Title: SUSY breaking and gauge mediation in G-Theory GUTs

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Abstract: TBA

SUSY breaking and gauge mediation in F-theory GUTs

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California Institute of Technology

November 4, 2008

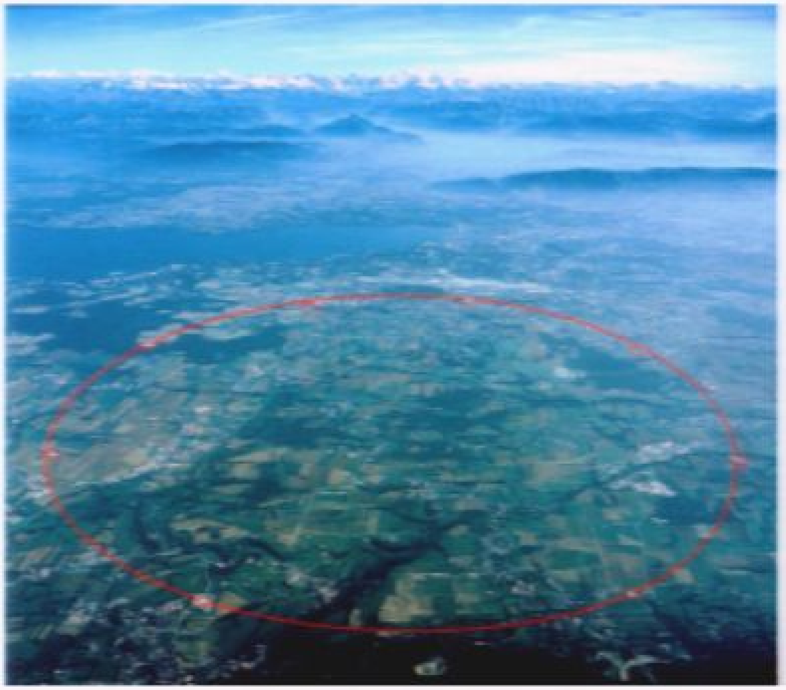
arXiv:0808.1286
with J. Heckman, N. Saulina, S. Schäfer-Nameki, C. Vafa

arXiv:0808.1571, arXiv:0808.2450
with N. Saulina, S. Schäfer-Nameki

The LHC is Here

- The LHC era has finally arrived!

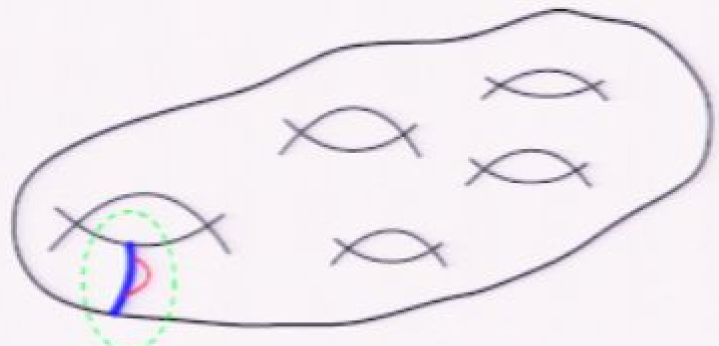
- We hope to learn many things about physics beyond the standard model
  - What explains the hierarchy?
    - (if anything?)
  - What comprises dark matter?
  - Will grand unification survive?
  - ...



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

$\Longrightarrow$ The LHC will provide data which, in a sense, encodes information about the local geometry of our string vacuum

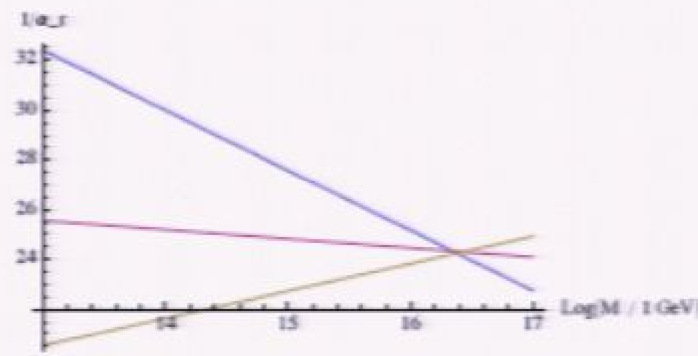
- We can try to incorporate this information by building local models
  - Can serve as starting points for constructing realistic string vacua
  - A bottom-up approach to string phenomenology

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)
- Can overcome these using techniques of geometric engineering

  Katz, Vafa

  - M-theory on G_2 manifolds

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

    - Difficult because not much is known about G_2 manifolds
  - F-theory on Calabi-Yau fourfolds
    - Holomorphy leads to powerful techniques for determining spectrum and couplings

  Donagi, Wijnholt

  Beasley, Heckman, Vafa

Outline

Review of F-Theory GUTs

Generating Scales with Instantons

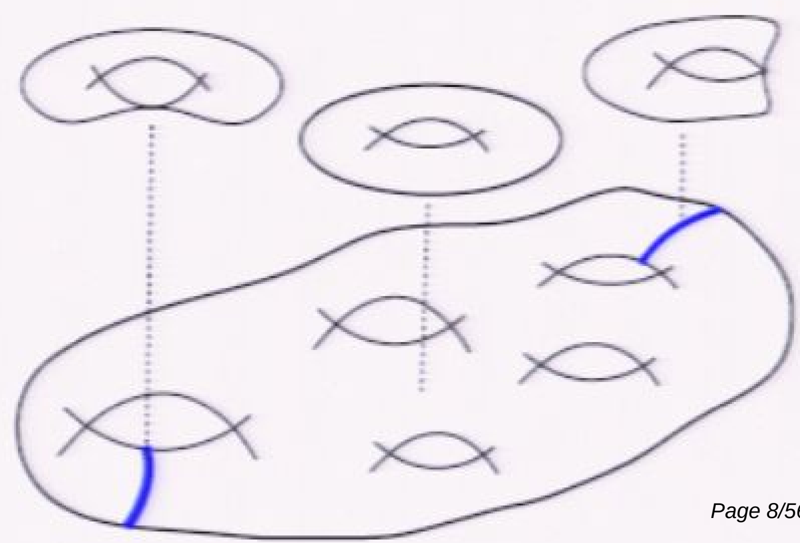
Gauge-Mediated SUSY Breaking

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 $\leftrightarrow$ locations of 7-branes
  - Monodromies of τ $\leftrightarrow$ types of 7-brane



Geometric Engineering in *F*-Theory

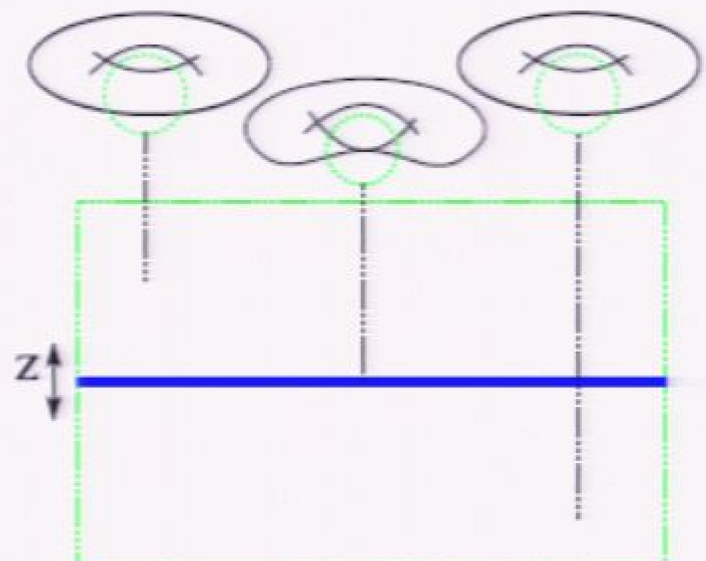
Katz, Vafa
Bershadsky, Intriligator, Kachru, Morrison, Sadov, Vafa

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

- $SU(N)$ singularity

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

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

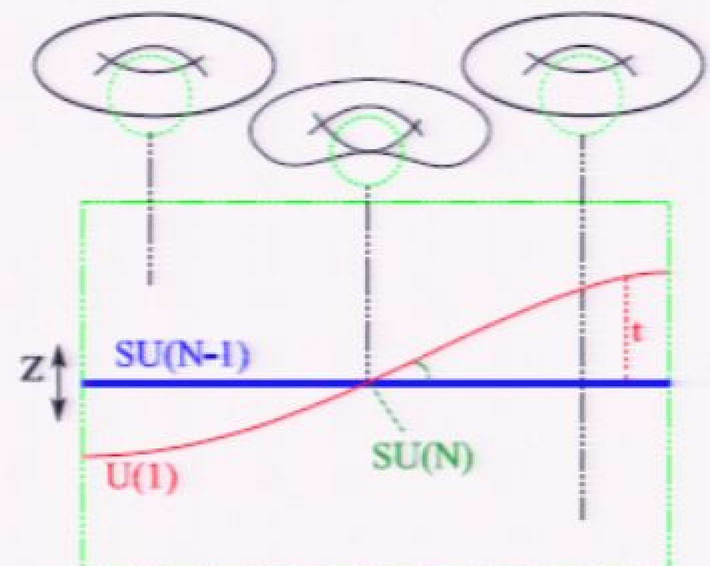


Geometric Engineering in *F*-Theory II

- Deformations of singularity ↔ Generators of Cartan subalgebra
  - Deformation parameters ↔ 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

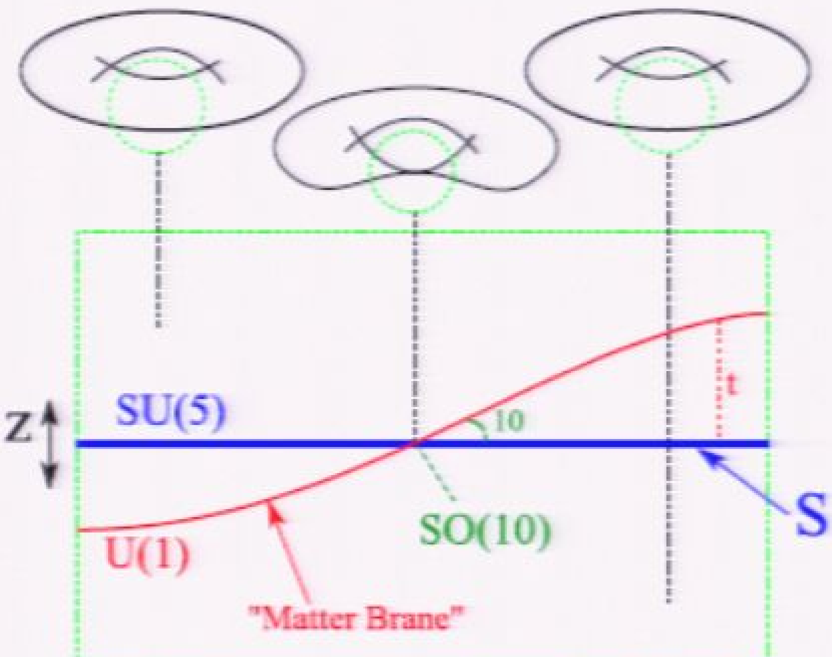
Bifundamental reps determined by group theory

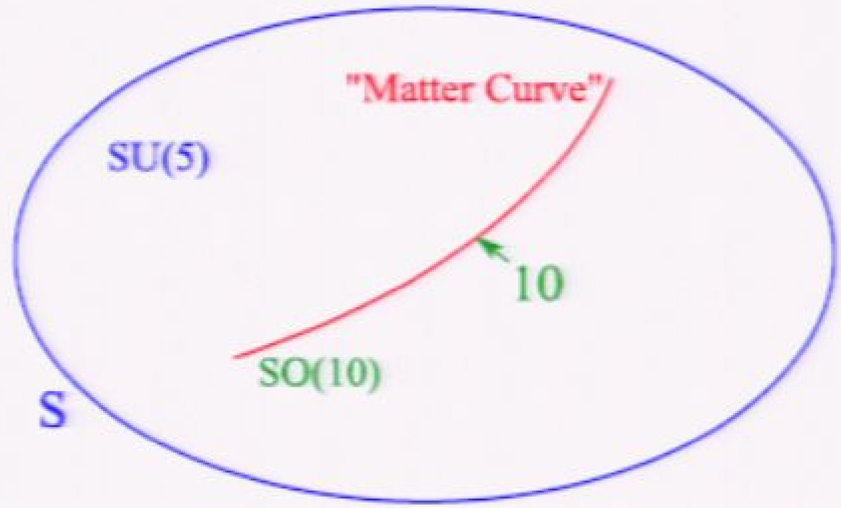
$$\mathrm{Adj}_{SU(N)} \to \mathrm{Adj}_{SU(N-1)} \oplus \mathrm{Adj}_{U(1)} \oplus \left([N-1]_{-N} + \overline{[N-1]}_{N} \right)$$

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

Geometric Engineering in *F*-Theory III

Example: Engineering a **10** of *SU*(5):





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

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

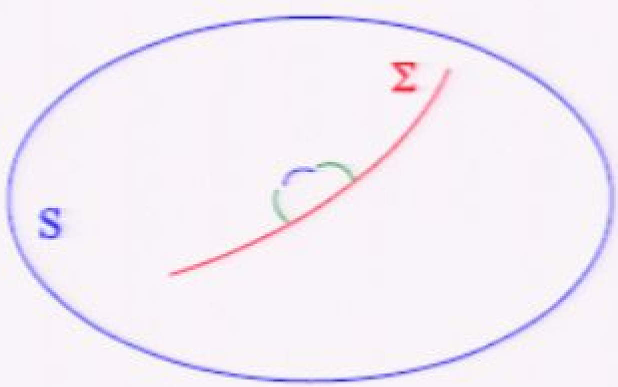
Spectrum and Superpotential Couplings

- Determined by studying 7-brane worldvolume theory

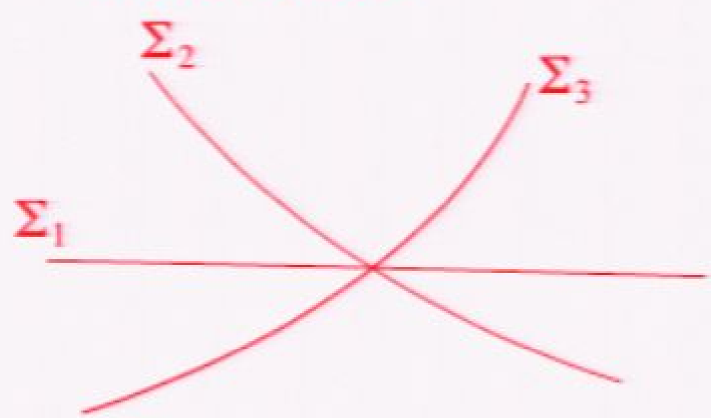
  Beasley, Heckman, Vafa

  - Fixed by SUSY
- Spectrum can include both adjoint and bifundamental modes
- Superpotential couplings constrained by $U(1)$'s

- Adj × Bif × Bif
  - Bifundamentals from a single matter curve



- Bif × Bif × Bif
  - Triple intersection of three matter curves



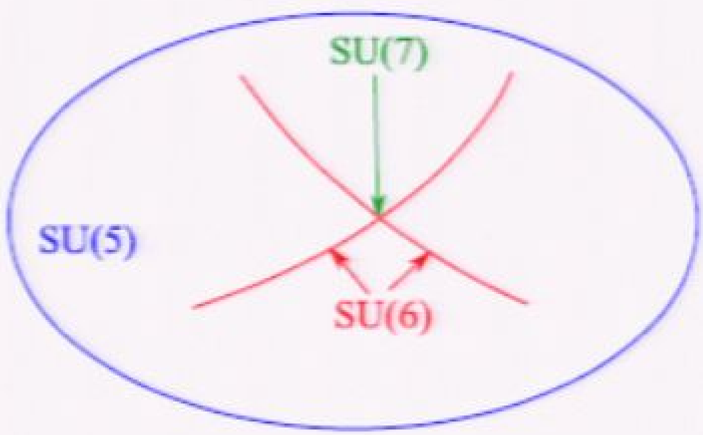
Couplings from triple intersections – *A*-type

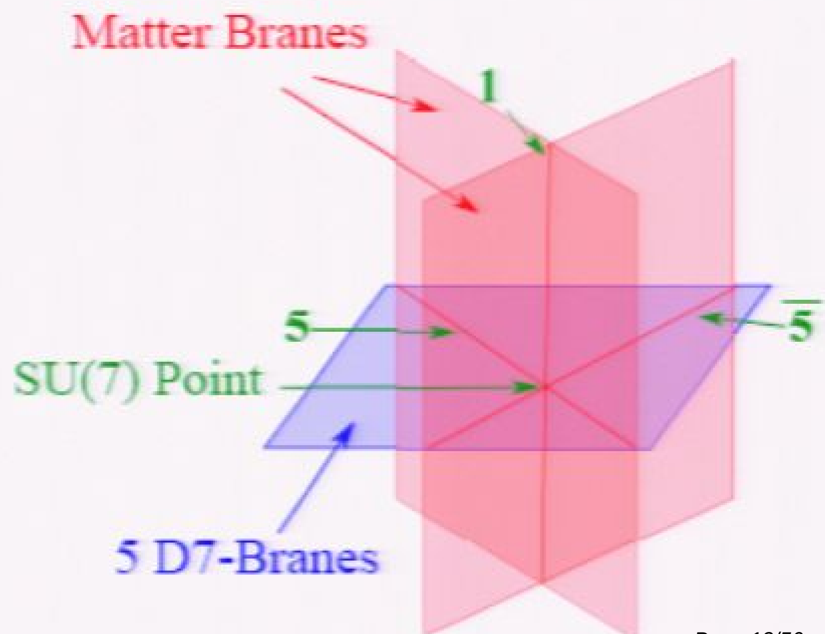
- Example: $SU(5)$ enhanced to $SU(7)$

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

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

$$\mathbf{48} \rightarrow \mathbf{24}_0 \oplus \mathbf{1}_0 \oplus \mathbf{1}_0 \oplus \left(\mathbf{5}_{0,6} \oplus \overline{\mathbf{5}}_{0,-6}\right) \oplus \left(\mathbf{5}_{6,0} \oplus \overline{\mathbf{5}}_{-6,0}\right) \oplus (\mathbf{1}_{6,-6} \oplus \mathbf{1}_{-6,6})$$





Coupling of form $\mathbf{5} \times \overline{\mathbf{5}} \times \mathbf{1}$

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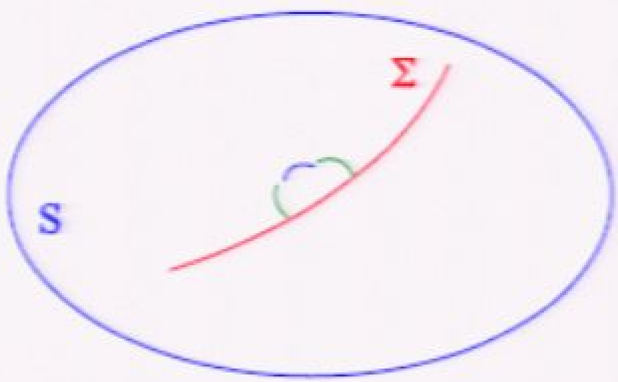

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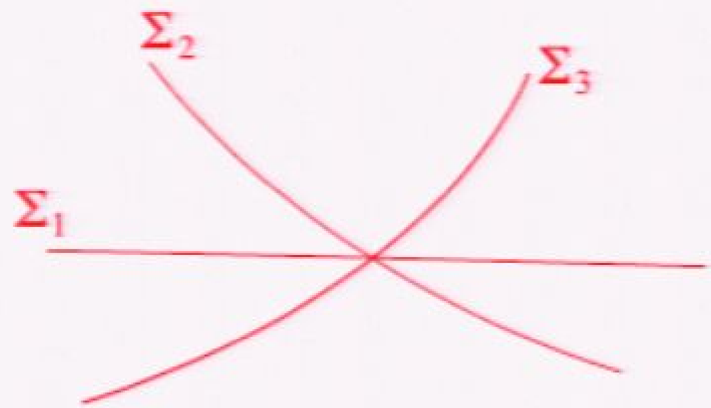

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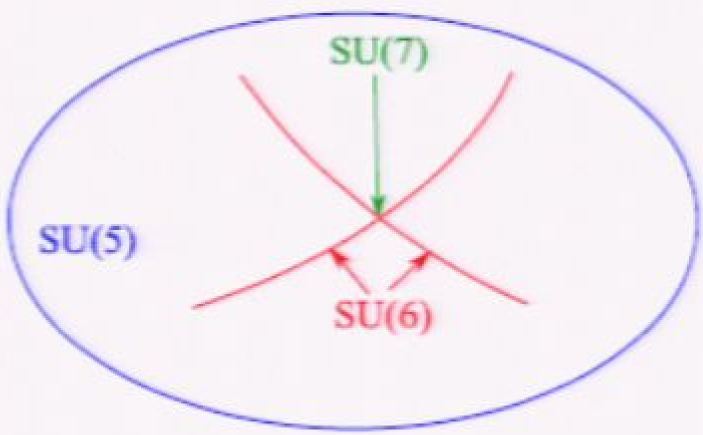

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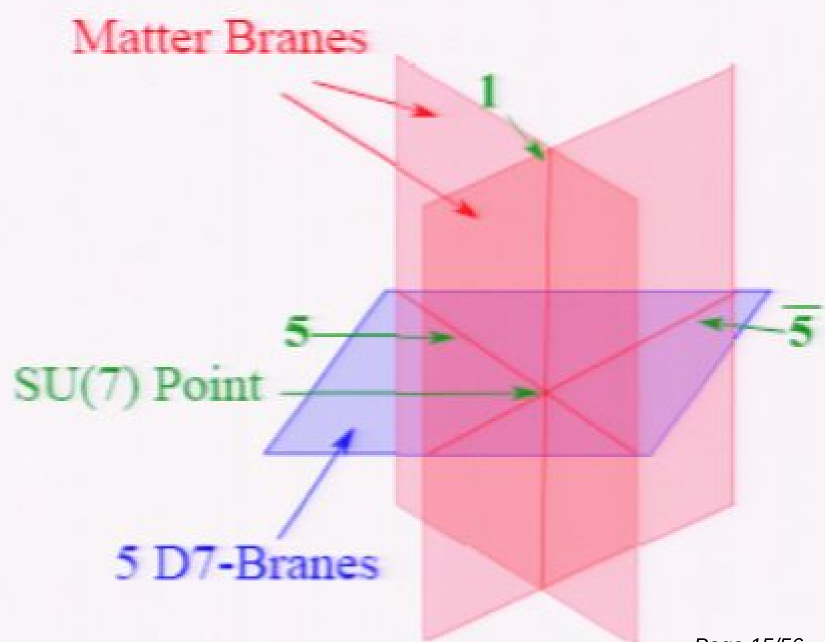
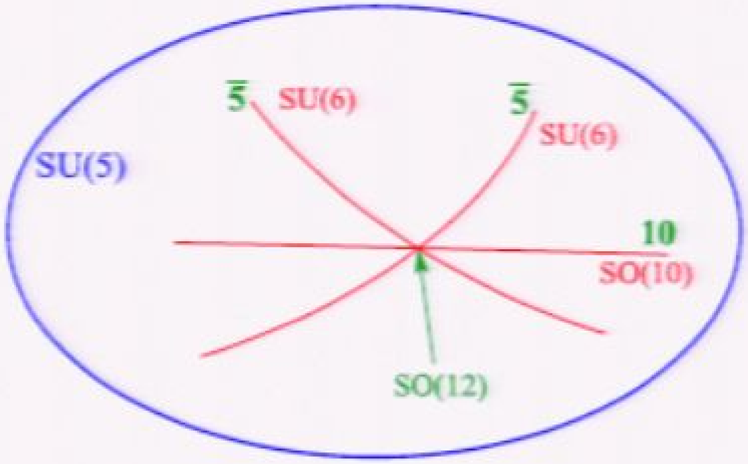


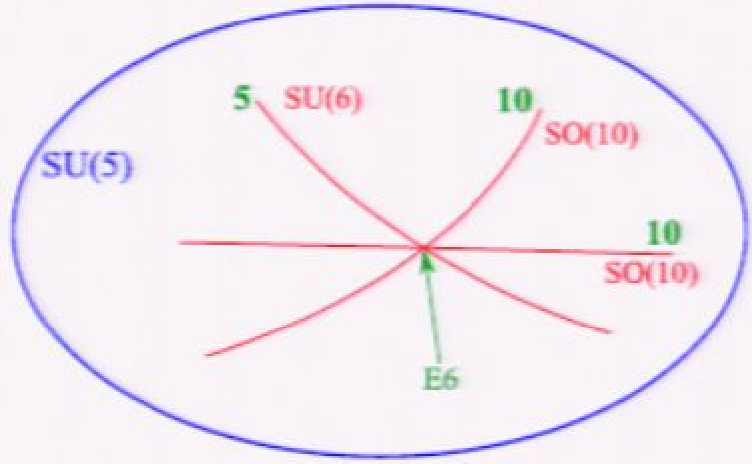
Couplings from triple intersections – *D*- and *E*-type

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



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

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



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

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

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Engineering SUSY GUTs in F-Theory

Beasley, Heckman, Vafa

- GUT branes wrap del Pezzo surface S
- WV fluxes can remove all exotic matter → $SU(5)$ GUTs
  → No Adjoints – all matter from matter curves
- Matter content and superpotential couplings:

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

$$H \sim \left\{ \begin{array}{cc} H_u & \sim (\mathbf{1},\mathbf{2})_{+1/2} \\ \cancel{H_u^{(3)}} & \sim (\mathbf{3},\mathbf{1})_{-1/3} \end{array} \right\} \qquad \overline{H} \sim \left\{ \begin{array}{cc} H_d & \sim (\mathbf{1},\mathbf{2})_{-1/2} \\ \cancel{H_d^{(3)}} & \sim (\overline{\mathbf{3}},\mathbf{1})_{+1/3} \end{array} \right\}$$

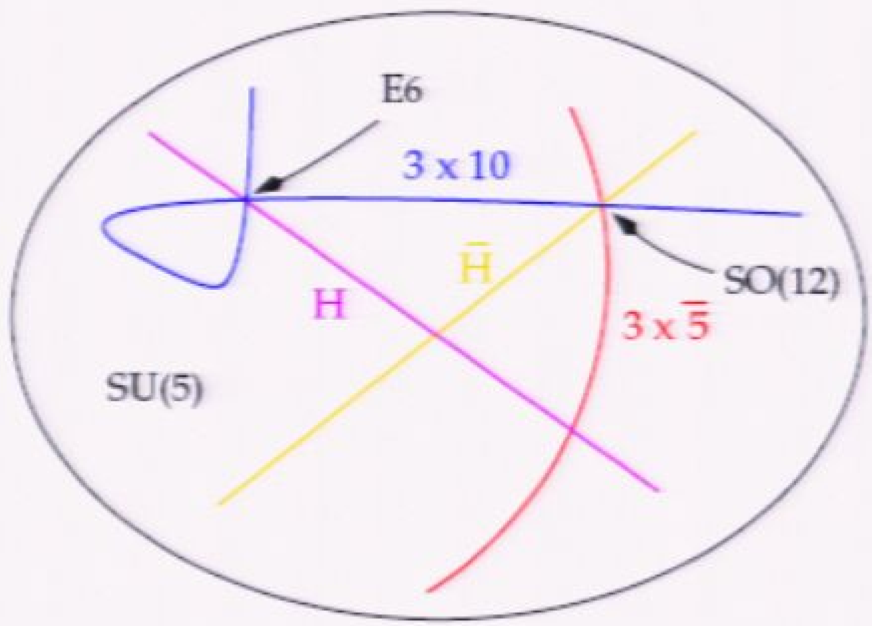
$$W \supset \Phi_{10}\Phi_{10}H, \quad \Phi_{10}\Phi_{\overline{5}}\overline{H}$$

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
  - GUT mass relations
  - Yukawa textures



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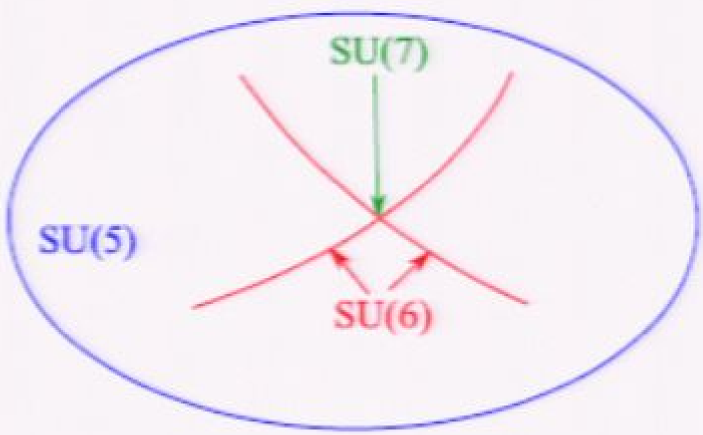

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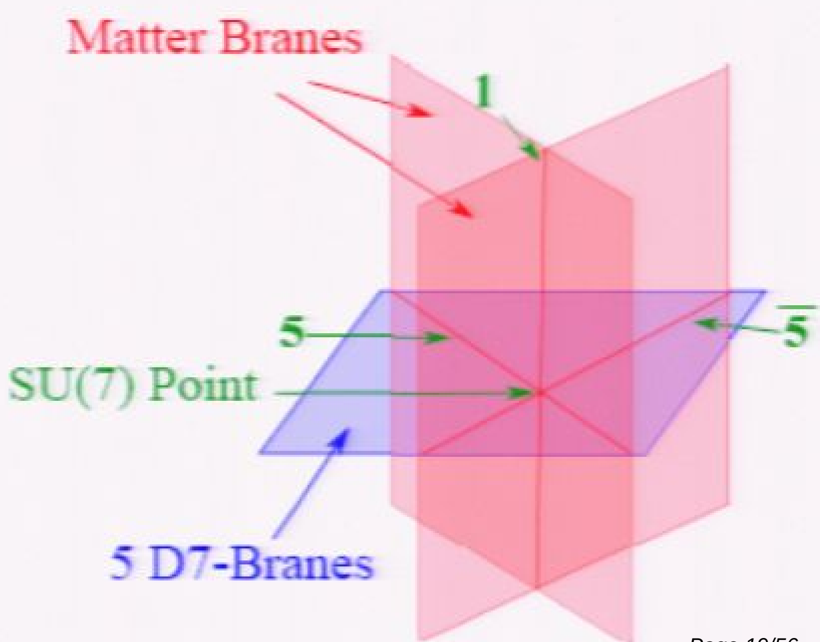

Geometric Engineering in *F*-Theory III

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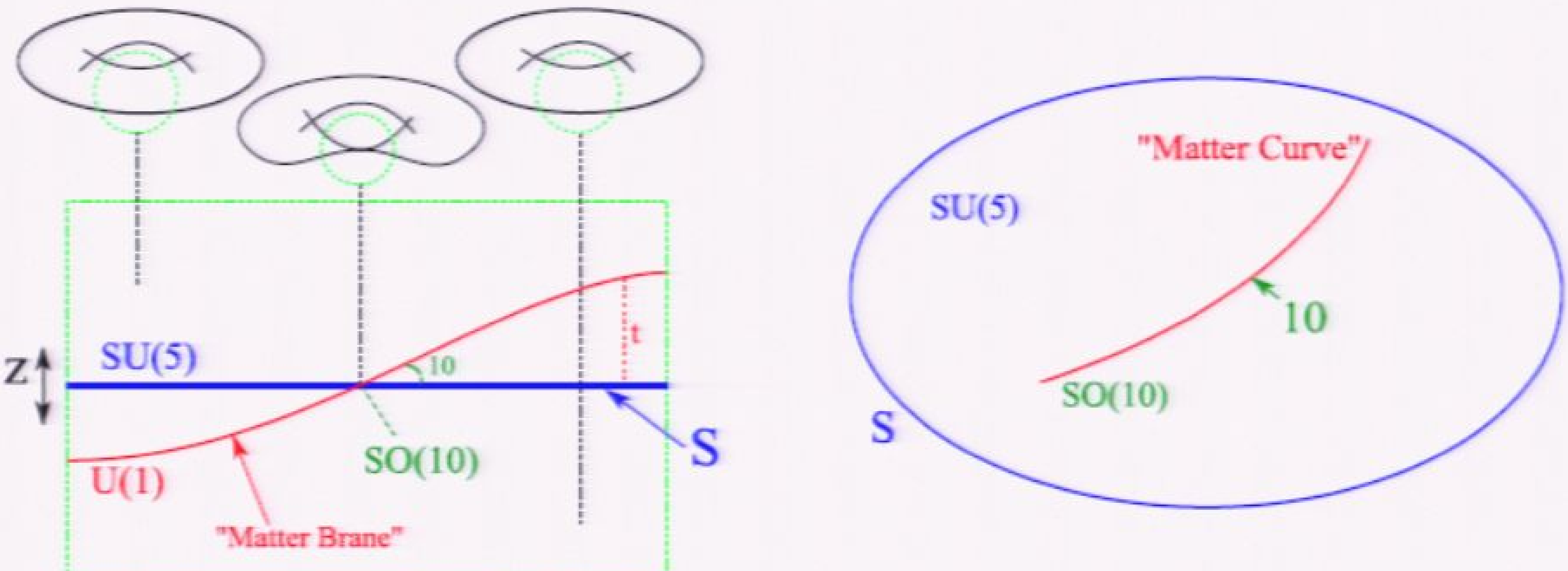

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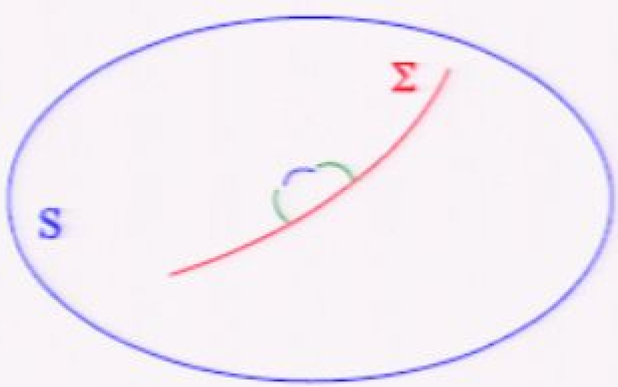

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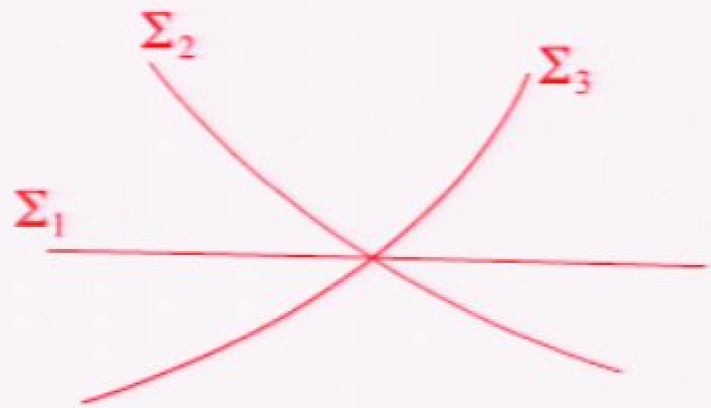

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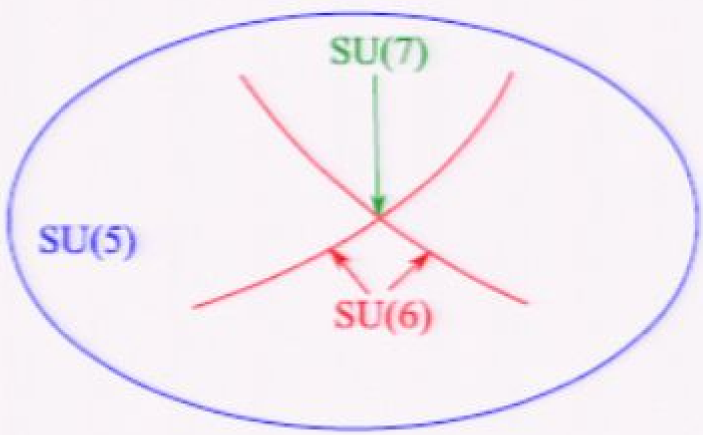

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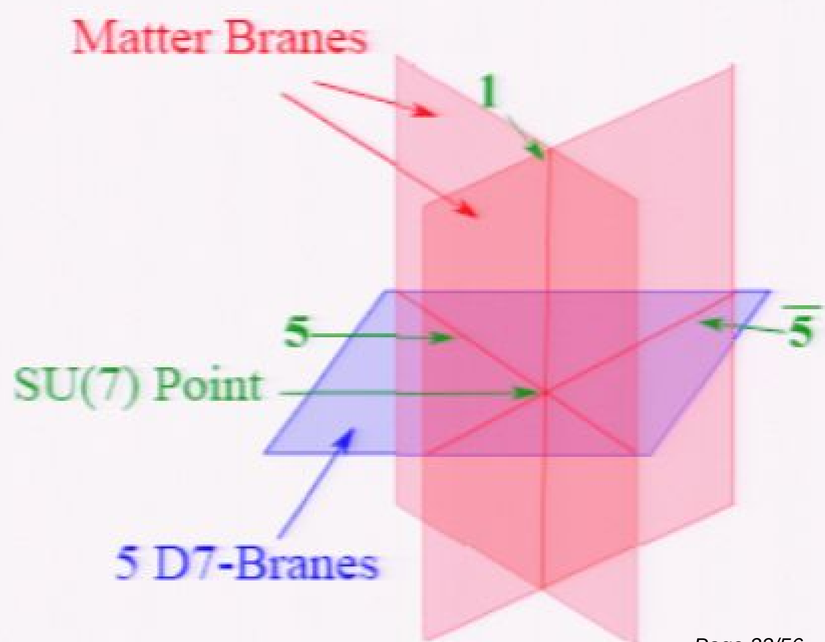

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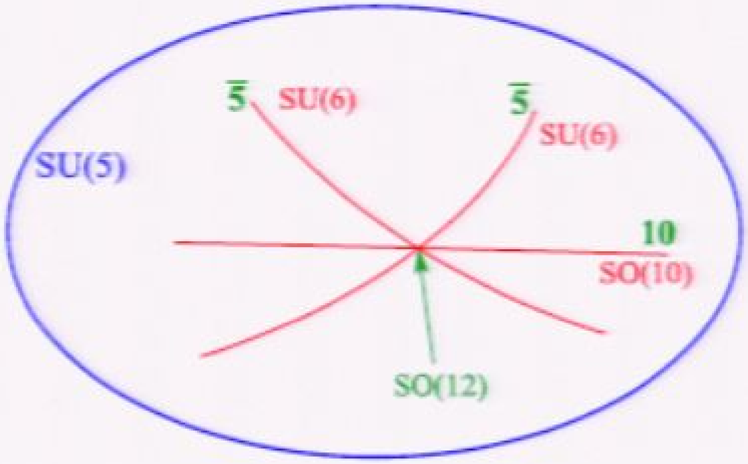

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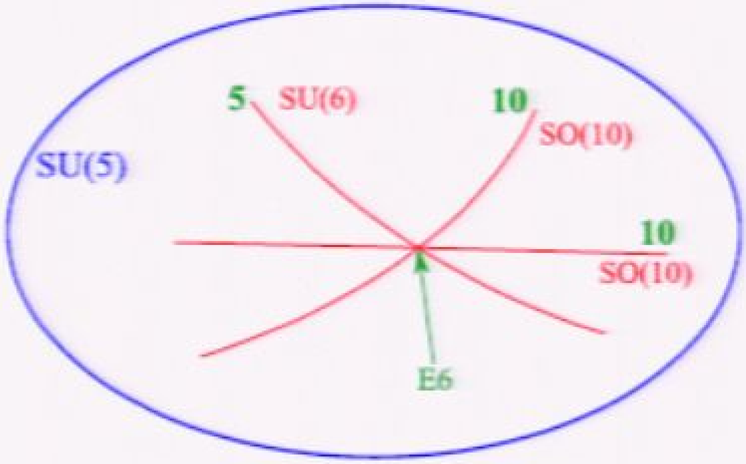

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  - Doublet-triplet splitting
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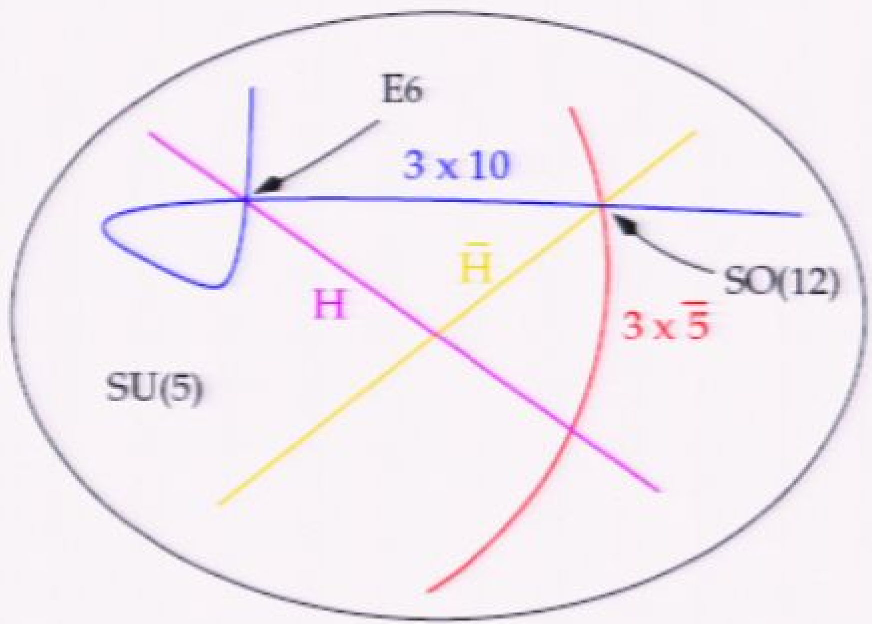
  - Yukawa textures



GUT breaking and doublet-triplet splitting

Beasley, Heckman, Vafa
Donagi, Wijnholt

- Break the GUT group by with $U(1)_Y$ bundle, $\mathcal{L}_Y$
  - Breaks $SU(5) \to SU(3) \times SU(2) \times U(1)_Y$
- Must require that $U(1)_Y$ gauge boson remains massless

  → Topological condition on compactification

Buican, Malyshev, Morrison, Verlinde, Wijnholt

- Effects particle content through restriction of $\mathcal{L}_Y$ to matter curves
  - Require $\mathcal{L}_Y$ to restrict trivially to Φ_{10} and $\Phi_{\overline{5}}$ matter curves
  - Require $\mathcal{L}_Y$ to restrict nontrivially to H and $\overline{H}$ matter curves

---

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

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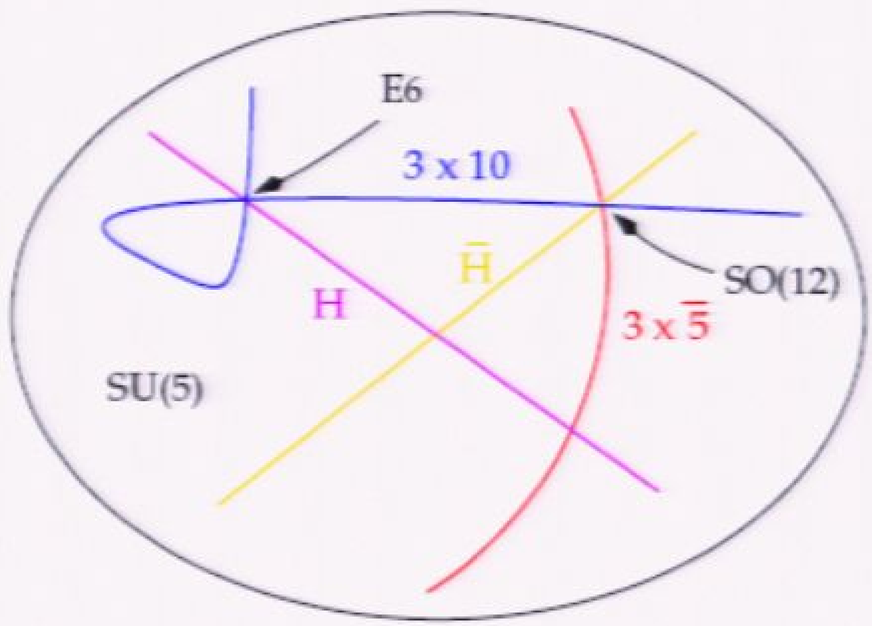


Dynamical Scales for SUSY GUTs

Any SUSY GUT Model requires several new scales

- SUSY-breaking

  Buchbinder

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

  Will focus on simple gauge mediated models

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

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

- μ Parameter

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

  Need $\mu \sim 10^2 - 10^3$ GeV

- Mass scale for neutrino sector
  - eg Right-handed neutrino masses

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

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

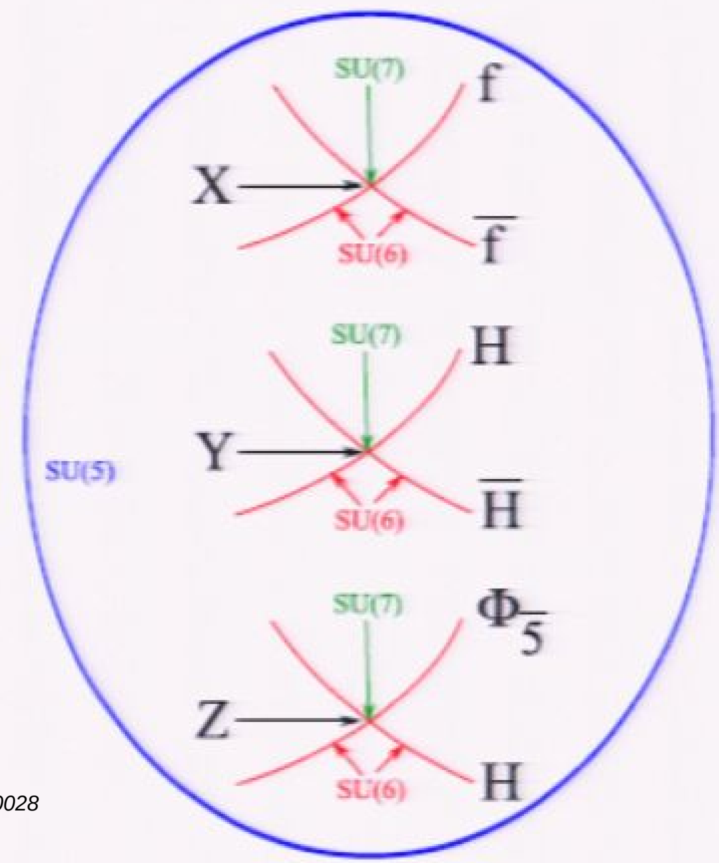
Adding dimensionful parameters to *F*-theory GUTs

- All necessary scales can be introduced at $SU(7)$ points

Beasley, Heckman, Vafa

$\rightarrow$ pair of intersecting D7-branes!

- Engineers coupling between GUT fields and a singlet: $\mathbf{5} \times \overline{\mathbf{5}} \times \mathbf{1}$

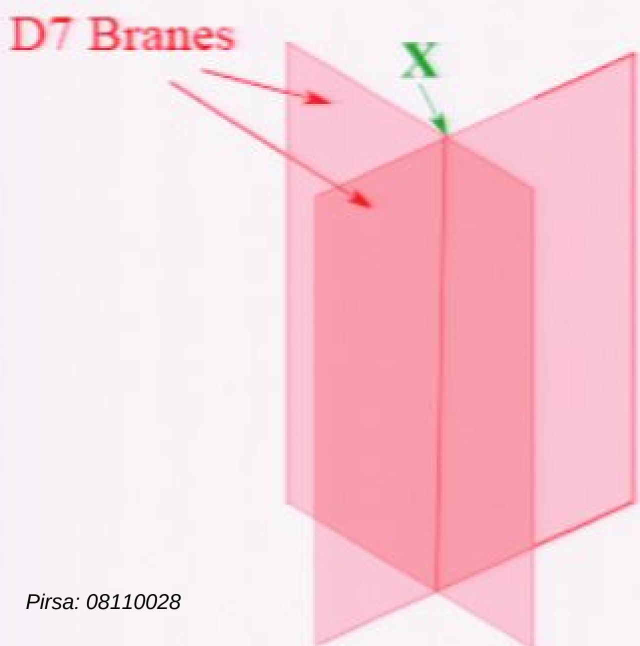


- Case 1: $\mathbf{5}$ and $\overline{\mathbf{5}}$ are new fields $f, \overline{f}$
  $W \sim X f \overline{f}$ – Ordinary Gauge Mediation
  Further need $\langle X \rangle \sim M_{\mathrm{Mess}} + \theta^2 F_X$
- Case 2: $\mathbf{5}$ and $\overline{\mathbf{5}}$ are Higgs multiplets $H, \overline{H}$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

Generating Small Scales with Instantons

Florea, Kachru, McGreevy, Saulina
Heckman, JM, Saulina, Schäfer-Nameki, Vafa

- 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!



- To determine if a D3-instanton can generate superpotential couplings we must study the structure of 3-3 zero modes

D3-Instantons and 3-3 Zero Modes

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

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

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

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 → 2 Goldstinos

- Instanton action contains coupling

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

- 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
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f	7-3	F	R
$\overline{f}$	3-7	F	$\overline{R}$
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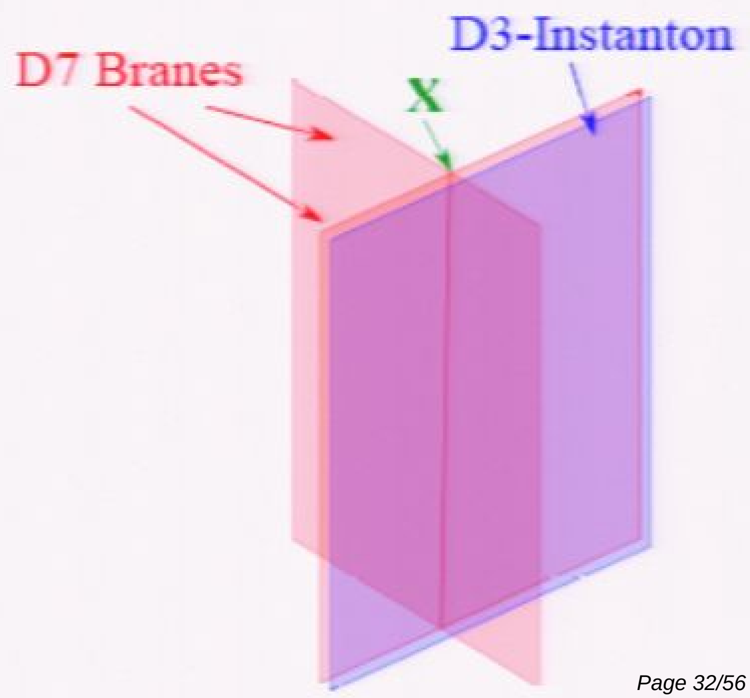
D3-Instantons with nontrivial $U(1)$ flux

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

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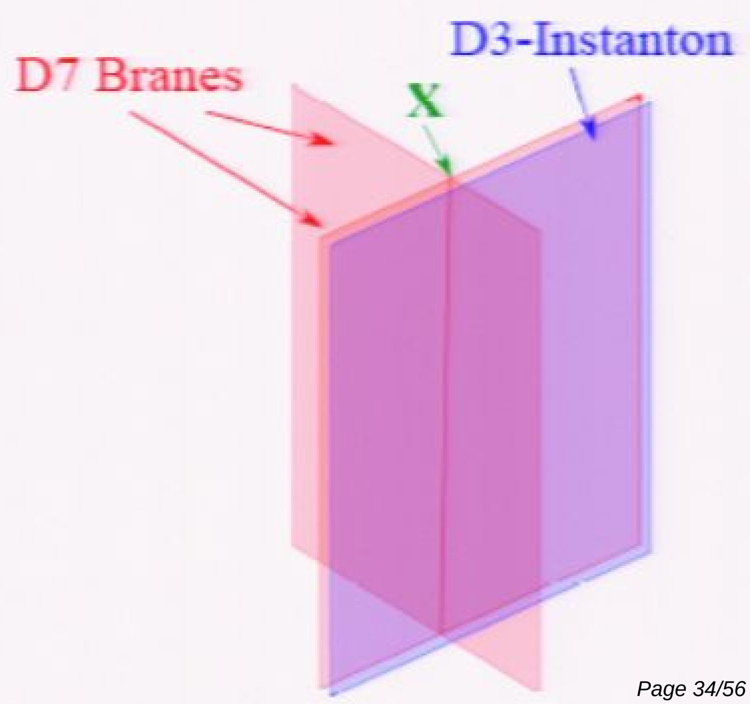

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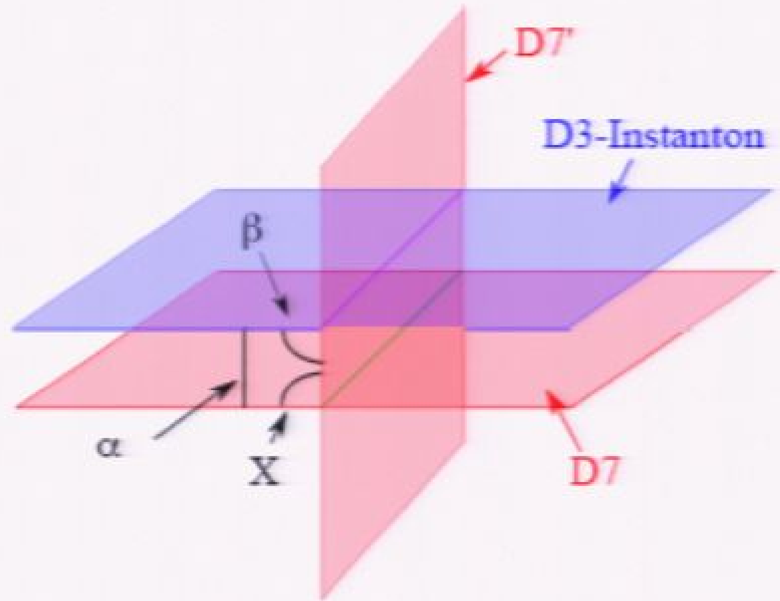

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  - α – fermi modes between D3 and D7
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- X couples to α and β via

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

- 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 $\boxed{W \sim e^{-S_{inst}} X^{n_\alpha}}$

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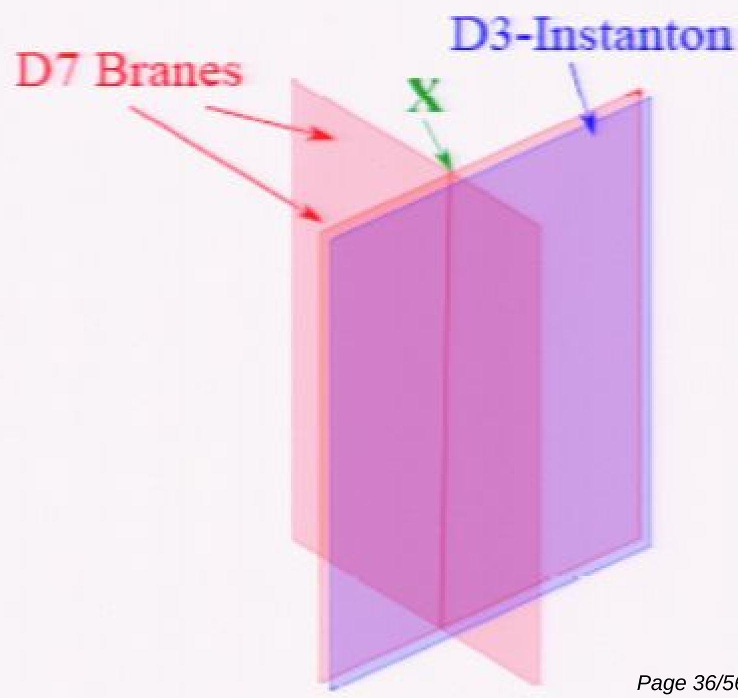

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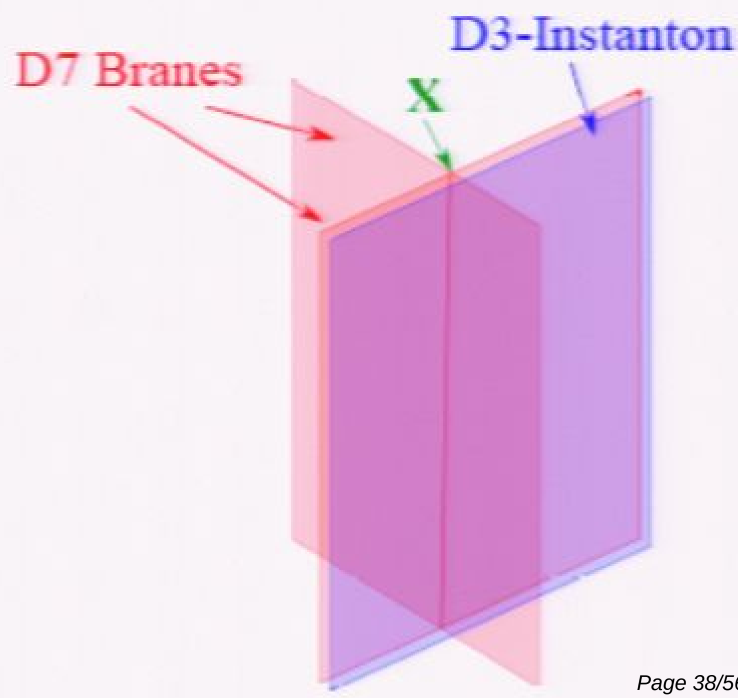

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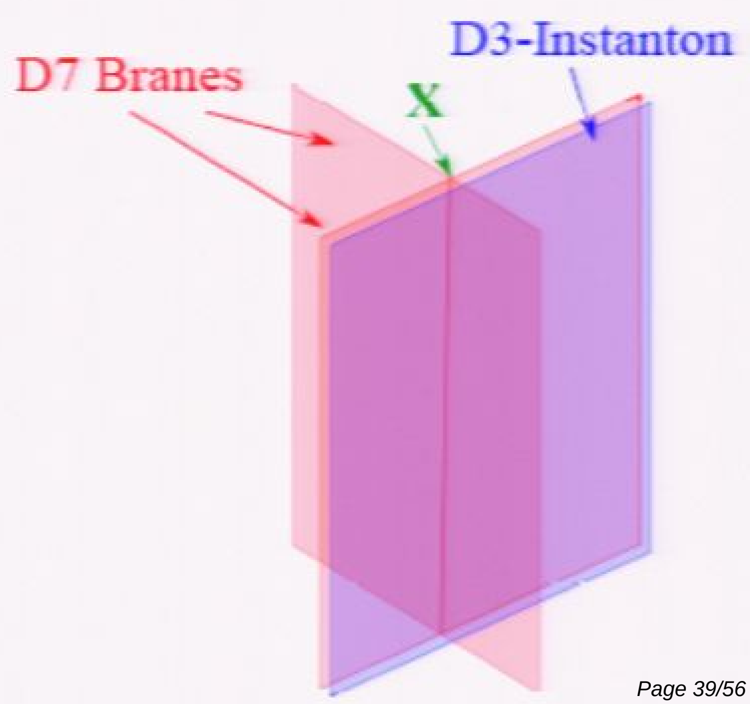

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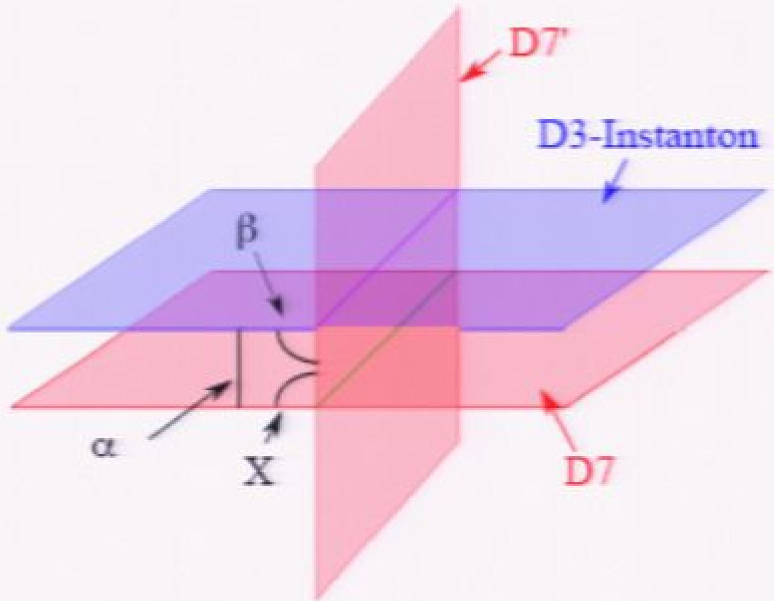

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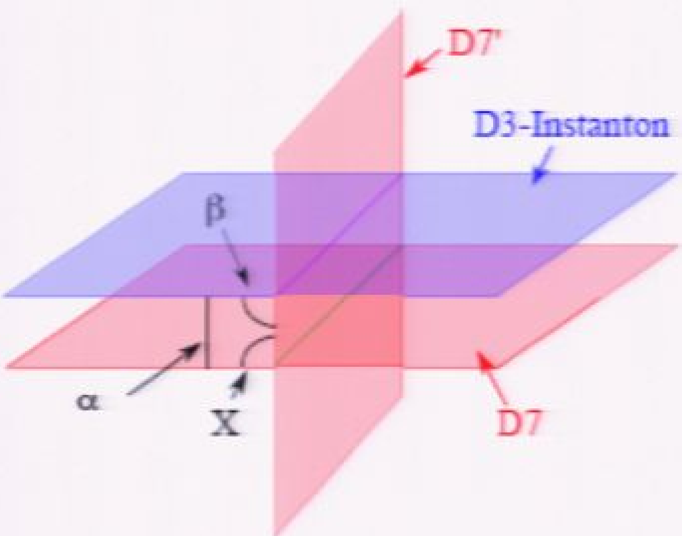
Generating $W(X)$ from Instantons

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

JM, Saulina, Schäfer-Nameki

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

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



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

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

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

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

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Coupling to GUTs

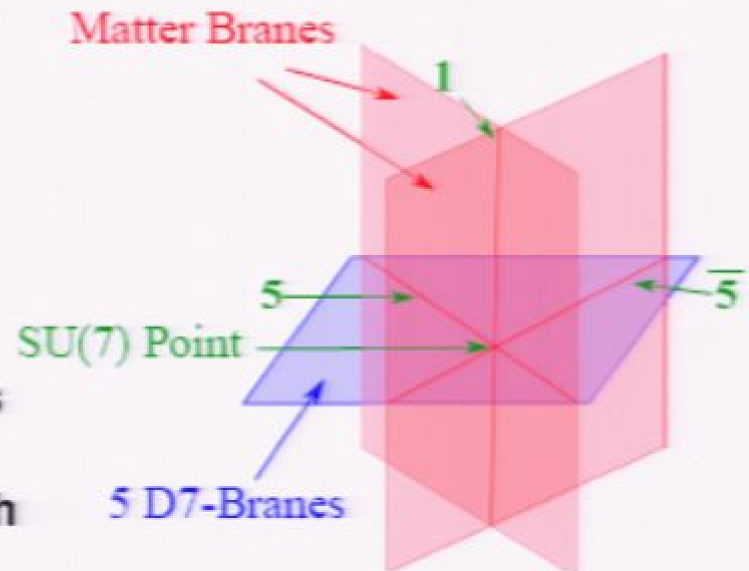
- Our D7-branes also intersect the GUT stack along matter curves
  - → D3-instanton also intersects GUT stack along a matter curve, Σ
- Extra fermi zero modes between the D3-instanton and GUT stack can spoil our superpotentials

JM, Saulina, Schäfer-Nameki

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

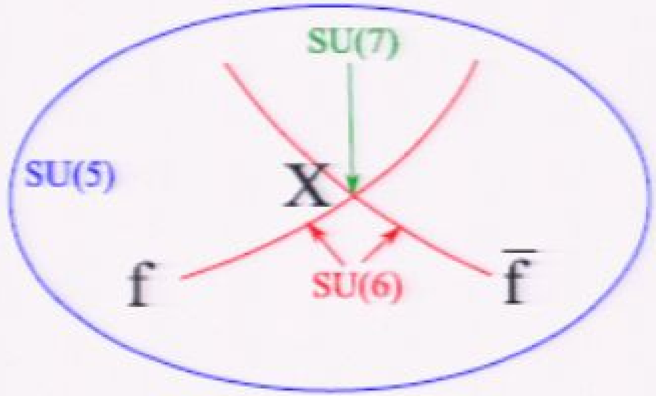
$$\mathcal{L}_{\text{inst}}|_{\Sigma} = \mathcal{O} \qquad \mathcal{L}_Y|_{\Sigma} = \mathcal{O}$$

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



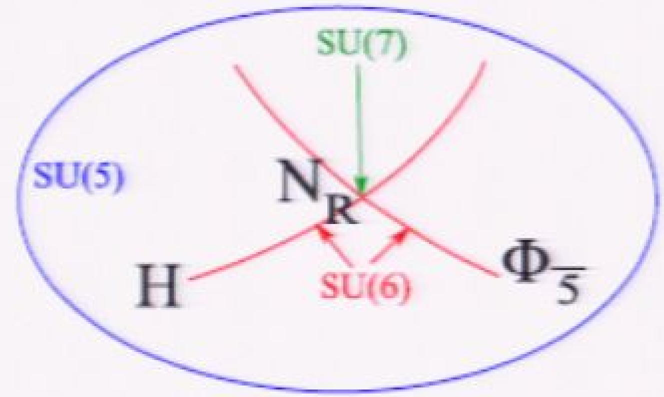
What can we do with D3-instantons?

SUSY-Breaking???



Yes

Neutrino Masses???



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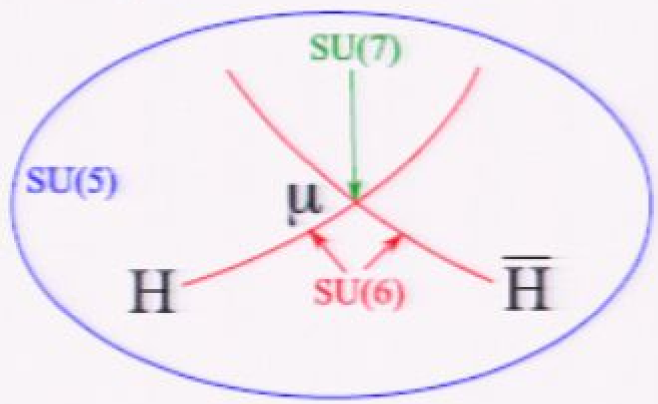
μ Parameter???

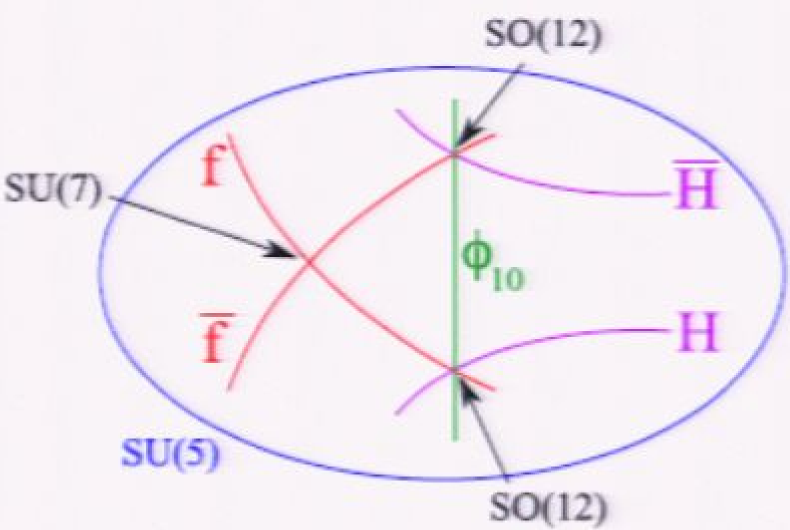


NO!

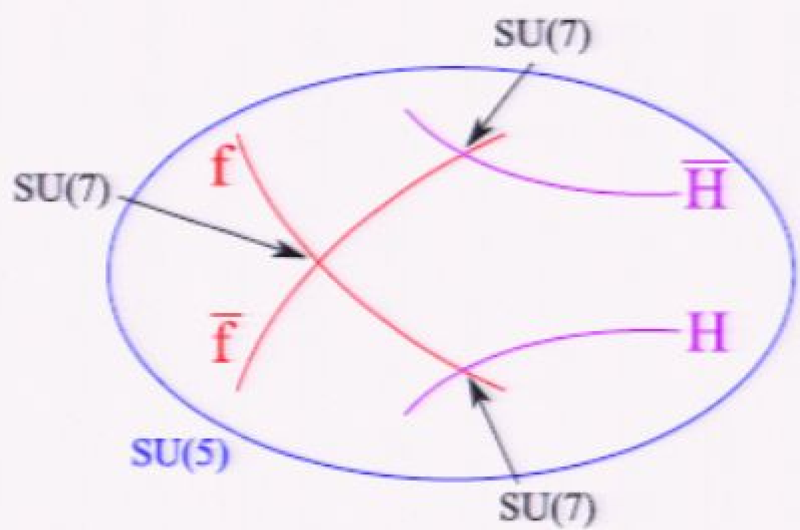
Getting μ

JM, Saulina, Schäfer-Nameki

- We cannot independenty generate the scale μ
  - $\rightarrow$ 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

What can we do with D3-instantons?

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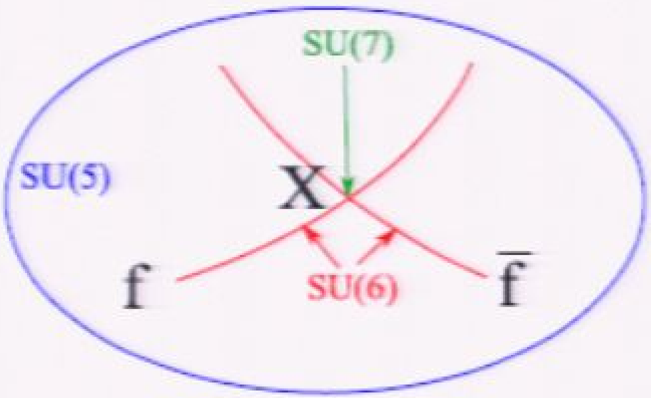

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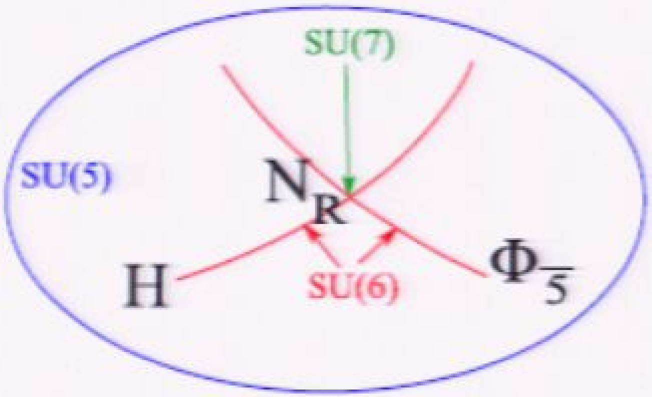

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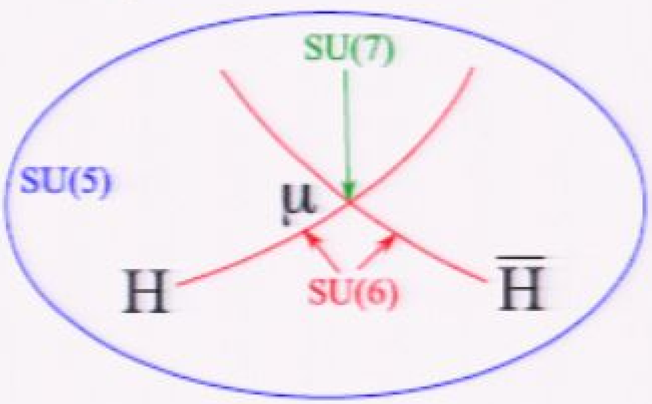

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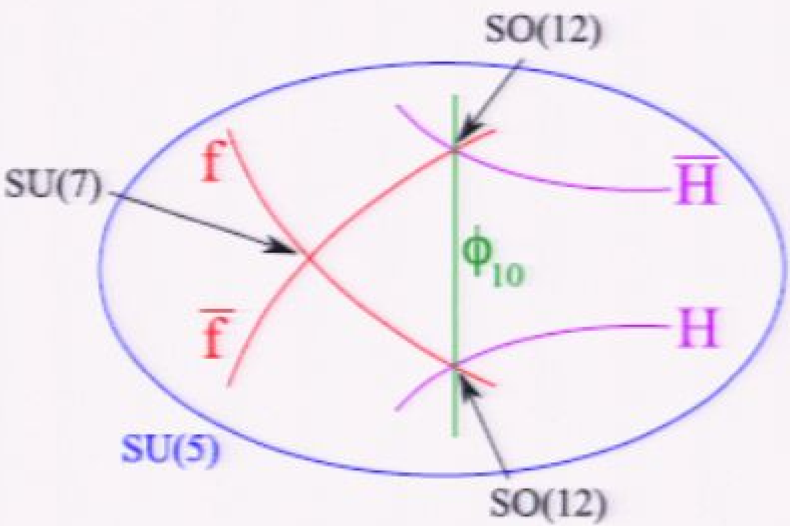

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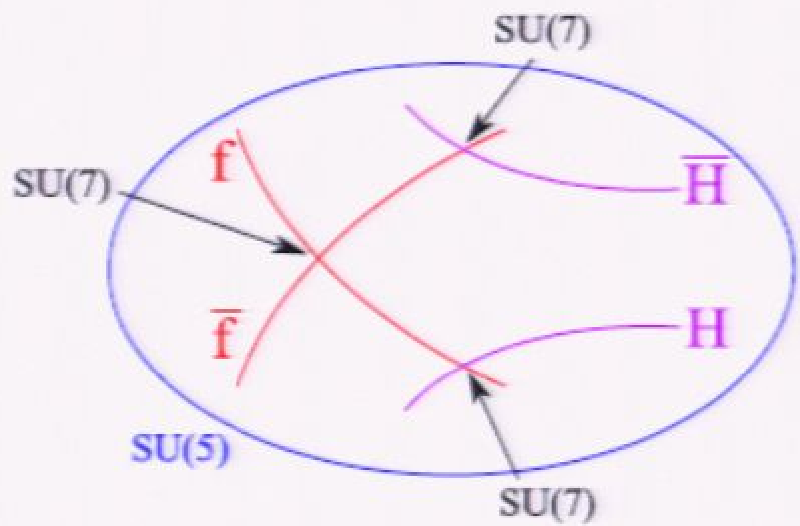


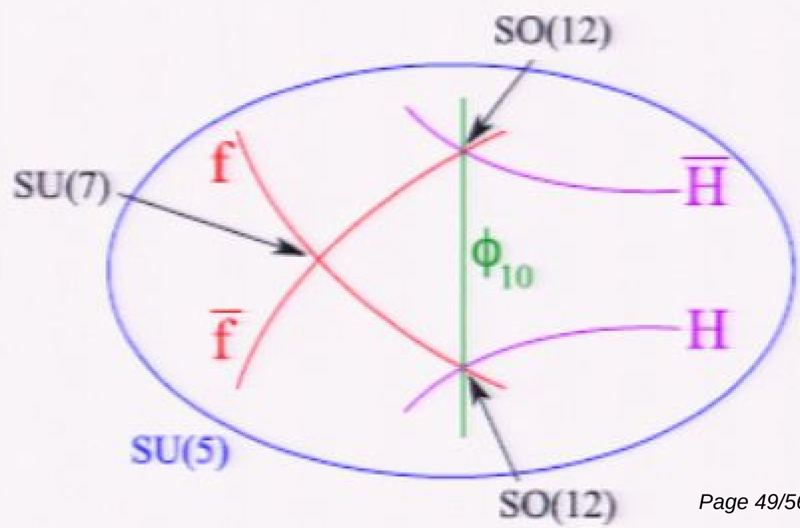
Higgs and messenger curves meet at $SU(7)$ points

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

- Arrange for ϕ_{10} curve to have KK modes only
- 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

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

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



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

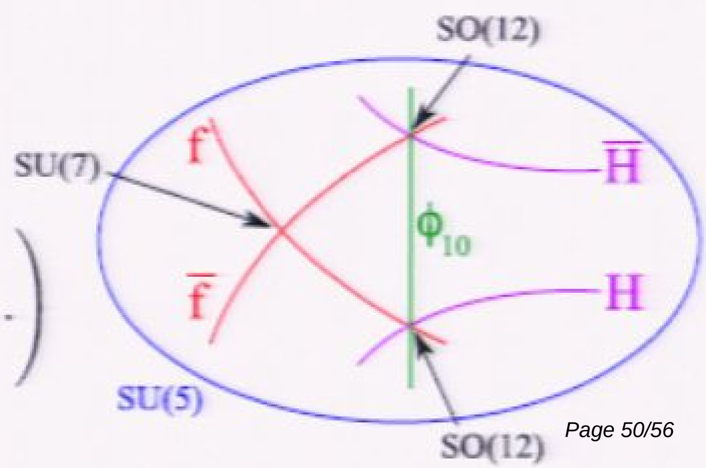
	H	$\overline{H}$	f	$\overline{f}$	ϕ_{10}	$\overline{\phi_{10}}$	X
$U(1)_{PQ}$	1	1	-1	-1	0	0	2

- Naturally obtain a $U(1)_{PQ}$ which forbids a bare μ term, $\mu H\overline{H}$
  - 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!!!

Ibe, Kitano

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

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



Generation of μ

	H	$\overline{H}$	f	$\overline{f}$	ϕ_{10}	$\overline{\phi_{10}}$	X
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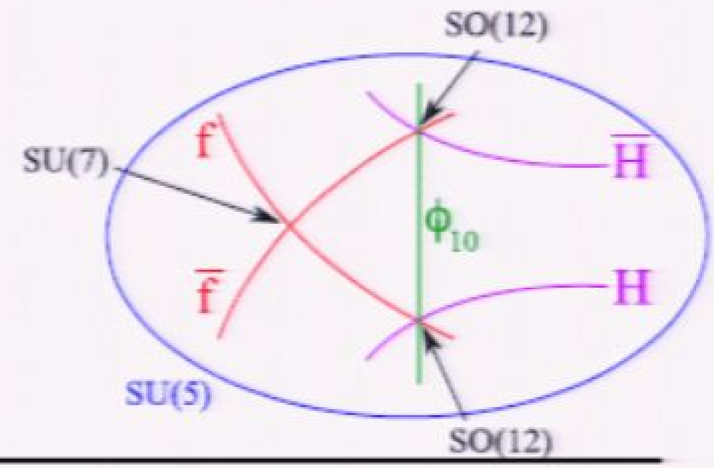

$$\int d^4\theta \left(\frac{c_\mu X^\dagger H\overline{H}}{M_{GUT}} + \frac{c_H X^\dagger X \left(H^\dagger H + \overline{H}\overline{H}^\dagger \right)}{M_{GUT}^2} + \dots \right)$$

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

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

$\rightarrow$ μ exhibits same suppression as SUSY-breaking

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

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

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

SUSY-Breaking Sector

- D3-instanton generated Polonyi superpotential

$$W \sim \nu X \qquad \nu \sim e^{-t}$$

  - Pseudo-moduli space of SUSY-breaking vacua
  - Lifted by corrections to Kähler potential from physics at high scales
- Two possible sources for such corrections
  - Massive $U(1)_{PQ}$ gauge boson

    Heckman, Vafa
  - KK modes at GUT scale

    JM, Saulina, Schäfer-Nameki
- In all that follows, we assume that $m^2_{U(1)_{PQ}} > M^2_{GUT}$

General Structure of KK Corrections

- Expect KK modes to correct Kähler potential

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

- 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

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

  - 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

$$W \sim \nu X + W_0$$

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

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

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

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

Sweet Spot Supersymmetry from F-Theory

Summary of Model

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

$$W \sim \nu X + \lambda X f\overline{f} + W_{MSSM} + \ldots$$

- 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

  - $\langle X \rangle$ stabilized at M_{GUT}^2/M_{Pl} via "gravitational gauge mediation"
  - "Viable" model when $m_{3/2} \sim 1$ GeV and $c_\mu \sim c_H \sim \mathcal{O}(1)$

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
  - D3-instantons can generate all of the necessary scales except μ
  - $\rightarrow$ μ is not an independent scale
- Naive coupling of Higgs and messenger sectors $\rightarrow U(1)_{PQ}$ 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