Realization of thermal inflation in SUSY discrete flavour symmetry model

Hiroaki Nagao (Niigata univ.)

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in collaboration with Y.Shimizu, T.Shimomura and Y.Nakagawa

Introduction

[ex: Ishimori et.al ('10)]

◎Discrete flavour symmetry

- suggested from neutrino experimental data,
- based on the non-Abelian discrete groups, (ex: A_4, S_4,Δ(54)…)
- elegantly derive the flavour structures of elementally particles,
- naturally explain the mass spectrum…

◎Flavon

[ex:Altarelli et.al ('05)]

- Gauge singlet scalar fields.
- VEVs of flavons derive the flavour structures via "*vacuum alignment*"
- generate the masses of leptons (ex: Heavy RH ν's)
- Controlled by flavour symm. & Z_n symm. & U(1)_R symm.

Problems of disc. flavour symm.

◎However, SUSY discrete flavour symmetry model has problems…

- Domain wall problem
- Origin of vacuum structure of flavon
- Deviation from Tri-bimaximal mixing

⋮

- Existence of pseudo moduli of flavon

Our focus!

Pseudo moduli flavon

◎F-flat direction among the flavon fields

Expected to spontaneously breaks the flavour symmetry

$$V(|u|) = V_0 - \tilde{m}_u^2 |u|^2 + \Delta V_{\nu_R} + \Delta V_{\tilde{\nu}_R} \qquad (W \ni y_R \, u \, \nu_R^c \nu_R^c)$$

Soft SUSY breaking mass

1-loop effective potential

[ex:Bando et.al ('93)]

$$\Delta V_{\nu_R} = - \sum_{i=1}^{3} \frac{|y_{R\,i}|^4 \, |u|^4}{32\,\pi^2} \left[\ln \left(\frac{|y_{R\,i}|^2 \, |u|^2}{\tilde{m}_u^2} \right) - \frac{3}{2} \right]$$

$$\Delta V_{\tilde{\nu}_R} = \sum_{i=1}^{3} \frac{\left(\tilde{m}_{\nu_R\,i}^2 + |y_{R\,i}|^2 \, |u|^2 \right)^2}{32\,\pi^2} \left[\ln \left(\frac{\tilde{m}_{\nu_R\,i}^2 + |y_{R\,i}|^2 \, |u|^2}{\tilde{m}_u^2} \right) - \frac{3}{2} \right]$$

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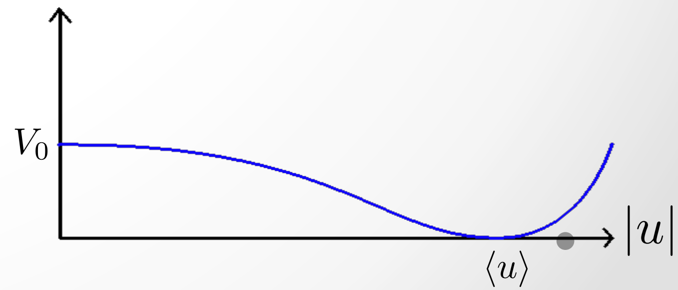
$$\Delta V_{\tilde{\nu}_R} = \sum_{i=1}^{3} \frac{\left(\tilde{m}_{\nu_R\,i}^2 + |y_{R\,i}|^2 \, |u|^2\right)^2}{32\,\pi^2} \left[\ln\left(\frac{\tilde{m}_{\nu_R\,i}^2 + |y_{R\,i}|^2 \, |u|^2}{\tilde{m}_u^2} \right) - \frac{3}{2} \right]$$

$$\langle u \rangle \simeq \frac{\tilde{m}_u}{\sqrt{|y_R|^2}} \exp\left(\frac{8\pi^2 \tilde{m}_u^2}{3\,|y_R|^2 \, \tilde{m}_{\nu_R}^2} \right)$$

Strongly depend on Soft SUSY breaking mass

[H.N & Y.Shimizu ('12)]

$$V_0 = \frac{3\,|y_R|^2}{16\,\pi^2} \, \tilde{m}_{\nu_R}^2 \, \langle u \rangle^2$$

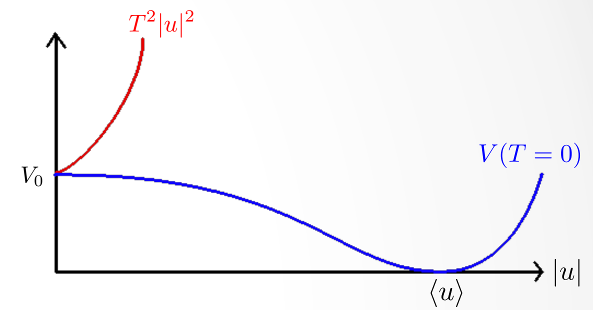


Thermal history of pseudo moduli flavon

- Once, we consider the thermal history of flavon…

$$V(|u|) = V_0 - \tilde{m}_u^2|u|^2 + \Delta V_{\nu_R} + \Delta V_{\tilde{\nu}_R} + cT^2|u|^2$$

◎Thermal evolution of flavon



T

$T \gg \tilde{m}_u$: u trapped at origin
by thermal potential

$T < \tilde{m}_u$: u rolls down to the minimum
→ u obtain non-vanishing VEV

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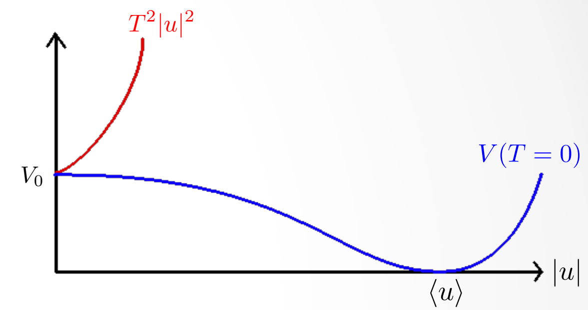


T

$T \gg \tilde{m}_u$: u trapped at origin by thermal potential

$T < V_0^{1/4}$ **: Start to dominate the energy of universe**

$T < \tilde{m}_u$: u rolls down to the minimum
→ u obtain non-vanishing VEV

$T = T_R^{(sec)}$ **: Energy transfer from u into SM**

Must above few MeV

Realize in the flavour symm. models??

Decay rate of flavon

[H.N & Y.Shimizu ('12)]

◎Interaction lagrangian $\left(W \ni y_R\, u\, \nu_R^c \nu_R^c \right)$

$$\mathcal{L}_{int} \ni \frac{y_R}{2\sqrt{2}} \delta u\, \nu_R^c \nu_R^c + h.c. + \frac{\delta u}{\sqrt{2}\, \langle u \rangle} \left(\partial_\mu a\right)^2$$

$$u \equiv \left(\langle u \rangle + \frac{\delta u}{\sqrt{2}} \right) \exp\left(i \frac{a}{\sqrt{2} v} \right)$$

◎Decay rate of pseudo moduli flavon

$$\Gamma(u \to 2a) \simeq \frac{1}{64\pi} \frac{m_u^3}{\langle u \rangle^2}$$

← **Dominate decays of u**

$$\mathrm{Br}(u \to 2a) \simeq 1$$

$$\Gamma(u \to 2\nu) \simeq \frac{3}{16\,\pi} \left(\frac{m_\nu}{\langle u \rangle} \right)^2 m_u$$

$$\left(m_u^2 \simeq \frac{3|y_R|^2 \tilde{m}_{\nu_R}^2}{4\pi^2} \qquad m_a \simeq 0 \right)$$

◎Reheating temperature after u domination

$$T_R^{(sec)} \simeq 0.45 \sqrt{\Gamma(a \to \mathrm{SM}) M_p}$$

$$T_R^{(sec)} \ll 1\mathrm{MeV}$$

Energy transfer from flavon does NOT complete before BBN!!

Possible solutions [H.N & Y.Shimizu ('12)]

Problem

Energy transfer from u complete before BBN?

(Realize Br(u→2a)<<1 ??)

2) Introduce the coupling with vector-like "quarks" $\Delta W = y_Q u Q \overline{Q}$

3) Explicit breaking term of disc. flav. symm.

$$\Delta \mathcal{L} = -\kappa \left(u + u^* \right)$$

+ Coupling with vector-like "quarks"

1) Light RH neutrino $m_{\nu_R} \leq m_u/2$ via higher-dim. operator

Light RH neutrino

◎Generate mass of RHν by suppressed interaction **[H.N et. al ('12)]**

$$W \ni y_R \frac{u^2}{\Lambda} \nu_R^c \nu_R^c \qquad \Lambda : \mathcal{O}(M_p)$$

$$m_{\nu_R} \simeq \frac{|y_R| \langle u \rangle^2}{\Lambda}$$

Allow $u \to \nu_R \nu_R$ on-shell

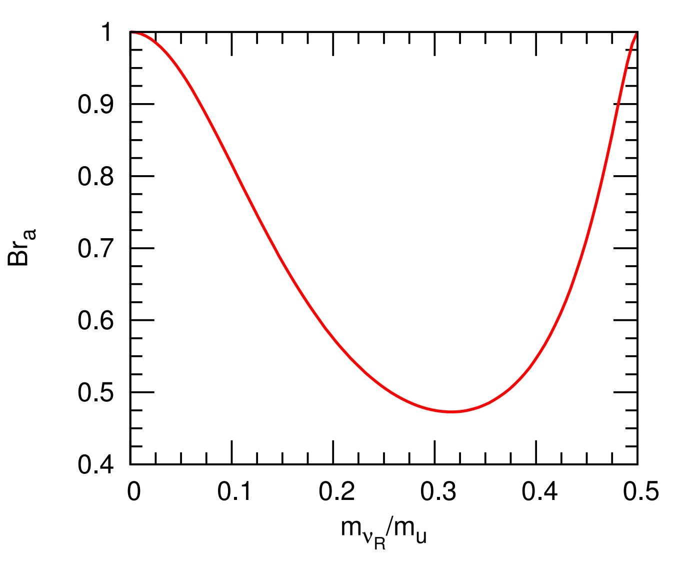
cf. usual charge assignment

$$W \ni y_R \, u \, \nu_R^c \nu_R^c$$

$$m_{\nu_R} \simeq |y_R| \langle u \rangle$$

$$\Rightarrow \mathcal{O}(10^{13}\mathrm{GeV})$$

◎Branching ratio of decays of u



$$\mathrm{Br}(u \to 2a) \simeq \frac{\Gamma(u \to 2a)}{\Gamma(u \to 2a) + \Gamma(u \to 2\nu_R)}$$

< 0.23 (BBN) [Cyburt et.al ('04)]

$$= \left(1 + 24 \frac{m_{\nu_R}^2}{m_u^2} \beta_f^3\right)^{-1}$$

$\gtrsim$ **45 %**

$$\beta_f \equiv \sqrt{1 - 4m_{\nu_R}^2 / m_u^2}$$

Not suppressed enough!

(※But can reproduce the DayaBay result)

Possible solutions [H.N & Y.Shimizu ('12)]

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→ Not enough moderate the problem

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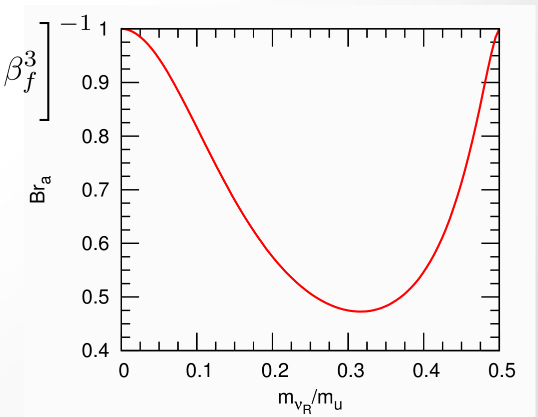
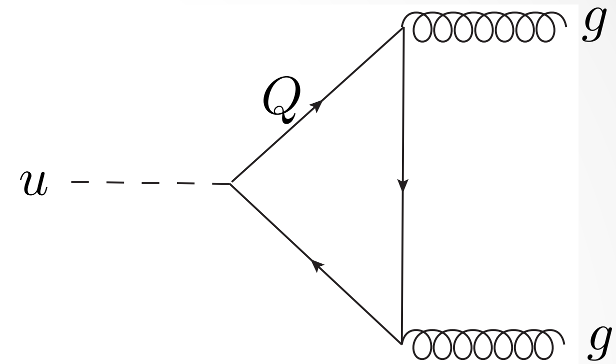


Coupling with vector-like "quarks"

◎Interaction btwn u and "quarks" [ex:Kim et.al ('08)]

$$\Delta W = y_Q u Q \overline{Q}$$

(Q: 5 rep. of SU(5), $\overline{Q}$:5* rep.)



◎Decay channel of u [ex:Chun et.al('00)]

$$\Gamma(u \to gg) \simeq \frac{N_q^2 \alpha_s^2}{144\pi^3} \frac{m_u^3}{\langle u \rangle^2}$$

$$\rightarrow \frac{\Gamma(u \to gg)}{\Gamma(u \to 2a)} = \frac{4 N_q^2 \alpha_s^2}{9\pi^2}$$

- To overcome u→2a, we should introduce $N_q > 100$

Huge number of "quarks"!!

↓ [ex:Morrissey et.al ('05)]

Gauge coupling will blow up below the GUT scale!

Possible solutions [H.N & Y.Shimizu ('12)]

Problem

Energy transfer from u complete before BBN?

(Realize Br(u→2a)<<1 ??)

2) ~~Introduce the coupling with vector-like "quarks"~~ $\Delta W = y_Q u Q\overline{Q}$

→ **100** flavors of "quarks"

Breaks pGCU below GUT scale

[ex:Morrissey et.al ('05)]

3) Explicit breaking term of disc. flav. symm.

$$\Delta\mathcal{L} = -\kappa\,(u + u^*)$$

\+ Coupling with vector-like "quarks"

1) ~~Light RH neutrino via higher dim. operator~~ $m_{\nu_R} \lesssim m_u/2$

→ Not enough moderate the problem

$$\mathrm{Br}(u \to 2a) \simeq \left[1 + 24\left(\frac{m_{\nu_R}}{m_u}\right)^2 \beta_f^3\right]^{-1}$$

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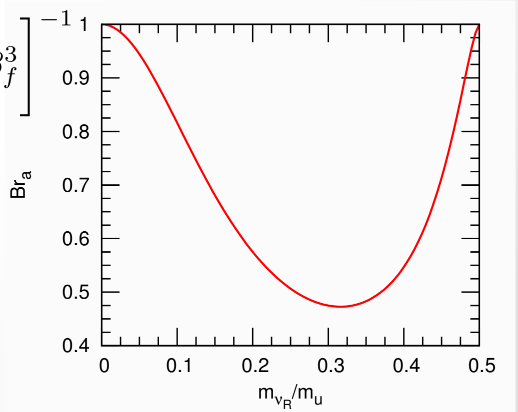
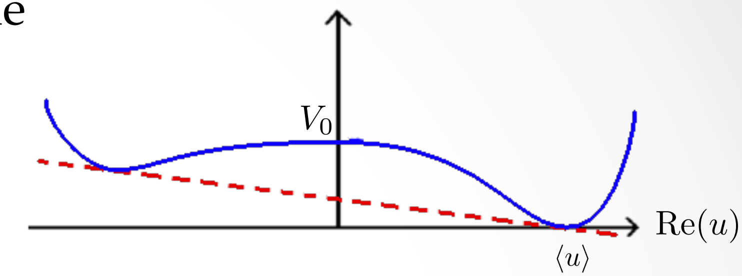


Explicit breaking term

◎ To kinematically forbid u→ 2a, we assume

$$\Delta\mathcal{L} = -\kappa\left(u + u^*\right)$$



◎Mass of circumferential comp. of u

$$m_a^2 = \frac{\kappa}{\langle v \rangle}$$

If $\kappa > \dfrac{m_u^2 \langle u \rangle}{4}$, u→ 2a forbidden kinematically!

- In addition, we introduce u$Q\overline{Q}$ coupling

$$\Gamma_{\rm tot} \simeq \Gamma(u \to gg) \simeq \frac{N_q^2 \alpha_s^2}{144\pi^3} \frac{m_u^3}{\langle u \rangle^2}$$

[ex:Chun et.al ('00)]

⇨

$$T_R^{(sec)} \simeq 0.45\sqrt{\Gamma_{\rm tot} M_p}$$
$$\simeq 6\,\mathrm{MeV}\left(\frac{m_u}{10^3\mathrm{GeV}}\right)^{3/2}\left(\frac{\langle u \rangle}{3\times 10^{12}\mathrm{GeV}}\right)^{-1}$$

Energy transfer from u into SMs can complete before BBN begins

Possible solutions [H.N & Y.Shimizu ('12)]

Problem

Energy transfer from u complete before BBN?

(Realize Br(u→2a)<<1 ??)

2) ~~Introduce the coupling with vector-like "quarks"~~ $\Delta W = y_Q u Q\overline{Q}$

→ 100 flavors of "quarks"

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\+ Coupling with vector-like "quarks"

↓

u→2a can be forbidden $m_a^2 = \frac{\kappa}{\langle u \rangle} > m_u^2$

& $T_R^{(sec)} \simeq$ few MeV $\quad (\, u \to gg \,)$

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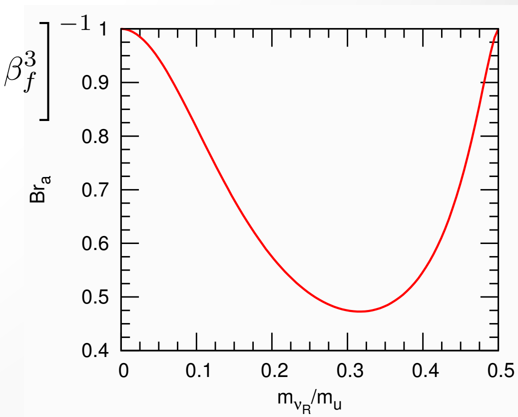

Possible solutions [H.N & Y.Shimizu ('12)]

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Energy transfer from u complete before BBN?

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2) ~~Introduce the coupling with vector-like "quarks"~~ ~~ΔW~~ $= y_Q u Q\overline{Q}$

→ 100 flavors of "quarks"

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[ex:Morrissey et.al ('05)]

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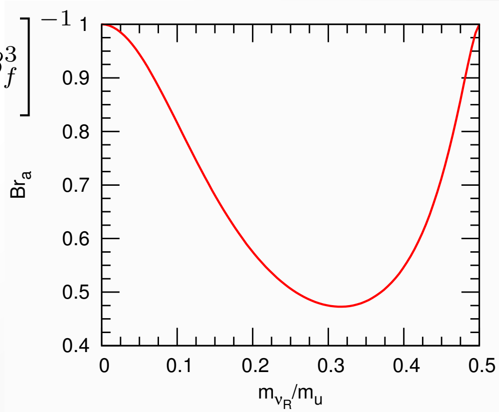
$\lesssim$ 45 %



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⇓

u→2a can be forbidden $m_a^2 = \frac{\kappa}{\langle u \rangle} > m_u^2$

& $T_R^{(sec)} \simeq$ few MeV $\quad (u \to gg)$

⇓

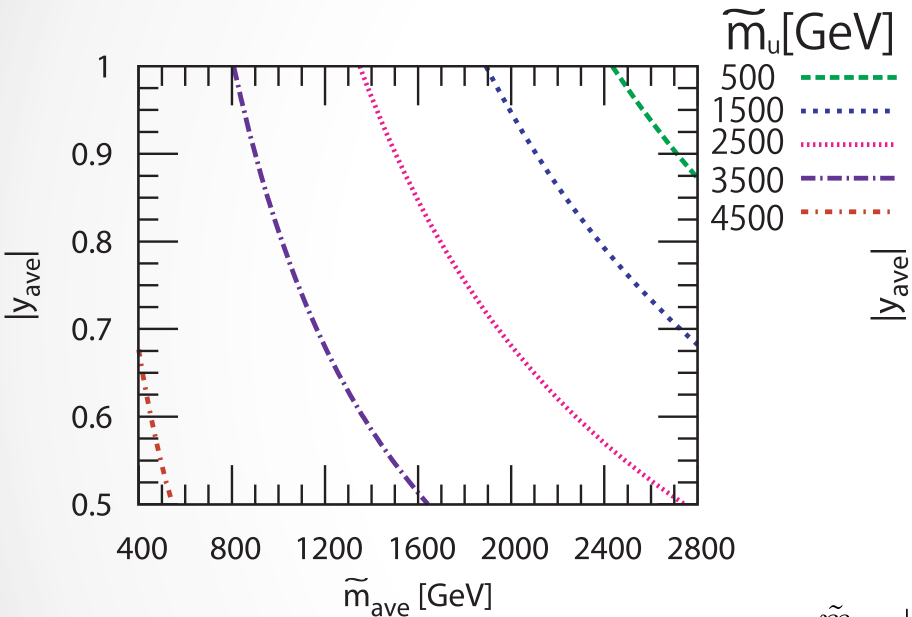
Applicable to thermal inflation by domination of flavon

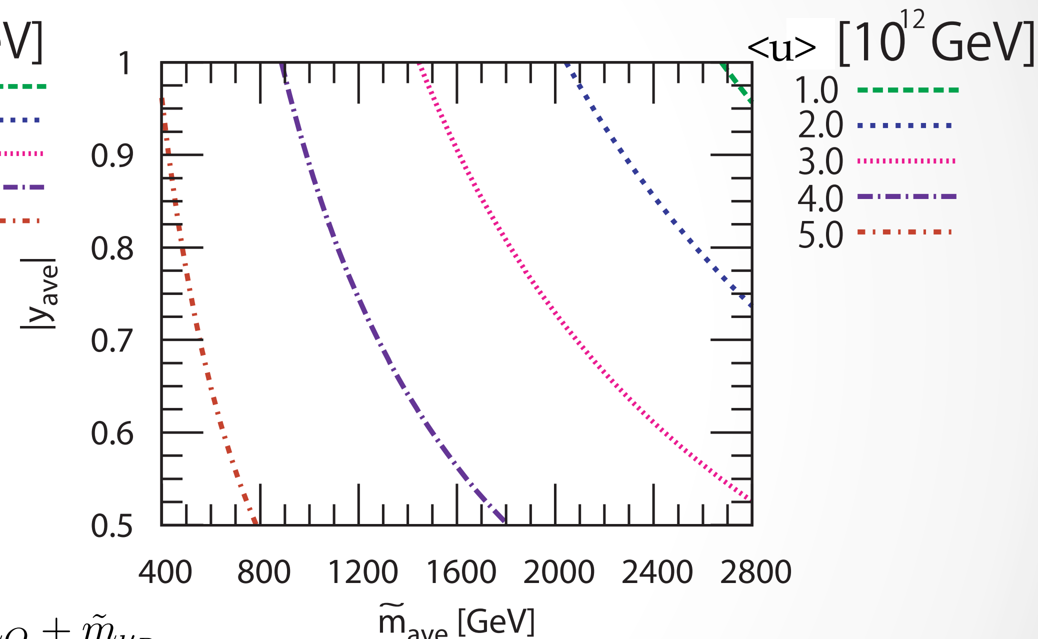
Realization of thermal inflation

[H.N & Y.Shimizu ('12)]

◎Contours satisfying $T_R^{(sec)} \simeq$ few MeV

$\left(\Leftrightarrow \Delta = 10^{20} \right)$ (← Primary moduli diluted enough)





$$\tilde{m}_{\text{ave}} \equiv \frac{\tilde{m}_Q + \tilde{m}_{\nu_R}}{2}$$

$$|y_{\text{ave}}|^2 \equiv \frac{|y_Q|^2 + |y_R|^2}{2}$$

Thermal inflation scenario can realize
by u domination in SUSY discrete flavour model

Summary

- Study the thermal evolution of pseudo moduli flavon in SUSY discrete flavour symmetry
  → Obtain analytic expression of VEV of flavon
  → Flavon can dominate the universe at $\tilde{m}_u < T < V_0^{1/4}$
- **Energy transfer from flavon does not complete before BBN** (at least minimal framework)
  → Br of $\mathrm{u} \to 2\mathrm{a}$ dominate the decay process
  → Should introduce linear potential into lagrangian
- Domination by u can be applied into thermal inflation scenario
- Apply to the continuous flavour symmetry ??