# *SUSY Breaking and Axino Cosmology*

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# *1. Introduction*

Fine Tuning Problems of Particle Physics

- **Smallness of electroweak scale**
- **Smallness of Strong CP phase**
- And others

# Strong CP problem

Why is the strong CP phase so small?

$$\mathcal{L}_{\bar{\Theta}} = \frac{g_3^2}{64\pi^2}\bar{\Theta}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

EDM measurements give constraint: $\Theta < 10^{-9}$

Solutions

- Vanishing up quark mass (unlikely?)
- Spontaneous CP violation
- Peccei-Quinn Symmetry (axion)

At present, the PQ symmetry is the most plausible solution.

# PQ solution

Global U(1) PQ symmetry with $SU(3)_C$ anomaly

U(1) PQ spontaneously broken at scale $f_a$

→NG boson = Axion a

$$\mathcal{L} = \frac{g_3^2}{64\pi^2}\left(\bar{\Theta} + \frac{a}{f_a}\right)\epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

$\Theta$ becomes dynamical. QCD dynamics makes this effective $\Theta$ zero at vacuum.

→ No Strong CP violation

# Naturalness of Electroweak Scale

Why is EW scale much smaller than Planck scale?

How is EW scale stable against radiative corrections?

Many ideas/models have been proposed.

**Supersymmetry**: a promising solution

# Marriage of PQ Sym. and SUSY

## Axion (NG boson) has superpartners

- Scalar partner: **saxion**
- Fermionic partner: **axino**

Exact SUSY →

- Axion/Saxion/Axino are degenerate in mass (essentially massless)
- Uncompactified flat direction (PQ scale is not determined)

SUSY breaking →

- Generation of saxion potential → stabilizing saxion
- Saxion and axino acquire masses

# *Interesting Issues …*

- Solution to $\mu/B\mu$ problem

Kim-Nilles ‘84

- Axino LSP → Axino DM

Rajagopal, Turner, Wilczek ‘91

- What about saxion cosmology?

  Rather flat potential for saxion

- ……

# *Talk Plan*

- Stabilization Mechanisms of PQ Potential
  – Case of one PQ field
  – Axino/saxion masses

- Axino Cosmology
  – Axino dark matter
  – Soln to moduli-induced gravitino problem

- Saxion Cosmology

# *2. Stabilization Mechanisms of PQ Potential*

Based on Kwang-Sik Jeong and MY, in preparation

# ***A Lesson: A Classic Example***

Consider the following example

**X(1), Y(-1), Z(0)**

**Superpotential W=Z( XY—f $^2$ )**

SUSY condition

$$\frac{\partial W}{\partial X} = ZY = 0 \qquad \frac{\partial W}{\partial Y} = ZX = 0 \qquad \frac{\partial W}{\partial Z} = XY - f^2 = 0$$

→ Z = 0, XY = f $^2$ fixed, but one complex direction X/Y undetermined

SUSY breaking effect generates potential for this direction

SUSY breaking effects can be incorporated by soft SUSY breaking terms.

$$V_{soft} = m_x^2 |X|^2 + m_y^2 |Y|^2 + m_z^2 |Z|^2 + AXYZ - A' f^2 Z + h.c.$$

$m_x, m_y, m_z, A, A'$ Soft Masses

Scalar Potential

$$V = V_{SUSY} + V_{soft} = |YZ|^2 + |XZ|^2 + |XY - f^2|^2 + V_{soft}$$

→ At minimum X,Y fixed and $Z \neq 0$ in general

Goto-MY '91

## Case A) Minimal SUGRA

$$m_x = m_y = m_z = m_0 \,, A, \; A' \sim O(m_{3/2})$$

$m_{3/2}$ : gravitino mass

$$|X| = |Y| = f, \qquad Z = A' - A$$

➔ saxion mass: $m_\sigma = O(m_{3/2})$

axino mass: $m_{\hat{a}} \approx Z = A' - A = O(m_{3/2})$

## Case B) no-scale model (i.e. gaugino mediation)

All soft masses except gaugino masses vanish @tree-level.
(They are generated @loop-level)

➔ $m_\sigma \,, m_{\hat{a}} \ll m_{3/2}$

Saxion/Axino masses: sensitive to

- SUSY Breaking Mediation (Goto-MY '91)
- Structure of Superpotential (Chun-Lukas, '95)

# Case of Single PQ Field

In the following, we shall consider the case of single PQ field.

Set Up

S (-1): PQ field

$\Psi$ (1/2) , $\Psi^c$ (1/2): 5, 5* under SU(5)

Kaehler potential $K = K_0 + Z_S|S|^2 + Z_\Psi|\Psi|^2 + Z_{\Psi^c}|\Psi^c|^2$

Superpotential $W = \omega_0 + \lambda_\Psi S\Psi\Psi^c,$

Absence of SUSY breaking→ no scalar potential for S field

Stabilization ← Incorporation of SUSY breaking

# Stabilization Mechanisms

## 1) Incorporation of higher term in Kaehler potential :

$K \supset c|S|^4/M_*^2$

$M_*$: UV cut-off

Scalar potential after SUSY breaking

$$V = m_s^2|S|^2 + m'^2_s|S|^4/M_*^2$$

With $m_s^2 < 0, m'^2_s > 0$ S develops a non-zero VEV.

$$S = \sqrt{-m_s^2/2m'^2_s}\ M_*$$

With $M_*$ close to Planck scale, the PQ scale tends to be larger than the conventional axion window.

# 2) Radiative Stabilization (similar to Coleman-Weinberg)

Integrating out $\Psi+\Psi^c$, one obtains

$$K_{\rm eff} = Z_S^{\rm eff}|S|^2, \quad W_{\rm eff} = \omega_0$$

$$Z_S^{\rm eff} = Z_S(Q = |y_\Psi S|)$$

Scalar potential

$$V = V_0 + m_S^2(Q = |y_\Psi S|)|S|^2$$

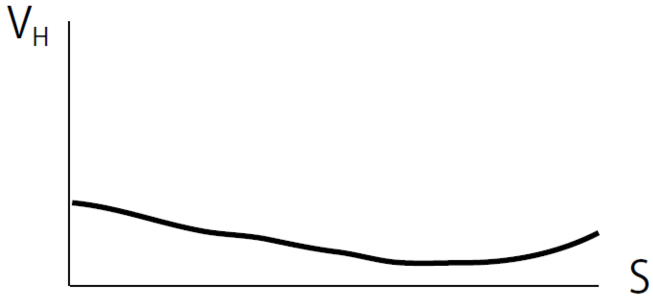
$$m_S^2 = -F^I F^{J*}\partial_I \partial_{\bar{J}} \ln\left(e^{-K_0/3} Z_S(Q = |y_\Psi S|)\right)$$

Soft mass $m_s^{\ 2}$ depends on running coupling constants , so it is a function of *S*.

Suppose , with proper choise of interactions,

$m_s^2 > 0$ for large S, $m_s^2 < 0$ for small S

S field develops non-zero VEV (hopefully in the axion window).




Saxion mass and Axino mass:

$$m_\sigma^2 = \frac{1}{16\pi^2}\sum_{ij} y_{Sij}^2 \left(m_i^2 + m_j^2 + |A_{Sij}|^2\right) \quad m_{\tilde{a}} = \frac{1}{16\pi^2}\sum_{ij} y_{Sij}^2 A_{Sij}$$

With all soft masses ~$M_0$ , one can realize relatively light saxion and axino.

$$m_\sigma = \mathcal{O}\left(\frac{M_0}{\sqrt{8\pi^2}}\right), \quad m_{\tilde{a}} = \mathcal{O}\left(\frac{M_0}{8\pi^2}\right)$$

# Some Exlicit Models

Asaka-MY, 98
Abe, Moroi, MY, 02
Nakamura,Okumura, MY, 08
Jeong-MY, in preparation

- Gravity mediation
- Anomaly mediation
- Mirage mediation (Anomaly+ Gravity)
- Gauge mediation

Here I will talk about the first two cases.

# Gravity Mediation

To be explicit, we consider the model

$$
\begin{aligned}
K &= K_0(T+T^*) + Z_S|S|^2 + Z_\Psi|\Psi|^2 + Z_{\Psi^c}|\Psi^c|^2 + Z_i|\Phi^i|^2, \\
W &= W_0(T) + \lambda_\Psi S\Psi\Psi^c + \lambda_u H_u Q U^c + \lambda_d H_d Q D^c + \lambda_e H_d L E^c \\
f_a &= kT + \text{constant},
\end{aligned}
$$

$$e^{-K_0/3} Z_I = (T+T^*)^{n_I}$$

Soft Masses

$$
\begin{aligned}
M_a &= \frac{k(T+T^*)}{2} g_{\rm GUT}^2 M_0, \\
A_{ijk} &= (n_i + n_j + n_k) M_0, \\
m_i^2 &= n_i |M_0|^2,
\end{aligned}
$$

$$M_0 = \frac{F^T}{T+T^*}$$ of the order gravitino mass

## Saxion stabilization:

For $n_s>0$, one gets $m_s^2 > 0$ at high scale.

Yukawa coupling of $S\Psi\Psi^c$ → $m_s^2 < 0$

→Saxion is radiatively stabilized and non-zero VEV for S

## Spectrum:

relatively light saxion and axino. Likely Axino LSP

$$m_\sigma = \mathcal{O}\left(\frac{M_0}{\sqrt{8\pi^2}}\right), \quad m_{\tilde{a}} = \mathcal{O}\left(\frac{M_0}{8\pi^2}\right)$$

## Higgs μ/Bμ term:

Both mechanisms work to give the correct order of μ/Bμ term.

1) Kim-Nilles: $$W = \lambda_H \frac{S^2}{M_{Pl}} H_u H_d$$

2) Giudice- Masiero: $$K = \kappa \frac{S^*}{S} H_u H_d + \text{h.c.}$$

# Anomaly Mediation

## Scenario:

- Heavy gravitino mass (>10TeV)
- SUSY breaking is mediated by superconformal anomaly

Jeong-MY, in preparation

## Model

$$K = K_0 + Z_S|S|^2 + Z_\Psi|\Psi|^2 + Z_{\Psi^c}|\Psi^c|^2 + Z_N|N|^2 + Z_i|\Phi^i|^2$$

$$\begin{aligned} W &= \omega_0 + \lambda_\Psi S\Psi\Psi^c + \lambda_N SNN + \lambda_\nu NLH_u \\ &\quad + \lambda_u H_u QU^c + \lambda_d H_d QD^c + \lambda_e H_d LE^c, \end{aligned}$$

## Saxion potential

$$\begin{aligned} m_S^2 &= -\frac{|m_{3/2}|^2}{32\pi^2}\frac{d\gamma_S(Q)}{d\ln Q}\bigg|_{\mathrm{Q=|y_\Psi S|}} \\ &= \Big[N_\Psi y_\Psi^2\Big(5(5N_\Psi+2)y_\Psi^2 - 16g_3^2 - 6g_2^2 - 2g_1^2\Big) \\ &\quad + 3y_N^2\Big(3y_N^2 + 10N_\Psi y_\Psi^2\Big)\Big]\left|\frac{m_{3/2}}{16\pi^2}\right|^2, \end{aligned}$$

# Note on Saxion Stabilization

Yukawa coupling of SNN is crucial.

Radiative stabilization is operative due to a delicate balance between 1st line and 2nd line.

In the absence of SNN

- impossible to realize radiative stabilization
- Need of higher order term in Kaehler pot

(see Abe, Moroi &MY, 02)

**Spectrum:** again relatively light saxion/axino Axino LSP

$$m_\sigma = \mathcal{O}\left(\frac{M_0}{\sqrt{8\pi^2}}\right), \quad m_{\tilde{a}} = \mathcal{O}\left(\frac{M_0}{8\pi^2}\right)$$

**Higgs μ/Bμ term:**

1)GM mechanism works $K_{\rm eff} = \kappa \frac{S^*}{S} H_u H_d + {\rm h.c.}$

$$\mu = \kappa\left(\frac{F^S}{S} + \frac{F^C}{C_0}\right)^* + \frac{m_{3/2}}{2}\frac{d\kappa}{d\ln Q}\bigg|_{Q=\Lambda_S},$$

$$B\mu = \left\{\frac{F^S}{S} + \frac{F^C}{C_0} - (\gamma_{H_u} + \gamma_{H_d})M_0\right\}\mu - \frac{|m_{3/2}|^2}{4}\frac{d^2\kappa}{(d\ln Q)^2}\bigg|_{Q=\Lambda_S}$$

2) KN mechanism does not work $W = \lambda_H \frac{S^2}{M_{Pl}} H_u H_d$

→ too large B parameter: $B \approx m_{3/2} \gg M_0$

# Common Features

Similar arguments apply to other mediations.

With appropriate choice of interactions, one PQ field models share similar feature:

1) Spectrum

Axino is lighter than LOSP, can be LSP

2) Higgs $\mu/B\mu$ term can be generated.

| Mediation | Gravity | Anomaly | Mirage | Gauge |
|---|---|---|---|---|
| LSP | axino | axino | axino | axino or gravitino |
| Higgs parameters | KN, GM | GM | GM | KN, GM |

# 3. Axino Cosmology

Axino is light in many models.

In particular in one PQ field models, axino mass~O(0.01) $M_0$

➔ Axino is LSP and a candidate for DM

**Production Mechanisms**

- Thermal Production
- From Moduli/Inflaton Decay
- From Gravitino Decay
- From LOSP Decay

Here instead of surveying all possibilities, I want to focus on one specific mechanism of axino dark matter

**Axino production in axionic mirage mediation**

# *Axionic Mirage Mediation: Motivation*

- **Mixed modulus-anomaly mediation of SUSY breaking (mirage mediation)**

  simple and attractive scenario

  Choi,Falkowski,Nilles, Olechowski 05
  Endo,MY,Yoshioka 05
  Choi,Jeong,Okumura 05

- **little hierarchy among masses**:

  Moduli $X$ gravitino sparticles
  (compensator $\Phi$)

  $F_X \sim m_{3/2}^2/m_X \ll F_\Phi = m_{3/2}$

  $m_X \gg m_{3/2} \gg m_{soft}$

- **Relatively heavy moduli**

  ← A consequence of a simple exponential factor

  $W \sim A \exp[-bX] + \text{constant}$

  typical example: KKLT set-up

- **This scenario seemed to provide a solution to cosmological moduli problem and gravitino problem.**

*However life is not that easy!*

# Moduli-Induced Gravitino Problem

Endo,Hamaguchi,Takahashi 06
Nakamura,MY 06

- Moduli decay into Gravitino Pair
  - significant branching ratio ~0.01 generically

- BBN is not spoiled: Gravitino lifetime much shorter than 1 sec.

- *But, Dangerous Decay Chain*

  Moduli→ Gravitino →(Sparticles) → Neutralino LSP

  **produce too many LSPs** (even after considering the effect of neutralino annihilation)

**Axionic Mirage Mediation solves this problem!**

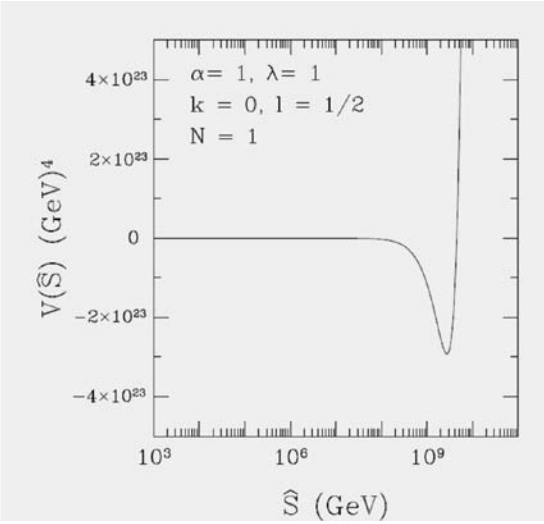
# *Axionic Mirage Mediation: The Model*

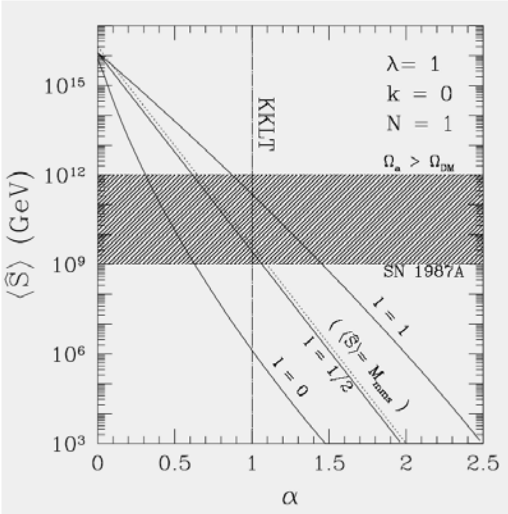
Nakamura,Okumura,
MY 08

**One PQ field model, coupling to new quark/leptons**

$$W = \lambda S \Psi \bar{\Psi}$$

Potential of *S:* generated at loop level



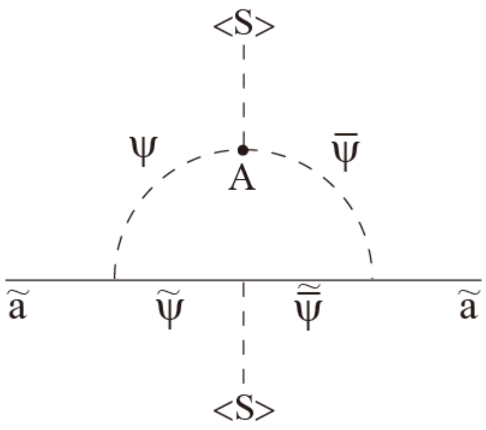




$$\alpha \equiv \frac{m_{3/2}}{(F_X/2X_R)\ln(M_{\rm Pl}/m_{3/2})}$$

**PQ scale can naturally fall into the axino window.**

# Axino Mass

$$m_{\tilde{a}} = \frac{1}{8\pi^2}\left(\frac{1}{2}\frac{\partial\gamma_S(|\hat{S}|)}{\partial X^\dagger}F_X^\dagger - \frac{1}{4}\dot{\gamma}_S(|\hat{S}|)F_\Phi^\dagger\right)\left\langle\frac{\hat{S}^\dagger}{\hat{S}}\right\rangle$$




( $\gamma_S$ : anomalous dimension of S )

**Axino mass arises at two-loop.**

cf. other soft masses at one-loop

⇒ **The axino becomes LSP**

# Cosmology Highlights

Nakamura,Okumura, MY 08

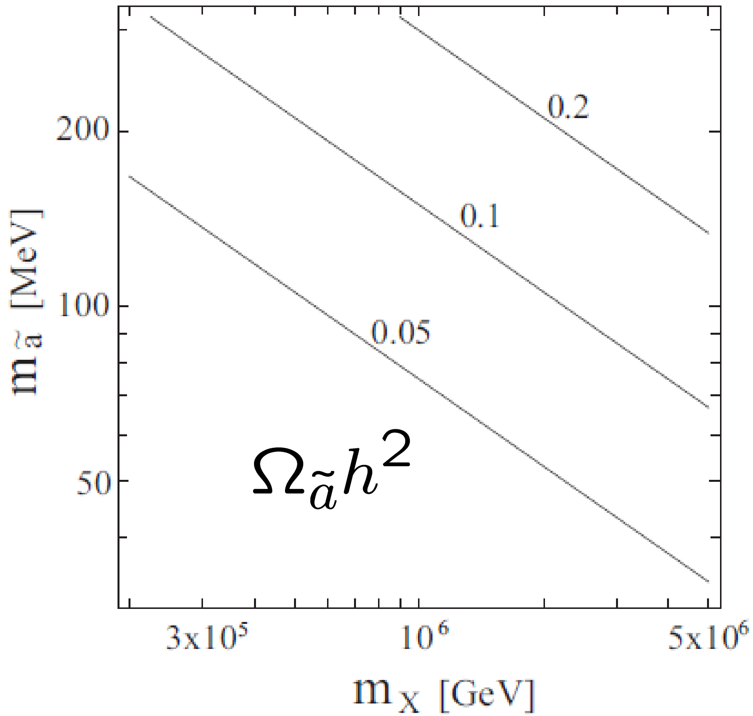
- **Moduli Decay:** entropy production (before BBN)
  gravitino (sparticle) production

- **Gravitino Decay:** life time shorter than 1 sec

- **Axino LSP abundance**
  dominant production mode:
  moduli→ gravitino → (sparticles) →NLSP → axino LSP

$$Y_{\tilde{a}} \sim 4 \times 10^{-9} \left( \frac{\mathrm{Br}(X \to \psi_{3/2}\psi_{3/2})}{0.01} \right) \times \left( \frac{m_X}{10^6 \mathrm{GeV}} \right)^{1/2}$$

# axino dark matter




axino abundance for typical NLSP

**Axino can be dark matter when mass ~0.1 GeV.**

Axinos are produced energitically.

→ **Free-streaming length O(0.1) MPc.**

Maybe some implication to (small) scale structure

# 4. Saxion Cosmology

- Properties
  - Saxion potential: rather flat
  - Saxion coupling: weak, suppressed by 1/fPQ

→ Saxion will play some non-trivial role in cosmology. The resulting cosmology is likely non-standard one.

- Important Issues:
  - Saxion couplings
  - Cosmological evolution of saxion zero mode

# Saxion Decay

- Saxion decay into axion/axino

$$\mathcal{L}_{\rm int} = \frac{1}{2\sqrt{2}}\left(\frac{\sigma}{S_0}(\partial a)^2 + \lambda_{\tilde{a}} m_{\tilde{a}} \frac{\sigma}{S_0}\tilde{a}\tilde{a}\right) + {\rm h.c.}$$

$$\Gamma_{\sigma\to aa} = \frac{1}{64\pi}\frac{m_\sigma^3}{S_0^2},$$

$$\Gamma_{\sigma\to\tilde{a}\tilde{a}} = \frac{\lambda_{\tilde{a}}^2}{32\pi}\frac{m_{\tilde{a}}^2 m_\sigma}{S_0^2}$$

- Saxion decay into gauge bosons
  - Suppressed by loop factor

- Saxion decay into b

$$\frac{\Gamma_{\sigma\to b\bar{b}}}{\Gamma_{\sigma\to aa}} \approx 48R^2\left(1-4\frac{m_b^2}{m_\sigma^2}\right)^{3/2}\left(1-\frac{|B|^2}{m_A^2}\right)^2\left(\frac{m_b^2}{m_\sigma^2}\right)\left(\frac{|\mu|^2}{m_h^2}\right)^2$$

$$R = \begin{cases} 1 & : \ \text{Kim-Nilles}, \\ \frac{d\kappa}{d\ln Q}\big|_{Q=\Lambda_S} = \mathcal{O}(1/8\pi^2) & : \ \text{Giudice-Masiero} \end{cases}$$

# Saxion Decay: Summary

- Saxion dominantly decays into $b\bar{b}$ if
  - Kim-Nilles mechanism is operative
  - Large higgsino mass parameter $\mu$

- Otherwise, saxion dominantly decays to axion pair.

# Saxion Evolution

- Assumption
  - Saxion mass scale < Hubble during inflation
  - Hubble induced mass term determines the location of zero mode during inflation

- Hubble induced mass term during inflation

$$\delta V = c_S H^2 |S|^2$$

- Two cases
  - 1) C<0: saxion zero mode located far away
  - 2) C>0: saxion zero mode trapped at origin

# Saxion Evolution (continued)

- **C<0: located far away**
  - Coherent oscillation of saxion → Decay (reheating)

  When saxion dominantly decays to axion, entropy production may be required.

- **C>0: trapped at origin**
  - Thermal effect → Thermal Inflation (Lyth-Stewart 95)
  - End of thermal inflation and subsequent reheating

  Viable only when saxion dominantly decays to SM.

# Case of Axionic Mirage Mediation

Kim-Nilles mechanism does not work

→ Saxion decay to axion is dominant

Saxion zero-mode has to be placed far from origin.

Axions produced at saxion decay are diluted by entropy production at moduli decay.

# Summary

- Axion in SUSY
  - Saxion/axion/axino form supermultiplet
- SUSY breaking → Stabilization of saxion, Axino mass
- Case of one PQ field is discussed: Axino is likely LSP
- Axino cosmology
  - Axionic mirage mediation→
    - Solution to gravitino problem
    - axino dark matter
- Saxion Cosmology
  - Evolution of Unvierse is likely non-standard
    - Entropy production after saxion oscillation or
    - Thermal inflation driven by saxion