# Affleck-Dine baryogenesis in the SUSY Dine-Fischler-Srednicki-Zhitnitsky axion model without R-parity

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# Introduction

Problems of the Standard Model:

- the origin of the tiny neutrino masses

Previously proposed solutions:

- Seesaw mechanism introducing the heavy right-handed neutrinos


- Small R-parity (lepton number) violating terms in supersymmetric (SUSY) theory

NOT introducing the right-handed neutrinos

R-parity: $R_p = (-1)^{2S+3B+L}$

R-parity violating term: $\mathcal{L} \supset \underbrace{\mu_i \nu_i \tilde{H}_u}_{\text{Neutrino mass terms}} + \text{c.c}$

$S$ : spin
$B$ : baryon number
$L$ : lepton number

We focus on this

Requirement: explanation of the smallness of R-parity violation.

# Introduction

## The SUSY DFSZ axion model achieves the small R-parity violation.

R-parity violating term: $\mathcal{L} \supset y_i \underbrace{\frac{S_1^3}{M_P^2}}_{\text{Planck mass}} \nu_i \tilde{H}_u + \text{c.c}$

| | $S_1$ | $\nu_i$ | $\tilde{H}_u$ |
|---|---|---|---|
| $U(1)_{PQ}$ | $1$ | $-2$ | $-1$ |

$U(1)_{PQ}$ Symmetry breaking :

$(S_1 : \text{PQ field})$

$$\mathcal{L} \supset \underbrace{y_i \frac{\langle S_1 \rangle^3}{M_P^2}}_{\text{The effective coupling}} \nu_i \tilde{H}_u + \text{c.c}$$

The magnitude of R-parity violation: controlled and suppressed for $\langle S_1 \rangle \ll M_P$

In addition the SUSY DFSZ axion model

- solves strong CP problem
- includes an axion dark matter

The SUSY DFSZ axion model can solve several problems.

# How about the baryon asymmetry in the SUSY DFSZ model?

$$\boxed{\frac{n_B}{s} \simeq 10^{-10}}$$

Our universe is baryon asymmetric to explain BBN and CMB observation


## Previously proposed solutions:

- Thermal leptogenesis

induced by the decay of heavy right-handed neutrinos.

- Affleck-Dine(AD) mechanism

induced by the decay of scalar field in supersymmetric theory.

Can the SUSY DFSZ axion model explain the baryon asymmetry via the AD mechanism without the right-handed neutrinos?

# Our SUSY DFSZ axion model

# Our model

We introduce $U(1)_{PQ}$ symmetry and the superpotential:

$$W = W_{MSSM} + W_{\not{R}_p} + W_{PQ}$$

| | $S_0$ | $S_1$ | $S_2$ | $H_u$ | $H_d$ | $\bar{u}_i$ | $\bar{d}_i$ | $Q_i$ | $\bar{e}_i$ | $L_i$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $PQ$ | $0$ | $1$ | $-1$ | $-1$ | $-1$ | $-1$ | $-1$ | $2$ | $3$ | $-2$ |
| $B$ | $0$ | $0$ | $0$ | $0$ | $0$ | $-1/3$ | $-1/3$ | $1/3$ | $0$ | $0$ |

$U(1)_{PQ}$ and baryon charges

$$W_{MSSM} = y_u \bar{u} Q H_u - y_d \bar{d} Q H_d - y_e \bar{e} L H_d + \frac{y_0 S_1^2}{M_P} H_u H_d$$

$$W_{\not{R}_p} = \frac{y' S_1^3}{M_P^2} L H_u + \frac{\gamma S_1}{M_P} L L \bar{e} + \frac{\gamma' S_1}{M_P} L Q \bar{d} + \frac{\gamma'' S_1^3}{M_P^3} \bar{u}\bar{d}\bar{d}$$

$$W_{PQ} = \kappa S_0 (S_1 S_2 - f^2) \qquad (S_0, S_1, S_2 : \text{PQ fields})$$

Let us consider the constraint of R-parity violating term $W_{\not{R}_p}$

# Constraint of R-parity violating couplings

After $U(1)_{PQ}$ symmetry breaking,

$$W_{\not R_p} = \frac{y'\langle S_1\rangle^3}{M_P^2} L H_u + \frac{\gamma\langle S_1\rangle}{M_P} L L \bar{e} + \frac{\gamma'\langle S_1\rangle}{M_P} L Q \bar{d} + \frac{\gamma''\langle S_1\rangle^3}{M_P^3} \bar{u}\bar{d}\bar{d}$$

$$\equiv \mu' L H_u + \lambda L L \bar{e} + \lambda' L Q \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d}$$

- For $M_P = 2.4 \times 10^{18}\ \mathrm{GeV}, \langle S_1 \rangle = 10^{12}\ \mathrm{GeV}$, dimensionless parameters =1,

$$\boxed{\mu'_i = 2 \times 10^{-1}\ \mathrm{GeV},\ \lambda_{ijk} = 2 \times 10^{-7},\ \underline{\lambda'_{ijk} = 2 \times 10^{-7}},\ \underline{\lambda''_{ijk} = 7 \times 10^{-20}}}$$

Unobservation of the proton decay: $|\lambda'_{imk} \lambda''^{*}_{11k}| < \mathcal{O}(1) \times 10^{-25} \left( \frac{m_{\tilde{d}}}{5\mathrm{TeV}} \right)^2$

down-type squark mass

SUSY DFSZ axion model avoid the constraints.

Our model can explain the proton decay in Hyper-Kamiokande.

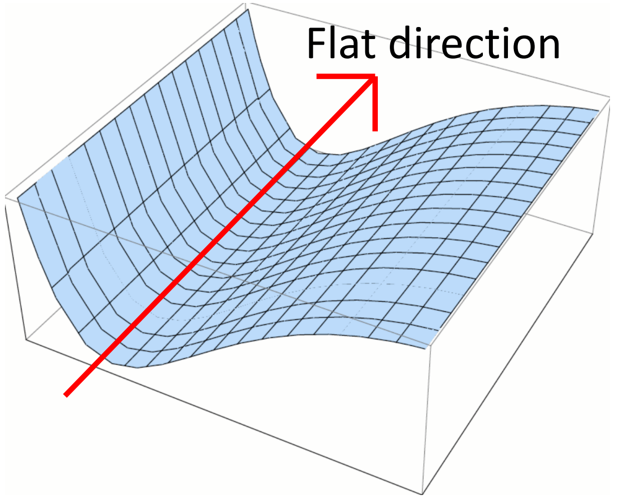
# Affleck-Dine baryogenesis

Affleck, Dine, Nucl. Phys. B249, 361 (1985)
Dine, Randall, Thomas , Nucl. Phys. B291, 458 (1996)

# Affleck-Dine(AD) baryogenesis

- In SUSY theory, scalar fields(squark, slepton) have baryon/lepton charge.
- Scalar potential include flat directions $\phi$ $(\mathrm{AD\ field})$
  at renormalizable level and supersymmetric limit.
- B number density: $n_B \propto i(\dot{\phi}^* \phi - \phi^* \dot{\phi}) = 2|\phi|^2 \dot{\theta}$ $\quad (\phi = |\phi| e^{i\theta})$

| Dynamics of AD field via B violating operator | ⇒ | Generate B number |
|---|---|---|




- B violating operator:

Conventional case: $W = \dfrac{\phi^n}{M^{n-3}} \quad (n \geq 4)$

This case: $\boxed{W = \dfrac{S_1^m \phi^n}{M_P^{n+m-3}} \quad (n, m \in N)}$

# Set-up

- B violating operator:

$$\boxed{W_{AD} = \gamma \frac{S_1^3 \overline{u}\overline{d}\overline{d}}{3M_P^3} = \gamma \frac{S_1^3 \phi^3}{3M_P^3}}$$

$$\overline{u} = \frac{1}{\sqrt{3}}\phi, \ \overline{d} = \frac{1}{\sqrt{3}}\phi$$

| | $S_1$ | $\overline{u}$ | $\overline{d}$ |
|---|---|---|---|
| $U(1)_{PQ}$ | $1$ | $-1$ | $-1$ |

- The scalar potential for $\phi, S_1$ :

$c_\phi, c_1 > 0$

$(m_\phi \simeq m_{S_1} \simeq m_{3/2})$

$$V = (m_\phi^2 - c_\phi H^2)|\phi|^2 + (m_{S_1}^2 - c_1 H^2)|S_1|^2 + \frac{\gamma^2 |S_1|^6 |\phi|^4}{M_P^4} + \frac{\gamma^2 |S_1|^4 |\phi|^6}{M_P^4}$$

$$+ (a_H H + a_m m_{3/2}) \frac{\gamma S_1^3 \phi^3}{M_P^3} + \text{h.c.} + \ldots$$

Phase dependent (B,CP-violating) terms

Let us investigate the potential and dynamics of $\phi, S_1$

# Dynamics of $\phi, S_1$ during inflation: $H = H_{\rm inf} > m_{3/2}$

$$V = (\cancel{m_\phi^2} - c_\phi H^2)|\phi|^2 + (\cancel{m_{S_1}^2} - c_1 H^2)|S_1|^2 + \frac{\gamma^2 |S_1|^6 |\phi|^4}{M_P^4} + \frac{\gamma^2 |S_1|^4 |\phi|^6}{M_P^4}$$

negative mass!

$$+ (a_H H + \cancel{a_m m_{3/2}}) \frac{\gamma S_1^3 \phi^3}{M_P^3} + \mathrm{h.c.} + \dots$$

A minimum for $a_H \gg c_\phi, c_1$: $(m_\phi \simeq m_{S_1} \simeq m_{3/2})$

$$\langle |\phi| \rangle \simeq \langle |S_1| \rangle \simeq (H M_P^3)^{1/4}$$
$$\langle 3\theta + 3\theta_{S_1} + \arg(\gamma a_H) \rangle = 0$$

$(\phi = |\phi| e^{i\theta}, \ S_1 = |S_1| e^{i\theta_{S_1}})$

$\phi, S_1$ will settle at the above minimum: $\boxed{n_B \propto |\phi|^2 \dot\theta = 0}$

# Dynamics of $\phi, S_1$ after inflation: $H = \dfrac{2}{3t} > m_{3/2}$

$$V = (\cancel{m_\phi^2} - c_\phi H^2)|\phi|^2 + (\cancel{m_{S_1}^2} - c_1 H^2)|S_1|^2 + \frac{\gamma^2 |S_1|^6 |\phi|^4}{M_P^4} + \frac{\gamma^2 |S_1|^4 |\phi|^6}{M_P^4}$$

$$\cancel{+ (a_H H + a_m m_{3/2}) \frac{\gamma S_1^3 \phi^3}{M_P^3} + \text{h.c.}} + \ldots$$

$$\to 0 \quad (H \propto \langle I \rangle = 0)$$

The inflaton start to oscillate.

inflaton

$$(m_\phi \simeq m_{S_1} \simeq m_{3/2})$$

The minimum → a saddle point!

We can follow the trajectory of $\phi, S_1$ numerically.

$\dot{\theta} = 0$ because new phase-dependent potential is not produced.

$$\boxed{n_B \propto |\phi|^2 \dot{\theta} = 0} \quad (\phi = |\phi| e^{i\theta})$$

# Dynamics of $\phi, S_1$ at $H = \frac{2}{3t} < m_{3/2}$

$\propto \frac{1}{t^2} < m_\phi$

$$V = (m_\phi^2 - \cancel{c_\phi H^2})|\phi|^2 + (m_{S_1}^2 - \cancel{c_1 H^2})|S_1|^2 + \frac{\gamma^2|S_1|^6|\phi|^4}{M_P^4} + \frac{\gamma^2|S_1|^4|\phi|^6}{M_P^4}$$

positive mass!

$$+ \underbrace{(\cancel{a_H H} + a_m m_{3/2})\frac{\gamma S_1^3\phi^3}{M_P^3}}_{} + \text{h.c.} + \dots$$

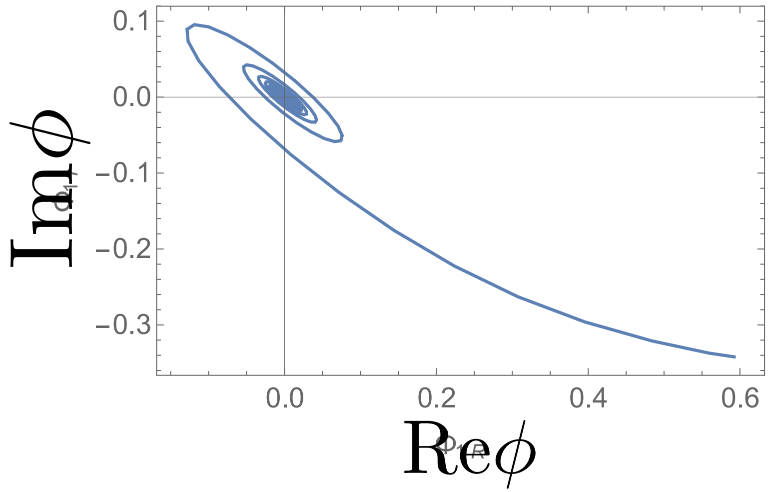
New phase-dependent term

: $\theta$ changes ⇨ $\dot\theta \neq 0$

$(m_\phi \simeq m_{S_1} \simeq m_{3/2})$

$\phi$ start to rotate around $\langle\phi\rangle = 0$ .

⇨ $\boxed{n_B \propto |\phi|^2\dot\theta \neq 0}$ $(\phi = |\phi|e^{i\theta})$



# Baryon asymmetry



Using E.O.M of $\phi$

$$\frac{\partial n_B}{\partial t} + 3Hn_B = -\mathrm{Im}\left[\frac{\partial V}{\partial \phi}\phi\right]$$

$$t_{\rm osc} \simeq \frac{1}{m_\phi}$$

These values are calculated numerically at $H \simeq m_\phi$

$$\Leftrightarrow \quad \boxed{n_B(t_{\rm osc}) \simeq \frac{1}{m_\phi}\frac{S_1^3(t_{\rm osc})\phi^3(t_{\rm osc})}{M_P^3}|\gamma a_m| m_{3/2}\delta_{\rm eff}}$$

$$\delta_{\rm eff} = \sin(\arg(ya_m) + 3\arg(S_1) + 2\theta)$$

Baryon asymmetry:

$$\frac{n_B}{s} \simeq \begin{cases} 0.5\times 10^{-10}\underline{\left(\frac{T_{\rm reh}}{10^5\mathrm{GeV}}\right)}\left(\frac{1}{|\gamma|}\right)^{\frac{1}{2}}\left(\frac{m_{3/2}}{m_\phi}\right)\left(\frac{m_\phi}{1\mathrm{TeV}}\right)^{-\frac{1}{2}} & \text{for} \quad c_\phi = \frac{1}{5},\ c_1 = \frac{1}{4} \\ 0.4\times 10^{-10}\underline{\left(\frac{T_{\rm reh}}{10^2\mathrm{GeV}}\right)}\left(\frac{1}{|\gamma|}\right)^{\frac{1}{2}}\left(\frac{m_{3/2}}{m_\phi}\right)\left(\frac{m_\phi}{1\mathrm{TeV}}\right)^{-\frac{1}{2}} & \text{for} \quad c_\phi = c_1 = 1 \end{cases}$$

The enough amount of baryon asymmetry is produced!

# Conclusion

The SUSY DFSZ axion model without R-parity

- explain the baryon asymmetry via Affleck-Dine mechanism
- explain the proton decay if this occur in Hyper-Kamiokande.
- may explain the neutrino masses and baryon asymmetry without introducing new fields such as right-handed neutrinos.

# Future work

- Investigating the detail of neutrino sector

# Appendix

# Neutrino masses

$$W \supset L_i H_u \quad \Rightarrow \quad \mathcal{L} \supset \mu'_i \nu_i \tilde{H}_u + \mathrm{c.c}$$

- neutrino mass matrix at tree level After diagonalizing other mass matrix part:

Hempfling, Nucl. Phys. B478, 3 (1996)

$$M^{\nu}_{\mathrm{tree}} \simeq -\frac{m_{\nu \mathrm{tree}}}{\Sigma^3_{i=1}\mu'^2_i} \begin{pmatrix} \mu'^2_1 & \mu'_1\mu'_2 & \mu'_1\mu'_3 \\ \mu'_1\mu'_2 & \mu'^2_2 & \mu'_2\mu'_3 \\ \mu'_1\mu'_3 & \mu'_3\mu'_2 & \mu'^2_3 \end{pmatrix} \longleftarrow \text{rank 1}$$

$$m_{\nu_{\mathrm{tree}}} \simeq \frac{m_z^2 \cos^2\beta (c_W^2 M_1 + s_W^2 M_2)}{M_1 M_2} \tan^2\xi$$

bino, wino mass

$$\tan^2\xi = \frac{\mu'^2_1 + \mu'^2_2 + \mu'^2_3}{\mu^2} + \mathcal{O}\left(\frac{\mu'_i\langle\tilde{\nu}_i\rangle}{\mu\langle H_d\rangle}\right)$$

$$W \supset \frac{y_0 S_1^2}{M_P} H_u H_d \equiv \mu H_u H_d$$

One neutrino has the mass of $m_{\nu_{\mathrm{tree}}}$.

although other neutrinos are massless at tree level.

# Neutrino masses

$$m_{\nu\mathrm{tree}} \simeq 5 \times 10^{-2}\ \mathrm{eV}\left(\frac{10}{1+\tan^2\beta}\right)\left(\frac{1\ \mathrm{TeV}}{M_1}\right)\underline{\left(\frac{\mu_i'/\mu}{4.4\times 10^{-5}}\right)^2}$$

- For $M_P = 2.4 \times 10^{18}\ \mathrm{GeV},\ f = 4.8 \times 10^{12}\ \mathrm{GeV}, y_0 = \frac{1}{6},\ y_i' = 4$ and $\gamma_{ijk} = \gamma'_{ijk} = \gamma''_{ijk} = \frac{1}{6}$

$$\mu = \frac{y_0 f^2}{M_P} = 1.6 \times 10^6\ \mathrm{GeV},\ \mu_i' = \frac{y_i' f^3}{M_P^2} = 7.7 \times 10^1 \mathrm{GeV} \Rightarrow \frac{\mu_i'}{\mu} = 4.8 \times 10^{-5}$$

This is consistent with the atmospheric squared-mass difference: $\sqrt{\Delta m_A^2} \simeq 5 \times 10^{-2}\ \mathrm{eV}$

* These parameters avoid the constraint of proton decay.