Tao Probing
the End of the World 1

- 道は世界の終わりを査ぐる パート1 -

Masato Taki RIKEN, iTHES group

Collaboration w/ S-S.Kim and F.Yagi (KIAS) [arXiv:1504.03672]

2015.11/12
@YITP WS

Tao Probing the End of the World
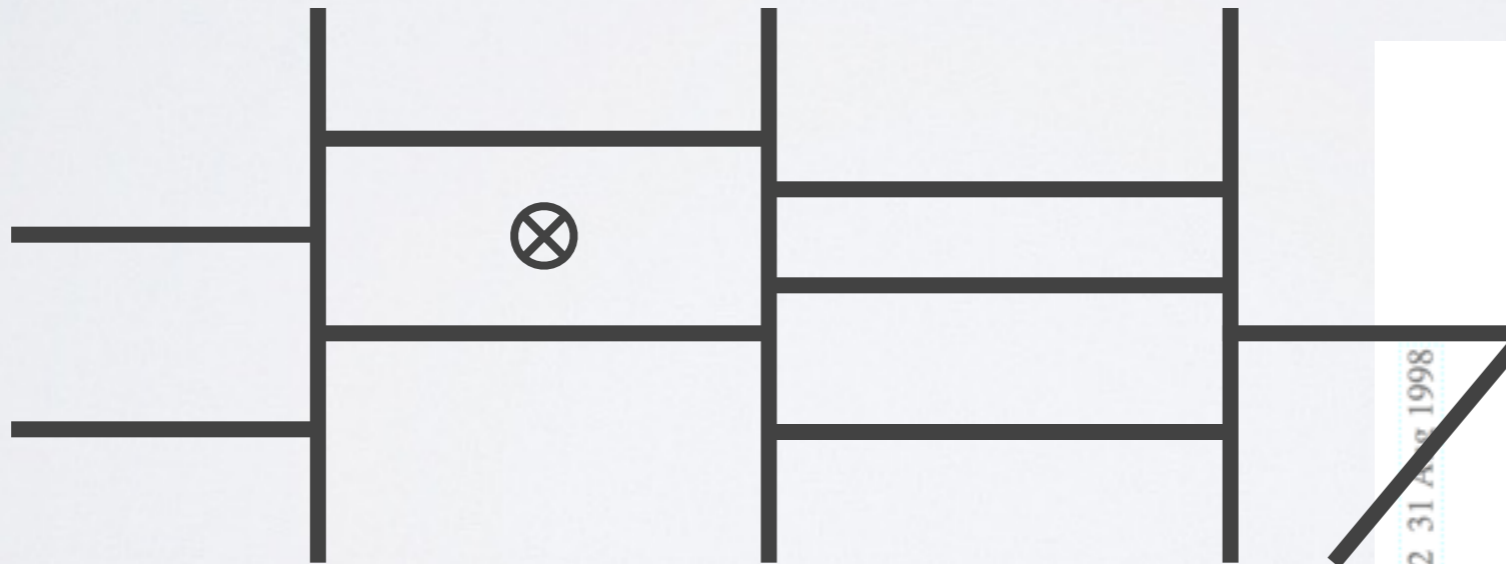
new type of brane configuration

Horava-Witten M9-brane

What I want to discuss Today.

What I want to discuss is...

Q. Is there any new brane system for gauge theories?

Braneology So Far [1995-2015]

hep-th/9802067, RI-2-98, EFI-98-06

Brane Dynamics and Gauge Theory

Amit Giveon

Racah Institute of Physics, The Hebrew University

Jerusalem 91904, Israel

David Kutasov

EFI and Department of Physics, University of Chicago

5640 South Ellis Avenue, Chicago, IL 60637, USA

and

Department of Particle Physics, Weizmann Institute of Science

Rehovot 76100, Israel

Abstract

We review some aspects of the interplay between the dynamics of branes in string theory and the classical and quantum physics of gauge theories with different numbers of supersymmetries in various dimensions.

arXiv:hep-th/9802067v2 31 Aug 1998

All?

What I want to discuss is...

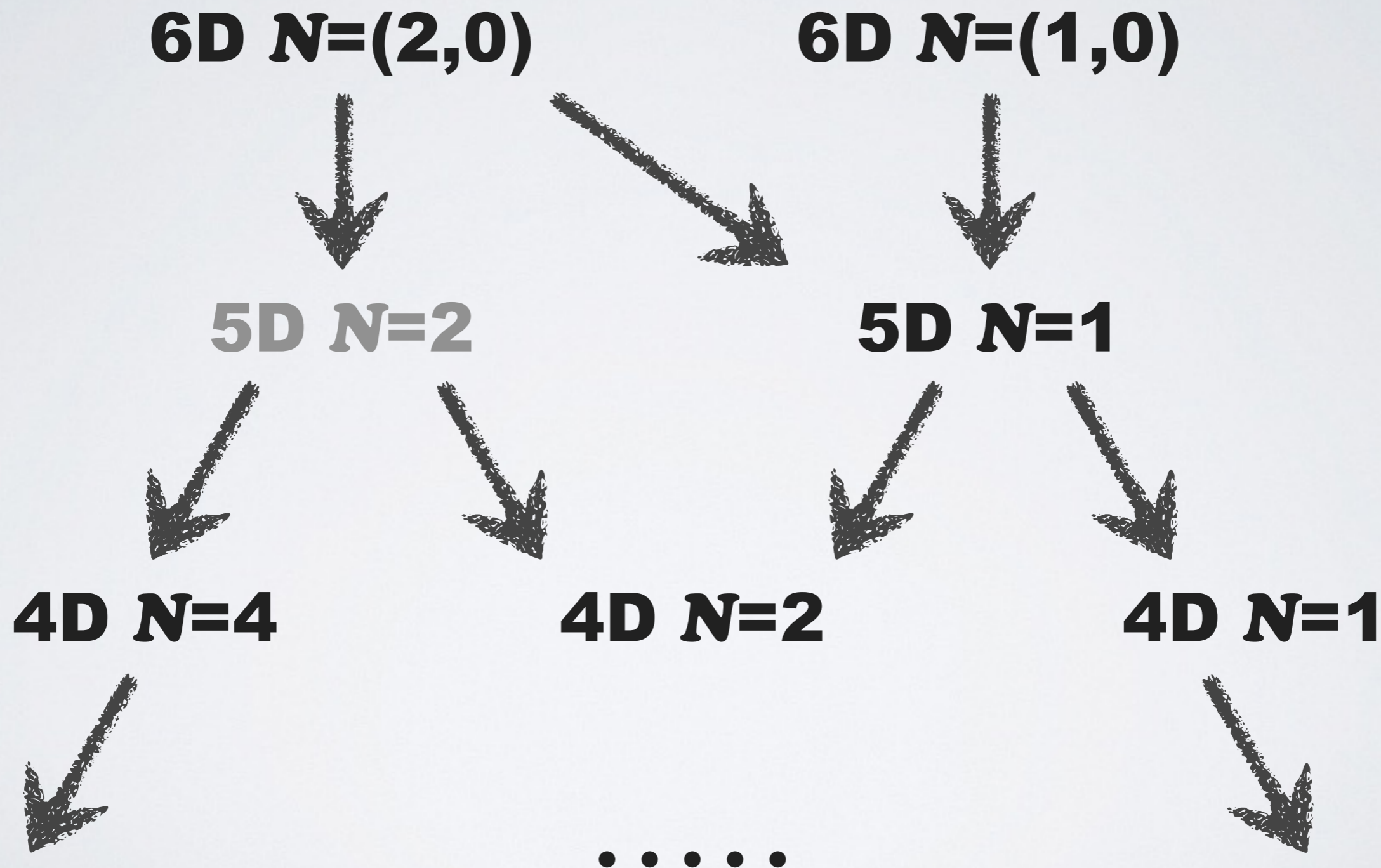Q. Is there any new brane system for gauge theories?
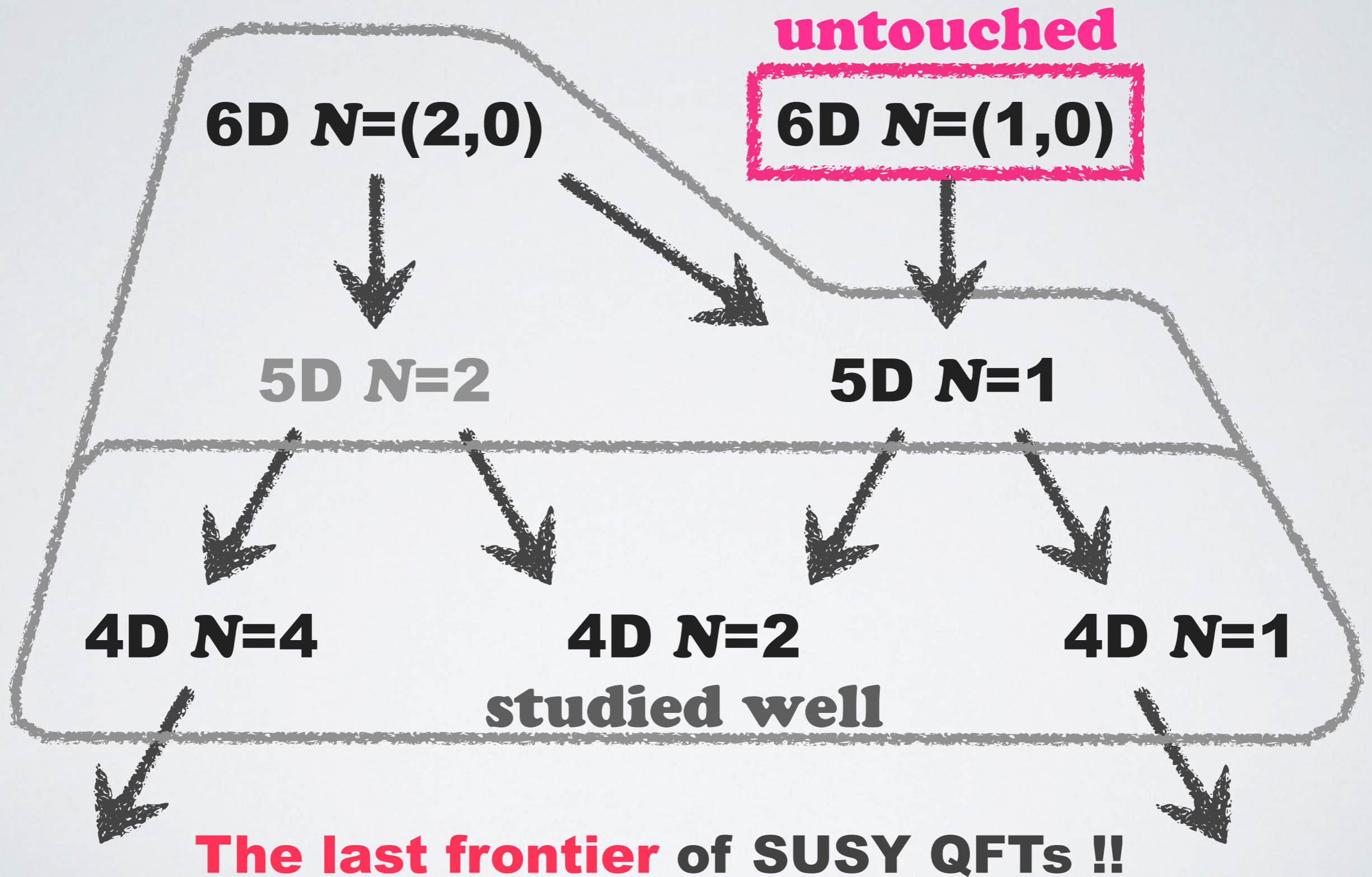
A. Yes！！

What is today's target?

Target is

$$6d \; \mathcal{N} = (1,0) \; \text{SCFTs}$$

Why 6d Now?

All possible non-trivial SCFTs live in d<7

6D *N*=(2,0)   6D *N*=(1,0)

5D *N*=2   5D *N*=1

4D *N*=4   4D *N*=2   4D *N*=1

· · · · ·

Braneology works well for

untouched

6D $N=(2,0)$

6D $N=(1,0)$

5D $N=2$

5D $N=1$

4D $N=4$

4D $N=2$

4D $N=1$

studied well

The last frontier of SUSY QFTs !!

Concrete example of 6d CFT

Prototype : 6d E-string Theory [Witten, 96]

E-string theory : 6d SCFT on M5 probing `M9-brane'

E-string theory : 6d SCFT on M5 probing `M9-brane'

$$\mathbb{R}^{10} \times S^1/\mathbb{Z}_2$$

E_8 E_8

M theory **for heterotic string**

E-string theory : 6d SCFT on M5 probing

`M9-brane'

End of the world

$\mathbb{R}^{10} \times S^1/\mathbb{Z}_2$

End of the world

E_8

E_8

M9

M9
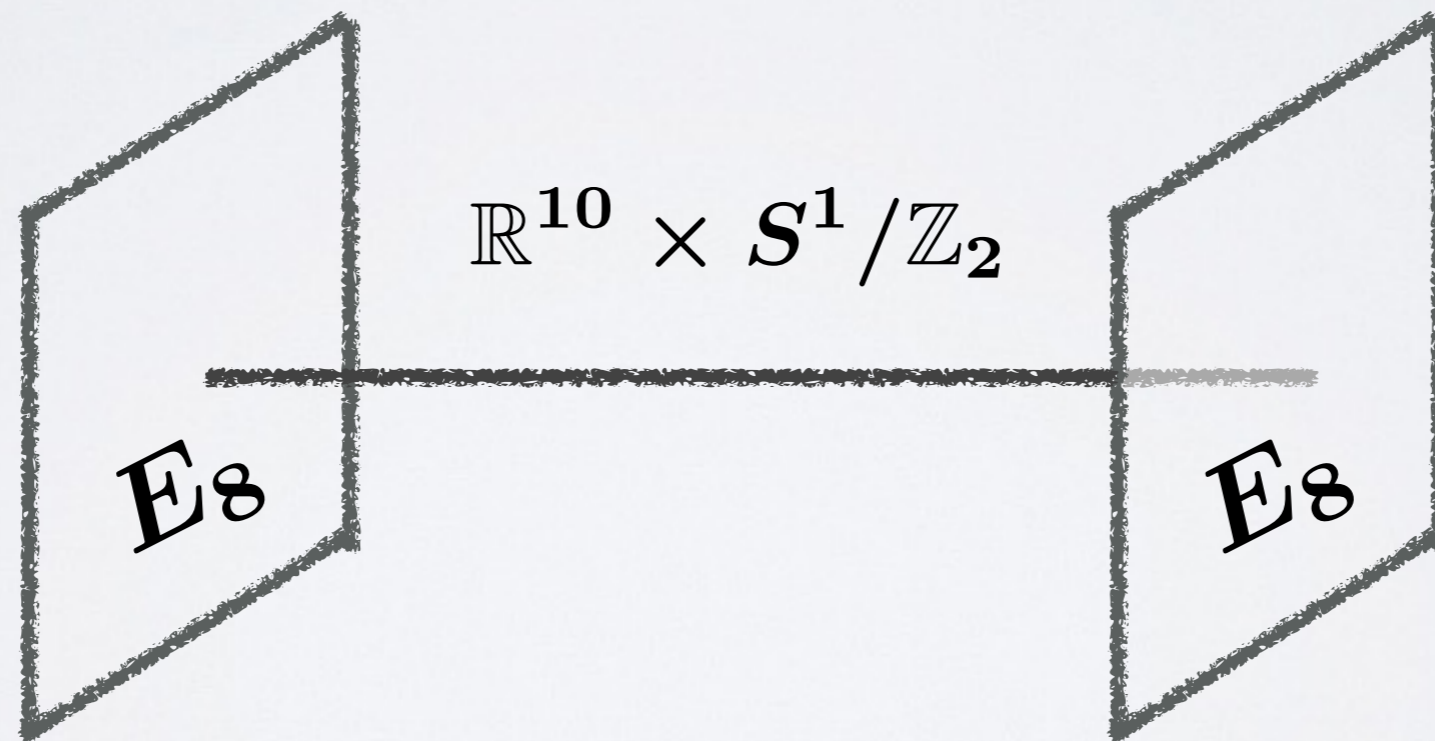
M theory for heterotic string

Prototype : 6d E-string Theory [Witten, 96]

E-string theory : 6d SCFT on M5 probing `M9-brane'

E_8

M9

M5

mysterious typical
N=(1,0) SCFT
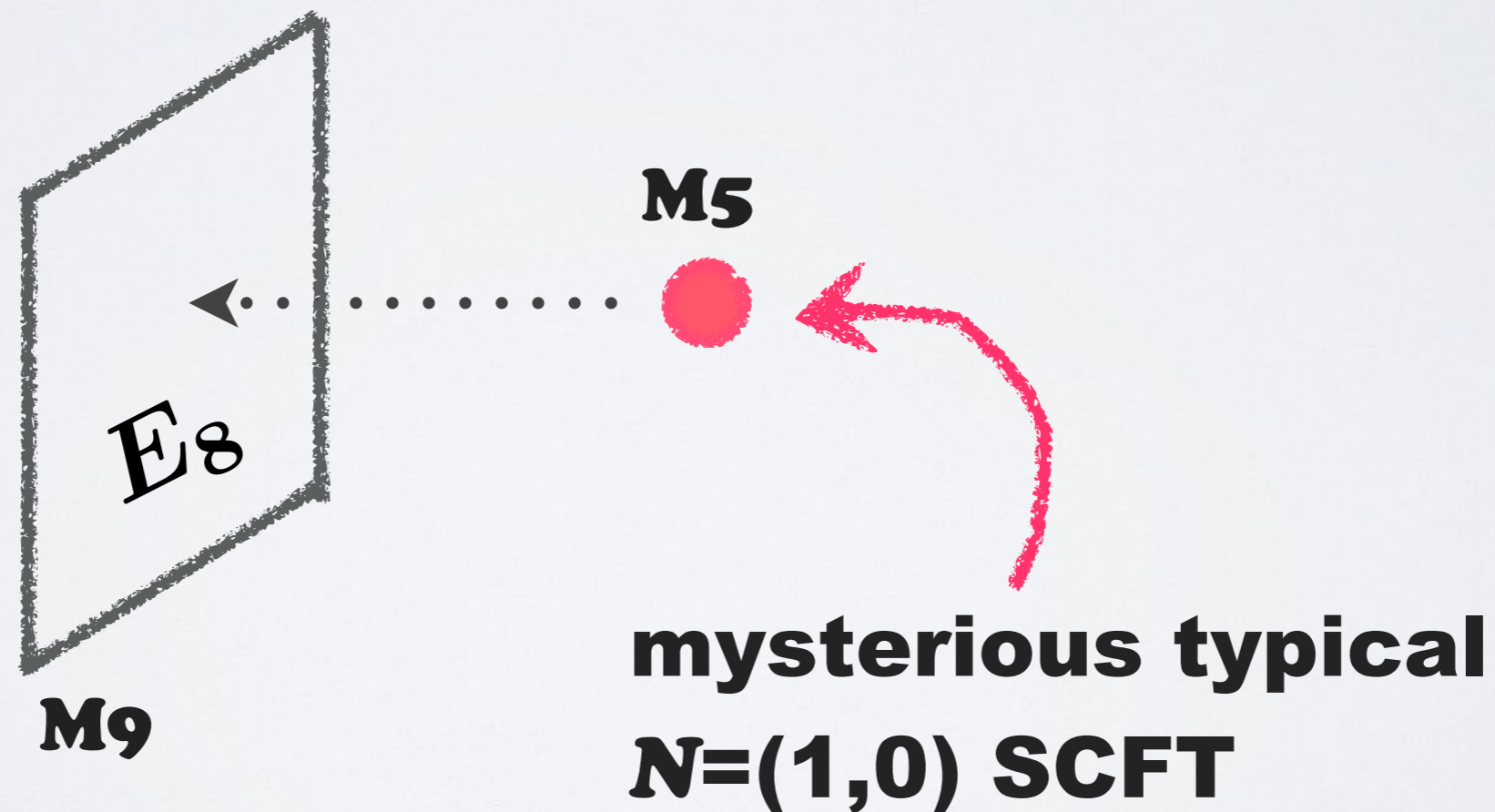
E-string theory : 6d SCFT on M5 probing

`M9-brane'

we will try to find new brane realization!

M5

E_8

M9
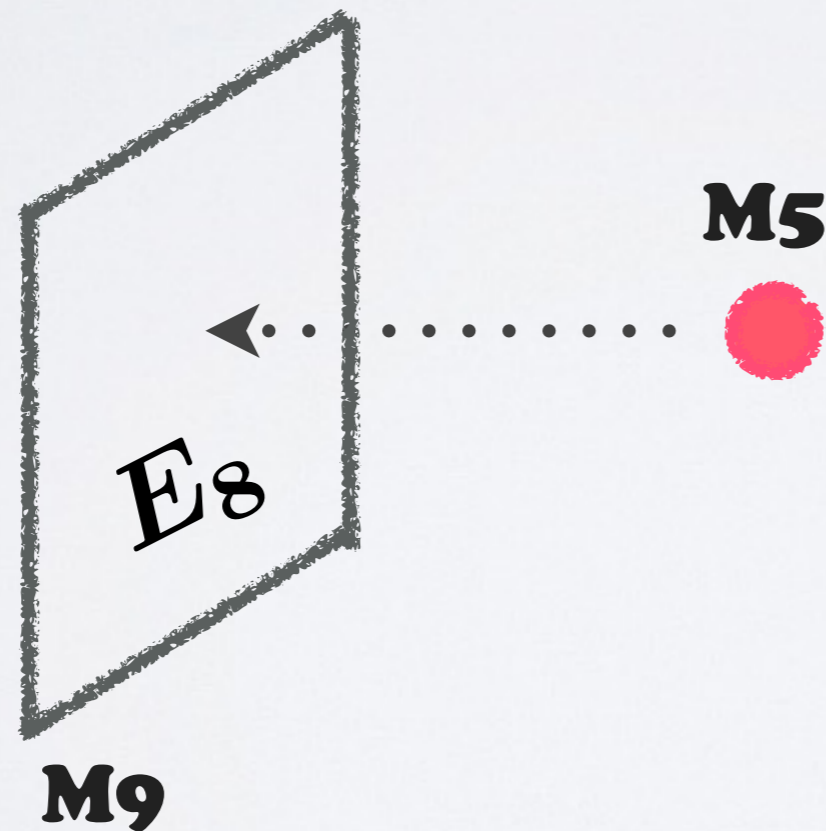
How to `re-make' E-string

How to `re-make' E-string

Ingredient 1

conjectural fact

6d E-string theory is strongly-coupled UV fixed point of the 5d theory:

$$N=1 \; SU(2) \; N_f=8 \; SQCD$$

✳ $N_f<8$ gives 5d fixed point

How To Make 6d Theory : Key Fact 1

* **Heterotic M**

M5

E_8

M9

strong coupling

* **Type IIA (I')**

D4

O8+8D8's

5d Sp(1) 8 flavors
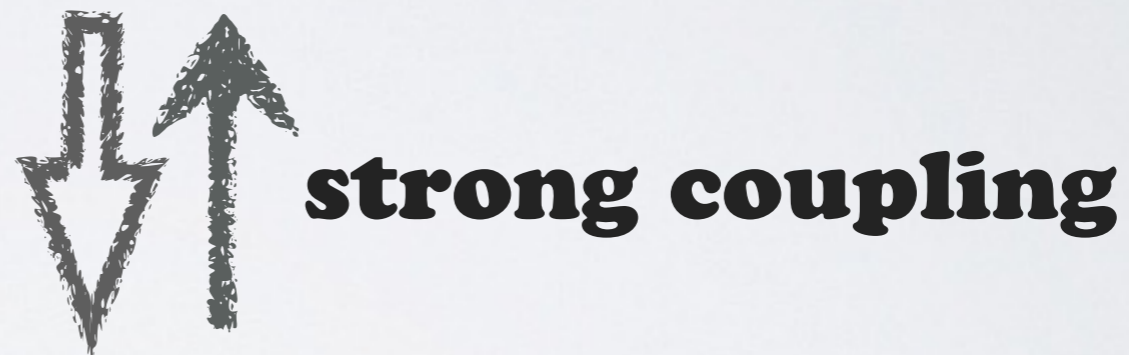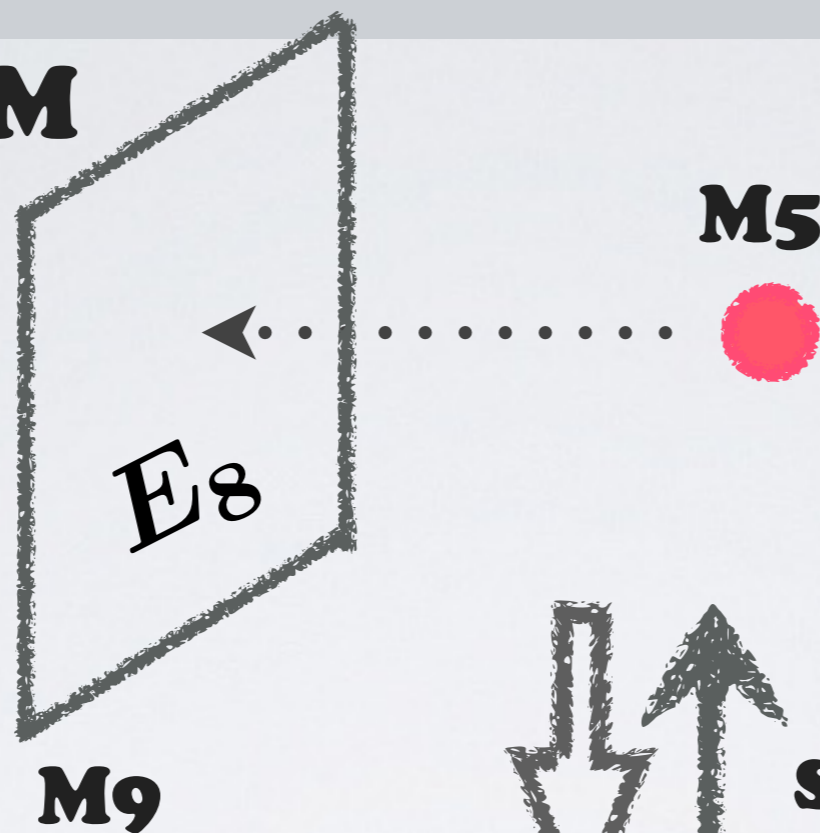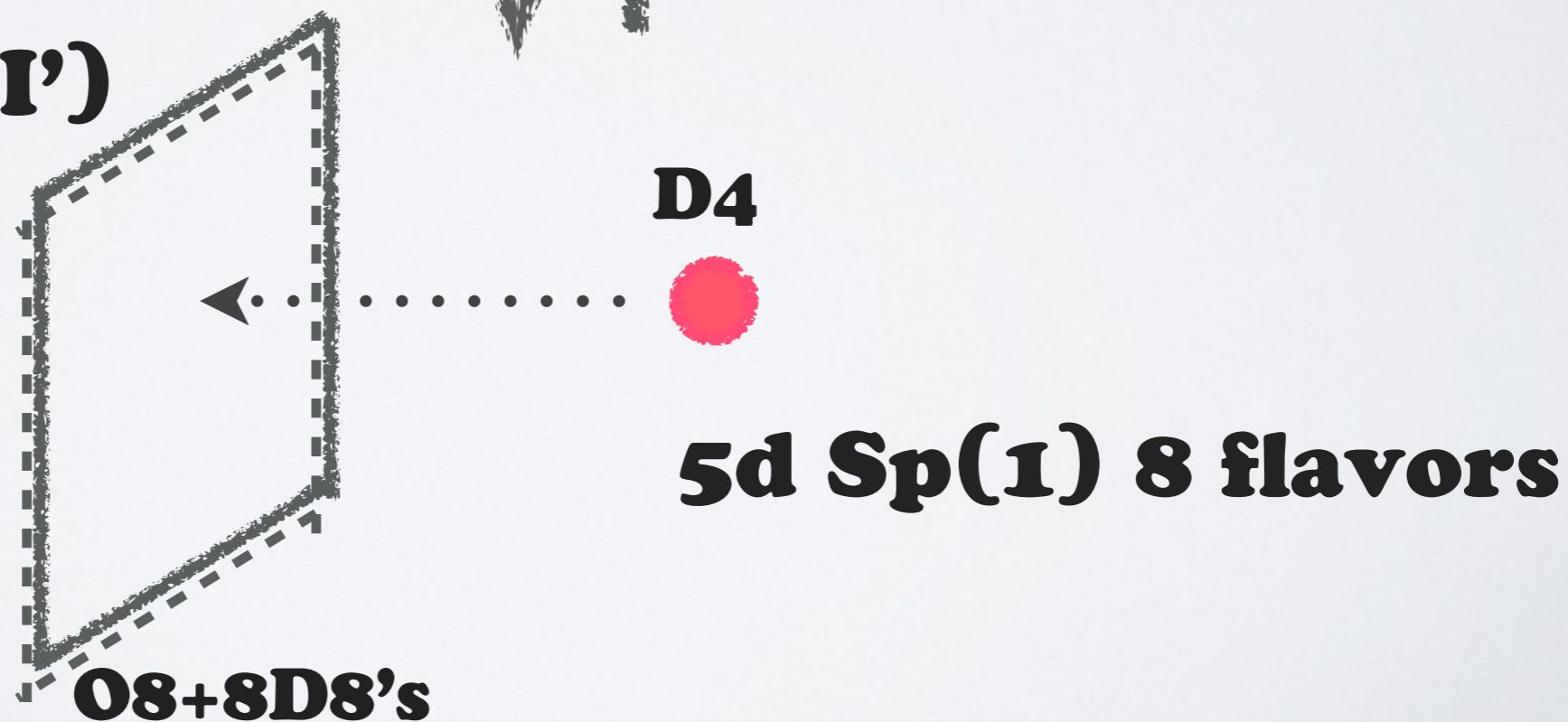
Analog to 6d N=(2,0) case

* M-theory

M5s

6d N=(2,0) SCFT

strong coupling

* Type IIA

D4s

5d N=2 SU(N) SYM

6d E-string theory is strongly-coupled UV fixed point of the 5d theory:

5D N=1 SU(2) Nf=8 SQCD

How to `re-make' E-string

Ingredient 2

How To Make 6d Theory : Key Fact 2

5d N=1 theory : realized by 5-brane web

5d *N*=1 gauge theories via 5-brane web

(p,q) 5-brane web configuration in Type IIB

(1,0) 5-brane : D5-brane

(0,1) 5-brane : NS5-brane

⬇ **bound state**

(p,q) 5-brane

5d N=1 SU(2) pure YM   [Aharony-Hanany, '97]

D5+NS5
(1,1)

D5-brane
(1,0)

(0,1)
NS5-brane

(1,-1)

5d *N*=1 SU(2) pure YM

[DeWolfe-Hanany-Iqbal-Katz, '99]

[1,-1] 7-brane   (1,-1)

[1,1] 7-brane   (1,1)
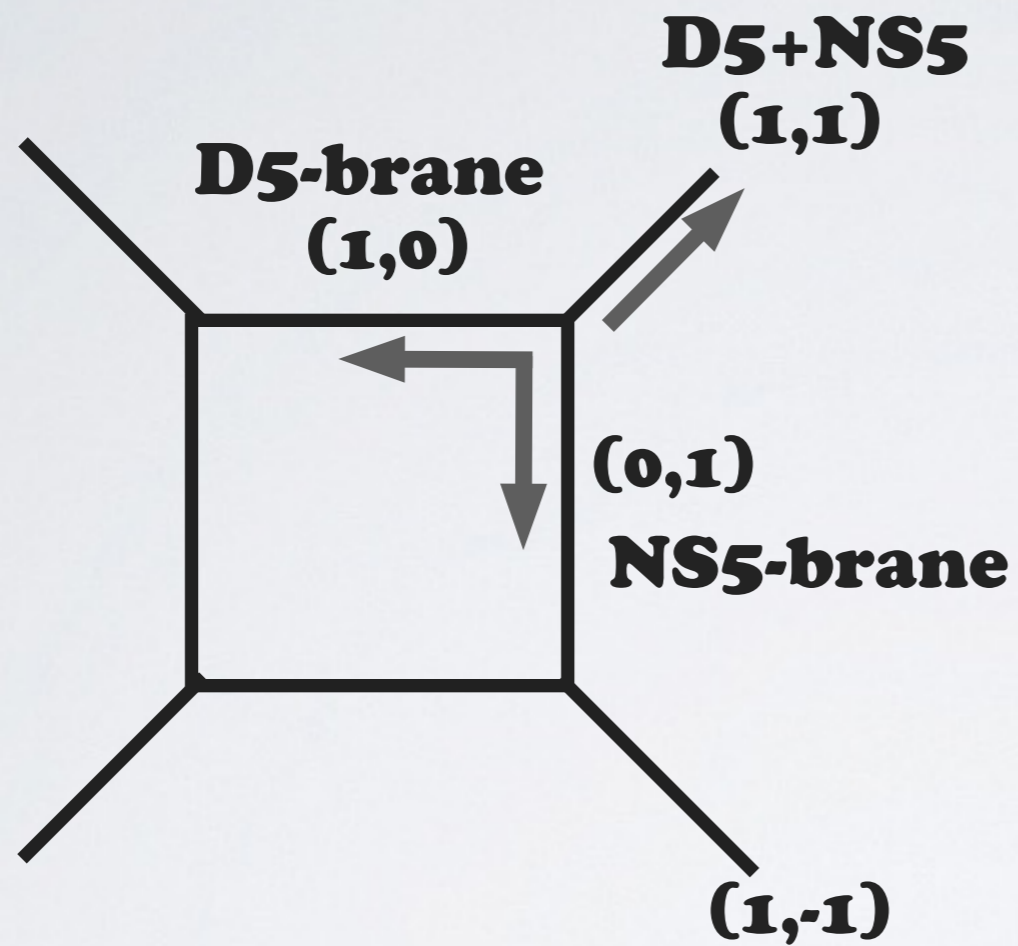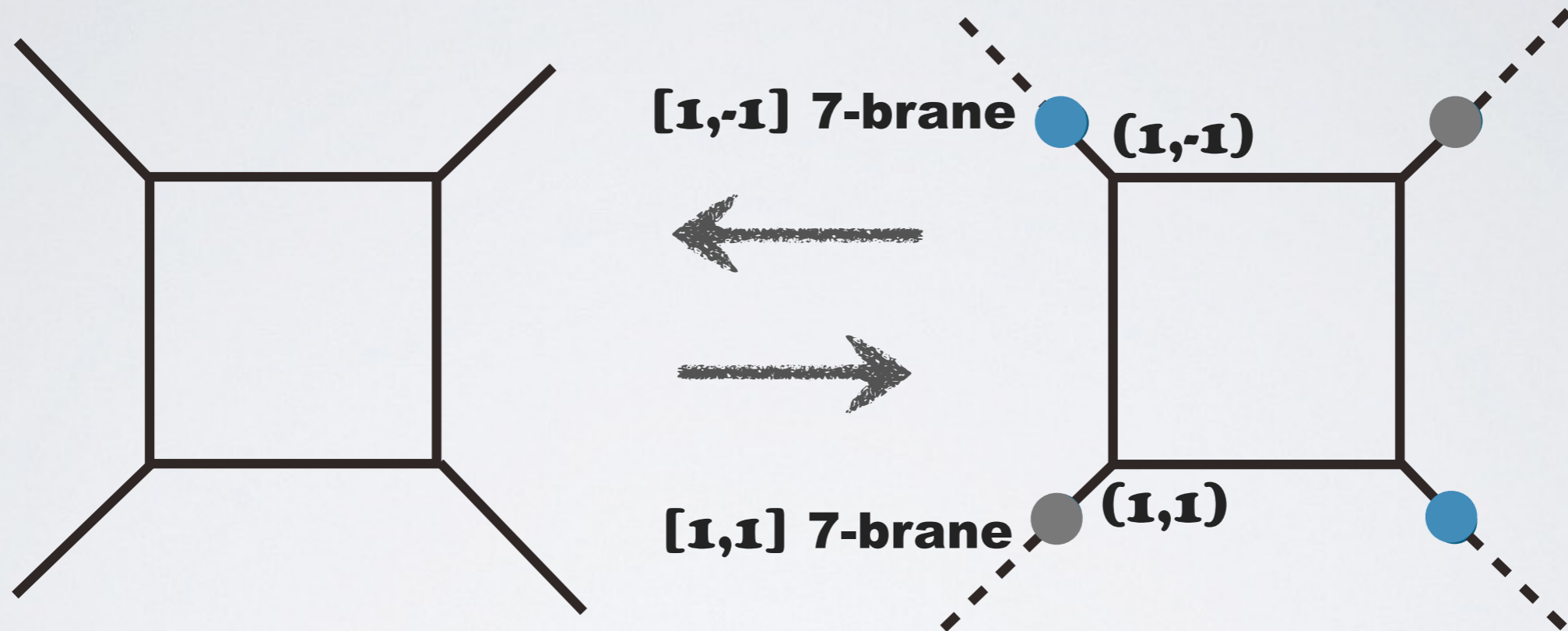
decoration by 7-branes

5d *N*=1 SU(2) pure YM

[DeWolfe-Hanany-Iqbal-Katz, '99]

[1,-1] 7-brane (1,-1)

[1,1] 7-brane (1,1)
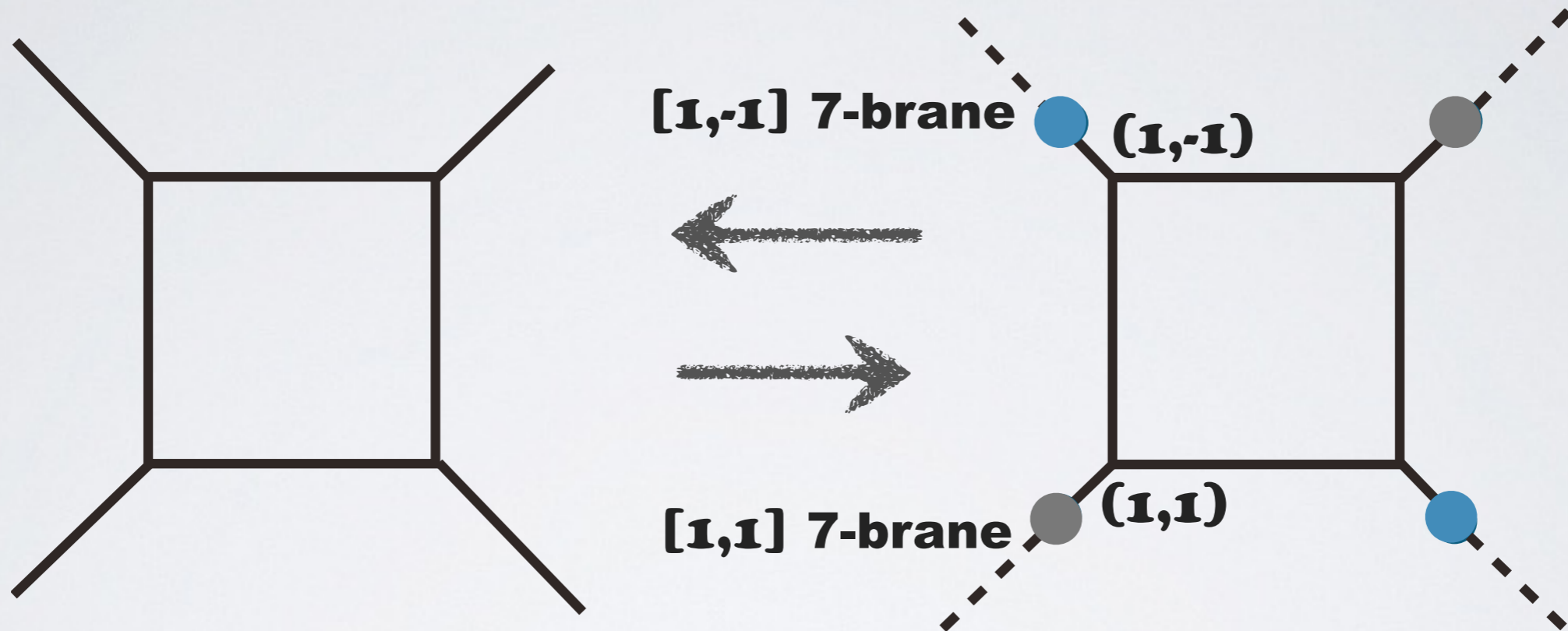
[p,q] 7-brane can move freely to (p,q)-direction

5d N=1 SU(2) pure YM

[DeWolfe-Hanany-Iqbal-Katz, '99]

Hanany-Witten

anti-Hanany-Witten
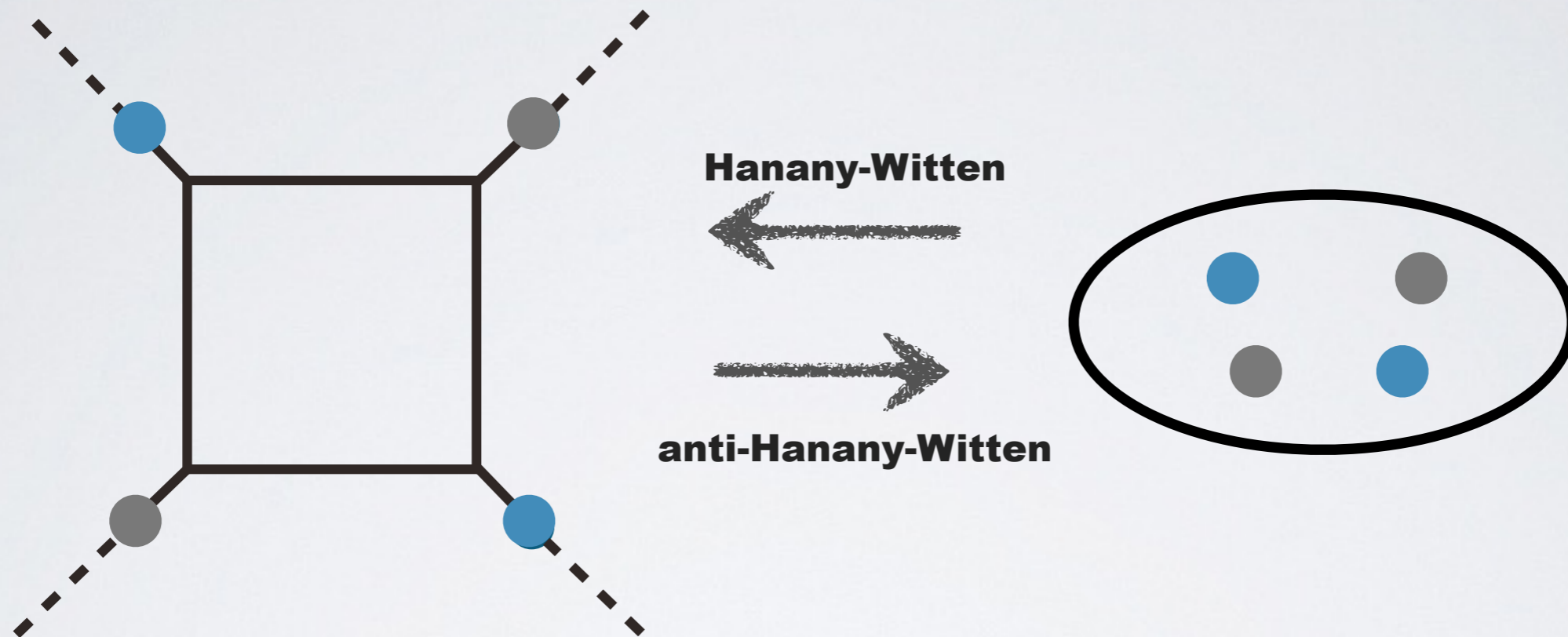
[p,q] 7-brane can move freely to (p,q)-direction

5d $N=1$ SU(2) SQCD

Hanany-Witten
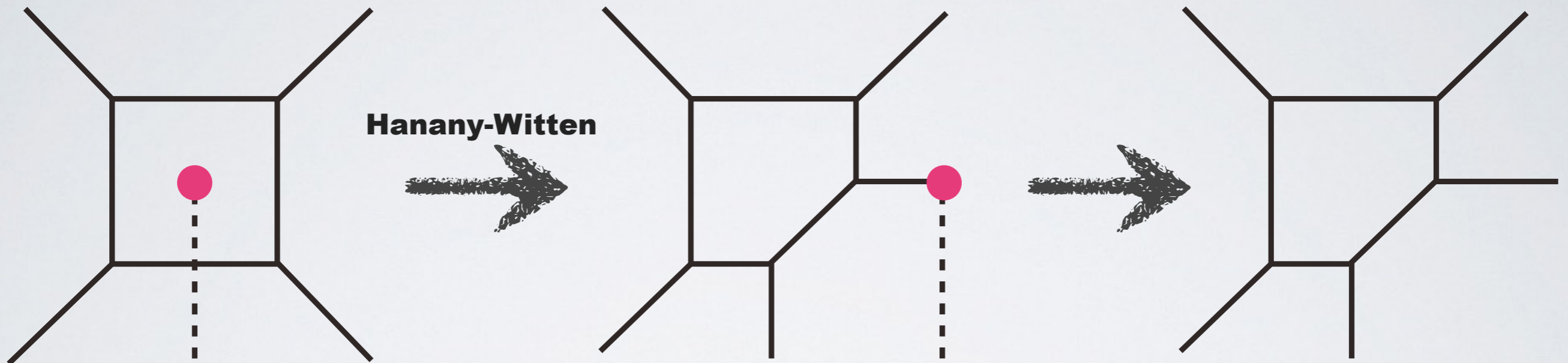
planing a corner

Web for N_f=0 theory

5d N=1 theory : realized by 5-brane web

D5+NS5

D5-brane

W-boson
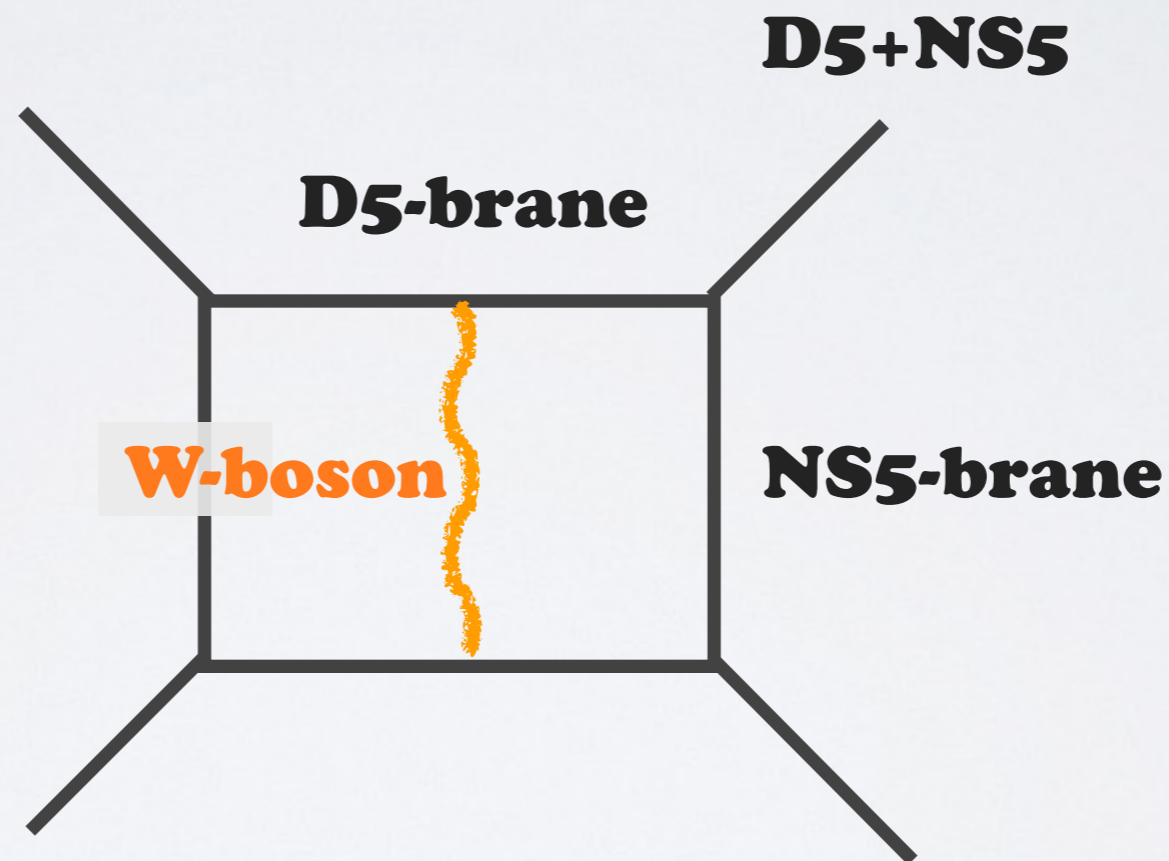
NS5-brane

5d N=1 theory : realized by 5-brane web
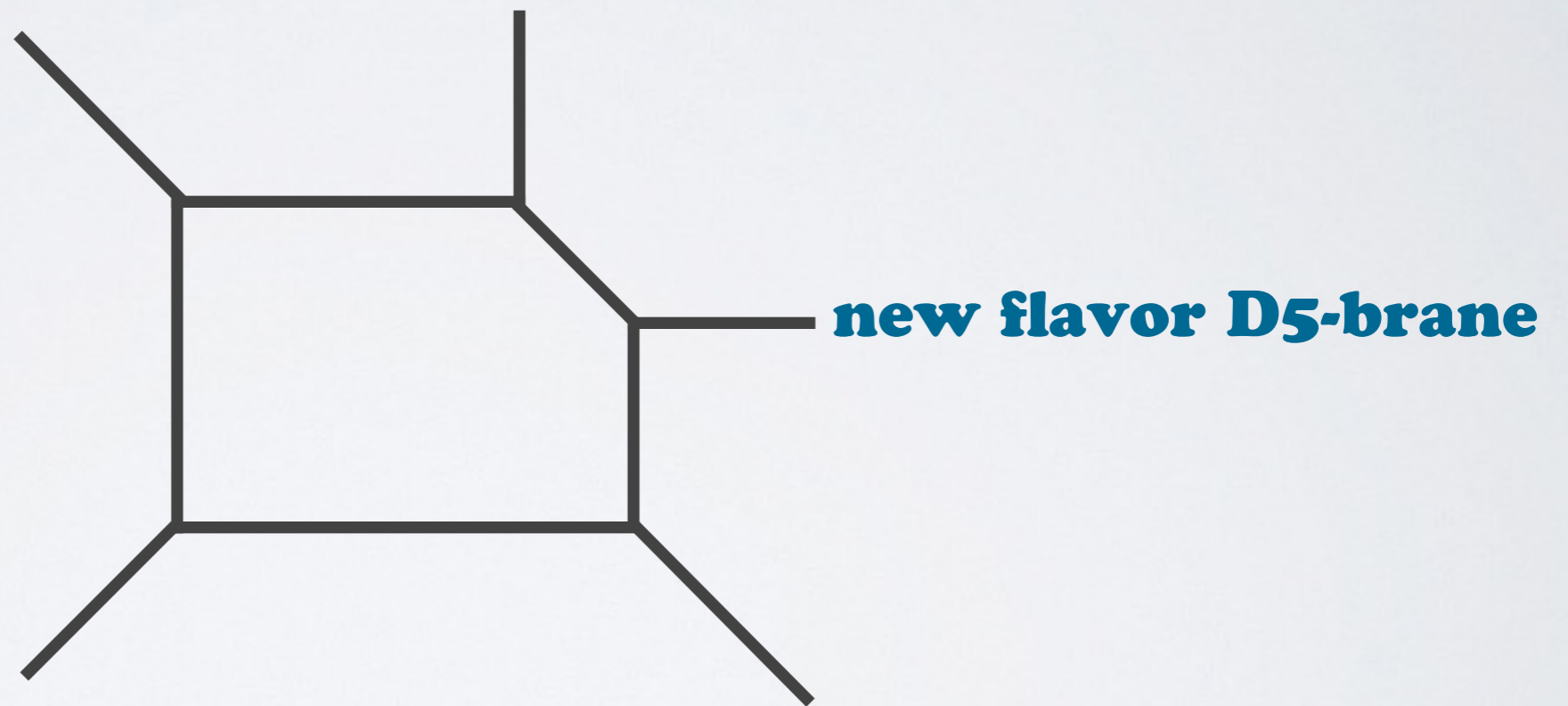
new flavor D5-brane

Web for N_f=2 theory

5d N=1 theory : realized by 5-brane web

new flavor D5-brane
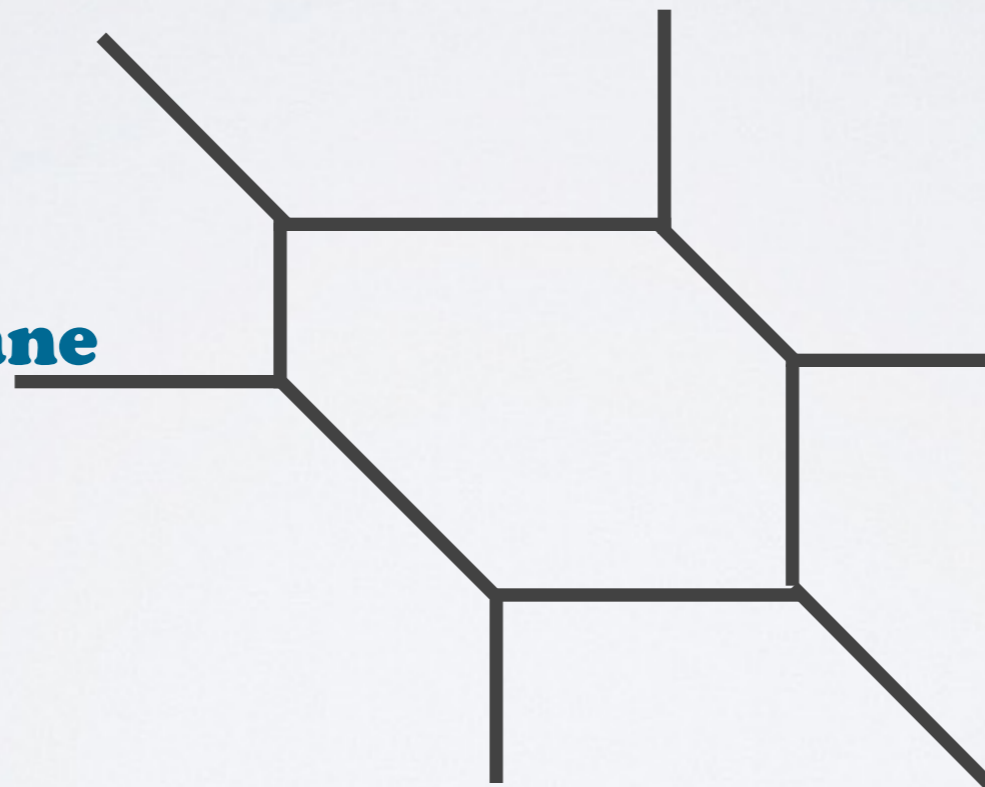
Web for N_f=3 theory

5d N=1 theory : realized by 5-brane web
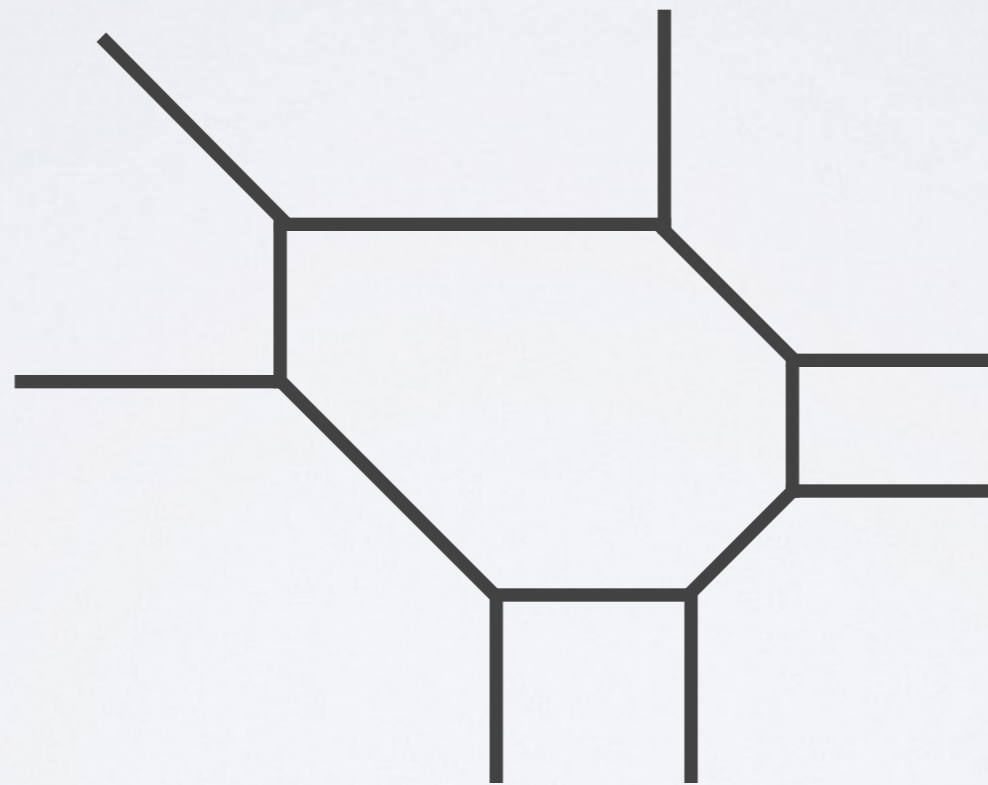
Web for *N*f=4 theory

5d *N*=1 theory : realized by 5-brane web
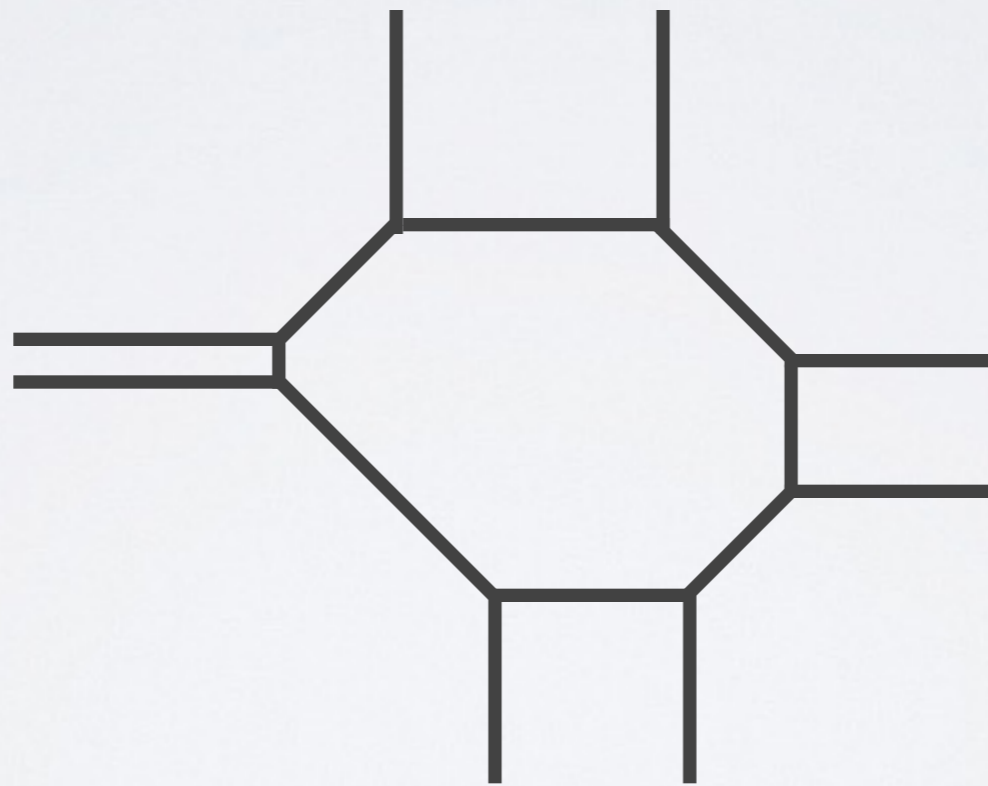
Web for N_f=5 theory

5d N=1 theory : realized by 5-brane web
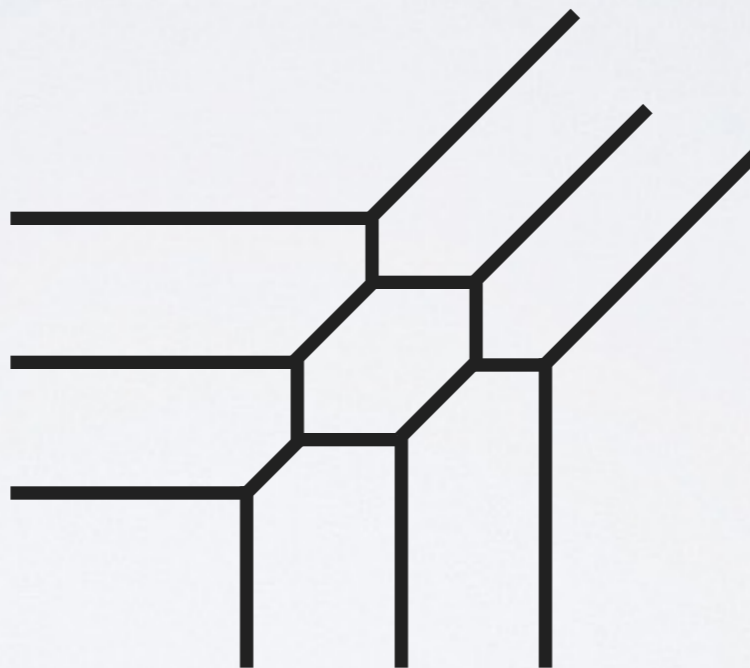
Web for N_f=6 theory
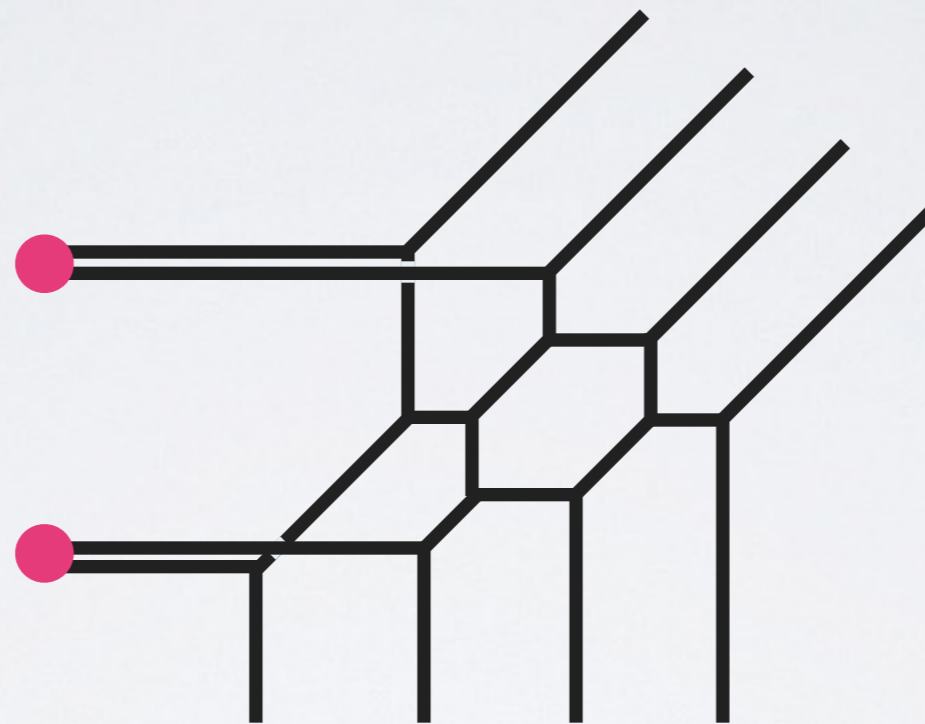
Web for *Nf*=7 theory
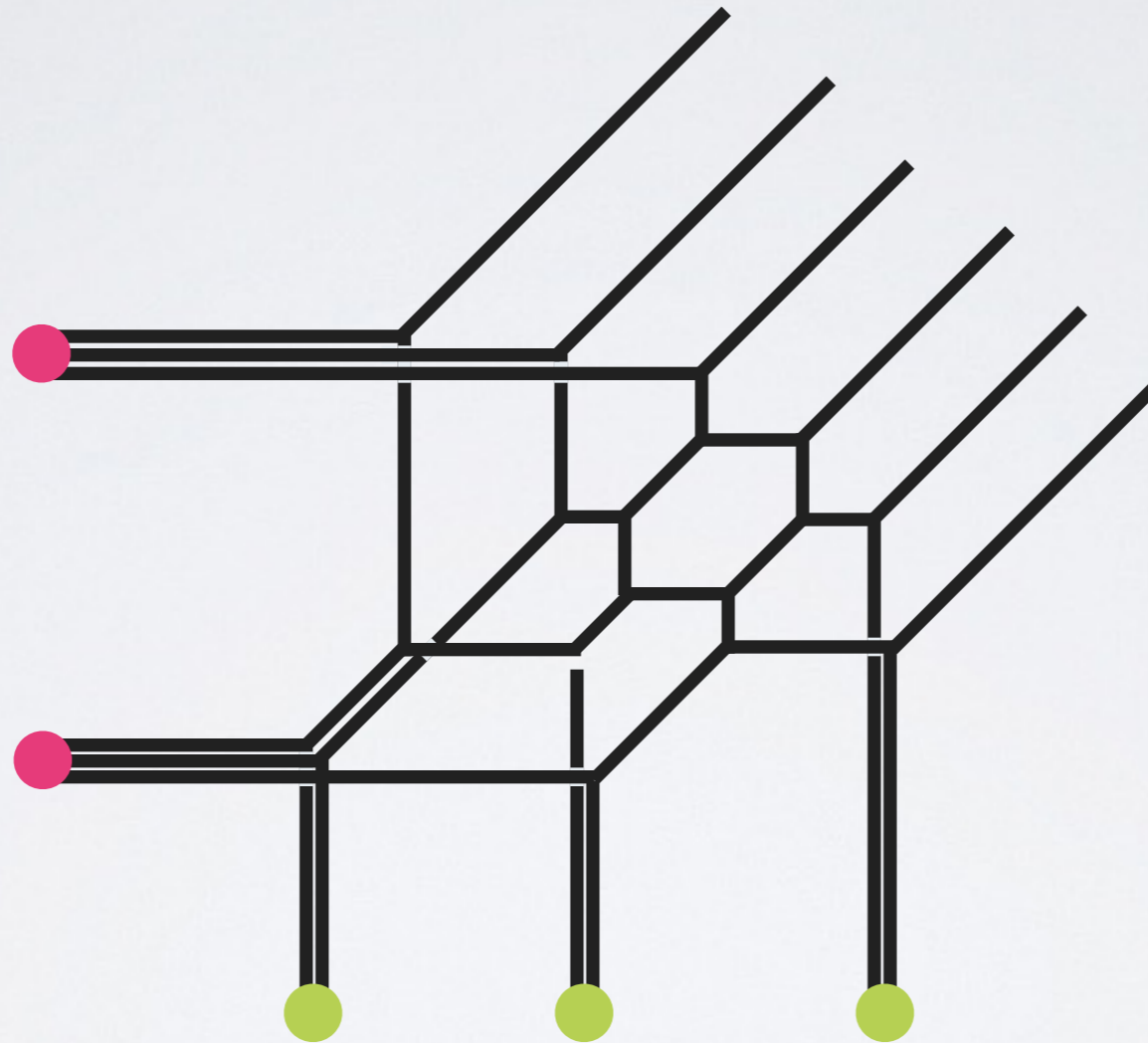
Let's cook up E-string !

Synthesize two key ideas

1. 6d E-string theory is UV fixed point of the **5d** N=1 SU(2) **Nf=8** SQCD

2. 5d N=1 theory can be engineered by **5-brane web**

Synthesize two key ideas

1. 6d E-string theory is UV fixed point of the **5d** N=1 SU(2) **Nf=8** SQCD

2. 5d N=1 theory can be engineered by **5-brane web**

Brane web for 5d SU(2) Nf=8 SQCD

⟶ 6d ??

How can we add Nf=8 flavors to web !?

How to add 8 flavors?

Nice starting point is 7-branes
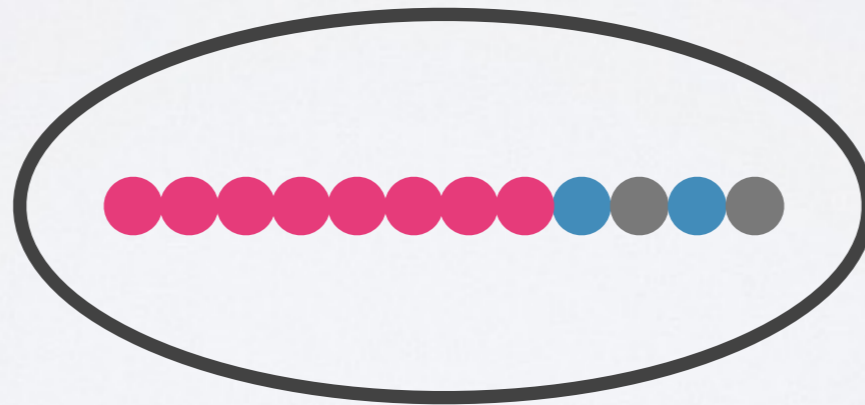
8[1,0]'s, [1,-1], [1,1], [1,-1], [1,1]

How to add 8 flavors?

Nice starting point is 7-branes
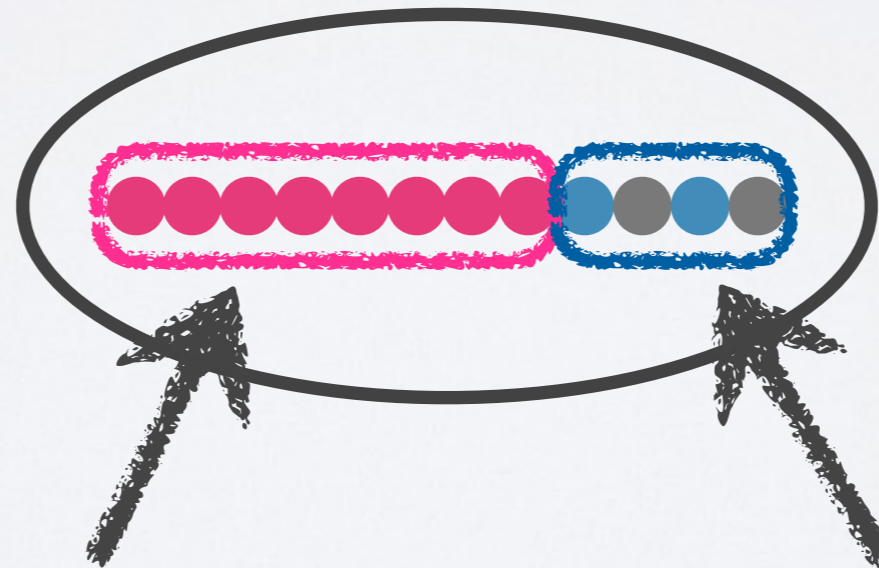
$8[1,0]$'s, $[1,-1], [1,1], [1,-1], [1,1]$

8 flavors   pure SYM

8[1,0]'s, [1,-1], [1,1], [1,-1], [1,1]

monodromic reordering

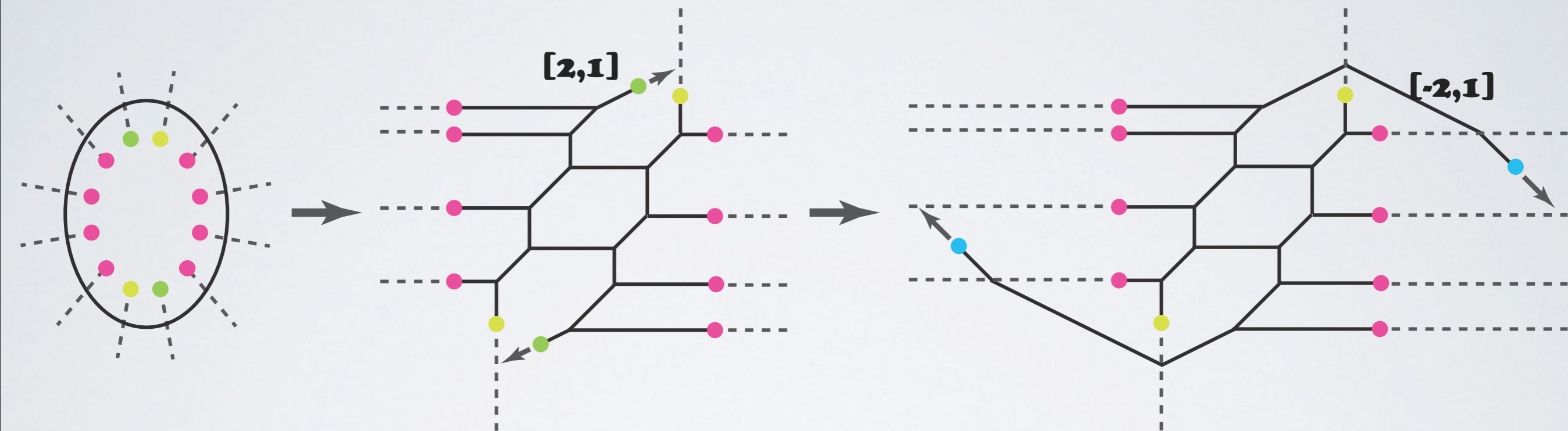4[1,0]'s, [0,1], [2,1], 4[1,0]'s, [0,1], [2,1]
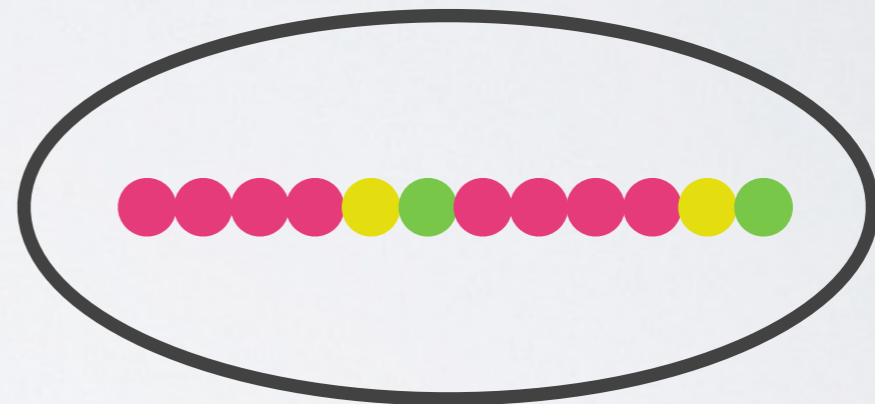
Tao-nization 1
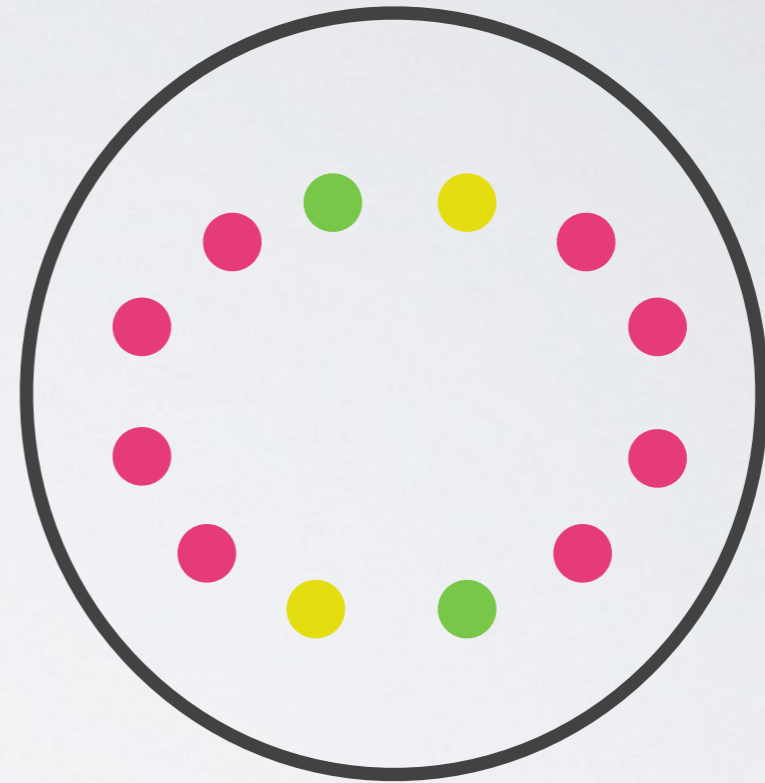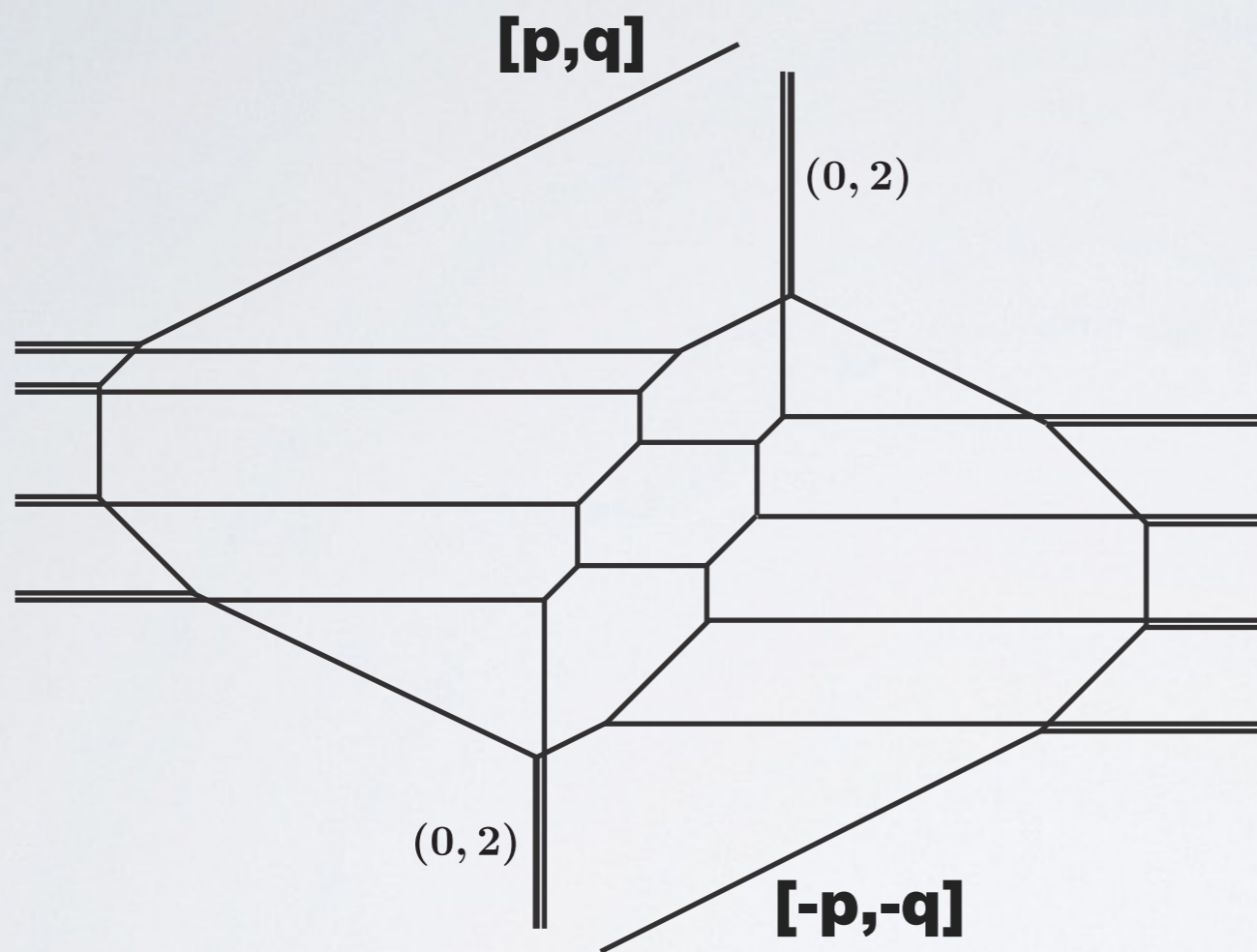
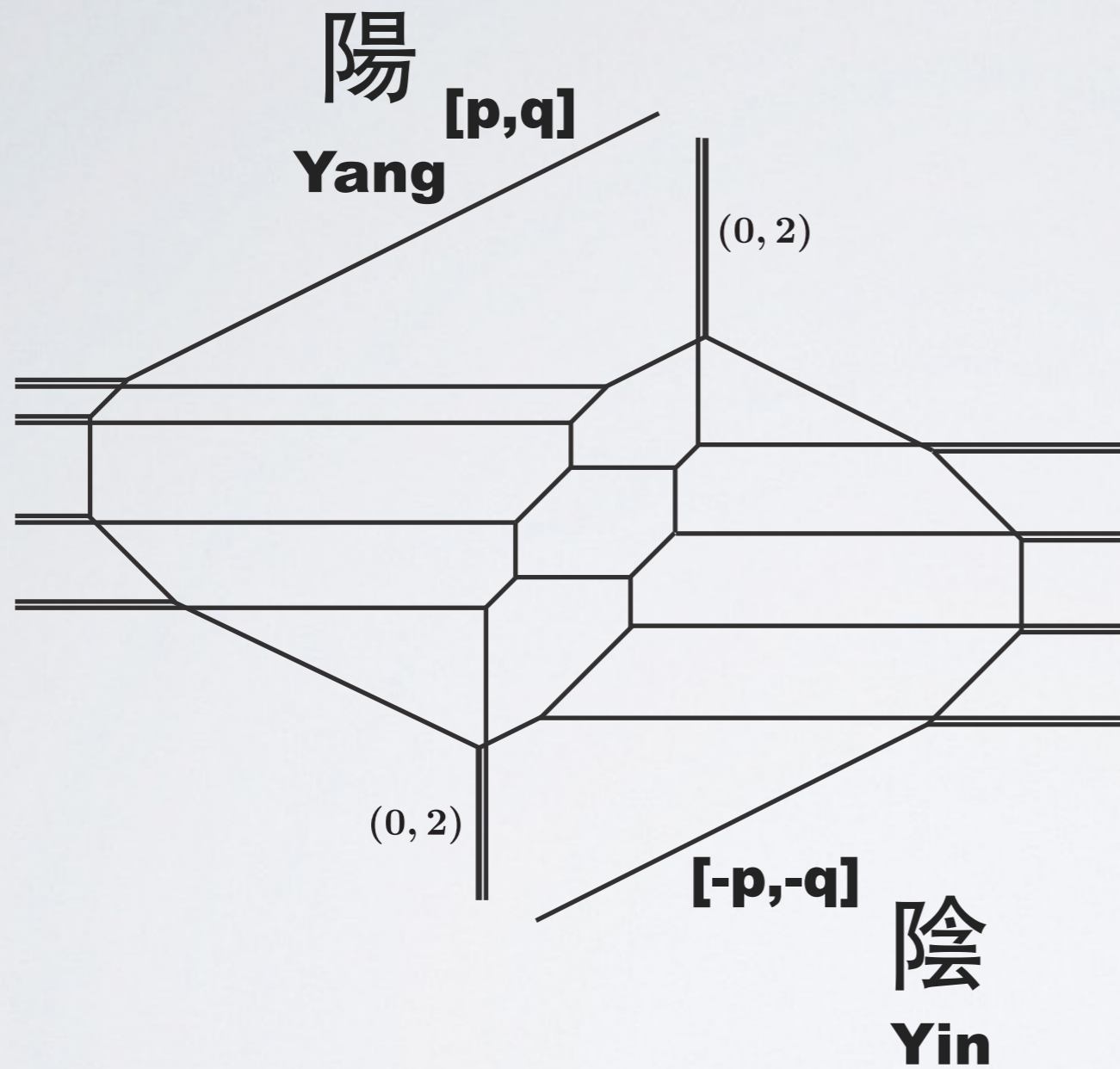**[p,q] 7-brane can move freely to (p,q)-direction**

Tao-nization 1

[2,1]

[-2,1]

[p,q] 7-brane can move freely to
(p,q)-direction
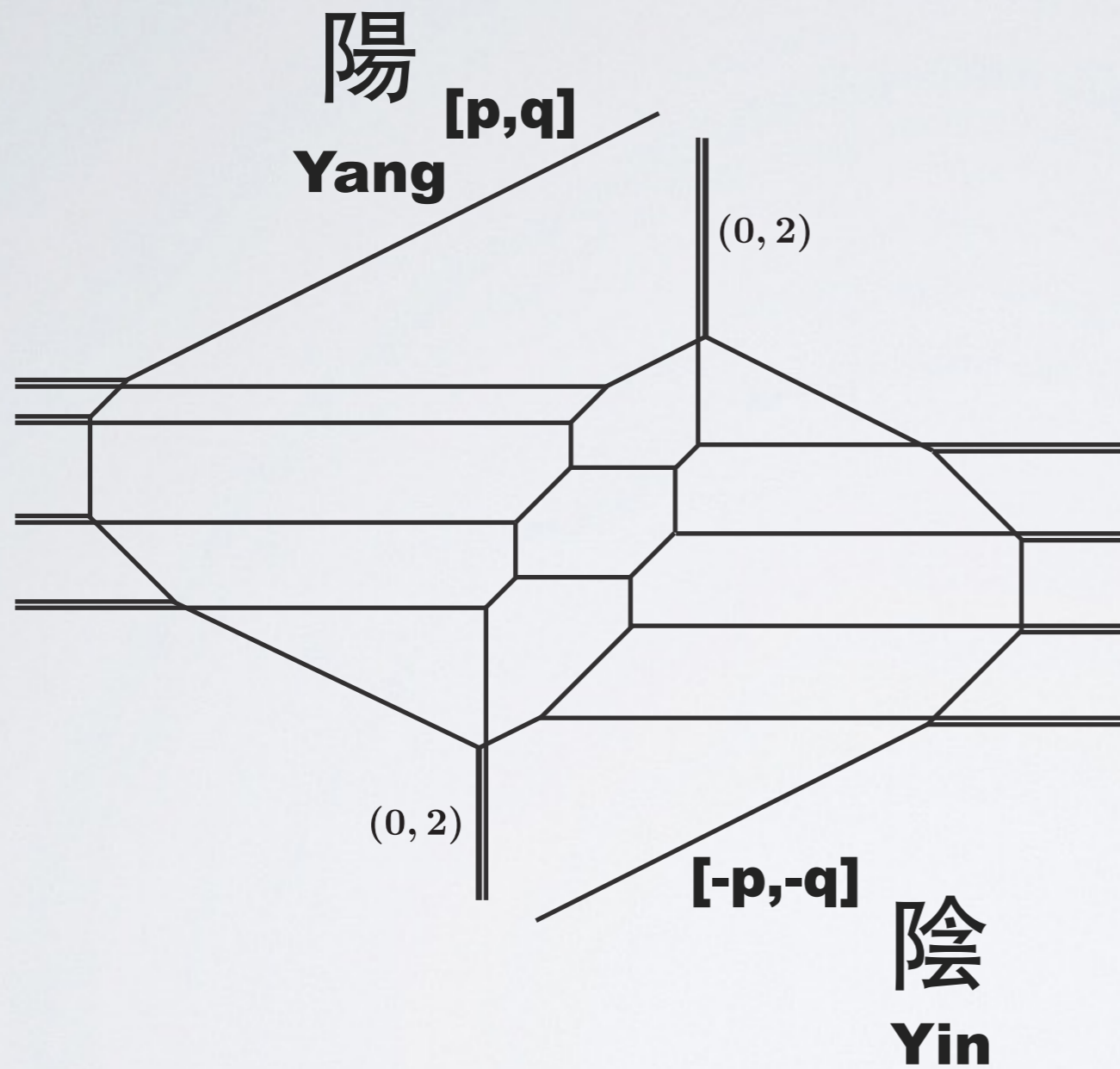
Now get it!

[p,q]

$(0, 2)$

$(0, 2)$

[-p,-q]

Tao-nization 1

陽
[p,q]
Yang

$(0, 2)$

$(0, 2)$

[-p,-q]

陰
Yin

Tao-nization 1

陽
[p,q]
Yang

$(0, 2)$

$(0, 2)$

[-p,-q]
陰
Yin

陽
[p,q]
Yang

$(0, 2)$

$(0, 2)$

[-p,-q]
陰
Yin
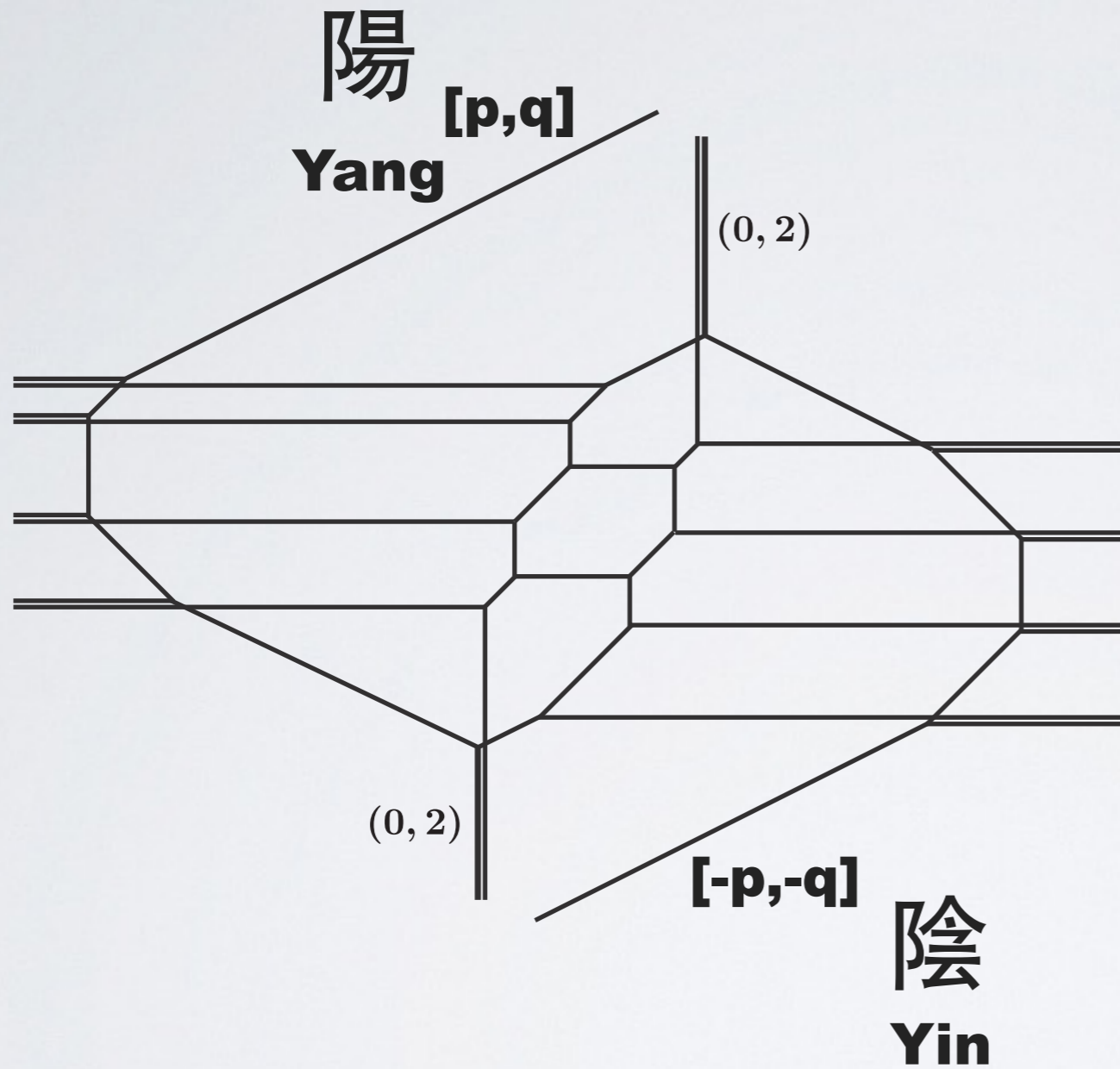
Tao brane web
道

Another Tao description

8 [1,0]'s, [1,-1], [1,1], [1,-1], [1,1]
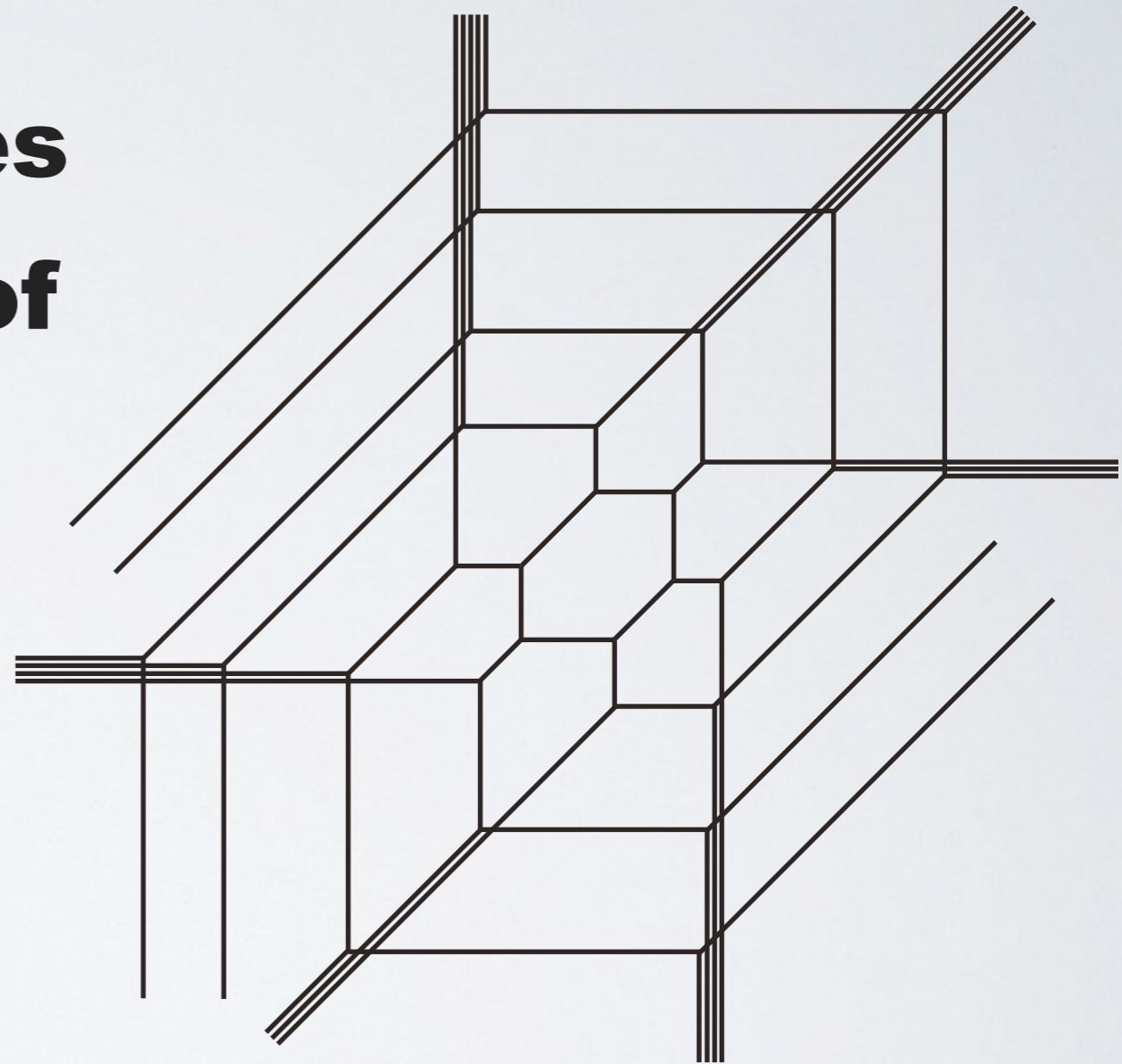

([1,0], [0,1], [1,1]) × 4

Tao-nization 2
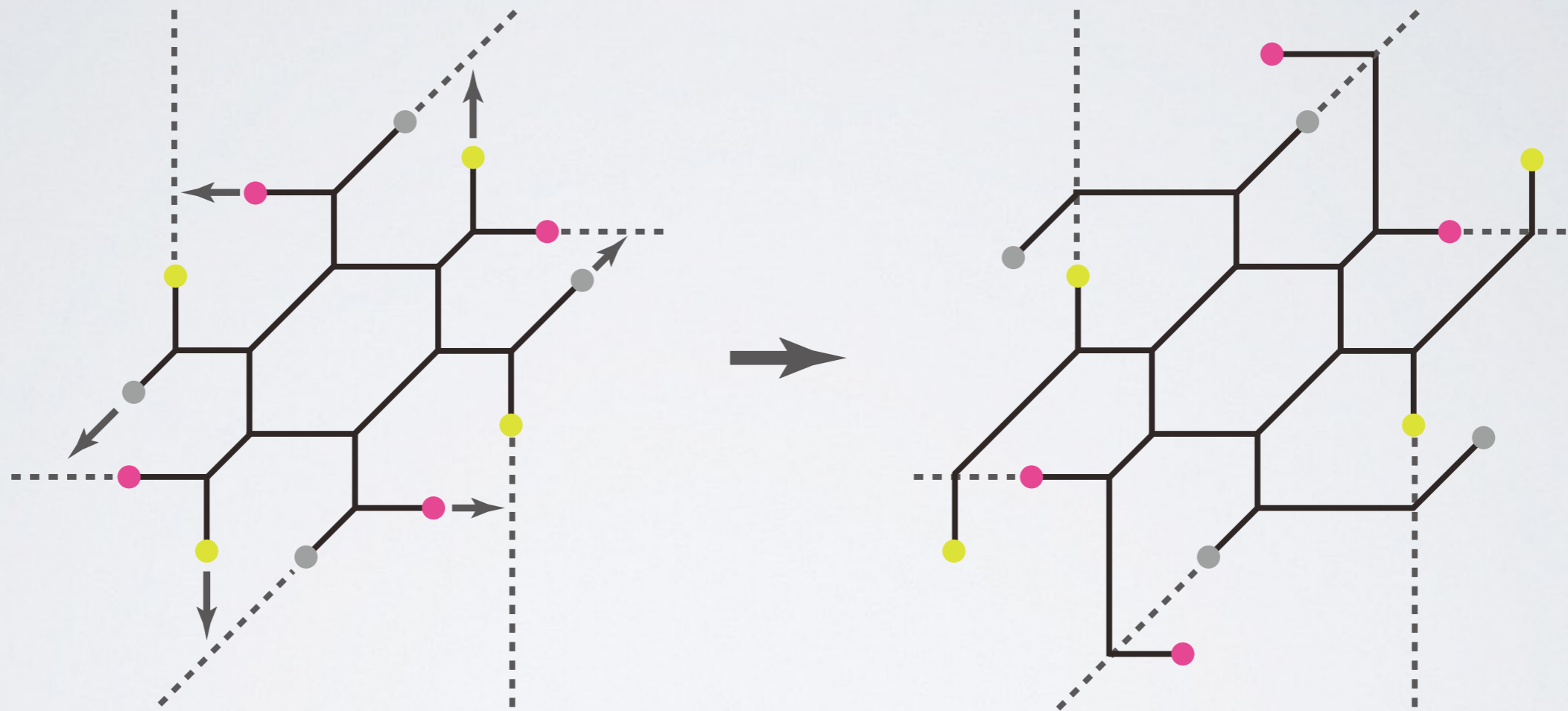
Tao-nization 2
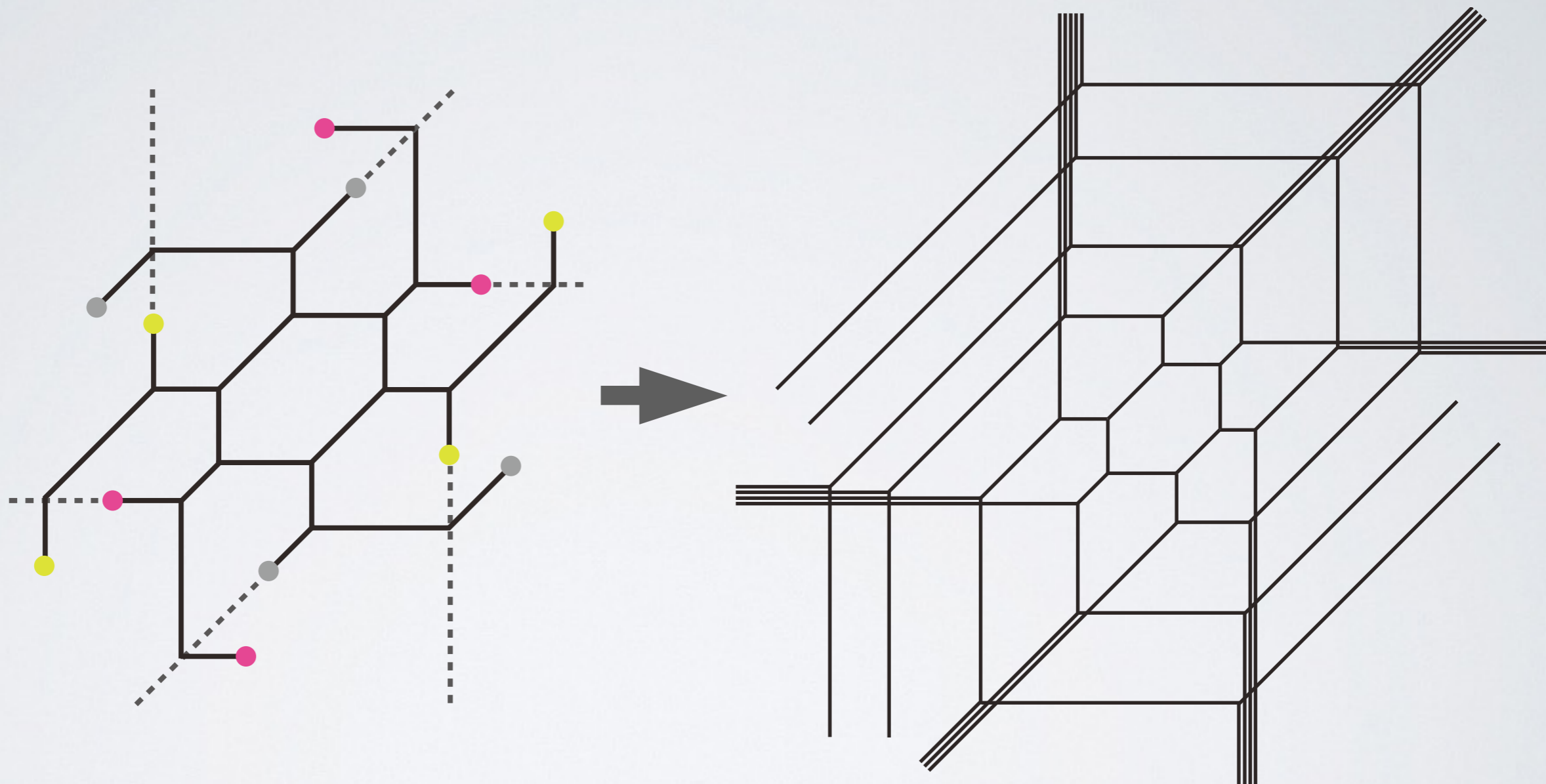
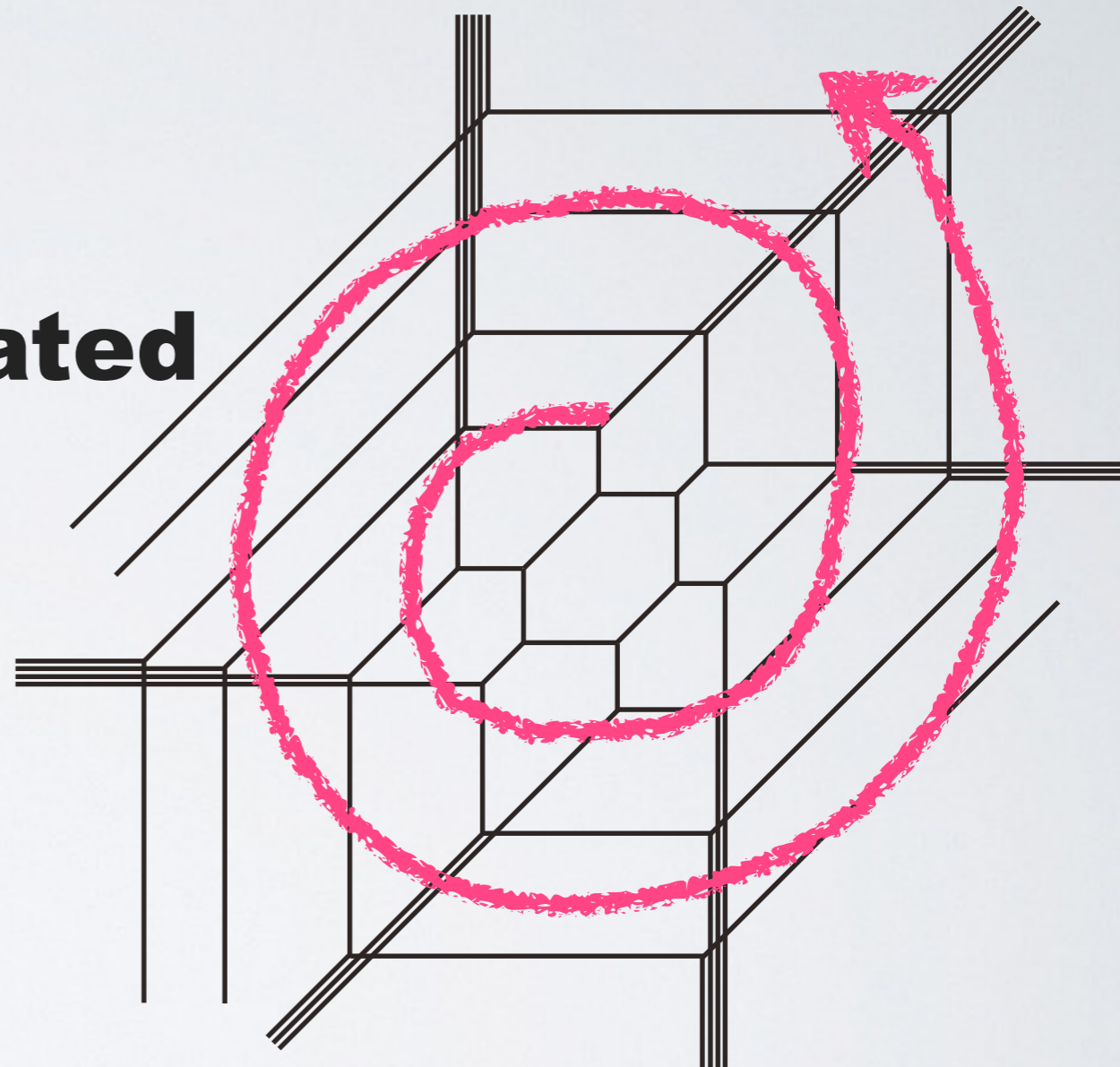# Tao realization of E-string theory

6d E-string theory lives on the world volume of the 5-brane web
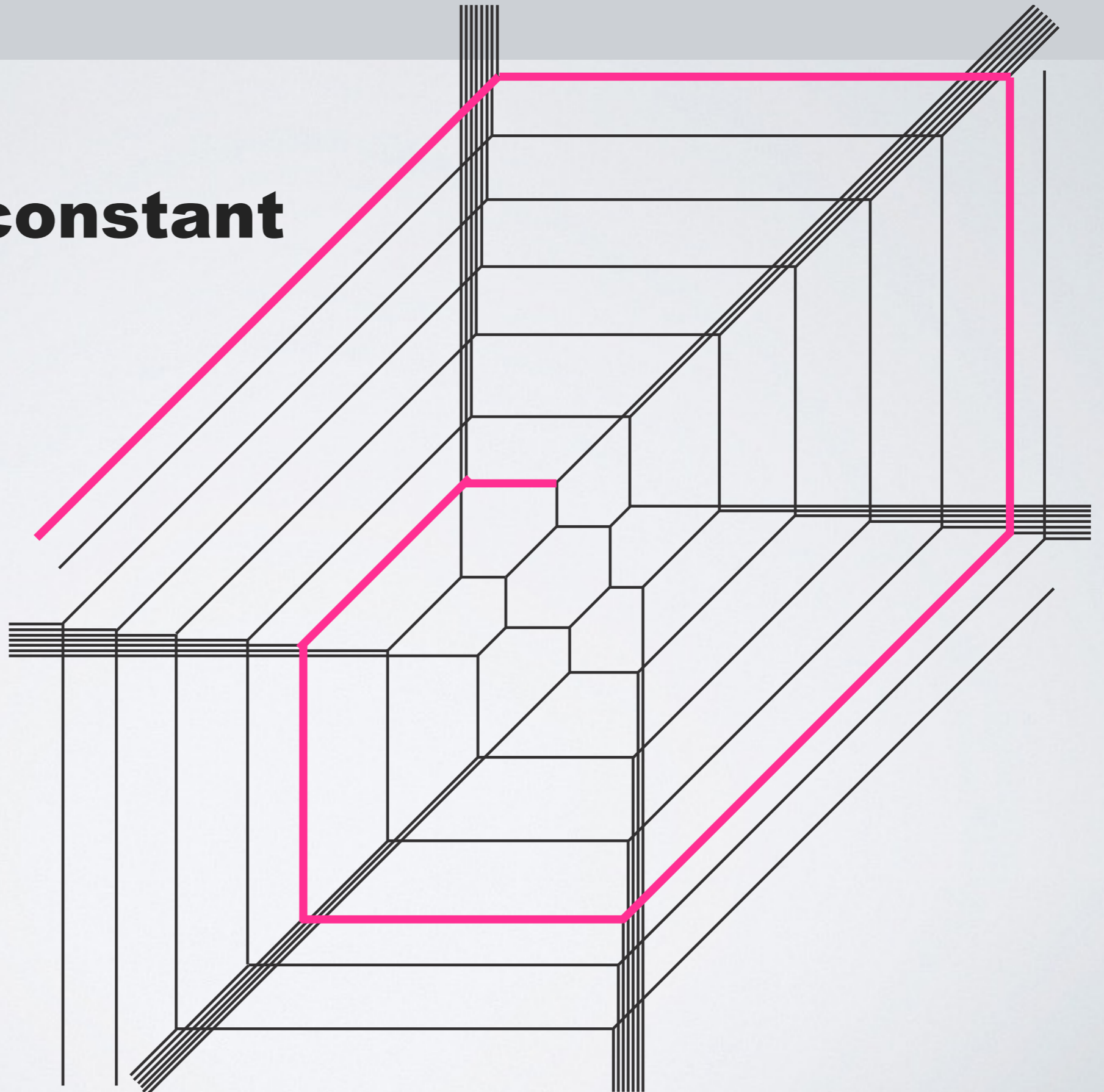
Charms of Tao Web

Intuitive origin of 6-th direction

6-th direction is generated by the spiral (periodic) direction (KK=winding)

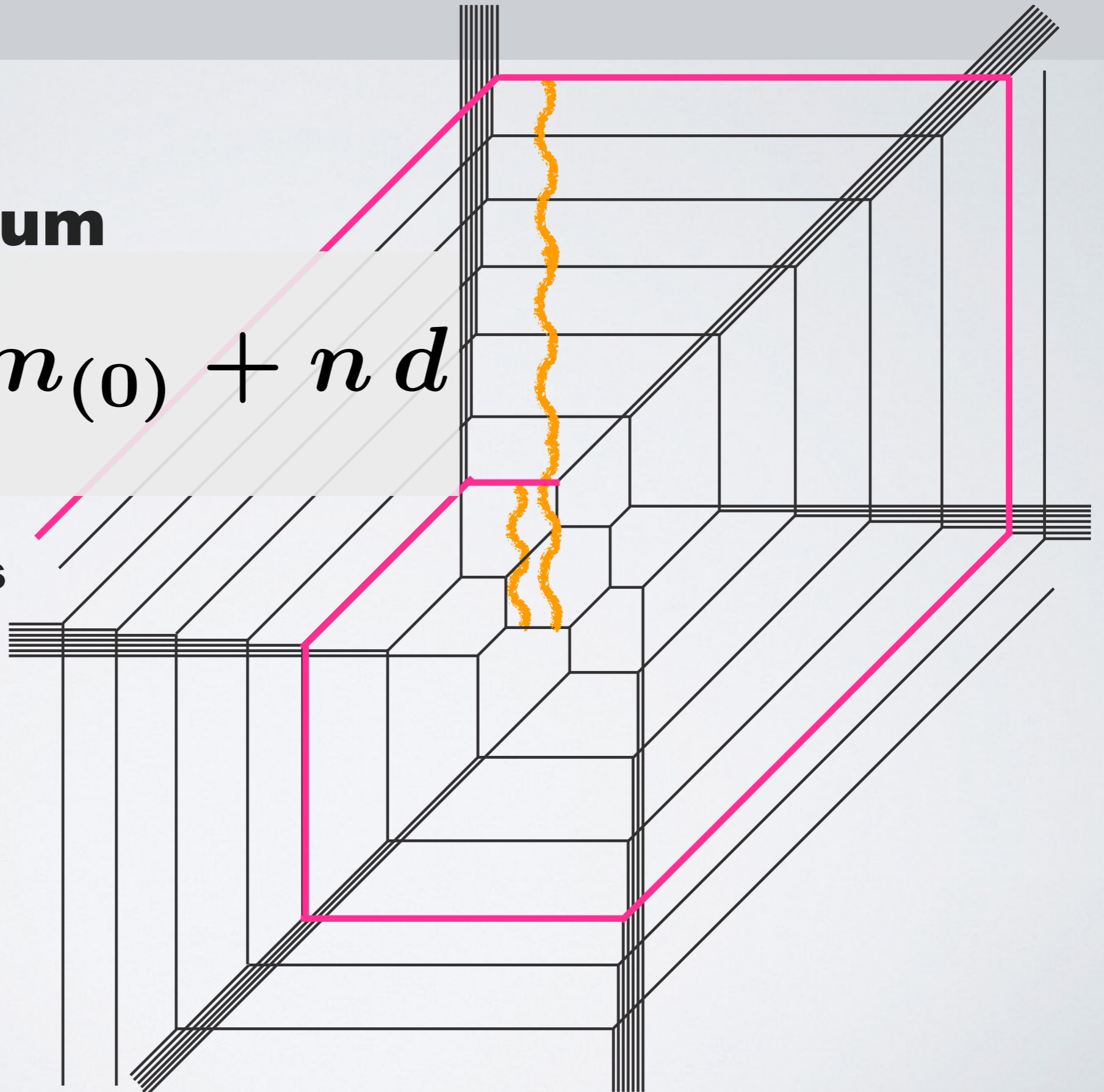# Intuitive origin of 6-th direction

spiral with constant period

Intuitive origin of 6-th direction

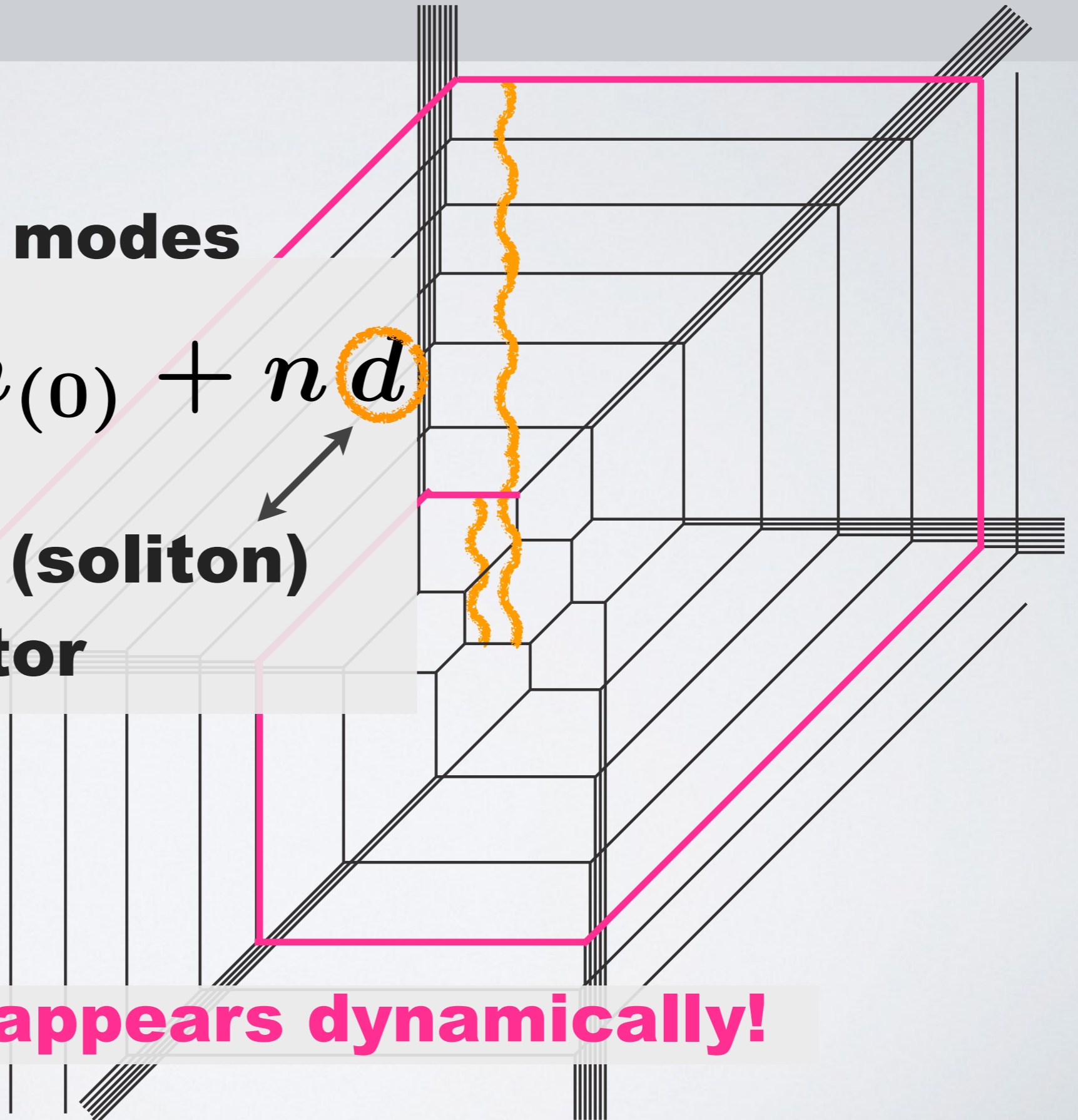**BPS spectrum**

$$m_{(n)} = m_{(0)} + n\,d$$

tension of strings

Intuitive origin of 6-th direction

KK (winding) modes

$$m_{(n)} = m_{(0)} + n\,d$$

instanton (soliton) factor
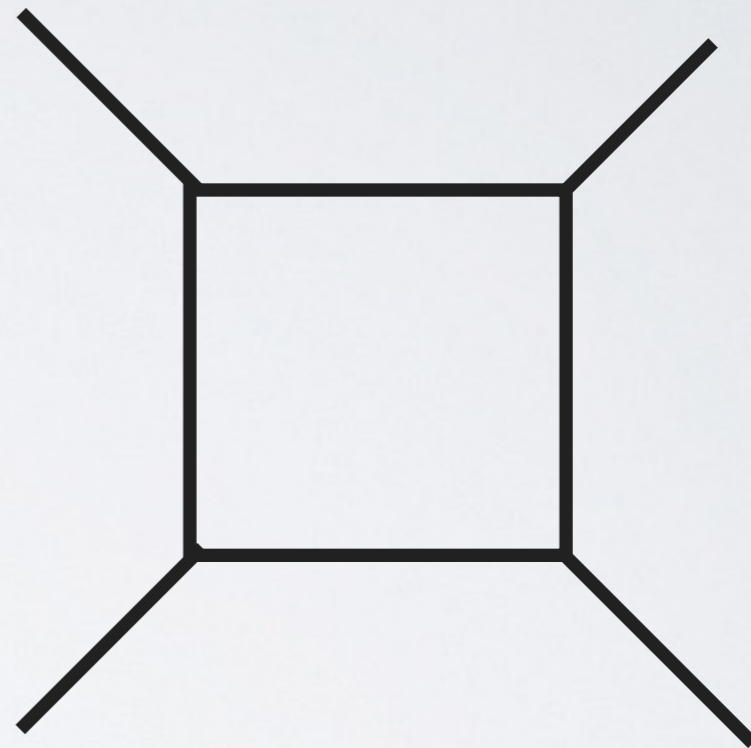
6d-th appears dynamically!

Topological Vertex and partition function

web

⬇

closed expression
of Nekrasov
partition function

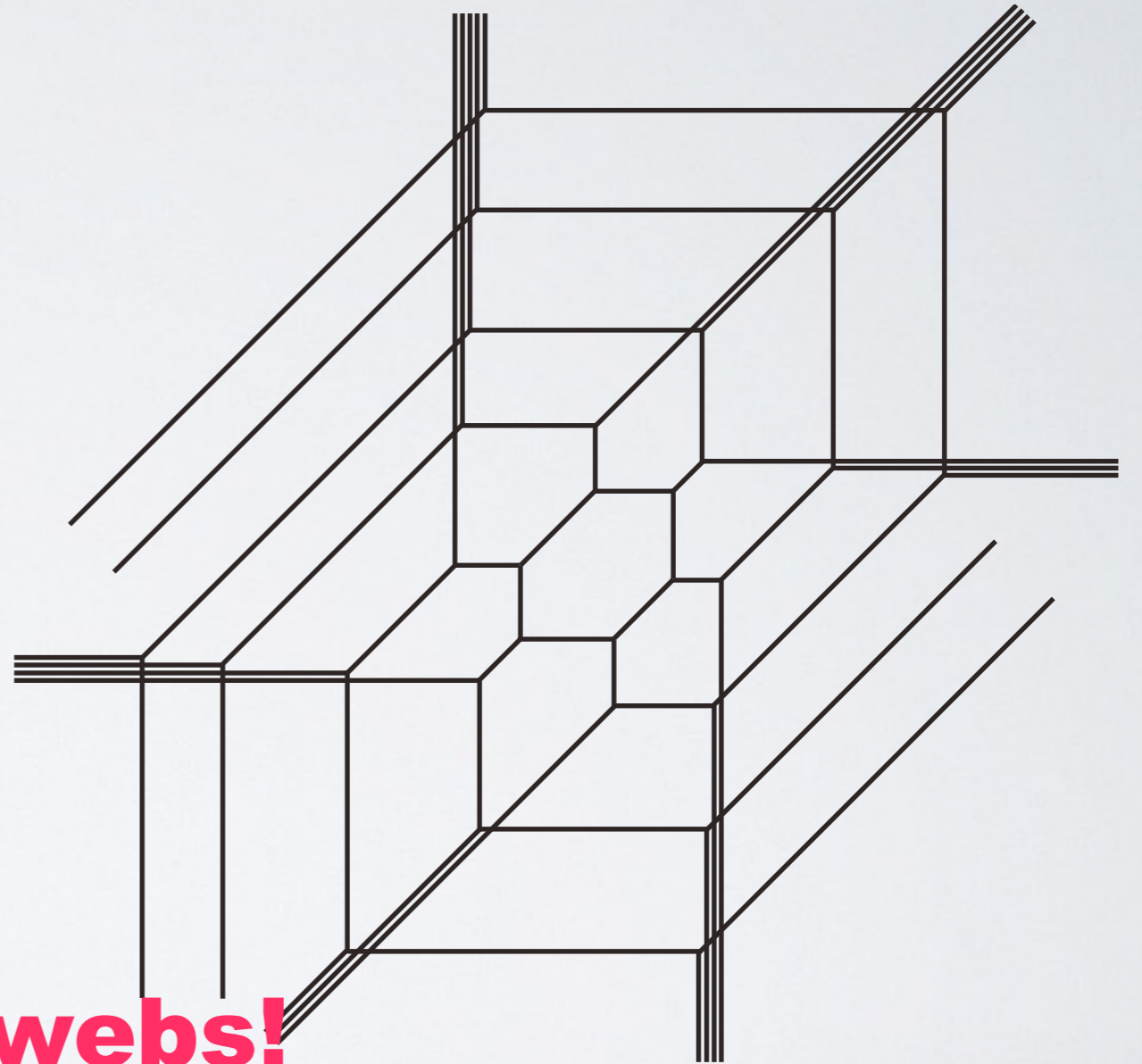$$Z = \cdots$$

Topological Vertex and partition function

web

⬇

**closed expression
of Nekrasov
partition function**

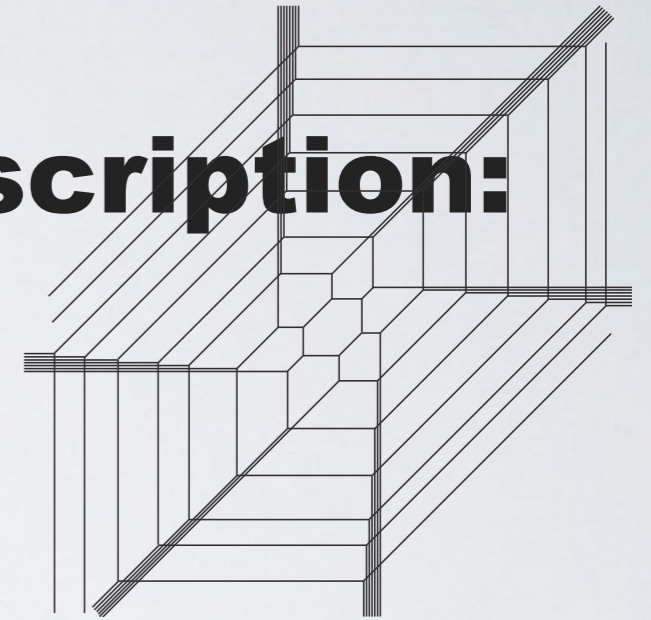**It works also for Tao webs!**
reproduces known results on E-string elliptic genus

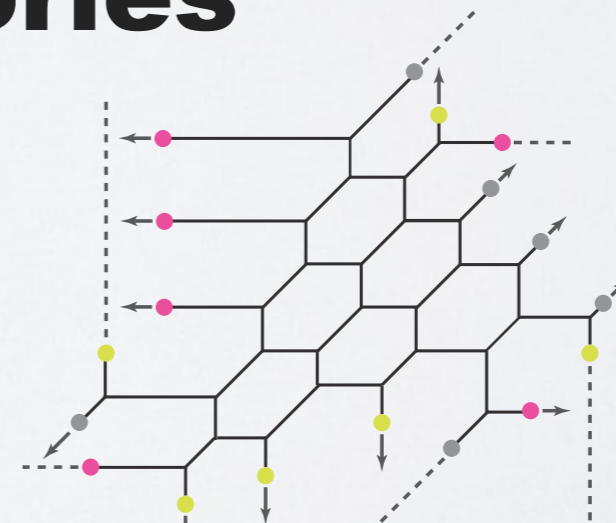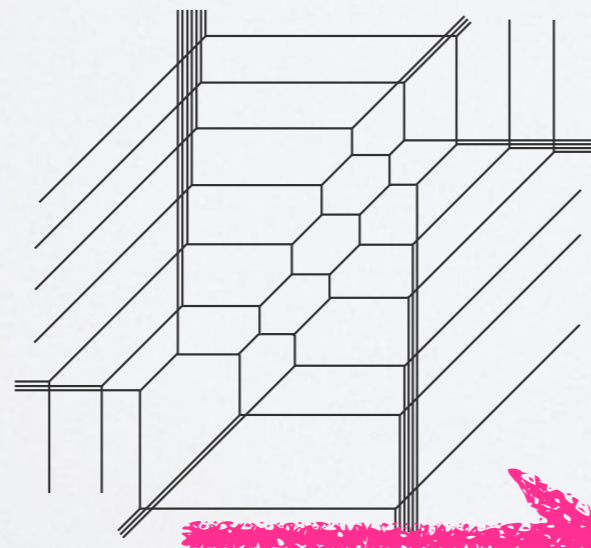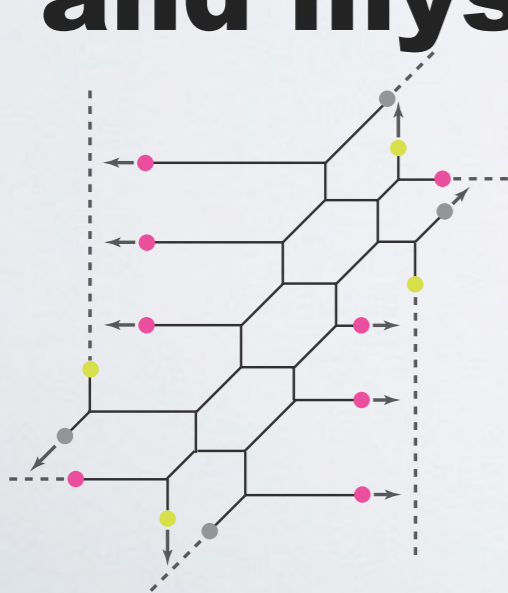**[Kim-Kim-Lee-Park-Vafa, '14]**

Conclusion

Message

6d theories has new brane description:
'Tao' 5-brane web

Infinitely many types of Tao webs
and mysterious 6d theories

Yagi-san's next talk

Message

6d theories has new brane description:

'Tao' 5-brane web

**Infinitely many types of Tao webs
and mysterious 6d theories**

The end of the talk about Tao

Generalizations: theories of class $T(ao)$

6d Theories of class $\mathcal{T}$

6d class $\mathcal{T}$ theories :

c.f.

4d class $\mathcal{S}$ [Gaiotto]

3d class $\mathcal{R}$ [Dimofte]

6d class $\mathcal{T}$ theories :

$\mathcal{T}$ao, $\mathcal{T}$riskelion, $\mathcal{T}$wo,
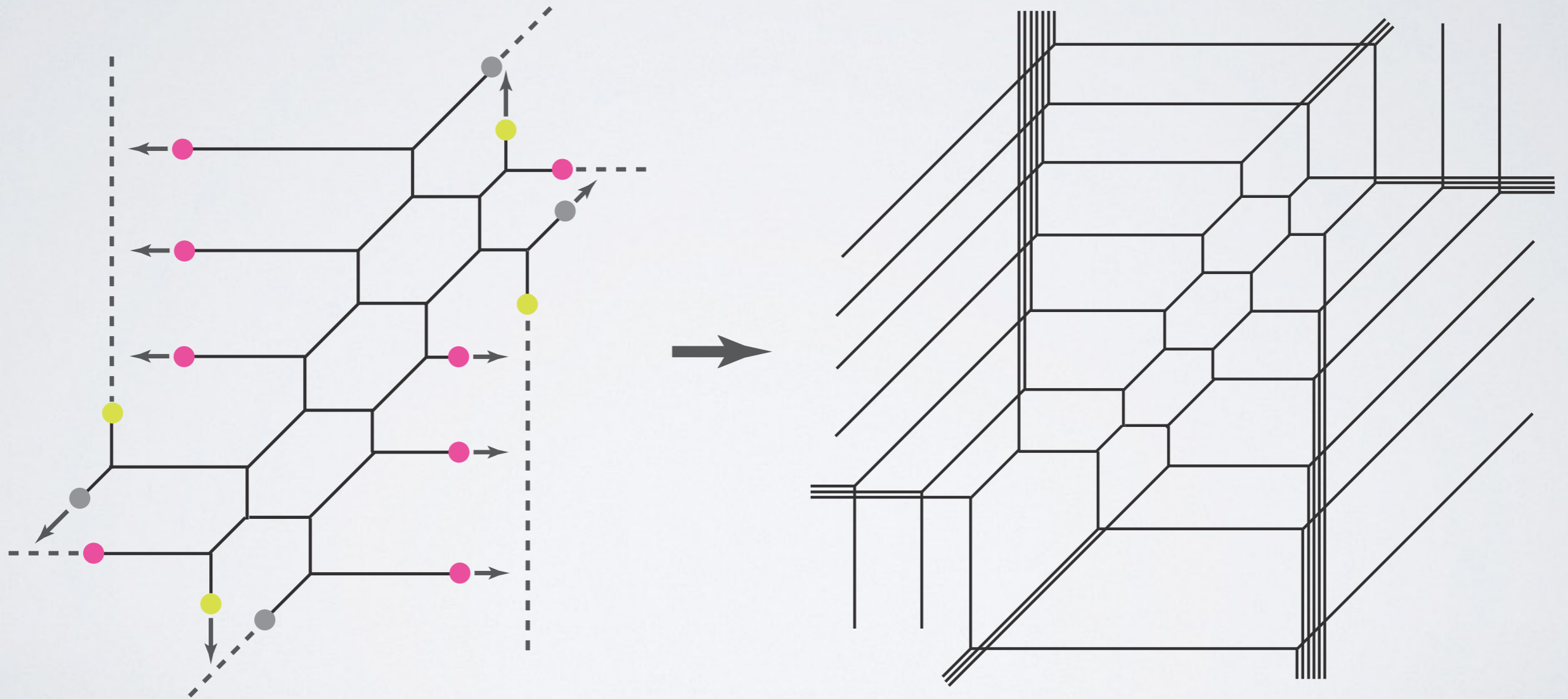
$\mathcal{T}$hree, $\mathcal{T}$hreshold, RS$\mathcal{T}$,

$\mathcal{T}$oric, $\mathcal{T}$rivalent,···

Mysterious 6d SCFTs of class T

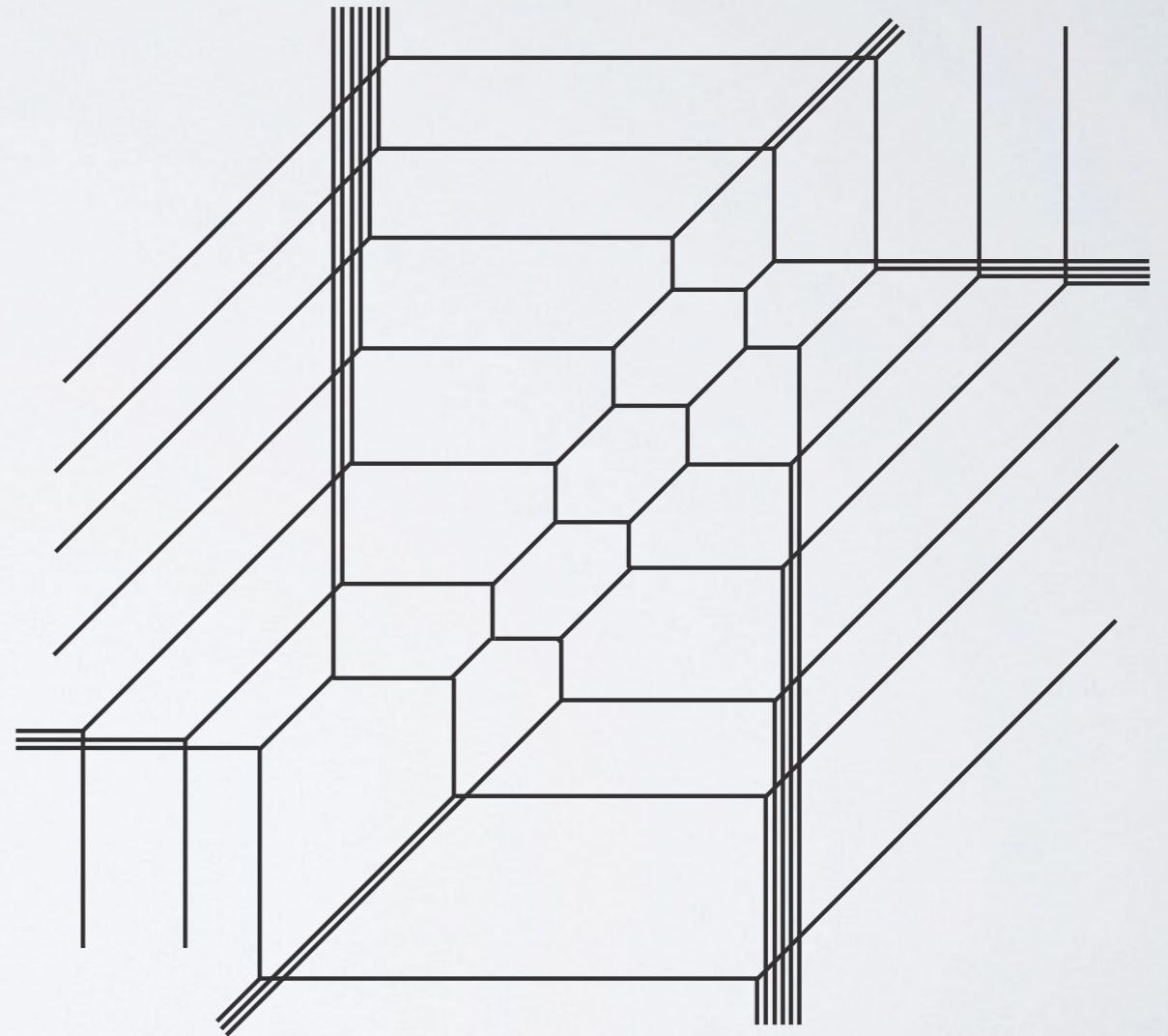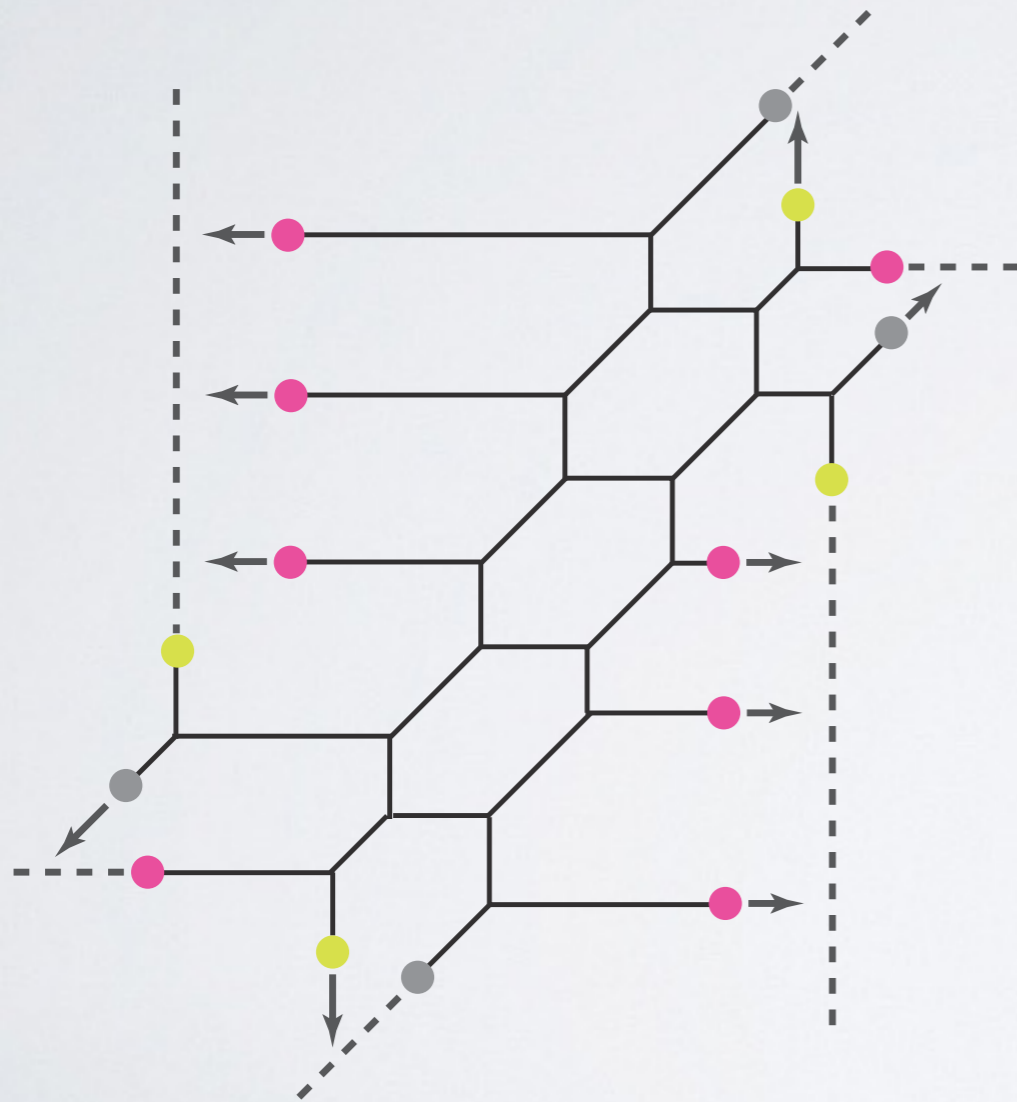## Beyond [Intriligator-Morrison-Seiberg '97]

6d Theories of class T

6d mysterious theory

Tao-nization of **SU(N) SQCD**

6d Theories of class T

6d mysterious theory

5d **SU(N)** **N$_f$=2N+4**

6d mysterious theory

5d SU(N>3) theories [Intriligator-Morrison-Seiberg '97]

"All" UV complete theories were classified.

6d Theories of class *T*

6d mysterious theory

5d SU(N>3) theories [Intriligator-Morrison-Seiberg '97]

$$N_f = \textcolor{magenta}{0, 1, \cdots, 2N}, 2N + 1, 2N + 2, 2N + 3, 2N + 4$$

5d SCFT

"dead" (Landau pole)

6d Theories of class *T*

6d mysterious theory (overlooked for 20 years)

5d SU(N>3) theories [Intriligator-Morrison-Seiberg '97]

$$N_f = 0, 1, \cdots, 2N, 2N+1, 2N+2, 2N+3, 2N+4$$
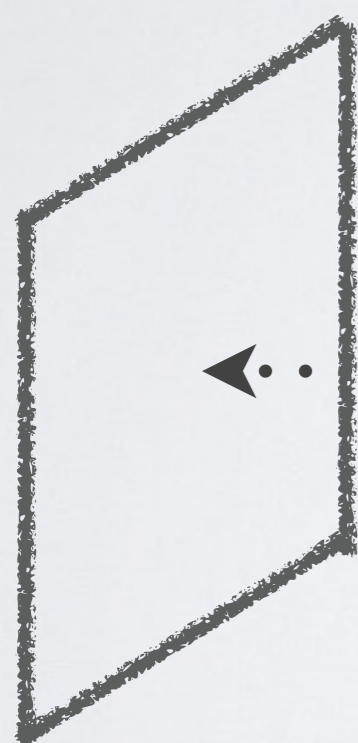
5d SCFT

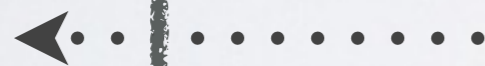**6d SCFT**

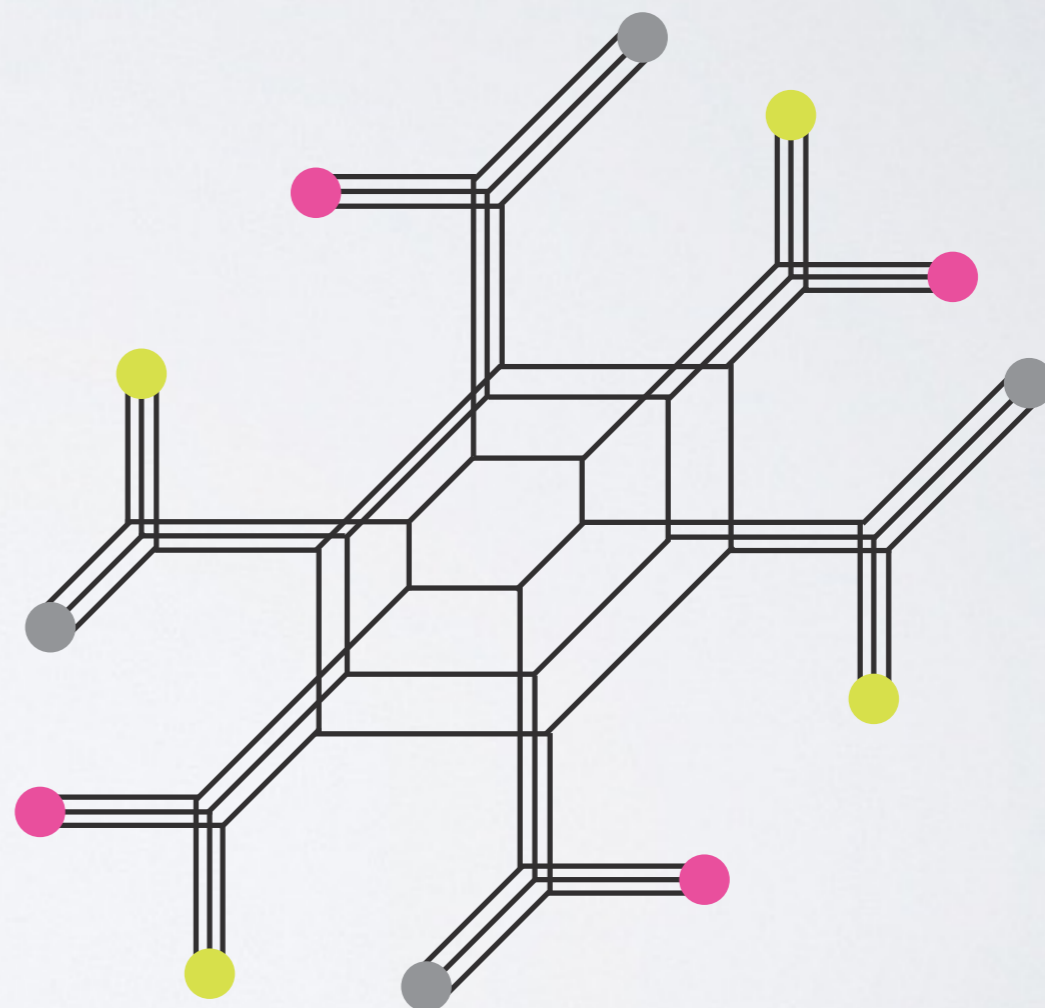⟶ **Yagi-san's next talk**

Infinitely many 6d SCFTs

higher-rank E-string (conjecture)
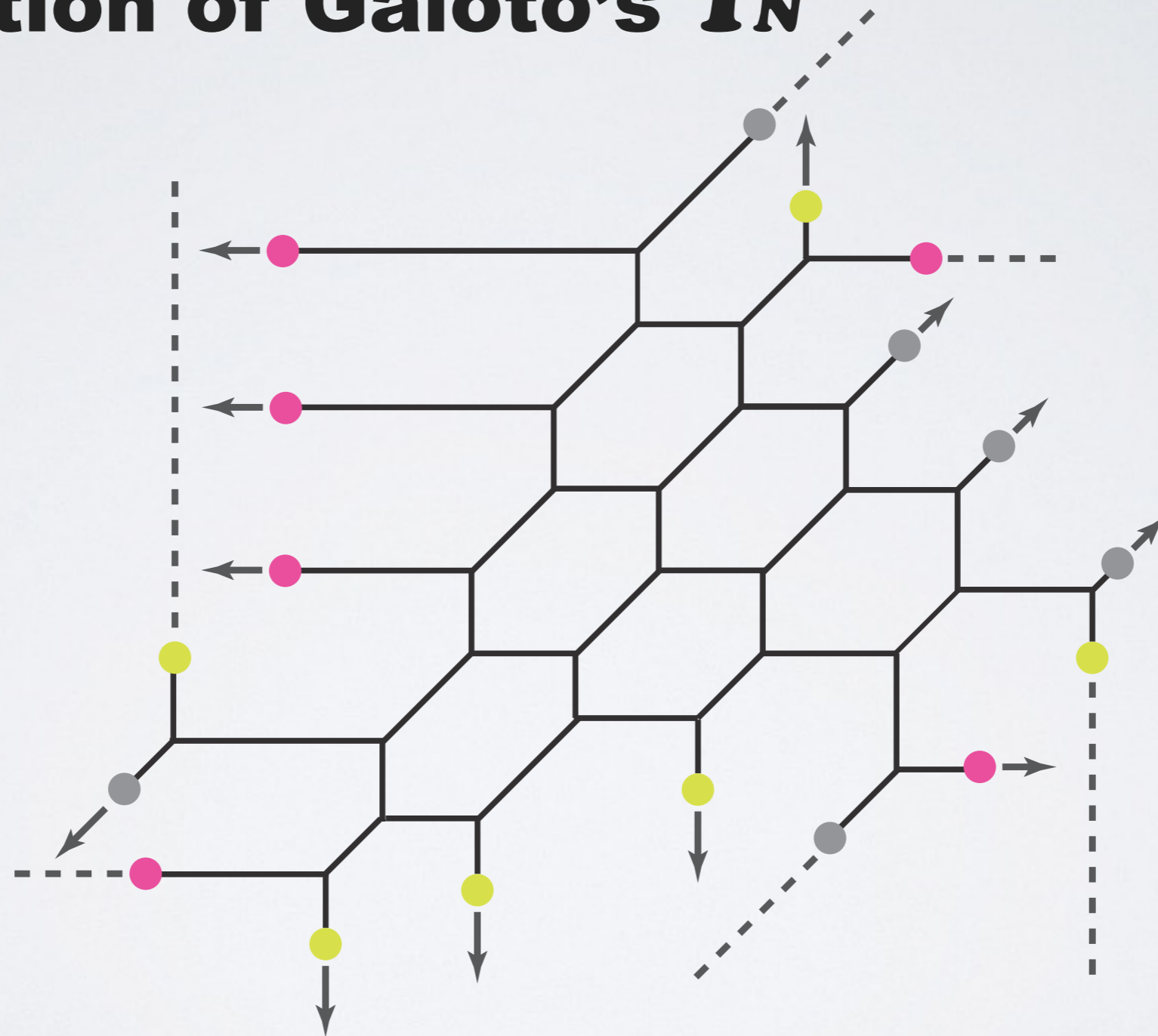
6d Theories of class *T*

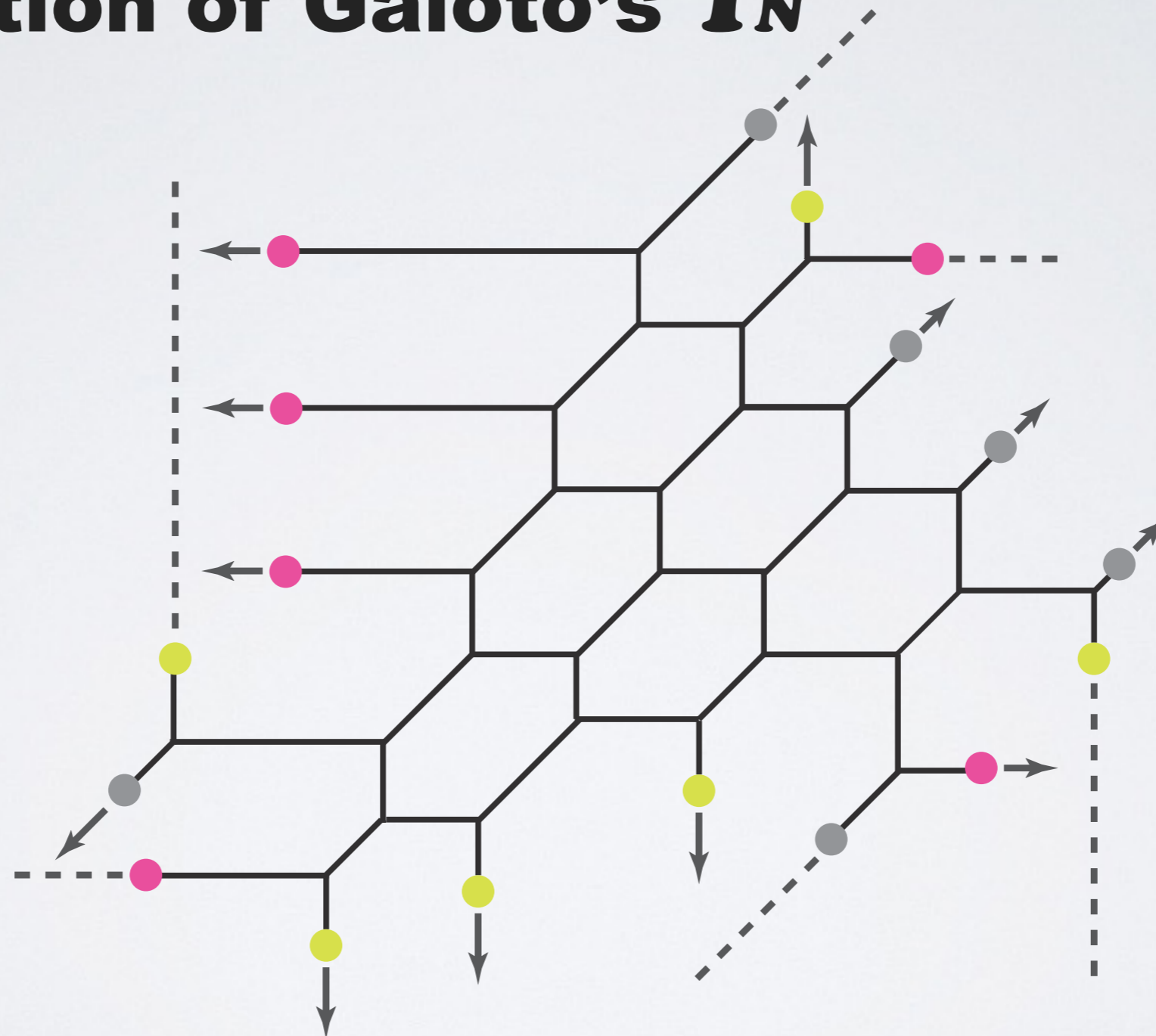## 6d more mysterious theory
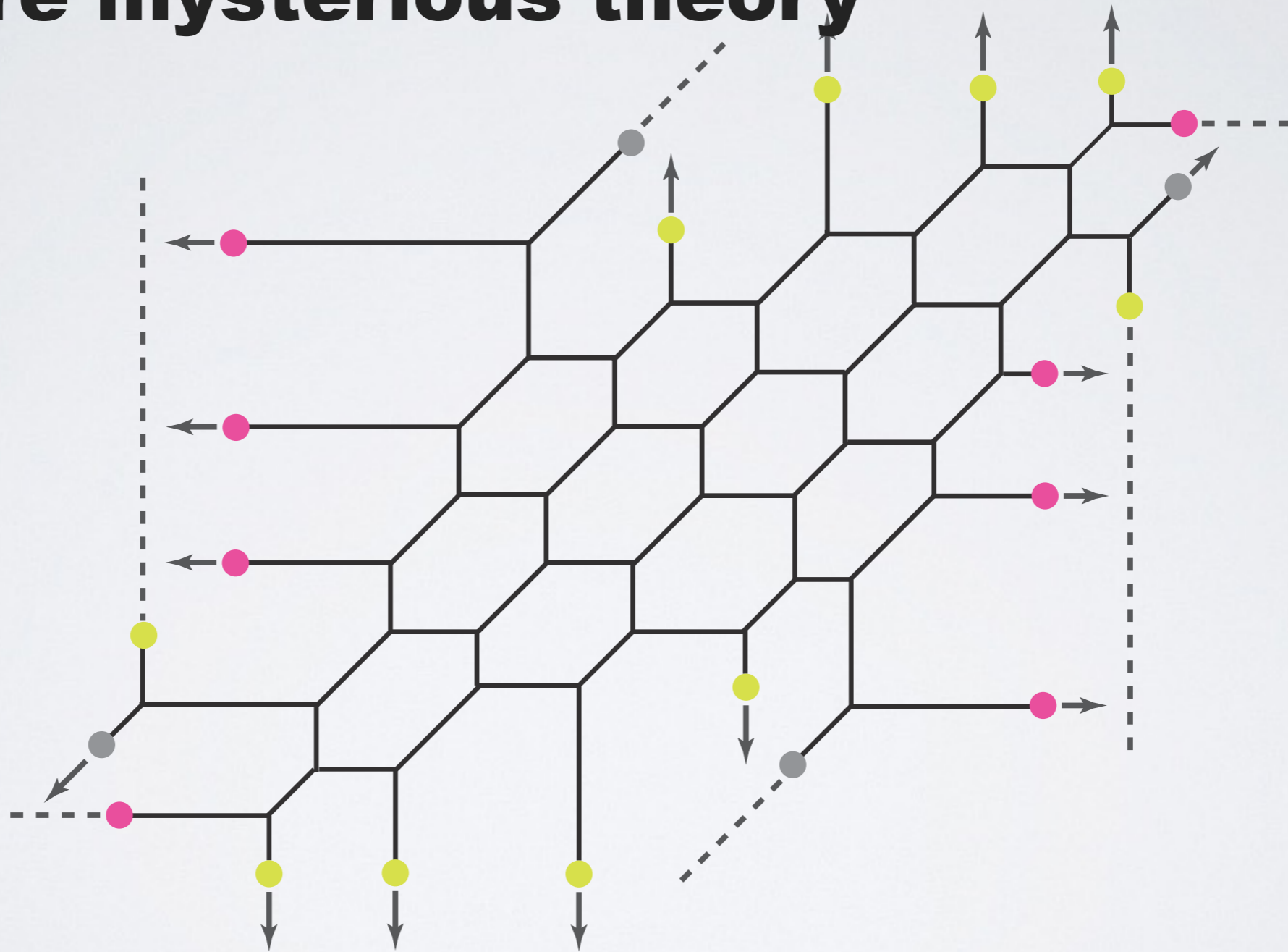
Tao-nization of SU(N) quiver

Tao-nization of Gaioto's T_N

6d Theories of class T

Tao-nization of Gaioto's T_N

more and more generalizations