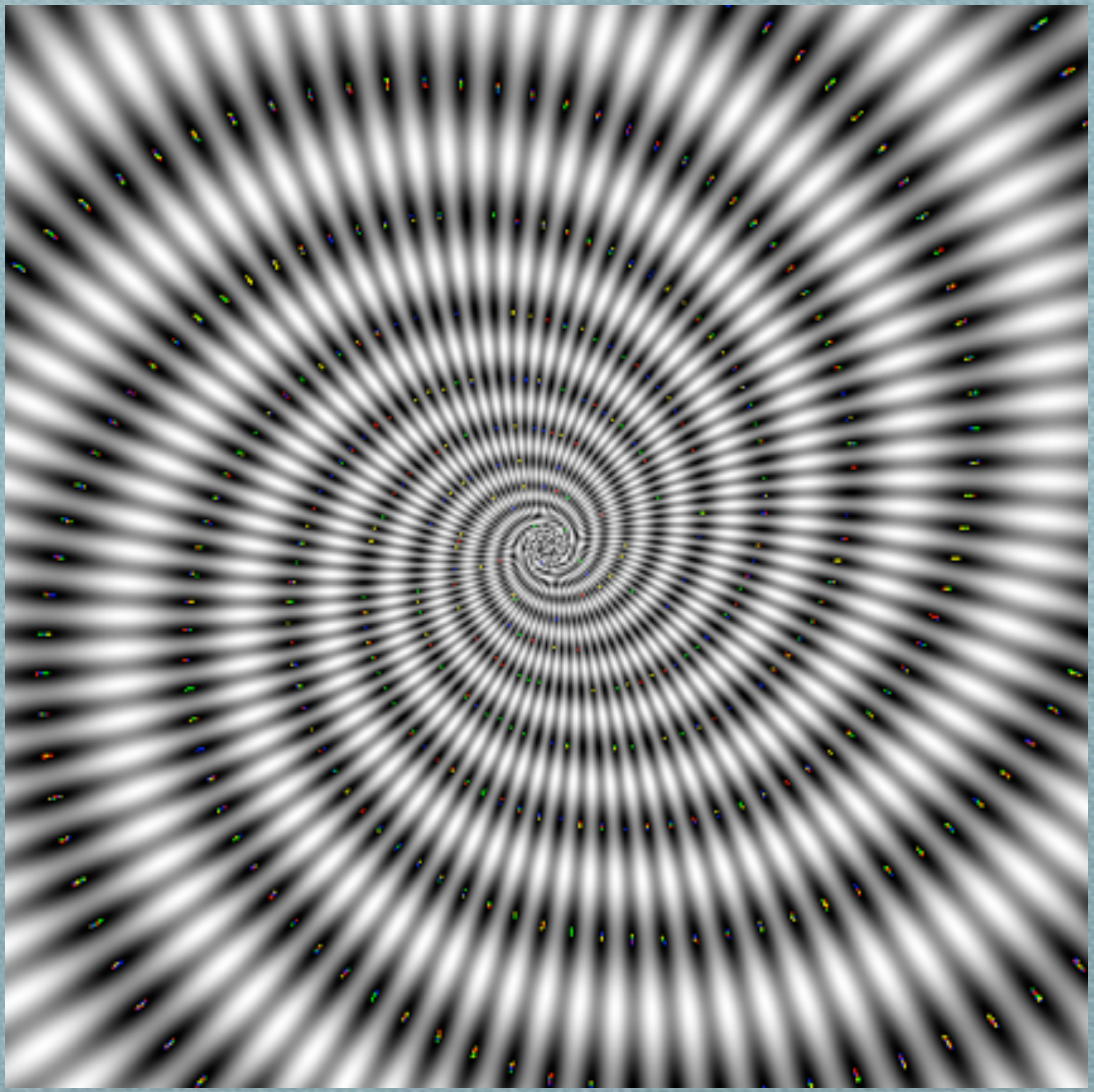 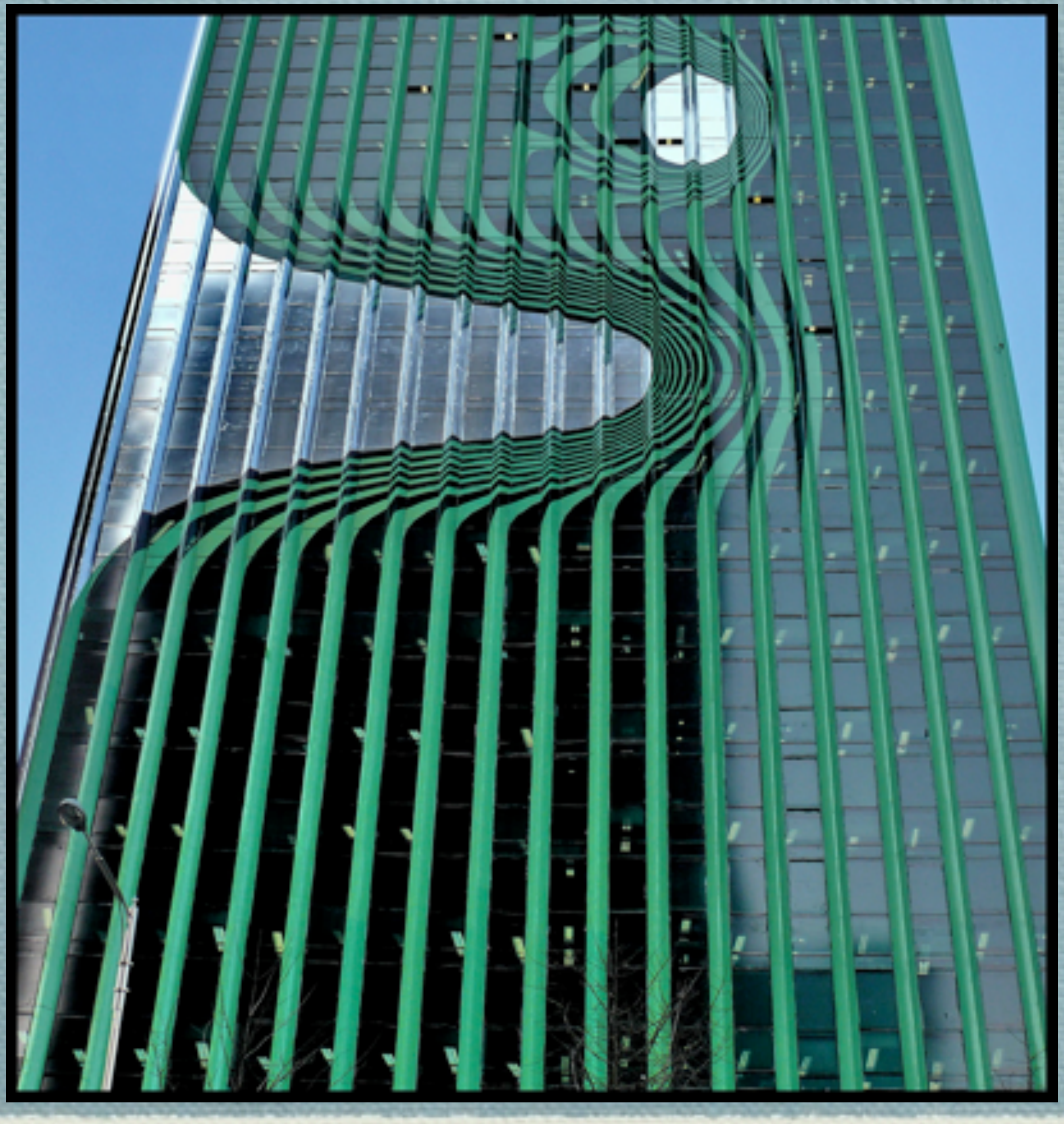

Open String Dynamics in Warped Backgrounds

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

$$
\begin{aligned}
\delta G^\mu_\nu =& \delta^\mu_\nu u^I \delta_I \left\{ e^{2A} \left[-2\tilde{\nabla}^2 A + 4(\widetilde{\nabla A})^2 - \frac{1}{2}\tilde{R} \right] \right\} + e^{-2A} \left(\partial^\mu \partial_\nu u^I - \delta^\mu_\nu \Box u^I \right) (4\delta_I A - \frac{1}{2}\delta_I \tilde{g}) \\
&+ \left(\partial^\mu \partial_\nu u^I - \delta^\mu_\nu \Box u^I \right) e^{2A} \tilde{\nabla}^p (B_{Ip} - \partial_p K_I) \\
&+ e^{-2A} f^K \delta_K G^{(4)\mu}_\nu - \frac{1}{2} \left(\delta_K g^\mu_\nu - \delta^\mu_\nu \delta_K g^\lambda_\lambda \right) e^{2A} \tilde{\nabla}^2 f^K \ ,
\end{aligned} \tag{A.14}
$$

$$
\begin{aligned}
\delta G^\mu_m = \delta R^\mu_m =& e^{-2A} \partial^\mu u^I \Bigg\{ 2\partial_m \delta_I A - 8\partial_m A \delta_I A - \frac{1}{2}\partial_m \delta_I \tilde{g} + \partial_m A \delta_I \tilde{g} \\
&- 2\partial^{\tilde{p}} A \delta_I \tilde{g}_{mp} + \frac{1}{2}\tilde{\nabla}^p \delta_I \tilde{g}_{mp} \\
&- \frac{1}{2}\tilde{\nabla}^p \left[e^{4A} \left(\tilde{\nabla}_p B_{Im} - \tilde{\nabla}_m B_{Ip} \right) \right] + 2(\partial_m A B_{Ip} - \partial_p A B_{Im}) \tilde{\nabla}^p e^{4A} \\
&+ \frac{1}{2} e^{8A} B_{Im} \tilde{\nabla}^2 e^{-4A} - e^{4A} \tilde{R}^n_m B_{In} \Bigg\} \ ,
\end{aligned} \tag{A.15}
$$

$$
\begin{aligned}
\delta G^m_n =& u^I \delta_I \left\{ e^{2A} \left[\tilde{G}^m_n + 4(\widetilde{\nabla A})^2 \delta^m_n - 8\nabla_n A \tilde{\nabla}^m A \right] \right\} - \frac{1}{2} e^{-2A} \Box u^I \tilde{g}^{mk} \delta_I \tilde{g}_{kn} \\
&+ \delta^m_n e^{-2A} \Box u^I (-2\delta_I A + \frac{1}{2}\delta_I \tilde{g}) \\
&\Box u^I \Bigg(\frac{1}{2} e^{-2A} \left\{ \tilde{\nabla}^m \left[e^{4A} \left(B_{In} - \partial_n K_I \right) \right] + \tilde{\nabla}_n \left[e^{4A} \left(B^{\tilde{m}}_I - \partial^{\tilde{m}} K_I \right) \right] \right\} \\
&- \delta^m_n \tilde{\nabla}^p \left[e^{2A} \left(B_{Ip} - \partial_p K_I \right) \right] \Bigg) \\
&+ \frac{1}{2} \delta_K g^\mu_\mu \left\{ -\frac{1}{2} e^{-2A} \left[\tilde{\nabla}^m \left(e^{4A} \partial_n f^K \right) + \tilde{\nabla}_n \left(e^{4A} \partial^{\tilde{m}} f^K \right) \right] + \delta^m_n \tilde{\nabla}^p \left[e^{2A} \partial_p f^K \right] \right\} \\
&- \frac{1}{2} \delta^m_n f^K e^{-2A} \delta_K R^{(4)} \ .
\end{aligned} \tag{A.16}
$$

$$
\delta T^\mu_\nu = -\delta^\mu_\nu \frac{1}{4\kappa^2_{10}} \left\{ u^I \delta_I \left[e^{-6A} (\widetilde{\nabla \alpha})^2 \right] - 2e^{-6A} \Box u^I S_{Im} \partial^{\tilde{m}} \alpha - 2\Box u^I K_I e^{-6A} (\widetilde{\nabla \alpha})^2 \right\} \ , \tag{A.37}
$$

$$
\delta T^\mu_m = \frac{1}{2\kappa^2_{10}} \partial^\mu u^I e^{-6A} \left[\partial_m S_{Ip} - \partial_p S_{Im} + \partial_m \alpha B_{Ip} - \partial_p \alpha B_{Im} \right] \partial^{\tilde{p}} \alpha \ , \tag{A.38}
$$

$$
\boxed{\delta G^M_N = \kappa^2_{10} \delta T^M_N}
$$

$$
\begin{aligned}
\delta T^m_n =& -\frac{1}{2\kappa^2_{10}} u^I \delta_I \left\{ e^{-6A} \left[\partial_n \alpha \partial^{\tilde{m}} \alpha - \frac{1}{2} \delta^m_n (\widetilde{\nabla \alpha})^2 \right] \right\} \\
&+ \frac{e^{-6A}}{2\kappa^2_{10}} \Box u^I \left\{ S_{In} \partial^{\tilde{m}} \alpha + \partial_n \alpha S^{\tilde{m}}_I - \delta^m_n S_{Ip} \partial^{\tilde{p}} \alpha + 2K_I \left[\partial_n \alpha \partial^{\tilde{m}} \alpha - \frac{1}{2} \delta^m_n (\widetilde{\nabla \alpha})^2 \right] \right\} \ .
\end{aligned} \tag{A.39}
$$

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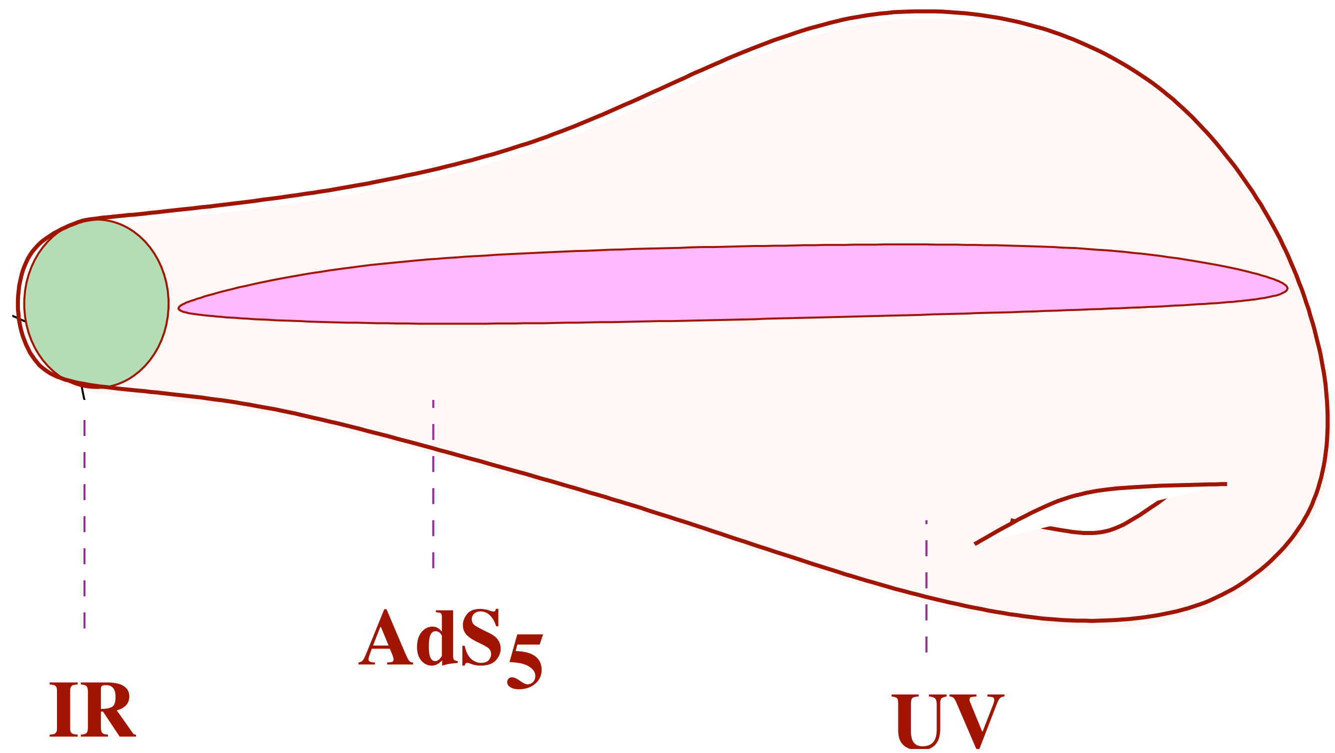
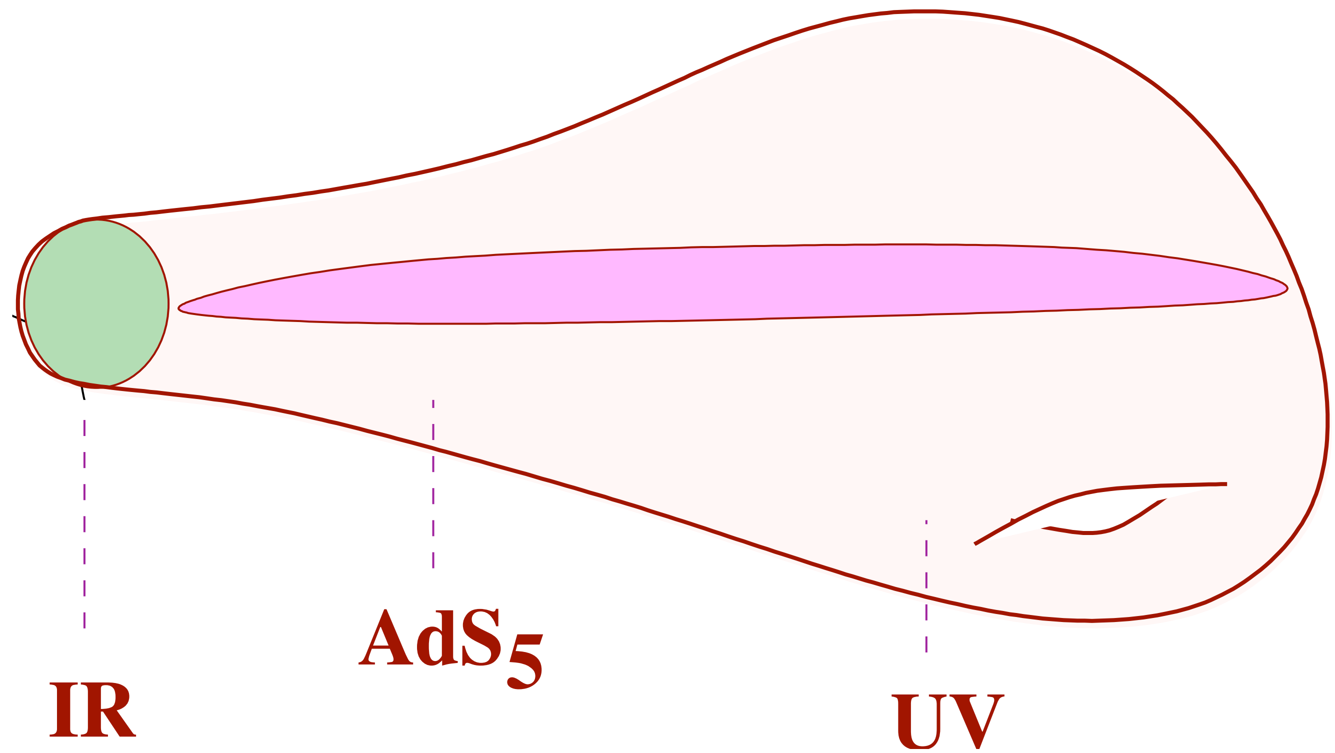
The Ubiquitous Throat



The Ubiquitous Throat



String Theory

Moduli stabilization

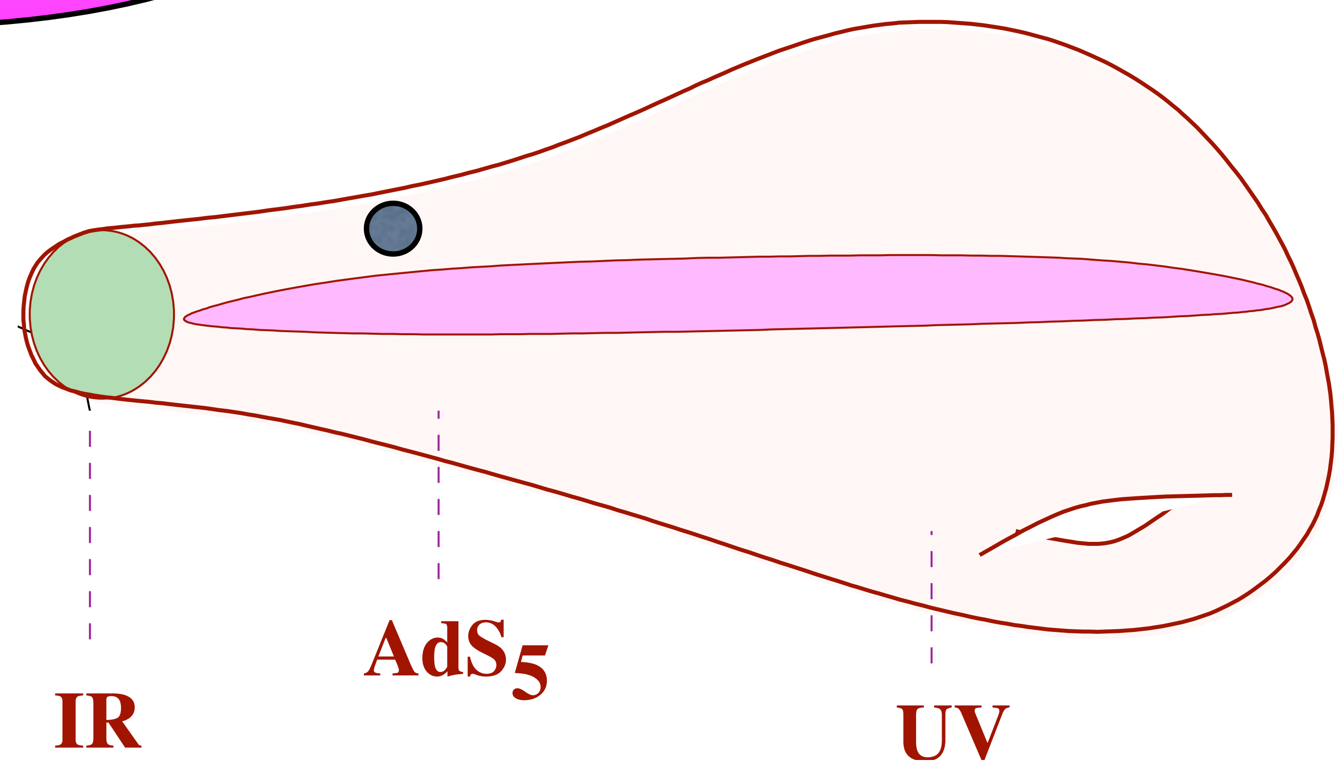
AdS/CFT, ...

The Ubiquitous Throat

Cosmology

Inflation, sequestered DM, ...

see Langlois, McAllister's talks



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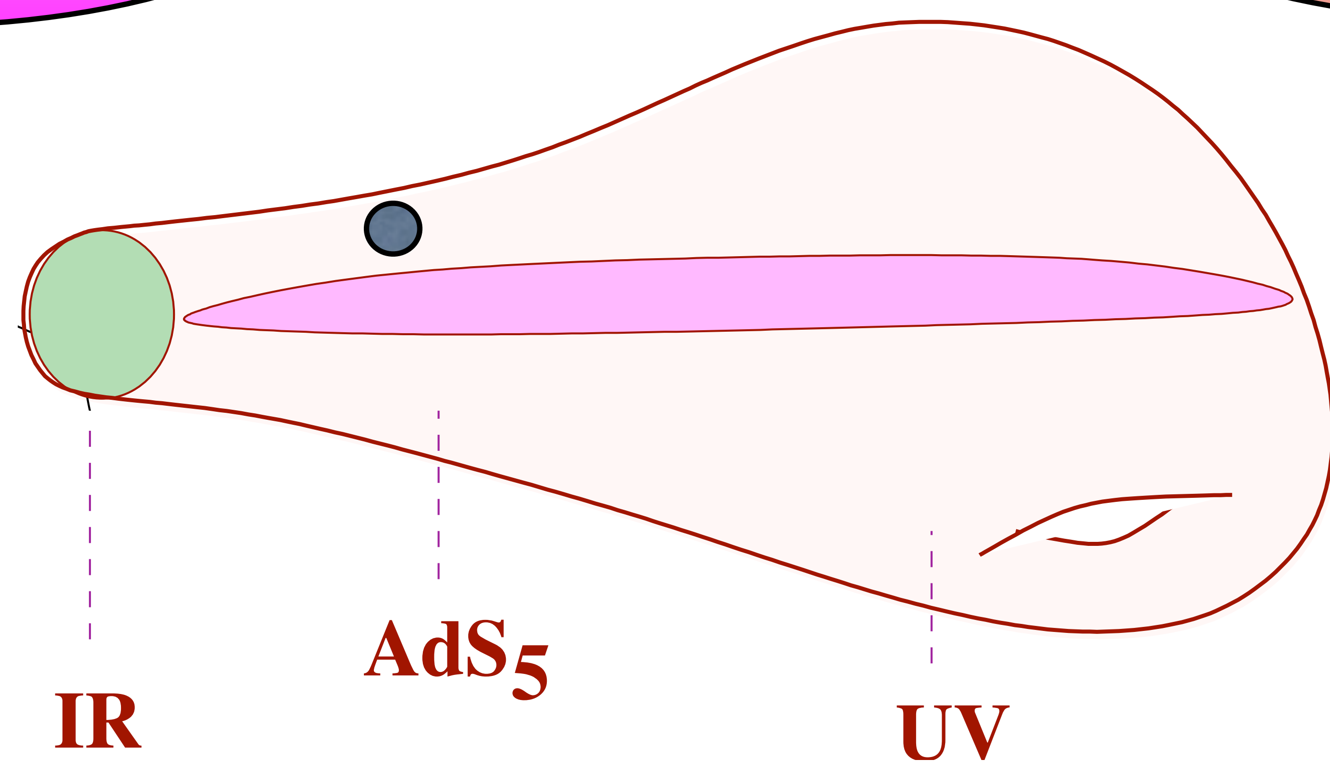
Particle Physics
Various BSM scenarios



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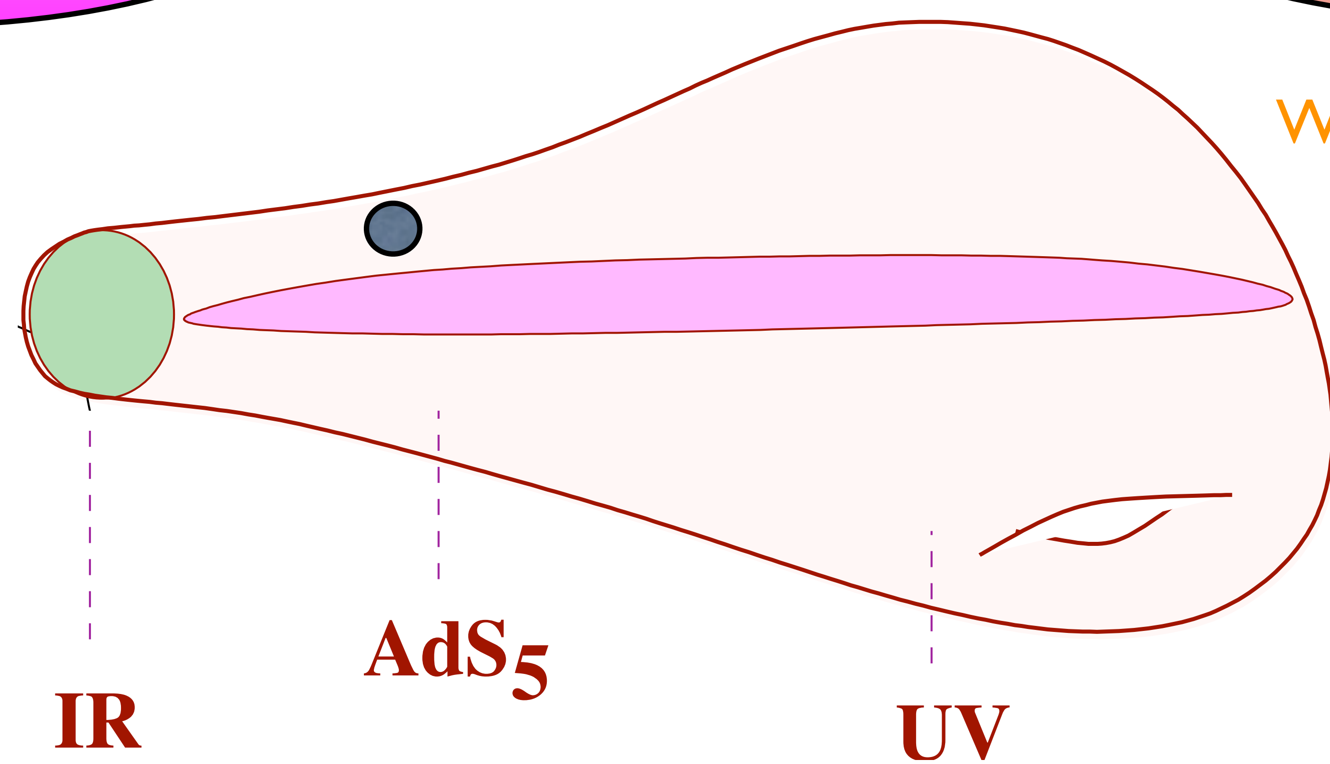
Warped Extra Dimensions
e.g., Randall-Sundrum



String Theory

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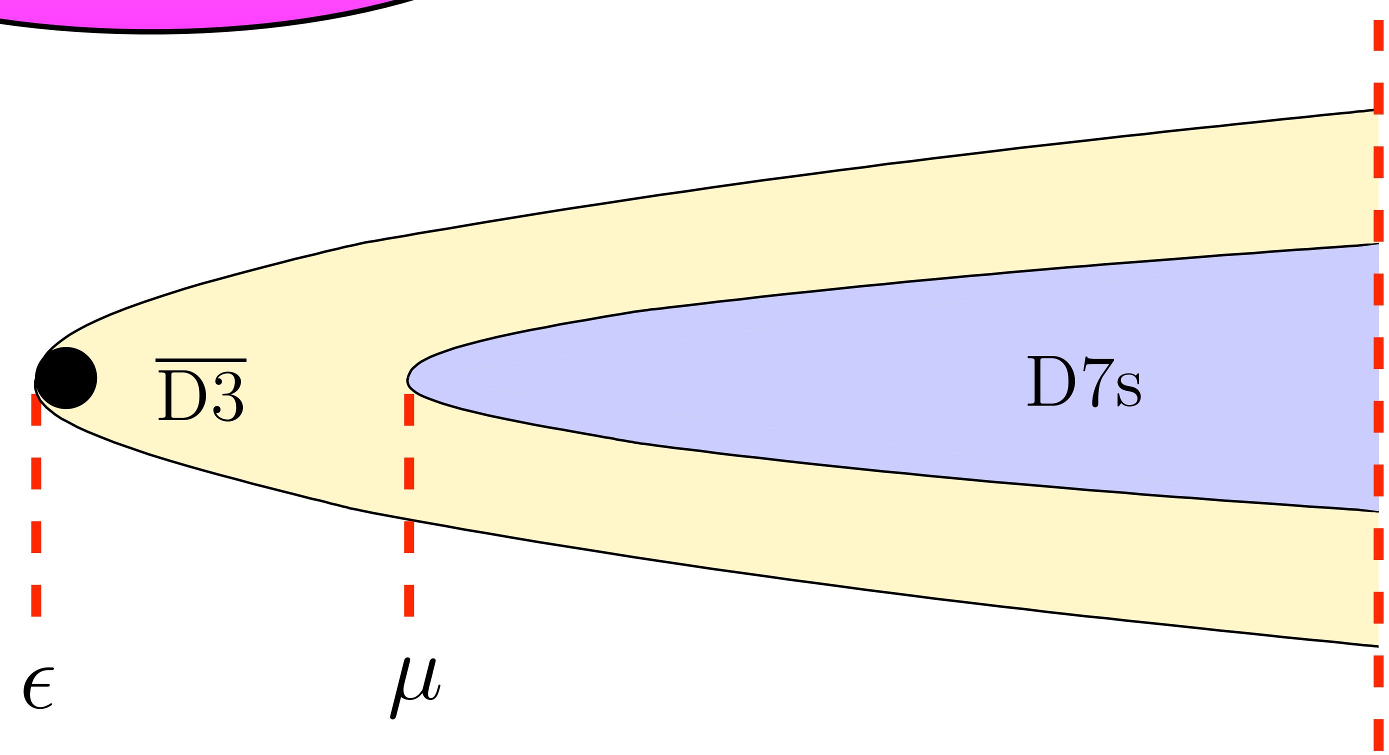


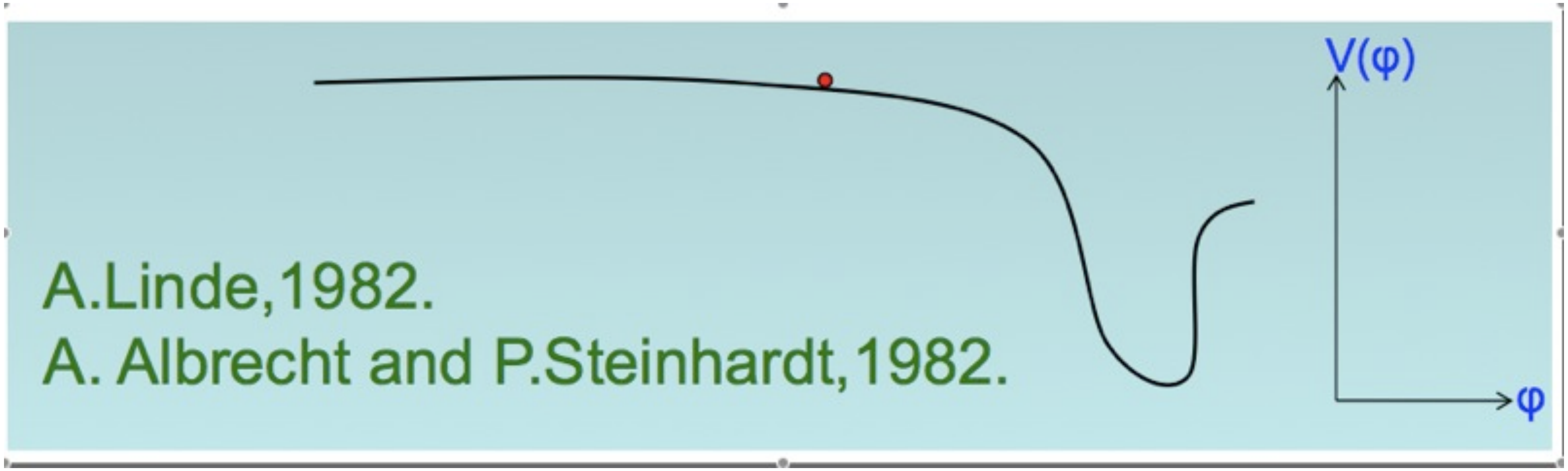
Holographic gauge mediation:

e.g., Benini, Dymarsky, Franco, Kachru, Simic, Verlinde

McGuirk, GS, Sumitomo (in progress)

String Theory
Moduli stabilization
AdS/CFT, ...

Inflation and UV Physics



sensitive to dimension 6, Planck suppressed corrections:

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

such corrections may come from the Kahler potential which is not protected by holomorphy.

BSM and UV Physics

In gravity mediation, soft terms are generated by Planck suppressed operators:

$$m_0 \sim m_{1/2} \sim m_{3/2} \sim \frac{< F >}{M_P}$$

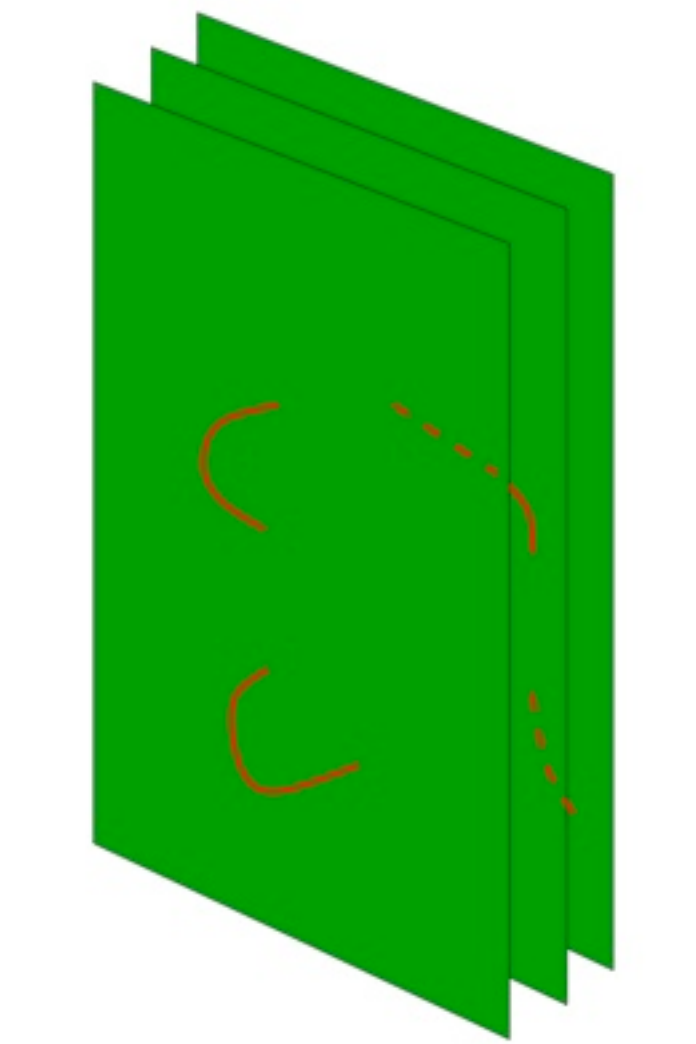
Issue of FCNC can only be addressed with knowledge of UV physics.

Again, the Kahler potential comes into play.

Warping Corrections

In addition to g_s and α', 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

$$g_s \quad \& \quad \alpha'$$

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:

  Giddings and Maharana'05
  Burgess, Cámara, de Alwis, Giddings, Maharana, Quevedo'06
  GS, Torroba, Underwood, Douglas'08
  Douglas, Torroba'08

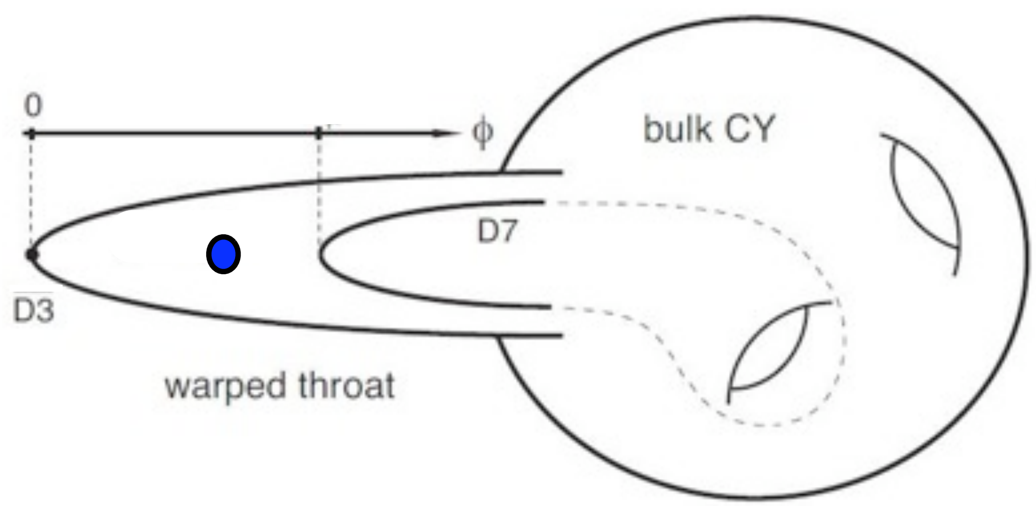
  - Many subtle issues
  - Simple expressions for certain subsectors (universal Kähler modulus)

  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

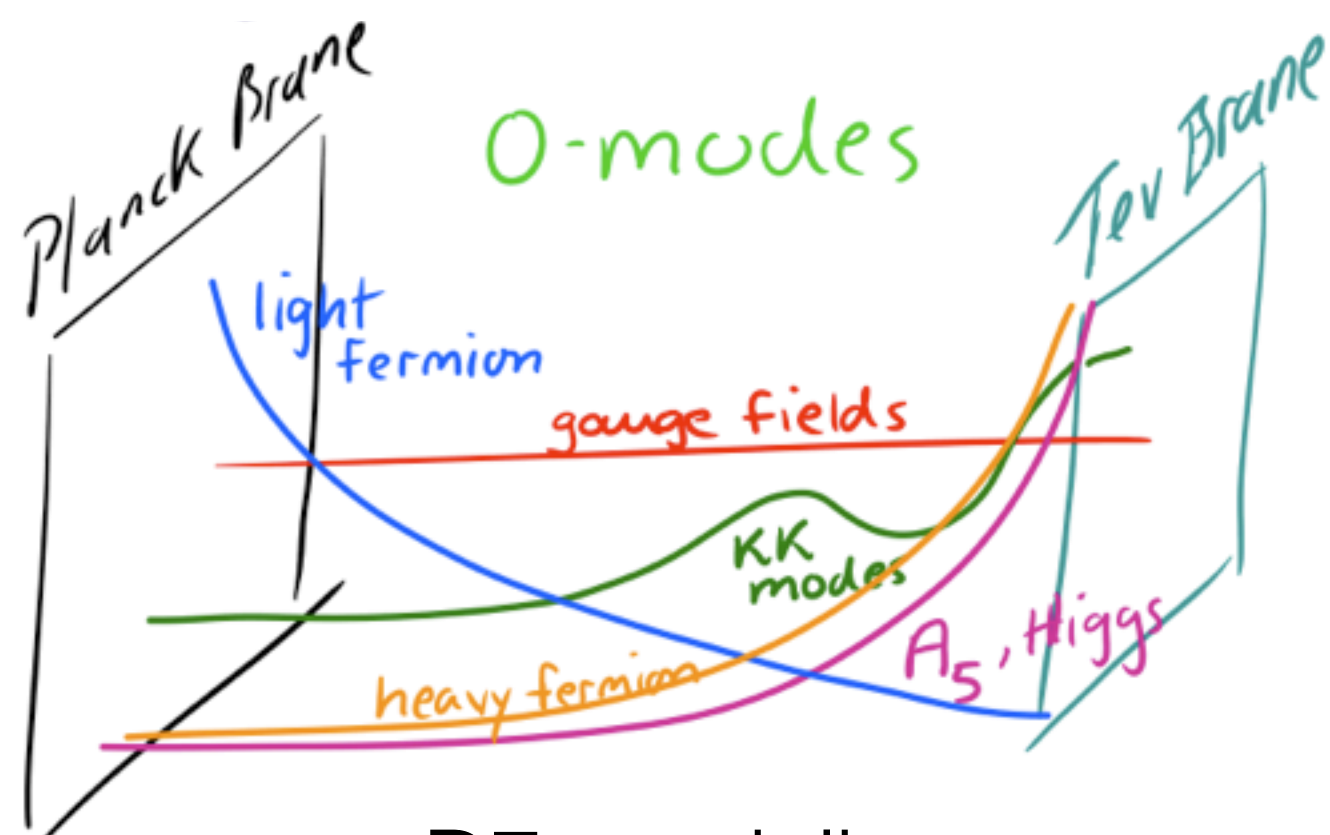
D-brane Inflation



D3-moduli

Chen, Nakayama, GS

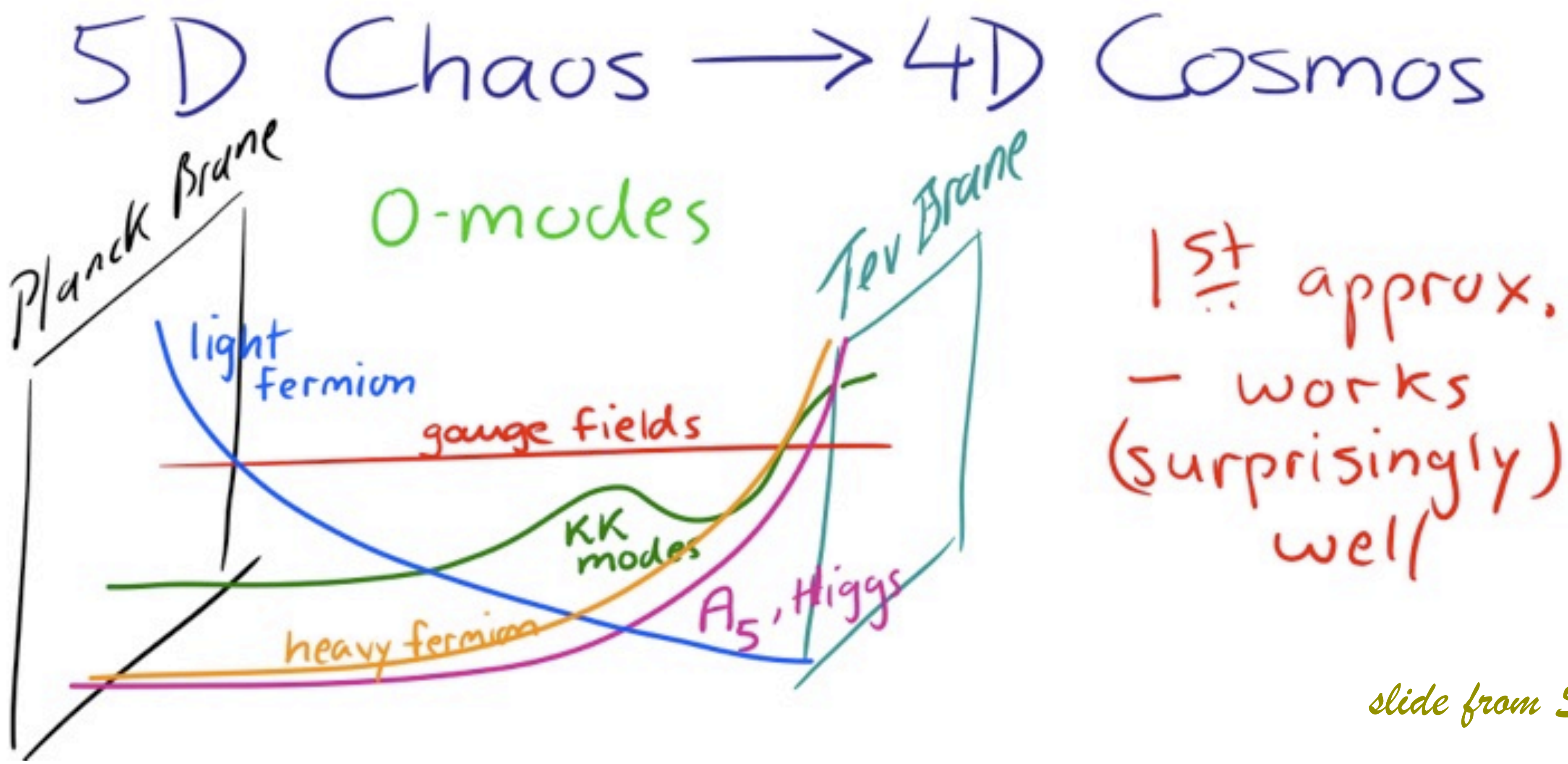
Warped Extra Dimensions



D7-moduli

Marchesano, McGuirk, GS

Warped Extra Dimensions

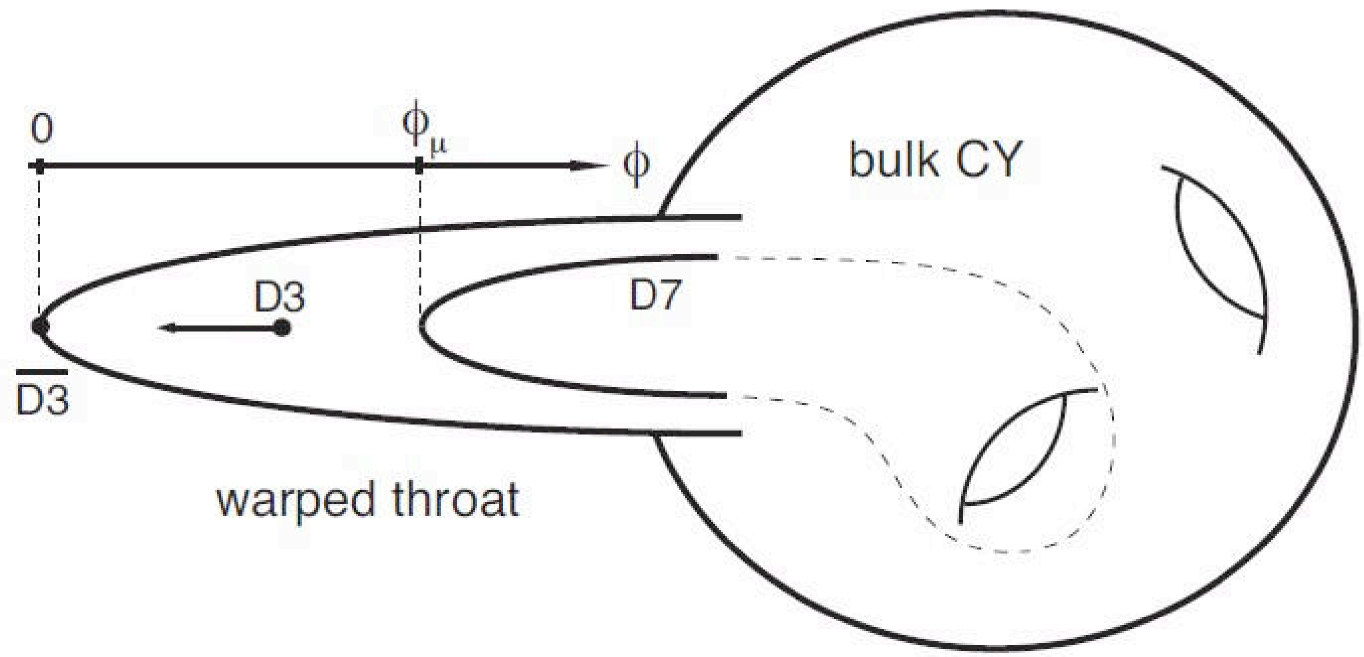


slide from Sundrum

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



D7-branes wrap

$$S_4 \subset X_6$$

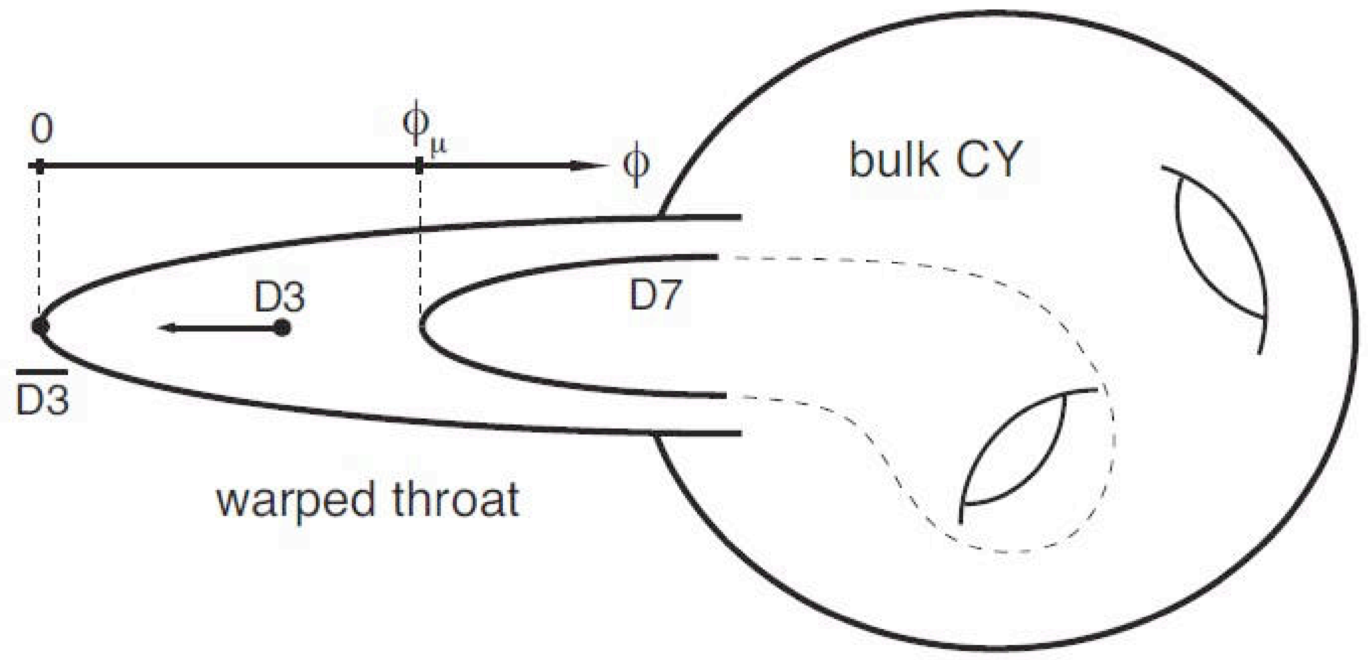
Type IIB warped background:

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

Consistency requires:

$$F_5 = (1 + *_{10})F_5^{\text{int}} \qquad F_5^{\text{int}} = \hat{*}_6 d\left(\Delta e^\Phi\right)$$

Warped Open Strings



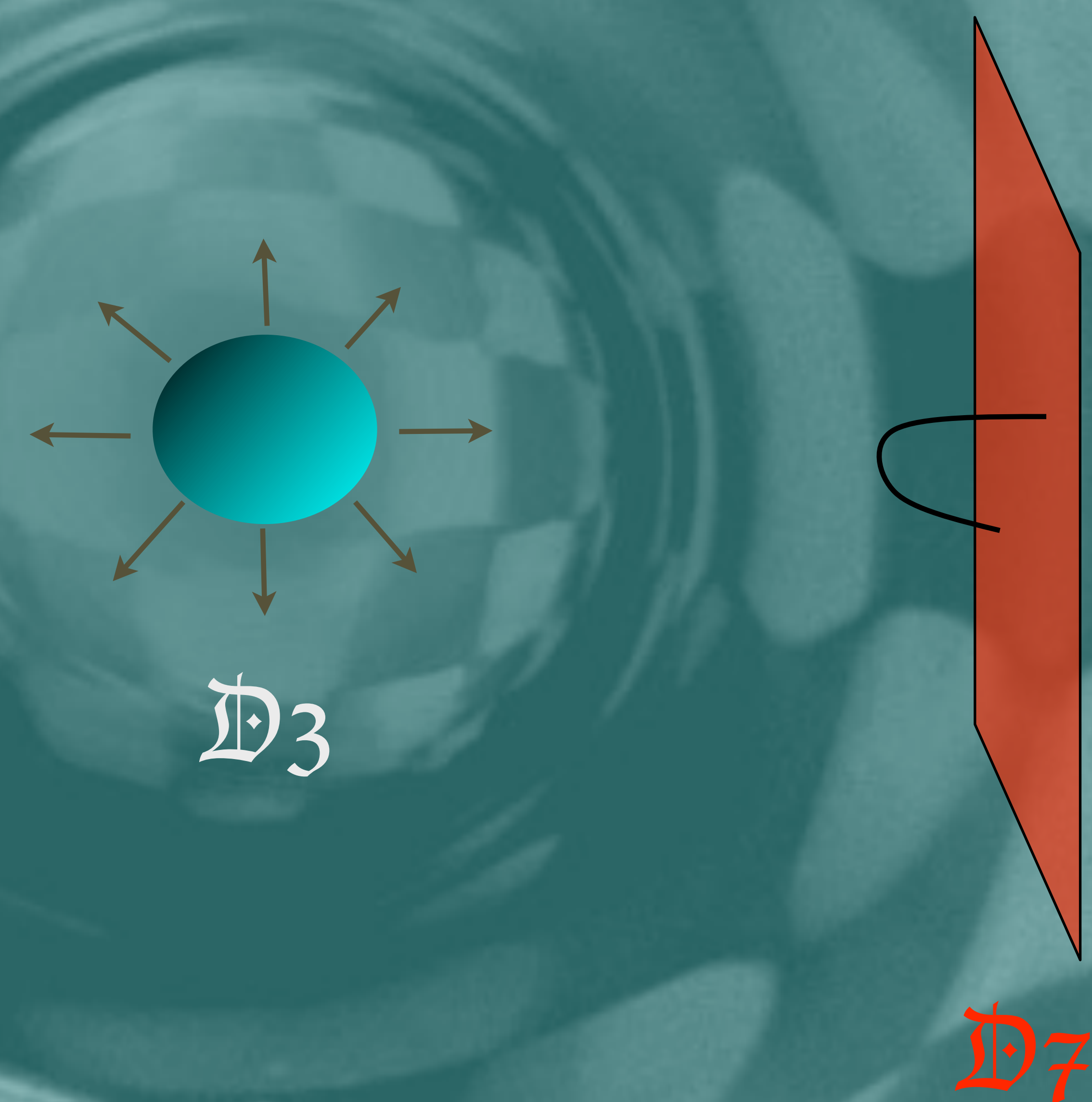
D7-branes wrap

$$S_4 \subset X_6$$

- ✦ Compute the open string wavefunctions in a warped background
- ✦ Deduce the open string Kähler potential

Warmup: Warped Flat Space

- Introduce a probe D7-brane in this background, see how its internal fluctuations are affected by the presence of Z and F_5



Warmup: Warped Flat Space

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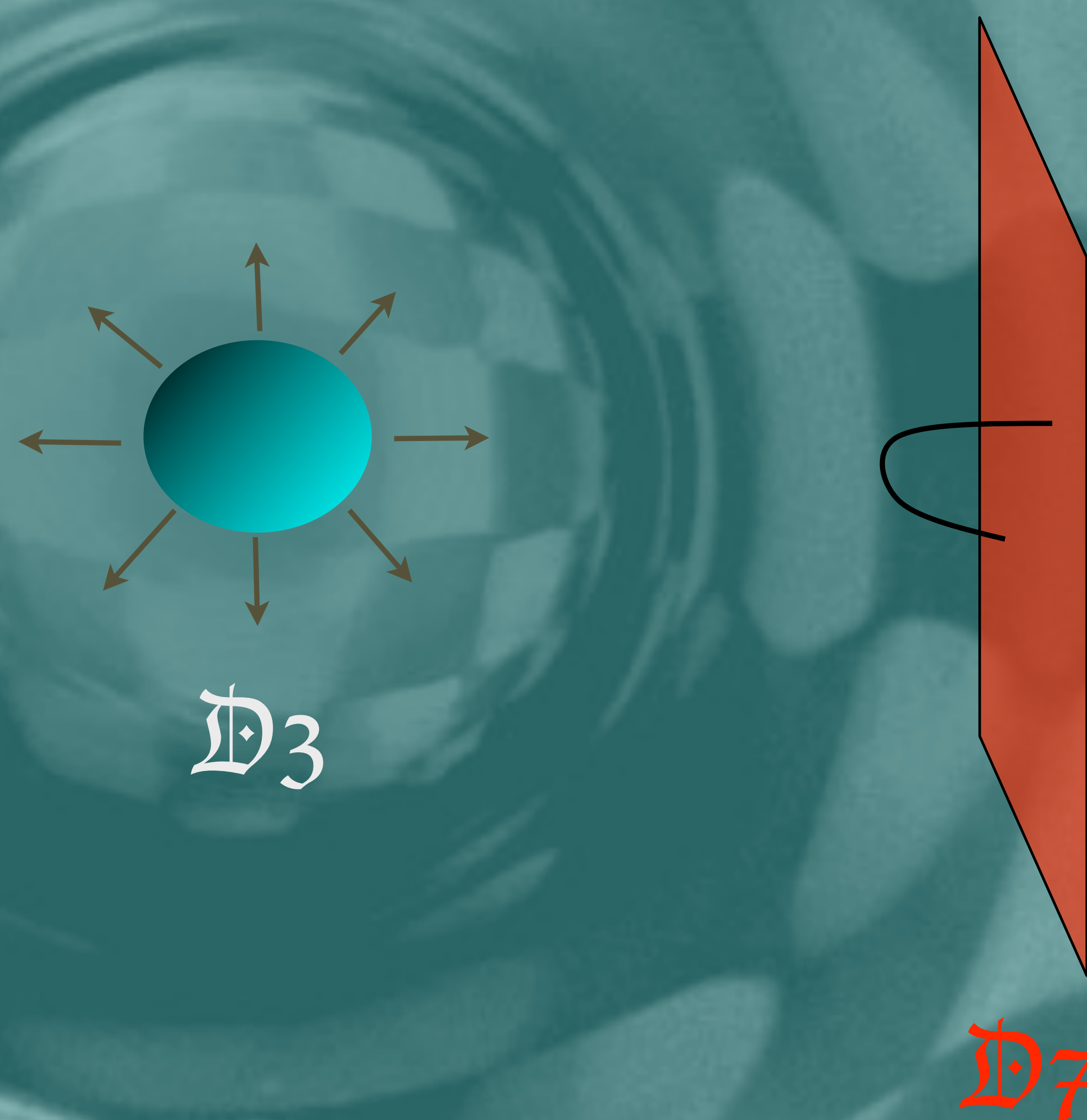
Our results will be generalized later to warped Calabi-Yau and backgrounds with other SUGRA and/or worldvolume fluxes



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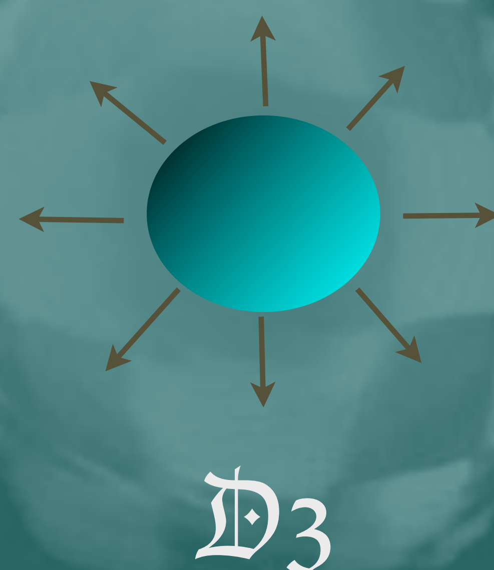

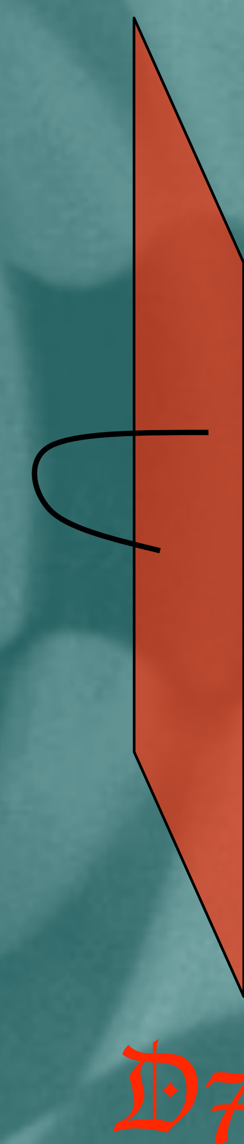

Q: How do the D7 wavefunctions couple to F_5?

D7-brane action

- Bosonic action $$S_{\rm D7}^{\rm bos} \;=\; S_{\rm D7}^{\rm DBI} + S_{\rm D7}^{\rm CS}$$
- Fermionic action

Martucci, Rosseel, Van den Bleeken, Van Proeyen '05

$$S_{\rm D7}^{\rm fer} \;=\; \tau_{\rm D7} \int d^8\xi\, e^{\Phi} \sqrt{|\det\, G|}\; \bar{\Theta}\, P_-^{\rm D7} \left(\Gamma^\alpha \mathcal{D}_\alpha + \frac{1}{2}\mathcal{O} \right) \Theta$$

see also Graña '02

Marolf, Martucci, Silva '03

D7-brane action

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$$S^{\rm fer}_{\rm D7} = \tau_{\rm D7} \int d^8\xi\, e^{\Phi} \sqrt{|\det G|}\, \bar{\Theta}\, P^{\rm D7}_{-} \left(\Gamma^{\alpha} \mathcal{D}_{\alpha} + \frac{1}{2} \mathcal{O} \right) \Theta$$

see also Graña'02

Marolf, Martucci, Silva'03

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

$$P^{\rm D7}_{\pm} = \frac{1}{2}\left(\mathbb{I} \mp \Gamma_{8D} \otimes \sigma_2\right)$$ halves the dof's down to $\mathcal{N}$=1 8D SYM

$$\delta_{\epsilon}\psi_M = \mathcal{D}_M \epsilon$$ type IIB gravitino variation

$$\delta_{\epsilon}\lambda = \mathcal{O}\epsilon$$ type IIB dilatino variation

(contain F_p)

Contains the coupling of fermions to RR fluxes

D7-brane action

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Martucci, Rosseel, Van den Bleeken, Van Proeyen '05

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κ -symmetry $$\Theta \to \Theta + P^{D7}_{-}\kappa$$

Convenient choices: $$\Theta = \begin{pmatrix} \theta \\ 0 \end{pmatrix}$$ or $$P^{\rm D7}_{-}\Theta = 0$$

D7-brane action

- In warped flat space:

$$
\begin{aligned}
\mathcal{O} &= 0 \\
\mathcal{D}_M &= \nabla_M + \frac{1}{8}\not{F}_5^{\text{int}}\Gamma_M i\sigma_2
\end{aligned}
$$

- The D7-brane sees the warped metric

along 4-cycle

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

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

- κ-fixing $\Theta = \begin{pmatrix}\theta \\ 0\end{pmatrix}$, the 8D Dirac action is given by

$$\begin{aligned} S^{\text{fer}}_{\text{D7}} &= \tau_{\text{D7}}\,e^{\Phi_0}\int_{\mathbb{R}^{1,3}} d^4x \int d^4y\,\bar{\theta}\not{D}^w\theta \\ \not{D}^w &= \sum_\mu \Gamma^\mu\mathcal{D}_\mu + \sum_a \Gamma^a\mathcal{D}_a + \frac{1}{2}\mathcal{O} \\ &= \not{\partial}_4^{\text{ext}} + \not{\partial}_4^{\text{int}} - \frac{1}{8}\left(\not{\partial}_4^{\text{int}}\ln Z\right)(1 + 2\Gamma_{\text{Extra}}) \end{aligned}$$

D7-brane action

- In warped flat space:

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D7-brane zero modes

If one now decomposes the 10D MW spinor as

$$\theta \;=\; \chi + B^* \chi^* \qquad \chi \;=\; \theta_{4D} \otimes \theta_{6D}$$

B: Majorana matrix

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

$$\left[\partial\!\!\!/_4^{\text{int}} - \frac{1}{8}\left(\partial\!\!\!/_4^{\text{int}} \ln Z\right)(1 + 2\Gamma_{\text{Extra}})\right] \theta_{6D}^0 \;=\; 0$$

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$$\left[\partial\!\!\!/_4^{\mathrm{int}} - \frac{1}{8} \left(\partial\!\!\!/_4^{\mathrm{int}} \ln Z \right) (1 + 2\Gamma_{\mathrm{Extra}}) \right] \theta^0_{6D} \;=\; 0$$

and so the 4D zero modes are

$$\theta^0_{6D} = Z^{-1/8} \eta_- \qquad \text{for} \qquad \Gamma_{\mathrm{Extra}}\, \eta_- \;=\; -\eta_-$$

$$\theta^0_{6D} = Z^{3/8} \eta_+ \qquad \text{for} \qquad \Gamma_{\mathrm{Extra}}\, \eta_+ \;=\; \eta_+$$

in contrast to $\theta^0_{6D} = Z^{1/8} \eta$, the result in the absence of F_5

Acharya, Benini, Valandro '06

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

$$S^{\rm fer}_{\rm D7} \;=\; \tau_{\rm D7}\, e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4x\, \bar\theta_{4D} \not{\partial}_{\mathbb{R}^{1,3}} \theta_{4D} \int d^4y\, \eta_-^\dagger \eta_-$$
$$S^{\rm fer}_{\rm D7} \;=\; \tau_{\rm D7}\, e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4x\, \bar\theta_{4D} \not{\partial}_{\mathbb{R}^{1,3}} \theta_{4D} \int d^4y\, Z \eta_+^\dagger \eta_+$$

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

$$S^{\text{fer}}_{\text{D7}} = \tau_{\text{D7}}\, e^{\Phi_0}\int_{\mathbb{R}^{1,3}} d^4x\,\bar\theta_{4D}\not\partial_{\mathbb{R}^{1,3}}\theta_{4D}\boxed{\int d^4y\,\eta^\dagger_-\eta_-}$$

usual volume

$$S^{\text{fer}}_{\text{D7}} = \tau_{\text{D7}}\, e^{\Phi_0}\int_{\mathbb{R}^{1,3}} d^4x\,\bar\theta_{4D}\not\partial_{\mathbb{R}^{1,3}}\theta_{4D}\boxed{\int d^4y\,Z\eta^\dagger_+\eta_+}$$

warped volume

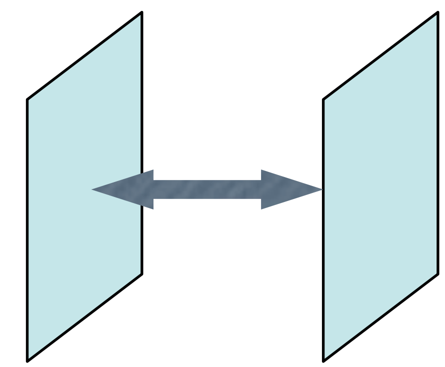
that indeed match the kinetic terms of the bosonic zero modes (e.g., $f_{D7} \sim \int Z + i\, C_4$). This allows to identify them in terms of their bosonic superpartners.

D7-brane zero modes

- Upon dimensional red., such fermion zero modes

$$\theta^0_{6D} = Z^{-1/8}\eta_- \qquad \text{Wilsonini} \qquad A_a$$

$$\theta^0_{6D} = Z^{3/8}\eta_+ \qquad \text{gaugino + modulino} \qquad A_\mu \,,$$



imply the following kinetic terms

$$S^{\rm fer}_{\rm D7} = \tau_{\rm D7}\, e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4x\, \bar\theta_{4D} \partial\!\!\!/_{\mathbb{R}^{1,3}} \theta_{4D} \boxed{\int d^4y\, \eta_-^\dagger \eta_-}$$

usual volume

$$S^{\rm fer}_{\rm D7} = \tau_{\rm D7}\, e^{\Phi_0} \int_{\mathbb{R}^{1,3}} d^4x\, \bar\theta_{4D} \partial\!\!\!/_{\mathbb{R}^{1,3}} \theta_{4D} \boxed{\int d^4y\, Z \eta_+^\dagger \eta_+}$$

warped volume

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.

A subtlety

- Our strategy to compute the zero modes appears to be:

$$S^{\rm fer}_{\rm D7} \;=\; \int d^8\xi\,\bar\theta \not{D}^w\theta \quad\rightarrow\quad \not{D}^w\theta^0 \;=\; 0$$

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

- For example:

$$\tau_{\rm D7}\int d^8\xi\,\bar\theta\Gamma^\alpha\partial_\alpha\theta \qquad \text{and} \qquad \tau_{D7}\int d^8\xi\,\bar\theta\Gamma^\alpha\big(\partial_\alpha - \partial_\alpha \ln f\big)\theta$$

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

- Naively, the warp factor dependence drops out in eom.

- But a careful analysis gives:

$$\delta S^{\rm fer}_{\rm D7} \;=\; \tau_{\rm D7}\, e^{\Phi_0}\int d^8\xi\, \overline{\delta\theta}\not{D}^w\theta + \bar\theta\not{D}^w\delta\theta \;=\; 2\tau_{\rm D7}\, e^{\Phi_0}\int d^8\xi\,\overline{\delta\theta}\not{D}^w\theta$$

A subtlety

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

$$P_{-}^{\mathrm{D7}}\left(\Gamma^{\alpha}\mathcal{D}_{\alpha}^{E}+\frac{1}{2}\mathcal{O}^{E}\right)\Theta=0$$

see Bandos and Sorokin'06

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

ex: gauge boson

8D | 4D

$$\delta_{\epsilon}A_{\alpha=\mu} = \bar{\epsilon}\Gamma_{\alpha=\mu}\theta \quad \longrightarrow \quad \delta_{\varepsilon}A_{\mu} = \bar{\varepsilon}\lambda$$

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

No warp factor

Recap

- In general, the open string wavefunctions have an internal profile of the form

$$\psi^{\rm int} = Z^{p}\eta, \qquad \eta = \text{const.}$$

- Their kinetic terms group into 4D $\mathcal{N}$=1 multiplets

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

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

D7		
4D Field	p	q
gauge boson/modulus	0	1
gaugino/modulino	3/8	
Wilson line	0	0
Wilsonino	$-1/8$	

Comparison to RS

RS			D7		
4D Field	p	q	4D Field	p	q
gauge boson	0	$1/4$	gauge boson/modulus	0	1
gaugino	$3/8$		gaugino/modulino	$3/8$	
matter scalar	$(3-2c)/8$	$(1-c)/2$	Wilson line	0	0
matter fermion	$(2-c)/4$		Wilsonino	$-1/8$	

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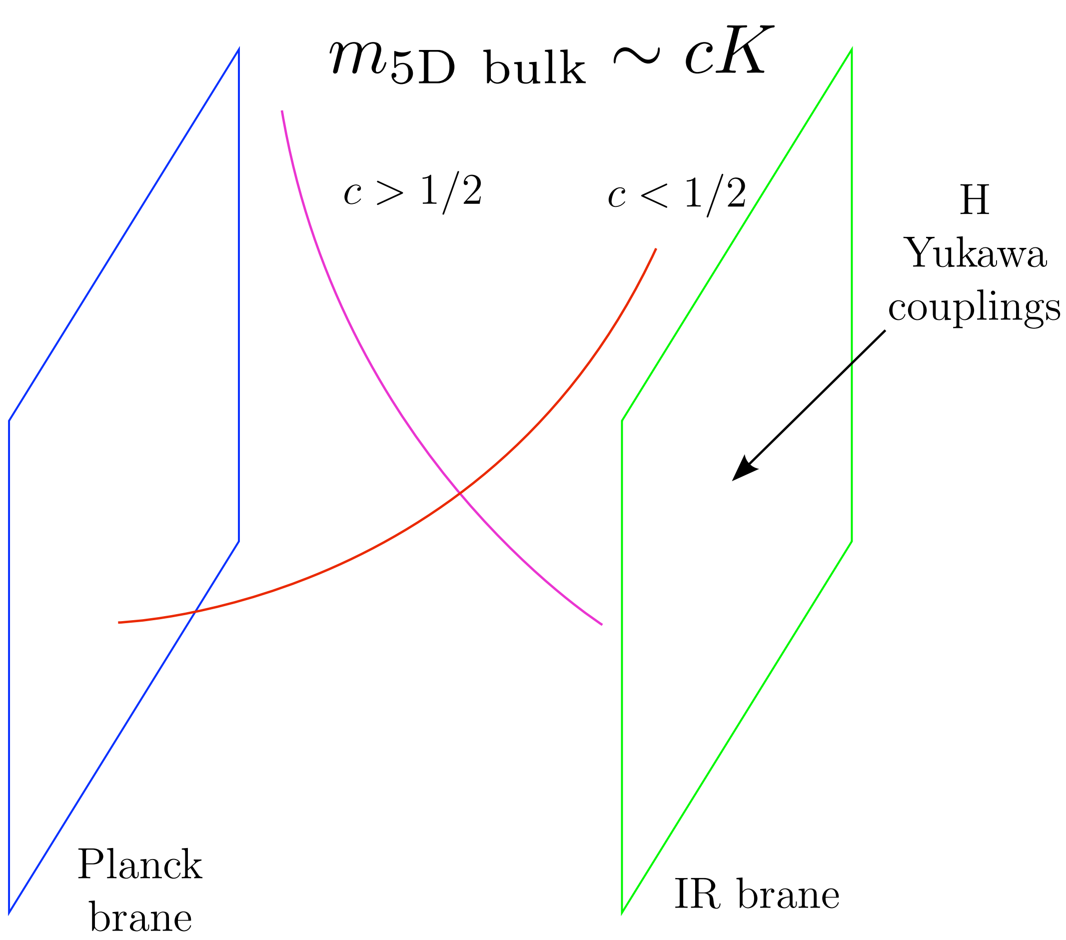

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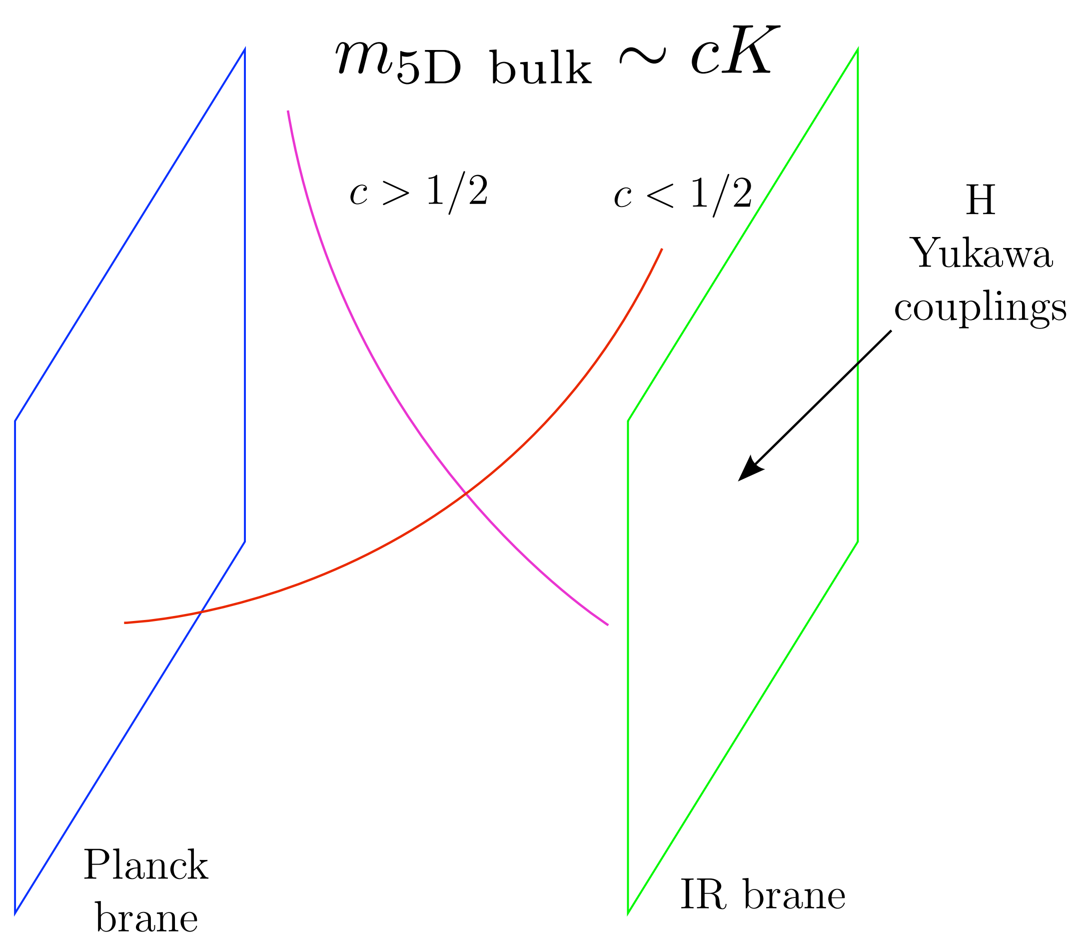

* 5-form fluxes

Comparison to RS

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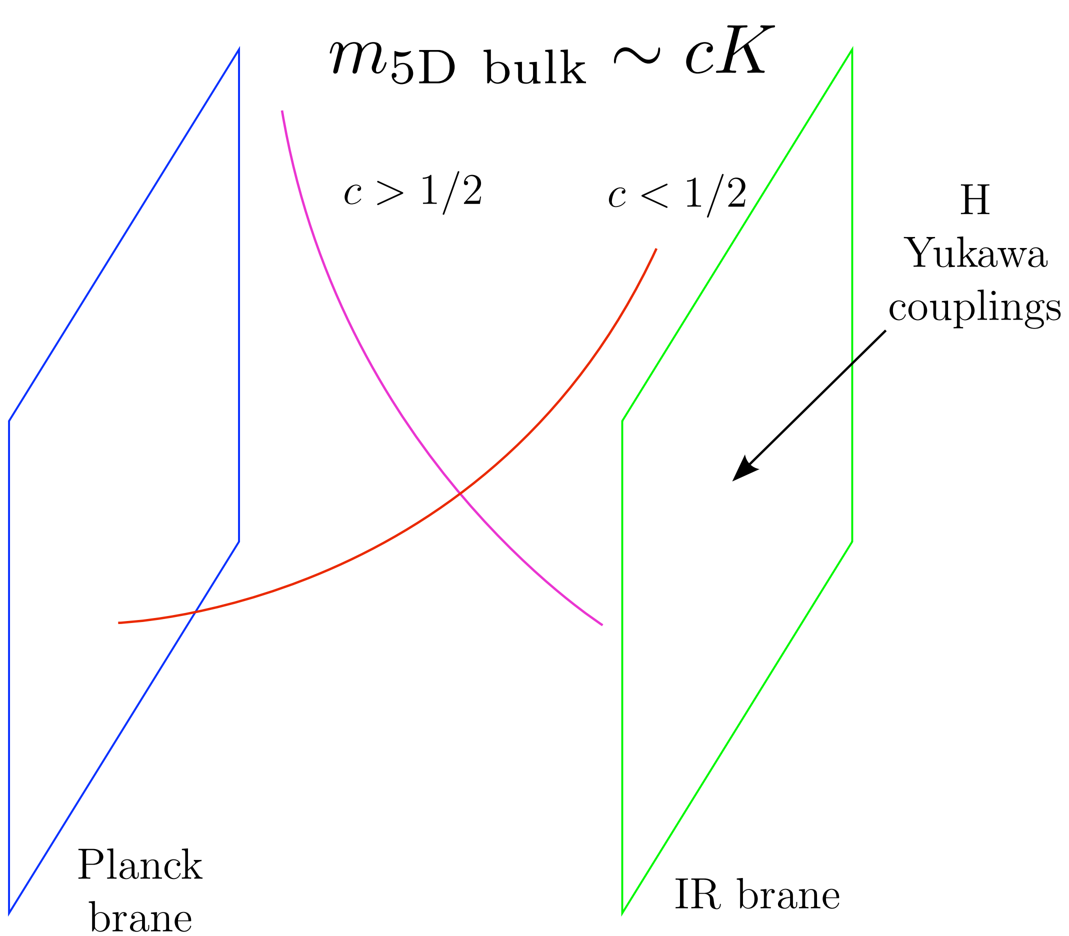

- 5-form fluxes
- 3-form fluxes

Comparison to RS

RS			D7		
4D Field	p	q	4D Field	p	q
gauge boson	0	1/4	gauge boson/modulus	0	1
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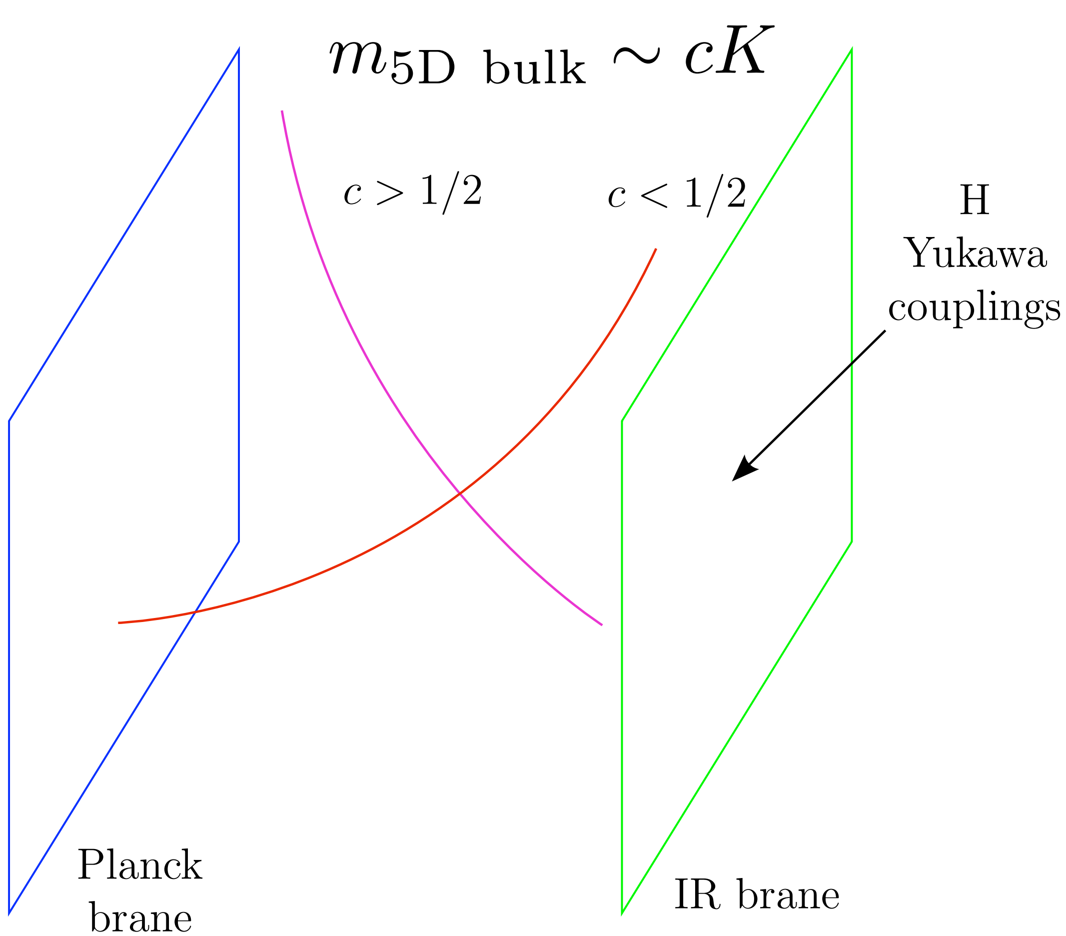
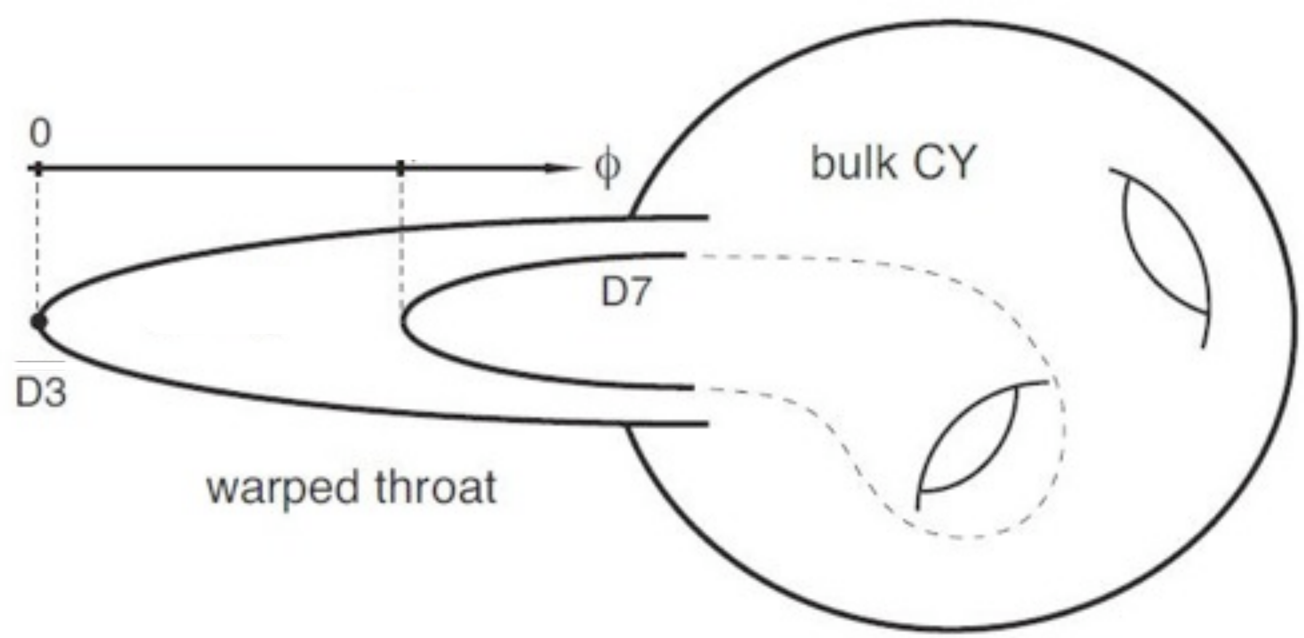


- 5-form fluxes
- 3-form fluxes
- D7-brane worldvolume flux

Generalizations

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

$$\psi^{\rm int} = Z^p \eta, \qquad \eta = {\rm const.} \quad \longrightarrow \quad \eta = {\rm cov.const.}$$



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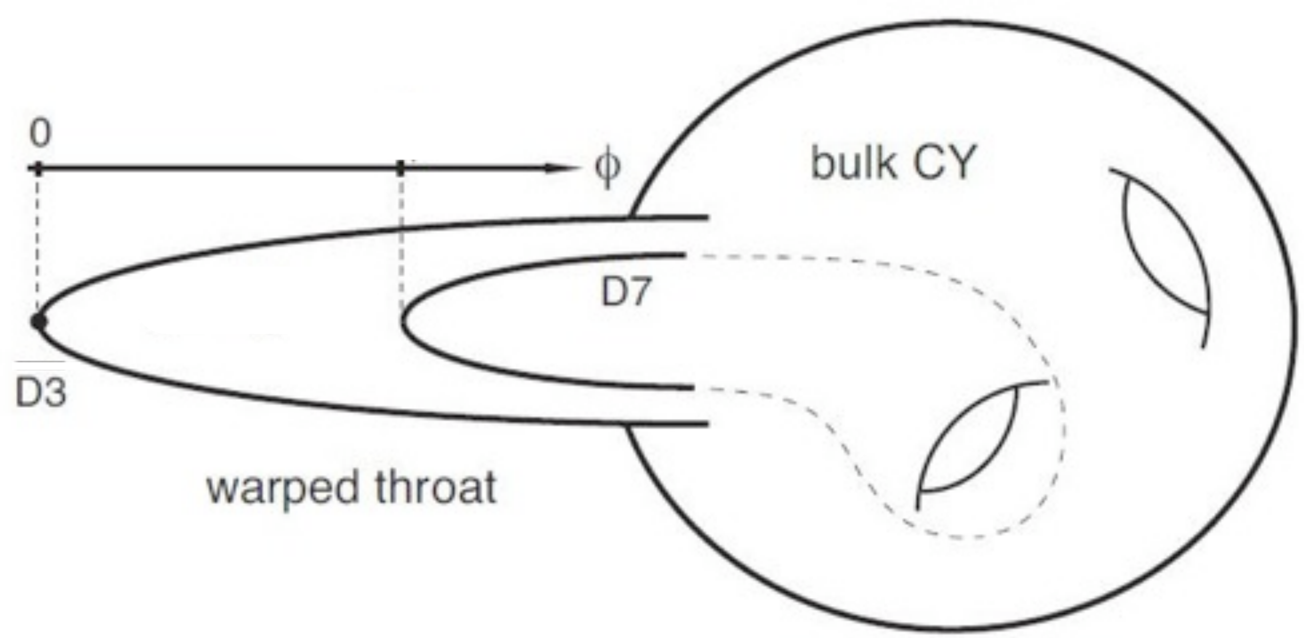
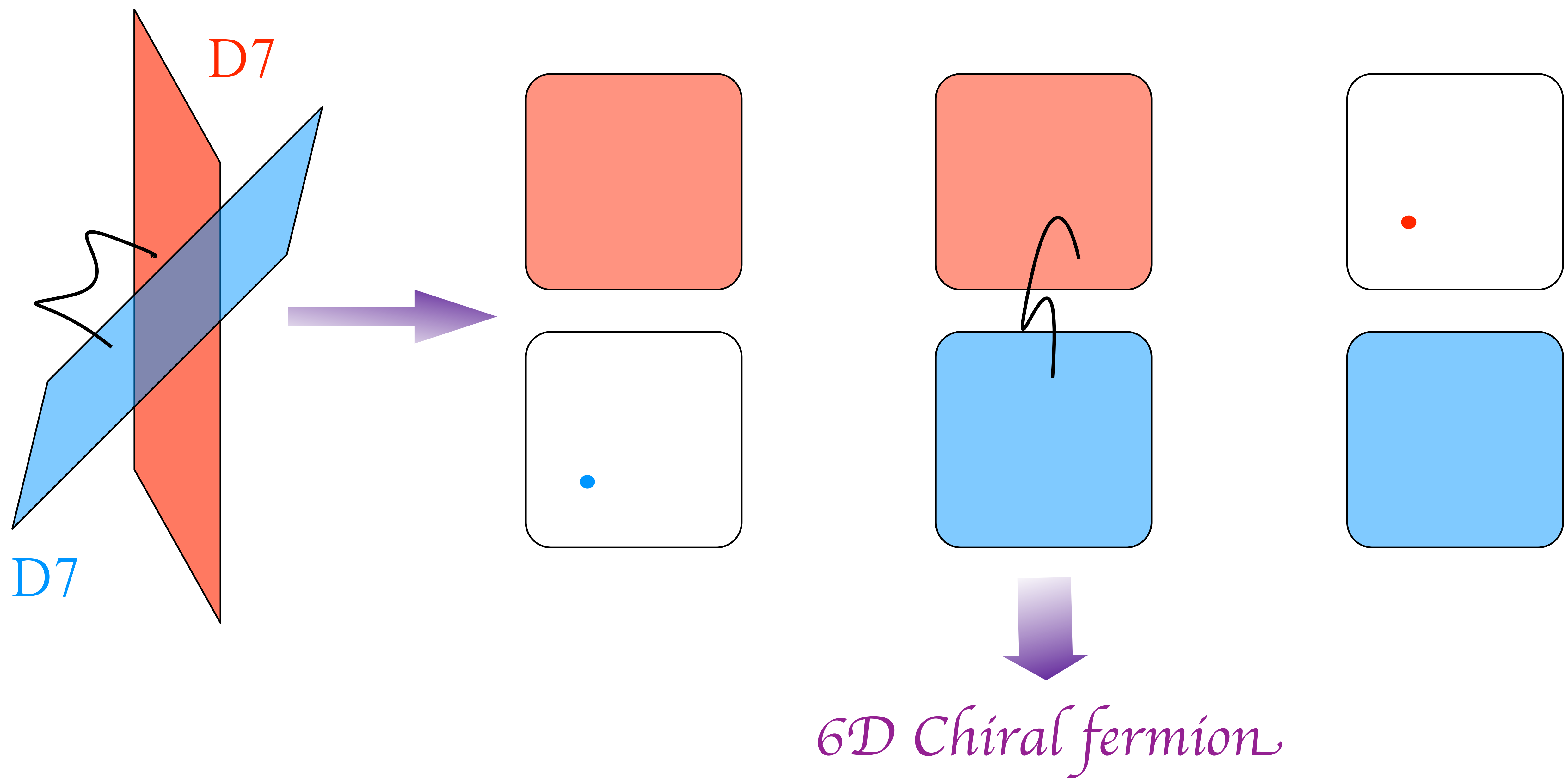
$$\psi^{\text{int}} = Z^p \eta, \qquad \eta = \text{const.} \quad \to \quad \eta = \text{cov.const.}$$

- In addition one may also consider type IIB backgrounds with G_3 fluxes, as well as with varying dilaton.



Magnetized D7-branes

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



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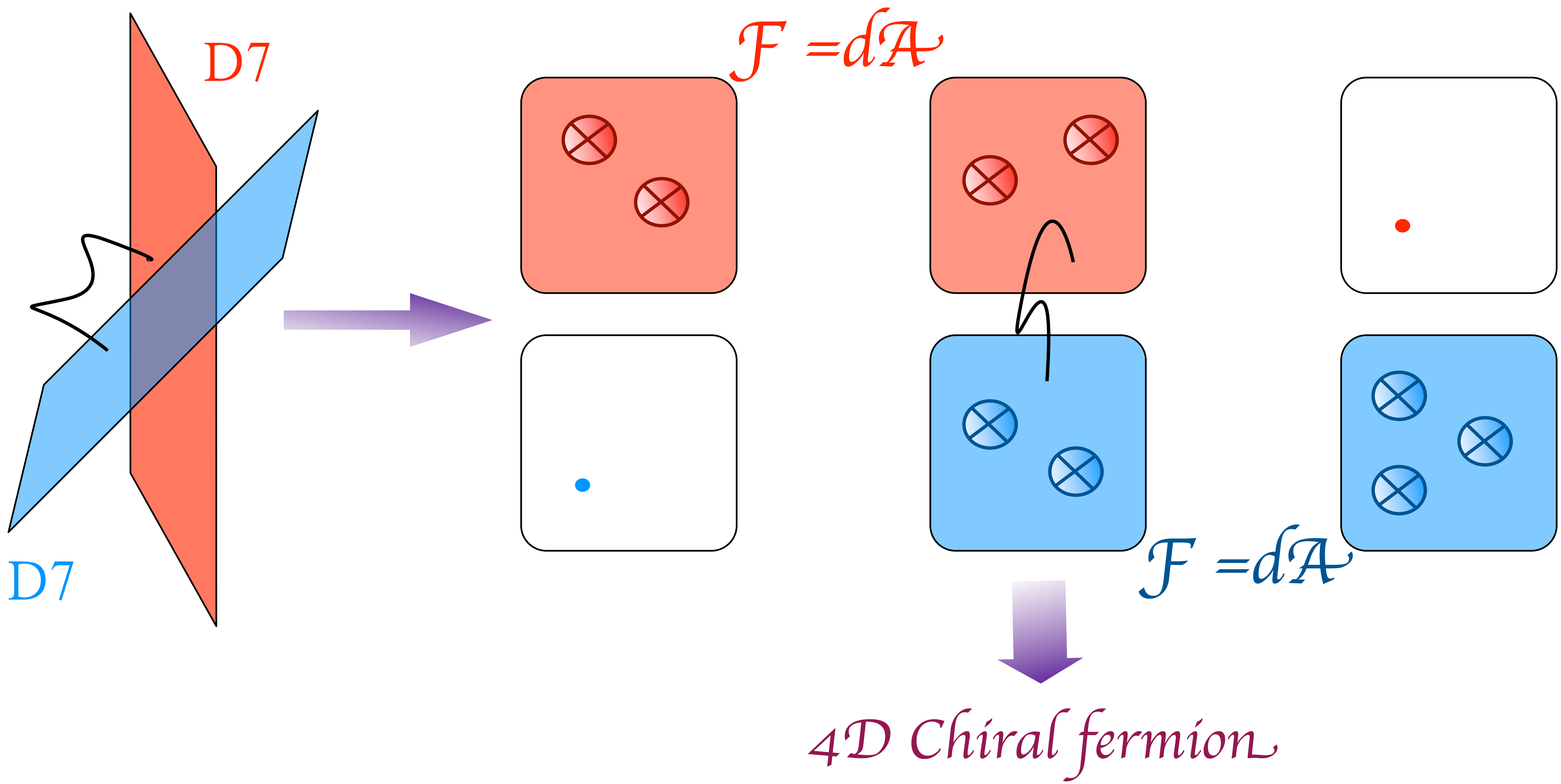


Magnetized D7-branes

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

$(\mathbf{T}^2)_i$ $(\mathbf{T}^2)_j$ $(\mathbf{T}^2)_k$

$$e^{-\Phi_0/2}\mathcal{F} \;=\; B_i\, \mathrm{dvol}_{(\mathbf{T}^2)_i} + B_j\, \mathrm{dvol}_{(\mathbf{T}^2)_j}$$

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

$$\mathrm{BPS} \iff b_i = -b_j$$

- Result:

$$\theta^0_{6D} = \frac{Z^{-1/8}}{1+iB_i\Gamma_{\mathbf{T}^2_i}}\eta_- \qquad \text{Wilsonini} \longrightarrow \boxed{\int d^4y\, \eta_-^\dagger \eta_-}$$

$$\theta^0_{6D} = Z^{3/8}\eta_+ \qquad \text{gaugino + modulino}$$

$$\longrightarrow \boxed{\int d^4y\, |Z^{1/2} + ie^{\Phi_0/2} b|^2 \eta_+^\dagger \eta_+}$$

Warped EFT

- Is all this compatible with the closed string results?
- Let us consider a D7-brane wrapping a 4-cycle $\mathcal{S}_4$ in a warped Calabi-Yau, and with $\mathcal{F} = 0$
- Gauge kinetic function:

$$f_{\rm D7} = \left(8\pi^3 k^2\right)^{-1} \int_{\mathcal{S}_4} \frac{\mathrm{d}\hat{\mathrm{vol}}_{\mathcal{S}_4}}{\sqrt{\hat{g}_{\mathcal{S}_4}}} \left(Z\sqrt{\hat{g}_{\mathcal{S}_4}} + iC_4^{\rm int}\right) \qquad k = 2\pi\alpha'$$

→ Can be understood as a holomorphic function

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

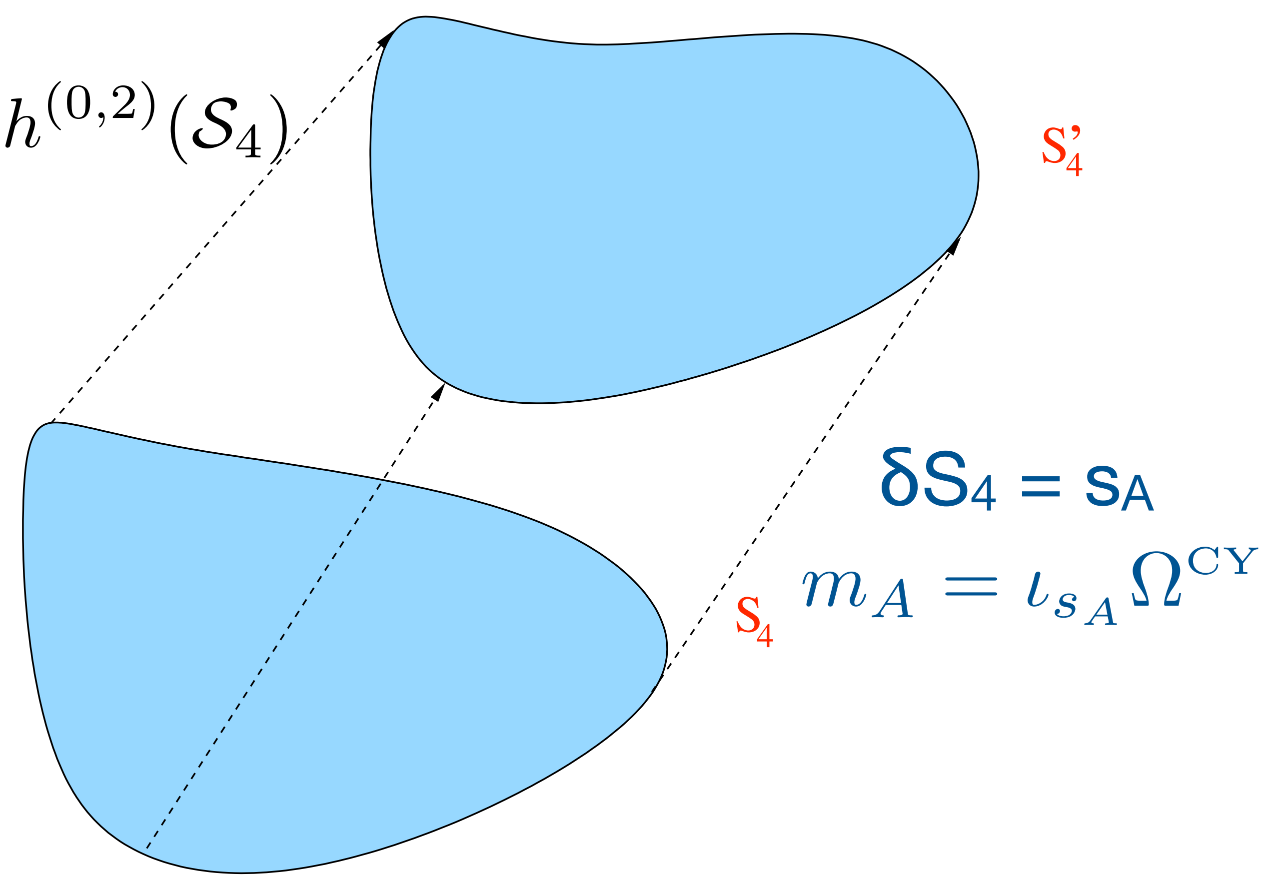
Warped EFT

- Is all this compatible with the closed string results?
- Geometric moduli ζ^a $\quad a = 1, \dots, h^{(0,2)}(\mathcal{S}_4)$

Unwarped kin. terms:

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

$$\mathcal{L}_{A\bar{B}} = \frac{\int_{\mathcal{S}_4} m_A \wedge m_{\bar{B}}}{\int_{X_6} \Omega^{\mathrm{CY}} \wedge \bar{\Omega}^{\mathrm{CY}}}$$



Couple to the dilaton as

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

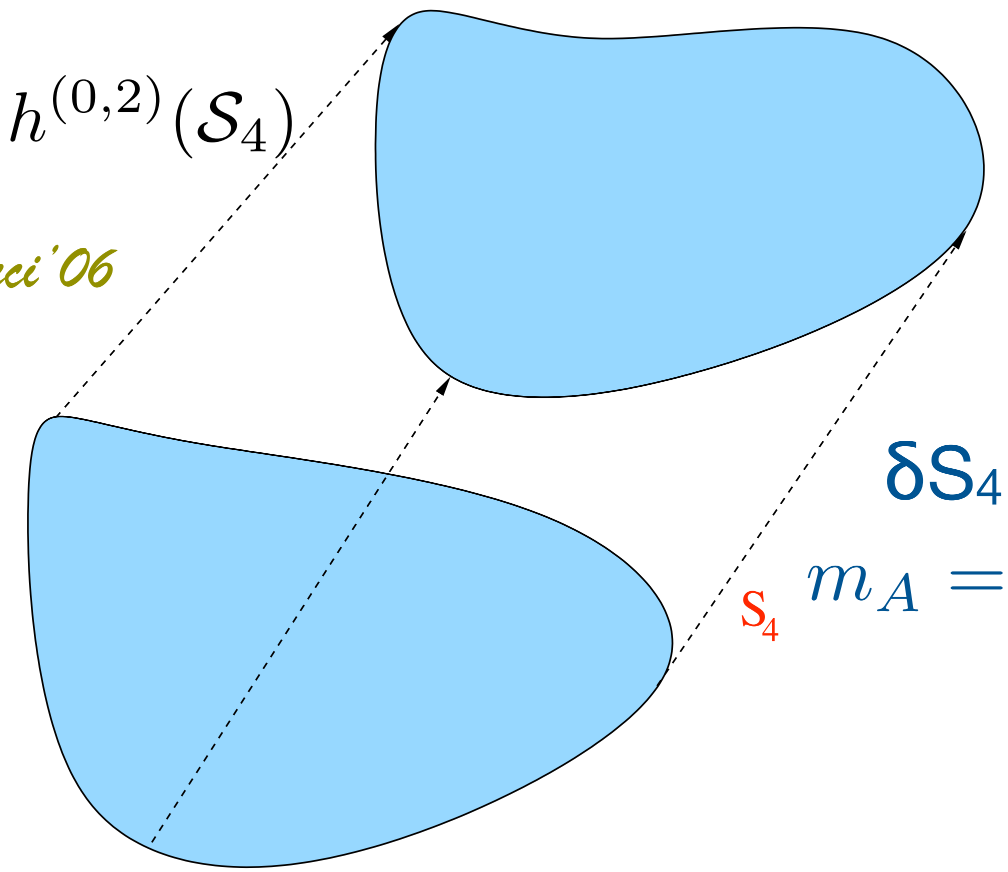
see, e.g., Jockers and Louis '04

Warped EFT

- Is all this compatible with the closed string results?

- Geometric moduli ζ^a $\quad a = 1, \ldots, h^{(0,2)}(\mathcal{S}_4)$

Warped kin. terms: *matches Martucci '06*



δS4 = sA

$$m_A = \iota_{s_A}\Omega^{\rm CY}$$

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

$$\mathcal{L}_{A\bar{B}} \to \mathcal{L}^{\rm w}_{A\bar{B}} = \frac{\int_{\mathcal{S}_4} Z\, m_A\wedge m_{\bar{B}}}{\int_{X_6} Z\,\Omega^{\rm CY}\wedge\bar{\Omega}^{\rm CY}}$$

Suggest a coupling

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

compatible with Shiu, Torroba, Underwood, Douglas '08

Warped EFT

- Is all this compatible with the closed string results?
- Wilson line moduli $W^I \quad I = 1, \dots, h^{(0,1)}(\mathcal{S}_4)$

Unwarped kin. terms:

$$i\frac{2\tau_{\mathrm{D}7}k^2}{\mathcal{V}}\int_{\mathbb{R}^{1,3}}\mathcal{C}_\alpha^{I\bar{J}}v^\alpha \mathrm{d}w_I\wedge *_4\mathrm{d}\overline{w}_{\bar{J}}$$

$$\mathcal{C}_\alpha^{I\bar{J}} = \int_{\mathcal{S}_4}P\left[\omega_\alpha\right]\wedge W^I\wedge\overline{W}^{\bar{J}}$$

$$J^{\mathrm{CY}} = v^\alpha\omega_\alpha$$

Couple to Kähler moduli as

$$T_\alpha + \overline{T}_\alpha = \frac{3}{2}\mathcal{K}_\alpha + 6i\kappa_4^2\tau_{\mathrm{D}7}k^2\mathcal{C}_\alpha^{I\bar{J}}w_I\overline{w}_{\bar{J}}$$

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

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

see again Jockers and Louis '04

Warped EFT

- Is all this compatible with the closed string results?
- Wilson line moduli $W^I \qquad I = 1, \ldots, h^{(0,1)}(\mathcal{S}_4)$

Warped kin. terms:

$$i\frac{2\tau_{\rm D7}k^2}{\mathcal{V}_{\mathbf{w}}}\int_{\mathbb{R}^{1,3}} \mathcal{C}_\alpha^{I\bar{J}} v^\alpha {\rm d}w_I \wedge *_4 {\rm d}\overline{w}_{\bar{J}}$$

$$\mathcal{C}_\alpha^{I\bar{J}} = \int_{\mathcal{S}_4} P\left[\omega_\alpha\right] \wedge W^I \wedge \overline{W}^{\bar{J}}$$

$$J^{\rm CY} = v^\alpha \omega_\alpha$$

Suggest the following def. for “warped Kähler modulus”

$$T_\alpha^{\mathbf{w}} + \overline{T}_\alpha^{\mathbf{w}} = \frac{3}{2}\mathcal{I}_{\alpha\beta\gamma}^{\mathbf{w}} v^\beta v^\gamma + 6i\kappa_4^2\tau_{\rm D7}k^2\mathcal{C}_\alpha^{I\bar{J}} w_I \overline{w}_{\bar{J}}$$

$$\mathcal{I}_{\alpha\beta\gamma}^{\mathbf{w}} = \int_{X^6} Z\, \omega_\alpha \wedge \omega_\beta \wedge \omega_\gamma \quad \Rightarrow \quad \mathcal{V}_{\mathbf{w}} = \frac{1}{6}\mathcal{I}_{\alpha\beta\gamma}^{\mathbf{w}} v^\alpha v^\beta v^\gamma$$

Warped EFT

- Is all this compatible with the closed string results?
- In addition, for a single Kähler modulus Λ we have that

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

the fluctuation of such modulus is $Z(x,y) = Z_0(y) + c(x)$

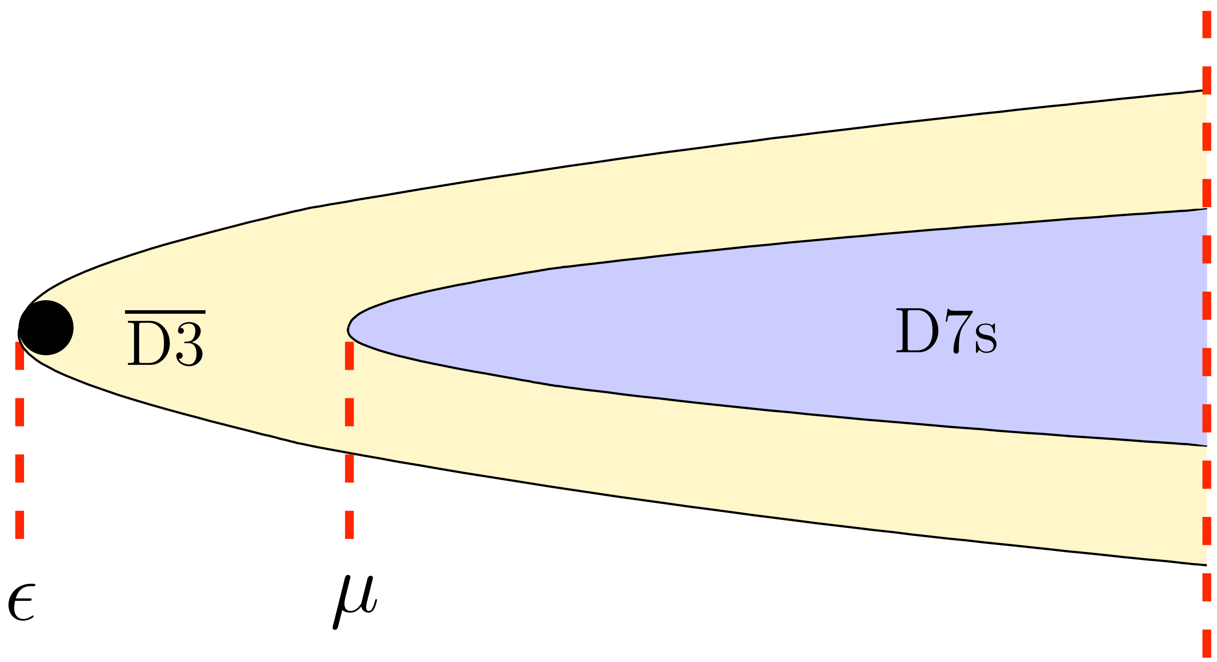
Giddings and Maharana '05

$$\Rightarrow \mathcal{V}_{\rm w}(x) = \mathcal{V}_{\rm w}^0 + c(x)\mathcal{V}_{\rm CY} \Rightarrow K \simeq -3\ln\left(c + \frac{\mathcal{V}_{\rm w}^0}{\mathcal{V}_{\rm CY}}\right) - 3\ln\frac{\mathcal{V}_{\rm CY}}{v^\Lambda}$$

reproduces Frey, Torroba, Underwood, Douglas '08
Chen, Nakayama, Shiu, 09

Holographic SUSY Breaking

McGuirk, GS, Sumitomo, in progress



Strongly coupled hidden sector ⟺ Warped Throat

Metastable ~~SUSY~~ state ⟺ Backreacted $\overline{\text{D3}}$ background

Messengers ⟺ 37 strings

Visible sector Gauge Multiplets ⟺ D7-brane fields

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

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

DeWolfe, Kachru, Mullugan

one finds the leading gravity computation gives vanishing gaugino mass.

Benini, Dymarsky, Franco, Kachru, Simic, Verlinde

Holographic SUSY Breaking

McGuirk, GS, Sumitomo, in progress

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

R-symmetry: $z_i \to e^{-i\alpha} z_i$ exact as $\epsilon \to 0$

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 $Z^{3/8}\eta_+$ Marchesano, McGuirk, GS

Gaugino mass: $\mathrm{Tr}(\lambda^2)\left(G^3_{\overline{123}}\right)^*$

c.f. Camara, Ibanez, Uranga
See also: Grana, Grimm, Jockers, Louis; Lust, Reffert, Stieberger

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

Open+Closed String Fluctuations

Chen, Nakayama, GS

$$\begin{aligned} \mathrm{P}(g)_{\mu\nu} &= e^{2A(Y,u)+2\Omega(u)}\left\{\tilde{g}_{\mu\nu}(x) + 2\partial_\mu\partial_\nu u^I(x)\mathbf{K}_I(Y) + 2\mathbf{B}_{iI}(Y)\partial_\mu u^I(x)\partial_\nu Y^i\right\} \\ &+ e^{-2A(Y,u)}\tilde{g}_{ij}(Y,u)\partial_\mu Y^i \partial_\nu Y^j \,. \end{aligned}$$

suggests a convenient gauge B=0

Hamiltonian constraints:

$$D^M\left(h^{-1/2}\pi_{M\alpha}\right) = 0\,,$$

$$D^M(h^{-1/2}\pi_{Mi}) + \kappa_{10}^2\delta^{(6)}(y-Y)\frac{P_i}{\sqrt{h}} = 0\,.$$

Combined Kahler potential:

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

where $$\rho = \left(c + \frac{\gamma}{2}k(Y,\overline{Y})\right) + i\chi\,.$$

$$\underbrace{c}_{\text{“breathing mode”}} \qquad \underbrace{\chi}_{\text{axion}}$$

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