Global type IIB models with moduli stabilisation

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Based on

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- arxiv:1206.5237 *in collaboration with M. Cicoli, S. Krippendorf, C. Mayrhofer and F. Quevedo*
- arxiv:1208.3208 *in collaboration with J. Louis, M. Rummel, A. Westphal*

Introduction

Two longstanding problems of string compactifications:

1) Moduli stabilisation;
2) Derivation of GUT- or MSSM-like constructions.

Md stab studied in many corners of Landscape. We chose to work in type IIB:

- Fluxes stabilise complex structure moduli and axiodilaton.
- Fluxes have mild backreaction to geometry (GKP).
- Viable mechanisms to fix Kähler moduli: KKLT, LVS, D-terms.

[Acharya, Antoniadis, Balasubramanian, Berglund, Blumenhagen, Braun, Burgess, Choi, Cicoli, Conlon, Cvetic, Dasgupta, deAlwis, Denef, Douglas, Dudas, Giddings, Goodsell, Grimm, Hebecker, Kachru, Kallosh, Linde, Louis, Lüst, Maharana, Mayr, Mayrhofer, Polchinski, Quevedo, Raby, Sethi, Taylor, Trivedi, Weigand, Westphal....]

In the last years increasing of model building in type IIB with D7-branes

- In type IIB model building, one can use complex geometry techniques.
- F-theory: 7-brane/geometric moduli and 3-form/gauge fluxes unified.
- Local model building with magnetized branes and recently global realistic models (both perturbative type IIB and F-theory).

[Beasley, Berglund, Blumenhagen, Braun, Collinucci, Conlon, Donagi, Dudas, Grimm, Heckman, Hebecker, Kreuzer, Marchesano, Marsano, Mayrhofer, Palti, Saulina, Schafer-Nameki, Shiu, Tatar, Vafa, Watari, Weigand, Wijnholt.....]

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Three crucial issues in combining (global) model build with md stabilisation:
[Blumenhagen,Moster,Plauschinn; Blumenhagen,V.Braun,Grimm,Weigand; Collinucci,Kreuzer,Mayrhofer,Walliser]

- Tension between moduli stabilisation via NP effects and Chirality (recently solution for $h^{1,1}_{-}(X) > 0$ [Grimm,Kerstan,Palti,Weigand]);
- Tension between moduli stabilisation via NP effects and cancellation of Freed-Witten anomaly;
- D-terms induce shrinking of 4-cycles (supporting visible sector) and can lead to the boundary of Kähler cone.

(Moreover one must have control over EFT and stabilise the Kähler moduli inside the Kähler cone.)

Further issue: stabilise moduli at a de Sitter (dS) vacuum.
(In type IIB various mechanisms: $\overline{D3}$ [Kachru, Kallosh, Linde, Trivedi], D-terms [Burgess, Kallosh, Quevedo], F-term from Kähler md $+\ \alpha'$ corr [Balasubramanian, Berglund; Rummel, Westphal], F-term from dilaton dependent non-pert effects [Burgess, Cicoli, Maharana, Quevedo], F-terms from matter fields [Lebedev,Nilles,Ratz].)

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Summary

Type IIB CY orientifolds, with D3/D7-branes and O3/O7-planes.

- Phenomenological requirements translate to geometric properties of the compact manifold.
  - ∗ Set of geometric constraints consistent with phenom viable model.
  - ∗ Search for glob defined compact manifold satisfying such constr's.
- We take CY 3-folds from reduced lists of hypersurfaces in toric varieties $\rightarrow$ allow to be very explicit on CY topology and systematic in the search.
- After choosing a proper O7-involution, take a phenomenologically interesting brane setup with intersecting and (fluxed) D7-branes or with D3-branes at dP_n singularities.
- Check consistency conditions (like D7/D5/D3-tadpole cancellation, FW anomaly cancellation,...).
- Assuming c.s. fixed by 3-form fluxes (W_0, g_s parameters), we studied Kähler md stab in detail in a way that overcomes previous problems.
- In two examples, we find a dS vacuum (uplift by D-terms and F-terms).
- In one of these, we stabilise explicitely also c.s. moduli.

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Outline

1. Moduli stabilisation (with focus on Kähler moduli) and phenomenological constraints.
2. Explicit example with intersecting D7-branes.
3. Explicit example with D3-branes at singularities.
4. Explicit example with F-term dS uplift and all geom md stab.
5. Conclusions and outlook.

Moduli stabilisation

Moduli Stabilisation in Type IIB

Take Type IIB compactified on CY_3 X with orientifold invol $(-1)^{F_L}\Omega_p\sigma$.

- Moduli: $h^{1,2}_-$ c.s., $h^{1,1}_+$ $\mathbb{C}$-fied Käh, $h^{1,1}_-$ (B, C_2) and $S = e^{-\phi} + iC_0$.
- The tree-level 4D Kähler potential takes the form [Grimm,Louis]:

$$K_{\text{tree}} = -2\ln\mathcal{V} - \ln\left(S+\bar{S}\right) - \ln\left(-i\int_X \Omega\wedge\bar{\Omega}\right)$$

  depends on c.s. md via Ω, while on Kähler md via the CY vol $\mathcal{V} = \frac{1}{6}\int_X J\wedge J\wedge J = \frac{1}{6}\, k_{ijk}t^i t^j t^k$, where $J = t^i\hat{D}_i$.

- A tree-level superpotential is generated by turning on bkgr fluxes $G_3 = F_3 + iSH_3$ ($F_3 = dC_2$ and $H_3 = dB_2$) [Gukov,Vafa,Witten]:

$$W_{\text{tree}} = \int_X G_3\wedge\Omega$$

- F-term potential:

$$V_F^{\text{tree}} = e^K\left(|D_I W|^2 - 3|W|^2\right) = e^K|D_i W|^2 \qquad i \text{ over } S \text{ and c.s. md}$$

$\hookrightarrow$ Tree-level potential has no-scale structure; at min, Kähler md are flat directions, while c.s. md and S are fixed (at $D_i W = 0$).

Kähler moduli stabilisation

Sources for Kähler md stab $\rightarrow$ other terms in the potential

$$V = V_F^{\rm tree} + V_D + \delta V_F^{\rm pert} + \delta V_F^{\rm np}$$

V_D : D-term potential (generated by fluxes on D7's) [Jockers,Louis].

$\delta V_F^{\rm pert}$: perturbative α' [Becker,Becker,Haack,Louis] and g_s [Becker,Haack, Kors, Pajer] corrections to the Kähler potential K.

$\delta V_F^{\rm np}$: non-perturbative corrections to the superpotential W (E3-instantons or gaugino condensation on a D7-stack) [Witten; Kachru,Kallosh,Linde,Trivedi].

- At leading order in $1/\mathcal{V}$, min at $V_F^{\rm tree} = 0$ and $V_D = 0$.
  $\hookrightarrow$ dilaton and c.s. md fixed at their flux-stabilised values.
- At subleading order $\rightarrow$ minimize δV_F
  (g_s and $W_0 = \langle W_{\rm tree} \rangle$ flux-dependent constants. $K = -2 \ln \mathcal{V}$, with c.s. and dilaton parts of K entering as an overall factor.)

Tension with NP effects and D-term problem

NP superpotential $W_{\rm np} = \sum_i A_i e^{-a_i T_i}$ (Re T_i=volD_i).

There is tension between Kähler md stab by NP effects and chirality.
[Blumenhagen,Moster,Plauschinn]

$\Rightarrow$ Constraint on vis-sect flux: no chirality at possible inters with NP cycle.
(Best place to put NP effect is 'diagonal del Pezzo'. [Cicoli,Kreuzer,Mayrhofer])

Freed-Witten anomaly generically prevents more than one NP effect.
[Blumenhagen,Braun,Grimm,Weigand; Collinucci,Kreuzer,Mayrhofer,Walliser]

$\mathcal{F} = F - B = 0$ on NP-cycle $\rightarrow$ B fixed. But generically $\mathcal{F} \neq 0$ elsewhere.

$\Rightarrow$ Generically Kähler moduli stabilisation by only one NP effect.
(In specific examples one can have more cycles contributing.)

Flux generated D-terms from $D7_{\rm vis}$ forces the wrapped cycle to shrink.
[Blumenhagen,Braun,Grimm,Weigand; Collinucci,Kreuzer,Mayrhofer,Walliser; Cicoli,Kreuzer,Mayrhofer]

Flux generates FI-term $\xi_a = \frac{1}{4\pi\mathcal{V}} \int_{D_a} J \wedge \mathcal{F}_a \propto \sum_j \left(\sum_k k_{ajk} \mathcal{F}_a^k\right) t^j$.

- $\xi_a = 0 \rightarrow$ generically some 4-cycles shrink (away sugra approx).
- This happens if visible sector is 'diagonal dP'.

$\Rightarrow$ If we don't want D3 at sing, avoid visible sector on 'diagonal dP'.

Explicit global chiral model

on intersecting branes

with moduli stabilisation

Explicit example

We take CY_3 X from the list of hypersurface in a 4d toric ambient variety that are K3-fibrations, with $h^{1,1} = 4$ and one 'diagonal dP' [Cicoli,Kreuzer,Mayrhofer].
Data are encoded in the following weight matrix and SR ideal:

z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	D_X
1	1	1	0	0	0	1	4	8
1	1	0	0	0	1	0	3	6
0	1	1	1	0	0	0	3	6
0	1	0	0	1	0	0	2	4

$$\mathrm{SR} = \{z_2 z_5, z_1 z_6, z_1 z_7, z_5 z_7, z_2 z_4 z_6, z_3 z_4 z_8, z_3 z_7 z_8\}$$

CY data obtained from PALP output [Kreuzer,Skarke].

- Hodge numbers: $h^{1,1}(X) = 4$, $h^{1,2}(X) = 106$.
- Integral basis of $H_4(X,\mathbb{Z})$: $\{\Gamma_i\}_{i=1,\dots,4} = \{D_7, D_2 + D_7, D_1, D_5\}$.
- Intersection form: $I_3 = 2\Gamma_1^3 + 4\Gamma_2^3 + 4\Gamma_4^3 + 2\Gamma_2^2\Gamma_3 - 2\Gamma_4^2\Gamma_3$.
- There is one 'diagonal' dP_7, corresponding to $\Gamma_1 = D_7$.
- There are other three divisors (D_4, D_5, D_6) with $h^{2,0} = h^{1,0} = 0$.
- We have the following Kähler cone (where $J = \sum_{i=1}^4 t_i \Gamma_i$):

$$-t_1 > 0\,, \qquad t_1 + t_2 + t_4 > 0\,, \qquad t_3 - t_4 > 0\,, \qquad -t_4 > 0$$

Orientifold projection and D7-brane config

Choice for holomorphic orientifold involution σ:

$$\sigma \; : \qquad z_8 \mapsto -z_8 \qquad\qquad (\; h^{1,1}_{-}(X) = 0 \;)$$

- O7-plane at $z_8 = 0 \rightarrow [O7] = D_8$. No O3-planes.
- Symmetric equation for CY_3:

$$z_8^2 = P_{8,6,6,4}(z_1, \ldots, z_7) \qquad \text{(canonical form for F-theory up-lift)}$$

To cancel D7-charge of O7, D7-br config on $[D7] = 8[O7]$: described by eq

$$D7 \; : \qquad \eta^2_{16,12,12,8} - z_8^2 \, \chi_{24,18,18,12} = 0$$

[Sen; Denef,Collinucci,Esole; A.Braun,Hebecker,Triendl]

- Since we want different stacks, we need this polynomial to factorise.

$$\eta = z_i^m \tilde{\eta} \, , \qquad \chi = z_i^{2m} \tilde{\chi} \qquad \Rightarrow \qquad \eta^2 - z_8^2 \chi = z_i^{2m} (\tilde{\eta}^2 - z_8^2 \tilde{\chi})$$

  $\hookrightarrow$ one $Sp(2m)$ stack along $z_i = 0$ plus a *Whitney brane*.
- Take N_a branes on D_4, N_b on D_5, N_{k3} on D_1 and N_{gc} on D_7 (& images):

$$\eta^2 - z_8^2 \chi \qquad \rightarrow \qquad z_1^{2N_{k3}} z_4^{2N_a} z_5^{2N_b} z_7^{2N_{gc}} (\tilde{\eta}^2 - z_8^2 \tilde{\chi})$$

Sufficient conditions for no further factorisation:

$$N_{gc} \leq 4 \, , \qquad N_{gc} + N_{k3} \leq 4 + N_a \, , \qquad N_a - N_b \leq N_{gc}$$

Example with two D-terms

We choose the following values for N_i:

$$N_a = 5\,, \qquad N_b = 2\,, \qquad N_{gc} = 4 \qquad \text{and } N_{k3} = 0$$

We switch on non-zero fluxes

- $\mathcal{F}_a^\sigma = \mathcal{F}_a$, $\sigma = 1, ..., 5$ (diag) on D_4
- $\mathcal{F}_b^1 = \mathcal{F}_b$, $\mathcal{F}_b^2 = 3\mathcal{F}_b$ (non-diag) on D_5.

(We set $\mathcal{F}_{gc} = 0 \Rightarrow B = F_{gc}$, in particular half-int along D_7.)

Gauge group is broken to:

$$U(5) \times U(1) \times U(1) \times Sp(8) \to SU(5) \times U(1) \times Sp(8)$$

(Second breaking by Stückelberg mechanism).

To summarise:

D7-stack	$D7_a$	$D7_b$	$D7_{gc}$	$D7_W$
N_i	5	2	4	–
divisor class	D_4	D_5	D_7	$2\,(7\Gamma_2 - 7\Gamma_1 + 5\Gamma_3 - \Gamma_4)$
topology	rigid	rigid	dP_7	Whitney brane

Flux choice, chiral matter, D3-charge

We considered the following choice of gauge fluxes and B-field ($\mathcal{F} = F - B$):

$$F_a = -D_1 + D_5 + \tfrac{1}{2} D_4 \qquad F_b = -4D_1 - \tfrac{9}{2} D_5 \qquad B = \tfrac{1}{2} D_7$$

(B-field chosen such that $\mathcal{F}_{gc} = 0$.)

- Non-zero fluxes induce chiral matter at the intersection of D7-branes and on their bulk. Chiral intersections (not zero for all flux choices) are:

$$\begin{array}{llll}
I_a^{(S)} = -2\,, & I_{b^1}^{(S)} = 0\,, & I_{b^2}^{(S)} = 0\,, & \\
I_{b^2\bar{b}^1} = -16\,, & I_{b^2 b^1} = -32\,, & I_{a\bar{b}^1} = -3\,, & I_{ab^1} = -5\,, \\
I_{a\bar{b}^2} = -1\,, & I_{ab^2} = -7\,, & I_{aW} = 0\,, & \\
I_{b^1 W} = 106 & I_{b^2 W} = 318 & I_{agc} = 0\,. &
\end{array}$$

  Note $I_{agc} = 0$ for our flux choice. For generic F_a, this number of chiral modes is non-zero.

- Fluxes contribute to D3-charge. Including the geometric contribution, the total D3-charge is

$$Q^{\text{tot}}_{(D3)} = -318$$

  $\rightarrow$ space for bulk 3-form and D7 (trivial) 2-form fluxes.

Scalar potential

D-term potential:

- We have two independent FI-terms:

$$\xi_a = \frac{1}{4\pi\mathcal{V}}\int_{D7_a} J\wedge\mathcal{F}_a = -\frac{1}{2\pi\mathcal{V}}\left(t_2 - t_3 + 2t_4\right) \qquad \xi_b = \frac{1}{4\pi\mathcal{V}}\int_{D7_b} J\wedge\mathcal{F}_b = \frac{1}{4\pi\mathcal{V}}\left(9t_3 - 8t_4\right)$$

- Solving $(\xi_a, \xi_b) = (0,0)$ gives following relations among div volumes:

$$\tau_4 = \frac{3}{19}\tau_1 - \tau_7\,, \qquad \tau_5 = \frac{18}{19}\tau_1$$

$\rightarrow$ Plug them in (subleading) F-term potential.

F-term potential:

- F-term potential given by NP and α' perturb corrections.

$$V \simeq \frac{32}{25}\pi^2 A^2 \frac{\sqrt{\tau_7}}{\mathcal{V}}\left(1 + \frac{\tau_7^{3/2}}{2\mathcal{V}}\right) e^{-\frac{4\pi\tau_7}{5}} - \frac{8}{5}\pi A W_0 \frac{\tau_7}{\mathcal{V}^2} e^{-\frac{2\pi\tau_7}{5}} + \frac{3W_0^2\hat{\xi}}{4\mathcal{V}^3}\left(1 + \frac{7\hat{\xi}}{\mathcal{V}}\right)$$

where $\hat{\xi} = \xi/g_s^{3/2}$ (with $\xi \simeq 0.5$) and $\mathcal{V} = \alpha(\tau_1^{3/2} - \gamma\tau_7^{3/2})$.

- Potential minimized both numerically for given value of param A, g_s, W_0 and analytically, using leading approximation.

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Solution

- From analytic minimization: $\mathcal{V} \sim W_0\, e^{\frac{2\pi\tau_7}{5}}$ and $\tau_7 \sim g_s^{-1}$
  $\Rightarrow$ to find acceptable sol, tune $W_0 \ll 1$ (hybrid KKLT-LVS model).
- For choice $W_0 \simeq 5.51 \cdot 10^{-9}$, $A = 0.10$, $g_s \simeq 0.04$, we find

$$\langle \tau_7 \rangle \simeq 20.3\,, \qquad \langle \mathcal{V} \rangle \simeq 6000$$

- The flux-corrected value of the visible coupling turns out to be:

$$\alpha_{\rm vis}^{-1} = \tau_4 - \frac{1}{2g_s} \int_{D_4} \mathcal{F}_a \wedge \mathcal{F}_a \simeq 150\,.$$

- Fixed values of Kähler md are inside Kähler cone.
- Volume of all div fixed above string scale $\rightarrow$ trust EFT.
- Volume of dual 2-cycle large $\rightarrow$ g_s corrections are subleading.
- Checked $\frac{\xi}{g_s^{3/2}\mathcal{V}} \sim 0.01$: trust approxim on α' corrections.
- The string scale is of the order $M_s \simeq \frac{M_P}{\sqrt{4\pi\mathcal{V}}} \simeq 8.9 \cdot 10^{15}\,\mathrm{GeV}$.
- TeV-scale supersymmetry is obtained:

$$m_{3/2} = \sqrt{\frac{g_s}{8\pi}}\frac{W_0 M_P}{\mathcal{V}} \simeq 95.63\,\mathrm{TeV} \quad \text{and} \quad M_{\rm soft} \simeq \frac{m_{3/2}}{\ln\left(M_P/m_{3/2}\right)} \simeq 3.1\,\mathrm{TeV}.$$

[Conlon,Quevedo,Suruliz]

Solution

- From analytic minimization: $\mathcal{V} \sim W_0\, e^{\frac{2\pi\tau_7}{5}}$ and $\tau_7 \sim g_s^{-1}$
  $\Rightarrow$ to find acceptable sol, tune $W_0 \ll 1$ (hybrid KKLT-LVS model).
- For choice $W_0 \simeq 5.51 \cdot 10^{-9}$, $A = 0.10$, $g_s \simeq 0.04$, we find

$$\langle \tau_7 \rangle \simeq 20.3\,, \qquad \langle \mathcal{V} \rangle \simeq 6000$$

- The flux-corrected value of the visible coupling turns out to be:

$$\alpha_{\rm vis}^{-1} = \tau_4 - \frac{1}{2g_s}\int_{D_4} \mathcal{F}_a \wedge \mathcal{F}_a \simeq 150\,.$$

- Fixed values of Kähler md are inside Kähler cone.
- Volume of all div fixed above string scale $\rightarrow$ trust EFT.
- Volume of dual 2-cycle large $\rightarrow$ g_s corrections are subleading.
- Checked $\frac{\xi}{g_s^{3/2}\mathcal{V}} \sim 0.01$: trust approxim on α' corrections.
- The string scale is of the order $M_s \simeq \frac{M_P}{\sqrt{4\pi\mathcal{V}}} \simeq 8.9 \cdot 10^{15}\,\mathrm{GeV}$.
- TeV-scale supersymmetry is obtained:

$$m_{3/2} = \sqrt{\frac{g_s}{8\pi}}\frac{W_0 M_P}{\mathcal{V}} \simeq 95.63\,\mathrm{TeV} \;\text{ and }\; M_{\rm soft} \simeq \frac{m_{3/2}}{\ln\left(M_P/m_{3/2}\right)} \simeq 3.1\,\mathrm{TeV}.$$

[Conlon,Quevedo,Suruliz]

Example with one D-term

We choose the following values for the other N_i:

$$N_a = 3\,, \qquad N_{k3} = 1\,, \qquad N_{gc} = 3 \qquad \text{and } N_b = 0$$

We choose $\mathcal{F}_{gc} = 0$ and $\mathcal{F}_{k3} = 0$, and we switch on

$$\mathcal{F}_a^\sigma = \mathcal{F}_a = -D_1 + D_5 + \tfrac{1}{2} D_4 - \tfrac{1}{2} D_7 \qquad \sigma = 1, ..., 3$$

Gauge group is broken to:

$$U(3) \times SU(2) \times Sp(6) \to SU(3) \times SU(2) \times Sp(6)$$

To summarise:

D7-stack	$D7_a$	$D7_{k3}$	$D7_{gc}$	$D7_W$
N_i	3	1	3	$-$
divisor class	D_4	D_1	D_7	$2\,(9\Gamma_2 - 8\Gamma_1 + 2\Gamma_3 - \Gamma_4)$
topology	rigid	rigid	dP_7	Whitney brane

Summary

- The non-zero chiral intersections are $I_a^{(S)} = -2$, $I_{ak3} = 2$, $I_{aW} = -20$
- The total D3-charge is $Q^{\rm tot}_{(D3)} = -606$.
- Moduli stabilisation (Take $\tau_s \equiv \tau_1 - \tau_5$ and $\tau_\ell \equiv \frac{10\tau_1 - \tau_5}{2}$):
  - D-term stabilisation: $\tau_4 = 3\,\tau_s - \tau_7$.
  - $\alpha' +$ NP corrections stabilise τ_7 and $\mathcal{V} = \frac{1}{3}\left(\sqrt{\tau_s}\,\tau_\ell - \tau_7^{3/2}\right)$.
  - Subleading 1-loop g_s correct's can stabilise τ_s small and τ_ℓ large.
  - This keeps $\tau_4 = 3\tau_s - \tau_7$ small and then visible gauge coupling:

$$\alpha_{\rm vis}^{-1} = \langle \tau_4 \rangle - \frac{1}{2g_s} \int_{D_4} \mathcal{F}_4 \wedge \mathcal{F}_4 \simeq 136$$

  - Anisotropic CY: $\mathcal{V} \sim t_b \tau_s$, where τ_s is vol of K3 fibre D_3 and t_b is vol of corresponding $\mathbb{P}^1$ base.
- For $W_0 \simeq 1$, $A = 0.10$, $g_s \simeq 0.05$, we find $\mathcal{V} \simeq 10^{12}$, $\tau_7 \simeq 16.4$ and $\tau_s \simeq 31 \rightarrow$ intermediate string scale $M_s \simeq \frac{M_P}{\sqrt{4\pi\mathcal{V}}} \simeq 10^{12}\,\mathrm{GeV}$.
- For $W_0 \simeq 1$, $A = 0.10$, $g_s \simeq 0.02$, we find $\mathcal{V} \simeq 10^{29}$, $\tau_7 \simeq 41 \rightarrow$ Very anisotropic CY with two micron-sized extradim and TeV-scale strings.

$\hookrightarrow$ First realisation of LVS in concrete chiral global model.

Explicit global quiver model

with

moduli stabilisation

Embedding of Quiver Theories

Consider Type IIB compactified on CY_3 X.
Visible sector on D3-branes at a singularity of X.

Take X with a point-like sing and put D3 branes on top of it.

- D3-branes split into fractional branes.
  [Douglas,Moore; Douglas,Diaconescu,Gomis]
- So far great attention on phenomenologically interesting local models, with MSSM-like gauge group and spectrum. [Aldazabal,Ibanez,Quevedo,Uranga; Berenstein,Jejjala,Leigh; Verlinde,Wijnholt; Dolan,Krippendorf,Quevedo...]
- We want globally defined compact models. Need to embed local quiver model into an orientifold of a compact singular CY_3.
- See [Diaconescu, Florea, Kachru, Svrcek; Buican, Malyshev, Morrison, H.Verlinde, Wijnholt] for first global embeddings of dP_n singularities, and more recently [Balasubramanian, Berglund, Braun, García-Etxebarria] for a sistematic construction of toric singularities in compact CYs and for the introduction of the flavor D7-branes into the global setting.

Explicit global quiver model

We study moduli stab for a globally embedded quiver (toy) model.
(We do not consider flavor D7-brane for the moment.)

We take CY_3 X, that is a hypersurface in a 4d toric ambient variety:

z_1	z_2	z_3	z_4	z_5	z_6	z_7	z_8	D_{eq_X}
1	1	1	0	3	3	0	0	9
0	0	0	1	0	1	0	0	2
0	0	0	0	1	1	0	1	3
0	0	0	0	1	0	1	0	2

$$\mathrm{SR} = \{z_4\, z_6,\ z_4\, z_7,\ z_5\, z_7,\ z_5\, z_8,\ z_6\, z_8,\ z_1\, z_2\, z_3\}$$

CY data obtained from PALP output [Kreuzer,Skarke].

- Hodge numbers: $h^{1,1}(X) = 4$, $h^{1,2}(X) = 112$.
- Basis of $H_4(X)$: $\Gamma_1 = D_6 + D_7$, $\Gamma_2 = D_4$, $\Gamma_3 = D_7$, $\Gamma_4 = D_8$.
- Intersection form $I_3 = 27\Gamma_1^3 + 9\Gamma_2^3 + 9\Gamma_3^3 + 9\Gamma_4^3$.
- There are three dP_0 at $z_4 = 0$, $z_7 = 0$ and $z_8 = 0$.

Orientifold projection and Kähler moduli

We take an orientifold involution that exchanges two (shrinking) dP_0s:

$$\sigma \ : \qquad z_4 \leftrightarrow z_7 \qquad \text{and} \qquad z_5 \leftrightarrow z_6 \qquad (h^{1,1}_-(X)=1 \text{ and } h^{1,1}_+(X)=3)$$

- The two dP_0s $\Gamma_2 = D_4$ and $\Gamma_3 = D_7$ are exchanged.
- There are no O3-planes and two O7-planes: $O7_1$ at $z_4 z_5 - z_6 z_7 = 0$ and $O7_2$ at $z_8 = 0 \to [O7_1] = \Gamma_1$ and $[O7_2] = \Gamma_4$.
- O7-planes do not intersect the (shrinking) dP_0s and do not intersect each others.
- Symmetric Kähler form: $J = t_1\Gamma_1 + t_4\Gamma_4 + t_{\rm shr}(\Gamma_2 + \Gamma_3)$:

$$\text{vol}(\Gamma_2) = \text{vol}(\Gamma_3) = \tfrac{9}{2} t_{\rm shr}^2 \,, \qquad \text{vol}(D_8) = \tfrac{9}{2} t_4^2 \,, \qquad \text{vol}(X) = \tfrac{3}{2}(3t_1^3 + 2t_{\rm shr}^3 + t_4^3)$$

- Kähler cone:

$$t_1 + t_4 > 0 \qquad -t_4 > 0 \qquad t_1 + t_{\rm shr} > 0 \qquad -t_{\rm shr} > 0$$

Singular CY at $t_{\rm shr} \to 0$.

Brane configuration

Visible sector from $N = 3$ D3-branes on top of each (of the two) sing.

- dP_0 quiver theory (trinification model - $SU(3)_c \times SU(3)_L \times SU(3)_R$ with chiral spectrum $3\left[\left(3,\overline{3},1\right)+\left(1,3,\overline{3}\right)+\left(\overline{3},1,3\right)\right]$).

To cancel D7-charge of O7-plane:
put 4 D7 (plus images) on top of each O7-plane.

- Hidden group
$$SO(8) \times SO(8).$$
- FW fluxes $F_1 = -\frac{\Gamma_1}{2}$ and $F_2 = -\frac{\Gamma_4}{2}$ both cancelled by $B = -\frac{\Gamma_1}{2} - \frac{\Gamma_2}{2}$.
  $\hookrightarrow$ $\mathcal{F}_1 = \mathcal{F}_2 = 0 \Rightarrow$ Zero chiral states from the hidden sector.
- Total D3-charge $Q_{D3}^{\rm excep} + Q_{D3}^{\rm D7_1} + Q_{D3}^{\rm D7_2} = -60 + 2N = -54$.

(To have larger (negative) D3-charge, one can consider a Whitney brane in the class $8[O7_1]$ instead of $SO(8)$-stack.)

Moduli Stabilisation

Again a 'step by step' stabilisation:

- Complex structure md and D7-deformations stabilised by fluxes.
- D-terms on the visible sector stabilise $t_{\rm shr} \to 0$:

$$V_D = \frac{1}{\mathrm{Re}(f_1)}\left(\sum_i q_{1i}K_iC_i - \xi_1\right)^2 + \frac{1}{\mathrm{Re}(f_2)}\left(\sum_i q_{2i}K_iC_i - \xi_2\right)^2$$

For vanishing vev of matter fields C_i, min at $\xi_1 = \xi_2 = 0$, where

$$\xi_1 = -4q_1\frac{\tau_+}{\mathcal{V}} \qquad (\tau_+ \propto t_{\rm shr}^2) \qquad\qquad \xi_2 = -4q_2\frac{b}{\mathcal{V}}$$

- Gaugino condensation on rigid Γ_4 (a dP_0), $W_0 \sim \mathcal{O}(1)$ and α' corr:

  $\hookrightarrow$ F-term potential stabilises τ_8 small and $\mathcal{V}$ LARGE.

- If we tune $W_0 << 1$, we can have KKLT minimum, using the possible gaugino condensation on the $SO(8)$ stack wrapping the other O7.

dS vacuum and susy breaking

In the LVS case, we can realize a dS vacuum:

- Switch on gauge flux on non-rigid $SO(8)$ stack: it generates bulk chiral matter and FI-term. $\Rightarrow$ D-term uplift: $V_{\rm uplift} \sim \frac{W_0^2}{\mathcal{V}^{8/3}}$.
  We obtain a 'tiny' dS for $W_0 \simeq 0.2$ and $g_s \simeq 0.03$ ($\mathcal{V} \simeq 4 \cdot 10^6$).

SUSY breaking:

- W does not depend on $T_+ = \tau_+ + i\, c_+$. Since $\tau_+ \sim t_{\rm shr}^2 \to 0$,

  $F^{T_+} = e^{K/2} K^{T_+ \bar{I}} D_I W = 2 e^{K/2} {\rm Re}(T_+) \left(\tau_s \partial_s W - W_0\right) = 0 \qquad (\text{similarly } F^G = 0)$

- SUSY broken in bulk by $F^{T_s} \sim \mathcal{O}\left(\mathcal{V}^{-1}\right)$, $F^{T_b} \sim \mathcal{O}\left(\mathcal{V}^{-1/3}\right)$
  $\to$ soft terms suppressed with respect to $m_{3/2} = \sqrt{\frac{g_s}{4\pi}} \frac{W_0 M_P}{\mathcal{V}} \simeq 5 \cdot 10^9\,\text{GeV}$
  [Blumenhagen, Conlon, Krippendorf, Moster, Quevedo]

$\hookrightarrow$ Sequestering of visible sector: get TeV-scale SUSY avoiding cosmological moduli problem and having $M_s \simeq \frac{M_P}{\sqrt{\mathcal{V}}} \sim \mathcal{O}(10^{15})$ GeV.

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Global model with

F-term dS uplift and

explicit stabilisation of all geometric moduli

dS uplift by α'-corrections

KKLT-like AdS minimum uplifted by α'-corrections to Kähler potential.

[Balasubramanian,Berglund; Rummel,Westphal]

- Interplay of gaugino condensation on D7-branes and α' correction, fix Kähler moduli in a susy breaking min.
- Vacuum energy can be dialed from AdS to dS by tuning the fluxes (correspondingly W_0, g_s).
- Both susy breaking and up-lift to dS driven by F-term of Kähler md.
- In this md stab mechanism, $\mathcal{V} \propto N^{3/2}$, where N is the rank of the condensing group.
  $\Rightarrow$ To keep volume large, construct vacua with large N.

The model $\mathbb{CP}^4_{11169}[18]$

We take CY_3 X, that is a hypersurface in a 4d toric ambient variety:

u_1	u_2	u_3	x	z	y	D_{eq_X}
1	1	1	6	0	9	18
0	0	0	2	1	3	4

$$\mathrm{SR} = \{u_1\, u_2\, u_3,\ x\, y\, z\}$$

- Hodge numbers: $h^{1,1}(X) = 2$, $h^{1,2}(X) = 272$.
- Basis of $H_4(X)$: $\{D_1, D_z\}$. Intersection form $I_3 = D_1^2 D_z - 3 D_1 D_z^2 + 9 D_z^3$.
- D_z is a $\mathbb{P}^2$ ($h^{0,1} = h^{0,2} = 0$). D_1 has $h^{0,1} = 0$ but $h^{0,2} = 2 \neq 0$.

Orientifold involution: σ: $y \mapsto -y$ $\quad [h^{1,1}_-(X) = 0]$.

- Symm CY eq: $y^2 = x^3 + f_{12}(u_i)\, x\, z^4 + g_{16}(u_i)\, z^6$.
- There are no O3 and two O7-planes: $O7_1$ at $y = 0$ and $O7_2$ at $z = 0$.

To cancel D7-tadpole $\rightarrow$ D7-brane configuration: $z^8(\eta^2_{36,12} - y^2 \chi_{54,18}) = 0$.

- Require $Sp(24)$ stack on $u_1 = 0$: $\eta_{36,12} = u_1^{24}\tilde{\eta}_{12,12}$ and $\chi_{54,18} = u_1^{48}\tilde{\chi}_{6,18}$

$\hookrightarrow$ degrees of $\tilde{\eta}, \tilde{\chi}$ force to have $SO(24)$ stack on $z = 0$.

Kähler moduli stabilisation

We want gaugino condensation on both stack on D_1 and on D_z.

- Choose $B = \frac{D_1}{2} \Rightarrow$ we can set $\mathcal{F}_{D_1} = 0$.
- Flux on D_z is $\mathcal{F}_{D_z} = f_1 D_1 + f_z D_z + \frac{D_z}{2} - \frac{D_1}{2}$ with $f_i \in \mathbb{Z}$. Since the pull-back of $\frac{D_z}{2} - \frac{D_1}{2}$ on D_z is in $H^2(D_z, \mathbb{Z})$, we can set also $\mathcal{F}_{D_z} = 0$.
- D_1 is non-rigid. We found an explicit 2-form flux on D_1 that is orthogonal to all the pulled-back 2-forms and that fixes the $h^{0,2} = 2$ deformations.

Under these conditions, pure SYM on both stacks, allowing gaugino condens. Moreover no D-terms are generated and total D3-charge: $Q_{D3} = -73$.

Scalar (F-term) potential $V(T_1, T_z)$ of two Kähler moduli T_1, T_z given by

$$W = W_0 + A_1 e^{-\frac{2\pi}{24} T_1} + A_z e^{-\frac{2\pi}{22} T_z} \qquad K = -2\log\left(\mathcal{V}(T_1, T_z) + \frac{\hat{\xi}}{2}\right)$$

For $W_0 \simeq 0.8$, $s \simeq 7$, $A_1 \simeq 1.1$ and $A_z \simeq 1.0$,
we minimized $V(T_1, T_z)$ and found a dS vacuum.

Complex structure moduli stabilisation

Find fluxes that stabilise c.s. moduli such that $W_0 \simeq 0.8$ and $s \simeq 7$.
(We have no control on A_1, A_z.)

C.s. md space has $\mathbb{Z}_6 \times \mathbb{Z}_{18}$ symmetry. We switch on only fluxes respecting this symmetry. This stabilise non-inv deformations at $D_i W = 0$.

[Giryavets,Kachru,Tripathy,Trivedi; Denef,Douglas,Florea]

- Need to stabilise explicitly only the $h^{2,1}_{\rm inv} = 2$ md U_1, U_2.

Strategy to find $\langle W_0 \rangle$, $\langle S \rangle$ suitable for Kähler uplifting

- W_0 depends on periods of Ω_3. For the actual form of the periods as functions of U_1, U_2, use mirror symmetry.
- Solve $(W_0, D_S W_0, D_{U_1} W_0, D_{U_2} W_0) = 0$, for the flux quanta $f_1, \ldots, f_6$, $h_1, \ldots, h_6$

After a scan on fluxes, solution:

$$(f, h) = (-16, 0, 0, 0, -4, -2; 0, 0, 2, -8, -3, 0)\,, \quad Q_{D3}^{RR,NS} = 66\,,$$

$$\langle S \rangle = 6.99\,, \quad \langle W_0 \rangle = 0.812\,, \qquad \frac{m^2_{U_1,U_2,S}}{m^2_{T_1,T_2}} \sim \mathcal{O}(100 - 1000)\,.$$

Conclusions

We have presented explicit models with Kähler moduli stabilised and chiral sector and/or dS uplift.

- We were able to combine various mechanisms to stabilise Kähler moduli, without violating global consistency conditions and overcoming problems found so far.
- Geometric data described by toric geometry. This allowed us to make specific choice of brane setup and fluxes that give rise to GUT- or MSSM-like models.
- We obtained a first realisation of LARGE volume scenario in a concrete chiral global model.
- We have found a globally embedded quiver model with geometric moduli stabilised (easy to generalise to higher dP_n embeddings).
- We found dS vacua (both D-term and F-term uplift).
- In one model, stabilised also c.s. moduli explicitly.

Outlook

- Study complex structure moduli stabilisation: see if one can stabilise all of them and what 3-form fluxes one can switch on.
- Find a model with correct spectrum.
- There is a long list of CY_3 in PALP output: try to automatise the search for a consistent and phenomenological viable model.
- Uplift to F-theory (more control over complex structure and open string moduli; flux quantisation).
- Moduli stabilisation in the case of quiver models with flavor D7-branes.
- F-term uplift plus chiral sector.