Moduli Stabilization in Stringy ISS Models

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In collaboration with Yu Nakayama and T.T. Yanagida

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We want SUSY!
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We want *dynamical* breaking of SUSY! [Witten '81]

\[ \Lambda = \Lambda_0 \exp\left( -\text{const.} / g(\Lambda_0)^2 \right) \ll \Lambda_0 \]
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...but difficult (Witten index, \( U(1)_R \) [Nelson-Seiberg ’93])

- Several DSB models, but quite contrived [Affleck-Dine-Seiberg, Izawa-Yanagida-Intriligator-Thomas ’96,...]
Introduction and motivation

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- Several DSB models, but quite contrived [Affleck-Dine-Seiberg, Izawa-Yanagida-Intriligator-Thomas '96,...]
- More recently, metastable SUSY breaking: ISS model [Intriligator-Seiberg-Shih '06]
  Model building made generic, viable, easy [Murayama-Nomura,... '06]

Here we study ISS model as a simple example of DSB models.
ISS from string theory

We want to construct ISS models from string theory!
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The goal of this talk

We want to solve moduli stabilization problem in ISS model (especially mass moduli). We consider compact CY with finite 4d Planck length.
ISS from string theory

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Landscape or Swampland?
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Swampland [Vafa '05, Ooguri-Vafa '06]

(semi)classically consistent but quantum inconsistent effective field theories

Are DSB models in the landscape or in the swampland?
The goal of this talk

We want to solve moduli stabilization problem in ISS model (especially mass moduli). We consider compact CY with finite 4d Planck length).

Basic idea

Gauge (anomalous) $U(1)$ and use its FI D-term
Plan of this talk

1. Introduction
   - Dynamical SUSY breaking
   - Moduli stabilization problem in ISS model

2. Moduli stabilization of ISS model in global SUSY limit
   - Brief review of ISS models
   - Our idea in global SUSY limit

3. Moduli stabilization of stringy ISS models
   - String theory setup
   - Moduli Stabilization of $\rho$ and $\tau$

4. Conclusions and Discussions
Brief review of ISS models

Electric Theory
\( \text{SU}(N_c) \) SQCD with \( N_f \) pairs of fundamental quarks \( \varphi_i, \bar{\varphi}^i \), (\( i = 1, \ldots, N_f, N_c < N_f < \frac{3}{2} N_c \)) with superpotential

\[
W_{\text{electric}} = m \varphi_i \bar{\varphi}^i .
\]
Brief review of ISS models

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\[ W_{\text{electric}} = m \varphi_i \bar{\varphi}^i. \]

Magnetic Theory
\[ SU(N_f - N_c) \text{ with dual fundamental quarks } q_i, \bar{q}^i \text{ and meson} \]
\[ M_{ij} = \varphi_i \bar{\varphi}^j \]
\[ W_{\text{magnetic}} = m \text{Tr}M + \frac{1}{\mu} q^i M_{ij} \bar{q}^j + \text{(nonperturbative term)} \]
Brief review of ISS models

**Electric Theory**

$\text{SU}(N_c)$ SQCD with $N_f$ pairs of fundamental quarks $\varphi_i, \bar{\varphi}^i$, ($i = 1, \ldots, N_f$, $N_c < N_f < \frac{3}{2}N_c$) with superpotential

$$W_{\text{electric}} = m\varphi_i\bar{\varphi}^i .$$

**Magnetic Theory**

$\text{SU}(N_f - N_c)$ with dual fundamental quarks $q_i, \bar{q}^i$ and meson $M_{ij} = \varphi_i\bar{\varphi}^j$

$$W_{\text{magnetic}} = m\text{Tr}M + \frac{1}{\mu}q^iM_{ij}\bar{q}^j + (\text{nonperturbative term})$$

We need $|m| \ll \Lambda$ to obtain sufficiently long-lived metastable vacua.
Impossible to set all F-terms for $M_{ij}$ to zero (rank condition)

$$m\delta_{ij} + \frac{1}{\mu} \frac{q_i \bar{q}_j}{\mu} \neq 0$$

$\text{rank} = N_f$  

$\text{rank} = N_f - N_c$
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SUSY broken with potential

$$V = N_c|m|^2|\Lambda|^2$$

up to a numerical constant of order 1 by setting $M = 0$, $q = \bar{q} = i\sqrt{m\mu}1_{N_f - N_c \times N_f - N_c}$
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If $m$ becomes dynamical variable $\rho$, then $m = 0$ and SUSY restored!
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If $m$ becomes dynamical variable $\rho$, then $m=0$ and SUSY restored!

$\Rightarrow$ Solution: we use D-term
Anomalous $\mathbf{U(1)}$ and its $D$-term

We introduce anomalous $\mathbf{U(1)}_D$, under which $\rho$ is charged.

<table>
<thead>
<tr>
<th>$\rho$</th>
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If we gauge this $\mathbf{U(1)}_D$ we have

$$V_D = \frac{g^2}{2} \left( \xi - |q|^2 - |\bar{q}|^2 - 2|\rho|^2 + 2 \frac{|M|^2}{|\bar{\Lambda}|^2} \right)^2$$

$$V = V_F + V_D = N_c |\rho|^2 |\Lambda|^2 + \frac{g^2}{2} \left( \xi - 2|\rho|^2 - 2(N_f - N_c)|\mu\rho| \right)^2$$

For small $\xi$, $\rho$ is stabilized at $|\rho| = \frac{g^2 |\mu| \xi(N_f - N_c)}{N_c |\Lambda|^2 + 2g^2 |\mu|^2 (N_f - N_c)^2}$
However, this is not the end of the story!
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- $U(1)_D$ is anomalous
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- $U(1)_D$ is anomalous
- SUSY restored when FI parameter $\xi$ becomes dynamical

$\implies$ These two problems are solved at once in string theory! ...
We discuss FI parameter stabilization in global SUSY

- Consider chiral superfield

\[ T(x; \theta) = \frac{1}{g^2(x)} + \frac{i}{8\pi^2} \phi(x) + O(\theta) \]

- Axion transforms as

\[ \phi(x) \rightarrow \phi(x) - 2N_f \alpha(x) \]

under the gauge transformation \( A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu \alpha(x) \) to cancel anomaly

- The Kähler potential, therefore, should depend on the gauge invariant combination

\[ T + T^\dagger - \frac{N_f}{4\pi^2} V \]

\((V: \text{vector superfield corresponding to the } U(1)_D)\)
Then the action contains both the dynamical FI-term and the Higgs-term:

$$\int d^4 \theta \ K(T + T^\dagger - \frac{N_f}{4\pi^2} V)$$

$$= \left( \frac{\partial K}{\partial V} \right)_{V=0} V|_{\theta^4} + \frac{1}{2} \left( \frac{\partial^2 K}{\partial V^2} \right)_{V=0} \left( \frac{\partial_\mu \phi}{2N_f} + A_\mu \right)^2 + \cdots$$
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FI-term

Higgs term
Then the action contains both the dynamical FI-term and the Higgs-term:

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\]

\[
= \left. \left( \frac{\partial K}{\partial V} \right) \right|_{V=0} V^{\theta^4} + \frac{1}{2} \left( \frac{\partial^2 K}{\partial V^2} \right)_{V=0} \left( \frac{\partial \mu \phi}{2N_f} + A_\mu \right)^2 + \cdots
\]

The introduced D-term is

\[
V_D = \frac{g^2}{2} \left( \frac{-N_f}{4\pi^2} \partial_T K + \sum_i q_i \phi_i \partial_{\phi_i} K \right)^2,
\]

\(\phi_i\): fields that couple linearly to \(U(1)_D\), \(q_i\): charges
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\[\downarrow\]
Fl-parameter \( \xi \) is stabilized
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In **SUGRA**, we have simple relation [Joichi-Kawamura-Yamaguchi ’94, Choi-Falkowski-Hilles-Olechowski ’05]

$$\sum_i \delta \phi_i \frac{D_i W}{W} = D ,$$

$\delta \phi_i$: a gauge transformation of the matter field.
SUSY broken both by D- and F-terms

In our case, SUSY is broken both by D-term ($U(1)_D$) and F-term (ISS).

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$$\sum_i \delta\phi_i \frac{D_i W}{W} = D,$$

$\delta\phi_i$: a gauge transformation of the matter field.

$\Rightarrow$ it is impossible to obtain D-term SUSY breaking without F-term SUSY breaking (unless $W = 0$).
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String theory setup

Consider type IIB flux compactification.

- All complex structures and dilaton are fixed [Giddings-Kachru-Polchinski '01].
- Consider CY orientifold compactification with one Kähler modulus.
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We consider D7-branes and O-plane.

- magnetic flux in one D7-brane around 4-cycle corresponding to Kähler modulus $T$.
- other D7-branes give $SU(N_c)$ SYM
- $G = U(1) \times SU(N_c)$

[Cremades-Carcia del Moral-Quevedo-Suruliz]
Matter contents: electric theory

The matter contents:

- The field $\varphi$ stretching between the magnetized brane and $\text{SU}(N_c)$ branes will be charged $(+1, N_c)$ under $U(1) \times \text{SU}(N_c)$.

- The field $\bar{\varphi}$ stretching between the magnetized brane and the orientifold images of $\text{SU}(N_c)$ branes will be charged $(+1, \bar{N}_c)$ under $U(1) \times \text{SU}(N_c)$.

- The field $\rho$ stretching between the magnetized brane and its orientifold images will be charged $-2$ under $U(1)$.

(we really need to fix $\text{SU}(N_f)$ flavor moduli)
Superpotential and FI-term

We have superpotential

\[ W = \rho \varphi_i \bar{\varphi}^i \]
Superpotential and FI-term

We have superpotential

$$W = \rho \varphi_i \bar{\varphi}^i$$

and necessary D-term interaction including the dynamical FI term coming from the Chern-Simons coupling [Dine-Seiberg-Witten '87]

$$\int_{D7} C_4 \wedge F \wedge F$$

If you write $C_4 = D_2 \wedge \omega$, then this contains

$$\int_{\Sigma} \omega \wedge f \int_{\mathbb{R}^4} D_2 \wedge F$$

and $\int_{\mathbb{R}^4} D \wedge F$ becomes $\int_{\mathbb{R}^4} \partial_\mu \phi A_\mu$, which is related by FI term by SUSY and gauge invariance.
Superpotential and Kähler potential in magnetic theory

Taking Seiberg duality, we have magnetic theory with superpotential

\[ W = W_0 + \rho \text{Tr} M + \frac{1}{\mu} q_i M_{ij} \bar{q}^j \]

with the Kähler potential \( (2\tau = T + T^\dagger) \)

\[ K = -2 \log(\tau^{3/2} + \zeta) + \frac{|\rho|^2}{\tau^n} + \frac{|q|^2 + |\bar{q}|^2}{\tau^n} + \frac{|M|^2}{\tau^n} e^{\frac{8\pi^2 \tau}{3N_c - 2N_f}} \]

Here \( \zeta \) is the \( \alpha' \)-correction proportional to the Euler number of CY [Becker-Becker-Haack-Louis '02], \( n \) is called modular weight and \( \frac{2}{3} \) in electric description [Conlon-Cremades-Quevedo '06].
Full potential

\[ V = V_F + V_D \]

where the supergravity F-term potential gives

\[ V_F = e^K (K^{ij} D_i W \bar{D}_j \bar{W} - 3|W|^2) \]

and the D-term potential gives:

\[ V_D = \frac{1}{2\tau} \left( \frac{3N_f}{8\pi^2\tau} (1 + \zeta \tau^{-3/2})^{-1} \right. \\
\left. - \frac{2|\rho|^2 + |q|^2 + |\bar{q}|^2 - 2|M|^2 e^{\frac{8\pi^2\tau}{3N_c - 2N_f}}}{\tau^n} \right. \\
\left. + \frac{N_f n(|\rho|^2 + |q|^2 + |\bar{q}|^2 + |M|^2 e^{\frac{8\pi^2\tau}{3N_c - 2N_f}})}{4\pi^2\tau^{n+1}} \right) \\
\left. - \frac{2N_f |M|^2 e^{\frac{8\pi^2\tau}{3N_c - 2N_f}}}{(3N_c - 2N_f)\tau^n} \right)^2 \]
Moduli stabilization

Full potential: very complicated, function of $\tau, \rho, q, \bar{q}, M$
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Full potential: very complicated, function of $\tau, \rho, q, \bar{q}, M$

- $1/\tau$-expansion

$$V = \frac{c_1}{\tau^3} + \frac{c_2 \zeta}{\tau^{4.5}} + \frac{c_3}{\tau^{\ldots}} \ldots$$

(higher powers)

If $c_1 > 0$, $c_2 \zeta < 0$, $c_3 > 0$, we expect $\tau$-moduli stabilization.
Moduli stabilization

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- More detailed analysis: when $n > 1/2$, F-term dominant. $\Rightarrow$ next slide
Stabilization of $\rho$

When F-term dominates, we have ISS vacuum (+ corrections suppressed by $1/\tau$) for $M, q, \bar{q}$. Then

$$V(\rho) \sim N_c \tau^{n-3} |\rho|^2 e^{-\frac{8\pi^2}{3N_c - 2N_f} \frac{\tau}{N_c \tau^n}}$$

$$+ \frac{1}{2\tau} \left( \frac{3N_f}{8\pi^2} \frac{1}{\tau} - \frac{2|\rho|^2 + 2(N_f - N_c)|\mu\rho|}{\tau^n} \right)^2$$

with $\rho$ fixed at

$$|\rho| = \frac{3N_f(N_f - N_c)|\mu|}{8\pi^2 \tau^{n+2}}$$

$$N_c \tau^{n-3} e^{-\frac{8\pi^2}{3N_c - 2N_f} \frac{\tau}{N_c \tau^n}} + \frac{2|\mu|^2(N_f - N_c)^2}{\tau^{2n+1}}$$
Stabilization of $\tau$

$$V_{\text{global}} = \frac{1}{2\tau} \left( \frac{3N_f}{8\pi^2 \tau} \right)^2 - \frac{(N_f - N_c)^2 \left( \frac{3N_f}{8\pi^2 \tau} \right)^2 |\mu|^2}{\tau^{2n+2}}$$

$$\frac{N_c \tau^{n-3} e^{-\frac{8\pi^2 \tau}{3N_c - 2N_f}} + \frac{2|\mu|^2(N_f - N_c)^2}{\tau^{2n+1}}}{N_c \tau^n}$$
Stabilization of $\tau$

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$$\delta V_{\text{SUGRA}} = \frac{3\zeta}{2\tau^{9/2}} |W_0|^2 + (*)$$

$$(*) = (1 - n - n^2) \frac{|\rho|^2 + 2(N_f - N_c)|\rho\mu|}{\tau^{3+n}} |W_0|^2 + \cdots$$

$$= (1 - n - n^2) \frac{2(N_f - N_c)^2 \left( \frac{3N_f}{8\pi^2} \right)^2 |\mu|^2 |W_0|^2}{\tau^{2n+5}} \frac{1}{N_c \tau^{n-3} e^{\frac{8\pi^2\tau}{3N_c - 2N_f}}} + \frac{2|\mu|^2(N_f - N_c)^2}{\tau^{2n+1}} + \cdots$$
It is possible to stabilize $\tau$ in a metastable de-Sitter vacuum with a vanishingly small cosmological constant by an appropriate fine-tuning.

For example, by taking $N_c = 500$, $N_f = 600$, $|\mu| = 0.38$, $\zeta = 12$, and $|W_0| = 3.47$ for $n = 1$, we will obtain a metastable vacuum as expected from the general argument for $\zeta > 0$.
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- Mass moduli fixed by gauging of a $\mathbf{U}(1)$ symmetry and its D-term potential
- Construction from string theory provided
- Possible to obtain de Sitter vacua with vanishingly small cosmological constant by fine-tuning
- All non-compact moduli fixed (Goldstone mode still left as compact moduli)
Discussions

- SUSY breaking scale $\sim$ Planck scale unless significant fine tuning. warped compactification?
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- Application to D-term gauge mediation
  [Nakayama-Taki-Watari-Yanagida '07] with very light gravitino ($\sim 1$eV) and composite messenger dark matter
  [Hamaguchi-Shirai-Yanagida '07]