# The Rise of the Octagon

## - Towards the geometric dual of dynamical susy breaking -


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based on 2207.00525, 2005.0967, 2007.13762 &1909.04682

w/ Argurio, Franco, Garcia-Valdecasas,
Meynet, Pasternak, Tatitscheff

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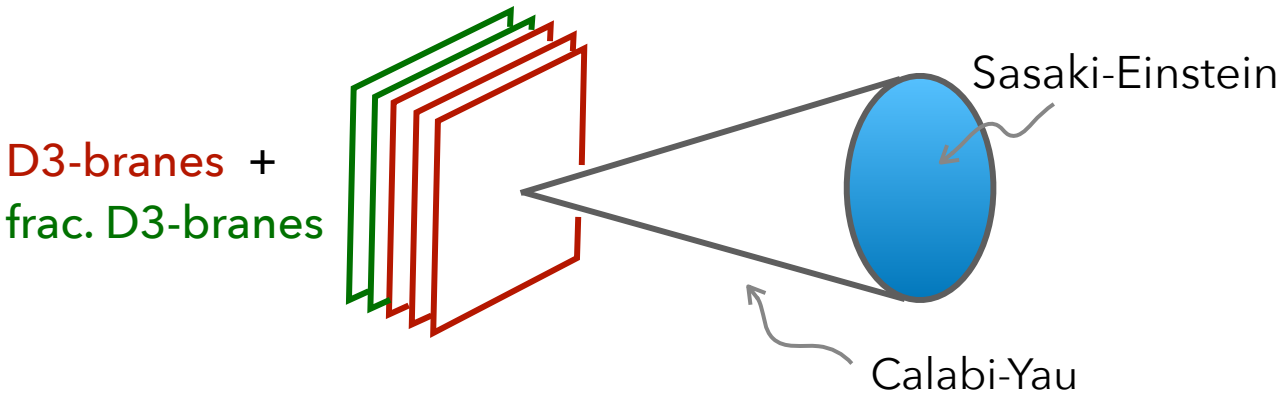
# Context, goals and tools

- The AdS/CFT correspondence is a remarkable duality which in its original form relates type IIB string theory on $\mathrm{AdS}_5 \times \mathrm{S}^5$ to N=4 SU(N) SYM in 4d, which is a SCFT.

[MALDACENA '97]

- Since the early days, generalizations were constructed to describe gauge theories with non-trivial RG-flows.

[MANY, INCLUDING PAOLO!]




*Regular* branes: low energy effective dynamics is a SCFT

*Fractional* branes **break** conformal invariance and induce an RG-flow.

**Quiver Gauge Theories :** SU groups, matter in bifundamental/adjoint reps

- Different phases that supersymmetric gauge theories can enjoy have been described in terms of gravity/geometric duals:
  - Confinement, generation of a chiral condensate, (local) $N = 2$ Coulomb-like dynamics, large $N$ version of SW curve.
    - Deformation fractional branes $\longrightarrow$ confinement via *complex structure* deformation [KLEBANOV-STRASSLER '00]
    - $N=2$ fractional branes $\longrightarrow$ Coulomb-like branch due to (local) *line singularity* [MB ET AL '00]
  - Models where vacua dynamically break supersymmetry (DSB) were also constructed. [BERENSTEIN ET AL, FRANCO ET AL, MB-BIGAZZI-COTRONE '05]
    - DSB fractional branes $\longrightarrow$ obstruction to complex structure deformation

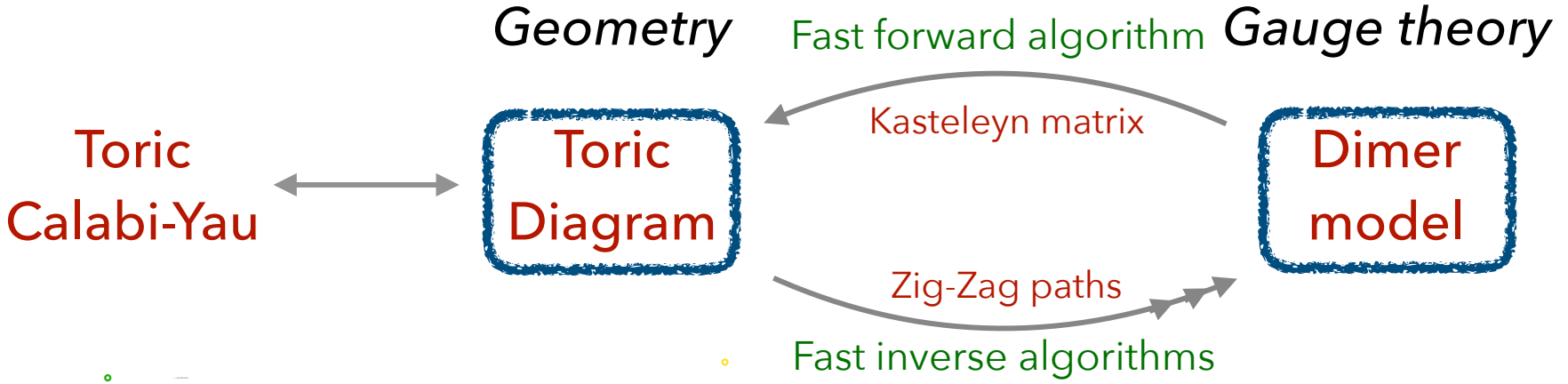
    However, these were ***unstable*** or, at best, ***metastable***.

Question: is ***stable*** DSB in the *swampland*?

- All (known) DSB models have properties that an ordinary QGT cannot reproduce. For instance:
  - One needs matter in reps other than bifundamental/adjoint, e.g. symmetric and antisymmetric reps.
  - The superpotential is not alternate in sign with each matter field appearing twice, as it happens in ordinary QGT.

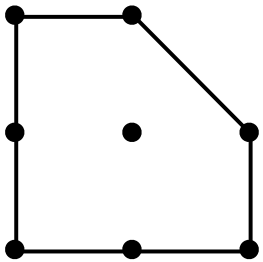
- A key ingredient for potentially promising set-ups are Orientifolds ⟶
  - Reps other than bifundamental/adjoint are possible.
  - The superpotential does not need to respect the +/- rule.
  - They provide *non-generic* contributions which can, e.g.
    - cure runaways [FRANCO ET AL '07]
    - change the *nature* of fractional branes [ARGURIO-MB '17]

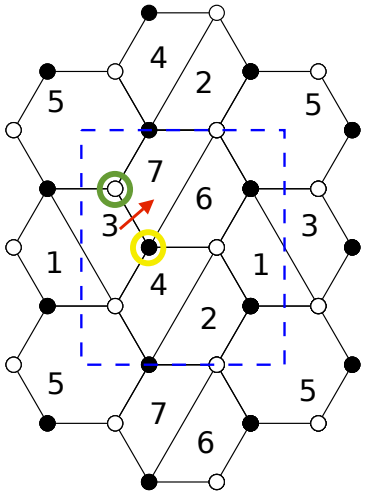
- Tool: dimer models. Powerful and efficient way to describe gauge theories on D-branes at CY singularities.

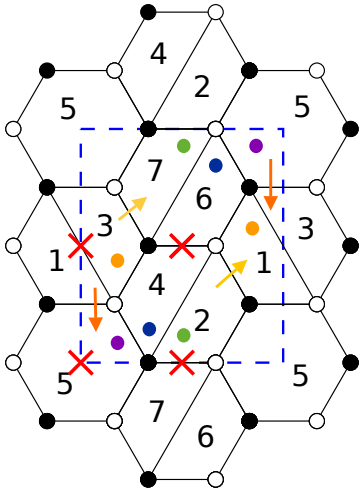



[HANANY-FENG-FRANCO-HE-KENNAWAY-URANGA-VEGH-... '02-'10]

*Ex*: Pseudo del Pezzo 4 singularity






Toric diagram: convex lattice polygon in 2d.

Dimer model: bipartite graph on a torus.

Orientifolds: $\mathbb{Z}_2$ involutions of the graph, either point or line reflections.

# D-brane models of dSB (and their large-N instability)

- Question: can one find D-brane configurations at CY *orientifolds* whose dimers reproduce DSB models?

  **Yes**! Remarkably, some of the most famous ones!

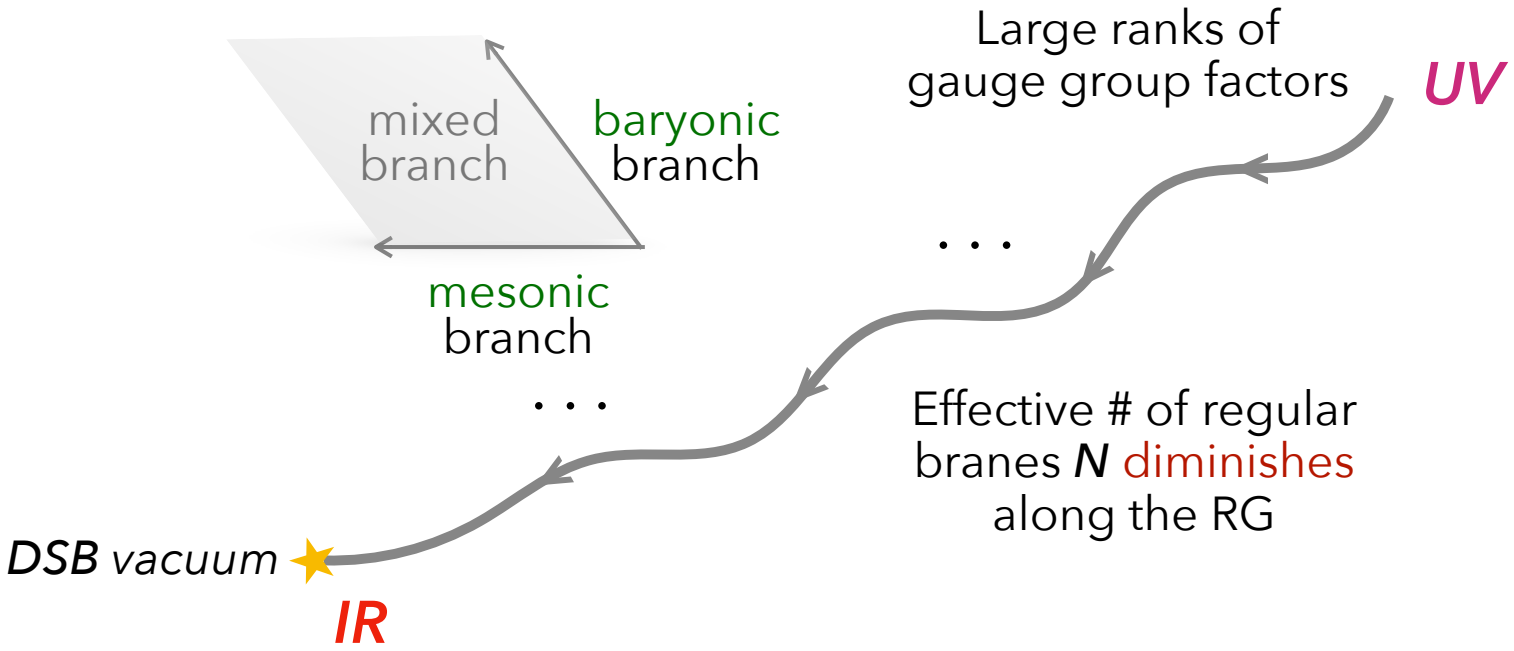
  the *SU(5)* and *3-2* models

  [Affleck-Dine-Seiberg '84-'85, Meurice-Veneziano '84]

- First instance of the *SU(5)* model was shown to be realized by *fractional* brane configurations at $PdP4$ and $\mathbb{C}^3/\mathbb{Z}_6$ (orientifold) singularities. [Franco et al '07]

- Later, in [Argurio et al '19] we showed that a ***large class*** of toric CY admit consistent *fractional* D-brane bound states giving the *SU(5)* and the *3-2* models.

- In the decoupling limit the addition of a large number *N* of *regular* D3-branes is required.
  - Gauge theory is richer and with a larger moduli space.
  - A duality cascade is generated which interpolates btw an (almost) UV-fixed point down to the DSB vacuum.



- It turns out that there exists an instability on the *mesonic* branch.

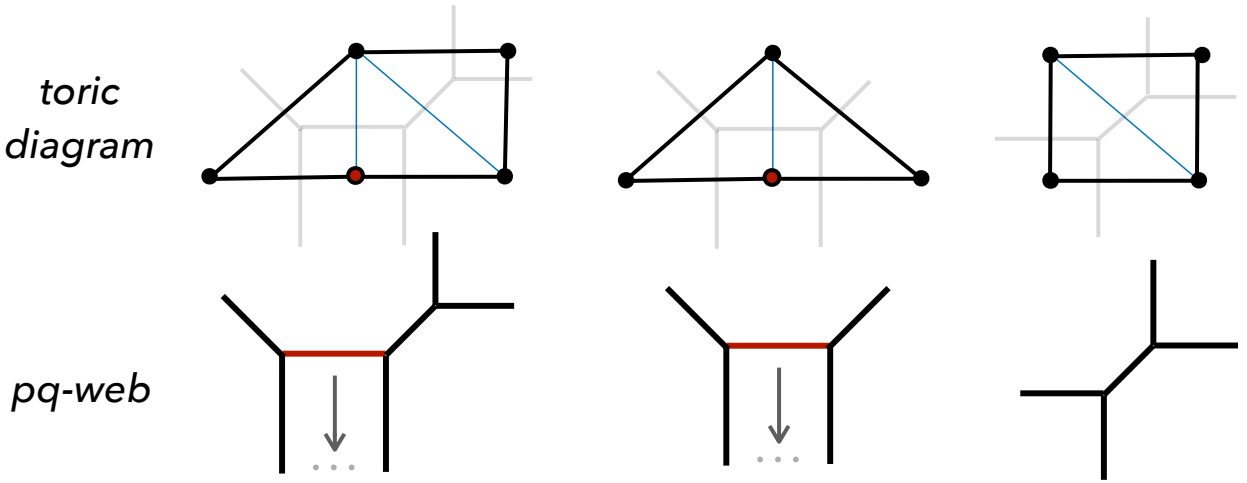
Mesonic branch

*N=2* branch: it exists whenever a CY displays, locally, a non-isolated $\mathbb{C}_2/\mathbb{Z}_n$ singularity. Parametrised by mobile *N=2* fractional branes. Vacuum energy depends on VEVs

$$E \sim \left(\frac{v'}{v}\right)^{\alpha} \Lambda \quad , \quad \alpha \neq 0$$

Upshot: DSB vacua at best metastable!

Non-isolated singularity: points inside the edges along the boundary of toric diagram



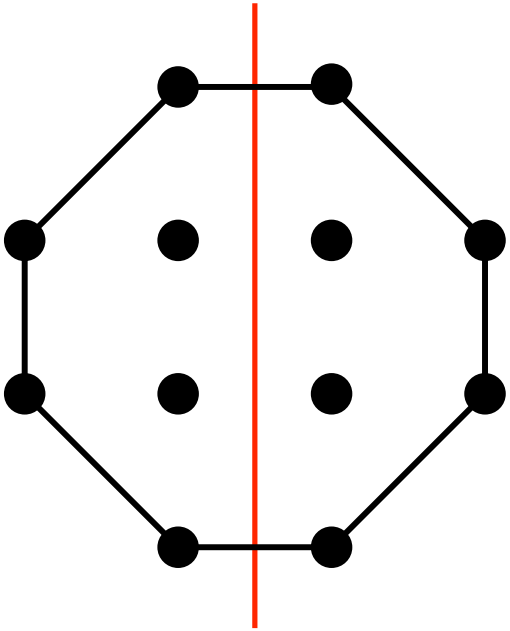
# Stable dSB: the rise of the Octagon

- Question: Is the existence of line singularities a *necessary condition* for a CY to host DSB models? If not, do CY of this sort (being also free of any other kind of instabilities) exist?

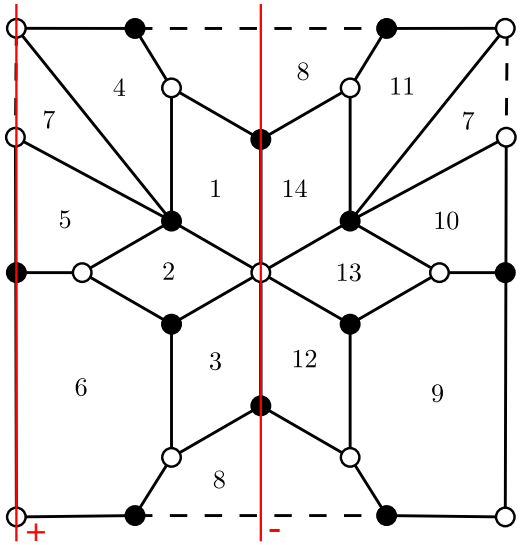
We were expecting a ***NO*** and therefore completely exclude DSB in D-brane models altogether… but the answer turns out to be a *YES*!

[Argurio et al '20]

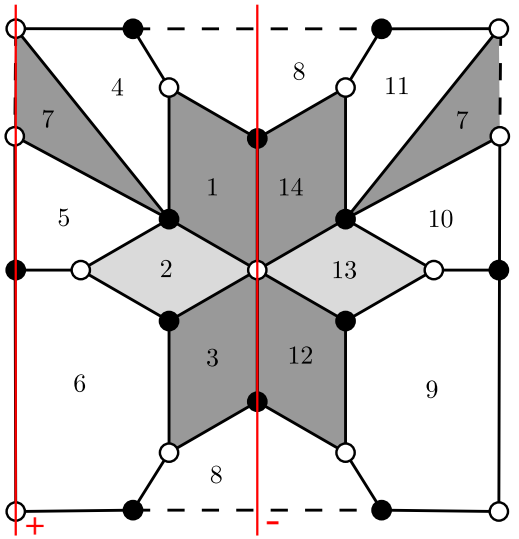
- The *simplest* CY which meets *all* criteria is an Octagon.



*toric diagram*




*dimer*




*dimer w/ frac branes*

The dual gauge theory has 14 gauge groups which, after orientifolding, become 8 which include a *SO* and a *USp* factor, matter in diverse reps and a non-trivial superpotential.

- The orientifold gauge theory, with *N* regular and *M* fractional D3-branes reads

$$SU(N+M+4)_1 \times SU(N+M)_2 \times SU(N+M+4)_3 \times$$
$$SU(N)_4 \times SU(N)_5 \times SU(N)_6 \times SO(N+M+4)_7 \times USp(N)_8$$

RG flow ⇝ (described by a *duality cascade*)

$$SU(M+4)_1 \times SU(M)_2 \times SU(M+4)_3 \times SO(M+4)_7$$

$X = (\overline{\square}_1, \square_2)$ $\quad Y = (\overline{\square}_2, \square_3)$ $\quad A_1 = \square\!\square_1$ $\quad A_3 = \overline{\square\!\square}_3$

isolated SYM factor

$$W = A_1 X Y A_3 Y^t X^t$$

- Taking *M*=1 one gets the following theory in the IR

$$SU(5)_1 \times SU(1)_2 \times SU(5)_3 \quad \text{and} \quad W = 0$$

$\square\!\square_1 \oplus \overline{\square}_1$ $\quad$ flavour index $\quad \overline{\square\!\square}_3 \oplus \square_3$

⟶ two decoupled DSB SU(5) models: twin SU(5)!

# Stability

- *Mesonic* branch stable. No N=2 instability: there are no points inside the edges along the boundary of the toric diagram.
- Any other decay channel is obstructed:
  - *Baryonic* branch: fusion of adjacent faces in the dimer. These correspond to *partial resolutions* of the CY. For the Octagon, this gives CYs admitting local non-isolated singularities! These resolutions are obstructed, because $M \neq 0$ or due to the orientifold.
  - *Stringy instantons*. They may provide (potentially dangerous) extra terms to the superpotential. All ingredients are there: orientifold + USp(0) and SU(1) nodes coupled to the SU(5) groups. Not there: chiral gauge invariants cannot be written.

- Question: is there anything special about *M*=1?
- For generic *M* the IR effective dynamics reduces to

$$SU(M+4)_1 \times SU(M)_2 \times SU(M+4)_3$$

$$X = (\overline{\square}_1, \square_2) \qquad Y = (\overline{\square}_2, \square_3) \qquad A_1 = \square\!\square_1 \qquad A_3 = \overline{\square\!\square}_3$$

$$W = h \,\mathrm{Tr}\, A_1 X Y A_3 Y^t X^t$$

- If $SU(M)_2$ were not gauged this is essentially a double copy of large *M* generalisations of SU(5) model: stable for *M* odd and runaway for *M* even. [AFFLECK-DINE-SIEBERG '85]
- In [ARGURIO ET AL '22] we showed that the same conclusion holds in the actual model, where $SU(M)_2$ is gauged!

Having *M* large paves the way to a *weakly coupled* gravity dual along the *whole* RG-flow, hence a geometric description of DSB!

# Towards the gravity dual of DSB

- Confinement corresponds to complex structure deformation of the CY geometry (a 3-cycle blows up).
- DSB into *runaway* vacua is due to geometric obstruction to such deformation: RR 3-form flux does not have a 3-cycle where to stabilize.

  F-eqs imply $V_3 \sim \frac{1}{X}$ , $X \to \infty$ [ARGURIO-CLOSSET '07]
- As far as fluxes, orientifolds behave as fractional branes.
- Octagon: for $M$=0 the gauge theory is a SCFT. Adding the orientifold it becomes runaway (orientifold ~ DSB frac brane). Adding deformation frac branes runaway cured: a deformation is induced and the orientifold flux has where to stabilize!

  Note: blown-up 3-cycle and orientifold flux *misaligned*!

- Question: how does the difference between *M* even and *M* odd enter, from geometric dual p.o.v.?

*M* even

$$SU(M+4)_1 \times SU(M)_2 \times SU(M+4)_3$$
$$\downarrow v \sim \Lambda$$
$$SU(4)_1 \times SU(4)_3 \times USp(M)$$

quantum effect: in undeformed geometry branes are stuck!

Note: M has to be *even*.

In LEET exist baryonic operators whose VEVs $\mathrm{Pf}A_1, \mathrm{Pf}A_3 \to \infty$: the dual blown-up 2-cycle diverges and makes the geometry singular.

*M* odd

$$SU(M+4)_1 \times SU(M)_2 \times SU(M+4)_3$$
$$\downarrow v \sim \Lambda$$
$$SU(5)_1 \times SU(5)_3 \times USp(M-1)$$

# of branes must be even!

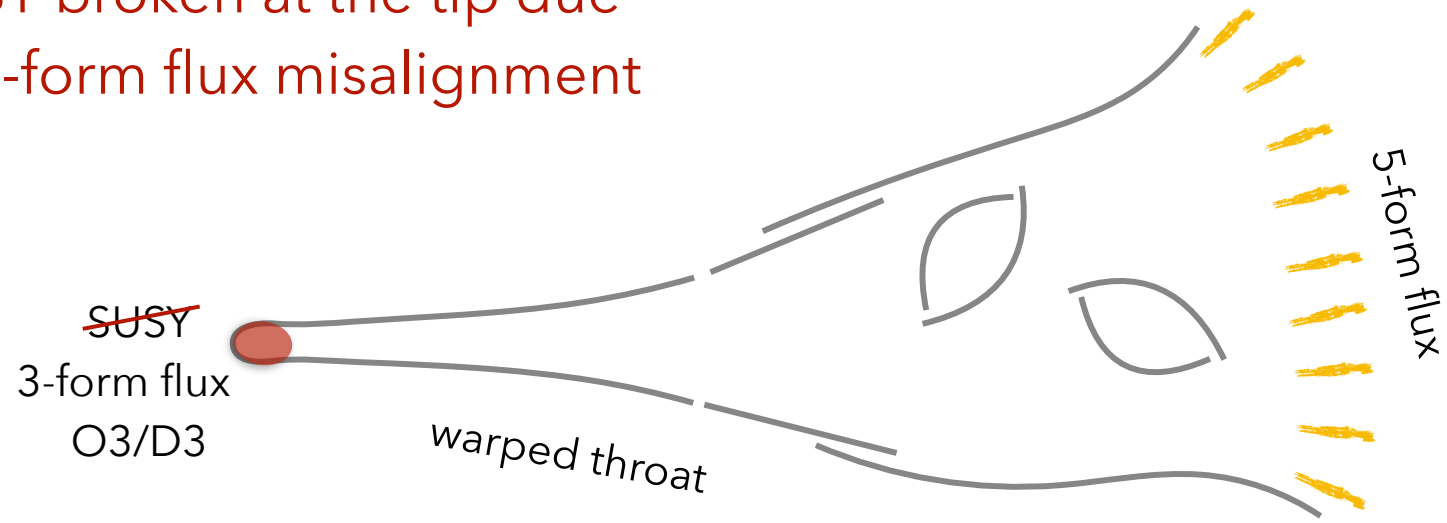
The *one* brane at the origin obstructs the resolution: no runaway!

- To get a gravity dual we need the (*deformed*) metric of the Octagon ⟶ toric technology can be used to extract a metric or (less ambitiously) its topology.


Warped throat with log-corrections wrt asymptotically AdS spacetime

SUSY broken at the tip due to 3-form flux misalignment

5-form flux increasing towards the boundary




- **Note**: geometric obstruction is a $\mathcal{O}(1)$effect, but $\mathcal{R} \sim 1/(\alpha' g_s M)$, which is small for large enough *M*!

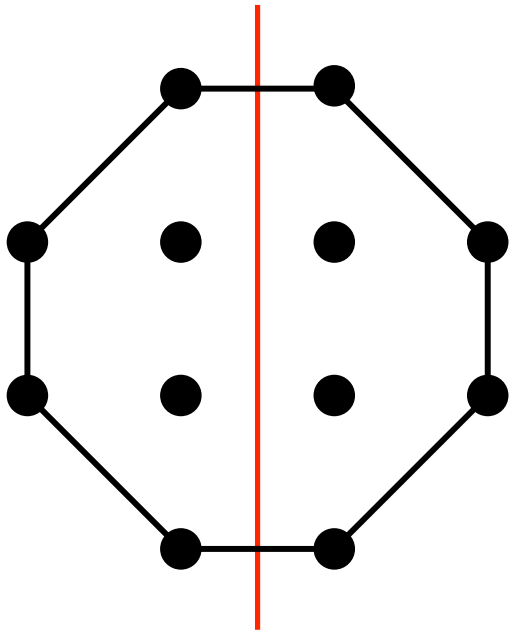
# Conclusions & Relation w/ string landscape and swampland program

- We have shown that stable DSB is possible in D-branes at CY singularities.
- By the very meaning of *gauge/string duality*, if SUSY is broken in a stable vacuum on the gauge theory side, then it is so on the dual side $\longrightarrow$ our results ***imply*** the existence of a stable SUSY breaking background of type IIB in *10d*.
- This means that warped throats w/ stable DSB D-brane sectors at their bottom, *i.e. stable non-supersymmetric locally AdS warped throats* are in the *landscape*.

- If embedded in a compact CY (a la GKP) the Octagon could be used as an ingredient to construct de Sitter vacua in 4d à la *KKLT* or *LVS*. [KACHRU ET AL '03, BALASUBRAMANIAN ET AL. '05]

  An alternative to *antiD3*, with possibly some advantages:

  - stable vs metastable, it avoids *e.g.* antiD3 decay channels;
  - no need to add external sources (antiD3): it is the dynamics of the supersymmetric brane system which spontaneously breaks SUSY $\longrightarrow$ more control.
  - one step vs two steps construction of dS vacua; could this challenge some recent criticism raised in [LUST ET AL. '22]?



# Thank you!