Type IIA flux vacua with mobile D6-branes

Dagoberto Escobar

Instituto de Física Teórica UAM-CSIC

X CPAN DAYS
Salamanca, October 2018

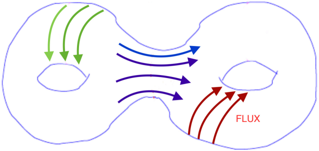
Based on D.E., F. Marchesano, W. Staessens (to appear)

Outline

1. Motivation
2. Overview of Type IIA flux compactification
3. New perspectives on Type IIA flux vacua
4. Flux-induced soft terms on D6-branes
5. Conclusions

Why Type IIA flux compactifications?

Turning on background fluxes



$$\Longrightarrow \qquad W_{\rm IIA} = \int_{\mathcal{M}_6} \Omega_c \wedge H + F \wedge e^{J_c}$$

Grimm et al'05

Phenomenologically very attractive

- Moduli stabilization
- SUSY breaking

Richness of background fluxes

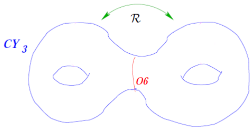
- Fluxes F_0, F_2, F_4, F_0 and H can stabilise all moduli classically in (non) supersymmetric AdS_4, DeWolfe et al. '05, Cámara et al. '05 , Villadoro et al. '05
- RR and NS fluxes together with non-geometric fluxes can stabilise all moduli in supersymmetric Minkowski Micu et al. '07

Type IIA flux compactifications

Type IIA compactified on CY orientifolds   Grimm & Louis '05

Massless closed string spectrum

- $h_{-}^{(1,1)}$ Kähler moduli T^a
- $h^{(2,1)}+1$ complex structure moduli $N_{\star}^{K}, U_{\star\Lambda}$
- $h_{+}^{(1,1)}$ vector multiplets A^{α}



The Kähler potential

$$K = -\log \frac{i}{3!}\mathcal{K}_{abc}(T^a-\bar{T}^a)(T^b-\bar{T}^b)(T^c-\bar{T}^c) - \log \mathrm{e}^{-4\mathrm{D}}$$

Flux-induced superpotential $W_{\mathrm{IIA}} = W_K + W_{\mathrm{Q}}$

$$\begin{aligned} W_{\mathrm{K}} &= e_0 + e_a T^a + \frac{1}{2}\mathcal{K}_{abc} q^a T^b T^c + \frac{m_0}{6}\mathcal{K}_{abc} T^a T^b T^c \\ W_{\mathrm{Q}} &= h_K N_{\star}^{K} + h^{\Lambda} U_{\star\Lambda} \end{aligned}$$

The axion polynomial perspective

Flux scalar potentials can be written as $V = \frac{1}{8\kappa_4^2} Z^{AB} \rho_A \rho_B$ Herráez et al. '18

Metric on the space of axion polynomials

$$Z^{AB} = 8e^K \begin{pmatrix} 4 & & & & & \\ & K^{a\bar{b}} & & & & \\ & & \frac{4}{9}\mathcal{K}^2 K_{a\bar{b}} & & & \\ & & & \frac{1}{9}\mathcal{K}^2 & \frac{2}{3}\mathcal{K} n_\star^I & \frac{2}{3}\mathcal{K} u_{\star\Lambda} \\ & & & \frac{2}{3}\mathcal{K} n_\star^J & K^{IJ} & K^{I\Sigma} \\ & & & \frac{2}{3}\mathcal{K} u_{\star\Sigma} & K^{\Lambda J} & K^{\Lambda\Sigma} \end{pmatrix}$$

Set of shift-invariant axion polynomials (related to Freed-Witten anomaly cancelation)

$$\begin{aligned} l_s\rho_0 &= e_0 + e_a b^a + \frac{1}{2}\mathcal{K}_{abc} m^a b^b b^c + \frac{m}{6}\mathcal{K}_{abc} b^a b^b b^c + h_K \xi_\star^K + h^\Lambda \xi_{\star\Lambda} \\ l_s\rho_a &= e_a + \mathcal{K}_{abc} m^b b^c + \frac{m}{2}\mathcal{K}_{abc} b^b b^c \\ l_s\tilde{\rho}^a &= m^a + m b^a \\ l_s\tilde{\rho} &= m \\ l_s\hat{\rho}_K &= h_K \\ l_s\hat{\rho}^\Lambda &= h^\Lambda \end{aligned}$$

Non-SUSY Minkowski flux vacua

Complex structure moduli $N_\star^{K\neq 0}$ are projected out   Palti et al. '08

$$K = -\log\left[\frac{4}{3}\mathcal{K}_{abc}t^a t^b t^c\right] - \log\left[2s_\star\right] - 2\log\left[\tilde{\mathcal{G}}_Q(u_{\star\Lambda})\right]$$

$$W = is_\star\hat{\rho}_0 + \rho_0 + it^a\rho_a - \frac{1}{2}\mathcal{K}_a\tilde{\rho}^a - \frac{i}{6}\mathcal{K}\tilde{\rho}$$

Mirror to Type IIB ISD flux vacua

Giddings et al '02

The scalar potential   Escobar et al. to appear

$$V = \frac{e^K}{\kappa_4^2}\underbrace{\left(4\rho_0^2 + K^{a\bar{b}}\rho_a\rho_b + \frac{4}{9}\mathcal{K}^2 K_{a\bar{b}}\tilde{\rho}^a\tilde{\rho}^b + K^{S\bar{S}}\left(\hat{\rho}_0 - \frac{i}{3}\tilde{\rho}\mathcal{K}K_S\right)^2\right)}_{\text{semi-definite positive}}$$

The absolute minimum $V = 0 \implies \rho_0 = 0,\ \rho_a = 0,\ \tilde{\rho}^a = 0,\ \hat{\rho}_0 s_\star = -\frac{1}{6}\tilde{\rho}\mathcal{K}$

$$\rho_0 = 0 \implies h_0\xi_\star^0 = -\frac{1}{m^2}\left(e_0 m^2 - \frac{1}{6}\mathcal{K}_{abc}m^a m^b m^c\right)$$

$$\tilde{\rho}^a = 0 \implies b^a = -\frac{m^a}{m}$$

$$\rho_a = 0 \implies 2me_a - \mathcal{K}_{abc}m^b m^c = 0$$

SUSY breaking in ISD flux vacua

SUSY is spontaneously broken in the CS sector

$$F^{U_{\star\Lambda}} = -2iu_{\star\Lambda} e^{\frac{1}{2}K^0} \bar{W}_0 \qquad \Longrightarrow \qquad \bar{m}_{3/2}^2 = \underbrace{m_{3/2}^2 + \frac{1}{3}V}_{\text{effective gravitino mass}}$$

corrected by vacuum energy

Apparent gravitino mass in the ρ-formalism $\quad m_{3/2}^2 = \frac{1}{\kappa_4^4} e^K \rho_A (\Pi^\dagger \ltimes \Pi)^{AB} \rho_B$

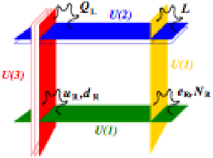
$$\Pi^\dagger \ltimes \Pi = \begin{pmatrix} 1 & 0 & -\frac{1}{2}\mathcal{K}_a & 0 & 0 & 0 \\ 0 & t^a t^b & 0 & -t^a \frac{\mathcal{K}}{6} & t^a n_\star^K & t^a u_{\star\Lambda} \\ -\frac{1}{2}\mathcal{K}_b & 0 & \frac{1}{4}\mathcal{K}_a\mathcal{K}_b & 0 & 0 & 0 \\ 0 & -t^b \frac{\mathcal{K}}{6} & 0 & \left(\frac{\mathcal{K}}{6}\right)^2 & -\frac{\mathcal{K}}{6} n_\star^K & -\frac{\mathcal{K}}{6} u_{\star\Lambda} \\ 0 & t^b n_\star^I & 0 & -n_\star^I \frac{\mathcal{K}}{6} & n_\star^I n_\star^K & n_\star^I u_{\star\Lambda} \\ 0 & t^b u_{\star\Sigma} & 0 & -u_{\star\Sigma}\frac{\mathcal{K}}{6} & u_{\star\Sigma} n_\star^K & u_{\star\Sigma} u_{\star\Lambda} \end{pmatrix}$$

$$\vec{\rho}_{ISD} = \left(0, 0, 0, \tilde{\rho}, -\frac{i}{3}\tilde{\rho}\mathcal{K}K_{U_\Lambda}\right) \qquad \Longrightarrow \qquad \bar{m}_{3/2}^2 = \frac{1}{\kappa_4^4} e^K \left(\frac{1}{3}\tilde{\rho}\mathcal{K}\right)$$

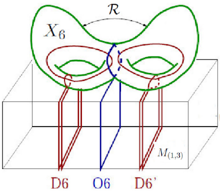
Mobile D6-branes and Supersymmetry

Adding D6-branes

- Gauge and matter fields localized at D6-branes intersections
- Source of RR fluxes



D6-branes preserving the $\mathcal{N} = 1$ supersymmetry of the bulk theory Blumenhagen et. al '02, Kachru & McGreevy '99



Π_3 is a Special Lagrangian 3-cycle

Supersymmetry conditions

- $J|_{\Pi_3} = 0, \quad \mathrm{Im}\left(e^{-i\theta}\Omega\right)|_{\Pi_3} = 0$
- $B - \frac{l_s^2}{2\pi} F = 0$

Deformations preserving SLag condition McLean '98 $\Longrightarrow b^1(\Pi_3)$ complex fields Φ^i_α

Field redefinitions and D6-brane superpotential

Mobile D6-branes modify the 4d effective action

- Complex structure moduli get modified — Carta et al. '16

$$N^K = N^K_\star + \frac{1}{2}\sum_\alpha \left(g^K_{\alpha i}\theta^i - T^a \mathbf{H}^K_{\alpha a} \right), \qquad U_\Lambda = U_{\star\Lambda} + \frac{1}{2}\sum_\alpha \left(g_{\alpha\Lambda i}\theta^i - T^a \mathbf{H}_{\alpha\Lambda a} \right)$$

$$K_Q = -2\log\left[\mathcal{G}_Q\left(n^K + \frac{1}{2}t^a \sum_\alpha \mathbf{H}^K_{\alpha\, a}, u_\Lambda - \frac{1}{2}t^a \sum_\alpha \mathbf{H}_{\alpha\,\Lambda\, a}\right)\right]$$

- Further contribution to the superpotential — Marchesano et. al '14

$$W_{\rm D6} = W^0_{\rm D6} + \sum_\alpha \Phi^i_\alpha \left(n^\alpha_{Fi} - n^\alpha_{ai} T^a \right)$$

Question

- Which kind of stable type IIA vacua exist in the presence of open string moduli?

Axion polynomials in the presence of D6-branes

Open string moduli are easily included (once geometry and field redefinitions are known)

The flux scalar potential $V = \frac{1}{8\kappa_4^2} Z^{AB} \varrho_A \varrho_B$, Herráez et al. '18

$$
Z^{AB} = 8e^K \begin{pmatrix}
4 & & & & & & & \\
& K^{a\bar{b}} & & & & & & \\
& & \frac{4}{9}\mathcal{K}^2 K_{a\bar{b}} & & & & & \\
& & & \frac{1}{9}\mathcal{K}^2 & \frac{2}{3}\mathcal{K} n_\star^I & \frac{2}{3}\mathcal{K} u_{\star\Lambda} & & \\
& & & \frac{2}{3}\mathcal{K} n_\star^J & K^{IJ} & K^{I\Sigma} & & \\
& & & \frac{2}{3}\mathcal{K} u_{\star\Sigma} & K^{\Lambda J} & K^{\Lambda\Sigma} & & \\
& & & & & & G_{\mathrm{D6}}^{ij} & \\
& & & & & & & G_{\mathrm{D6}}^{ij} t^a t^b
\end{pmatrix}
$$

Set of shift-invariant axion polynomials (related to the Hanany-Witten effect)

$$
\begin{aligned}
l_s \varrho_0 &= e_0 + e_a b^a + \frac{1}{2}\mathcal{K}_{abc} m^a b^b b^c + \frac{m}{6}\mathcal{K}_{abc} b^a b^b b^c + h_K \xi^K + h^\Lambda \xi_\Lambda + \hat{\theta}^i_\alpha (n^\alpha_{Fi} - n^\alpha_{ai} b^a) \\
l_s \varrho_a &= e_a + \mathcal{K}_{abc} m^b b^c + \frac{m}{2}\mathcal{K}_{abc} b^b b^c - n^\alpha_{ai} \hat{\theta}^i_\alpha \\
l_s \tilde{\varrho}^a &= m^a + m b^a \\
l_s \tilde{\varrho} &= m \\
l_s \hat{\varrho}_K &= h_K \\
l_s \hat{\varrho}^\Lambda &= h^\Lambda \\
l_s \varrho^\alpha_i &= n^\alpha_{Fi} - b^a n^\alpha_{ai} \\
l_s \varrho^\alpha_{ai} &= n^\alpha_{ai}
\end{aligned}
$$

Non-SUSY Minkowski flux vacua with D6-branes

Complex structure moduli $N^{K\neq 0}$ are projected out

$$
\begin{aligned}
K &= -\log\left[\frac{4}{3}\mathcal{K}_{abc}t^a t^b t^c\right] - \log\left[2s + t^a\mathbf{H}^0_{\alpha a}\right] - 2\log\left[\tilde{\mathcal{G}}_Q(2u_\Lambda - t^a\mathbf{H}_{\alpha\Lambda a})\right] \\
W &= is_\star\hat{\rho}_0 + \rho_0 + it^a e_a - \frac{1}{2}\mathcal{K}_a\tilde{\rho}^a - \frac{i}{6}\mathcal{K}\tilde{\rho} + \varrho_{ai}t^a\phi^i_\alpha + i\varrho_i\phi^i_\alpha
\end{aligned}
$$

The scalar potential   Escobar et al. to appear

$$
V = \frac{e^K}{\kappa_4^2}\underbrace{\left(4\varrho_0^2 + K_K^{a\bar{b}}\varrho'_a\varrho'_b + \frac{4}{9}\mathcal{K}^2(K_K)_{a\bar{b}}\tilde{\varrho}^{a\prime}\tilde{\varrho}^{b\prime} + K^{S\bar{S}}\left(\hat{\varrho}_0 - \tilde{\varrho}\mathcal{K}\frac{i}{3}K_S\right)^2 + G^{ij}_{\mathrm{D6}}\left[\varrho'_i\varrho'_j + t^a t^b\varrho_{ai}\varrho_{bj}\right]\right)}_{\text{semi-definite positive}}
$$

The absolute minimum $V = 0$ leads to

$$
\rho_0 = 0, \quad \rho_a = \frac{1}{2}\left(\mathbf{H}^0_{\alpha a} - f^i_a g^0_i\right)\hat{\varrho}_0, \quad \tilde{\rho}^a = \mathcal{K}^{ab}\phi^i_\alpha\varrho_{bi}, \quad \hat{\rho}_0 s_\star = -\frac{1}{6}\tilde{\rho}\mathcal{K},
$$

$$
\varrho_i = \frac{1}{2}g^0_i\hat{\varrho}_0, \qquad t^a\varrho_{ai} = 0
$$

SUSY breaking in Minkowski vacua with D6-branes

SUSY is spontaneously broken in the CS sector (CSD vacua)

$$F^{U_\Lambda} = -2iu_{\star\Lambda}e^{\frac{1}{2}K^0}\bar{W}_0 \qquad \Longrightarrow \qquad \bar{m}^2_{3/2} = m^2_{3/2} + \frac{1}{3}V$$

Apparent gravitino mass in the ρ-formalism $\quad m^2_{3/2} = \frac{1}{\kappa_4^4}e^K\varrho_A(\Pi^\dagger \ltimes \Pi)^{AB}\varrho_B$

$$\Pi^\dagger \ltimes \Pi = \begin{pmatrix} 1 & 0 & -\frac{1}{2}\mathcal{K}_a & 0 & 0 & 0 & 0 & t^a\phi^i \\ 0 & t^a t^b & 0 & -t^a\frac{\mathcal{K}}{6} & t^a n^K & t^a u_\Lambda & t^a\phi^i & 0 \\ -\frac{1}{2}\mathcal{K}_b & 0 & \frac{1}{4}\mathcal{K}_a\mathcal{K}_b & 0 & 0 & 0 & 0 & -\frac{1}{2}\mathcal{K}_b t^a\phi^i \\ 0 & -t^b\frac{\mathcal{K}}{6} & 0 & \left(\frac{\mathcal{K}}{6}\right)^2 & -\frac{\mathcal{K}}{6}n^K & -\frac{\mathcal{K}}{6}u_\Lambda & -\frac{\mathcal{K}}{6}\phi^i & 0 \\ 0 & t^b n^I & 0 & -n^I\frac{\mathcal{K}}{6} & n^I n^K & n^I u_\Lambda & n^I\phi^i & 0 \\ 0 & t^b u_\Sigma & 0 & -u_\Sigma\frac{\mathcal{K}}{6} & u_\Sigma n^K & u_\Sigma u_\Lambda & u_\Sigma\phi^i & 0 \\ 0 & t^b\phi^j & 0 & -\frac{\mathcal{K}}{6}\phi^j & n^K\phi^j & u_\Lambda\phi^j & \phi^i\phi^j & 0 \\ t^b\phi^j & 0 & -\frac{1}{2}\mathcal{K}_b t^a\phi^j & 0 & 0 & 0 & 0 & t^a t^b\phi^i\phi^j \end{pmatrix}$$

$$\vec{\varrho}_{CSD} = \left(0,0,0,\tilde{\rho},-\frac{i}{3}\tilde{\rho}\mathcal{K}K_{U_\Lambda},0,0\right) \qquad \Longrightarrow \qquad \bar{m}^2_{3/2} = \frac{1}{\kappa_4^4}e^K\left(\frac{1}{3}\tilde{\rho}\mathcal{K}\right)$$

Flux-induced soft terms on D6-branes

Soft SUSY breaking terms for the (non)-chiral matter fields localized at D6-branes intersections are generated (gravity mediation)

Soft masses, A-terms, B-terms and gaugino masses can be written as

$$\begin{aligned} m_\alpha^2 &= \frac{1}{\kappa_4^2} e^{K^0} \varrho_A \left(\left(\Pi^\dagger \ltimes \Pi\right)^{AB} + \frac{1}{8} Z^{AB} - \left(\mathbb{M}^\dagger \mathcal{P} \mathbb{M}\right)^{AB} \right) \varrho_B \\ \hat{A}_{\alpha\beta\gamma} &= -i \hat{Y}_{\alpha\beta\gamma} \left(\partial_{\vec{\mathcal{H}}} K^{0T} + \vec{\gamma}^{\,T} \right) \cdot \mathbb{M} \cdot \vec{\rho} \\ \hat{B}_{\alpha\beta} &= \hat{\mu}_{\alpha\beta} \left[-i \left(\partial_{\vec{\mathcal{H}}} K^{0\,T} + \vec{\daleth}^{\,T} \right) \cdot \mathbb{M} \cdot \vec{\rho} - m_{3/2} \right] \\ M_\alpha &= \frac{1}{2} e^{K^0/2} \mathrm{Im}\,(f_\alpha{}^{-1}) (\partial_{\vec{\mathcal{H}}} f_\alpha)^t \cdot \mathbb{M} \cdot \vec{\varrho} \end{aligned}$$

- $\partial_{\vec{\mathcal{H}}} K^{0\,T} \equiv \left(\partial_{T^a} K^0, \partial_S K^0, \partial_{U_\Lambda} K^0, \partial_{\Phi^i_\alpha} K^0 \right)$
- $\mathcal{P}$ matter Kähler metric matrix (unknown for generic CY)
- $\vec{\gamma}^{\,T}$ and $\vec{\daleth}^{\,T}$ enclose model-dependent contributions
- $\mathbb{M}$ contains the saxion-dependent terms appearing in the contra-variant F-terms

Example: Soft Terms in Type IIA non-SUSY Minkowski vacua with D6-branes

Observation: The functional structure of $\mathcal{P}$, $\overrightarrow{\gamma}^T$ and $\overrightarrow{\beth}^T$ suggest that only the scaling behaviour of the matter Kähler metrics is needed to fully determine the model-dependent contributions.

Assumption: Matter Kähler metrics on generic CY are homogeneous functions of degree n_α in the complex structure moduli $u_{\star\Lambda}$ (as in toroidal backgrounds Conlon et al. '06, Aparicio et al. '08)

Summary of soft SUSY breaking terms in CSD vacua	
Soft masses	$m_\alpha^2 = m_{3/2}^2(1 + n_\alpha)$
A-terms	$\hat{A}_{\alpha\beta\gamma} = \hat{Y}_{\alpha\beta\gamma} m_{3/2} \left(3 + n_\alpha + n_\beta + n_\gamma\right)$
B-terms	$\hat{B}_{\alpha\beta} = \hat{\mu}_{\alpha\beta} m_{3/2} \left(2 + n_\alpha + n_\beta\right)$
Gaugino masses	$M_i = m_{3/2}$

Conclusions

- Type IIA flux compactification is a rich framework, where the backgroud fluxes used simultaneously to stabilise moduli and break SUSY also induce soft SUSY breaking terms for the matter fields living at the D6-branes intersections.
- The axion polynomial formalism allows us to treat flux vacua with D-branes in the same way as the pure closed string vacua, providing a wider understanding of type IIA compactifications with fluxes and D-branes, and eventually, a better overview of the landscape of flux vacua.
  - When generalising the ISD flux set-up by adding D6-branes, the resulting CSD vacua rely on weaker vacuum constraints than the pure ISD flux vacua.
  - CSD vacua leads to the same structure of contravariant F-terms as the pure ISD flux vacua.
- The axion polynomial formalism can also be extended to the soft terms for massless open string excitations located at the D6-branes intersections.
  - A universal pattern of soft SUSY breaking terms arises from CSD vacua.

Thank you