SU$\not{S}$Y and its mediation, in string theory

Based on:

Diaconescu, Florea, Sk, Svrcek 0512170

Sk, McGreevy, Svrcek 0601111

Florea, Sk, McGreevy, Saulina 06xxxxx

Introduction

The LHC may uncover evidence of low-energy SUSY. It then becomes interesting to ask (as people have for 20+ years):

- How did $\cancel{SUSY}$ occur? And, in "natural" theories $\langle F \rangle \lesssim (10^{11}\,\mathrm{GeV})^2$ -- what dynamics $\to$ $\sqrt{F} \ll M_{pl}$?
- How was $\cancel{SUSY}$ mediated to the SM?

In many interesting cases, answers are UV sensitive $\to$ makes sense to study in string theory.

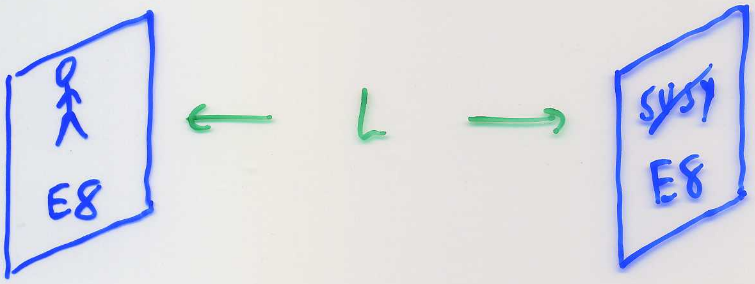
I plan to discuss:

- elementary observations about mediation mechanisms in string compactifications
- New "geometrical" criterion for DSB, suggested by study of branes $\in$ string theory

Mediation of ~~SUSY~~ in String Theory

Fairly typical set-up for SUSY GUTs:

Heterotic M-theory



$L \gg \frac{1}{M_{GUT}}$

- 6 other compact dims on Calabi-Yau X
- Moduli of metric on X

$h^{1,1}(X)$ size moduli

$h^{2,1}(X)$ shape moduli

+ <u>Dilaton</u> (L)

→ many scalar moduli fields ϕ_i

- Known mechanisms for generating moduli potential (Fluxes, instantons, kähler corrections)

$\Rightarrow$ typically <u>many</u> ϕ_i have

$$m_{\phi_i} \ll \text{KK scales}$$

[This kind of analysis $\rightarrow$ same conclusion in IIB, IIA and M-theory models].

- Also, in heterotic picture, <u>no</u> <u>light</u> <u>fields</u> charged under both E8 s.

<u>Therefore</u>:

- Gauge mediation doesn't occur in vanilla heterotic setup
- Anomaly mediation is also disfavored by light bulk fields, unless they have special constraints on their couplings to MSSM.

Then, vanilla models have gravity mediation.

PROBLEM:

Say $X = \cdots + \theta^2 F_X$ has dominant F-term.

Terms of the form

$$\mathcal{L} \supset \int d^4\theta \; c_i \frac{X^\dagger X}{M_P^2} \; Q_i^\dagger Q_i$$

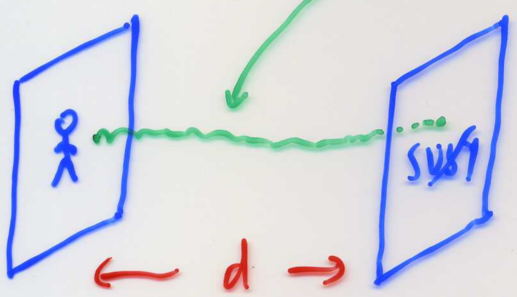
with $\mathcal{O}(1)$ c_i will be generated, coupling ~~sysy~~ to squarks.

FCNC bounds $\Rightarrow$
squarks should have
equal masses $\Rightarrow$
$c_1 = c_2 = c_3$

But <u>WHY</u>?? Without special assumptions, X in general <u>doesn't</u> couple universally.

Gauge-mediation does allow natural sol'n to flavor problem, and does NOT require absence of bulk fields below KK scale → natural to look for modifications of vanilla scenario that allow gauge mediation.

Cartoon:



Lightest stretched strings have mass ~d ⇒ want $d \ll \ell_s$.

This suggests we should:

a) Find ways to realize SM / GUTs on D-branes (lots of work on this!!)

b) Find natural DSB models that arise on D-branes (← our focus)

DSB from D-branes

There are a few known "general classes" of $\mathcal{N}=1$ QFTs that should $\Rightarrow$ DSB (developed by e.g. Affleck-Dine-Seiberg + ... starting ~1984).

Example: "Non-calculable models"

- Consider an $\mathcal{N}=1$ gauge theory with <u>no</u> <u>flat</u> <u>directions</u> at tree level, and with sufficiently little matter that it should confine in the IR.
- 't Hooft anomaly matching can constrain possible IR pion Lagrangians. In some cases, the required field content (assuming global symmetries are unbroken) is <u>so</u> <u>contrived</u> <u>looking</u> that one must postulate <u>global</u> ~~symmetry~~ in IR.

- This means that there must be Goldstone bosons. But unbroken SUSY $\Rightarrow$ they must be complexified into full chiral mults. which are flat dirs.

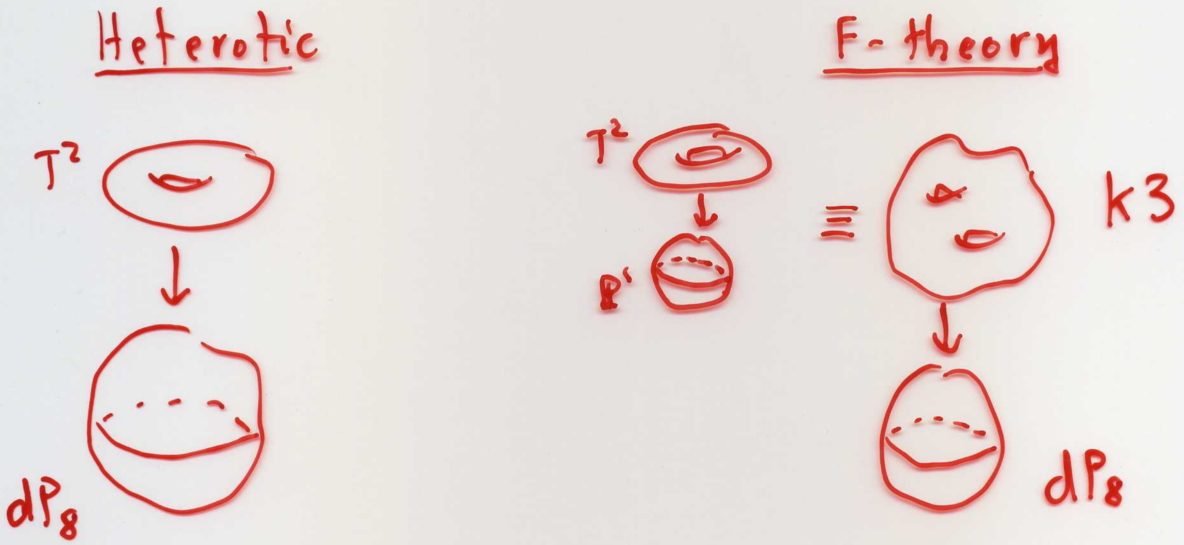
This is very implausible in a theory w/o tree lvl flat directions $\Rightarrow$ theory must have DSB.

Simplest examples: (ADS)

- $SO(10)$ with 1 $\underline{16}$.
- $SU(5)$ with 1 $\underline{\bar{5} + 10}$.

Murayama gave additional decisive evidence that these theories break SUSY by studying theories w/ additional vector-like matter, and decoupling it...

These are naturally engineered in heterotic / F-theory dual pairs. E.g.



The heterotic E8s $\Rightarrow$ D7 stacks in F-theory.

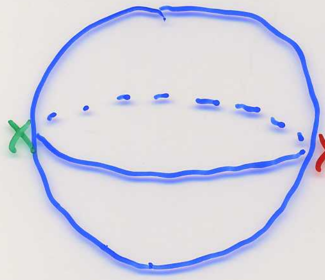
- Using technology of Donagi / Pantev / Ovrut and Friedmann / Morgan / Witten, we can:

- Find bundles $V_{1,2}$ to embed in $E8 \times E8$ with structure group $SU(5)$

$$ch_3(V_1) = \pm 1 \qquad ch_3(V_2) = \pm 3$$

+ satisfying anomaly cancellation.

Dualize to IIB / F-theory picture $\Rightarrow$



- In F-theory, $\exists$ complex structure moduli that allow us to move the $\cancel{SUSY}$ brane stack close to SM stack $\rightarrow$ control <u>messenger</u> <u>masses</u>.

- With natural choices, find

$$\langle F \rangle \sim \left(\frac{\Lambda_{hidden}}{4\pi}\right)^2 \sim (10^{10}\ GeV)^2$$

$\rightarrow$ need messengers $M \sim 10^{15}$ GeV

[Messengers in $(5, \bar{5}) \oplus (\bar{5}, 5)$ at this M

$\rightarrow$ no problem with unification].

OBVIOUSLY, <u>NOT</u> <u>REALISTIC</u>. But systematic improvement using <u>same</u> <u>techniques</u> is possible.

Using the IIb or F-theory dual picture $\rightarrow$

- Can control limit where $M \ll M_s$
- Can stabilize closed string moduli as in KKLT (this fourfold seems appropriate for that, i.e. has plentiful $\chi = 1$ divisors).

Related work: Garcia-Etxebarria, Saad, Uranga

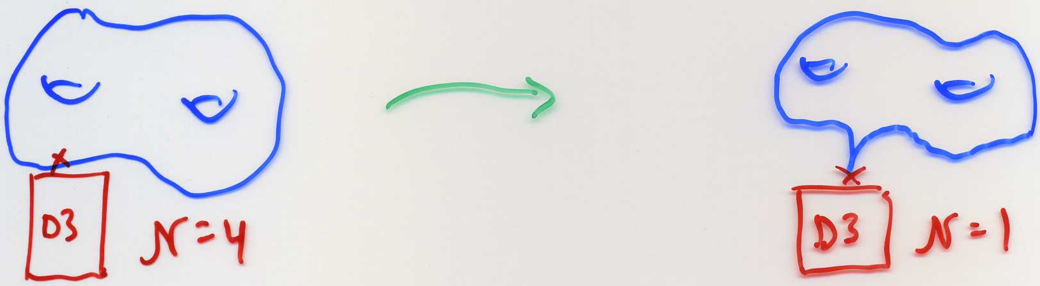
Can string theory suggest <u>new</u> classes of DSB models on branes?

The answer seems to be <u>yes</u>. Recent work of several groups highlights a promising <u>geometrical</u> criterion for ~~SUSY~~.

Berenstein, Herzog, Ouyang, Pinansky;
Franco, Hanany, Saad, Uranga;
Bertolini, Bigazzi, Cotrone

Basic intuition:

D3 branes @ smooth point on Calabi-Yau $\to$ (in IR) $\mathcal{N}=4$ SYM. But at a singular point SUSY is reduced even locally $\to$ can get interesting $\mathcal{N}=1$ SCFTs:



Douglas / Moore
SK / Silverstein
Lawrence, Nekrasov, Vafa

To break conformal invariance, you can add "fractional branes" (~ D5s wrapping collapsed rigid $\mathbb{P}^1$'s in singular locus).

Famous example: D3s @ conifold

Klebanov, Witten

Conifold: $\sum_{i=1}^{4} w_i^2 = 0$

The conifold is a cone over $S^3 \times S^2$:

N D3s @ tip $\Rightarrow$ an $SU(N) \times SU(N)$ CFT

matter $2 \times (N, \bar{N})$ $2 \times (\bar{N}, N)$ + quartic W.

Klebanov + Strassler (also Vafa):

Add D5s (M) wrapping $\mathbb{P}^1$ at tip $\Rightarrow$ end up with an RG cascade. For $N = kM$, after k Seiberg dualities, result is pure $\mathcal{N}=1$ SYM.

$\delta W = \Lambda^3_{SU(M)}$ + $U(1)_R$ breaking $\Longleftrightarrow$ Deformation of geometry: $\sum w_i^2 = O(\Lambda)$

Important point:

- Moduli space of CFT ~ conifold geometry
- Moduli space of fractional brane theory (+ probe) ~ **deformed** conifold geometry

Also generally in a SUSY gauge theory

Moduli space $\mathcal{M}$ of SUSY vacua $\approx$ Variety given by Chiral ring of gauge invt ops / relations, dW

The several groups I cited previously noted the suggestive fact:

Rather large classes of CY singularities = incomplete intersections

Altmann

E.g. when a dP_1 ($\mathbb{P}^2$ blown up @ pt) collapses in CY, the singularity is of this type.

<u>Incomplete</u> $\Rightarrow$ N variables $\phi_1 \cdots \phi_N$

K equations

$$\mathcal{M} : P_1(\phi) = 0 \;\cdots\; P_K(\phi) = 0$$

but $\dim(\mathcal{M}) > N - K$

Intuitively, "equations aren't independent," but you <u>cannot</u> remove any & get same $\mathcal{M}$.

<u>SO WHAT</u>?

- N D3s probe singularity $\to$ moduli space is (N copies of) $\mathcal{M}$ above
- But adding fractional branes (rigid) $\Rightarrow$??

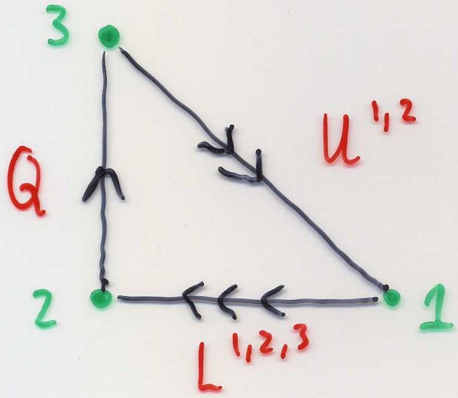
Intuitively, the singularity will "want" to deform due to gaugino condensates / IR dynamics on D5s ; but it can't !

Conclusion : { pts satisfying $dW = 0$ empty }

$\Rightarrow$ $\cancel{\text{SUSY}}$, dynamically.

[Obvious generalization : Singularities with n deformations but m > n types of fractional branes.]

Simplest Example : (subquiver of dP_1 quiver)



$W \sim Q\,U\,L + \ldots$

(preserves global SU(2))

(reminiscent of Affleck-Dine-Seiberg 3-2 model)

- SU(3) has $N_F = N_c - 1$ $\rightarrow$ instanton generates non-perturbative $\Delta W_{SU(3)}$.

Resulting vacuum structure?

- The nodes $\rightarrow$ $U(3) \times U(2) \times U(1)$ gauge group
- 2 U(1)s are anomalous (3rd decouples); anomalies are cancelled via Green-Schwarz mechanism in string theory

RR axion(s) $\longrightarrow$ $a\, F \wedge F \rightarrow (a + \delta a)\, F \wedge F$

so $\delta_{gauge} \mathcal{L} + (\delta a)\, F \wedge F = 0$

- U(1) gauge bosons get mass, M (can be $\ll M_s$ in these theories)

If you take $M \rightarrow \infty$, U(1)s decouple.

Resulting theory: no vacuum.

Intriligator, Seiberg

In compact realizations, M is finite.

In a theory with such a massive $U(1)$, even integrating it out, the $U(1)$ D-term constraints need to be imposed.

Arkani-Hamed, Dine, Martin

$$V = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 - \frac{1}{2 g_x^2} D_x^2 - D_x \left(\sum_i q_i |\phi_i|^2 + \xi^2 \right)$$

ξ^2: kähler modulus partner of a

At a stationary pt of V, gauge inv. $\Rightarrow$

$$\langle D_x \rangle = - \frac{g_x^2}{M_x^2} \sum_i q_i \, |\langle F_i \rangle|^2$$

$$M_x^2 = g_x^2 \sum_i q_i^2 |\phi_i|^2 \quad \Big\} \text{ mass of } U(1) \text{ gauge fld}$$

Integrating out $U(1)_x$ field $\Rightarrow$

$$\Delta K = - \frac{g_x^2}{M_x^2} q_i q_j \, \phi_i^* \phi_i \, \phi_j^* \phi_j$$

and in the presence of any nonzero F_{ϕ_i}, this –

soft masses:

$$m_{\phi i}^2 = -q_i \langle D_X \rangle$$

identical to keeping D-term constraint around.

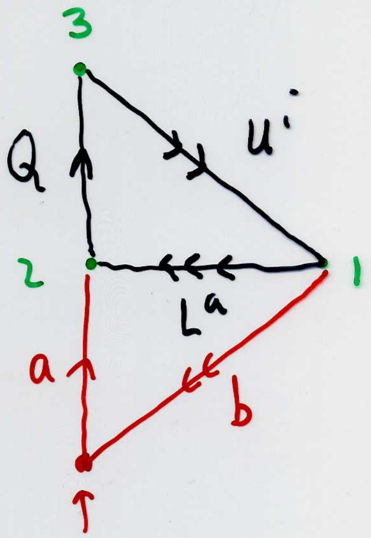
So, the behavior of this system for large, finite M_X differs from its behavior at $M_X = \infty$.

Imposing U(1) D-terms with fixed FI parameters $\xi \Rightarrow$ DSB.

But ξ = kähler modulus partners of the U(1) charged axions

So to properly understand these theories, we need to analyze instantons in the geometries with dP singularities.

Simplest e.g.:



Euclidean D3 on node 3

Instantons are Euclidean D3s w/ bundles on them; they have strings stretching to space-filling branes!

Ganor '96

$$L_{disc} \sim a\,(Q\cdot u^i)\,b_i$$

c.f. Bershadsky et al

$$\Delta W \sim \int da\, db\; e^{-L_{disc}} \sim \frac{1}{\det Q\cdot u}$$

But <u>more</u> <u>general</u> D3s, which are <u>NOT</u> gauge instantons, can also have such Ganor strings & contribute to W.

Questions:

- How do the selection rules for Euclidean D3 contributions to W get modified for instantons that intersect space-filling branes?

  Witten '96 "$\chi = 1$" $\to$??

- Do these contributions change qualitative physics or vacuum structure of e.g. the (compactified) dP quiver theories or their more general F-theory cousins?

These questions ... and more ... will be discussed in McGreevy's talk tomorrow.