モジュラー不変な超対称模型における
ニュートリノ混合とインフレーション

arXiv:2208.10086

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2022年9月2日 基研研究会 素粒子物理学の進展2022 @ 基礎物理学研究所

1. Introduction

Standard Model (SM)

SM describes well phenomena of elementary particles below TeV scale

The phenomena unexplained in SM:

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

…

Neutrino masses & mixing

Observed values by neutrino oscillation experiments

NuFIT 5.0 ’20

	NH	IH
$\theta_{12}/^\circ$	$31.27 - 35.86$	$31.27 - 35.87$
$\theta_{23}/^\circ$	$40.1 - 51.7$	$40.3 - 51.8$
$\theta_{13}/^\circ$	$8.20 - 8.93$	$8.24 - 8.96$
$\delta_{CP}/^\circ$	$120 - 369$	$193 - 352$
$\frac{\Delta m^2_{21}}{10^{-5}\,\mathrm{eV}^2}$	$6.82 - 8.04$	$6.82 - 8.04$
$\frac{\Delta m^2_{3l}}{10^{-3}\,\mathrm{eV}^2}$	$2.435 - 2.598$	$-2.581 - -2.414$

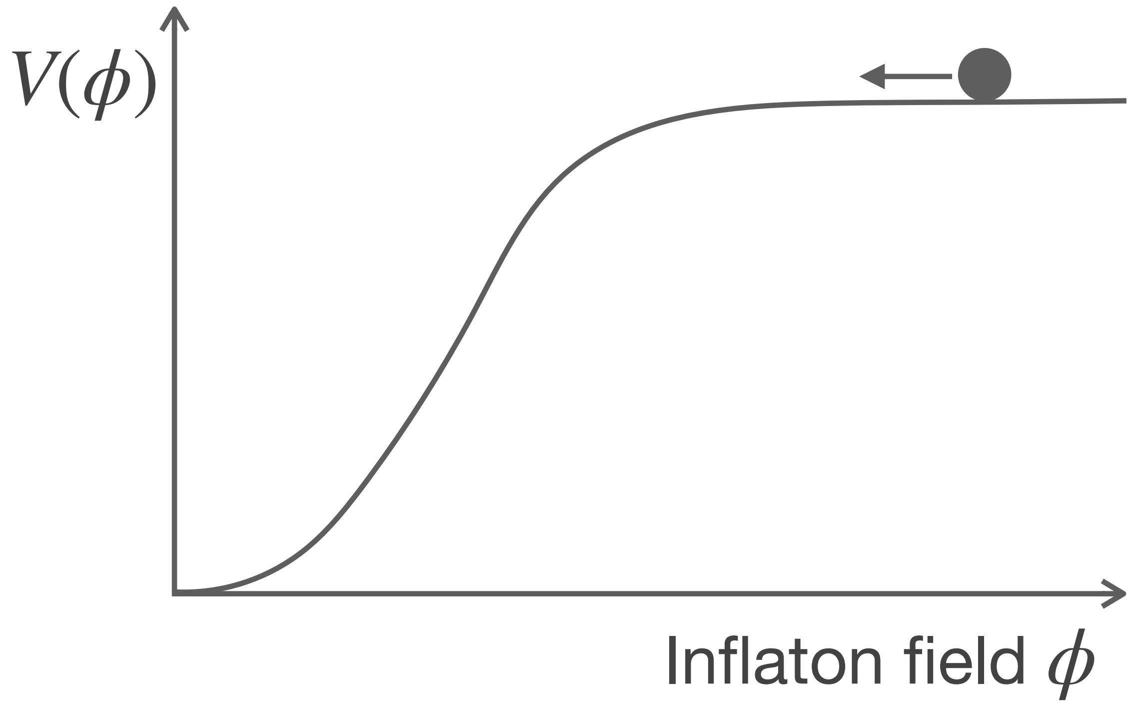
Large mixing angles

Light masses

SM cannot explain these results since neutrinos are massless in SM

Inflation

- Paradigm of accelerated expansion of the early universe
- Supported by cosmic microwave background (CMB) observations
- Realized by the potential energy of a slow-rolling scalar field (inflaton)



SM cannot explain inflation

The phenomena unexplained in SM:

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

…

The phenomena unexplained in SM:

The phenomena unexplained in SM indicate the existence of physics beyond the SM (BSM)

- Light neutrino masses & mixing

- Dark matter

…

Superstring theory

- A candidate for BSM
- Promising as a unified theory including gravity
- It has symmetries not found in SM

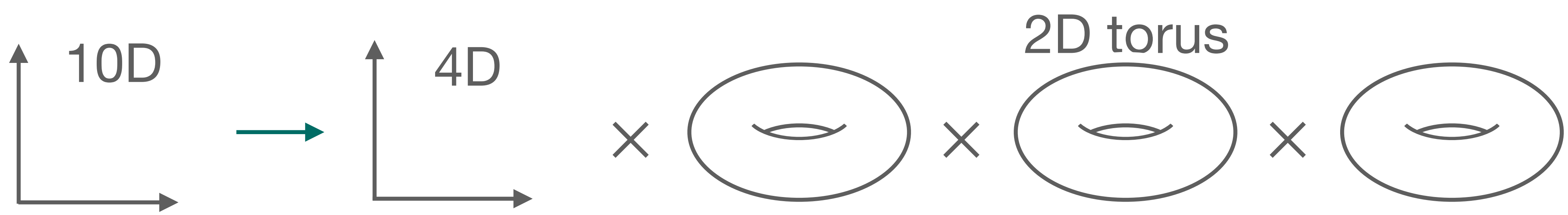
ex) Modular sym., Conformal sym., Supersymmetry (SUSY)

Phenomena unexplained in SM may originate from such symmetries

Modular symmetry

Approach to explain ν mass hierarchies & mixing by modular symmetry

Feruglio '17



- Appears trough torus compactification in superstring theory
- Geometric symmetry of 2D torus characterized by modulus τ
- Modular group has non-Abelian discrete groups as subgroups Γ_N :

$$\Gamma_2 \simeq S_3,\ \Gamma_3 \simeq A_4,\ \Gamma_4 \simeq S_4,\ \Gamma_5 \simeq A_5$$

Modular Γ_N symmetry have been considered to explain neutrino problems

Modular symmetry

eg.) Modular A_4 symmetric model Feruglio '17
Kobayashi, et.al., '18

- Yukawa & mass structures are determined by the symmetry
- Neutrino mass hierarchy & mixing patterns are explained
- Characteristic CP phases are predicted

Models that explain problems in SM based on the symmetries may provide clues to BSM

For neutrino & inflation

- Measurement accuracy has improved significantly in recent years
- Plans exist for future observations & experiments

→ Further findings are expected

Plan for model building

Consider a supersymmetric model with:

- Modular A_4 symmetry
- Inflation mechanism
- Three right-handed neutrinos N_i^c $(i = 1\text{-}3)$ with Majorana masses

Modular A_4 & SUSY

N_i^c — Neutrino masses & mixing

$\tilde{N}_i^c$ — Inflation

Identify the prediction of the model

Outline

2. The model

The model

- Superpotential

$$W_\lambda = \lambda S_+ S_- (N^c Y)_{\mathbf{1}}$$

$$W_N = \Lambda (N^c N^c Y)_{\mathbf{1}}$$

$$W_D = g_1 (N^c H_u (LY)_{\mathbf{3s}})_{\mathbf{1}} + g_2 (N^c H_u (LY)_{\mathbf{3a}})_{\mathbf{1}}$$

	L	N^c	H_u	S_+	S_-
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
U(1)	0	0	0	$+q$	$-q$

g_i, λ: Yukawa coupling

Λ: Mass scale of N^c

- A_4 triplet modular form Feruglio '17

$$Y = (Y_1(\tau), Y_2(\tau), Y_3(\tau))^T$$

Yukawa & mass structures are characterized by $Y(\tau)$

The model

- Superpotential

$$W_\lambda = \lambda S_+ S_- (N^c Y)_{\mathbf{1}}$$

Inflation

$$W_N = \Lambda (N^c N^c Y)_{\mathbf{1}}$$

$$W_D = g_1 (N^c H_u (LY)_{\mathbf{3s}})_{\mathbf{1}} + g_2 (N^c H_u (LY)_{\mathbf{3a}})_{\mathbf{1}}$$

Neutrino masses & mixing

	L	N^c	H_u	S_+	S_-
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
U(1)	0	0	0	$+q$	$-q$

g_i, λ: Yukawa coupling

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- A_4 triplet modular form Feruglio '17

$$Y = (Y_1(\tau), Y_2(\tau), Y_3(\tau))^T$$

Yukawa & mass structures are characterized by $Y(\tau)$

3. Neutrino masses & mixing pattern

Light neutrino masses

$$W_{\text{neu}} = W_D + W_N + W_\lambda$$

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

$$\tilde{M}_D = \langle H_u \rangle \begin{pmatrix} 2g_1Y_1 & (-g_1+g_2)Y_3 & (-g_1-g_2)Y_2 \\ (-g_1-g_2)Y_3 & 2g_1Y_2 & (-g_1+g_2)Y_1 \\ (-g_1+g_2)Y_2 & (-g_1-g_2)Y_1 & 2g_1Y_3 \\ 0 & 0 & 0 \end{pmatrix}$$

4×3 matrix

$$\tilde{M} = \Lambda \begin{pmatrix} 2Y_1 & -Y_3 & -Y_2 & rY1 \\ -Y_3 & 2Y_2 & -Y_1 & rY_3 \\ -Y_2 & -Y_1 & 2Y_3 & rY_2 \\ rY_1 & rY_3 & rY_2 & 0 \end{pmatrix}$$

4×4 matrix

$r = \lambda \langle S_+ \rangle / \Lambda$
$\langle S_+ \rangle$: VEV of S_+
$\langle H_u \rangle$: VEV of H_u

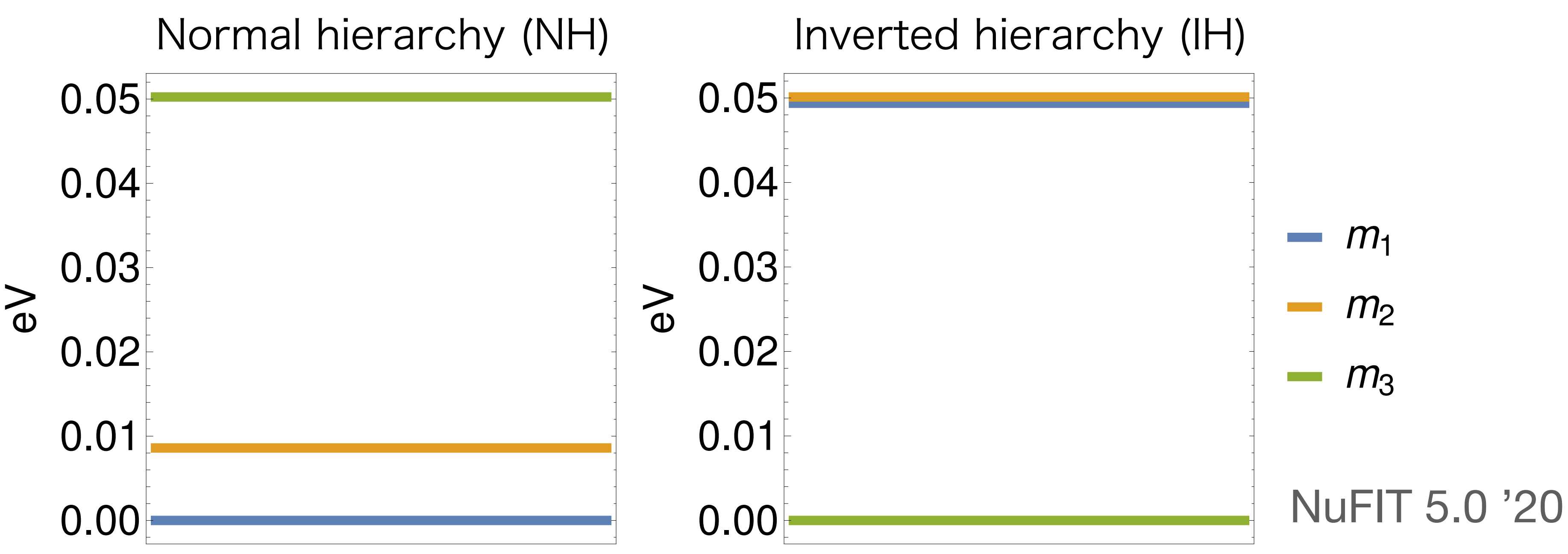
The mass matrix is different from a conventional one

Light neutrino masses

$$W_{\rm neu} = W_D + W_N + W_\lambda$$

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

Lightest neutrino mass is zero ($\because$ rank $M_\nu = 2$)



Neutrino mixing

Lightest neutrino mass is zero

↓

One of the two Majorana phases in mixing matrix U_{PMNS} vanishes

U_{PMNS} is parametrized by:

- Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$
- Two CP phases $\delta_{\mathrm{CP}},\ \alpha_{21}$

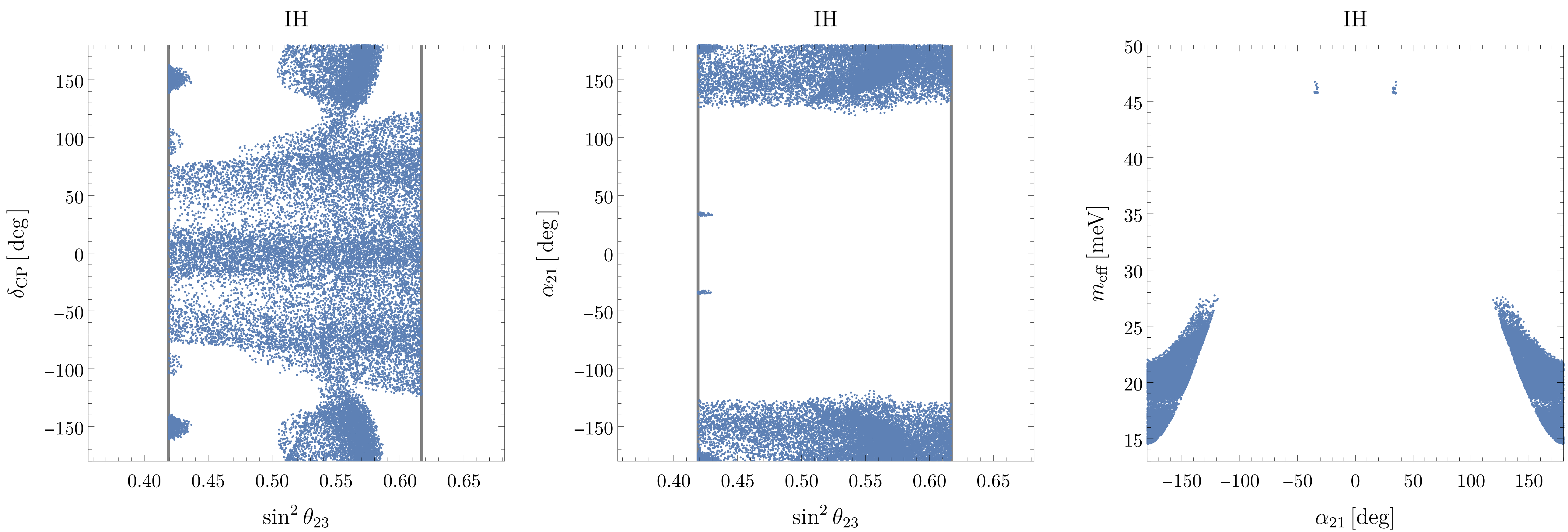
δ_{CP}: Dirac phase

α_{21}: Majorana phase

We have investigated consistency of this model with neutrino expt.

- Consider both NH & IH cases
- Identify predicted value for CP phases $\delta_{\mathrm{CP}},\ \alpha_{21}$

Numerical results



- Only IH is allowed
- δ_{CP} has characteristic pattern
- α_{21} is localized around $\pm(120°\text{-}180°)$
- m_{eff} of $0\nu\beta\beta$ has relatively large value

Effective mass of $0\nu\beta\beta$ decay

$$m_{\mathrm{eff}} \equiv \left| \sum_i U_{ei}^2\, m_i \right|$$

→ Results can be tested in future experiments

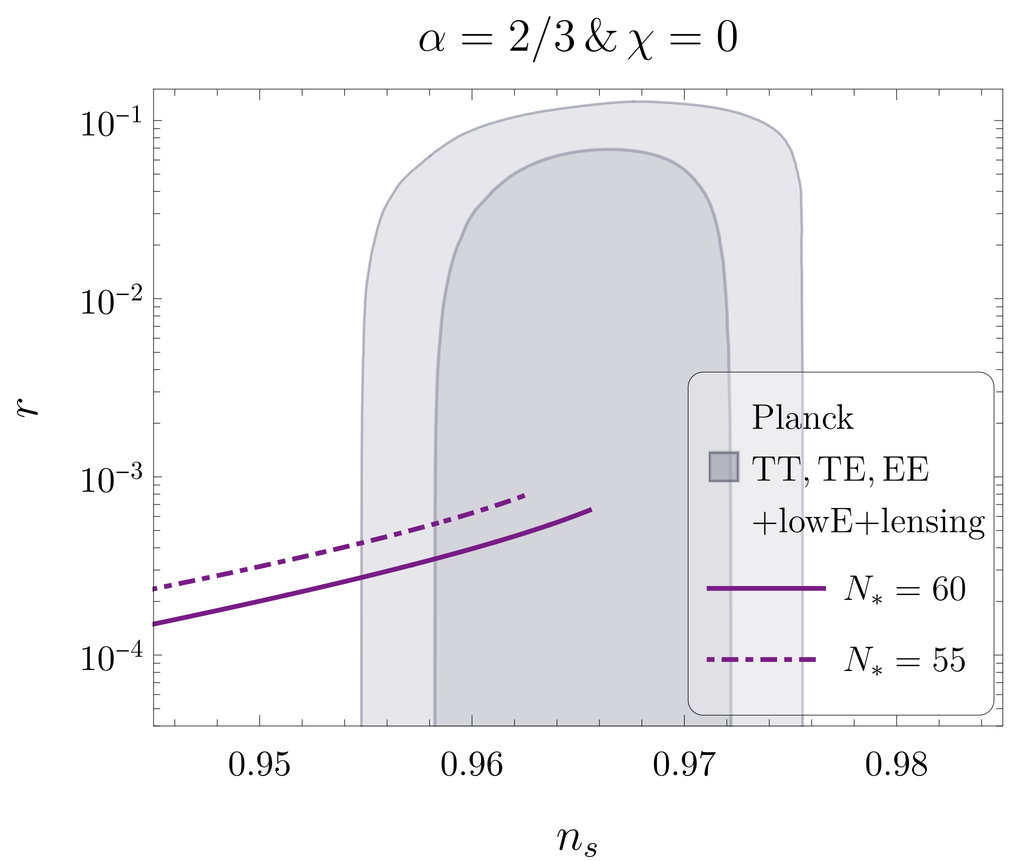
4. Inflation

Plan for inflation

YG & Ishiwata '21

Consider the hybrid type inflation proposed in a superconformal model

Consistent with CMB observations



Superpotential

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

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

$$q > 0$$

Inflaton field

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

Inflation

- One of the right-handed sneutrinos plays the role of inflaton

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

- Superpotential on inflation

  $W_{\rm inf} = W_\lambda + \underline{W_N}$ Term not in the superconf. model

  $W_\lambda = \lambda S_+ S_- (N^c Y)_{\mathbf{1}}$
  $W_N = \Lambda (N^c N^c Y)_{\mathbf{1}}$

- Assume $\Lambda \ll 1$
  - To ignore the impact of W_N on inflaton potential ($W_N \propto \Lambda$)
  - To realize the same inflation as in superconf. model

→ Estimate how small Λ must be

Impact of Majorana masses on inflation

Λ dependent term may disturb inflation trajectory

$$V_{\text{inf}} = V + \Delta V(\Lambda) \qquad \Delta V(\Lambda) \propto \Lambda^2$$

To avoid the impact of Λ dependent term on the inflation trajectory

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

↓

The upper bound on Λ

$$\Lambda \lesssim 10^{10}\ \text{GeV} \quad (\ll m_\phi)$$

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

Future work

Remaining the other problems unexplained in SM:

✓ Inflation

- Reheating ⟵ Inflaton decay
- Baryon asymmetry ⟵ Leptogenesis

✓ Light neutrino masses & mixing

- Dark matter

…

Summary

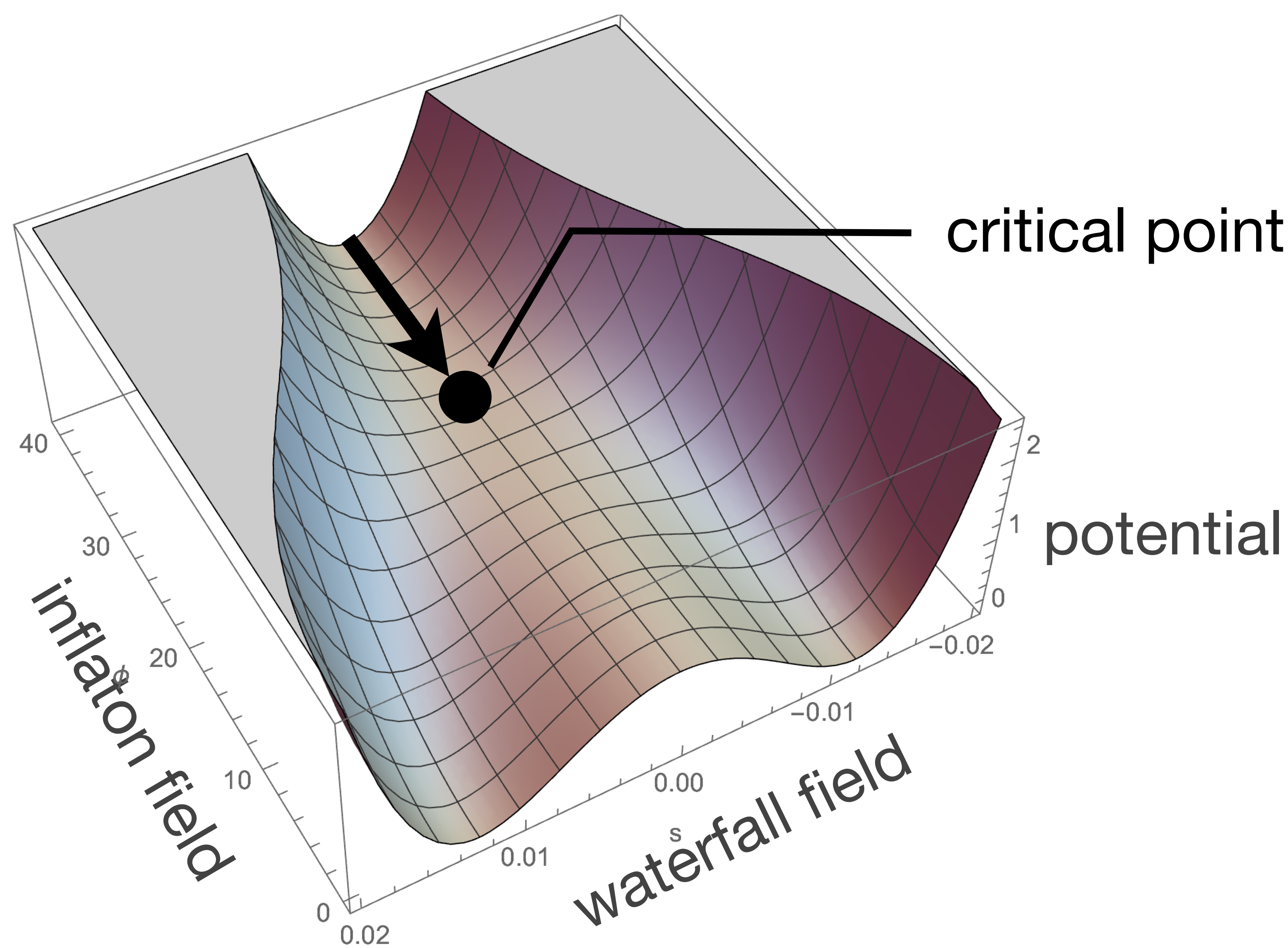
We have studied neutrino mixing & inflation in a SUSY model with modular A_4 symmetry

- Light neutrino mass matrix given by seesaw mechanism has an unconventional pattern
- Only IH is consistent with neutrino experiments & characteristic pattern of CP phases are predicted
- One of the right-handed sneutrinos plays the roll of inflaton & $\Lambda \lesssim 10^{10}\,\mathrm{GeV}$ is required for successful inflation
- Thermal history after the inflation will be studied in the future work

Backup

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



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)

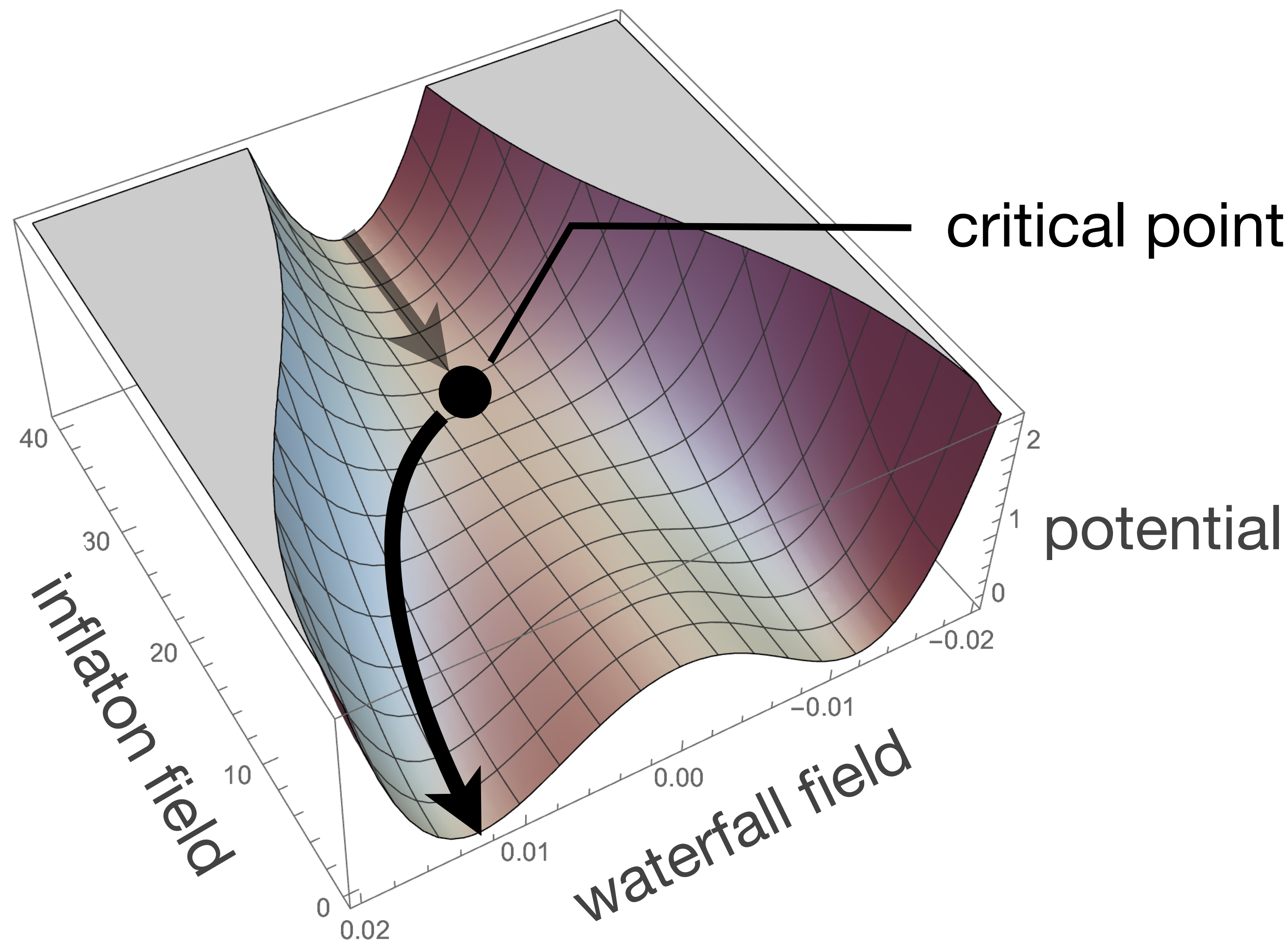
  Ishiwata '18

- Generlalized superconf. — Various types depending on params. (below critical point)

  YG & Ishiwata '21

Subcritical hybrid inflation

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



Superconformal subcritical hybrid inflation

Ishiwata '18
YG & Ishiwata '21

- Superpotential

$W = \lambda S_+ S_- N$

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

$q > 0$

- Kähler potential

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

$\alpha > 0$

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

superconf. breaking term

- Constant Fayet-Iliopoulos term ξ (>0)

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

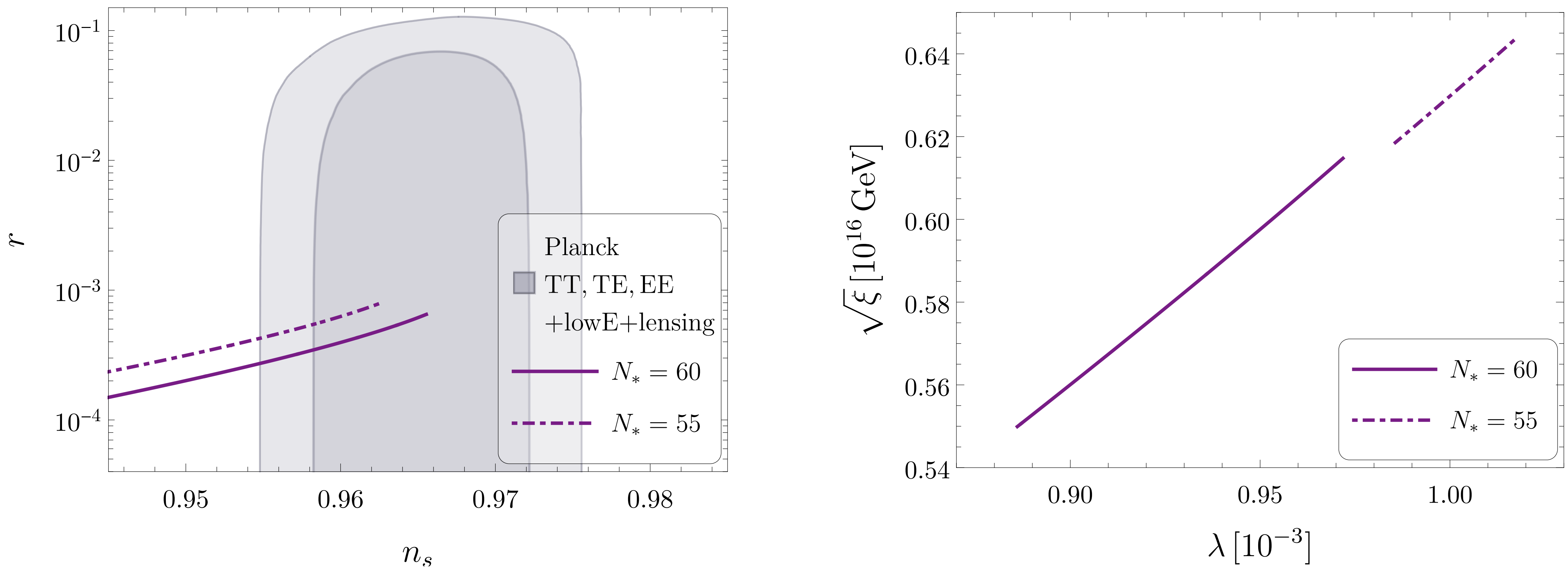
$s \equiv \sqrt{2}\,|S_+|$: Waterfall field

$M_{\rm pl} = 1$

Superconformal subcritical hybrid inflation

YG & Ishiwata '21

Simple case: $\alpha = 2/3$ & $\chi = 0$



- Parameter values consistent with CMB: $\lambda \simeq 10^{-3}, \sqrt{\xi} \simeq 0.6 \times 10^{16}\,\mathrm{GeV}$
- Inflaton mass: $m_\phi \simeq \lambda\sqrt{\xi} \simeq 10^{13}\,\mathrm{GeV}$

Modular transformation

Modular transformation:

$$\tau \to \gamma\tau = \frac{a\tau + b}{c\tau + d} \qquad (a, b, c, d \in \mathbb{Z},\ ad - bc = 1)$$

Modular group consists of two generators S & T:

$$S : \tau \to -1/\tau, \quad T : \tau \to \tau + 1$$

Transformation laws under modular transformation:

- Chiral superfields X^I

  $$X^I \to (c\tau + d)^{-k_I}\rho^I(\gamma)X^I$$

- Modular form $f(\tau)$ of weight k

  $$f(\tau) \to (c\tau + d)^k\rho(\gamma)f(\tau)$$

$c, d \in \mathbb{Z}$

k, k_I: Modular weight

$\rho(\gamma), \rho^I(\gamma)$: Unitary representation of Γ_N

Γ_N : Finite subgroup

$\Gamma_2 \simeq S_3,\ \Gamma_3 \simeq A_4,\ \Gamma_4 \simeq S_4,\ \Gamma_5 \simeq A_5$

The model (Kähler potential)

Kähler potential: $K = K^{\mathrm{m}} + K^{\tau}$

$$K^{\mathrm{m}} = -3\alpha \log\left(-\frac{\Phi}{3}\right), \quad \Phi = -3 + \underbrace{\sum_I \frac{|X^I|^2}{(2\mathrm{Im}\,\tau)^{k_I}}}_{\text{Modular inv.}}$$

$X^I = \{X^{\mathrm{MSSM}}, N_i^c, S_\pm\}$

k^I: Modular weight of X^I

$$K^{\tau} = -3n \log(2\mathrm{Im}\,\tau) \xrightarrow{\text{Modular transf.}} K^{\tau} + 3n \log|c\tau + d|^2$$

The model (Modular weight)

Modular symmetry in SUGRA

- Combination of Kähler potential & superpotential should be invariant

Feruglio '17

$$G = K + \log |W|^2$$

Modular inv.

K : Kähler potential

W: Superpotential

- Superpotential has modular weight $-3n$

$$W \longrightarrow (c\tau + d)^{-3n} W \qquad \because K \to K + 3n \log |c\tau + d|^2$$

Modular transf.

The model (Assignment of modular weights)

Superpotential

$$W_\lambda = \lambda S_+ S_- (N^c Y)_{\mathbf{1}}$$

$$W_N = \Lambda (N^c N^c Y)_{\mathbf{1}}$$

$$W_D = g_1 (N^c H_u (LY)_{\mathbf{3s}})_{\mathbf{1}} + g_2 (N^c H_u (LY)_{\mathbf{3a}})_{\mathbf{1}}$$

	L	$e^c,\ \mu^c,\ \tau^c$	N^c	$H_{u,d}$	$S_\pm$
A_4	$\mathbf{3}$	$\mathbf{1},\ \mathbf{1}',\ \mathbf{1}''$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$
k_I	k_L	k_{e^c,μ^c,τ^c}	k_{N^c}	$k_{H_{u,d}}$	$k_{S_\pm}$

g_i, λ: Yukawa coupling const.

Λ: Majorana mass scale of N^c

A_4 triplet modular form of weight 2

Feruglio '17

$$Y = (Y_1(\tau), Y_2(\tau), Y_3(\tau))^T$$

Assignment of modular weights

$$k_L = 1,\ k_{N^c} = k_{e^c,\mu^c,\tau^c} = 2k_{S_\pm} = k_{H_{u,d}} + 1 = (3n+2)/2$$

Tensor product of A_4

$$\begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}_{\mathbf{3}} \otimes \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}_{\mathbf{3}} = (a_1b_1 + a_2b_3 + a_3b_2)_{\mathbf{1}} \oplus (a_3b_3 + a_1b_2 + a_2b_1)_{\mathbf{1}'}$$

$$\oplus\, (a_2b_2 + a_1b_3 + a_3b_1)_{\mathbf{1}''}$$

$$\oplus\, \frac{1}{3}\begin{pmatrix} 2a_1b_1 - a_2b_3 - a_3b_2 \\ 2a_3b_3 - a_1b_2 - a_2b_1 \\ 2a_2b_2 - a_1b_3 - a_3b_1 \end{pmatrix}_{\mathbf{3s}} \oplus \frac{1}{2}\begin{pmatrix} a_2b_3 - a_3b_2 \\ a_1b_2 - a_2b_1 \\ a_3b_1 - a_1b_3 \end{pmatrix}_{\mathbf{3a}} ,$$

$$\mathbf{1} \otimes \mathbf{1} = \mathbf{1}\,, \quad \mathbf{1}' \otimes \mathbf{1}' = \mathbf{1}''\,, \quad \mathbf{1}'' \otimes \mathbf{1}'' = \mathbf{1}'\,, \quad \mathbf{1}' \otimes \mathbf{1}'' = \mathbf{1}$$

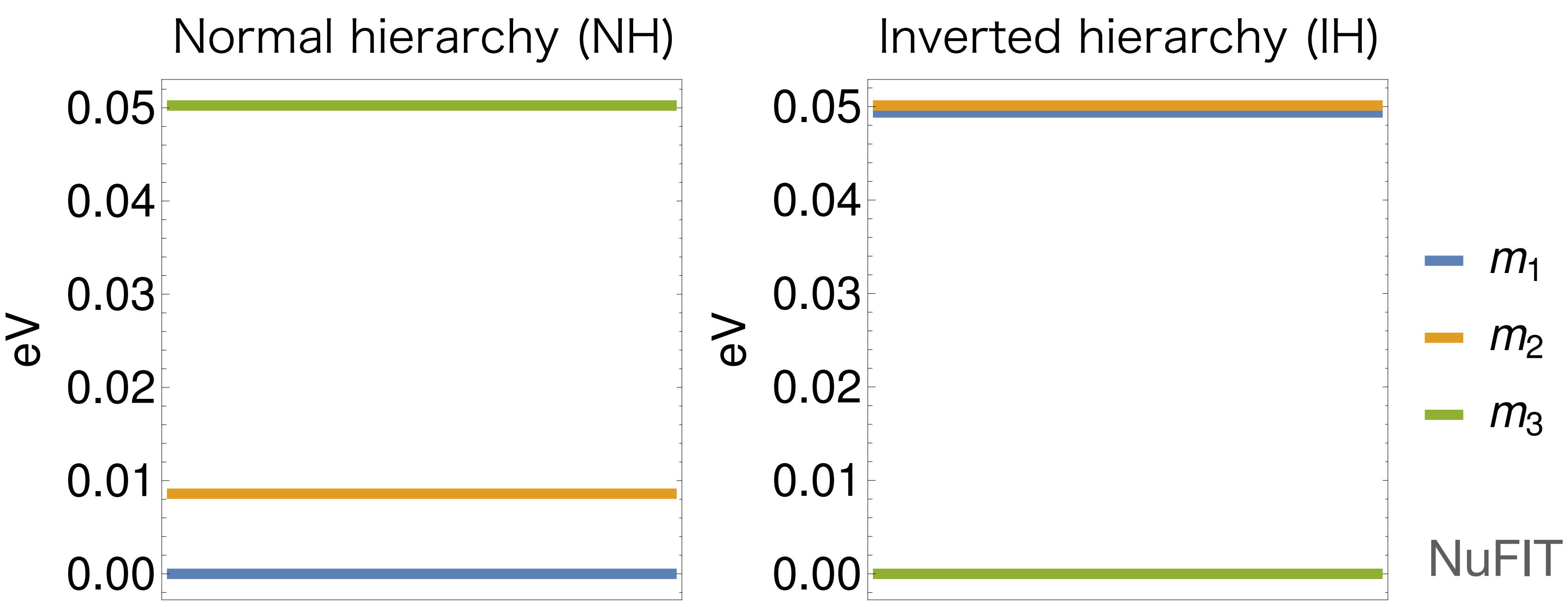
Light neutrino masses

$$W_{\text{neu}} = W_D + W_N + W_\lambda$$

Seesaw mechanism: $M_\nu = A\, f(g_2/g_1, \tau) \qquad A \propto g_1^2/\Lambda$

- Λ, λ, ξ are not restricted from neutrino experiments
  become free parameters

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



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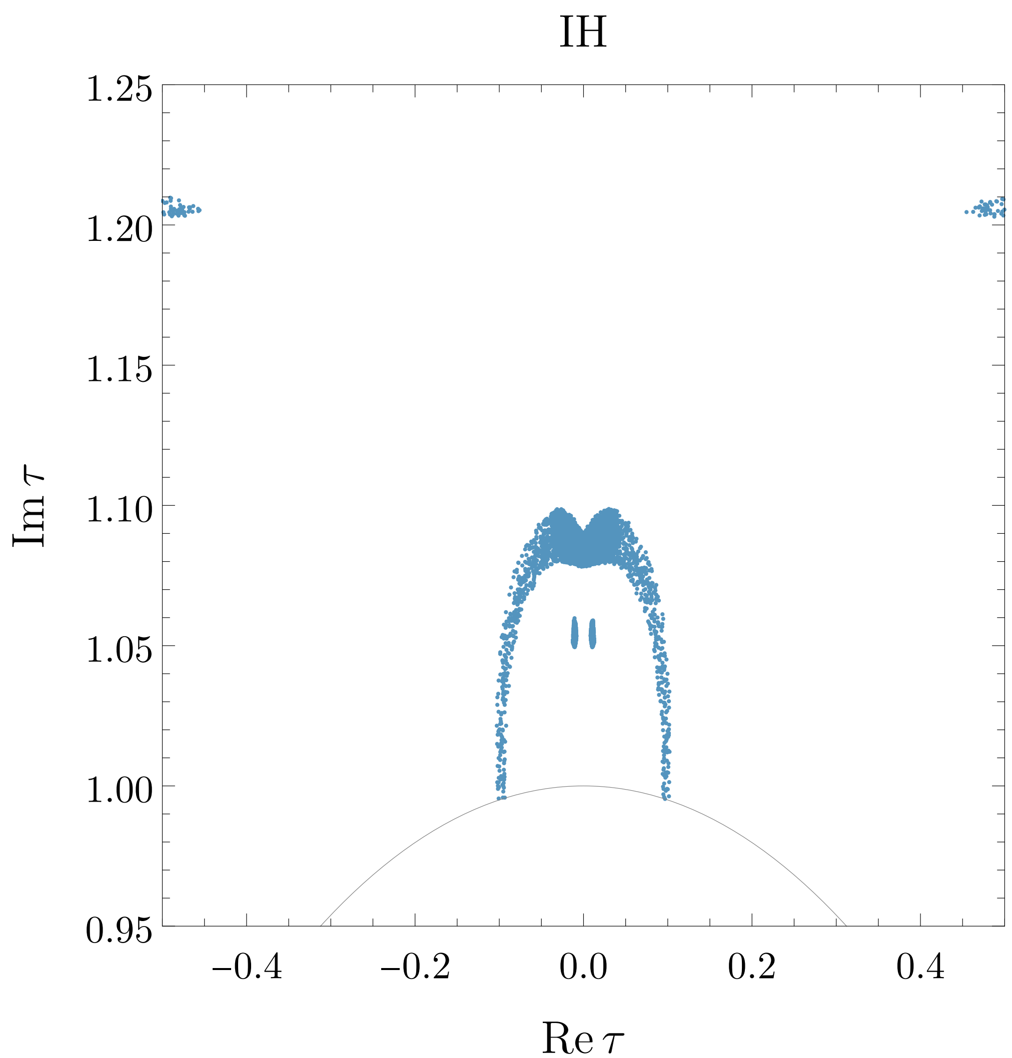
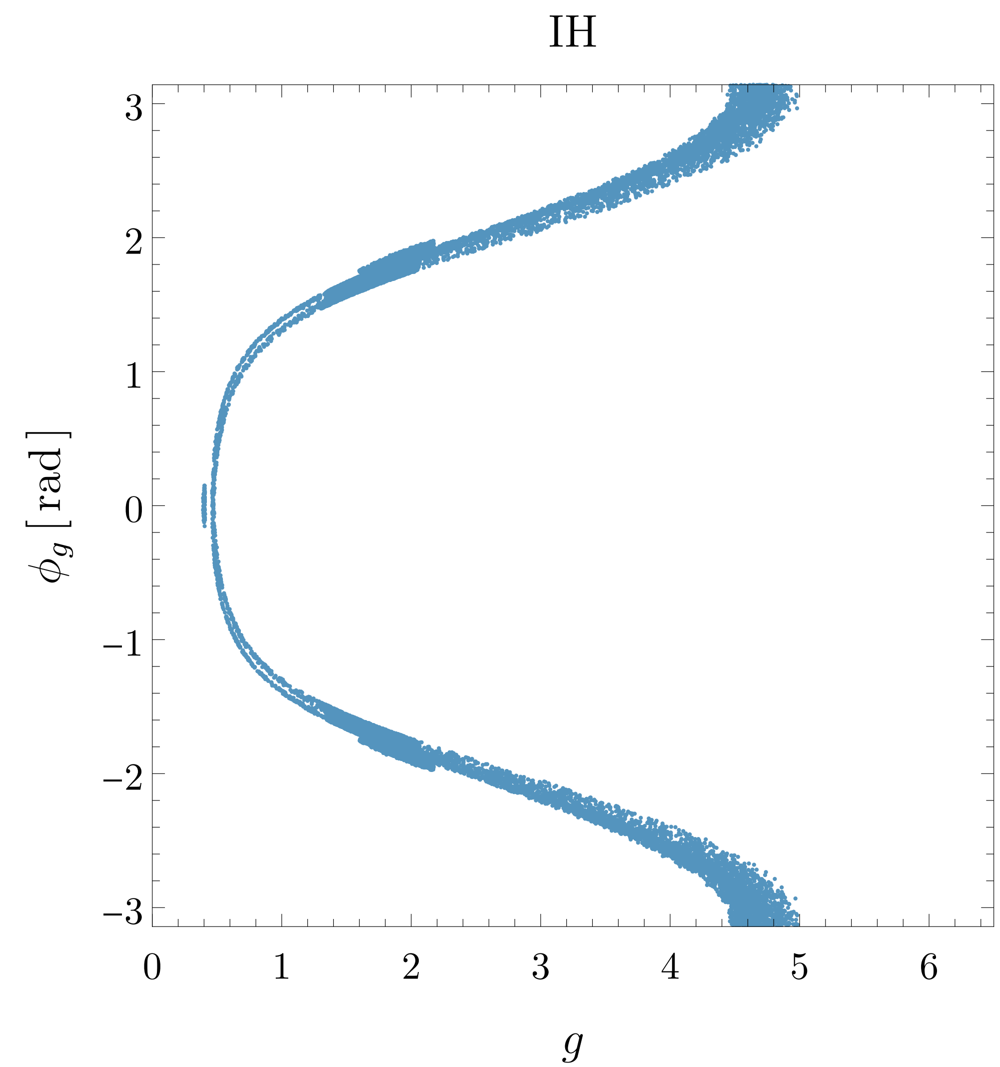
Numerical results (Allowed region for τ & g_2/g_1)

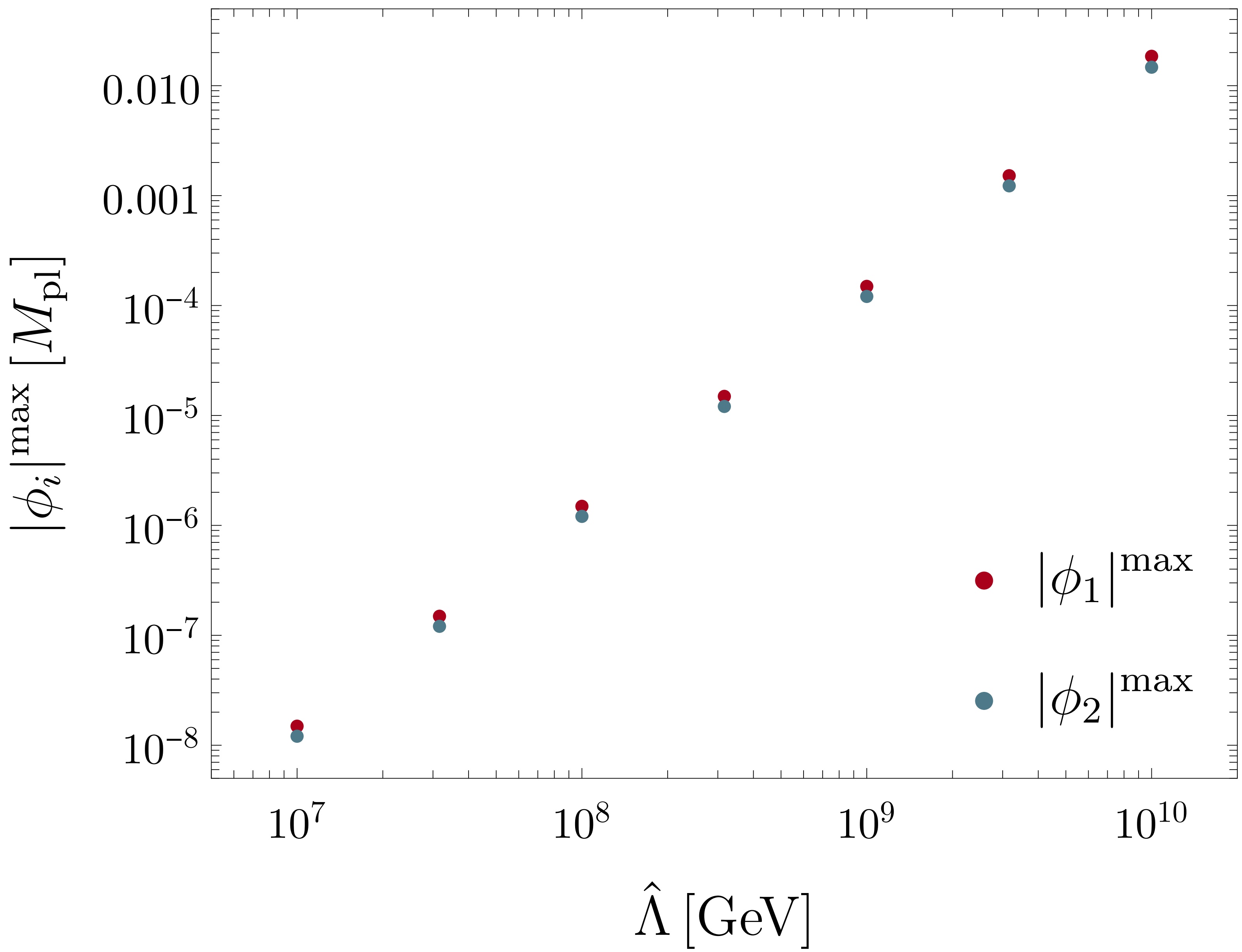




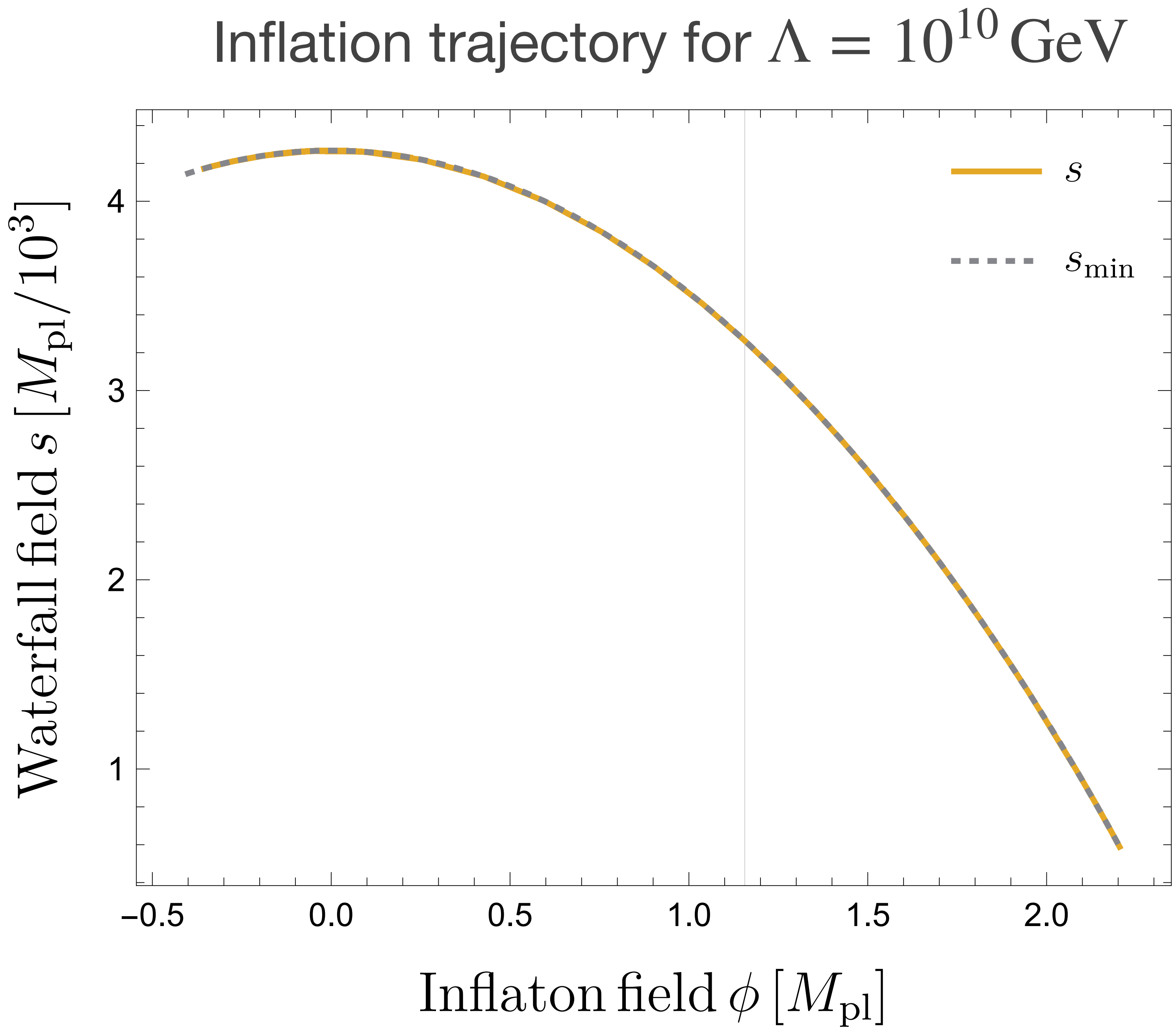
$$g_2/g_1 \equiv g e^{i\phi_g}$$

Impact of Majorana masses on inflation

Growth of $\tilde{N}^c_{1,2}$ during inflation through the Majorana mass term



Impact of Majorana masses on inflation



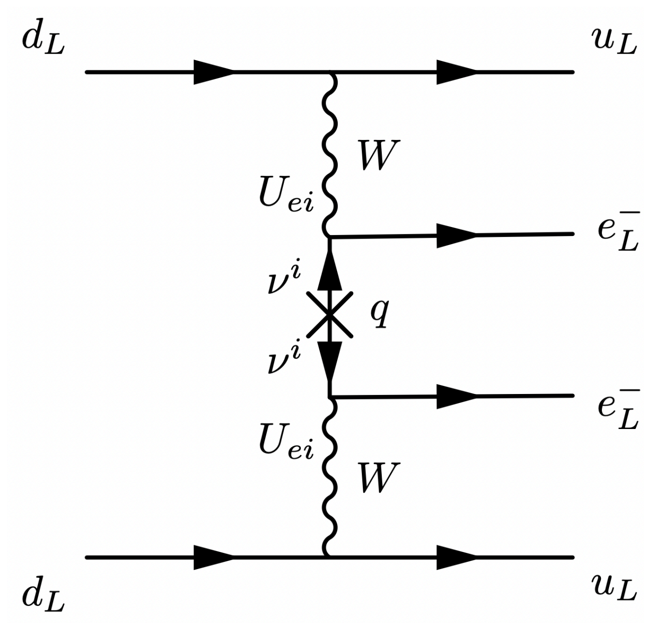
Neutrinoless double beta decay

- A lepton number violating process in low-energy

$$(A, Z) \to (A, Z+2) + 2e^-$$

A : Atomic number

Z : Mass number



- Decay rate is proportional to $m_{\rm eff}^2$

$$T_{1/2}^{0\nu\,-1} = G\,|\,\mathcal{M}\,|^2 m_{\rm eff}^2$$

G : Phase-space factor $\sim \mathcal{O}(10^{-25})/(\mathrm{y\ eV^2})$

$\mathcal{M}$: Nuclear matrix element

$m_{\rm eff}$: Effective mass

- Experimental upper bound on $m_{\rm eff}$

$m_{\rm eff} < 36\text{-}156\ \mathrm{meV}$ KamLAND-Zen '22

(There is uncertainty of $\mathcal{M}$ in decay process)