Generalized Particle/Vortex Duality from Holography

Andreas Karch (University of Washington, Seattle)

work with Kyle Aitken and Andrew Baumgartner

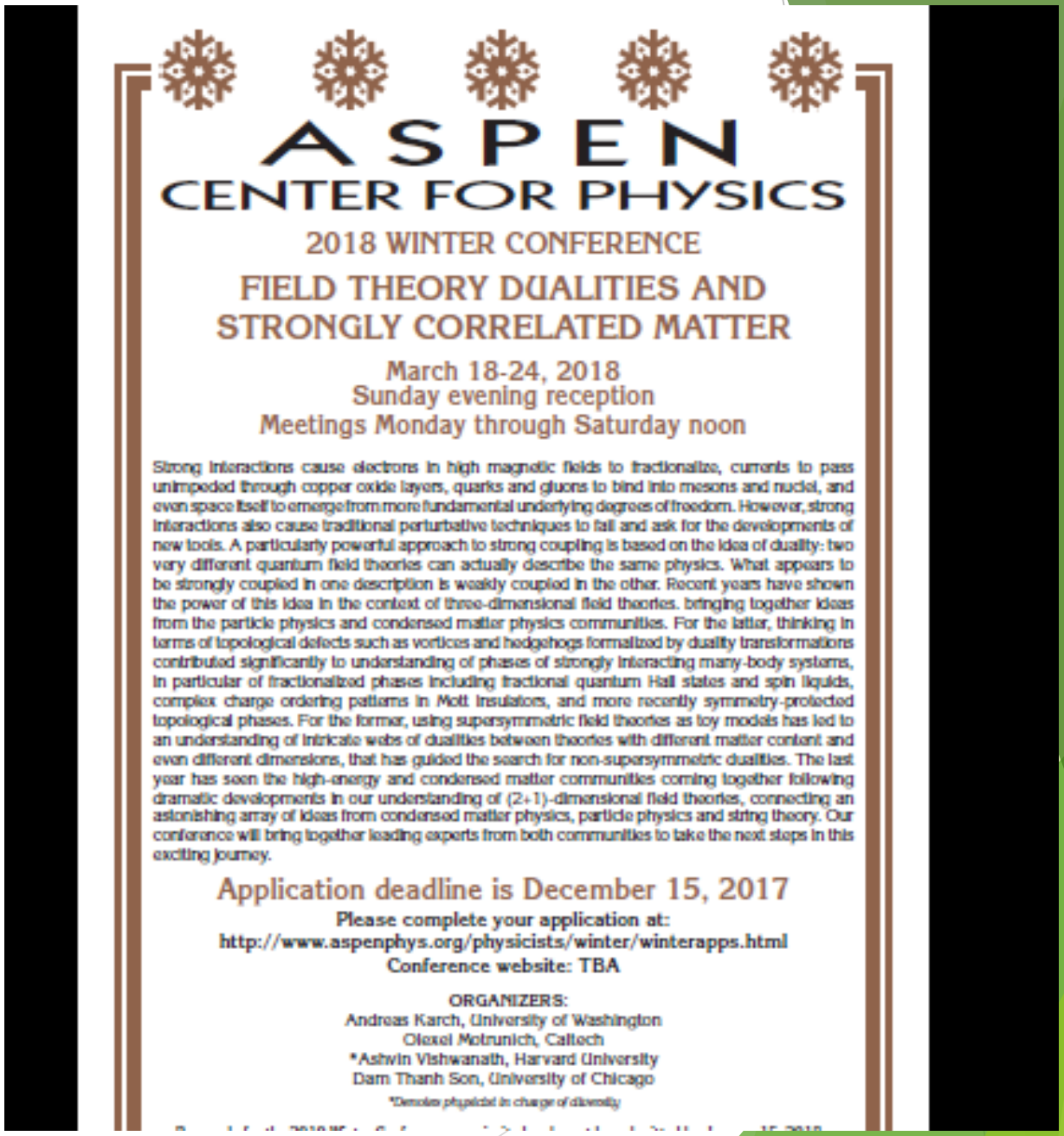
Talk at Gauge/Gravity duality 2018, Wuerzburg, August 2 2018

3d Dualities

The last few years have seen a "mini-revolution"
in our understanding of non-supersymmetric 2+1 dimensional field theories.

"90s – retro"

(just no SUSY)



ASPEN
CENTER FOR PHYSICS

2018 WINTER CONFERENCE

FIELD THEORY DUALITIES AND STRONGLY CORRELATED MATTER

March 18-24, 2018
Sunday evening reception
Meetings Monday through Saturday noon

Strong interactions cause electrons in high magnetic fields to fractionalize, currents to pass unimpeded through copper oxide layers, quarks and gluons to bind into mesons and nuclei, and even space itself to emerge from more fundamental underlying degrees of freedom. However, strong interactions also cause traditional perturbative techniques to fail and ask for the developments of new tools. A particularly powerful approach to strong coupling is based on the idea of duality: two very different quantum field theories can actually describe the same physics. What appears to be strongly coupled in one description is weakly coupled in the other. Recent years have shown the power of this idea in the context of three-dimensional field theories, bringing together ideas from the particle physics and condensed matter physics communities. For the latter, thinking in terms of topological defects such as vortices and hedgehogs formalized by duality transformations contributed significantly to understanding of phases of strongly interacting many-body systems, in particular of fractionalized phases including fractional quantum Hall states and spin liquids, complex charge ordering patterns in Mott insulators, and more recently symmetry-protected topological phases. For the former, using supersymmetric field theories as toy models has led to an understanding of intricate webs of dualities between theories with different matter content and even different dimensions, that has guided the search for non-supersymmetric dualities. The last year has seen the high-energy and condensed matter communities coming together following dramatic developments in our understanding of (2+1)-dimensional field theories, connecting an astonishing array of ideas from condensed matter physics, particle physics and string theory. Our conference will bring together leading experts from both communities to take the next steps in this exciting journey.

Application deadline is December 15, 2017

Please complete your application at:
http://www.aspenphys.org/physicists/winter/winterapps.html
Conference website: TBA

ORGANIZERS:
Andreas Karch, University of Washington
Olexei Motrunich, Caltech
*Ashvin Vishwanath, Harvard University
Dam Thanh Son, University of Chicago
*Denotes physicist in charge of diversity

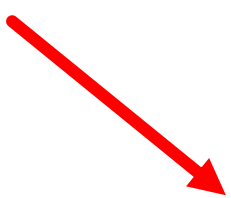
A miraculous meeting of minds

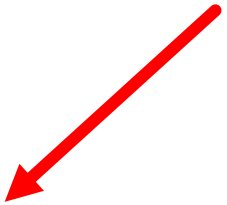
Different Chern-Simons matter theories have the same higher spin holographic duals.

(Giombi, Minwalla, Prakash, Trivedi, Wadia, Yin, Aharony, Gur-Ari, Yacoby)

Giving a particle hole symmetric description of the half-filled Landau level

(Son, Metlitski, Vishwanath, Wang, Senthil)

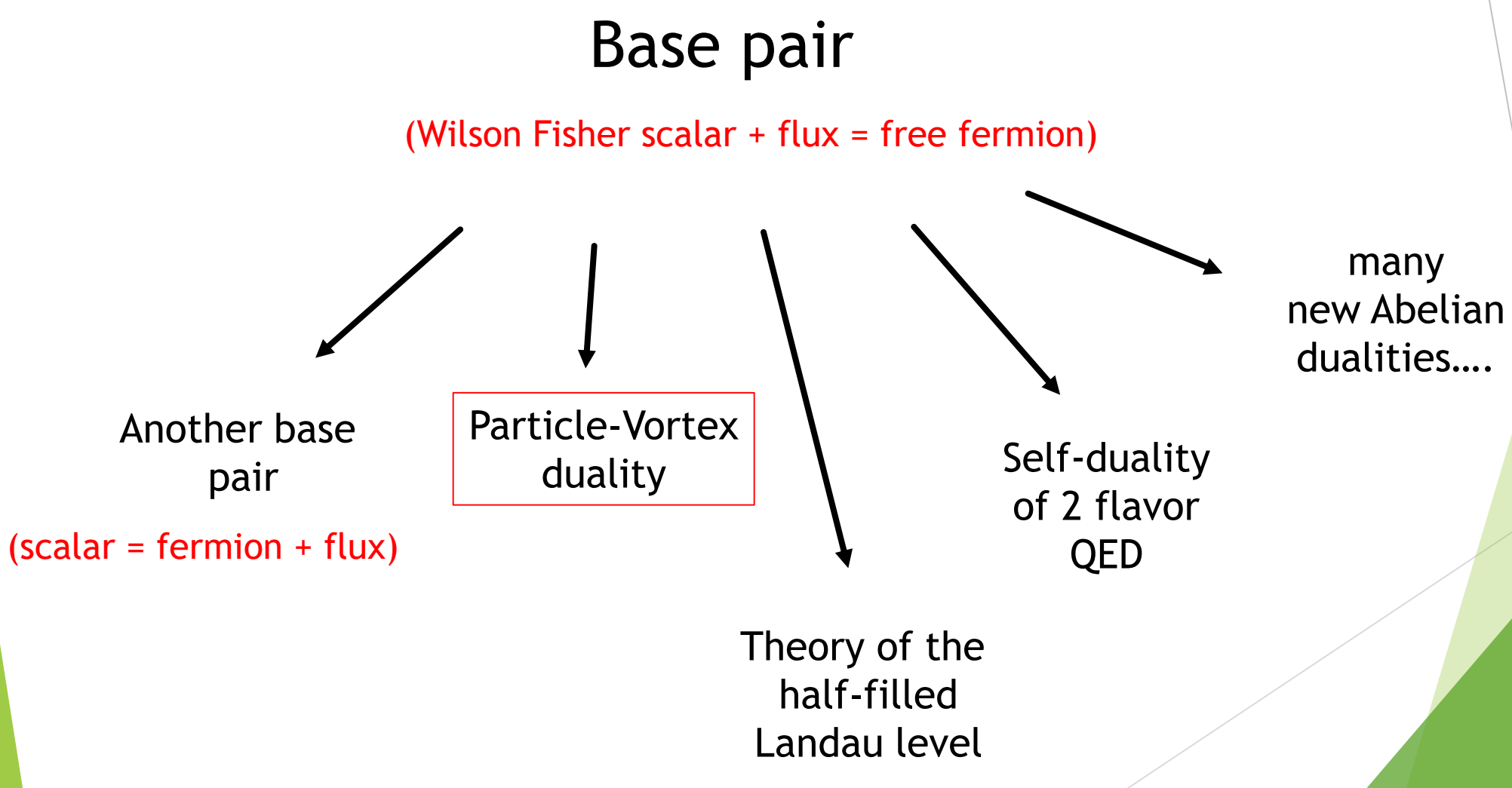




A rich web of non-SUSY dualities in 2+1 dimensions

Abelian Dualities

(Tong, AK, Seiberg, Senthil, Wang, Witten)



Particle-Vortex Duality

(Peskin '78, Dasgupta and Halperin '81)

Theory A:

Wilson-Fisher scalar

$$S = \int d^3x \; |(\partial_\mu - iA_\mu)\phi|^2 - V(\phi)$$

Theory B:

Abelian Higgs Model

$$S = \int d^3x \; |(\partial_\mu - ia_\mu)\Phi|^2 - \tilde{V}(\Phi) + \frac{1}{2\pi}\epsilon^{\mu\nu\rho} A_\mu \partial_\nu a_\rho$$

dynamical gauge field

background gauge field

Boson $\Longleftrightarrow$ **Monopole operator**

$$j^\mu = \epsilon^{\mu\nu\rho} F_{\nu\rho}$$

Well established, numerically confirmed

Non-Abelian case: 3d Bosonization

(Aharony, …)

$$SU(N)_{-k+N_f/2} \; with \; N_f \; fermions$$

$$\leftrightarrow$$

$$U(k)_N \; with \; N_f \; scalars$$

CS theory with scalar matter

= CS theory with fermionic matter

Abelian base pair is the $k=N=N_f=1$ case.

Non-Abelian case: Master duality

(Benini, Jensen)

$$SU(N)_{-k+N_f/2} \text{ with } N_f \text{ fermions and } N_s \text{ scalars}$$

$$\leftrightarrow$$

$$U(k)_{N-N_s/2} \text{ with } N_f \text{ scalars and } N_s \text{ fermions}$$

Crucial role played by Fermion^2 Scalar^2 coupling.
Scalar vev gives some fermions mass.

Evidence:

- Explicit calculations in ‘t Hooft large N limit
- Global symmetries and anomalies match
- Deformation of SUSY parents
- Lattice Construction
- massive phases from deformations agree

Topological Field theory of massive phases

CFT

relevant
deformation

gapped theory
(TFT)

Topological Field theory of massive phases

CFT

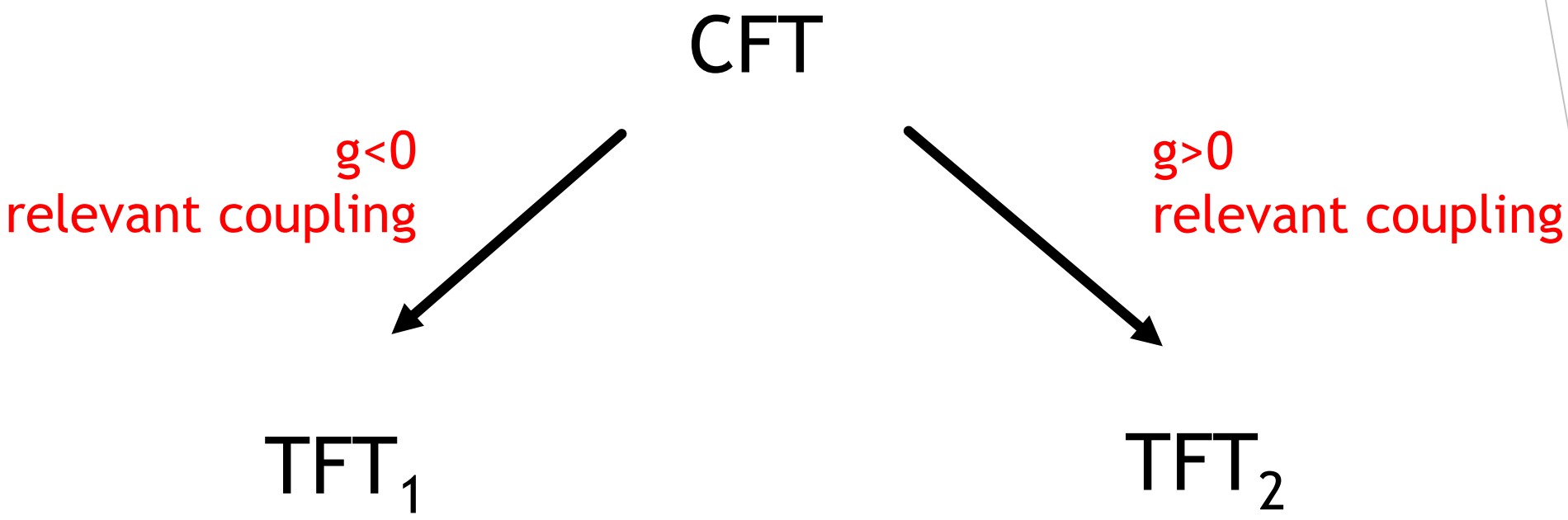
gapped theory (TFT)

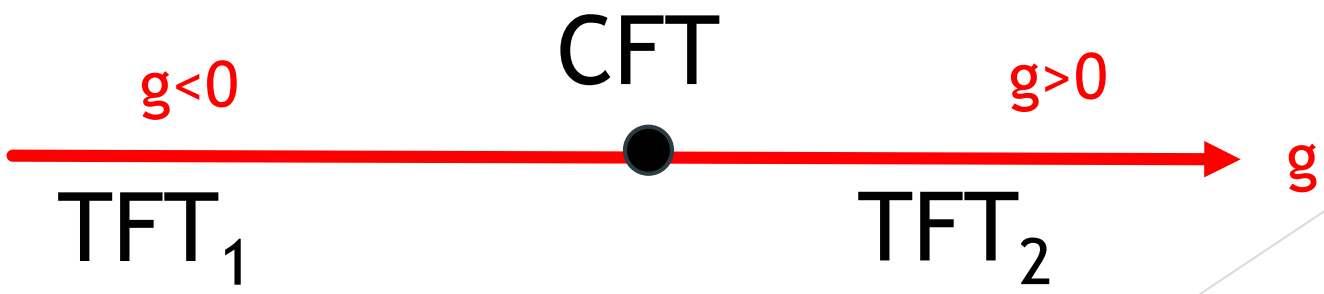
$U(k)_N \; with \; N_f \; scalars$

mass for all scalars

pure $U(k)_N \; CS$

Different phases depending on sign





Different phases depending on sign

$$U(k)_N \; with \; N_f \; scalars$$

$M^2<0$ $M^2>0$

$$U(k-N_f)_N \qquad U(k)_N$$

Scalars get vev
Higgsing of gauge group

Different phases depending on sign

$$SU(N)_{-k+N_f/2} \; with \; N_f \;\; fermions$$

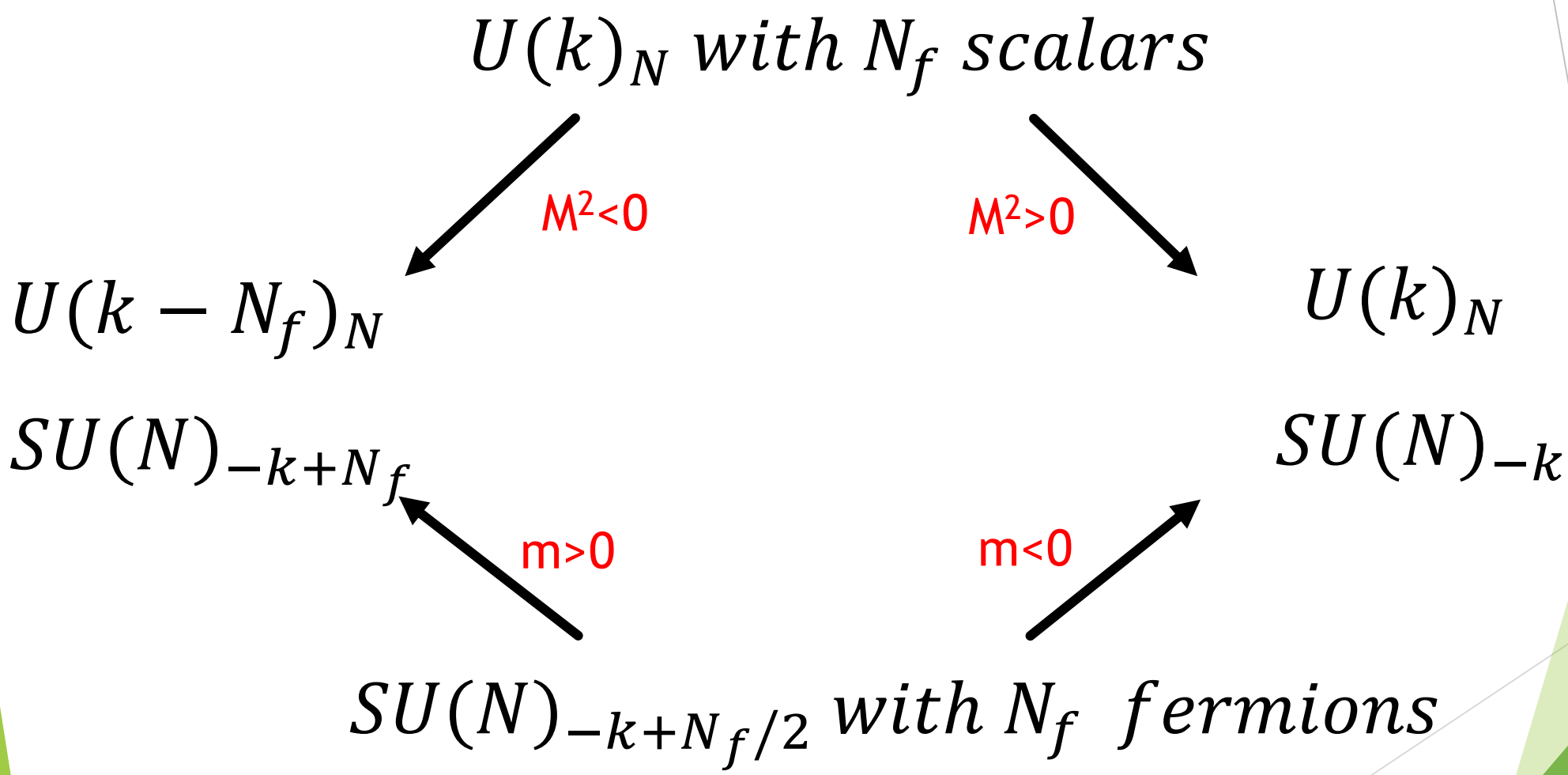
m>0

m<0

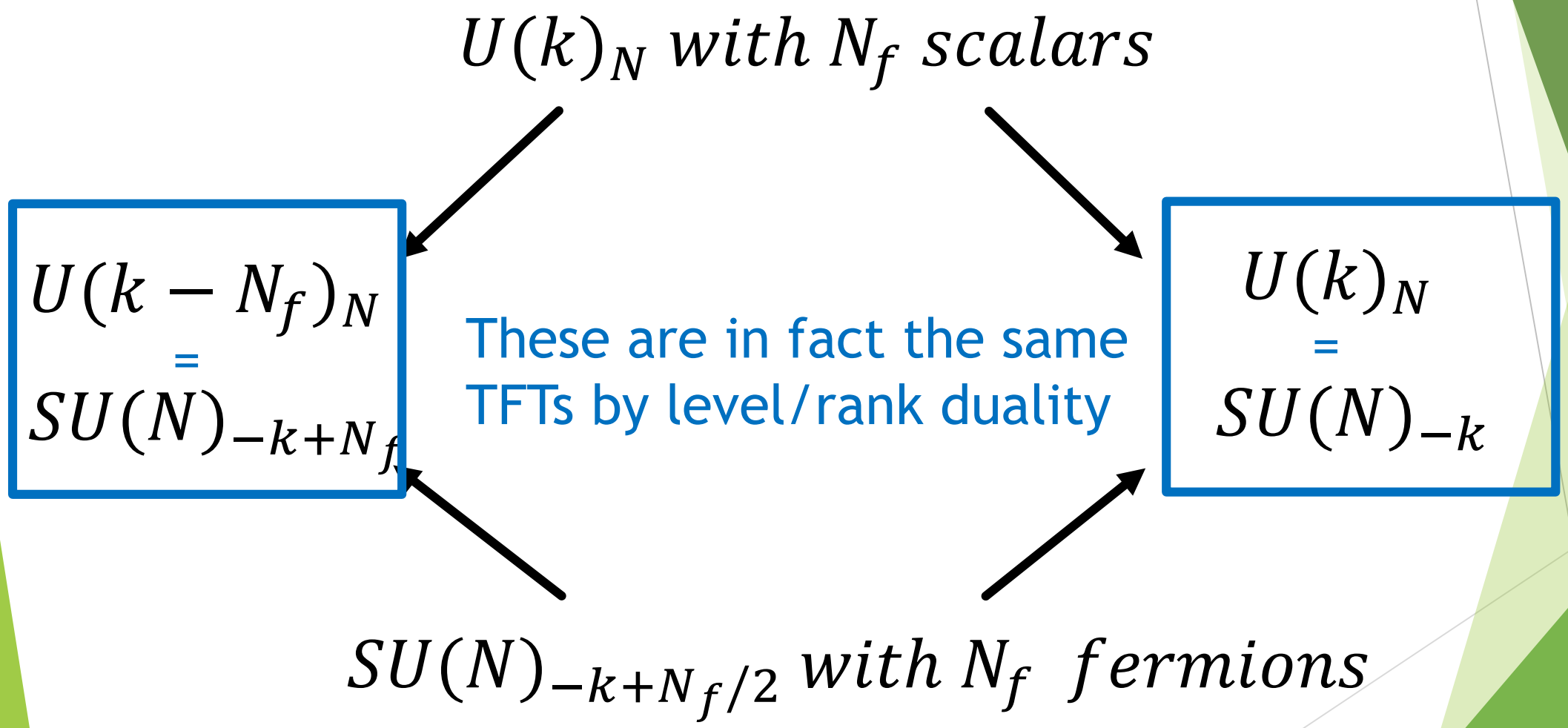
$$SU(N)_{-k+N_f} \qquad SU(N)_{-k}$$

- Heavy Fermions shift |CS| term by ½
- Sign depends on sign of m

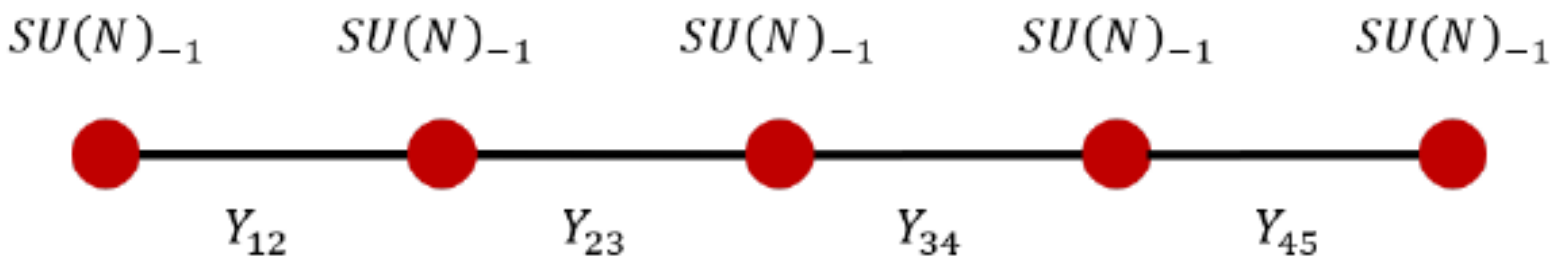
Different phases depending on sign



Different phases depending on sign



Generalized Particle/Vortex Duality



(k=5 nodes).

$\leftrightarrow$

$U(k)_N$ *with adjoint scalar*

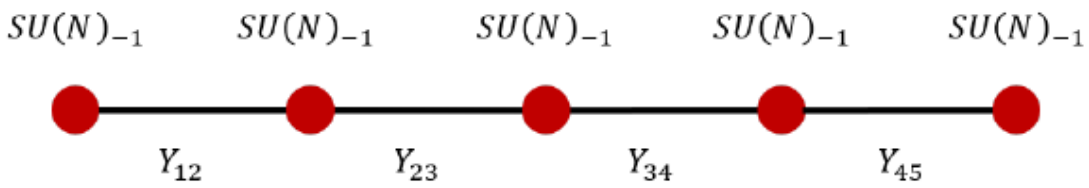
Evidence:

- Basic check: Phases agree
- “Derivation” from node-by-node duality
- Gauge/gravity duality = Particle/Vortex

Phase Matching:

quiver mass squareds	Quiver
all positive	$[SU(N)_{-1}]^k$
all negative	$SU(N)_{-k}$
mixed	$\prod_i SU(N)_{-n_i}$

$\{n_i\}$: Partition of k



Phase Matching:

Vacua=Eigenvalues of X

$\underline{U(k)_N + \text{adjoint}}$

all different
(like D-brane physics)

$[U(1)_N]^k$

vev vanishes (positive mass only)

$U(k)_N$

some eigenvalues conicide

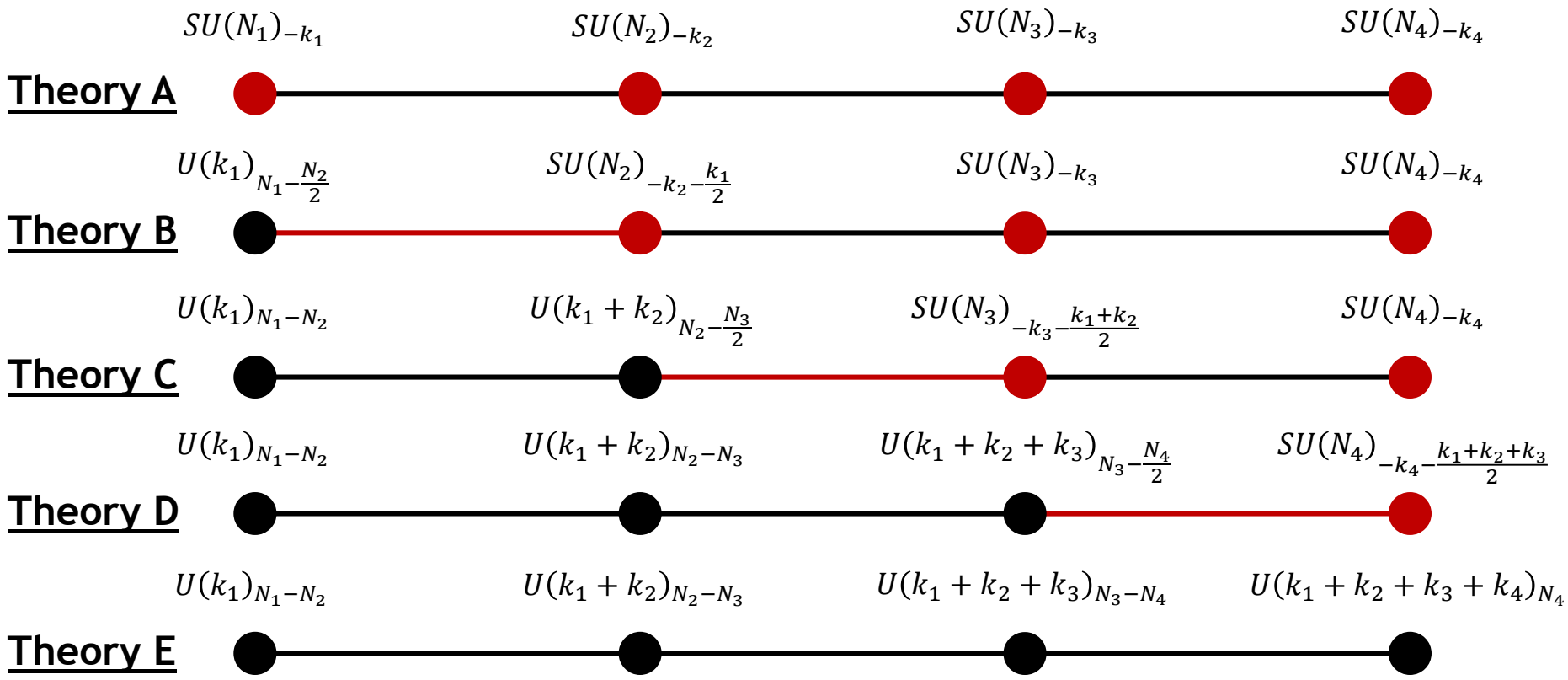
$\prod_i U(n_i)_N$

Phase Matching:

Quiver		$U(k)_N$ + adjoint
$[SU(N)_{-1}]^k$	$\longleftrightarrow$	$[U(1)_N]^k$
$SU(N)_{-k}$	$\longleftrightarrow$	$U(k)_N$
$\prod_i SU(N)_{-n_i}$	$\longleftrightarrow$	$\prod_i U(n_i)_N$

Node by node duality:

(following earlier work with Jensen)



SU gauge group

U gauge group

Boson

Fermion

Node by node duality:

Theory A: $SU(N_1)_{-k_1} \times SU(N_2)_{-k_2} \times SU(N_3)_{-k_3} \times SU(N_4)_{-k_4}$.

Theory E: $U(k_1)_{N_1-N_2} \times U(k_1+k_2)_{N_2-N_3} \times U(k_1+k_2+k_3)_{N_3-N_4} \times U(k_1+k_2+k_3+k_4)_{N_4}$

- If all ranks (N_i) are equal in theory A, all but one level is 0 in theory E.
- All but last node confine
- Bifundamental scalars turn into adjoint "meson"
- 2 nodes, $N_1=N_2=k_1=1$, $k_2=0$ is standard PV

Derivation from Holography:

General Strategy for getting 3d dualities from Holography:

(Fujita, Li, Ryu Takayanagi, AK, Jensen)

- Start with known holographic dual for confining gauge theory
- Low energy physics trivial. All gravitational excitations gapped
- Add a few non-trivial IR excitations e.g. via probe brane
  Both boundary and bulk become 3d field theory.

Level/Rank: $SU(N)_{-k}$ from N=4 SYM

Step 1:

- **Start with N=4 SYM on circle**
- **Anti-periodic BC for fermions** ← **Massive**
- **Scalars get mass via loop**
- **3d SU(N) YM + massive matter**
- **3d theory with Mass gap**
- **No non-trivial dynamics in IR**

$SU(N)_{-k}$ from N=4 SYM

Step 2:

Let theta vary linearly with y

$$\theta = 2\,\pi\,k\,y/L$$

$$y \to y + L \;\; \Rightarrow \;\; \theta \to \;\; \theta + 2\,\pi\,k$$

$$\int dy\,\theta\,F \wedge F = -2\pi\,k\,A \wedge F$$

CS term at level -k

$SU(N)_{-k}$ from N=4 SYM

UV $SU(N)\ SYM\ in\ 3+1$

circle w/
antiperiodic BC and
linear theta angle:

IR pure $SU(N)_{-k}\ CS$

Non-trivial topological field theory

Holographic embedding of level/rank

N=4 SYM has holographic dual description as type IIB on $AdS_5 \times S^5$

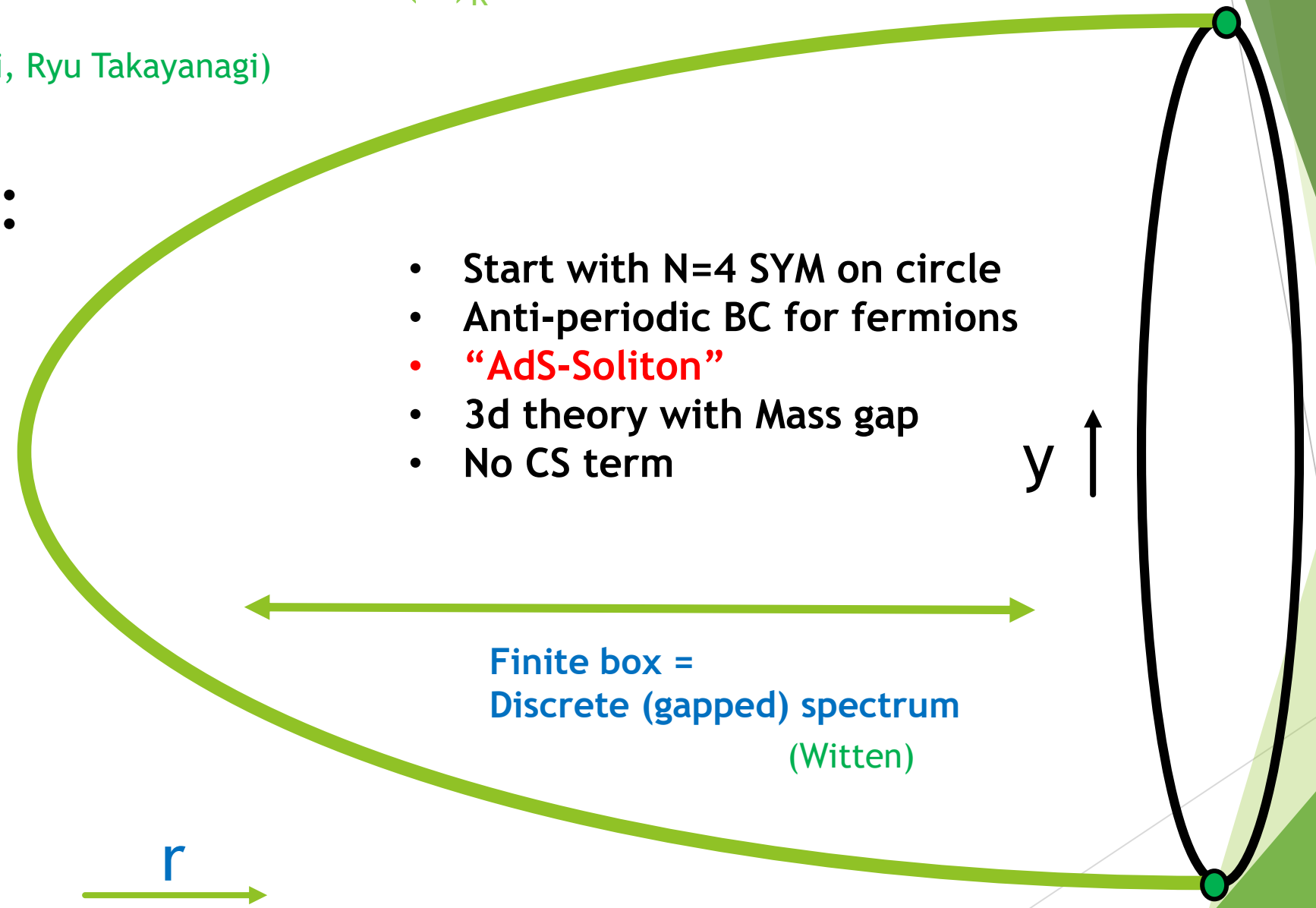
All we need to do is implement step 1 and 2 also in the holographic dual

Stringy Realization of $SU(N)_k$

(Fujita, Li, Ryu Takayanagi)

Step 1:

- Start with N=4 SYM on circle
- Anti-periodic BC for fermions
- "AdS-Soliton"
- 3d theory with Mass gap
- No CS term

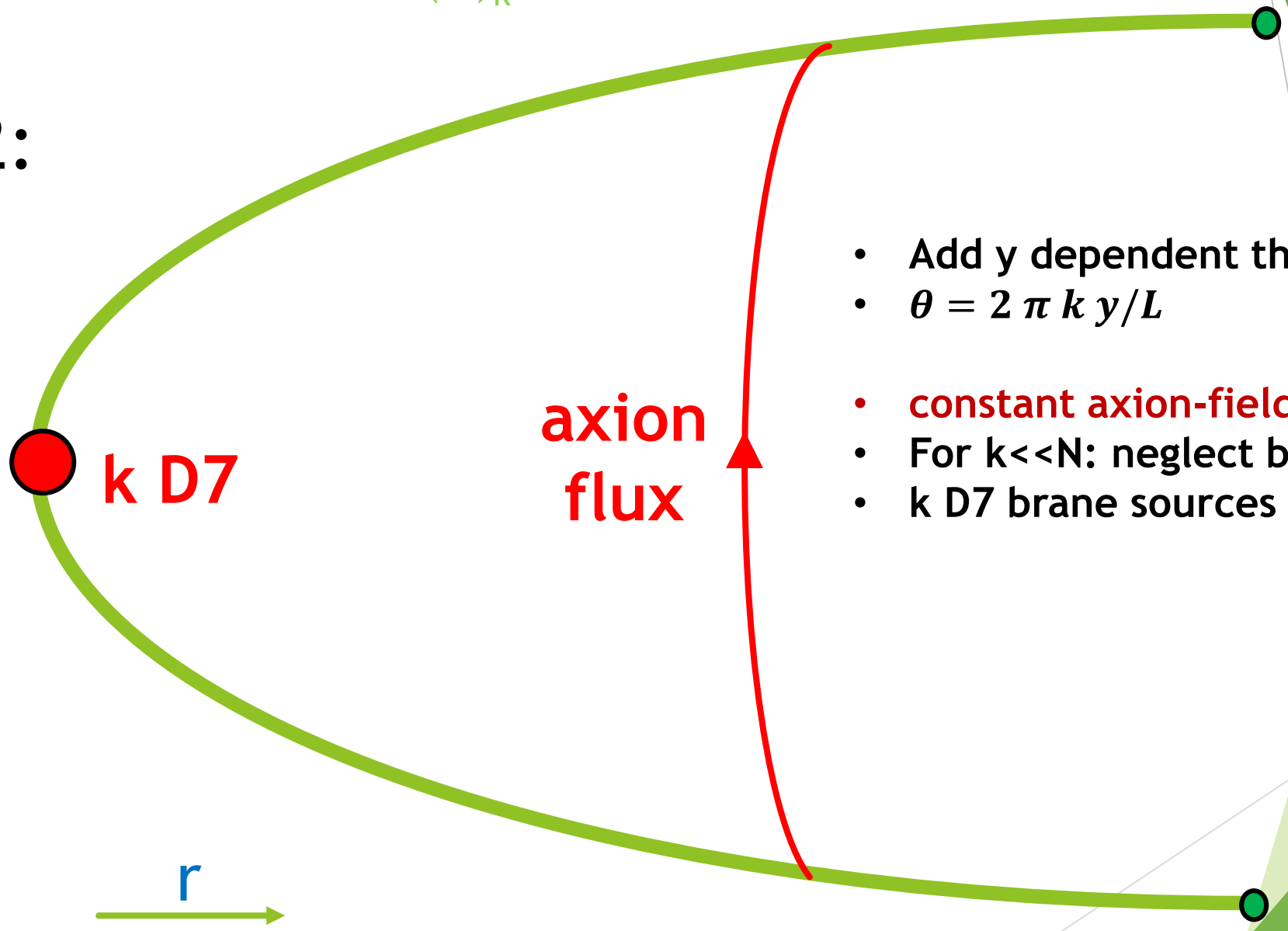


Finite box =
Discrete (gapped) spectrum

(Witten)

Stringy Realization of $SU(N)_k$

Step 2:

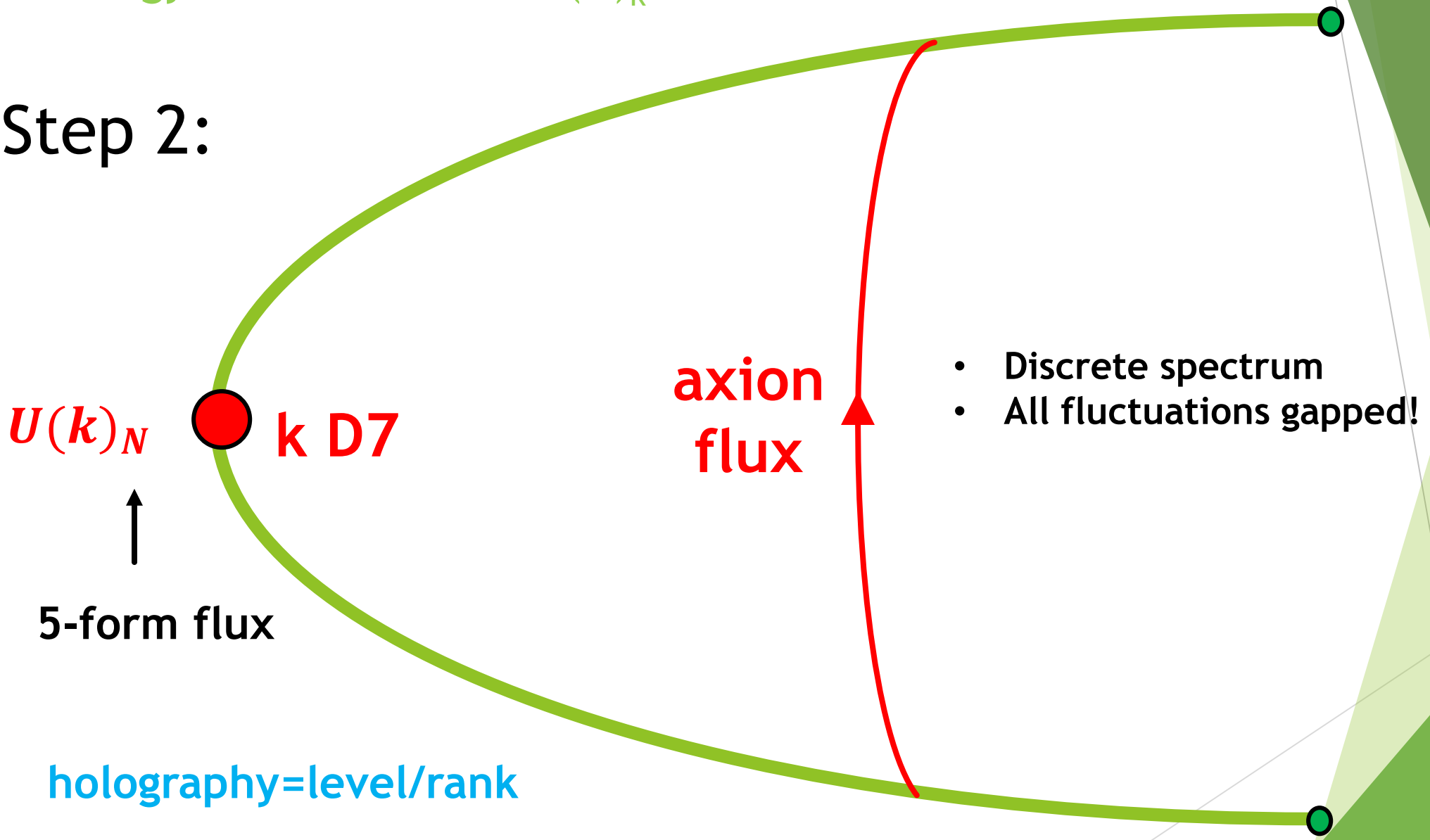


- Add y dependent theta angle
- $\theta = 2\,\pi\,k\,y/L$

- constant axion-field strength
- For k<<N: neglect backreaction
- k D7 brane sources needed

Stringy Realization of $SU(N)_k$

Step 2:



- Discrete spectrum
- All fluctuations gapped!

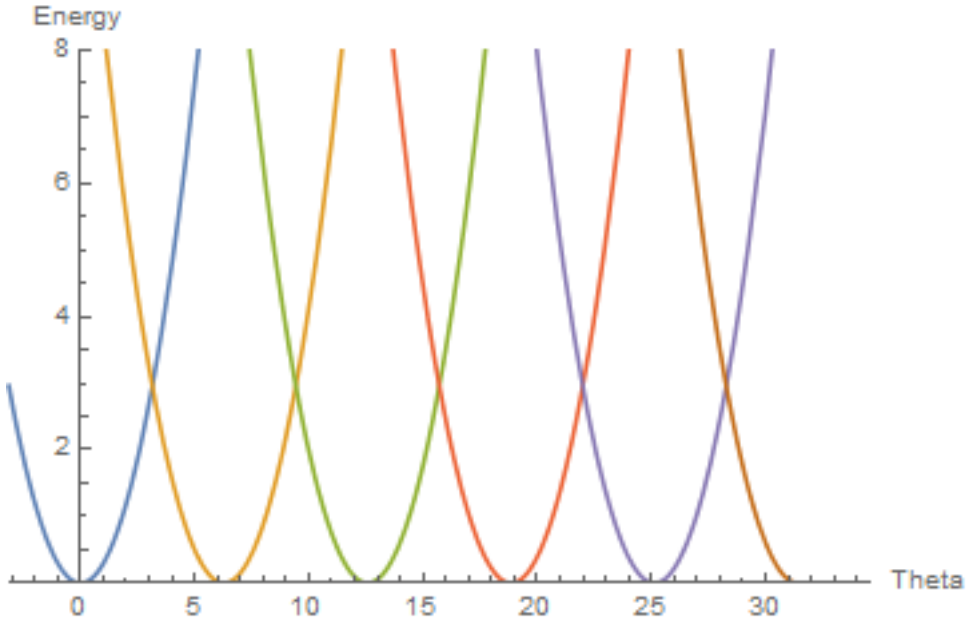
holography=level/rank

To get 3d bosonization simply add flavor branes (Jensen, AK).

Linear quiver from Holography

Confining 3+1 dimensional gauge theory has multiple vacua related to theta angle.

(Witten)

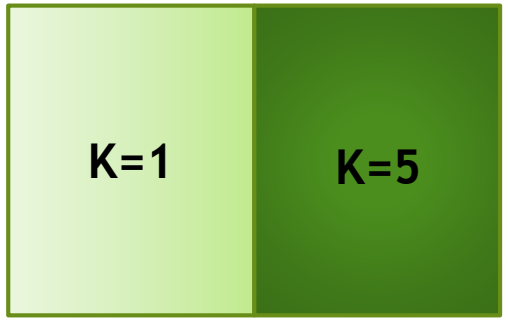


Can build interface or domain walls across which $\theta + 2\pi K$ jumps.

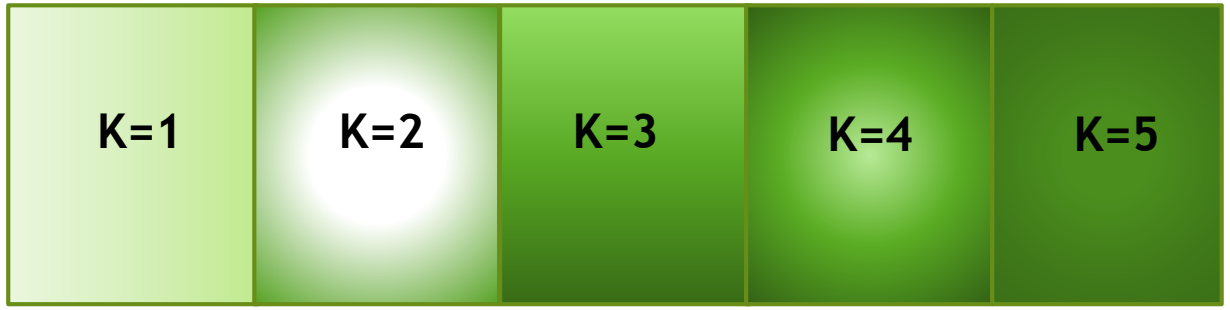
(Gaiotto, Komargodski,Seiberg)

Linear quiver from Holography

(Gaiotto, Komargodski,Seiberg)



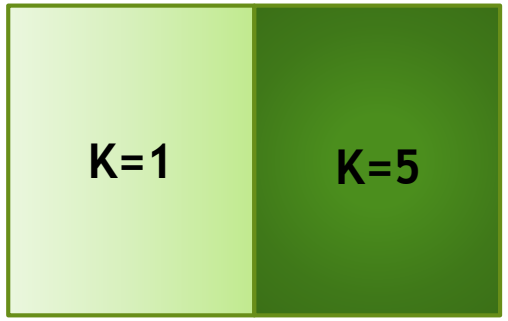
$$SU(N)_{-5}$$



$$[SU(N)_{-1}]^5$$

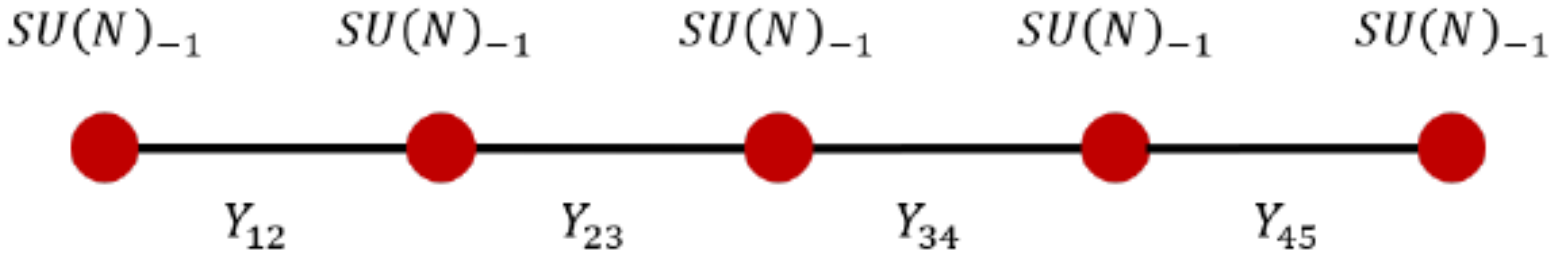
Linear quiver from Holography

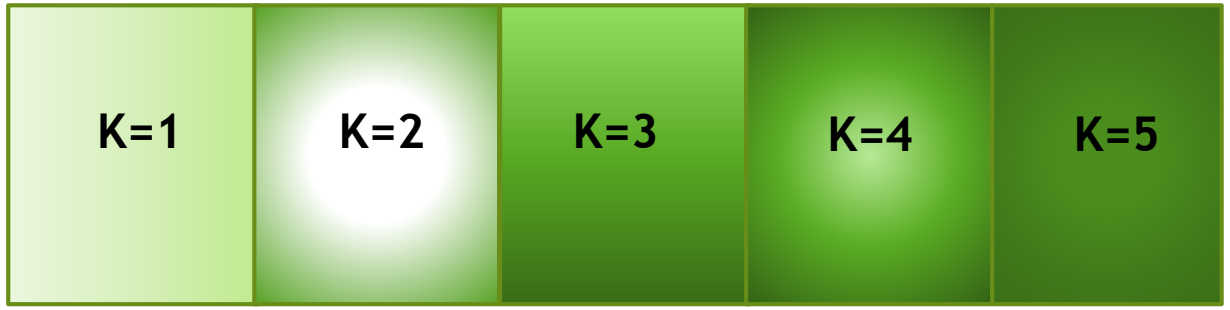
(Gaiotto, Komargodski,Seiberg)



$SU(N)_{-5}$

In between:

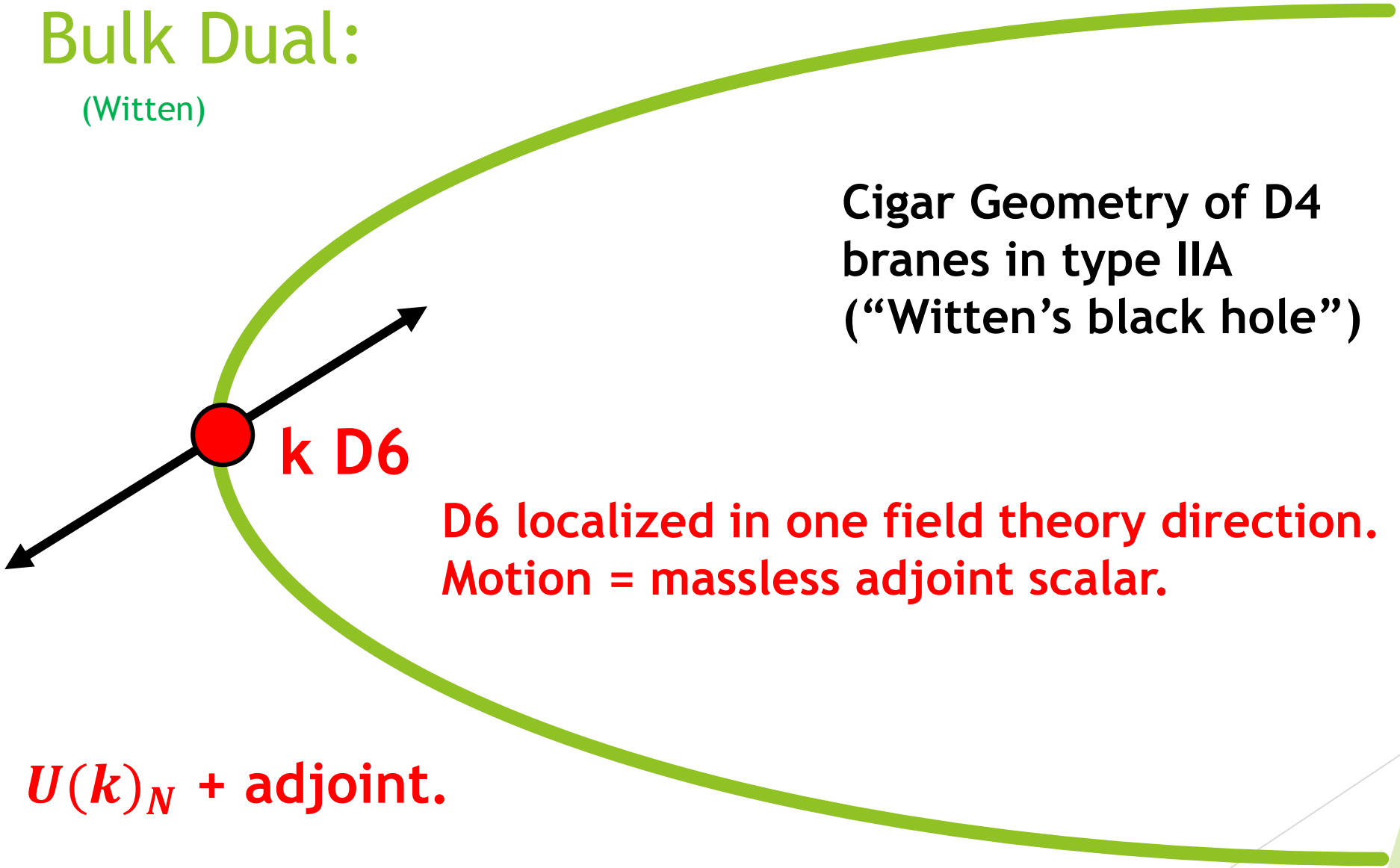




$[SU(N)_{-1}]^5$

Bulk Dual:

(Witten)

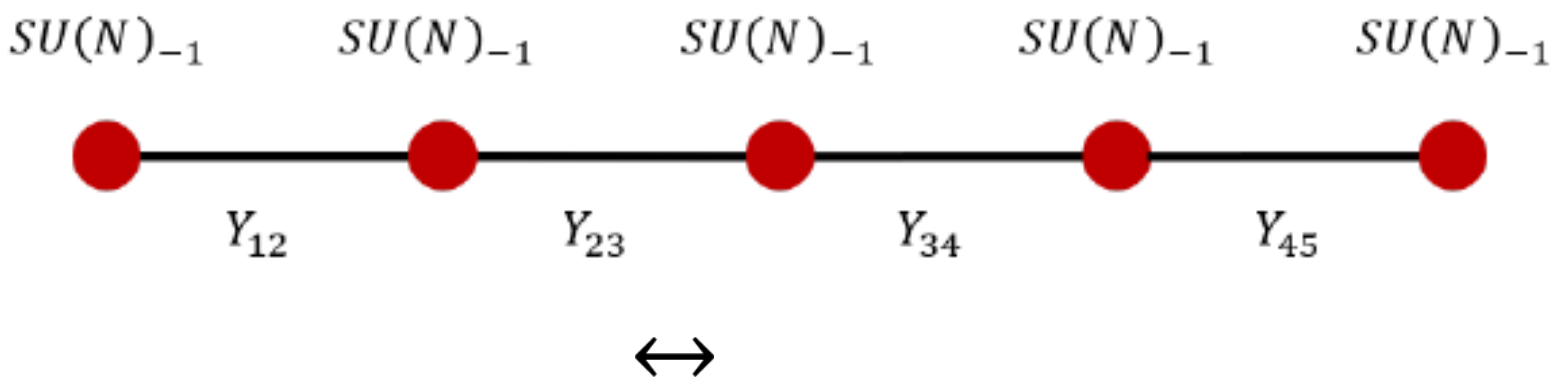


Cigar Geometry of D4 branes in type IIA ("Witten's black hole")

D6 localized in one field theory direction.
Motion = massless adjoint scalar.

$U(k)_N$ + adjoint.

Summary:



$\leftrightarrow$

$U(k)_N$ *with adjoint scalar*

From Gauge/Gravity duality.