T-branes and 3d Mirror Symmetry

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Based on 1602.0XXXX with A. Collinucci, S. Giacomelli and R. Savelli

Introduction

F-theory: connection between geometry and gauge theory (+ sugra):

IIB/IIA gauge theory on D7/D6	$\leftrightarrow$	F/M-theory on (singular) T^2/S^1 fibrations
Eg, $N = 4$ D-branes: $G = U(4)$	$\leftrightarrow$	$u \cdot v = z^4$: A_3 sing
Vev for complex adj Φ deform of D-br config	$\leftrightarrow$	$u \cdot v = \det(z\,\mathbf{1}_N - \Phi)$ deform of sing
$\Phi = \begin{pmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 \\ 0 & 0 & 0 & \lambda_4 \end{pmatrix}$	$\leftrightarrow$	$u \cdot v = \prod_{i=1}^4 (z - \lambda_i)$
D-branes split: $G = U(1)^4$	$\leftrightarrow$	No singularity (deformed away)

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T-brane	$\leftrightarrow$	???

[Cecotti, Cordova, Heckman, Vafa; Heckman, Tachikawa, Vafa, Wecht; Donagi, Wijnholt]

Geometry does not see all possible vevs: sensible only to Casimirs

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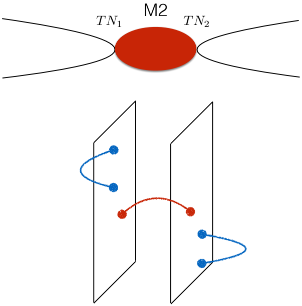
Introduction

T-brane is vev for Φ (strings between D6/D7s). What is M-theory lift?



- $\color{blue}{\Phi_{11}}$ and $\color{blue}{\Phi_{22}}$ lift to geometric c.s. deformations,
- $\color{red}{\Phi_{12}}$ lift to M2-brane wrapping the vanishing cycle.

T-brane (vev for Φ_{12}) $\rightsquigarrow$ coherent state of M2-branes on vanishing cycles.

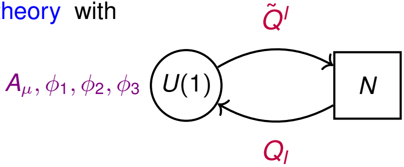
In absence of formulation for microscopic M2, find a framework that allows to describe this extra data in M-theory. [Anderson, Heckman, Katz; Collinucci, Savelli]

Here we turn to the 3d perspective of a probe M2-brane that see this effect.

Let's start by considering a stack of N D6-branes and we probe them by a D2.

	0	1	2	3	4	5	6	7	8	9
$N \times$ D6	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$	$\times$			
D2	$\times$	$\times$	$\times$							

$\mathcal{N} = 4$ $d = 3$ $U(1)$ theory with



- $\star$ One Abelian vector multiplet

$$A_\mu, \quad \phi_3, \quad \varphi \equiv \phi_1 + i\phi_2$$

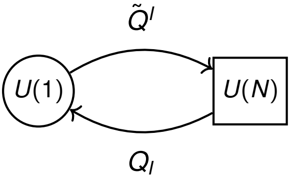
- $\star$ N flavors hypermultiplets

$$Q_I, \ \tilde{Q}^I \qquad\qquad \text{with } I = 1, ..., N$$

- $\star$ Superpotential

$$W_A = \varphi \sum_I \tilde{Q}^I Q_I$$

- $\star$ Moduli space separates into two branches.



Coordinates: gauge invariant mesons. $M_I^{\ J} \equiv Q_I \tilde{Q}^J$ ($I = 1, ..., N$) s.t.

$$\text{rk}\, M = 1 \qquad \text{and} \qquad \text{Tr}\, M = 0 \qquad\qquad (\dim_{\mathbb{C}} = 2N - 2)$$

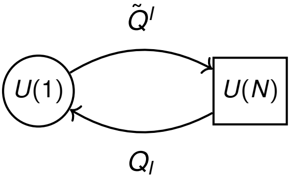
$\rightarrow$ It has manifest $U(N)$ global symmetry.

Deformations (lift some directions):

- complex masses $\delta W = m_c Q_1 \tilde{Q}^1$
- real masses $\int d^4\theta Q_1^\dagger e^{m_r \theta\bar{\theta}} Q_1$

(m_c, m_r) are the vev for the D6-brane scalars: move D6s apart from D2.

Theory A - Higgs Branch



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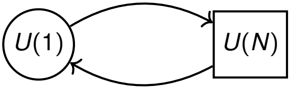
Theory A - Coulomb Branch

Photon can be dualised: $*F = d\gamma (= J_T)$

$$A_\mu,\ \ \phi_1,\, \phi_2,\, \phi_3 \qquad \hookrightarrow \qquad V_\pm \sim e^{\pm(\phi_3 + i\gamma)},\ \varphi \equiv \phi_1 + i\phi_2$$

$V_\pm, \varphi$



Coordinates: $V_\pm$ and φ s.t.

$$V_+ V_- = \varphi^N \qquad\qquad (\dim_{\mathbb{C}} = 2)$$

A_{N-1} singularity (dual photon $\leftrightarrow$ M-theory circle)

Deformations:

- $m_c \Rightarrow$ deformations of CB: $\varphi^N \mapsto \varphi^{N-1}(\varphi + m_c)$
- $m_r \Rightarrow$ resolutions of CB.

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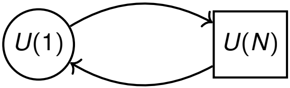

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Theory A

T-brane deformation: (For 4D analog, see [Heckman, Tachikawa, Vafa, Wecht])

$$\langle \Phi_{D6} \rangle = m_T = \begin{pmatrix} 0 & 0 & \cdots & 0 \\ m & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & & 0 \end{pmatrix} \quad \rightsquigarrow \quad \delta W = m\, Q_1 \tilde{Q}^2$$

- ∗ It breaks $U(N)$ flavor symmetry to $U(1) \times U(N-2)$ and makes two chiral multiplets massive.
- ∗ What about Coulomb branch? Integrating out massive flavors, obtain $N-2$ flavors with couplings $\varphi Q_I \tilde{Q}^I$ and one with $\frac{\varphi^2}{m} Q' \tilde{Q}'$. Hence

$$V'_+ V'_- = \varphi^{N-2} \frac{\varphi^2}{m}$$

A_{N-1} singularity untouched. [Benini,Closset,Cremonesi]

This description is ok and we could proceed and study T-brane from this p.o.v., but intrinsically perturbative and hard to generalise to more interesting groups.

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3d mirror symmetry [Intriligator, Seiberg]

Theory A (3d SQED with N flav) dual to another 3d theory, Theory B.

String theory interpretation: TST composition or through '9-11' flip

M2 at $\mathbb{C}^2/\mathbb{Z}_N \times \mathbb{R}^3 \times \mathbb{C}^2$

S^1 S^1

D2, N $\times$ D6's on $\mathbb{R}^{10}$ $\longleftrightarrow$ D2, D6 on $\mathbb{C}^2/\mathbb{Z}_N \times \mathbb{R}^6$

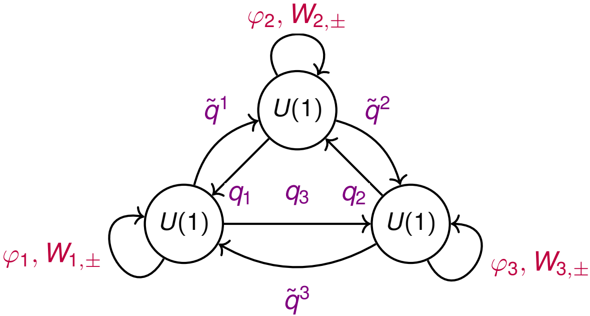
TST

Theory B: completely different theory, but

- ⋆ on the same singular space of M-theory: form that can be generalized;
- ⋆ string theory at sing: power of quiver techniques.

$\Rightarrow$ Map T-brane deformations here.

Theory B



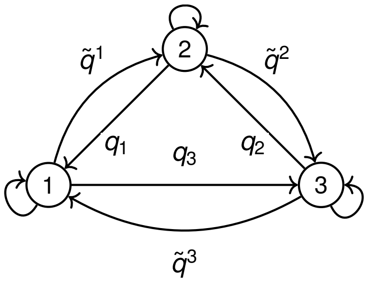
$\mathcal{N} = 4$ $U(1)^N$ gauge theory

* Each node comes with a vector multiplet $\rightsquigarrow$ dualize photon: $(\varphi_i, W_{i,\pm})$
* N hypermultiplets $(q_i, \tilde{q}^i)$, connecting the nodes.
* Superpotential

$$W = \sum_{i=1}^{N} S_i q_i \tilde{q}^i \qquad (S_i \equiv \varphi_i - \varphi_{i+1})$$

* Again, HB and CB.

Theory B - Higgs Branch



Coordinates: gauge inv comb's $q_i \tilde{q}_i$, $B \equiv q_1 q_2 \ldots q_N$ and $\tilde{B} \equiv \tilde{q}_1 \tilde{q}_2 \ldots \tilde{q}_N$

- Superpotential $W = \sum_{i=1}^N S_i q_i \tilde{q}^i - \Psi \sum_{i=1}^N S_i \to$ F-terms:

$$q_i \tilde{q}_i = \Psi \;\; \forall i \qquad \Rightarrow \qquad B \tilde{B} = \Psi^N \qquad (A_{N-1} \text{ sing})$$

Deformations

- complex FI-terms $\delta W = \zeta S_1 \Rightarrow q_1 \tilde{q}_1 = \Psi - \zeta \rightsquigarrow$ deform.
- real FI-terms $\xi \int d^4\theta V_i \rightsquigarrow$ blow-up.

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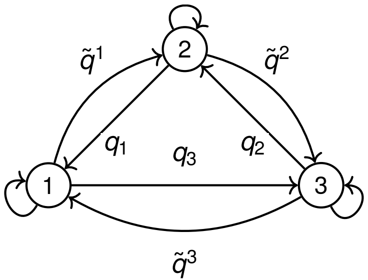

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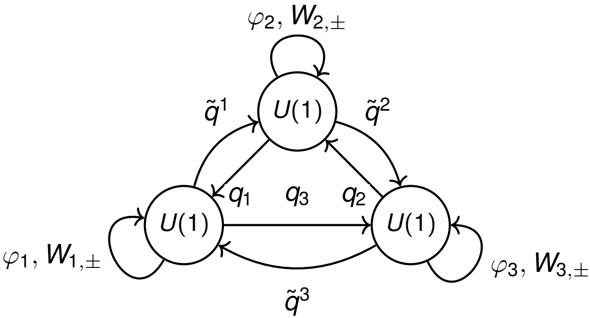


Coordinates: $(\varphi_i, W_{i,\pm})$ s.t.

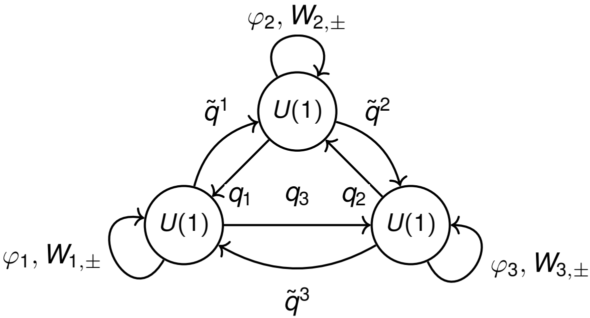
$$W_{i,+} W_{i,-} = S_i \, S_{i-1} \qquad\qquad (S_i \equiv \varphi_i - \varphi_{i+1})$$

Symmetries

- $U(1)^{N-1}$ topological sym: $\gamma_i \mapsto \gamma_i + c_i$ $\rightsquigarrow$ currents: $J_{U(1)_i} = *F_i = d\gamma_i$.
- $W_{i,\pm} \sim e^{\pm(\varphi_i + i\gamma_i)}$ have $q_i = \pm 1$ $\rightsquigarrow$ in supermultiplets with currents $J_{i,\pm}$.

$\Rightarrow$ enhanced global sym: $SU(N)$.

Theory B - Coulomb Branch



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3d Mirror Map [Intriligator, Seiberg; Aharony, Hanany, Intriligator, Strassler, Seiberg]

Map between gauge invariant coord defining $\text{CB}_A \leftrightarrow \text{HB}_B$ and $\text{HB}_A \leftrightarrow \text{CB}_B$:

$\text{CB}_A \leftrightarrow \text{HB}_B$:

$$\varphi \;\leftrightarrow\; \Psi = q_i \tilde{q}_i \qquad V_+ \;\leftrightarrow\; B \qquad V_- \;\leftrightarrow\; \tilde{B}$$

$$V_+ V_- = \varphi^N \;\leftrightarrow\; B\tilde{B} = \Psi^N$$

$\text{HB}_A \leftrightarrow \text{CB}_B$:

$$M_i{}^i \;\leftrightarrow\; S_i \qquad M_{i-1}{}^i \;\leftrightarrow\; W_{i,+} \qquad M_i{}^{i-1} \;\leftrightarrow\; W_{i,-}$$

$$\text{rk}\, M = 1 \;\rightsquigarrow\; M_{i-1}{}^{i-1} M_i{}^i - M_{i-1}{}^i M_i{}^{i-1} \;\leftrightarrow\; S_{i-1} S_i = W_{i,+} W_{i,-}$$

$$\text{Tr}\, M = 0 \qquad \leftrightarrow \qquad \sum_i S_i = 0$$

($SU(N)$ symmetry)

T-brane

Theory A: off-diagonal mass term $+m\, Q_1 \tilde{Q}^2$

$$W = \varphi \sum_I Q_I \tilde{Q}^I + \sum_{I,J} (m_T)_J{}^I Q_I \tilde{Q}^J \qquad \text{with} \qquad m_T^k = 0$$

F-terms:

$$(\varphi \mathbf{1} + m_T) \cdot Q = 0 \qquad \tilde{Q} \cdot (\varphi \mathbf{1} + m_T) = 0$$

Construct gauge invariant F-term:

$$(\varphi \mathbf{1} + m_T) \cdot M = 0 \qquad M \cdot (\varphi \mathbf{1} + m_T) = 0$$

Theory B: by mirror map obtain how $+m\, W_{2,+}$ should modify F-terms

$$(\Psi \mathbf{1} + m_T) \cdot \begin{pmatrix} S_1 & W_{2,+} & \\ W_{2,-} & S_2 & \\ & & \ddots \end{pmatrix} = 0$$

m_T breaks $SU(N)$ symmetry

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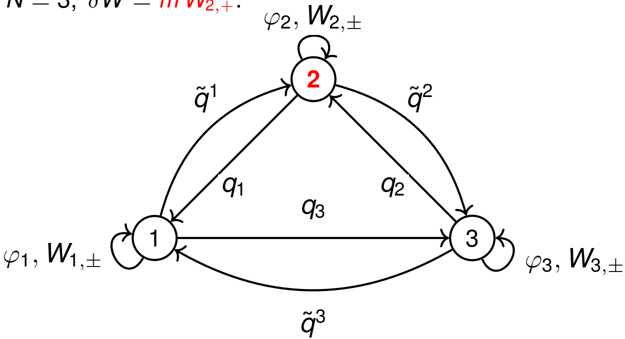
T-brane in theory B

Example $N = 3$, $\delta W = m\, W_{2,+}$:



$$\begin{pmatrix} \Psi & 0 & 0 \\ m & \Psi & 0 \\ 0 & 0 & \Psi \end{pmatrix} \cdot \begin{pmatrix} S_1 & W_{2,+} & W_{1,-} \\ W_{2,-} & S_2 & W_{3,+} \\ W_{1,+} & W_{3,-} & S_3 \end{pmatrix} = 0$$

One can apply a bi-unitary transformation to bring into the form:

T-brane in theory B

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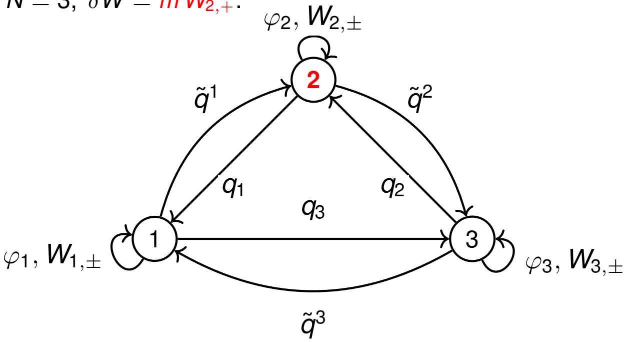

$$\begin{pmatrix} m & 0 & 0 \\ 0 & \frac{\Psi^2}{m} & 0 \\ 0 & 0 & \Psi \end{pmatrix} \cdot \begin{pmatrix} \divideontimes & \divideontimes & \divideontimes \\ \divideontimes & S_2' & W_{3,+} \\ \divideontimes & W_{3,-}' & S_3 \end{pmatrix} = 0$$

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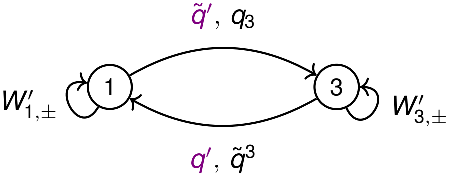


$$\begin{pmatrix} m & 0 & 0 \\ 0 & \frac{\Psi^2}{m} & 0 \\ 0 & 0 & \Psi \end{pmatrix} \cdot \begin{pmatrix} * & * & * \\ * & S' & W'_{3,+} \\ * & W'_{3,-} & S_3 \end{pmatrix} = 0$$

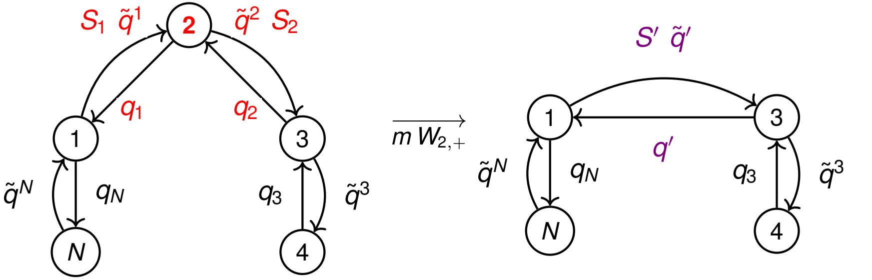
New F-terms captured by effective superpotential:

$$W_{\text{eff}} = S' q' \tilde{q}' + S_3 q_3 \tilde{q}^3 - \frac{\Psi^2}{m} S' + \Psi\, S_3$$

$$\text{HB}_B : \qquad q_3 \tilde{q}^3 = \Psi \qquad q' \tilde{q}' = \frac{\Psi^2}{m} \qquad \Rightarrow B' \tilde{B}' = \frac{\Psi^3}{m} \qquad A_2 \text{ sing}$$

$$\text{CB}_B : \qquad W'_{3,+} W'_{3,-} = S' S_3$$

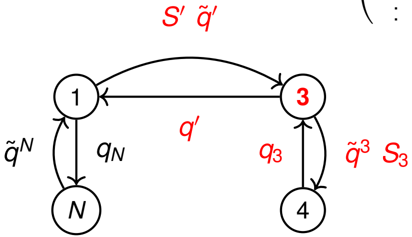
Effective quiver and effective superpotential



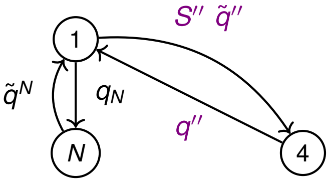
$$W = \sum_{i=1}^{N} S_i (q_i \tilde{q}^i - \Psi) \qquad \longrightarrow \qquad W_{\text{eff}} = S' \left(q' \tilde{q}' - \frac{\Psi^2}{m} \right) + \sum_{i=3}^{N} S_i (q_i \tilde{q}^i - \Psi)$$

(Check: if add $m\, W_{2,-} = m\, S'$, nodes 1 and 3 fuse togehter and sing becomes A_{N-3}
$\rightarrow$ consistent with mirror of diagonalisable mass deform)

$$m_T = \begin{pmatrix} 0 & 0 & 0 & \cdots \\ m & 0 & 0 & \cdots \\ 0 & m & 0 & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$



$$\xrightarrow{m\, W_{3,+}}$$

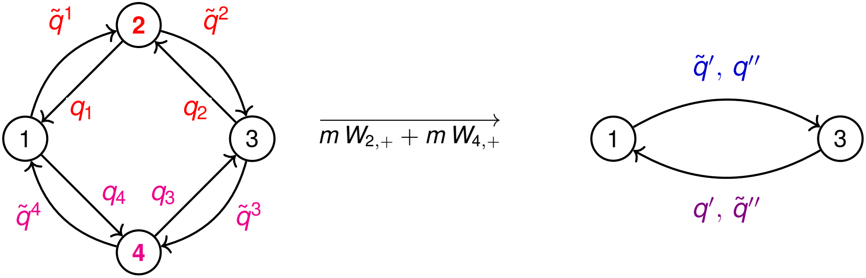


$$W_{\text{eff}} \longrightarrow W'_{\text{eff}} = S''\left(q''\tilde{q}'' - \frac{\Psi^3}{m^2}\right) + \sum_{i=4}^{N} S_i(q_i\tilde{q}^i - \Psi)$$

$$B''\tilde{B}'' = \frac{\Psi^3}{m^2}\Psi^{N-3} \qquad (\text{ still } A_{N-1} \text{ sing })$$

$SU(4) \to SU(2)$

$$m_T = \begin{pmatrix} 0 & 0 & 0 & 0 \\ m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 \end{pmatrix} \qquad \rightsquigarrow \qquad \delta W = mW_{2,+} + mW_{4,+}$$



$$W = \sum_{i=1}^{N} S_i (q_i \tilde{q}^i - \Psi) \qquad \to \qquad W_{\rm eff} = S' \left(q' \tilde{q}' - \frac{\Psi^2}{m} \right) + S'' \left(q'' \tilde{q}'' - \frac{\Psi^2}{m} \right)$$

Obstruction of blow-up by T-brane

Theory A:

- Blow-up $\leftrightarrow$ real mass ($m_r \in$ bkgr vector-multiplet)

$$\int d^4\theta \left(Q_i^\dagger e^{m_r^i \theta\bar\theta} Q_i - \tilde{Q}^{i\dagger} e^{m_r^i \theta\bar\theta} \tilde{Q}^i \right)$$

- $\delta W = m\, Q_1 \tilde{Q}^2$ breaks background sym $U(1)_{1-2}$

  corresponding bckgrnd vector mult no more available $\Rightarrow m_r^1 = m_r^2$

$\Rightarrow$ mass terms with $m_r^1 \neq m_r^2$ forbidden ($D6_1$ and $D6_2$ are bound together).

Theory B:

- Blow-up $\leftrightarrow$ real FI-term $\int d^4\theta\, \xi_b\, V_{U(1)_2} \sim \int d^4\theta\, V_b\, \Sigma_{U(1)_2}$.
- $\delta W = m\, W_{2,+}$ breaks topological $U(1)_2$ symmetry

  V_b has gone and the above coupling forbidden

$\Rightarrow$ blow-up relative to node 2 is obstructed. [Anderson,Heckman,Katz]

Conclusions

We find the mirror theory for D2-branes probing a stack of T-branes.

- On the A-side, off-diagonal mass deformation. On the B-side, via monopole operators.

⇒ This provides us with definition of a T-brane directly in terms of a membrane probing a singularity.

- Found effects of T-brane on HB and CB on B-side: HB describing probed geometry does not change, CB is partially lifted and global symmetry broken.
- Effective description of probe theory by W_{eff} and effective quiver.

Open problems:

* What about other ADE grops?
* Probing more complicated geometries (e.g. with matter curves).
* Impact of T-brane on Hilbert series approach to 3d moduli spaces.

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Thank you!