Supersymmetric Flaxion

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Based on
Y. Ema, DH, K. Hamaguchi, T. Moroi and K. Nakayama,
JHEP **04** (2018) 094, [arXiv:1802.07739]

Outline

1. Flaxion
2. SUSY Flaxion
3. Thermal Leptogenesis without gravitino problem
4. Inflation in SUSY Flaxion model
5. Summary

Flaxion: Solution to SM puzzles

Flaxion = SM + Global U(1) + $\boldsymbol{\phi}$ (+ RHν)

$$-\mathcal{L} \supset y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj} + y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^\ell_{ij}\left(\frac{\phi}{M}\right)^{n^\ell_{ij}} \overline{L}_i H \ell_{Rj}$$

$$+ y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha} + \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

M : cut-off scale, $y \simeq \mathcal{O}(1)$, $N_{R\alpha}$: RH neutrino

[Ema-Hamaguchi-Moroi-Nakayama '17]

[Calibbi-Goertz-Redigolo-Ziegler-Zupan '17]

$$\mathbf{U(1)_F = U(1)_{PQ}}$$

Complex scalar:

$$\underset{\text{flavon}}{\boldsymbol{\phi}} = \frac{1}{\sqrt{2}}\left(\overset{\text{inflaton}}{\boldsymbol{\varphi}} + i\, \underset{\text{flaxion}}{\boldsymbol{a}}\right)$$

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after U(1) and EW breaking

$$\underline{y^u_{ij} \epsilon^{n^u_{ij}} v_{EW}}\ \overline{Q}_i u_{Rj}$$

$y^u_{ij} \simeq \mathcal{O}(1)$, $\boldsymbol{\epsilon} \equiv \frac{\langle \phi \rangle}{M} \simeq \mathbf{0.23}$

$$n^u_{ij} = \begin{pmatrix} 8 & 4 & 3 \\ 7 & 3 & 2 \\ 5 & 1 & 0 \end{pmatrix}$$

$$\Downarrow$$

$$m^u_{ij} \simeq v_{EW} \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^7 & \epsilon^3 & \epsilon^2 \\ \epsilon^5 & \epsilon^1 & 1 \end{pmatrix}$$

Flavor structure

[Froggatt-Nielsen '79]

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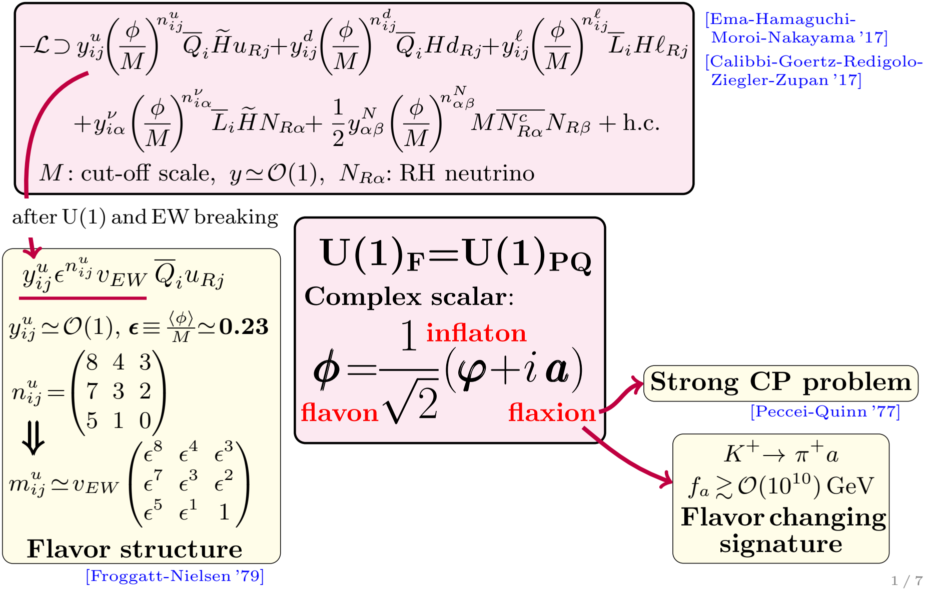

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inflaton

flavon

flaxion

Strong CP problem

[Peccei-Quinn '77]

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

$f_a\gtrsim\mathcal{O}(10^{10})$ GeV

Flavor changing signature

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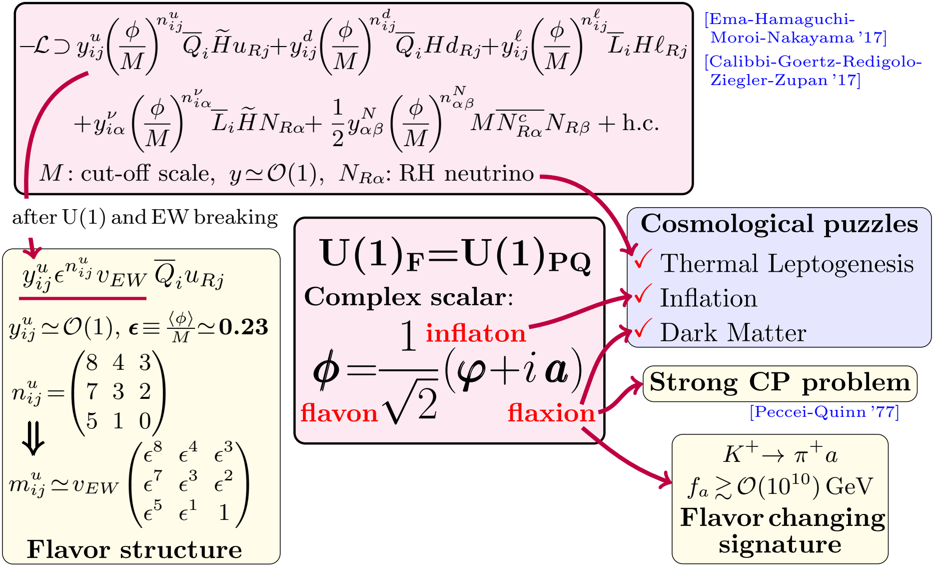

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- ✓ Inflation
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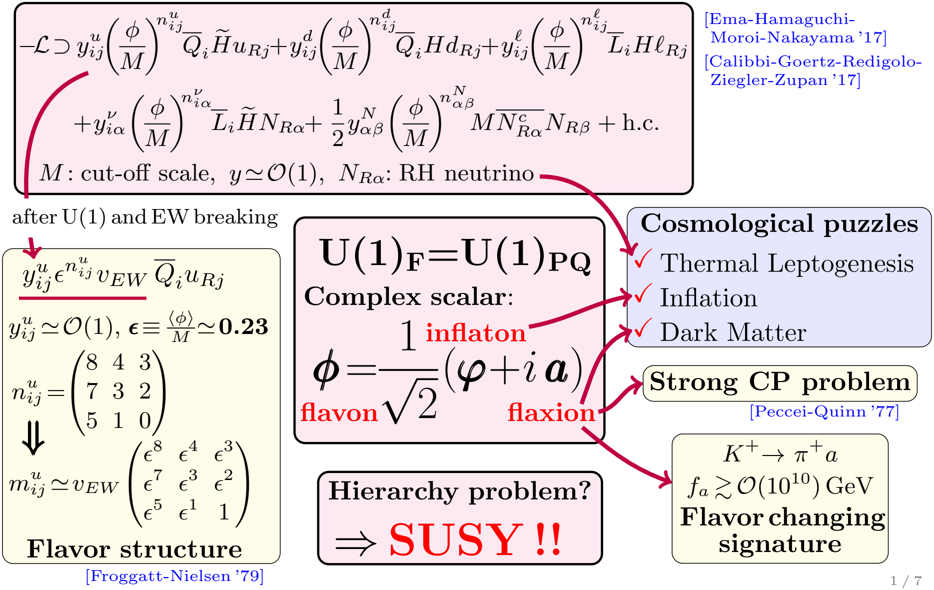

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Hierarchy problem?

$\Rightarrow$ **SUSY !!**

SUSY Flaxion

Superpotential:

$$W_{\mathrm{MSSM}+N} = y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} Q_i \bar{U}_j H_u + y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} Q_i \bar{D}_j H_d + y^\ell_{ij}\left(\frac{\phi}{M}\right)^{n^\ell_{ij}} L_i \bar{E}_j H_d$$

$$+ y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} L_i N_\alpha H_u + \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M N_\alpha N_\beta + \underline{y^\mu \left(\frac{\phi}{M}\right)^{n^\mu} M H_u H_d}$$

$\Rightarrow$ μ-term

M: cut-off scale, $Q_i, \bar{U}_j, \ldots$: superfields, $y \simeq \mathcal{O}(1)$

$$\begin{cases} \phi = v_\phi + \frac{1}{2}(\chi + i\eta + \sigma - ia) \\ \bar{\phi} = v_\phi + \frac{1}{2}(\chi + i\eta - \sigma + ia) \end{cases}$$

a: flaxion, χ: inflaton, σ: sflaxion

U(1) breaking sector:

$$\begin{cases} W_{\mathrm{flaxion}} = \lambda S(\phi\bar{\phi} - v_\phi^2) \\ K_{\mathrm{flaxion}} = |\phi|^2 + |\bar{\phi}|^2 + |S|^2 \end{cases}$$

Superparticles cause some problems...

- gravitino/axino → **Thermal Leptogenesis ??**
- holomorphy (the presence of $\bar{\phi}$) → **Inflation model ??**

$\Rightarrow$ Cosmological scenario??

Charge Assignment and R-parity Violation

Charge Assignment

- flavor structure of fermions (b, ℓ, h, q_{N_α}: free parameters)

$\Rightarrow$

q_X	Q_i	$\bar{U}_i$	$\bar{D}_i$	L_i	$\bar{E}_i$	H_u	H_d	N_α	ϕ
$i=1$	$b+3$	$-b+5$	$-b-h+3$	$\ell+1$	$-\ell-h+7$	0	h	q_{N_α}	-1
2	$b+2$	$-b+1$	$-b-h+2$	ℓ	$-\ell-h+4$				
3	b	$-b$	$-b-h+2$	ℓ	$-\ell-h+2$				

- μ-term $\sim \epsilon^{h} M \simeq \mathcal{O}(1\text{–}10^3)$ TeV $\Rightarrow$ h fixed!
- neutrino mass $m_{\nu,3} \sim \epsilon^{2\ell}\frac{\langle H_u\rangle^2}{M} \simeq 0.05\,\mathrm{eV} \Rightarrow \ell$ fixed!

R-parity Violation

	$L_iL_j\bar{E}_k, L_iQ_j\bar{D}_k, L_iH_u$	$\bar{U}_i\bar{D}_j\bar{D}_k$
q_X	$\ell+m$ $(m\in\mathbf{Z})$	$-3b+m$

we do not impose R-parity!

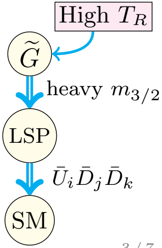
- $\ell = n+1/2$ $(n\in\mathbf{Z}) \Rightarrow$ forbid $L_iL_j\bar{E}_k$, $L_iQ_j\bar{D}_k$ and L_iH_u!
- $b \Rightarrow$ control $\bar{U}_i\bar{D}_j\bar{D}_k$, solving the gravitino problem!

e.g. bino LSP, $m_{3/2}\gtrsim\mathcal{O}(10^2)$ TeV, $W_{\bar{U}\bar{D}\bar{D}}=\frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$

$$\mathcal{O}(10^{-8})\left(\frac{m_{\tilde{q}}}{10\,\mathrm{TeV}}\right)^2\left(\frac{m_{\tilde{B}^0}}{1\,\mathrm{TeV}}\right)^{-5/2}\lesssim\underbrace{|\lambda''_{\max}|}_{\propto\,\epsilon^{|3b|}}\lesssim\mathcal{O}(10^{-6})\left(\frac{m_{\tilde{q}}}{10\,\mathrm{TeV}}\right)^{1/2}$$

Decay before BBN

No baryon washout



High T_R

$\widetilde{G}$

heavy $m_{3/2}$

LSP

$\bar{U}_i\bar{D}_j\bar{D}_k$

SM

Inflation in Flaxion model

Non-SUSY case

[Galante-Kallosh-Linde-Roest '14]

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The flavon ϕ can cause inflation in an attractor inflation model!

$$\mathcal{L} = -\frac{|\partial\phi|^2}{\underset{\text{pole?}}{\underline{\left(1 - \frac{|\phi|^2}{\Lambda^2}\right)^2}}} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2$$

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$$\frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right), \quad \varphi \equiv |\phi|$$

$$\mathcal{L} = -\underset{\text{canonical!}}{\underline{\frac{(\partial\widetilde{\varphi})^2}{2}}} - \lambda_\phi \left[\Lambda^2 \tanh^2\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right) - v_\phi^2\right]^2$$

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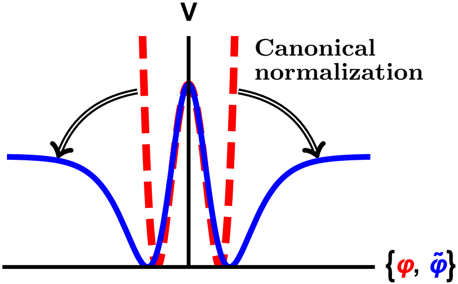

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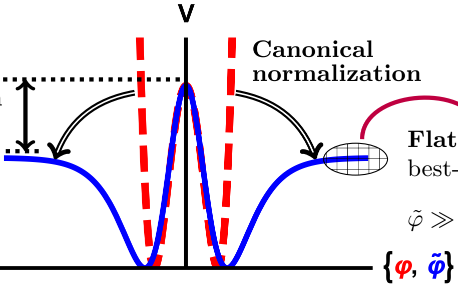

No U(1) restoration
$V(\tilde{\varphi}=0) > V(\tilde{\varphi}=\infty)$
$\Leftrightarrow \Lambda \sim v_\phi$

Flat ⇒ inflation!
best-fit (n_s, r) for $N_e \simeq 50$

$\tilde{\varphi} \gg 1 \rightarrow \begin{cases}\text{no DW problem}\\ \text{suppressed } \mathcal{P}_S\end{cases}$

Inflation in SUSY Flaxion model

U(1) symmetric Kähler potential and Superpotential

$$K = -\Lambda^2 \log \left[\underbrace{\frac{(1-|\Phi|^2/\Lambda^2)(1-|\overline{\Phi}|^2/\Lambda^2)}{(1-\Phi\overline{\Phi}/\Lambda^2)(1-\Phi^\dagger\overline{\Phi}^\dagger/\Lambda^2)}}_{\equiv\, h(\Phi,\overline{\Phi})} \right] + |S|^2$$

$$W = \kappa S(\Phi\overline{\Phi} - v_\phi^2) + W_0 + W_{\mathrm{MSSM}+N}$$

Mass scale:
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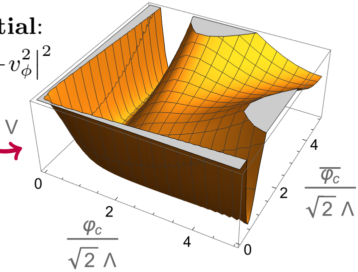

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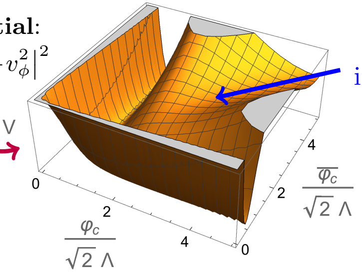

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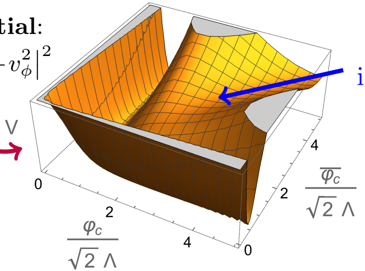

inflaton: $\chi = \frac{1}{\sqrt{2}}(\varphi_c + \overline{\varphi}_c)$

- Specific form of Kähler potential ⇒ Flat and Stable trajectory!
- U(1) is broken during and after inflation ⇒ No DW problem!
- Large field value during inflation ⇒ Suppressed isocurvature perturbation!

Consistent Cosmological Scenario

SUSY Flaxion

Attractor-like Inflation

$$\Rightarrow \begin{cases} \text{best-fit } (n_s, r) \\ \text{no isocurvature/DW prob.} \end{cases}$$

$\times\mathcal{O}(0.1)$ $\times\epsilon\simeq 0.23$

Mass scales: $f_a < v_\phi \sim \Lambda \sim M$

Charge Assignment

ℓ: neutrino mass

h: μ-problem

b: gravitino problem

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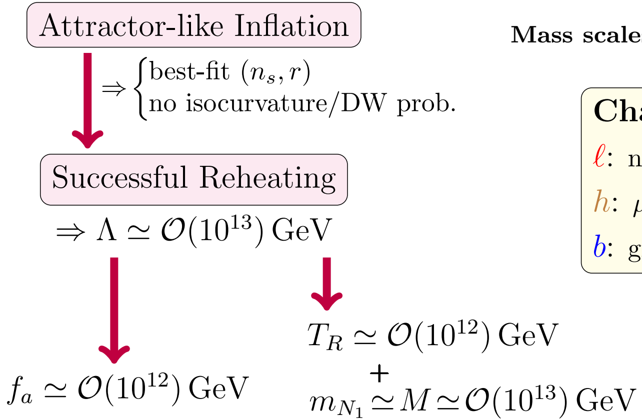

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$T_R \simeq \mathcal{O}(10^{12})$ GeV

+

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⇒ Flaxion DM!

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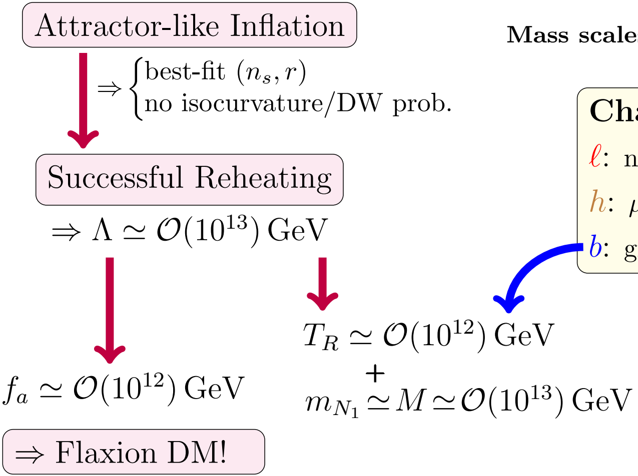

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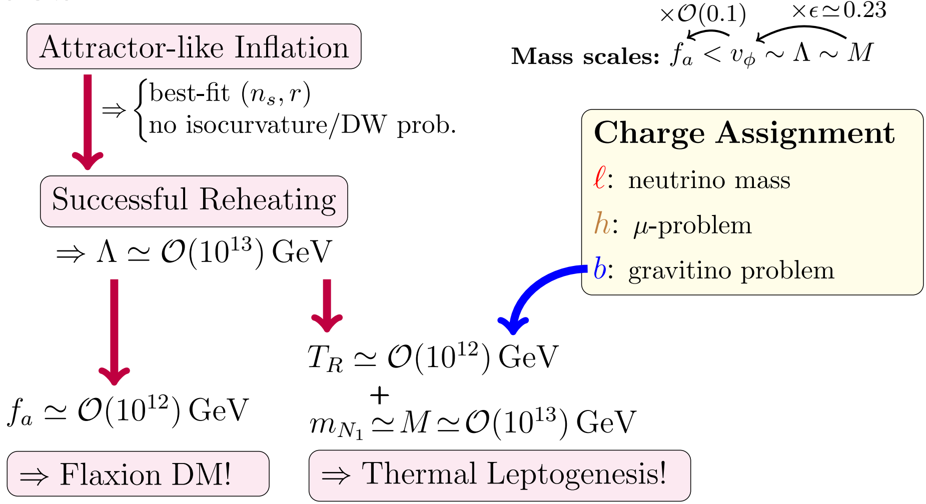

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⇒ Flaxion DM!

⇒ Thermal Leptogenesis!

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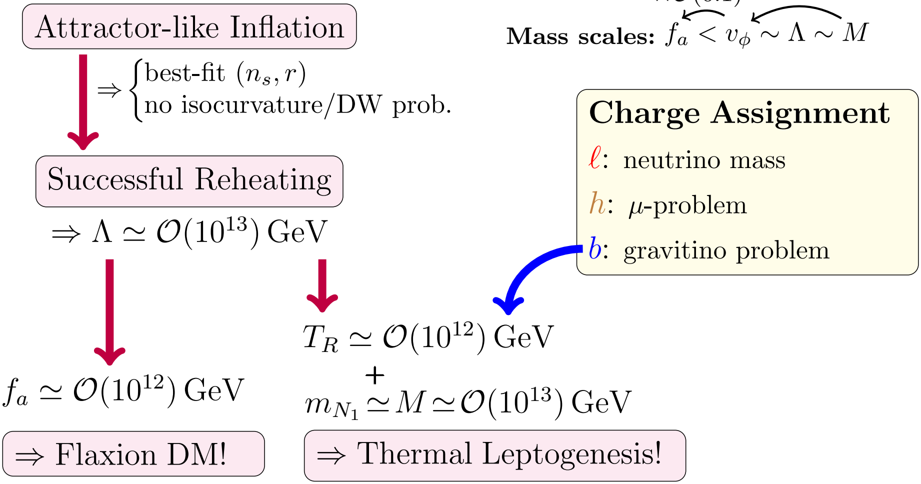

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+

$m_{N_1} \simeq M \simeq \mathcal{O}(10^{13})$ GeV

$\Rightarrow$ Thermal Leptogenesis!

Consistent cosmological scenario!!

Summary

- Flaxion model can solve SM puzzles by $\mathrm{U(1)_F}$=$\mathrm{U(1)_{PQ}}$.
  ⇒ flavor puzzle, strong CP problem, thermal leptogenesis, inflation, DM, ...

- Hierarchy problem ⇒ SUSY Flaxion

- U(1) can control the R-parity violation.
  ⇒ Thermal Leptogenesis without the gravitino problem!

- U(1) symmetric attractor-like inflation
  ⇒ a successful cosmological scenario!

Thank you for listening!

Back up

Flavor and CP Violations due to Superparticles

Soft SUSY breaking mass terms

$$\mathcal{L}_{\rm mass} = m_{\tilde{f}}^2 \sum_{F=Q,\bar{U},\bar{D},L,\bar{E}} \Delta_{\tilde{F}_{ij}} \tilde{F}_i^\dagger \tilde{F}_j \,, \quad \text{with } \underline{\Delta_{\tilde{F}_{ij}}} \sim \mathcal{O}(\epsilon^{|q_{F_i}-q_{F_j}|})$$

almost determined by
U(1)$_{\rm F}$ charge assignment

⇒ Flavor/CP violation

- K^0-$\bar{K}^0$ mixing

$$\epsilon_K^{\rm (SUSY)} \sim 2\times 10^{-3} \times \left(\frac{m_{\tilde{f}}}{1000\,\mathrm{TeV}}\right)^{-2} \mathrm{Im}\left[\left(\frac{\Delta_{\tilde{Q}_{12}}}{0.23}\right)\left(\frac{\Delta^*_{\tilde{\bar{D}}_{12}}}{0.23}\right)\right].$$

$$\epsilon_K^{\rm (exp)} \simeq 1.596\times 10^{-3} \Rightarrow m_{\tilde{f}} \gtrsim \mathcal{O}(10^3)\,\mathrm{TeV}$$

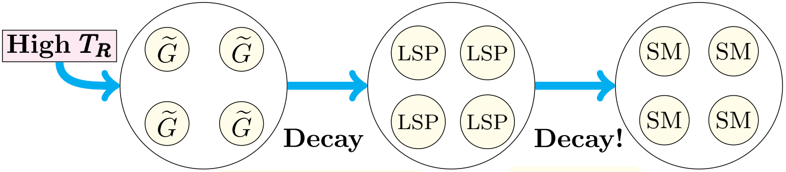
- $\mu \to e\gamma$

$$\mathrm{Br}(\mu\to e\gamma) \sim 3\times 10^{-12} \left(\frac{\tan\beta}{10}\right)^2 \left(\frac{m_{\tilde{f}}}{10\,\mathrm{TeV}}\right)^{-4} \left|\frac{\Delta_{\tilde{L}_{12}}}{0.23}\right|^2.$$

$$\mathrm{Br}^{\rm (exp)}(\mu\to e\gamma) < 4.2\times 10^{-13} \Rightarrow m_{\tilde{f}} \gtrsim \mathcal{O}(10)\,\mathrm{TeV} \text{ for } \tan\beta \sim \mathcal{O}(10)$$

Large sfermion masses evade Flavor/CP violation!

R-parity Violation and Gravitino Problem



$m_{3/2} \gtrsim \mathcal{O}(10^2)\mathrm{TeV}$

$\bar{U}_i \bar{D}_j \bar{D}_k$!!

can be controlled by b!

For Bino LSP, $W_{\bar{U}\bar{D}\bar{D}} = \frac{1}{2}\lambda''_{ijk}\bar{U}_i\bar{D}_j\bar{D}_k$, $\propto \epsilon^{|3b|}$

$$\mathcal{O}(10^{-8})\left(\frac{m_{\tilde{q}}}{10\,\mathrm{TeV}}\right)^2\left(\frac{m_{\tilde{B}^0}}{1\,\mathrm{TeV}}\right)^{-5/2} \lesssim |\lambda''_{\max}| \lesssim \mathcal{O}(10^{-6})\left(\frac{m_{\tilde{q}}}{10\,\mathrm{TeV}}\right)^{1/2}$$

LSP Decay before BBN

Baryon Wash Out

We can choose b to solve gravitino problem!!

Axino Problem

We assume $m_{\tilde{a}} \simeq m_{3/2}$.

The heaviest PQ and gauge charged fields are the sfermions and/or Higgs fields.
The dominant interaction responsible for thermal production depends on T_R.

- $T_R > m_{\tilde{f}} \Rightarrow \tilde{a}$-$\tilde{h}$-$h$ (tree), abundance is independent of T (DFSZ)
- $T_R < m_{\tilde{f}} \Rightarrow \tilde{a}$-gauge-gaugino (1-loop), abundance $\propto T$ (KSVZ)

$\Rightarrow$ The present model is similar to the DFSZ model.

The dominant decay mode is $\tilde{a} \to \tilde{H} H$, which is fast enough for $\tilde{a}$ to decay

$$\text{before} \begin{cases} \text{BBN} \\ \tilde{a}\text{-domination of the energy density of the universe} \end{cases}.$$

The axino decay temperature:

$$T_{\tilde{a}}^{\text{decay}} \simeq 4 \times 10^5\ \text{GeV} \left(\frac{n^\mu}{10}\right) \left(\frac{10^3\ \text{TeV}}{m_{\tilde{a}}}\right)^{1/2} \left(\frac{\mu}{10^3\ \text{TeV}}\right) \left(\frac{10^{13}\ \text{GeV}}{M}\right)$$

$\Rightarrow$ The charge assignment evading the gravitino problem makes the axino harmless!

Thermal Leptogenesis in SUSY flaxion model (1)

The effective neutrino mass is calculated as

$$\tilde{m}_{\nu 1} \equiv \sum_k |\epsilon^{n^\nu_{k1}} y^\nu_{k1}|^2 \frac{v_{\rm EW}^2}{m_{N_1}} \sim \sum_k \epsilon^{2q_{L_k}} \frac{v_{\rm EW}^2}{M} \sim m_{\nu_3}$$

$m_{\nu_3} \sim 0.05\,\mathrm{eV} \Rightarrow$ Strong washout regime!

$$\left(\begin{array}{l}\text{efficiency factor for } T_R \gg m_{N_1} \\ \kappa_f \sim 0.02 \left(\frac{\tilde{m}_{\nu 1}}{0.01\,\mathrm{eV}}\right)^{-1.1} \sim 0.003\end{array}\right)$$

Assuming $m_{N_1} \ll m_{N_{2(3)}}$ and the maximal CP asymmetry,

$$\text{Thermal Leptogenesis} \Rightarrow \frac{n_B}{s} \simeq 6 \times 10^{-11}\ \gamma \left(\frac{m_{N_1}}{10^{11}\,\mathrm{GeV}}\right)$$

the observed baryon asymmetry: $n_B/s \simeq 9 \times 10^{-11}$

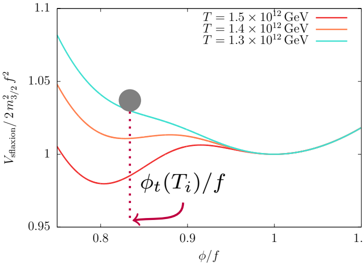
- $\gamma \simeq 1 \Rightarrow m_{N_1} \sim \mathcal{O}(10^{11})\,\mathrm{GeV}$ suffices.
- $\gamma \ll 1 \Rightarrow m_{N_1} \gg \mathcal{O}(10^{11})\,\mathrm{GeV}$ is required.

Derivation of Dilution factor

We assume $\mu = m_\sigma = m_{3/2}$ for simplicity.

$$\text{Dilution factor: } \gamma \equiv \frac{s_{\text{before}}}{s_{\text{after}}} \simeq \min\left[\frac{3}{4}T_\sigma\left(\frac{\rho_{\sigma,i}}{s_i}\right)^{-1}, 1\right]$$

Decay temp. for $\sigma \to HH$: $T_\sigma \simeq 6 \times 10^5\ \text{GeV}\left(\frac{n^\mu}{10}\right)\left(\frac{10^{13}\ \text{GeV}}{M}\right)\left(\frac{m_{3/2}}{10^3\ \text{TeV}}\right)^{3/2}$



$$\boldsymbol{V(\phi) \simeq m_{3/2}^2\phi^2 + m_{3/2}^2\frac{f^4}{\phi^2} + \frac{1}{8}M^2T^2\left(\frac{\phi}{M}\right)^{2n}}$$

minimum position:

$$\partial_\phi V(\phi_t(T), T) = 0 \Rightarrow \phi_t(T) \simeq M\left(\frac{8\epsilon^4}{n}\frac{m_{3/2}^2}{T^2}\right)^{1/(2n+2)}$$

temp. when oscillation begins:

$$M_{\text{eff}}(\phi_t(T_i)) = T_i \Rightarrow T_i \simeq M\left(\frac{8\epsilon^4}{n}\frac{m_{3/2}^2}{M^2}\right)^{n/(4n+2)}$$

$$\Rightarrow \frac{\rho_{\sigma,i}}{s_i} \simeq \frac{m_{3/2}^2\frac{f^4}{\phi_i^2}}{\frac{2\pi^2}{45}g_* T_i^3} = \frac{45}{2\pi^2 g_*}\frac{m_{3/2}^2 f^4}{T_i^3\phi_i^2}$$

Combine above equations

$$\Rightarrow \gamma \simeq \begin{cases} 0.06\left(\frac{n^\mu}{10}\right)\left(\frac{m_{3/2}}{10^3\ \text{TeV}}\right)^{7/6}\left(\frac{10^{12}\ \text{GeV}}{m_{N_1}}\right)^{5/3} & \text{for } n = 1 \\ 0.001\left(\frac{n^\mu}{10}\right)\left(\frac{m_{3/2}}{10^3\ \text{TeV}}\right)^{15/14}\left(\frac{10^{12}\ \text{GeV}}{m_{N_1}}\right)^{11/7} & \text{for } n = 3 \end{cases}$$

Unless $m_{3/2}$ is extremely large, γ is very small.
$\Rightarrow$ difficult to obtain sufficient amount of baryon asymmetry through Thermal Leptogenesis

Sflaxion Cosmology

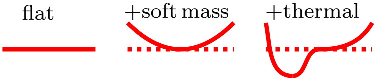
Sflaxion potential ($f\equiv\langle\phi\rangle$, $y^N_{11}\simeq 1$, $n\equiv n^N_{11}=2\,q_{N_1}$)

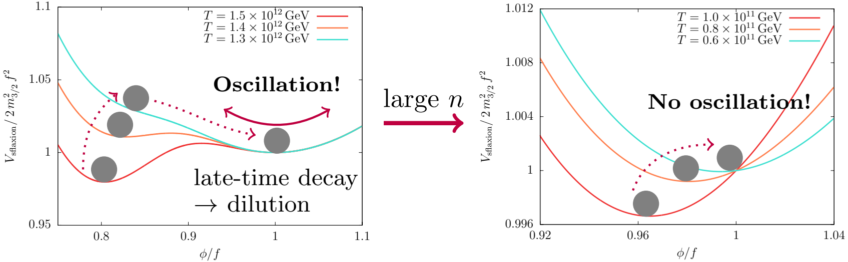
$$\boxed{V(\phi)\simeq m_{3/2}^2\phi^2+m_{3/2}^2\frac{f^4}{\phi^2}+\frac{1}{8}M^2T^2\left(\frac{\phi}{M}\right)^{2n}}$$

$T\gg M_{\rm eff}(\phi)$

RH (s)neutrinos:

$$W\supset \underbrace{\frac{1}{2}y^N_{11}\left(\frac{\phi}{M}\right)^{n^N_{11}}M}_{M_{\rm eff}(\phi)}N_1N_1$$





No oscillation for large q_{N_α}!! (or $q_{N_\alpha}=0$)

e.g. $q_{N_1}=9/2\,(n=9)$, $M=10^{17}$ GeV, $m_{3/2}=10^3$ TeV

→ $m_{N_1}=2\times10^{11}$ GeV Thermal Leptogenesis!

$f_a=2\times10^{15}$ GeV Flaxion DM!

+ an appropriate choice of b

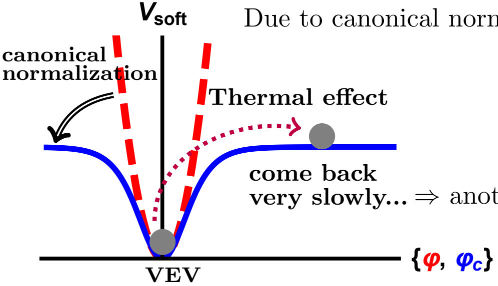
Consistent scenario!!

Thermal Effect on Sflaxion in Attractor Inflation

Instantaneous reheating: $T_R \sim \mathcal{O}(10^{12})\,\text{GeV} \Rightarrow$ Sflaxion receives thermal effect

Problems:
Sflaxion oscillation + **Flat soft mass**

Due to canonical normalization



⇒ another inflation

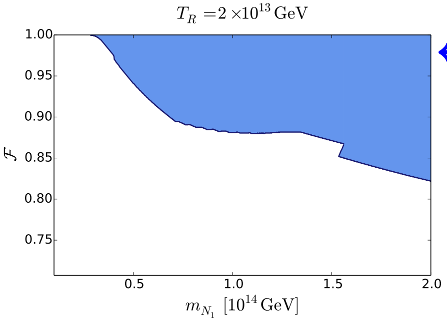
We consider the case the sflaxion has no bilinear coupling with RHν.

$$\begin{cases} W \supset \frac{1}{2} y^N_{\alpha\beta} \left(\frac{\Phi}{M}\right)^{n^N_{\alpha\beta}} M N_\alpha N_\beta \\ n^N_{\alpha\beta} = q_{N_\alpha} + q_{N_\beta} \end{cases} \Rightarrow q_{N_\alpha} = 0$$

- Other thermal effects are negligible.
- Lepton parity is necessary.

Sflaxion Dynamics with bilinear couplings

Can S stabilize the sflaxion near the VEV?



the sflaxion stay at around the minimum

$$m_\chi \simeq 3 \times 10^{13}\,\mathrm{GeV} \left(\frac{\mathcal{F}}{\Lambda}\right)\left(\frac{50}{N_e}\right) \Rightarrow m_{N_1} > m_\chi$$

Reheating must be completed through $\chi \to aa$.

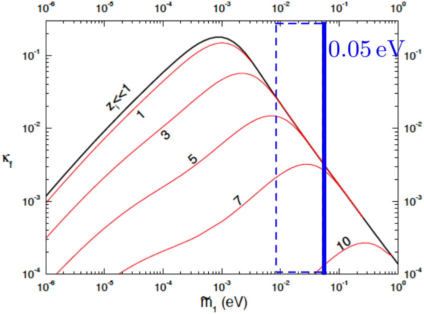
It is difficult to realize reheating and thermal leptogenesis at the same time...

Thermal Leptogenesis in SUSY flaxion model (2)

Decay parameter $K = \dfrac{\Gamma_D(z=\infty)}{H(z=1)} = \dfrac{\widetilde{m_1}}{m_*} \sim 50 \gg 1 \Rightarrow$ Strong washout regime

$$\begin{cases} \text{the effective neutrino mass: } \widetilde{m}_1 \simeq m_{\nu_3} \simeq 0.05\,\text{eV} \\ \text{the equilibrium neutrino mass: } m_* \simeq 1.08 \times 10^{-3}\,\text{eV} \end{cases}$$

The final efficiency factor κ_f for different values of $z_i = m_{N_1}/T_R$



[Buchmüller-Bari-Plümacher hep-ph/0401240]

For $z_i \gtrsim z_B$ there is a significant suppression.

Now $z_B \simeq z_{\text{out}} \simeq 8 \Rightarrow \mathcal{O}(0.1)$ suppression at most!

(The suppression can be compensated by the large m_{N_1}.)

Constraints on Λ

Mass scale Λ ($\simeq \mathcal{F} \equiv \langle \Phi \rangle$) is almost fixed.

WMAP normalization $\Rightarrow \Lambda \simeq 2.5 \times 10^{13}\,\mathrm{GeV} \left(\frac{1}{\kappa\Delta}\right)\left(\frac{50}{N_e}\right)$

$\Delta \equiv 1 - \mathcal{F}^2/\Lambda^2$
$0 < \Delta < 1/2$

- Flaxion thermalization

  $q_{N_\alpha} = 0 \Rightarrow$ dominant decay mode: $\chi \rightarrow \underline{\text{flaxions/sflaxions}}$
  must be thermalized

$$\Gamma(aa \to Q_3 \overline{U}_2 H_u) \gg H_{\mathrm{inf}} \Leftrightarrow A(\kappa\Delta^2)^3 g(\Delta)\left(\frac{N_e}{50}\right) \gtrsim 0.8 \quad \begin{cases} A \gtrsim 1 \\ 0 < g(\Delta) < \sqrt{2} \end{cases}$$

$$\Rightarrow \kappa\Delta^2 \gtrsim 1$$

- Perturbativity

  perturbativity bound on the inflaton coupling $\Rightarrow \kappa\Delta^2 \lesssim 4\pi$

Thermalization and Perturbativity $\Rightarrow 1 \lesssim \kappa\Delta^2 \lesssim 4\pi$

$$\Downarrow$$

$f_a = \frac{2\mathcal{F}}{N_{\mathrm{DW}}}\frac{1}{\Delta}, \mathcal{F} \simeq \Lambda$

$\Gamma(\chi \to aa/\sigma\sigma) \gg H_{\mathrm{inf}} \Rightarrow$
instantaneous reheating!

$$\boxed{\mathbf{\Lambda \simeq \mathcal{O}(10^{13})\ GeV}}$$

$f_a \simeq \mathcal{O}(10^{12})\,\mathrm{GeV}$

$T_R \simeq \mathcal{O}(10^{12})\,\mathrm{GeV}$