Generalized N=0 vacua

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In collaboration with
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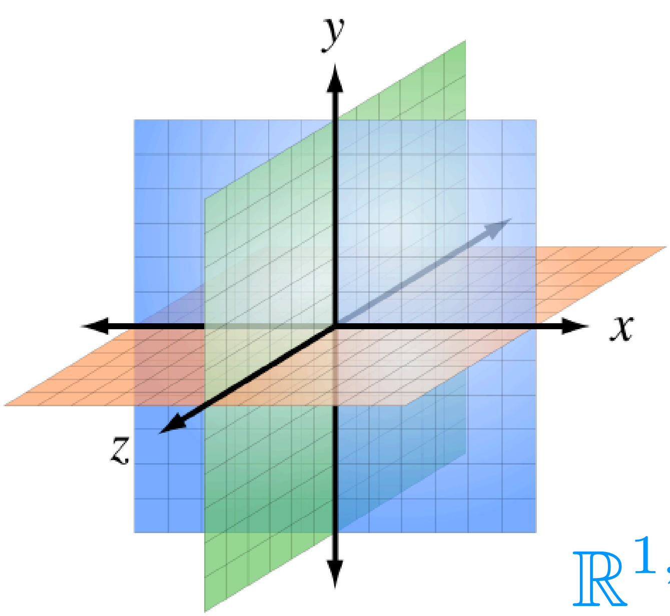
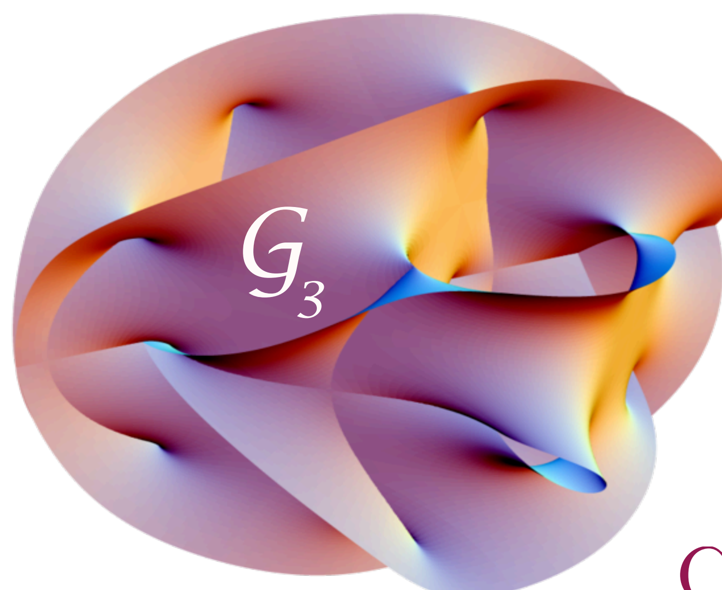
Motivation

- Some significant progress in string phenomenology has been based in exploring new and more general string vacua
- Classical example: type IIB on a warped Calabi-Yau, threaded by background fluxes



$\mathbb{R}^{1,3}$ $\times_w$



CY_3

Motivation

- Some significant progress in string phenomenology has been based in exploring new and more general string vacua
- Classical example: type IIB on a warped Calabi-Yau, threaded by background fluxes
  - Moduli stabilization — *Dasgupta, Rajesh, Sethi'99*; *Kachru, Schulz, Trivedy'02*
  - Randall-Sundrum scenario — *Giddings, Kachru, Polchinski'01*
  - SUSY-breaking
  - de Sitter vacua — *Kachru, Kallosh, Linde, Trivedi'03*; *Balasubramanian, Berglund, Conlon, Quevedo'05*
  - Inflationary scenarios — *Kachru, Kallosh, Linde, Maldacena, McGreevy, Trivedi'03*

Motivation

- In this setup, at the 10D supergravity level
  - $\mathcal{N}$=1 and $\mathcal{N}$=0 vacua share the same geometry

$$ds^2 = e^{2A} ds^2_{\mathbb{R}^{1,3}} + e^{-2A+\Phi} ds^2_{X_6}$$

  - The flux introduces a new scale m_{flux}
  - The SUSY-breaking parameter is a geom. quantity $\mathcal{G}_3^{(0,3)}$
- By considering $\mathcal{N}$=0 vacua and some stringy effects
  - D-instantons
  - α' corrections
  - anti-D3-branes

... one may obtain de Sitter vacua

Kachru, Kallosh, Linde, Trivedi '03
Balasubramanian, Berglund, Conlon, Quevedo '05

Motivation

- If we neglect the warp factor
  - We can understand 4D physics in terms of the CY light fields, Kähler potential, and a flux-induced superpotential

$$W = \int_{X_6} \mathcal{G}_3 \wedge \Omega$$

Gukov, Vafa, Witten '99

  - SUSY-breaking is modulus dominated $\langle F^T \rangle \neq 0$
  - The scalar pot. does not depend on $\langle F^T \rangle \Rightarrow$ no-scale vacuum

- On the other hand the warp factor can have important effects
  - It will modify the spectrum of light fields
  - It will modify the Kähler potential

see Shiu's talk

  - It is essential to create hierarchies, suppress soft terms and to uplift to de Sitter via anti-D3-branes

Motivation

Questions:

Can we find similar families of N=0 vacua?

Are they all no-scale?

Which new features can we obtain?

- These questions are hard to answer even in supergravity:
  - We need to solve e.o.m. which are 2nd order
  - We need to check stability

Towards new $\mathcal{N}=0$ vacua

Towards new $\mathcal{N}$=0 vacua

- Main strategy in the literature:
  - Minimize a flux-inspired D=4 effective potential V_{flux}
  - Guess the 10D geometry from its minima and K, W_{flux}

see Camara's talk

Towards new $\mathcal{N}$=0 vacua

- Main strategy in the literature:
  - Minimize a flux-inspired D=4 effective potential V_{flux}
  - Guess the 10D geometry from its minima and K, W_{flux}

see Camara's talk

- However:
  - We are neglecting all kinds of warp factor effects
  - We do not know if W_{flux} captures all the light degrees of freedom of the theory

$\Rightarrow$ We could be missing important 4D physics!!!

Towards new $\mathcal{N}$=0 vacua

Idea:

Construct N=0, 10D backgrounds similar to the warped Calabi-Yau case
Analyze later on their 4D physics

Generalized geometry

- What is the right way to generalize $\mathcal{N}$=0 warped Calabi-Yau?

$$\Downarrow$$

Idea: use generalized complex geometry

see Louis' talk

- Basically, this amounts to take the background "Killing" spinor ϵ and express it in terms of polyforms

$$\epsilon = \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \end{pmatrix} \qquad \epsilon_i = \zeta_i \otimes \eta_i + \zeta_i^* \otimes \eta_i^*$$

$$\{\eta_1, \eta_2\} \quad \leftrightarrow \quad \{\Psi_1, \Psi_2\} \qquad \left\{ \begin{array}{lcl} \Psi_1 & = & \psi_0 + \psi_2 + \psi_4 + \psi_6 \\ \Psi_2 & = & \psi_1 + \psi_3 + \psi_5 \end{array} \right.$$

Generalized geometry

- What is the right way to generalize $\mathcal{N}$=0 warped Calabi-Yau?

$$\Downarrow$$

Idea: use generalized complex geometry

- Basically, this amounts to take the background “Killing” spinor ϵ and express it in terms of polyforms

- This can be done in $\mathcal{N}$=1 backgrounds and in backgrounds with approximate SUSY, like in $\mathcal{N}$=0 wCY/F-theory compactifications

see also Graña, Louis, Waldram '05

GKP from GCG

GKP from GCG

- The e.o.m. constraints found by GKP are *see also Graña and Polchinski'00*

$$
\begin{aligned}
*_6\mathcal{G}_3 &= i\mathcal{G}_3 \\
*_6 de^{\Phi-4A} &= F_5 \\
\bar{\partial}\tau &= 0
\end{aligned}
$$

GKP from GCG

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see also Graña and Polchinski '00

$$\begin{aligned} *_6\mathcal{G}_3 &= i\mathcal{G}_3 \\ *_6 de^{\Phi-4A} &= F_5 \\ \bar{\partial}\tau &= 0 \end{aligned}$$

- These can be rewritten as:

$$d_H\left[e^{4A-\Phi}\mathrm{Re}\left(e^{iJ}\right)\right] = e^{4A}\tilde{*}_6 F_{\mathrm{RR}}$$

$$\begin{aligned} J &= e^{\Phi-2A} J^{X_6} \\ F_{\mathrm{RR}} &= F_1 + F_3 + F_5^{\mathrm{int}} \end{aligned}$$

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$$\Downarrow$$

$$d_H\left[e^{4A-\Phi}\mathrm{Re}\,\Psi_1\right] = e^{4A}\tilde{*}_6 F_{\mathrm{RR}}$$

$$\Psi_1^{\mathrm{wCY}} = e^{iJ}$$

GKP from GCG

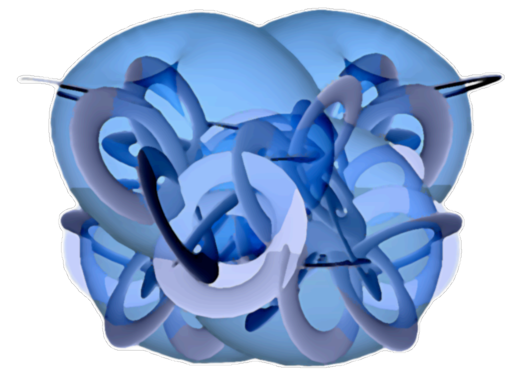
- $d_H\left[e^{4A-\Phi}\mathrm{Re}\,\Psi_1\right] = e^{4A}\tilde{*}_6 F_{\mathrm{RR}}$ is a differential condition satisfied by general $\mathcal{N}$=1 type II vacua

Graña, Minasian, Petrini, Tomasiello '05

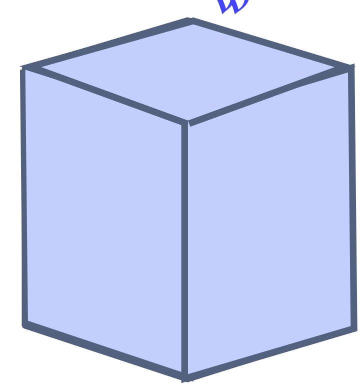
- It has also a nice D=4 interpretation

Martucci '06

  - $e^{4A-\Phi}$ Re Ψ_1 is a generalized calibration for space-time filling probe D-branes
  - This calibration is "closed" when the condition above is satisfied
  - ➡ A calibrated D-brane minimizes its energy with respect to any continuous deformation



$X_{\mathfrak{w}}$



$\Rightarrow$ **BPS lower bound** $\mathcal{V}(\Sigma, \mathcal{F})_{\mathrm{BPS}} \leq \mathcal{V}(\Sigma', \mathcal{F}')$

BPS bounds

- BPS bounds for D-branes are usual in $\mathcal{N}$=1 backgrounds, but they can also appear in absence of bulk supersymmetry

- In the present context

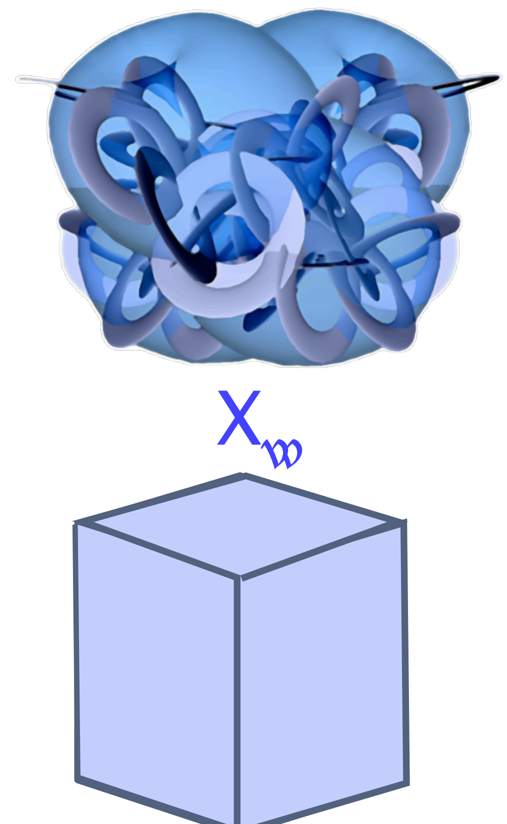
  BPS bound $\Leftrightarrow$ $\exists$ gen. calibration ω

- If the latter is true everything works like in $\mathcal{N}$=1 backgrounds $\Rightarrow$ same BPS conditions

- In the GKP case $\omega^{sf} = \mathrm{Re}\, e^{iJ}$, so the BPS D-branes are

  - D3-branes

  - D7-branes with $\mathcal{F}^{SD} = 0$



More GKP from GCG

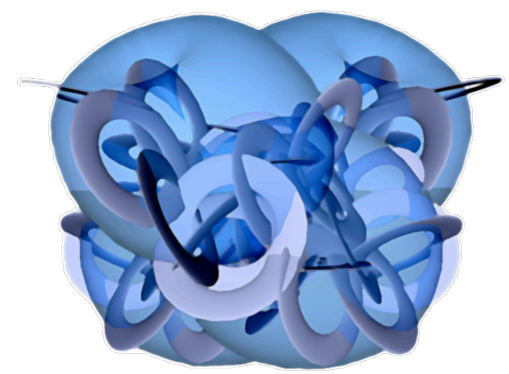
- What about other kinds of D-branes?
- The wCY/F-theory construction implies that
  - $dJ^{X_6} = d(e^{2A-\Phi} J) = 0$
  - H harm. + $b_1(X_6) = 0 \Rightarrow H \wedge J = 0$

➡ $$d_H\left[e^{2A-\Phi}\mathrm{Im}\left(e^{iJ}\right)\right] = 0$$

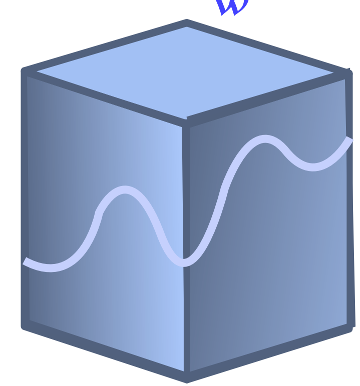
$$\Updownarrow$$

$$d_H\left[e^{2A-\Phi}\mathrm{Im}\,\Psi_1\right] \equiv d_H\omega^{\rm st} = 0$$

$\Rightarrow$ 4D strings also develop a BPS lower bound



$X_{\mathfrak{w}}$



More GKP from GCG

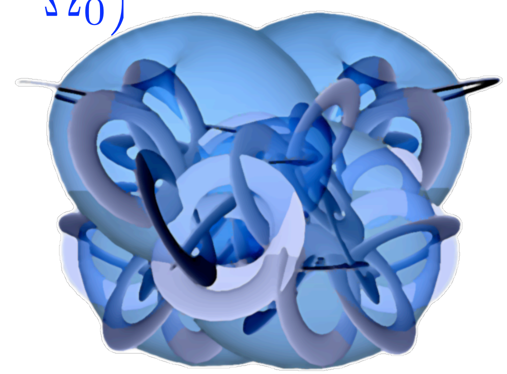
- There is a last kind of calibrated D-brane in $\mathcal{N}$=1 vacua : 4D domain walls

Martucci '06

- The gen. calibration in this case is

$$\omega^{DW} = e^{3A-\Phi}\mathrm{Re}\left(e^{i\theta}\Psi_2\right) = e^{-\Phi/2}\mathrm{Re}\left(e^{i\theta}\Omega_{X_6}\right) \equiv \mathrm{Re}\left(e^{i\theta}\Omega_0\right)$$

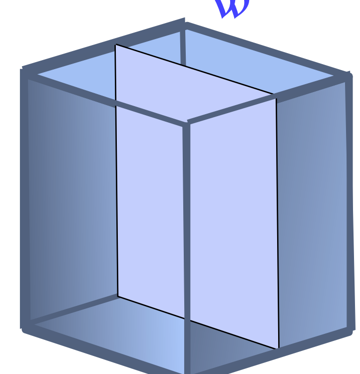
where Ω_0 is a closed, holomorphic (3,0)-form



Is $d_H\omega^{DW}=0$?

  - $d\,\Omega_0 = 0$ ⇒ D5-branes wrapping SL's are BPS like in $\mathcal{N}$=1 vacua
  - $H \wedge \Omega_0 = 0 \Leftrightarrow H^{(0,3)} = 0 \Leftrightarrow \mathcal{G}_3^{(0,3)} = 0$!! ⇒ D7-branes in coisotropic 5-cycles are not BPS for $\mathcal{N}$=0 vacua

$X_{\mathfrak{w}}$



⇒ BPSness breaks down for 4D DW

Generalized SUSY breaking

- For general $\mathcal{N}$=1 backgrounds we have

Graña, Minasian, Petrini, Tomasiello '05

Martucci '06

Equation	D=4 interpretation
$d_H\left(e^{4A-\phi}\mathrm{Re}\Psi_1\right) = e^{4A}F_{RR}$	gauge BPSness
$d_H\left(e^{2A-\phi}\mathrm{Im}\Psi_1\right) = 0$	D-string BPSness
$d_H\left(e^{3A-\phi}\Psi_2\right) = 0$	Domain Wall BPSness

- In a warped Calabi-Yau

$$\Psi_1^{\mathrm{wCY}} = e^{iJ} \qquad \Psi_2^{\mathrm{wCY}} = \Omega_0$$

Generalized SUSY breaking

- For an $\mathcal{N}$=0 warped Calabi-Yau

Equation	D=4 interpretation
$d_H\left(e^{4A-\phi}\mathrm{Re}\Psi_1\right) = e^{4A}F_{RR}$	gauge BPSness
$d_H\left(e^{2A-\phi}\mathrm{Im}\Psi_1\right) = 0$	D-string BPSness
$d_H\left(e^{3A-\phi}\Psi_2\right) \neq 0$	DW non-BPSness

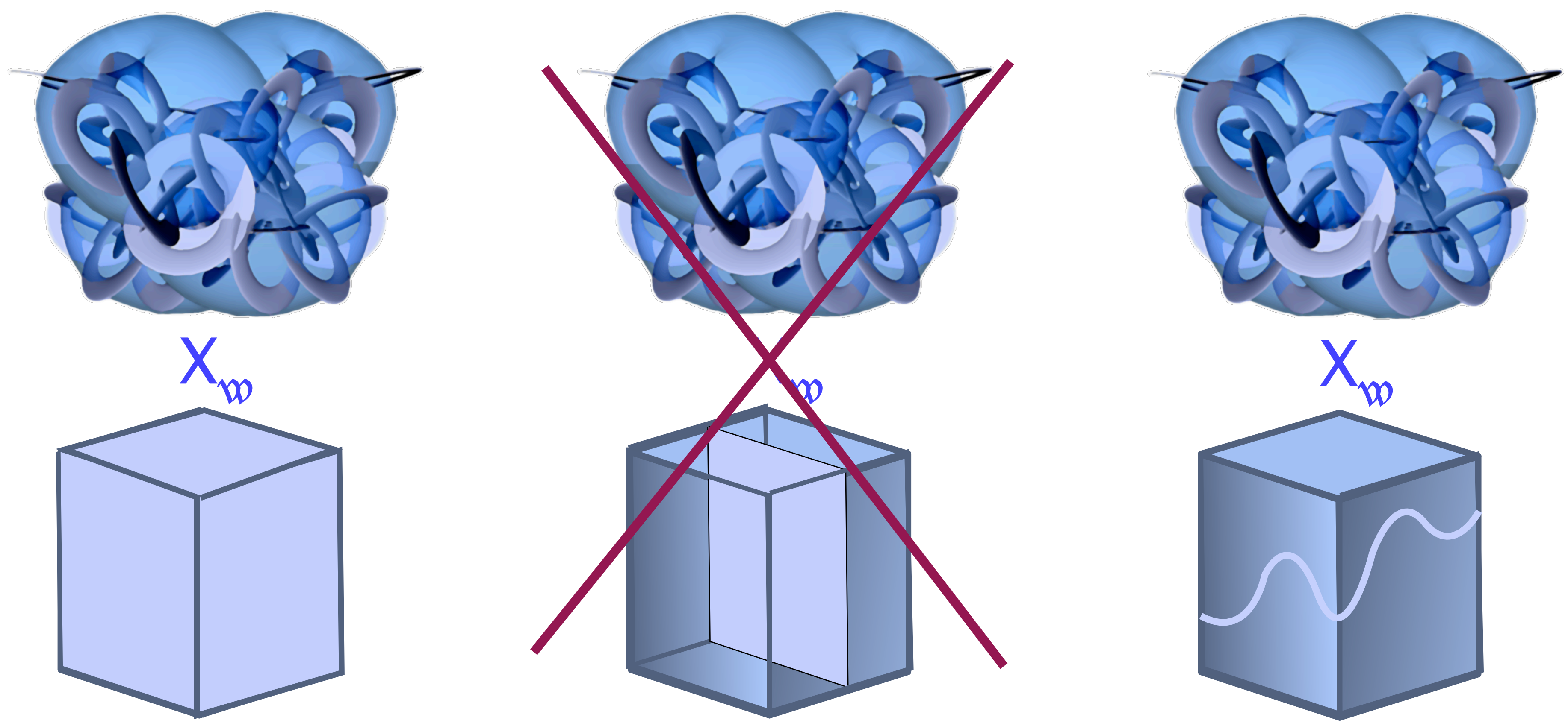
- In a warped Calabi-Yau

$$\Psi_1^{\mathrm{wCY}} = e^{iJ} \qquad \Psi_2^{\mathrm{wCY}} = \Omega_0$$

Generalized SUSY breaking

- We will focus on $\mathcal{N}=0$ backgrounds that fulfill the gauge and D-string BPSness conditions but not the DW BPSness cond.

DWSB backgrounds



Generalized SUSY breaking

- We will focus on $\mathcal{N}$=0 backgrounds that fulfill the gauge and D-string BPSness conditions but not the DW BPSness cond.

DWSB backgrounds

- If such background leads to a D=4 effective theory the BPSness conditions will imply

  - gauge BPSness ⇒ stable gauge theories, no tachyons
  - string BPSness ⇒ no D-terms generated by fluxes

Koerber and Martucci '07

DWSB

- In terms of gravitino and dilatino var. DWSB gives a constrained, but still complicated, SUSY-breaking ansatz. We can consider the subansatz

$$\delta\psi_\mu = r\,\Gamma_\mu\zeta\otimes\begin{pmatrix}\eta_1^*\\ \eta_2^*\end{pmatrix} + cc.$$

$$\delta\psi_m = -r\,\zeta\otimes\begin{pmatrix}\Lambda_{mn}\Gamma^n\eta_1^*\\ \Lambda_{nm}\Gamma^n\eta_2^*\end{pmatrix} + cc.$$

$$\delta\lambda' = -2r\,\zeta\otimes\begin{pmatrix}\eta_1^*\\ \eta_2^*\end{pmatrix} + cc.$$

where $\Lambda^m{}_n$ is a local O(6) transformation that, in the spinorial rep. satisfies

$$\eta_1 = i\Lambda\eta_2$$

- The DW non-BPSness condition then reads

$$d_H\left(e^{3A-\phi}\Psi_2\right) = ire^{3A-\phi}\left[\mathrm{Im}\Psi_1 + \frac{1}{2}\Lambda_{mn}\Gamma^m(\mathrm{Im}\Psi_1)\Gamma^n\right]$$

DWSB

- We can further simplify things by assuming that Λ has the form of a certain "D-brane rotation"
  - $T_{X_6} = T_\Pi \oplus T_\Pi^\perp$
  - $R \in \Lambda T^*_\Pi$

$$\left.\begin{array}{l} T_{X_6} = T_\Pi \oplus T_\Pi^\perp \\ R \in \Lambda T^*_\Pi \end{array}\right\} \quad \Lambda = 1_\perp - (g|_\Pi + R)^{-1}(g|_\Pi - R)$$

- The DWSB condition then reads

$$d_H(e^{3A-\Phi}\Psi_2) = 4i\,r\,(-)^{|\Psi_2|}e^{3A-\Phi}\frac{\sqrt{\det g|_\Pi}}{\sqrt{\det(g|_\Pi + R)}}e^{-R} \wedge \sigma(d\mathrm{Vol}_\perp)$$

  - T_Π is integrable and $dR = H|_\Pi \Rightarrow$ generalized foliation
  - A gauge D-brane wrapping Π and with $\mathcal{F} = R$ is BPS (aligned)
  - Because of d_H-exactness *r* cannot be any function

GKP as DWSB

- This subansatz contains the warped Calabi-Yau case

$$\Psi_1^{\mathrm{wCY}} = e^{iJ} \qquad \Psi_2^{\mathrm{wCY}} = \Omega_0$$
$$\mathcal{G}^{(0,3)} = -\frac{i}{2} r e^{-3A}\,\bar{\Omega}_0 \qquad \Lambda_{mn} = g_{mn}$$

- And $d_H(e^{3A-\Phi}\Psi_2)$ = six-form ⇒ Π = point ⇒ aligned D3-branes
- In this case, r and Λ are related to 4D quantities
  - $r\,e^{-3A} \approx W_0 \approx F_T$ (T : overall Kähler modulus)
  - Λ_{mn} structure of soft terms on D7-branes
- Does this apply to more general DWSB vacua?

Effective potential

- But... are these backgrounds actually vacua?
- At the supergravity level, one can check if the 10D e.o.m.'s are satisfied by extremizing the effective 4D action

warped internal vol.

$$S_{\rm eff} \;=\; \int_{X_4} d^4x\sqrt{-g_4}\Big(\frac{1}{2}\,\mathcal{N}R_4 - 2\pi\mathcal{V}_{\rm eff}\Big)$$

4D curvature

$$\mathcal{V}_{\rm eff} \;=\; \int_{X_6} d{\rm Vol}_6\, e^{4A}\Big\{e^{-2\Phi}[-R_6 + \frac{1}{2}H^2 - 4(d\Phi)^2 + 8\nabla^2 A + 20(dA)^2] - \frac{1}{2}F^2_{\rm RR}\Big\}$$

closed strings

$$+ \sum_{i\in \text{loc. sources}} \tau_i\Big(\int_{\Sigma_i} e^{4A-\Phi}\sqrt{\det(g|_{\Sigma_i} + \mathcal{F}_i)} - \int_{\Sigma_i} C^{\rm el}|_{\Sigma_i}\wedge e^{\mathcal{F}_i}\Big)$$

open strings
+ O-planes

Effective potential

- Extremizing S_{eff} one obtains the full set of e.o.m.'s to be imposed on a type II flux compactification to 4D of the form

$$ds_{10}^2 = e^{2A(y)} ds_{X_4}^2 + g_{mn} dy^m dy^n$$

- For instance, one can derive that the external 4D space must be Einstein, with $R_4 = 8\pi\, \mathcal{V}_{eff}/\mathcal{N}$

- One can also rewrite $\mathcal{V}_{eff}$ in terms of Ψ_1 and Ψ_2, and check that SUSY backgrounds automatically satisfy the e.o.m.'s

see also Koerber and Tsimpis '07

- For our DWSB subansatz to Minkowski, only the variation of the B-field and internal metric give non-trivial constraints, which however are automatically satisfied in simple examples

Tachyons?

- This effective potential is also useful to exclude the presence of tree-level closed string tachyons
- For the DWSB subansatz above two conditions need to be imposed to make $\mathcal{V}_{\text{eff}}$ semi-definite positive
- Namely, when going off-shell
  - No vectors under SU(3) x SU(3) must appear in $\delta\lambda'$
  - X_6 must still be a generalized foliation

$$d_H(e^{3A-\Phi}\Psi_2) = ir\tilde{\jmath}_{(\Pi,R)}$$

Tachyons?

- We then obtain:

$$
\begin{aligned}
\mathcal{V}_{\rm eff}^{\rm DWSB} \quad = \quad & \frac{1}{2}\int_{X_6} d\mathrm{Vol}_6\, e^{4A}\left[F_{\rm RR} - e^{-4A} d_H (e^{4A-\Phi}\mathrm{Re}\,\Psi_1)\right]^2 \\
& + \frac{1}{2}\int_{X_6} d\mathrm{Vol}_6 \left[d_H (e^{2A-\Phi}\mathrm{Im}\,\Psi_1)\right]^2 \\
& + \frac{1}{2}\int_{X_6} e^{-2A}|r|^2\left[\langle \tilde{*}_6 \tilde{\jmath}_{(\Pi,R)}, \tilde{\jmath}_{(\Pi,R)}\rangle - \frac{|\langle \Psi_1, \tilde{\jmath}_{(\Pi,R)}\rangle|^2}{d\mathrm{Vol}_6}\right] \\
& + \sum_{i\in \text{D-branes}} \tau_i \int_{X_6} e^{4A-2\Phi}\Big(d\mathrm{Vol}_6\, \rho_i^{\rm loc} - \langle \mathrm{Re}\,\Psi_1, j_i\rangle\Big)
\end{aligned}
$$

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\mathcal{V}_{\text{eff}}^{\text{DWSB}} \;=\;& \frac{1}{2}\int_{X_6} d\text{Vol}_6\, e^{4A}\left[F_{\text{RR}} - \cancel{e^{-4A} d_H(e^{4A-\Phi}}\text{Re}\,\Psi_1)\right]^2 \quad \textit{gauge BPSness} \\
&+ \frac{1}{2}\int_{X_6} d\text{Vol}_6 \left[d_H(e^{2A-\Phi}\text{Im}\,\Psi_1)\right]^2 \\
&+ \frac{1}{2}\int_{X_6} e^{-2A}|r|^2\left[\langle \tilde{*}_6 \tilde{\jmath}_{(\Pi,R)}, \tilde{\jmath}_{(\Pi,R)}\rangle - \frac{|\langle \Psi_1, \tilde{\jmath}_{(\Pi,R)}\rangle|^2}{d\text{Vol}_6}\right] \\
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&+ \frac{1}{2}\int_{X_6} d\text{Vol}_6\,\left[d_H\cancel{\big(e^{2A-\Phi}\,\text{Im}}\,\Psi_1\big)\right]^2 \\
&+ \frac{1}{2}\int_{X_6} e^{-2A}|r|^2\left[\langle \tilde{*}_6 \tilde{j}_{(\Pi,R)}, \tilde{j}_{(\Pi,R)}\rangle - \frac{|\langle \Psi_1, \tilde{j}_{(\Pi,R)}\rangle|^2}{d\text{Vol}_6}\right] \\
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string BPSness

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\end{aligned}
$$

string BPSness

calibration cond.

Tachyons?

- We then obtain:

$$\mathcal{V}_{\text{eff}}^{\text{GKP}} = \frac{1}{4}\int_{X_6} d\text{Vol}_6\, e^{4A}\left|(1+i*_6)\mathcal{G}_3\right|^2$$

Shiu et al '08

$$\begin{aligned}
\mathcal{V}_{\text{eff}}^{\text{DWSB}} \;=\;& \frac{1}{2}\int_{X_6} d\text{Vol}_6\, e^{4A}\left[F_{\text{RR}} - e^{-4A} d_H\left(e^{4A-\Phi}\,\text{Re}\,\Psi_1\right)\right]^2 \\
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BPSness

string

calibration cond.

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\end{aligned}
$$

gauge BPSness

string BPSness

calibration cond.

- Notice that on-shell $\mathcal{V}_{\mathrm{eff}}$ does not depend on r

$\Rightarrow$ No-scale structure

4D Interpretation

- Without truncating the theory, one may give a 4D interpretation of these vacua by using a 4D Weyl invariant formalism *Koerber and Martucci '07*
- One then finds a 4D gravitino mass of the form

$$\mathcal{N} m_{3/2} = \int_{X_6} r\, e^{3A-2\Phi} d\mathrm{Vol}_6$$

- An F-term proportional to *r* for a field Δ ["orthogonal" to $\Delta^\perp \sim d_H(e^{3A-\Phi}\Psi_2)$]
  - ➡ A superpot. W independent of Δ ⇒ no-scale structure
  - ➡ Non-vanishing gaugino masses for all but aligned D-branes whose gauge kinetic function depends on $\Delta^\perp$
  - ➡ An F-term pattern that can be understood as Δ-dominated, quaternionic SUSY breaking in the constant warp factor limit

What else is in the book?

- The DWSB subansatz contains many classes of vacua beyond the GKP class. One can describe their 10D geometry and provide explicit examples based on twisted-tori and β-deformed bkgs.
- One can compute moduli mediated soft-term masses microscopically, by using the fermionic D-brane action
- One can include anti-D-branes into these backgrounds and compute their effective potential
- One can generalize the DWSB ansatz to AdS_4 compactifications
- One can follow a complementary approach to construct $\mathcal{N}$=0 vacua, based on integrability techniques, and construct novel classes of AdS_4 vacua in this way

Conclusions

- We have discussed a very particular class of $\mathcal{N}$=0 backgrounds, where the 4D BPS bounds of $\mathcal{N}$=1 vacua are partially present
- We have considered backgrounds which contain the BPS bounds for gauge D-branes, with model-building applications in mind
- We have also imposed D-flatness in our backgrounds, aiming to reproduce the features of warped Calabi-Yau/F-theory $\mathcal{N}$=0 vacua
- We have achieved this by considering a very particular subansatz, but this is clearly only the tip of the iceberg. Many more vacua with different features are out there
- Our discussion has remained in the supergravity limit of type II theories, but the main idea of classifying vacua via their 4D BPS bounds is general. It could be applied to other $\mathcal{N}$=0 vacua!!

Schellekens' talk