Supersymmetry breaking by constant boundary superpotentials in warped space

Nobuhiro Uekusa (Helsinki)

Based on collaboration with N. Maru and N. Sakai
Phys. Rev. D74, 045017 (2006) [hep-th/0602123];
to be appeared

3rd Vienna Central European Seminar
on Particle Physics and Quantum Field Theory

Supersymmetry and extra dimensions

- solutions to the gauge hierarchy problem
- string theory

Arkani-Hamed, Dimopoulos, Dvali ’98

Randall-Sundrum ’98, Luty-Sundrum ’99

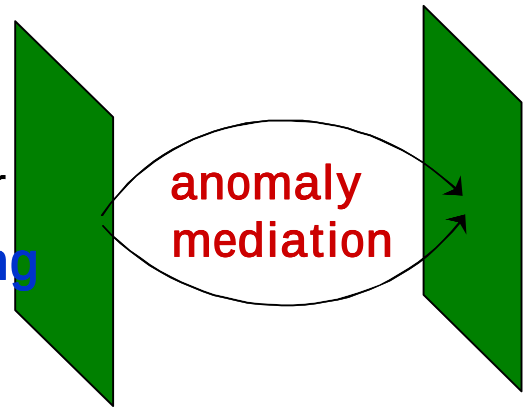
Another motivation

- **Mediation of SUSY breaking**

Unlike 4D SUGRA, we do not need flavor symmetry

hidden sector

SUSY breaking



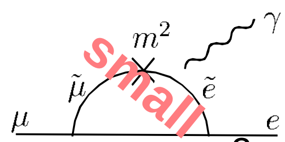
visible sector

soft mass

e.g. scalar masses depend only on the gauge quantum # of the scalars

Other contributions except for anomaly mediation are from non local interactions and they can be easily small

No SUSY FCNC problem



I restrict myself to 1 extra dimension.

SUSY breaking in higher dimensinal space

- Simple way: the Scherk-Schwarz (SS) mechanism

$$\phi(x, y + 2\pi R) = \text{twist} \cdot \phi(x, y) \qquad \text{on } S^1$$

Distinctive twists for bosons and fermions $\longrightarrow$ mass splitting

- ***In flat space***

Marti-Pomarol '01, Bagger-Feruglio-Zwirner '02, Gherghetta-Riotto '02

SS SUSY breaking ⟺ (equivalent) ⟺ **SUSY breaking by a constant superpotential**

- These two scenarios generate the same mass spectrum

In warped space

SS SUSY breaking ⟺ **?** **SUSY breaking by a constant superpotential**

- It is natural to ask whether this equivalence still holds in warped space such as Randall-Sundrum geometry.
- This issue has been discussed in several interesting papers so far.

Hall-Nomura-Okui-Oliver, Bagger-Belyaev, Abe-Sakamura…

- ***In warped space***

SS SUSY breaking

- Whether SUSY is broken by the SS twist or not might depend on the way of gauging

– **Gauging in supergravity (required for bulk cosmological constant)**

$$D(\omega) \to \hat{D} = D + A$$
$$\mathcal{L} \supset \psi \hat{D} \psi$$
$$\delta(\psi A \psi) = \psi F \epsilon + \cdots$$

$$\mathcal{L} \supset \psi \psi$$
$$\delta \psi = \hat{D} \epsilon + F \epsilon$$
$$\delta(\psi \psi) = \psi F \epsilon + \cdots$$

$$\psi \hat{D} \psi \to \psi \tilde{D} \psi = \psi(\hat{D} + m)\psi$$
$$[\tilde{D}, \tilde{D}] = R + F + m^2$$

cosmological constant

In warped space

SUSY breaking by a constant superpotential

Obviously the consistent definition is possible

Then

- Radius stablization?
- Radion mass?
- Soft mass?
- No FCNC problem?

Plan of Talk

Model

Nontrivial background solutions

Radion potential

Radion mass

Anomaly-mediated soft mass

Gravitino mass

No SUSY FCNC problem

Summary

Future work

Model

- **metric** $ds^2 = e^{-2R\sigma}\eta_{\mu\nu}dx^\mu dx^\nu + R^2 dy^2, \quad \sigma(y) \equiv k|y|$ radius R

  $\eta_{\mu\nu} = \text{diag.}(-1, +1, +1, +1),$ AdS_5 curvature k

  5th coordinate $y(0 \le y \le \pi)$ of the orbifold S_1/Z_2

- **Lagrangian** (in terms of superfields)

Marti-Pomarol '01

$$\mathcal{L}_5 = \int d^4\theta \frac{1}{2}\varphi^\dagger\varphi(T+T^\dagger)e^{-(T+T^\dagger)\sigma}(\Phi^\dagger\Phi + \Phi^c\Phi^{c\dagger} - 6M_5^3)$$
$$+ \int d^2\theta \left[\varphi^3 e^{-3T\sigma}\left\{\Phi^c\left[\partial_y - \left(\frac{3}{2} - c\right)T\sigma'\right]\Phi + W_b\right\} + \text{h.c.}\right]$$

$\sigma' \equiv d\sigma/dy$

Φ, Φ^c *hypermultiplet* with *bulk mass parameter* c

The Z_2 parity is assigned to be even (odd) for $\Phi(\Phi^c)$.

$W_b \equiv 2M_5^3 w_0 \delta(y)$ **constant (field independent) superpotential localized at the fixed point y=0**

w_0 a dimensionless constant

$\varphi = 1 + \theta^2 F_\varphi$ **compensator** chiral supermultiplet (of supergravity)

$T = R + \theta^2 F_T$ **radion** chiral supermultiplet

Equations of motion for auxiliary fields

$$F = -\frac{e^{-R\sigma}}{R}\left[-\partial_y \phi^{c\dagger} + \left(\frac{3}{2}+c\right) R\sigma' \phi^{c\dagger} + \frac{\phi}{2M_5^3} W_b \right.$$
$$\left. + \frac{1}{6M_5^3}\phi^\dagger \phi \partial_y \phi^{c\dagger} + \frac{1}{3M_5^3}\phi^{c\dagger}\phi\partial_y\phi^\dagger - \frac{1}{6M_5^3}\phi^\dagger\phi\phi^{c\dagger}\left(\frac{9}{2}-c\right)R\sigma'\right]$$

$$F^c = -\frac{e^{-R\sigma}}{R}\left[\partial_y \phi^{\dagger} - \left(\frac{3}{2}-c\right) R\sigma' \phi^{\dagger} + \frac{\phi^c}{2M_5^3} W_b \right.$$
$$\left. + \frac{1}{6M_5^3}\phi^c \phi^\dagger \partial_y \phi^{c\dagger} + \frac{1}{3M_5^3}\phi^{c\dagger}\phi^c\partial_y\phi^\dagger - \frac{1}{6M_5^3}\phi^c\phi^\dagger\phi^{c\dagger}\left(\frac{9}{2}-c\right)R\sigma'\right]$$

$$F_\varphi = -\frac{e^{-R\sigma}}{R}\left[-\frac{1}{6M_5^3}\phi^\dagger\partial_y\phi^{c\dagger} - \frac{1}{3M_5^3}\phi^{c\dagger}\partial_y\phi^\dagger + \frac{1}{6M_5^3}\phi^\dagger\phi^{c\dagger}\left(\frac{9}{2}-c\right)R\sigma' - \frac{1}{2M_5^3}W_b \right.$$
$$\left. -\frac{3(1-2R\sigma)}{r}\phi^{c\dagger}\partial_y\phi^\dagger - \frac{3(1-2R\sigma)}{r}W_b + \frac{1-2R\sigma}{r}\phi^{c\dagger}\phi^\dagger\left(\frac{3}{2}-c\right)R\sigma'\right]$$

$$F_T = -\frac{e^{-R\sigma}}{r}\left[6\phi^{c\dagger}\partial_y\phi^\dagger - 2\phi^{c\dagger}\phi^\dagger\left(\frac{3}{2}-c\right)R\sigma' + 6W_b\right]$$

where the partial integration has been performed in the equation for *F*

$$r \equiv \phi^\dagger\phi + \phi^{c\dagger}\phi^c - 6M_5^3$$

Background solution

We consider a perturbative treatment for small values of w_0

- $w_0 = 0$

  SUSY solution $F = F^c = F_\varphi = F_T = 0$

$$\phi(y) = N_2 \exp\left[\left(\frac{3}{2} - c\right) R\sigma\right] \equiv \phi_s(y)$$

$$\phi^c(y) = 0$$

N_2 a complex parameter

- $w_0 \ll 1$

$$\phi(y) = \phi_s(y) + \chi(y)$$

$$\phi^c(y) = \widehat{\epsilon}(y)\chi^c(y)$$

$$\widehat{\epsilon}(y) \equiv \begin{cases} +1, & 0 < y < \pi \\ -1, & -\pi < y < 0 \end{cases}$$

We work out perturbative solutions of the equations of motion for $\chi(y)$ and $\chi^c(y)$ as deviations from the SUSY solution

Potential

After substituting the background solutions into Lagrangian and integrating over *y*

$$V = \frac{3M_5^3 k w_0^2}{2}\left\{\frac{-2(1-2c)}{(1-2c)(e^{2Rk\pi}-1)\hat{N}+2(e^{(2c-1)Rk\pi}-1)}\hat{N}^{4-2c-\frac{1}{3-2c}} + \frac{\hat{N}}{1-\hat{N}}\left(-4c^2+12c-6+\frac{3-2c}{3(1-\hat{N})}\right)\right\}$$

$$\hat{N} \equiv |N_2|^2/(6M_5^3)$$

Stationary condition for the radius *R* and the modulus N_2

$$\frac{\partial V}{\partial R} = 0 \quad \text{and} \quad \frac{\partial V}{\partial \hat{N}} = 0$$

We find that there is a unique **nontrivial minimum** provided $c < c_{cr}$ with

$$c_{\mathrm{cr}} \equiv \frac{17-\sqrt{109}}{12} \approx 0.546$$

- At c_{cr} the minimum occurs at infinite radius

$$\hat{N}(c_{\mathrm{cr}}) = 0, \quad R(c_{\mathrm{cr}}) = \infty$$

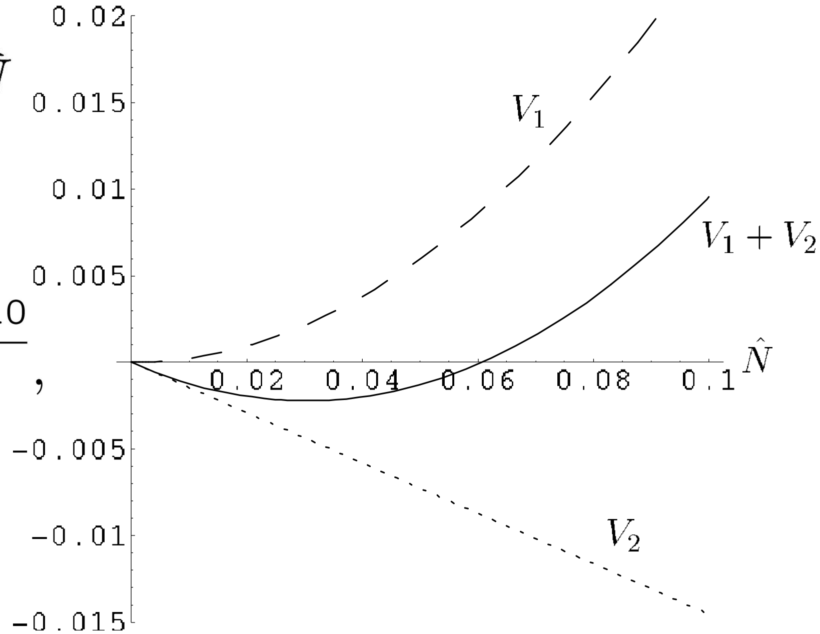
- To examine the stabilization more closely, we parametrize $c = c_{\rm cr} - \Delta c$ with a small Δc.

At the leading order of Δc and $\hat{N}$

$$V \approx \frac{3M_5^3 k w_0^2}{2}(V_1 + V_2),$$

$$V_1 \equiv \frac{2(2c_{\rm cr} - 1)}{3 - 2c_{\rm cr}} \hat{N}^{\frac{4c_{\rm cr}^2 - 12c_{\rm cr} + 10}{3 - 2c_{\rm cr}}},$$

$$V_2 \equiv -\hat{N}\left(-8c_{\rm cr} + \frac{34}{3}\right)\Delta c$$

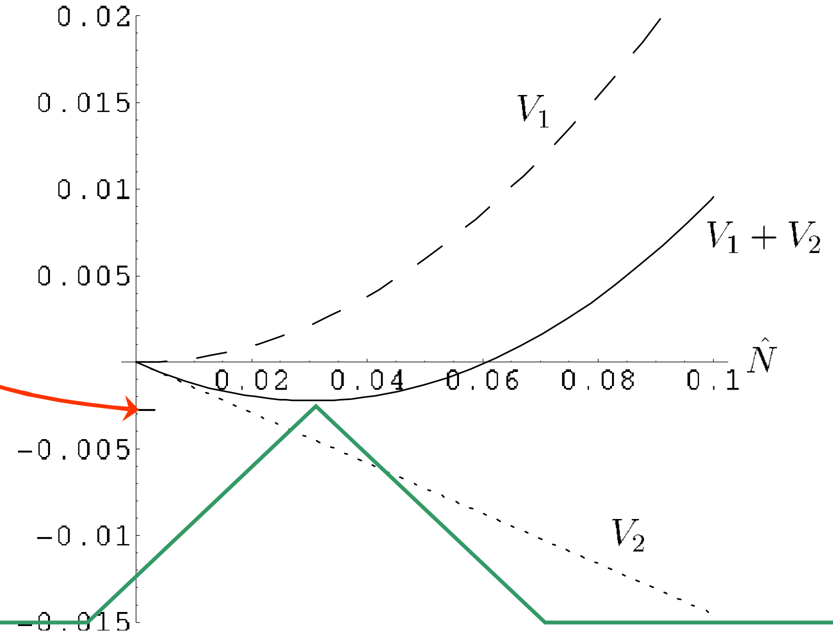


The radius is stabilized at

$$R \approx \frac{1}{10k}\left(\ln\frac{1}{\Delta c} - 3.4\right)$$

which means $Rk > 1$ for $\Delta c < 10^{-6}$

$V \approx -(10^{11}(\Delta c)^{0.3}\ \text{GeV})^4$



At the stationary point the potential becomes negative. This negative vacuum energy may be shifted by contributions of other sources for SUSY breaking. Localized F term is a candidate of such a source . With this cancellation of the cosmological constant, we will work with **4D flat** background rather than AdS4 background.

Radion and moduli masses

We introduce quantum fluctuation fields around the background classical solution to define the radion $\tilde{R}$ and the moduli field $\tilde{N}_2$:

$$R+\tilde{R}, \quad N_2+\tilde{N}_2, \quad \tilde{N}_2=\tilde{N}_{2R}+i\tilde{N}_{2I}$$

After writing down kinetic lagrandian and normalizing it canonically

we find that the lighter physical mode is almost exclusively made of the radion

$$m^2_{\text{light}} \approx k^2 w_0^2 0.38(3.4+\ln\Delta c)^2(\Delta c)^{1.7}$$

The heavier eigenmode is found to be exclusively made of the moduli field

$$m^2_{\text{heavy}} \approx k^2 w_0^2 0.47(\Delta c)^{0.70}$$

For $\Delta c < 10^{-6}$ $(RK > 1)$

$$m_{\text{light}} < kw_0 \times 10^{-4}$$

$$m_{\text{heavy}} < kw_0 \times 10^{-2}$$

For $w_0 \sim (10^7\text{GeV}/k)$ and $\Delta c \sim 10^{-6}$

$$m_{\text{light}} \sim 1\text{TeV}, \qquad m_{\text{heavy}} \sim 100\text{TeV}$$

radion **moduli**

Anomaly-mediated soft mass

$$\tilde{m}_{\rm AMSB} = \frac{g^2}{16\pi^2}(F_\varphi - F_T\sigma)|_{y=\pi}$$

$$\sim 10^{-4} \times g^2 k w_0$$

$$\tilde{m}_{\rm AMSB} = \frac{g^2}{16\pi^2}\left\langle \frac{F_\omega}{\omega} \right\rangle$$

$$\omega = \varphi e^{-T\sigma}$$

For $g^2 k w_0 \sim 10^6 \mathrm{GeV}$

$$\tilde{m}_{\rm AMSB} \sim 100 \mathrm{GeV}$$

Gravitino mass

Lagrangian (bulk + brane)

Gherghetta-Pomarol '00

$$\mathcal{L}_{\rm bulk} = iM_5\sqrt{-g}\left[\bar{\Psi}_M\gamma^{MNP}D_N\Psi_P - \frac{3}{2}\sigma'\bar{\Psi}_M\gamma^{MN}(\sigma_3)\Psi_N\right]$$

$$\mathcal{L}_{\rm boundary} = -i\frac{W_b}{2M_5^2}\left[\psi_\mu^1\sigma^{\mu\nu}\psi_\nu^1 - \bar{\psi}_\mu^1\sigma^{\mu\nu}\bar{\psi}_\nu^1\right]$$

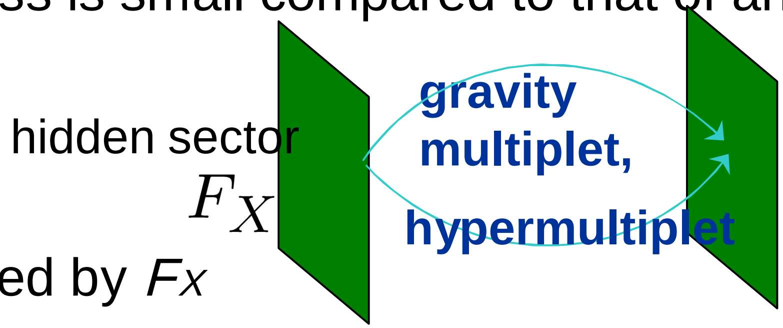
For the lightest mode $\frac{m_n}{k} \ll 1, \quad \frac{m_n}{k}e^{Rk\pi} \ll 1$

$$m_{\rm lightest} \approx 2w_0 k$$

$$\sim 10^7 \mathrm{GeV} \text{ for } w_0 \sim (10^7 \mathrm{GeV}/k)$$

No SUSY FCNC problem

We must check whether localized F term cancels the cosmological constant and induced soft mass is small compared to that of anomaly mediation.



visible sector

Soft mass induced by F_X

Gregoire-Rattazzi-Scrucca-Strumia-Trincherini '04

mediation by gravity multiplet

$$\Delta\tilde{m}^2_{\rm bbg} = -\frac{c_w k^4}{18\pi^2 M_5^6} e^{-4k\pi R}|F_X|^2 \qquad c_w \sim \mathcal{O}(1)$$

mediation by hypermultiplet

Maru-Okada '03

$$\Delta\tilde{m}^2_{\rm bbh} \sim \frac{c_{ij}}{16\pi^2}\left(\frac{F_X}{\sqrt{3}M_4}\right)^2\left(\frac{k}{M_4}\right)^2\left(\frac{1-2c}{e^{(1-2c)Rk\pi}-1}\right)^2 e^{(3-2c)Rk\pi} \qquad c_{ij} \sim \mathcal{O}(1)$$

$$\Delta\tilde{m}^2_{\rm bbg}, \Delta\tilde{m}^2_{\rm bbh} \lesssim \tilde{m}^2_{\rm AMSB} \times 10^{-2} \quad \Rightarrow \quad \sqrt{F_X} \lesssim 10^9 \,{\rm GeV}$$

We finally estimate the size of F_X to cancel the cosmological constant.

$$\sqrt{F_X} \approx 10^{11}(\Delta c)^{0.3}\ {\rm GeV} \approx 10^9\ {\rm GeV} \quad {\rm for} \quad \Delta c \sim 10^{-6}$$

The cancellation of the cosmological constant can occur wihtin the FCNC constraint.

Summary

In numerically evaluating various masses, we have chosen

$$w_0 \sim (10^7\,\text{GeV}/k),\ M_5 \sim (M_4^2 k)^{1/3} \qquad c = c_{\text{cr}} - \Delta c$$

$$c_{\text{cr}} \approx 0.546,\ \Delta c \sim 10^{-6}$$

Radius k^{-1} stabilized

<u>Masses</u>

Radion $1\,\text{TeV}$

Moduli $100\,\text{TeV}$

Such a comparatively small radion mass appears as a common feature of warped space model and its value is in experimentally allowed region (PDG).

Soft $100\,\text{GeV}$

It is generated by anomaly mediation. Therefore there is no FCNC problem.

(Soft masses induced by KK-modes are also shown to be small.)

Gravitino $10^7\,\text{GeV}$

Such a large gravitino mass is similar to that of the anomaly mediation scenario given before.

Hyperscalar k

It is much heavier than other fields. Therefore the hyperscalar primarily acts as a part of the background configuration.

Future work

- $$T = R + \theta^2 F_T$$

  ($R \to iB$)

We have not considered the imaginary part for the lowest component of the radion supermultiplet.

In the present model, the mass seems to vanish because the potential can be seen to include only real part of the radion supermultiplet.
However, the mass would be induced by quantum loop effect similarly to the case of gauge-Higgs unification model.

If the induced mass is very small, it would have to be examined whether the coupling with other particles can be very small as in the case of axion.

- The issue of radius statilization by Casimir energy also remains to be examined.