Comments on Anti-Branes

Shamit Kachru (Stanford and SLAC)

Based in part on work with:

McAllister and Sundrum (hep-th/0703105)

Argurio, Bertolini and Franco (hep-th/0610202, hep-th/0703236)

The construction of (meta)stable vacua which break supersymmetry in string compactifications, is a problem of significant interest for several reasons. My talk will make contact with two:

i) We now have techniques (growing out of AdS/CFT and the study of geometric transitions) that can teach us about novel SUSY breaking models that are hard to understand directly in weakly coupled quantum field theory, i.e. are in some sense "stringy."

Kachru, Pearson, Verlinde;
Aganagic, Beem, Seo, Vafa;
Douglas, Shelton, Torroba;
.....

ii) Some of these models may have features that could be useful for (LHC-related) model building.

I will try to illustrate both of these possibilities, in this talk.

I. Stringy SUSY breaking via Anti-branes

The simplest and most explicit example of a gravity dual to a confining gauge theory is the warped, deformed conifold solution.

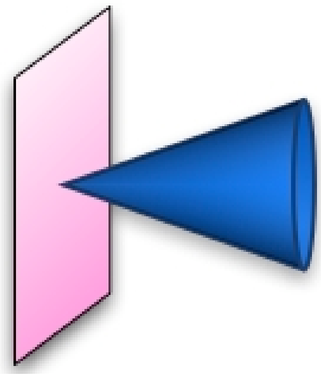
The starting point is the singular conifold geometry:

$$x^2 + y^2 + z^2 + w^2 = 0 \subset C^4$$

The singularity can be viewed as a cone over $S^3 \times S^2$.

There are two interesting gauge/gravity dualities associated with this geometry:

i. Placing N D3 branes at the tip of the cone :



one finds a near horizon geometry $AdS_5 \times T^{1,1}$.

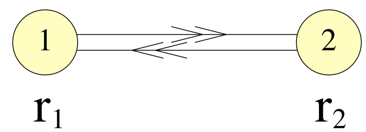
The metric and five-form in the gravity solution are :

$$ds^2 = h^{-1/2}\eta_{\mu\nu}dx^\mu dx^\nu + h^{1/2}(dr^2 + r^2 ds^2_{T^{1,1}})$$

$$(F_5)_{rtx^1x^2x^3} = \partial_r h^{-1}$$

where: $$h(r) = \frac{27\pi}{4}\frac{1}{r^4}(\alpha')^2 g_s N$$

This is dual to a conformal field theory described by Klebanov and Witten, with the quiver diagram (with equal occupation numbers at the nodes) :



and with superpotential:

$$W = h\epsilon^{ij}\epsilon^{kl}A_iB_kA_jB_l \ .$$

ii. Adding M (<< N) wrapped D5s:

Klebanov, Strassler; Vafa

The quiver and superpotential remain as above, but the theory is no longer conformal. While the large r behavior of the gravity solution is as before (only modified by a logarithm in h(r)), the small r behavior (field theory IR) is different.

It is useful to think of this modified solution as being related to the "deformed" conifold geometry:

$$x^2 + y^2 + z^2 + w^2 = \epsilon^2$$

This geometry has two 3-cycles, a so-called A-cycle which is the three-cycle generated by real choices of x,y,z,w, and a B-cycle which is swept out by the 2-sphere and the radial directon of the cone.

For N = KM, we can think of this geometry being sourced by fluxes:

$$\int_A F_3^{RR} = M \qquad \int_B H_3^{NS} = -K$$

Using the standard conifold periods

$$\int_A \Omega = z, \quad \int_B \Omega = \frac{z}{2\pi i}\log(z) + \text{regular}$$

and plugging into the GVW superpotential

$$W = \int (F - \tau H) \wedge \Omega$$

one finds that the deformation of the conifold is dynamically generated, and the deformation parameter is given by

$$\epsilon \sim \exp(-\pi K/g_s M)$$

The metric at the tip in the gravity dual is given by:

$$ds^2 = a_0^2 \; dx_\mu dx^\mu + g_s M \; b_0^2 \; (dr^2 + d\Omega_3^2 + r^2 d\Omega_2^2)$$

i.e. there is a three sphere of size set by gM while the two-sphere vanishes at r=0. The coefficients are:

$$a_0 \sim e^{-4\pi K/3g_s M}, \quad b_0 \sim \mathcal{O}(1)$$

The RR three form (which has flux through the finite sized three-sphere at the tip) takes the form:

$$F_{kjl} \sim f \epsilon_{kjl}, \quad f \sim \frac{1}{b_0^3 \sqrt{g_s^3 M}}$$

This solution is supersymmetric and carries N units of D3 brane charge, but has no explicit probe D3s. So if one wishes to break supersymmetry by modifying the solution, an obvious option is to add some number p (<< M,N) of anti-D3 branes.

Kachru, Pearson, Verlinde

The resulting theory will have a total D3-brane charge

$$Q_3 = \int H_3 \wedge F_3 - p = KM - p$$

which matches that of a theory with one less unit of NS flux, and M-p probe D3-branes. The latter is SUSY, so one should think of the anti-D dynamics as describing some state in that supersymmetric theory. (To really justify this one should worry about the full asymptotics in the cascading solution and interpret these states via AdS/CFT; this is in progress).

Chuang, DeWolfe, Kachru, Mulligan

The resulting dynamics of the anti-D3s is as follows:

I: They will be attracted to the tip of the warped, deformed conifold. The gravity solution has a nontrivial five-form flux which we described at large r, and the anti-D3s feel a force:

$$F_{radial}(r) = -2\mu_3 F_5(r)$$

II: They will undergo the famous Myers effect. Namely, the presence of the nontrivial RR 3-form flux threading the three-sphere at the tip of the deformed conifold, will cause them to "blow up" into NS 5 branes wrapping a two-sphere in the three-sphere.

Plugging the background RR and NS fields at the tip into the Born-Infeld + Chern-Simons action which governs the anti-D3, we find a potential for its worldvolume scalars:

$$g_s V_{eff}(\phi) \sim e^{-8\pi K/3g_s M}(p - i\frac{4\pi}{3}F_{kjl}Tr([\phi^k,\phi^j]\phi^l) - \frac{\pi^2}{g_s^2}Tr([\phi^i,\phi^j]^2) + ...)$$

It is then a moments work to see that critical points of V occur when the phi matrices satisfy the commutation relations:

$$[\phi^i,\phi^j] \sim i\epsilon_{ijk}\phi^k$$

These are (after rescaling) the commutation relations of a p dimensional matrix representation of SU(2)! So the critical points are in 1-1 correspondence with (generally reducible) SU(2) reps; the solution with lowest energy is the p-dimensional irreducible representation.

Intuitively, what happens is that the anti-D3 brane "blows up" into a 5-brane wrapping 2-sphere in the 3-sphere. The resulting state for $p \ll M$ is a metastable state which breaks supersymmetry; it can decay to the supersymmetric vacuum with the same global quantum numbers, by a tunneling process.

For p closer to M (the dividing line is about $p = M/10$), the size of the 2-sphere approaches and surmounts the size of the equator of the S^3; in the full string theory, at this point, the 5-brane becomes perturbatively unstable, and directly rolls back to a supersymmetric vacuum with the same quantum numbers as the initial state.

Summary: For $p << M,N$ the system of p anti-D3s in the warped-deformed conifold gives rise to a stable non-supersymmetric state with exponentially small supersymmetry breaking scale (due to warping of the anti-D3 tensions)!

Two natural questions about these states:

i) Recently, Intriligator, Seiberg and Shih discovered that very simple vector-like SUSY quantum field theories (like SUSY QCD with slightly massive flavors) have metastable, SUSY breaking vacua. The conifold quiver (and its generalizations) give QCD-like theories (with gauged flavor groups). Are there cases where these anti-D states at large gN are present in a theory which has ISS vacua at small gN?

ii) It is easy to compactify this situation (by constructing compact solutions with a warped, deformed conifold region). In such models, how do branes in the bulk of the Calabi-Yau feel the anti-D SUSY breaking? Are there novel features that could be useful?

Giddings, Kachru, Polchinski; KKLT

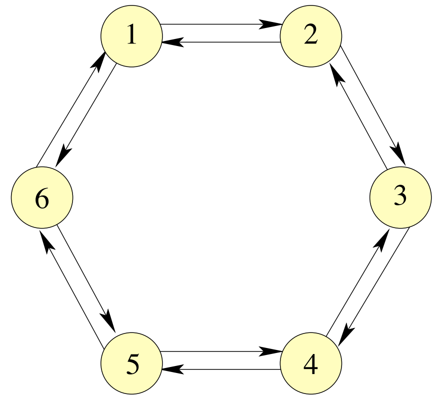
II. Conifold quivers and metastable states

The KS field theory itself does not have evident metastable vacua at weak gauge coupling. However, simple generalizations of it do.

Argurio, Bertolini, Franco, Kachru; see also Franco, Uranga; Ooguri, Ookouchi; Giveon, Kutasov; Hirano;...

There exist simple Z_K quotients of the conifold whose quiver diagrams take the form (e.g. for K=3):

Uranga

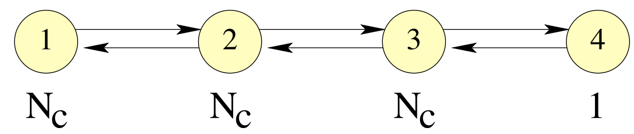


The corresponding superpotentials take the form:

$$W = h \sum_{i=1}^{2N} (-1)^{i+1} X_{i,i+1} X_{i+1,i+2} X_{i+2,i+1} X_{i+1,i} \ ,$$

For suitable choices of occupation numbers, these theories also have RG cascades and simple gravity duals in an appropriate large gN limit.

The simplest model which seems to have close relatives of the metastable states of massive QCD, is the K=3 model with quiver:



This theory has a superpotential:

$$W = h(X_{12}X_{23}X_{32}X_{21} - X_{23}X_{34}X_{43}X_{32}) + mX_{43}X_{34}\ .$$

(I will explain the origin of the mass term momentarily).

In the regime where: $\Lambda_3 >> \Lambda_1 >> \Lambda_2$

it can be analyzed by standard field theory techniques.

Intuitively, one should think of node 3 as SQCD with N_f = N_c + 1. The other nodes are either flavor nodes, or present to dynamically generate the needed light quark masses (so there is no fine tuning).

Roughly this happens as follows. Since the group at node 1 has N_f = N_c, its moduli space is quantum modified.

Seiberg

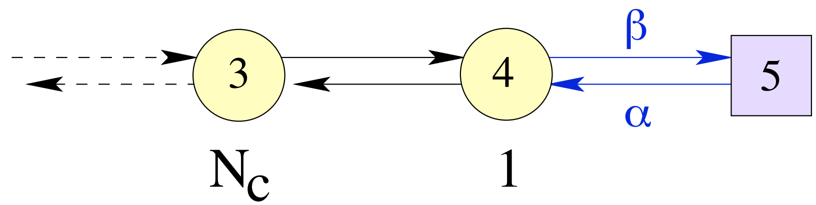
If we call the node 1 meson M, then on the mesonic branch

$$detM = \Lambda_1^{2N_c}$$

Taking M to have equal eigenvalues, it is easy to see that the quartic couplings in the superpotential then generate masses for N_c of the flavors of node 3:

$$hX_{12}X_{23}X_{32}X_{21} \to h\Lambda_1^2 X_{23}X_{32}$$

This dynamically generates the tiny quark masses for all but the last flavor. The last flavor, coming from node 4, receives a contribution to its superpotential from a Euclidean brane wrapping (unoccupied) node 5 of the quiver:



In suitable circumstances, this generates a mass m with scale that can be tuned by varying the "size" of node 5 in the dual geometry. Similar stringy instantons have been investigated by many groups and used to generate e.g. mu terms in recent papers.

Blumenhagen, Cvetic, Weigand;
Ibanez, Uranga;
Florea, Kachru, McGreevy, Saulina;
....

In any case, for $h\Lambda_1^2 < m << \Lambda_3$
the resulting theory at node 3 is roughly SQCD in the regime where it has been shown to have a metastable SUSY breaking false vacuum. One can go back and justify that the assumption of the mesonic branch on node 1 is justified (no evident local instability to move to the baryonic branch and relax the quark masses); the full quartic W is crucial in doing this.

This model and its relatives have three interesting features:

a) All mass scales are generated dynamically; roughly speaking the fine tuned small mass of ISS has been "retrofitted."

Dine, Feng, Silverstein

b) The quartic superpotential in fact deforms the original ISS theory by a quadratic in the magnetic meson field. This breaks the R-symmetry, which is good if one is interested in model building.

Kitano, Ooguri, Ookouchi

c) There is a reasonably simple dual geometry for these models, based on deformation of $(xy)^3 = zw$, where one can propose concrete gravity duals involving also wrapped D5 branes and anti-D3 branes. The understanding is however very incomplete at present.

III. Warped Sequestering of SUSY breaking

"Sequestering" is an idea to help solve the following problem (the so-called supersymmetric flavor problem).

In gravity mediated supersymmetry breaking, the squark and slepton masses of the MSSM arise from terms of the form

$$\int d^4\theta \; \frac{1}{M_P^2} X^\dagger X c_{ij} Q_i (Q_j)^\dagger$$

Here, X is the chiral multiplet with the dominant SUSY breaking F-term:

$$X = ... + \theta^2 \langle F_X \rangle$$

and the Qs are the three generations of squark superfields.

It has been appreciated for many years that if

$$\langle F_X \rangle \sim (10^{11} GeV)^2$$

then one can successfully generate TeV scale squark/slepton masses with this type of coupling. But the past twenty years of absent new sources of FCNCs / EDMs has led to the following mystery: why is

$$c_{ij} \sim \delta_{ij}$$

to such high precision?

The idea of "sequestering" was proposed by Randall and Sundrum in 1998 to solve this problem. They advocated a scenario where (due to locality in extra dimensions and spatial separation of the SUSY breaking and Standard Model branes) the dangerous dimension six terms in K are simply absent (or exponentially suppressed).

Then, one can use anomaly mediation or some other high-scale mediation mechanism (gaugino mediation, high scale gauge mediation, mirage mediation,...) to generate the flavor blind squark masses.

We will just worry about the first part: sequestering is a question of dimension six, Planck suppressed operators. It is UV sensitive. Can one sequester in string theory? In many cases, Dine et al have argued that the answer is no.

In recent work with McAllister and Sundrum, we argue that, if one breaks SUSY at the end of a warped throat (as in the first half of my talk), the breaking can robustly be sequestered from "Standard Model" or GUT branes localized elsewhere in the Calabi-Yau.

The basic intuition follows from AdS/CFT duality, and uses CFT language. We should think of SUSY breaking at the end of a warped throat as AdS/CFT dual to an approximate CFT which undergoes RG flow starting at a high scale Λ_{UV} and then confines and breaks SUSY at a (much) lower scale Λ_{IR}.

In CFT language, if some operator $\mathcal{O}$ of the CFT (made of the X fields) couples to $Q^\dagger Q$

$$\int d^4\theta \; c \; \mathcal{O} \; Q^\dagger Q$$

then the coefficient c runs between the UV scale and IR scale where SUSY breaking occurs. So if $\mathcal{O}$ has anomalous dimension γ , on top of any standard suppressions

$$c_{ij} \sim (\frac{\Lambda_{IR}}{\Lambda_{UV}})^\gamma$$

So for order 1 anomalous dimensions, which are generic in strongly coupled CFT, and normal choices of the SUSY breaking and UV scales, this kills the unwanted cross couplings.

In gravity dual language, this has a straightforward translation:

* The hierarchy between the IR and UV scales translates into the requirement that the throat length L be greater than a few AdS radii

* The conformal dimension of $\mathcal{O}$ maps to the KK mass of the gravity mode dual to $\mathcal{O}$

* Then the suppression of c is just the Yukawa fall off of the propagator of the dual gravity mode as it travels "up the throat"!

This leaves a question: is it common for strongly coupled CFTs not to have non-chiral operators of dimension 2, but only non-chiral operators of dimension ≥ 3

Unfortunately, the answer is no: if the CFT has any global symmetry group G, then the supermultiplet of the G conserved current includes a component whose dimension is precisely 2 and is protected by current conservation.

$$X^\dagger T^a X \quad \text{has} \quad \Delta = 2$$

So why doesn't this couple to squarks and sleptons, and ruin sequestering?

Theorem: If G is not explicitly broken by the CFT dynamics that lead to confinement and SUSY breaking, then the SUSY-breaking F-component of this operator vanishes.

Schmaltz, Sundrum

So, such operators do NOT harm sequestering.
And, in common examples, all non-chiral operators which aren't protected in this manner, DO have dimension larger than 3 due to large anomalous dimensions from strong dynamics.

In particular, the SUSY breaking by anti-D3 branes in the warped deformed conifold satisfies all of our requirements. Hence, such SUSY breaking is sequestered from any realization of the Standard Model in the bulk of the Calabi-Yau space.

This is one example of a phenomenological feature that certain "stringy" examples of SUSY breaking natural exhibit. Are there others? Could they be relevant at LHC?