

SUSY breaking and gauge mediation in F-theory GUTs

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arXiv:0808.1286

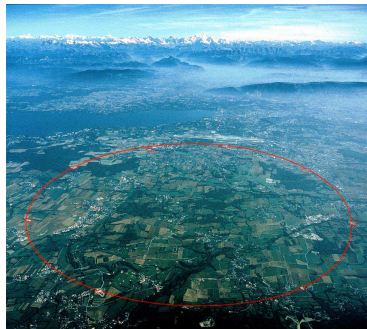
with J. Heckman, N. Saulina, S. Schäfer-Nameki, C. Vafa

arXiv:0808.1571, arXiv:0808.2450

with N. Saulina, S. Schäfer-Nameki

The LHC is Here

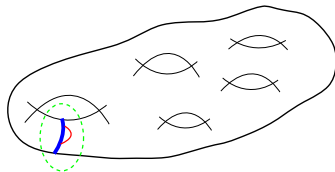
- The LHC era has finally arrived!
- We hope to learn many things about physics beyond the standard model
 - What explains the hierarchy?
 - (if anything?)
 - What comprises dark matter?
 - Will grand unification survive?
 - ...



As string theorists, what can we learn from the LHC?

Bottom-up String Phenomenology

- The LHC will primarily teach us about particle physics
- In string theory, we typically get gauge groups from **D-branes** and charged particles from **open strings** which end on them

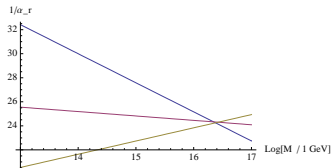


- At low energies, the open strings can only explore nearby regions of the geometry
 - ⇒ The LHC will provide data which, in a sense, encodes information about the **local geometry** of our string vacuum
- We can try to incorporate this information by building **local models**
 - Can serve as starting points for constructing realistic string vacua
 - A **bottom-up** approach to string phenomenology

Aldazabal, Ibanez, Quevedo, Uranga
 Gray, He, Jejjala, Nelson
 Verlinde, Wijnholt

Help from the LHC

- The LHC can help string theory meet particle physics because of the promise of **low-energy SUSY**
 - Easier to reliably engineer SUSY theories in string theory than non-SUSY ones
- Why might we expect low-energy SUSY?
 - Address hierarchy problem
 - Provides a dark matter candidate
 - Unification
 - Important clue for BSM physics



Optimistic scenario: SUSY GUT with TeV scale SUSY-breaking

Even more optimistic for local models: Gauge Mediation

Engineering SUSY GUTs in String Theory

- Obstacles to building SUSY GUTs with D-branes in Type IIA/B
 - E_n GUT – tough to engineer exceptional gauge groups
 - $SO(10)$ GUT – tough to engineer the **16**
 - $SU(5)$ GUT – D-brane realization extra gauged $U(1) \subset U(5)$
 - Forbids $\mathbf{10}_M \times \mathbf{10}_M \times \mathbf{5}_H$ coupling (though it can be generated nonperturbatively)
 - Some compact models constructed recently in IIB
- Can overcome these using techniques of **geometric engineering**
 - M -theory on G_2 manifolds
 - Difficult because not much is known about G_2 manifolds
 - F -theory on Calabi-Yau fourfolds
 - CY4's better understood

Blumenhagen, Braun, Grimm, Wiegand

Katz, Vafa

Acharya, Bobkov, Kane, Kumar, Shao, Vaman, Watson

Donagi, Wijnholt
Beasley, Heckman, Vafa

Outline

Review of F-Theory GUTs

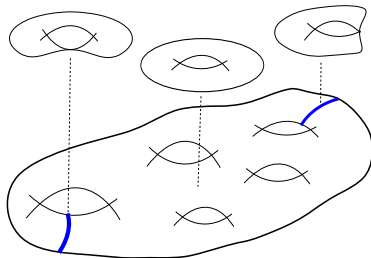
Generating Scales with Instantons

Gauge-Mediated SUSY Breaking

What is F -Theory?

Vafa

- F -theory is a framework for studying IIB compactifications with varying axio-dilaton τ
- Can be used to describe collections of mutually **non-perturbative** type IIB 7-branes
 - D7-brane – $(1,0)$ strings can end
 - Generic 7-brane – (p, q) strings can end
- Interpret τ as **modulus** of an elliptic fiber
 - Loci where fiber degenerates
↔ locations of 7-branes
 - Monodromies of τ
↔ types of 7-brane



Geometric Engineering in F -Theory

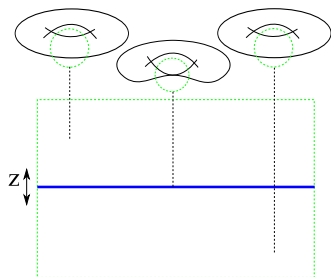
Katz, Vafa
Bershadsky, Intriligator, Kachru, Morrison, Sadv, Vafa

- Fiber degenerations described locally by ADE singularities
 - Singularity type \rightarrow gauge group on the 7-brane

- $SU(N)$ singularity

$$x^2 + y^2 + z^N = 0$$

- \rightarrow describes N D7-branes at $z = 0$
- \rightarrow Gauge group is $SU(N)$



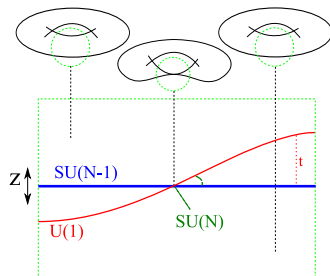
Geometric Engineering in F-Theory II

- Deformations of singularity \leftrightarrow Generators of Cartan subalgebra
 - Deformation parameters \leftrightarrow adjoint vevs

- Ex: Deformed $SU(N)$ singularity

$$x^2 + y^2 + (z + t)z^{N-1} = 0$$

- Nonzero t "rotates" one D7-brane away from the rest
- **Bifundamental matter** localized at the intersection where singularity type is enhanced



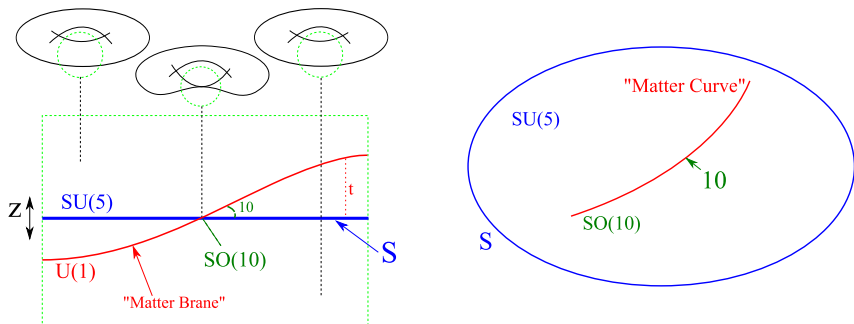
Bifundamental reps determined by group theory

$$\text{Adj}_{SU(N)} \rightarrow \text{Adj}_{SU(N-1)} \oplus \text{Adj}_{U(1)} \oplus \left([N-1]_{-N} + \overline{[N-1]}_N \right)$$

Number determined by $n_R = h^0(\Sigma, K_\Sigma^{1/2} \otimes V_R)$

Geometric Engineering in F -Theory III

Example: Engineering a $\mathbf{10}$ of $SU(5)$:



$$SO(10) \rightarrow SU(5) \times U(1)$$

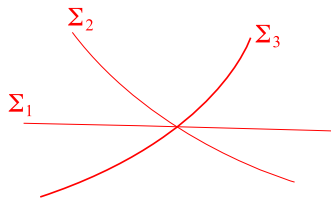
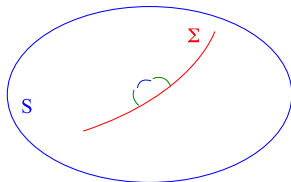
$$\mathbf{45} \rightarrow \mathbf{24}_0 \oplus \mathbf{1}_0 \oplus (\mathbf{10}_4 \oplus \overline{\mathbf{10}}_{-4})$$

Spectrum and Superpotential Couplings

- Determined by studying 7-brane worldvolume theory

Beasley, Heckman, Vafa

- Fixed by SUSY
 - Spectrum can include both **adjoint** and **bifundamental** modes
 - Superpotential couplings constrained by $U(1)$'s
- **Adj** \times **Bif** \times **Bif**
 - **Bifundamentals** from a single **matter curve**
 - **Bif** \times **Bif** \times **Bif**
 - Triple intersection of three **matter curves**



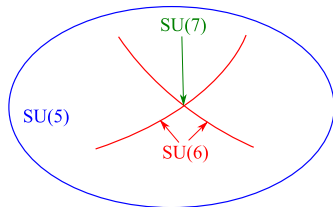
Couplings from triple intersections – A-type

- Example: $SU(5)$ enhanced to $SU(7)$

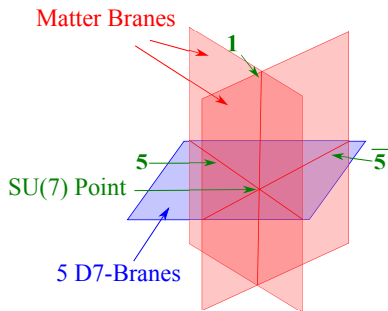
$$SU(7) \rightarrow SU(5) \times U(1) \times U(1)$$

$$x^2 + y^2 = z^5(z + t_1)(z + t_2)$$

$$48 \rightarrow 24_0 \oplus 1_0 \oplus 1_0 \oplus (5_{0,6} \oplus \bar{5}_{0,-6}) \oplus (5_{6,0} \oplus \bar{5}_{-6,0}) \oplus (1_{6,-6} \oplus 1_{-6,6})$$

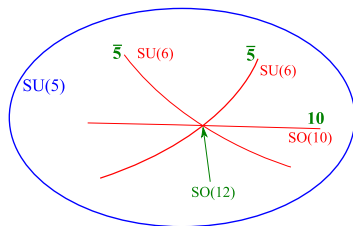


Coupling of form $5 \times \bar{5} \times 1$



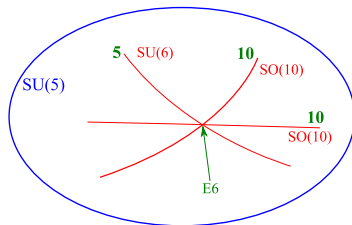
Couplings from triple intersections – D - and E -type

- Example $SU(5) \rightarrow SO(12)$



Coupling of form $\mathbf{10} \times \bar{\mathbf{5}} \times \bar{\mathbf{5}}$

- Example: $SU(5) \rightarrow E_6$



Coupling of form $\mathbf{10} \times \mathbf{10} \times \mathbf{5}$

$$SO(12) \rightarrow SU(5) \times U(1) \times U(1)$$

$$66 \rightarrow \mathbf{24}_{0,0} \oplus \mathbf{1}_{0,0} \oplus \mathbf{1}_{0,0} \oplus (\mathbf{10}_{0,4} \oplus \bar{\mathbf{10}}_{0,-4}) \oplus (\mathbf{5}_{2,2} \oplus \bar{\mathbf{5}}_{2,-2}) \oplus (\mathbf{5}_{-2,2} \oplus \bar{\mathbf{5}}_{-2,-2})$$

$$E_6 \rightarrow SU(5) \times U(1) \times U(1)$$

$$78 \rightarrow \mathbf{24}_{0,0} \oplus \mathbf{1}_{0,0} \oplus \mathbf{1}_{0,0} \oplus (\mathbf{10}_{0,4} \oplus \bar{\mathbf{10}}_{0,-4}) \oplus (\mathbf{10}_{-3,-1} \oplus \bar{\mathbf{10}}_{3,1}) \oplus (\mathbf{5}_{3,-3} \oplus \bar{\mathbf{5}}_{-3,3}) \oplus (\mathbf{1}_{3,5} \oplus \mathbf{1}_{-3,-5})$$

Engineering SUSY GUTs in F-Theory

- Take GUT branes to wrap del Pezzo surface S
 - Explicit matter content calculated by indices
- Require WV fluxes to remove all exotic matter → $SU(5)$ GUTs
 - No **Adjoint**s – all matter from **matter curves**
- Matter content and superpotential couplings:

$$\Phi_{10} \sim \left\{ \begin{array}{l} Q \sim (\mathbf{3}, \mathbf{2})_{+1/6} \\ U^c \sim (\bar{\mathbf{3}}, \mathbf{1})_{-2/3} \\ E^c \sim (\mathbf{1}, \mathbf{1})_{+1} \end{array} \right\} \quad \Phi_{\bar{5}} \sim \left\{ \begin{array}{l} D^c \sim (\bar{\mathbf{3}}, \mathbf{1})_{+1/3} \\ L \sim (\mathbf{1}, \mathbf{2})_{-1/2} \end{array} \right\}$$

$$H \sim \left\{ \begin{array}{l} H_u \sim (\mathbf{1}, \mathbf{2})_{+1/2} \\ \cancel{H_u^{(3)}} \sim (\mathbf{3}, \mathbf{1})_{-1/3} \end{array} \right\} \quad \bar{H} \sim \left\{ \begin{array}{l} H_d \sim (\mathbf{1}, \mathbf{2})_{-1/2} \\ \cancel{H_d^{(3)}} \sim (\bar{\mathbf{3}}, \mathbf{1})_{+1/3} \end{array} \right\}$$

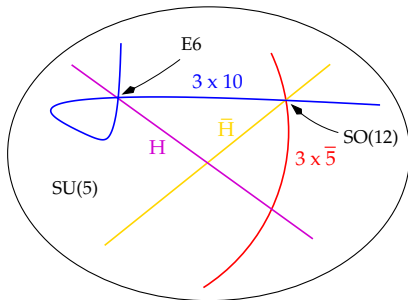
$$W \supset \Phi_{10} \Phi_{10} H, \quad \Phi_{10} \Phi_{\bar{5}} \bar{H}$$

BHV $SU(5)$ GUT

- Using these tools **Beasley, Heckman, and Vafa** have successfully engineered local $SU(5)$ GUT models with **no exotic matter**

arXiv:0806.0102

- Some phenomenological issues addressed
 - Doublet-triplet splitting
Beasley, Heckman, Vafa
Donagi, Wijnholt
 - Yukawa textures
Font, Ibanez
 - Hierarchies!!!**
Heckman and Vafa
 - Threshold corrections
Blumenhagen



GUT breaking and doublet-triplet splitting

Beasley, Heckman, Vafa
Donagi, Wijnholt

- Break the GUT group with $U(1)_Y$ bundle, \mathcal{L}_Y
 - Breaks $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)_Y$
- Effects particle content through restriction of \mathcal{L}_Y to **matter curves**
 - Require \mathcal{L}_Y to restrict trivially to Φ_{10} and $\Phi_{\bar{5}}$ matter curves
 - Require \mathcal{L}_Y to restrict **nontrivially** to H and \bar{H} matter curves

$$n_R = h^0(\Sigma, K_\Sigma^{1/2} \otimes V_R) \quad V_R \sim \mathcal{L}_Y^{\text{Q}_Y}|_\Sigma \otimes V_\Sigma^{-1}$$

Dynamical Scales for SUSY GUTs

Any SUSY GUT Model requires several new scales

- SUSY-breaking

- Soft masses $m_{1/2}, m_s^2$
- Gravitino mass $m_{3/2}$

Will focus on simple gauge mediated models

$$\langle X \rangle = M_{\text{Mess}} + \theta^2 F_X$$

$$\frac{F_X}{M_{\text{Mess}}} \sim 10^3 \text{ GeV} \text{ and } \frac{F_X}{M_{\text{Pl}}} \ll 10 \text{ GeV}$$

- μ Parameter

$$W \supset \mu H_u H_d + \dots$$

Need $\mu \sim 10^2 - 10^3 \text{ GeV}$

- Mass scale for neutrino sector

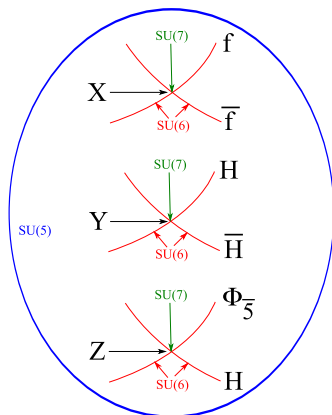
- eg Right-handed neutrino masses

$$W \supset M_{N_R} N_R^2$$

- $M_{N_R} \sim 10^{12} \text{ GeV}$

Adding dimensionful parameters to F -theory GUTs

- All necessary scales can be introduced at $SU(7)$ points
 → pair of intersecting D7-branes!
- Engineers coupling between GUT fields and a singlet: $\mathbf{5} \times \bar{\mathbf{5}} \times \mathbf{1}$



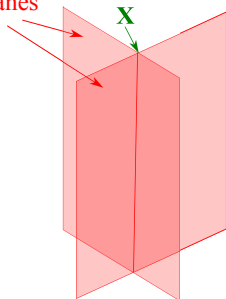
- Case 1: $\mathbf{5}$ and $\bar{\mathbf{5}}$ are new fields f, \bar{f}
 $W \sim Xf\bar{f}$ – Ordinary Gauge Mediation
 Further need $\langle X \rangle \sim M_{\text{Mess}} + \theta^2 F_X$
- Case 2: $\mathbf{5}$ and $\bar{\mathbf{5}}$ are Higgs multiplets H, \bar{H}
 $W \sim YH\bar{H}$ – μ Term
 Further need $\langle Y \rangle \sim \mu \neq 0$
- Case 3: $\mathbf{5}$ is H and $\bar{\mathbf{5}}$ is $\Phi_{\bar{\mathbf{5}}}$
 $W \sim ZH\Phi_{\bar{\mathbf{5}}}$ – Z is right-handed neutrino
 Further need $W \sim M_{N_R} Z^2$

Generating Small Scales with Instantons

Florea, Kachru, McGreevy, Saulina
+ many others

- Sufficient to study pair of intersecting D7-branes
 - Charged field X localized at intersection
 - Need to generate small scales for SUSY-breaking, expectation values, mass terms, etc
 - Natural mechanism: D3-instantons!

D7 Branes



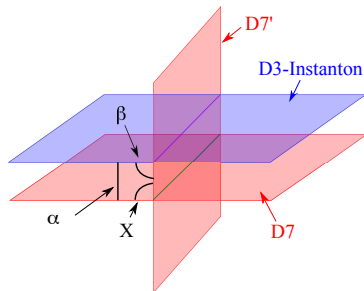
- To determine if a D3-instanton can generate superpotential couplings we must study the structure of 3-3 zero modes (Uranga's talk)
- Zero mode structure allows nontrivial contributions if D3 wraps the **same 4-cycle** as a D7

Billo, Frau, Fucito, Lerda, Liccardo, Pesando
Akerblom, Blumenhagen, Lust, Plauschinn,
Schmidt-Sommerfeld
Heckman, JM, Saulina, Schäfer-Nameki, Vafa

What couplings are generated?

- 3-7 and 3 – 7' fermi zero mode structure determines which couplings are actually generated

- α – fermi modes between D3 and D7
- β – fermi modes between D3 and D7'



- X couples to α and β via

$$S \sim \int \alpha \beta X + \dots$$

- Integrations over α 's and β 's bring down powers of X
 - Must have $n_\alpha = n_\beta$ to generate a coupling

- Actual coupling generated is $W \sim e^{-S_{\text{inst}}} X^{n_\alpha}$

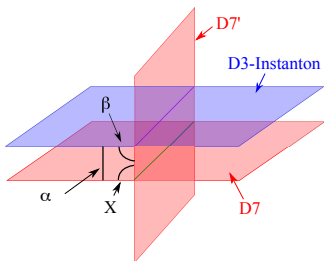
Generating $W(X)$ from Instantons

- To generate $W \sim X^m$, we need $n_\alpha = n_\beta = m$
- Easy to study these constraints with two assumptions

JM, Saulina, Schäfer-Nameki

- The D3-instanton wraps a del Pezzo surface dP_m
- The Kähler form on dP_m is of "large volume" type

$$J \sim AH - \sum_i B_i E_i \quad A, B_i > 0 \quad A \gg B_i$$



- Can find all instanton configs with $n_\alpha = m$

$$\mathcal{L}_{\text{inst}} \sim \mathcal{O}(E_1 - \sum_{j=2}^{m+2} E_j)$$

→ Specific B_i determine which are SUSY

- Imposing further $n_\beta = m$ leads to

$$\mathcal{L}_{\text{inst}}|_{\Sigma} = -m - 1$$

→ Condition on homology class of Σ

Masses, Expectation Values, and SUSY-Breaking

Heckman, JM, Saulina, Schäfer-Nameki, Vafa
JM, Saulina, Schäfer-Nameki

With these results, one can easily use D3-instantons to manipulate X, Y, Z

- Case 1: Break SUSY
 - Use D3-instantons to generate Polonyi superpotential $W \sim F_X X$
- Case 2: Give Y an expectation value
 - Engineer Y as a KK mode
 - Use D3-instantons to generate $W \sim F_X Y$
 - Net superpotential is

$$W \sim F_X Y + M_{KK} Y^2$$

so that $\langle Y \rangle \sim \frac{F_X}{M_{KK}}$

- Case 3: Give Z a mass
 - Use D3-instantons to generate explicit mass term $W \sim MZ^2$

Coupling to GUTs

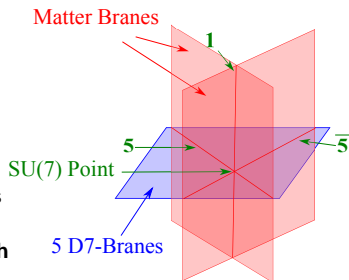
- Our D7-branes also intersect the GUT stack along **matter curves**
 - D3-instanton also intersects GUT stack along a **matter curve, Σ**
- Extra fermi zero modes between the D3-instanton and GUT stack can spoil our superpotentials

JM, Saulina, Schäfer-Nameki

- A necessary condition to lift the "3-GUT" zero modes is

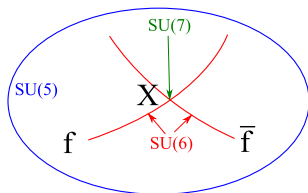
$$\mathcal{L}_{\text{inst}}|_{\Sigma} = \mathcal{O} \quad \mathcal{L}_{\gamma}|_{\Sigma} = \mathcal{O}$$

- We used \mathcal{L}_{γ} to lift Higgs triplets!
 - \mathcal{L}_{γ} does **not** restrict trivially to Higgs matter curves
 - **Cannot "use" D3-instantons which wrap Higgs matter branes**



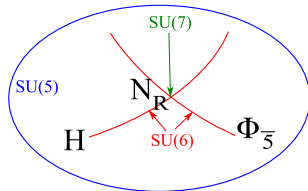
What can we do with D3-instantons?

SUSY-Breaking???



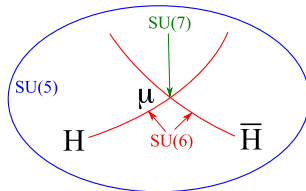
Yes

Neutrino Masses???



Yes

μ Parameter???

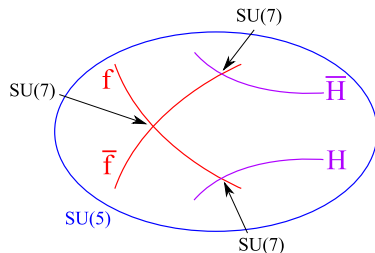
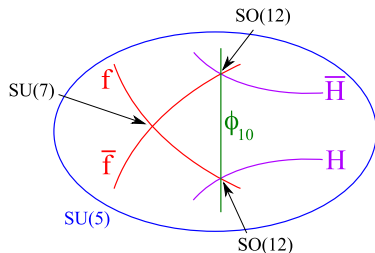


NO!

Getting μ

JM, Saulina, Schäfer-Nameki

- We cannot independently generate the scale μ
 - μ is a "derived scale"
 - Natural for phenomenology – EWSB requires $\mu \sim m_{\text{soft}}$
- We suppose that μ is related to SUSY-breaking sector
 - How to generate?



Higgs and messenger curves meet at
SO(12) points

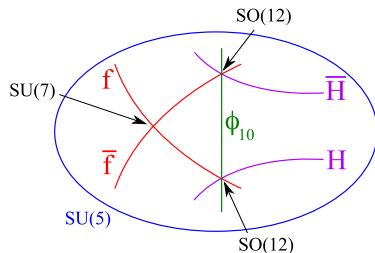
Higgs and messenger curves meet at
SU(7) points

Emergence of $U(1)_{PQ}$

- Effective action below $M_{GUT} \sim M_{KK}$ includes corrections from KK modes
- Form of effective action constrained by (approx) global $U(1)$ symmetries
- Can obtain $U(1)$'s directly from geometry
 - Easier to read them off directly from superpotential

$$W \sim Xf\bar{f} + Hf\bar{\phi}_{10, KK} + \bar{H}\bar{f}\phi_{10, KK} + M_{KK}\phi_{10, KK}\phi_{\bar{10}, KK}$$

Field	$U(1)_{PQ}$	$U(1)_a$	$U(1)_b$
H	1	1	1
\bar{H}	1	-1	-1
f	-1	-1	1
\bar{f}	-1	1	-1
ϕ_{10}	0	0	-2
$\phi_{\bar{10}}$	0	0	2
X	2	0	0



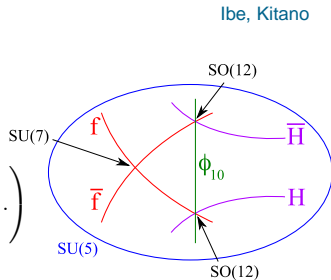
Importance of $U(1)_{PQ}$

	H	\bar{H}	f	\bar{f}	ϕ_{10}	$\bar{\phi}_{10}$	X
$U(1)_{PQ}$	1	1	-1	-1	0	0	2

- Naturally obtain a $U(1)_{PQ}$ which forbids a bare μ term, $\mu H\bar{H}$
 - Often invoked to explain why $\mu \ll M_{Pl}$
- Moreover, X carries $U(1)_{PQ}$ charge
 - Connects SUSY-breaking with breaking of $U(1)_{PQ}$
 - **Connects SUSY-breaking with generation of μ !!!**

- $U(1)_{PQ}$ constrains effective action below M_{GUT} to be of form

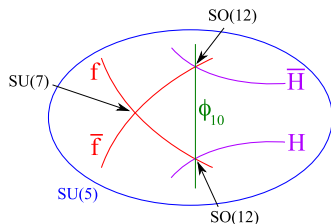
$$\int d^4\theta \left(\frac{c_\mu X^\dagger H\bar{H}}{M_{GUT}} + \frac{c_H X^\dagger X (H^\dagger H + \bar{H}\bar{H}^\dagger)}{M_{GUT}^2} + \dots \right)$$



Generation of μ

	H	\bar{H}	f	\bar{f}	ϕ_{10}	$\bar{\phi}_{10}$	X
$U(1)_{PQ}$	1	1	-1	-1	0	0	2

$$\int d^4\theta \left(\frac{c_\mu X^\dagger H \bar{H}}{M_{GUT}} + \frac{c_H X^\dagger X (H^\dagger H + \bar{H} \bar{H}^\dagger)}{M_{GUT}^2} + \dots \right)$$



- For $\langle X \rangle \sim M_{\text{Mess}} + \theta^2 F_X$ this leads to generation of

$$\mu \sim \frac{c_\mu F_X}{M_{GUT}} \quad m_H^2 \sim c_H \left(\frac{F_X}{M_{GUT}} \right)^2$$

→ μ exhibits same suppression as SUSY-breaking

- Term which could generate B_μ is **forbidden** by $U(1)_{PQ}$!

$$\int d^4\theta \frac{X^\dagger X H \bar{H}}{M_{GUT}^2}$$

→ $B_\mu = 0$ at messenger scale – solution to μ/B_μ problem

Sweet Spot Supersymmetry from F -Theory

Summary of Model

$$\mathcal{L} \sim \int d^4\theta \left(|X|^2 - \frac{a|X|^4}{M_{GUT}^2} + \frac{c_\mu X^\dagger H \bar{H}}{M_{GUT}} + \frac{c_H X^\dagger X (H^\dagger H + \bar{H} \bar{H}^\dagger)}{M_{GUT}^2} + \dots \right)$$

$$W \sim F_X X + \lambda X f \bar{f} + W_{MSSM} + \dots$$

- Structure fixed by $U(1)_{PQ}$ symmetry with respect to which X is charged
- **D3-instanton** generated W simultaneously breaks SUSY and $U(1)_{PQ}$
- Realization of the "Sweet Spot Supersymmetry" scenario

Ibe, Kitano

- Can obtain from explicit $SU(5)$ GUT constructions in F -theory

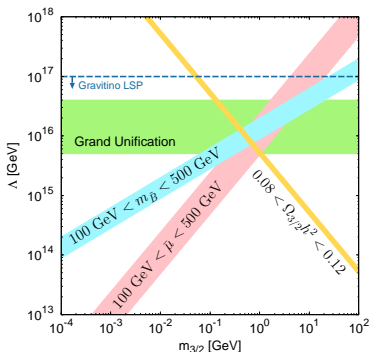
JM, Saulina, Schäfer-Nameki

- "Viable" model when $m_{3/2} \sim 1$ GeV and $c_\mu \sim c_H \sim \mathcal{O}(1)$

Why "Sweet Spot"?

- Ibe and Kitano studied model with $U(1)_{PQ}$ assuming that Higgs and messenger sectors were coupled at an unspecified scale, Λ
 - Leads to model has two parameters: Λ and $m_{3/2}$

- Simple considerations fix $m_{3/2} \sim 1$ GeV and $\Lambda \sim 10^{16}$ GeV
- GUT scale emerges without asking for it
 - Highly suggestive!



Ibe and Kitano, [arXiv:0705.3686](https://arxiv.org/abs/0705.3686)

Conclusions

- Local models are a promising way for string theory to make contact with particle physics
- F -theory is a natural and effective arena for engineering local models of SUSY GUTs
- Dimensionful parameters are easily incorporated into F -theory GUTs
 - Simplest D3-instantons can generate all of the necessary scales except μ
→ suggests μ is not an independent scale
- Naive coupling of Higgs and messenger sectors → $U(1)_{PQ}$ symmetry
 - SUSY-breaking field X has nonzero PQ charge
 - Connects SUSY-breaking to generation of μ
- $U(1)_{PQ}$ leads to "Sweet Spot Supersymmetry"
 - Viable class of models when $m_{3/2} \sim 1$ GeV

D3-Instantons and 3-3 Zero Modes

- Generic D3-instanton has 4 "universal" 3-3 fermi zero modes:

$$\theta_\alpha, \mu_{\dot{\alpha}}, \quad \alpha, \dot{\alpha} = 1, 2$$

- Goldstinos associated to 4 Q 's preserved by background and broken by $D3$
- In general, D3-instanton contributes $\int d^2\theta d^2\mu \dots$
 - If $\mu_{\dot{\alpha}}$ are lifted or $\int d^2\mu$ is saturated then instanton contributes superpotential coupling $\int d^2\theta \dots$
 - We assume D3 wraps a rigid cycle so no extra 3-3 fermi zero modes

D3-Instantons "bound" to D7's

Billo, Frau, Fucito, Lerda, Liccardo, Pesando
Akerblom, Blumenhagen, Lust, Plauschinn, Schmidt-Sommerfeld

- Expect $\mu_{\dot{\alpha}}$ "lifted" when D3-instanton with trivial $U(1)$ flux wraps the same 4-cycle as a D7
 - D3 and D7 can form a bound state
 - Background + D7 preserve only 4 SUSY's
 - D3 breaks 2 of the remaining SUSY's \rightarrow 2 Goldstinos
-

- Instanton action contains coupling

$$\mu_{\dot{\alpha}} \left(b^{\dot{\alpha}} \bar{f} + \bar{b}^{\dot{\alpha}} f \right)$$

- Saturates $\mu_{\dot{\alpha}}$ integration

3-3 and 3-7 zero modes for D3-instanton
and D7 wrapping del Pezzo

Mode	Origin	F/B	Gauge Rep
x^μ	3-3	B	1
θ_α	3-3	F	1
$\mu_{\dot{\alpha}}$	3-3	F	1
f	7-3	F	R
\bar{f}	3-7	F	\bar{R}
$b_{\dot{\alpha}}$	7-3	B	R
$\bar{b}_{\dot{\alpha}}$	3-7	B	\bar{R}

D3-Instantons with nontrivial $U(1)$ flux

Heckman, JM, Saulina, Schäfer-Nameki, Vafa

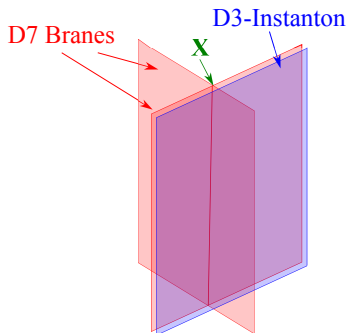
- Should sum over all SUSY $U(1)$ flux configurations on the D3
- Nontrivial $U(1)$ flux generically lifts all 3-7 zero modes
 - Lifts the Higgs branch of the D3 worldvolume
 - Prevents formation of "honest" D3/D7 bound state
- What about the bound state at threshold?
 - Do such configurations still contribute to W ?

Yes!

- $\mu_{\dot{\alpha}}$ still couples to 3-7 KK modes through

$$\mu_{\dot{\alpha}} \left(b_{KK}^{\dot{\alpha}} \bar{f}_{KK} + \bar{b}_{KK}^{\dot{\alpha}} f_{KK} \right)$$

$\mu_{\dot{\alpha}}$ integration is still saturated



SUSY-Breaking Sector

- D3-instanton generated Polonyi superpotential

$$W \sim F_X X \quad F_X \sim e^{-t}$$

- Pseudo-moduli space of SUSY-breaking vacua
- Lifted by corrections to Kähler potential from physics at high scales
- Two possible sources for such corrections

- KK modes at GUT scale
 - Sweet Spot Supersymmetry

JM, Saulina, Schäfer-Nameki
Ibe, Kitano

- Massive $U(1)_{PQ}$ gauge boson
 - New Gauge Mediation Scenario

Heckman, Vafa

- In all that follows, we assume that $m_{U(1)_{PQ}}^2 > M_{GUT}^2$

General Structure of KK Corrections

- Expect KK modes to correct Kähler potential

$$K \sim |X|^2 - \frac{a|X|^4}{M_{GUT}^2} + \dots$$

- Two natural scales for $\langle X \rangle$

$$a > 0 \implies \boxed{\langle X \rangle = 0} \qquad a < 0 \implies \boxed{\langle X \rangle \sim M_{GUT}}$$

- Recall that $\langle X \rangle$ sets the messenger scale via $W_{OGM} \sim Xf\bar{f}$
 - $\langle X \rangle \sim M_{GUT}$ too large for gauge mediation
 - $\langle X \rangle = 0$ leads to vanishing messenger masses
 - SUSY-breaking vacuum rendered unstable to SUSY one

"Gravitational" Gauge Mediation

Kitano

- In general, nothing prevents SUGRA from generating a linear term

$$V \sim m \left(F_X X + F_X^* X^\dagger \right)$$

- Not negligible because it is the **leading** contribution
- Indeed, we can see how such a term might arise
 - In general, expect flux contribution to W
 - Model with constant W_0

$$W \sim F_X X + W_0$$

- W_0 has no effect in strict $M_{Pl} \rightarrow \infty$ limit
 - At finite but large M_{Pl} , however, it leads to linear term in V

$$V \sim \frac{W_0}{M_{Pl}^2} \left(F_X X + F_X^* X^\dagger \right) + \frac{a|F_X|^2|X|^2}{M_{GUT}^2} + \dots$$

- Vacuum at $\langle X \rangle = 0$ is shifted to nonzero value

$$\langle X \rangle \sim \left(\frac{W_0}{F_X M_{Pl}} \right) \frac{M_{GUT}^2}{M_{Pl}} \sim \left(\frac{W_0}{F_X M_{Pl}} \right) \times 10^{14} \text{ GeV}$$