Open String Dynamics in Warped Backgrounds

Gary Shiu
University of Wisconsin
Based on:

- Marchesano, McGuirk, GS, 0812.2247
- Chen, Nakayama, GS, 0905.4463
- McGuirk, GS, Sumitomo, in progress

See also:

- GS, Torroba, Underwood, Douglas, 0803.3068
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Compensators and Warping

\[ \delta G_{\mu}^\nu = \delta I^{\nu} u^I \left\{ e^{2A} \left[ -2n^2 A + 4(nA)^2 - \frac{1}{2} R \right] \right\} + e^{-2A} \left( \partial^{\mu} \partial_{\nu} u^I - \delta^{\mu}_{\nu} \partial^I \right) \left( 4 \delta_I A - \frac{1}{2} \delta_I g^I \right) + \left( \partial^{\mu} \partial_{\nu} u^I - \delta^{\mu}_{\nu} \partial^I \right) e^{2A} g^{\nu} \left( B_{1p} - \partial_{\nu} K_I \right) \\
+ e^{-2A} f^{\nu} K \delta^{\nu} G_{\nu}^{(4)\mu} - \frac{1}{2} \left( \delta K g^{\mu}_{\nu} - \delta_{\nu}^{\mu} \delta_{\nu} K \right) e^{2A} \bar{\omega}^2 f^K, \]
(A.14)

\[ \delta G_{\mu}^\nu = \delta R_{mn}^{\mu} = e^{-2A} \partial^{\mu} u^I \left\{ 2 \partial_n \delta_I A - 8 \partial_n A \delta_I A - \frac{1}{2} \partial_n \delta_I g^I + \partial_n \delta_I \tilde{g}^I \tilde{g}^I - 2 \tilde{g}^I \partial_I \tilde{g}^I m_{np} \\
- \frac{1}{2} \bar{\nabla} p e^{2A} \left( \bar{\nabla}_p B_{1m} - \bar{\nabla}_m B_{1p} \right) + 2 \left( \partial_m A \partial_I B_{1p} - \partial_{\nu} A \partial_m \partial_{1p} \right) \bar{\nabla}_p e^{2A} \\
+ \frac{1}{2} e^{2A} \partial_I B_{1m} \bar{\nabla}^2 - 4 A \partial^I \tilde{g}^I B_{1m} \right\}, \]
(A.15)

\[ \delta R_{mn}^{\mu} = u^I \delta I \left\{ e^{2A} \left[ G_n^m + 4(nA)^2 \delta_n^m - 8 \nabla_n A \tilde{g}^m \right] \right\} - \frac{1}{2} e^{-2A} u^I \delta_I g^{mn} \delta_I \tilde{g}^{m} \\
+ \frac{1}{2} e^{-2A} \left( 2 \nabla^I - \frac{1}{2} \delta_I \tilde{g}^I \right) \\
\left\{ \frac{1}{2} \bar{\nabla} p e^{2A} \left[ \bar{\nabla}^m \left( e^{2A} \left( B_{1m} - \partial_n K_I \right) \right) \right] + \nabla_n \left[ e^{2A} \left( B_{1m} - \partial_n K_I \right) \right] \\
- \delta_n \nabla_p \left[ e^{2A} \left( B_{1m} - \partial_n K_I \right) \right] \right\} \\
\left\{ \frac{1}{2} \delta K g^{\mu}_{\nu} \left[ \frac{1}{2} e^{-2A} \bar{\nabla}^m \left( e^{2A} \partial_m f^K \right) + \nabla_n \left( e^{2A} \partial^m f^K \right) \right] + \delta^{\mu}_{\nu} \nabla_p \left[ e^{2A} \partial_p f^K \right] \right\} \\
- \frac{1}{2} e^{2A} \delta_n f^K e^{-2A} \delta K \bar{R}^{(4)}. \]
(A.16)

\[ \delta G_M^M = \kappa^{2}_{10} \delta T^M_N \]

\[ \delta T_{\mu}^\nu = - \delta_{\nu}^\mu \frac{1}{4 \kappa_{10}} \left\{ u^I \delta_I \left[ e^{-6A} (\bar{\nabla}^\alpha)^2 \right] - 2 e^{-6A} \left[ \partial_{\mu} S_{1m} \partial^m \tilde{g}^\alpha - 2 \bar{\nabla}^I K_I e^{-6A} (\bar{\nabla}^\alpha)^2 \right] \right\}, \]
(A.37)

\[ \delta T_{\mu}^\nu = \frac{1}{2 \kappa_{10}} \partial^\nu u^I \left[ e^{-6A} [\partial_m S_{1p} - \partial_p S_{1m} + \partial_m A B_{1p} - \partial_p A B_{1m} \partial^m t \partial^\alpha \right], \]
(A.38)

\[ \delta T_{\mu}^n = - \frac{1}{2 \kappa_{10}} u^I \delta_I \left\{ e^{-6A} \left[ \partial_{\alpha} \partial^{\alpha} - \frac{1}{2} \delta_{\alpha}^{\alpha} (\bar{\nabla}^\alpha)^2 \right] \right\} \\
+ \frac{e^{-6A}}{2 \kappa_{10}} \left\{ S_{1n} \partial^\alpha \partial^m - \delta_{\alpha}^{\alpha} S_{1n} \partial^{\alpha} + 2 K_I \left[ \partial_{\alpha} \partial^{\alpha} - \frac{1}{2} \delta_{\alpha}^{\alpha} (\bar{\nabla}^\alpha)^2 \right] \right\}. \]
(A.39)
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The Ubiquitous Throat

IR  AdS$_5$  UV
The Ubiquitous Throat

Cosmology
Inflation, sequestered DM, ...

see Langlois, McAllister’s talks

String Theory
Moduli stabilization
AdS/CFT, ...

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Warped Extra Dimensions
e.g., Randall-Sundrum

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Holographic gauge mediation:
e.g., Benini, Dymarsky, Franco, Kachru, Simic, Verlinde
McGuirk, GS, Sumitomo
(in progress)
sensitive to dimension 6, Planck suppressed corrections:

\[ \delta V \sim \frac{V}{M_P^2} \phi^2 \quad \eta \equiv M_P^2 \frac{V''}{V} \sim \mathcal{O}(1) \]

such corrections may come from the Kahler potential which is not protected by holomorphism.
In *gravity mediation*, soft terms are generated by Planck suppressed operators:

\[ m_0 \sim m_{1/2} \sim m_{3/2} \sim \frac{\langle F \rangle}{M_P} \]

Issue of FCNC can only be addressed with knowledge of UV physics.

Again, the *Kahler potential* comes into play.
Warping Corrections

In addition to $g_s$ and $\alpha'$, yet another correction:

For example: N D3-branes

Warp Factor:

$$Z \equiv e^{-4A} = 1 + \frac{g_s N \alpha'^2}{r^4}$$

Warping corrections can be important even for small $g_s$ & $\alpha'$
Warped Closed Strings

**Question:**

What is the effect of warping in string models?
Warped Closed Strings

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* One can quantify such effect in terms of a modified 4D EFT, including a “warped Kähler potential” $K^w$
Warped Closed Strings

Question:

What is the effect of warping in string models?

- One can quantify such effect in terms of a modified 4D EFT, including a “warped Kähler potential” $K^w$.

- Closed string/gravity sector:
  - Many subtle issues
  - Simple expressions for certain subsectors (universal Kähler modulus)

References:
- Giddings and Maharana’05
- Burgess, Câmara, de Alwis, Giddings, Maharana, Quevedo’06
- GS, Torroba, Underwood, Douglas’08
- Douglas, Torroba’08
- Frey, Torroba, Underwood, Douglas’08
- Chen, Nakayama, GS’09
Warped Open Strings

- Open string/gauge sector of the theory: $K^w$ unexplored
- Many immediate applications to particle physics & cosmology

**D-brane Inflation**

D3-moduli
Chen, Nakayama, GS

**Warped Extra Dimensions**

D7-moduli
Marchesano, McGuirk, GS
Warped Extra Dimensions

Q: Are there new features when embedded in string theory?

Analogous ideas for F-theory, magnetized/intersecting branes, twisted tori, etc, see talks of Heckman, Marchesano, Kobayashi, Bourjaily, Camara, Ohki,...
Warped Open Strings

**Type IIB warped background:**

\[
ds_{10}^2 = \Delta^{-1/2} \eta_{\mu\nu} dx^\mu dx^\nu + \Delta^{1/2} e^\Phi \hat{g}_{mn} dy^m dy^n
\]

**Consistency requires:**

\[
F_5 = (1 + *_{10}) F_5^{\text{int}} \quad F_5^{\text{int}} = \ast_6 d \left( \Delta e^\Phi \right)
\]

D7-branes wrap $S_4 \subset X_6$
Warped Open Strings

Compute the open string wavefunctions in a warped background

Deduce the open string Kähler potential

D7-branes wrap $S_4 \subset X_6$
Introduce a probe D7-brane in this background, see how its internal fluctuations are affected by the presence of Z and F_5.
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Our results will be generalized later to warped Calabi-Yau and backgrounds with other SUGRA and/or worldvolume fluxes.
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Our results will be generalized later to warped Calabi-Yau and backgrounds with other SUGRA and/or worldvolume fluxes.

Q: How do the D7 wavefunctions couple to $F_5$?
D7-brane action

- **Bosonic action**
  \[ S_{D7}^{bos} = S_{D7}^{DBI} + S_{D7}^{CS} \]

- **Fermionic action**
  \[ S_{D7}^{fer} = \tau_{D7} \int d^8\xi \ e^\Phi \sqrt{\det G} \ \bar{\Theta} \ P_{D7}^{\alpha} \left( \Gamma^\alpha D_\alpha + \frac{1}{2} \mathcal{O} \right) \Theta \]

See also Graña’02, Marolf, Martucci, Silva’03
D7-brane action

**Bosonic action**

\[ S_{D7}^{\text{bos}} = S_{D7}^{\text{DBI}} + S_{D7}^{\text{CS}} \]

**Fermionic action**

\[ S_{D7}^{\text{fer}} = \tau_{D7} \int d^8 \xi \, e^{\Phi} \sqrt{|\det G|} \, \bar{\Theta} \, P_{D7}^{\pm} \left( \Gamma^\alpha D_\alpha + \frac{1}{2} \mathcal{O} \right) \Theta \]

\[ \Theta = \begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix} \]

10D MW bispinor (type IIB superspace)

\[ P_{D7}^{\pm} = \frac{1}{2} \left( \mathbb{I} \mp \Gamma_{8D} \otimes \sigma_2 \right) \]

halves the dof’s down to \( \mathcal{N}=1 \) 8D SYM

\[
\delta_{\epsilon} \psi_M = \mathcal{D}_M \epsilon \\
\delta_{\epsilon} \lambda = \mathcal{O}_\epsilon
\]

type IIB gravitino variation

type IIB dilatino variation

(contain \( F_p \))

Contains the coupling of fermions to RR fluxes
D7-brane action

- **Bosonic action**
  \[ S_{D7}^{\text{bos}} = S_{D7}^{\text{DBI}} + S_{D7}^{\text{CS}} \]

- **Fermionic action**
  \[ S_{D7}^{\text{fer}} = \tau_{D7} \int d^8\xi \, e^\Phi \sqrt{|\det G|} \, \tilde{\Theta} \, P_{D7}^{-} \left( \Gamma^\alpha \mathcal{D}_\alpha + \frac{1}{2} \mathcal{O} \right) \Theta \]

  \( \Theta = \begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix} \) 10D MW bispinor (type IIB superspace)

  \( P_{D7}^{\pm} = \frac{1}{2} (\mathbb{I} \mp \Gamma_{8D} \otimes \sigma_2) \) halves the dof’s down to \( \mathcal{N}=1 \) 8D SYM

  **\( \kappa \)-symmetry**
  \[ \Theta \rightarrow \Theta + P_{D7}^{D7} \kappa \]

  **Convenient choices:**
  \[ \Theta = \begin{pmatrix} \theta \\ 0 \end{pmatrix} \] or \[ P_{D7}^{D7} \Theta = 0 \]
D7-brane action

*In warped flat space:*

\[ \mathcal{O} = 0 \]

\[ \mathcal{D}_M = \nabla_M + \frac{1}{8} F_5^{\text{int}} \Gamma_M i \sigma_2 \]

*The D7-brane sees the warped metric*

\[ ds_{D7}^2 = Z^{1/2} \eta_{\mu\nu} dx^\mu dx^\nu + Z^{-1/2} \sum_{a,b=4}^7 \delta_{ab} dy^a dy^b \]
**D7-brane action**

- **In warped flat space:**
  \[
  \mathcal{O} = 0 \\
  \mathcal{D}_M = \nabla_M + \frac{1}{8} F_5^{\text{int}} \Gamma_M i \sigma_2
  \]

- The D7-brane sees the warped metric
  \[
  ds^2_{D7} = Z^{-1/2} \eta_{\mu \nu} dx^\mu dx^\nu + Z^{1/2} \sum_{a,b=4} \delta_{ab} dy^a dy^b
  \]

- **\( \kappa \)-fixing** \( \Theta = \begin{pmatrix} \theta \\ 0 \end{pmatrix} \), the 8D Dirac action is given by

  \[
  S_{D7}^{\text{fer}} = \tau_{D7} e^\Phi_0 \int_{\mathbb{R}^{1,3}} d^4 x \int d^4 y \, \bar{\theta} \mathcal{D}^w \theta \\
  \mathcal{D}^w = \sum_{\mu} \Gamma^\mu \mathcal{D}_\mu + \sum_{a} \Gamma^a \mathcal{D}_a + \frac{1}{2} \mathcal{O} \\
  = \phi_4^{\text{ext}} + \phi_4^{\text{int}} - \frac{1}{8} \left( \phi_4^{\text{int}} \ln Z \right) (1 + 2 \Gamma_{\text{Extra}})
  \]
In warped flat space:

\[ \mathcal{O} = 0 \]

\[ \mathcal{D}_M = \nabla_M + \frac{1}{8} F_5^{\text{int}} \Gamma_M i \sigma_2 \]

The D7-brane sees the warped metric

\[ ds^2_{D7} = Z^{-1/2} \eta_{\mu \nu} dx^\mu dx^\nu + Z^{1/2} \sum_{a,b=4}^7 \delta_{ab} dy^a dy^b \]

\[ \kappa\text{-fixing } \Theta = \begin{pmatrix} \theta \\ 0 \end{pmatrix}, \text{ the 8D Dirac action is given by} \]

\[ S_{D7}^{\text{fer}} = \tau_{D7} e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4 x \int d^4 y \bar{\theta} \slashed{D}^w \theta \]

\[ \slashed{D}^w = \sum_{\mu} \Gamma^\mu \slashed{D}_\mu + \sum_{a} \Gamma^a \slashed{D}_a + \frac{1}{2} \mathcal{O} \]

\[ = \phi^\text{ext}_4 + \phi^\text{int}_4 - \frac{1}{8} \left( \phi^\text{int}_4 \ln Z \right) (1 + 2 \Gamma_{\text{Extra}}) \]
D7-brane zero modes

If one now decomposes the 10D MW spinor as

\[ \theta = \chi + B^* \chi^* \quad \chi = \theta_{4D} \otimes \theta_{6D} \]

and performs a KK reduction, the 4D mass eigenstate eq. is

\[
\left[ \phi^\text{int}_4 - \frac{1}{8} \left( \phi^\text{int}_4 \ln Z \right) (1 + 2 \Gamma_{\text{Extra}}) \right] \theta^0_{6D} = 0
\]
D7-brane zero modes

If one now decomposes the 10D MW spinor as

\[ \theta = \chi + B^* \chi^* \quad \chi = \theta_{4D} \otimes \theta_{6D} \quad \text{B: Majorana matrix} \]

and performs a KK reduction, the 4D mass eigenstate eq. is

\[
\left[ \varphi_{4}^{\text{int}} - \frac{1}{8} \left( \varphi_{4}^{\text{int}} \ln Z \right) (1 + 2 \Gamma_{\text{Extra}}) \right] \theta_{6D}^0 = 0
\]

and so the 4D zero modes are

\[
\theta_{6D}^0 = Z^{-1/8} \eta_- \quad \text{for} \quad \Gamma_{\text{Extra}} \eta_- = -\eta_-
\]
\[
\theta_{6D}^0 = Z^{3/8} \eta_+ \quad \text{for} \quad \Gamma_{\text{Extra}} \eta_+ = \eta_+
\]

in contrast to \( \theta_{6D}^0 = Z^{1/8} \eta \), the result in the absence of F_5

Acharya, Benini, Valandro '06
Upon dimensional red., such fermion zero modes

\[
\begin{align*}
\theta_{6D}^0 &= Z^{-1/8} \eta_- \\
\theta_{6D}^0 &= Z^{3/8} \eta_+ 
\end{align*}
\]

imply the following kinetic terms

\[
S_{D7}^{\text{fer}} = \tau_{D7} e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4 x \bar{\theta}_{4D} \bar{\phi}_{\mathbb{R}^{1,3}} \theta_{4D} \int d^4 y \eta_+^\dagger \eta_-
\]

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\]

that indeed match the kinetic terms of the bosonic zero modes (e.g., \( f_{D7} \sim \int Z + i C_4 \)). This allows to identify them in terms of their bosonic superpartners.
D7-brane zero modes

Upon dimensional red., such fermion zero modes

\[ \theta^0_{6D} = Z^{-1/8} \eta_- \]
\[ \theta^0_{6D} = Z^{3/8} \eta_+ \]

imply the following kinetic terms

\[ S^\text{fer}_{D7} = \tau_{D7} e^\Phi_0 \int_{\mathbb{R}^{1,3}} d^4 x \, \bar{\theta}_4 D \frac{1}{\theta_{R^{1,3}} \theta_{4D}} \int d^4 y \, \eta^\dagger \eta_- \]
\[ S^\text{fer}_{D7} = \tau_{D7} e^\Phi_0 \int_{\mathbb{R}^{1,3}} d^4 x \, \bar{\theta}_4 D \frac{1}{\theta_{R^{1,3}} \theta_{4D}} \int d^4 y \, Z \eta^\dagger \eta_+ \]

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\[
\begin{align*}
S^{\text{fer}}_{\text{D7}} &= \tau_{\text{D7}} e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4x \, \overline{\theta}_{4D} \overline{\Phi}_{\mathbb{R}^{1,3}} \theta_{4D} \quad \int d^4y \, \eta_-^\dagger \eta_-
\end{align*}
\]

that indeed match the kinetic terms of the bosonic zero modes (e.g., \( f_{\text{D7}} \sim \int Z + i C_4 \)). This allows to identify them in terms of their bosonic superpartners.
A subtlety

Our strategy to compute the zero modes appears to be:

\[ S_{D7}^{\text{fer}} = \int d^8 \xi \bar{\theta} \mathcal{D}^w \theta \rightarrow \mathcal{D}^w \theta^0 = 0 \]

For a 10D MW spinor, θ and \( \bar{\theta} \) cannot be varied independently.

For example:

\[ \tau_{D7} \int d^8 \xi \bar{\theta} \Gamma^\alpha \partial_\alpha \theta \quad \text{and} \quad \tau_{D7} \int d^8 \xi \bar{\theta} \Gamma^\alpha (\partial_\alpha - \partial_\alpha \ln f) \theta \]

both give \( \Gamma^\alpha \partial_\alpha \theta = 0 \) since \( \bar{\theta} \Gamma^{a_1 \ldots a_n} \theta \neq 0 \) only if \( n = 3, 7 \)

Naively, the warp factor dependence drops out in eom.

But a careful analysis gives:

\[ \delta S_{D7}^{\text{fer}} = \tau_{D7} e^{\Phi_0} \int d^8 \xi \bar{\theta} \mathcal{D}^w \theta + \bar{\theta} \mathcal{D}^w \delta \theta = 2 \tau_{D7} e^{\Phi_0} \int d^8 \xi \bar{\theta} \mathcal{D}^w \theta \]
A subtlety

Implicitly a choice of gauge is made in the D-brane fermionic action (choice of supercoord. system)

\[ P_{D7}^8 \left( \Gamma^\alpha D^E_\alpha + \frac{1}{2} \mathcal{O}^E \right) \Theta = 0 \]

The gauge choice should be consistent with the gauge choices in the bosonic sector. One can check this by dimensionally reducing the SUSY variations

\[ \delta_\epsilon A_{\alpha=\mu} = \bar{\epsilon} \Gamma_{\alpha=\mu} \theta \quad \rightarrow \quad \delta_\epsilon A_\mu = \bar{\epsilon} \lambda \]

ex: gauge boson

\[ Z^0 = Z^{-\frac{1}{8} - \frac{1}{4} + \frac{3}{8}} \]

No warp factor
Recap

- In general, the open string wavefunctions have an internal profile of the form
  \[ \psi_{\text{int}} = Z^p \eta, \quad \eta = \text{const.} \]

- Their kinetic terms group into 4D \( \mathcal{N}=1 \) multiplets
  \[ \int_{\mathbb{R}^{1,3}} d^4x \, \bar{\phi} D\phi \int d^4y Z^q \]
Recap

- In general, the open string wavefunctions have an internal profile of the form
  \[ \psi^{\text{int}} = Z^p \eta, \quad \eta = \text{const}. \]

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  \[ \int_{\mathbb{R}^{1,3}} d^4 x \bar{\phi} D\phi \int d^4 y Z^q \]

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<thead>
<tr>
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<tbody>
<tr>
<td>4D Field</td>
</tr>
<tr>
<td>gauge boson/modulus</td>
</tr>
<tr>
<td>gaugino/modulino</td>
</tr>
<tr>
<td>Wilson line</td>
</tr>
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<td>Wilsonino</td>
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Comparison to RS

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<tr>
<td></td>
<td>$p$</td>
<td>$q$</td>
</tr>
<tr>
<td>gauge boson</td>
<td>0</td>
<td>1/4</td>
</tr>
<tr>
<td>gaugino</td>
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<td></td>
</tr>
<tr>
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<td>$(1 - c)/2$</td>
</tr>
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<td></td>
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</table>

The table compares the warp factor dependence for internal wavefunctions and $K$-adS curvature for the RS scenario and the construction considered here. In RS, the gauge boson and gaugino come from a vector multiplet, while the matter scalar and fermion come from a hypermultiplet. The additional degrees of freedom from these supermultiplets are projected out by the orbifold action in RS. The wavefunctions in SUSY RS are worked out in conventions slightly different from theirs in that we take the ansatz for the matter fermion to be $\Psi_L, R_c x, dx, \psi_L, R_c y$ while RS uses a power of the warp factor in the decomposition. In the construction here, the supersymmetry algebra in $K$-adS 5 implies that component fields have different 5D masses. Unlike the flat space case, the supersymmetry algebra in $K$-adS implies that component fields have different 5D masses. The 5D gauge boson and gaugino come from a 5D vector supermultiplet. Gauge invariance requires that the 5D vector component is massless, while SUSY requires that the 5D gaugino has mass $\frac{1}{2} K$, where $K$ is the $K$-adS curvature. Similarly, the matter fields result from the reduction of a 5D hypermultiplet, the component fields of which each have a different mass. The differences between the RS scenario and string theory implementations of the scenario result in different behavior of the internal wavefunctions.
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\[ m_{5D \ bulk} \sim cK \]

- Planck brane
- IR brane
- H Yukawa couplings
- c > 1/2
- c < 1/2

\[ \frac{1}{2}, \frac{1}{2} \]

- gauge boson/modulus
- gaugino/modulino
- Wilson line
- Wilsonino

\[ \text{Comparison to RS} \]

\[ \text{4D Field} \quad p \quad q \]

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<td>gauge boson</td>
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</tr>
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Comparison to RS

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<th>D7</th>
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</tr>
<tr>
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</tr>
<tr>
<td>matter fermion</td>
<td>$(2 - c)/4$</td>
<td>$1 - c)/2$</td>
</tr>
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\[ m_{5D \text{ bulk}} \sim cK \]

\[ c > 1/2 \quad c < 1/2 \]

\[ H \text{ Yukawa couplings} \]

\[ \bullet \quad 5\text{-form fluxes} \]
Comparison to RS

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5-form fluxes

3-form fluxes
Comparison to RS

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$m_{5D \text{ bulk}} \sim cK$

- ♠ 5-form fluxes
- ♠ 3-form fluxes
- ♠ D7-brane worldvolume flux
Generalizations

The same is obtained if, instead of warped flat space, one considers a warped Calabi-Yau and a BPS D7-brane

\[ \psi^{\text{int}} = Z^p \eta, \quad \eta = \text{const.} \quad \rightarrow \quad \eta = \text{cov.const.} \]
The same is obtained if, instead of warped flat space, one considers a warped Calabi-Yau and a BPS D7-brane

\[ \psi^{\text{int}} = Z^p \eta, \quad \eta = \text{const.} \rightarrow \eta = \text{cov. const.} \]

In addition one may also consider type IIB backgrounds with $G_3$ fluxes, as well as with varying dilaton.
Finally, one can consider internally magnetized D7-branes, a necessary ingredient for 4D chirality in CY/F-theory models.
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Magnetized D7-branes

Finally, one can consider internally magnetized D7-branes, a necessary ingredient for 4D chirality in CY/F-theory models.

\[ e^{-\Phi_0/2} \mathcal{F} = B_i \text{dvol}(T^2)_i + B_j \text{dvol}(T^2)_j \]

\[ B_i = e^{-\Phi_0/2} Z^{-1/2} b_i \]

\[ \text{BPS} \iff b_i = -b_j \]

**Result:**

\[ \theta_{6D}^0 = \frac{Z^{-1/8}}{1 + i B_i \Gamma_{T^2_i}} \eta_- \]

\[ \theta_{6D}^0 = Z^{3/8} \eta_+ \]

**Wilsonian**

\[ \text{gaugino + modulino} \]

\[ \int d^4 y \eta_\dagger \eta_- \]

\[ \int d^4 y |Z^{1/2} + i e^{\Phi_0/2} b|^{2} \eta_\dagger \eta_+ \]
Warped EFT

* Is all this compatible with the closed string results?

* Let us consider a D7-brane wrapping a 4-cycle $S_4$ in a warped Calabi-Yau, and with $\mathcal{F} = 0$

* Gauge kinetic function:

$$ f_{D7} = (8\pi^3 k^2)^{-1} \int_{S_4} \frac{d\text{vol}_{S_4}}{\sqrt{\hat{g}_{S_4}}} \left( Z \sqrt{\hat{g}_{S_4}} + iC_4^{\text{int}} \right) \quad k = 2\pi\alpha' $$

→ Can be understood as a holomorphic function

Baumann, Dymarsky, Klebanov, Maldacena, McAllister, Murugan '06
Warped EFT

Is all this compatible with the closed string results?

Geometric moduli $\zeta^a \quad a = 1, \ldots, h^{(0,2)}(S_4)$

Unwarped kin. terms:

$$i\tau_D \int_{\mathbb{R}^{1,3}} e^\Phi \mathcal{L}_{AB} \ d\zeta^A \wedge *_4 d\bar{\zeta}^B$$

$$\mathcal{L}_{AB} = \frac{\int_{S_4} m_A \wedge m_{\bar{B}}}{\int_{X_6} \Omega_{CY} \wedge \bar{\Omega}_{CY}}$$

Couple to the dilaton as

$$S = t - \kappa_4^2 \tau_D \mathcal{L}_{AB} \zeta^A \zeta^B \quad \Rightarrow \quad \mathcal{K} \equiv \ln \left[ -i(S - \bar{S}) - 2i\kappa_4^2 \tau_D \mathcal{L}_{AB} \zeta^A \zeta^B \right]$$

see, e.g., Jockers and Louis '04
Warped EFT

Is all this compatible with the closed string results?

Geometric moduli \( \zeta^a \) \( a = 1, \ldots, h^{(0,2)}(S_4) \)

Warped kin. terms:

\[
i \tau_{D7} \int_{\mathbb{R}^{1,3}} e^\Phi \mathcal{L}_{A\bar{B}}^w \, d\zeta^A \wedge *_4 d\bar{\zeta}^\bar{B}
\]

\[
\mathcal{L}_{A\bar{B}} \rightarrow \mathcal{L}_{A\bar{B}}^w = \frac{\int_{S_4} \mathcal{Z} \, m_B \wedge \bar{m}_\bar{B}}{\int_{X_6} \mathcal{Z} \, \Omega_{CY}^2 \wedge \bar{\Omega}_{CY}^2}
\]

Suggest a coupling

\[
S^w = t - \kappa_4^2 \tau_{D7} \mathcal{L}_{A\bar{B}}^w \zeta^A \bar{\zeta}^\bar{B} \Rightarrow \mathcal{K} \supset \ln \left[ -i(S^w - \bar{S}^w) - 2i\kappa_4^2 \tau_{D7} \mathcal{L}_{A\bar{B}}^w \zeta^A \bar{\zeta}^\bar{B} \right]
\]

compatible with Shiu, Torroba, Underwood, Douglas '08
Warped EFT

Is all this **compatible** with the closed string results?

**Wilson line moduli** \( W^I \quad I = 1, \ldots, h^{(0,1)}(S_4) \)

Unwarped kin. terms:

\[
i \frac{2\kappa_D^2 k^2}{\mathcal{V}} \int_{\mathbb{R}^{1,3}} C^{I\bar{J}} v^\alpha d\omega_I \wedge *_4 d\bar{\omega}_{\bar{J}}
\]

Couple to Kähler moduli as

\[
T_\alpha + \bar{T}_\alpha = \frac{3}{2} \mathcal{K}_\alpha + 6i\kappa_4^2 \tau_{D7} k^2 C^{I\bar{J}} w_I w_{\bar{J}}
\]

\[
\mathcal{K}_\alpha = \mathcal{I}_{\alpha\beta\gamma} v^\beta v^\gamma
\]

\[
\mathcal{V} = \frac{1}{6} \mathcal{I}_{\alpha\beta\gamma} v^\alpha v^\beta v^\gamma
\]

see again Jockers and Louis '04
Warped EFT

Is all this compatible with the closed string results?

Wilson line moduli  \( W^I \quad I = 1, \ldots, h^{(0,1)}(S_4) \)

Warped kin. terms:

\[
i \frac{2 \tau_D k^2}{\cal V_w} \int_{\mathbb{R}^{1,3}} C^{I\bar{J}} v^\alpha dw_I \wedge \ast_4 d\bar{w}_\bar{J} \quad C^{I\bar{J}} = \int_{S_4} P[\omega_\alpha] \wedge W^I \wedge \bar{W}^{\bar{J}}
\]

\[
J_{CY} = v^\alpha \omega_\alpha
\]

Suggest the following def. for “warped Kähler modulus”

\[
T_w^\alpha + \overline{T}_\alpha^w = \frac{3}{2} I_{\alpha\beta\gamma} v^\beta v^\gamma + 6 i \kappa_4^2 \tau_D k^2 C^{I\bar{J}} w_I \bar{w}_\bar{J}
\]

\[
I_{\alpha\beta\gamma} = \int_{X^6} Z \omega_\alpha \wedge \omega_\beta \wedge \omega_\gamma \quad \Rightarrow \quad \mathcal{V}_w = \frac{1}{6} I_{\alpha\beta\gamma} v^\alpha v^\beta v^\gamma
\]
Warped EFT

* Is all this compatible with the closed string results?

* In addition, for a single Kähler modulus $\Lambda$ we have that

$$K = -3 \ln \left[ T^w_\Lambda + \bar{T}^w_\Lambda \right] \simeq -3 \ln \frac{V^w}{v^\Lambda}$$

the fluctuation of such modulus is

$$Z(x, y) = Z_0(y) + c(x)$$

Giddings and Maharana’05

$$\Rightarrow V^w(x) = V^w_0 + c(x)V_{CY} \Rightarrow K \simeq -3 \ln \left( c + \frac{V^w_0}{V_{CY}} \right) - 3 \ln \frac{V_{CY}}{v^\Lambda}$$

reproduces Frey, Torroba, Underwood, Douglas’08

Chen, Nakayama, Shiu, 09
Holographic SUSY Breaking

![Diagram showing D3 and D7 branes]

Via gauge/gravity duality, analyze strong dynamics from a weak coupling gravity dual!

However, using the backreacted $\overline{D3}$ background valid in large $r$ region:

DeWolfe, Kachru, Mulligan

one finds the leading gravity computation gives vanishing gaugino mass.

Benini, Dymarsky, Franco, Kachru, Simic, Verlinde
Holographic SUSY Breaking

Deformed Conifold: \[ \sum_{i=1}^{4} z_i^2 = \epsilon^2 \]

R-symmetry: \[ z_i \rightarrow e^{-i\alpha} z_i \quad \text{exact as} \quad \epsilon \rightarrow 0 \]
is broken to \( \mathbb{Z}_2 \) only in the IR.

Backreacted solution in the IR sources \((0,3)+(3,0)\) besides the \((1,2)+(2,1)\) fluxes already present in the UV.

Using gaugino wavefunction \( Z^{3/8} \eta_+ \)

Gaugino mass: \[ \mathbf{Tr}(\lambda^2) \left( G^3_{123} \right)^* \]

Gravitino mass: \[ m_{3/2} \sim \int \Omega \wedge G_3 \]

McGuirk, GS, Sumitomo, in progress

Marchesano, McGuirk, GS

c.f. Camara, Ibanez, Uranga
See also: Grana, Grimm, Jockers, Louis;
Lust, Reffert, Stieberger
Open+Closed String Fluctuations

Chen, Nakayama, GS

\[ P(g)_{\mu\nu} = e^{2A(Y,u)+2\Omega(u)} \{ \tilde{g}_{\mu\nu}(x) + 2\partial_\mu \partial_\nu u^I(x)K_I(Y) + 2B_{iI}(Y)\partial_\mu u^I(x)\partial_\nu Y^i \} + e^{-2A(Y,u)}\tilde{g}_{ij}(Y,u)\partial_\mu Y^i \partial_\nu Y^j. \]

suggests a convenient gauge B=0

Hamiltonian constraints:

\[ D^M \left( h^{-1/2}\pi_{M\alpha} \right) = 0, \]
\[ D^M (h^{-1/2}\pi_{Mi}) + \kappa_4^2 \delta^{(6)}(y-Y) P_i \sqrt{h} = 0. \]

Combined Kahler potential:

\[ \kappa_4^2 K(\rho, Y) = -3 \log \left[ \rho + \bar{\rho} - \gamma k(Y, \bar{Y}) + 2\frac{V_W^0}{V_{CY}} \right], \quad \gamma = \frac{T_3 \kappa_4^2}{3}, \]

where

\[ \rho = \left( c + \frac{\gamma}{2} k(Y, \bar{Y}) \right) + i\chi. \]

```
“breathing mode”
```

```
axion
```
Summary

- Effective action for warped compactifications is much needed in drawing *precise* predictions of such models.

- Many subtleties in deriving warped Kahler potential. Inclusion of open string moduli essential for several applications to warped string models of particle physics and cosmology.

- Computed open string wavefunctions in warped backgrounds, and extracted the *open string wEFT*. Results agree with closed string computation.

- Combined Kahler potential involving both D3 and universal Kahler modulus.
THANKS