Hidden Local Symmetry as magnetic gauge theory

Ryuichiro Kitano (KEK, Sokendai)

celebration of 30th anniversary of Hidden Local Symmetry in QCD

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Vector mesons as gauge bosons

It is probably necessary that the vector mesons are described as the gauge bosons if there is an effective field theory description for them.

Sakurai 60's

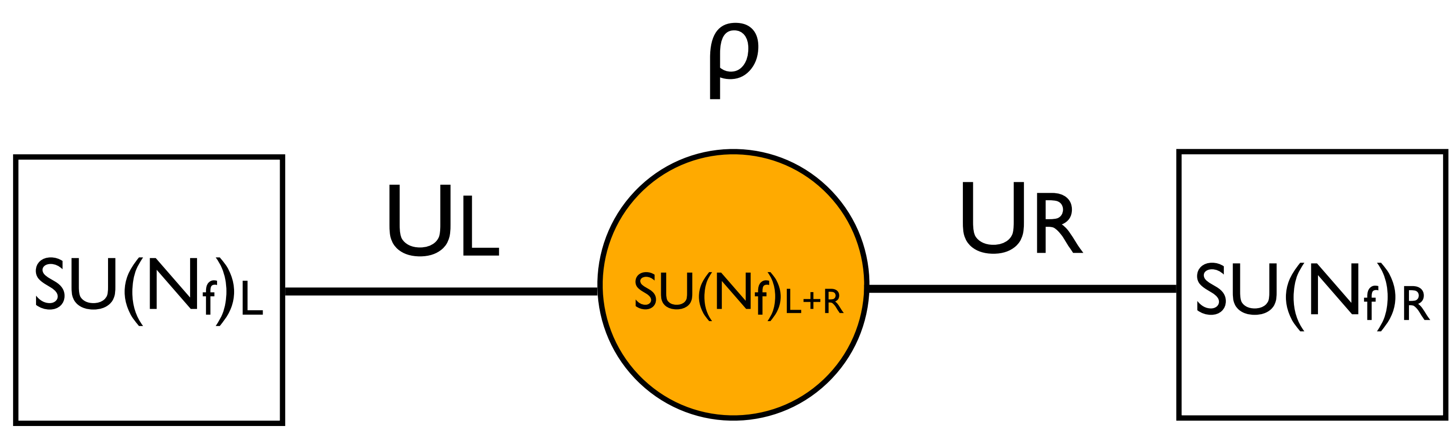
Bando, Kugo, Uehara, Yamawaki, Yanagida '85

Son, Stephanov '03

Sakai, Sugimoto '04

Hidden Local Symmetry

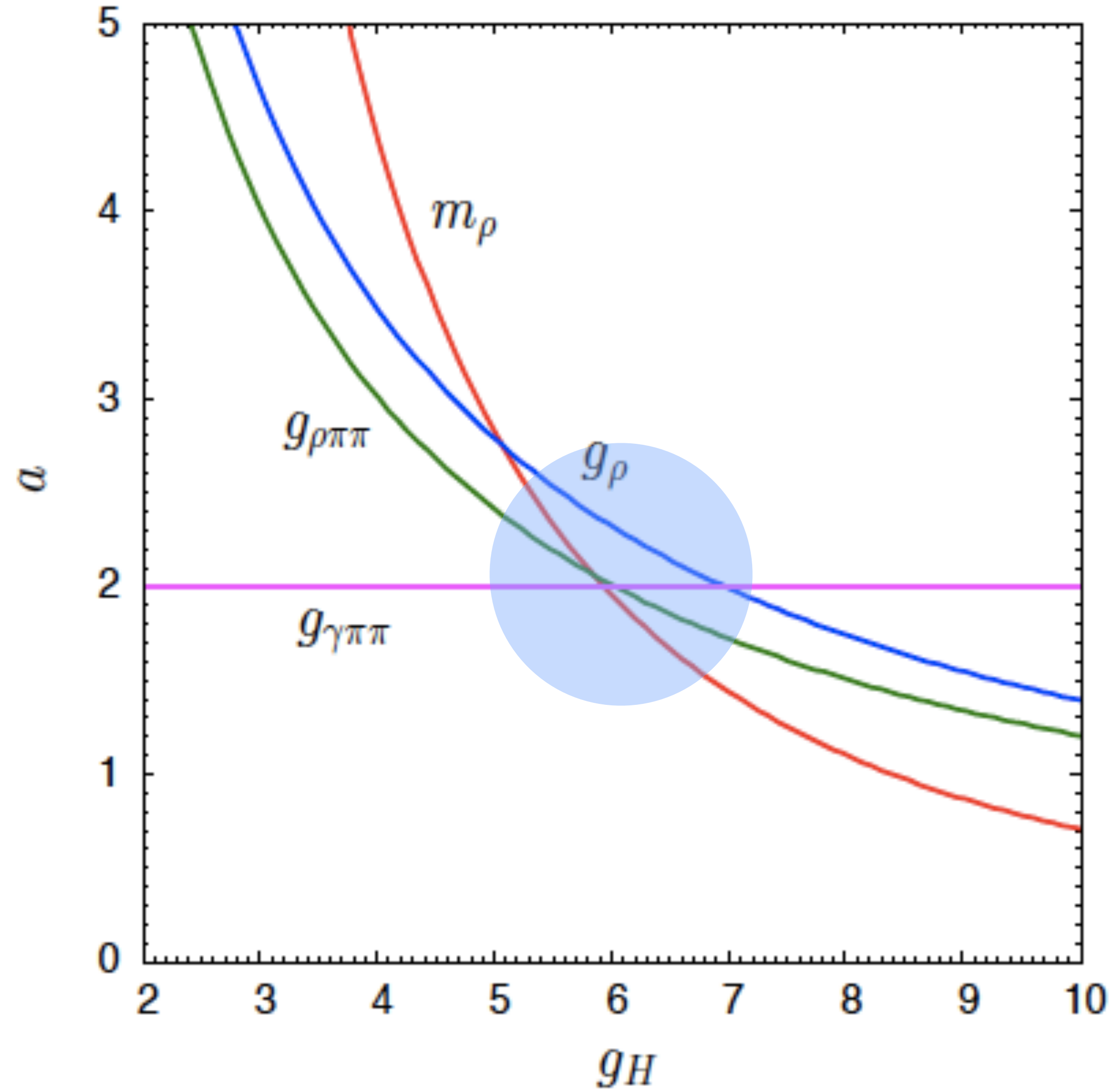
[Bando, Kugo, Uehara, Yamawaki, Yanagida '85]



$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4g_H^2} F^a_{\mu\nu} F^{a\mu\nu} \\
& + \frac{a f_\pi^2}{2} \mathrm{tr}\left[|D_\mu U_L|^2 + |D_\mu U_R|^2 \right] \\
& + \frac{(1-a) f_\pi^2}{4} \mathrm{tr}\left[|\partial_\mu (U_L U_R)|^2 \right] .
\end{aligned}
$$

Two-parameter model for π-ρ-γ system.

It is quite successful.



Maybe there is an effective description.

In this talk,

We discuss the possibility that the relation
between the QCD and
the Hidden Local Symmetry
is the electric-magnetic duality.

ρ meson = magnetic gauge boson?

[Komargodski '10][RK '11]
[Harada, Yamawaki '99]

Crazy?

This isn't necessarily a crazy idea.

- Hidden Local Symmetry (ρ meson as a gauge boson)
- Seiberg duality (Low energy description of UV free gauge theory as IR free magnetic gauge theory)

Unification

ρ meson = magnetic gauge boson?

This provides us with a unified picture of hadron world.

$$\langle \bar{q} q \rangle \neq 0 \leftrightarrow \langle \bar{m} m \rangle \neq 0$$

chiral symmetry breaking

electric-magnetic duality

(non-abelian) monopole condensation

= confinement

trial

If the ρ/ω meson are the magnetic gauge boson,
the string made of the mesons should
be the confining string.

Linear potential

[Nambu'74, Mandelstam '75, 't Hooft '75]

linearized HLS

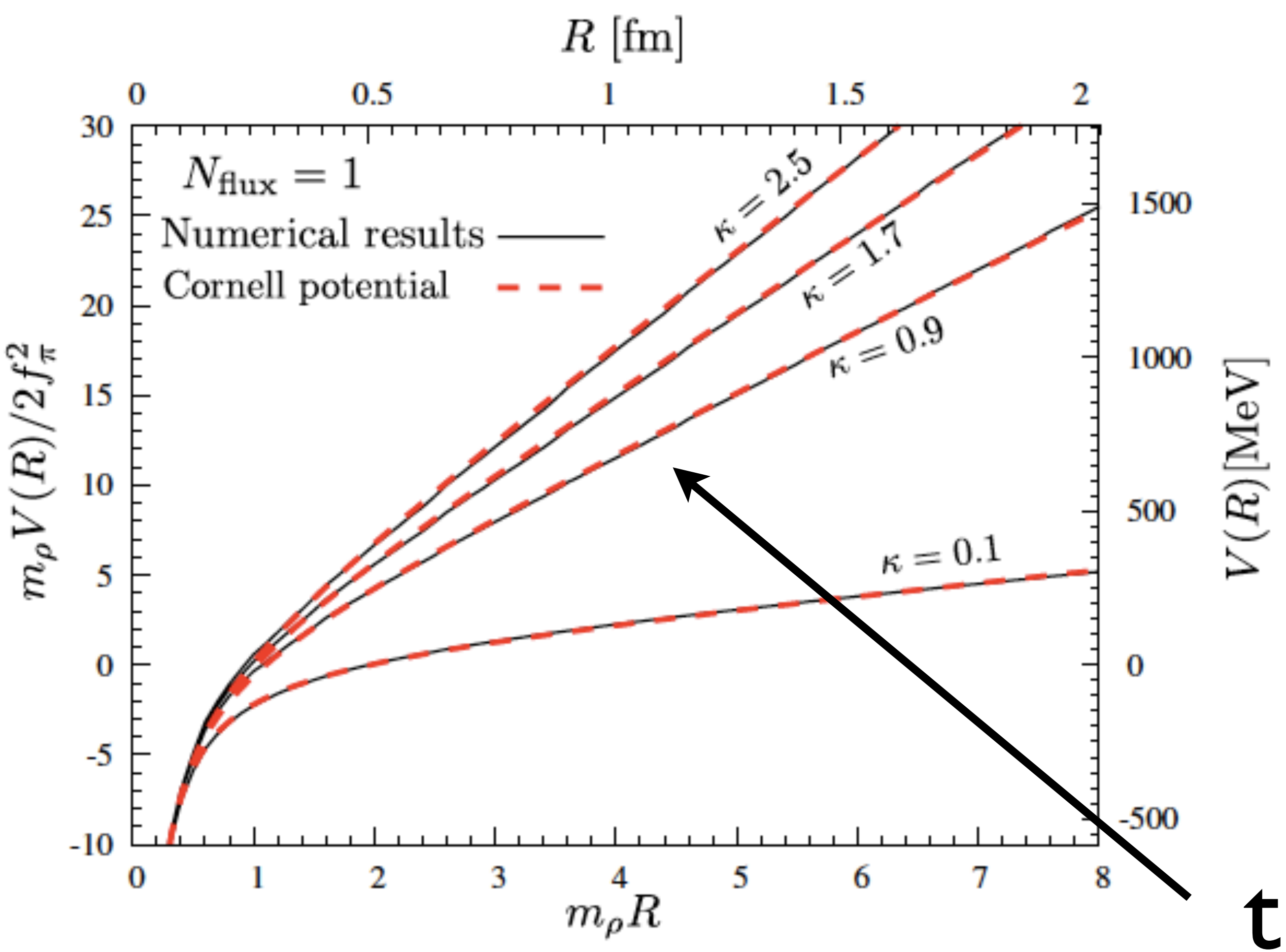
$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4}F^{(\omega)}_{\mu\nu}F^{(\omega)\mu\nu} - \frac{1}{4}F^{(\rho)a}_{\mu\nu}F^{(\rho)\mu\nu a} \\
& +\frac{f_\pi^2}{2}\mathrm{Tr}\left[|D_\mu H_L|^2 + |D_\mu H_R|^2\right] \\
& -V(H_L, H_R).
\end{aligned}
$$

Hidden Local Symmetry with the Higgs bosons.

[RK, Nakamura, Yokoi '12]

String made of mesons

construct a string configuration
made of ρ, ω, and f_0 and calculate an energy.



this line

$$g_\rho = (340\ \mathrm{MeV})^2,$$

$$m_\rho = 770\ \mathrm{MeV},$$

$\sim m_\omega$

$$m_S = m_A = 980\ \mathrm{MeV},$$

(scalar meson masses)

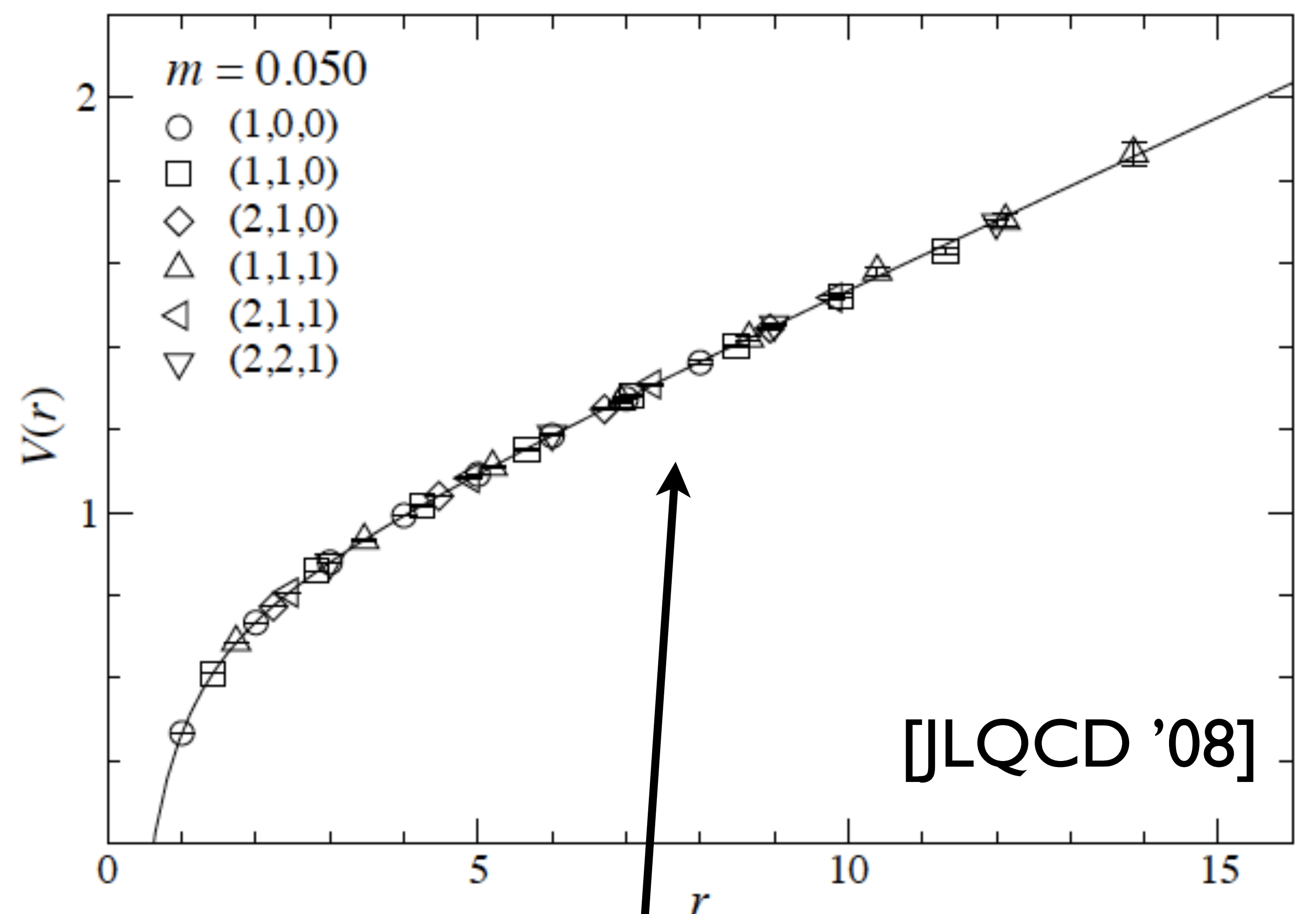
$$V(R) = -\frac{A}{R} + \sigma R. \qquad A = 0.25 \quad \sqrt{\sigma} = 400\ \mathrm{MeV}$$

Not bad.

Lattice QCD

$$V(R) = -\frac{A}{R} + \sigma R.$$

$$A \sim 0.25 - 0.5, \quad \sqrt{\sigma} \sim 430 \text{ MeV}.$$



linear potential

trial (theoretical)

$$\begin{tikzcd}
\text{QCD} & \text{SUSY QCD} \arrow[l, "\text{add SUSY breaking}"'] \arrow[d, leftrightarrow, "\text{Seiberg duality}"] \\
\text{Hidden Local Symmetry?} & \text{dual magnetic theory} \arrow[l, "\text{add SUSY breaking}"]
\end{tikzcd}$$

Model

	$SU(N_c)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$SU(N_c)_V$	$U(1)_{B'}$	$U(1)_R$
Q	N_c	N_f	1	1	1	0	$(N_f - N_c)/N_f$
$\overline{Q}$	$\overline{N_c}$	1	$\overline{N_f}$	-1	1	0	$(N_f - N_c)/N_f$
Q'	N_c	1	1	0	$\overline{N_c}$	1	1
$\overline{Q}'$	$\overline{N_c}$	1	1	0	N_c	-1	1

auxiliary flavors

$\longrightarrow$ massive

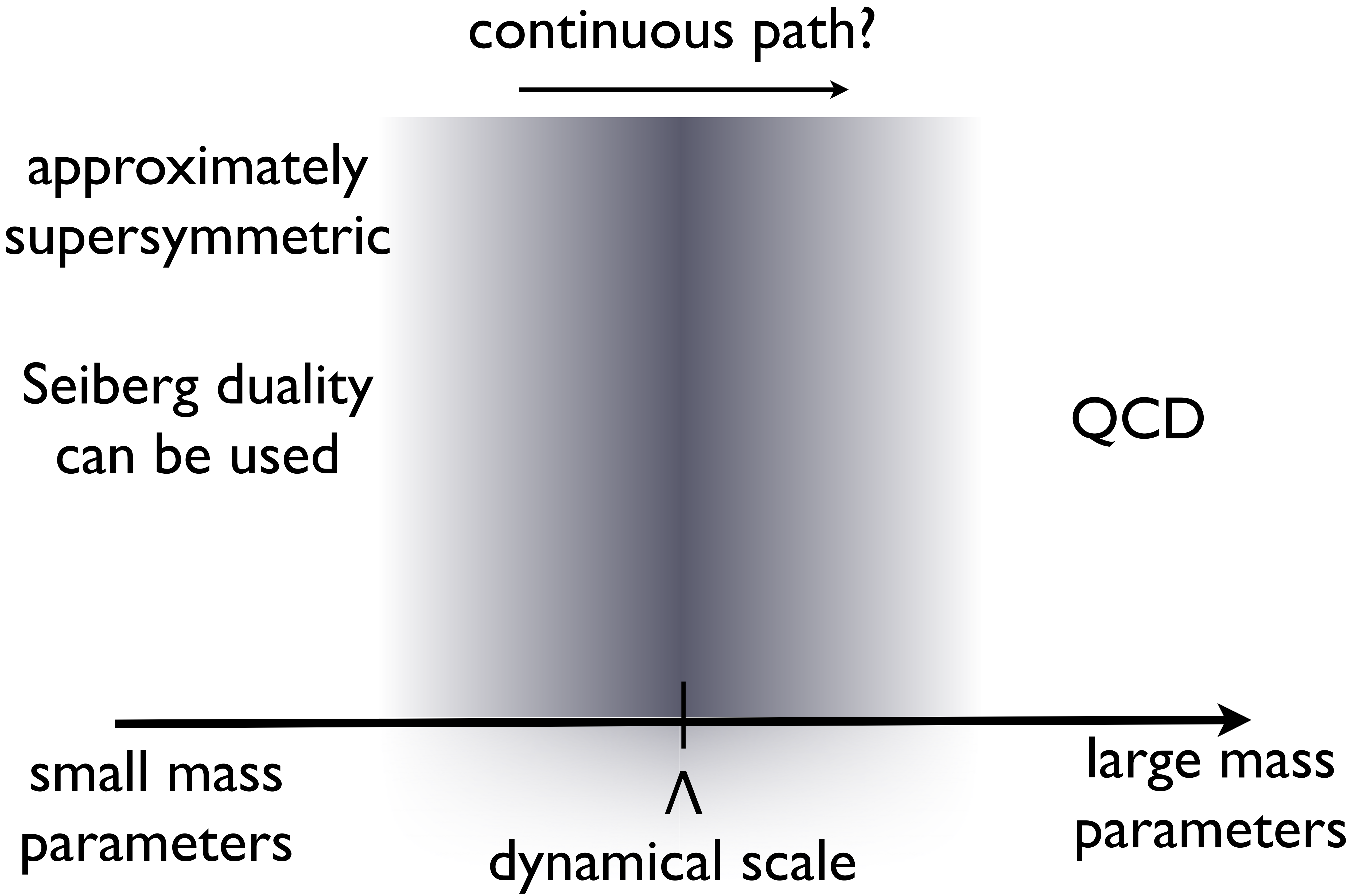
$$W = mQ'\bar{Q}'$$

enhanced symmetry

$\longrightarrow$ gauging

SUSY $\longrightarrow$ break by hand

$$\mathcal{L}_{\rm soft} = -\tilde{m}^2(|Q|^2 + |\bar{Q}|^2 + |Q'|^2 + |\bar{Q}'|^2) - \left(\frac{m_\lambda}{2}\lambda\lambda + \text{h.c.}\right) - (BmQ'\bar{Q}' + \text{h.c.})$$


continuous path?
approximately supersymmetric
Seiberg duality can be used
QCD
small mass parameters
Λ
dynamical scale
large mass parameters

dual picture

electric

	$SU(N_c)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$SU(N_c)_V$	$U(1)_{B'}$	$U(1)_R$
Q	N_c	N_f	1	1	1	0	$(N_f - N_c)/N_f$
$\overline{Q}$	$\overline{N_c}$	1	$\overline{N_f}$	-1	1	0	$(N_f - N_c)/N_f$
Q'	N_c	1	1	0	$\overline{N_c}$	1	1
$\overline{Q}'$	$\overline{N_c}$	1	1	0	N_c	-1	1

magnetic

gauged

	$SU(N_f)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$SU(N_c)_V$	$U(1)_{B'}$	$U(1)_R$
q	N_f	$\overline{N_f}$	1	0	1	N_c/N_f	N_c/N_f
$\overline{q}$	$\overline{N_f}$	1	N_f	0	1	$-N_c/N_f$	N_c/N_f
Φ	1	N_f	$\overline{N_f}$	0	1	0	$2(N_f - N_c)/N_f$
q'	N_f	1	1	1	N_c	$-1 + N_c/N_f$	0
$\overline{q}'$	$\overline{N_f}$	1	1	-1	$\overline{N_c}$	$1 - N_c/N_f$	0
Y	1	1	1	0	$1 + \text{Adj.}$	0	2
Z	1	1	$\overline{N_f}$	-1	$\overline{N_c}$	1	$(2N_f - N_c)/N_f$
$\overline{Z}$	1	N_f	1	1	N_c	-1	$(2N_f - N_c)/N_f$

Hidden Local Symmetry

Higgsing this direction gives massive ρ/ω mesons and massless pions.

	$SU(N_f)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$SU(N_c)_V$	$U(1)_{B'}$	$U(1)_R$
q	N_f	$\overline{N_f}$	1	0	1	N_c/N_f	N_c/N_f
$\overline{q}$	$\overline{N_f}$	1	N_f	0	1	$-N_c/N_f$	N_c/N_f
Φ	1	N_f	$\overline{N_f}$	0	1	0	$2(N_f - N_c)/N_f$
q'	N_f	1	1	1	N_c	$-(N_f - N_c)/N_f$	0
$\overline{q}'$	$\overline{N_f}$	1	1	-1	$\overline{N_c}$	$(N_f - N_c)/N_f$	0
Y	1	1	1	0	$1 + \text{Adj.}$	0	2
Z	1	1	$\overline{N_f}$	-1	$\overline{N_c}$	1	$(2N_f - N_c)/N_f$
$\overline{Z}$	1	N_f	1	1	N_c	-1	$(2N_f - N_c)/N_f$

Consistent with Vafa-Witten theorem.

SUSY breaking terms in the dual picture

[Cheng, Shadmi '98][Arkani-Hamed, Rattazzi '98]
[Karch, Kobayashi, Kubo, Zoupanos '98]
[Luty, Rattazzi '99][Abel, Buican, Komargodski '11]

$$
\begin{aligned}
\mathcal{L}_{\rm soft} \;\; = \;\; & -\tilde{m}_q^2(|q|^2+|\bar{q}|^2+|q'|^2+|\bar{q}'|^2)-\tilde{m}_M^2(|Y|^2+|Z|^2+|\bar{Z}|^2+|\Phi|^2) \\
& -\left(\frac{m_{\tilde{\lambda}}}{2}\tilde{\lambda}\tilde{\lambda}+\tilde{B}m\Lambda Y+Ah\left(q'Y\bar{q}'+q'Z\bar{q}+q\bar{Z}\bar{q}'+q\Phi\bar{q}\right)+\mathrm{h.c.}\right).
\end{aligned}
$$

$$\tilde{m}^2=\frac{2N_c-N_f}{3(N_f+N_c)}D_R,$$

$$\frac{m_\lambda}{g^2}=-\frac{2N_c-N_f}{16\pi^2}F_\phi,$$

$$\tilde{m}_q^2=-\frac{N_c-2N_f}{3(N_f+N_c)}D_R,$$

$$\tilde{m}_M^2=\frac{2(N_c-2N_f)}{3(N_f+N_c)}D_R,$$

$$\frac{m_{\tilde{\lambda}}}{g_H^2}=-\frac{2N_f-N_c}{16\pi^2}F_\phi,$$

$$A=2(\gamma_M+\gamma_q+\gamma_{\bar{q}})F_\phi,$$

Indeed

In the free-magnetic range ($N_f < N_c/2$),

$$\frac{\tilde{m}^2}{\tilde{m}_q^2} = \frac{2N_c - N_f}{-N_c + 2N_f} < 0$$

[Luty, Rattazzi '99]

positive mass^2 for squarks in the electric picuture

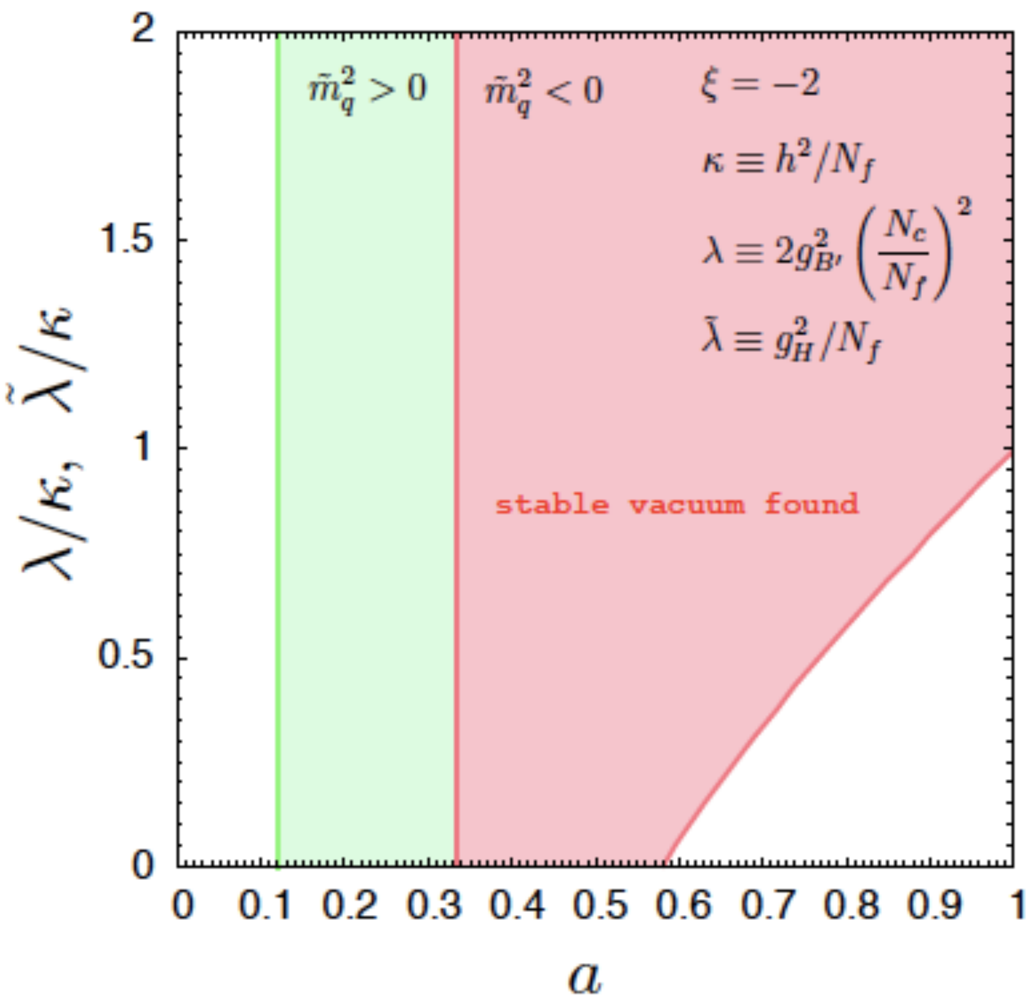
$\downarrow$

negative mass^2 for squarks in the magnetic picuture!

$\longrightarrow$ triggers squark condensation!

QCD vacuum

Indeed, one can find a vacuum where SU(Nf) magnetic gauge group is Higgsed and the chiral symmetry is spontaneously broken as well.



$$\tilde{m}_M^2 = -2\tilde{m}_q^2$$

$$a = \frac{v^2}{v^2 + 2v_\Phi^2}.$$

Realization of HLS as the dual gauge theory.

trial (confinement?)

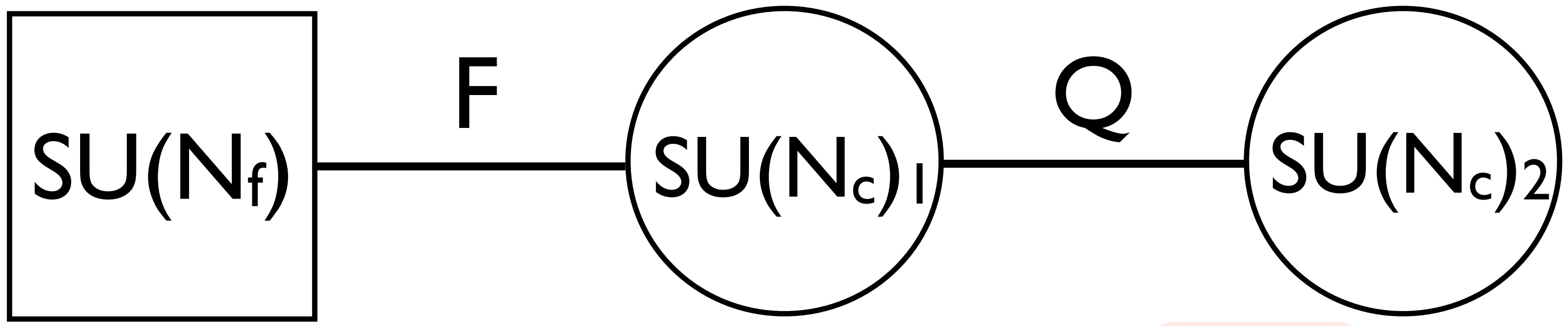
In Seiberg dualities, relation between confinement and Higgsing (namely electric and magnetic) is not completely clear.
This is because the dualities are between massless degrees of freedom.

Motivate us to consider N=2 SUSY model.

N=2 SUSY model

[RK, Yokoi '13]

Similar models in [Shifman, Yung '07..]



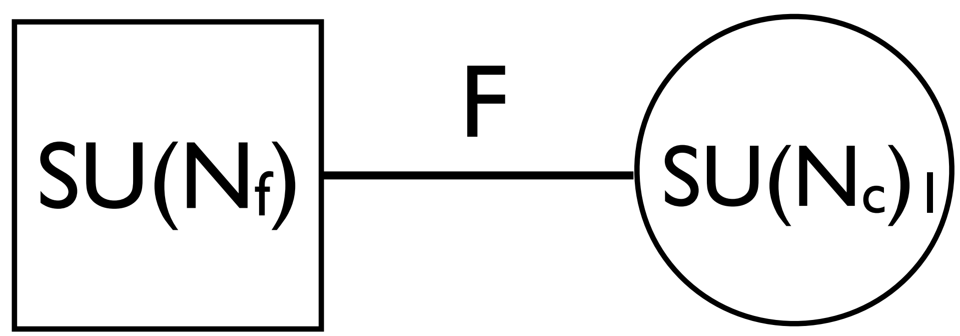
gauge group → (columns $SU(N_c)_1$, $SU(N_c)_2$)

	$SU(N_c)_1$	$SU(N_c)_2$	$SU(N_f)$	$U(1)_B$	$U(1)_{B'}$
Q	N_c	$\bar{N}_c$	1	0	1
F	N_c	1	N_f	1	0

global

gauged but frozen

non zero <Q>=μ reduces to N=2 QCD.



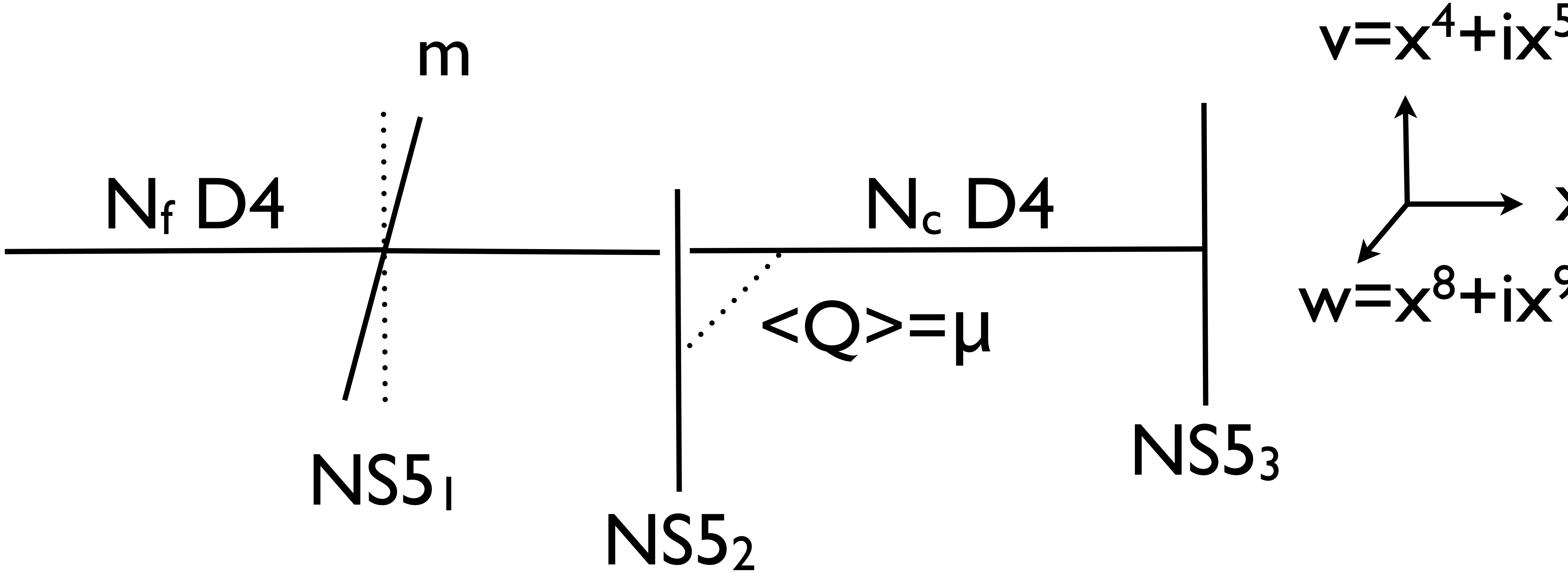
Adding a superpotential term reduce to N=1 SUSY

$$W \ni \frac{m}{2}\mathrm{Tr}\Phi_1^2.$$

D-brane construction

[Witten '97]

Following Witten, one can construct 4D gauge theory by branes and solve this theory.



One can get full quantum information from the SW curve.

Exact results (SW curve)

For Nc=3, Nf=2 (μ=0, m=0), we get

$$\Lambda_2^3 t^3 - (v-\phi_1')(v-\phi_2')(v-\phi_3')t^2 + \left(v-\hat{\phi}_1\right)\left(v-\hat{\phi}_2\right)\left(v-\hat{\phi}_3\right)t + \Lambda_1 v^2 = 0,$$

$$\hat{\phi}_1 + \hat{\phi}_2 + \hat{\phi}_3 = -\Lambda_1, \quad \phi_1' + \phi_2' + \phi_3' = 0.$$

[Giveon, Pelc '97][Erlich, Naqvi, Randall '98]

from this, one can identify the vacua which remain after turning on μ and m:

$$\rho = \frac{\Lambda_1^2}{2} + c_1\Lambda'^2, \quad \sigma = c_2\Lambda'^3, \quad \rho' = c_1\Lambda'^2 \quad \sigma' = -\Lambda_2^3 + c_2\Lambda'^3,$$

$$\rho = \frac{1}{2}(\hat{\phi}_1^2 + \hat{\phi}_2^2 + \hat{\phi}_3^2), \quad \rho' = \frac{1}{2}(\phi_1'^2 + \phi_2'^2 + \phi_3'^2),$$

$$\sigma = \hat{\phi}_1\hat{\phi}_2\hat{\phi}_3, \quad \sigma' = \phi_1'\phi_2'\phi_3',$$

$$\Lambda'^4 = \Lambda_1\Lambda_2^3.$$

$$(c_1, c_2) =$$

$$\left(\frac{2i}{\sqrt{3}}, \pm\frac{8\sqrt{2}}{9\cdot 3^{1/4}}(1+i)\right), \left(-\frac{2i}{\sqrt{3}}, \pm\frac{8\sqrt{2}}{9\cdot 3^{1/4}}(1-i)\right)$$

[Carlino, Konishi, Murayama '00]

	$SU(N_c)_1$	$SU(N_c)_2$	$SU(N_f)$	$U(1)_B$	$U(1)_{B'}$
Q	N_c	$\bar{N}_c$	1	0	1
F	N_c	1	N_f	1	0

Nc=3, Nf=2

Consider the parameter region with

For $\Lambda_1 \gg \Lambda_2,\ \mu \ll \Lambda_1$

VEV of Q

magnetic IR free

	$SU(2)_1$	$U(1)_1$	$SU(3)_2$	$SU(2)_f$	$U(1)_B$	$U(1)_{B'}$
q	2	1/2	1	2	0	-1
q'	2	1/2	$\bar{3}$	1	-1	0
e	1	-1	1	1	0	-1

effective theory below Λ_1

[Argyres, Plesser, Seiberg '96]

$SU(3)_2$ factor gets strong at a scale

$$\Lambda' = (\Lambda_1 \Lambda_2^3)^{1/4}$$

There is a point at which massless monopoles appear.

[Carlino, Konishi, Murayama '00]

	$SU(2)_1$	$U(1)_{1'}$	$U(1)_2$	$U(1)_{2'}$	$SU(2)_f$	$U(1)_B$	$U(1)_{B'}$
q	2	$1/2$	0	0	2	0	-1
e	1	-1	0	0	1	0	-1
e_1	1	0	1	0	1	0	0
e_2	1	0	0	1	1	0	0

effective theory below Λ'

N=2 to N=1

$$W \ni \frac{m}{2}\mathrm{Tr}\Phi_1^2.$$

$$\downarrow$$

[Argyres, Plesser, Seiberg '96]

$$W \ni e\Phi_{D1}\bar{e} - e_1\Phi_{D2}\bar{e}_1 - e_2\Phi_{D2'}\bar{e}_2 + m\Lambda_1 x_1\Phi_{D1} + m\Lambda' x_2\Phi_{D2} + m\Lambda' x_{2'}\Phi_{D2'},$$

	$SU(2)_1$	$U(1)_{1'}$	$U(1)_2$	$U(1)_{2'}$	$SU(2)_f$	$U(1)_B$	$U(1)_{B'}$
q	2	1/2	0	0	2	0	−1
e	1	−1	0	0	1	0	−1
e_1	1	0	1	0	1	0	0
e_2	1	0	0	1	1	0	0

condensations of e, e_1, e_2

$$\downarrow$$

<e> would not cause confinement since $U(1)_{B'}$ is not dynamical

magnetic gauge group

	$SU(2)_1$	$U(1)_X$	$SU(2)_f$	$U(1)_B$
q	2	3/2	2	0

effective theory below $(m\Lambda')^{1/2}$

turn on μ

$$W \ni -\frac{3}{2}\mathrm{Tr}(q\Phi_X\bar{q}) + \mu^2\Phi_X, \quad \longrightarrow \quad q = \bar{q} = \frac{\mu}{\sqrt{3}} \cdot 1,$$

$SU(2)_I \times SU(2)_f \longrightarrow SU(2)_{I+f}$

color-flavor locking

magnetic gauge boson $\longrightarrow$ vector meson (ρ)

$U(1)_X$ breaking $\longrightarrow$ string formation

$\longrightarrow$ quark confinement

This is what we wanted.

We have seen that

Quiver deformation provides us with
an understanding of HLS as
the magnetic gauge theory.

large μ $\longleftrightarrow$ small μ

QCD

HLS as
magnetic theory

Summary

- The success of the Hidden Local Symmetry in QCD may have a deep reason.
- We studied the possibility that the HLS is actually the magnetic picture of QCD.
- Electric-magnetic duality in SUSY QCD looks like a promising approach.
- It is exciting that the confining string maybe made of mesons.