5-brane webs and 5d, 6d SCFTs

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Based on the collaboration with

- Sung-Soo Kim, Kimyeong Lee, Masato Taki, Futoshi Yagi [arXiv:1505.04439] and [arXiv:1512.08239]

- Sung-Soo Kim, Kimyeong Lee, Futoshi Yagi [arXIv:1509.03300]

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1. Introduction

- Understanding quantum field theories in higher dimensions.

Assumptions: supersymmetry and without gravity

What are UV complete higher dimensional gauge theories?

- Higher dimensional gauge theories are not renormalizable. The gauge coupling becomes infinitely strong at high energies.

- Those theories may make sense if they admit a non-trivial fixed point at UV.

- Superconformal field theories exist when $d \leq 6$. Nahm 78

- Therefore, 5d or 6d gauge theories may be UV complete, but not all of them.

- 6d gauge theories are very restrictive. In particular they always require a tensor multiplet due to the cancellation of anomalies. Seiberg 96

- Recently, it is argued that all the 6d SCFTs may be classified by using F-theory compactifications.

Heckman, Morrison, Vafa 13
Heckman, Morrison, Rudelius, Vafa 15

- What about the classification of UV complete 5d gauge theories?

- They are less restrictive compared to 6d gauge theories due to the absence of the anomalies (there can be a condition for coefficients of cubic terms in the prepotential from the gauge invariance).

- Example: 5d SU(2) gauge theories with N_f flavors

(i) $N_f \leq 7 \rightarrow$ 5d SCFT with E_{N_f+1} flavor symmetry

Seiberg 96
Morrison, Seiberg 96
Douglas, Katz, Vafa 96

(ii) $N_f = 8 \rightarrow$ 6d SCFT called "E-string"

An M5-brane probing an M9-wall

Ganor, Hanany 96
Klemm, Mayr, Vafa 96
Ganor, Morrison, Seiberg 96

From the 5d viewpoint, instantons become KK modes of S^1 compactification of the 6d theory. In other words, after summing up all the instantons the S^1 direction appears.

- How about the higher rank cases?

- The field theory analysis gives:

Intriligator, Morrison, Seiberg 97

Ex. 5d SU(N) gauge theory with N_f flavors and k CS level

$$N_f + 2|k| \leq 2N$$

- The 5d SU(N) gauge theories that satisfy this condition are supposed to have 5d UV fixed points

- A natural question:

No 5d SU(N) gauge theory admits a 6d UV completion?

- I will revisit the question of UV complete 5d gauge theories by using string theory.

- String theory predicts new UV complete 5d gauge theories that admit a 6d UV completion.

- String theory also implies new 5d “UV dualities”.

1. Introduction

2. 5d gauge theories from string theory

3. 6d SCFTs from 5-brane webs

4. New 5d UV dualities

5. Conclusion

2. 5d gauge theories from string theory

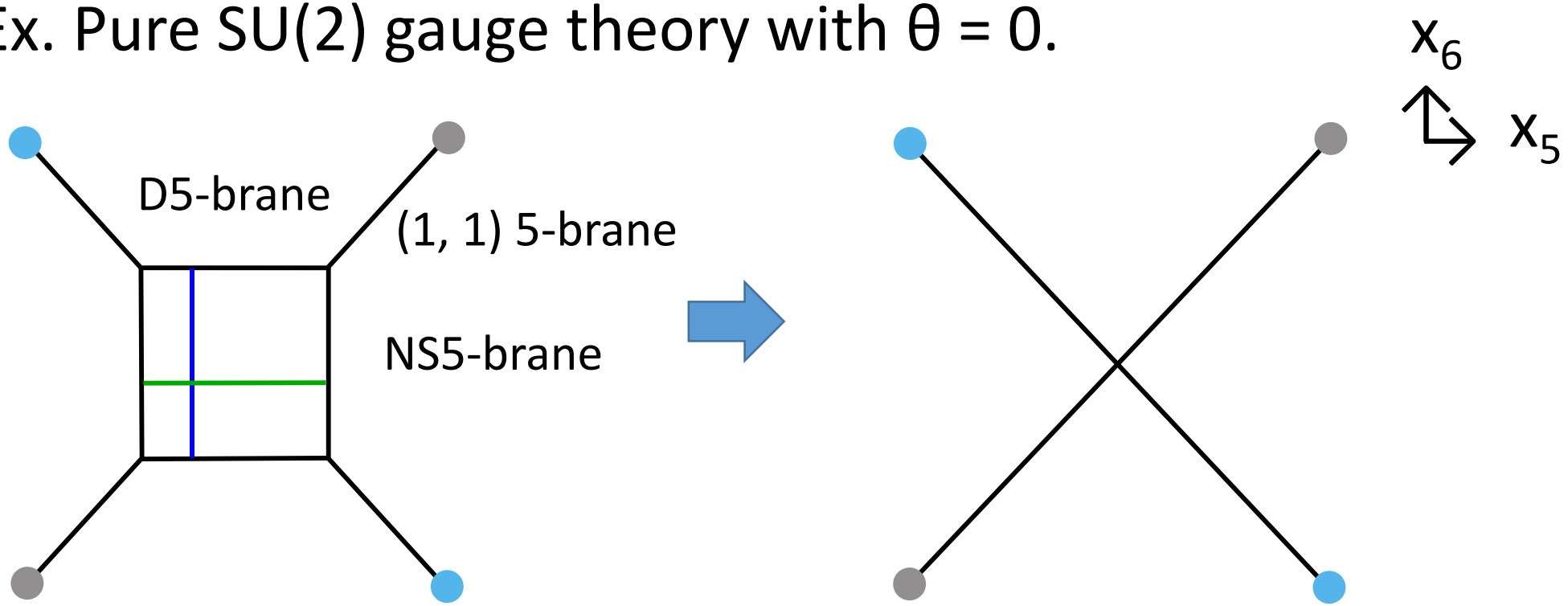
- We construct a 5d supersymmetric field theory with eight supercharges as the worldvolume theory on a 5-brane web.

- The 5-brane configuration in Type IIB string theory.

	0	1	2	3	4	5	6	7	8	9
D5-brane	×	×	×	×	×	×				
NS5-brane	×	×	×	×	×		×			
(p, q) 5-brane	×	×	×	×	×	angle				
7-brane	×	×	×	×	×			×	×	×

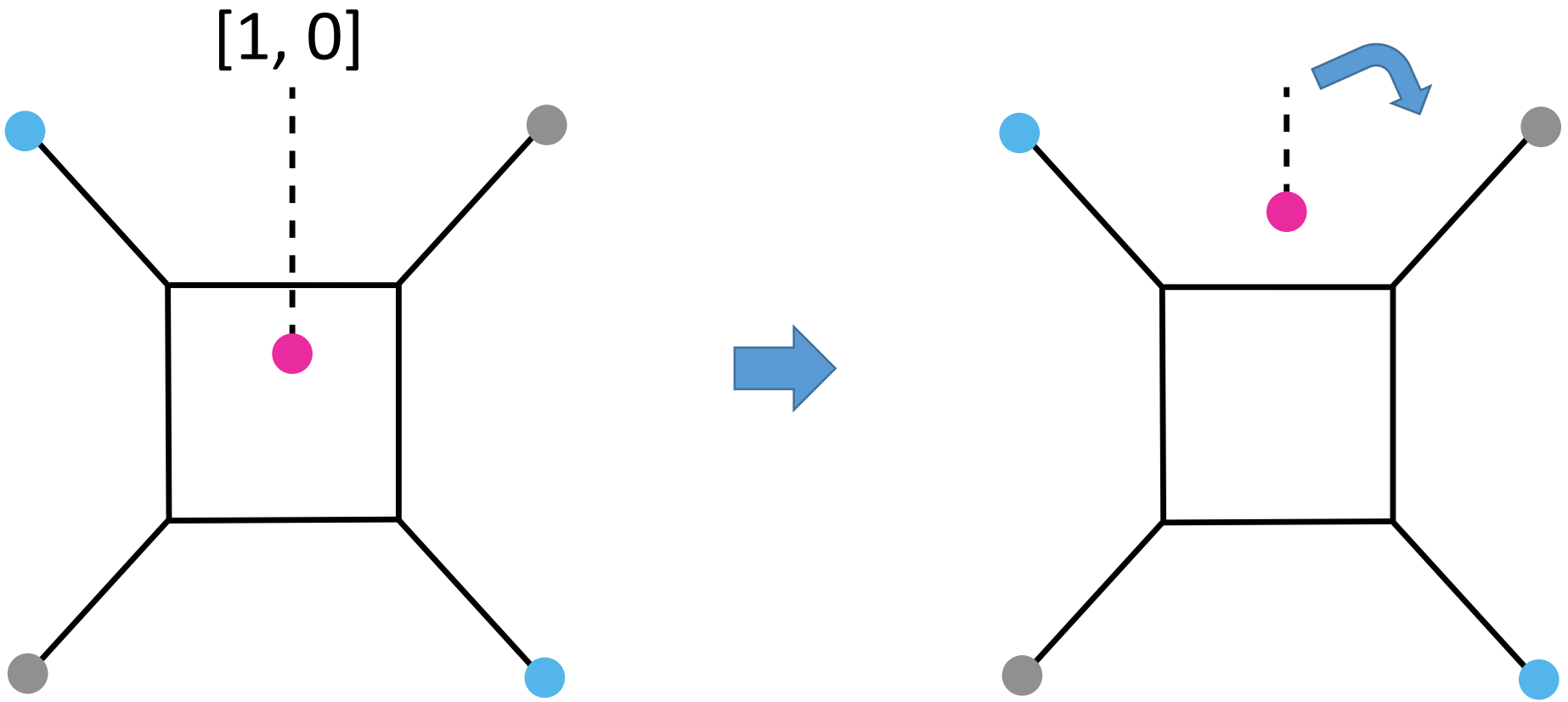
Aharony, Hanany 97
Aharony, Hanany, Kol 97
DeWolfe, Iqbal, Hanany, Katz 99

- Ex. Pure SU(2) gauge theory with $\theta = 0$.

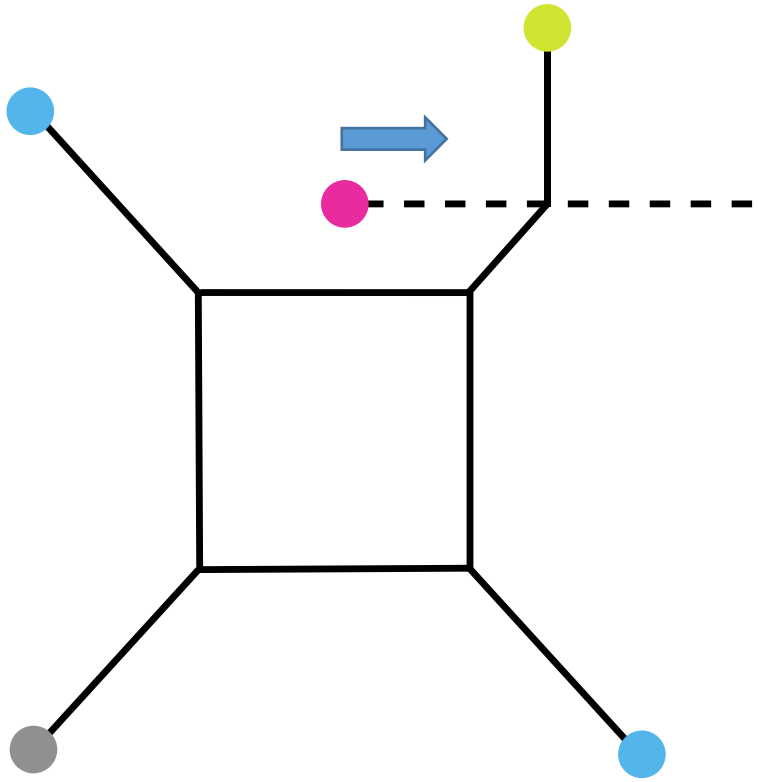


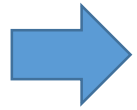
- This theory has a fixed point where the gauge coupling is infinitely strong. Seiberg 96
- Enhancement of flavor symmetry: U(1) $\rightarrow$ SU(2) = E_1.

- Ex. 1 flavor : [U(1) x U(1) → SU(2) x U(1) = E_2]

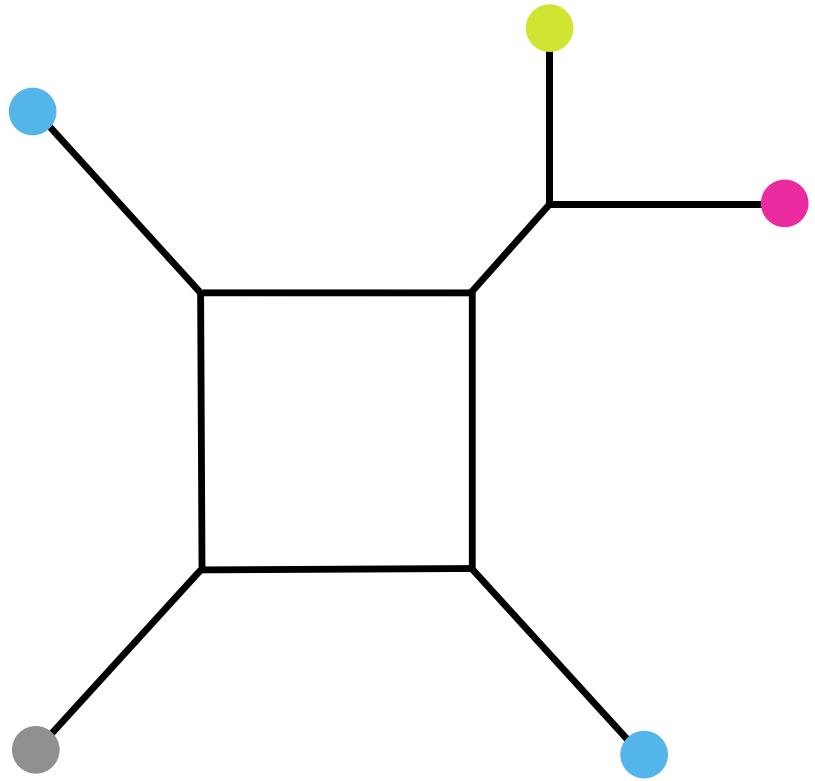


[0, 1]



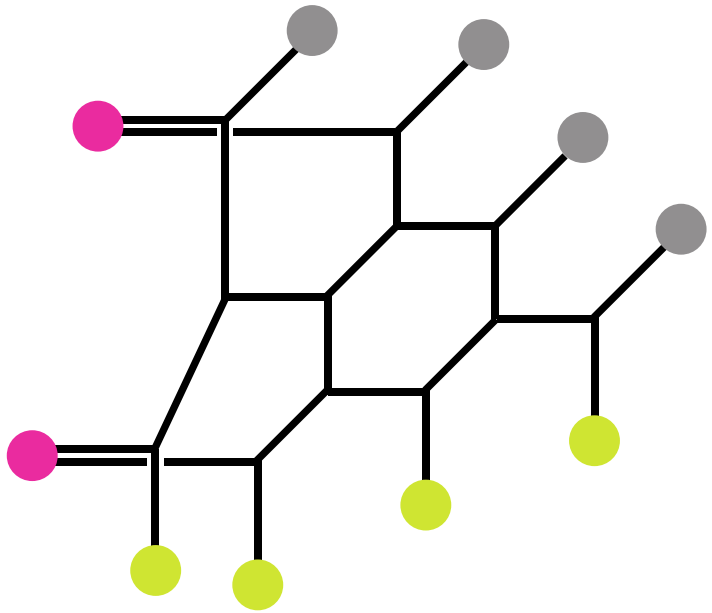


SU(2) with $N_f = 1$

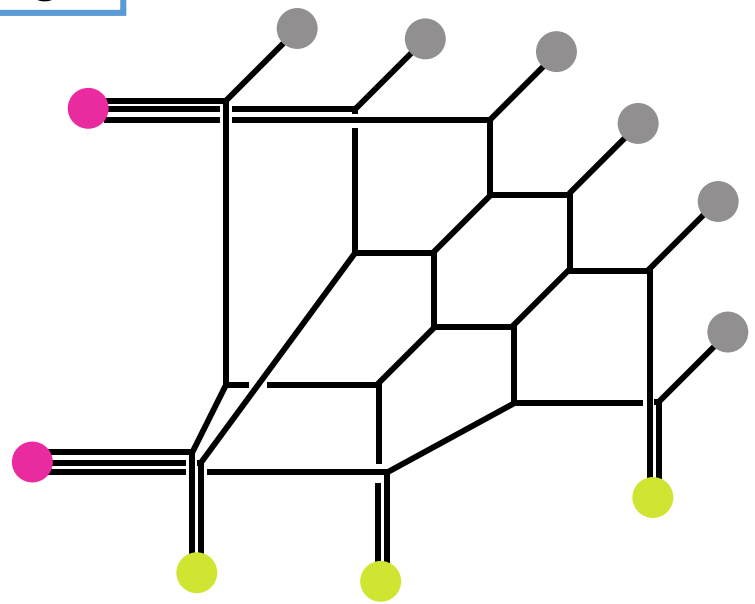


- Further addition of the flavors can be done systematically.

$N_f = 6$ $[E_7]$

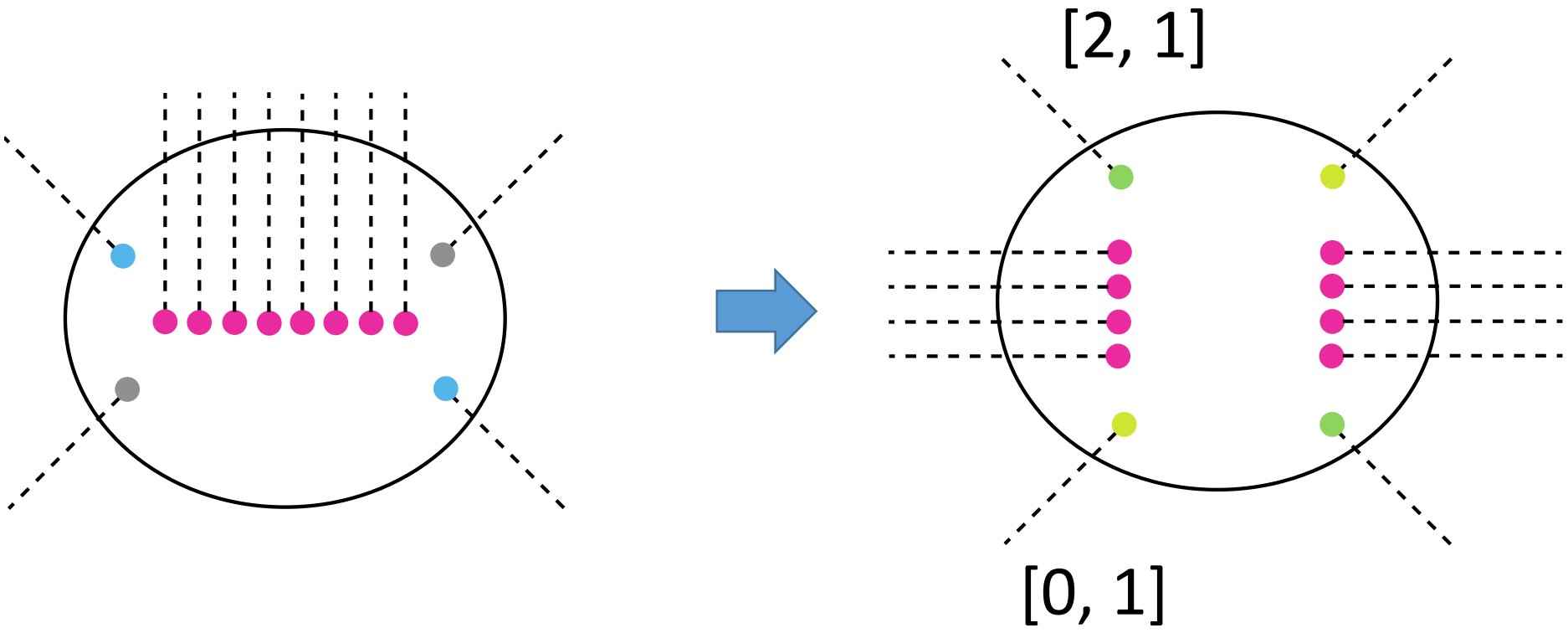


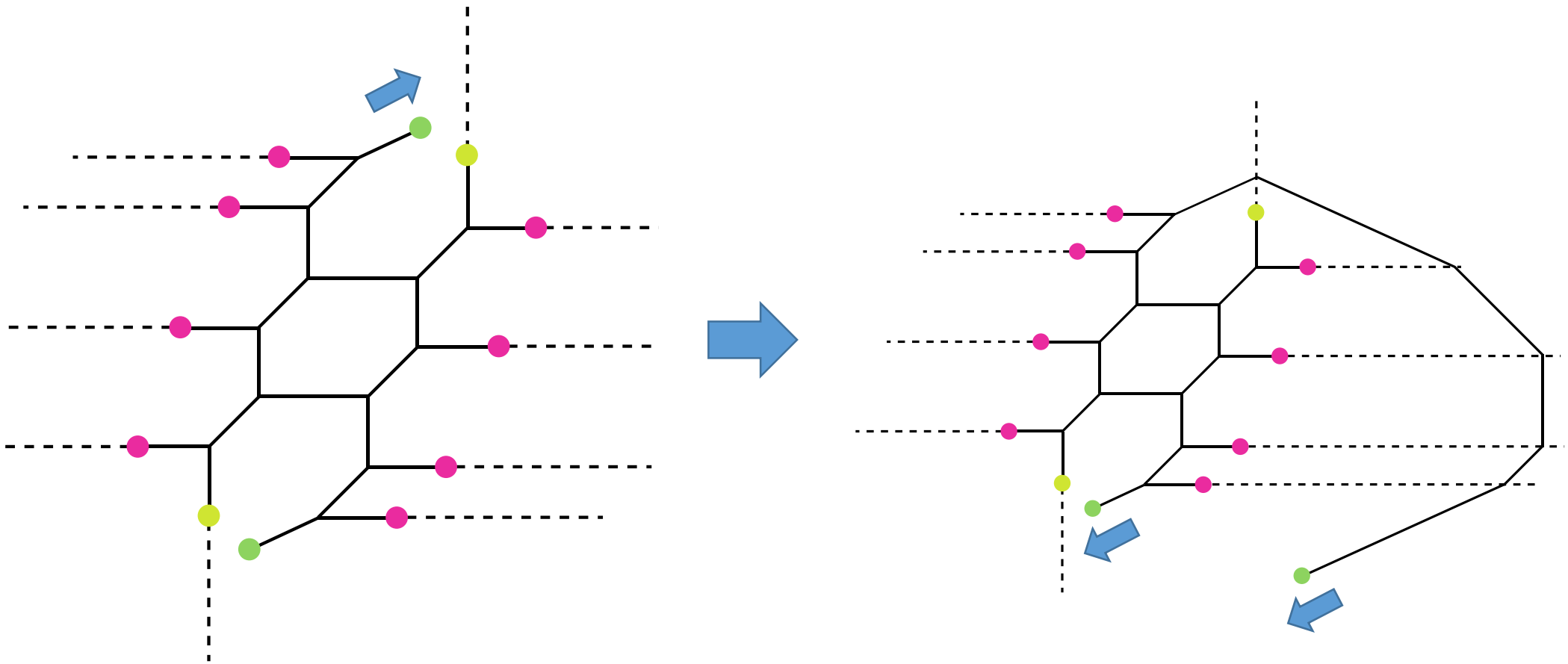
$N_f = 7$ $[E_8]$



Benini, Benvenuti, Tachikawa 09

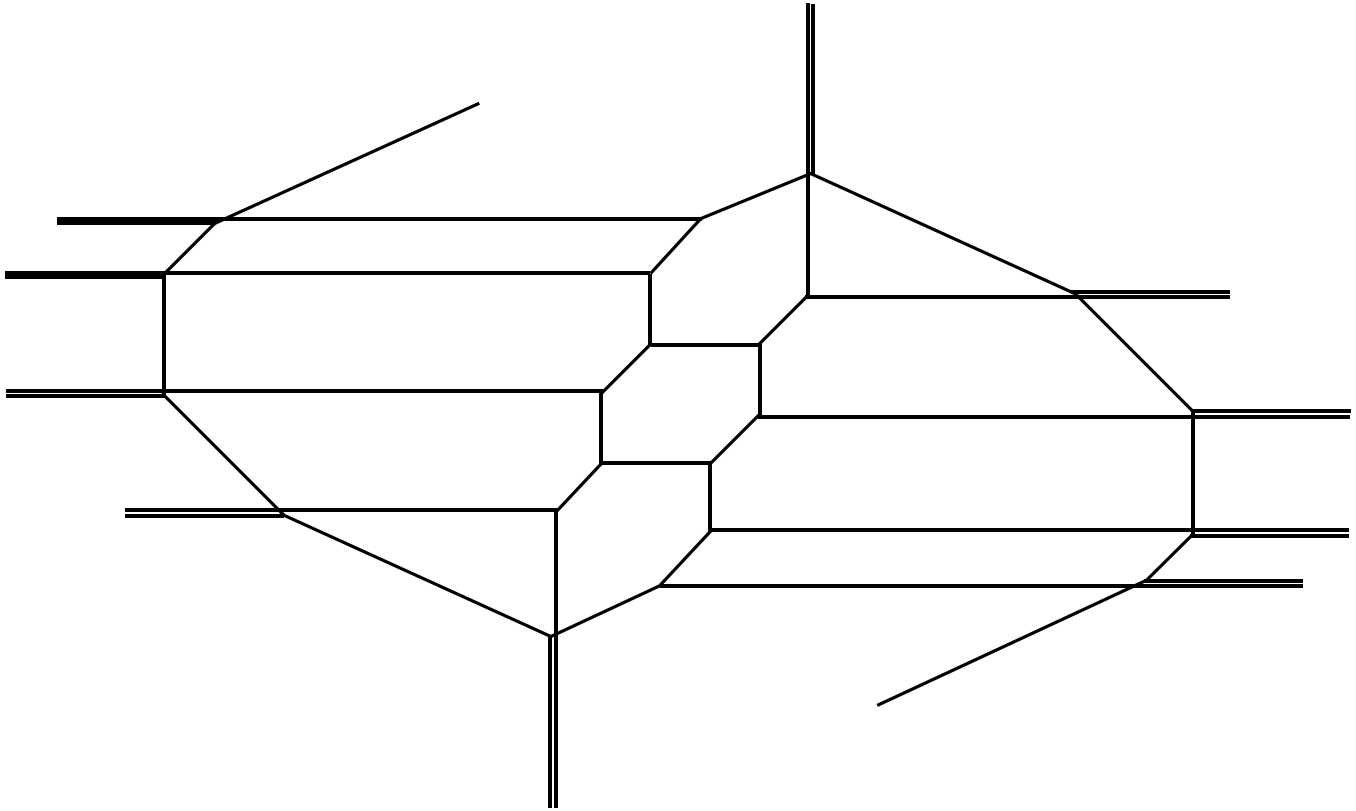
- What happens if we consider the SU(2) gauge theory with 8 flavors? We know that its UV fixed point is the 6d E-string theory.



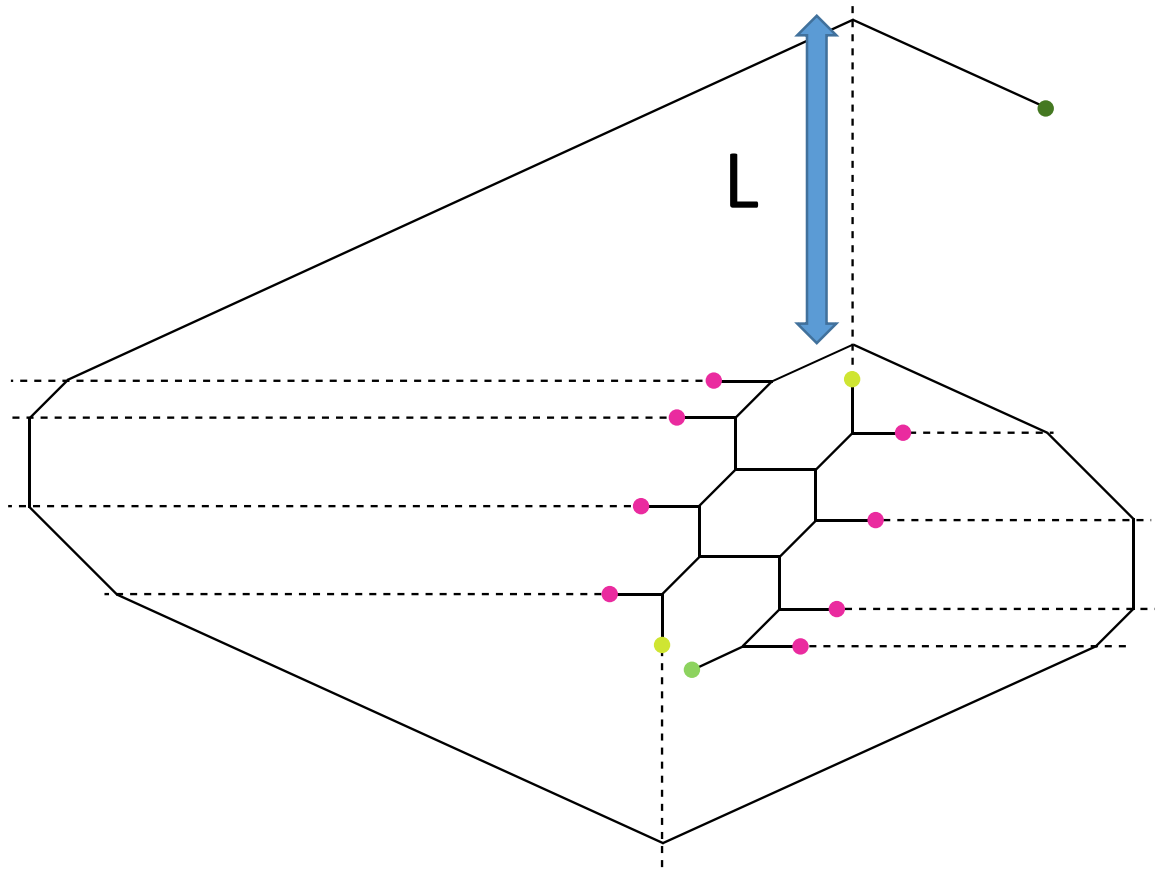


- Then the 5-brane web starts rotating when we pull 7-branes to infinity.

Kim, Taki, Yagi 15



- The “period” of the 5-brane web diagram can be identified with the inverse of the radius of the S^1.



$L \approx 1/g^2 \approx R^{-1}$

- String theory predictions:

- The existence of a standard 5-brane web implies the corresponding 5d theory has a 5d UV fixed point.

- The existence of an infinitely rotating 5-brane web (or a 5-brane web which has an "S^1" direction) implies the corresponding 5d theory has a 6d UV fixed point.

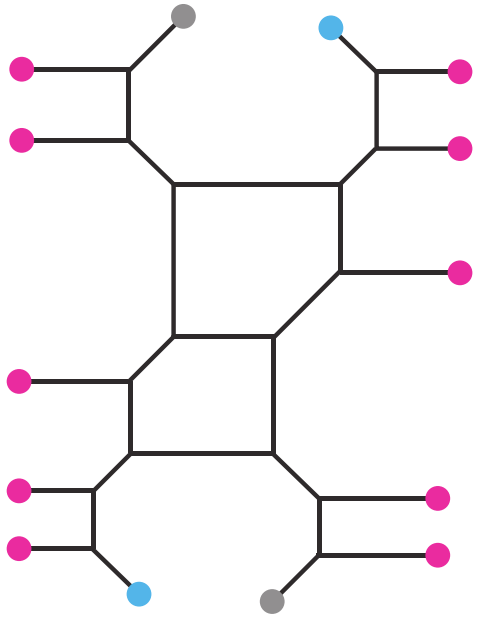
- Then let us think about the generalization by utilizing the infinitely rotating structure of 5-brane webs!

3. 6d SCFTs from 5-brane webs

- The higher rank generalization. The infinitely rotating structure of a 5-brane web predicts the existence of a 5d SU(N) gauge theory with $N_f = 2N+4$.

Kim, Taki, Yagi 15

Ex. 5-brane web for 5d SU(3) with 10 flavors



- Does it corresponds to a 6d SCFT at UV? → Yes!

Hayashi, Kim, Lee, Taki, Yagi 15
Yonekura 15

- Our claim is

6d (D_{n+2}, D_{n+2}) minimal conformal matter theory

S^1 compactification

5d SU(n) gauge theory with $N_f = 2n+4$ & CS-level 0

- In fact, we can "prove" this claim by using a brane construction in string theory.

Hayashi, Kim, Lee, Taki, Yagi 15

- A derivation by branes

- The 6d (D_{n+2}, D_{n+2}) minimal conformal matter theory is a 6d SCFT realized on a single M5-brane probing the D_{n+2} type singularity.

Del Zotto, Heckman, Tomasiello, Vafa 14

"tensor (Coulomb) branch"

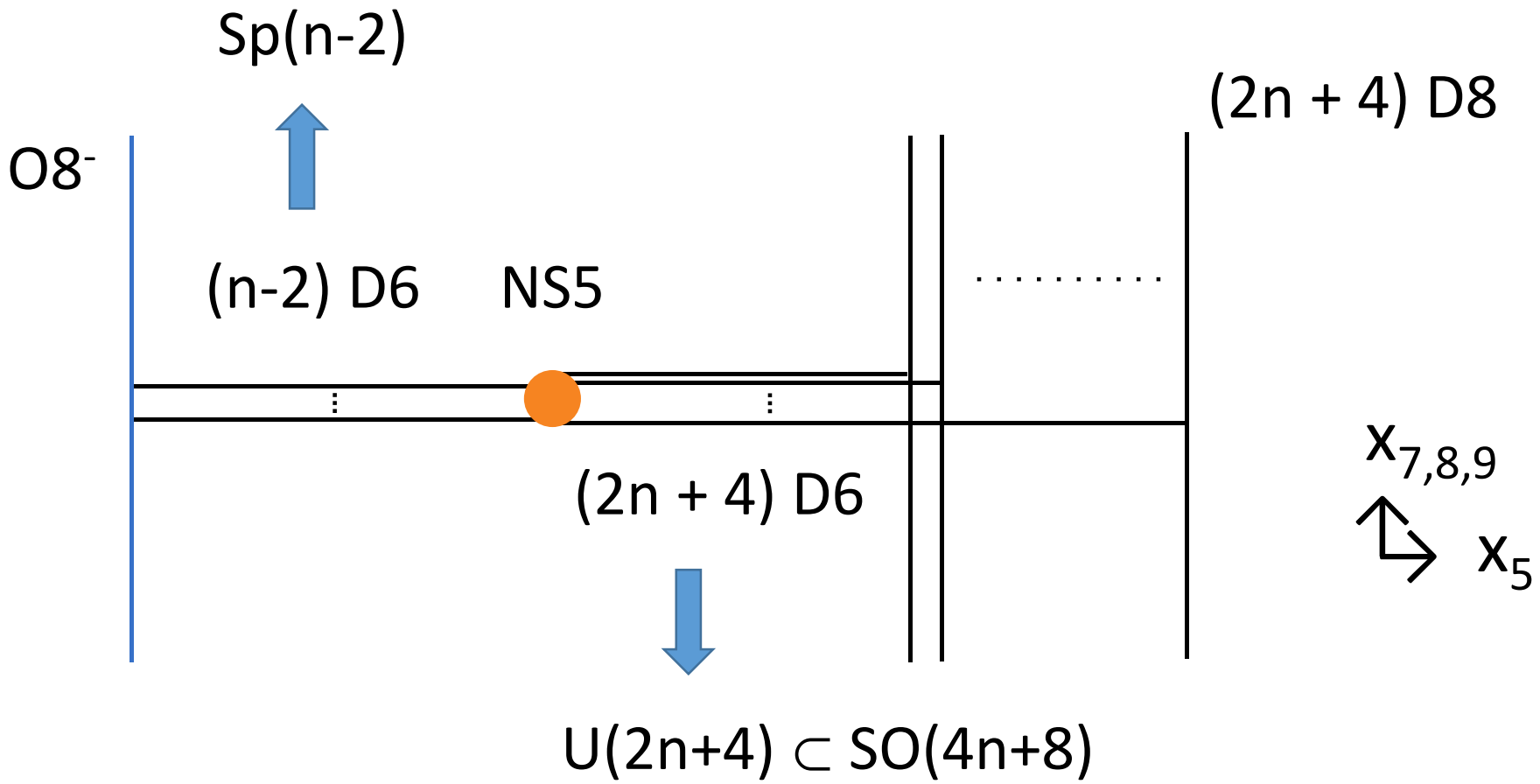
- In the tensor branch, the 6d theory is an Sp(n-2) gauge theory with 2n+4 fundamental hypermultiplets, coupled to a tensor multiplet.

- The same 6d theory can be realized by a brane configuration in Type IIA string theory.

	0	1	2	3	4	5	6	7	8	9
D6-brane	×	×	×	×	×	×	×			
NS5-brane	×	×	×	×	×		×			
D8-brane	×	×	×	×	×		×	×	×	×
O8-plane	×	×	×	×	×		×	×	×	×

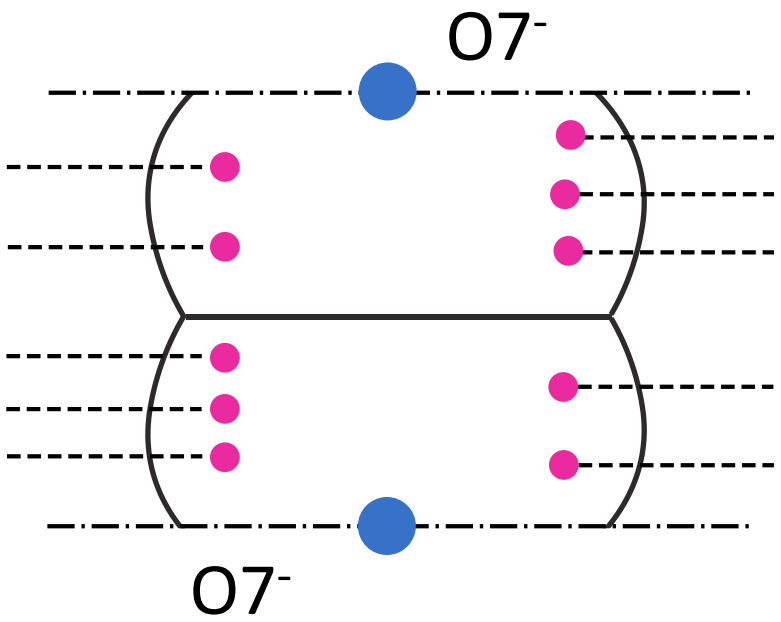
Brunner, Karch 97
Hanany, Zaffaroni 97

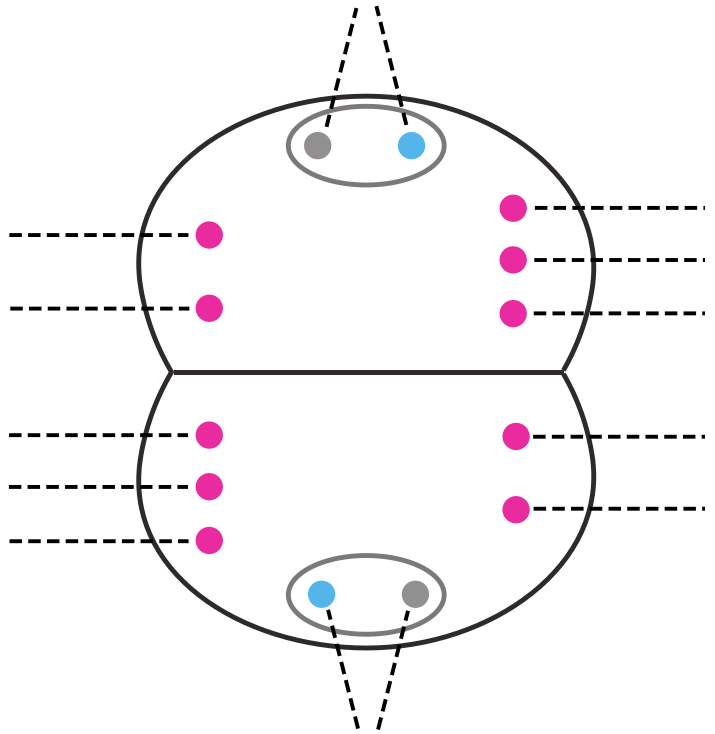
- The brane configuration



- We then compactify x_6-direction on S^1 and perform the T-duality along the direction.

Ex. n = 3



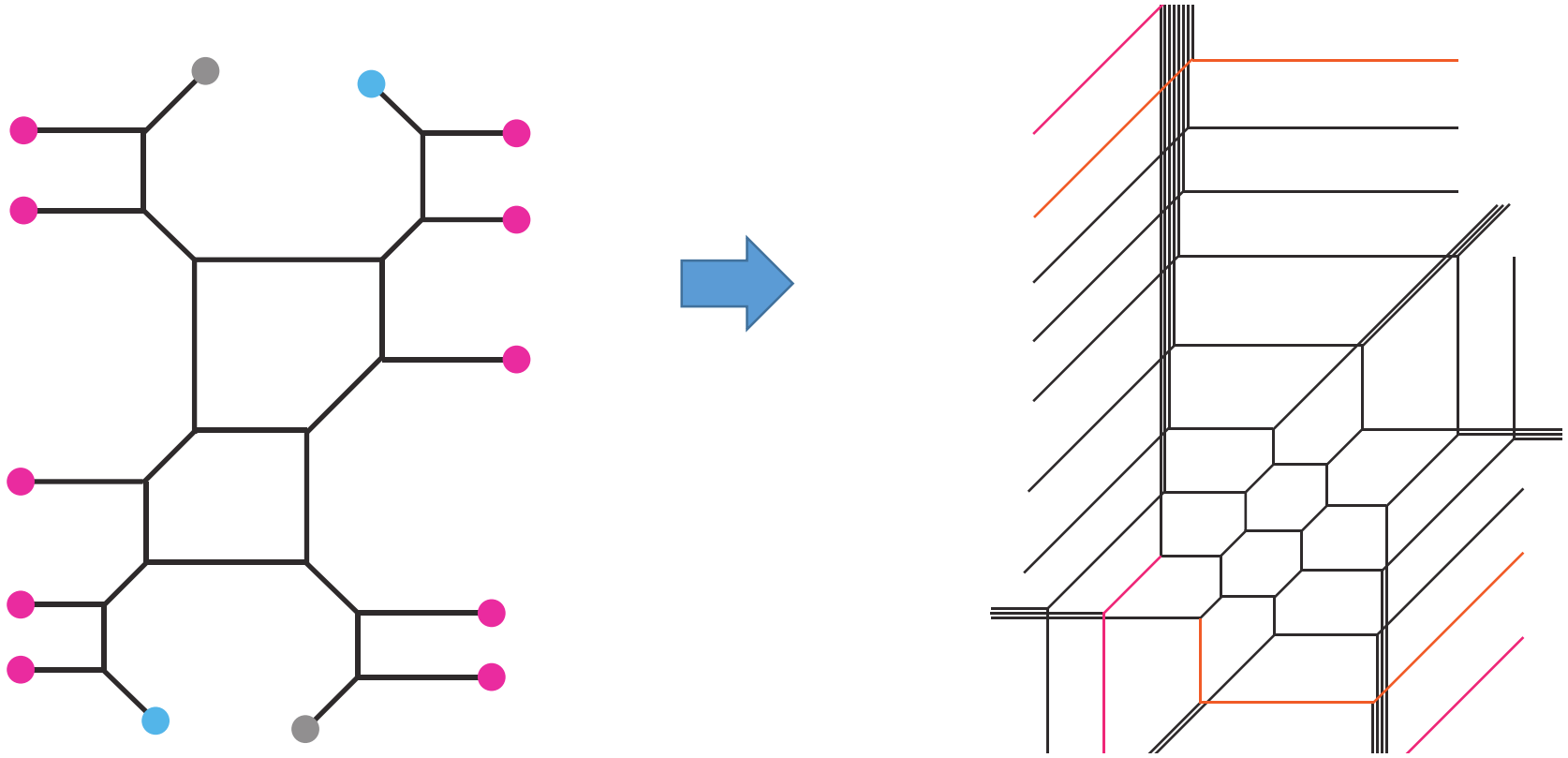


X_6

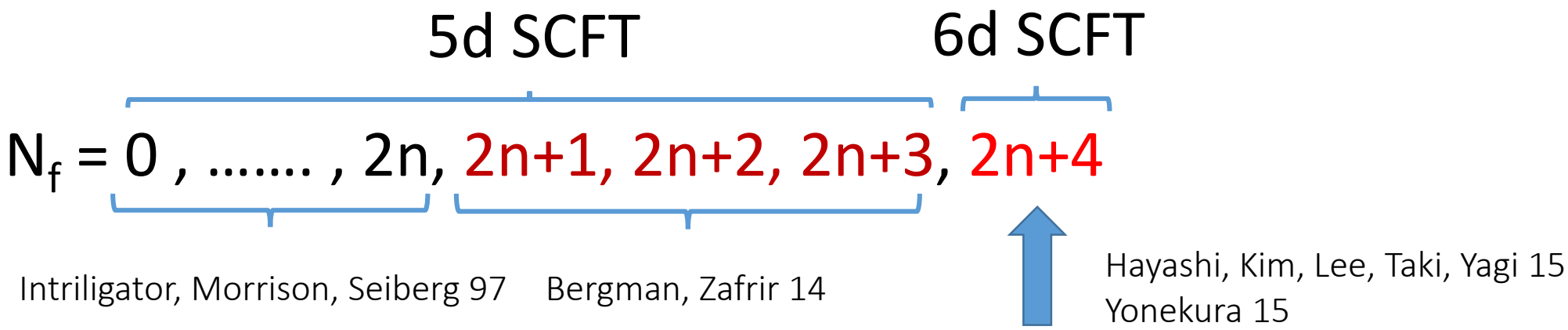
x_5

Resolving two O7-planes

- By pulling out the 7-branes outside the 5-brane loop, we obtain the 5-brane web for the SU(3) gauge theory with $N_f = 10$ flavors.



- By decoupling flavors, we obtain 5d theories whose UV completion is 5d SCFTs.



6d (D_{n+2}, D_{n+2}) minimal conformal matter

- The new condition

$$N_f + 2|k| \leq 2N + 4$$

- It is possible to generalize the analysis to other 6d SCFTs constructed by type IIA brane configurations.

(i) Including more NS5-branes, which gives new 5d A-type quiver gauge theories.

Yonekura 15
Zafrir 15,
Hayashi, Kim, Lee, Yagi 15
Ohmori, Shimizu 15

(ii) Including an ON^0-plane with or without an $O8^-$-plane, which often gives new 5d D-type quiver gauge theories.

Hayashi, Kim, Lee, Taki, Yagi 15

- Largely expands the landscape of 5d gauge theories!

Examples:

(i) 6d SU(2n) with $N_f = 2n+8$ and $N_a = 1$

S^1

5d [n+3] – SU(n+1) – SU(n+1) – [n+3]

(ii) 6d [8] – SU(2n) – Sp(2n-4) – SO(4n) – Sp(2n-4) – [2n]

S^1

5d [4] – SU(n+3) / [4] – SU(n+3) — SU(2n+2) – SU(2n-2) – SU(2n-6) – [2n-8]

4. New 5d UV dualities

- The derivation using the brane configuration also implies another interesting 5d dualities.

- 5d SU(n) $\leftrightarrow$ 5d Sp(n-1) duality

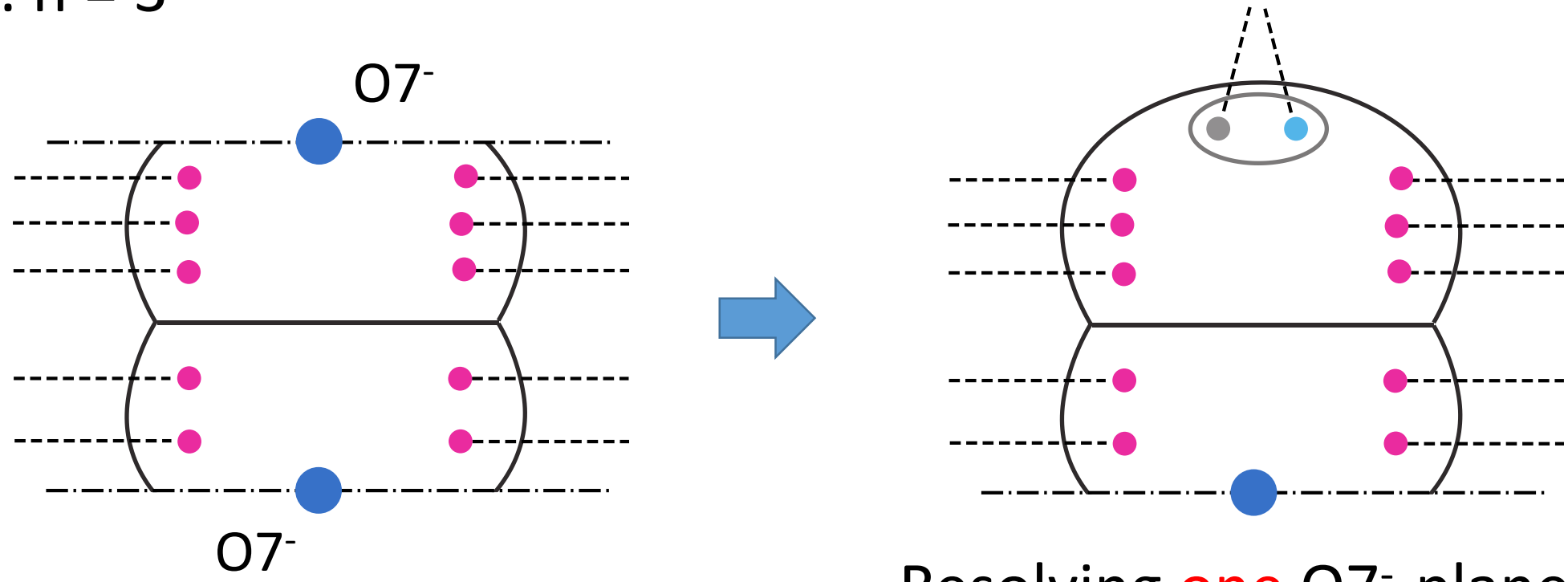
Gaiotto, Kim 15

5d SU(n) gauge theory with N_f flavors & $\kappa = \pm(N + 2 - N_f/2)$

5d Sp(n-1) gauge theory with N_f flavors

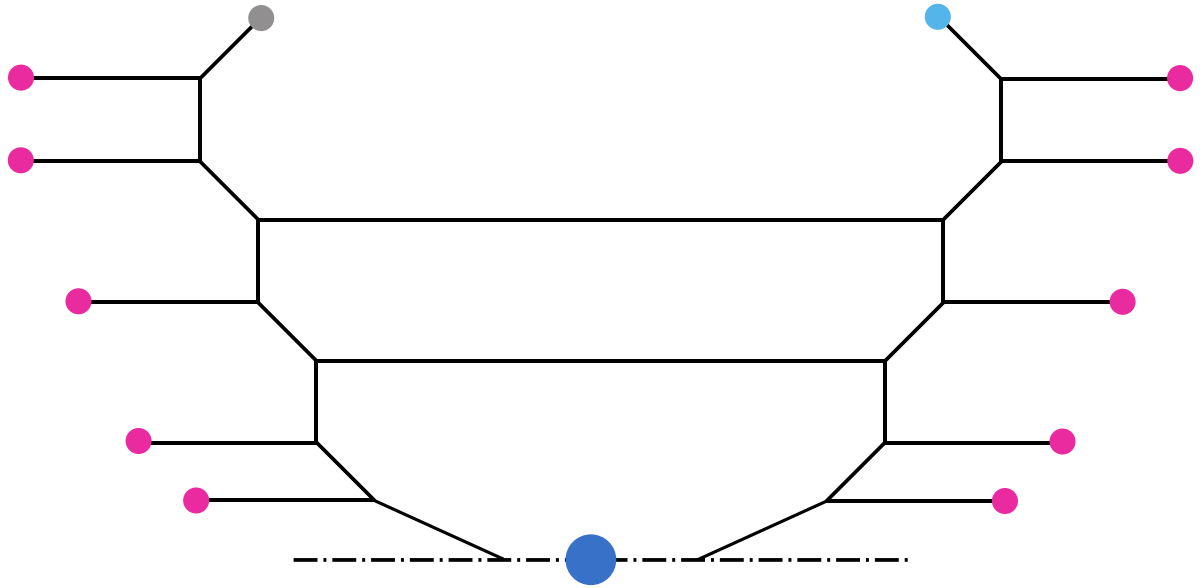
- The derivation again starts from the Type IIA brane configuration for the 6d Sp(n-2) gauge theory with N_f = 2n+4 flavors, coupled to a tensor multiplet.

Ex. n = 3



Resolving one O7-plane

- The resulting brane configuration is a 5d Sp(2) gauge theory with $N_f = 10$.



- In general, we obtain a 5d Sp(n-1) gauge theory with $N_f = 2n+4$.

Hayashi, Kim, Lee, Yagi 15

(D_{n+2}, D_{n+2}) minimal conformal matter

$SU(n)$ with $N_f = 2n+4$ $\quad$ $Sp(n-1)$ with $N_f = 2n+4$

- Decoupling flavors on both sides in the same way reproduces the 5d SU – Sp duality.

- The generalization to other 6d SCFTs yields various new 5d UV dualities.

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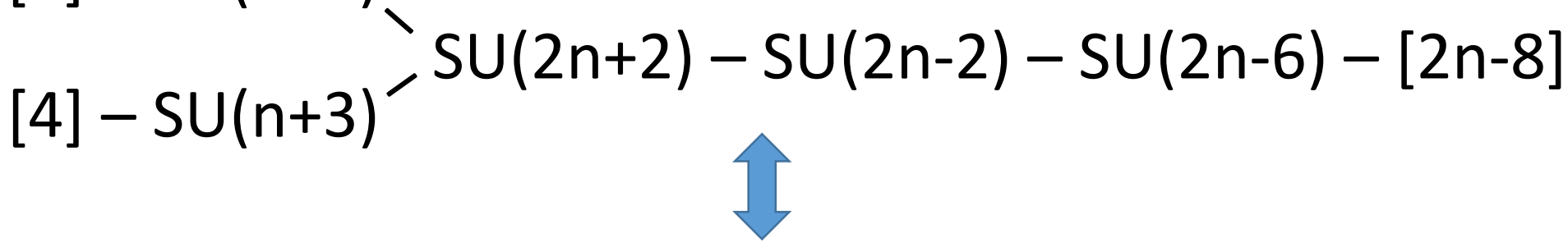
Hayashi, Kim, Lee, Taki, Yagi 15

Examples:

(i) $[n+3] - SU(n+1) - SU(n+1) - [n+3]$

$SU(2n+1)$ with $N_f = 2n+7$ and $N_a = 1$

(ii)


$[8] - SU(2n+3) - Sp(2n-1) - SO(4n-2) - Sp(2n-5) - [2n-4]$

5. Conclusion

- String theory predicts new 5d gauge theories that have a 5d or 6d UV completion.

- The brane configuration and T-duality give a way to directly identify the 6d UV completion of the new 5d gauge theories.

- The method also implies various new 5d UV dualities.