A NEW LANDSCAPE OF ORIENTIFOLD VACUA

at de Sitter constructions in string theory
12/10/2019 - Paris

based on 1912.XXXXX & 1902.01412 with Carta and Westphal
and 1812.03999 & with Hebecker, Leonhardt and Westphal

Jakob Moritz (Cornell University)

OUTLINE

INTRO

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ORIENTIFOLD VACUA OF CICYs

→ distributions of topological data:
D3 tadpole, # O3/O7 planes, # C_2/B_2 axions, # CS moduli.

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APPLICATIONS

→ as byproduct: explore new landscape of CY threefolds.

→ observe interesting $\mathcal{N} = 1$ transitions

→ explicit realizations of recent models of ultra light throat axions

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CONCLUSIONS

O3/O7 ORIENTIFOLDS

One way to construct $\mathcal{N} = 0, 1$ vacua in string theory is to compactify type IIB string theory on a Calabi-Yau threefold X, and pick a holomorphic involution

$$\mathcal{I} : X \longrightarrow X \text{ with } \mathcal{I}^*(\Omega) = -\Omega.$$

Then, modding out $\mathcal{I} \circ (-1)^{F_L} \circ$ (worldsheet parity) gives rise to orientifold vacua with orientifold planes on the fixed locus of $\mathcal{I}$.

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The fixed point locus of this is the union of a divisor D^o hosting an O7 plane and isolated fixed points hosting O3 planes.

The classical effective action is very well understood [Grimm,Louis'04]

O3/O7 ORIENTIFOLDS (continued)

[Collinucci,Denef,Esole'08]

In a weakly coupled type IIB vacuum, the negative D7 brane charge of the O7-plane must be canceled by a D7 brane wrapping

$$[8D^o] \in H^4(X, \mathbb{Z}).$$

Importantly, D7 branes, O7 planes, and O3 planes carry (induced) D3 brane charge

$$Q \equiv Q^{D3}_{D7/O7/D3} = \begin{cases} -(\frac{1}{4}\chi_f + 7[D^o]^3) & \text{generic D7} \\ -\frac{1}{4}\chi_f & \text{4 D7s on O7} \end{cases}$$

where χ_f = Euler char. of fixed locus.

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In the latter case, the dilaton is constant, and we get a non-abelian gauge group $SO(8)^{n_{O7}}$. Moreover, the tadpole is strongly bounded by the Lefschetz fixed point theorem:

$$-Q = h^{2,1}_- - h^{1,1}_- + \frac{1}{2}(h^{1,1} - h^{2,1}) + 1 \leq \frac{1}{2}(h^{1,1} + h^{2,1}) + 1.$$

FLUX VACUA IN TYPE IIB STRING THEORY

If $\chi_f > 0$, the negative D3 charge can be canceled by introducing three-form fluxes and D3 branes,

$$0 = Q + N_{D3} + \frac{1}{2} \int_X F_3 \wedge H_3.$$

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If $H_3(X, \mathbb{Z}) \ni [F_3], [H_3] \neq 0$, complex structure moduli and dilaton obtain a potential due to the flux superpotential

$$W_{flux}(\tau, z) = \int_X (F_3 - \tau H_3) \wedge \Omega(z).$$

[Gukov,Vafa,Witten'99;Giddings,Kachru,Polchinski'01]

FLUX VACUA IN TYPE IIB STRING THEORY (continued)

It's vacuum value W_0 is key ingredient and control parameter for KKLT type moduli stabilization, and sets the mass scale of Kähler moduli. [Kachru,Kallosh,Linde,Trivedi'03]

We expect to be able to tune it down to

$$\min(||W_0||^2) \propto Q^{-(2h_-^{2,1}+1)}$$ [Denef,Douglas'04]

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Note however, that while small W_0 leads to parametrically controlled SUSY AdS vacua, regimes of good control for the corresponding de Sitter vacua are much harder to establish because size of warped throat does not decouple from size of CY in large volume limit $W_0 \to 0$.

$$\frac{L^4_{CY}}{N_{D7}} \overset{D_T W=0}{\sim} \log(|W_0|^{-1}) \overset{\text{stable dS}}{\sim} \log(a^{-1}_{\text{warp}}) \sim \frac{KM}{g_s M^2} \sim \frac{L^4_{\text{throat}}}{g_s M^2}.$$

[Carta,JM,Westphal'19]

see also [Bena,Dudas,Graña,Lüst'18] & Severin's talk

LIGHT AXIONS FOR AXION MONODROMY

The orientifold-odd Hodge number $h^{1,1}_{-}$
counts the number of light axions

$$G^I = \int_{\Sigma_I} C_2 - \tau B_2 \,, \quad \Sigma_I \in H^2(X, \mathbb{Z}).$$

These are interesting (inflaton-)candidates in models of axion monodromy.

[Silverstein,Westphal'08;McAllister,Silverstein,Westphal'08]

[Marchesano,Shiu,Uranga'14;Blumenhagen,Plauschinn'14;Hebecker,Kraus,Witkowski'14]

...

[Hebecker,Leonhardt,JM,Westphal'18]

COMPLETE INTERSECTION CY THREEFOLDS

[Candelas,Dale,Lutken,Schimmrigk'87]

The famous database of CICY threefolds is usually presented as a set of 7890 *configuration matrices*

$$\left[\begin{array}{c|ccc} \mathbb{P}^{n_1} & m_1^1 & \cdots & m_1^K \\ \vdots & \vdots & & \vdots \\ \mathbb{P}^{n_r} & m_r^1 & \cdots & m_r^K \end{array}\right]$$

each defining a CY threefold X as the intersection of K homogeneous polynomial constraints in $\mathbb{P}^{n_1} \times ... \times \mathbb{P}^{n_r}$.

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$$c_1(X) = 0: \qquad n_i + 1 = \sum_{j=1}^{K} m_i^j.$$
$$\dim_{\mathbb{C}}(X) = 3: \qquad \sum_{i=1}^{r} n_i = 3 + K.$$

INVOLUTIONS OF CICYs

Strategy: Go through all involutions of the ambient spaces & transformation properties of polynomials.

Intuitively, a general ambient space involution can be thought of as a composition of swaps of equal $\mathbb{P}^n$ factors and involutions of individual $\mathbb{P}^n$s.

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$\rightarrow$ Candidate CICY involution defined by

$\mathcal{I}$	$\leftarrow$	list of $\mathbb{P}^n$ involutions
$\mathcal{S}$	$\leftarrow$	list of swapped pairs of $\mathbb{P}^n$s
$\mathcal{S}_c$	$\leftarrow$	list of swapped pairs of polynomials
$\mathcal{P}$	$\leftarrow$	list of parities of polynomials

Crucial input: Due to [Anderson,Gao,Gray,Lee'17] all but 70 configuration matrices are *favorable* in that all CY divisors descend from the ambient space hyperplane classes. Therefore, $h^{1,1}_{-} = |\mathcal{S}|$.

INVOLUTIONS OF CICYs (continued)

Consistency conditions:

1) Composition of swaps of rows and columns must leave the configuration matrix invariant.

2) Each connected component of the ambient space fixed locus $\mathcal{F}_i$ must intersect X at co-dimension one (O7-plane), three (O3-plane) or not at all.

3) Across each fixed locus, *any* collection of n anti-symmetric polynomials must depend non-trivially on at least $n + 1$ transverse coordinates. If it depends only on n, the CY threefold has singularities at co-dimension one.

SINGULARITIES AT CODIMENSION 3

It is easy to convince yourself that generic CICYs are non-singular, but this changes drastically for $\mathbb{Z}_2$ isometric loci in moduli space:

Consider a component $\mathcal{F}_k$ of the ambient space fixed locus, of co-dimension k, intersecting X in a surface S (O7 plane). This means that

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Singularities along S occur when differentials of anti-symmetric polynomials develop linear dependence. If the polynomials are sections of the same divisor line bundle $\mathcal{O}(E)$, their differentials pulled back to $\mathcal{F}$ take values in $N^*\mathcal{F} \otimes \mathcal{O}(E)$.

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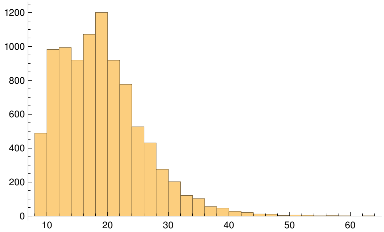
$$\rightarrow n_{\text{conifolds}} = \int_S c_2(N^*\mathcal{F} \otimes \mathcal{O}(E)).$$

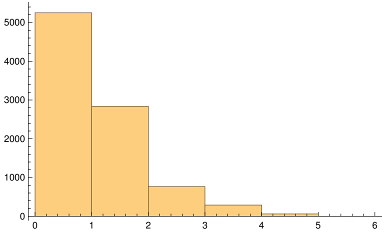
RESULTS FOR SMOOTH ORIENTIFOLDS OF CICYS

As a first step, let us also impose $n_{\text{conifolds}} = 0$. For $h^{1,1} \leq 10$, we obtain $\geq 9,200$ *distinct* orientifolds. Here are some results:

$h^{2,1}_{-}$



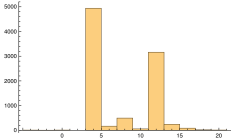
$h^{1,1}_{-} \leq [h^{1,1}/2]$



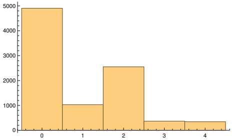
Note:
- Small $h^{1,1}_{-}$ appears to be favored.
- But, for each $h^{1,1}$ we find cases saturating $h^{1,1}_{-} \to [h^{1,1}/2]$.

RESULTS FOR SMOOTH ORIENTIFOLDS OF CICYS
(continued)

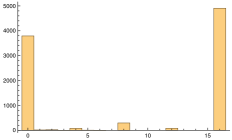
-Q≡D3 tadpole



n_{O7}



n_{O3}

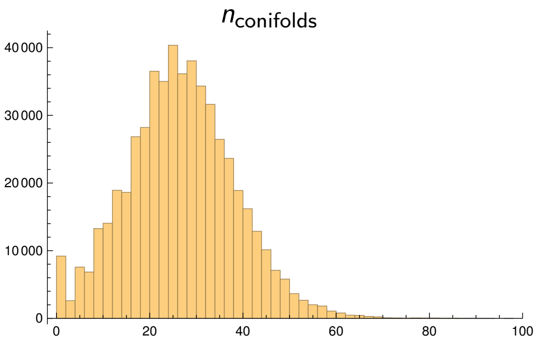


(Un)fortunately, these distributions do not look like anything reasonable. It appears that the smooth orientifolds of CICYs that we have found are not a fair sample of the space of all orientifolds.

Can we do better?

ORIENTIFOLDS WITH CONIFOLDS

We have been rather restrictive in requiring $n_{\text{conifolds}} = 0$.



Note: $\#(n_{\text{conifolds}} = 1) = 0$.

Naturally, we should ask if we can understand the $\mathcal{N} = 1$ Physics of these singularities!

ORIENTIFOLDS WITH CONIFOLDS (continued)

At the $\mathcal{N} = 2$ level, conifolds can be deformed (Coulomb branch) and sometimes resolved (Higgs branch).

[Candelas,Green,Hübsch'90;Greene,Morrison,Strominger'95]

Clearly, the orientifolding projects out the Coulomb branch, but can we resolve?

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It turns out that:

1. Upon deforming, the surface S hosting the conifolds becomes a four-chain whose boundary is a set of $n_{\text{conifolds}}$ small three-spheres. This implies the existence of the Higgs branch at the $\mathcal{N} = 2$ level.
2. the orientifolding does not project out the Higgs branch (if it exists).

(In fact, there exist *two* distinct resolution branches.)

$\mathcal{N} = 1$ CONIFOLD RESOLUTION BRANCHES

May parameterize deformed conifold as

$$\det \begin{pmatrix} x & v \\ u & y \end{pmatrix} = \epsilon.$$ [Candelas,de la Ossa'90]

We define the local involution via $(v, y) \longrightarrow (-v, -y)$.

This becomes symmetry if $\epsilon = 0$.

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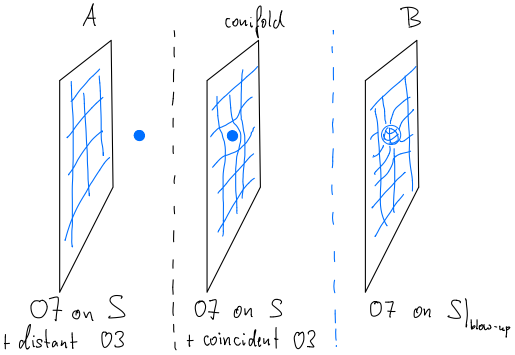
This becomes symmetry if $\epsilon = 0$. The two resolution branches are:

A-type	B-type	
$\begin{pmatrix} x & v \\ u & y \end{pmatrix} \cdot \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = 0$	$\begin{pmatrix} x & u \\ v & y \end{pmatrix} \cdot \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = 0$	$[\alpha,\beta] \in \mathbb{P}^1$.
$[\alpha,\beta] \to [-\alpha,\beta]$	$[\alpha,\beta] \to [\alpha,\beta]$	$\leftarrow$ involution
O7 on $\mathbb{C}^2$ + O3	O7 on $\mathbb{C}^2\|_{\text{blown up}}$	$\leftarrow$ fixed locus

$\mathcal{N} = 1$ CONIFOLD RESOLUTION BRANCHES (continued)

The geometric flop-transition A-type → B-type induces a collision of an O7 and an O3 merging into a single O7 on a *different* surface. This transition preserves the D3 tadpole.

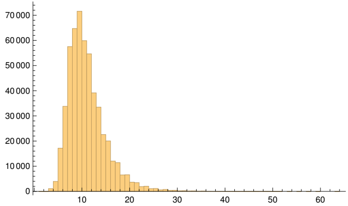
cf. [Denef,Douglas,Florea,Grassi,Kachru'05]



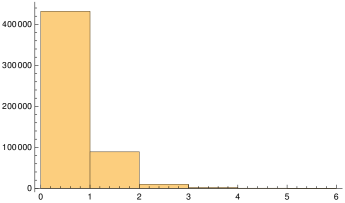
RESULTS FOR ALL ORIENTIFOLDS OF...

Here are some results of $\geq 533,000$ orientifolds of *some* CYs:

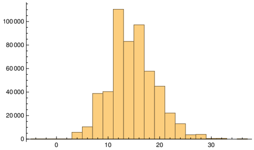
$h_-^{2,1}$



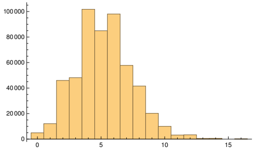
$h_-^{1,1}$



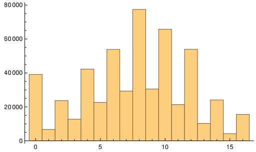
D3 tadpole



n_{O7}



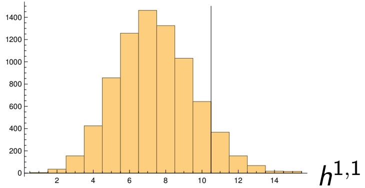
n_{O3}



THE STATUS

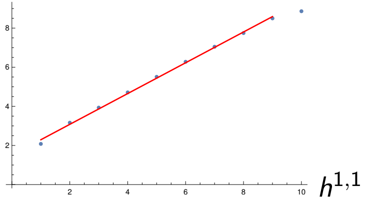
So far, we have scanned through $\sim 90\%$ of the CICYs:

CICYs

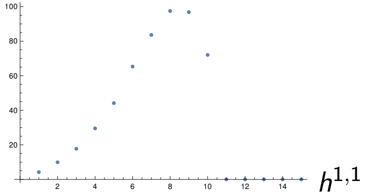


We have produced about 1.5×10^7 orientifolds, many of which are probably equivalent:

Log(<# orientifolds>)

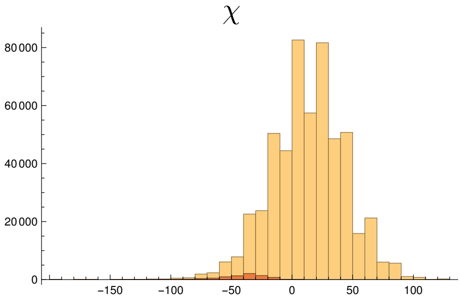


<# "distinct" orientifolds>



TOWARD A NEW LANDSCAPE OF CY THREEFOLDS

As a by-product of our search for orientifolds, we have found a (possibly new) set of CY threefolds:



For these, we are able to compute a subset of the topological data characterizing it (such as χ), but not all (such as the pair $(h^{1,1}, h^{2,1})$).

ORIENTIFOLDS FOR THROAT AXIONS

So far, we only considered favorable CICYs. The non-favorable ones can instead be written as anti-canonical hypersurfaces in a product of del-Pezzo surfaces or $dP_9 \times dP_9$. [Anderson,Gao,Grey,Lee'17]

Involutions of del-Pezzo surfaces have been classified in [Blumenhagen,Braun,Grimm,Weigand'08], so we can construct orientifolds in an analogous way.

It is easy to see that shrinking exceptional curves in del-Pezzo surfaces induces conifold transitions in the CY hypersurface.

E.g. $(dP_3, \mathcal{I}_{dP_3}) \times \mathbb{P}^2 \longrightarrow (dP_1, \mathcal{I}_{dP_1}) \times \mathbb{P}^2$

is a $\mathbb{Z}_2$ invariant conifold transition, with $\delta h^{1,1}_+ = \delta h^{1,1}_- = 1$.

Then, according to [Hebecker,Leonhardt,JM,Westphal], stabilizing near the transition locus gives rise to an ultra-light (thr)axion with superpotential

$W(G) \sim \sum_i M_i z_i \exp(iG/M_i)$, with $\sum_i M_i = 0$.

CONCLUSIONS

- I have outlined the construction of a new landscape of orientifolds that I hope will be a useful pool for model building.
- So far, we have gone through about 90% of the CICY database, and we hope to be done soon.
- The construction algorithm leads us outside the CICY database and into possibly uncharted CY-territory.
- Flop transitions between pairs of these CYs induce non-trivial recombinations of O-planes.
- Using the database, we can find explicit models of "thraxions".

D3 TADPOLE AND CS MODULI