

Hadron physics as Seiberg dual of QCD

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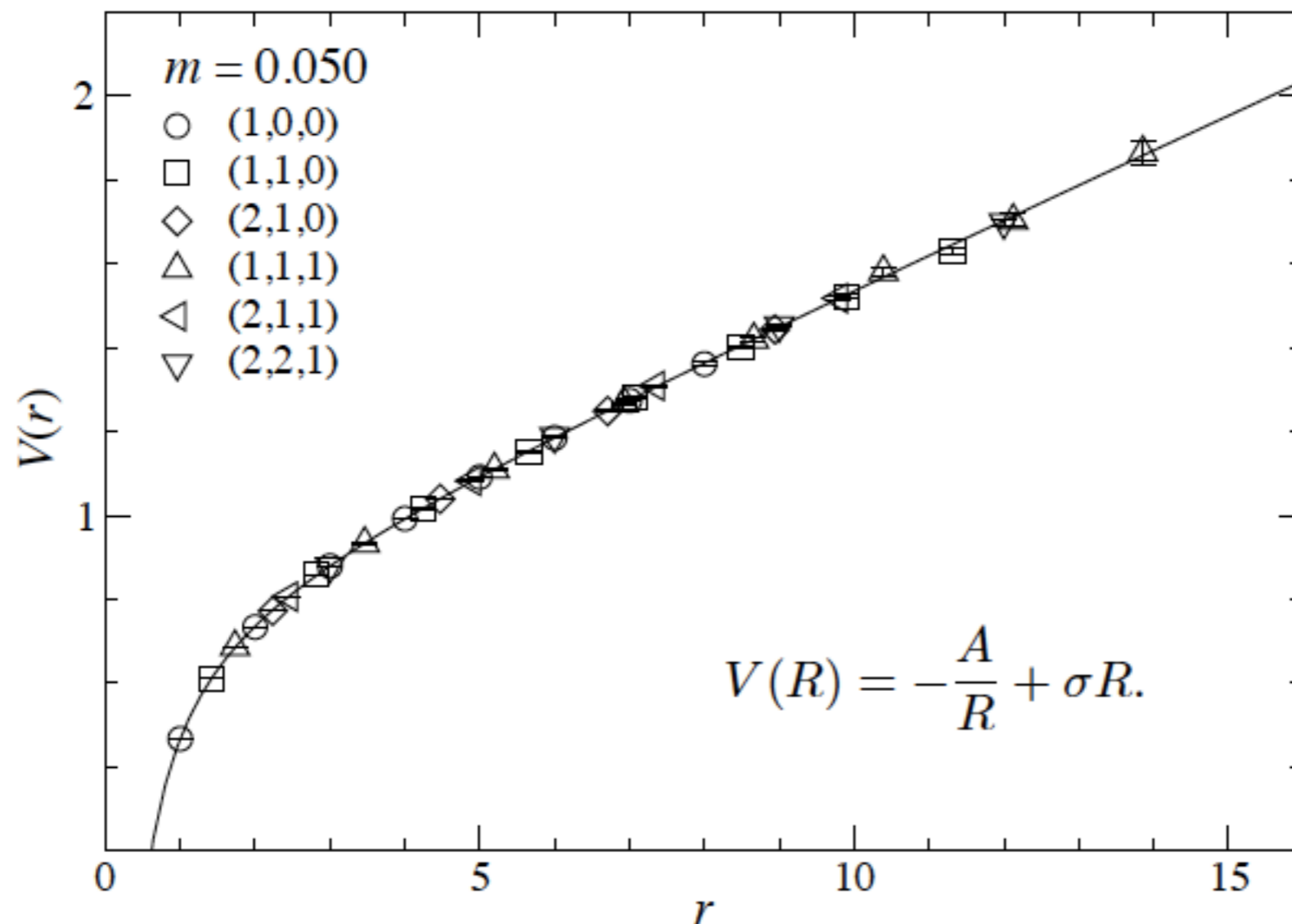
Higgs at 125GeV

What is this?

I try to approach to this question from
the quark confinement in QCD.

Quark Confinement

Quarkonium mass spectrum and lattice simulations both support the Coulomb+linear type potential model for the static quark anti-quark system.



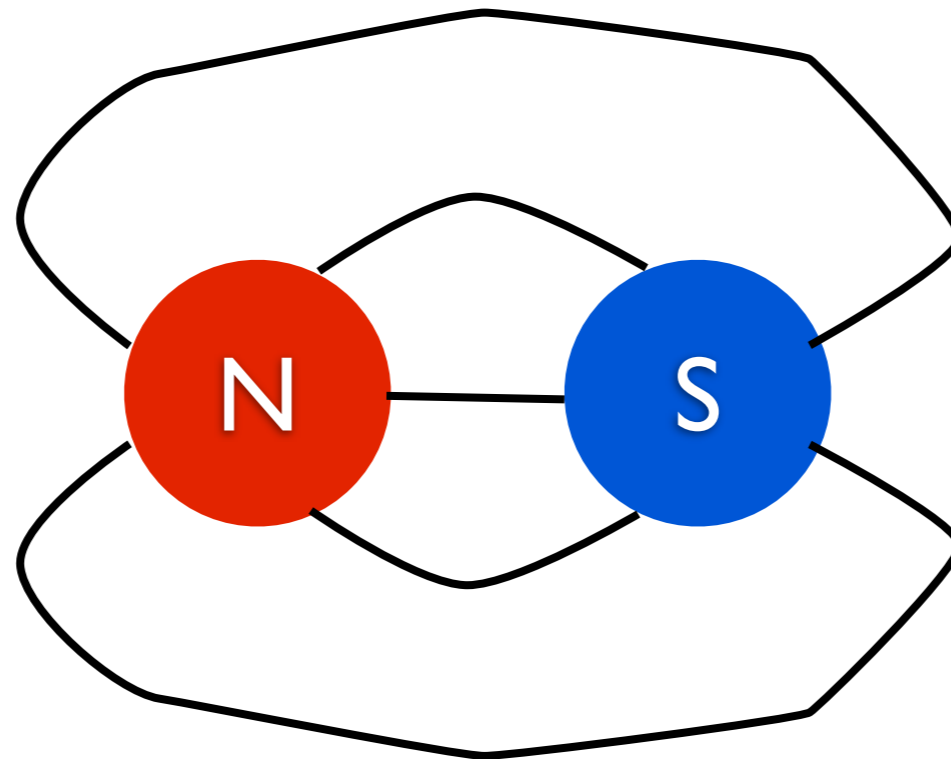
[JLQCD '08]

Why?

There is a pretty simple picture.

Confinement is dual to Higgs mechanism, and in the dual picture, the quarks are magnetic monopoles.

[Mandelstam '75, 't Hooft '75]



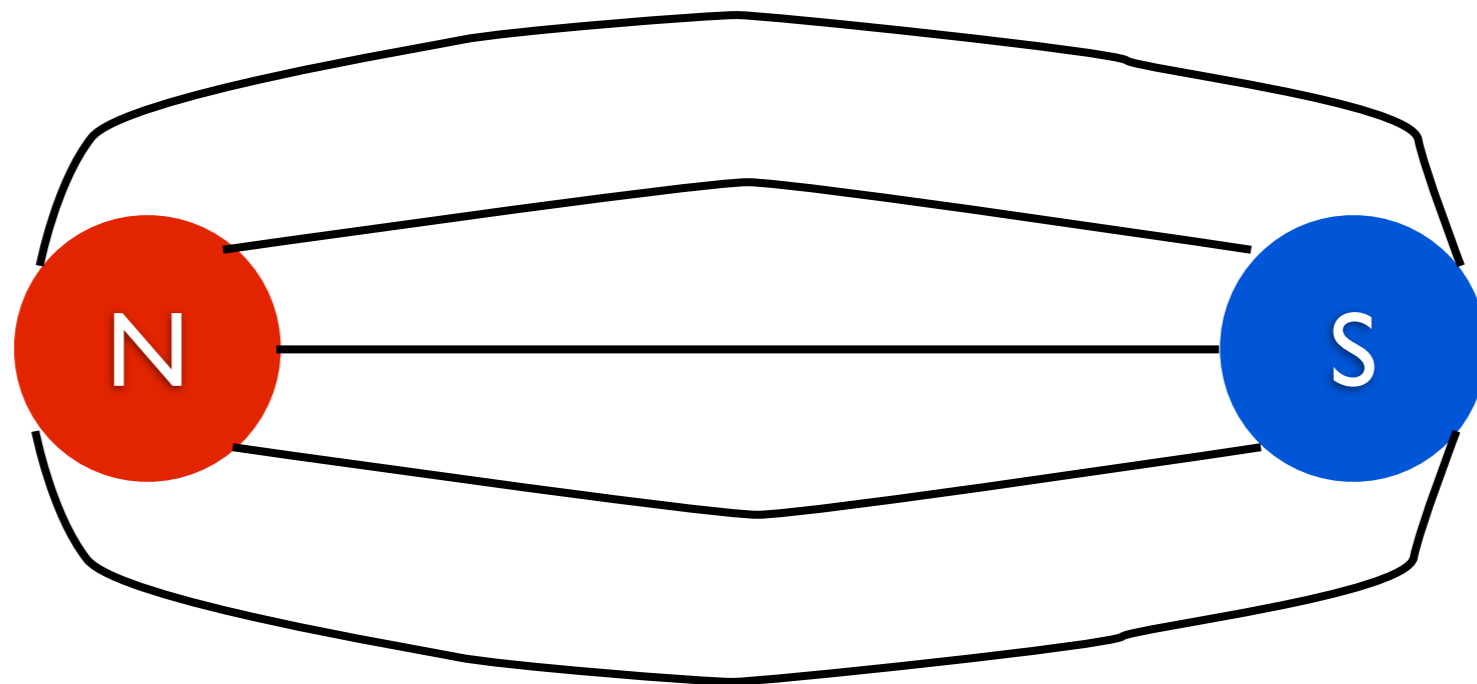
Coulomb like

Why?

There is a pretty simple picture.

Confinement is dual to Higgs mechanism, and in the dual picture, the quarks are magnetic monopoles.

[Mandelstam '75, 't Hooft '75]



Why?

There is a pretty simple picture.

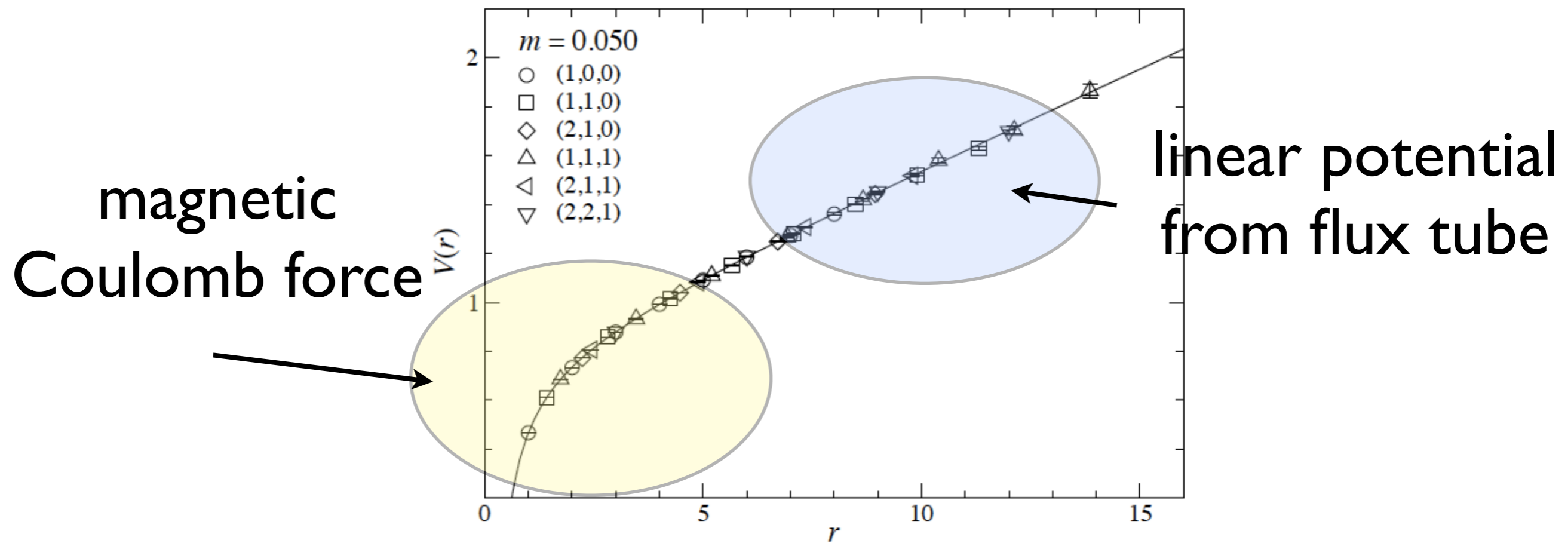
Confinement is dual to Higgs mechanism, and in the dual picture, the quarks are magnetic monopoles.

[Mandelstam '75, 't Hooft '75]



Linear potential

This mechanism provides us with a classical picture for the quark confinement.



$$V(R) = -\frac{A}{R} + \sigma R. \quad A \sim 0.25 - 0.5, \quad \sqrt{\sigma} \sim 430 \text{ MeV}.$$

If there is such a classical picture,

**Where is the magnetic
gauge boson in QCD?**

There are massive vector mesons $\rho(770)$, $\omega(782)$.

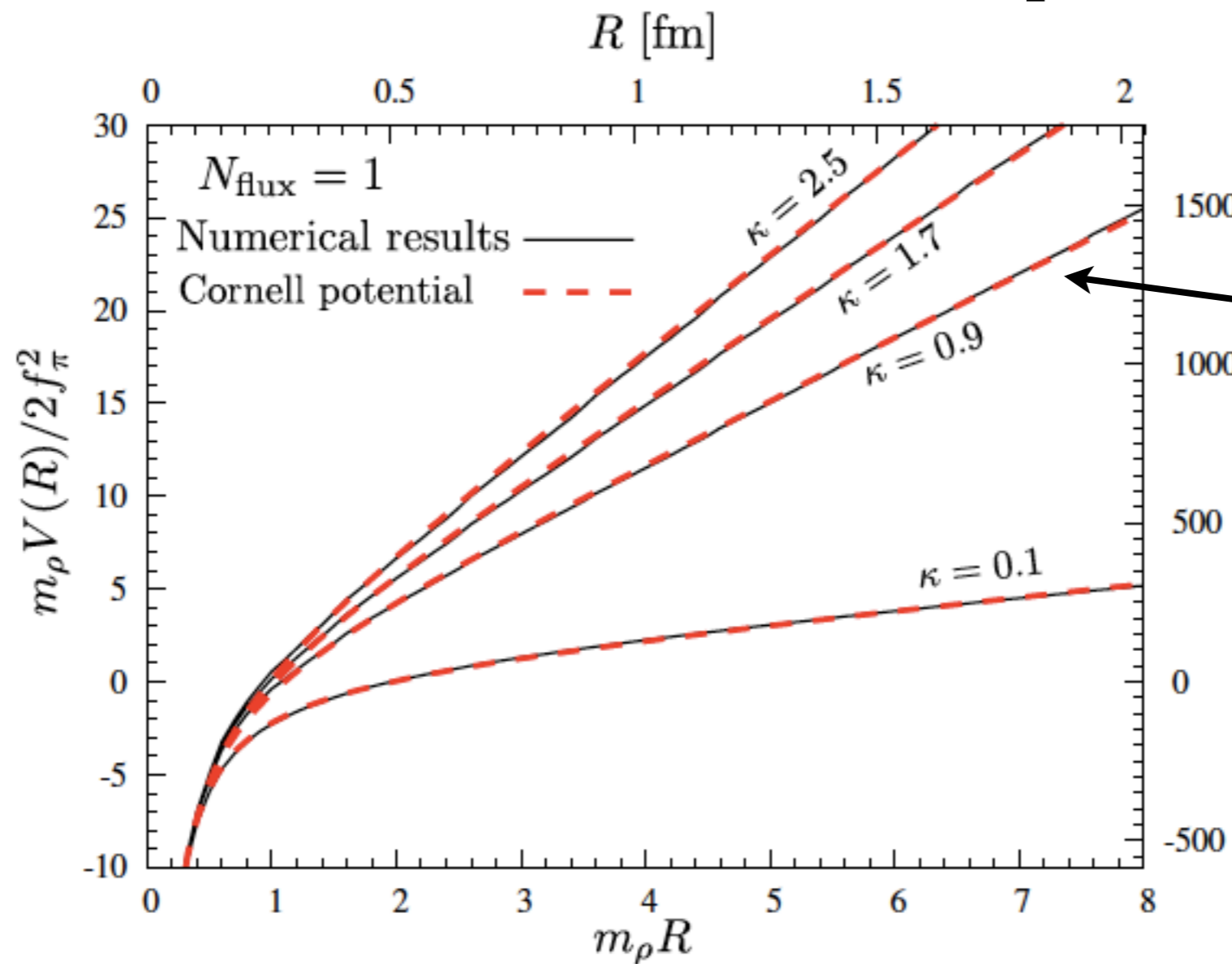
If there is such a classical picture,

Where is the magnetic
Higgs boson in QCD?

There are massive scalar mesons $\sigma(600)$, $f_0(980)$.

We constructed a model of $\rho/\omega/f_0/a_0$ system as a Higgsed gauge theory, and calculated the energy of the monopole-antimonopole system.

[RK, Nakamura, Yokoi '12]



this line

$$A = 0.25$$

$$\sqrt{\sigma} = 400 \text{ MeV}$$

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

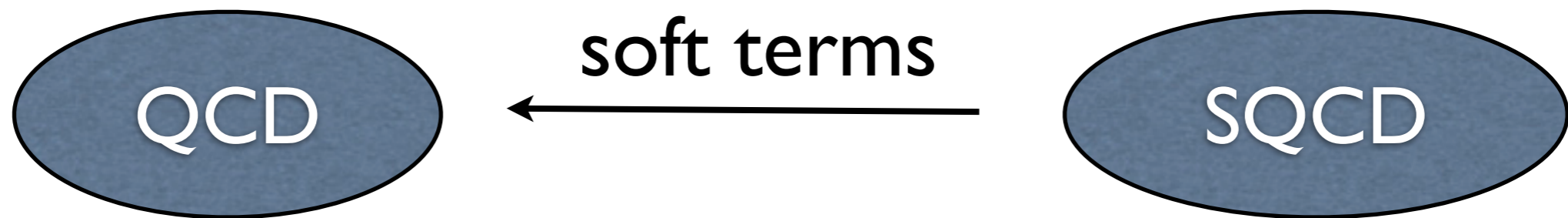
We could reproduce the QCD potential.

Can we derive the magnetic model from QCD?

It's difficult. But I will try here by using electric-magnetic duality in SUSY QCD.

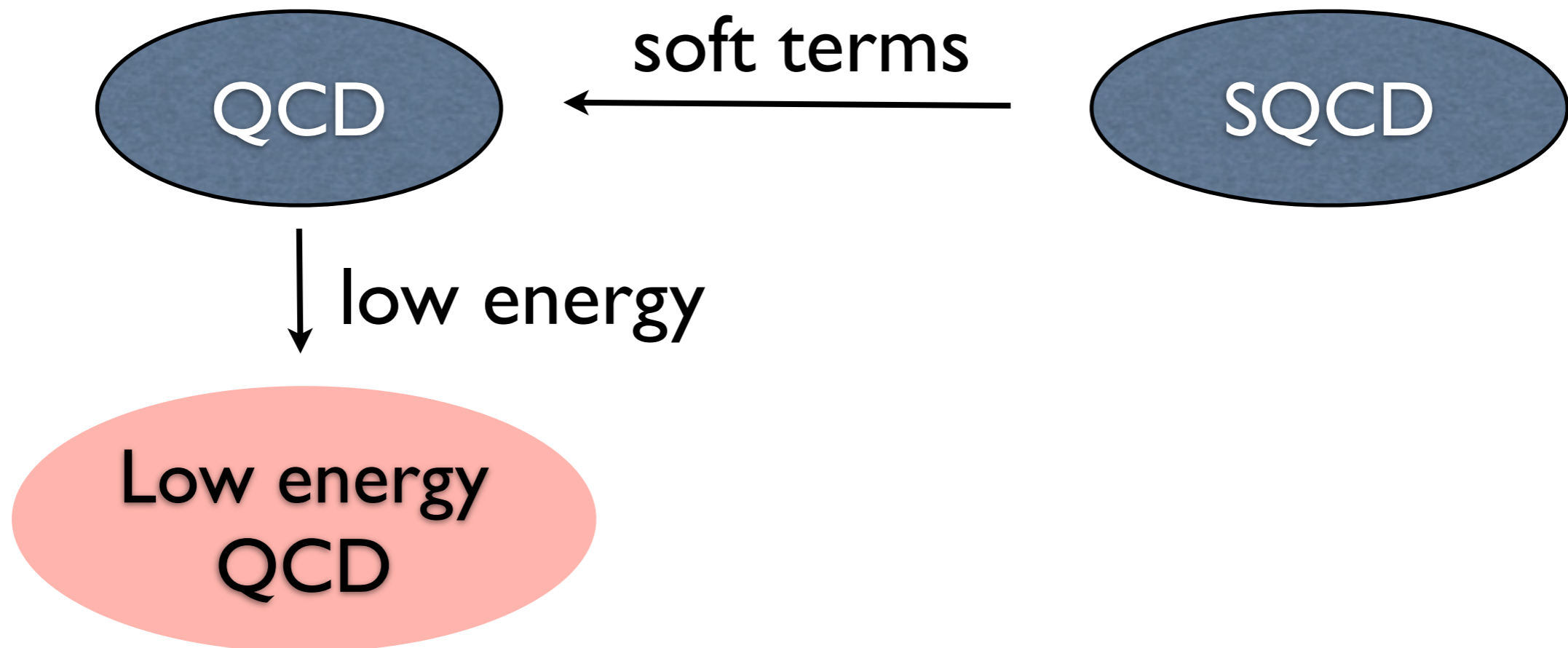
QCD from SQCD

QCD can be obtained by adding soft mass terms for the gaugino and squarks.



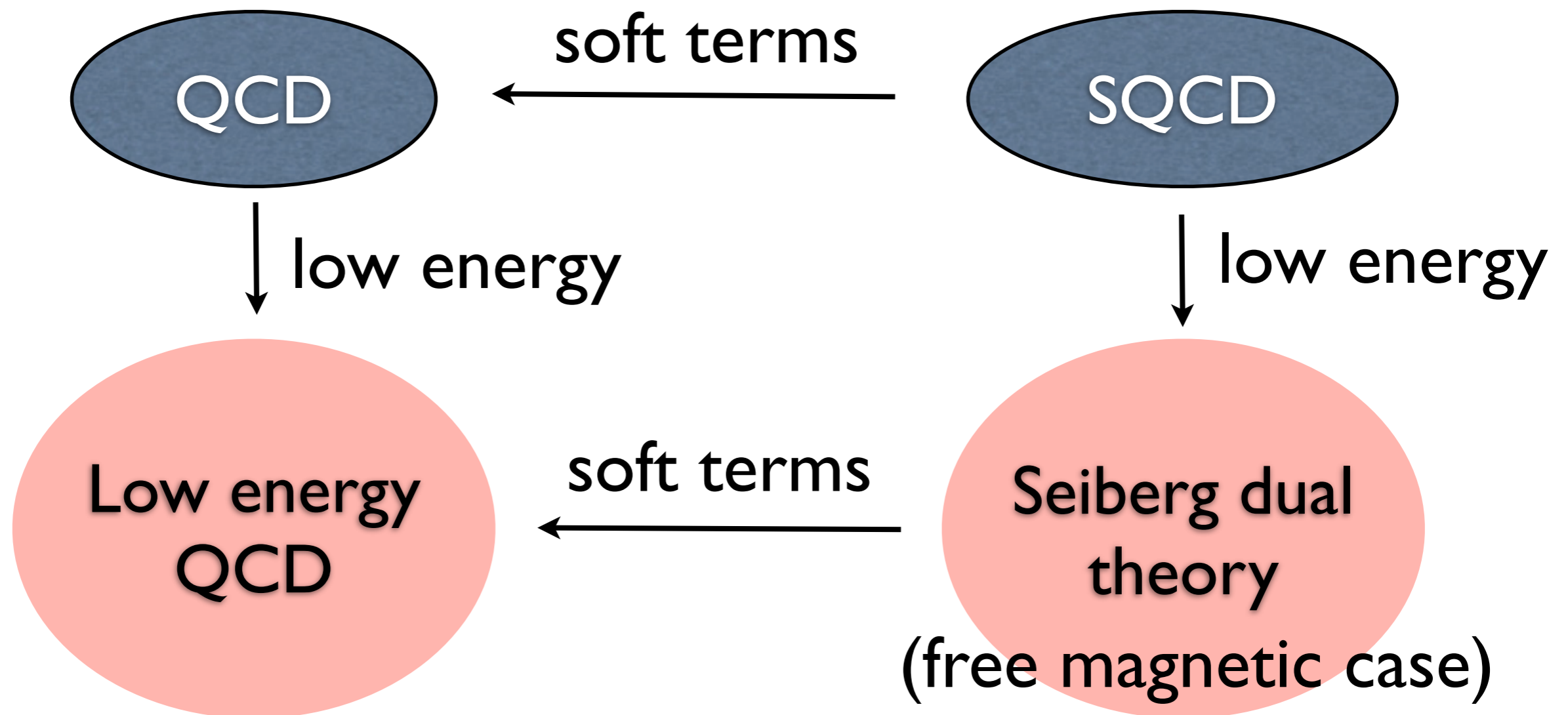
QCD from SQCD

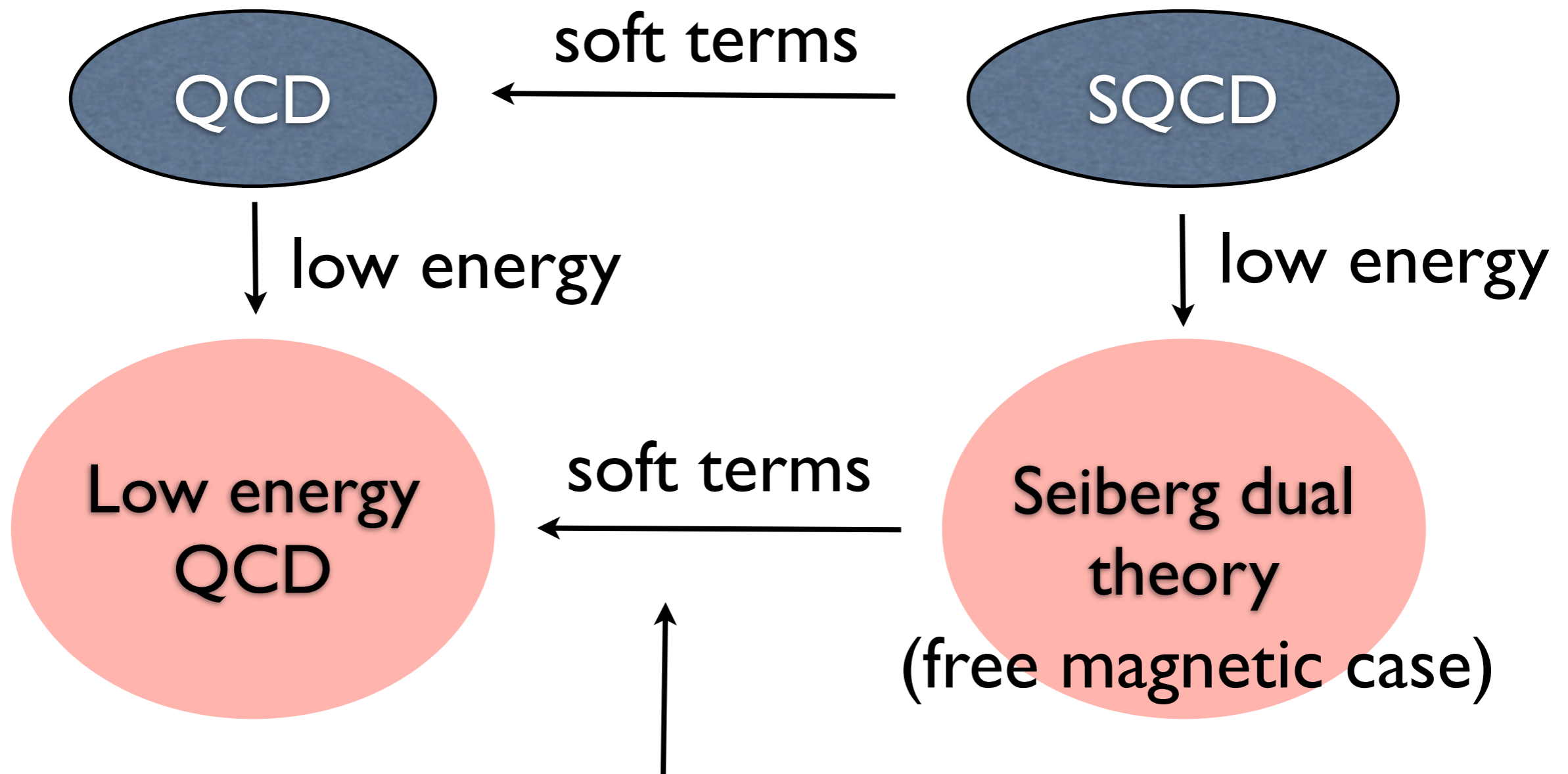
QCD can be obtained by adding soft mass terms for the gaugino and squarks.



QCD from SQCD

QCD can be obtained by adding soft mass terms for the gaugino and squarks.





The question is the smoothness of this limit.

[Aharony, Sonnenschein, Peskin, Yankielowicz '95]

And unfortunately, it has been shown that it is **not smooth** based on the Vafa-Witten theorem.

[Arkani-hamed, Rattazzi '98]

The problem was the spontaneous $U(1)_B$ breaking due to tachyonic soft masses for the squarks.

Actually, one can easily evade this.

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	$(N_f - N_c)/N_f$
\bar{Q}	\bar{N}_c	1	\bar{N}_f	-1	1	0	$(N_f - N_c)/N_f$
Q'	N_c	1	1	0	\bar{N}_c	1	1
\bar{Q}'	\bar{N}_c	1	1	0	N_c	-1	1

auxiliary massive flavors

$W = mQ'\bar{Q}'$. (mass term for the auxiliary flavors)

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

(soft SUSY breaking terms)

magnetic picture

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

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



$$Y = -\frac{\tilde{B}m\Lambda}{\tilde{m}_M^2}.$$

split into two sectors.

Hidden Local Symmetry

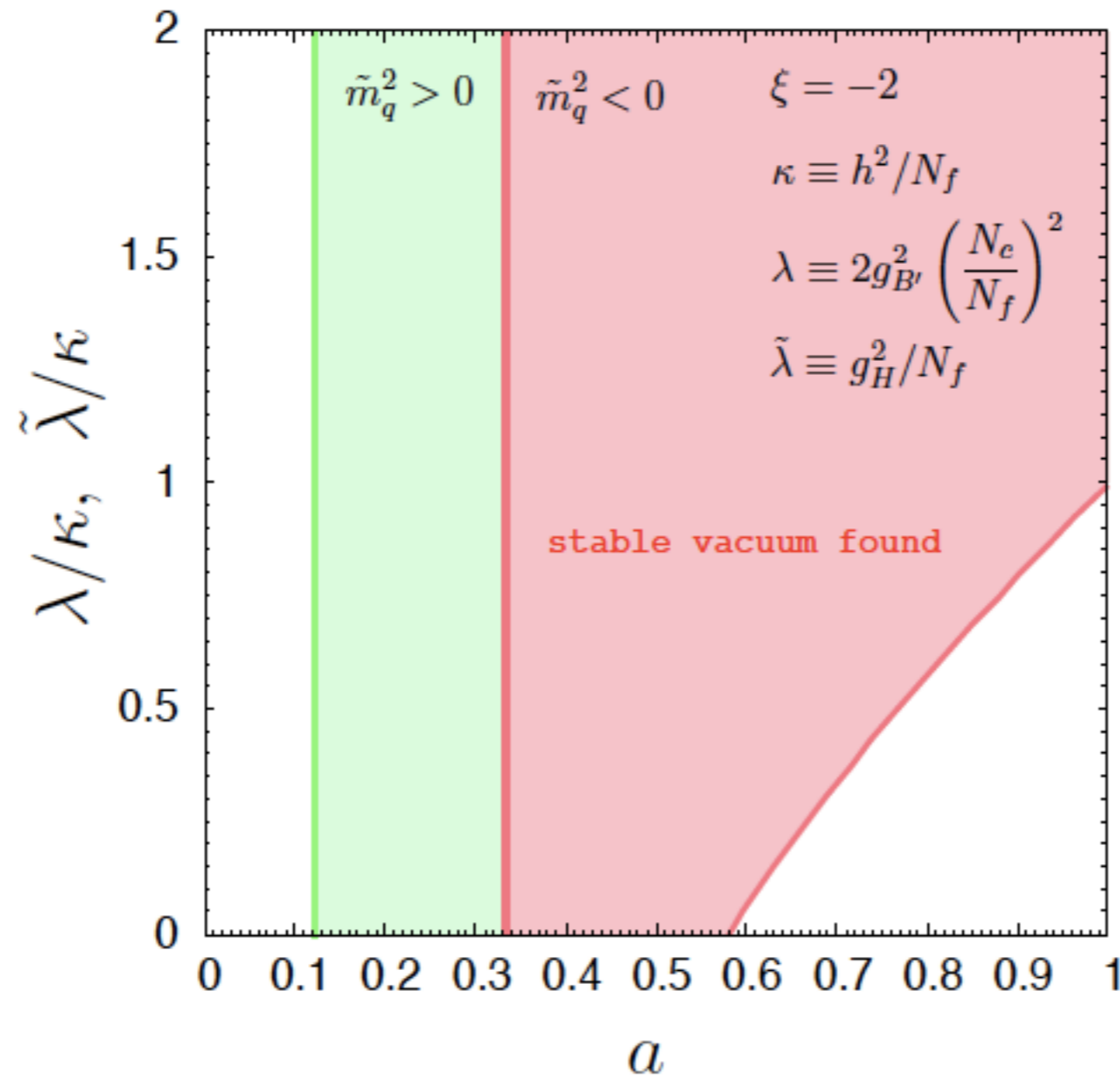
	$SU(N_f)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$SU(N_c)_V$	$U(1)_{B'}$	$U(1)_R$
q	N_f	$\overline{N_f}$	1	0	1	N_c/N_f	N_c/N_f
\bar{q}	$\overline{N_f}$	1	N_f	0	1	$-N_c/N_f$	N_c/N_f
Φ	1	N_f	$\overline{N_f}$	0	1	0	$2(N_f - N_c)/N_f$
q'	N_f	1	1	1	N_c	$-(N_f - N_c)/N_f$	0
\bar{q}'	$\overline{N_f}$	1	1	-1	$\overline{N_c}$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

This sector has the same structure as the HLS.

$$q = \bar{q} = v\mathbf{1} \neq 0, \quad \Phi = v_\Phi \mathbf{1} \neq 0,$$

break chiral symmetry and give masses to magnetic gauge bosons (ρ meson) while leaving $U(1)_B$ symmetry unbroken.

Indeed,



one can find such a vacuum is realized in a large region of the parameter space.

I think SQCD is smoothly connected to QCD through the mass deformed $N_f + N_c$ flavor theory.



If that's the case,

chiral symmetry breaking = magnetic Higgs mechanism
= confinement

ρ meson is the magnetic gauge boson!

[Seiberg '95, Harada, Yamawaki '99, Komargodski '10, RK '11, Abel, Barnard '12]

so?

Electroweak symmetry breaking may be similar.
Namely, the SM may be the magnetic picture of some
fundamental theory.

[Seiberg '95, Maekawa'96, Strassler '96, ..., RK, Fukushima, Yamaguchi '10
Craig, Stolarsky, Thaler '11, Csaki, Shirman, Terning '11, Csaki, Randall, Terning '11]

I think it is very important to look for
a magnetic gauge boson (vector resonance) next
at the LHC!

electroweak physics is similar?

Higgs = composite field

= Magnetic degree of freedom?

= dual to some dynamical system

But we know that theories too similar to QCD will not be good, since that's just the QCD-like technicolor paradigm.

→ We need a light Higgs boson.

→ SUSY is now essential. It's not just a tool.

model building

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

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

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

As the first trial, I consider the very same model as the one used for QCD.

model

$N_c=3, N_f=2$

embed $SU(2)_L \times U(1)_Y$



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

anomalous?

model

$N_c=3, N_f=2$

embed $SU(2)_L \times U(1)_Y$

embed $SU(3)_c$

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

anomalous?



Subtract top+bottom (and Higgs)
from the MSSM

model

$N_c=3, N_f=2$

embed $SU(2)_L \times U(1)_Y$

embed $SU(3)_c$

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

top+bottom (but colored under different $SU(3)$)

This is the super-topcolor model.

[RK, Fukushima, Yamaguchi '10]

dual theory

We obtain the MSSM coupled to weakly coupled CFT.

Higgs sector!

$SU(2)_L \times U(1)_Y$

$SU(3)_c$

	$SU(N_f)$	$SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$SU(N_c)_V$	$U(1)_{B'}$	$U(1)_R$
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
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\overline{Z}	1	N_f	1	1	N_c	-1	$(2N_f - N_c)/N_f$

top+bottom quarks! (they now have color)

Sketch

- Higgs mass can be enhanced by a coupling to the CFT sector (Nakai's talk on Thursday).
- stop mass has IR fixed point at zero when we ignore the gluino mass and D-terms. The stop is naturally light, and it is good for naturalness.

Summary

- A possible smooth path from SQCD to QCD is found.
- The ρ meson can be interpreted as the magnetic gauge boson.
- The Higgs mechanism in the SM may also be the magnetic picture.
- I think it is very important to look for a vector resonance! (We now have a huge room for the S parameter because of the light Higgs boson!)