IR Dynamics and Supersymmetry Breaking from D-branes at singularities

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Based on:

S.Franco, A. Hanany, F. Saad, A. U, hep-th/0505040

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String Phenomenology, KITP, August 2006

Why D-branes at singularities?

• Chirality: Natural setup to construct (MS)SM gauge sectors in string theory
[Aldazabal, Ibáñez, Quevedo, A.U; Berenstein, Jejjala, Leigh; Verlinde, Wijnholt]

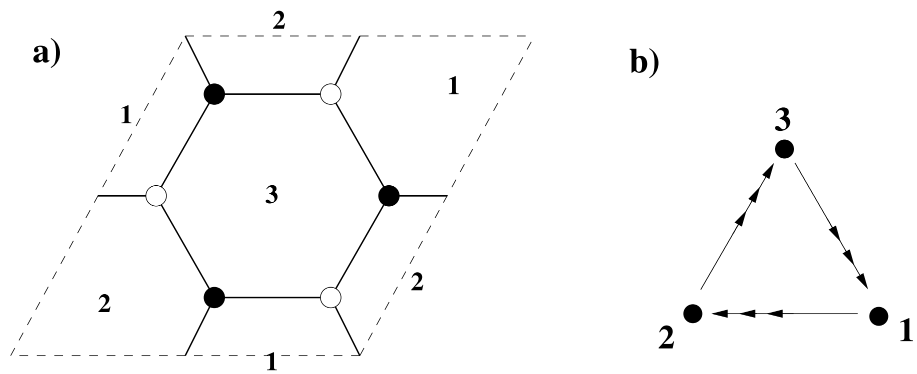
• IR Dynamics: Gauge sectors with interesting IR dynamics
Motivated by gauge/gravity correspondence
→ Confining gauge theories holographically dual to warped throats with fluxes [Vafa; Klebanov, Strassler; Franco, Hanany, A.U.]
→ Dynamical supersymmetry breaking gauge theories from singularities with obstructed deformations
[Berenstein, Herzog, Ouyang, Pinansky; Franco, Hanany, Saad, A.U; Bertolini, Bigazzi, Cotrone]

• Possible model building applications of these ideas

• In this talk, emphasis on supersymmetry breaking dynamics

D3-branes at singularities

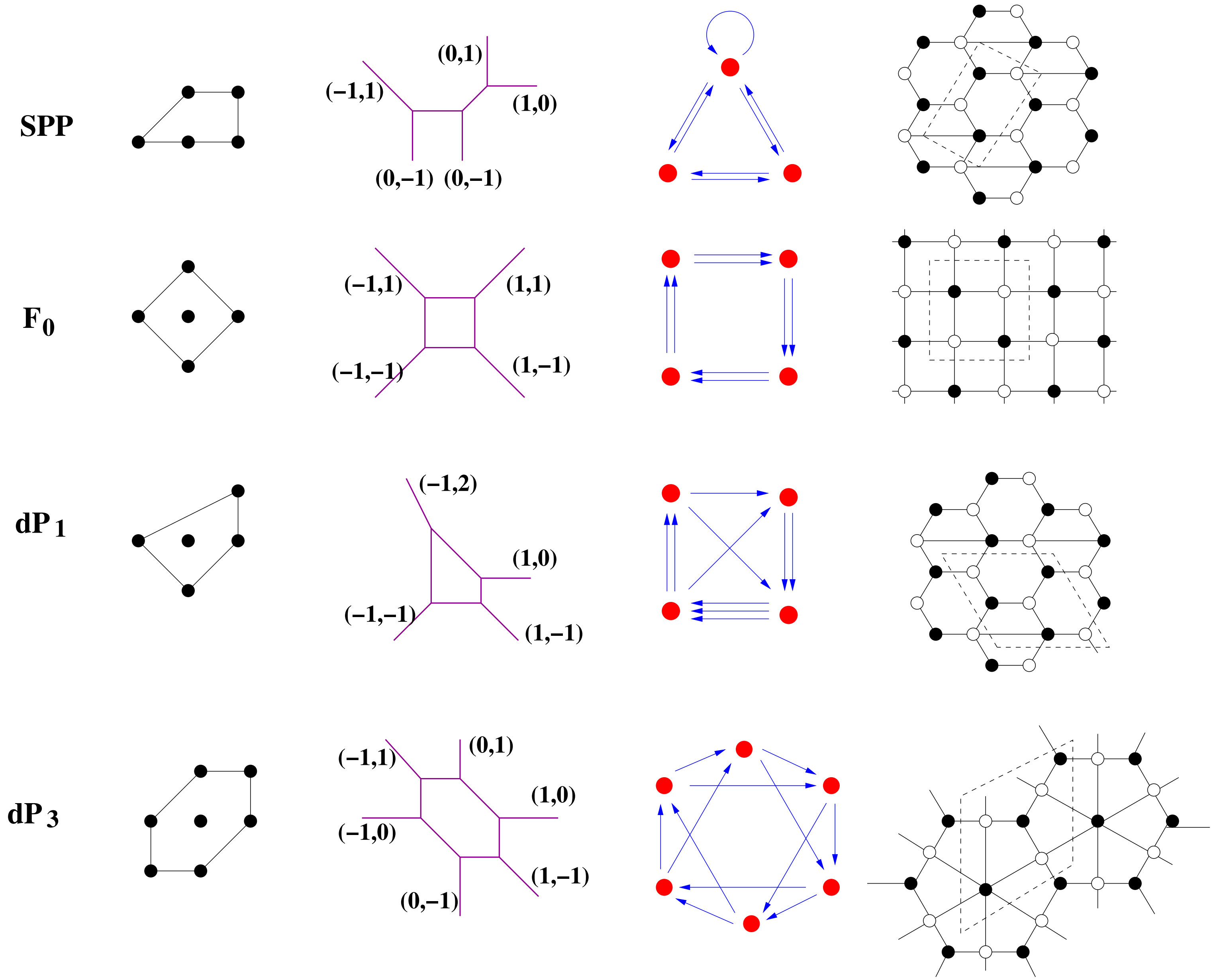
• D3-branes at singular CY lead to intricate $N = 1$ gauge theories, nicely encoded in dimer diagrams
→ Periodic tiling of the plane, with faces giving gauge factors, edges giving chiral bi-fundamentals, and nodes giving superpotential couplings
[Hanany, Kennaway; Franco, Hanany, Kennaway, Vegh, Wecht]



• Dimer techniques allow to obtain the gauge theory on D3-branes at any toric singularity

• Fractional branes: Anomaly free assignments of ranks on gauge factors (faces) → Non-conformal theories

Examples of toric, web, quiver and dimer diagrams



D-branes at singularities

as holographic duals of warped throats

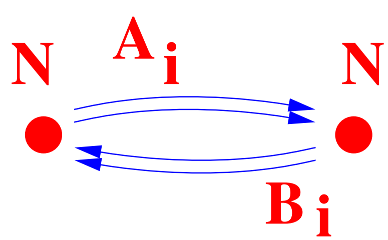
• D3-branes at singularity $\mathbf{X}_6$ correspond to 4d conformal field theories
→ Holographically dual to IIB theory on $\mathrm{AdS}_5 \times \mathbf{Y}_5$
with $\mathbf{Y}_5$ the base of the real cone $\mathbf{X}_6$.

• Addition of fractional branes breaks conformal invariance

• The case of the conifold

Conformal case: The gauge theory $SU(N) \times SU(N)$ [Klebanov,Witten]

$$W = \mathrm{tr}\,(A_1 B_1 A_2 B_2 - A_1 B_2 A_2 B_1)$$



→ Dual to $AdS_5 \times T^{11}$.

Non-conformal case: [Klebanov, Strassler]

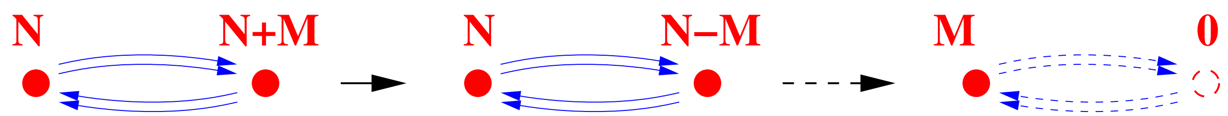
- Addition of fractional branes (change of ranks consistent with anomaly cancellation) breaks conformal invariance

The gauge theory $SU(N) \times SU(N+M)$

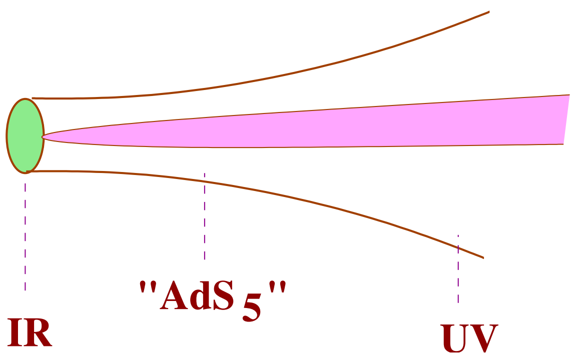
-It suffers a cascade of Seiberg dualities as it runs to the IR

$$SU(N) \times SU(N+M) \to SU(N) \times SU(N-M) \to \\ \to SU(N-2M) \times SU(N-M) \to \cdots$$

- For $N = KM$, this proceeds for K steps, the left over IR theory is pure $SU(M)$, confines and develops a gaugino condensate.



- IIB dual is the KS solution: Warped deformed conifold $xy - zw = \epsilon$ with M units of RR 3-form flux on $\mathbf{S}^3$ and K units of NSNS 3-form flux on dual 3-cycle.



- NSNS flux $\rightarrow$ RG varying couplings
- RR flux $\rightarrow$ dual to D5-branes
- Varying F_5 $\rightarrow$ Duality cascade
- $\mathbf{S}^3$ size $e^{-\frac{K}{Mg_s}}$ $\rightarrow$ Strong dynamics scale

- A particular case of CY with 3-form fluxes:

[Beckers; Dasgupta, Rajesh, Sethi; Giddings, Kachru, Polchinski]

Flux is ISD and in fact $(2,1)$ and stabilizes size of $\mathbf{S}^3$

- Lesson: Confinement $\leftrightarrow$ Complex deformation

Moduli space of gauge theory with fractional branes is the complex deformed geometry

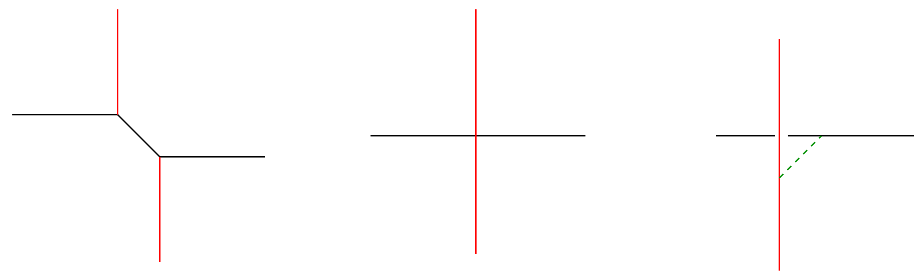
Complex deformations

- Complex deformations are easily identified in web diagram as recombinations of external legs into subwebs

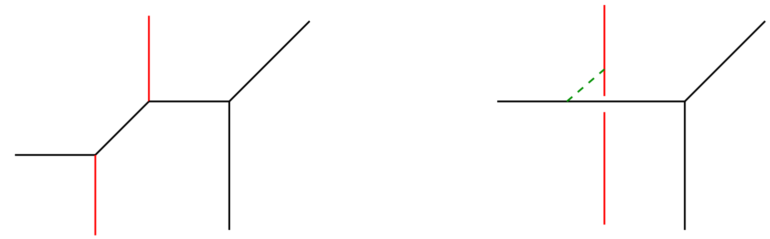
→ Higgs branch of 5d theory [Seiberg, Morrison; Aharony, Hanany, Kol]

→ Decomposition of toric polygon as Minkowski sum [Altmann]

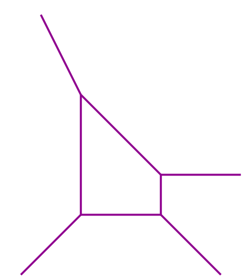
- Familiar example: Conifold



- But other examples too! Ex: SPP



- Also cases with no deformation: $Y^{p,q}$

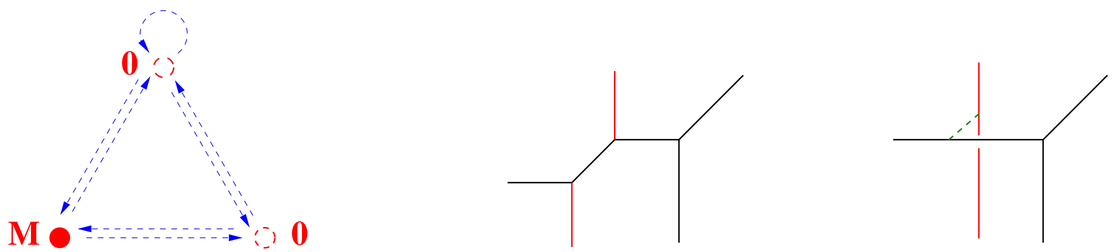


- One to one map with gauge theory behaviour!

IR confinement vs. deformation: The SPP example

• Systematic study of duality cascades, etc, possible.
Today, center on IR behaviour, e.g. for the SPP case.

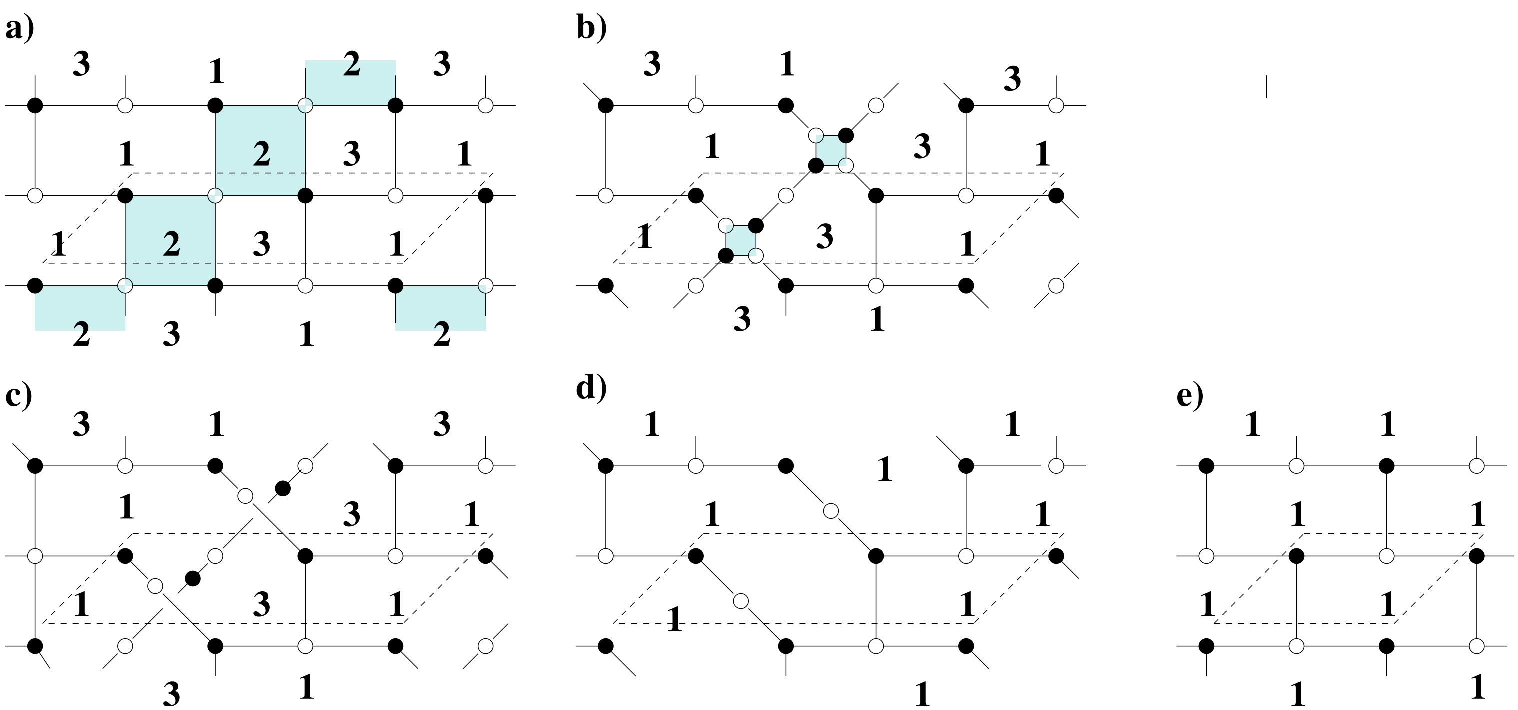
• IR behaviour of fractional branes is a confining theory, reminiscent of the conifold. Suggests a matching with the complex deformation to a smooth geometry $xy - zw^2 = \epsilon w$.



• To verify, add D3-brane probe: Moduli space of the gauge theory should be that of a D-brane moving in a smoothed space

Gauge theory check: Moduli space is deformed geometry

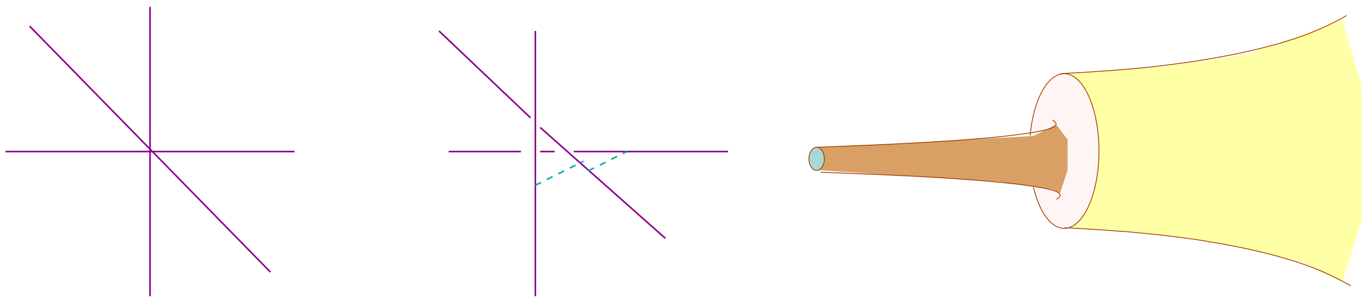
- Lenghty gauge theory computation [Franco, Hanay, A.U.]
simple in terms of dimer diagram [García-Etxebarria, Saad, A.U.]



- After confinement, gauge theory is $N = 4$ SYM: D-brane on smoothed out geometry!

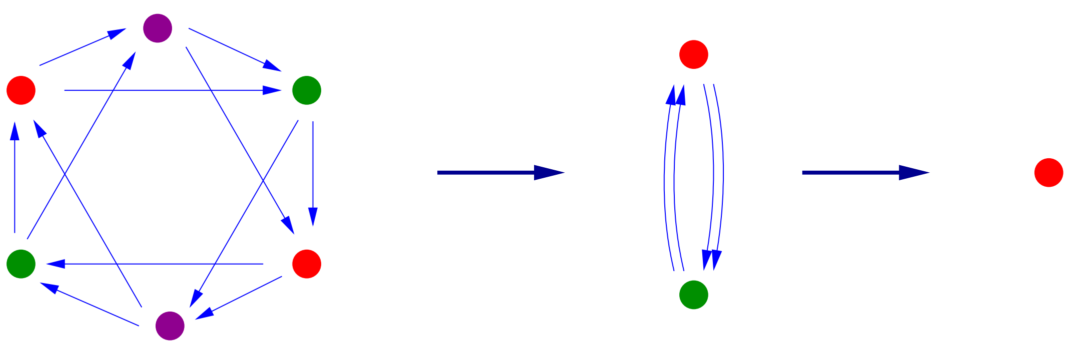
The cone over dP_3

• The geometry has a two-dimensional branch of complex deformations



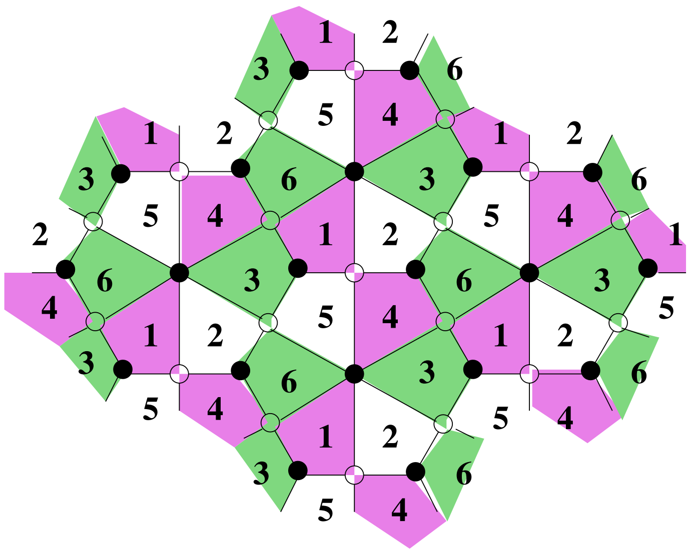
• In the regime of hierarchically different sizes, sequential deformation:
cone over $\text{dP}_3 \to$ conifold $\to$ smooth

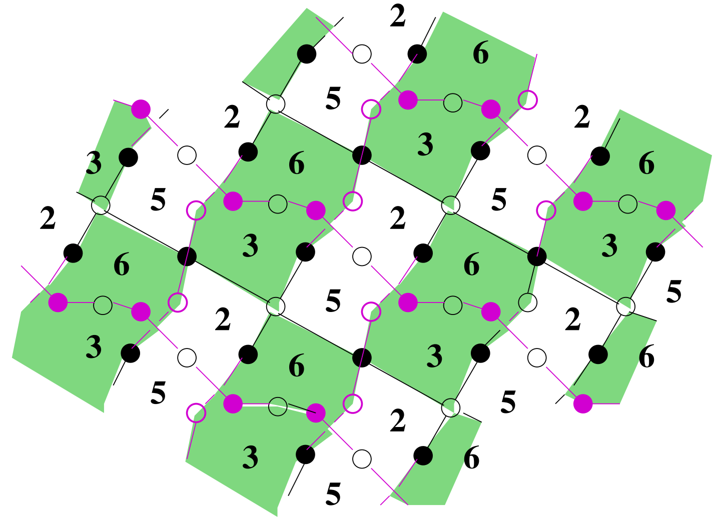
• Suggests two stages of infrared partial confinement
• Full agreement with gauge theory pattern:
Duality cascade $\to$ Partial confinement. to conifold th. $\to$
$\to$ Subsequent cascade $\to$ Confinement

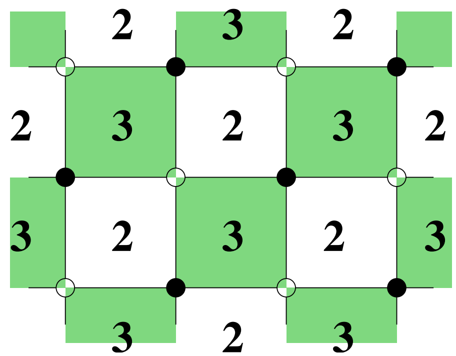


Gauge dynamics of the probe using the dimer diagram

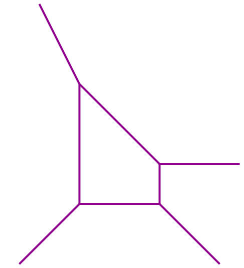
[García-Etxebarria, Saad, A.U.]







Cases with no deformation: DSB branes



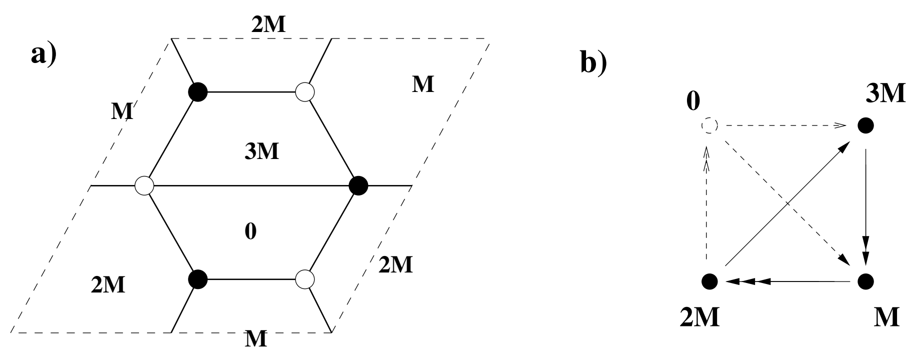
- Many geometries do not admit complex deformations

For instance, $Y_{p,q}$

- But UV cascades, and dual throats, exist (albeit IR singular).

[Herzog, Ejaz, Klebanov] $\rightarrow$ What is the IR behaviour?

- Analyze using gauge theory! [Berenstein, Herzog, Ouyang, Pinansky; Franco, Hanany, Saad, A.U; Bertolini, Bigazzi, Cotrone] e.g. for dP_1 theory



- We have $U(3M) \times U(2M) \times U(1)$ with $W = X_{23}X_{31}Y_{12} - X_{23}Y_{31}X_{12}$

- The $U(1)$'s have Green-Schwarz anomaly cancellation and disappear; their FI terms are dynamical vevs of closed Kahler moduli.

$\rightarrow$ Effectively neither $U(1)$ vector multiplet, nor D-term constraint.

DSB branes: No SUSY vacuum

• In the regime where the $SU(3M)$ dominates, we have an Affleck-Dine-Seiberg superpotential $M_{21} = X_{23}X_{31}$, $M'_{21} = X_{23}Y_{31}$

$$W = (\, M_{21}Y_{12} - M'_{21}X_{12}\,) + M \left(\frac{\Lambda_3^{7M}}{\det \mathcal{M}} \right)^{\frac{1}{M}} \quad ; \quad \mathcal{M} = (M_{21}; M'_{21})$$

• No SUSY vacuum

$F_{X_{12}}$, $F_{Y_{12}}$ send $M_{21}, M'_{21} \to 0$, and then $F_{M_{21}}$, $F_{M'_{21}}$ send $X_{12}, Y_{12} \to \infty$.
[Berenstein, Herzog, Ouyang, Pinansky; Franco, Hanany, Saad, A.U; Bertolini, Bigazzi, Cotrone]

• Assuming canonical Kahler potential, scalar potential has runaway behaviour [Franco, Hanany, Saad, A.U; Intriligator, Seiberg]

• Runaway can be stopped if e.g. Kahler moduli are fixed, so FI terms are effectively no longer dynamical, and $U(1)$ D-terms reappear.

• All similar to $SU(5)$ with $10 + \overline{5}$ in [Lykken, Poppitz, Trivedi]

Stopping the runaway:

$\to$ Embedding in compact space, and include instantons to stabilize Kahler moduli (FI terms) [McGreevy, Strings06]

$\to$ Remain local, and modify to get local meta-stable minima, following [Intriligator, Seiberg, Shih]

The ISS model [Intriligator, Seiberg, Shih]

• Consider $SU(N_c)$ SYM with N_f massive flavors, $(m \ll \Lambda_{SQCD})$ in free magnetic phase $(N_c + 1 \leq N_f \leq \frac{3}{2}N_c)$,

$\to$ Seiberg dual has canonical Kahler potential.

• Dual is $SU(N)$ SYM with $N = N_f - N_c$, with N_f flavors q, $\tilde{q}$, and mesons Φ, with $W = h \mathrm{Tr}\, q\Phi\tilde{q} - h\mu^2 \mathrm{Tr}\,\Phi$

$\to$ SUSY breaking at tree level: $F_\Phi = \tilde{q}^i q_j - \mu^2 \delta^i_j \neq 0$

• Classical moduli space with $V_{min} = (N_f - N)|h^2\mu^4|$

$$\Phi = \begin{pmatrix} 0 & 0 \\ 0 & \Phi_0 \end{pmatrix} \; ; \; q = \begin{pmatrix} \varphi_0 \\ 0 \end{pmatrix} \; ; \; \tilde{q}^T = \begin{pmatrix} \tilde{\varphi}_0 \\ 0 \end{pmatrix}, \text{ with } \tilde{\varphi}_0\varphi_0 = \mu^2 \mathbf{1}_N$$

• One-loop Coleman-Weinberg potential leads to a minimum at

$$\Phi_0 = 0, \qquad \varphi_0 = \tilde{\varphi}_0 = \mu \mathbf{1}_N$$

• Include the $SU(N)$ gauge interactions
For generic Φ, flavors q, $\tilde{q}$ are integrated out, leaving $SU(N)$ SYM with scale Λ'

$$\Lambda'^{3N} = h^{N_f} \det \Phi \, \Lambda^{-(N_f - 3N)}$$

with Λ the Landau pole scale of the IR free theory.

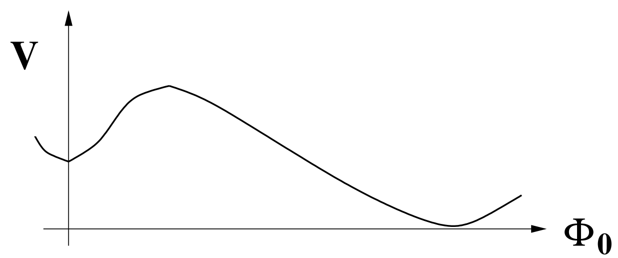
→ Complete superpotential

$$W = N \left(h^{N_f} \Lambda^{-(N_f-3N)} \det \Phi \right)^{1/N} - h\mu^2 \,\mathrm{Tr}\, \Phi$$

→ There are $N_f - N$ supersymmetric minima

$$\langle h\Phi_0 \rangle = \mu \epsilon^{-\frac{N_f-3N}{N_f-N}} \mathbf{1}_{N_f} \text{ where } \epsilon \equiv \frac{\mu}{\Lambda}$$

• For $\epsilon \ll 1$, local SUSY breaking minimum is parametrically long-lived

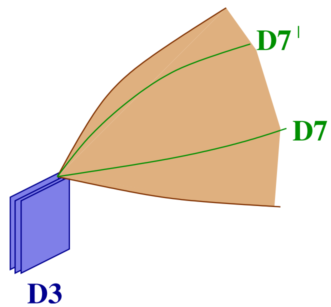


$$S \simeq |\epsilon|^{-\frac{4(N_f-3N)}{N_f-N}} \gg 1$$

ISS in String Theory (I)

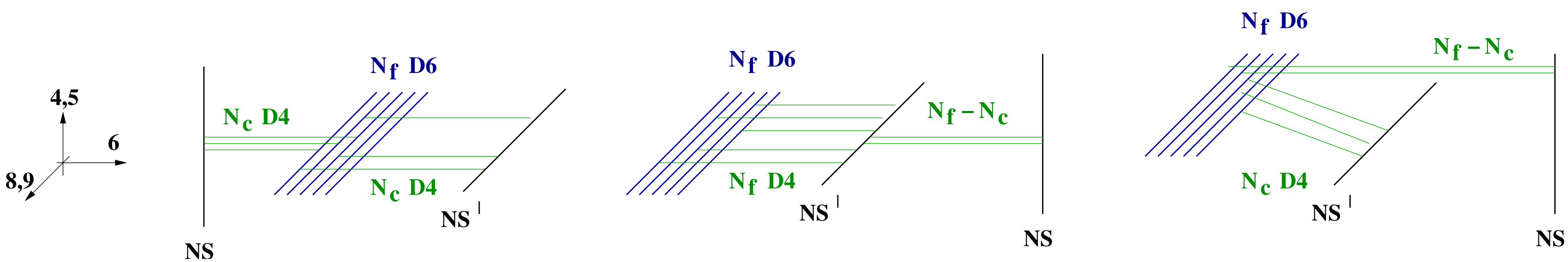
[Ooguri, Ookouchi; Franco, Garcia-Etxebarria, A.U.]

- Realize $N = 1$ SYM with flavors by adding D7-branes to the conifold with fractional branes



- T-dualize to obtain system of NS-, D4- and D6-branes

[Hanany, Witten; Elitzur, Giveon, Kutasov]



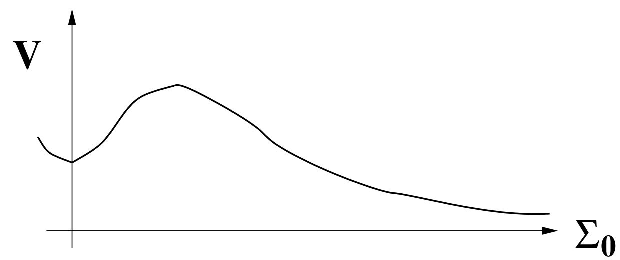
→ Classical properties are geometrized

→ 1-loop stabilization is non-BPS attraction

Generalizing ISS with extra massless flavours [Franco, A.U.]

• SQCD Consider $SU(N_c)$ with $N_{f,0}$ massless and $N_{f,1}$ massive flavours
To have rank SUSY breaking in dual theory, need $N_{f,1} > N$
i.e. $N_{f,1} > N_{f,1} + N_{f,0} - N_c \rightarrow N_{f,0} < N_c$
Repeat ISS-like analysis:
- Almost local minimum: $\Phi_{00} (= \tilde{Q}_0 Q_0)$ remains flat at one loop
- At large fields, Φ_{00} is a runaway direction (as without ISS flavours)
$\rightarrow$ Suggests no local minimum, but saddle point and runaway

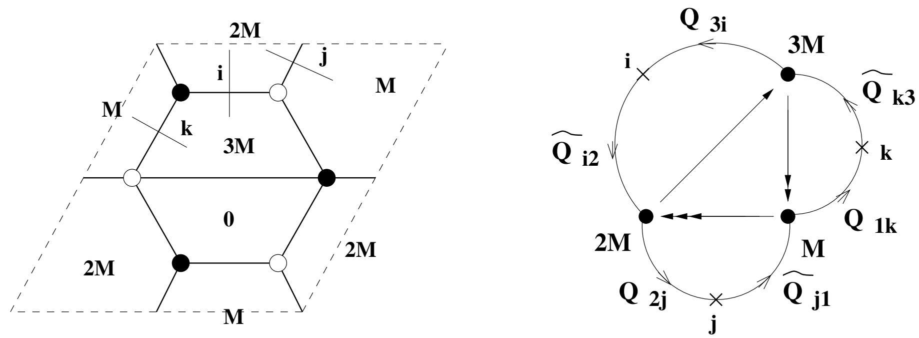
• SSQCD Add field Σ_0, with $W = Q_0 \Sigma_0 \tilde{Q}_0$ to render Φ_{00} massive
Repeat ISS-like analysis;
$\rightarrow$ Local minimum for all fields!
$\rightarrow$ At large fields, Σ_0 is a runaway direction (as without ISS flavours)



• The condition $N_{f,0} < N_c$, and the cubic coupling to Σ_0 are present in gauge theories of D-branes at obstructed geometries

Flavoured dP_1 [Franco, A.U.]

- Add massive flavours to the theory of fractional branes at dP_1



$$
\begin{aligned}
W &= \lambda\,(\,X_{23}X_{31}Y_{12} - X_{23}Y_{31}X_{12}\,) \\
W_{flav.} &= \lambda'\,(\,Q_{3i}\tilde{Q}_{i2}X_{23} + Q_{2j}\tilde{Q}_{j1}X_{12} + Q_{1k}\tilde{Q}_{k3}X_{31}\,) \\
W_m &= m_3\,Q_{3i}\tilde{Q}_{k3}\delta_{ik} + m_2\,Q_{2j}\tilde{Q}_{i2}\delta_{ji} + m_1\,Q_{1k}\tilde{Q}_{j1}\delta_{kj}
\end{aligned}
$$

- For $SU(3M)$, $N_{f,0} < N_c$, hence the dual is IR free

$$
\begin{aligned}
W &= h\,\Phi_{ki}\tilde{Q}_{i3}Q_{3k} - h\mu^2\mathrm{tr}\,\Phi + h\mu_0\,(\,M_{21}Y_{12} - M'_{21}X_{12}\,) + \\
&+ h\,(\,M_{21}X_{13}X_{32} + M'_{21}Y_{13}X_{32} + N'_{k1}Y_{13}Q_{3k}\,) + \\
&+ \lambda'\,Q_{2j}\tilde{Q}_{j1}X_{12} - h_1\,\tilde{Q}_{k1}X_{13}Q_{3k} - h_2\,Q_{2i}\tilde{Q}_{i3}X_{32}
\end{aligned}
$$

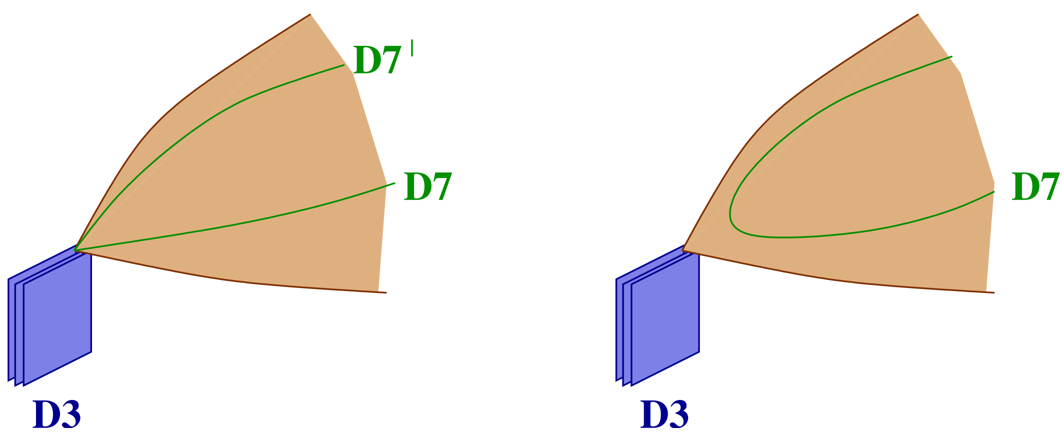
- Repeating ISS-like analysis: One-loop potential for classical moduli

$\rightarrow$ Local minimum separated by a large barrier from runaway at infinity

String theory realization

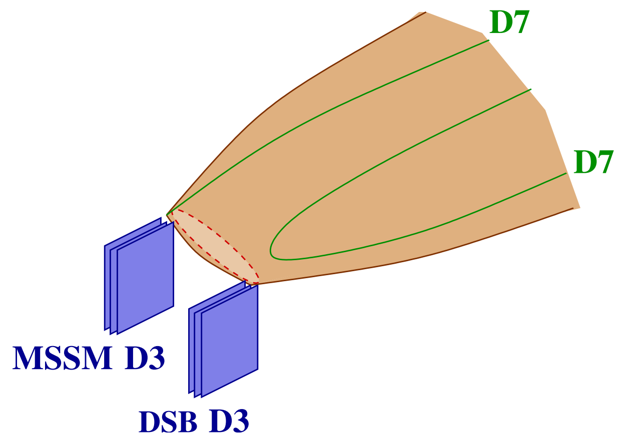
• Consider D3-branes at a singularity, and add D7-branes passing through it
→ D7-branes wrap non-compact supersymmetric 4-cycles in toric singu
→ Flavours arise from D3-D7 open strings
→ Flavour masses from D7-D7' field vevs (due to 73-37-77' couplings): D7-branes recombine and move away from D3-branes
• Dimer diagrams efficiently describe these properties for general toric singularities (and dP_1 in particular).
[Franco, A.U.]

• Geometric picture



Local models of GMSB [García-Etxebarria, Saad, A.U.]

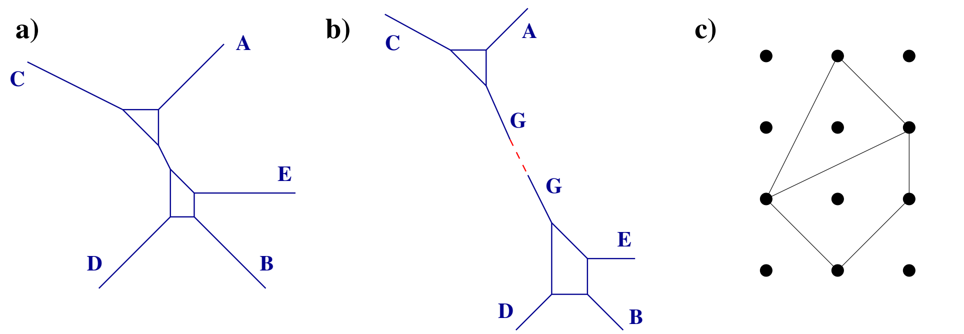
• Consider local CY's with two singular points, with D-branes
→ Two chiral gauge sectors decoupled at massless level
• For suitable singularities, and D-brane systems at them,
→ MSSM-like sector e.g. D3/D7's at $\mathbf{C}^3/\mathbf{Z}_3$ [Aldazabal, Ibáñez, Quevedo, A.U.]
→ Gauge sector with DSB e.g. D3/D7's at dP_1 singularity

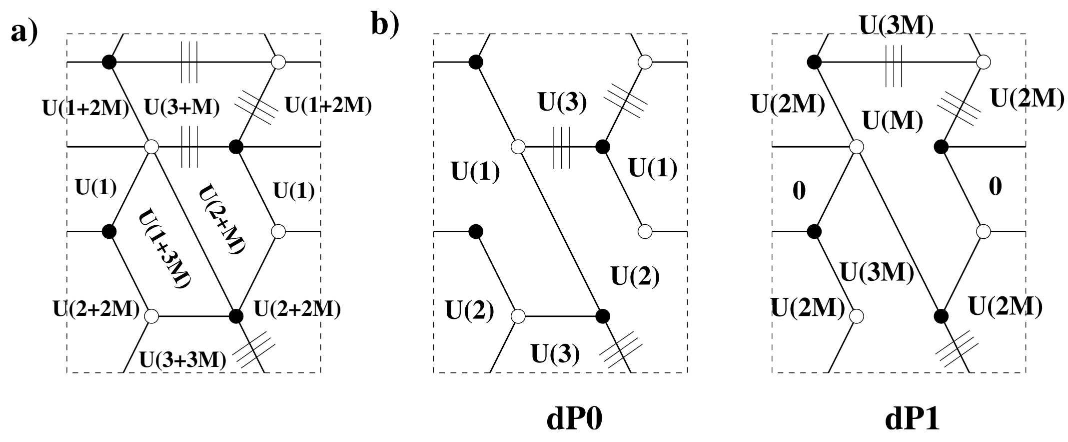


• Models of Gauge mediation in string theory
→ Similar in spirit to [Diaconescu, Florea, Kachru, Svrcek]
→ Local model, enough for substringy separation: UV insensitivity
→ Separation related to Kahler or complex modulus
→ Spectrum and interactions of massive messengers is computable

A simple example

- For sub-stringy separtion, better described as small blow-up of gauge theory of D-branes at the singularity in the coincident limit
- A simple example: Partial resolution of $X^{3,1}$ singu to $C^3/\mathbf{Z}_3$ and dP_1





- General framework, flexible enough to implement many other models

Conclusions

• D-branes at singularities can be used to engineer gauge theories with interesting infrared dynamics
- Complex deformations and IR confinement
- Absence of complex deformations and SUSY breaking

• Aspects of SUSY breaking from D-branes at singularities
Important role of fractional D-branes at obstructed geometries (DSB branes), like dP_1 theory
→ Runaway for systems of just D3-branes
→ Local SUSY-breaking minimum for D3/D7's

• Many applications come to mind
→ String models of GMSB
→ Supergravity dual of DSB gauge theories (subtle...)
→ DSB systems as source of tension in KKLT

• Need to improve techniques to carry out gauge theory analysis
→ Insight from dimer diagrams?

• We expect interesting progress in these directions