# Global Embeddings of the Nilpotent Goldstino Multiplet in String Theory

## (Towards easy de Sitter model building in string cosmology)

MAX-PLANCK-GESELLSCHAFT

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# Motivation

In string phenomenology we want to reproduce the observed physics. We are faced with numerous problems, here I want to focus on the breaking of supersymmetry:

- Nature is not supersymmetric, at least up to the energy scales we are currently able to probe.
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# Motivation

Starting with supersymmetric string configurations in high dimensions has some advantages

- Few starting options ($d \in \{10, 11\}$), related by duality. (Some degree of universality in the conclusions, and duality helps in analyzing models.)
- We can try to engineer models where susy breaking is a "small correction" to a susy computation, which is technically simpler.

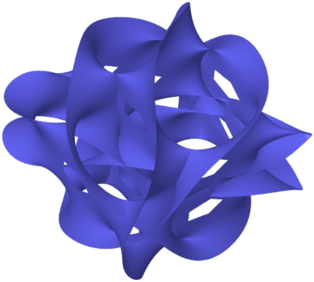
There are many variations of this "almost susy" theme, here we focus on models in the KKLT class. [{2003} Kachru, Kallosh, Linde, Trivedi]

# A quick review of IIB/F-theory

We work in **IIB** string theory (and its generalization, **F-theory**).

At low energies, IIB string theory is a 10d supergravity theory preserving 32 supercharges in flat space. To get physics closer to the real world, we split the manifold as $\mathbb{R}^{1,3} \times X$, where $X$ is a *Calabi-Yau threefold*.

If $X$ is small enough, at low energies we see a 4d theory preserving 8 supercharges ($\mathcal{N} = 2$). The features of the four dimensional theory are determined by the choice of $X$.



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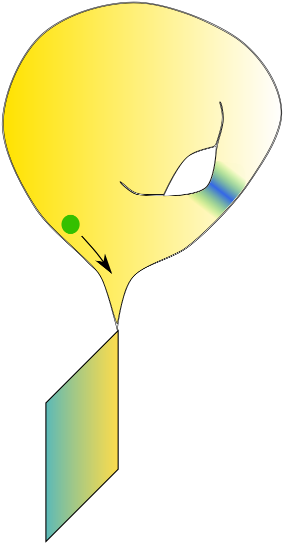
(Also, not in KKLT: we need to engineer the SM particle content somehow, lots of recent progress.)

# Artist's impression of KKLT



# Problems with $(N > 1)$ anti-D3 branes

There is a fair amount of controversy about the last step in the KKLT construction, discussed in [{2009} Bena, Graña, Halmagyi] and many follow-ups.

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In part due to these problems, recently the limit with one (or just a few) anti-D3 branes has been the focus of attention. In this case it seems like we can more reliably discuss the EFT on the anti-D3 stack. [{2014} Michel, Mintun, Polchinski, Puhm, Saad], [{2014} Kallosh, Wrase]. This configuration seems to enjoy enhanced stability properties.

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**Simplest case**

At low energies, anti-D3+O3 is described by a **nilpotent Goldstino multiplet**.

# 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

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For the purposes of this talk, this gives a controlled EFT description of the dynamics of a susy breaking sector in string theory. **(More on Friday by Timm.)**

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

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To reproduce the Volkov-Akulov action, with a single fermionic degree of freedom, we introduce $(2, 1)$ fluxes and a O3 [{2000} Dudas, Mourad], . . . , [{2014} Kallosh, Wrase], [{2014} Bergshoeff, Dasgupta, Kallosh, Van Proeyen, Wrase], [{2015} Kallosh, Quevedo, Uranga]

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

# 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.
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- More complicated singularities ($xy = z^3w^2$) with O3 planes.

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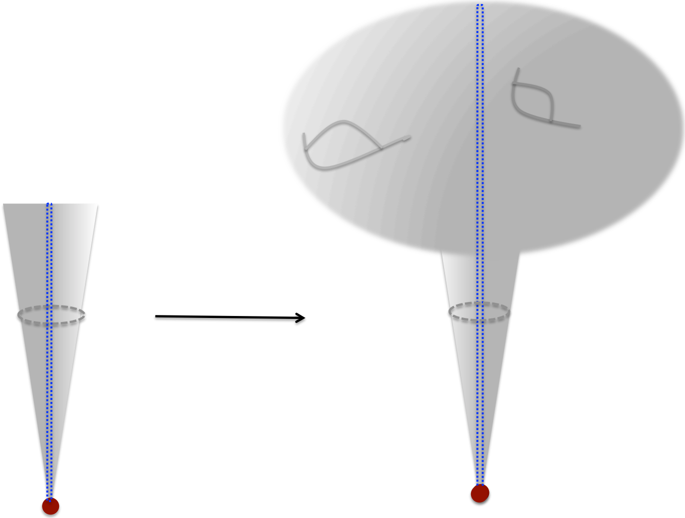
- More complicated singularities $(xy = z^3 w^2)$ with O3 planes.

## In this talk

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

# Finding a global embedding



# Outline

# Review of the conifold

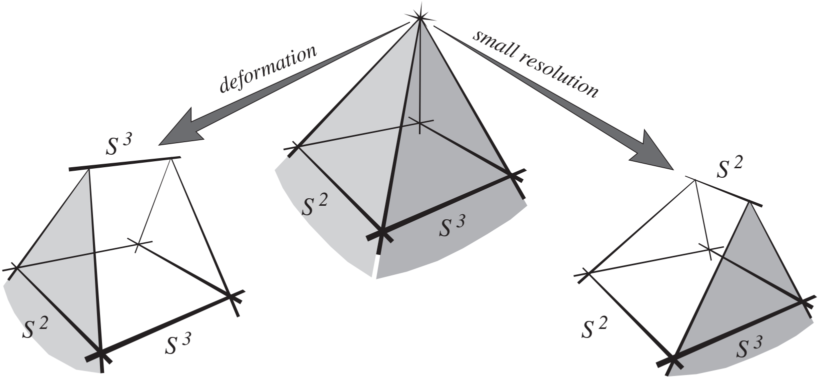
Defined by $\{f = 0\} \in \mathbb{C}^4$ where

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

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.

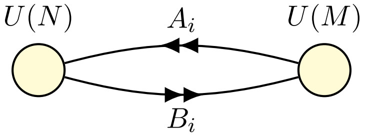
# Review of the conifold




(Figure by Tristan Hubsch.)

# D3 branes probing the conifold

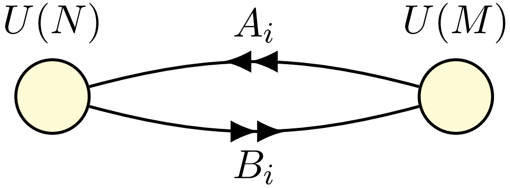
The theory on D3 (possibly fractional) branes at the singularity was worked out by [{1998} Klebanov,Witten] and [{2000} Klebanov,Strassler]. It is a $\mathcal{N} = 1$ theory defined by the quiver and superpotential




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

# 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:

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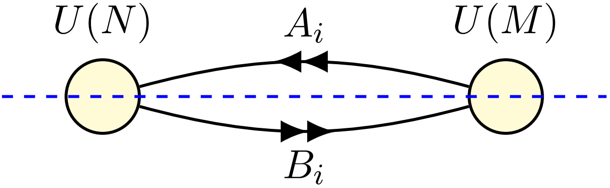


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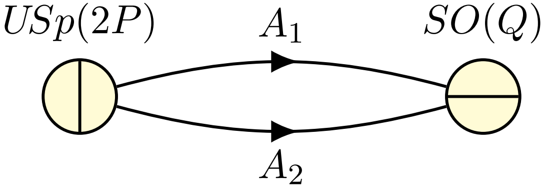


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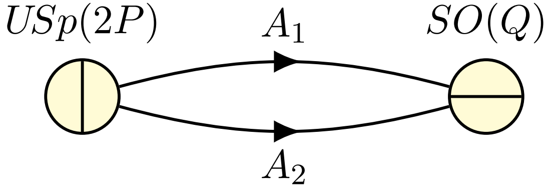


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(This involution was constructed in [{2001} Ahn,Nam,Sin], [{2001} Imai,Yokono], and classified in [{2007} Franco, Hanany, Krefl, Park, Uranga, Vegh] as a "line orientifold" of the conifold.)

# 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

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

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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

$$xy - zw = \sum_{i=1}^{4} z_i^2 = t \tag{7}$$

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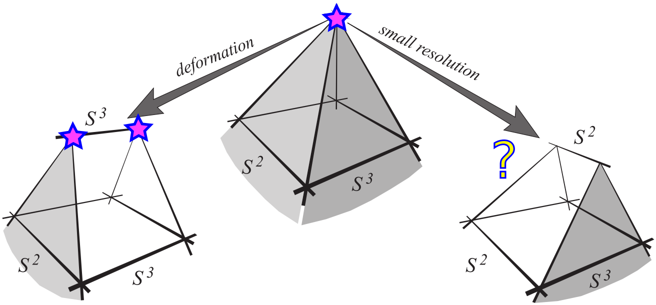
The orientifold action $(x, y, z, w) \to (y, x, -z, -w)$ leaves fixed the (two) points

$$\{x, x, 0, 0 | x^2 = t\} \,. \tag{8}$$

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

# Three questions




- What happens to the resolved phase?
- Relatedly, how come we have an O3 keeping fractional branes invariant?
- 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.

# Answer to the first 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

$$\sigma\colon S^2 \to \mathbb{RP}^2 \tag{9}$$

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

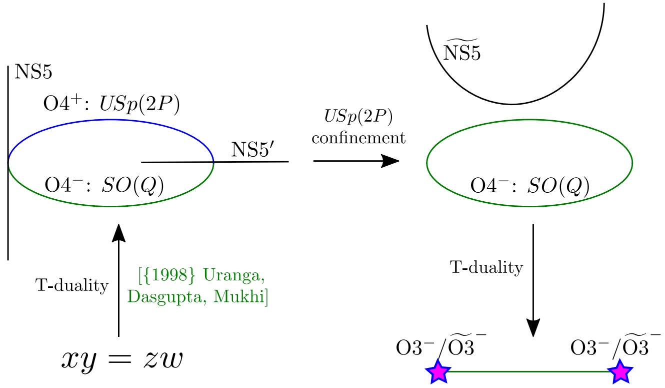
And relatedly, the volume of the $S^2$ at the bottom of the conifold gets projected out:

$$\int_{S^2} B + iJ \in \mathbb{R}\,. \tag{10}$$

Or, in the GLSM language, the orientifold acts as $\xi \to -\xi$.

# Reading the orientifold charges

## O3 planes on the conifold: IIA perspective



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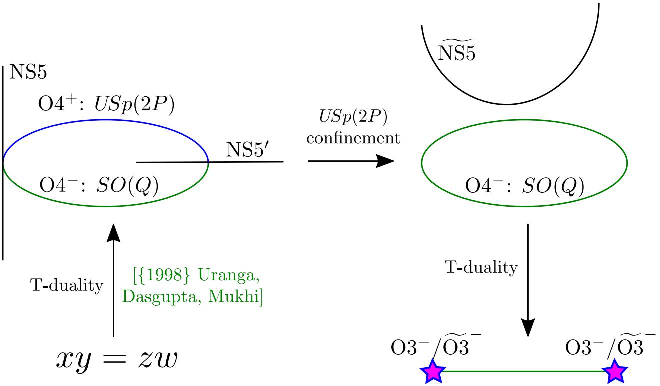


(This conclusion corrects [{2001} Ahn,Nam,Sin], [{2001} Imai,Yokono], and can be double checked by explicitly analysing probe dynamics.)

# A metastable decay channel

In order to engineer local symmetry breaking, we choose to put a stuck $\overline{\mathrm{D3}}$ 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**.

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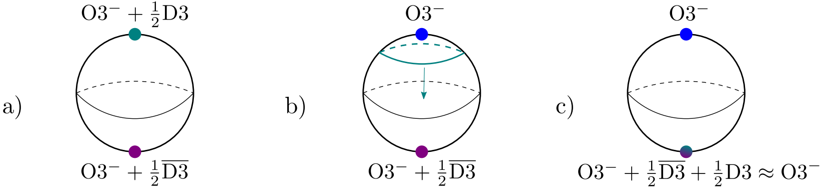
There is then a decay channel (reminiscent of [{2001} Kachru, Pearson, Verlinde]), visible using the [{2000} Hyakutake,Imamura,Sugimoto] description of the stuck D3 as a D5 on $\mathbb{RP}^2 \in H_2(X, \widetilde{\mathbb{Z}})$



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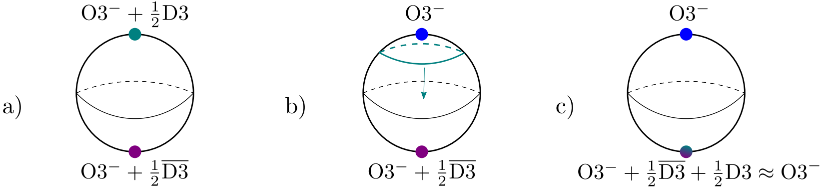


May be more tractable than brane-flux annihilation.

# 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.

More generally, a classification of all (weak coupling) orientifolds of the conifold seems worthwhile.

# 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.)
2. The vanishing fiber limit for M-theory on a Calabi-Yau torus fibration.

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

$$\sigma\colon (x,y,z) \to (-x,-y,-z)\,. \tag{11}$$

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.)

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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.

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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 $\sigma$ 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

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

$$\sum_{i=1}^{4}(z_5^2 + z_i^2)z_i^2 - t^2 z_5^4 = 0 \tag{11}$$

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.

# A global F-theory model

It is slightly easier, for technical reasons, to deal with a blown-up version of this space along $z_2 = z_5 = 0$ (this does not intersect the conifold point at $z_1 = z_2 = z_3 = z_4 = 0$)

$$\begin{array}{c|cccccc} & z_1 & z_2 & z_3 & z_4 & z_5 & \lambda \\ \hline \mathbb{C}^*_1 & 1 & 1 & 1 & 1 & 1 & 0 \\ \mathbb{C}^*_2 & 1 & 0 & 1 & 1 & 0 & 1 \end{array} \tag{12}$$

with SRI $\{z_1 z_3 z_4 \lambda, z_2 z_5\}$. The new equation describing the Calabi-Yau is

$$\hat{P} = \sum_{i=1,3,4} (z_5^2 \lambda^2 + z_i^2) z_i^2 + (z_5^2 + z_2^2) z_2^2 \lambda^4 - t^2 z_5^4 \lambda^4 = 0\,. \tag{13}$$

In this representation, the involution of interest is $\lambda \to -\lambda$.

# A global F-theory model

The quotient $\mathcal{B} = X/\mathbb{Z}_2$ is then simply given by introducing $\Lambda = \lambda^2$

$$\begin{array}{c|cccccc} & z_1 & z_2 & z_3 & z_4 & z_5 & \Lambda \\ \hline \mathbb{C}^*_1 & 1 & 1 & 1 & 1 & 1 & 0 \\ \mathbb{C}^*_2 & 1 & 0 & 1 & 1 & 0 & 2 \end{array} \tag{14}$$

with SR-ideal $\{z_1 z_3 z_4 \Lambda, z_2 z_5\}$. The equation describing $\mathcal{B}$ is then

$$\mathsf{P} = \sum_{i=1,3,4} (z_5^2 \Lambda + z_i^2) z_i^2 + (z_5^2 + z_2^2) z_2^2 \Lambda^2 - t^2 z_5^4 \Lambda^2 = 0\,. \tag{15}$$

On a neighborhood of the original conifold we have

$$\widetilde{\mathsf{P}} = \sum_{i=1,3,4} (1 + z_i^2) z_i^2 + (z_2^2 + 1) z_2^2 - t^2 = 0 \tag{16}$$

quotiented by a $\mathbb{Z}_2$ acting as $(z_1, z_2, z_3, z_4) \to (-z_1, z_2, -z_3, -z_4)$.

# A global F-theory model

We are now ready to lift to F-theory, we just build a CY fourfold with base $\mathcal{B} = X/\mathbb{Z}_2$. It will be a complete intersection on

$$\begin{array}{c|ccccccccc} & z_1 & z_2 & z_3 & z_4 & z_5 & \Lambda & x & y & z \\ \hline \mathbb{C}^*_1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & -1 \\ \mathbb{C}^*_2 & 1 & 0 & 1 & 1 & 0 & 2 & 0 & 0 & -1 \\ \mathbb{C}^*_3 & 0 & 0 & 0 & 0 & 0 & 0 & 2 & 3 & 1 \end{array} \tag{17}$$

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We have also checked tadpole cancellation, and the absence of Freed-Witten anomalies.

# Global F-theory embeddings: summary

One needs a CY threefold that admits

1. A conifold singularity
2. A $\mathbb{Z}_2$ involution acting on the conifold in an appropriate way.

F-theory then ensures that we get the right result.

# Nilpotent Goldstino Retrofitting

# IIB embedding: basic strategy

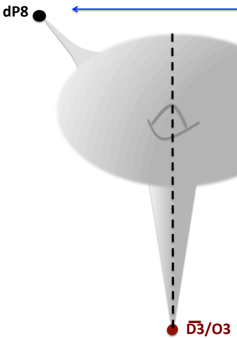
Sometimes we can follow a different strategy, and **retrofit** an existing model already having O3 planes. In this case we require

- 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! it has been 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.

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**Onwards to explicit de Sitter model building!**

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