Flaxion
– Axion from Flavor Symmetry –

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Ema, Hamaguchi, TM, Nakayama, JHEP 1701 (2017) 096

Ema, Hagihara, Hamaguchi, TM, Nakayama, 1802.07739

Benasque, Spain, '18.05.09

1. Introduction

We often try to explain small parameters by symmetries

- Hierarchies in the fermion masses and mixings

  $\Rightarrow$ Flavor symmetry

  Here, I assume that the flavor symmetry is $U(1)_{\mathsf{F}}$

- Strong CP problem (i.e., smallness of the θ parameter)

  $\Rightarrow$ Peccei-Quinn symmetry

The subject today:

Identify $U(1)_{\mathsf{F}}$ and $U(1)_{\mathsf{PQ}}$

[Wilczek ('82)]

I will discuss a scenario with $U(1)_{\mathsf{F}} = U(1)_{\mathsf{PQ}}$

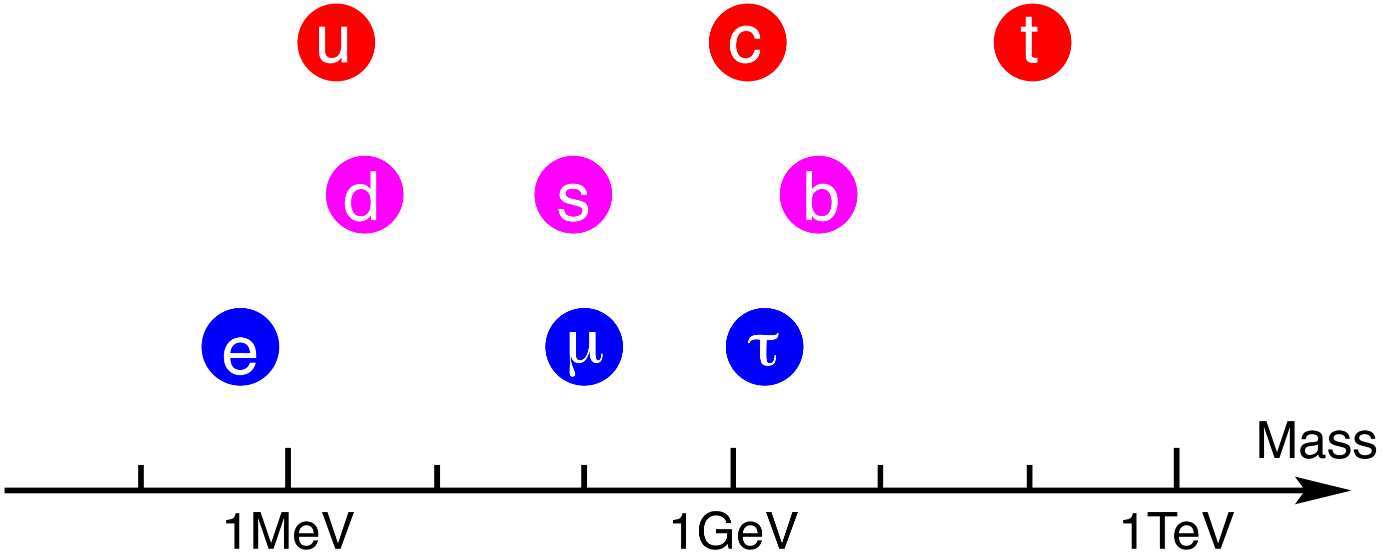
- Phenomenological constraints
- Cosmological issues

Outline

1. Introduction
2. $U(1)_{\mathsf{F}}$ as $U(1)_{\mathsf{PQ}}$
3. Phenomenological Issues
4. Sflaxion as Inflaton
5. Summary

2. $U(1)_{\mathsf{F}}$ as $U(1)_{\mathsf{PQ}}$

Fermion masses (and mixings) in the SM are hierarchical



⇒ Why?

One possibility for the fermion mass hierarchies

Flavor symmetry with Froggatt-Nielsen mechanism

We assume global $U(1)_{\mathsf{F}}$ symmetry

$$\mathcal{L}_{\mathsf{Yukawa}} = \hat{y}^{(f)}\overline{f_L}f_R H \to y^{(f)}\left(\frac{\phi}{M}\right)^{q_{F_L}-q_{F_R}}\overline{f_L}f_R H$$

- ϕ: Flavon (with flavor charge -1)
- $q_{f_{L,R}}$: Flavor charges of fermions
- M: Cut-off scale

Assumption: hierarchies are due to the smallness of $\epsilon \equiv \dfrac{\langle\phi\rangle}{M}$

$$\Rightarrow y^{(F)} \sim 1$$

$$\Rightarrow \epsilon = \frac{\langle\phi\rangle}{M} \ll 1$$

Hereafter, we take $\epsilon \sim 0.2$

Our canonical choice (for the quark sector)

$$\begin{pmatrix} q_{Q_{L,1}} & q_{Q_{L,2}} & q_{Q_{L,3}} \\ q_{U_{R,1}} & q_{U_{R,2}} & q_{U_{R,3}} \\ q_{D_{R,1}} & q_{D_{R,2}} & q_{D_{R,3}} \end{pmatrix} = \begin{pmatrix} 3 & 2 & 0 \\ -5 & -1 & 0 \\ -4 & -3 & -3 \end{pmatrix}$$

Then, after diagonalizing the mass matrices

- $m_U \sim \left(\epsilon^8, \epsilon^3, 1\right) \langle H \rangle$
- $m_D \sim \left(\epsilon^7, \epsilon^5, \epsilon^3\right) \langle H \rangle$
- $V_{\mathsf{CKM}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$

Lepton sector (with right-handed neutrinos)

$$\mathcal{L} \ni -y^{(e)}_{ij}\left(\frac{\phi}{M}\right)^{q_{L_i}-q_{e_j}} \overline{L}_i e_{Rj} H - y^{(\nu)}_{i\alpha}\left(\frac{\phi}{M}\right)^{q_{L_i}-q_{N_\alpha}} \overline{L}_i N_{R\alpha} \widetilde{H}$$

$$-\frac{1}{2} y^{(N)}_{\alpha\beta} M \left(\frac{\phi}{M}\right)^{-q_{N_\alpha}-q_{N_\beta}} \overline{N^c_{R\alpha}} N_{R\beta}$$

Choice of charges

$$\begin{pmatrix} q_{L_1} & q_{L_2} & q_{L_3} \\ q_e & q_\mu & q_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -8 & -5 & -3 \end{pmatrix}$$

Low-energy phenomenology is independent of q_N's

- $m_E \sim \left(\epsilon^8, \epsilon^3, 1\right) \langle H \rangle$
- Neutrino masses and MNS matrix are also OK

$U(1)_{\mathsf{F}}$ has gauge anomaly (in a large class of models)

$\Rightarrow$ $U(1)_{\mathsf{PQ}}$ can be naturally embedded into flavor symmetry

[Wilczek ('82)]

NG boson for the $U(1)_{\mathsf{F}}$ breaking becomes axion

Flaxion

[Ema, Hamaguchi, TM, Nakayama, 1612.05492]

Axiflavon

[Calibbi, Goertz, Redigolo, Ziegler, Zupan, 1612.08040]

After the spontaneous breaking of $U(1)_{\mathsf{F}}$:

$$\phi = v_\phi + \frac{1}{\sqrt{2}}(s + ia) \quad \text{with} \begin{cases} a = \text{flaxion} \\ s = \text{sflaxion} \end{cases}$$

3. Phenomenological Issues

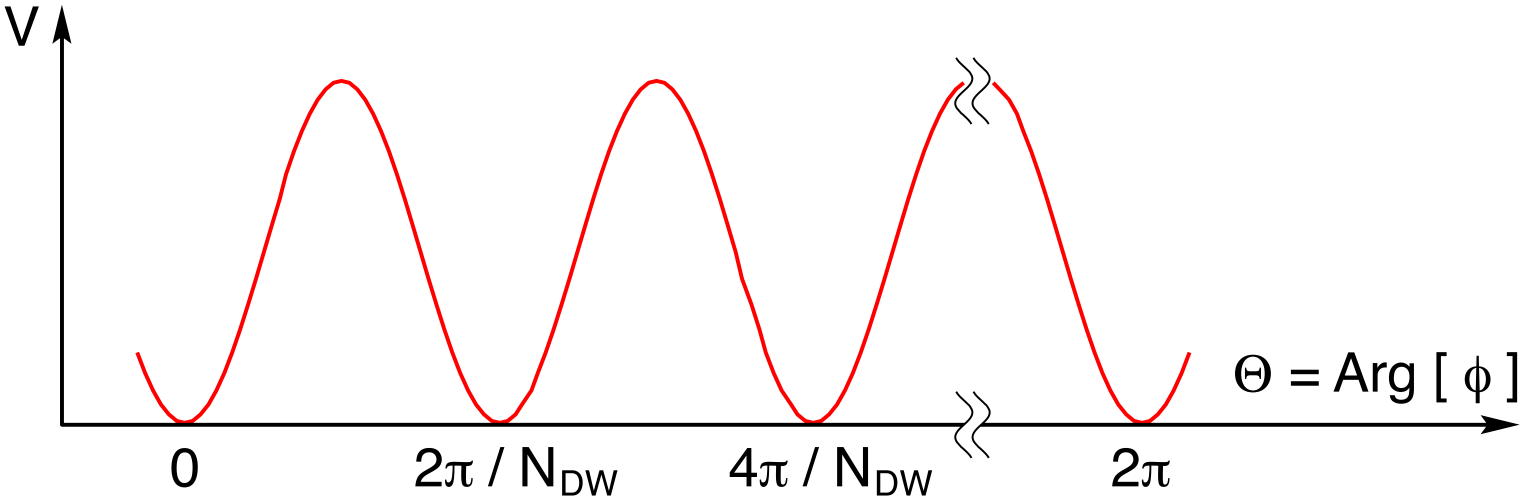
Interaction of the flaxion

$$\mathcal{L}_{\text{eff}} = \frac{g_3^2}{32\pi^2}\frac{1}{f_a} a G^{(A)}_{\mu\nu}\tilde{G}^{(A)}_{\mu\nu} \quad \text{with} \quad f_a = \frac{\sqrt{2} v_\phi}{N_{\text{DW}}}$$

$$N_{\text{DW}} = \text{Tr}(2q_Q - q_U - q_D)$$

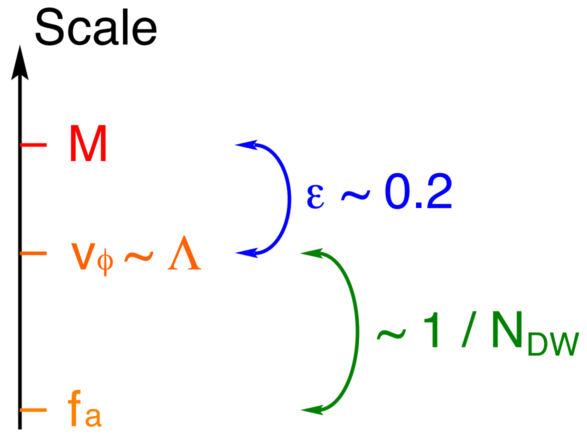
$N_{\text{DW}} = 26$ for our choice of flavor charges

There are N_{DW} degenerate vacua: $\phi = v_\phi e^{2\pi i/N_{\text{DW}}}$

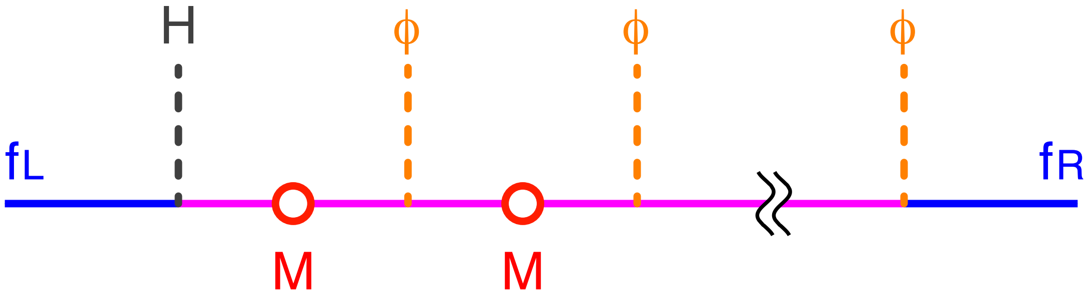


Comments:

- Relation among the scales



- M may be a mass scale of heavy particles, or a cut-off



Flaxion phenomenology

- Flaxion solves the strong CP problem
- Coherent oscillation of the flaxion can be dark matter

$$\Omega_a \simeq 0.18\theta_i^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19}$$

$-\pi < \theta_i < \pi$: initial misalignment angle

- Interaction of the flaxion is not flavor-diagonal

$$\mathcal{L}_{\mathrm{int}} = \sum_{ij}\left[m_{ij}^{(f)} + \frac{m_{ij}^{(f)}(q_{f_L i} - q_{f_R j})}{\sqrt{2}v_\phi}(s + ia)\right]\overline{f_{Li}}f_{Rj} + \mathrm{h.c.}$$

$m_{ij}^{(f)}$ and $m_{ij}^{(f)}(q_{f_L i} - q_{f_R j})$ cannot be simultaneously diagonalized

The most stringent flavor constraint: $K^+ \to \pi^+ a$

- Prediction of our model

$$Br(K^+ \to \pi^+ a) \simeq 3 \times 10^{-10} \times \left(\frac{f_a}{10^{10}\ \mathsf{GeV}}\right)^{-2} \left(\frac{N_{\mathsf{DW}}}{26}\right)^{-2}$$

- Experimental constraint

  [E949 and E787 Collaborations ('08)]

$$Br(K^+ \to \pi^+ a) < 7.3 \times 10^{-11}$$

- We obtain lower bound on f_a

$$f_a \gtrsim 2 \times 10^{10}\ \mathsf{GeV}$$

- The bound may be improved by CERN NA62

4. Sflaxion as Inflaton

In the flaxion scenario, $N_{\mathsf{DW}} \neq 1$ may happen

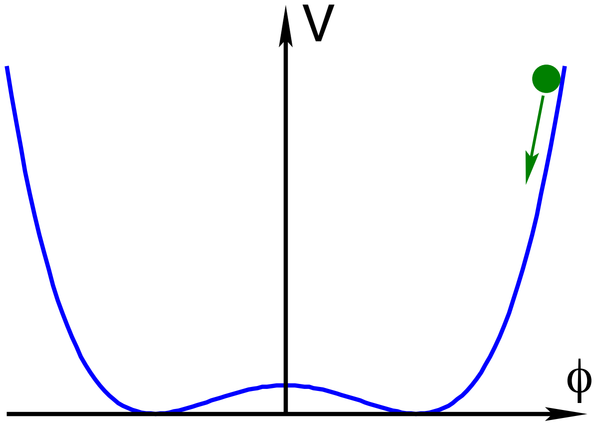
$\Rightarrow$ We should worry about cosmological DW problem

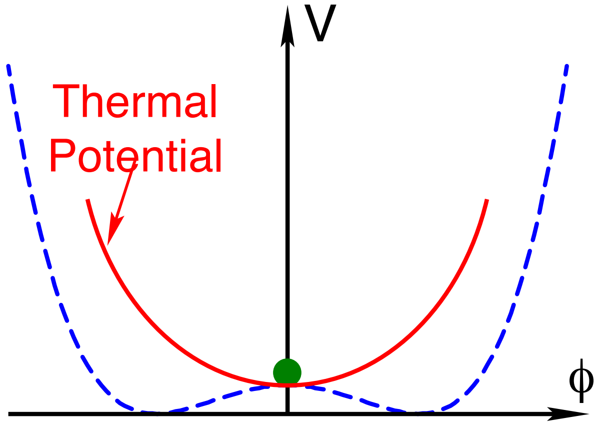
One possibility:

$\Rightarrow$ $U(1)_{\mathsf{F}}$ is broken during and after inflation

The reheating temperature should be low enough

$\Rightarrow$ Otherwise, $U(1)_{\mathsf{F}}$ is restored due to the thermal effect





Our proposal: an attractor inflation with sflaxion

- Lagrangian for the attractor inflation

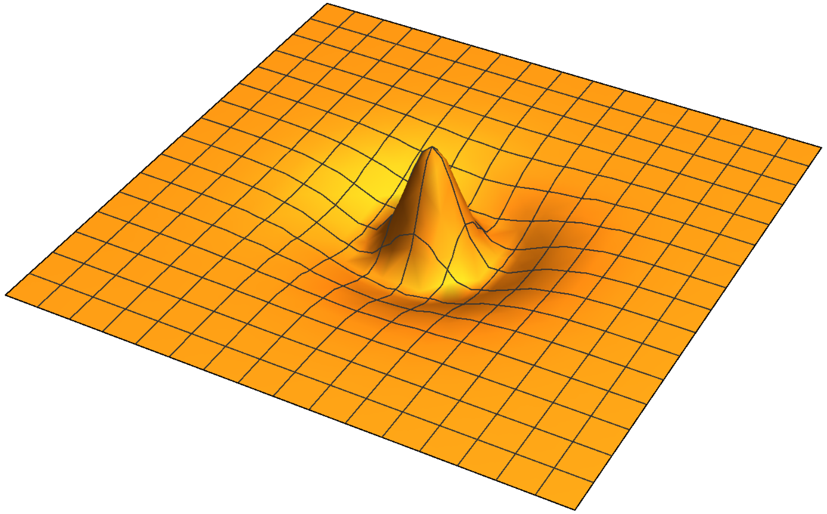
  [Kallosh & Linde ('13); $\cdots$; Alexander Westphal's talk yesterday]

$$\mathcal{L} = \frac{1}{(1-|\phi|^2/\Lambda^2)^2}|\partial_\mu \phi|^2 - \lambda_\phi(\phi^\dagger\phi - v_\phi^2)^2$$

- Canonically normalized field: $\tilde{\varphi}$

$$\text{Re } \phi = \Lambda \tanh \frac{\tilde{\varphi}}{\sqrt{2}\Lambda}$$

$$V = \lambda_\phi \left[\Lambda^2 \tanh^2 \frac{\tilde{\varphi}}{\sqrt{2}\Lambda} - v_\phi^2\right]^2$$

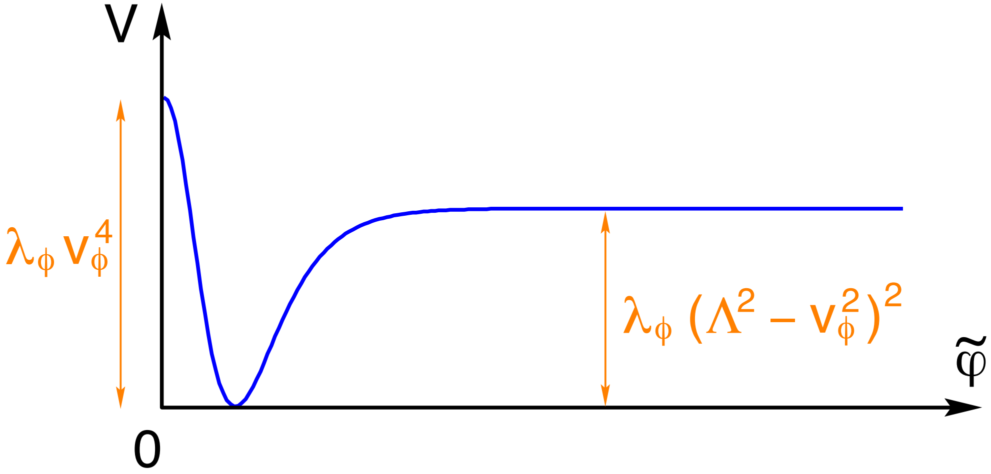


- $\tilde{\varphi}$ has a large initial amplitude

  $\Rightarrow$ Inflation, without DW problem

To solve the DW problem, $v_\phi < \Lambda < \sqrt{2}v_\phi$

$\Rightarrow V(0) > V(\infty)$



$\Rightarrow$ We assume $\Lambda \ll M_{\rm Pl}$

Evolution of the inflaton (with slow-roll approximation)

$$\tilde{\varphi} \simeq \frac{\Lambda}{\sqrt{2}} \ln\left(\frac{16 N_e M_P^2}{\Lambda^2 - v_\phi^2}\right)$$

Density perturbation

$$\mathcal{P}_\zeta \simeq \frac{N_e^2}{6\pi^2}\frac{\lambda_\phi(\Lambda^2 - v_\phi^2)^2}{\Lambda^2 M_P^2}$$

Observation: $\mathcal{P}_\zeta \simeq 2.2 \times 10^{-9}$

[Planck collaboration ('15)]

$$\lambda_\phi \simeq 3 \times 10^{-2} \times \left(\frac{50}{N_e}\right)^2 \left(\frac{10^{14}\,\mathsf{GeV}}{\Lambda}\right)^2 \left(\frac{\Lambda^2}{\Lambda^2 - v_\phi^2}\right)^2$$

λ_ϕ is perturbative for $\Lambda \gtrsim 10^{13}$ GeV

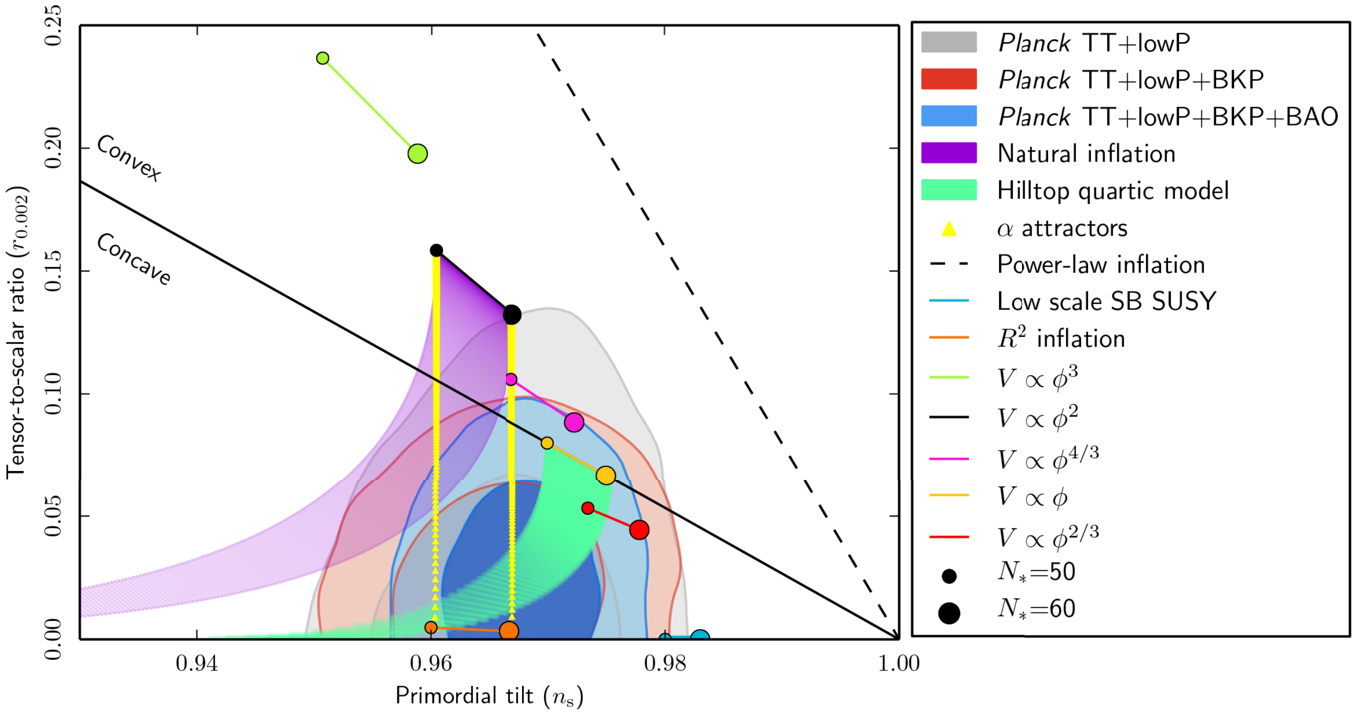
Scale of inflation

$$H_{\mathsf{inf}} \simeq 5 \times 10^8\,\mathsf{GeV} \times \left(\frac{\Lambda}{10^{14}\,\mathsf{GeV}}\right)$$

The spectral index and the tensor-to-scalar ratio

$$n_s \simeq 1 - \frac{2}{N_e}, \quad r \simeq \frac{4}{N_e^2}\left(\frac{\Lambda}{M_P}\right)^2$$

$\Rightarrow$ Consistent with the Planck result for $N_e \sim 50 - 60$



[Planck collaboration 1502.02114]

Isocurvature perturbation

The phase direction (i.e, the flaxion) acquires quantum fluctuation during the inflation

Fluctuation of the misalignment angle: $\Theta = \mathrm{Arg}\phi$

$$\mathcal{P}_{\delta\Theta} \simeq \frac{H_{\mathsf{inf}}^2}{128\pi^2\Lambda^2}\left(\frac{\Lambda^2 - v_\phi^2}{N_e M_P^2}\right)^2 \qquad \Leftrightarrow \qquad \tilde{a} \simeq \frac{\Lambda}{\sqrt{2}}\sinh\left(\frac{\sqrt{2}\tilde{\varphi}}{\Lambda}\right)\Theta$$

Planck constraint: $\mathcal{P}_S \lesssim 0.1\mathcal{P}_\zeta$

[Planck collaboration 1502.02114]

$$\frac{\mathcal{P}_S}{\mathcal{P}_\zeta} \simeq \frac{N_{\mathsf{DW}}^2}{64\theta_i^2 N_e^4}\frac{\left(\Lambda^2 - v_\phi^2\right)^2}{M_P^4} \ll 1 \qquad \text{using} \qquad \begin{cases} \delta S = \dfrac{\delta\rho_a}{\rho_a} = \dfrac{2\delta\theta_i}{\theta_i} \\ \delta\theta_i = N_{\mathsf{DW}}\delta\Theta_i \end{cases}$$

Reheating: the inflaton can decay as

- $\tilde{\varphi} \to NN$: $4\lambda_\phi \Delta^2 \gtrsim (y^N_{\alpha\alpha}\epsilon^{n^N_{\alpha\alpha}-1})^2$ for $m_\varphi > 2m_{N_\alpha}$

$$\Gamma(\tilde{\varphi} \to N_R N_R) \simeq \sum_{\alpha\beta} \frac{|y^N_{\alpha\beta} n^N_{\alpha\beta} \epsilon^{n^N_{\alpha\beta}-1}|^2}{32\pi} \Delta^2 m_\varphi$$

- $\tilde{\varphi} \to H^\dagger H$ (with $\mathcal{L}_{\text{int}} \ni \lambda_{\phi H}|\phi|^2|H|^2$)

$$\Gamma(\tilde{\varphi} \to HH) \simeq \frac{1}{32\pi}\frac{\lambda^2_{\phi H}}{\lambda_\phi} m_\varphi$$

- $\tilde{\varphi} \to aa$

$$\Gamma(\tilde{\varphi} \to aa) \simeq \frac{\lambda_\phi}{8\pi}\Delta^4 m_\varphi$$

$$\Delta \equiv 1 - \frac{v_\phi^2}{\Lambda^2}$$

$\Gamma \gg H_{\mathrm{inf}}$

- The reheating is instantaneous
- The reheating temperature is quite high

$$T_{\mathrm{R}} \sim 10^{13}\ \mathrm{GeV} \times \left(\frac{\Lambda}{10^{14}\,\mathrm{GeV}}\right)^{1/2}$$

- Flaxions are thermalized even if its produced by the inflaton decay

A possible origin of the baryon asymmetry of the universe

Leotogenesis

[Fukugita & Yanagida]

$\Leftrightarrow$ The reheating temeprature is high enough to realize conventional leptogenesis

Leptogenesis in the present setup

$$\frac{n_B}{s} \simeq 1.3 \times 10^{-3} \epsilon_1 \kappa_f$$

[Buchmuller, Di Bari & Plumacher ('05)]

$$\epsilon_1 \simeq 1 \times 10^{-4} \left(\frac{m_{N_1}}{10^{12}\,\mathsf{GeV}}\right)\left(\frac{m_{\nu 3}}{0.05\,\mathsf{eV}}\right)\delta_{\mathsf{eff}}$$

$$\kappa_f \simeq 0.02 \times \left(\frac{\widetilde{m}_{\nu 1}}{0.01\ \mathsf{eV}}\right)^{-1.1} \text{ with } \widetilde{m}_{\nu 1} \equiv \sum_k \frac{|\hat{y}_{k1}|^2}{m_{N_1}} \langle H \rangle^2$$

We are in strong-washout regime

In our setup, $\widetilde{m}_{\nu 1} \sim m_{\nu_3}$

Let's take $m_{\nu_3} \sim 0.05$ eV and $m_{N_1} \sim 10^{12}$ GeV, for e.g.

$\Rightarrow M \sim 10^{14} - 10^{17}$ GeV for $q_{N_1} = 1 - 5$

5. Summary

I discussed a scenario to identify $U(1)_{\mathsf{F}}$ and $U(1)_{\mathsf{PQ}}$

$\Leftrightarrow$ It naturally happens in a class of models with $U(1)_{\mathsf{F}}$ flavor symmetry

Important check point

$$K^+ \to \pi^+ a$$

I also discussed an idea to use sflaxion as inflaton

- Domain-wall problem can be avoided
- Flaxion oscillation can be dark matter
- Leptogenesis works due to high enough reheating temperature