Supersymmetry Breaking and Radius Stabilization by Constant Boundary Superpotentials in a Warped Space

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References

- Supersymmetry Breaking by Constant Boundary Superpotentials in Warped Space,
  N.M., N. Sakai (TWCU) & N. Uekusa (Helsinki),
  PRD74 (2006) 045017
- Radius Stabilization by Constant Boundary Superpotentials in Warped Space,
  N.M., N. Sakai & N. Uekusa, PRD75 (2007) 125014
- N.M., N. Sakai & N. Uekusa, in preparation

Plan

①Introduction
②Model of radius stabilization
③SUSY breaking spectrum
④Summary

Introduction

Motivations of considering Extra Dimensions:

(Alternative) Solution to the gauge hierarchy problem without SUSY

Large extra dimensions

Arkani-Hamed, Dimopoulos & Dvali, PLB429 (1998) 263

Warped extra dimensions

Randall & Sundrum, PRL83 (1999) 3370, 4690

etc

"Alternative Motivation" to consider Extra Dimensions

Solution to SUSY flavor problem

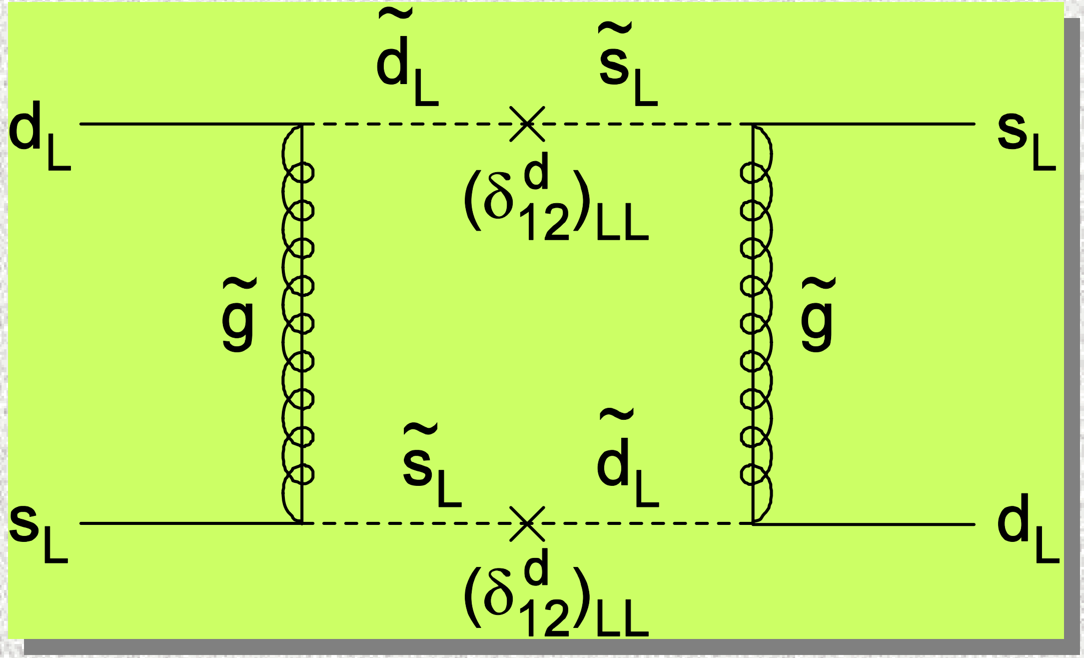
In 4D SUGRA, once SUSY is broken,
SUSY breaking is mediated to the visible sector
by Planck suppressed contact terms (Gravity mediation)

$$\int d^4\theta\, c_{ij} \frac{X^\dagger X Q_i^\dagger Q_j}{M_4^2} \Rightarrow c_{ij} m_{3/2}^2 \tilde{Q}_i^\dagger \tilde{Q}_j$$

i,j: flavor index
Q: MSSM superfield
X: hidden sector superfield

$c_{ij} \neq \delta_{ij}$ in general,
No symmetry reason to be flavor diagonal
$\Rightarrow$ SUSY FLAVOR PROBLEM

Ex. $K_0 - \bar{K}_0$ mixing



Off diagonal elements of squark mass matrix for 1st & 2nd generations

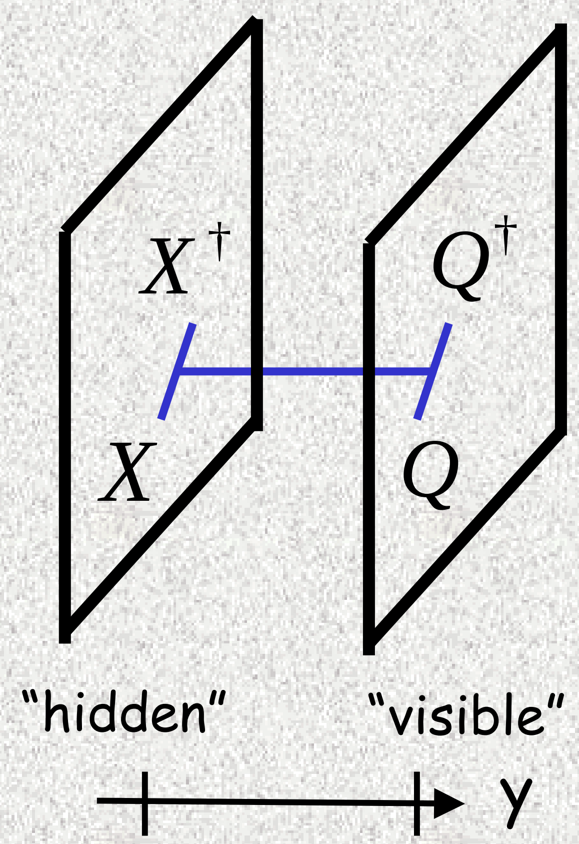
$$\Rightarrow \left(\delta^d_{12}\right)_{LL} \equiv \frac{m^2_{Q,12}}{\tilde{m}^2} \leq \mathcal{O}\left(10^{-2}\right)$$

Squark mass average

1st & 2nd gen. squark mass matrix should be diagonal

If visible sector & hidden sector are separated in extra dimensional spaces, there is no contact terms by the LOCALITY in higher dimensional theory

Randall & Sundrum, NPB557 (1999) 79
Luty & Sundrum, PRD62 (2000) 035008



SUSY breaking spectrum is induced by superconformal anomaly (ANOMALY MEDIATION)

Randall-Sundrum, NPB557 (1999) 79
Giudice, Luty, Murayama & Rattazzi. JHEP9812 (1998) 027

$$M_{\lambda_i} = -\frac{\beta_i\left(g^2\right)}{2g_i^2} m_{3/2},$$

$$\tilde{m}^2 = -\frac{1}{4}\left[\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right] m_{3/2}^2$$

(Almost) Flavor blind!!

Not the end of the story ⇒ "RADIUS STABILIZATION"

Phenomenological viable Brane World Scenario
= Compactification Radius should be stabilized

From PDG

Limits on Mass of Radion

This section includes limits on mass of radion, usually in context of Randall-Sundrum models. See the "Extra Dimension Review" for discussion of model dependence.

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[51] ABBIENDI	05	OPAL	$e^+e^- \rightarrow Z$ radion
$\gtrsim 35$	[52] MAHANTA	00		$Z \rightarrow$ radion $\ell\overline{\ell}$
>120	[53] MAHANTA	00B		$p\overline{p} \rightarrow$ radion $\rightarrow \gamma\gamma$

[51] ABBIENDI 05 use e^+e^- collisions at $\sqrt{s} = 91$ GeV and $\sqrt{s} = 189$–209 GeV to place bounds on the radion mass in the RS model. See their Fig. 5 for bounds that depend on the radion-Higgs mixing parameter ξ and on $\Lambda_W = \Lambda_\phi/\sqrt{6}$. No parameter-independent bound is obtained.

[52] MAHANTA 00 obtain bound on radion mass in the RS model. Bound is from Higgs boson search at LEP I.

[53] MAHANTA 00B uses $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV; production via gluon-gluon fusion. Authors assume a radion vacuum expectation value of 1 TeV.

Not the end of the story ⇒ "RADIUS STABILIZATION"

Phenomenological viable Brane World Scenario
= Compactification Radius should be stabilized

No radion potential in SUSY limit
since **the radion is a moduli**

⇒ Size of radius is undetermined

⇒ Once SUSY is broken,
nontrivial radion potential is generated

⇒ Radius is unlikely to be stabilized only by gravity
N.M. & N.Okada, hep-ph/0508113

⇒ Additional bulk fields should be introduced

⇒ New flavor-violating soft SUSY breaking
vs Anomaly Mediation

[For stabilization by classical SUSY background, see
N.M. & Okada, PRD70 025002 (2004), Eto, N.M., Sakai, PRD70 086002 (2004)]

What we have done

We constructed
a (probably) Simplest Model of
Radius Stabilization
with Anomaly Mediation dominated

Model of Radius Stabilization

5D SUSY model of a massive hypermultiplet on the Randall-Sundrum background

$$ds^2 = e^{-2R\sigma}\eta_{\mu\nu}dx^\mu dx^\nu + R^2 dy^2,\ \sigma(y) = k|y|,\ 0 \le y \le \pi$$

Marti & Pomarol, PRD64 (2001) 105025

$$\mathcal{L}_5 = \int d^4\theta \frac{1}{2}\varphi^\dagger\varphi\left(T+T^\dagger\right)e^{-\left(T+T^\dagger\right)\sigma}\left(\Phi^\dagger\Phi + \Phi^c\Phi^{c\dagger} - 6M_5^3\right)$$
$$+\int d^2\theta\left[\varphi^3 e^{-3T\sigma}\left\{\Phi^c\left[\partial_y - \left(\frac{3}{2}-c\right)T\sigma'\right]\Phi + \underbrace{2M_5^3 w_0\delta(y)}_{\text{Constant superpotential@y=0}}\right\} + h.c.\right]$$

Bulk mass

Constant superpotential@y=0

$$\varphi = 1 + \theta^2 F_\varphi,\quad T = R + \theta^2 F_T$$

Compensator multiplet (Auxiliary multiplet)

Radion multiplet

$\Phi^{(c)}$ even (odd)

Background solution (leading order of w_0(<<1))

$$\phi(y)=N_2\exp\left[\left(\frac{3}{2}-c\right)Rk|y|\right]$$

$$\phi^c(y)=\hat{\varepsilon}(y)\,w_0\left(\frac{|\phi|^2}{6M_5^3}-1\right)^{-1}\left(\frac{|\phi|^2}{6M_5^3}\right)^{\frac{5/2-c}{3-2c}}\left[c_1+c_2\left(\frac{|\phi|^2}{6M_5^3}\right)^{-\frac{1-2c}{3-2c}}\left(\frac{|\phi|^2}{6M_5^3}+\frac{2}{1-2c}\right)\right]\left(c\neq\frac{1}{2},\frac{3}{2}\right)$$

$$\hat{\varepsilon}(y)\equiv+1(0<y<\pi),-1(-\pi<y<0),\;\;\hat{N}\equiv|N_2|^2/6M_5^3$$

$$c_1=-\left(\frac{N_2^\dagger}{2\hat{N}^{(5-2c)/2(3-2c)}}\right)\frac{(1-2c)\,\hat{N}e^{2Rk\pi}+2e^{-(1-2c)Rk\pi}}{(1-2c)\,\hat{N}\left(e^{2Rk\pi}-1\right)+2\left(e^{-(1-2c)Rk\pi}-1\right)},\;c_2=\left(\frac{N_2^\dagger}{2\hat{N}^{(3+2c)/2(3-2c)}}\right)\frac{(1-2c)}{(1-2c)\,\hat{N}\left(e^{2Rk\pi}-1\right)+2\left(e^{-(1-2c)Rk\pi}-1\right)}$$

$W_0=0$ case $\Rightarrow$ SUSY solution (solution of F-flatness)

3 parameters (N_2, c_1, c_2) are integration constants

2 of them (c_1, c_2) are fixed by boundary conditions @ y=0, π

1 of them (N_2) is fixed by the minimization of the potential

Potential

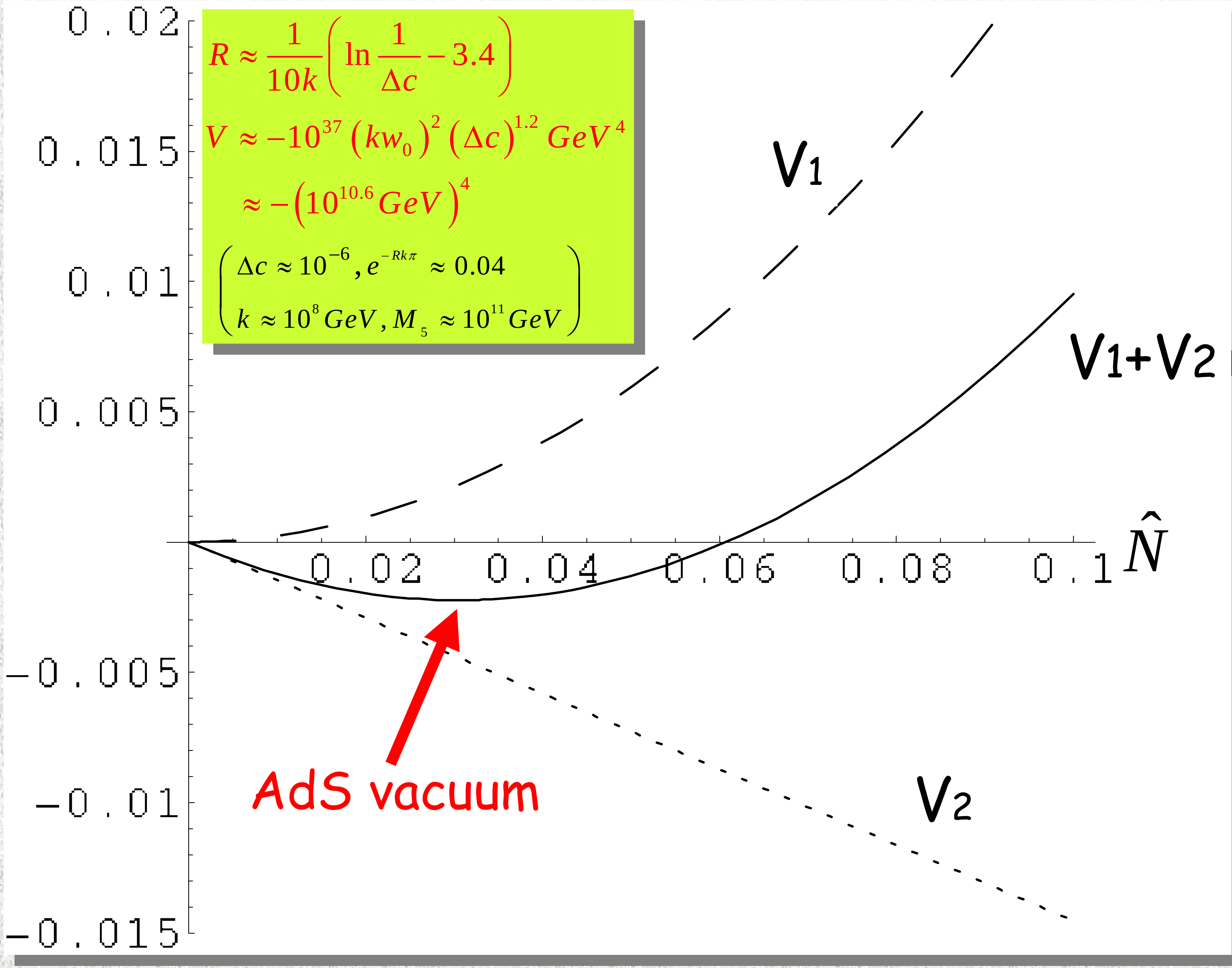
$$V=\frac{3M_5^3kw_0^2}{2}\left[\frac{-2(1-2c)}{(1-2c)\left(e^{2Rk\pi}-1\right)\hat{N}+2\left(e^{(2c-1)Rk\pi}-1\right)}\hat{N}^{4-2c-\frac{1}{3-2c}}\right.$$

$$\left.+\frac{\hat{N}}{1-\hat{N}}\left(-4c^2+12c-6+\frac{3-2c}{3\left(1-\hat{N}\right)}\right)\right]$$

$$\approx\frac{3M_5^3kw_0^2}{2}\left(\underbrace{\frac{2(2c_{cr}-1)}{3-2c_{cr}}\hat{N}^{\left(4c_{cr}^2-12c_{cr}+10\right)/(3-2c_{cr})}}_{V_1}\underbrace{-\hat{N}\left(-8c_{cr}+\frac{34}{3}\right)\Delta c}_{V_2}\right)$$

$$\left(c=c_{cr}-\Delta c,|\Delta c|\ll 1,\hat{N}=e^{-(3-2c)Rk\pi}\right)$$

We found a potential minimum with $\partial V/\partial R=\partial V/\partial\hat{N}=0$ for $c<c_{cr}\equiv\frac{17-\sqrt{109}}{12}\approx 0.546$



$R \approx \frac{1}{10k}\left(\ln\frac{1}{\Delta c} - 3.4\right)$
$V \approx -10^{37}\,(kw_0)^2\,(\Delta c)^{1.2}\ GeV^4$
$\approx -\left(10^{10.6}\,GeV\right)^4$
$\left(\begin{array}{l}\Delta c \approx 10^{-6},\ e^{-Rk\pi} \approx 0.04\\ k \approx 10^8\,GeV,\ M_5 \approx 10^{11}\,GeV\end{array}\right)$
0.02
0.015
0.01
0.005
-0.005
-0.01
-0.015
0.02
0.04
0.06
0.08
0.1
$\hat{N}$
V1
V1+V2
V2
AdS vacuum

Radion & Moduli Masses

$$m_{light}^2 \approx k^2 w_0^2 0.38 \left(3.4 + \ln \Delta c\right)^2 \Delta c^{1.7}$$

$$m_{heavy}^2 \approx k^2 w_0^2 0.47 \Delta c^{0.7}$$

Almost radion

Almost N_{2R},
N_{2I} has a same mass

We obtain for $kw_0 \sim 10^7\,\mathrm{GeV}$ & $\Delta c \sim 10^{-6}$

$$m_{light} \sim 1\,\mathrm{TeV},\; m_{heavy} \sim 100\,\mathrm{TeV}$$

Radion

Moduli

Canceling Cosmological Constant

The radion potential has a negative vacuum energy
(~ − (10^10 GeV)^4)
⇒ should be canceled by some positive energy

F-term cancellation

We add a SUSY breaking chiral multiplet "X"@y=0

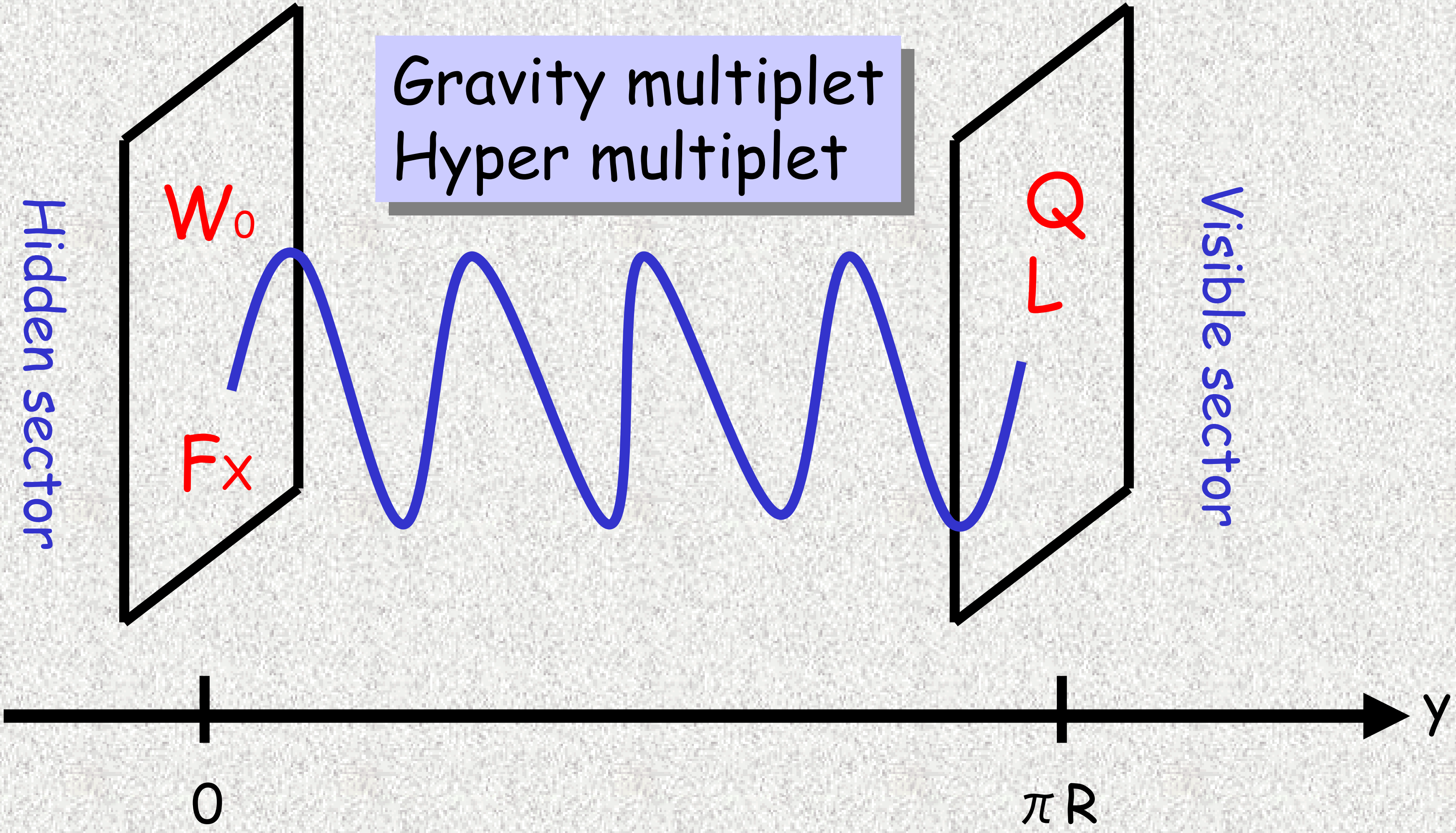
$$\mathcal{L}_X = \delta(y)\left[\int d^4\theta \varphi^\dagger \varphi X^\dagger X + \int d^2\theta \left(\varphi^3 m^2 X + h.c.\right)\right]$$

$$\rightarrow \Delta V = \left|F_X\right|^2 = m^4 \Rightarrow \sqrt{F_X} \approx 10^{10}\, GeV$$

SUSY Breaking Spectrum

SUSY breaking transmission to our world

SUSY breaking and Our world are assumed to be separated in the direction of 5th dimension



Anomaly Mediation

In this setup, NO GRAVITY MEDIATION@tree level,
and we get anomaly mediated SUSY breaking spectrum
We would like to make this SUSY breaking effects dominant
because of flavor-blindness

Gaugino, Sfermion masses

Luty, PRL89 (2002) 141801

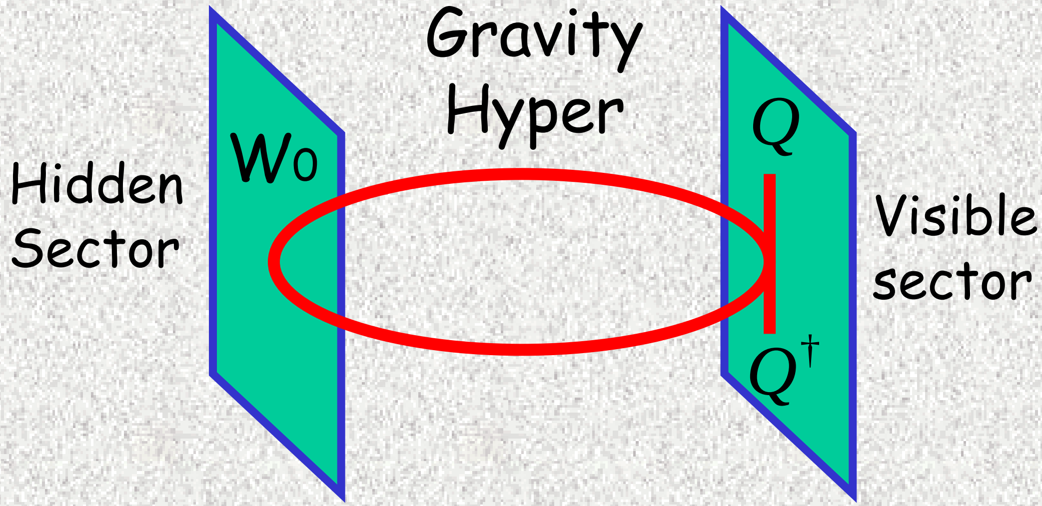
$$\tilde{m}_{AMSB} \sim \frac{g^2}{16\pi^2} \left\langle \frac{F_\omega}{\omega} \right\rangle \Bigg|_{y=\pi} \sim 10^{-4} g^2 k w_0$$

$$\sim 100 GeV \left(g^2 k w_0 \sim 10^6 GeV \right)$$

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

Anomaly mediation v.s. W_0 induced sfermion masses@1-loop

Antoniadis-Quiros
NPB505 (1997) 109

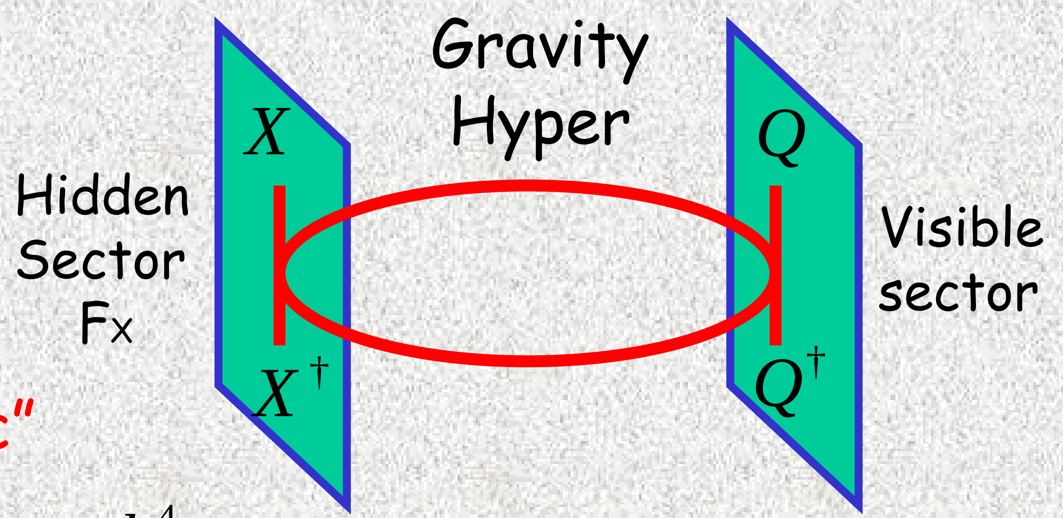


- W_0 induces mass splitting in gravity & hyper multiplets
- Sfermion masses are generated by loop effects of all KK
- Biggest mass splitting is gravitino ⇒ $M_{3/2} \sim 10^4$ TeV

$$\tilde{m}_{KK} \sim 0.1 \frac{\Delta m^2}{M_p} \leq 10^{-5} GeV \ll \tilde{m}_{AMSB}$$

Tiny!!

Anomaly mediation v.s. F_X induced sfermion masses@1-loop



"Tachyonic"

$$\Delta\tilde{m}^2_{gravity} = -\frac{k^4}{18\pi^2 M_5^6} e^{-4k\pi R} \left|F_X\right|^2$$

Gregoire, Rattazzi, Scrucca, Strumia & Trincherini, NPB720 (2005) 3

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

N.M. & Okada, PRD70 (2004) 025002

"Flavor dependent"

$$\Delta\tilde{m}^2_{gravity}, \Delta\tilde{m}^2_{hyper} \leq 10^{-2}\,\tilde{m}^2_{AMSB} \Rightarrow \sqrt{F_X} \leq 10^{11}\,GeV$$

μ -problem

N.M., Sakai & Uekusa
in preparation

Higgs mass term in MSSM

$$W = \mu H_u H_d, V \supset B\mu H_u H_d$$

"Why μ^2~Bμ~Mw^2 ??"

If Higgs is localized on a brane@y=0,
Giudice-Masiero mechanism works Giudice & Masiero (1988)

$$K = \delta(y)\varphi^\dagger\varphi\left[\left(\frac{X^\dagger}{M_4} + \frac{X^\dagger X}{M_4^2}\right)H_u H_d + h.c.\right]$$

$$\Rightarrow \mu = \frac{F_X}{M_4} \approx 100GeV, B\mu = \left(\frac{F_X}{M_4}\right)^2$$

Point: Fx ~(10^10 GeV)^2 for cancellation of CC
Same order of SUSY breaking scale in Gravity mediation

Canceling CC & Solving μ -problem can be done simultaneously

Summary

- We have presented a simple model of radius stabilization & SUSY breaking in SUSY RS model with a massive hypermultiplet & a constant W@y=0
- Radius & the moduli are shown to be stabilized

  $\Rightarrow m_{radion} \sim 1$ TeV, $m_{moduli} \sim 100$ TeV
- SUSY breaking is dominated by anomaly mediation

  $\Rightarrow$ No SUSY flavor problem
- Gravitino mass ~ 10^4 TeV
- C. C. cancellation & solving μ-problem can be done by the same localized F-term SUSY breaking