## The $\mu$ -problem and sneutrino inflation

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K. Choi, E. J. Chun, H. D. Kim, WIP & C. S. Shin, PRD83(2011)
 Y.G. Kim, H. M. Lee & WIP, JHEP 1108:126(2011)
 J. Gong, J. H, WIP, M. Sasaki &Y. Song, JCAP 1109:023(2011)

# Outline

### Motivation

 $\mu\text{-}\mathrm{problem}$  Gravitino problem in NMSSM Higgs inflation

### The model

A low energy model Vacuum property Generation of  $B_{\mu}$ 

### Sneutrino inflation

Jordan frame supergravity Slow-roll inflation Conformal invariance of  $\mathcal R$ Instability problem

### Post-inflation cosmology

Reheating Thermal inflation Baryon asymmetry Dark matter

#### Remarks QCD-axion

### Conclusion

 $\mu$ -problem[Kim & Nilles, PLB138(1984)]

MSSM superpotential:

$$W_{\rm MSSM} = y_u Q H_u \bar{u} + y_d Q H_d \bar{d} + y_e L H_d \bar{e} + \mu H_u H_d$$

Demand from a correct electroweak symmetry-breaking:

$$\mu = \mathcal{O}(10^{2-3})\,\mathrm{GeV} \sim m_\mathrm{soft}$$

Note:  $\mu$  is a supersymmetric parameter, and hence seems to have nothing to do with soft SUSY-breaking scale.

Q: How can soft scale  $\mu$  be generated?

Possible solutions:

- Z<sub>4</sub><sup>R</sup> consistent with SO(10) GUT and anomaly free [Lee et al., PLB694(2011);NPB850(2011))]
- U(1)PQ[Kim & Nilles, PLB138(1984); Chun, Kim & Nilles, NPB370(1992)]

## Gravitino problem in NMSSM Higgs inflation Jordan frame supergravity[Ferrara et al.,PRDB2(2010)] In 4D $\mathcal{N} = 1$ supergravity, under a Weyl transformation with

$$egin{array}{rcl} g^E_{\mu
u}&=&(-\Omega/3)\,g^J_{\mu
u}\ \Omega&=&-3e^{-\kappa(\phi^i,ar\phi^{ar l})/3} \end{array}$$

one can relate a general Lagrangian from Einstein-frame to Jordan-frame so that

$$\mathcal{L} = \sqrt{-g_E} \left( \frac{1}{2} R - K_{i\bar{j}} D_\mu \phi^i D^\mu \bar{\phi}^{\bar{j}} - V_E \right) \rightarrow \sqrt{-g_J} \left( -\frac{1}{6} \Omega R - \Omega_{i\bar{j}} D_\mu \phi^i D^\mu \bar{\phi}^{\bar{j}} - V_J \right)$$

where  $V_E = (9/\Omega^2) V_J$  and

$$V_{E} = e^{K} \left[ D_{i} W \left( K^{-1} \right)^{i \bar{j}} D_{\bar{j}} \bar{W} - 3 |W|^{2} \right]$$

with  $D_i = W_i + K_i W$ .

Gravitino problem in NMSSM Higgs inflation

NMSSM Higgs inflation[Einhorn & Jones, JHEP1003:026(2010)]

$$\begin{split} \Omega &= -3 + |S|^2 + |H_u|^2 + |H_d|^2 + \frac{3}{2}\chi \left(H_u H_d + \text{H.c.}\right) - \gamma |S|^4 \\ W &= -\lambda S H_u H_d + \frac{1}{3}\rho S^3 \end{split}$$

For  $\chi \gg 1$ , at large  $\langle H_u H_d \rangle$ , the potential of canonical field is

$$V = \frac{|\lambda|^2}{4\chi^2} \left[ 1 - 2e^{-2\varphi/\sqrt{6}} \right] \Rightarrow \text{Inflation at large } \varphi$$

where  $\varphi \equiv (\sqrt{6}/2) \ln \left[ \chi |h|^2 \right]$  with  $h^2 \equiv \langle H_u H_d \rangle$ .

$$\begin{split} \delta\Omega &= \frac{3}{2}\chi \left(H_u H_d + \text{H.c.}\right) \quad \Rightarrow \quad \delta W = \frac{3}{2}\chi m_{3/2} H_u H_d \\ &\Rightarrow \quad m_{3/2} \lesssim \mu/\chi = \mathcal{O}(1-10)\,\text{GeV} \end{split}$$

NMSSM Higgs inflation can work in the scenario of gauge-mediated SUSY-breaking.

Gravitino problem of Higgs inflation in NMSSM

Gravitino problem

Due to the large Yukawa and gauge couplings of Higgs, inflaton decays soon after the end of inflation, resulting in [Bezrukov,Gorbunov & Shaposhnikov, JCAP0906:029(2009); Garcia-Bellido,Figueroa & Rubio, PRD79(2009)]

$$T_{\rm R} = \mathcal{O}(10^{-1}) V_E^{1/4} = \mathcal{O}(10^{-1}) \left(\frac{|\lambda|}{\chi}\right)^{1/2} \sim 10^{15} \, {\rm GeV}$$



[Moroi, Murayama & Yamaguchi, PLB303]

Can we do Higgs inflation without gravitino problem in SUSY-framework?

#### Idea

- Thermal inflation which is quite natural in supersymmetry solves the gravitino problem.
- The Pecci-Quinn(PQ) field in DFSZ-type axion model can play the role of the flaton for thermal inflation.
- The field generates MSSM μ-term by its VEV.
- It can also provide large Majorana mass to right-handed neutrinos if it couples to the neutrino fields.
- The coupling of the flaton to right-handed neutrino field would provide a proper potential for an inflation like the one in NMSSM.

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### The model

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### Sneutrino inflation

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### A low energy model

Assume gauge-mediated SUSY-breaking and consider

 $W = y_u Q H_u \bar{u} + y_d Q H_d \bar{d} + y_e L H_u \bar{e}$ 

- SM guage symmetries
- ► *R*-parity
- U(1)<sub>PQ</sub> with charges assigned as

Field	Ζ	X	Y	Hu	H <sub>d</sub>	Qu <sup>c</sup>	Qd <sup>c</sup>	Le <sup>c</sup>	ΨΨ <sup>c</sup>	ΦΦ <sup>c</sup>	$N^2$
PQ charge	0	1	-3	-1	-1	1	1	1	-1	0	3

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$$W = y_u Q H_u \bar{u} + y_d Q H_d \bar{d} + y_e L H_u \bar{e}$$
$$+ \lambda_X X \Psi \bar{\Psi} + \frac{1}{2} \lambda_\mu \frac{X^2 H_u H_d}{\Lambda} + \lambda_{XY} \frac{X^3 Y}{\Lambda}$$

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$$+ \frac{1}{2} \lambda_Y Y N^2 + \lambda_N L H_u N$$

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Assume gauge-mediated SUSY-breaking and consider

$$W = y_{u}QH_{u}\bar{u} + y_{d}QH_{d}\bar{d} + y_{e}LH_{u}\bar{e}$$
$$+ \lambda_{X}X\Psi\bar{\Psi} + \frac{1}{2}\lambda_{\mu}\frac{X^{2}H_{u}H_{d}}{\Lambda} + \lambda_{XY}\frac{X^{3}Y}{\Lambda}$$
$$+ \frac{1}{2}\lambda_{Y}YN^{2} + \lambda_{N}LH_{u}N$$
$$+ \lambda_{7}Z\Phi\bar{\Phi}$$

- SM guage symmetries
- R-parity
- U(1)<sub>PQ</sub> with charges assigned as

Field	Z	X	Y	Hu	H <sub>d</sub>	Qu <sup>c</sup>	Qd <sup>c</sup>	Le <sup>c</sup>	ΨΨ <sup>c</sup>	ΦΦ <sup>c</sup>	$N^2$
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## Vacuum property

Assume

$$\lambda_Y, \lambda_N \ll \lambda_i \sim 1$$
 ,  $\Lambda \sim M_{\rm GUT}$ 

Then,  $\lambda_X$  derives soft mass-squard of X be negative, resulting in

$$\begin{aligned} |X_0| &\sim & (m_{\text{soft}} \Lambda)^{1/2} = \mathcal{O}(10^{10}) \, \text{GeV} \\ \frac{Y_0}{X_0} \bigg| &\sim & \frac{A_{XY}}{m_{\text{soft}}} = \mathcal{O}(10^{-2}) \\ m_X &\sim & m_Y \sim m_{\tilde{a}} \sim m_{\text{soft}} \end{aligned}$$

The  $\mu$  parameter is given by

$$\mu = \frac{1}{2} \lambda_{\mu} \frac{X_0^2}{\Lambda} \sim \lambda_{\mu} m_{\rm soft}$$

What about  $B_{\mu}$  ?

# Generation of $B_{\mu}$ [Choi, Chun, Kim, WIP & Shin, PRD83(2011)]

The RGE of  $\mu$  and  $B_{\mu}$  are

$$\begin{aligned} \frac{d}{d\ln\mu_r}\mu &\simeq \frac{1}{16\pi^2}\mu\left[3|y_t|^2+3|y_b|^2+|y_\tau|^2-3g_2^2-\frac{3}{5}g_1^2\right]\\ \frac{d}{d\ln\mu_r}B_\mu &\simeq \frac{1}{16\pi^2}B_\mu\left[3|y_t|^2-3g_2^2-\frac{3}{5}g_1^2\right]+\mu\left[6A_t|y_t|^2+6g_2^2M_2+\frac{6}{5}g_1^2M_1\right]\\ \Rightarrow \mu &\simeq \mu_0 \text{Exp}\left[\frac{3}{16\pi^2}|y_t|^2\right]\\ B_\mu &\sim \frac{1}{16\pi^2}\mu\left[6g_2^2M_2+\frac{6}{5}g_1^2M_1\right]\ln\left(\frac{m_{\text{soft}}}{M_{\Phi}}\right)\end{aligned}$$

For  $m_{\rm soft} = 1 \, {\rm TeV}$  and  $M_{\phi} = 10^{10} \, {\rm GeV}$ ,

$$B\sim 0.3~\mu_0$$

Intermediate scale  $M_{\Phi}$  can produce a sizable  $B_{\mu}$  through large RG-running.

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QCD-axion

Conclusion

# Sneutrino inflation

## Jordan frame supergravity

In Jordan frame with a Lagrangian

$$\frac{\mathcal{L}}{\sqrt{-g_J}} = -\frac{1}{6}\Omega R - \Omega_{i\bar{j}}D_{\mu}\phi^i D_{\mu}\bar{\phi}^{\bar{j}} - V_J$$

we define our theory as

$$\Omega = -3 + |Y|^2 \left( 1 - \gamma |Y|^2 - \sum_{i \neq 1} \delta_i |N_i|^2 \right) + \sum_{i=1}^3 \left[ |N_i|^2 - \frac{3}{2} \left( \xi_i N_i^2 + \text{h.c.} \right) \right]$$
  
$$W = \frac{1}{2} \sum_{i=1}^3 \lambda_{Yi} Y N_i^2 + \dots$$

where

$$\gamma = ?$$
,  $\delta_i = ?$ ,  $\xi_i \gg 1$ 

and  $\Omega = -3e^{-K/3}$  is chosen to recover Einstein-Hilbert action in Einstein frame.

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# Sneutrino inflation

### Slow-roll inflation

In Einstein frame, for the direction with  $Y = N_2 = N_3 = 0$  and  $\chi N_1 \gg 1$ 

$$\frac{\mathcal{L}_{\textit{E}}}{\sqrt{-g_{\textit{E}}}}\simeq\frac{1}{2}\textit{R}-\frac{1}{2}(\partial_{\mu}\varphi)^2-\frac{9|\lambda_{\rm Y1}|^2}{4(3\xi_1-1)^2}\Big(1-e^{-a\varphi}\Big)^2$$

where  $a\varphi \equiv \ln \left[1 + (\xi_1 - 1/3) |N_1|^2\right]$  with  $a \equiv [2/3 - 2/(9\xi_1)]^{-1/2}$ .



This potential derives an inflation at  $|N_1| \gg 1/\sqrt{\xi}$  where  $m_{\varphi} \ll H$ . The slow-roll parameters are given by

$$\epsilon_* \simeq \left(2a^2 N_e^2\right)^{-1} \quad , \quad \eta_* \simeq -N_e^{-1}$$

Including post inflation effect, we take  $N_e = 52$ . Then, inflationary observables are

	$WMAP7 + BAO + H_0$	ours
$\Delta_{\mathcal{R}}^2$	$\left(2.441^{+0.088}_{-0.092} ight)  imes 10^{-9}$	$\frac{N_{\theta}^{2}}{8\pi^{2}} \frac{ \lambda_{Y1} ^{2}}{(3\xi_{1}-1)^{2}}$
ns	$0.963\pm0.012$	$1-6\epsilon+2\eta\simeq 0.96$
r	< 0.24 (95% CL)	$16\epsilon\simeq 4.4 imes 10^{-3}$

Table: [Astrophys.J.Suppl.192:14(2011)]

In particular, WMAP 7-year data on  $\Delta^2_{\mathcal{R}}$  implies that

$$\lambda_{Y1} \simeq 2.4 imes 10^{-3} \left(rac{\xi_1}{100}
ight)$$

Combined with  $Y_0 = \mathcal{O}(10^{-2})X_0$ , the mass of the associated right-handed neutrino is

$$M_{N_1} = 10^5 \,\mathrm{GeV}\left(\frac{\lambda_{Y1}}{10^{-3}}\right) \left(\frac{X_0}{10^{10} \,\mathrm{GeV}}\right)$$

## Sneutrino inflation

### Conformal invariance of curvature perturbation $(\mathcal{R})$

[Gong, Hwang, WIP, Sasaki & Song, JCAP1109:023(2011)] Consider a conformal transformation,

$$egin{array}{rcl} g_{\mu
u} &
ightarrow & \Omega^2 g_{\mu
u} \ \Omega &=& \Omega_0 e^\omega \end{array}$$

Spatial metric can be expressed as

$$\begin{array}{lll} \gamma_{ij} & = & a^2 e^{\mathcal{R}} \tilde{\gamma}_{ij} \rightarrow a^2 \Omega_0^2 e^{\mathcal{R} + \omega} \tilde{\gamma}_{ij} \\ \Rightarrow \mathcal{R}^J & = & \mathcal{R}_c^{\mathcal{E}} + \omega \end{array}$$

For  $\Omega = \Omega(\varphi)$  with  $\varphi$  being the inflaton, on the comoving slice,

$$\delta 
ho = \mathbf{0} \quad \Rightarrow \quad \omega = \mathbf{0}$$
  
 $\Rightarrow \quad \mathcal{R}_{c}^{J} = \mathcal{R}_{c}^{E}$ 

 $\mathcal{R}_c$  is invariant under conformal transformation for single field inflation

# Sneutrino inflation

## Instability problem

The Einstein-frame potential along directions orthogonal to inflaton becomes

$$\begin{split} V_E &\simeq & \frac{1}{4} \frac{\lambda_{Y1}^2}{\xi_1^2} \left[ 1 + \left( 4\gamma - \frac{2}{3\xi_1 |N_1|^2} \right) |Y|^2 \right] & \text{for} \quad N_2 = N_3 = 0 \\ V_E &\simeq & \frac{1}{4} \frac{\lambda_{Y1}^2}{\xi_1^2} \left[ 1 + \sum_{i \neq 1} \delta_i |N_i|^2 - \sum_{i \neq 1} \left| \frac{\lambda_{Yi}}{\lambda_{Y1} N_1^2} \right| \left( N_i^2 + \bar{N}_i^2 \right) \right] & \text{for} \quad Y = 0 \end{split}$$

The stability of non-inflaton directions requires

$$\begin{split} \gamma &> & \frac{1}{6\xi_1|N_1|^2(t_e)}\simeq 0.1, \\ \delta_i &> & 2\left|\frac{\lambda_{YI}}{\lambda_{Y1}N_1^2(t_e)}\right|\simeq 7\times 10^4|\lambda_{YI}| \end{split}$$

$$\Rightarrow \quad \lambda_{Yi} \quad \lesssim \quad 10^{-5} \\ \Rightarrow M_{N_{2,3}} \quad \lesssim \quad 1 \text{ TeV} \quad \text{for} \quad Y_0 \sim 10^8 \text{ GeV}$$

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## Reheating

$$\begin{split} \Gamma_I &= \frac{\sqrt{3/2}}{8\pi} \sum_i |(\lambda_N)_{il}|^2 \lambda_{Yl} N_l \\ \Rightarrow T_{\rm R} &\simeq 3 \times 10^5 \, {\rm GeV} \left(\frac{g_*(T_{\rm R})}{200}\right)^{-1/4} \left(\frac{(\lambda_N)_{il}}{10^{-5}}\right)^2 \left(\frac{(\lambda_{Yl})}{10^{-3}}\right)^{1/2} \end{split}$$

Gravitino problem still exists for  $m_{3/2} \lesssim \mathcal{O}(1) \, \text{MeV}$ .

Thermal inflation is the natural solution to the problem in our scenario

Thermal inflation[Lyth & Stewart, PRL75(1995)]

$$W = y_{u}QH_{u}\bar{u} + y_{d}QH_{d}\bar{d} + y_{e}LH_{u}\bar{e}$$

$$+\frac{1}{2}\lambda_{Y}YN^{2} + \lambda_{N}LH_{u}N$$

$$+\lambda_{X}X\Psi\bar{\Psi} + \frac{1}{2}\lambda_{\mu}\frac{X^{2}H_{u}H_{d}}{\Lambda} + \lambda_{XY}\frac{X^{3}Y}{\Lambda}$$

$$+\lambda_{Z}Z\Phi\bar{\Phi}$$

$$0$$

$$V$$

$$T < T_{c}$$

$$V_{0}$$

$$V_$$

- λ<sub>X</sub> provides thermal mass and tachyonic zero-temp. mass around the origin, hence thermal inflation can occur when V<sub>0</sub><sup>1/4</sup> ≫ T > T<sub>c</sub>.
- >  $\lambda_{XY}$  stabilizes X at a point far away from the origin after thermal inflation ends.
- $\lambda_{\mu}$  reheats the universe to form radiation background composed of SM particles.

For  $\mu \sim m_x \sim m_{\text{soft}}$  and  $X_0 = \mathcal{O}(10^{10}) \,\text{GeV}$ ,

$$\Gamma_{|X|} \simeq \frac{3}{4\pi} \frac{\mu^4}{m_X X_0^2} \Rightarrow T_{\rm d} \sim 1 \, {\rm TeV} \Rightarrow {\rm Dilution \ by \ } \mathcal{O}(10^{14})$$

- Preexisting gravitinos are diluted sufficiently.
- Pre-existing baryon asymmetry is also diluted out.

## Baryon asymmetry (Late-time Affleck-Dine leptogenesis)

[Jeong,Kadota,Park & Stewart, JHEP 0411:046 (2004)]

For  $T_c < T_{LH_u}$ , Affleck-Dine leptogenesis works along  $LH_u$  flat direction.

$$V = g^2 T^2 |\ell|^2 - m_{LH_u}^2 |\ell|^2 + \left[ \frac{A_\nu \lambda_\nu \ell^4}{4M_\nu} + \text{c.c.} \right] + \left| \frac{\lambda_\nu \ell^3}{M_\nu} \right|^2$$



Present baryon number asymmetry is

$$\frac{n_B}{s} \sim \frac{n_B}{n_x} \frac{T_d}{m_x} \sim \frac{n_L}{n_{AD}} \frac{m_{L_i H_u}}{m_x} \left(\frac{|l_0|}{X_0}\right)^2 \frac{T_d}{m_x}$$

$$\sim 10^{-10} \left(\frac{n_L/n_{AD}}{10^{-4}}\right) \left(\frac{m_{LH_u}}{m_x}\right) \left(\frac{\ell_0/X_0}{10^{-3}}\right)^2 \left(\frac{T_d}{1 \text{ TeV}}\right) \left(\frac{1 \text{ TeV}}{m_x}\right)$$

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$$V = \mu^{2}(|X|)|\ell|^{2} - m_{LH_{u}}^{2}|\ell|^{2} + \left[\left(1 + 2\frac{h_{d}^{*}}{h_{u}}\frac{\mu(|X|)}{A_{\nu}}\right)\frac{A_{\nu}\lambda_{\nu}\ell^{4}}{4M_{\nu}} + \text{c.c.}\right] + \left|\frac{\lambda_{\nu}\ell^{3}}{M_{\nu}}\right|^{2}$$



Present baryon number asymmetry is

ľ

$$\frac{n_B}{s} \sim \frac{n_B}{n_x} \frac{T_d}{m_x} \sim \frac{n_L}{n_{AD}} \frac{m_{L_i H_u}}{m_x} \left(\frac{|l_0|}{X_0}\right)^2 \frac{T_d}{m_x}$$

$$\sim 10^{-10} \left(\frac{n_L/n_{AD}}{10^{-4}}\right) \left(\frac{m_{LH_u}}{m_x}\right) \left(\frac{\ell_0/X_0}{10^{-3}}\right)^2 \left(\frac{T_d}{1 \text{ TeV}}\right) \left(\frac{1 \text{ TeV}}{m_x}\right)$$

### Dark matter CDM candidates

- ▶ Axion: PQ scale is  $v_{PQ} \simeq X_0 = O(10^{10}) \text{ GeV}$  which is too small for present CDM
- Gravitino: LSP, can fit well to CDM relic density

#### **Production processes**

Thermal: scatterings and decays of the particles in thermal bath

$$\Omega_{3/2}^{\rm TH} h^2 \simeq 0.1$$
 if  $m_{3/2} \sim 100 \, {\rm keV}$  for  $T_{\rm d} \sim 1 \, {\rm TeV}$  (19)

Non-thermal: out-of-equilibrium decays of OLSP or axino

$$\frac{\Gamma_{\rm MSSM\to\tilde{a}}}{\Gamma_{\rm MSSM\to\Psi_{3/2}}}\sim \frac{m_{3/2}^2M_P^2}{m_{\rm soft}^2v_{\rm PQ}^2} = 10^2\left(\frac{m_{3/2}}{10^{-7}m_{\rm soft}}\right)^2\left(\frac{10^{-8}M_P}{v_{\rm PQ}}\right)^2$$

 $\Rightarrow$  In the decay of neutralinos in thermal bath, axino production is dominant.

Dark matter

If axino is NLSP, it decays to only gravitino, and

- $\Omega_{3/2}h^2 \gg 0.1$
- gravtino would be too warm for  $m_{\tilde{a}} \lesssim 1 \text{ TeV}$ .

Hence axino should be able to decay dominantly to at least OLSP, then

- OLSP is rapidly thermalized or co-annihilated to freeze-out abundance.
- the contribution of frozen-out OLSP to gravitino is negligible.

Present abundance

$$\Omega_{
m CDM}\simeq\Omega_{3/2}^{
m TH}\sim 0.1$$
 for  $\frac{m_{3/2}\sim 100\,
m keV}{}$ 

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## Remarks

QCD-axion: Problematic 1-loop tadpole contribution

$$\begin{split} \Omega &\supset -\frac{3}{2} \left( \xi_i N_i^2 + \mathrm{h.c.} \right) \Rightarrow W_\nu = \frac{3}{2} m_{3/2} \xi_i N_1^2 \\ V &\supset \frac{3}{2} B_\nu m_{3/2} \xi_1 N_1^2 + A_Y \lambda_{Y1} Y N_1^2 \\ \Rightarrow \Delta V(Y) &\sim \frac{\lambda_{Y1}}{16\pi^2} A_Y B_\nu m_{3/2} \xi_1 \log \left( \Lambda^2 / M_1^2 \right) Y \end{split}$$

Axion solution to strong CP problem requires

$$m_{3/2} < \left(10^2/\xi_1\right)^{2/3} 100 \,\mathrm{eV}$$

Gauge mediation o.k? No! baryon asymmetry and dark matter are not enough.

Axion for strong *CP*-problem can not be included in scenario.

## Conclusion

- Higgs-inflation type sneutrino-inflation can be realized and its observables matches well observation.
- Thermal inflation arises naturally and solves gravitino problem.
- The origin of electroweak scale µ-parameter can be explained by the VEV of PQ-field.
- Axion for strong *CP*-problem can not be accommodated into our model.
- Affleck-Dine leptogenesis after thermal inflation can provide a right amount of baryon number asymmetry at present.
- Thermally produced gravitino LSP with about 100 keV mass can provides the observed dark matter relic density.

### Back-up UV-realization of Ω (1/2)

### Tree level

$$\Omega = -3 + |Y|^2 + \sum_{i}^{3} \left[ |N_i|^2 - \frac{3}{2} \left( \xi_i N_i^2 + \text{H.C.} \right) \right] + \sum_{a}^{4} |\Phi_a|^2$$
$$W = \frac{1}{2} \kappa Y \Phi_1^2 + M_1 \Phi_1 \Phi_2 + \frac{1}{2} \alpha_i N_{i \neq 1} \Phi_3^2 + M_2 \Phi_3 \Phi_4 + \frac{\rho_i}{2\Lambda} Y N_{i \neq 1} \Phi_4^2$$

	Y	N <sub>1</sub>	$N_{i\neq 1}$	Φ <sub>1</sub>	Φ2	Φ3	Φ <sub>4</sub>
PQ	-3	3/2	3/2	3/2	-3/2	-3/4	3/4
Z <sub>2</sub>	+1	+1	+1	-1	-1	-1	-1

Table: PQ charges and  $Z_2$  parities in a UV completion

- $\Phi_a$ : heavy chiral superfields to be integrated out.
- $\Phi_a$  and  $N_{i\neq 1}$  are localized on a hidden brane.

 $(\Rightarrow$  geometric suppression of the couplings between  $N_1$  and  $\Phi_a$ )



### 1-loop correction

$$\begin{split} \Delta \Omega &= -\frac{1}{32\pi^2} \sum_{a}^{4} m_{F,a}^2 \ln \left[ \frac{m_{F,a}^2}{\mu_r^2} \right] \\ &\supset -\frac{1}{32\pi^2} \left\{ \frac{\kappa^4}{6} \frac{|Y|^4}{M_1^2} + \left[ \ln \left( \frac{M_2^2}{\mu_r^2} \right) + 2 \right] \rho_i^2 \frac{|YN_i|^2}{\Lambda^2} + \dots \right\} \\ \Rightarrow \gamma &= \frac{\kappa^4}{192\pi^2 M_1^2} \\ \delta_i &= \frac{\rho_i^2}{32\pi^2 \Lambda^2} \left[ \ln \left( \frac{M_2^2}{\mu_r^2} \right) + 2 \right] \end{split}$$

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