Neutrino masses and Baryon asymmetry in SUSY DFSZ axion model without R-parity

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On-going work with

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Introduction

The Standard Model is successful but still includes many problems.

We focus on

- Naturalness of Electroweak scale
- Strong CP problem
- Dark matter
- Tiny neutrino masses
- Baryon asymmetry

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  μ-problem, additional symmetry(R-parity)

- Strong CP problem → Peccei-Quinn mechanism and Axion

  SUSY DFSZ axion model without R-parity!

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- Baryon asymmetry → Affleck-Dine mechanism in SUSY

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Can SUSY DFSZ axion model without R-parity solve neutrino masses and baryon asymmetry economically?

Talk Plan

- Our model
- Neutrino masses in SUSY DFSZ axion without R-parity
- Affleck-Dine baryogenesis in SUSY DFSZ axion without R-parity
- Conclusion

R-parity (violation)

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

Farrar, Fayet, Phys. Lett. B76, 575 (1978)

S : spin

B : baryon number

L : lepton number

$R_p = +1$ for SM particles

$R_p = -1$ for superpartners

- R-parity violating superpotential

$$W_{\not R_p} = \underbrace{\mu' L H_u + \lambda L L \bar{e} + \lambda' L Q \bar{d}}_{\Delta L = 1} + \underbrace{\lambda'' \overline{u} \overline{d} \overline{d}}_{\Delta B = 1}$$

→See the constraint of the R-parity violating couplings

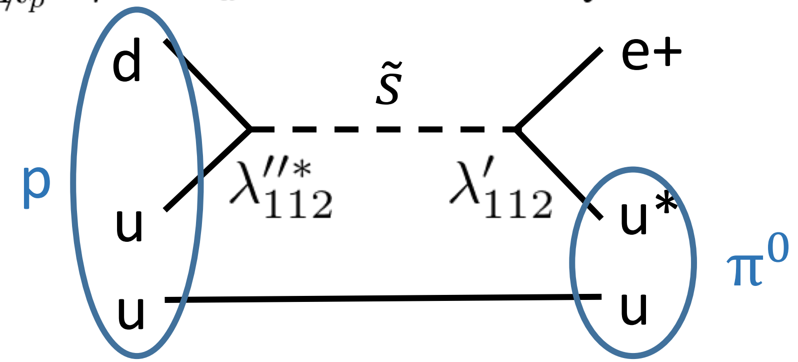
Constraint of R-parity violating couplings

Barbier et al., Phys.Rept. 420, 1 (2005)
J. Beringer et al. (Particle Data Group), Phys.Rev. D86, 010001 (2012)

(1)Observation of the proton decay

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

$$W_{\not{R}_p} = \mu' L H_u + \lambda L L \bar{e} + \lambda' L Q \bar{d} + \lambda'' \overline{u}\overline{d}\overline{d}$$



(2)To avoid the baryon washout

Constraint of 2→1 process:

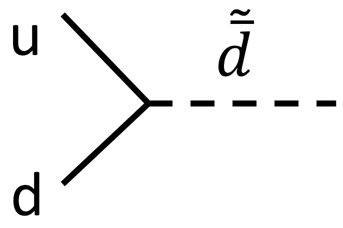
Campbell, Davidson, Ellis, Olive, Astropart. Phys. 1, 77 (1992)
Dreiner, Ross, Nucl. Phys. B410, 188 (1993)

$$\frac{\Gamma}{H} = \frac{\sqrt{10}\lambda^2 g_*(T)^{-1/2}}{3\pi^2\zeta(3)}\frac{m_{\tilde{f}}^2 M_{\mathrm{P}}}{T^3} f\left(\frac{m_{\tilde{f}}^2}{T^2}\right) < 1$$

⇔

$$\lambda, \lambda', \lambda'' < 4\times 10^{-7}\left(\frac{g_*(m_{\tilde{f}})}{100}\right)^{1/4}\left(\frac{m_{\tilde{f}}}{1\mathrm{TeV}}\right)^{1/2}$$

$$\left(T = m_{\tilde{f}}\right)$$



Our model

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

$$W = W_{MSSM} + W_{\not R_p} + W_{PQ}$$

	S_0	S_1	S_2	H_u	H_d	$\overline{u}_i$	$\overline{d}_i$	Q_i	$\overline{e}_i$	L_i
PQ	0	1	−1	−1	−1	−1	−1	2	3	−2
L	0	0	0	0	0	0	0	0	−1	1

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

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

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

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

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

Constraint of R-parity violating couplings

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

In the current universe, $U(1)_{PQ}$ is spontaneously broken by W_{PQ} and SUSY breaking:

$$\langle S_1 \rangle \simeq \langle S_2 \rangle \simeq f$$

The effective R-parity violating terms:

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

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

Constraint of R-parity violating couplings

$$W_{\not R_p} = \frac{y'\langle S_1\rangle^3}{M_P^2} L H_u + \frac{\gamma\langle S_1\rangle}{M_P} L L \bar{e} + \frac{\gamma'\langle S_1\rangle}{M_P} L Q \bar{d} + \frac{\gamma''\langle S_1\rangle^3}{M_P^3} \bar{u}\bar{d}\bar{d} \qquad \langle S_1\rangle \simeq \langle S_2\rangle \simeq f$$

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

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

(2)To avoid the baryon washout: $\lambda, \lambda', \lambda'' < 4 \times 10^{-7} \left(\frac{g_*(m_{\tilde{f}})}{100}\right)^{1/4} \left(\frac{m_{\tilde{f}}}{1\mathrm{TeV}}\right)^{1/2}$

For $M_P = 2.4 \times 10^{18}$ GeV, $f = 10^{12}$ GeV, $y_0 = y'_i = 1$, $\gamma_{ijk} = \gamma'_{ijk} = \frac{1}{2}$ and $\gamma''_{ijk} = 1$

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

SUSY DFSZ axion without R-parity avoid the constraints (1),(2)!

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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)

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

$$m_{\nu_{\rm tree}} \simeq \frac{m_z^2 \cos^2\beta(c_W^2 M_1 + s_W^2 M_2)}{M_1 M_2}\tan^2\xi \qquad \tan^2\xi = \frac{\mu'^2_1 + \mu'^2_2 + \mu'^2_3}{\mu^2} + \mathcal{O}\left(\frac{\mu'_i\langle\tilde{\nu}_i\rangle}{\mu\langle H_d\rangle}\right)$$

Gaugino mass

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

One neutrino has the mass of the order $m_{\nu_{\rm tree}}$
although other neutrinos are massless at tree level.

Neutrino masses

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

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

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

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

* These parameters avoid the constraint (1),(2).

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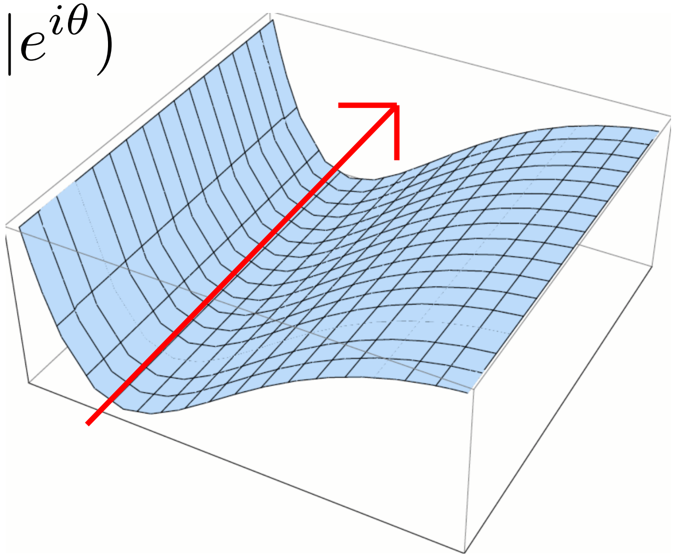
Affleck-Dine(AD) baryogenesis

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

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

Dynamics of AD field via B/L violating operator → Generate B/L number



- B/L violating operator

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

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

Setup

LH_u - flat direction of the scalar potential:

$$L = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi \\ 0 \end{pmatrix}, \quad H_u = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \phi \end{pmatrix}$$

The superpotential during and after the inflation:

$$W = W_{AD} + W_{PQ} + W_{\rm inf}$$

$$W_{AD} = y' \frac{S_1^3 L H_u}{M_P^2} = y' \frac{S_1^3 \phi^2}{M_P^2}, \quad W_{PQ} = \kappa S_0 (S_1 S_2 - f^2)$$

The lepton number density:

$$n_L = \frac{1}{2} i (\dot{\phi}^* \phi - \phi^* \dot{\phi}) = |\phi|^2 \dot{\theta} \qquad (\phi = |\phi| e^{i\theta})$$

→Let us investigate the potential and dynamics of AD/PQ scalar fields

Dynamics of AD/PQ fields during the inflation: $H = H_{\rm inf}$

F-term potential: $V_F = \left|\frac{\partial W}{\partial S_0}\right|^2 + \left|\frac{\partial W}{\partial S_1}\right|^2 + \left|\frac{\partial W}{\partial S_2}\right|^2 + \left|\frac{\partial W}{\partial \phi}\right|^2$

Hubble-induced potential:

$$V_H = c_0 H^2 |S_0|^2 - c_1 H^2 |S_1|^2 + c_2 H^2 |S_2|^2 - c_3 H^2 |\phi|^2$$

(H : Hubble parameter)

$$V_{HA} = -a_H H \frac{y' S_1^3 \phi^2}{2M_P^2} + \text{h.c.}$$

A minimum during the inflation for $a_H \gg c_1, c_3$:

$$\langle |S_0| \rangle = \frac{|\kappa| \langle |S_2| \rangle}{|\kappa|^2 \langle |S_1| \rangle^2 + |\kappa|^2 \langle |S_2| \rangle^2 + c_0 H^2} \frac{3|y'| \langle |S_1| \rangle^2 \langle |\phi| \rangle^2}{2M_P^2}$$

$$\langle |S_2| \rangle \simeq \frac{f^2}{\langle |S_1| \rangle} \quad , \langle |S_1| \rangle \simeq \langle |\phi| \rangle \simeq (H M_P^2)^{1/3}$$

*Phases of AD/PQ fields are fixed except for one phase(NG boson)

The AD/PQ fields will settle at the above minimum during the inflation.

Dynamics of AD/PQ fields after the inflation: $H = \frac{2}{3t}$

After the inflation, the inflaton oscillates and V_{HA} decrease exponentially

Kasuya, Kawasaki, Takahashi, JCAP 0810, 017 (2008)

$$V_{HA} = -a_H H \frac{y' S_1^3 \phi^2}{2M_P^2} + \text{h.c.} \rightarrow 0$$

The minimum changes into a saddle point!

The masses of AD/PQ fields just after the inflation are

$$m_{S_0} \simeq m_{S_2} \simeq \langle |S_1| \rangle \gg |m_{S_1}|, \ |m_\phi| \simeq H$$

S_0, S_2 are fixed at $\langle |S_0| \rangle = \frac{|\kappa| \langle |S_2| \rangle}{|\kappa|^2 \langle |S_1| \rangle^2 + |\kappa|^2 \langle |S_2| \rangle^2 + c_0 H^2} \frac{3|y'| \langle |S_1| \rangle^2 \langle |\phi| \rangle^2}{2M_P^2}$, $\langle |S_2| \rangle \simeq \frac{f^2}{\langle |S_1| \rangle}$.

<u>Let us investigate the dynamics of S_1, ϕ until $H \simeq m_{\text{soft}}$ numerically .</u>

The soft SUSY breaking terms become effective!

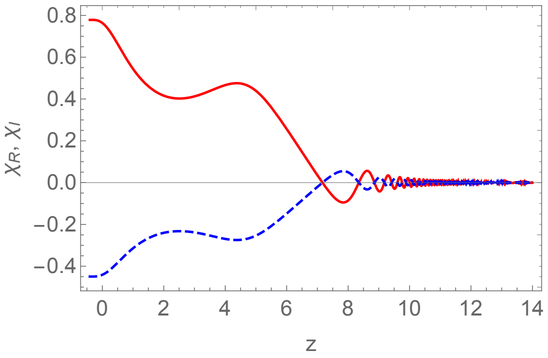
Dynamics of AD/PQ fields after the inflation: $H = \frac{2}{3t}$

We solve the E.O.M of S_1, ϕ until $H \simeq m_{\rm soft} \simeq 1~\mathrm{TeV}$ reparametrizing

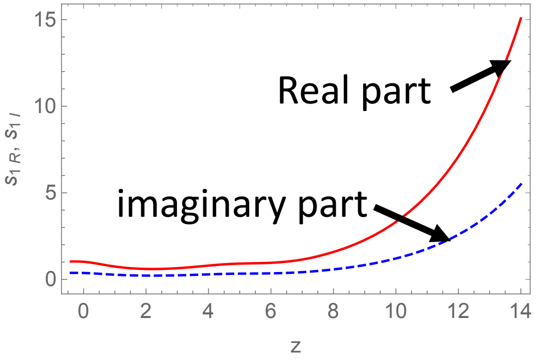
$$z = \log H_{\rm inf} t, \quad S_1 = s_1 \left(\frac{2 H_{\rm inf} M_P^2}{3y'} e^{-z} \right)^{\frac{1}{3}}, \quad \phi = \chi \left(\frac{2 H_{\rm inf} M_P^2}{3y'} e^{-z} \right)^{\frac{1}{3}}$$

For $c_1 > c_3$ $\left(a_H = 5, c_1 = \frac{1}{4}, c_3 = \frac{1}{5} \right)$ $(H_{\rm inf} = 10^9~\mathrm{GeV})$

χ



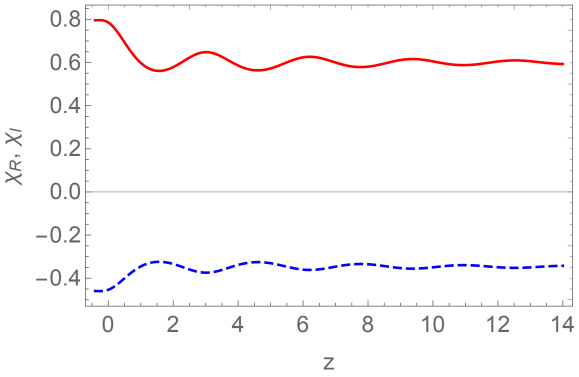
s_1



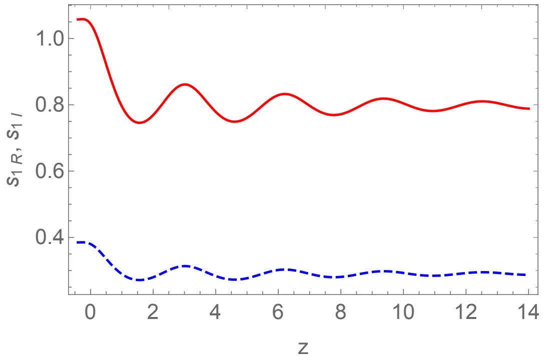
χ decreases.
s_1 increases.

For $c_1 = c_3$ $(a_H = 5, c_1 = c_3 = 1)$ $(H_{\rm inf} = 10^9~\mathrm{GeV})$

χ



s_1



s_1, χ oscillate
along the ridge
of the saddle point.

Dynamics of AD/PQ fields at $H < m_{\rm soft}$

The soft SUSY breaking terms become effective.

The effective potential:

$$V_F = \left|\frac{\partial W}{\partial S_0}\right|^2 + \left|\frac{\partial W}{\partial S_1}\right|^2 + \left|\frac{\partial W}{\partial S_2}\right|^2 + \left|\frac{\partial W}{\partial \phi}\right|^2$$

$$V_{\rm soft} = m_{S_0}^2|S_0|^2 + m_{S_1}^2|S_1|^2 + m_{S_2}^2|S_2|^2 + m_\phi^2|\phi|^2$$

$$V_{\rm softA} = \underbrace{-a_m m_{3/2}\frac{y' S_1^3\phi^2}{2M_P^2} + {\rm h.c.}}_{\text{B-L,CP breaking term}}$$

:the minimum of θ changes ➡ $\frac{\partial\theta}{\partial t} \neq 0$

$$(m_{S_0} \simeq m_{S_1} \simeq m_{S_2} \simeq m_\phi \simeq m_{3/2} \simeq m_{\rm soft})$$

➡

$$\langle|S_0|\rangle = 0, \langle|S_1|\rangle \simeq \langle|S_2|\rangle \simeq f, \langle|\phi|\rangle = 0$$

$$n_L = \frac{1}{2}i\left(\frac{\partial\phi^*}{\partial t}\phi - \phi^*\frac{\partial\phi}{\partial t}\right) = |\phi|^2\frac{\partial\theta}{\partial t} \neq 0 \quad (\theta = \arg\phi)$$

Baryon asymmetry

Using E.O.M of ϕ

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

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

These values are calculated numerically at $H \simeq m_\phi (z=14)$

$$n_L(t_{\rm osc}) \simeq \frac{1}{m_\phi}\frac{S_1^3(t_{\rm osc})\phi^2(t_{\rm osc})}{M_P^2}|y' a_m| m_{3/2}\delta_{\rm eff}$$

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

Baryon asymmetry via sphaleron process:

Kuzmin, Rubakov, Shaposhnikov, Phys. Lett. B155, 36 (1985)

$$\frac{n_B}{s} \simeq \begin{cases} 7.0\times 10^{-10}\left(\frac{T_{\rm reh}}{10^8\,\mathrm{GeV}}\right)\left(\frac{1}{|y'|}\right)^{\frac{1}{3}}\left(\frac{m_{3/2}}{m_\phi}\right)\left(\frac{m_\phi}{1\mathrm{TeV}}\right)^{-\frac{1}{3}} & \text{for} \quad c_1 = \frac{1}{4},\ c_3 = \frac{1}{5} \\ 6.8\times 10^{-10}\left(\frac{T_{\rm reh}}{10^6\,\mathrm{GeV}}\right)\left(\frac{1}{|y'|}\right)^{\frac{1}{3}}\left(\frac{m_{3/2}}{m_\phi}\right)\left(\frac{m_\phi}{1\mathrm{TeV}}\right)^{-\frac{1}{3}} & \text{for} \quad c_1 = c_3 = 1 \end{cases}$$

The enough amount of baryon asymmetry will be produced!

Conclusion

We propose SUSY DFSZ axion model without R-parity which can

- explain the atmospheric squared-mass difference
- explain baryon asymmetry via Affleck-Dine mechanism

This model has the following advantages:

We need NOT introduce R-parity in SUSY theory.

We may explain Neutrino masses and Baryon asymmetry only introducing $U(1)_{PQ}$ symmetry in SUSY theory without introducing a new field.