Charting the Landscape of 3D Orientifold Flux Vacua

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Based on work with Álvaro Arboleya and Matteo Morittu [arXiv: 2408.01403]

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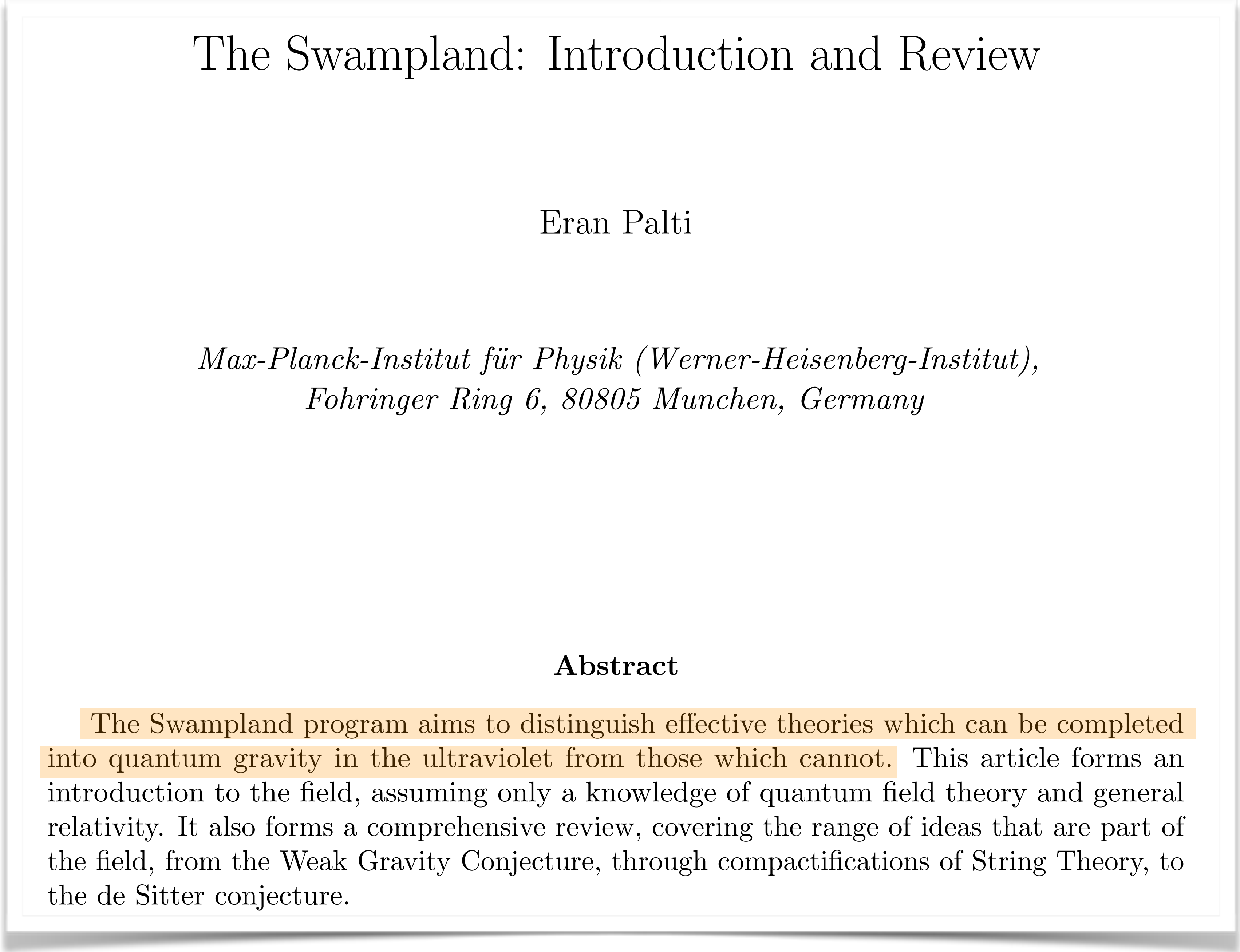
[Vafa, '05] [see Palti's review, '19]



The Swampland: Introduction and Review

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Abstract

The Swampland program aims to distinguish effective theories which can be completed into quantum gravity in the ultraviolet from those which cannot. This article forms an introduction to the field, assuming only a knowledge of quantum field theory and general relativity. It also forms a comprehensive review, covering the range of ideas that are part of the field, from the Weak Gravity Conjecture, through compactifications of String Theory, to the de Sitter conjecture.

Many conjectures stated: non-susy AdS, distance conjecture, …

Can we systematically study **type II flux vacua in 3D** to test them?

[Farakos, Tringas, van Riet, '20]
[Emelin, Farakos, Tringas, '21]

Type II orientifold reductions to 3D

- Type II on $\mathcal{M}_{10} = \mathcal{M}_3 \times \mathbb{T}^7_\omega$ with **single type** of Op/Dp-sources

Half-maximal $\mathcal{N} = 8$ supergravities in D=3

- Background fluxes $(m = 1, \ldots, 7)$

[Scherk, Schwarz, '79]
[Hull, Reid-Edwards, '05]

(internal) **gauge fluxes**

$$H_{(3)} = H_{mnp}\, \eta^m \wedge \eta^n \wedge \eta^p$$

$$F_{(3)} = F_{mnp}\, \eta^m \wedge \eta^n \wedge \eta^p$$

$$\ldots$$

[see Graña's review, '05]

twisted tori with **metric fluxes**

(Scherk-Schwarz reduction)

$$\eta^m = U(y)^m{}_n\, dy^n \;\Rightarrow\; d\eta^p = \tfrac{1}{2}\omega_{mn}{}^p\, \eta^m \wedge \eta^n$$

- Bianchi identities & Tadpole cancellation $(D = d + \omega)$

$$DH_{(3)} = 0$$

[No NS5-branes]

$$DF_{(8-p)} - H_{(3)} \wedge F_{(6-p)} = J_{\text{O}p/\text{D}p}$$

[tadpole cancellation for Op/Dp sources]

$$\omega_{[mn}{}^r\, \omega_{p]r}{}^q = 0$$

[$D^2 = 0$: No KK monopoles]

Half-maximal supergravities in 3D

[Nicolai, Samtleben, '01]
[Deger, Eloy, Samtleben, '19]

- Reduction without fluxes ➡ *ungauged* theory with global symmetry SO(8,8)

- Reduction with fluxes ➡ *gauged* theory with local symmetry G ⊂ SO(8,8)

- Scalar field content (coset geometry) = **64 scalars**

$$\mathcal{V} = \begin{pmatrix} \mathbb{I} & 0 \\ \boldsymbol{b} & \mathbb{I} \end{pmatrix} \begin{pmatrix} \boldsymbol{e} & 0 \\ 0 & \boldsymbol{e}^{-T} \end{pmatrix} \in \frac{\mathrm{SO}(8,8)}{\mathrm{SO}(8)\times\mathrm{SO}(8)}$$

in terms of $\boldsymbol{e} \in \frac{\mathrm{GL}(8)}{\mathrm{SO}(8)}$ (36 scalars) and $\boldsymbol{b} = -\boldsymbol{b}^T$ (28 scalars)

- We introduce the *scalar-dependent matrix* (à la DFT)

Note: T-duality = SO(7,7)

$$M = \mathcal{V}\,\mathcal{V}^T = \begin{pmatrix} \boldsymbol{g} & -\boldsymbol{g}\,\boldsymbol{b} \\ \boldsymbol{b}\,\boldsymbol{g} & \boldsymbol{g}^{-1} - \boldsymbol{b}\,\boldsymbol{g}\,\boldsymbol{b} \end{pmatrix} \in \mathrm{SO}(8,8) \quad \text{with} \quad \boldsymbol{g} = \boldsymbol{e}\,\boldsymbol{e}^T$$

Half-maximal supergravities in 3D

[Nicolai, Samtleben, '01]
[Deger, Eloy, Samtleben, '19]

- Interactions induced by fluxes are encoded in a so-called embedding tensor (ET)

$$\Theta_{MN|PQ} = \theta_{MNPQ} + 2\left(\eta_{M[P}\theta_{Q]N} - \eta_{N[P}\theta_{Q]M}\right) + 2\eta_{M[P}\eta_{Q]N}\theta \qquad (M = 1, \dots, 16)$$

consisting of three irreducible representations of SO(8,8)

$$\theta_{MNPQ} = \theta_{[MNPQ]} \in \mathbf{1820} \qquad \theta_{MN} = \theta_{(MN)} \in \mathbf{135} \qquad \theta \in \mathbf{1}$$

- Consistency of the gauging requires a set of Quadratic Constraints (QC)

$$\Theta \cdot \Theta = 0$$

→ **ET / Flux dictionary** →

Bianchi identities
&
Tadpole cancellation

- Scalar potential

$$V(\Theta\,;M) = \Theta\,\Theta\left(M^4 + M^3\,\eta + \dots\right)$$

[see Samtleben's review, '08]

Goals

1. Derive the type II ET/Flux dictionary for all the possible half-maximal supergravities compatible with a single type of O*p*/D*p*-sources

[Group Theory]

[4D: Angelantonj, Ferrara, Trigiante '03]
[4D: Dibitetto, AG, Roest '11, '12]

2. Classify the extrema of the scalar potential of the resulting half-maximal supergravities

[Algebraic Geometry]

Group Theory Part

Warming up: M-theory on $\mathcal{M}_{11} = \mathcal{M}_3 \times \mathbb{T}^8_\omega$

- Internal diffeomorphisms $\mathrm{GL}(8) = \mathrm{SL}(8) \times \mathbb{R}_1 \subset \mathrm{SO}(8,8)$

  - Coordinates & derivatives : $y^A \in \mathbf{8}_{-3}$, $\partial_A \in \mathbf{8}'_{+3}$ $(A = 1, \ldots, 8)$

  - Metric & gauge potentials : $e_A{}^B \in (\mathbf{63}+\mathbf{1})_0$, $C_{(3)} \in \mathbf{56}'_{+1}$, $C_{(6)} \in \mathbf{28}_{+2}$

  - Fluxes : $\omega_{AB}{}^C \in (\mathbf{216}'+\mathbf{8}')_{+3}$, $G_{(4)} \in \mathbf{70}_{+4}$, $G_{(7)} \in \mathbf{8}_{+5}$

$\mathrm{SO}(8,8)$	Half-Maximal	$\mathrm{SL}(8) \times \mathbb{R}_1$
$\mathbf{120}$	scalars	$\mathbf{28}'_{-2} \oplus (\mathbf{63}+\mathbf{1})_0 \oplus \mathbf{28}_{+2}$
$\mathbf{1}$	θ	$\mathbf{1}_0$
$\mathbf{135}$	θ_{MN}	$\mathbf{36}'_{-2} \oplus \mathbf{63}_0 \oplus \mathbf{36}_{+2}$
$\mathbf{1820}$	θ_{MNPQ}	$\mathbf{70}_{-4} \oplus \mathbf{28}'_{-2} \oplus \mathbf{420}'_{-2}$ $\mathbf{720}_0 \oplus \mathbf{63}_0 \oplus \mathbf{1}_0$ $\mathbf{70}_{+4} \oplus \mathbf{28}_{+2} \oplus \mathbf{420}_{+2}$

Scalars : $e_A{}^B \in \frac{\mathrm{GL}(8)}{\mathrm{SO}(8)}$, $C_{(6)}$

Fluxes : $G_{(4)}$

$$\theta^{ABCD} = \frac{1}{4!}\,\varepsilon^{ABCDEFGH} G_{EFGH}$$

Mkw$_3$ vacua with a massless ***no-scale*** direction

Type IIA with O2/D2 sources

x^0	x^1	x^2	y^1	y^2	y^3	y^4	y^5	y^6	y^7
$\times$	$\times$	$\times$							

- Internal diffeomorphisms $\mathrm{GL}(7) = \mathrm{SL}(7) \times \mathbb{R}_2 \subset \mathrm{SL}(8) \times \mathbb{R}_1 \subset \mathrm{SO}(8,8)$

- A group-theoretical analysis shows that $(m = 1, \ldots, 7)$

$$\text{Scalars} \quad : \quad e_m{}^n \in \frac{\mathrm{GL}(7)}{\mathrm{SO}(7)} \quad , \quad C_{(1)} \quad , \quad \Phi \quad , \quad B_{(6)} \quad , \quad C_{(5)}$$

$$\text{Fluxes} \quad : \quad H_{(3)} \quad , \quad F_{(4)} \quad , \quad F_{(0)}$$

$$\theta^{mnpq} = \tfrac{1}{3!}\, \varepsilon^{mnpqrst} H_{rst} \quad , \quad \theta^{mnp8} = \tfrac{1}{4!}\, \varepsilon^{mnpqrst} F_{qrst} \quad , \quad \theta^{88} = F_{(0)}$$

- Quadratic Constraints : $\Theta \cdot \Theta = 0$ → (ET / Flux dictionary) $F_{(0)}\, H_{(3)} = 0$

No O6/D6 sources !!

- No new vacua (same no-scale Mkw$_3$)

Type IIB with O5/D5 sources

x^0	x^1	x^2	y^1	$\tilde{y}^2$	y^3	$\tilde{y}^4$	y^5	$\tilde{y}^6$	y^7
$\times$	$\times$	$\times$		$\times$		$\times$		$\times$	

- Internal diffeomorphisms

$$\mathrm{GL}(4) \times \mathrm{GL}(3) = \mathrm{SL}(4) \times \mathrm{SL}(3) \times \mathbb{R}_3 \times \mathbb{R}_2 \subset \mathrm{SL}(8) \times \mathbb{R}_1 \subset \mathrm{SO}(8,8)$$

- A group-theoretical analysis shows that $(\, \hat{a} = 1,3,5,7 \quad \text{and} \quad i = 2,4,6 \,)$

$$\begin{array}{rcl c rcl}
e_i{}^j & \in & (\mathbf{1}, \mathbf{8}+\mathbf{1})_{(0,0,0)} & , & C_{i\hat{a}\hat{b}\hat{c}} & \in & (\mathbf{4}, \mathbf{3})_{(-1,+2,+2)} \\
e_{\hat{a}}{}^{\hat{b}} & \in & (\mathbf{15}+\mathbf{1}, \mathbf{1})_{(0,0,0)} & , & C_{ijk\hat{a}} & \in & (\mathbf{4}', \mathbf{1})_{(-3,-8,0)} \\
\Phi & \in & (\mathbf{1}, \mathbf{1})_{(0,0,0)} & , & C_{ij} & \in & (\mathbf{1}, \mathbf{3}')_{(+4,-8,0)} \\
B_{i\hat{a}} & \in & (\mathbf{4}', \mathbf{3})_{(-7,0,0)} & , & C_{\hat{a}\hat{b}} & \in & (\mathbf{6}, \mathbf{1})_{(+6,+2,+2)} \\
B_{ijk\hat{a}\hat{b}\hat{c}} & \in & (\mathbf{4}, \mathbf{1})_{(+3,-6,+2)} & , & C_{ij\hat{a}\hat{b}\hat{c}\hat{d}} & \in & (\mathbf{1}, \mathbf{3}')_{(-8,+2,+2)}
\end{array}$$

Fluxes	Flux components	Embedding tensor
ω	${\omega_{ij}}^{k} \in (\mathbf{1},\mathbf{6}+\mathbf{3})_{(-4,-6,+2)}$	${\theta^{ij8}}_{k}$
	${\omega_{\hat{a}\hat{b}}}^{i} \in (\mathbf{6},\mathbf{3}')_{(-2,+4,+4)}$	$\theta^{\hat{c}\hat{d}jk}$
	${\omega_{\hat{a}i}}^{\hat{b}} \in (\mathbf{15}+\mathbf{1},\mathbf{3})_{(-4,-6,+2)}$	${\theta^{i\hat{b}8}}_{\hat{a}}$
$H_{(1)}$	$H_{i} \in (\mathbf{1},\mathbf{3})_{(-4,-6,+2)}$	θ^{i8}
$F_{(1)}$	$F_{\hat{a}} \in (\mathbf{4}',\mathbf{1})_{(+9,-4,+4)}$	$-\theta^{\hat{b}\hat{c}\hat{d}8}$
$H_{(3)}$	$H_{\hat{a}\hat{b}\hat{c}} \in (\mathbf{4},\mathbf{1})_{(-9,+4,+4)}$	$-\theta^{\hat{d}ijk}$
	$H_{ij\hat{c}} \in (\mathbf{4}',\mathbf{3}')_{(-11,-6,+2)}$	${\theta^{ij8}}_{\hat{c}}$
$F_{(3)}$	$F_{ijk} \in (\mathbf{1},\mathbf{1})_{(0,-14,+2)}$	$-\theta^{88}$
	$F_{\hat{a}\hat{b}k} \in (\mathbf{6},\mathbf{3})_{(+2,-4,+4)}$	$\theta^{\hat{c}\hat{d}k8}$
$F_{(5)}$	$F_{\hat{a}\hat{b}\hat{c}ij} \in (\mathbf{4},\mathbf{3}')_{(-5,-4,+4)}$	$\theta^{\hat{d}ij8}$
$F_{(7)}$	$F_{\hat{a}\hat{b}\hat{c}\hat{d}ijk} \in (\mathbf{1},\mathbf{1})_{(-12,-4,+4)}$	$-\theta^{ijk8}$

Too many fluxes and scalars !!

SO(3)-invariant sector: RSTU-model

- SO(3)-invariant scalars : $\mathrm{SO}(8,8) \supset \mathrm{SO}(2,2) \times \mathrm{SO}(6,6) \supset \mathrm{SO}(2,2) \times \mathrm{SO}(2,2) \times \mathrm{SO}(3)$

$$\mathcal{M}_{\text{scal}} = \left[\frac{\mathrm{SL}(2)}{\mathrm{SO}(2)}\right]^4 \subset \frac{\mathrm{SO}(8,8)}{\mathrm{SO}(8) \times \mathrm{SO}(8)}$$

4 complex scalars : $R\,,\,S\,,\,T\,,\,U$

RSTU-model

Note: analogue of the STU-model in 4D

- SO(3)-invariant fluxes : $(\,\hat{a} = \overbrace{1,3,5}^{a},\ 7\,)$

$$\begin{array}{lll} \omega_{ab}{}^{k} = \omega_1\,\epsilon_{ab}{}^{k} \,, & \omega_{7a}{}^{i} = \omega_2\,\delta_a^i \,, & \omega_{7i}{}^{a} = \omega_3\,\delta_i^a \\ \omega_{ia}{}^{7} = \omega_4\,\delta_{ia} \,, & \omega_{ia}{}^{b} = \omega_5\,\epsilon_{ia}{}^{b} \,, & \omega_{ij}{}^{k} = \omega_6\,\epsilon_{ij}{}^{k} \end{array}$$

$$H_{abc} = h_{31}\,\epsilon_{abc} \,,\quad H_{aij} = h_{32}\,\epsilon_{aij} \,,\quad F_{ijk} = f_{31}\,\epsilon_{ijk} \,,\quad F_{ia7} = f_{32}\,\delta_{ia} \,,\quad F_{ibc} = f_{33}\,\epsilon_{ibc}$$
$$F_{abij7} = f_5\,\delta_{ai}\,\delta_{bj} \,,\quad F_{abcijk7} = f_7\,\epsilon_{abc}\,\epsilon_{ijk} \,,$$

Summary: 4 complex scalars & 13 flux parameters

- Quadratic Constraints : $\Theta \cdot \Theta = 0$

$$\begin{aligned} \omega_3\,\omega_4 + \omega_5\,(\omega_5+\omega_6) &= 0 \quad , \quad & \omega_4\,(2\,\omega_5+\omega_6) &= 0 \\ \omega_1\,\omega_3 - \omega_2\,(\omega_5+\omega_6) &= 0 \quad , \quad & \omega_3\,(2\,\omega_5+\omega_6) &= 0 \quad , \quad \omega_1\,\omega_4 = 0 \\ \omega_2\,\omega_4 - \omega_1\,(\omega_5+\omega_6) &= 0 \quad , \quad & \omega_1\,\omega_3 - 2\,\omega_2\,\omega_5 &= 0 \end{aligned}$$

$\Rightarrow$ **No KK monopoles** $\quad \omega_{[mn}{}^{r}\,\omega_{p]r}{}^{q} = 0$

$$\begin{aligned} \omega_3\,h_{32} &= 0 \\ 2\,\omega_2\,h_{32} - \omega_3\,h_{31} &= 0 \end{aligned}$$

$\Rightarrow$ $DH_{(3)} = 0$ **No NS5-branes**

$$3\,\omega_4\,f_5 - h_{31}\,f_{31} + 3\,h_{32}\,f_{33} = 0$$

$\Rightarrow$ $DF_{(5)} - H_{(3)} \wedge F_{(3)} = 0$ **No O3/D3 sources**

$$\begin{aligned} \omega_2\,f_{31} + (2\,\omega_5+\omega_6)\,f_{32} + 2\,\omega_3\,f_{33} &= 0 \\ \omega_1\,f_{31} - (2\,\omega_5+\omega_6)\,f_{33} - 2\,\omega_4\,f_{32} &= 0 \end{aligned}$$

$\Rightarrow$ $DF_{(3)} = 0$ **No other type of O5/D5 sources**

… but …

$$DF_{(3)}\big|_{dy^{\hat{a}}\wedge dy^{\hat{b}}\wedge dy^{\hat{c}}\wedge dy^{\hat{d}}} = \omega_1\,f_{32} - \omega_2\,f_{33} = J_{\text{O5/D5}}$$

$\Rightarrow$ **O5/D5 sources (orientifold) unrestricted !!**

Algebraic Geometry Part

The algebraic problem

$$V(\Theta\,;M) = \Theta\,\Theta\,\left(M^4 + M^3\,\eta + \ldots\right)$$

Quadratic on the ET
(13 flux parameters)

High powers of the scalars
(4 complex scalars)

Trick :

fixed fluxes
&
scan scalar VEV's

Complicated problem

→

fixed scalar VEV's
&
scan fluxes

Quadratic problem

Quadratic algebraic problem :

Ideal = multivariate polynomial system

$$I = \left\langle\ \partial V\Big|_{\langle R\rangle=\langle S\rangle=\langle T\rangle=\langle U\rangle=i} = 0 \ \ , \ \ \Theta\cdot\Theta = 0\ \right\rangle$$

[SINGULAR project: Decker, Greuel, Pfister, Schönemann]

A SINGULAR approach to the algebraic problem

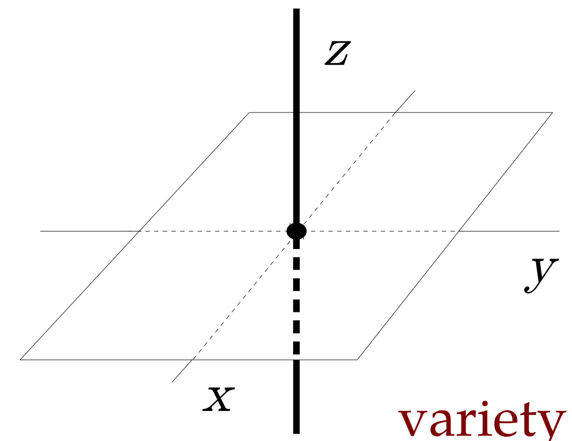
- Algebraic Geometry studies multivariate polynomial systems and their link to geometry (space of solutions)

$$I = \langle P_1 \, , \, P_2 \rangle$$

$$\begin{aligned} P_1(x,y,z) &= x\,z \\ P_2(x,y,z) &= y\,z \end{aligned}$$

algebraic system

$\Longleftrightarrow$



variety

- Prime decomposition (analogous to integer decomp. 15 = 3 x 5)

$$I = J_1 \cap J_2 \quad \text{where} \quad \begin{cases} J_1 = \langle z \rangle \longrightarrow xy\text{-plane} \\ J_2 = \langle x \, , \, y \rangle \longrightarrow z\text{-axis} \end{cases}$$

$\Rightarrow$

$$\boxed{J_1 \cap J_2 \longleftrightarrow V(J_1) \cup V(J_2)}$$

algebra-geometry dictionary

- Our specific ideal $I = \left\langle \; \partial V \Big|_{\langle \Phi \rangle = i} \; , \; \Theta \cdot \Theta \; \right\rangle \; \ldots$ **15 prime factors !!**

A landscape of 3D orientifold flux vacua

			ω						$H_{(3)}$		$F_{(3)}$			$F_{(5)}$	$F_{(7)}$
ID	Type	SUSY	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	h_{31}	h_{32}	f_{31}	f_{32}	f_{33}	f_5	f_7
vac 1	Mkw_3	$\mathcal{N}=0,4$	κ	ξ	0	0	0	0	0	0	0	κ	$-\xi$	0	0
vac 2		$\mathcal{N}=0$	0	κ	0	0	0	0	0	0	0	0	$-\kappa$	0	0
vac 3 $\ast$		$\mathcal{N}=0$	0	κ	κ	0	0	0	0	0	0	0	0	0	0
vac 4 $\dagger$	AdS_3	$\mathcal{N}=4$	0	0	0	0	0	κ	0	0	$\pm\kappa$	0	0	0	$-\kappa$
vac 5 $\dagger$		$\mathcal{N}=0$	0	0	0	0	0	κ	0	0	$\pm\kappa$	0	0	0	κ
vac 6 $\ast$	AdS_3	$\mathcal{N}=3$	κ	0	0	0	$-\kappa$	κ	0	0	$\mp\kappa$	0	$\pm\kappa$	0	-2κ
vac 7 $\ast$		$\mathcal{N}=1$	κ	0	0	0	$-\kappa$	κ	0	0	$\mp\kappa$	0	$\pm\kappa$	0	2κ
vac 8 $\dagger$	AdS_3	$\mathcal{N}=1$	0	0	0	0	$-\kappa$	κ	0	0	$\pm\kappa$	0	0	0	κ
vac 9 $\dagger$		$\mathcal{N}=0$	0	0	0	0	$-\kappa$	κ	0	0	$\pm\kappa$	0	0	0	$-\kappa$
vac 10	AdS_3	$\mathcal{N}=0$	0	2κ	κ	0	0	0	0	0	κ	$\pm\kappa$	$-\kappa$	0	$\pm\kappa$
vac 11	AdS_3	$\mathcal{N}=0$	0	2κ	κ	0	0	0	0	0	κ	$\pm\kappa$	$-\kappa$	0	$\mp\kappa$
vac 12 $\dagger$	AdS_3	$\mathcal{N}=4$	0	0	$\pm\kappa$	$\pm\kappa$	κ	-2κ	0	0	$\pm2\kappa$	0	0	0	2κ
vac 13 $\dagger$		$\mathcal{N}=1$	0	0	$\pm\kappa$	$\pm\kappa$	κ	-2κ	0	0	$\pm2\kappa$	0	0	0	-2κ
vac 14 $\dagger$		$\mathcal{N}=0$	0	0	$\pm\kappa$	$\pm\kappa$	κ	-2κ	0	0	$\mp2\kappa$	0	0	0	2κ
vac 15 $\dagger$		$\mathcal{N}=0$	0	0	$\pm\kappa$	$\pm\kappa$	κ	-2κ	0	0	$\mp2\kappa$	0	0	0	-2κ

$\ast$ **embeddable into maximal (N=16) supergravity** **&** $\dagger$ **gSS reduction of O(8,8) DFT**

$$J_{\mathrm{O5/D5}} = 0$$

$$\theta_{[M_1 M_2 M_3 M_4}\,\theta_{M_5 M_6 M_7 M_8]} = 0$$

[Hohm, Musaev, Samtleben, '17]

Scalar mass spectra

	ID	Scalar spectrum
	vac 1	$g^{-2}\,m^2 = 0_{(30)}, \left(\frac{\kappa^2}{16}\right)_{(9)}, \left(\frac{\kappa^2}{4}\right)_{(9)}, \left(\frac{\xi^2}{4}\right)_{(9)}, \left(\frac{9\kappa^2}{16}\right)_{(1)}, \left[\frac{(\kappa-2\xi)^2}{16}\right]_{(3)}, \left[\frac{(\kappa+2\xi)^2}{16}\right]_{(3)}$
	vac 2	$g^{-2}\,m^2 = \left(\frac{\kappa^2}{4}\right)_{(15)}, 0_{(49)}$
*	**vac 3**	
†	**vac 4**	$m^2L^2 = 8_{(19)},\ 0_{(45)}$ $\Delta = 4_{(19)},\ 2_{(45)}$
†	**vac 5**	
*	**vac 6**	$m^2L^2 = 8_{(10)},\ 4_{(18)},\ 0_{(36)}$ $\Delta = 4_{(10)},\ (1+\sqrt{5})_{(18)},\ 2_{(36)}$
*	**vac 7**	
†	**vac 8**	$m^2L^2 = 24_{(10)},\ 8_{(25)},\ 0_{(29)}$ $\Delta = 6_{(10)},\ 4_{(25)},\ 2_{(29)}$
†	**vac 9**	
	vac 10	$m^2L^2 = 80_{(3)},\ 48_{(9)},\ 24_{(4)},\ 8_{(7)},\ 0_{(41)}$ $\Delta = 10_{(3)},\ 8_{(9)},\ 6_{(4)},\ 4_{(7)},\ 2_{(41)}$
	vac 11	$m^2L^2 = 48_{(15)},\ 8_{(13)},\ 0_{(36)}$ $\Delta = 8_{(15)},\ 4_{(13)},\ 2_{(36)}$
†	**vac 12**	$m^2L^2 = 15_{(8)},\ 8_{(19)},\ 3_{(8)},\ 0_{(29)}$ $\Delta = 5_{(8)},\ 4_{(19)},\ 3_{(8)},\ 2_{(29)}$
†	**vac 13**	
†	**vac 14**	
†	**vac 15**	

Only non-negative masses (pert. stable non-susy vacua) & integer Δ's

[Ooguri, Vafa, '16] [Apers, Conlon, Ning, Revello, '06]

Moduli stabilisation

scale-separated
AdS$_3$ vacua →

[Farakos, Tringas, van Riet, '20]
[Emelin, Farakos, Tringas, '21]
[Van Hemelryck, '22]
[Farakos, Morittu, Tringas, '23]
[Farakos, Morittu, '23]

			$\langle R \rangle$		$\langle S \rangle$		$\langle T \rangle$		$\langle U \rangle$	
	ID	$V_0 \equiv \langle V \rangle$	r	ρ	s	σ	t	τ	u	μ
	vac 1	0		$-\frac{f_{33}}{\omega_2}\ \tau$	0	$\frac{\omega_1}{f_{32}}\mu$			0	
	vac 2	0		$-\frac{f_{33}}{\omega_2}\ \tau$	0				0	
*	**vac 3**	0			0	$\frac{\omega_2}{\omega_3}\ \tau^{-1}$			0	
†	**vac 4**	$-\frac{g^2}{32}\frac{\omega_6^6}{f_{31}^2 f_7^2}$		$-\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$	0		$\frac{f_5}{\omega_6}$	$-\frac{f_7}{\omega_6}\mu$	0	
†	**vac 5**			$\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$				$\frac{f_7}{\omega_6}\mu$		
*	**vac 6**	$-\frac{g^2}{2}\frac{\omega_6^6}{f_{31}^2 f_7^2}$		$\frac{\omega_1 f_{31}^2}{\omega_6^3}\mu^{-1}$	0	$-\frac{2\omega_1}{f_7}\mu^{-1}$	$-\frac{f_5}{\omega_6}$	$-\frac{f_7}{2\omega_6}\mu$	0	
*	**vac 7**					$\frac{2\omega_1}{f_7}\mu^{-1}$		$\frac{f_7}{2\omega_6}\mu$		
†	**vac 8**	$-\frac{g^2}{32}\frac{\omega_6^6}{f_{31}^2 f_7^2}$		$\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$	0		$-\frac{f_5}{\omega_6}$	$\frac{f_7}{\omega_6}\mu$	0	
†	**vac 9**			$-\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$				$-\frac{f_7}{\omega_6}\mu$		
	vac 10	$-\frac{g^2}{32}\frac{\omega_3^6 f_{33}^6}{f_{31}^2 f_{32}^6 f_7^2}$		$-\frac{f_{31}(f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3^2 f_{33}}$	0	$\frac{\omega_3 f_{33}^2}{f_{31}(f_{32}^3 f_7)^{\frac{1}{2}}}$		$-\frac{(f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3 f_{33}}$	0	$\left(\frac{f_{32}}{f_7}\right)^{\frac{1}{2}}$
	vac 11			$-\frac{f_{31}(-f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3^2 f_{33}}$		$\frac{\omega_3 f_{33}^2}{f_{31}(-f_{32}^3 f_7)^{\frac{1}{2}}}$		$-\frac{(-f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3 f_{33}}$		$\left(-\frac{f_{32}}{f_7}\right)^{\frac{1}{2}}$
†	**vac 12**	$-2g^2\frac{\omega_5^6}{f_{31}^2 f_7^2}$		$\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$	0	$\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$\frac{f_7}{2\omega_5}\mu$	0	
†	**vac 13**			$-\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$		$\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$-\frac{f_7}{2\omega_5}\mu$		
†	**vac 14**			$-\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$		$-\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$\frac{f_7}{2\omega_5}\mu$		
†	**vac 15**			$\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$		$-\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$-\frac{f_7}{2\omega_5}\mu$		

Moduli stabilisation

			$\langle R \rangle$		$\langle S \rangle$		$\langle T \rangle$		$\langle U \rangle$	
	ID	$V_0 \equiv \langle V \rangle$	r	ρ	s	σ	t	τ	u	μ
	vac 1	0		$-\frac{f_{33}}{\omega_2}\ \tau$	0	$\frac{\omega_1}{f_{32}}\mu$			0	
	vac 2	0		$-\frac{f_{33}}{\omega_2}\ \tau$	0				0	
*	**vac 3**	0			0	$\frac{\omega_2}{\omega_3}\ \tau^{-1}$			0	
†	**vac 4**	$-\frac{g^2}{32}\frac{\omega_6^6}{f_{31}^2 f_7^2}$		$-\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$	0		$\frac{f_5}{\omega_6}$	$-\frac{f_7}{\omega_6}\mu$	0	
†	**vac 5**			$\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$				$\frac{f_7}{\omega_6}\mu$		
*	**vac 6**	$-\frac{g^2}{2}\frac{\omega_6^6}{f_{31}^2 f_7^2}$		$\frac{\omega_1 f_{31}^2}{\omega_6^3}\mu^{-1}$	0	$-\frac{2\omega_1}{f_7}\mu^{-1}$	$-\frac{f_5}{\omega_6}$	$-\frac{f_7}{2\omega_6}\mu$	0	
*	**vac 7**					$\frac{2\omega_1}{f_7}\mu^{-1}$		$\frac{f_7}{2\omega_6}\mu$		
†	**vac 8**	$-\frac{g^2}{32}\frac{\omega_6^6}{f_{31}^2 f_7^2}$		$\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$	0		$-\frac{f_5}{\omega_6}$	$\frac{f_7}{\omega_6}\mu$	0	
†	**vac 9**			$-\frac{f_{31}^2 f_7}{\omega_6^3}\ \sigma$				$-\frac{f_7}{\omega_6}\mu$		
	vac 10	$-\frac{g^2}{32}\frac{\omega_3^6 f_{33}^6}{f_{31}^2 f_{32}^6 f_7^2}$		$-\frac{f_{31}(f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3^2 f_{33}}$	0	$\frac{\omega_3 f_{33}^2}{f_{31}(f_{32}^3 f_7)^{\frac{1}{2}}}$		$-\frac{(f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3 f_{33}}$	0	$\left(\frac{f_{32}}{f_7}\right)^{\frac{1}{2}}$
	vac 11			$-\frac{f_{31}(-f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3^2 f_{33}}$		$\frac{\omega_3 f_{33}^2}{f_{31}(-f_{32}^3 f_7)^{\frac{1}{2}}}$		$-\frac{(-f_{32}^3 f_7)^{\frac{1}{2}}}{\omega_3 f_{33}}$		$\left(-\frac{f_{32}}{f_7}\right)^{\frac{1}{2}}$
†	**vac 12**	$-2g^2\frac{\omega_5^6}{f_{31}^2 f_7^2}$		$\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$	0	$\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$\frac{f_7}{2\omega_5}\mu$	0	
†	**vac 13**			$-\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$		$\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$-\frac{f_7}{2\omega_5}\mu$		
†	**vac 14**			$-\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$		$-\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$\frac{f_7}{2\omega_5}\mu$		
†	**vac 15**			$\frac{f_{31} f_7}{4\omega_3\omega_5}\mu$		$-\frac{2\omega_5^2}{\omega_3 f_{31}}\mu$		$-\frac{f_7}{2\omega_5}\mu$		

[Eloy, '20]
[Eloy, Larios, '23, '24]

KK spectrometry
&
distance conjecture

[Ooguri, Vafa, '06]

Summary

- Group Theory + Algebraic Geometry **=** systematic approach to the Landscape
- Embedding tensor/flux dictionary for *all* the **single O*p*-plane** setups ($p = 2,\ldots,9$)
- Type IIB with O5/D5 landscape appetizer

  - Rich structure of AdS_3 vacua both SUSY & non-SUSY
  - Perturbatively stable & integer Δ's (non-susy & non Ricci-flat spaces)
    [AdS conjecture] **[CFT_2 ?]**
  - Evidence for scale separation (purely 3D story)

[Ooguri, Vafa, '16]

[Apers, Conlon, Ning, Revello, '22]
[Quirant, '22]
[Plauschinn, '22]

To-Do List

- Complete the Landscape with the other O*p*-plane setups [Arboleya, AG, Morittu, in progress]
- Top-down construction : G-structures, scale separation, … [Farakos, Tringas, van Riet, '20] [Emelin, Farakos, Tringas, '21]
- Precise tests of the distance conjecture via KK spectrometry [Ooguri, Vafa, '06] [Eloy, '20] [Eloy, Larios, '23, '24]

ευχαριστώ !

thanks !