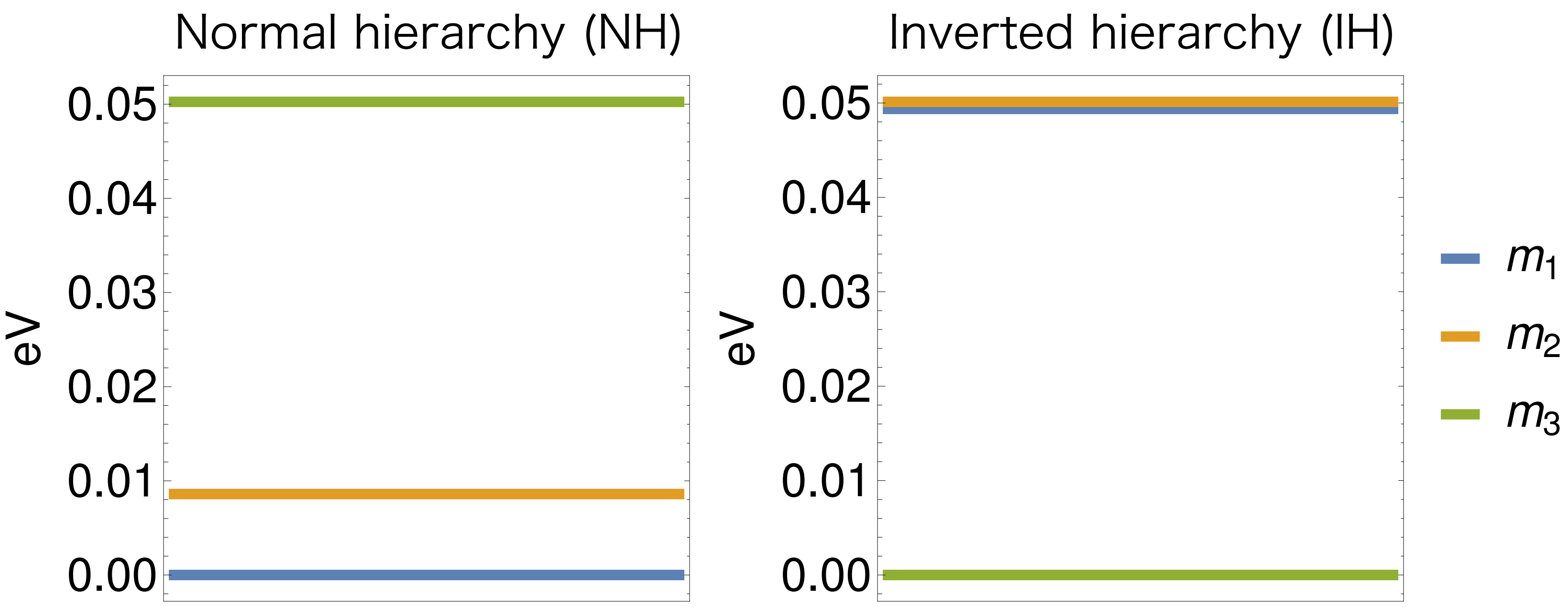
4×4 matrix

The mass matrix is different from a conventional one

Light neutrino masses

$$M_{\nu ij} \simeq \langle H_u^0 \rangle^2 \sum_{k=1}^{2} \frac{y_{\nu ki} y_{\nu kj}}{M_k}$$

- The lightest neutrino mass is zero ($\because \mathrm{rank}\, M_\nu = 2$)

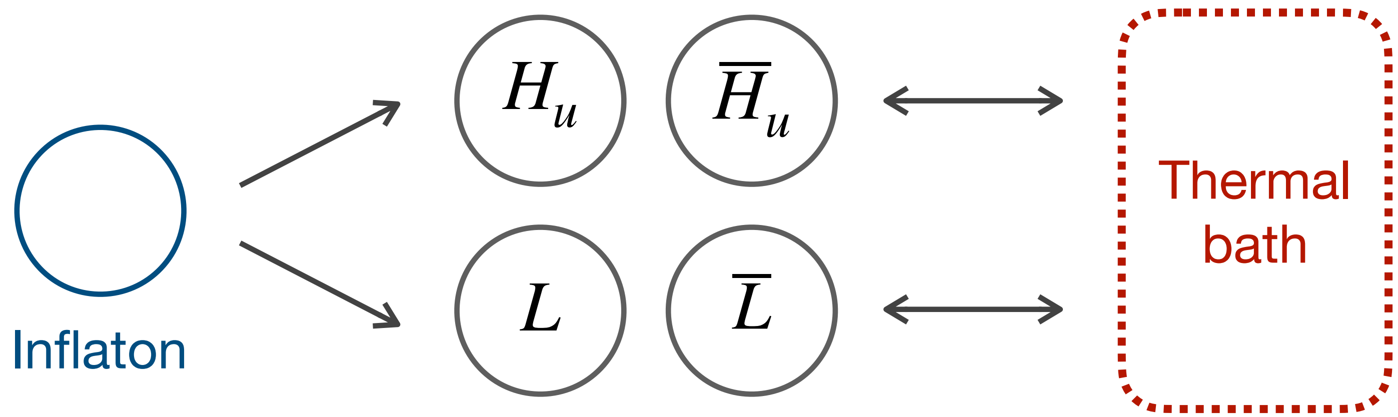


- m_ϕ, M_3, and $y_{\nu 3i}$ are not restricted from neutrino experiments

It determines the reheating temperature

Reheating

The universe becomes radiation dominated by the inflaton decay



Reheating temperature

$$T_R \simeq 1.4 \times 10^{10}\ \text{GeV} \left(\frac{(y_\nu y_\nu^\dagger)_{33}}{10^{-9}} \right)^{1/2} \propto |y_{\nu 3i}|$$

$\cdots T_R$ is a free parameter

For simplicity, we focus on a simple situation, $T_R < m_\phi$

Leptogenesis

Lepton asymmetry is produced, which is then converted to baryon asymmetry

Fukugita, Yanagida '86

We have considered two representative cases:

$(\mathrm{I})\,.\ M_1, M_2 < m_\phi$ $\cdots$ Thermal leptogenesis

$(\mathrm{II})\,.\ M_1, M_2 > m_\phi$ $\cdots$ Non-thermal leptogenesis $\qquad m_\phi \simeq 10^{13}\ \mathrm{GeV}$

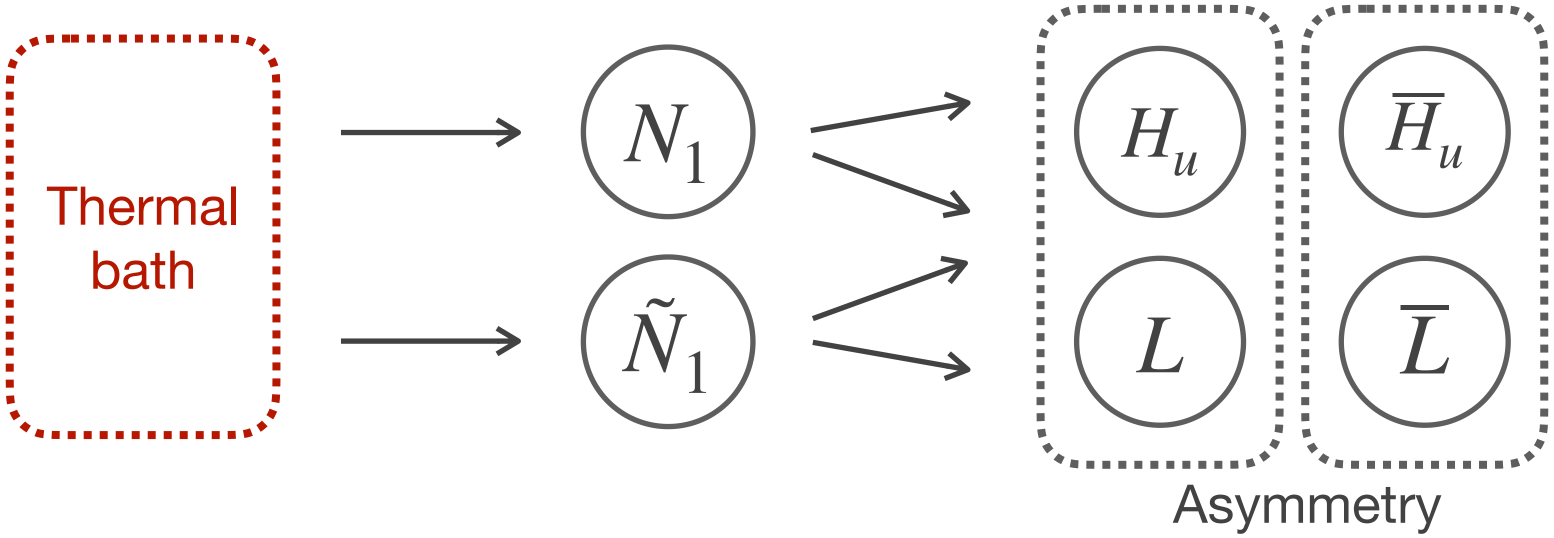
Current baryon asymmetry

$$\eta_B^{\mathrm{obs}} \equiv \frac{n_{B0}}{n_{\gamma 0}} = (6.12 \pm 0.03) \times 10^{-10}$$

Planck '18

Case (I) . $M_1, M_2 < m_\phi$

Leptogenesis by decay of thermally produced right-handed (s)neutrinos



Simple situation $M_1 \ll M_2$ & $M_1 \lesssim T_R$

Produced baryon asymmetry

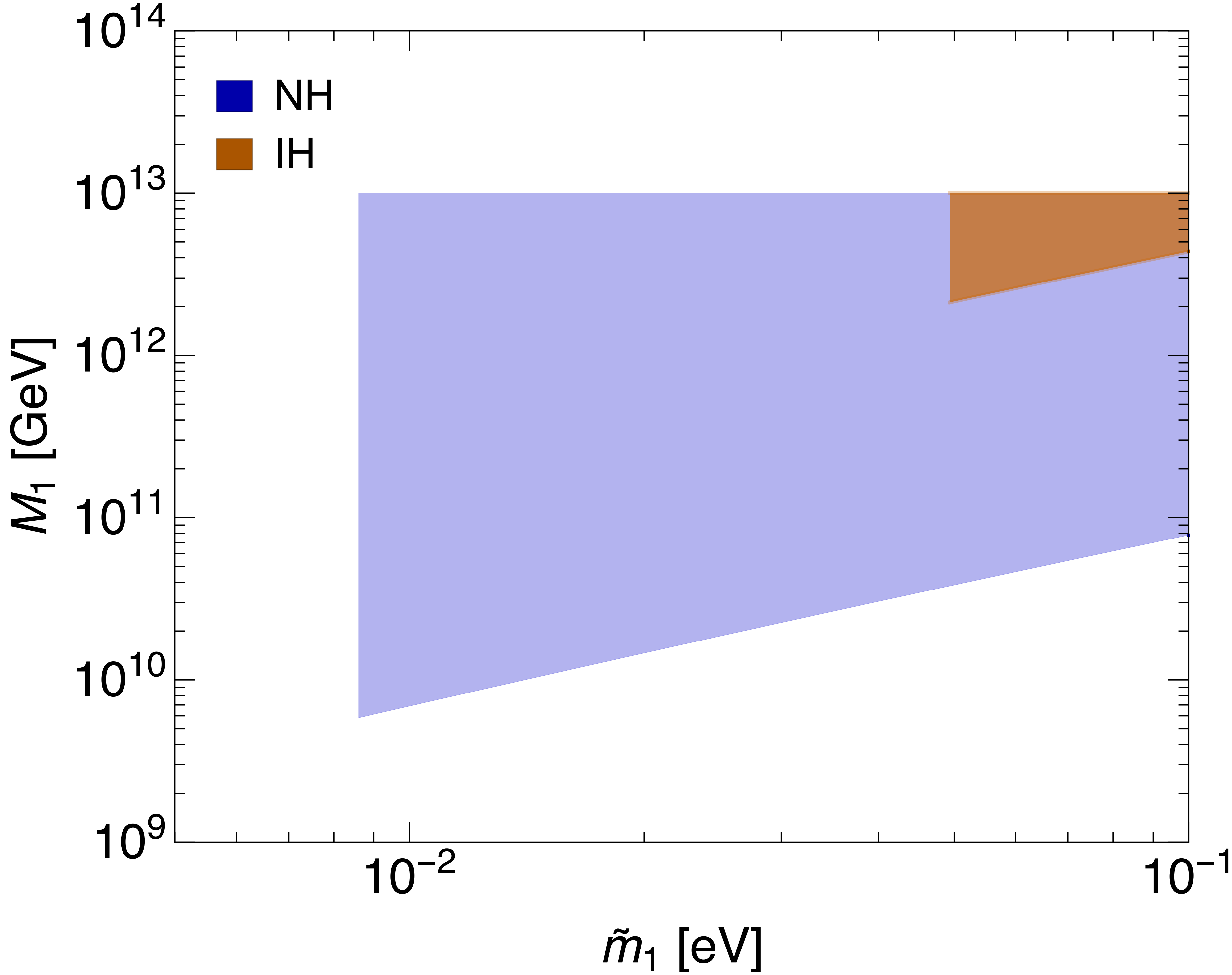
$$\eta_B \equiv \frac{n_B}{n_\gamma} \simeq 2.7 \times 10^{-10} \left(\frac{\epsilon_1}{10^{-6}}\right)\left(\frac{\kappa_f}{2 \times 10^{-2}}\right)$$

Buchmüller, Di Bari, Plümacher '05

Asymmetric parameter

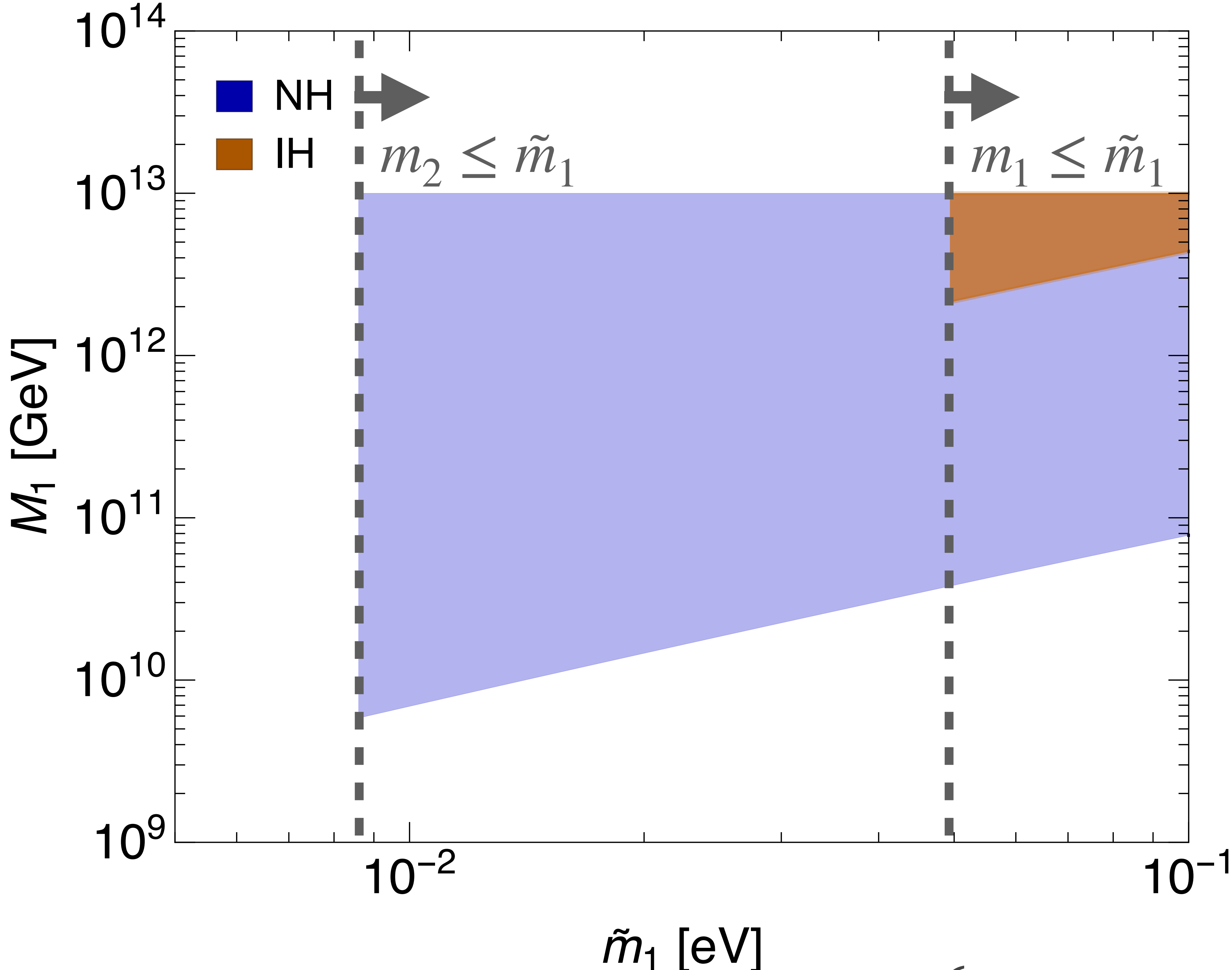
$$\epsilon_1 = \begin{Bmatrix} 8.2 \times 10^{-7} \ (\mathrm{NH}) \\ 1.5 \times 10^{-8} \ (\mathrm{IH}) \end{Bmatrix} \times \left(\frac{M_1}{10^{10}\ \mathrm{GeV}}\right)\left(\frac{\sin\delta}{0.5}\right)$$

Case (I) . $M_1, M_2 < m_\phi$



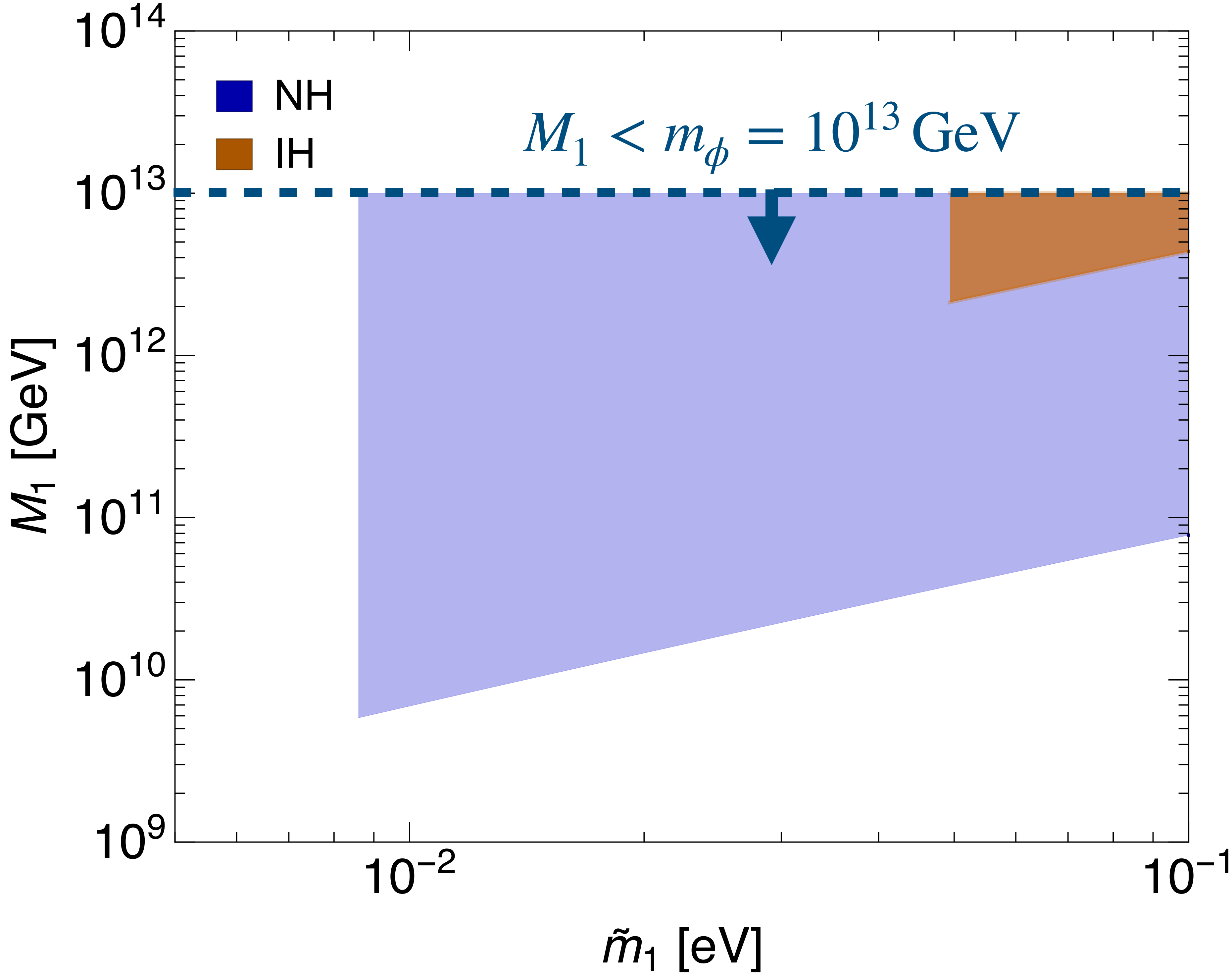
$$\tilde{m}_1 \equiv \frac{(m_\nu m_\nu^\dagger)_{11}}{M_1}$$

Case (I) . $M_1, M_2 < m_\phi$



$$\tilde{m}_1 \geq \begin{cases} m_2 \simeq 8.6 \times 10^{-3}\text{eV (NH)} \\ m_1 \simeq 4.9 \times 10^{-2}\text{eV (IH)} \end{cases}$$

Case (I) . $M_1, M_2 < m_\phi$



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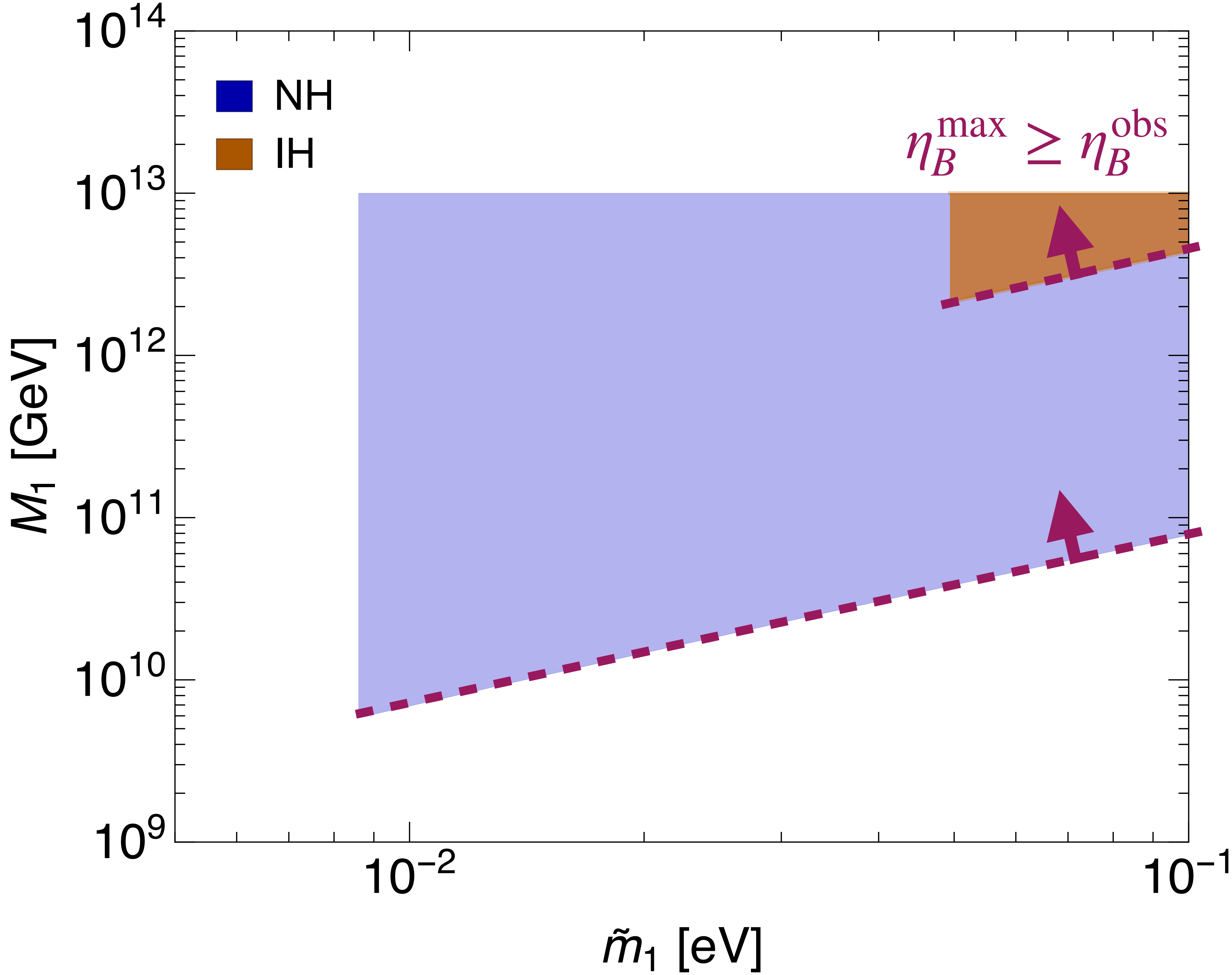
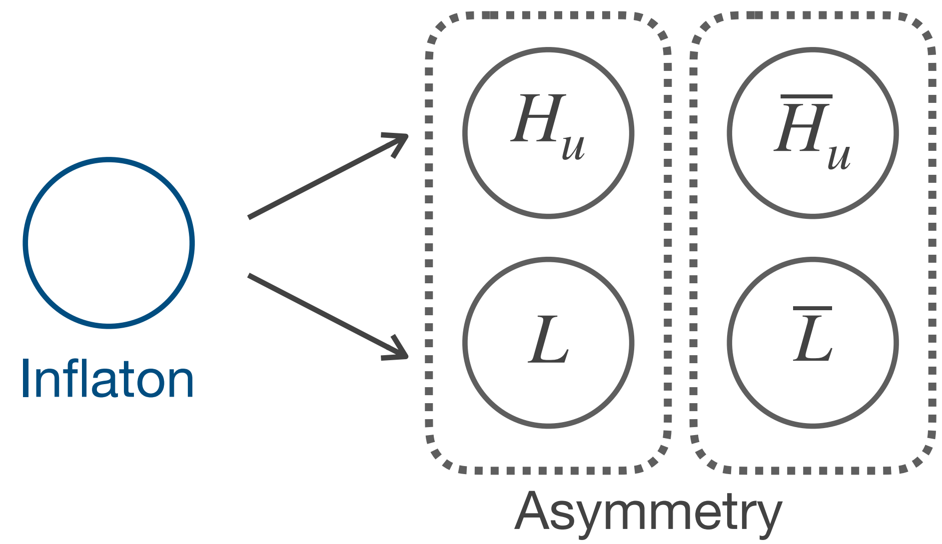


Successful leptogenesis is realized in wide range of parameter space

Case (II) . $M_1, M_2 > m_\phi$

Leptogenesis by the inflaton decay

Murayama, Suzuki, Yanagida, Yokoyama '93
Hamaguchi, Murayama, Yanagida '02
Ellis, Raidal, Yanagida '04
Nakayama, Takahashi, Yanagida '16



Simple situation $T_R/m_\phi \ll 1$

Produced baryon asymmetry

$$\eta_B = \frac{3}{4}\frac{T_R}{m_\phi} a_{\rm sph}\, d\, \epsilon_\phi$$

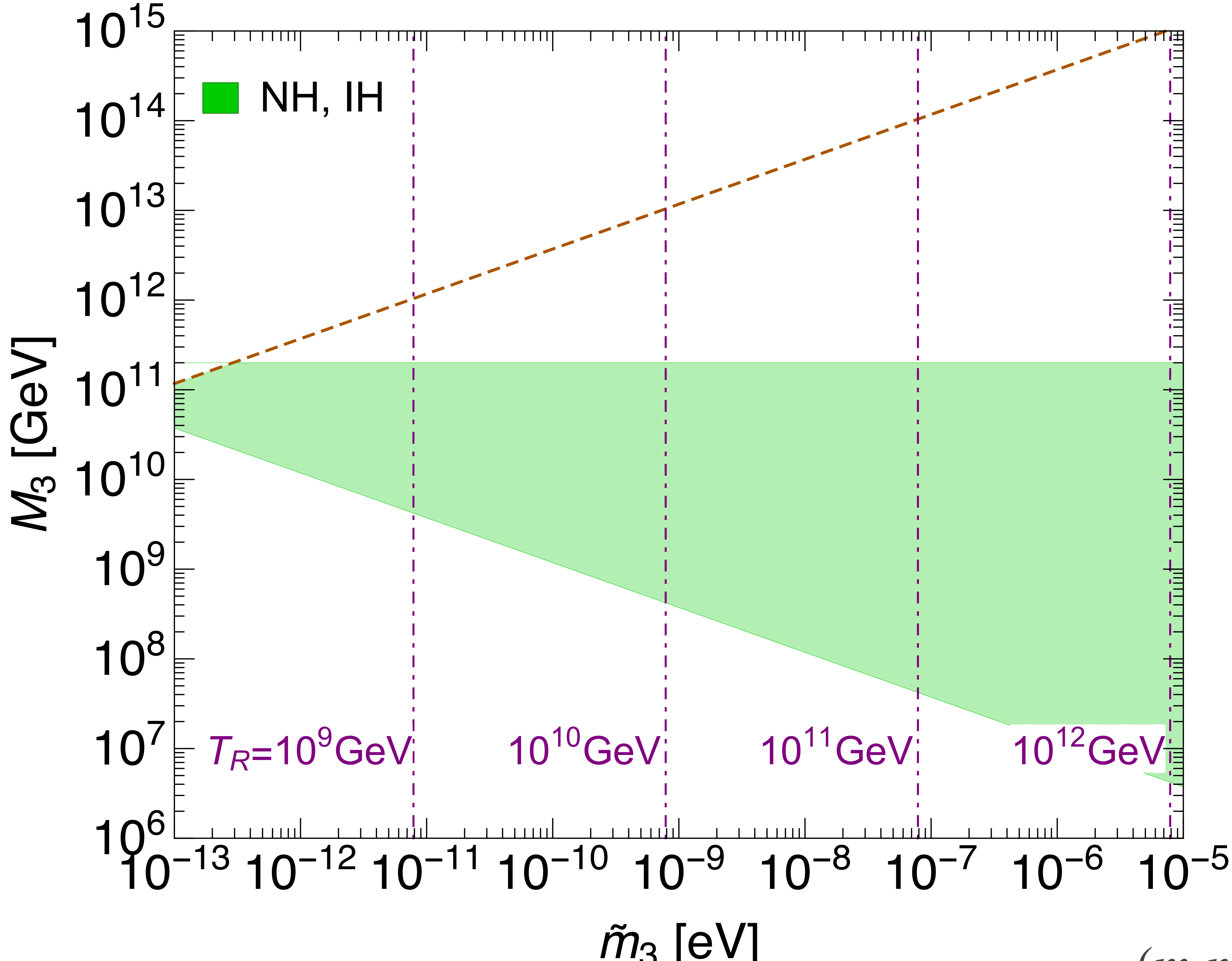
$a_{\rm sph} = 28/79$

$d = s_0 / n_{\gamma 0}$

Asymmetric parameter

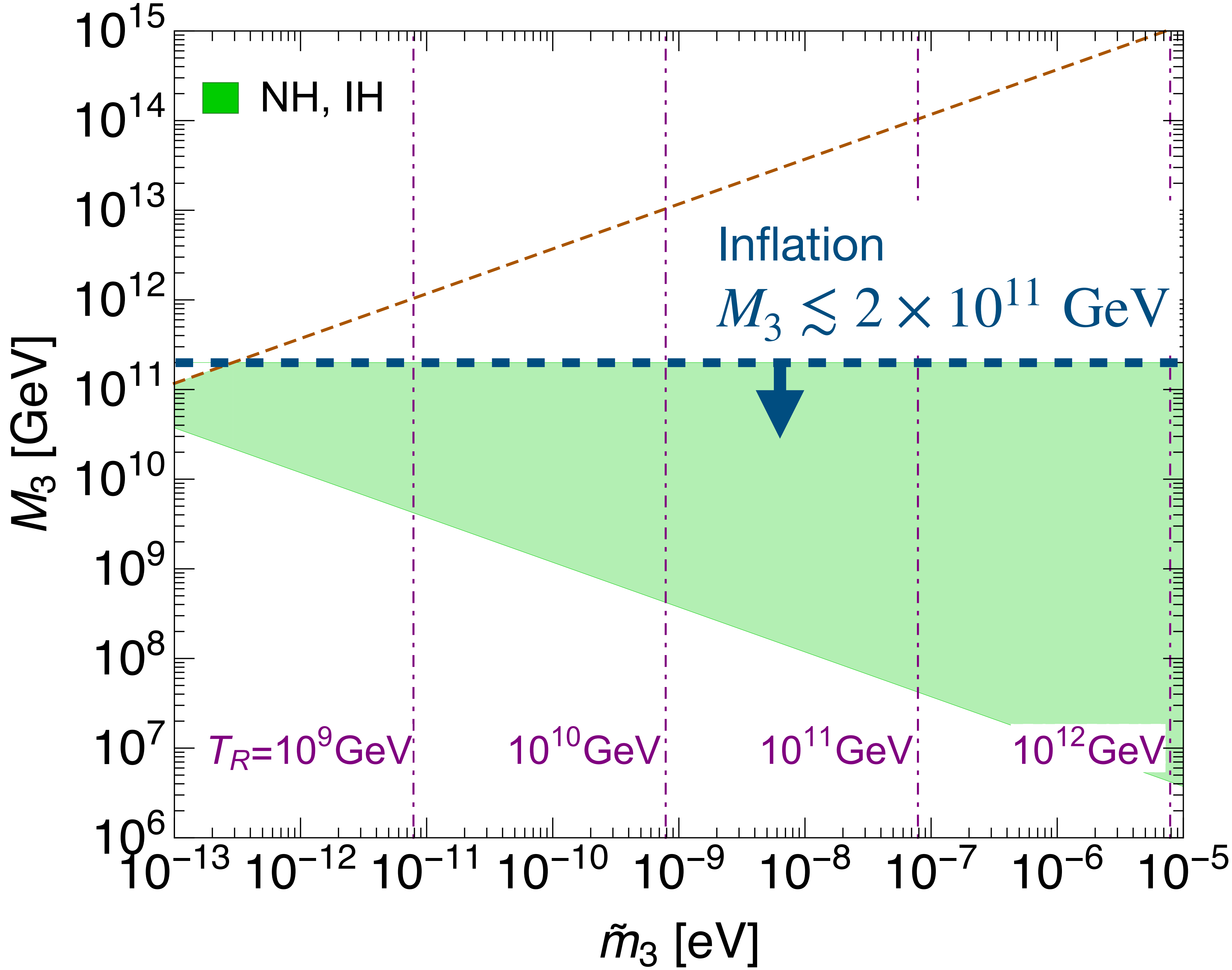
$$\epsilon_\phi \simeq 3.9 \times 10^{-9} \left(\frac{M_3}{10^7\ \mathrm{GeV}}\right)\left(\frac{\sin\delta'}{0.5}\right)$$

Case (II) . $M_1, M_2 > m_\phi$



$$\tilde{m}_3 \equiv \frac{(m_\nu m_\nu^\dagger)_{33}}{m_\phi} \propto |y_{\nu 3i}|^2$$

Case (II) . $M_1, M_2 > m_\phi$



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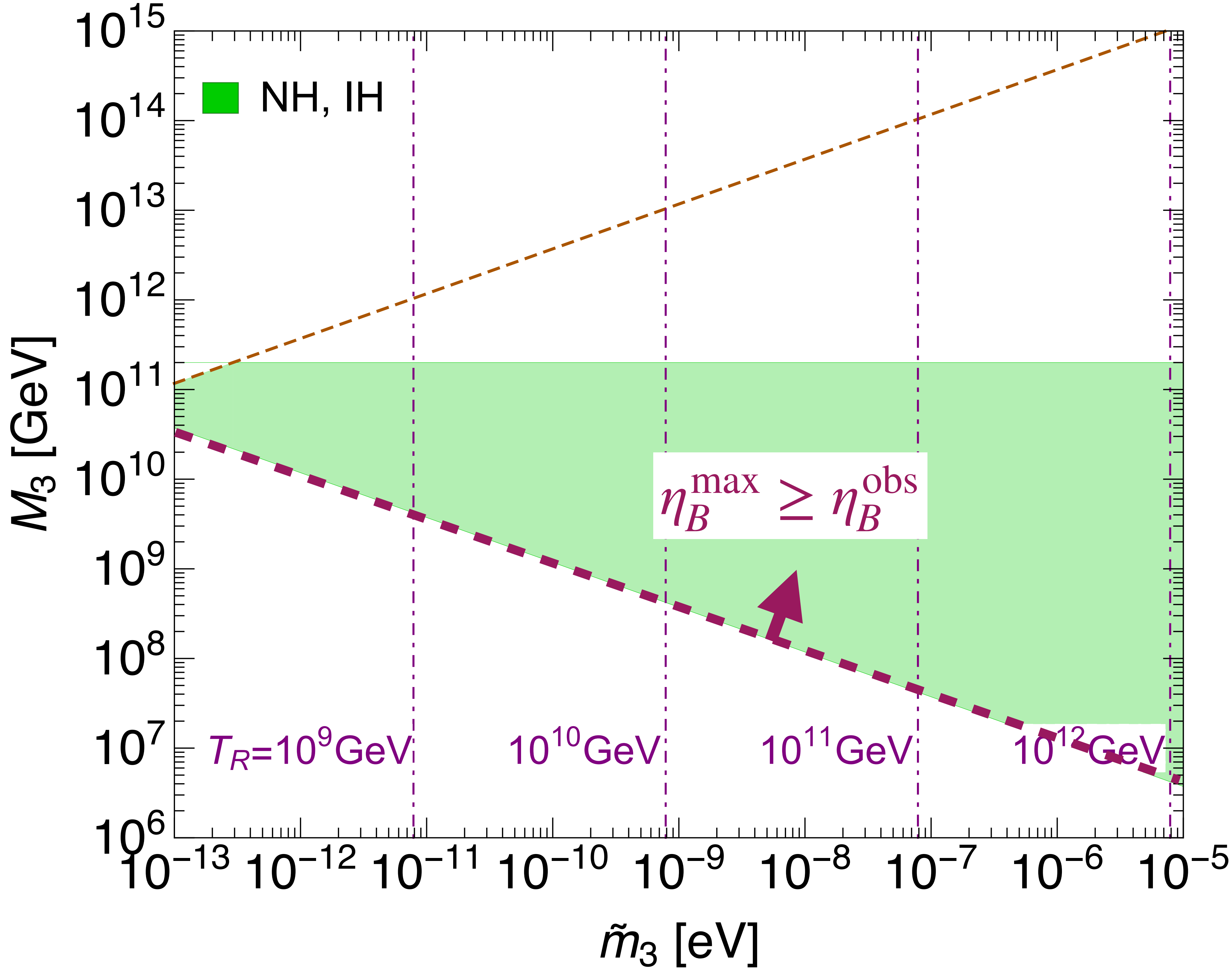


Successful leptogenesis is realized in wide range of parameter space

Summary

We have studied the leptogenesis after superconformal subcritical hybrid inflation in an extended model by introducing three right-handed neutrinos

- One of the right-handed sneutrinos plays a roll of inflaton
- Light neutrino mass matrix given by seesaw mechanism has an unconventional structure
- Inflaton decay reheat the universe and the temperature is a free parameter
- Thermal or Non-thermal leptogenesis can be realized

3. Generalized superconformal subcritical hybrid inflation

The generalized model

YG & Ishiwata '21

- Superpotential

$$W = \lambda S_+ S_- N$$

	S_+	S_-	N
U(1)	q	$-q$	0

$q > 0$

- Kähler potential

$$K = -3\alpha \log\left(-\frac{\Phi}{3}\right)$$

$\alpha = 1$ in typical model

$\alpha > 0$ in this model

with $\Phi = -3 + |S_+|^2 + |S_-|^2 + |N|^2 + \frac{\chi}{2}(N^2 + \bar{N}^2)$

superconf. breaking term

$\phi \equiv \sqrt{2}\,\mathrm{Re}\,N$: inflaton field

$s \equiv \sqrt{2}\,|S_+|$: waterfall field

$M_{\rm pl} = 1$

The generalized model

YG & Ishiwata '21

- *F*-term potential

$$V_F = \left(-\frac{\Phi(\phi, s)}{3}\right)^{1-3\alpha} \frac{\lambda^2}{4\alpha}\phi^2 s^2$$

- *D*-term potential

$$V_D = \frac{g^2}{8}\left[\left(-\frac{\Phi(\phi, s)}{3}\right)^{-1} \alpha q s^2 - 2\xi\right]^2$$

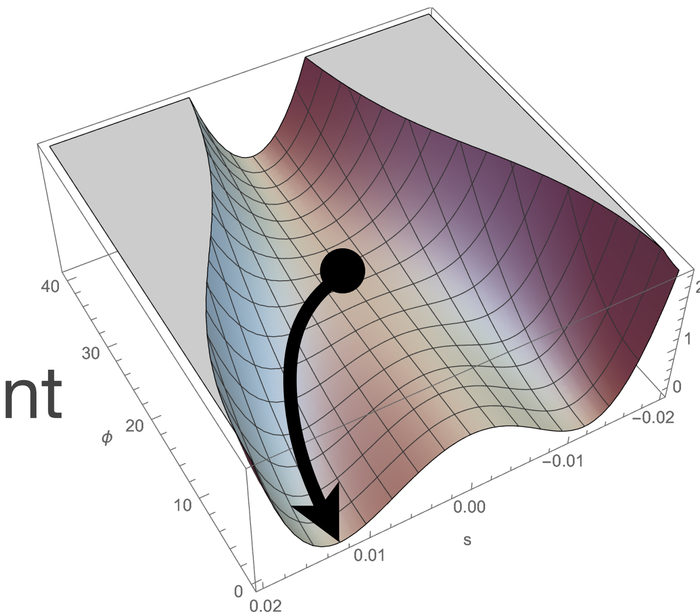
$$\Phi(\phi, s) = -3 + \frac{1}{2}\left(s^2 + (1+\chi)\phi^2\right)$$

g : gauge coupling constant

ξ : constant Fayet-Iliopoulos term ($\xi > 0$)

Inflaton potential

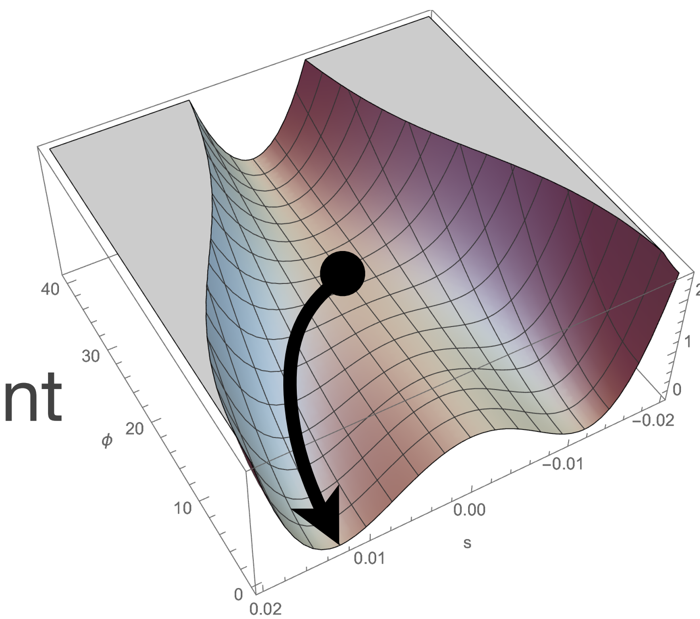
$s = s_{\rm min}(\phi)$ after critical point



Inflaton potential

$$V_{\rm tot}(\phi, s) = V_F + V_D$$

$s = s_{\rm min}(\phi)$ after critical point



Potential in subcritical regime

$$V(\phi) = g^2 \xi^2 \, \Psi(\phi)\left(1 - \frac{1}{2}\Psi(\phi)\right)$$

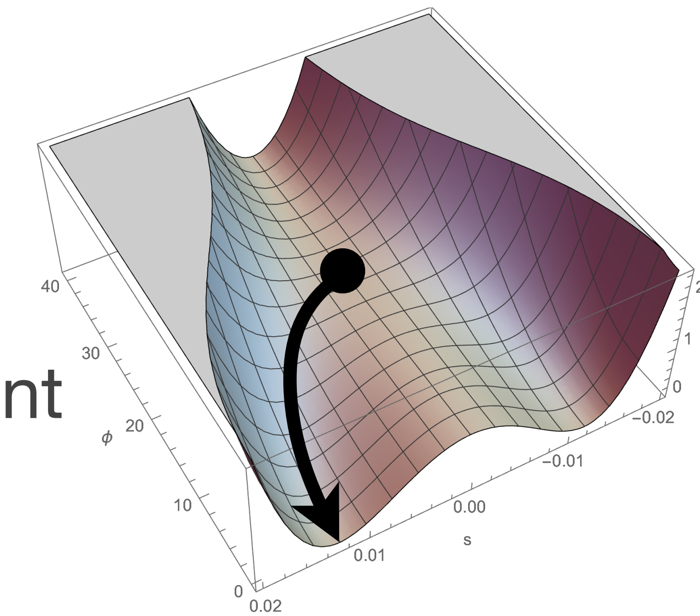
$$\Psi(\phi) = \frac{k}{2\alpha^2}\left(\frac{\Phi(\phi,0)}{3}\right)^{2-3\alpha}\phi^2$$

$$k \equiv \lambda^2 / q g^2 \xi$$

Inflaton potential

$$V_{\rm tot}(\phi, s) = V_F + V_D$$

$s = s_{\rm min}(\phi)$ after critical point



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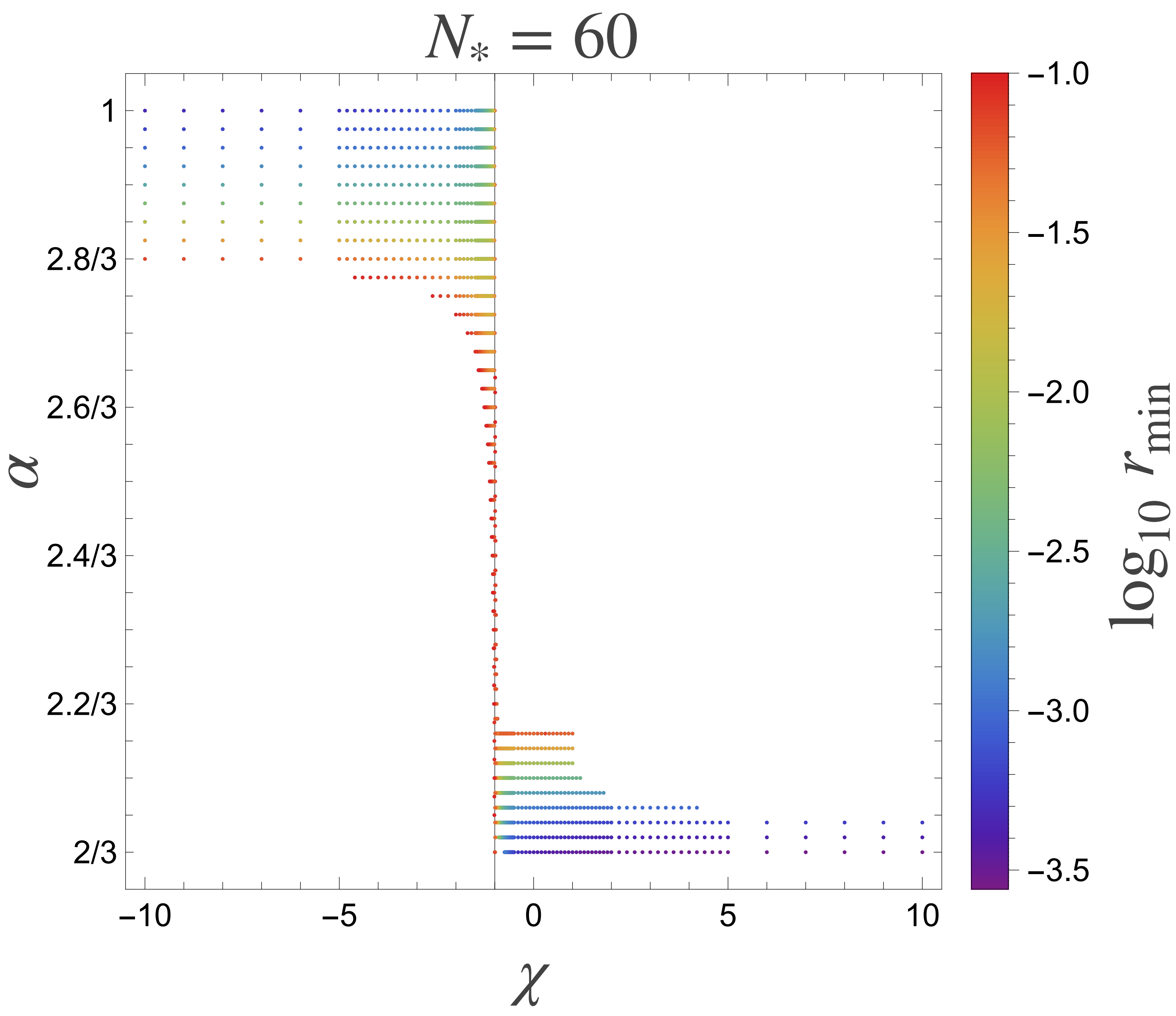
$$\Psi(\phi) = \frac{k}{2\alpha^2}\left(\frac{\Phi(\phi,0)}{3}\right)^{2-3\alpha}\phi^2$$

$$k \equiv \lambda^2/qg^2\xi$$

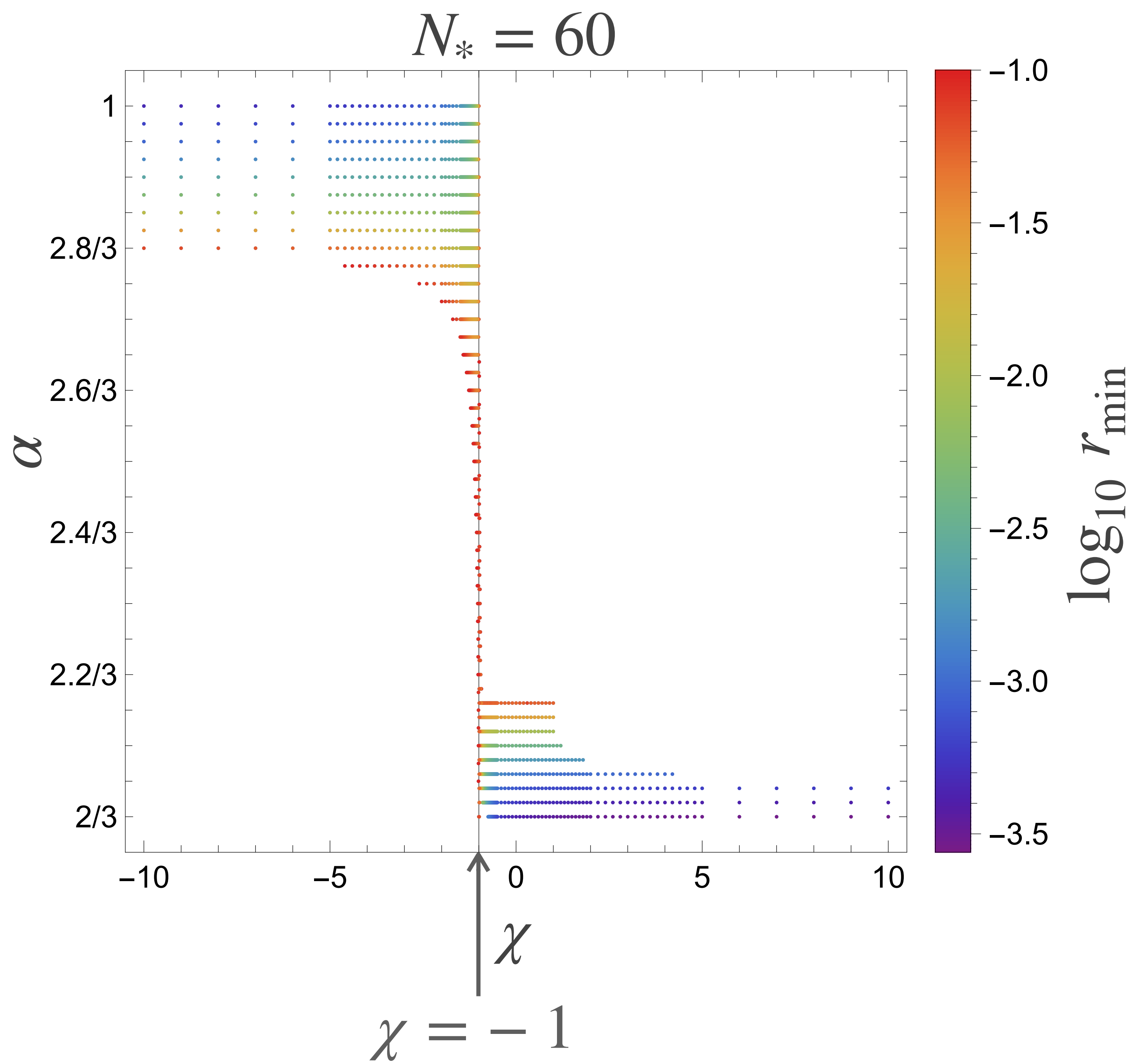
Use $V(\phi)$ to identify params. consistent with CMB

& to clarify prediction of tensor-to-scalar ratio r

Allowed region for α & χ



Allowed region for α & χ



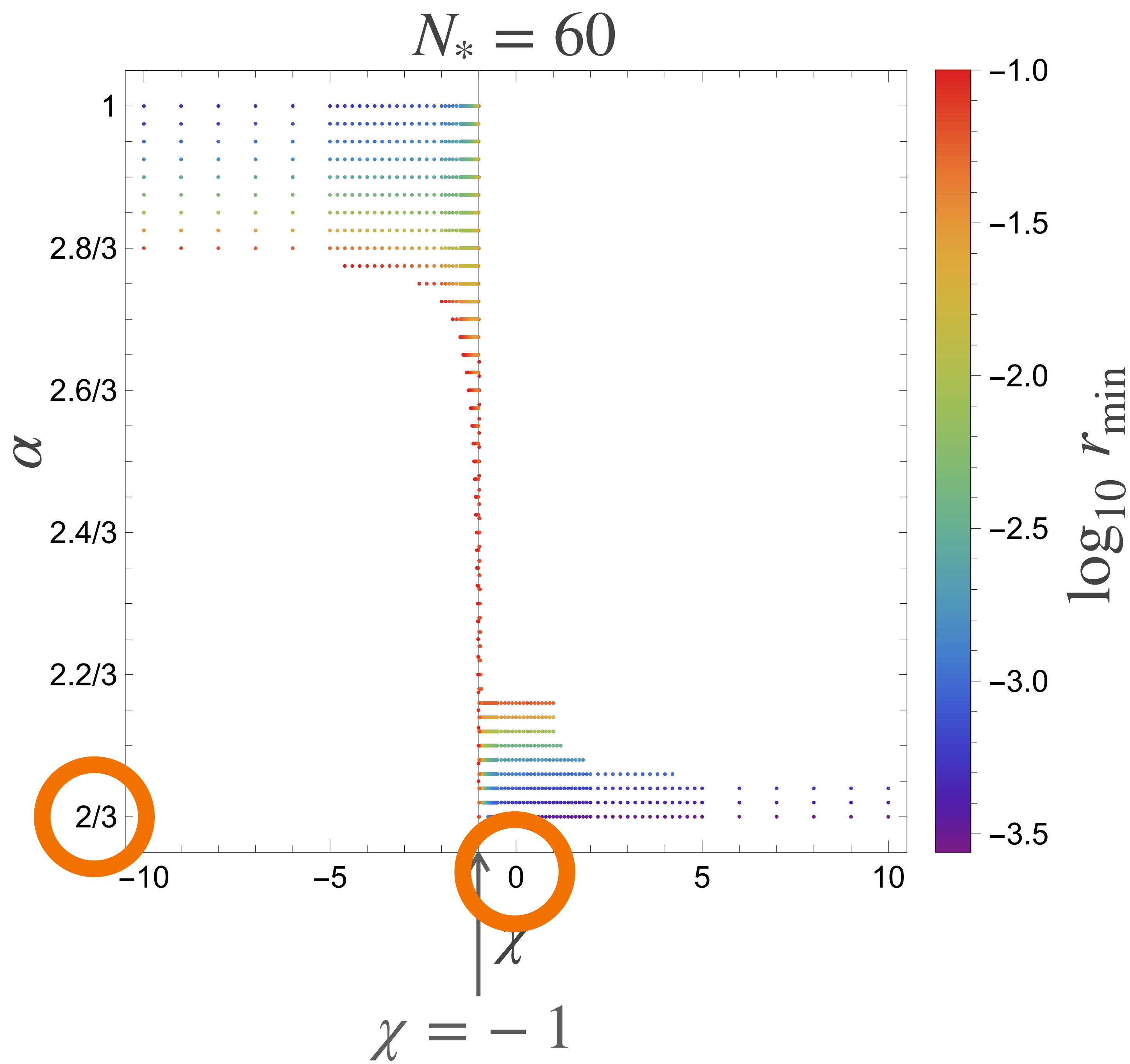
- Behavior of allowed region changes around $\chi = -1$

$$\begin{cases} \alpha \simeq 1 & (\chi \lesssim -5) \\ 2/3 \lesssim \alpha \lesssim 1 & (\chi \simeq -1) \\ \alpha \simeq 2/3 & (\chi \gtrsim 5) \end{cases}$$

- Predicted r changes depending on α & χ

$$10^{-4} \lesssim r \lesssim 10^{-1}$$

Allowed region for α & χ



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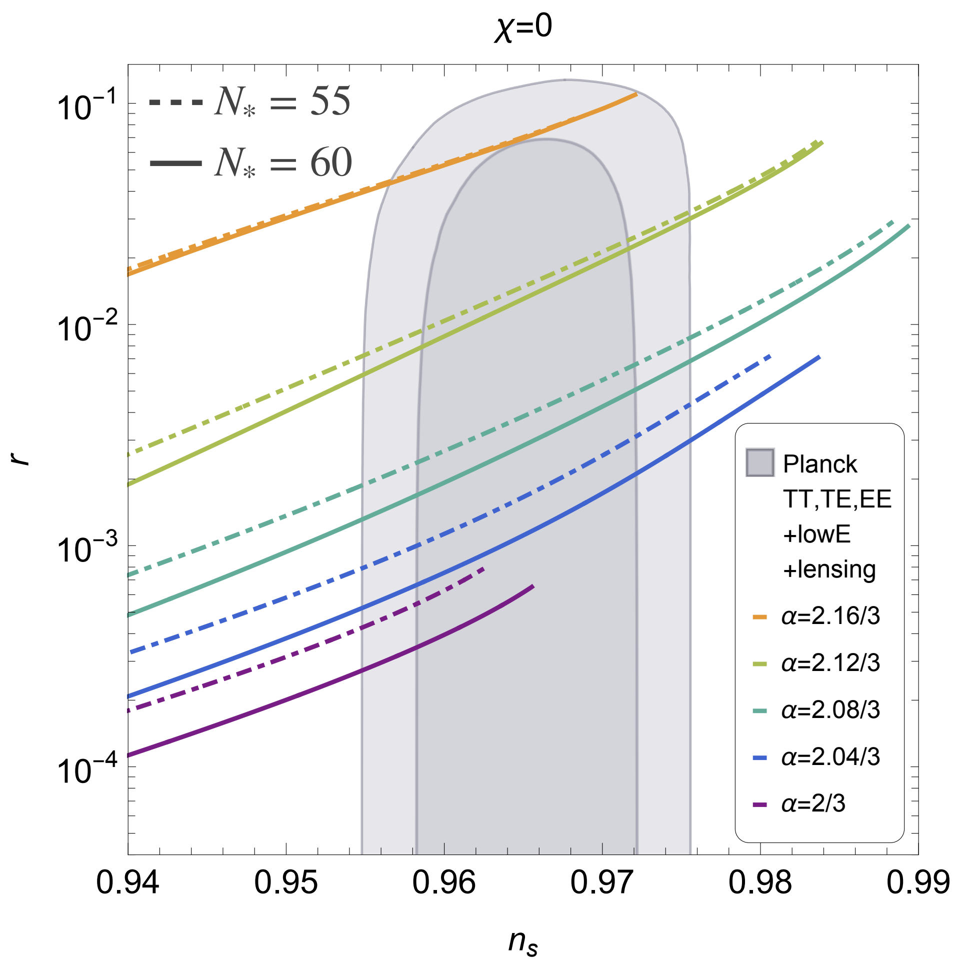
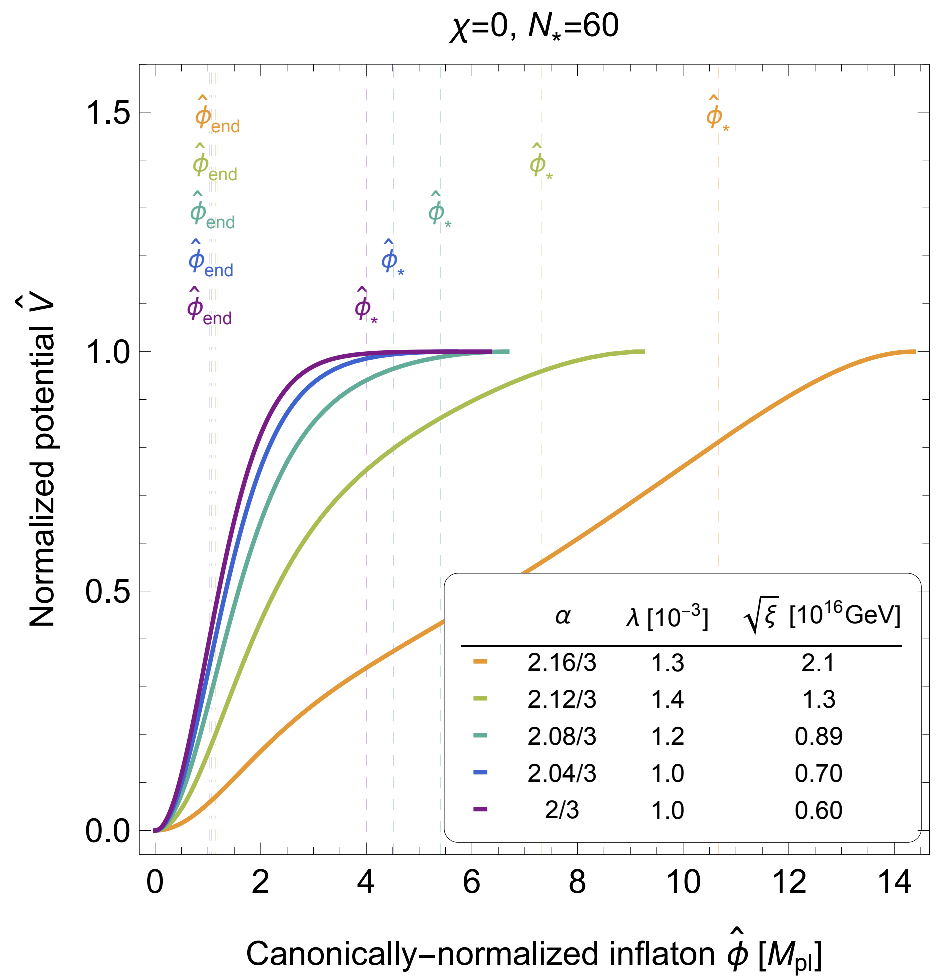
- Predicted r changes depending on α & χ

$$10^{-4} \lesssim r \lesssim 10^{-1}$$

$\chi = 0$ case





As $\alpha \to 2/3$:

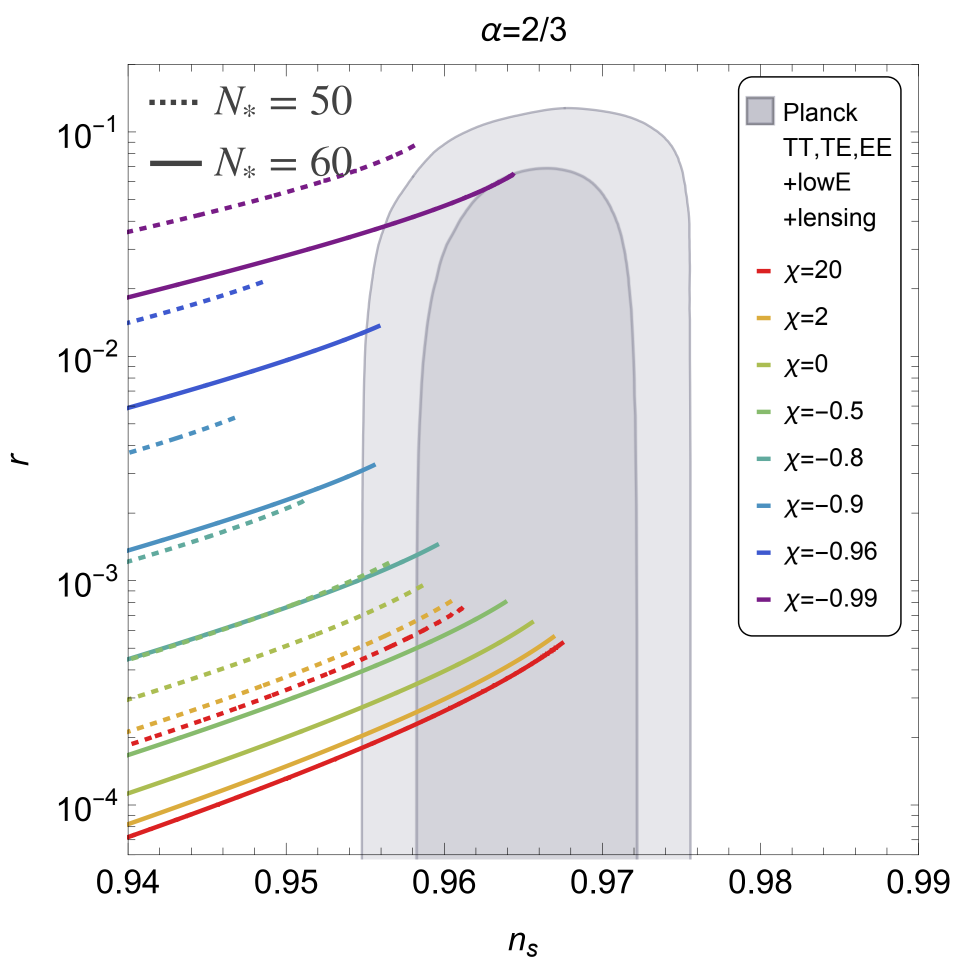
- $\hat{V}$ becomes flatter
- $\hat{\phi}_*$ becomes smaller
- r becomes smaller

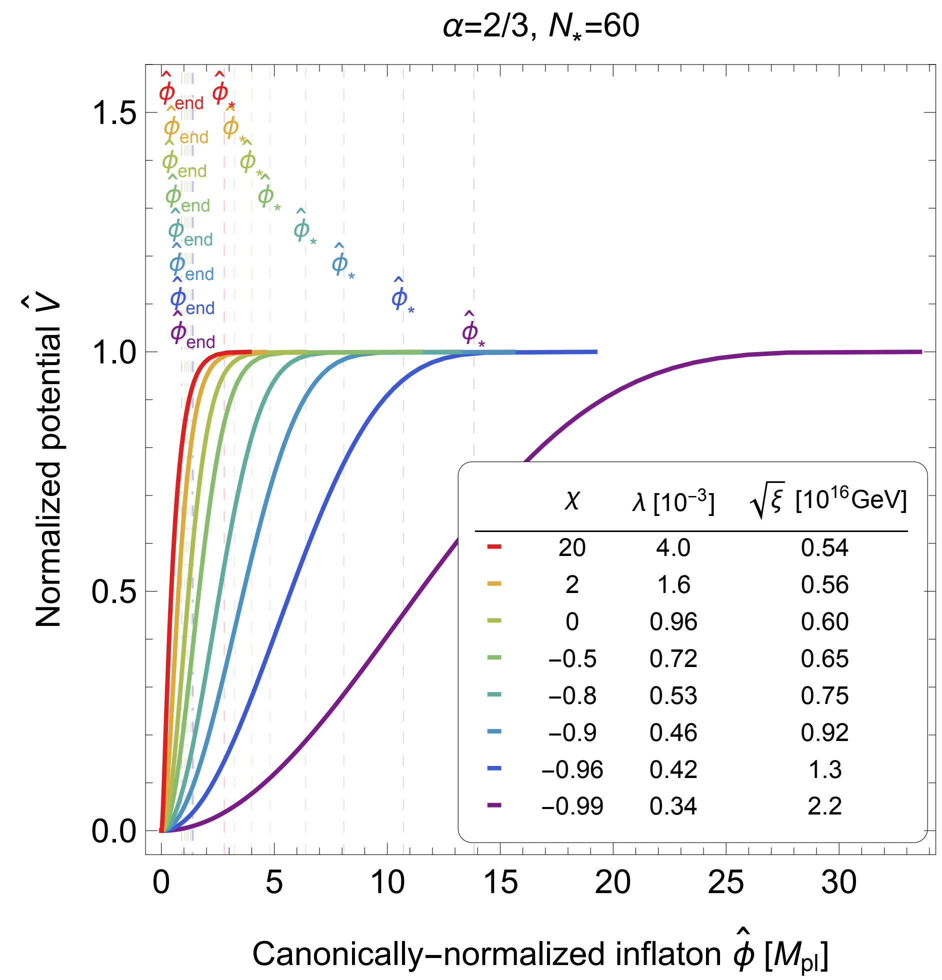
$\hat{V} = V/V(\phi_c)$

$\hat{\phi} = \hat{\phi}_{\rm end}$ at the end of inflation

$\hat{\phi} = \hat{\phi}_*$ at 60 e-folds

$\alpha = 2/3$ case





As χ increases:

- $\hat{V}$ becomes flatter
- $\hat{\phi}_*$ becomes smaller
- r becomes smaller

$\hat{V} = V/V(\phi_c)$

$\hat{\phi} = \hat{\phi}_{\rm end}$ at the end of inflation

$\hat{\phi} = \hat{\phi}_*$ at 60 e-folds

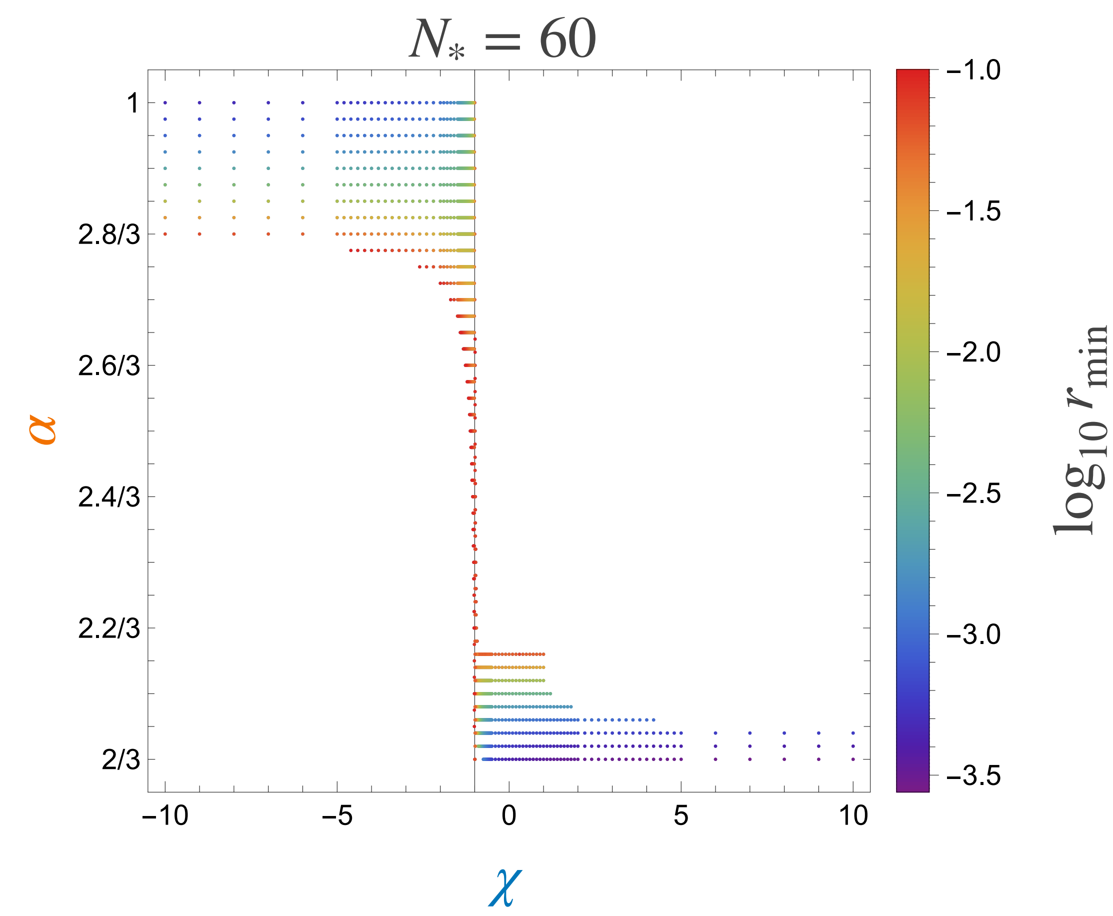
Summary

We have studied subcritical hybrid inflation in a generalized superconfomal model

- Successful inflation is realized in wide range of parameters

- Potential changes drastically depending on α & χ

- r is fond to range from 10^{-4} to 10^{-1}



Conclusions

Conclusions

We have studied the phenomenology of superconformal subcritical hybrid inflation

- Successful leptogenesis is realized in the extended model
- Subcritical hybrid inflation is realized in a generalized model

Leptogenesis after the inflation
YG & Ishiwata '19

- Light neutrino masses
- Reheating
- Baryon asymmetry

extension

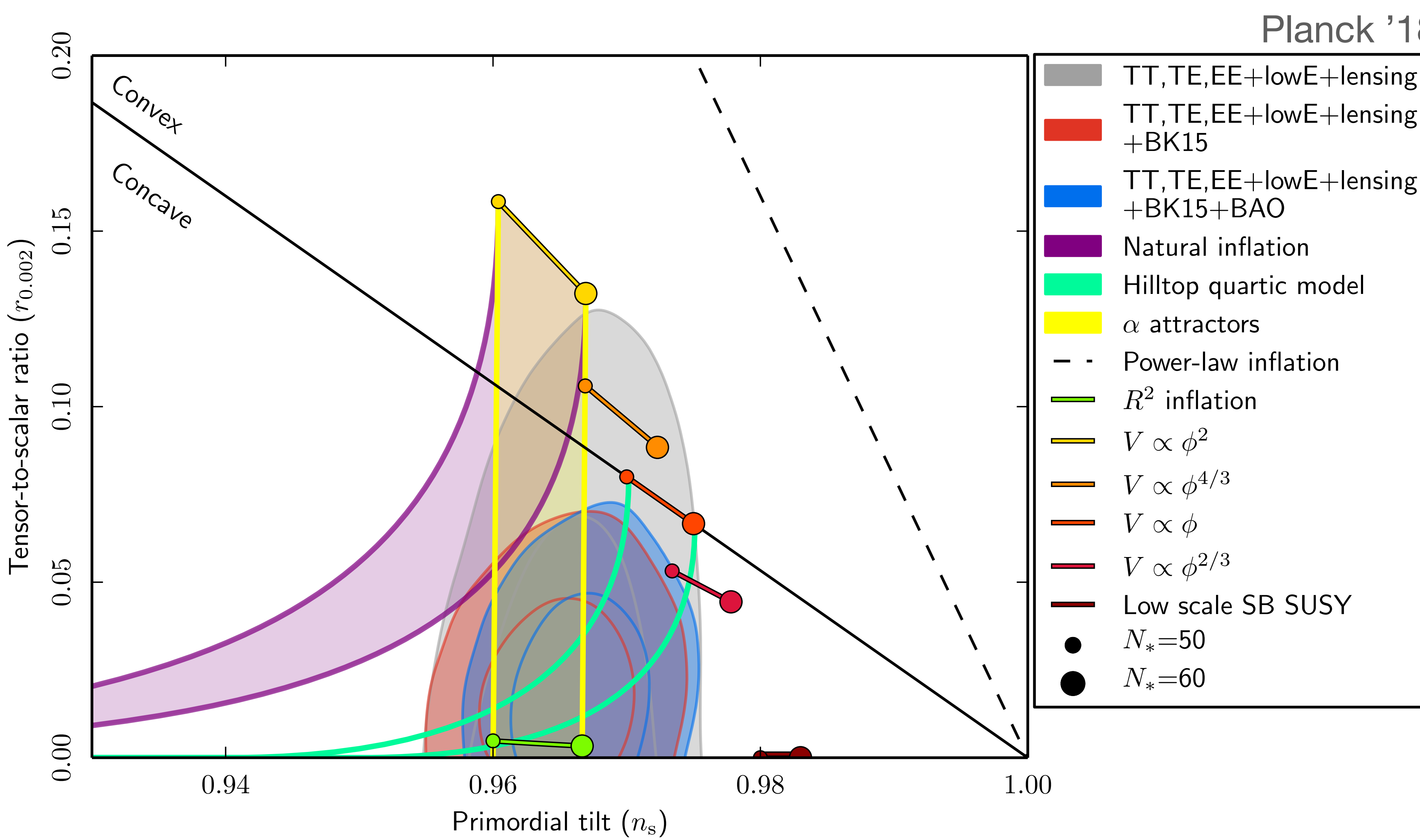
Superconformal subcritical hybrid inflation
Ishiwata '18

generalization

Generalized superconformal subcritical hybrid inflation
YG & Ishiwata '21

Back up

Inflation



CMB constraints on inflationary models
may provide hints for new physics

Inflation

Supersymmetry (SUSY) is one of the candidates for new physics

- Superstring theory requires SUSY
- Dark matter candidate exists
- Flat directions appear ⟶ Suitable for inflation

Many F, D-term hybrid inflation models have been considered

$$V_{\mathrm{scalar}} = V_F + V_D$$

Inflation

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$$V_{\rm scalar} = V_F + \boxed{V_D}$$

D-term hybrid inflation has been revisited from new point of view

Reheating

Decay width

$$\Gamma_\phi \simeq \frac{(y_\nu y_\nu^\dagger)_{33}}{8\pi} m_\phi$$

$$\Gamma_{\phi \to L\tilde{H}_u} = \Gamma_{\phi \to \bar{L}\bar{\tilde{H}}_u} = \frac{(y_\nu y_\nu^\dagger)_{33}}{16\pi} m_\phi, \quad \Gamma_{\phi \to \tilde{L}H_u} = \Gamma_{\phi \to \tilde{L}^* H_u^*} = \frac{(y_\nu y_\nu^\dagger)_{33}}{16\pi} \frac{M_3^2}{m_\phi}$$

Reheating temperature

$$T_R \simeq \left(90/\pi^2 g_*(T_R)\right)^{1/4} \sqrt{\Gamma_\phi M_{pl}}$$

$$\simeq 1.4 \times 10^{10} \mathrm{GeV} \left(\frac{m_\phi}{10^{13}\mathrm{GeV}}\right)^{1/2} \left(\frac{(y_\nu y_\nu^\dagger)_{33}}{10^{-9}}\right)^{1/2} \left(\frac{g_*(T_R)}{228.75}\right)^{-1/4}$$

Case (I) . $M_1, M_2 < m_\phi$

Produced baryon asymmetry

Buchmüller, Di Bari, Plümacher '05

$$\eta_B = \frac{3}{4}\frac{a_{\rm sph}}{f}\epsilon_1\kappa_{\rm f}$$

Efficiency factor in strong washout regime ($\tilde{m}_1 > m_* \sim 10^{-3}\,{\rm eV}$)

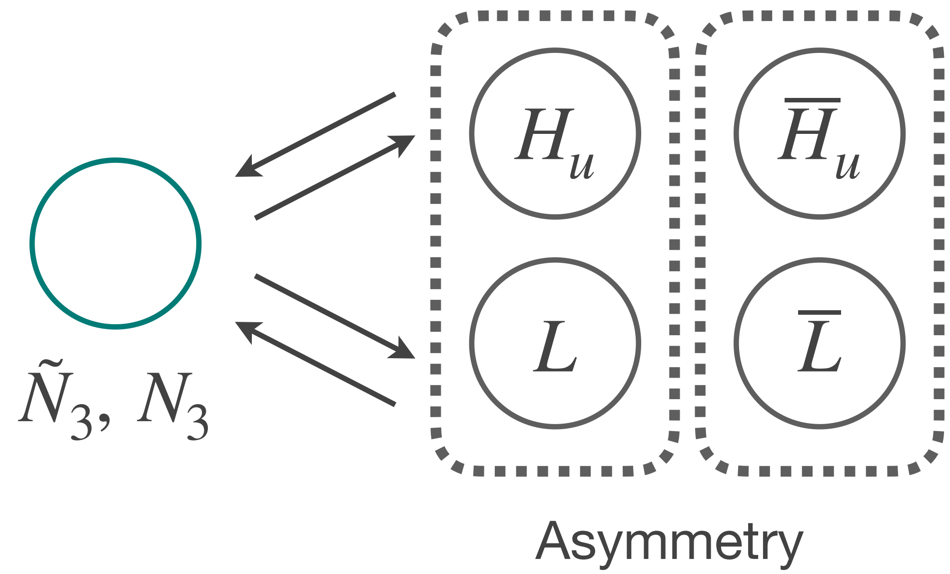
$$\kappa_{\rm f} = (2 \pm 1) \times 10^{-2}\left(\frac{0.01\,{\rm eV}}{\tilde{m}_1}\right)^{1.1\pm0.1} \qquad \tilde{m}_1 \geq \begin{cases} m_2 \simeq 8.6 \times 10^{-3}{\rm eV} & ({\rm NH}) \\ m_1 \simeq 4.9 \times 10^{-2}{\rm eV} & ({\rm IH}) \end{cases}$$

Asymmetric parameter

$$\epsilon_1 = \begin{Bmatrix} 8.2 \times 10^{-7} \ ({\rm NH}) \\ 1.5 \times 10^{-8} \ ({\rm IH}) \end{Bmatrix} \times \left(\frac{M_1}{10^{10}\ {\rm GeV}}\right)\left(\frac{\sin\delta}{0.5}\right)$$

Case (II) . $M_1, M_2 > m_\phi$

When $T_R \gtrsim m_\phi$, $\tilde{N}_3$ & N_3 are thermally produced



We need to evaluate the time evolution equation of the lepton asymmetry

$$\begin{cases} \dot{n}_L + 3Hn_L = (\text{source}) - (\text{washout}) \\ \dot{n}_{\tilde{N}_3^c} + 3Hn_{\tilde{N}_3^c} = -D_{\tilde{N}_3^c} + ID_{\tilde{N}_3^c} - S_{\tilde{N}_3^c} \\ \dot{n}_{N_3} + 3Hn_{N_3} = -D_{N_3} + ID_{N_3} - S_{N_3} \end{cases}$$

Case (II) . $M_1, M_2 > m_\phi$

Inflation

$M_3 \lesssim 2 \times 10^{11}$ GeV

$T_R \ll m_\phi$

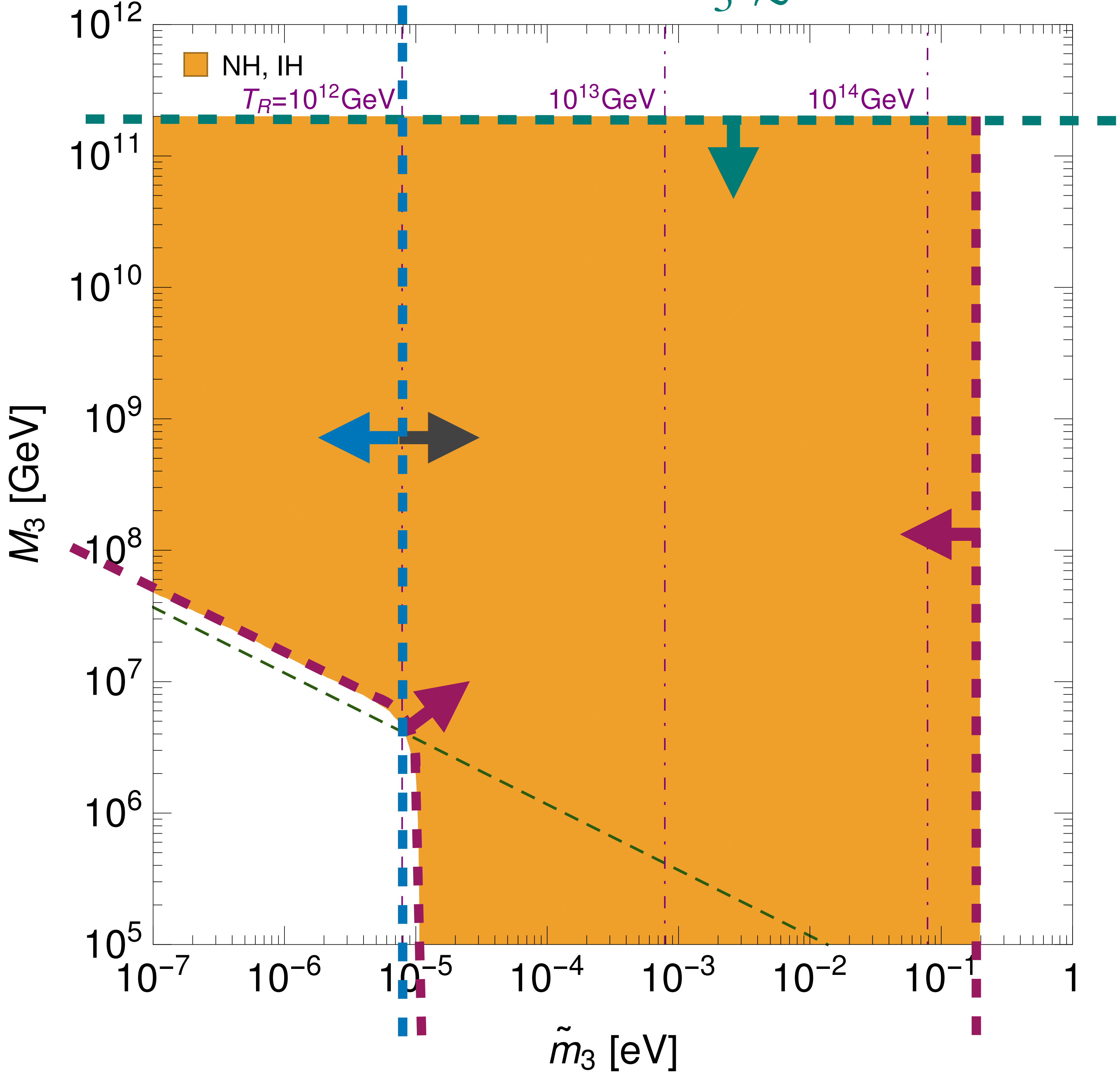
Non-thermal leptogenesis

(by the inflaton decay)

$T_R \gtrsim m_\phi$

Thermal leptogenesis

(by thermally-produced neutrino decay)



$\eta_B^{max} \geq \eta_B^{obs}$

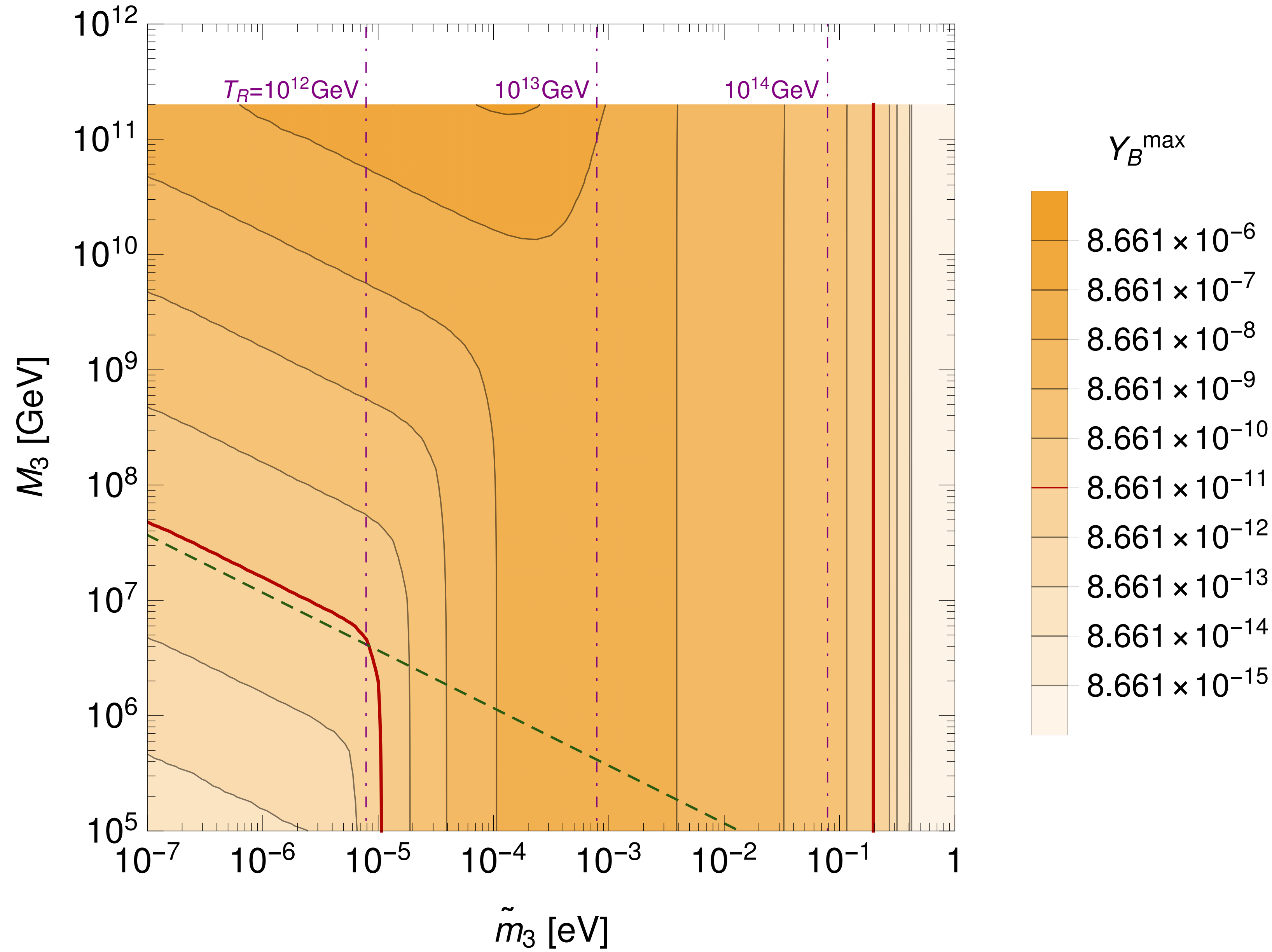
Case (II) . $M_1, M_2 > m_\phi$

Non-thermal leptogenesis

$$Y_B^{\max} \propto \tilde{m}_3^{1/2} M_3$$

Thermal leptogenesis

$$Y_B^{\max} = Y_B^{\max}(\tilde{m}_3, m_\phi)$$



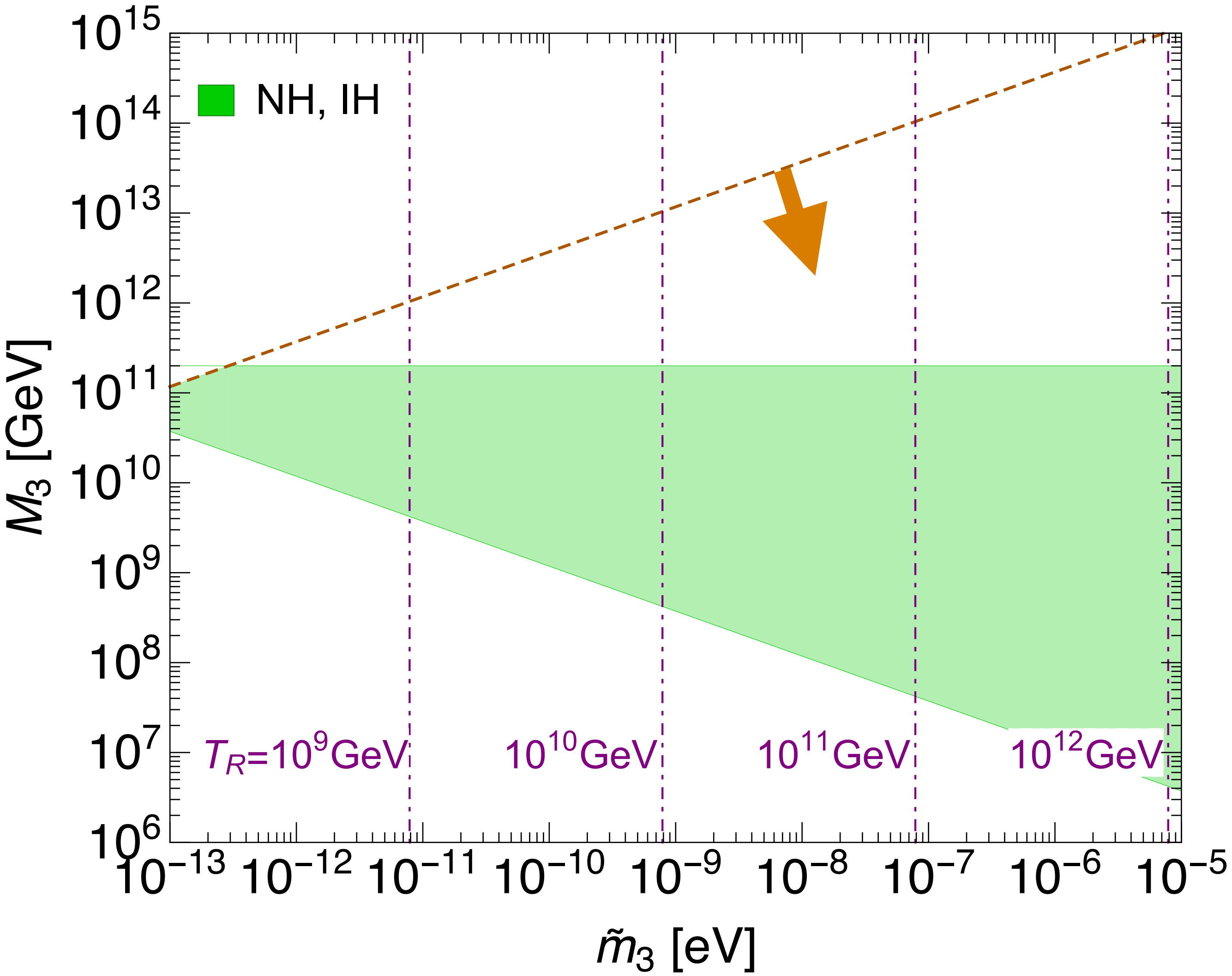
ϕ decay

N_3 decay

$$\epsilon_\phi \simeq 4 \times 10^{-9} \left(\frac{M_3}{10^7 \text{ GeV}} \right) \left(\frac{\sin \delta'}{0.5} \right) \ll \epsilon_3 \simeq 2 \times 10^{-4} \left(\frac{m_\phi}{10^{13} \text{ GeV}} \right) \left(\frac{\sin \delta'}{0.5} \right)$$

Stability of inflationary trajectory

$$W_{\rm neu} = \lambda_3 N_3^c S_+ S_- + \frac{1}{2} M_i N_i^c N_i^c + \boxed{y_{\nu ij} N_i^c L_j H_u}$$

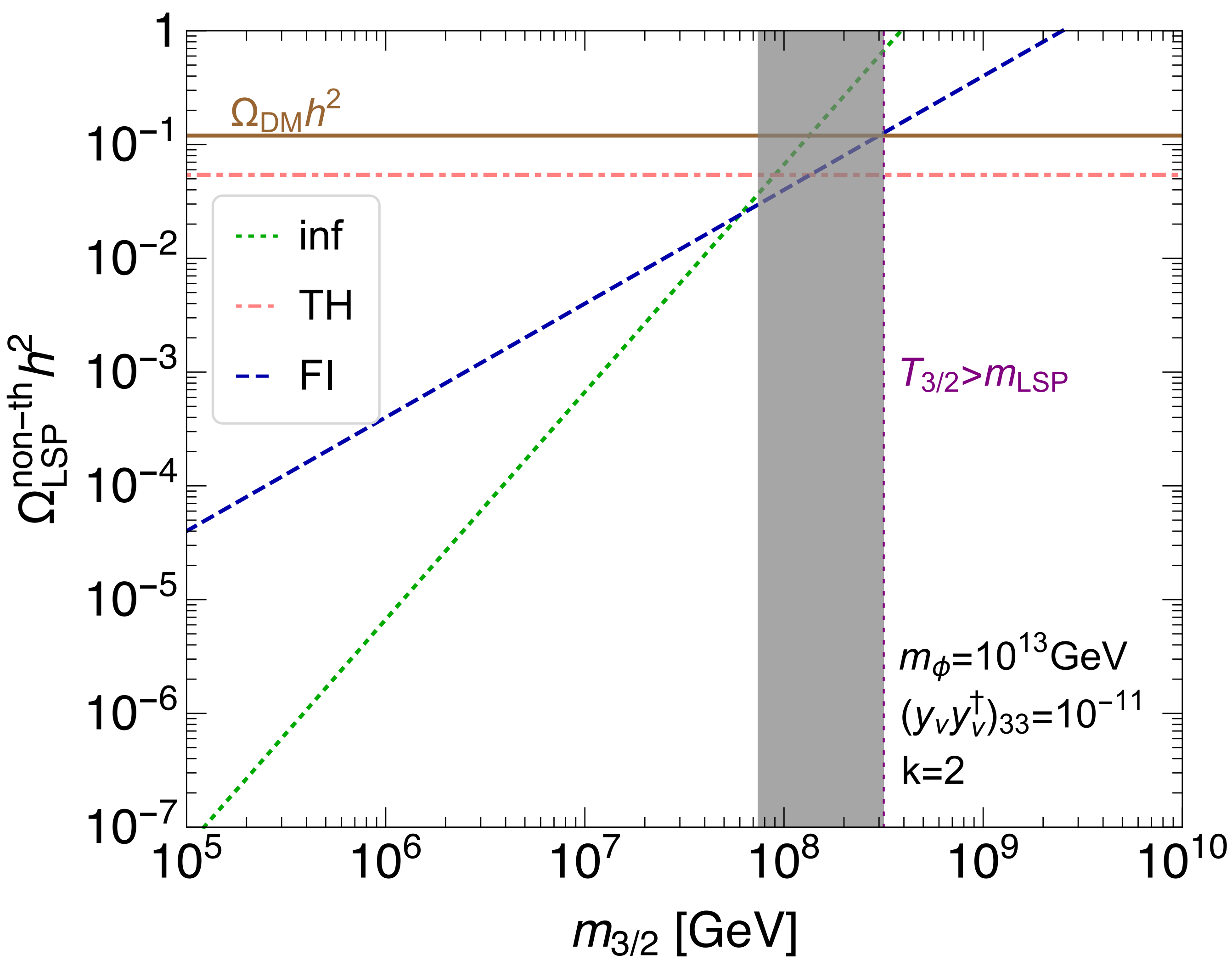


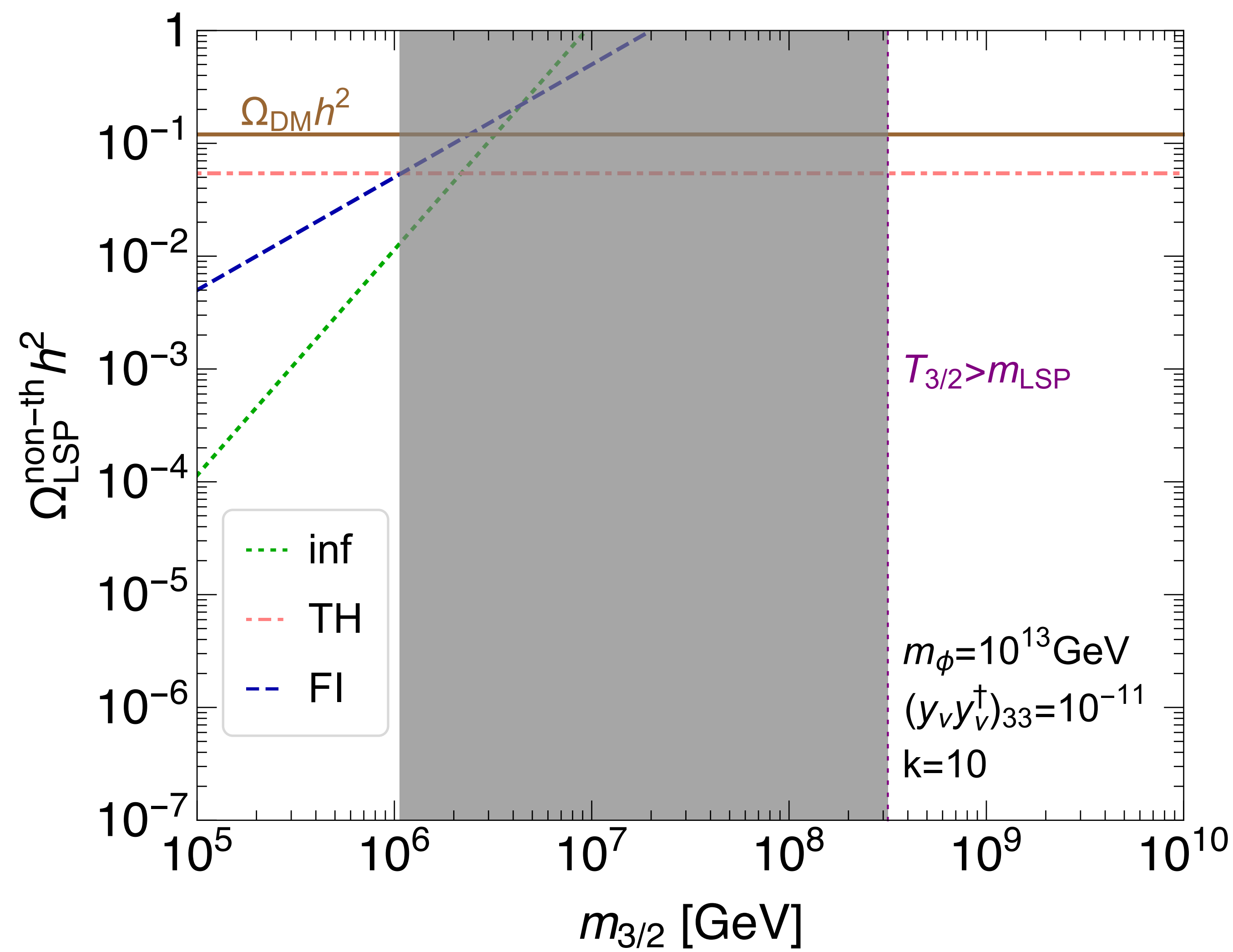
Consistency with the inflation

$$|M_3| \leq 1.4 \times 10^{14}\ \mathrm{GeV} \left(\frac{(y_\nu y_\nu^\dagger)_{33}}{10^{-7}} \right)^{1/2}$$

LSP production by gravitino decay

Gravitino decays to the lightest supersymmetric particles (LSP)
When *R*-Parity is conserved, LSP becomes DM





Gravitino production processes

(i) Inflaton decay

(ii) Thermal production by scattering

(iii) SUSY particle decay in thermal bath

$k \equiv \tilde{m}/m_{3/2}$

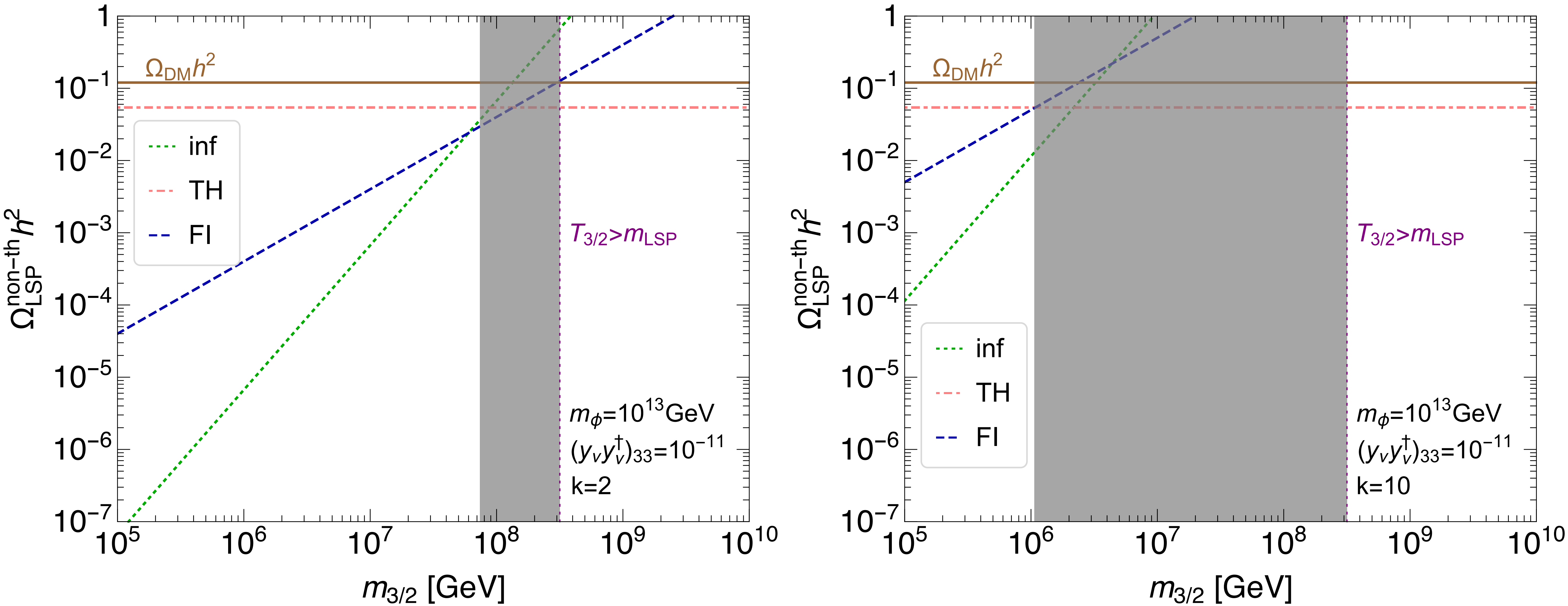
$m_{3/2}$: gravitino mass

$\tilde{m} = km_{2/3}$: soft ~~SUSY~~ mass scale ($k > 1$)

$m_{\rm LSP}$: LSP mass scale ($\sim 1\,\rm TeV$)

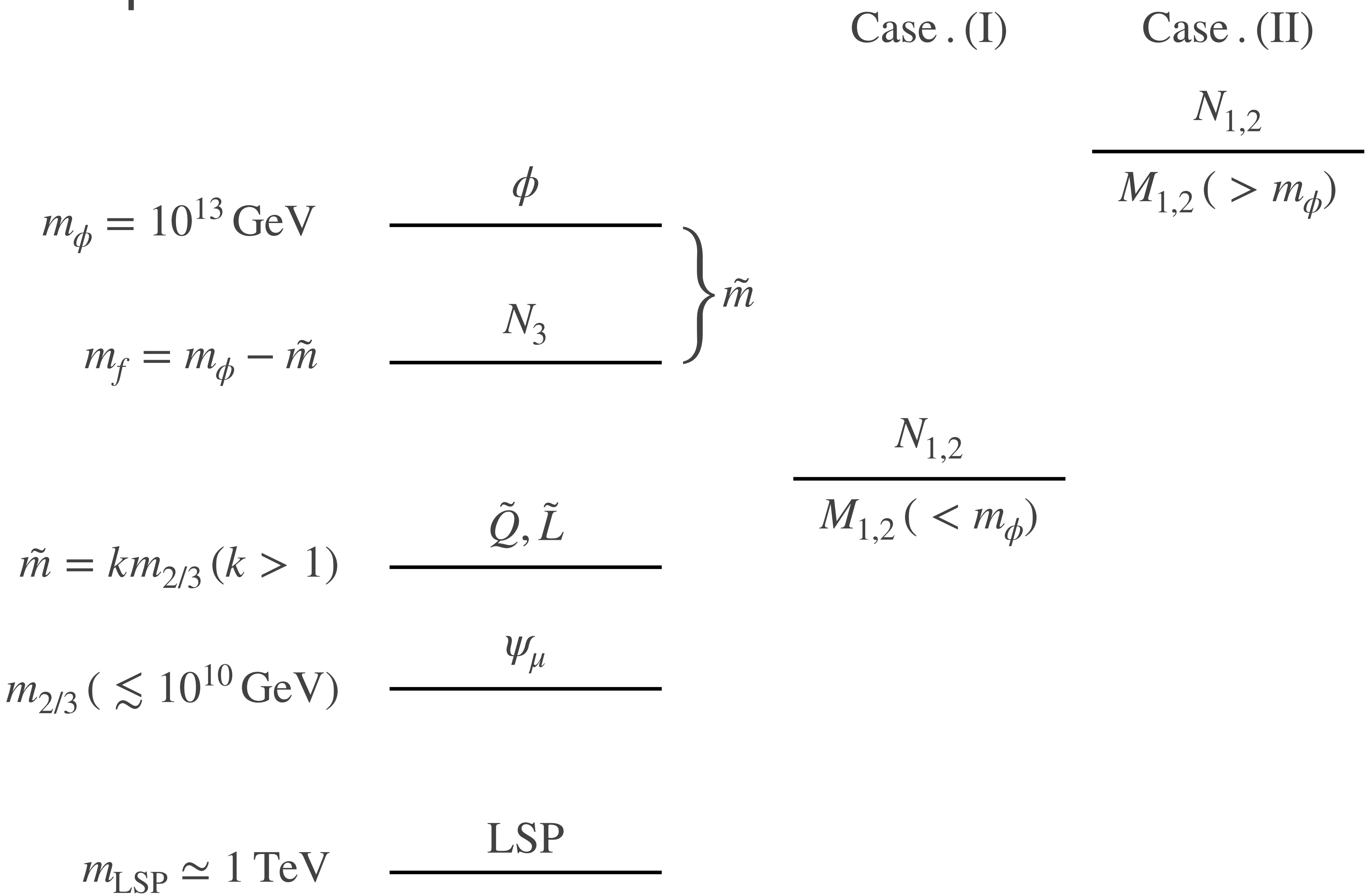
LSP production by gravitino decay

Gravitino decays to the lightest supersymmetric particles (LSP)
When *R*-Parity is conserved, LSP becomes DM



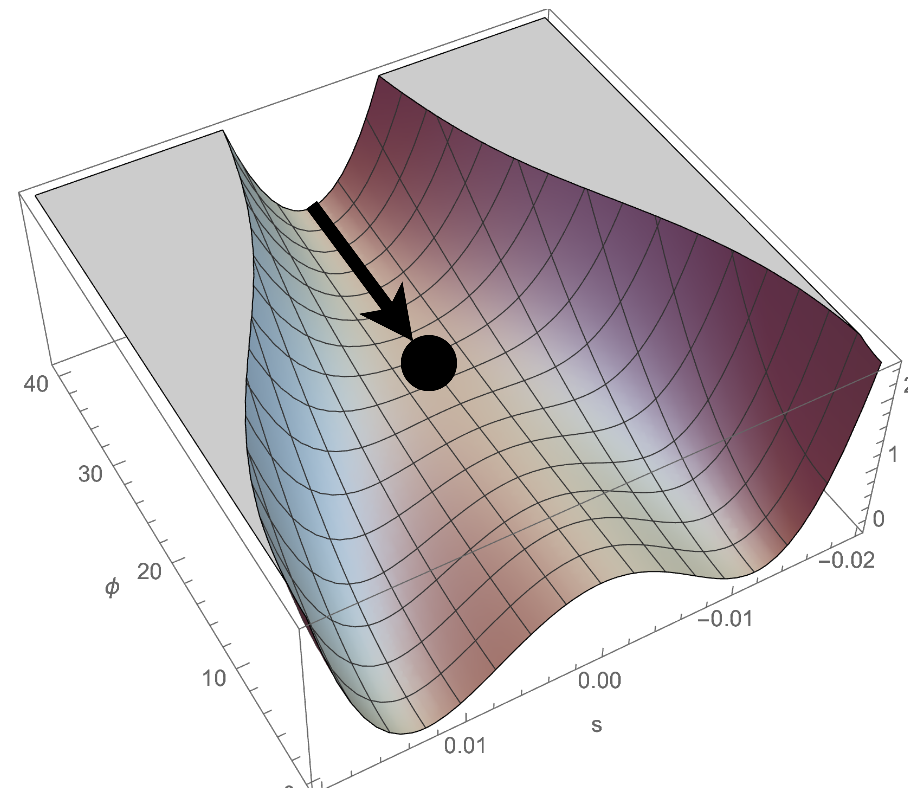
- Gravitino decays to LSP before thermal freeze-out of LSP when $m_{2/3} \gtrsim 3 \times 10^8\,\mathrm{GeV}$
- $m_{2/3} \lesssim 10^{10}$-$10^{11}\,\mathrm{GeV}$ should be satisfied to realize the reheating $(\mathrm{Br}_{\phi\to\psi_\mu N_3} \lesssim 0.1)$

Mass spectrum



Potential in the pre-critical regime

$$V(\phi) = V_{\text{tree}} + V_{1\,\text{loop}}$$



$$V_{\text{tree}} = g^2\xi^2/2$$

$$V_{1\,\text{loop}} = \frac{g^4 q^2 \xi^2}{32\pi^2} L(\Psi)$$

$$L(\Psi) = (\Psi - 1)^2 \ln(\Psi - 1) + (\Psi + 1)^2 \ln(\Psi + 1) - 2\Psi^2 \ln \Psi - \ln 16$$

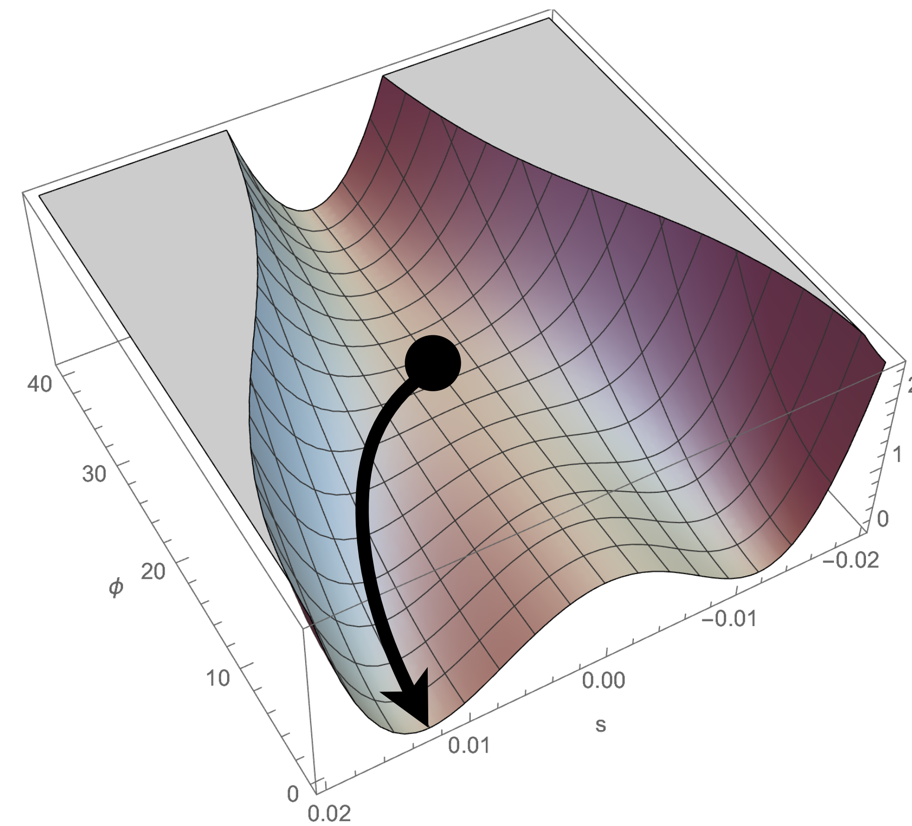
$$\Psi(\phi) = \frac{k}{2\alpha^2}\left(\frac{\Phi(\phi, 0)}{3}\right)^{2-3\alpha} \phi^2$$

Potential in the subcritical regime

$$V(\phi) = g^2\xi^2\,\Psi(\phi)\left(1 - \frac{1}{2}\Psi(\phi)\right)$$

$$\Psi(\phi) = \frac{k}{2\alpha^2}\left(\frac{\Phi(\phi,0)}{3}\right)^{2-3\alpha}\phi^2$$

$k \equiv \lambda^2/qg^2\xi$



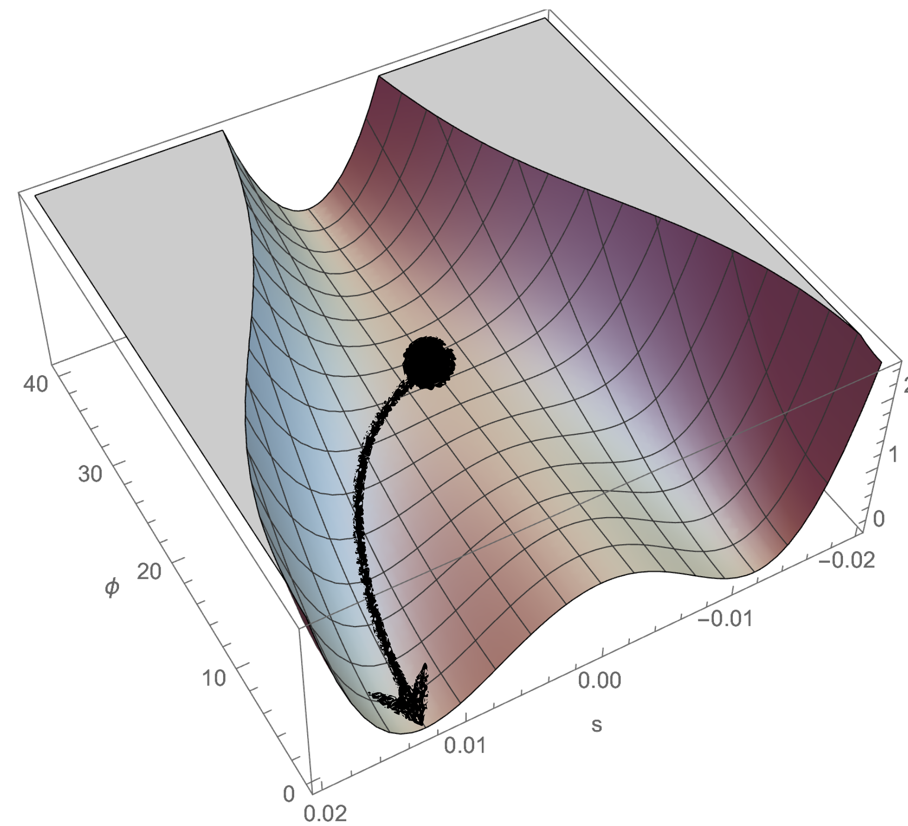
q & g can be absorbed into redefining λ & ξ

$\cdots$ We take $q = g = 1$ in numerical analysis

Masses of $S_\pm$

$$m_\pm^2 = \left(-\frac{\Phi(\phi)}{3}\right)^{2-3\alpha} \frac{\lambda^2}{2\alpha^2}\phi^2 \mp qg^2\xi$$

$$\Phi(\phi) = 1 - \frac{1}{6}(1+\chi)\phi^2$$



The critical point value ϕ_c can be determined from $m_+^2 = 0$, *i.e.*,

$$\left(-\frac{\Phi(\phi_c)}{3}\right)^{2-3\alpha} \phi_c^2 = \frac{2\alpha}{k}$$

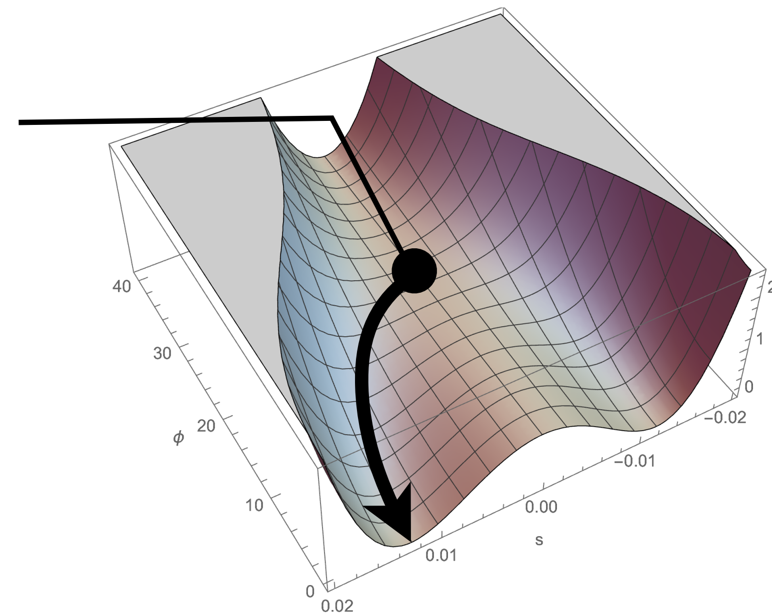
$$k \equiv \lambda^2 / qg^2\xi$$

$\phi = \phi_c$ at the critical point

Waterfall field value in subcritical regime

$\phi = \phi_c$ at the critical point

$s = s_{\rm min}(\phi)$ for $\phi < \phi_c$

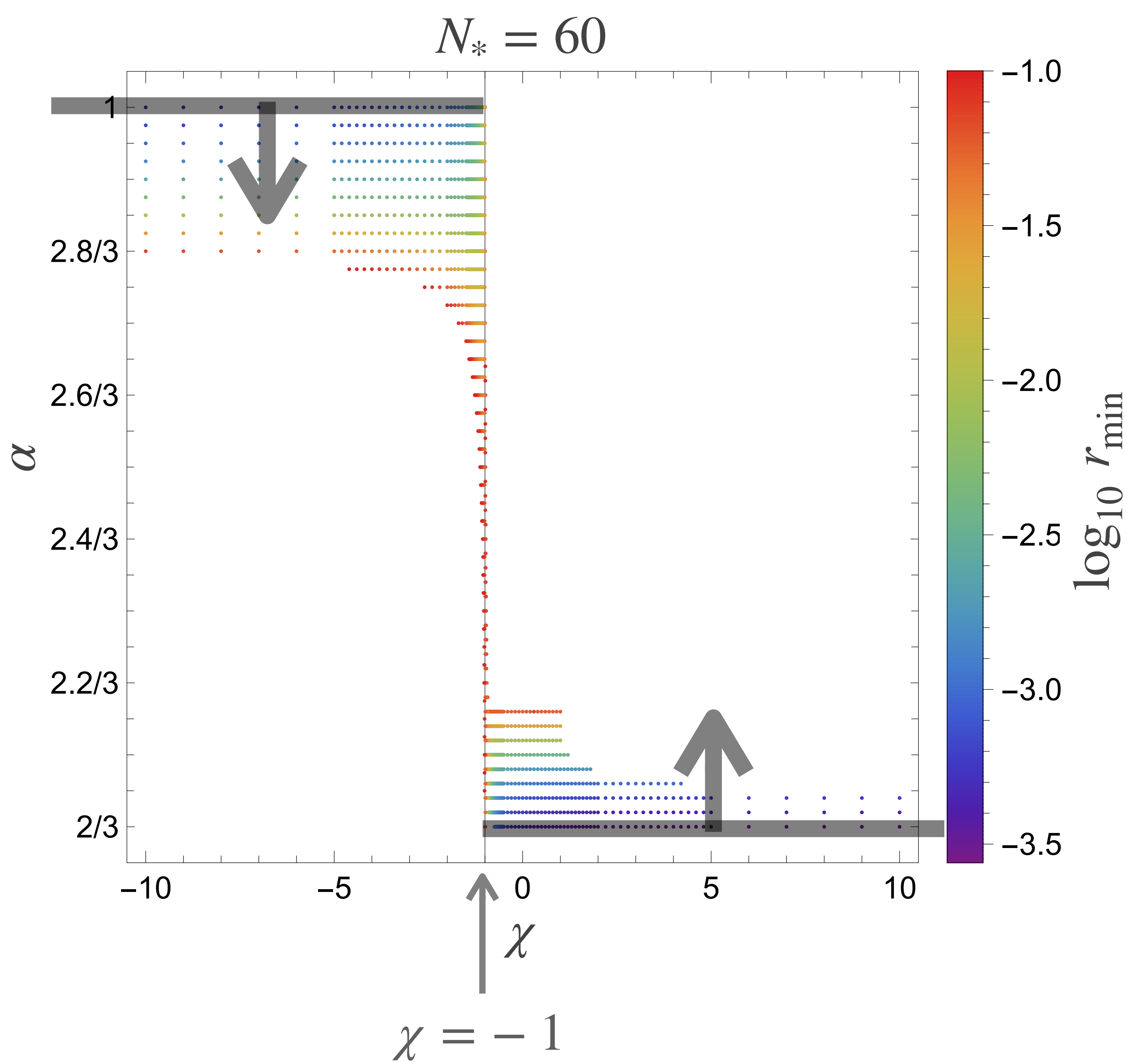


$$s^2_{\rm min}(\phi) = -\frac{\Phi(\phi)}{3}\frac{2\xi}{q\alpha}\big(1 - \Psi(\phi)\big)$$

$$\Phi(\phi) = 1 - \frac{1}{6}(1+\chi)\phi^2$$

$$\Psi(\phi) = \left(\frac{\Phi(\phi)}{\Phi(\phi_c)}\right)^{2-3\alpha}\frac{\phi^2}{\phi_c^2} = \frac{k}{2\alpha}\left(-\frac{\Phi(\phi)}{3}\right)^{2-3\alpha}\phi^2$$

Allowed region for α & χ

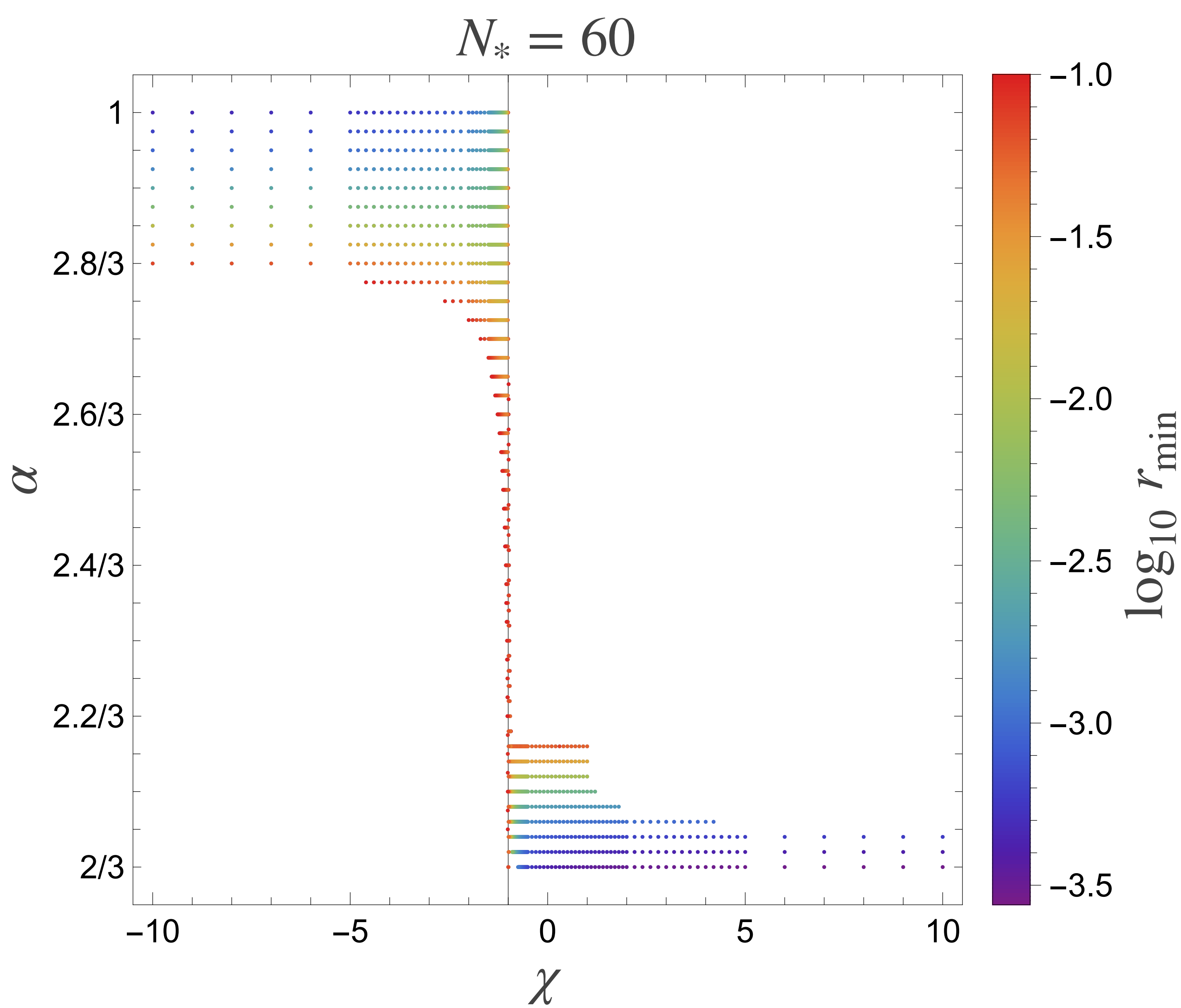


We focus on

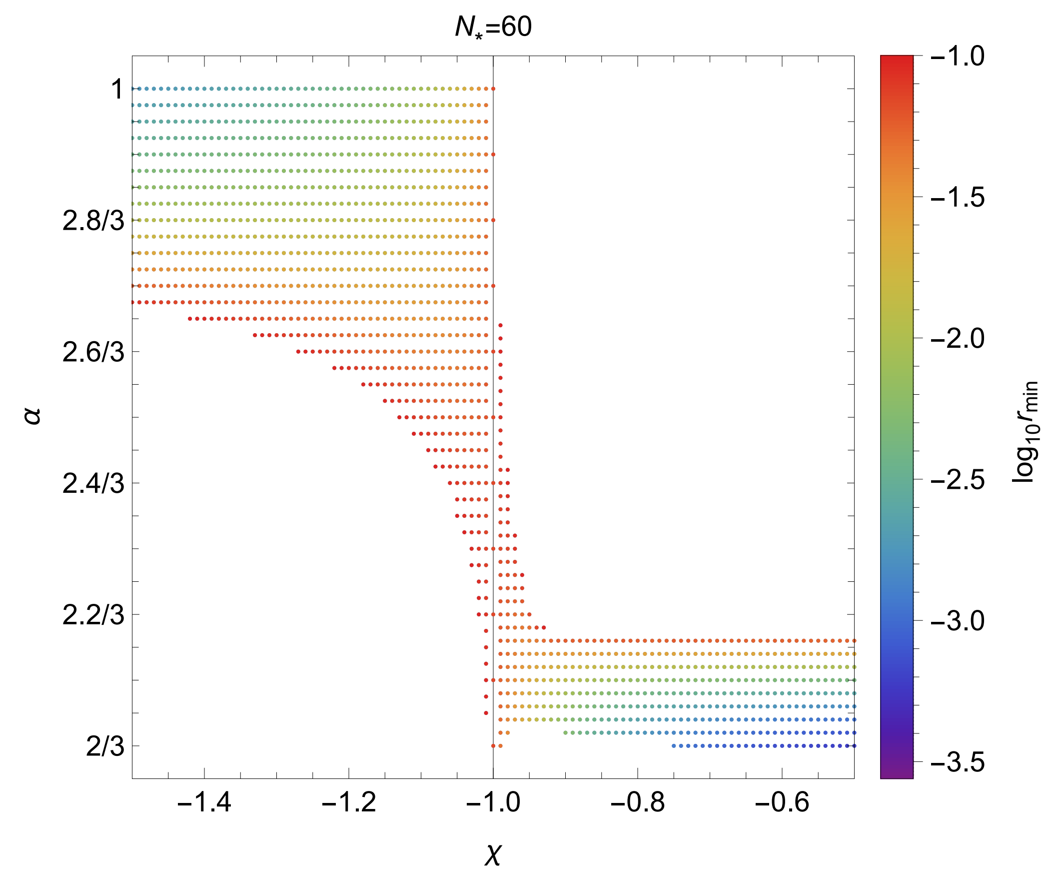
$$\begin{cases} \alpha \leq 1 & (\chi < -1) \\ \alpha \geq 2/3 & (\chi > -1) \end{cases}$$

to give single critical point

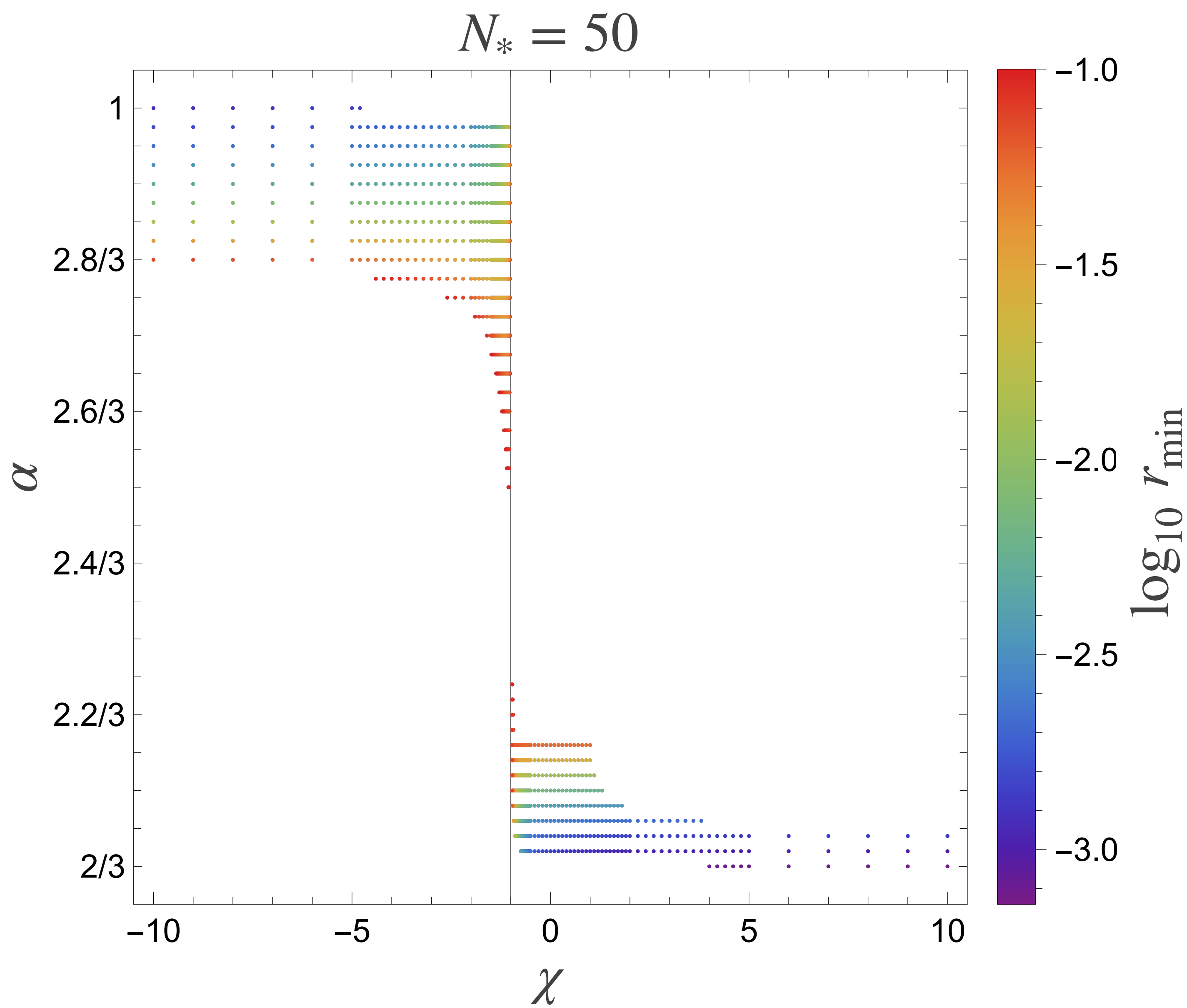
Allowed region for α & χ

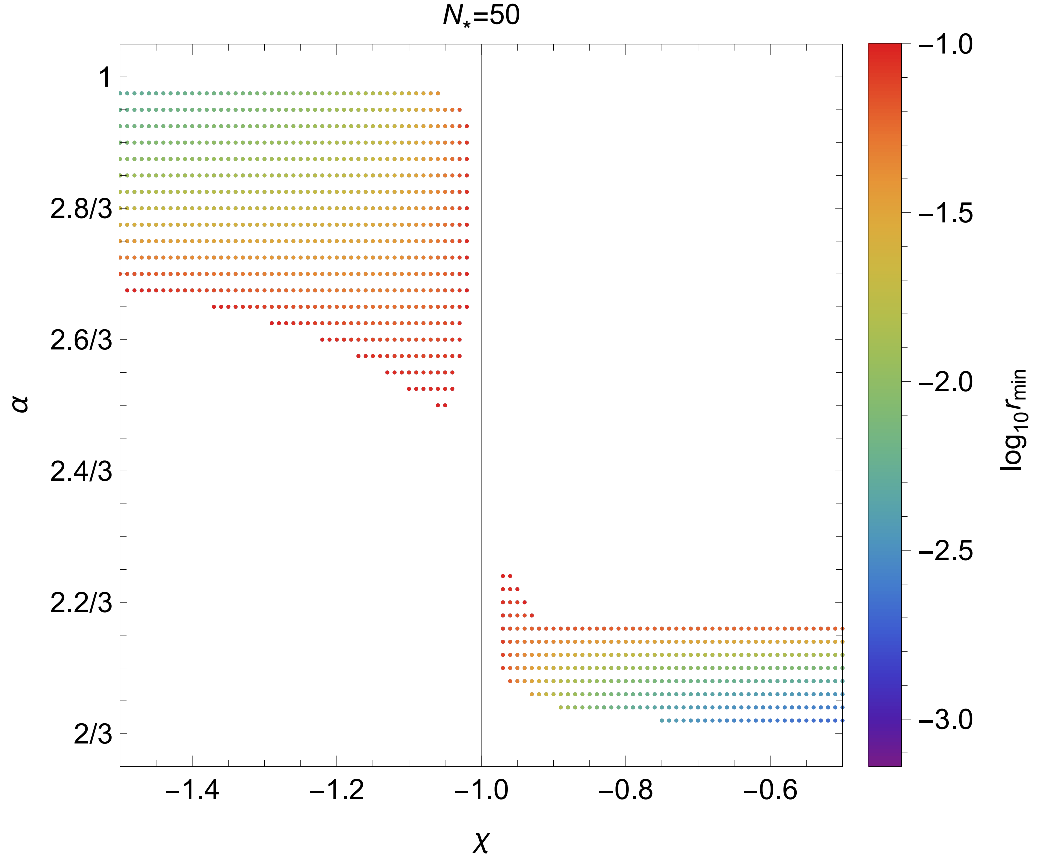


Zoom of $-1.5 \leq \chi \leq -0.5$



Allowed region for α & χ





The generalized Model

Lagrangian in a Jordan frame:

$$\frac{\mathscr{L}_J}{\sqrt{-g_J}} = -\frac{1}{6}R_J \mathscr{N} - \mathscr{N}_{\beta\bar{\beta}}\, g_J^{\mu\nu}\, \mathscr{D}_\mu z^\beta\, \mathscr{D}_\nu \bar{z}^{\bar{\beta}} - V_J \qquad z^\beta = \{S_+, S_-, N\}$$

$$\mathscr{N} = -|X^0|^2 \left[1 - \frac{|S_+|^2 + |S_-|^2 + |N|^2}{|X^0|^2} - \frac{\chi}{2}\left(\frac{N^2 \bar{X}^0}{X^0} + \frac{\bar{N}^2 X^0}{\bar{X}^0}\right)\right]^\alpha$$

Gauge fixing $X^0 = \bar{X}^0 = \sqrt{3}$

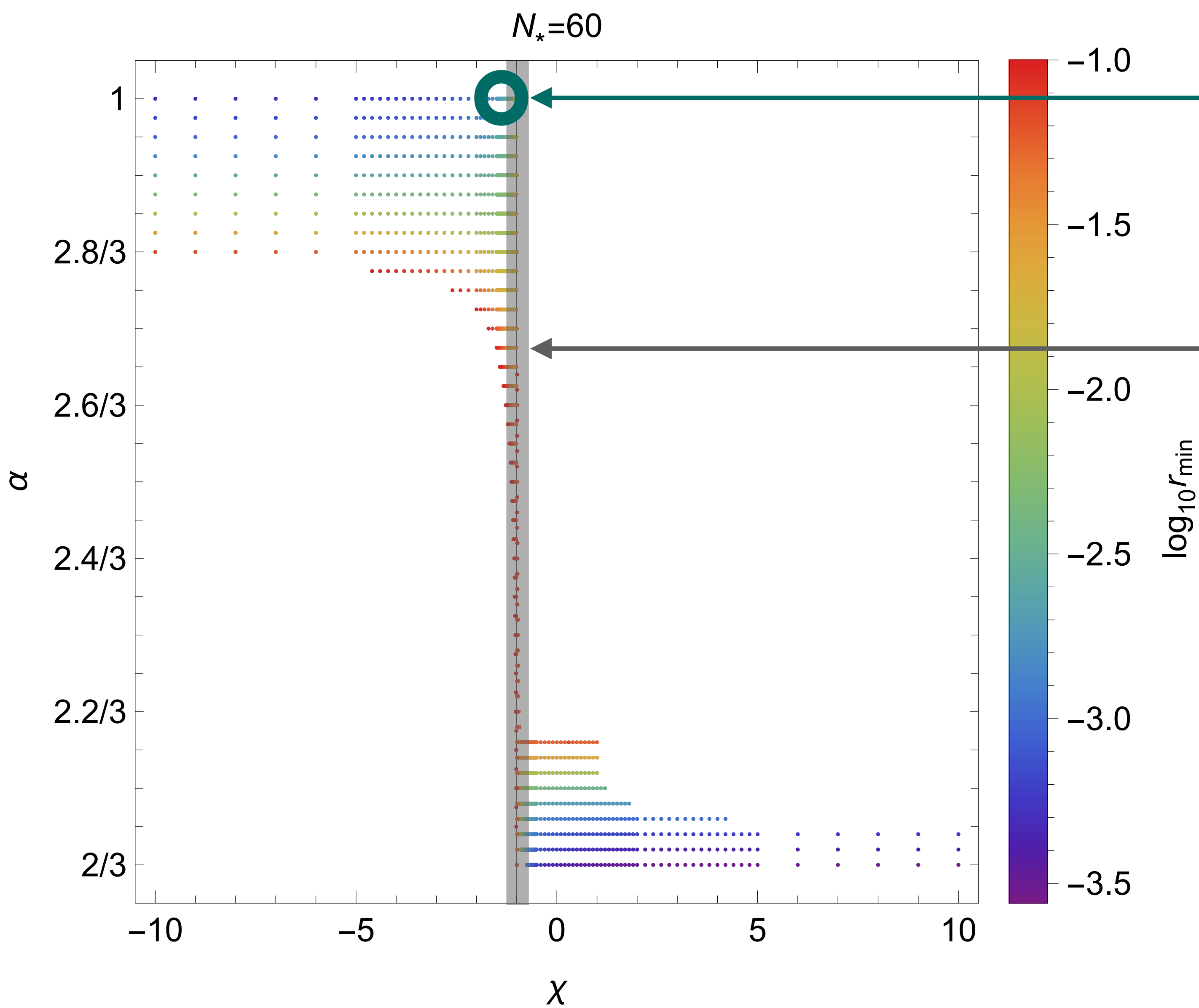
Weyl transformation $g_{J\,\mu\nu} = (-\mathscr{N}/3)^{-1}\, g_{E\,\mu\nu}$

Lagrangian in the Einstein frame:

$$\frac{\mathscr{L}_E}{\sqrt{-g_E}} = \frac{1}{2}R_E - K_{\beta\bar{\beta}}\, g_E^{\mu\nu}\, \mathscr{D}_\mu z^\beta\, \mathscr{D}_\nu \bar{z}^{\bar{\beta}} - V_E, \quad V_E = \left(\frac{\mathscr{N}}{3}\right)^{-2} V_J = V_F + V_E$$

$$K = -3\alpha \log\left(-\frac{\Phi}{3}\right), \quad \Phi = -3 + |S_+|^2 + |S_-|^2 + |N|^2 + \frac{\chi}{2}(N^2 + \bar{N}^2)$$

Correspondence with the previous studies



$\alpha = 1, \chi \simeq -1$

Superconf. + approx. shift sym. model

Ishiwata ‘18

$\chi = -1$

Shift symmetric model

Buchmuller, Domcke, Schmitz ’14

Buchmuller, Ishiwata ‘13

The generalized Model

Constant Fayet-Iliopoulos term

Introduce an additional term in the Lagrangian in the Jordan frame

Buchmuller, Domcke, Schmitz '13

$$\frac{\Delta \mathscr{L}_J}{\sqrt{-g_J}} = g \frac{-\mathcal{N} \xi}{3} \mathscr{P}$$

$$\mathscr{P} = -\, g Q z^\beta \mathcal{N}_\beta - g \mathcal{N} \xi / 3$$

Constant FI term appears in *D*-term potential in the Einstein frame

$$V_D = \frac{g^2}{2} \left(K_\beta Q z^\beta - \xi \right)^2$$

Effect of s to the adiabatic curvature perturbation

Trajectory of the inflation is almost straight along the inflation field

The effect on the scalar amplitude

$$A_s \to A_s' = e^{\beta} A_s$$

$\cdots$ e^{β} gives an impact on A_s

The effect is sufficient small

$$e^{\beta} - 1 \simeq \eta_{\perp}^2 \xi \sim 10^{-10}$$

$\cdots$ The effective description in the subcritical regime is valid

Stability of $\mathrm{Im}N$

Mass of $\tau \equiv \sqrt{2}\,\mathrm{Im}N$ in subcritical regime

$$m_\tau = \frac{g^2\xi^2 k}{\alpha^2}\left(-\frac{\Phi(\phi)}{3}\right)^{1-3\alpha}\left(1-\Psi(\phi)\right)\left[1-\frac{\phi^2}{6}\{3-\chi+3\alpha(\chi-1)\}\right]$$

Proffered region to satisfy stability condition, *i.e.*, $m_\tau^2 > 0$:

- $\chi < -1$

  $$\begin{cases} 1/3 + 2/3(1-\chi) < \alpha \leq 1 \\ \alpha < 1/3 + 2/3(1+\chi), \text{ depending on other parameter} \end{cases}$$

- $\chi > -1$

  - $$\begin{cases} \chi < 1 \\ \chi \gg 1 \text{ and small } \alpha \text{ (but } \leq 2/3) \end{cases}$$

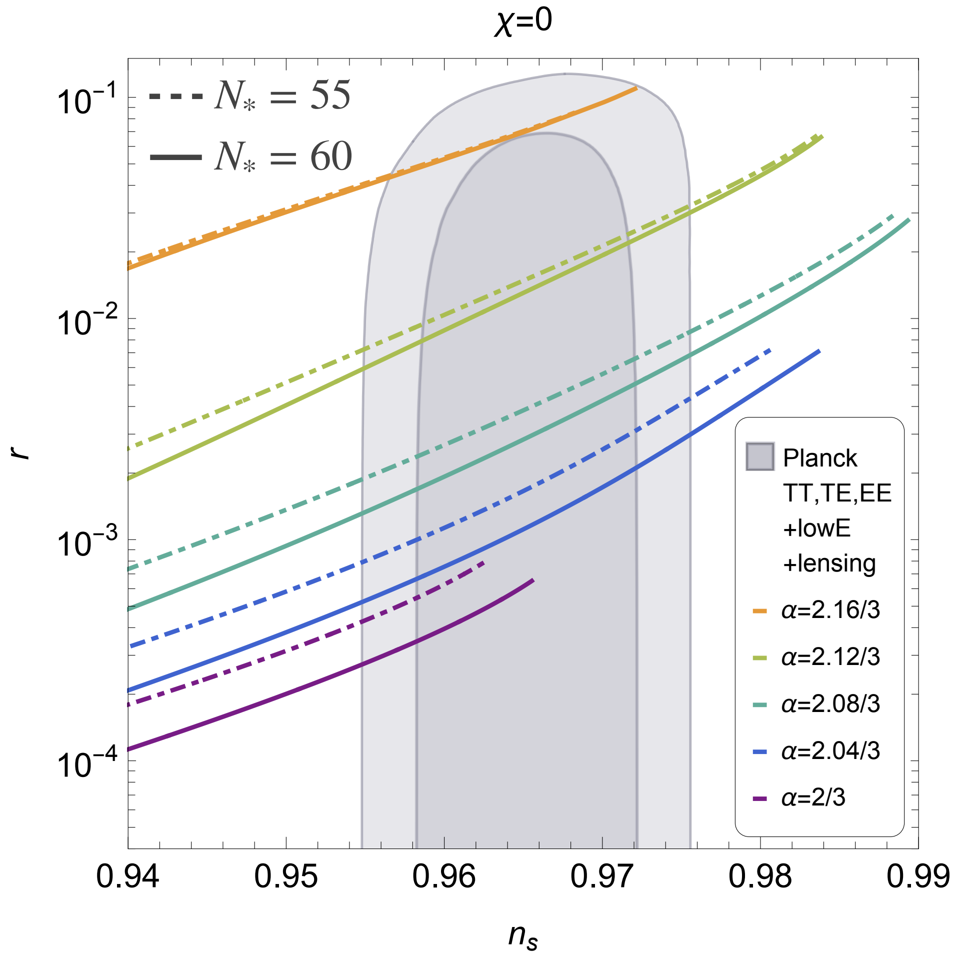
Canonically normalized inflaton

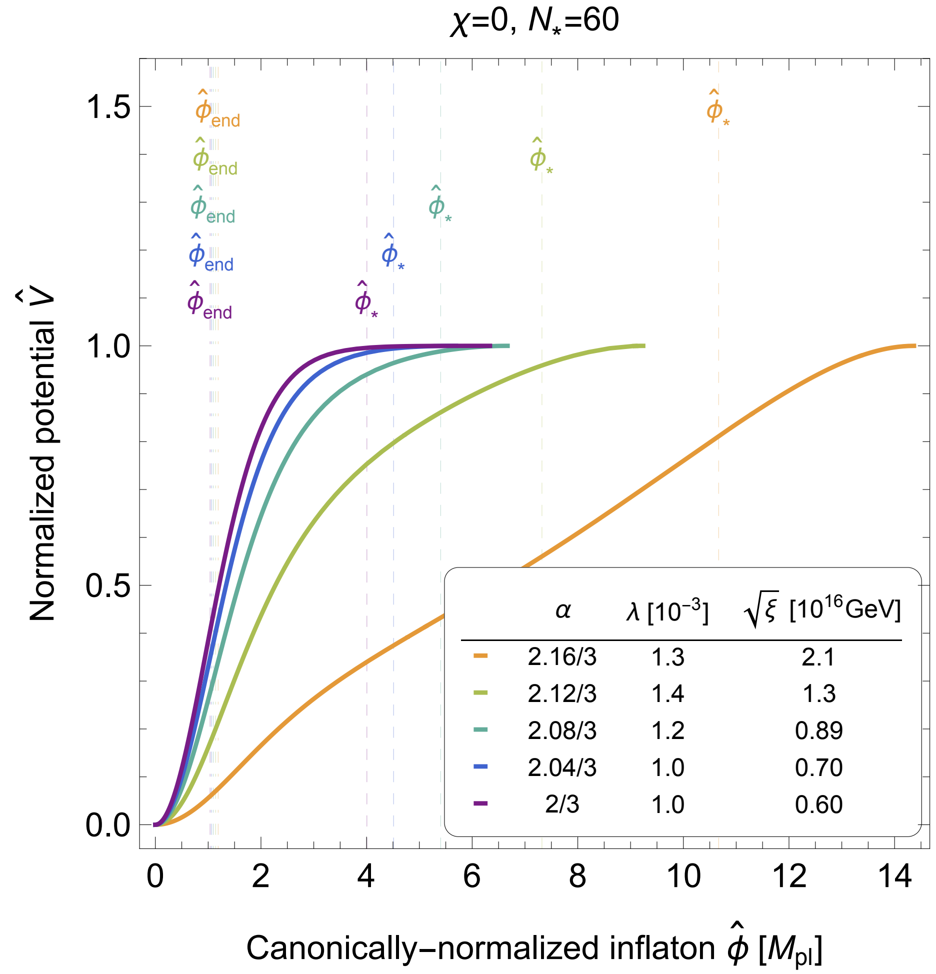
Canonically normalized inflaton $\hat{\phi}$ determined by solving the equation:

$$\frac{d\hat{\phi}}{d\phi} = K_{N\bar{N}}^{1/2}\Big|_{s=s_{\rm min}}$$

$$K_{N\bar{N}} \simeq \frac{3\alpha}{-\Phi(\phi)}\left[1 + \frac{(1+\chi)^2\phi^2}{-2\Phi(\phi)}\right] \quad (\because\ s_{\rm min} \simeq 0)$$

$\chi = 0$ case



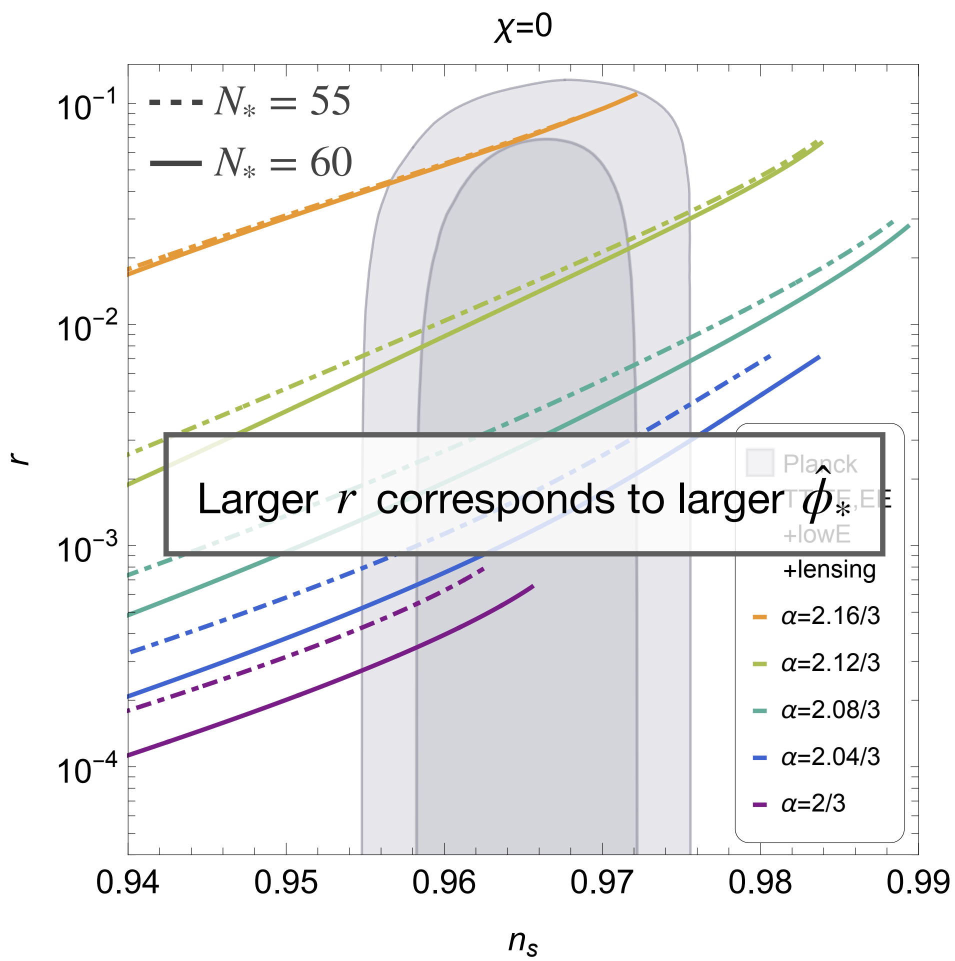


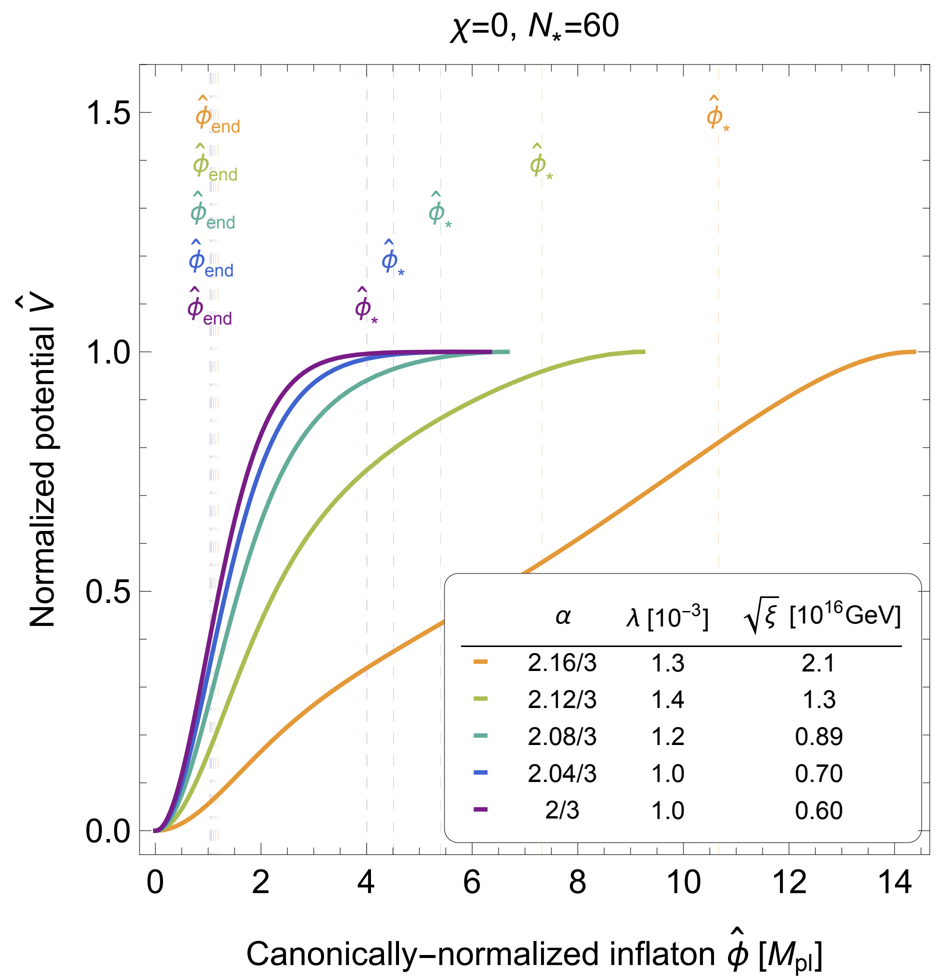
$$V = g^2 \xi^2 \Psi \left(1 - \frac{1}{2}\Psi\right)$$

$$\phi^2 = 6 \tanh^2 \frac{\hat{\phi}}{\sqrt{6\alpha}}$$

$$\Psi = \frac{3k}{\alpha^2} \tanh^2 \frac{\hat{\phi}}{\sqrt{6\alpha}} \times \cosh^{2(3\alpha-2)} \frac{\hat{\phi}}{\sqrt{6\alpha}}$$

$\chi = 0$ case





Potential in large field value limit for $\alpha \neq 2/3$

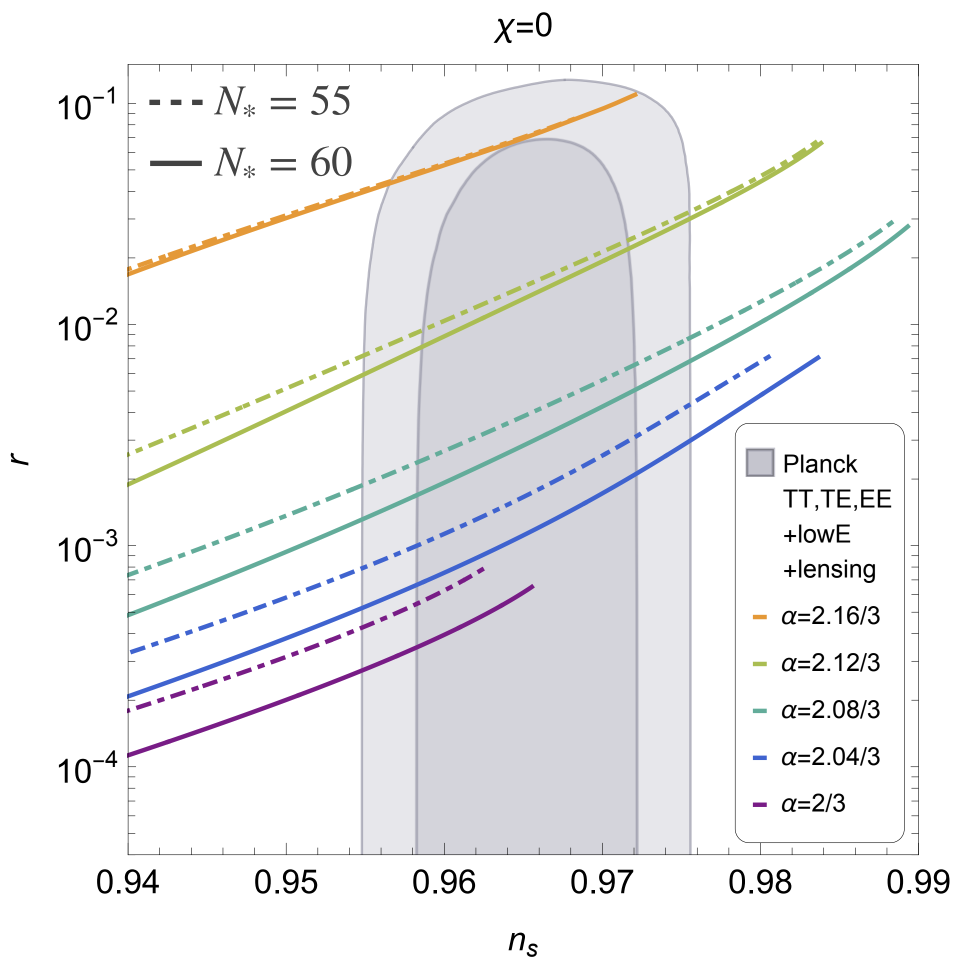
$$V = g^2\xi^2\Psi\left(1 - \frac{1}{2}\Psi\right) \sim V_0 e^{p\hat{\phi}} \qquad (\because \Psi \sim Ce^{p\hat{\phi}}) \qquad p = \sqrt{2/3\alpha}(3\alpha - 2)$$

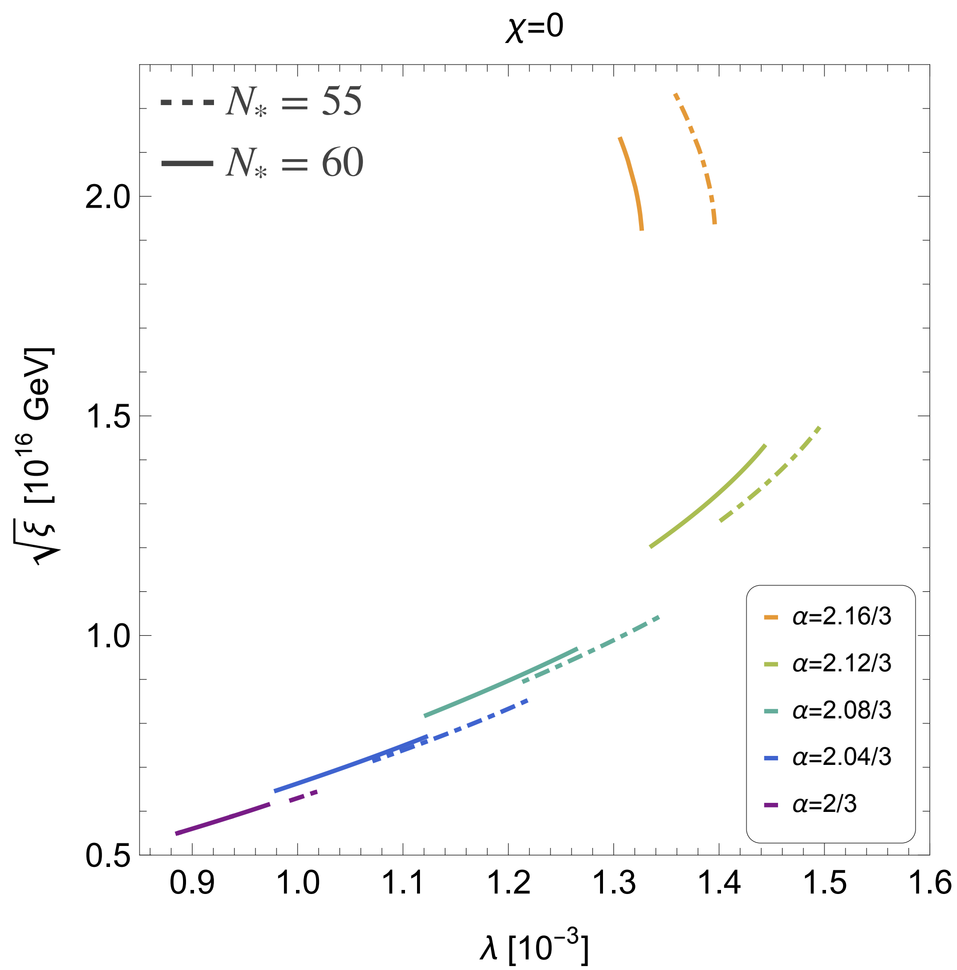
$$C = 3k/4^{3\alpha-2}\alpha^2$$

$$(n_s, r) \sim (1 - p^2, 8p^2) \qquad k = \lambda^2/qg^2\xi$$

Numerical results deviate from the approximation due to Ψ^2 term in the potential

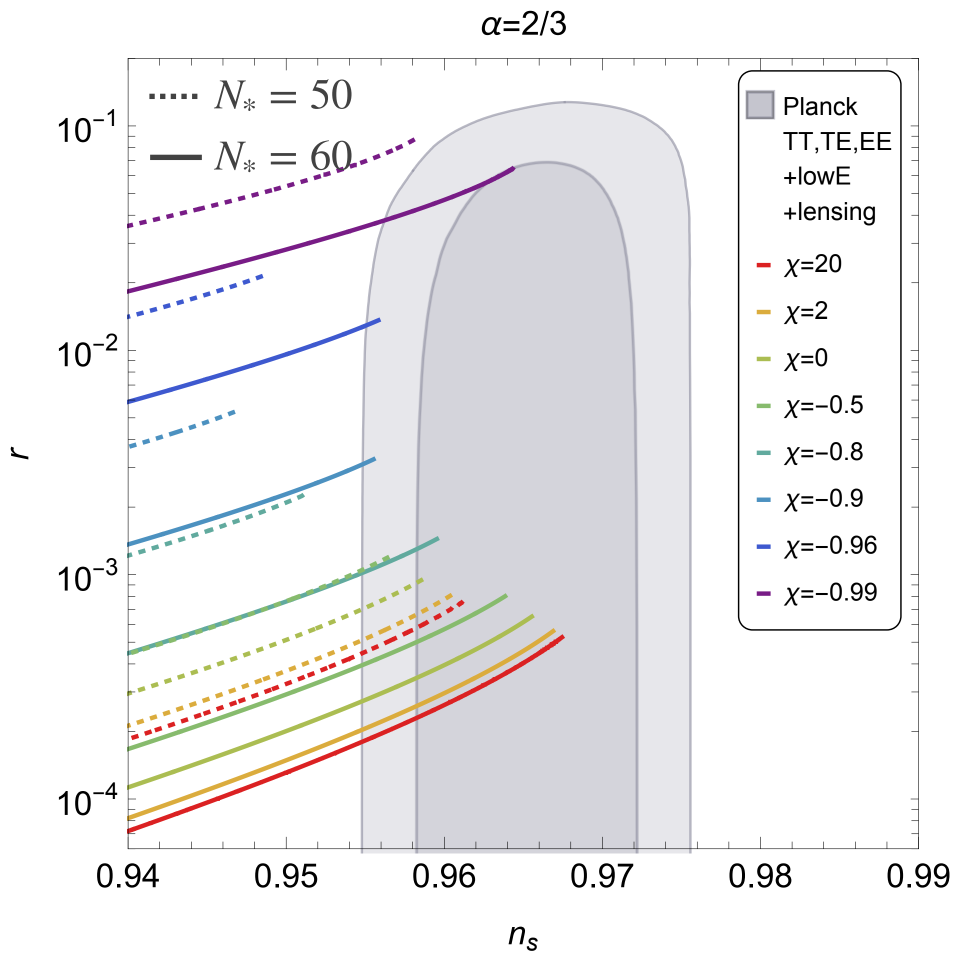
$\chi = 0$ case

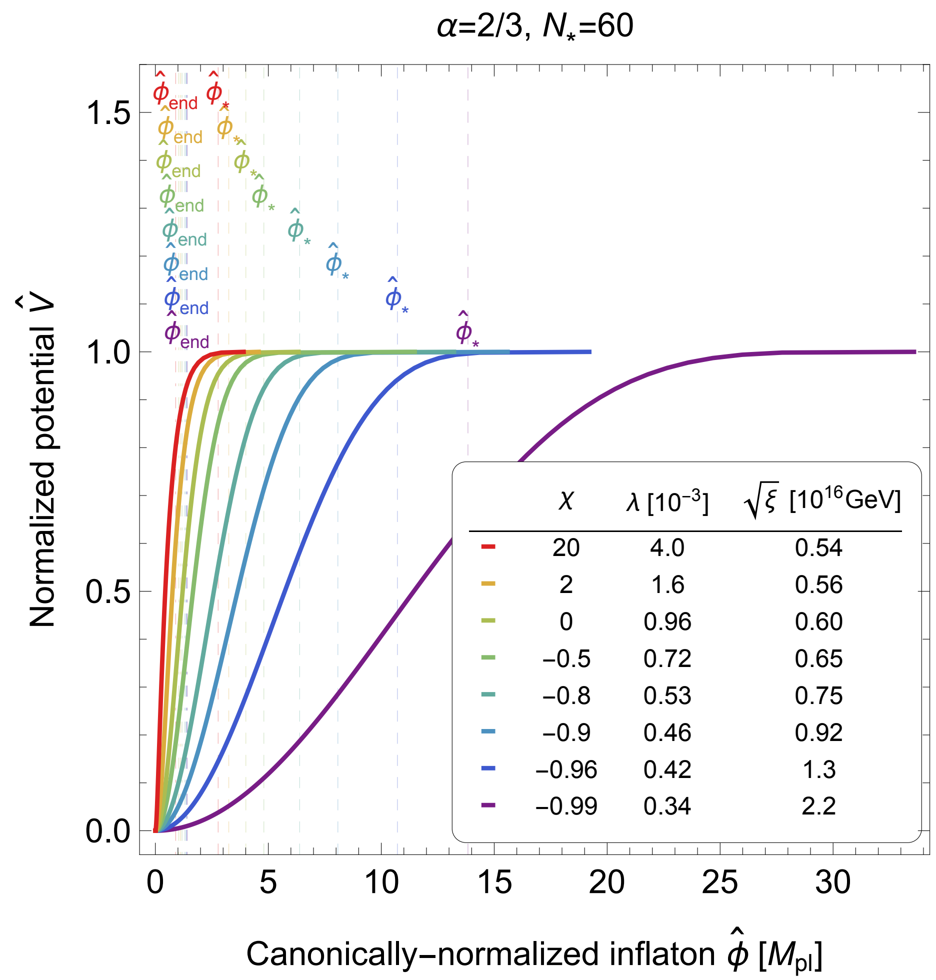




Allowed λ & $\sqrt{\xi}$ are $\lambda \sim 10^{-3}$ & $\sqrt{\xi} \sim 10^{16}\,\mathrm{GeV}$

$\alpha = 2/3$ case

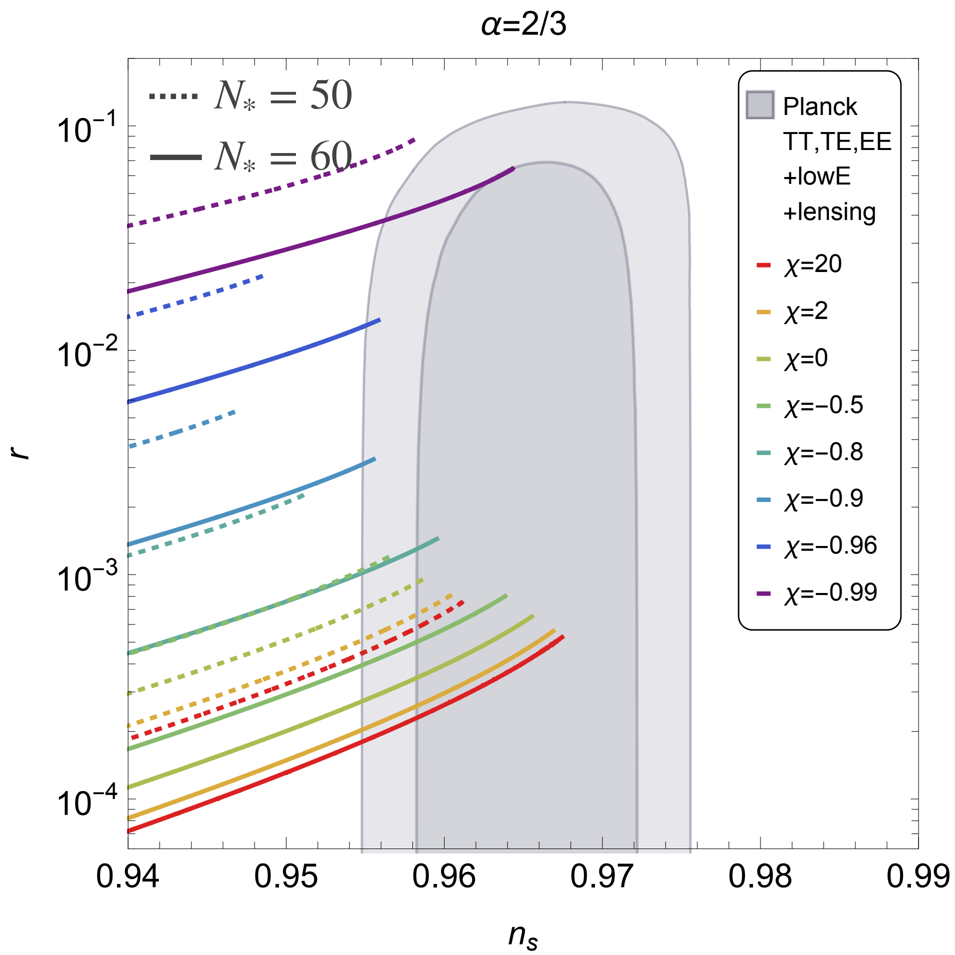


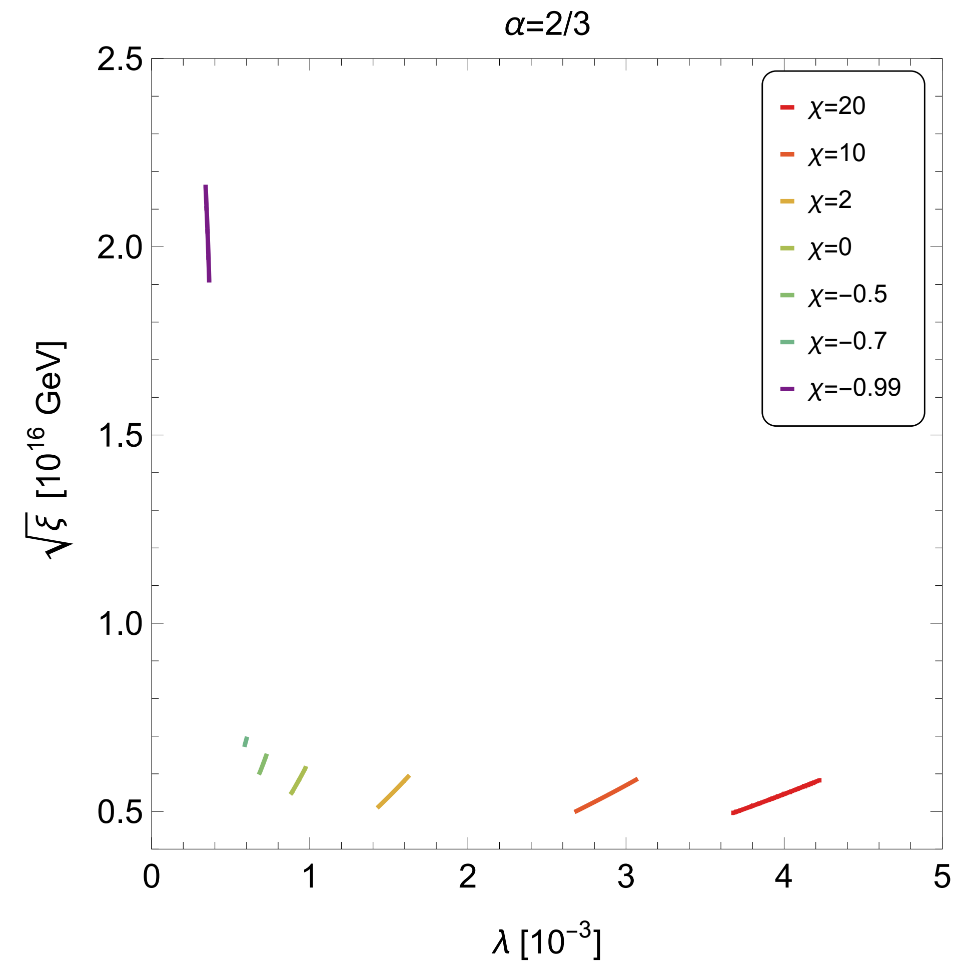


- Larger r corresponds to smaller k $\;(k = \lambda^2/qg^2\xi)$
- Largest r is determined by $\underline{k > 4(1+\chi)/27}$

This is give by $-\Phi(\phi_c)/3 > 0$, *i.e.*, $\phi_c < \sqrt{6/(1+\chi)}$

$\alpha = 2/3$ case





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