SU$\cancel{\text{SY}}$ and its mediation, in string theory

Based on:

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Introduction

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

- How did ~~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 ~~SUSY~~ mediated to the SM?

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

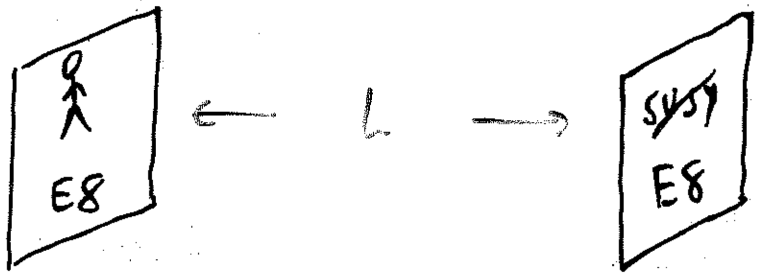
I plan to discuss:

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

<u>Mediation of ~~SUSY~~ in String Theory</u>

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)

$\rightarrow$ 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

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

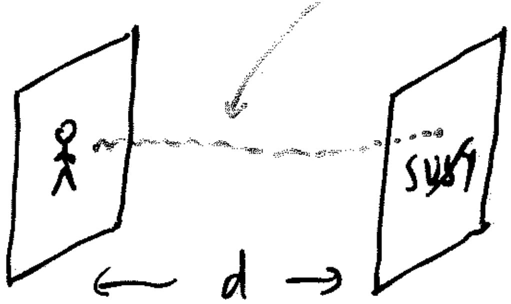
with $\mathcal{O}(1)$ c_i will be generated, coupling ~~susy~~ to squarks.

$$\boxed{\begin{array}{c}\text{FCNC bounds} \Rightarrow \\ \text{squarks should have} \\ \text{equal masses} \Rightarrow \\ c_1 = c_2 = c_3\end{array}}$$

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

<u>Gauge</u> - mediation does allow natural sol'n to flavor problem, and does NOT require absence of bulk fields below KK scale $\Rightarrow$ natural to look for modifications of vanilla scenario that allow gauge mediation.

<u>Cartoon</u>:



Lightest stretched strings have mass $\sim d$ $\Rightarrow$ want $d \ll l_s$.

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 ($\leftarrow$ our focus)

DSB from D-branes

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

Example: "Non-calculable models"

· Consider an $\mathcal{N}=1$ gauge theory with no flat directions 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 so contrived looking that one must postulate global symmetry in IR.

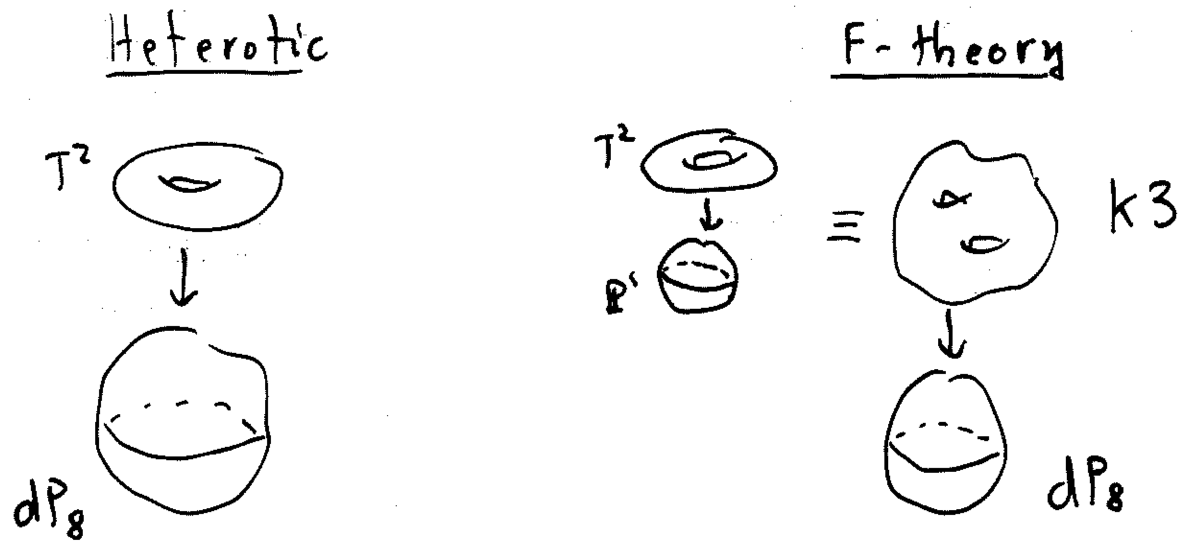
- This means that there must be Goldstone bosons. But <u>unbroken</u> SUSY $\Rightarrow$ they must be complexified into full chiral mults. which are flat dirs. This is very implausible in a theory w/o tree lvl flat directions $\rightarrow$ theory must have <u>DSB</u>.

<u>Simplest examples</u>: (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:

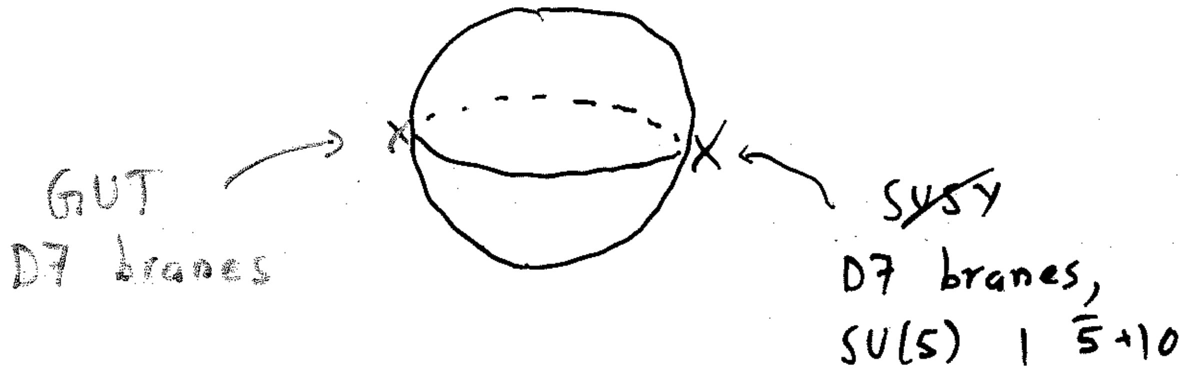
- Find bundles $V_{1,2}$ to embed in $E8 \times E8$ with structure group $SU(5)$

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

+ satisfying anomaly cancellation.

⑨

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



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

· With natural choices, find

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

$\rightarrow$ 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 new techniques 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

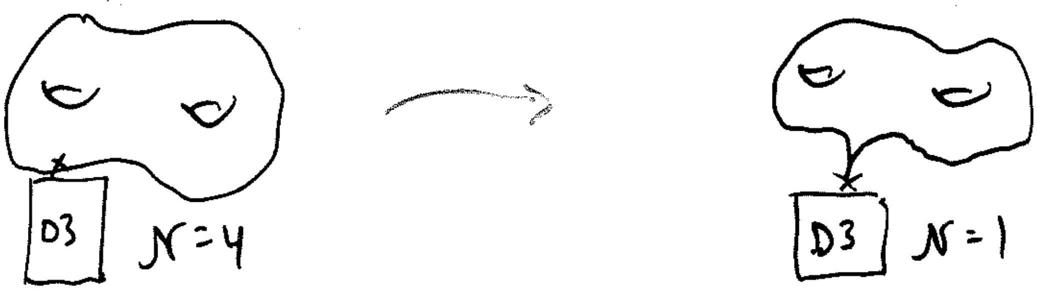
Can string theory suggest <u>new</u> classes of DSB models on branes?

The answer seems to be <u>yes</u>. Recent work of several groups highlights a promising <u>geometrical</u> criterion for $\cancel{\text{SUSY}}$.

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:



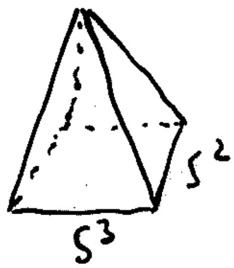
Douglas / Moore; Sk / Silverstein; Lawrence, Nekrasov, Vafa

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

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

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.

<u>Klebanov + Strassler</u> (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 <u>pure</u> $\mathcal{N}=1$ SYM.

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

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.

Incomplete $\Rightarrow$ 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 cannot remove any & get same $\mathcal{M}$.

SO WHAT?

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

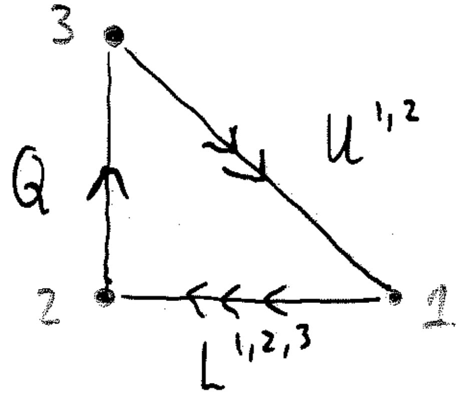
Intuitively, the singularity will "want" to <u>deform</u> due to gaugino condensates / IR dynamics on D5s; but it <u>can't</u>!

<u>Conclusion</u>: { pts satisfying $dW = 0$ empty }

$\Rightarrow$ ~~SUSY~~, dynamically.

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

<u>Simplest Example</u>: (subquiver of dP_1 quiver)



$W \sim QUL + \cdots$

(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 $\Delta W_{SU(3)}$.

<u>Resulting vacuum structure</u>?

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

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

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)

<u>IF</u> you take $M \rightarrow \infty$, $U(1)$s decouple.

Resulting theory: <u>no</u> <u>vacuum</u>. Intriligator, Seiberg

In <u>compact</u> realizations, M is <u>finite</u>.

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

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

kähler modulus partner of a

At a stationary pt of V, <u>gauge</u> <u>inv</u>. $\Rightarrow$

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

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

<u>Integrating</u> <u>out</u> $U(1)_x$ 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.

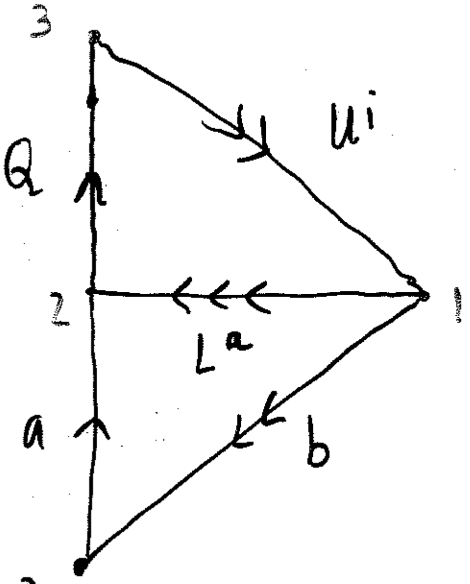
So, the behavior of this system for large, finite M_X differs from its behavior at $M_X = \infty$.

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 brane on node 3

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

Ganor '96

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

c.f. Bershadsky et al

$$\Delta W \sim \int da \; db \; e^{a(Q \cdot u)\, b} = \frac{1}{\det Q \cdot u}$$

BUT MORE GENERAL D3s, <u>NOT</u> gauge instantons, also have Ganor strings + can contribute.

Path integral over Ganor strings yields QFT op $\mathcal{O}$

$\Rightarrow$ instanton contributes if $\boxed{2\chi + q_R(\mathcal{O}) = 2}$

Generalizes Witten '96, $\chi = 1$

With Florea, McGreevy and Saulina, we are now working out the results for these dP theories, and general techniques for analyzing instanton effects using the extended quiver diagrams w/ nodes for instantons.

These can be <u>important</u>: Some UV completions of dP_1 quiver $\Rightarrow$

$$W = W_{tree} + W_{SU(3)} + e^{-\rho} \det(L^1, L^3)$$

$\rightarrow$ ~~Flavor symmetry~~ and ~~SUSY~~ <u>even</u> <u>if</u> one decouples $U(1)$s.

Other, very interesting, recent work on DSB: Intriligator, Shih, Seiberg; Franco, Uranga; Ooguri, Ookouchi; ...