Moduli Stabilization in Stringy ISS Models

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In collaboration with Yu Nakayama and T.T. Yanagida

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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.

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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.

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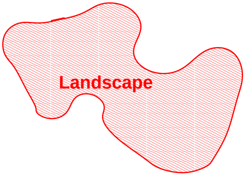
cf.[Dudas-Papineau-Pokorski, Abe-Higaki-Kobayashi-Omura, Lebedev-Lowen-Mambrini-Nilles-Ratz...], [Serone-Westphal]

Landscape or Swampland?



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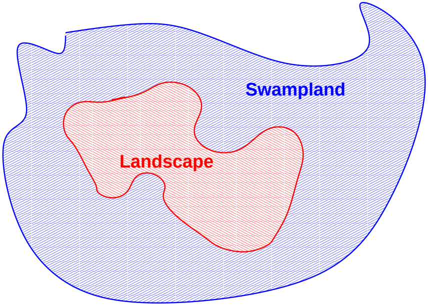

Swampland [Vafa '05, Ooguri-Vafa '06]

(semi)classically consistent but quantum inconsistent effective field theories

Are DSB models in the landscape or in the swampland?

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Basic idea

Gauge (anomalous) $\mathbf{U(1)}$ 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 ρ and τ
4. Conclusions and Discussions

Brief review of ISS models

Electric Theory

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

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

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Magnetic Theory

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

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

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We need $|m| \ll \Lambda$ to obtain sufficiently long-lived metastable vacua

- Impossible to set all F-terms for $\mathbf{M_{ij}}$ to zero (rank condition)

$$\underbrace{\mathbf{m}\delta_{\mathbf{ij}}}_{\mathbf{rank=N_f}} + \underbrace{\frac{\mathbf{1}}{\mu}\mathbf{q_i\bar{q}_j}}_{\mathbf{rank=N_f-N_c}} \neq \mathbf{0}$$

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- SUSY broken with potential

$$\mathbf{V = N_c|m|^2|\Lambda|^2}$$

up to a numerical constant of order 1 by setting $\mathbf{M = 0}$, $\mathbf{q = \bar{q} = i\sqrt{m\mu}1_{N_f-N_c\times N_f-N_c}}$

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- If $\mathbf{m}$ becomes dynamical variable ρ, then $\mathbf{m}$=0 and SUSY restored!

$\Rightarrow$ Solution: we use D-term

Anomalous $U(1)$ and its D-term

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

Charge Assignment

ρ	$\varphi, \bar{\varphi}$	$\mathbf{M}$	$\mathbf{q}, \bar{\mathbf{q}}$	$\Lambda^{3N_c-2N_f}$	$\tilde{\Lambda}^{2N_f-3N_c}$
-2	$+1$	$+2$	-1	$2N_f$	$-2N_f$

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If we gauge this $U(1)_D$ we have

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

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

For small ξ, ρ is stabilized at $|\rho| = \frac{g^2|\mu|\xi(N_f - N_c)}{N_c|\Lambda|^2 + 2g^2|\mu|^2(N_f - N_c)^2}$

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- $\mathbf{U(1)_D}$ is anomalous
- SUSY restored wen FI parameter ξ becomes dynamical

$\Rightarrow$ These two problems are solved at once in string theory! ...

FI parameter stabilization from global SUSY viewpoint

We discuss FI parameter stabilization in global SUSY

- Consider chiral superfield

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

- Axion transforms as

$$\phi(\mathbf{x}) \longrightarrow \phi(\mathbf{x}) - 2\mathbf{N_f}\alpha(\mathbf{x})$$

  under the gauge transformation $\mathbf{A}_\mu(\mathbf{x}) \longrightarrow \mathbf{A}_\mu(\mathbf{x}) + \partial_\mu\alpha(\mathbf{x})$ to cancel anomaly

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

$$\mathbf{T} + \mathbf{T}^\dagger - \frac{\mathbf{N_f}}{4\pi^2}\mathbf{V}$$

  ($\mathbf{V}$: vector superfield corresponding to the $\mathbf{U(1)_D}$)

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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The introduced D-term is

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

ϕ_i: fields that couple linearly to $U(1)_D$, q_i: charges

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FI-parameter ξ is stabilized

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$$\text{FI-parameter } \boldsymbol{\xi} \text{ is stabilized}$$

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SUSY broken both by D- and F-terms

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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.

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$\delta\phi_{\mathbf{i}}$: a gauge transformation of the matter field.
$\Rightarrow$ it is impossible to obtain D-term SUSY breaking without F-term SUSY breaking (unless $\mathbf{W} = \mathbf{0}$).

Plan of this talk

String theory setup

Consider type IIB flux compactification.

- All complex structures and dilaton are fixed [Gidding-Kachru-Polchinski '01].
- Consider CY orientifold compactification with one Kähler modulus.

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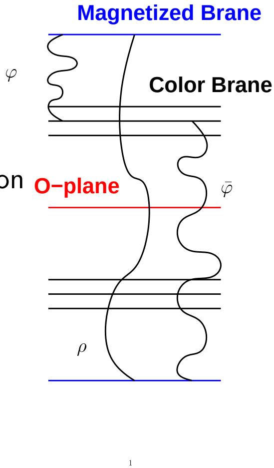
We consider D7-branes and O-plane.

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

[Cremades-Carcia del Moral-Quevedo-Suruliz]

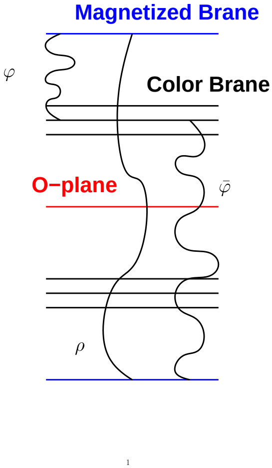


Matter contents: electric theory

The matter contents:

- The field φ stretching between the magnetized brane and $\mathbf{SU(N_c)}$ branes will be charged $\mathbf{(+1, N_c)}$ under $\mathbf{U(1) \times SU(N_c)}$.
- The field $\bar{\varphi}$ stretching between the magnetized brane and the orientifold images of $\mathbf{SU(N_c)}$ branes will be charged $\mathbf{(+1, \bar{N}_c)}$ under $\mathbf{U(1) \times SU(N_c)}$.
- The field ρ stretching between the magnetized brane and its orientifold images will be charged $\mathbf{-2}$ under $\mathbf{U(1)}$.

(we really need to fix $\mathrm{SU}\mathbf{(N_f)}$ flavor moduli)



Superpotential and FI-term

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

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

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

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

and $\int_{\mathbb{R}^4} \mathbf{D} \wedge \mathbf{F}$ becomes $\int_{\mathbb{R}^4} \partial_\mu \phi \mathbf{A}_\mu$, 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

$$\mathbf{W} = \mathbf{W}_0 + \rho \mathrm{Tr}\mathbf{M} + \frac{1}{\mu}\mathbf{q}^i \mathbf{M}_{ij}\bar{\mathbf{q}}^j$$

with the Kähler potential $(2\tau = \mathbf{T} + \mathbf{T}^\dagger)$

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

Here ζ is the α'-correction propotional to the Euler number of CY [Becker-Becker-Haack-Louis '02], $\mathbf{n}$ 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

$$V_F = e^K(K^{i\bar{j}} D_i W \bar{D}_{\bar{j}} \bar{W} - 3|W|^2)$$

and the D-term potential gives:

$$V_D = \frac{1}{2\tau}\Bigg(\frac{3N_f}{8\pi^2\tau}(1+\zeta\tau^{-3/2})^{-1} - \frac{2|\rho|^2+|q|^2+|\bar{q}|^2-2|M|^2 e^{\frac{8\pi^2\tau}{3N_c-2N_f}}}{\tau^n} + \frac{N_f n(|\rho|^2+|q|^2+|\bar{q}|^2+|M|^2 e^{\frac{8\pi^2\tau}{3N_c-2N_f}})}{4\pi^2\tau^{n+1}} - \frac{2N_f|M|^2 e^{\frac{8\pi^2\tau}{3N_c-2N_f}}}{(3N_c-2N_f)\tau^n}\Bigg)^2$$

Moduli stabilization

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

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- $\mathbf{1}/\boldsymbol{\tau}$-expansion

$$\mathbf{V} = \frac{\mathbf{c}_1}{\boldsymbol{\tau}^3} + \frac{\mathbf{c}_2\zeta}{\boldsymbol{\tau}^{4.5}} + \underbrace{\frac{\mathbf{c}_3}{\boldsymbol{\tau}^{\cdots}} \cdots}_{\textbf{higher powers}}$$

If $\mathbf{c}_1 > \mathbf{0}$, $\mathbf{c}_2\zeta < \mathbf{0}$, $\mathbf{c}_3 > \mathbf{0}$, we expect $\boldsymbol{\tau}$-moduli stabilization.

Moduli stabilization

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- $1/\tau$-expansion

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If $\mathbf{c}_1 > 0$, $\mathbf{c}_2\zeta < 0$, $\mathbf{c}_3 > 0$, we expect τ-moduli stabilization.

- More detailed analysis: when $\mathbf{n} > 1/2$, F-term dominant. $\Rightarrow$ next slide

Stabilization of ρ

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

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

with ρ fixed at

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

Stabilization of τ

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

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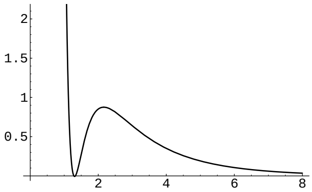
$$\begin{aligned}
\delta V_{\rm SUGRA} &= \frac{3\zeta}{2\tau^{9/2}}|W_0|^2 + (*) \\
(*) &= (1-n-n^2)\frac{|\rho|^2 + 2(N_f-N_c)|\rho\mu|}{\tau^{3+n}}|W_0|^2 + \cdots \\
&= (1-n-n^2)\frac{2(N_f-N_c)^2\left(\frac{3N_f}{8\pi^2}\right)\frac{|\mu|^2|W_0|^2}{\tau^{2n+5}}}{N_c\tau^{n-3}e^{-\frac{8\pi^2\tau}{3N_c-2N_f}} + \frac{2|\mu|^2(N_f-N_c)^2}{\tau^{2n+1}}} + \cdots
\end{aligned}$$

Fine-tuning possible

- It is possible to stabilize τ in a metastable de-Sitter vacuum with a vanishingly small cosmological constant by an appropriate fine-tuning

For example, by taking $\mathbf{N_c = 500}$, $\mathbf{N_f = 600}$, $|\mu| = \mathbf{0.38}$, $\zeta = \mathbf{12}$, and $|\mathbf{W_0}| = \mathbf{3.47}$ for $\mathbf{n = 1}$, we will obtain a metastable vacuum as expected from the general argument for $\zeta > \mathbf{0}$.



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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

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- τ: light moduli, typically gravitino mass scale. Cosmological implications?
- Application to D-term gauge mediation [Nakayama-Taki-Watari-Yanagida '07] with very light gravitino ($\sim$ 1eV) and composite messanger dark matter [Hamaguchi-Shirai-Yanagida '07]