Global String Embeddings

for the

Nilpotent Goldstino

Iñaki García-Etxebarria

Max-Planck-Gesellschaft

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

in collaboration with F. Quevedo and R. Valandro

arXiv:1512.06926

What is a nilpotent Goldstino multiplet?

[{1972} Volkov-Akulov]

A chiral multiplet X such that $X^2 = 0$. Expanding in components

$$X = X_0 + \psi\theta + F\theta\bar{\theta} \tag{1}$$

the constraint requires

$$X_0 \sim \psi\psi/F \tag{2}$$

so the bosonic component does not propagate (and $F \neq 0$).

Why nilpotent Goldstinos

A supersymmetric road to de Sitter vacua?

In the context of KKLT models, one typically requires the introduction of an "uplift" term in order to make the string model have positive vacuum energy.

Why nilpotent Goldstinos

A supersymmetric road to de Sitter vacua?

In the context of KKLT models, one typically requires the introduction of an "uplift" term in order to make the string model have positive vacuum energy. A popular (and natural) idea is to introduce $\overline{\text{D3}}$ branes at the bottom of some warped throat, but this had a couple of problems:

- It was not clear whether the metastable vacuum really exists for many $\overline{\text{D3}}$s. [{2009} Bena, Graña, Halmagyi] [{2015} Polchinski]
- In part, because no manifestly supersymmetric EFT was known for the $\overline{\text{D3}}$ at the bottom of the throat.

Why nilpotent Goldstinos

A supersymmetric road to de Sitter vacua?

In the context of KKLT models, one typically requires the introduction of an "uplift" term in order to make the string model have positive vacuum energy. A popular (and natural) idea is to introduce $\overline{\text{D3}}$ branes at the bottom of some warped throat, but this had a couple of problems:

- It was not clear whether the metastable vacuum really exists for many $\overline{\text{D3}}$s. [{2009} Bena, Graña, Halmagyi] [{2015} Polchinski]
- In part, because no manifestly supersymmetric EFT was known for the $\overline{\text{D3}}$ at the bottom of the throat.

This second problem has been partially overcome recently, with the realization in [{2014} Kallosh, Wrase], [{2014} Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase], [...] that the theory on a stuck $\overline{\text{D3}}$ on top of an O3 plane realizes the Volkov-Akulov goldstino multiplet action.

Nilpotent Goldstinos on the $\overline{\text{D3}}$

Consider the theory on a $\overline{\text{D3}}$ in flat space. It is just 4d $U(1)$ $\mathcal{N} = 4$ SYM.

Nilpotent Goldstinos on the $\overline{\text{D3}}$

Consider the theory on a $\overline{\text{D3}}$ in flat space. It is just 4d $U(1)$ $\mathcal{N}=4$ SYM.

To reproduce the Volkov-Akulov action, with a single fermionic degree of freedom, we introduce $(2,1)$ fluxes and a O3 [{2014} Kallosh, Wrase], [{2014} Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase], [{2015} Kallosh, Quevedo, Uranga]

$$\begin{array}{ccccccc} & SO(6)_R & & \text{Flux} & & \text{O3} \\ A_\mu & \mathbf{1} & \to & \mathbf{1} & \to & \mathbf{0} \\ \lambda^i_\alpha & \mathbf{4} & \to & \mathbf{1} & \to & \mathbf{1} \\ \Phi^I & \mathbf{6} & \to & \mathbf{0} & \to & \mathbf{0} \end{array} \tag{3}$$

Nilpotent Goldstinos on the $\overline{\text{D3}}$

Consider the theory on a $\overline{\text{D3}}$ in flat space. It is just 4d $U(1)$ $\mathcal{N}=4$ SYM.

To reproduce the Volkov-Akulov action, with a single fermionic degree of freedom, we introduce $(2,1)$ fluxes and a O3 [{2014} Kallosh, Wrase], [{2014} Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase], [{2015} Kallosh, Quevedo, Uranga]

$$\begin{array}{cccccc} & SO(6)_R & & \text{Flux} & & \text{O3} \\ A_\mu & \mathbf{1} & \to & \mathbf{1} & \to & \mathbf{0} \\ \lambda^i_\alpha & \mathbf{4} & \to & \mathbf{1} & \to & \mathbf{1} \\ \Phi^I & \mathbf{6} & \to & \mathbf{0} & \to & \mathbf{0} \end{array} \quad (3)$$

More on V.-A. goldstino actions in I. Bandos' talk on Friday.

Nilpotent Goldstinos on the $\overline{\text{D3}}$

Consider the theory on a $\overline{\text{D3}}$ in flat space. It is just 4d $U(1)$ $\mathcal{N}=4$ SYM.

To reproduce the Volkov-Akulov action, with a single fermionic degree of freedom, we introduce $(2,1)$ fluxes and a O3 [{2014} Kallosh, Wrase], [{2014} Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase], [{2015} Kallosh, Quevedo, Uranga]

$$\begin{array}{cccccc} & SO(6)_R & & \text{Flux} & & \text{O3} \\ A_\mu & \mathbf{1} & \rightarrow & \mathbf{1} & \rightarrow & \mathbf{0} \\ \lambda^i_\alpha & \mathbf{4} & \rightarrow & \mathbf{1} & \rightarrow & \mathbf{1} \\ \Phi^I & \mathbf{6} & \rightarrow & \mathbf{0} & \rightarrow & \mathbf{0} \end{array} \qquad (3)$$

In my talk, I will focus on how to engineer stuck D3s on O3s.

The basic idea for the local embedding

Orientifolding Klebanov-Strassler

A nice strategy for engineering this setup, introduced in [{2015} Kallosh, Quevedo, Uranga], is to find orientifolds of Klebanov-Strassler-like throats [{2000} Klebanov, Strassler]:

The confining theory on branes at singularities is known to (often) give rise to fluxed throats. We would like to identify some orientifold involution playing the role of the O3 plane in projecting out gauge bosons.

Towards global embeddings

Desiderata

- Isolated O3 planes.
- Simplest local geometry possible.

Towards global embeddings

Desiderata

- Isolated O3 planes.
- Simplest local geometry possible.

In [{2015} Kallosh, Quevedo, Uranga] there are concrete examples

- **Conifold** with non-compact $O7^+$ plane.
- More complicated singularities ($xy = z^3w^2$) with O3 planes.

Towards global embeddings

Desiderata

- Isolated O3 planes.
- Simplest local geometry possible.

In [{2015} Kallosh, Quevedo, Uranga] there are concrete examples

- **Conifold** with non-compact O7$^+$ plane.
- More complicated singularities ($xy = z^3 w^2$) with O3 planes.

In this talk

- We construct an orientifold of the **conifold with O3 planes**.
- We provide **embeddings** of the local setup **into explicit models**.

Outline

Review of the conifold

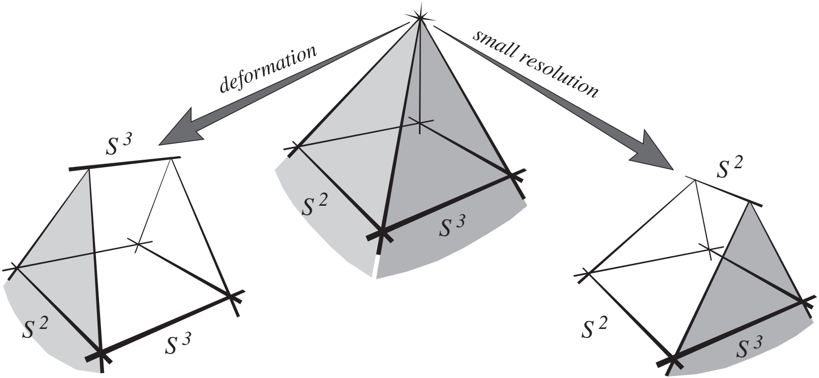
Defined by $\{f = 0\} \in \mathbb{C}^4$ where

$$f = xy - zw = 0\,. \tag{4}$$

This has a singularity at $f = df = 0$, i.e. at $x = y = z = w = 0$.

Topologically, the conifold is the real cone over $S^2 \times S^3$. We can define two one-parameter families of smooth spaces having the conifold as their singular limit by making the S^2 or S^3 finite size at the bottom of the throat.

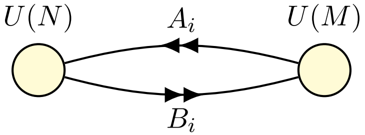
Review of the conifold



(Figure by Tristan Hubsch.)

D3 branes probing the conifold

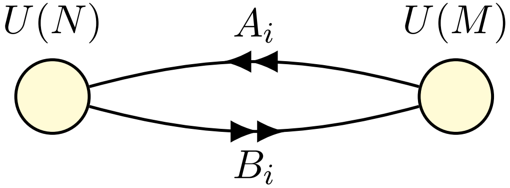
The theory on D3 (possibly fractional) branes at the singularity was worked out by [{1998} Klebanov,Witten] and [{2000} Klebanov,Strassler]. It is a $\mathcal{N} = 1$ theory defined by the quiver and superpotential



$$W = \varepsilon^{ij}\varepsilon^{lm}\,\mathrm{Tr}(A_i B_l A_j B_m)$$

The orientifolded conifold: quiver

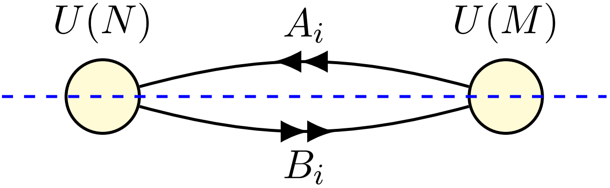
We are interested in a particular orientifold of the conifold theory. We start by describing the effect in the field theory, where it is manifested as a $\mathbb{Z}_2$ involution:



$$W = \varepsilon^{ij}\varepsilon^{lm}\,\mathrm{Tr}(A_i B_l A_j B_m)$$

The orientifolded conifold: quiver

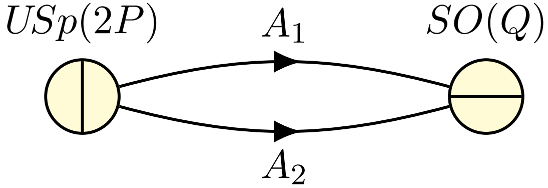
We are interested in a particular orientifold of the conifold theory. We start by describing the effect in the field theory, where it is manifested as a $\mathbb{Z}_2$ involution:



$$W = \varepsilon^{ij}\varepsilon^{lm}\,\mathrm{Tr}(A_i B_l A_j B_m)$$

The orientifolded conifold: quiver

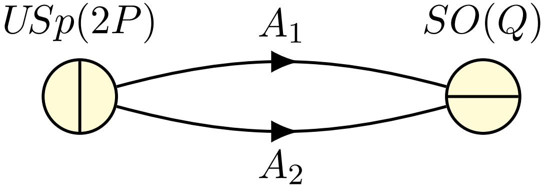
We are interested in a particular orientifold of the conifold theory. We start by describing the effect in the field theory, where it is manifested as a $\mathbb{Z}_2$ involution:



$$W = \varepsilon_{ij}\varepsilon_{lm}\,\mathrm{Tr}\left(A_i\gamma_{USp}A_l^t\gamma_{SO}A_j\gamma_{USp}A_m^t\gamma_{SO}\right)$$

The orientifolded conifold: quiver

We are interested in a particular orientifold of the conifold theory. We start by describing the effect in the field theory, where it is manifested as a $\mathbb{Z}_2$ involution:



$$W = \varepsilon_{ij}\varepsilon_{lm}\,\mathrm{Tr}\left(A_i\gamma_{USp}A_l^t\gamma_{SO}A_j\gamma_{USp}A_m^t\gamma_{SO}\right)$$

(This involution was constructed in [{2001} Ahn,Nam,Sin], [{2001} Imai,Yokono], and classified in [{2007} Franco, Hanany, Krefl, Park, Uranga, Vegh] as a "line orientifold" of the conifold.)

Geometric action

We can reproduce the action of the orientifold on the geometry by reading the action on a probe D3 brane. More precisely, the mesonic branch of the probe $U(1) \times U(1)$ theory is parameterized by the fields

$$x = A_1 B_1 \quad ; \quad y = A_2 B_2 \quad ; \quad z = A_1 B_2 \quad ; \quad w = A_2 B_1$$

subject to the constraint $xy - zw = 0$.

Geometric action

We can reproduce the action of the orientifold on the geometry by reading the action on a probe D3 brane. More precisely, the mesonic branch of the probe $U(1) \times U(1)$ theory is parameterized by the fields

$$x = A_1 B_1 \quad ; \quad y = A_2 B_2 \quad ; \quad z = A_1 B_2 \quad ; \quad w = A_2 B_1$$

subject to the constraint $xy - zw = 0$. By reading the action of the field theory orientifold on these fields [{2001} Imai, Yokono], [{2007} Franco, Hanany, Krefl, Park, Uranga, Vegh] we can identify the geometric action:

$$(x, y, z, w) \mapsto (y, x, -z, -w) \tag{5}$$

with fixed locus at

$$\{x - y = z = w = 0\} \cap \{xy - zw = 0\} = \{x = y = z = w = 0\}\,. \tag{6}$$

So an isolated fixed point, good!

The orientifold on the deformed picture

The deformed conifold (finite size S^3 at the bottom), appearing after confinement of the fractional branes [{2000} Klebanov Strassler], is given by $xy - zw = t$, with ISD flux and t determined by the scale of confinement in the field theory.

The orientifold on the deformed picture

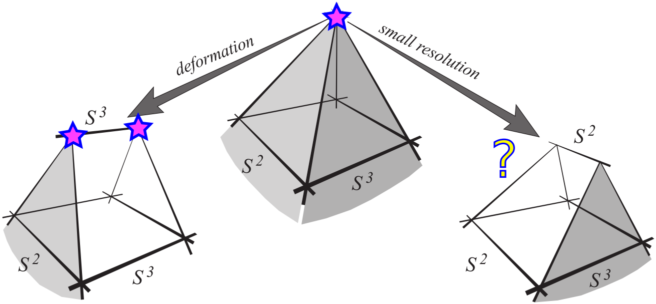
The deformed conifold (finite size S^3 at the bottom), appearing after confinement of the fractional branes [{2000} Klebanov Strassler], is given by $xy - zw = t$, with ISD flux and t determined by the scale of confinement in the field theory.

The orientifold action $(x, y, z, w) \to (y, x, -z, -w)$ leaves fixed the (two) points

$$\{x, x, 0, 0 | x^2 = t\} \,. \tag{7}$$

This can be seen to lie on the poles of the S^3 at the bottom of the cascade.

Three questions



- For model building (computing tadpoles, in particular) we need a way to read the sign of the O3 planes at these two fixed points from data of the brane system before confinement.
- What happens to the resolved phase?
- Relatedly, how come we have an O3 keeping fractional branes invariant?

Answer to the last two questions

If we look to the action of the orientifold on the $S^2 \times S^3$ away from the origin, for a fixed point on the S^3 the involution acts as the orientation reversal map

$$\sigma\colon S^2 \to \mathbb{RP}^2 \tag{8}$$

Answer to the last two questions

If we look to the action of the orientifold on the $S^2 \times S^3$ away from the origin, for a fixed point on the S^3 the involution acts as the orientation reversal map

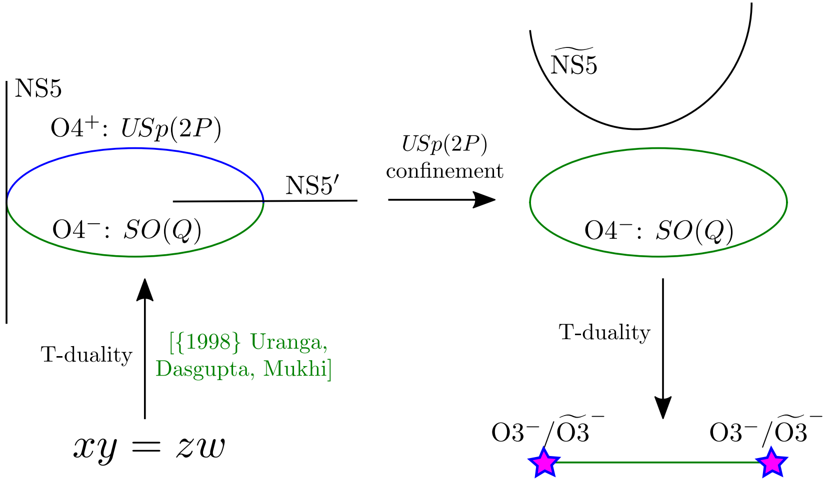
$$\sigma \colon S^2 \to \mathbb{RP}^2 \tag{8}$$

So D5 branes wrapping the collapsing cycle get a (-1) from $(-1)^{F_L}\Omega$ and *another* (-1) from σ, so they survive the projection.

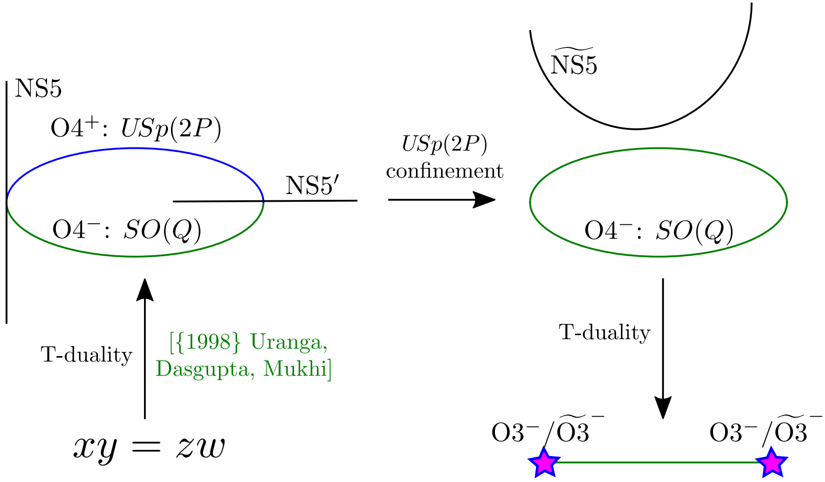
And relatedly, the volume of the S^2 at the bottom of the conifold gets projected out:

$$\int_{S^2} B + iJ \in \mathbb{R}\,. \tag{9}$$

O3 planes on the conifold: IIA perspective



O3 planes on the conifold: IIA perspective



(This conclusion corrects [{2001} Ahn,Nam,Sin], [{2001} Imai,Yokono], and can be double checked by explicitly analysing probe dynamics.)

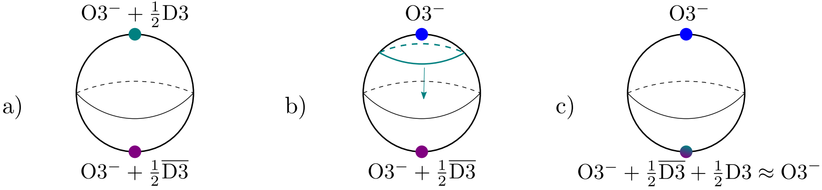
A metastable decay channel

In order to engineer local symmetry breaking, we choose to put a stuck $\overline{\text{D3}}$ on one O3^-, and a stuck D3 on the other O3^-. In this way, **the total charge is as if there were no stuck D3 branes**.

A metastable decay channel

In order to engineer local symmetry breaking, we choose to put a stuck $\overline{\text{D3}}$ on one O3^-, and a stuck D3 on the other O3^-. In this way, **the total charge is as if there were no stuck D3 branes**.

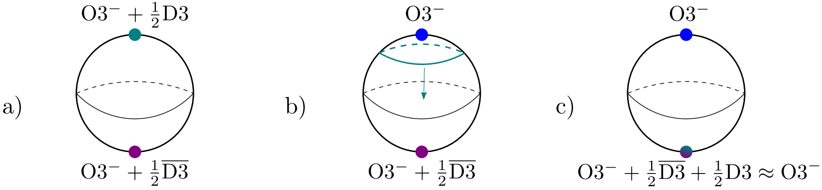
There is then a decay channel (reminiscent of [{2001} Kachru, Pearson, Verlinde]), visible using the [{2000} Hyakutake,Imamura,Sugimoto] description of the stuck D3 as a D5 on $\mathbb{RP}^2 \in H_2(X, \widetilde{\mathbb{Z}})$



A metastable decay channel

In order to engineer local symmetry breaking, we choose to put a stuck $\overline{\mathrm{D3}}$ on one $\mathrm{O3}^-$, and a stuck D3 on the other $\mathrm{O3}^-$. In this way, **the total charge is as if there were no stuck D3 branes**.

There is then a decay channel (reminiscent of [{2001} Kachru, Pearson, Verlinde]), visible using the [{2000} Hyakutake,Imamura,Sugimoto] description of the stuck D3 as a D5 on $\mathbb{RP}^2 \in H_2(X, \widetilde{\mathbb{Z}})$



May be more tractable than brane-flux annihilation.

One more puzzle

What happens if we choose opposite signs on the two fixed points?

Not needed for our current purposes, but it seems interesting.

F-theory embedding: the isolated O3 plane

Two useful definitions for F-theory:

1. IIB with a non-trivial dilaton. (More generally, a non-trivial $SL(2,\mathbb{Z})$ bundle on the IIB spacetime, see D. Regalado's talk.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration. (D. Regalado's talk.)

From the first perspective, an O3 plane arises when IIB string theory lives on the (non-Calabi-Yau) $\mathbb{C}^3/\mathbb{Z}_2$ orbifold

$$\sigma\colon (x,y,z) \to (-x,-y,-z)\,. \tag{10}$$

Supersymmetry is restored if we put a non-trivial $SL(2,\mathbb{Z})$ bundle on this orbifold, such that as we go around the non-trivial one-cycle on $S^5/\mathbb{Z}_2 = \mathbb{RP}^5$ we act with $-1 \in SL(2,\mathbb{Z})$. (One can identify this element with $(-1)^{F_L}\Omega$ in the worldsheet language.)

F-theory embedding: the isolated O3 plane

Two useful definitions for F-theory:

1. IIB with a non-trivial dilaton. (More generally, a non-trivial $SL(2,\mathbb{Z})$ bundle on the IIB spacetime, see D. Regalado's talk.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration. (D. Regalado's talk.)

In the second perspective the O3 plane is given by a fourfold $(\mathbb{C}^3 \times T^2)/\mathbb{Z}_2$ with four $\mathbb{C}^4/\mathbb{Z}_2$ terminal singularities.

F-theory embedding: the isolated O3 plane

Two useful definitions for F-theory:

1. IIB with a non-trivial dilaton. (More generally, a non-trivial $SL(2,\mathbb{Z})$ bundle on the IIB spacetime, see D. Regalado's talk.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration. (D. Regalado's talk.)

We combine both perspectives for constructing the embeddings.

F-theory embedding: the isolated O3 plane

Two useful definitions for F-theory:

1. IIB with a non-trivial dilaton. (More generally, a non-trivial $SL(2,\mathbb{Z})$ bundle on the IIB spacetime, see D. Regalado's talk.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration. (D. Regalado's talk.)

We combine both perspectives for constructing the embeddings.

1. We take a IIB background which is locally a conifold.

F-theory embedding: the isolated O3 plane

Two useful definitions for F-theory:

1. IIB with a non-trivial dilaton. (More generally, a non-trivial $SL(2,\mathbb{Z})$ bundle on the IIB spacetime, see D. Regalado's talk.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration. (D. Regalado's talk.)

We combine both perspectives for constructing the embeddings.

1. We take a IIB background which is locally a conifold.
2. We quotient it adequately, so that it has $\mathbb{C}^3/\mathbb{Z}_2$ singularities at the right places.

F-theory embedding: the isolated O3 plane

Two useful definitions for F-theory:

1. IIB with a non-trivial dilaton. (More generally, a non-trivial $SL(2,\mathbb{Z})$ bundle on the IIB spacetime, see D. Regalado's talk.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration. (D. Regalado's talk.)

We combine both perspectives for constructing the embeddings.

1. We take a IIB background which is locally a conifold.
2. We quotient it adequately, so that it has $\mathbb{C}^3/\mathbb{Z}_2$ singularities at the right places.
3. We construct an elliptically fibered Calabi-Yau fourfold over this base. SUSY (the CY_4 condition) then imposes that we are taking the $(-1)^{F_L}\Omega$ involution locally, so we do have an O3.

A global F-theory model

It is easy to find examples: all we need is a IIB background $\mathcal{B}$ (even with varying dilaton, so an arbitrary F-theory base) with

- The capacity to develop a conifold in the base somewhere in moduli space.
- An involution σ compatible with the local involution we want.

We then simply have to construct the elliptic Calabi-Yau fourfold fibration over $\mathcal{B}/\sigma$.

A global F-theory model

It is easy to find examples: all we need is a IIB background $\mathcal{B}$ (even with varying dilaton, so an arbitrary F-theory base) with

- The capacity to develop a conifold in the base somewhere in moduli space.
- An involution σ compatible with the local involution we want.

We then simply have to construct the elliptic Calabi-Yau fourfold fibration over $\mathcal{B}/\sigma$.

An example, from [{2001} Giddings, Kachru, Polchinski]:

$$\sum_{i=1}^{4}(z_5^2 + z_i^2)z_i^2 - t^2 z_5^4 = 0 \tag{10}$$

inside $\mathbb{P}^4$. For $t = 0$ there is a conifold singularity close to $z_i = (0, 0, 0, 0, 1)$. The parameter t gives a deformation of the conifold, and $(z_1, z_2, z_3, z_4, z_5) \mapsto (-z_1, z_2, -z_3, -z_4, z_5)$ induces the right local structure. (Details in the paper.)

IIB embedding: basic strategy

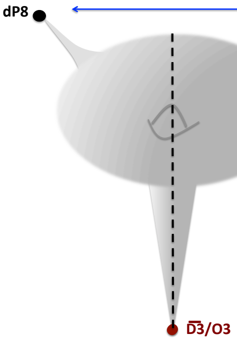
Sometimes we can follow a different strategy, and **retrofit** an existing model already having O3 planes. In this case we require

- A locus in moduli space where two orientifolds come together.
- That the local structure is that of the orientifolded conifold we constructed.

Then, by running our previous analysis backwards we can add a Goldstino+flux sector by going to the singular locus, adding condensing fractional branes in the right amount, and then the tadpole-free metastable sector on top.

IIB embedding example

In fact, we identified a state-of-the-art model with the right ingredients: [{2007} Diaconescu, Donagi, Florea], [{2012} Cicoli,Krippendorf,Mayrhofer,Quevedo,Valandro].



- Chiral matter.
- Moduli stabilization.
- Tadpole-free.
- **Nilpotent Goldstino sector**.

Conclusions

- Getting *very* close (finally! on Friday it will be 13 years since KKLT!!) to realizing KKLT and LVS:
  - Robust uplift mechanism,
  - a chiral sector,
  - and moduli stabilization.
- The key point was realizing the susy breaking sector in a generic enough setting; the conifold fits the bill perfectly (after understanding some peculiar facts of the orientifolded case).
- We provided search strategies in F-theory and IIB, giving explicit, phenomenologically interesting, examples.

Conclusions

- Getting *very* close (finally! on Friday it will be 13 years since KKLT!!) to realizing KKLT and LVS:
  - Robust uplift mechanism,
  - a chiral sector,
  - and moduli stabilization.
- The key point was realizing the susy breaking sector in a generic enough setting; the conifold fits the bill perfectly (after understanding some peculiar facts of the orientifolded case).
- We provided search strategies in F-theory and IIB, giving explicit, phenomenologically interesting, examples.
- **Open question:** Field theory description of the metastable vacuum?

Conclusions

- Getting *very* close (finally! on Friday it will be 13 years since KKLT!!) to realizing KKLT and LVS:
  - Robust uplift mechanism,
  - a chiral sector,
  - and moduli stabilization.
- The key point was realizing the susy breaking sector in a generic enough setting; the conifold fits the bill perfectly (after understanding some peculiar facts of the orientifolded case).
- We provided search strategies in F-theory and IIB, giving explicit, phenomenologically interesting, examples.
- **Open question:** Field theory description of the metastable vacuum?

Onwards to explicit de Sitter model building!

(But techniques for computing Kähler potentials very much needed!!!)