Non-supersymmetric metastable vacua from brane configurations

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Outline

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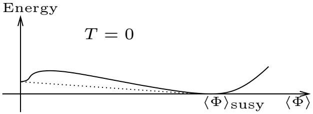
The three posibilities

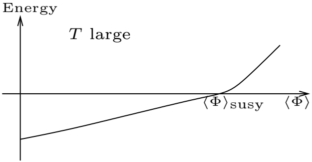
We want to break supersymmetry spontaneously, *generically* there are three scenarios:

1. There is no R-symmetry:
   - There are supersymmetric vacua.
2. There is an R-symmetry, but it is spontaneously broken:
   - Spontaneous susy breaking, but there is a massless Goldstone boson (R-axion).
3. There is an R-symmetry, and it is unbroken in the vacuum:
   - Spontaneous susy breaking, but this forbids Majorana gaugino masses.

Breaking R-symmetry slightly

- We will find that if we break the R-symmetry explicitly and slightly by a mass term, a metastable vacuum appears. [th/0602239]
- We expect this phenomenon to be quite common.
- If we start from the susy vacuum, we tunnel to the metastable one as the universe cools down. This comes because the metastable vacuum has more light degrees of freedom, and so at high temperatures it is more populated [th/0610334]:





Outline

1. Motivation
   - Some remarks about R-symmetry
   - A way out: metastable vacua
2. Review of the ISS construction
3. String theory embedding

SQCD with $\mathcal{N} = 1$

Pure glue

$$\mathcal{L}_g = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - i\lambda^{a\dagger} \bar{\sigma}^\mu D_\mu \lambda^a + \frac{1}{2} D^a D^a \quad (1)$$

This is a well known theory:

- There are N_c vacua (gaugino condensates).
- All of them are supersymmetric.

SQCD with $\mathcal{N} = 1$

Adding N_f massive flavors

Add N_f massive chiral multiplets in the fundamental (i.e., matter):

$$W = \operatorname{Tr} m\phi\widetilde{\phi}. \tag{2}$$

with

$$N_c + 1 \leq N_f < \frac{3}{2} N_c \tag{3}$$

We still have the original N_c susy vacua:

- Massive matter can be integrated out.

So what is new?

- Non susy vacua elsewhere in field space.
- Metastable, but phenomenologically viable.
- Tractable.

SQCD with $\mathcal{N} = 1$

Symmetries of the model

The model has the following symmetries (treating the mass as a spureous field):

	$SU(N_c)$	$[SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$U(1)_R$	$U(1)_A]$
ϕ	$\square$	$\square$	$\mathbf{1}$	1	$1 - \frac{N_c}{N_f}$	1
$\widetilde{\phi}$	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	-1	$1 - \frac{N_c}{N_f}$	1
m	$\mathbf{1}$	$\overline{\square}$	$\square$	0	$2\frac{N_c}{N_f}$	-2
$\Lambda^{3N_c - N_c}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	0	$2N_f$

(4)

We see that no anomaly-free R-symmetry can survive, so we expect supersymmetric vacua.

SQCD with $\mathcal{N}=1$

The Seiberg dual theory

Seiberg duality allows us to study the vacuum structure in terms of a simpler theory, the $SU(n = N_f - N_c)$ "magnetic" dual, equivalent in the (free) IR, with superpotential:

$$W = h\mathrm{Tr}\,(q\Phi\widetilde{q}) - h\mu^2\mathrm{Tr}\,\Phi \tag{5}$$

- The matter content is given by dual quarks q and $\widetilde{q}$ and a meson $\Phi = \widetilde{\phi}\phi$, transforming as:

	$SU(n)$	$[SU(N_f)_L$	$SU(N_f)_R$	$U(1)_B$	$U(1)_R$	$U(1)_A]$
q	$\square$	$\overline{\square}$	$\mathbf{1}$	$\frac{N_c}{n}$	$1-\frac{n}{N_f}$	-1
$\widetilde{q}$	$\overline{\square}$	$\mathbf{1}$	$\square$	$-\frac{N_c}{n}$	$1-\frac{n}{N_f}$	-1
Φ	$\mathbf{1}$	$\square$	$\overline{\square}$	0	$2\frac{n}{N_f}$	2

(6)

SQCD with $\mathcal{N} = 1$

The magnetic theory without gauge dynamics

- We choose $N_c + 1 \leq N_f < \frac{3}{2} N_c$, so the dual is IR-free:

$$\beta_{\text{magnetic}} \propto 3(N_f - N_c) - N_f < 0 \tag{7}$$

  and we can take a trivial Kähler potential:

$$K = \frac{1}{\alpha} \Phi^\dagger \Phi + \frac{1}{\beta} (q^\dagger q + \widetilde{q}^\dagger \widetilde{q}) \tag{8}$$

- For our setup, ignoring gauge dynamics, we have an O'Raifeartaigh-like model with superpotential:
  - $W = h \mathrm{Tr}\,(q \Phi \widetilde{q}) - h\mu^2 \mathrm{Tr}\,\Phi$
  - Susy is broken at tree level due to the *rank condition*:

$$-\overline{F}_{\Phi_{ij}} = h q^i \cdot \widetilde{q}^j - h\mu^2 \delta^{ij}. \tag{9}$$

SQCD with $\mathcal{N} = 1$

The metastable minimum

- At tree level there is a pseudomoduli space of susy breaking minima given by:

$$\Phi = \begin{pmatrix} 0 & 0 \\ 0 & \Phi_0 \end{pmatrix}, \quad q = \begin{pmatrix} q_0 \\ 0 \end{pmatrix}, \quad \tilde{q}^{\mathrm{T}} = \begin{pmatrix} \tilde{q}_0 \\ 0 \end{pmatrix} \tag{10}$$

with $q_0 \tilde{q}_0^{\mathrm{T}} = \mu^2 \mathbf{1}_{N_c}$ and energy given by:

$$V_{min} = N_c |h^2 \mu^4| \tag{11}$$

- It gets lifted (with positive masses) at one loop:

$$V_{eff}^{(1-loop)} = \frac{1}{64\pi^2} \mathrm{STr}\,(\mathcal{M}^4 \log \mathcal{M}^2). \tag{12}$$

SQCD with $\mathcal{N} = 1$

Restoring gauge dynamics near the origin of field space

Just a few remarks:

- The D-terms are satisfied around the metastable vacuum:

$$V_D = \frac{1}{2} \sum_A (\mathrm{Tr}\, q^\dagger t_A q - \tilde{q}^\dagger t_A q)^2 \tag{13}$$

- The gauge dynamics does not enter at one loop into the vacuum energy, since gauge multiplets are supersymmetric at tree level:

$$V_{eff}^{(1-loop)} = \frac{1}{64\pi^2} \mathrm{STr}\,(\mathcal{M}^4 \log \mathcal{M}^2). \tag{14}$$

- The nonperturbative contribution is small, as we see next.

SQCD with $\mathcal{N} = 1$

Restoring gauge dynamics far in field space

The theories in the Seiberg dual pair supposed to be equivalent in the IR, in particular they should have the same vacua. Where are the N_c original vacua?

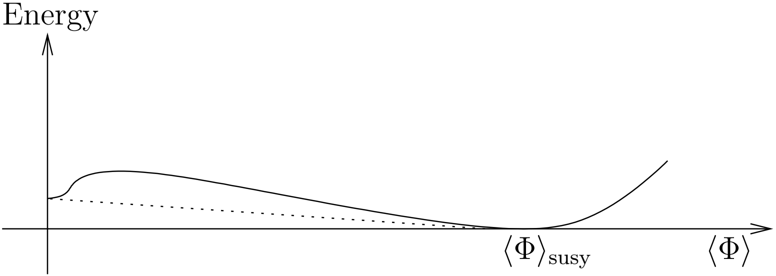
They arise from nonperturbative effects, which we can compute reliably by noticing that far from $\langle\Phi\rangle = 0$ the magnetic quarks get a mass from the superpotential, and can be integrated out. A nonperturbative ADS term then appears:

$$W = h\mathrm{Tr}\,(q\Phi\widetilde{q}) - h\mu^2\mathrm{Tr}\,\Phi \longrightarrow n(h^{N_f}\Lambda_m^{-(N_f-3n)}\det\Phi)^{1/n} - h\mu^2\mathrm{Tr}\,\Phi \tag{15}$$

This has N_c vacua, exactly as the electric theory.

SQCD with $\mathcal{N} = 1$

A picture of field space



- These vacua are metastable (because of susy), but long-lived.
  - $S \approx |\epsilon|^{4(2N_f - 3N_c)/N_c} \gg 1$ (with $\epsilon = \sqrt{m/\Lambda}$)

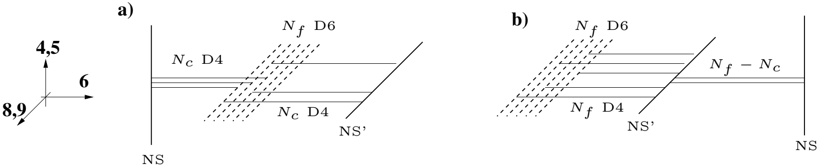
Outline

Since the ISS paper quite a few realizations have been found:

- Hanany Witten configurations [Franco, I.G.-E., Uranga 06] [Ooguri, Ookouchi 06]
- Branes at singularities with obstructed complex deformations [Franco, Uranga 06] [I.G.-E., Saad, Uranga 07]
- Brane-antibrane systems in trivial cycles. [Aganagic, Beem, Seo, Vafa 06]
- Orbifolds of the conifold with D-instantons. [Argurio, Bertolini, Franco, Kachru 07]

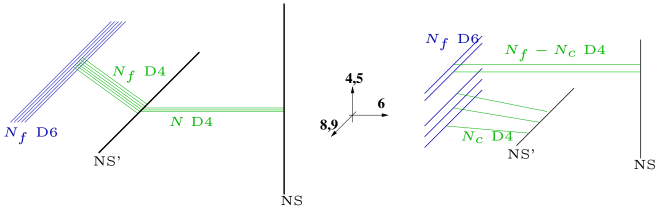
Rudiments of Hanany-Witten configurations

- Webs of D6, D4 and NS5 branes in type IIA.
- Many interesting gauge theory phenomena are apparent.



Realizing the ISS vacua

- Our starting point was massive SQCD in the magnetic dual.



- Seiberg duality returns us to the supersymmetric minimum.
- Mesonic moduli space, pseudomoduli stabilization, tachyonic mode.

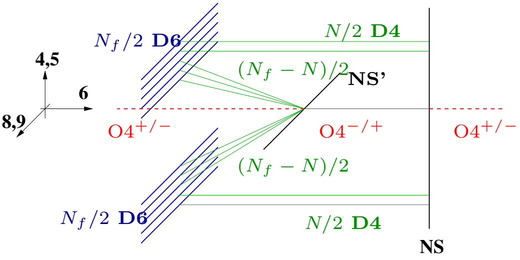
A word of caution

Everything we do here must be continued carefully to the strongly coupled gauge theory limit, see [Giveon, Kutasov 07].

Orientifolded generalizations I

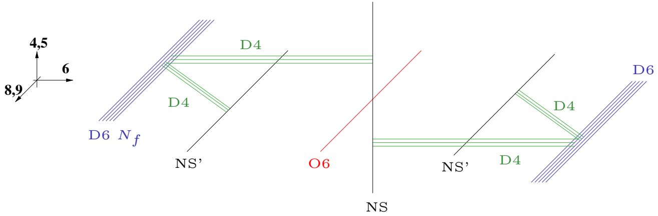
Metastable vacua for SO/Sp groups

- Introducing orientifolds is easy for Hanany-Witten setups.
- We can construct in this way various generalizations of the previous constructions.



Orientifolded generalizations II

$SU(N_c)$ with matter in $\square\!\square$ or $\begin{smallmatrix}\square\\\square\end{smallmatrix}$



- Plenty of other configurations are constructible, for example $SU(N_c)$ with chiral matter $(\overline{\square\!\square} + \begin{smallmatrix}\square\\\square\end{smallmatrix} + 8\square)$.
- See also Changhyun Ahn's work.

Conclusions

Good news

We have some control over metastable supersymmetry breaking vacua in $\mathcal{N} = 1$ gauge theory.

- We expect them to be very common, and easy to construct.
- They can be realized in string theory in many different ways.
- They are of phenomenological interest.
- They can be useful for string model building [hep-th/0605166].