The Octagon and the Non-supersymmetric String Landscape

SISSA

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based on

2005.09671 w/ R. Argurio, S. Franco , E. Garcia-Valdecasas, S. Meynet, A. Pasternak & V. Tatitscheff

(also 1711.08983, 1909.04682, 2007.13762, 2009.11291)

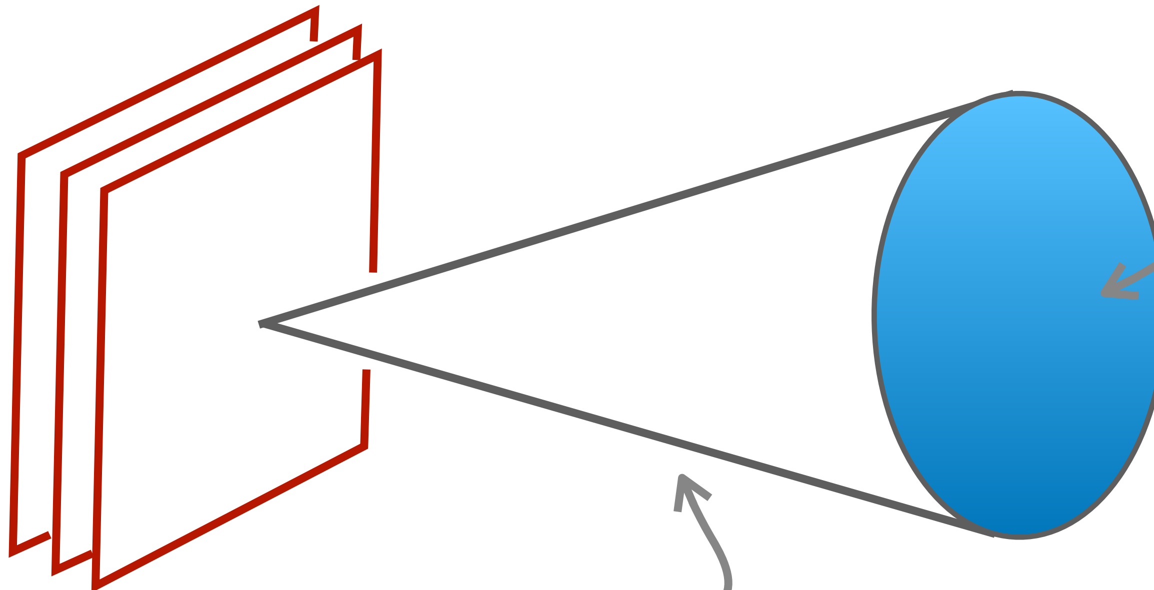
Framework & goal

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

[Maldacena '97]

- Since the early days, generalizations were constructed to describe gauge theories with non-trivial RG-flows and a variety of low energy effective dynamics. These have many applications, the most obvious ones being:
  - Alternative tools (weakly coupled dual description, geometry) to understand QFT *strong coupling regimes*
  - Extra dimension model building
  - Key ingredients within *string compactifications* (à la GKP)

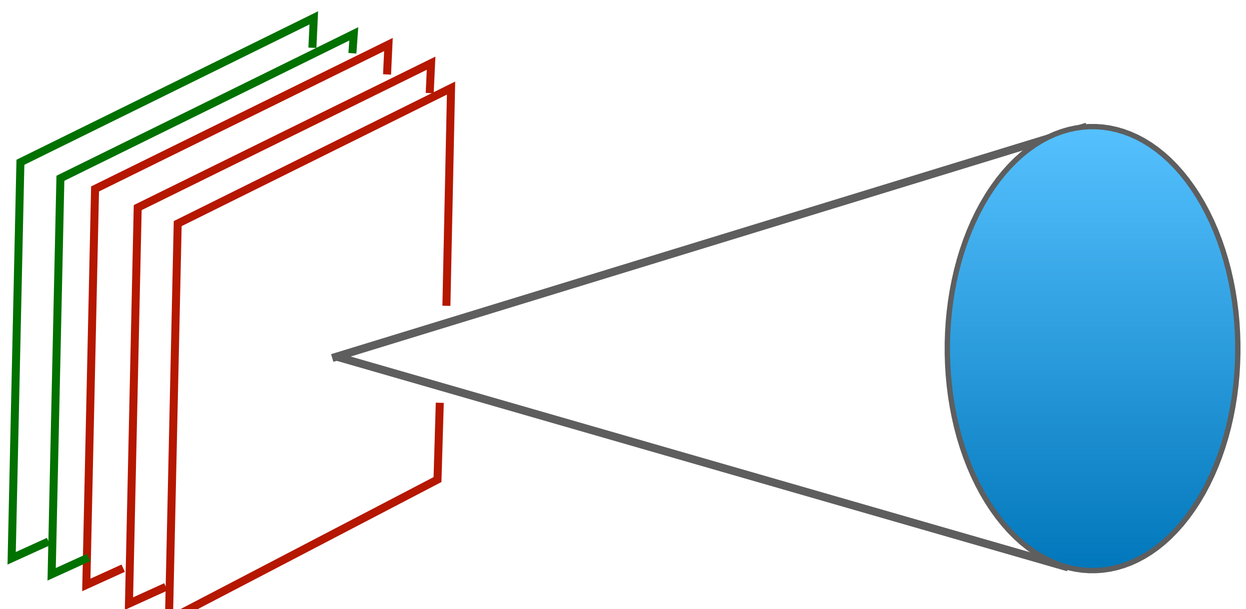
[Giddings-Kachru-Polchisnki '01]



SCFT w/ product gauge groups + bi-fundamental matter + tree-level W

A plethora of N=1 SUSY gauge theories!

Note: Full control for toric CYs only.

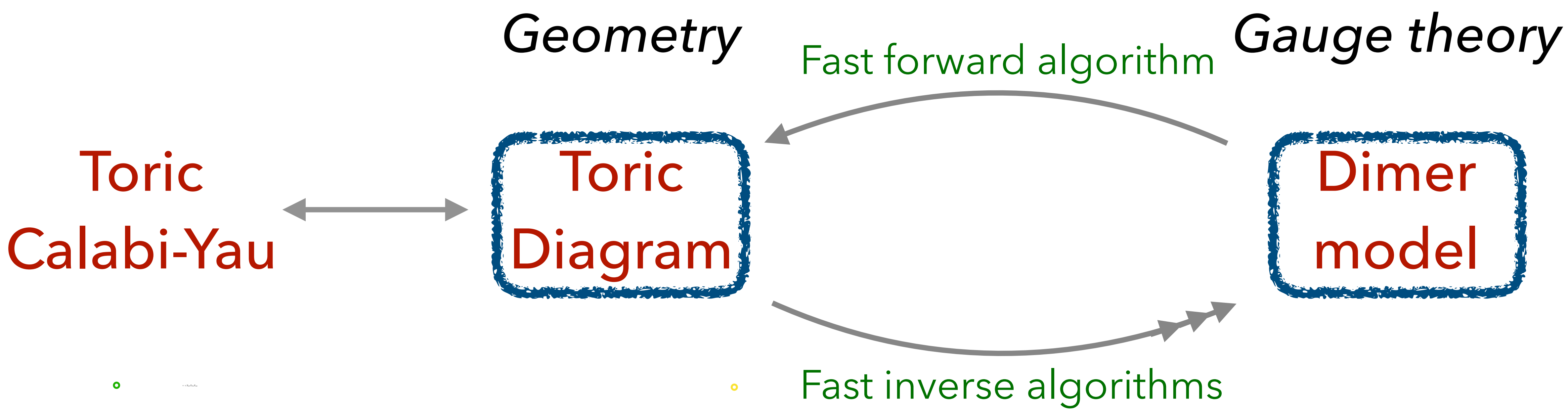


Fractional branes **break** conformal invariance and induce an RG-flow

- This way, different IR dynamics of 4D N=1 supersymmetric gauge theories has been described:
  - Confinement, generation of a mass gap and of a chiral condensate, local $N = 2$ Coulomb-like dynamics. Finally, models where vacua dynamically break supersymmetry (DSB) were also constructed. However, these were either *metastable* or *runaway*.
  - All efforts to find DSB models into *stable vacua* turned out *not* to work so far!

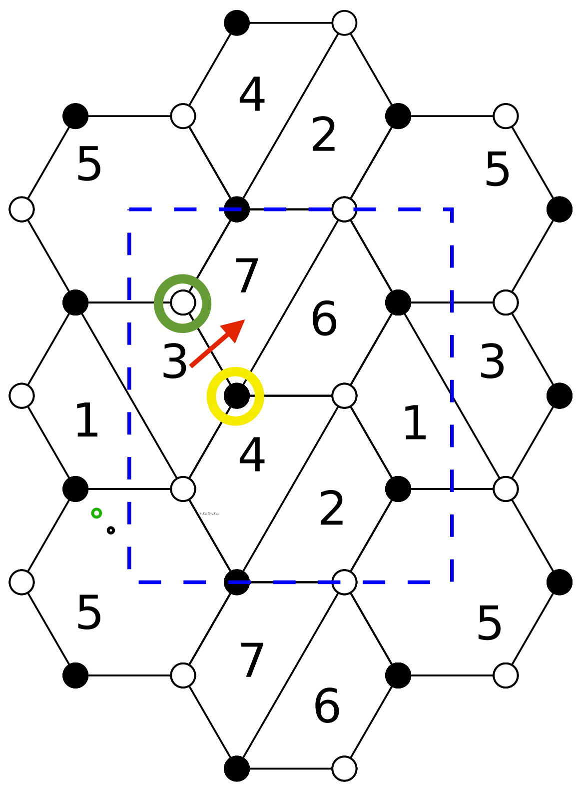
Question: Is ***stable*** DSB in the *swampland*?

- A key ingredient for potentially promising set-ups are Orientifolds. Orientifolds allow for a variety of *non-generic* dynamical effects in D-brane models, including the possibility of curing runaways.
- Hint: on top of orientifolds, fractional D-branes can *change* their *nature*! [ARGURIO-MB '17]
- Tool: dimer techniques. Powerful way to describe gauge theories on D-branes at CY singularities.



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

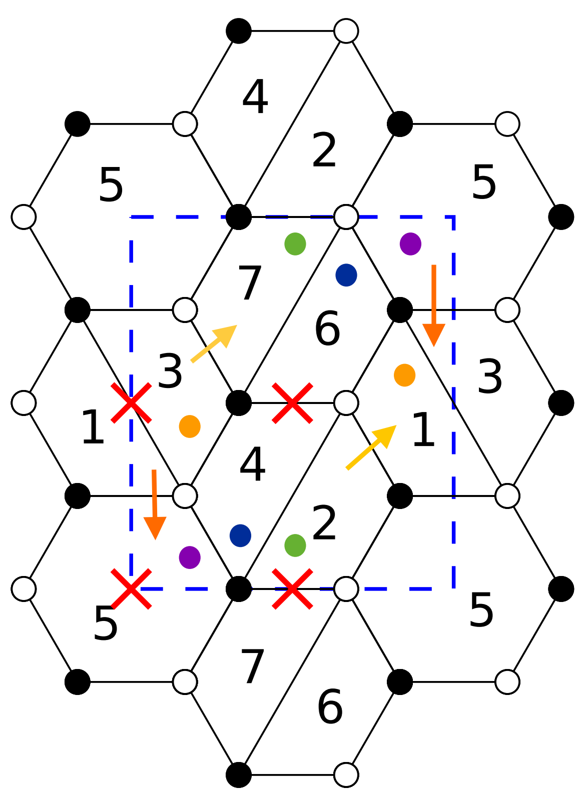
Dimer model (aka **brane tiling**): bipartite graph on a 2-torus.



- Every face is a *SU* gauge group.
- Every edge is a bi-fundamental X_{ij} in the $(\overline{\square}_i, \square_j)$.
- Every vertex is a superpotential term, obtained contracting all fields ending on the node, *e.g.*

$$\bigcirc = +X_{37}X_{75}X_{53} \qquad \bigcirc = -X_{37}X_{76}X_{64}X_{43}$$

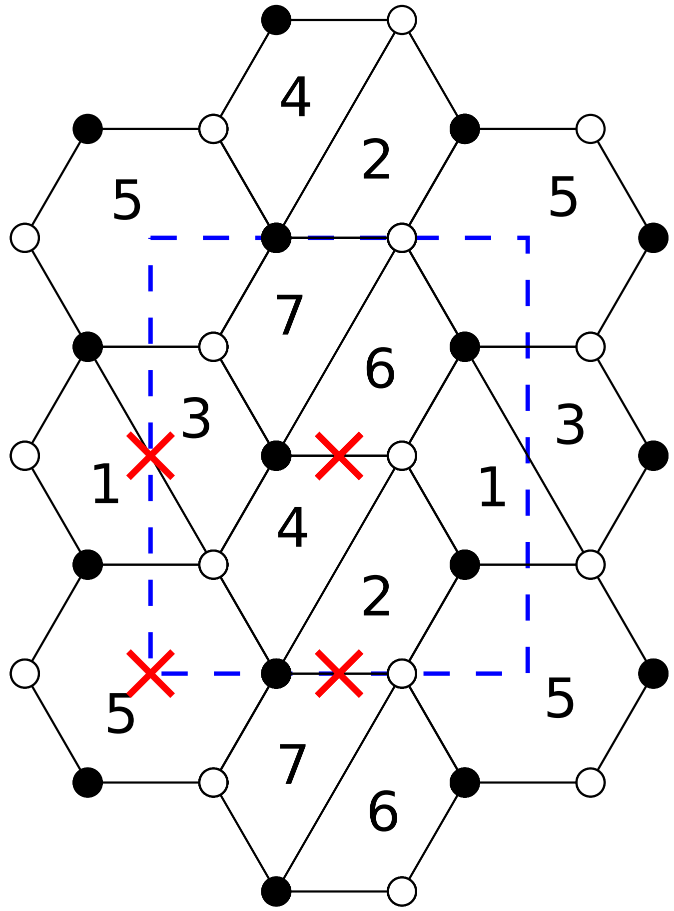
Orientifolds: $\mathbb{Z}_2$ involutions of the graph, either point or line reflections.



- Every face reflected into itself becomes a *USp* or *SO* group. All other faces get identified with their reflection and remain *SU*.
- Every edge on top of point or line becomes a $\begin{smallmatrix}\square\\\square\end{smallmatrix}$ or $\square\square$, all other remain bifundamentals.
- O-planes carry a charge; the sign is arbitrary for line reflections and depends on number of white vertices in the unit cell for point reflections.

A prototype and its many fellows

Complex cone on *PdP4*



Gauge group: $\prod_{i=1}^{7} SU(N_i)$

Superpotential:

$$W = X_{1543} + X_{375} + X_{1642} + X_{5276}$$
$$-X_{152} - X_{7643} - X_{5427} - X_{5316}$$

$X_{lmn} \equiv X_{lm}X_{mn}X_{nl}$ where $X_{lm} \in (\overline{\square}_l, \square_m)$

- Orientifold projection: $1 \Longleftrightarrow 3 \quad 2 \Longleftrightarrow 7 \quad 4 \Longleftrightarrow 6 \quad 5 \Longleftrightarrow 5$

Gauge group: $SU(N_1) \times SU(N_2) \times SU(N_4) \times SO(N_5)$

Matter content:

$$X_1 = (\overline{\square}_1, \square_5) \quad X_2 = (\square_5, \square_2) \quad X_4 = (\square_5, \square_4) \quad Y_1 = (\overline{\square}_4, \overline{\square}_1)$$

$$Y_2 = (\overline{\square}_4, \square_2) \quad Z = (\overline{\square}_2, \square_1) \quad A_1 = \begin{smallmatrix}\square\\\square\end{smallmatrix}_1 \quad A_2 = \overline{\begin{smallmatrix}\square\\\square\end{smallmatrix}}_2 \quad S_4 = \square\square_4$$

Anomaly cancellation condition: $N_1 + N_2 - N_4 - N_5 - 4 = 0$

- SU(5) Model

[AFFLECK-DINE-SEIBERG '84]

Taking $N_1 = 5, N_2 = N_4 = 0, N_5 = 1$ gives

$SU(5) \times SO(1)$ w/ $\begin{smallmatrix}\square\\\square\end{smallmatrix} \oplus \overline{\square}$ SU(5) matter content and $W = 0$

flavour index

Exactly the SU(5) DSB model!

[FRANCO ET AL. '07]

- 3-2 Model

[AFFLECK-DINE-SEIBERG '85]

Taking $N_1 = 3, N_2 = 2, N_4 = 0, N_5 = 1$ gives

flavour index

$$SU(3) \times SU(2) \times SO(1)$$

w/ matter $Q = (3,2) \oplus \overline{D} = (\bar{3},1) \oplus \bar{U} = (\bar{3},1) \oplus L = (1,2)$ and

$$W = \overline{D}QL$$

Exactly the 3-2 DSB model!

- Remarkably, in [ARGURIO-MB-MEYNET-PASTERNAK '19] we showed that a *large class* of toric CY admit anomaly-free rank assignments (*i.e.* consistent D-brane bound states) giving exactly the SU(5) and/or the 3-2 models.

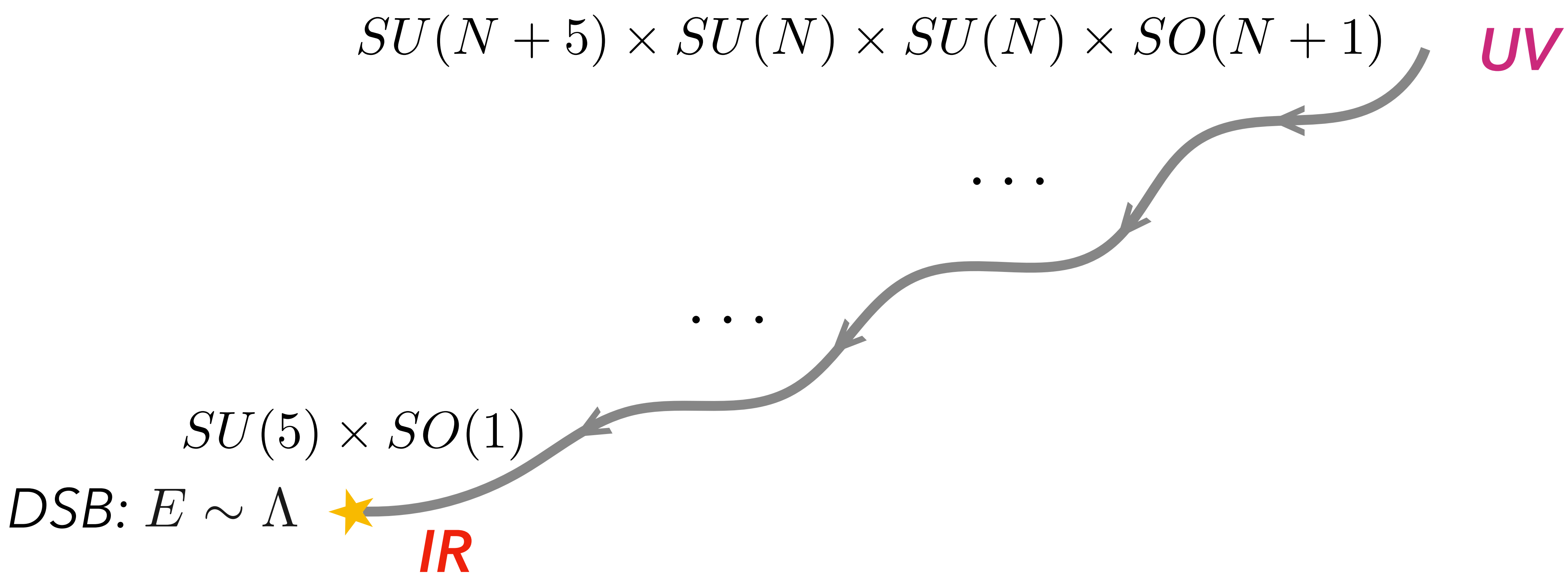
- Upshot: using *Orientifolds* one can construct many D-brane models with DSB into stable vacua!

Duality cascades and a large-N instability

- Q: What happens in the decoupling limit?

$$\textit{PdP4}: \quad SU(N+5)\times SU(N)\times SU(N)\times SO(N+1)$$

$\longrightarrow$ a duality cascade is generated which interpolates btw an (almost) UV-fixed point down to a DSB vacuum!



- Q: Do things change at *generic* points on the moduli space?

- *N*=4-like **Coulomb branch**: Moving the *N* D3's away corresponds to maximally Higgsing

$$SU(N+5) \times SU(N) \times SU(N) \times SO(N+1) \xrightarrow{v} SU(5) \times SO(1)$$

By scale matching one can see that the vacuum energy does *not* depend on the VEV

$$E \sim \Lambda \longrightarrow \text{DSB vacuum stable!}$$

- *N*=2-like **Coulomb branch**: There are other directions in the moduli space, parametrized by *N=2 fractional branes*

$$SU(N+5) \times SU(N) \times SU(N) \times SO(N+1) \xrightarrow{v}$$
$$SU(5) \times SU(N) \times SU(N) \times SO(1) \xrightarrow{v'} SU(5) \times SO(1)$$

The vacuum energy depends on the VEV's now:

$$E \sim \left(\frac{v'}{v}\right)^{\frac{3}{20}N} \Lambda \longrightarrow$$ DSB vacuum relaxes to SUSY vacuum, E=0!

[BURATTI-GARCIA VALDECASAS-URANGA '18]

- Exactly the same story holds for *all* other models! $\longrightarrow$ All corresponding CYs admit a *N*=2 Coulomb branch and along such branch the vacuum energy goes as

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

where α is a model-dependent # proportional to *N*.

N=4 branch is stable, *N*=2 branch displays an instability, associated to ***N*=2 fractional branes dynamics** $\longrightarrow$ DSB vacua at most metastable!

- In order for this not to happen, one needs $\alpha = 0$. Using pure geometric, *model-independent* arguments we proved that:

$$\alpha \neq 0$$

$\longrightarrow$ the presence of *N*=2 fractional branes *implies* the instability: **no-go theorem**! [Argurio-MB-Meynet-Pasternak '19]

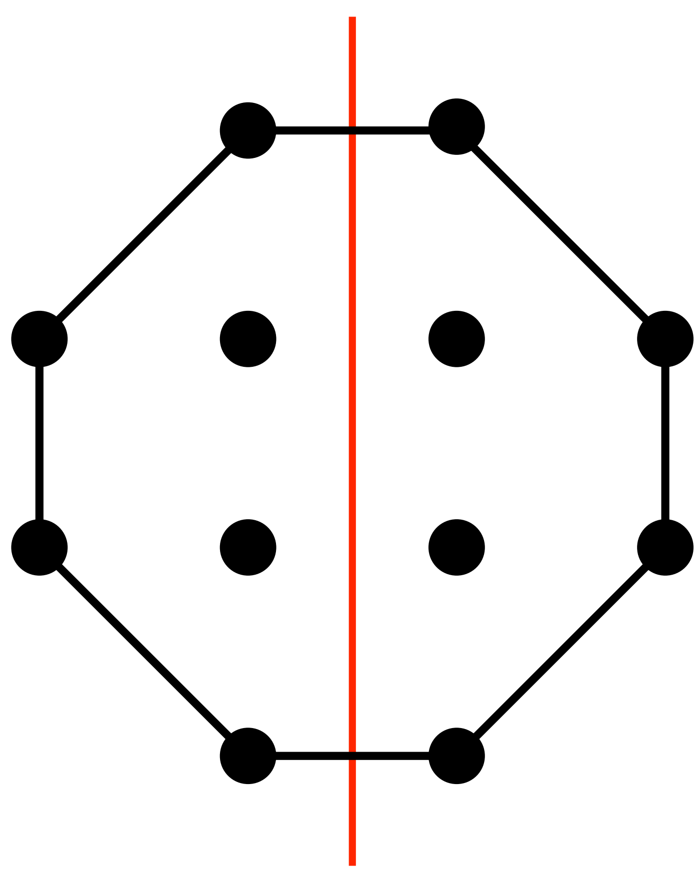
THE RISE OF THE OCTAGON

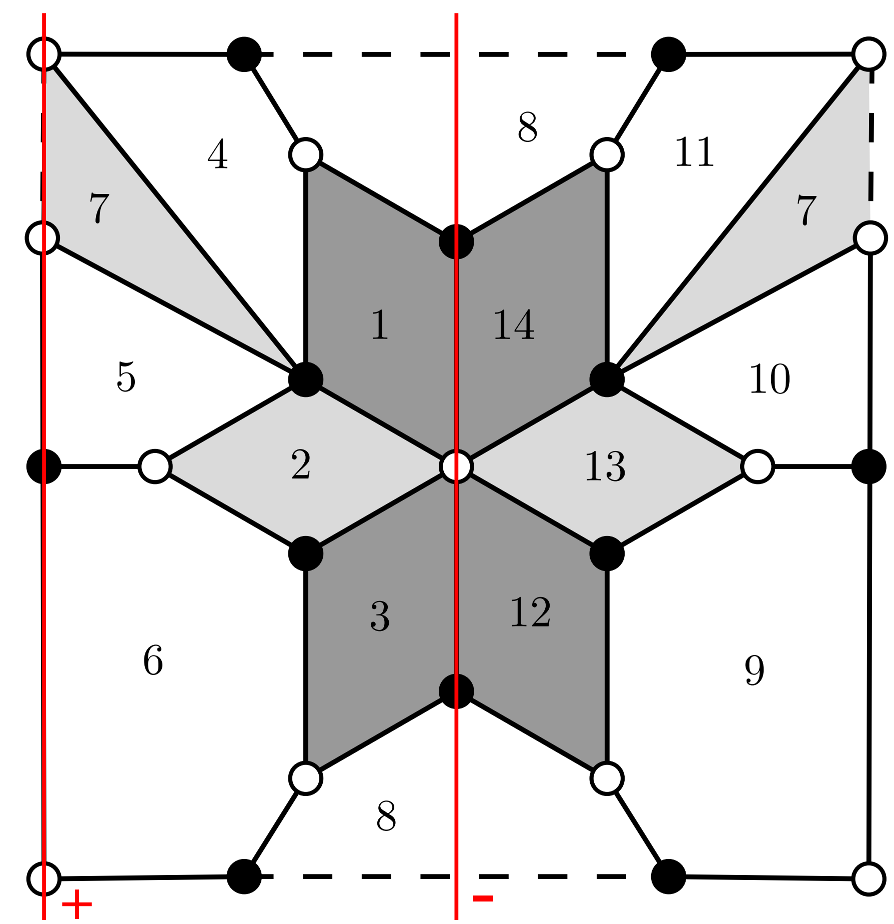
- Q: Do CY orientifolds free of local $\mathbb{C}^2/\mathbb{Z}_n$ singularities exist which admit stable DSB configurations?
- While we were looking for a **NO** and finally exclude DSB in D-brane models altogether… the answer happens to be a **YES**!

[ARGURIO ET AL '20]

- Strategy:
  - Look for a sub-dimer which can host a DSB model (after orientifolding) and does not involve N=2 fractional branes.
  - Try to embed it in a consistent dimer (*i.e.*, a CY singularity).
  - Check that the full theory is anomaly-free and the moduli space free of instabilities.

- One should look for line orientifolds since point reflection orientifolds admitting DSB models always have local $\mathbb{C}^2/\mathbb{Z}_n$ singularities (hence *ruled out* by our no-go theorem).
- One can show that the *3-2* model cannot be embedded in a sub-dimer without *N*=2 fractional branes directions $\longrightarrow$ we should focus on the SU(5) model (and generalizations).
- Simplest example which meets *all* criteria is the **Octagon**





- The orientifolded 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 $\downarrow$ (... at the bottom of a *duality cascade*)

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

$$X = (\overline{\Box}_1, \Box_2) \qquad Y = (\overline{\Box}_2, \Box_3) \qquad A_1 = \begin{smallmatrix}\Box\\\Box\end{smallmatrix}_{\,1} \qquad A_3 = \overline{\begin{smallmatrix}\Box\\\Box\end{smallmatrix}}_{\,3}$$

isolated node which confines

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

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

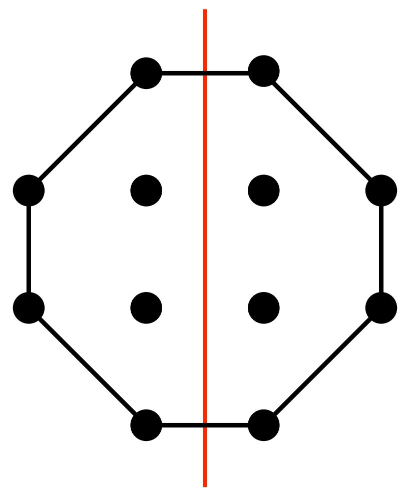
$$SU(5)_1 \times SU(1)_2 \times SU(5)_3 \quad \text{and} \quad W = 0$$

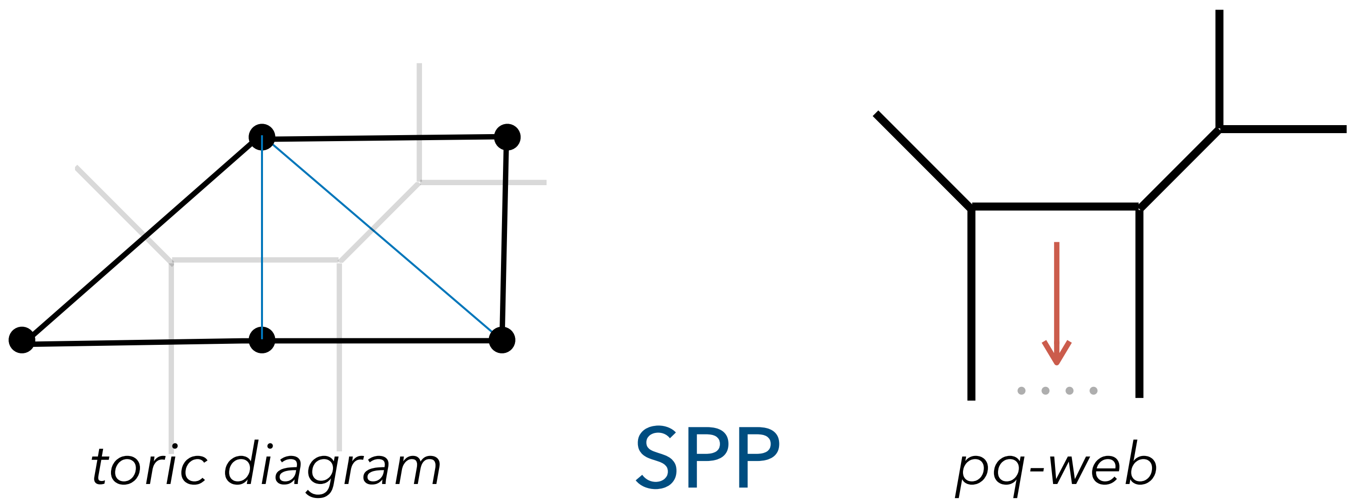
flavour index

$\longrightarrow$ two decoupled DSB SU(5) models: **twin SU(5)**!

Stability

- **No** N = 2 instabilities. By construction, the singularity does not host local non-isolated singularities (no points inside the edges along the boundary of toric diagram)

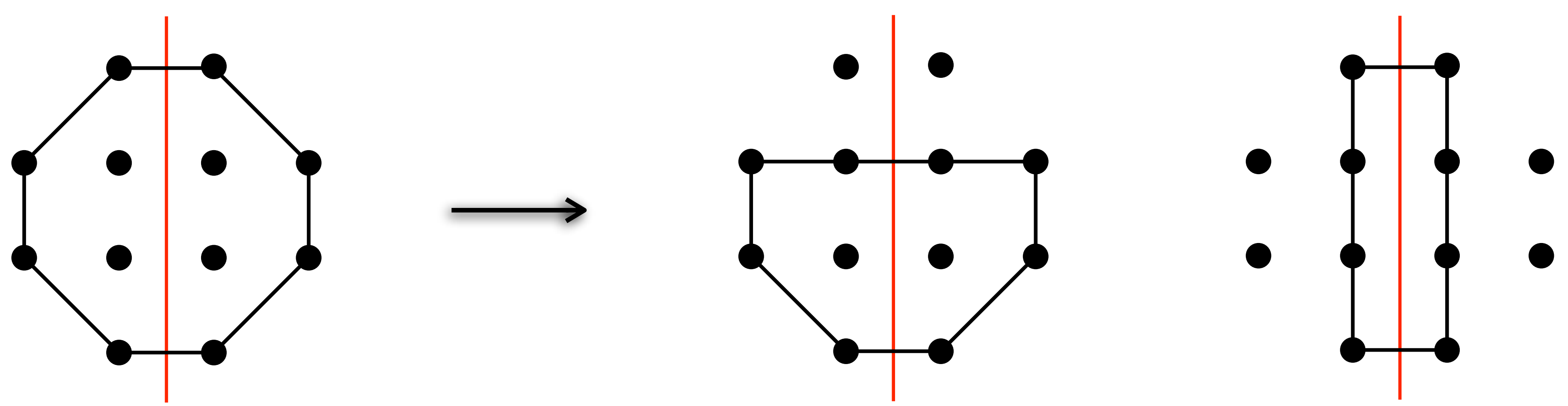




- Stringy instantons may provide extra contributions to the superpotential and spoil the stability of the vacuum (USp(0) and SU(1) nodes coupled to the SU(5) groups can host them). **No**: chiral gauge invariants cannot be written.

- **No** N = 4 instabilities. Moving away regular D3-branes does not affect the twin SU(5) vacuum. *N=4 branch* stable.
- The Octagon has *partial resolutions* generating CYs which admit non-isolated singularities and hence make the DSB vacuum potentially unstable towards *N*=2-like decay.

Partial resolutions corresponds to give VEV to *di-baryons* operators (fusion of adjacent faces in the dimer).



In present case they *cannot* occur due to rank unbalance of corresponding adjacent faces, either because of *M ≠ 0* or due to the orientifold.

⟶ Resolutions are *obstructed*. **No** instability!

Summary and comments

Summary

- We have shown that a large class of CY Orientifold singularities exist which can host DSB theories via suitable D-brane configurations. However, in decoupling limit they become *unstable* towards SUSY vacua, due to a *model-independent* decay channel.
- We showed how to overcome this instability and provided the *first instance* of a stable DSB model in D-brane constructions. The answer to our original question:

  ‘*Is stable SUSY breaking possible in D-brane models?*’

  is hence (and finally) Yes!

Comments

- By the very meaning of gauge/string *duality*, if SUSY is broken dynamically in a stable vacuum on the gauge theory side, then it is so on the dual side. Hence, the ***Yes*** to previous question implies the existence of a stable SUSY breaking background of type IIB string theory in 10d.
- Stability comes from non-trivial interplay btw *geometry*, *branes* probing it, and *orientifold* acting on it. What is the picture from the dual string theory side?
- What about a gravity dual? We discussed low-rank models. To get a gravity dual valid *all* the way to the deep IR we need to get *larger rank* realizations (*i.e*. generic M).

[WORK IN PROGRESS]

- Having a gravity dual would provide a dual geometric description of DSB…. and the nearest to a gravity dual of *non-supersymmetric confining theories*, as QCD!
- Our model could have an impact on the *swampland program*, in at least two ways:

  - It could be used as an ingredient to construct *de Sitter vacua* in 4d à la *KKLT*, similarly to *antiD3* in warped throats… but possibly with more control!

  - If a gravity dual is found, it would mean that warped throats with stable DSB D-brane sectors at their bottom, that is *stable non-supersymmetric locally AdS warped throats* are in the *landscape* (unlike pure AdS, which has been conjectured not to).

Thank you!