Hierarchy Stabilization in Warped Supersymmetry

Markus A. Luty

Department of Physics, University of Maryland
College Park, Maryland 20742, USA
mluty@physics.umd.edu

Raman Sundrum

Department of Physics and Astronomy, Johns Hopkins University
Baltimore, Maryland 21218, USA
sundrum@pha.jhu.edu

Abstract

We show that exponentially large warp factor hierarchies can be dynamically generated in supersymmetric compactifications. The compactification we consider is the supersymmetric extension of the Randall–Sundrum model. The crucial issue is the stabilization of the radius modulus for large warp factor. The stabilization sector we employ is very simple, consisting of two pure Yang–Mills sectors, one in the bulk and the other localized on a brane. The only fine-tuning required in our model is the cancellation of the cosmological constant, achieved by balancing the stabilization energy against supersymmetry breaking effects. Exponentially large warp factors arise naturally, with no very large or small input parameters. To perform the analysis, we derive the 4-dimensional effective theory for the supersymmetric Randall–Sundrum model, with a careful treatment of the radius modulus. The manifestly (off-shell) supersymmetric form of this effective lagrangian allows a straightforward and systematic treatment of the non-perturbative dynamics of the stabilization sector.
1 Introduction

Following the work of Refs. [1, 2] there has been a great deal of interest in the phenomenological possibilities of warped higher-dimensional spacetimes of the form

\[ ds^2 = \omega^2(y)\eta_{\mu\nu}dx^\mu dx^\nu + h_{mn}(y)dy^m dy^n, \]  

where \( x^\mu (\mu = 0, \ldots, 3) \) are the 4 noncompact spacetime dimensions, and \( y^m \) are compactified. In particular, the \( y \)-dependent renormalization of effective four-dimensional mass scales implied by the ‘warp factor’ \( \omega(y) \) provides a powerful mechanism for generating hierarchies in nature. Ref. [1] presented a very simple warped five-dimensional compactification with an exponential warp factor (the ‘RS1’ model), which exploited this mechanism to explain the hierarchy between the weak and the Planck scales, without appealing to supersymmetry.

Warped spacetimes may also be important in models with supersymmetry (SUSY). One motivation is to allow phenomenological effective field theory approaches to make contact with warped superstring backgrounds [3]. A particularly interesting string background is \( \text{AdS}_5 \times S^5 \), which plays a central role in the Maldacena realization of holographic duality [4]. Refs. [5] have emphasized that such dualities may have a profound connection to the Randall–Sundrum models, based on the (partial) \( \text{AdS}_5 \) geometry of these models. Supersymmetry may allow a more precise understanding. Another example is eleven-dimensional heterotic M-theory compactified on a six-dimensional Calabi–Yau space and an \( S^1/\mathbb{Z}_2 \) orbifold [6]. This \( \mathcal{N} = 1 \) supersymmetric theory has been taken as the starting point for phenomenological studies, where the warp factor may play an important role [7]. There are also purely phenomenological motivations; warp factors can generate hierarchies required in realistic supersymmetric theories [8]. It is also an interesting open question to ask what patterns of SUSY breaking can arise in warped spacetimes. In the future we hope to focus on the effect of warping on higher-dimensional SUSY mediation mechanisms such as anomaly-mediated SUSY breaking [9], gaugino-mediated SUSY breaking [10], and radion-mediated SUSY breaking [11].

In this paper we will study the minimal supersymmetric extension of the simplest warped compactification, namely RS1. This extension has been constructed in Refs. [12]. Our first result is a derivation of the 4-dimensional effective theory of the supersymmetric RS1 model valid at long wavelengths, including a careful treatment of the radius modulus.\(^1\) This effective lagrangian is valid to 2-derivative order, but

\( ^1\)A related derivation and discussion of the four-dimensional effective theory by J. Bagger, D. Nemeschansky and Ren-Jie Zhang will appear at the same time as the present paper.
to all orders in the fields, including the radion field. The effective lagrangian will be presented in terms of off-shell SUSY multiplets, which will greatly simplify the analysis of non-perturbative effects and SUSY breaking.

The other main result of our paper is a dynamical mechanism to stabilize the radius modulus in the supersymmetric RS1 model. This mechanism naturally stabilizes the radius at a sufficiently large value that the warp factor hierarchy across the extra dimension is large. The stabilization sector consists of two super-Yang–Mills (SYM) sectors, one in the bulk and the other localized on one of the 4-dimensional boundaries. The radius of the extra dimension is stabilized by the balance between brane and boundary gaugino condensate contributions to the supergravity (SUGRA) potential. We first proposed this mechanism in Ref. [13], where it was shown to stabilize the radius in a supersymmetric compactification with negligible warp factor. We stress that for any value of the warp factor, the mechanism is completely natural (except for the cosmological constant problem) and controlled in an effective field theory expansion. In the non-supersymmetric RS1 model, a simple classical mechanism that stabilized a large warp factor was presented in Ref. [14]. The supersymmetric mechanism we present here is intrinsically non-perturbative.

We believe that it is an important development to have a supersymmetric model of radius stabilization that is both complete and calculable. Moduli describing the size and shape of the extra dimensions are a generic feature of higher-dimensional compactifications with supersymmetry, and in particular superstring theory. These moduli must be stabilized both to avoid phenomenological and cosmological problems of light scalars, and also to select an appropriate vacuum. This problem has been extensively discussed in string-inspired contexts; see e.g. Ref. [15]. The stabilization problem is especially severe because of the constraints of higher-dimensional local supersymmetry. Our model gives a simple stabilization mechanism consistent with these constraints, even if it does not display the full complexity of string compactifications. We hope that some of the tools we have developed can be extended to superstring/M-theory.

This paper is organized as follows. In section 2 we describe the model we will study. In section 3 we derive the supersymmetric 4-dimensional effective field theory of the supersymmetric RS1 model. In section 4 we analyze the non-perturbative gauge dynamics needed for stabilization using the effective 4-dimensional description. These results are summarized and discussed in Section 5. In the interest of readability, some details of the derivation of the effective theory in section 3 are relegated to the appendix, which however gives a self-contained account.
2 The Model

The theory we are interested in is minimal 5-dimensional SUGRA, where the 5th dimension is a finite interval realized as a $S^1/Z_2$ orbifold. We will also couple this theory to matter and gauge fields in the bulk or localized on the orbifold boundaries.

Our starting point is the on-shell lagrangian for 5-dimensional SUGRA [16]

$$L_{\text{SUGRA,5}} = -M_5^3 \left\{ \sqrt{-G} \left[ \frac{1}{2} R(G) + \frac{1}{4} C^{MN} C_{MN} - 6k^2 \right] + \frac{1}{6\sqrt{6}} \epsilon^{MNPQR} B_M C_{NP} C_{QR} + \text{fermion terms} \right\},$$

(2.1)

where $M,N, \ldots = 0, \ldots, 3, 5$, are 5-dimensional spacetime indices, $G_{MN}$ is the 5-dimensional metric, $C_{MN} = \partial_M B_N - \partial_N B_M$ is the field strength for the graviphoton $B_M$, and $k$ is a mass scaled defined so that $-6M_4^3 k^2$ is the 5-dimensional cosmological constant. Unbroken SUSY requires that the cosmological constant have AdS sign ($k^2 > 0$). In order to realize this theory on an $S^1/Z_2$ orbifold, the $Z_2$ parity assignments of the bosonic fields must be taken as in Table 1.

We now couple 5-dimensional SUGRA to localized energy density on the orbifold boundaries:

$$\Delta L_5 = -\delta(\vartheta) \sqrt{-g_1} V_1 - \delta(\vartheta - \pi) \sqrt{-g_2} V_2,$$

(2.2)

where $g_{1,2}$ are the induced 4-dimensional metrics on the boundaries, and $V_{1,2}$ are constants, and $-\pi < \vartheta \leq \pi$ parameterizes the 5th dimension. This theory admits the Randall–Sundrum solution [1]

$$ds^2 = e^{-2kr_0|\vartheta|} \eta_{\mu\nu} dx^\mu dx^\nu + r_0^2 d\vartheta^2,$$

$$B_\vartheta = b_0, \quad B_\mu = 0,$$

(2.3)

provided that

$$k = \frac{V_1}{6M_5^3} = -\frac{V_2}{6M_5^3}.$$

(2.4)

This metric is a slice of AdS$_5$. The exponential factor $e^{-2kr_0|\vartheta|}$ is the ‘warp factor’ that gives rise to mass hierarchies across the 5th dimension. The theory including the boundary terms Eq. (2.2) can be made supersymmetric by the addition of suitable fermion terms, and the ‘vacuum’ solution Eq. (2.3) then preserves 4 real supercharges [12]. The bulk lagrangian Eq. (2.1) is invariant under 8 real supercharges, but half of
the supersymmetry is explicitly broken by the orbifold projection and the boundary terms.

Eq. (2.3) is a solution for any value of $r_0$ and $b_0$; $r_0$ is the radius of the compact $S^1$, while $b_0$ is the Aharonov-Bohm phase of the graviphoton around the $S^1$. When we consider fluctuations about the solution Eq. (2.3), these integration constants become propagating massless modes. The mode corresponding to $r_0$ (the radion) is particularly important, since it controls the couplings in the 4-dimensional effective theory. In this paper we will show how to stabilize the radion in the interesting case where the warp factor is a large effect.

In addition, we will couple this theory to bulk super-Yang–Mills (SYM) theory. The minimal 5-dimensional SYM multiplet consists of a vector field $A_M$, a real scalar $\Phi$, and a symplectic Majorana gaugino $\lambda^j$ ($j = 1, 2$). The bulk lagrangian is [17]

$$L_5 = -\sqrt{-G} \frac{1}{2g_5^2} \text{tr} F^{MN}F_{MN} - \frac{1}{2\sqrt{6}g_5^2} \epsilon^{MNPQR} B_M \text{tr} F_{NP}F_{QR}$$

(2.5)

+ scalar and gaugino terms.

The SYM fields are taken to transform under the orbifold $\mathbb{Z}_2$ as shown in Table 2. The even fields form an $\mathcal{N} = 1$ SYM multiplet.

To obtain realistic models we will couple these bulk fields to fields localized on the orbifold boundaries. Working out these couplings and verifying that they preserve supersymmetry is nontrivial. An off-shell construction of the boundary couplings was given by Ref. [18] using the method of Mirabelli and Peskin [19]. The off-shell couplings of bulk SYM to SUGRA were constructed in Ref. [20]. It is clearly crucial for the results of this paper that these couplings exist and preserve SUSY. However, the results of this paper will be derived using only the on-shell bosonic lagrangian together with consistency arguments.

We can now summarize the theory that we will analyze in this paper. The theory consists of minimal 5-dimensional SUGRA, with a SYM sector in the bulk, and an

| Field    | $\mathbb{Z}_2$ Parity |
|----------|----------------------|
| $G_{\mu\nu}$ | +                    |
| $G_{5\mu}$  | -                    |
| $G_{55}$    | +                    |
| $B_{\mu}$   | -                    |
| $B_5$       | +                    |

Table 1. Bosonic fields of 5-dimensional SUGRA with their $\mathbb{Z}_2$ parity assignments.
| Field | $\mathbb{Z}_2$ Parity |
|-------|---------------------|
| $A_\mu$ | +                  |
| $A_5$  | −                  |
| $\Phi$ | −                  |
| $\lambda^1$ | +            |
| $\lambda^2$ | −            |

Table 2. Fields of 5-dimensional super-Yang–Mills sector with their $\mathbb{Z}_2$ parity assignments.

additional SYM sector on one of the orbifold boundaries, the ‘hidden brane.’ The bulk lagrangian has dimensionful parameters $M_5$ and $g_5$ that we take to be of order the Planck scale. Additionally, we assume that there is a SUSY breaking sector also localized on the hidden brane. The SYM multiplets together with the SUSY breaking sector will play the role of the radius stabilization sector, as we will see. For a fully realistic model, one would want to add standard model fields, presumably some or all of them localized on the other boundary, the ‘visible brane.’ These play no role in the stabilization dynamics. We will study complete realistic models in future work.

3 The 4-Dimensional Effective Lagrangian

At sufficiently low energies, the dynamics of the theory above is approximately 4-dimensional. The matching scale between the 5-dimensional and 4-dimensional effective theories is determined by the mass of the lowest KK mode, given by $[1, 2]$

$$m_{KK}^2 \sim \left( \frac{k}{1 + e^{\pi kr_0}} \right)^2. \quad (3.1)$$

We assume that the theory is weakly interacting at this scale, justifying the use of classical matching. This will be true as long as the radius of compactification $r_0$ and the radius of curvature $1/k$ are larger than the 5-dimensional Planck length.

In this section, we will derive the 4-dimensional effective theory below the scale Eq. (3.1). Our strategy is to match enough bosonic terms between the 5-dimensional and 4-dimensional lagrangians, so that we can infer the remaining terms using $N = 1$ SUSY. The justification of some of the steps is relegated to an appendix. The appendix gives a complete self-contained derivation, including a discussion of some subtleties of classical matching.

We begin by considering the massless bosonic fields arising from the 5-dimensional SUGRA sector. The solution Eq. (2.3) has undetermined integration constants $r_0$
and $b_0$ whose long-wavelength fluctuations are massless moduli. Also, unbroken 4-dimensional Lorentz invariance implies that there is a massless graviton in the 4-dimensional effective theory. These massless 4-dimensional fluctuations can be parameterized by making the replacements $\eta_{\mu\nu} \rightarrow g_{\mu\nu}(x)$, $r_0 \rightarrow r(x)$, and $b_0 \rightarrow b(x)$ in Eq. (2.3):

$$ds^2 = e^{-2kr(x)|\vartheta|}g_{\mu\nu}(x)dx^\mu dx^\nu + r^2(x)d\vartheta^2, \quad -\pi < \vartheta \leq \pi,$$

$$B_\varphi(x, \vartheta) = b(x), \quad B_\mu(x, \vartheta) = 0.$$  \hspace{1cm} (3.2)

If this satisfied the 5-dimensional equation of motion, one could obtain the classical 4-dimensional effective action by substituting Eq. (3.2) into the 5-dimensional action and integrating over the 5th dimension. Eq. (3.2) does not satisfy the 5-dimensional equations of motion [21]. However, in the appendix we show that for the metric in Eq. (3.2), this ‘naïve’ procedure gives a result that differs from the exact classical effective action only by terms with four or more $x$ derivatives. We can therefore use the metric in Eq. (3.2) to parameterize the radion at leading order in the derivative expansion.\footnote{Ref. [21] gives an alternate parameterization of the radion that satisfies the 5-dimensional equations of motion at linear order in fluctuation fields, but to all orders in $x$ derivatives.} For the graviphoton, the naïve procedure does not work; the graviphoton can still be parameterized by $b(x)$ defined by Eq. (3.2), but there is a nontrivial correction to the classical effective lagrangian that is computed in the appendix. However, to determine the effective theory it is sufficient to know the terms that depend only on the radion, which can be determined by substituting Eq. (3.2) into the 5-dimensional action. The terms depending on the graviphoton can then be inferred from SUSY. Therefore, the calculation of the graviphoton effective lagrangian carried out in the appendix serves only as a redundant check on our results.

We turn to the 5-dimensional SYM sector. It is straightforward to verify that

$$A_\mu(x, \vartheta) = a_\mu(x), \quad A_\vartheta(x, \vartheta) = 0$$ \hspace{1cm} (3.3)

is a solution to the 5-dimensional equations of motion if $a_\mu(x)$ is a solution to the 4-dimensional YM equation of motion. Therefore, $a_\mu(x)$ parameterizes a 4-dimensional vector zero mode. The fact that the zero mode is independent of $\vartheta$ despite the presence of the warp factor can be traced to the classical conformal invariance of 4-dimensional Yang–Mills theory. Note that there are no massless $A_\vartheta$ or $\Phi$ fluctuations because of the orbifold projection.

We wish to relate the massless bosonic fields defined above (and their fermionic superpartners) to a manifestly $\mathcal{N} = 1$ supersymmetric formulation of the 4-dimensional
effective theory. The massless bosonic fields are two real scalars \( r(x) \) and \( b(x) \), a real vector multiplet \( a_\mu(x) \), and the metric \( g_{\mu\nu}(x) \). Given that these bosonic fluctuations are part of an \( \mathcal{N} = 1 \) locally supersymmetric theory, they can be parameterized by one chiral superfield \( T \), one non-Abelian vector superfield \( V \), and the minimal SUGRA multiplet. The most general effective lagrangian at 2-derivative order can be written

\[
\mathcal{L}_{4,\text{eff}} = \int d^4 \theta \phi^\dagger \phi f(T, T^\dagger) + \left[ \int d^2 \theta S(T) \text{tr}(W^\alpha W_\alpha) + \text{h.c.} \right].
\] (3.4)

There is no superpotential for \( T \) because the radion modulus does not have a potential. We are using the superconformal approach to SUGRA [22]. The field \( \phi \) is the superconformal compensator [23, 22] that is responsible for breaking the local superconformal symmetry down to local super-Poincaré:

\[
\phi = 1 + \theta^2 F_\phi.
\] (3.5)

\( F_\phi \) is the scalar auxiliary field of the minimal off-shell \( \mathcal{N} = 1 \) SUGRA multiplet. We are using superspace notation as a shorthand for expressions that can be rigorously defined using the superconformal tensor calculus approach [22]. In particular, factors of the metric (or vierbein) are implicit in this notation.

We now make a holomorphic field redefinition \( S(T) \to T/g_5^2 \) in the effective theory so that the effective lagrangian has the form

\[
\mathcal{L}_{4,\text{eff}} = \int d^4 \theta \phi^\dagger \phi f(T, T^\dagger) + \left[ \int d^2 \theta \frac{T}{g_5^2} \text{tr}(W^\alpha W_\alpha) + \text{h.c.} \right].
\] (3.6)

From this, we have

\[
\frac{1}{2g_4^2} = \frac{\text{Re}(T)}{g_5^2}.
\] (3.7)

We can also calculate the 4-dimensional gauge coupling \( g_4 \) by substituting the zero mode gauge field Eq. (3.3) into the 5-dimensional action and integrating over the 5\(^{th}\) dimension. This yields

\[
\frac{1}{g_4^2} = \frac{2\pi r}{g_5^2}.
\] (3.8)

Therefore, we see that

\[
\text{Re}(T) = \pi r.
\] (3.9)

Similarly, from Eq. (3.6) we see that \( \text{Im}(T) \) is proportional to the 4-dimensional theta angle, which in turn is proportional to \( B_\theta \) from the mixed Chern-Simons term.
in the 5-dimensional theory:

\[
\Delta \mathcal{L}_5 = -\frac{1}{2\sqrt{6} g_5^2} \epsilon^{MNPQR} B_M \text{tr} (F_{NP} F_{QR})
\]

\[
= -\frac{1}{2\sqrt{6} g_5^2} \epsilon^{\mu\rho\sigma} B_\vartheta \text{tr} (F_\mu F_\rho) + \cdots
\]

(3.10)

This determines

\[
\text{Im}(T) = \frac{2\pi}{\sqrt{6}} b.
\]

(3.11)

Thus we have fixed the relation between \( T \) and the component fields \( r(x) \) and \( b(x) \). Note that Eqs. (3.9) and (3.11) are exactly the same as in flat space [13]. This is ultimately due to the classical conformal invariance of Yang–Mills theory in 4 dimensions.

It still remains to fix the relation between the metric that appears in the 4-dimensional \( \mathcal{N} = 1 \) SUGRA multiplet, and the metric \( g_{\mu\nu} \) defined by Eq. (3.2). This is nontrivial because in the 4-dimensional effective theory, we have the freedom to make field redefinitions \( g'_{\mu\nu} = c(r) g_{\mu\nu} \), where \( c(r) \) is an arbitrary function. However, such field redefinitions in general do not preserve the property that \( T \) transforms independently of the 4-dimensional SUGRA multiplet under \( \mathcal{N} = 1 \) SUSY. In the appendix, it is shown that imposing this condition implies that the two metrics are identical (as implicitly assumed in the notation used above).

Expanding the 4-dimensional SUGRA lagrangian Eq. (3.4) in component fields, we obtain

\[
\mathcal{L}_{\text{SUGRA},4} = \sqrt{-g} \left[ -\frac{1}{6} f R(g) - \frac{1}{4f} (f_T \partial^\mu T - \text{h.c.})(f_T \partial_\mu T - \text{h.c.)} \right.
\]

\[
\left. - f_{TT} \partial^\mu T^\dagger \partial_\mu T + \text{fermion terms} \right],
\]

(3.12)

where \( f_T = \partial f / \partial T \), etc., and \( R(g) \) is the 4-dimensional Ricci scalar associated with the metric \( g \). As discussed above, the terms depending on the metric and the radion \( r \) can be obtained by substituting Eq. (3.2) into the 5-dimensional action and integrating over the 5th dimension. We can use this procedure to determine \( f \) by calculating the coefficient of \( R(g) \) (see Eq. (3.12)). One obtains

\[
f = \frac{3 M_5^3}{k} \left( e^{-2\pi kr} - 1 \right).
\]

(3.13)
Note that for \( r \to r_0 \) \( f \) is the 4-dimensional Planck scale computed in Ref. [1]. The graviphoton Aharonov–Bohm phase cannot contribute to the coefficient of \( R(g) \). Using Eqs. (3.9) and (3.11) therefore gives

\[
f(T, T^\dagger) = + \frac{3M_5^3}{k} \left( e^{-k(T+T^\dagger)} - 1 \right).
\]

(3.14)

Having fixed the function \( f \), the other 2-derivative terms in Eq. (3.12) that depend on \( r \) and \( b \) are fixed. In the Appendix we show that these agree with a direct matching calculation, giving a highly nontrivial check of this derivation.

We now turn to fields localized on the boundary. Note that in terms of the components fields, we have chosen coordinates so that the warp factor is unity at \( \vartheta = 0 \) (the hidden brane). Therefore the radion (as parameterized above) does not couple to the fields on the hidden brane. Correspondingly, it is shown in the appendix that the terms arising from the hidden brane are independent of \( T \). Therefore the general form of the effective lagrangian involving the hidden fields is

\[
\mathcal{L}_{4,\text{hid}} = \int d^4\vartheta \phi^\dagger \phi f_{\text{hid}}(\Sigma, \Sigma^\dagger) + \int d^2\theta \left[ S_{\text{hid}}(\Sigma) \text{tr} W' e_{\alpha} W' + \phi^3 W_{\text{hid}}(\Sigma) \right] + \text{h.c.},
\]

(3.15)

where \( \Sigma \) are hidden sector chiral multiplets and \( W'_\alpha \) is the field strength of the hidden sector gauge multiplets. The terms arising from the visible brane do have couplings to the radion, since by Eq. (3.2) the induced metric on the brane is \( e^{-2\pi k r(x)} g_{\mu\nu}(x) \). The unique supersymmetrization of these terms is

\[
\mathcal{L}_{4,\text{vis}} = \int d^4\vartheta \phi^\dagger \phi e^{-k(T+T^\dagger)} f_{\text{vis}}(Q, Q^\dagger) + \int d^2\theta \left[ S_{\text{vis}}(Q) \text{tr} \tilde{W} e_{\alpha} \tilde{W} + \phi^3 e^{-3kT} W_{\text{vis}}(Q) \right] + \text{h.c.},
\]

(3.16)

where \( Q \) is a visible sector chiral multiplet, and \( \tilde{W}_\alpha \) is the field strength of the visible sector gauge multiplets. Note that Eq. (3.16) has the same form as Eq. (3.15) with \( \phi \) replaced by \( \phi e^{-kT} \). This is not a coincidence. The radion dependence of \( \mathcal{L}_{4,\text{vis}} \) is entirely due to the fact that the induced metric is a Weyl rescaling of \( g_{\mu\nu} \), which is precisely equivalent to a rescaling of the conformal compensator \( \phi \).

Comparing Eqs. (3.15) and (3.16) one readily sees that, relative to fundamental mass parameters, physical mass scales in the visible sector (including UV regulator and renormalization scales) are rescaled by a factor of \( e^{-k\pi r_0} \), while scales on the hidden sector are not. For \( k > 0 \), mass scales are suppressed on the visible sector,
while for \( k < 0 \) mass scales are enhanced on the visible sector. This is the warp factor effect that can naturally generate exponentially large hierarchies.

It is more conventional to describe the kinetic terms in supergravity in terms of the Kähler potential. This is given by

\[
K \equiv -3M_4^2 \ln \left[ -\frac{f(T, T^\dagger) + f_{\text{vis}}(Q, Q^\dagger) + f_{\text{hid}}(\Sigma, \Sigma^\dagger)}{3M_4^2} \right]. \tag{3.17}
\]

The properties of supersymmetry breaking and renormalization are easier to see in terms of \( f \), but the Kähler potential is more useful for determining the sigma model couplings of the bosonic fields.

## 4 The Radius Modulus Effective Potential

In this section, we construct the effective potential for the model described above and minimize the potential to show that the the radius is in fact stabilized. The model was analyzed in Ref. [13] for the case where the warp factor is a small effect, \( e^{-kT} \approx 1 \). We will therefore be interested in the case where the warp factor is a large effect.

Just below the KK matching scale Eq. (3.1), the 4-dimensional effective theory is

\[
\mathcal{L}_{4,\text{eff}} = \frac{3M_5^3}{k} \int d^4 \theta \phi^\dagger \phi \left( e^{-k(T+T^\dagger)} - 1 \right) + \int d^2 \theta \left( \frac{T}{g_5^2} \text{tr} W^\alpha W_\alpha + \frac{1}{2g_4^2} \text{tr} W'^\alpha W'^\alpha \right) + \text{h.c.} + \mathcal{L}_{\text{SB}}. \tag{4.1}
\]

Here the first gauge kinetic term arises from the bulk SYM sector, while the second arises from the SYM sector localized on the hidden brane. \( \mathcal{L}_{\text{SB}} \) is the lagrangian for the SUSY breaking sector, also assumed to be localized on the hidden brane. We are using coordinates where the warp factor is unity on the hidden brane (so that \( \mathcal{L}_{\text{SB}} \) is independent of \( T \)). There are therefore two cases to consider: the warp factor at the visible brane is either smaller or larger than unity. In the formulas above, these cases correspond to \( k > 0 \) and \( k < 0 \), respectively, so we can analyze both cases using Eq. (4.1). Classical matching is justified by assuming that the asymptotically free gauge forces are weak at the KK matching scale, and that the spacetime curvature is also small, \(|k| < M_5\).

The SYM sectors become strong in the infrared of the 4-dimensional effective theory and give rise to a dynamical superpotential from gaugino condensation. In
addition, the hidden SUSY breaking sector is assumed to dynamically generate a nonzero vacuum energy. This vacuum energy will be positive provided that SUGRA is a perturbation to the SUSY breaking dynamics. We also assume that the SUSY breaking dynamics has a mass gap, except for the Goldstino. The effective lagrangian below the scale where these effects occur is then

$$\mathcal{L}_{\text{4,eff}} = \frac{3M_5^3}{k} \int d^4 \theta \phi^\dagger \phi \left( e^{-k(T+T^\dagger)} - 1 \right) + \left[ \int d^2 \theta \phi^3 \left( a e^{-cT} + c \right) + \text{h.c.} \right] - V_{\text{SB}} + \text{Goldstino terms.}$$  \hspace{1cm} (4.2)

If the bulk SYM gauge group is $SU(N)$, we have

$$a = \mathcal{O} \left( \frac{1}{N^4g_5^6} \right), \quad \zeta = \frac{16\pi^2}{3Ng_5^2}. \hspace{1cm} (4.3)$$

The exact $T$ dependence in the superpotential term of Eq. (4.2) is fixed by holomorphy and the anomalous shift symmetry in $T$ [13].

It is straightforward to integrate out the auxiliary fields for $T$ and $\phi$ to obtain the effective potential. However, additional insight into the form of the answer is given by writing the lagrangian in terms of the ‘warp factor superfield’

$$\omega \equiv \phi e^{-kT}$$  \hspace{1cm} (4.4)

in place of $T$. This gives

$$\mathcal{L}_{\text{4,eff}} = \frac{3M_5^3}{k} \int d^4 \theta \left( \omega^\dagger \omega - \phi^\dagger \phi \right) + \left[ \int d^2 \theta \left( a\phi^3 - n \omega^n + c\phi^3 \right) + \text{h.c.} \right] - V_{\text{SB}} + \text{Goldstino terms,}$$  \hspace{1cm} (4.5)

where

$$n \equiv \frac{\zeta}{k}. \hspace{1cm} (4.6)$$

From Eq. (4.5) one can immediately read off the potential

$$V_{\text{eff}} = \frac{k}{3M_5^3} \left[ n^2|a|^2(\omega^\dagger \omega)^{n-1} - |(3-n)a\omega^n + 3c|\right] + V_{\text{SB}}$$  \hspace{1cm} (4.7)

$$= \frac{k}{3M_5^3} \left[ n^2|a|^2|\omega|^{2(n-1)} - (n-3)^2|a|^2|\omega|^{2n} - 9|c|^2 - 6(n-3)|a||c||\omega|^n \cos \gamma \right] + V_{\text{SB}},$$  \hspace{1cm} (4.8)
where

\[ \gamma \equiv \arg(a) - \arg(c) + n \arg(\omega). \]  

(4.9)

We now minimize the potential as a function of \(|\omega|\) and \(\gamma\).

We first consider \(k > 0\), corresponding to the case where the warp factor is smaller than unity on the visible brane. If the warp factor is an important effect, then \(|\omega| \ll 1\) and we can neglect the second term in Eq. (4.8) compared to the first. (We assume that \(n\) is not much larger than unity.) Minimizing with respect to \(\gamma\) simply sets \(\cos \gamma = \text{sgn}(n - 3)\). There is a nontrivial minimum provided that \(n > 3\), which is satisfied provided that the bulk SYM sector is weakly coupled at the KK matching scale. We then obtain

\[ |\omega| = e^{-\pi kr} = \left( \frac{3(n - 3)}{n(n - 1)} \frac{|c|}{|a|} \right)^{1/(n-2)}. \]  

(4.10)

We see that for any given \(n\) we can obtain \(|\omega| \ll 1\) provided that \(|c|/|a|\) is sufficiently small.\(^3\) This is perfectly natural, since \(|c|\) is exponentially small in terms of the fundamental couplings. Thus, if we want to use the small warp factor to explain some mass hierarchy in nature, the small warp factor itself can be explained in terms of order-1 fundamental parameters in this model of stabilization.

To complete our analysis of this case, we find the other extrema of the potential. There is an obvious extremum where \(|\omega| \to 0\). It is easy to check that this has higher energy than the solution Eq. (4.10). We must also look for solutions with \(|\omega| \sim 1\). In this case we can neglect the last term of Eq. (4.8) since \(|c|/|a|\). This gives another extremum

\[ |\omega| = \left( \frac{n(n - 1)}{(n - 3)^2} \right)^{1/2}. \]  

(4.11)

However this solution has \(|\omega| > 1\) (which is outside the physical region \(r > 0\)) for \(n > 1\) and is therefore unphysical for the values of \(n\) we are considering. It is also easy to see that this extremum has higher energy than the solution Eq. (4.10).

Combining the results above, we conclude that Eq. (4.10) is in fact the true (global) minimum. In order to cancel the 4-dimensional cosmological constant, we note that the term \(-9|c|^2\) in Eq. (4.8) dominates the vacuum energy in the solution, so we must fine-tune

\[ V_{SB} \simeq \frac{3|c|^2}{M_4^2}. \]  

(4.12)

\(^3\)This assumes that \(n\) is not too large. The regime \(n \gg 1\) corresponds to \(k \ll \zeta\), i.e. small bulk curvature. As shown in Ref. [13], the model also stabilizes the radius in this regime.
where $M_4^2 = M_5^3/k$. Note that this gives $V_{SB} > 0$, as desired. We obtain

$$m_{3/2}^2 = \frac{|c|^2}{M_4^4} \sim \frac{V_{SB}}{M_4^2}. \quad (4.13)$$

The masses of the radion fields at the minimum of the potential is straightforward to work out using the component lagrangian given above, or in terms of the standard 4-dimensional supergravity potential. Parameterizing the radion by $\omega$ greatly simplifies the calculation. We find

$$m_{\text{scalar}}^2 = \frac{|c|^2}{M_4^4} \frac{(n-2)(n-3)^2}{n-1}, \quad m_{\text{pseudoscalar}}^2 = \frac{|c|^2}{M_4^4} \frac{n(n-3)^2}{(n-1)}. \quad (4.14)$$

Note that $m_{\text{scalar}} \sim m_{\text{pseudoscalar}} \sim m_{3/2}$. The radion is lighter than the KK matching scale Eq. (3.1) provided that $|c|/M_5^3 \ll |\omega|$, which is guaranteed by Eq. (4.10) since $|c| \ll |a| \ll M_5^3$.

We now consider $k < 0$, corresponding to the case that the warp factor is larger than unity on the visible brane. Note that in this case $n < 0$. We again look for solutions where the warp factor is a large effect, so that $|\omega| \gg 1$. We can therefore neglect the first term of Eq. (4.8) compared to the second. Because the factor in front of Eq. (4.8) is now negative, minimizing with respect to the phase $\gamma$ now gives

$$\cos \gamma = -\text{sgn}(n-3).$$

We then obtain the solution

$$|\omega| = \left(\frac{|n-3|}{3} \frac{|a|}{|c|}\right)^{1/|n|}. \quad (4.15)$$

We see that $|\omega| \gg 1$ provided that $|c| \ll |a|$. Again, Eq. (4.11) is an extremum, as is $|\omega| \to +\infty$. As before, Eq. (4.11) is outside the physical region, and both Eq. (4.11) and the ‘runaway’ solution $|\omega| \to +\infty$ have higher energy than the solution Eq. (4.15).

Together, these results imply that Eq. (4.15) is in fact the true (global) minimum. In order to cancel the 4-dimensional cosmological constant, we note that the first term in Eq. (4.8) dominates the vacuum energy, and we must fine-tune

$$V_{SB} \simeq \frac{3|c|^2}{M_4^2} \frac{n^2}{(n-3)^2}, \quad (4.16)$$

where $M_4^2 = M_5^3 |\omega|^2/|k|$. Again $V_{SB} > 0$ as desired. We find

$$m_{3/2}^2 = \frac{|c|^2}{M_4^4} \frac{(n-6)^2}{(n-3)^2} \sim \frac{V_{SB}}{M_4^2}. \quad (4.17)$$

The radion masses are

$$m_{\text{scalar}}^2 = m_{\text{pseudoscalar}}^2 = \frac{|c|^2}{M_4^4} |n|^2 |\omega|^4. \quad (4.18)$$
Note that $m_{\text{scalar}} = m_{\text{pseudoscalar}} \gg m_{3/2}$ in this case. The radion is lighter than the KK matching scale Eq. (3.1) provided only that $|c|/M_5^3 \ll 1$.

We conclude that the simple model we are considering does in fact stabilize the radius modulus in the regime where the warp factor is large, provided only that $|c| \ll |a|$. This works both in the case where the warp factor is largest on the hidden brane or on the visible brane. In both cases, the cosmological constant can be cancelled by positive vacuum energy from the SUSY breaking sector.

5 Discussion

Let us summarize what has been accomplished. The 4-dimensional effective lagrangian describing the supersymmetric Randall–Sundrum model at long distances was derived. Like the non-supersymmetric Randall–Sundrum model it has a vanishing potential for the radius modulus, now a chiral superfield. We also showed that the mechanism proposed in Ref. [13] stabilizes this modulus in the interesting regime where the warp factor is a large effect.

The stabilizing sector consists of two types of supersymmetric Yang-Mills sectors, one in the bulk and the other on one of the boundaries, the ‘hidden brane.’ These two sectors become strongly coupled in the infrared, where the dynamics can be controlled using holomorphy in the 4-dimensional description. The two resulting non-perturbative gaugino condensates were shown to provide a stabilizing potential for the radius modulus. In order to cancel the effective 4-dimensional cosmological constant a source of spontaneous supersymmetry breaking is required. We analyzed the simplest possibility that a supersymmetry-breaking sector is also localized on the hidden brane.

The stabilized radius is in the regime where the warp factor effect is large provided that (i) the hidden brane gaugino condensate is small compared to the 5-dimensional Planck scale; and (ii) the bulk radius of curvature $1/k$ is not much larger than the bulk super-Yang–Mills coupling $g_5^2$. Neither condition requires any fine-tuning. In particular, the first condition is very natural, since the non-perturbative gaugino condensate is exponentially suppressed in terms of the fundamental gauge coupling.

We emphasize that the fact that the radius potential is dominated by non-perturbative super-Yang–Mills dynamics is crucially dependent on supersymmetry. In a non-supersymmetric theory, there would be perturbative contributions to the radius potential at the compactification scale from Casimir energy that would dominate the exponentially smaller contribution from non-perturbative bulk Yang–Mills dynamics. In our model, these effects are absent because supersymmetry is unbroken at the
A heuristic understanding of how stabilization is achieved in our model is to note that the infrared confinement of the bulk Yang-Mills theory gives a field-theoretic realization of composite extended states in the bulk, namely the confined hadrons. The spectrum of such extended states is certainly sensitive to the radius and it is not surprising that their virtual effects can generate a radius potential. It is indeed possible that the stabilization role could instead be played by fundamental extended objects, in a string/M-theory description. A virtue of our mechanism is that it involves only the infrared dynamics of point particles, and is therefore under full theoretical control.

We hope to use the stabilization mechanism presented in this paper as the basis for further studies of supersymmetric and supersymmetry-breaking physics in warped compactifications.

Acknowledgements

We are very grateful to J. Bagger for discussions of closely related work prior to publication. We also thank H. Nishino for discussions. M.A.L. was supported by NSF grant PHY-98-02551.

Appendix A: Derivation of Effective Theory

In this appendix, we give a complete and self-contained derivation of the 4-dimensional effective lagrangian.

A.1 Matching and Heavy Tadpoles

We begin by explaining the formalism we will use to integrate out heavy fields at tree level. We consider a general classical and local theory of some light fields $L(x)$ interacting with some heavy fields $H(x)$. We will truncate the effective lagrangian at two-derivative order, higher derivatives being subdominant at long wavelengths. While $x$ denotes a point in a spacetime of fixed dimensionality (4 in the case of interest) this spacetime need not be exactly flat but may have small curvatures relative to the heavy masses. We will be interested in the case where the heavy fields are an infinite tower of KK states; however we will suppress indices on the fields since it will be obvious where they go at the end.

Let $S[H, L]$ denote a local classical action that we start with. We will assume (by shifting the definitions of fields if necessary) that $L = H = 0$ is a classical solution,
and we will expand our theory about this ‘vacuum’ solution. Expanding the action in heavy fields and $x$ derivatives gives

$$
S[H, L] = S_{\text{light}}[L] + \int d^4 x \left[ \lambda(L) H - \frac{1}{2} M^2(L) H^2 + \Phi(L) (\partial L) H \\
+ \mathcal{O}(\partial^2 H) + \mathcal{O}(H \partial H) + \mathcal{O}(H^3) \right].
$$

(A.1)

$S_{\text{light}}[L]$ consists of the part of the fundamental action which is independent of $H$; by assumption the mass terms in $S_{\text{light}}$ are small compared to $M^2(L = 0)$, the mass scale of the heavy fields. Note that the remaining terms in the action contain terms linear in $H$, which we call ‘heavy tadpole’ terms. The first two terms in the integral contain all terms linear and quadratic in $H$ but containing no derivatives. The third term contains all terms linear in $H$ with at least one derivative, which by integration by parts can be taken to act only on light fields. The remaining terms contain terms linear in $H$ with two or more derivatives, terms quadratic in $H$ with one or more derivative, and terms of cubic and higher order in $H$.

Without loss of generality we can set $\lambda \equiv 0$, by making the field redefinition

$$
H \rightarrow H + \frac{\lambda}{M^2(L)}.
$$

(A.2)

Since the fields $H$ are heavy by assumption we can expand this in powers of $L$, with higher-order terms suppressed by $M^2(L = 0)$, the mass scale of the heavy fields. With this choice, the only heavy tadpoles involve derivatives.

The equations of motion for $H$ then read,

$$
H = \frac{1}{M^2(L)} \left[ \Phi(L) \partial L + \mathcal{O}(\partial^2) + \mathcal{O}(H \partial L) + \mathcal{O}(H^2) \right].
$$

(A.3)

(In the $\mathcal{O}(\partial^2)$ terms, the derivatives act on light fields.) This equation can be solved iteratively by expanding in powers of $L$, starting with the leading order solution

$$
H = \frac{\Phi(L) \partial L}{M^2(L)} + \mathcal{O}(\partial^2).
$$

(A.4)

Subleading terms are suppressed by additional powers of $M^2(L)$.

We now substitute the solution for $H$ back into the fundamental action, thereby obtaining an effective action purely for the light fields. To determine the long-wavelength action up to two derivative order, only the leading order solution Eq. (A.4) for $H$ is required. At this order, we therefore obtain

$$
S_{\text{eff}}[L] = S_{\text{light}}[L] + \int d^4 x \frac{[\Phi(L) \partial L]^2}{2M^2(L)} + \mathcal{O}(\partial^3).
$$

(A.5)
We see that at 2-derivative order there is a correction to the naïve effective action $S_{\text{light}}[L]$ when the original action has heavy tadpoles with one derivative.

A.2 Radion Effective Field Theory

We now apply the ideas above to derive the effective lagrangian for the radion effective lagrangian. We parameterize the light modes by generalizing the solution for the metric Eq. (2.3) by $r_0 \rightarrow r(x)$, $\eta_{\mu\nu} \rightarrow g_{\mu\nu}(x)$:

$$ds^2 = e^{-2kr(x)|\vartheta|}g_{\mu\nu}(x)dx^\mu dx^\nu + r^2(x)d\vartheta^2. \quad (A.6)$$

Note that $g_{\mu\nu}(x)$ transforms under 4-dimensional general coordinate transformations as a 2-index tensor, and therefore its couplings in the 4-dimensional action are precisely those of the 4-dimensional metric. There are no non-derivative couplings of $g_{\mu\nu}$ provided we cancel the 4-dimensional cosmological constant. Also note that $r(x)$ is derivatively coupled, since $r(x) = r_0$ is a solution for any constant $r_0$. Therefore the action $S_{\text{light}}$ obtained by substituting the metric Eq. (A.6) into the 5-dimensional action does not contain mass terms for the light fields.

We parameterize the heavy modes in terms of the 5-dimensional metric

$$ds^2 = e^{-2kr(x)|\vartheta|}[g_{\mu\nu}(x) + H_{\mu\nu}(x, \vartheta)]dx^\mu dx^\nu$$

$$+ 2H_{\vartheta\mu}(x, \vartheta)d\vartheta dx^\mu + r^2(x)[1 + H_{\vartheta\vartheta}(x, \vartheta)]d\vartheta^2. \quad (A.7)$$

This must be supplemented with a restriction on $H_{\mu\nu}$ to ensure that it is ‘orthogonal’ to the zero mode $g_{\mu\nu}$, and we must impose a gauge on the fluctuations $H_{MN}$. The details of this will not be needed for our discussion.

As explained in Section A.1, the correct effective action at 2-derivative order differs from $S_{\text{light}}$ if there are heavy tadpoles containing a single $x$ derivative. By 4-dimensional Lorentz invariance, the only terms of this form involve the metric fluctuation $H_{\vartheta\mu}$, e.g. $\partial^\mu r H_{\vartheta\mu}$. Direct calculation shows that this vanishes in the metric Eq. (A.7). Therefore, there are no corrections to the effective action at 2-derivative order, and the correct effective action is obtained simply by using the metric Eq. (A.6). This gives

$$S_{4,\text{eff}} = -\frac{M_5^3}{k} \int d^4x \sqrt{-g} \left[ \left(1 - e^{-2\pi kr(x)}\right) R(g) + \cdots \right]. \quad (A.8)$$

A.3 The Graviphoton

We now turn to the graviphoton $B_M$. In this case, there is a classical solution $B_{\mu} \equiv 0$, $B_{\vartheta} \equiv b_0$ for constant $b_0$. In analogy with the radion, we parameterize the light modes
by generalizing this solution by \( b_0 \to b(x) \):
\[
B_\mu = 0, \quad B_\theta(x, \vartheta) = b(x). \tag{A.9}
\]

In this case there are \( \mathcal{O}(\partial_\mu) \) heavy tadpoles involving the massive modes \( B_\mu \):
\[
S_5 = -M_5^3 \int d^5 X \partial_\vartheta \left[ \sqrt{-G} G^{\mu\nu} G^{\vartheta\vartheta} \partial_\nu B_\vartheta \right] B_\mu + \mathcal{O}(B_\mu^2) + \mathcal{O}(\partial_\mu^2). \tag{A.10}
\]

Here \( G_{MN} \) is the 5-dimensional metric Eq. (A.6), which includes the light modes \( g_{\mu\nu}(x) \) and \( r(x) \).

As explained in Section A.1, the presence of the tadpole Eq. (A.10) means that there are corrections to the effective lagrangian at \( \mathcal{O}(\partial_\mu^2) \). We must therefore integrate out the heavy fields \( B_\mu \), including the effects of the tadpole in Eq. (A.10). The fields \( B_\mu \) have nonzero KK masses because they are odd under the orbifold \( \mathbb{Z}_2 \); the mass terms are contained in the \( \mathcal{O}(\partial_\vartheta^2 B_\mu^2) \) terms in the action. Including these mass terms and the \( B_\mu \) tadpole in Eq. (A.10), the \( B_\mu \) equation of motion is
\[
\partial_\vartheta \left[ e^{-2k|\vartheta|r(x)} (\partial_\vartheta B_\mu(x, \vartheta) - \partial_\mu b(x)) \right] = 0. \tag{A.11}
\]
The solution is
\[
e^{-2k|\vartheta|r(x)} (\partial_\vartheta B_\mu(x, \vartheta) - \partial_\mu b(x)) = c_\mu(x) \tag{A.12}\]
where \( c_\mu(x) \) is independent of \( \vartheta \). The function \( c_\mu(x) \) is determined by demanding the periodicity of \( B_\mu \) in \( \vartheta \):
\[
c_\mu(x) = -2\pi kr(x) \frac{\partial_\mu b(x)}{e^{2\pi kr(x)} - 1}. \tag{A.13}
\]

We now substitute this back into the action using the result for the graviphoton field strength
\[
C_{\vartheta\mu}(x, \vartheta) = e^{+2k|\vartheta|r(x)} c_\mu(x). \tag{A.14}
\]

In this way, we obtain
\[
\Delta S_{4, \text{eff}} = -2\pi^2 M_5^3 k \int d^4 x \sqrt{-g} \frac{\partial^\mu b \partial_\mu b}{e^{2\pi kr} - 1}. \tag{A.15}
\]

### A.4 The Radion Supermultiplet

We have derived the low-energy effective theory in terms of \( r(x) \) and \( g_{\mu\nu}(x) \) (defined by Eq. (A.6)) and \( b(x) \) (defined by Eq. (A.9)). In a manifestly supersymmetric
description, these degrees of freedom can be parameterized by a $\mathcal{N} = 1$ supergravity multiplet and a chiral superfield $T$. We wish to find the relation between the fields $g_{\mu\nu}(x)$, $r(x)$, and $b(x)$, and the components of the supermultiplets in an off-shell supersymmetric formulation. To do this it is useful to couple the 5-dimensional theory to various probes, and track how these probes appear in the 4-dimensional effective action. Matching the component and manifestly supersymmetric forms of the 4-dimensional action gives the relation between the component fields and superfields.

We first couple the SUGRA theory to a bulk SYM multiplet. The additional massless bosonic fields in the 4-dimensional effective theory are then the gauge field $A_\mu$ and an adjoint scalar $\Phi$. Because these both transform in the adjoint representation of the gauge group, there is no possibility of mixing between the gauge and gravitational modes in the 4-dimensional effective theory. The SYM zero modes form a 4-dimensional $\mathcal{N} = 1$ SYM multiplet. The vector zero mode is given by

$$A_{\mu}(x, \vartheta) = a_{\mu}(x).$$  \hspace{1cm} (A.16)

The fact that the zero mode is independent of the warp factor is due to the classical conformal invariance of Yang–Mills theory.

In the 4-dimensional theory effective theory, the gauge kinetic term can be written in the manifestly supersymmetric form

$$\Delta \mathcal{L}_{4,\text{eff}} = \int d^2\theta \ S(T) \ \text{tr}(W^\alpha W_\alpha) + \text{h.c.},$$  \hspace{1cm} (A.17)

where $S(T)$ is holomorphic. We will make a holomorphic field redefinition $S(T) \to T/g_5^2$ so that the action becomes

$$\Delta \mathcal{L}_{4,\text{eff}} = \int d^2\theta \ \frac{T}{g_5^2} \ \text{tr}(W^\alpha W_\alpha) + \text{h.c.}$$  \hspace{1cm} (A.18)

Expanding this in components, we see that

$$\frac{T}{g_5^2} = \frac{1}{2g_4^2} + \frac{i\Theta}{16\pi^2} + \cdots$$  \hspace{1cm} (A.19)

where $g_4$ is the gauge coupling and $\Theta$ is the gauge theta angle. Substituting Eqs. (A.6) and (A.16) into the 5-dimensional SYM action and integrating over $\vartheta$ gives

$$\frac{1}{g_4^2} = \frac{2\pi r}{g_5^2},$$  \hspace{1cm} (A.20)

which yields

$$\text{Re}(T) = \pi r.$$

(A.21)
The gauge theta angle gets a contribution from the graviphoton from the 5-dimensional SUGRA coupling \cite{17}

$$\Delta L_5 = -\frac{1}{2\sqrt{6}g_5^2}\epsilon^{MNPQR}B_M \text{tr} F_N F_{QR},$$

which gives

$$\frac{\Theta}{16\pi^2} = \frac{2\pi}{\sqrt{6}} b.$$ (A.23)

We therefore obtain

$$\text{Im}(T) = \frac{2\pi}{\sqrt{6}} b.$$ (A.24)

A.5 Supersymmetry and Weyl Rescaling

At two derivative order, the most general locally $\mathcal{N} = 1$ supersymmetric lagrangian for the radion chiral multiplet $T$ can be written

$$L_{\text{SUGRA},4} = \int d^4\theta \phi^\dagger \phi f(T, T^\dagger)$$

$$= \sqrt{-g} \left[ -\frac{1}{6} f R(g) - \frac{1}{4f} \tilde{g}^{\mu\nu} (f_T \partial_\mu T - \text{h.c.}) (f_T \partial_\nu T - \text{h.c.}) 
- f_T \tilde{g}^{\mu\nu} \partial_\mu T \partial_\nu T + \text{fermion terms} \right].$$ (A.26)

Note that the metric $\tilde{g}_{\mu\nu}$ that appears here is not assumed to be the same as the metric $g_{\mu\nu}$ introduced above. The most general relation between them compatible with general coordinate invariance is

$$\tilde{g}_{\mu\nu} = h(r, b) g_{\mu\nu}.$$ (A.27)

The function $h$ is not well-defined until we completely fix the definition of $\tilde{g}_{\mu\nu}$ in the manifestly supersymmetric theory. We do this by considering a probe consisting of a superpotential term $\int d^2\theta J$ localized on the hidden brane at $\vartheta = 0$. In the 4-dimensional effective theory, this gives rise to

$$\Delta L_{4,\text{eff}} = \int d^2\theta \phi^3 \ell(T) J + \text{h.c.}$$ (A.28)

where $\phi$ is the conformal compensator and $\ell(T)$ is holomorphic.

\footnote{By 4-dimensional parity, $h$ must be an even function of $b$.}
We can now make a field redefinition to set $\ell(T) \equiv 1$. This can be done by means of a Kähler transformation. In the superconformal formalism, this is a redefinition of the conformal compensator

$$
\phi' = [\ell(T)]^{1/3} \phi
$$

that is made prior to fixing the superconformal gauge Eq. (3.5). That is, we break the superconformal invariance by the choice

$$
\phi' = 1 + \theta^2 F'\phi.
$$

Note that since the gauge kinetic term is classically scale invariant, it is independent of $\phi$. Therefore this does not affect the field definition made in Eq. (A.18). In components, this field redefinition involves a Weyl rescaling of the metric $\bar{g}_{\mu\nu}$, and fixes its definition completely.

With this choice, we now compare the effective action for the brane superpotential to what is obtained by substituting the metric Eq. (A.6) into the component form. In the supersymmetric form, the brane action is independent of $T$, and in the component form it is independent of $r, b$. This can only be the case if

$$
\bar{g}_{\mu\nu} = g_{\mu\nu}.
$$

Having established this, we can read off the function $f$ from Eq. (A.8). Note that the graviphoton Aharonov–Bohm phase does not contribute to the coefficient of $R(g)$ in the effective action. Therefore,

$$
f = \frac{3 M_5^2}{k} \left( e^{-\pi k (T + T^\dagger)} - 1 \right). \tag{A.32}
$$

Having determined $f$, the remaining terms in Eq. (A.26) are fixed. With the identification of $T$ in Eqs. (A.21) and (A.24), we have checked that these terms agree with the direct component calculation of the $(\partial r)^2$ and $(\partial b)^2$ terms. In particular, both the nontrivial functional form and the coefficient of the graviphoton kinetic term Eq. (A.15) agree with Eq. (A.26) with $f$ given by Eq. (A.32).

### A.6 Brane Couplings

We now consider arbitrary couplings localized on the hidden brane. In the 4-dimensional effective theory, local $\mathcal{N} = 1$ SUSY implies that these take the form

$$
\mathcal{L}_{4,\text{hid}} = \int d^4 \theta \phi^+ \phi f_{\text{hid}}(\Sigma, \Sigma^\dagger, T, T^\dagger) \\
+ \int d^2 \theta \left[ S_{\text{hid}}(\Sigma, T) \text{tr}(W^\alpha W_\alpha) + \phi^3 \mathcal{W}_{\text{hid}}(\Sigma, T) \right] + \text{h.c.} \tag{A.33}
$$
In the coordinates we have chosen, the induced metric on the hidden brane is independent of $r$ (see Eq. (A.6)). Therefore, by locality $\mathcal{L}_{4,\text{hid}}$ is independent of $r$. Since $S_{\text{hid}}$ and $W_{\text{hid}}$ are holomorphic, this immediately implies that they are independent of $T$. For the non-holomorphic function $f_{\text{hid}}$, the argument requires a few steps. Because there are no derivative couplings involving $r$, we have

$$f_{\text{hid}} = c \cdot (T - T^\dagger) + \text{independent of } T,$$

where $c$ is a constant. Because the 4-dimensional Planck scale is independent of the Aharonov-Bohm phase $b_0$, we have $c = 0$. Therefore, $f_{\text{hid}}$ is also independent of $T$, and we have

$$\mathcal{L}_{4,\text{hid}} = \int d^4\theta \phi^\dagger \phi f_{\text{hid}}(\Sigma, \Sigma^\dagger) + \int d^2\theta \left[ S_{\text{hid}}(\Sigma) \text{ tr}(W'^\alpha W'^\alpha) + \phi^3 W_{\text{hid}}(\Sigma) \right] + \text{h.c.}$$

(A.35)

For couplings localized on the visible brane, the induced metric is $e^{-2\pi kr(x)}g_{\mu\nu}(x)$, and the couplings localized on the visible brane will depend on $T$. Using arguments similar to those above, it is easy to see that the result is

$$\mathcal{L}_{4,\text{vis}} = \int d^4\theta \phi^\dagger \phi e^{-k(T+T^\dagger)} f_{\text{vis}}(Q, Q^\dagger) + \int d^2\theta \left[ S_{\text{vis}}(Q) \text{ tr} \tilde{W}^\alpha \tilde{W}_\alpha + \phi^3 e^{-3kT} W_{\text{vis}}(Q) \right] + \text{h.c.},$$

(A.36)

Summarizing, the full 4-dimensional effective lagrangian is the sum of Eqs. (A.25), (A.35), and (A.36).

**References**

[1] L. Randall, R. Sundrum, *Phys. Rev. Lett.* **83** (1999) 3370, hep-ph/9905221.

[2] L. Randall, R. Sundrum, *Phys. Rev. Lett.* **83** (1999) 4690, hep-th/9906064.

[3] H. Verlinde, *Nucl. Phys.* **B580** (2000) 264, hep-th/9906182; K. Dasgupta, G. Rajesh, S. Sethi, *JHEP* **9908** (1999) 023, hep-th/9908088; B.R. Greene, K. Schalm, G. Shiu, *Nucl. Phys.* **B584** (2000) 480, hep-th/0004103; C.S. Chan, P.L. Paul, H. Verlinde, *Nucl. Phys.* **B581** (2000) 156, hep-th/0003236; K. Becker, M. Becker, hep-th/0010282.
[4] J. Maldacena, Adv. Theor. Math. Phys. 2 (1998) 231, hep-th/9711200; S.S. Gubser, I.R. Klebanov, A.M. Polyakov, Phys. Lett. B428 (1998) 105, hep-th/9802109; E. Witten, Adv. Theor. Math. Phys. 2 (1998) 253, hep-th/9802150; O. Aharony, S.S. Gubser, J. Maldacena, H. Ooguri, Y. Oz, Phys. Rept. 323 (2000) 183, hep-th/9905111.

[5] H. Verlinde, Nucl. Phys. B580 (2000) 264, hep-th/9906182; O. DeWolfe, D.Z. Freedman, S.S. Gubser, A. Karch, Phys. Rev. D62 (2000) 046008, hep-th/9909134; S.S. Gubser, hep-th/9912001; J. de Boer, E. Verlinde, H. Verlinde, JHEP 0008 (2000) 003, hep-th/9912012; M.J. Duff, J.T. Liu, Phys. Rev. Lett. 85 (2000) 2052, hep-th/0003237; M. Cvetic, H. Lu, C.N. Pope, hep-th/0007209.

[6] P. Hořava, E. Witten, Nucl. Phys. B460 (1996) 506; E. Witten, Nucl. Phys. B471 (1996) 135; P. Hořava, E. Witten, Nucl. Phys. B475 (1996) 94; P. Hořava, Phys. Rev. D54 (1996) 7561.

[7] I. Antoniadis, M. Quiros, Nucl. Phys. B505 (1997) 109; Z. Lalak, S. Thomas, Nucl. Phys. B515 (1998) 55; E. Dudas, Phys. Lett. B416 (1998) 309; A. Lukas, B.A. Ovrut, D. Waldram, Nucl. Phys. B532 (1998) 43; K. Choi, H.B. Kim, C. Muñoz, Phys. Rev. D57 (1998) 7521; T. Banks, M. Dine, Nucl. Phys. B479 (1996) 173; A. Lukas, B.A. Ovrut, K.S. Stelle, D. Waldram, Phys. Rev. D59 (1999) 086001; H.P. Nilles, M. Olechowski, M. Yamaguchi, Nucl. Phys. B530 (1998) 43; K. Choi, H. B. Kim, H. D. Kim, Mod. Phys. Lett. A14 (1999) 125; A. Lukas, B.A. Ovrut, K.S. Stelle, D. Waldram, Nucl. Phys. B552 (1999) 246; J. Ellis, Z. Lalak, S. Pokorski, W. Pokorski, Nucl. Phys. B540 (1999) 149.

[8] T. Gherghetta, A. Pomarol, Nucl. Phys. B586 (2000) 141, hep-ph/0003129; A. Pomarol, Phys. Rev. Lett. 85 (2000) 4004, hep-ph/0005293.

[9] L. Randall, R. Sundrum, Nucl. Phys. B557 (1999) 79, hep-th/9810155; G.F. Giudice, M.A. Luty, H. Murayama, R. Rattazzi, JHEP 9812 (1998) 027, hep-ph/9810442.

[10] D.E. Kaplan, G.D. Kribs, M. Schmaltz, Phys. Rev. D62 (2000) 035010, hep-ph/9911293; Z. Chacko, M.A. Luty, A.E. Nelson, E. Pontón, JHEP 0001 (2000) 003, hep-ph/9911323.

[11] Z. Chacko, M.A. Luty, hep-ph/0008103.

[12] M. Cvetic, H. Lu, C.N. Pope, hep-th/0002054; R. Altendorfer, J. Bagger, D. Nemeschansky, hep-th/0003117; T. Gherghetta, A. Pomarol, hep-ph/0003129;
N. Alonso-Alberca, P. Meessen, T. Ortin, *Phys. Lett.* **B482** (2000) 400, hep-th/0003248; A. Falkowski, Z. Lalak, S. Pokorski, hep-th/0004093; E. Bergshoef, R. Kallosh, A. Van Proeyen, JHEP 0010 (2000) 033, hep-th/0007044; M. Zucker, hep-th/0009083; H. Nishino, S. Rajpoot, hep-th/0011066.

[13] M.A. Luty, R. Sundrum, *Phys. Rev.* **D62** (2000) 035008, hep-th/9910202.

[14] W.D. Goldberger, M.B. Wise, *Phys. Rev. Lett.* **83** (1999) 4922, hep-ph/9907447.

[15] M. Dine, N. Seiberg, *Phys. Lett.* **162B** (1985) 299; T.R. Taylor, *Phys. Lett.* **B252** (1990) 59; V. Kaplunovsky, J. Louis, *Phys. Lett.* **B417** (1998) 45, hep-th/9708049; M. Dine, Y. Nir, Y. Shadmi, *Phys. Lett.* **B438** (1998) 61, hep-th/9806124; T. Banks, M. Dine, A. Nelson, *JHEP* **9906** (1999) 014, hep-th/9903019; M. Dine, Y. Shirman, hep-th/9906246.

[16] E. Cremmer in *Cambridge 1980 Proceedings: Superspace and Supergravity*, eds. S.W. Hawking, M. Roček (Cambridge University Press, 1981) 267; A.H. Chamseddine, H. Nicolai, *Phys. Lett.* **96B** (1980) 89.

[17] M. Günyaydin, G. Sierra, P.K. Townsend, *Nucl. Phys.* **B242** (1984) 244; *Nucl. Phys.* B253 (1985) 573.

[18] M. Zucker, hep-th/0009083.

[19] E.A. Mirabelli, M.E. Peskin, *Phys. Rev.* **D58** (1998) 065002.

[20] T. Kugo, K. Ohashi, hep-ph/0010288.

[21] C. Charmousis, R. Gregory, V.A. Rubakov, *Phys. Rev.* **D62** (2000) 067505, hep-th/9912160.

[22] S. Ferrara, P. van Nieuwenhuizen, *Phys. Lett.* **76B** (1978) 404; K.S. Stelle, P.C. West, *Nucl. Phys.* **B145** (1978) 175; E. Cremmer, S. Ferrara, L. Girardello, A. Van Proeyen, *Nucl. Phys.* **B212** (1983) 413.

[23] W. Siegel, S.J. Gates, Jr., *Nucl. Phys.* **B147** (1979) 77.