Moduli Stabilization in Toroidal Type IIB Orientifolds

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in collaboration with
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Outline

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- Toroidal Orientifold models
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    - Example: Finding cplx structure and Kähler moduli
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- The non-perturbative superpotential
- Generalizations: Resolved Orbifolds
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Introduction

Most string theory compactifications come with a large number of moduli which would lead to a fifth force if they were to stay. Are they just an artifact of the leading approximation? The complex structure moduli and the dilaton can be stabilized via 3-form fluxes.

Giddings, Kachru, Polchinski

Are the Kähler moduli stabilized via non-perturbative effects?

Kachru, Kallosh, Linde, Trivedi, etc.

Type IIB toroidal orientifold models exhibit many features of the standard model such as non-Abelian gauge groups, chiral fermions and family repetition.

$\mathbf{Z}_2 \times \mathbf{Z}_2$ is very well studied, but what about the other orbifolds?

Denef, Douglas, Florea, Grassi, Kachru

Here: No full-fledged models, only general properties of the orbifolds: geometry, allowed fluxes, existence of stable vacua...

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Toroidal Orientifold Models

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We look at orientifolds of type IIB string theory compactified on $X_6 = T^6/Z_N$ or $X_6 = T^6/Z_N \times Z_M$: Specify the lattice Λ and the point group Γ.

Orbifold: Abelian point groups, no discrete torsion, no vector structure.

N=2 SUSY ⇒ Γ ⊂ SU(3), crystallographic action:

$\mathbf{Z}_N$: $\mathbf{Z}_3$, ~~$\mathbf{Z}_4$~~, $\mathbf{Z}_{6-I}$, $\mathbf{Z}_{6-II}$, $\mathbf{Z}_7$, ~~$\mathbf{Z}_{8-I}$~~, ~~$\mathbf{Z}_{8-II}$~~, $\mathbf{Z}_{12-I}$, ~~$\mathbf{Z}_{12-II}$~~.

$\mathbf{Z}_N \times \mathbf{Z}_M$: $\mathbf{Z}_2 \times \mathbf{Z}_2$, $\mathbf{Z}_3 \times \mathbf{Z}_3$, ~~$\mathbf{Z}_2 \times \mathbf{Z}_4$~~, ~~$\mathbf{Z}_4 \times \mathbf{Z}_4$~~,
$\mathbf{Z}_2 \times \mathbf{Z}_6$, $\mathbf{Z}_2 \times \mathbf{Z}_{6'}$, $\mathbf{Z}_3 \times \mathbf{Z}_6$, $\mathbf{Z}_6 \times \mathbf{Z}_6$.

Aldazabal, Font, Ibanez ,Violero; Zwart

Orientifold action: ΩI_6, Ω : WS-orientation reversal,
$I_6 : z^i \to -z^i$. O3/O7-planes.
Tadpole cancellation by adding D3/D7-branes

Toroidal Orientifold Models

Twist Γ	Lattice	$h^{untw.}_{(1,1)}$	$h^{untw.}_{(2,1)}$	$h^{twist.}_{(1,1)}$	$h^{twist.}_{(2,1)}$
Z_3	$SU(3)^3$	9	0	27	0
Z_{6-I}	$SU(3) \times G_2^2$	5	0	24	5
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Z_{12-I}	$SU(3) \times F_4$	3	0	26	5
Z_{12-I}	E_6	3	0	22	1

Ibanez, Mas, Nilles, Quevedo; Erler, Klemm

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$Z_2 \times Z_2$	3	3	48	0
$Z_3 \times Z_3$	3	0	81	0
$Z_6 \times Z_6$	3	0	81	0
$Z_3 \times Z_6$	3	0	70	1
$Z_2 \times Z_6$	3	1	48	2
$Z_2 \times Z_6'$	3	0	33	0

Font, Ibanez, Quevedo

Toroidal Orientifold Models

Closed String Moduli Space:

- $h^{(1,1)}$ Kähler moduli $\mathcal{T}^i$ (size),
- $h^{(2,1)}$ complex structure moduli $\mathcal{U}^i$ (shape),
- dilaton $S = i\, C_0 + e^{-\phi_{10}}$

The total moduli space is a direct product:

$$\mathcal{M} = \mathcal{M}_S \otimes \mathcal{M}_K \otimes \mathcal{M}_{CS}$$

$\mathcal{T}^i$ and $\mathcal{U}^i$ follow directly from the geometry of the compactification manifold. For the effective field theory treatment, we must define new moduli:

$$T^i = e^{-\phi_{10}} \frac{\partial}{\partial \mathcal{T}^i} Vol(X_6(\mathcal{T}^j)) + i \int_{C_i} C_4 \qquad U^i = \mathcal{U}^i$$

What do the Kähler potentials of the different moduli spaces look like?

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$$\kappa_4^{-2}\, K_K = -\ln(S+\overline{S}) - \sum_{i=1}^{3} \ln(T^i+\overline{T}^i) - \sum_{i=1}^{3} \ln(U^i+\overline{U}^i)$$

$$\kappa_4^{-2}\, K_K = -\ln(S+\overline{S}) - \ln\left\{(T^5+\overline{T}^5)\left[(T^1+\overline{T}^1)(T^2+\overline{T}^2)-(T^3+\overline{T}^3)(T^4+\overline{T}^4)\right]\right\}$$

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$$\kappa_4^{-2}\, K_K = -\ln(S+\overline{S}) - \ln\det(M+\overline{M})$$

Finding the Complex Structure and Kähler moduli

All orbifolds in our list are Coxeter-orbifolds, i.e. the twist acting on the lattice is the Coxeter element of the respective Lie-algebra: $Q = S_1 S_2 ... S_{rank}$. It consists of successive Weyl-reflections:

$$S_i(\mathbf{x}) = \mathbf{x} - 2\frac{\langle \mathbf{x}, e_i \rangle}{\langle e_i, e_i \rangle} e_i$$

For the complex structure, we make the following ansatz:

$$dz^i = a_1^i \, dx^1 + a_2^i \, dx^2 + a_3^i \, dx^3 + a_4^i \, dx^4 + a_5^i \, dx^5 + a_6^i \, dx^6$$

We find the coefficients via

$$Q^t \, dz^i = e^{2\pi i v^i} \, dz^i$$

Twist must leave the scalar product invariant → metric

$$Q^t \, g \, Q = g$$

Finding the Complex Structure and Kähler moduli

Metric → Kähler form J

Find the $h^{(1,1)}$ invariant (1,1)-forms of the orbifold, expand J in the real cohomology → Kähler moduli.

Complexified Kähler moduli:

Ramond 4-form

$$\mathcal{T}^i = \int_{C_2^i} J + i \int_{C_4^i} C_4$$

2-cycle ↔ 4-cycle

Hodge-dual

Example: $\mathbf{Z}_{6-I}$ on $G_2^2 \times SU(3)$

$\mathbf{Z}_{6-I}$-twist: $z^i \to e^{2\pi i v^i} z^i\,,\quad v^1 = \frac{1}{6}\,, v^2 = \frac{1}{6}\,, v^3 = -\frac{2}{6}$

Coxeter twist:

G_2 $\qquad$ $SU(3)$

$$Q = \begin{pmatrix} 2 & -1 & 0 & 0 & 0 & 0 \\ 3 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & -1 & 0 & 0 \\ 0 & 0 & 3 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 1 & -1 \end{pmatrix}$$

Metric:

$$g = \begin{pmatrix} R_1^2 & -\frac{1}{2}R_1^2 & R_1R_3\cos\theta_{13} & y & 0 & 0 \\ -\frac{1}{2}R_1^2 & \frac{1}{3}R_1^2 & \frac{1}{\sqrt{3}}R_1R_3\cos\theta_{23} & \frac{1}{3}R_1R_3\cos\theta_{13} & 0 & 0 \\ R_1R_3\cos\theta_{13} & \frac{1}{\sqrt{3}}R_1R_3\cos\theta_{23} & R_3^2 & -\frac{1}{2}R_3^2 & 0 & 0 \\ y & \frac{1}{3}R_1R_3\cos\theta_{13} & -\frac{1}{2}R_3^2 & \frac{1}{3}R_3^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_5^2 & -\frac{1}{2}R_5^2 \\ 0 & 0 & 0 & 0 & -\frac{1}{2}R_5^2 & R_5^2 \end{pmatrix}$$

$$y = -\frac{1}{3}(3R_1R_3\cos\theta_{13} - \sqrt{3}R_1R_3\cos\theta_{23})$$

5 metric degrees of freedom!

Complex structure:

$$dz^1 = dx^1 + \frac{1}{\sqrt{3}}e^{5\pi i/6}dx^2,\quad dz^2 = dx^3 + \frac{1}{\sqrt{3}}e^{5\pi i/6}dx^4,\quad dz^3 = dx^5 + e^{2\pi i/3}dx^6.$$

Example: $\mathbb{Z}_{6-I}$ on $G_2^2 \times SU(3)$

Five invariant (1,1)-forms:

$$\begin{aligned} \omega_1 &= dx^1 \wedge dx^2, \quad \omega_2 = dx^3 \wedge dx^4, \quad \omega_3 = dx^5 \wedge dx^6, \\ \omega_4 &= dx^2 \wedge dx^3 - dx^1 \wedge dx^4, \\ \omega_5 &= 3\, dx^1 \wedge dx^3 - 3\, dx^1 \wedge dx^4 + dx^2 \wedge dx^4. \end{aligned}$$

Kähler form (real cohomology):

$$\begin{aligned} J &= \underbrace{\frac{1}{\sqrt{3}} R_1^2}_{\mathrm{Re}\,(\mathcal{T}^1)} \omega_1 + \underbrace{\frac{1}{\sqrt{3}} R_3^2}_{\mathrm{Re}\,(\mathcal{T}^2)} \omega_2 \underbrace{- \sqrt{3}\, R_5^2}_{\mathrm{Re}\,(\mathcal{T}^3)} \omega_3 \underbrace{- \frac{2}{\sqrt{3}} R_1 R_3 \cos\theta_{13}}_{\mathrm{Re}\,(\mathcal{T}^4)} \omega_4 \\ &\quad + \underbrace{\frac{2}{3} R_1 R_3 \left(13\sqrt{3}\, \cos\theta_{13} + 29 \cos\theta_{23}\right)}_{\mathrm{Re}\,(\mathcal{T}^5)} \omega_5 \end{aligned}$$

Turning on Fluxes

3-form flux: $F_3 = dC_2$ $H_3 = dB_2$

$$G_3 = F_3 + i\ S\ H_3$$

Fluxes are quantized: $\frac{1}{(2\pi)^2\alpha'}\int_{C_3} F_3 \in n_0\,\mathbf{Z}\,, \quad \frac{1}{(2\pi)^2\alpha'}\int_{C_3} H_3 \in n_0\,\mathbf{Z}$

Expressed in cplx basis: $H^3 = H^{(3,0)} \oplus H^{(2,1)} \oplus H^{(1,2)} \oplus H^{(0,3)}$

$$\frac{1}{(2\pi)^2\alpha'} G_3 = \sum_{i=0}^{3}(A^i\omega_{A_i} + B^i\omega_{B_i}) + \sum_{j=1}^{6}(C^j\omega_{C_j} + D^j\omega_{D_j})$$

$dz^1 \wedge dz^2 \wedge dz^3$ $dz^1 \wedge d\overline{z}^1 \wedge dz^2$

Expressed in the real basis:

$$\frac{1}{(2\pi)^2\alpha'} G_3 = \sum_{i=0}^{3}\left[(a^i + iSc^i)\alpha_i + (b_i + iSd_i)\beta^i\right] + \sum_{j=1}^{6}\left[(e^j + iSg^j)\gamma_j + (f_j + iSh_j)\delta^j\right]$$

On T^6, there are 20 3-forms. Which of them survive the orbifold-twist?

always: $(3,0)\; dz^1 \wedge dz^2 \wedge dz^3, \quad (0,3)\; d\bar{z}^1 \wedge d\bar{z}^2 \wedge d\bar{z}^3$

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$d\bar{z}^1 \wedge dz^2 \wedge dz^3$
$dz^1 \wedge d\bar{z}^2 \wedge dz^3$
$dz^1 \wedge dz^2 \wedge d\bar{z}^3$

$dz^1 \wedge dz^2 \wedge d\bar{z}^3$

LMU Fluxes for $\mathbf{Z}_{6-I}$ on $G_2^2 \times SU(3)$

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In this case, $h^{(2,1)} = 0$, therefore

$$\frac{1}{(2\pi)^2\alpha'} G_3 = A_0\,\omega_{A_0} + B_0\,\omega_{B_0}$$

4 real parameters

Complex structure →

$$\omega_{A_0} = dx^1 \wedge dx^2 \wedge dx^3 + \frac{1}{\sqrt{3}} e^{5\pi i/6} (dy^1 \wedge dx^2 \wedge dx^3 + dx^1 \wedge dy^2 \wedge dx^3) + e^{2\pi i/3} dx^1 \wedge dx^2 \wedge dy^3 + \frac{1}{3} e^{2\pi i/6} dy^1 \wedge dy^2 \wedge dy^3$$

Complex coefficients:

Integers

$$A_0 = \frac{1}{\sqrt{3}} (e^{2\pi i/12} a^0 - i\sqrt{3}\, b_0 + iS\,[e^{2\pi i/12} c^0 - i\sqrt{3}\, d_0]),$$

$$B_0 = \frac{1}{\sqrt{3}} (e^{-2\pi i/12} a^0 + i\sqrt{3}\, b_0 - iS\,[e^{-2\pi i/12} c^0 + i\sqrt{3}\, d_0])$$

The Vacuum Structure

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Effective N=1 superpotential:

$$W = W_{\rm flux}(S, U^j) + W_{\rm np}(T^i) = \kappa_{10}^{-2} \int G_3 \wedge \Omega + \sum_{i=1}^{3} g^i \, e^{-h^i T^i}$$

Scalar potential:

$$V = e^{\kappa_4^2 K} \left(|D_S W|^2 + \sum_i |D_{T^i} W|^2 + \sum_j |D_{U^j} W|^2 - 3|W|^2 \right)$$

Impose SUSY-conditions:

$$D_i W = \partial_i W + \kappa_4^2 \; W \; \partial_i K = 0 \, , \quad i = S, U^i, T^i$$

Stability: The eigenvalues of the scalar mass matrix must be > 0.

$$\frac{\partial^2 V}{\partial M \partial \overline{N}} > 0, \quad (M, N = S, U^j, T^i)$$

$\leftrightarrow$ determinants of all upper-left sub-matrices must be positive

Are there stable minima?

Dilaton and 1 Kähler modulus: no! Choi, Falkowski, Nilles, Olechowski, Pokorski

Dilaton and 3 Kähler moduli: no!

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Dilaton and 1 Kähler modulus: no! Choi, Falkowski, Nilles, Olechowski, Pokorski

Dilaton and 3 Kähler moduli: no!

Dilaton and 5 Kähler moduli: no!

Dilaton and 9 Kähler moduli: no!

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Are there stable minima?

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Dilaton and 3 Kähler moduli: no!

Dilaton and 5 Kähler moduli: no!

Dilaton and 9 Kähler moduli: no!

Dilaton and 3 Kähler moduli and 1 complex structure modulus: YES!

Dilaton and 3 Kähler moduli and 3 complex structure moduli: YES!

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The non-perturbative superpotential

Two possible origins for the non-perturbative superpotential:

(i) Euclidean D3/M5-brane instantons wrapping internal 4-cycles

$$W_{\rm np} \sim \; g_i \; e^{-2\pi V_i}$$

(ii) Gaugino condensation in the world-volume of D7-branes wrapped on internal 4-cycles

$$W_{\rm np} \sim \; g_i \; e^{-\frac{2\pi V_i}{b}}$$

Condition for existence of non-vanishing non-pert. superpotential:
F/M-Theory:

Witten

$$\chi(\text{wrapped divisor}) = 1$$

Arithmetic genus changes in the presence of 3-form flux!

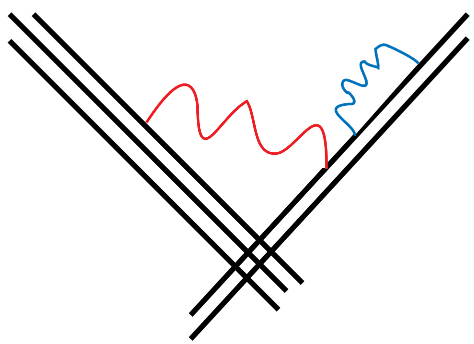
Tripathy, Trivedi; Kallosh, Kashani-Poor, Tomasiello; Saulina

The non-perturbative superpotential

D3/M5-instantons: F-theory lift seems inevitable

Gaugino condensates: field theoretic arguments

Existence of np-superpotential: pure super-Yang-Mills theory
↔ no massless bi-fundamental matter, no massless adjoint matter.
Depends again on the topology of the wrapped divisors.



If the brane stacks don't intersect →
no bi-fundamental matter!

If massless adjoint matter (D7-brane position fields and Wilson lines) exists, we can try to make them massive via 3-form fluxes!

Generalizations: Resolved Orbifolds

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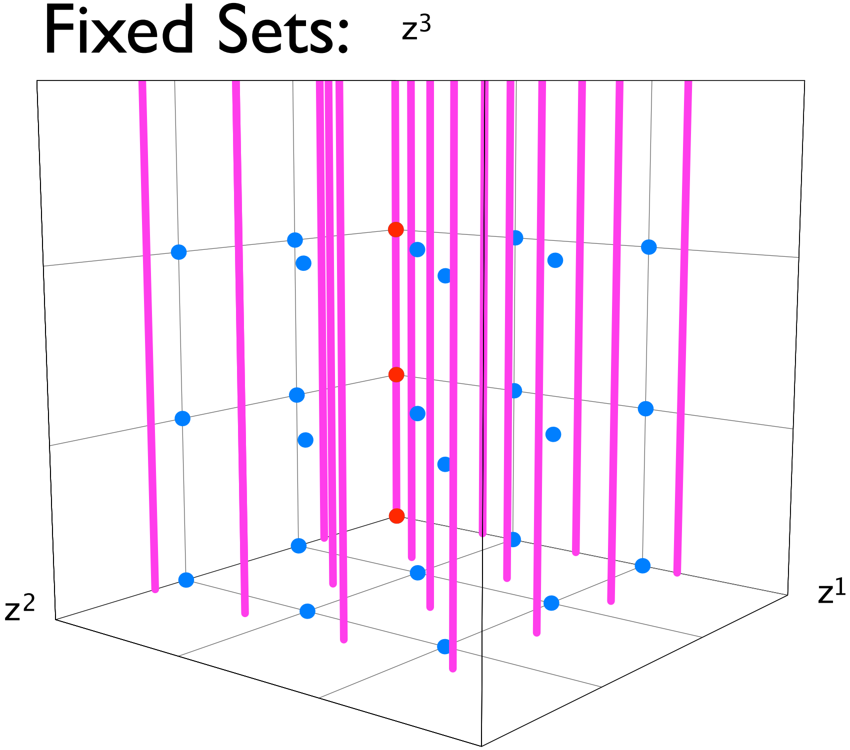
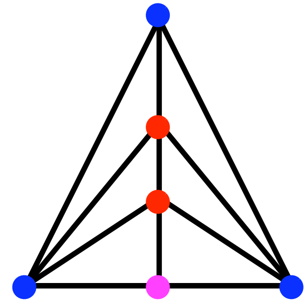
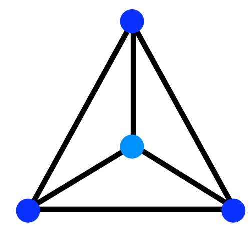
$\mathbf{Z}_{6-I}$ on $G_2^2 \times SU(3)$

Fixed Sets:

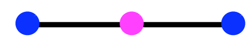




Blowup of $\mathbf{C}^3/\mathbf{Z}_{6-I}$



Blowup of $\mathbf{C}^3/\mathbf{Z}_3$



Blowup of $\mathbf{C}^2/\mathbf{Z}_2$

Group El.	Twist	Fixed set	Conj. Cl.
θ	$\mathbf{Z}_{6-I}$	3 fixed points	3
θ^2	$\mathbf{Z}_3$	27 fixed points	15
θ^3	$\mathbf{Z}_2$	16 fixed lines	6

Divisor count:
3•2+12•1+6•1=24

LMU

Conclusions

MAX-PLANCK-GESELLSCHAFT

Complex structures and geometric parameterization of Kähler moduli, allowed fluxes, existence of stable vacua at the orbifold point. “Phone book”

Open Questions:

- Do we indeed get contributions to the non-perturbative superpotential for those models who allow stable vacua?
- What about resolved orbifolds?
  Exceptional divisors seem very likely to contribute to non-pert. superpotential.
- For which of these orbifold models, an F-theory lift exists?
- For which of these models can we get gaugino condensates?
- Consistent models with all moduli fixed other than $\mathbf{Z}_2 \times \mathbf{Z}_2$?

work in progress

Thank you!