SUSY breaking in F-theory GUTs

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A Case for String Effective Field Theories

The LHC will scan effective field theory (EFT) landscape

Consider String EFT : String-motivated SUSY GUTs $\supset$ MSSM
with SUSY-breaking/mediation
cut-off scale

Advantage: UV completion is well-defined

In this talk: explore EFT landscape from 7-branes in F-theory

F-theory EFTs

In this talk we will explore the String EFT landscape of F-theory 7-branes.

F-theory [Vafa], [Morrison, Vafa], [Sen]
=Type IIB [Green, Schwarz] vacua with varying axio-dilaton:

$$\tau = C_0 + ie^{-\phi}$$

F-theory on $\mathbb{R}^{1,3} \times X_4$ where X_4 = elliptically fibered Calabi-Yau fourfold with three-fold base B_3:

$$\begin{array}{ccc} \mathbb{E}_\tau & \longrightarrow & X_4 \\ & & \downarrow \\ & & B_3 \supset S \end{array}$$

Loci $S \subset B$ where fibres degenerate	$\Leftrightarrow$	Surfaces S wrapped by 7-branes in B
ADE singularity type of degeneration	$\Leftrightarrow$	Gauge group G_S of 7-branes on S

Locally in the vicinity of the 7-brane extending along $\mathbb{R}^{1,3} \times S$ the CY4 is modeled by a local K3-fibration

$$\begin{array}{ccc} K3 & \longrightarrow & X_4 \\ & & \downarrow \\ & & S \end{array}$$

Singularity type of the K3-surface: ADE

Singularity type of degeneration determines gauge group:

G_S: Perturbative type

A_n: IIB with D7-branes

D_n: IIB orientifolded with D7-branes and O-planes

E_n: no perturbative IIB picture, ”exceptional 7-branes”

F-theory GUT models [Donagi,Wijnholt] [Beasley, Heckman, Vafa]

SUSY GUT models from 7-branes

Gauge fields:	surface S wrapped by 7-branes
	GUT gauge group G_S
Bifundamental Chiral Matter:	lives at intersection of surfaces: Σ
Interactions:	Triple-intersection of three curves in a point p
Decoupling M_{GUT} and M_{Pl}:	S is del Pezzo dP_8
Cut-off scale:	$M_{GUT} \sim 10^{16}$ GeV set by $Vol(S) \sim \frac{1}{M_{GUT}^4}$

GUT breaking flux on S sets mass-scale $F_S \sim M_{GUT}^2$, which is measured in $1/\text{Length}^2$ on S.

Gauge coupling $\alpha_{GUT} \sim \frac{1}{Vol(S)M_*^4}$, $M_* =$ 7-brane-tension.

Advantages over conventional intersecting brane models

- S=del Pezzo dP_8: separation of gauge dynamics from gravity
- GUT: gauge coupling unification
- GUT breaking by hypercharge flux without rendering $U(1)_Y$ massive
- Yukawa couplings: in perturbative IIB SU(5)

$$W \supset \lambda_{\text{bottom}} \bar{\mathbf{5}}_H \times \bar{\mathbf{5}} \times \mathbf{10} + \lambda_{\text{top}} \mathbf{5}_H \times \mathbf{10} \times \mathbf{10}$$

λ_{top} forbidden perturbatively. Generated non-perturbatively by D-instanton effects. $\Rightarrow$ Inverse hierarchy

In F-theory GUTs: all Yukawas are generated by same mechanism

String EFT/local model building philosophy:

- First: construct EFT in local string setup
- Then embedd into full-fledged compact string model

1-page summary: Complete Local Models

Ingredient 1 : Starting point: $SU(5)$ GUT model without exotics.

Ingredient 2 : SUSY breaking sector

⇒ Introduce scales by non-perturbative D3-instanton effects [HMSS-NV]

⇒ Generate Polonyi model $W = e^{-S_{inst}} X$

Ingredient 3 : Gauge mediation in F-theory GUTs [MSS-N]

Final result : Complete model of GUT, SUSY-breaking and mediation, which has many phenomenologically interesting features (”Sweet-spot” of Ibe-Kitano) [MSS-N]

Future : Embed into compact model.

Plan

1. F-theory GUTs: Review
2. Supersymmetry breaking and D3-instanton effects
3. Gauge-mediation in F-theory GUTs: the Sweet-Spot
4. Conclusions and Outlook

1. F-theory GUTs Review of [DW], [BHV]

Effective theory of 7-branes wrapped on $\mathbb{R}^{1,3} \times S$ with S = del Pezzo

$\Rightarrow$ Partially twisted $\mathcal{N} = 1$ SYM with ADE gauge group G_S

$\Rightarrow$ Main example: $SU(5)$ GUT from 5 D7-branes

$$y^2 = x^2 + z^5$$

Require: GUT breaking mechanism, chiral matter, Yukawa couplings.

Gauge-bundles and GUT breaking

Fields on S transform in adjoint of G_S.
Switch on susy $U(1)$ bundle $\mathcal{L}$, breaks adjoint

$$\mathfrak{g}_S \longrightarrow \mathfrak{u}(1) \oplus \mathfrak{g} \oplus \bigoplus_i \sigma_i^{(\alpha_i)}$$

Chiral spectrum in representation σ_i of $\mathfrak{g}$ is determined by

$$\#_{\sigma_i} = -\chi_S(\mathcal{L}^{\alpha_i})$$

[$S = dP_n$: $h^1(S, \mathcal{R}) = -\chi_S(\mathcal{R})$.]

$\left[\ \chi_S(\mathcal{L}) = 1 - \frac{1}{2}c_1(\mathcal{L}) \cdot \mathcal{K}_S + \frac{1}{2}c_1(\mathcal{L})^2 \quad \text{and} \quad \mathcal{K}_S = -3H + \sum_i E_i\ \right]$

$SU(5)$ GUT [DW], [BHV]

$G_S = SU(5)$ with $U(1)_Y$ hypercharge gauge bundle

$$SU(5) \rightarrow SU(3) \times SU(2) \times U(1)_Y$$

$$\mathbf{24} \rightarrow (\mathbf{8},\mathbf{1})_0 \oplus (\mathbf{1},\mathbf{3})_0 \oplus (\mathbf{1},\mathbf{1})_0 \oplus (\mathbf{3},\overline{\mathbf{2}})_{-5} \oplus (\overline{\mathbf{3}},\mathbf{2})_{+5}$$

Gauge Fields Exotics

Choose $U(1)$ gauge bundle $\mathcal{L}$ such that

$$\chi_S(\mathcal{L}^{\pm 5}) = 0$$

Denote generators of

$$H_2(dP_8,\mathbb{Z}) : \quad \begin{cases} H & = \text{hyperplane class} \\ E_i & = \text{exceptional classes} \end{cases}$$

Then following choice will remove exotics: $\mathcal{L}^5 = \mathcal{O}(E_i - E_j)\,, \qquad i \neq j.$

Vanishing theorems on del Pezzo imply:

Yukawa couplings between three fields on S vanish.

$\Rightarrow$ Seek other source of matter!

Bifundamental matter from Curves

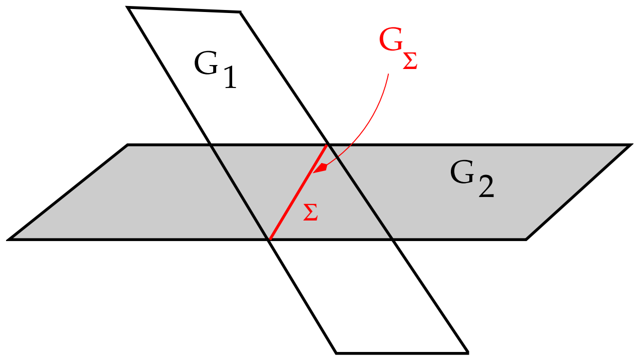
Consider: two del Pezzo surfaces S_1 and S_2 with G_i gauge group.

$S_1 \cap S_2 = \Sigma =$Riemann surface

$\Rightarrow$ Bifundamental matter localized on Σ

$\Rightarrow$ Gauge group enhances to G_Σ

$$\mathfrak{g}_\Sigma \longrightarrow \mathfrak{g}_1 \oplus \mathfrak{g}_2 \oplus \bigoplus_i (\rho_i^1, \rho_i^2)$$



Group theoretic analysis directly reflected in deformation of singularities [Johansen]: Defomations parametrized by Cartan Subalgebra elements

$$A_n : \qquad y^2 = x^2 + \prod_{i=1}^{n+1}(z - t_i) \,, \qquad \sum_i t_i = 0$$

$\Rightarrow$ t_i correspond to adjoint vevs

Example: $SU(6)$ enhancement

Simplest case: Switching on a single deformation on A_5 singularity

$$y^2 = x^2 + z^6 \quad \rightarrow \quad y^2 = x^2 + (z-t)z^5$$

corresponds to breaking $SU(6) \rightarrow SU(5) \times U(1)$.

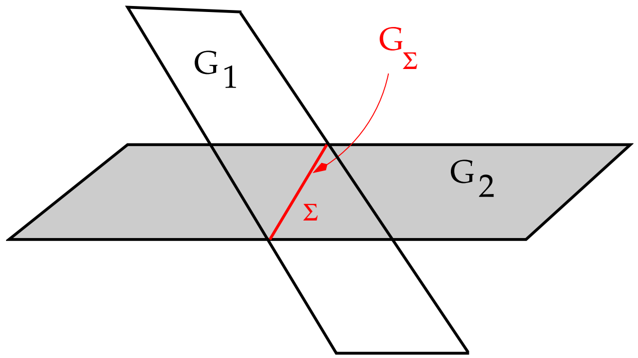
From the point of view of local enhancements:

$G_1 = SU(5)$, $G_2 = U(1)$:

$$G_\Sigma = SU(6) \quad \rightarrow \quad SU(5) \times U(1)$$

$$\mathbf{35} \quad \rightarrow \quad \mathbf{24}_0 \oplus \mathbf{1}_0 \oplus \mathbf{5}_6 \oplus \overline{\mathbf{5}}_{-6}$$

Adjoints Bifundamentals



$\mathbf{5} \oplus \overline{\mathbf{5}}$ are the bifundamental matter fields localized at Σ.

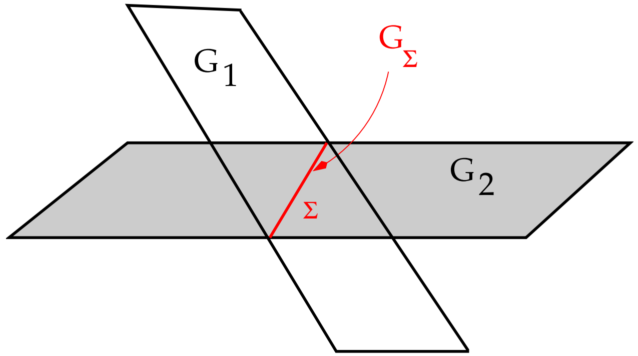
Chiral matter from Curves

Chirality is introduced by switching on gauge bundles on intersecting 7-branes: $U(1)$-bundles $\mathcal{L}_{1,2}$ on S_1 and S_2:

Decompose bifundamentals:

$$G_1 \times G_2 \quad \rightarrow \quad H_1 \times H_2 \times U(1)_1 \times U(1)_2$$

$$(\rho^1, \rho^2) \quad \rightarrow \quad \bigoplus_j (r_j^1, r_j^2)_{\alpha_j, \beta_j}$$



Zero modes in representation (r_j^1, r_j^2) of $H_1 \times H_2$ with $U(1)$ charges α_j, β_j is

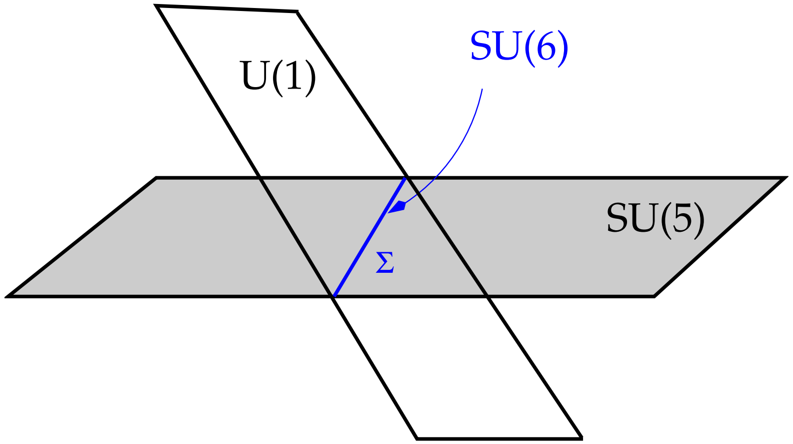
$$N_{(r_j^1, r_j^2)_{\alpha_j, \beta_j}} = h^0(\Sigma, K_\Sigma^{1/2} \otimes \mathcal{L}_1^{\alpha_j}|_\Sigma \otimes \mathcal{L}_2^{\beta_j}|_\Sigma)$$

$K_\Sigma^{1/2}$ = spin-bundle on Σ

$\mathcal{L}$ susy bundles: $J \wedge \mathcal{L} = 0$. Large volume $J = AH - \sum B_i E_i$, $A \gg B_i > 0$

Example: $SU(6)$ and $SO(10)$ Enhancements

$G_S = SU(5)$. Consider $\mathbf{\Sigma} = \mathbb{P}^1$, and generate matter $3 \times \overline{\mathbf{5}}$ and $3 \times \mathbf{10}$. In particular we want complete $SU(5)$ multiplets, so $\mathcal{L}_Y|_\Sigma = \mathcal{O}$



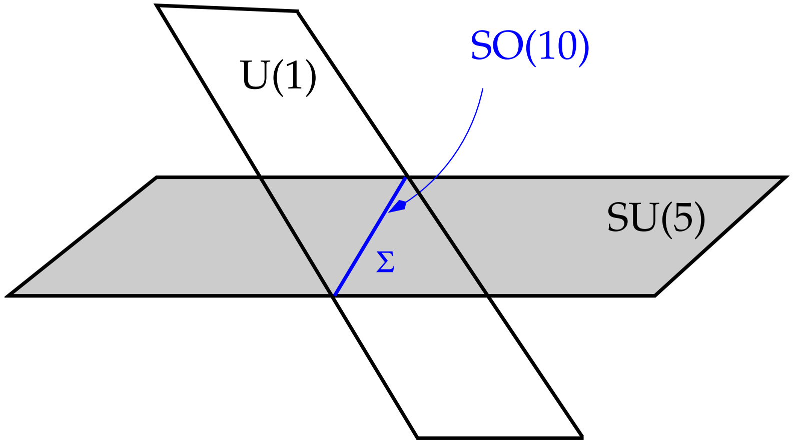
$$SU(6) \longrightarrow SU(5) \times U(1)_a$$

$$\mathbf{35} \longrightarrow \mathbf{24}_0 \oplus \mathbf{1}_0 \oplus \mathbf{5}_{+6} \oplus \overline{\mathbf{5}}_{-6}$$

$$h^0(\mathbb{P}^1, \mathcal{O}(-1) \otimes \mathcal{L}_a^{+6}|_\Sigma) = 0$$

$$h^0(\mathbb{P}^1, \mathcal{O}(-1) \otimes \mathcal{L}_a^{-6}|_\Sigma) = 3$$

$$\Rightarrow \mathcal{L}_a^{-6}|_\Sigma = \mathcal{O}(3)$$



$$SO(10) \longrightarrow SU(5) \times U(1)_b$$

$$\mathbf{45} \longrightarrow \mathbf{24}_0 \oplus \mathbf{1}_0 \oplus \mathbf{10}_{+4} \oplus \overline{\mathbf{10}}_{-4}$$

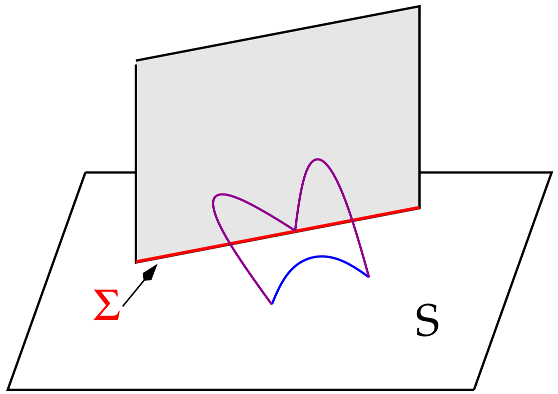
$$h^0(\mathbb{P}^1, \mathcal{O}(-1) \otimes \mathcal{L}_b^{+4}|_\Sigma) = 3$$

$$h^0(\mathbb{P}^1, \mathcal{O}(-1) \otimes \mathcal{L}_b^{-4}|_\Sigma) = 0$$

$$\Rightarrow \mathcal{L}_b^{4}|_\Sigma = \mathcal{O}(3)$$

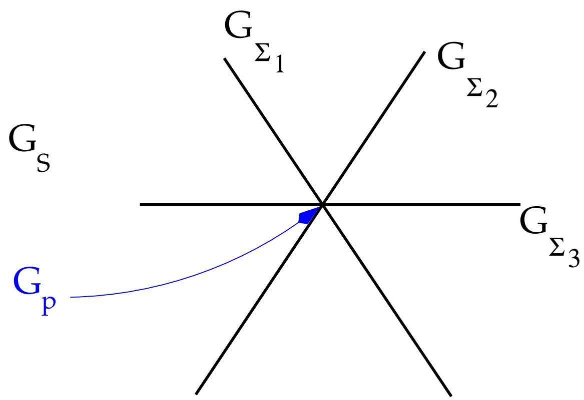
Yukawa couplings from Triple-Intersections

Yukawa couplings from $\Sigma\Sigma S$:
However, $SU(5)$ GUT: no chiral matter in the bulk



Yukawa couplings from $\Sigma_1 \cap \Sigma_2 \cap \Sigma_3$ triple intersection points p. Double-enhancement of G_S to

$$G_p \longrightarrow G_S \times U(1)_1 \times U(1)_2$$



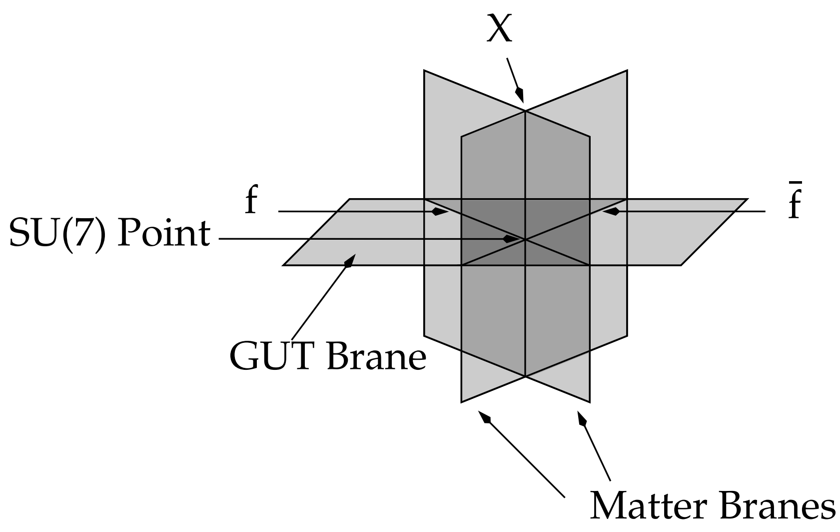
Coupling from $SU(7)$ Enhancements

$$SU(7) \rightarrow SU(5) \times U(1)_1 \times U(1)_2$$

$$\begin{aligned} \mathbf{48} \rightarrow & \left(\mathbf{24}_{0,0} \oplus \mathbf{1}_{0,0} \oplus \mathbf{1}_{0,0}\right) \\ & \oplus \left(\mathbf{5}_{0,+6} \oplus \overline{\mathbf{5}}_{0,-6}\right) \\ & \oplus \left(\mathbf{5}_{-6,0} \oplus \overline{\mathbf{5}}_{+6,0}\right) \\ & \oplus \left(\mathbf{1}_{+6,+6} \oplus \mathbf{1}_{-6,-6}\right) \end{aligned}$$

$$f = \mathbf{5}_{0,+6}\,,\ \bar{f} = \overline{\mathbf{5}}_{+6,0}\,,\ X = \mathbf{1}_{-6,-6}$$

$$\Rightarrow \qquad W \sim X f \bar{f}$$



GUT couplings from $SO(12)$ and E_6 Enhancements

Higgs-Matter couplings that are essential for $SU(5)$ GUTs can be generated from two types of enhancements:

$$SO(12) \rightarrow SU(5) \times U(1)_1 \times U(1)_2$$

$$\begin{aligned} \mathbf{66} \rightarrow & \left(\mathbf{24}_{0,0} \oplus \mathbf{1}_{0,0} \oplus \mathbf{1}_{0,0}\right) \\ & \oplus \left(\mathbf{5}_{2,2} \oplus \overline{\mathbf{5}}_{-2,-2}\right) \\ & \oplus \left(\mathbf{5}_{-2,2} \oplus \overline{\mathbf{5}}_{2,-2}\right) \\ & \oplus \left(\mathbf{10}_{0,4} \oplus \overline{\mathbf{10}}_{0,-4}\right) \end{aligned}$$

$$W \sim \mathbf{5} \times \mathbf{5} \times \overline{\mathbf{10}} + \overline{\mathbf{5}} \times \overline{\mathbf{5}} \times \mathbf{10}$$

$$\Rightarrow W \sim \bar{H}_{\overline{\mathbf{5}}} \Phi_{\overline{\mathbf{5}}} \Phi_{\mathbf{10}}$$

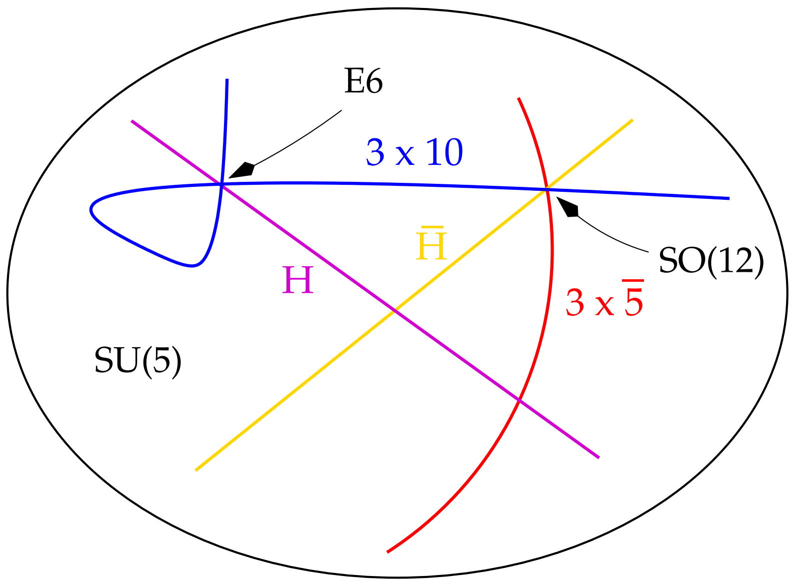
$$E_6 \rightarrow SU(5) \times U(1)_1 \times U(1)_2$$

$$\begin{aligned} \mathbf{78} \rightarrow & \left(\mathbf{24}_{0,0} \oplus \mathbf{1}_{0,0} \oplus \mathbf{1}_{0,0}\right) \\ & \oplus \left(\mathbf{5}_{-3,3} \oplus \overline{\mathbf{5}}_{3,-3}\right) \\ & \oplus \left(\mathbf{10}_{-1,-3} \oplus \overline{\mathbf{10}}_{1,3}\right) \\ & \oplus \left(\mathbf{10}_{4,0} \oplus \overline{\mathbf{10}}_{-4,0}\right) \oplus \left(\mathbf{1}_{-5,-3} \oplus \mathbf{1}_{5,3}\right) \end{aligned}$$

$$W \sim \mathbf{5} \times \mathbf{10} \times \mathbf{10} + \overline{\mathbf{5}} \times \overline{\mathbf{10}} \times \overline{\mathbf{10}}$$

$$\Rightarrow W \sim H_{\mathbf{5}} \Phi_{\mathbf{10}} \Phi_{\mathbf{10}}$$

Ingredient 1: An $SU(5)$ GUT à la [BHV]



$$W \sim \bar{\mathbf{5}} \times \bar{\mathbf{5}} \times \mathbf{10} + \mathbf{5} \times \mathbf{10} \times \mathbf{10}$$

$$\sim \lambda^d_{ij}\, \bar{H}_{\bar{\mathbf{5}}} \Phi^i_{\bar{\mathbf{5}}} \Phi^j_{\mathbf{10}} + \lambda^u_{ij}\, H_{\mathbf{5}} \Phi^i_{\mathbf{10}} \Phi^j_{\mathbf{10}} \Rightarrow QDH_d + LEH_d + QUH_u$$

Intersections realized within one del Pezzo.

Comments

1. Note: we do not want to generate $\mu H\bar{H}$, and neither right-handed neutrino masses here. There will be better ways of doing this.

2. Proton decay: H and $\bar{H}$ on different matter curves: by missing parter mechanism, triplets are paired up and become massive. No $QQQL$ operators can be generated from QQH, $QL\bar{H}$ and $H\bar{H}$.

F-theory GUT summary

- 7-branes wrapped on dP_n surface
- Bulk gauge group G_S
- GUT-breaking in $SU(5)$ by $U(1)_Y$ flux
- Chiral matter from intersection of 7-branes over curves Σ
- Yukawa couplings from triple intersections over points p
- Exotic-free $SU(5)$ GUT

2. SUSY breaking and scales via D3-instantons

Successful EFT: GUT plus

- SUSY-breaking, in particular generation scales (intermediate, not M_{GUT}, M_{Pl})
- Mediation of SUSY-breaking

To generate scales: use D-instanton effects: in other context studied in [Billo et al], [Blumenhagen et al], [Florea et al], [Ibanez, Uranga],...

Retrofitting simplest SUSY-breaking models: [Aharony, Kachru, Silverstein]
Polonyi for chiral superfield X

$$W = F_X X\,, \qquad F_X \sim e^{-S_{inst}}$$

$\Rightarrow$ How to construct SUSY-breaking sector in F-theory?

Instantons: general considerations

Consider D3-instantons: can these contribute to the superpotential?

Setup: 7-brane on S, and wrap in addition D3-instanton on S.

Types of strings: "3-3", "3-7", "7-7".

To contribute: saturate "3-3" fermionic zero-mode integrals!

D3-D3: 4 universal fermionic zero-modes

$\theta_\alpha \in S_+ \otimes H^2(S, K_S)$, $\mu_{\dot\alpha} \in S_- \otimes H^0(S, \mathcal{O})$

"Goldstinos from 4 broken SUSY that are preserved by background but broken by instanton"

D3-D7: bosonic zero-modes: $b_{\dot\alpha}, \bar{b}_{\dot\alpha} \in S_- \otimes H^0(S, \mathcal{O})$

fermionic zero-modes: $f, \bar{f} \in H^2(S, K_S)$

Instanton-constribution

- Without world-volume flux: 2 modes $\mu_{\dot\alpha}$ should be lifted: D7-brane breaks already half of the modes, so only 4 SUSY left. D3 breaks 2. Indeed, coupling to ″3-7″ strings saturates integral:

$$S_{\text{inst}} \supset \mu_{\dot\alpha}^{3-3} \left(b^{\dot\alpha} \bar{f} + \bar{b}^{\dot\alpha} f\right)^{3-7}$$

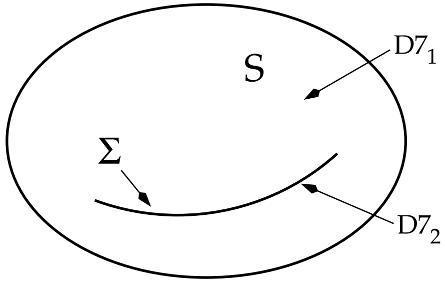
- Including world-volume flux: ″3-7″ zero-modes are generically lifted! No D3-effect?
  However, same coupling exists to KK-modes of ″3-7″ strings exist from 8d reduction: [HMSS-NV]

$$S_{\text{inst}} \supset \mu_{\dot\alpha} \left(\bar{b}^{\dot\alpha}_{KK} f_{KK} + b^{\dot\alpha}_{KK} \bar{f}_{KK}\right) + M_{b,KK} \bar{b}_{KK} b_{KK} + M_{f,KK} \bar{f}_{KK} f_{KK}$$

Polonyi from D3-instantons [Heckman, Marsano, Saulina, SSN, Vafa]

D3-instanton should contribute. Produce $W = F_X X$!

$S_1 \cap S_2 = \Sigma$, then $U(1)_1 \times U(1)_2$ charged chiral matter:



$$7_1\text{-}7_2: \quad \begin{cases} n_{+-} = h^0(\Sigma, K_\Sigma^{1/2} \otimes \mathcal{L}_1|_\Sigma \otimes \mathcal{L}_2^{-1}|_\Sigma) = 1 \Rightarrow X_{+-0} \\ n_{-+} = h^0(\Sigma, K_\Sigma^{1/2} \otimes \mathcal{L}_1^{-1}|_\Sigma \otimes \mathcal{L}_2|_\Sigma) = 0 \end{cases}$$

Include D3-instanton with gauge-bundle $\mathcal{L}_{\rm inst}$ to generate coupling to S

$\Rightarrow$ fermi-zero-modes, charged under $U(1)_1 \times U(1)_2 \times U(1)_{\rm inst}$:

$$\text{D3-}7_1: \quad \begin{cases} n_{+0-} = h^1(S_1, \mathcal{L}_1 \otimes \mathcal{L}_{\rm inst}^{-1}) & = 0 \\ n_{-0+} = h^1(S_1, \mathcal{L}_1^{-1} \otimes \mathcal{L}_{\rm inst}) & = 1 \Rightarrow \beta_{-0+} \end{cases}$$

$$7_2\text{-D3}: \quad \begin{cases} n_{0+-} = h^0(\Sigma, \mathcal{L}_2|_\Sigma \otimes \mathcal{L}_{\rm inst}^{-1}|_\Sigma) & = 1 \Rightarrow \alpha_{0+-} \\ n_{0-+} = h^0(S_1, \mathcal{L}_2^{-1}|_\Sigma \otimes \mathcal{L}_{\rm inst}|\Sigma) & = 0 \end{cases}$$

$\Rightarrow$ Coupling $\alpha_{0+-}\beta_{-0+}X_{+-0}$

D3-instanton generated superpotential

Contribution to superpotential $\langle \psi_1^\dagger \psi_2^\dagger \rangle \sim \partial_t^2 W_{\rm inst}$:

$$W_{\rm inst} \sim e^{-t_{S_1}} \int d\alpha\, d\beta\, d\mu\, d f_{KK}\, d b_{KK}\, d\bar{f}_{KK}\, d\bar{b}_{KK}$$

$$e^{-\alpha\beta X - \mu_{\dot\alpha}\left(\bar{b}^{\dot\alpha}_{KK} f_{KK} + b^{\dot\alpha}_{KK}\bar{f}_{KK}\right) - M_{b,KK}\bar{b}_{KK}b_{KK} - M_{f,KK}\bar{f}_{KK}f_{KK}} \,.$$

where $t_{S_1} \sim \int_{S_1} (J + c_1(\mathcal{L}_{\rm inst}))^2 + S_{\rm WZW}$.

Integrating over fermi-zero modes yields

$$W_{\rm inst} = F_X X\,, \qquad F_X \sim M_{S_1}^2 e^{-t_{S_1}}$$

$M_{S_1}^4 \sim 1/Vol(S_1)$ is characteristic mass scale. E.g. for GUT-cycle M_{GUT}.

Exponential suppression of F_X by Kähler parameter on S_1.

Will discuss SUSY breaking later in complete model.

Ingredient 2: Instantons at the $SU(7)$ point [Marsano, Saulina, SSN]

In $SU(5)$ GUT: generate Polonyi + coupling to gauge messengers:

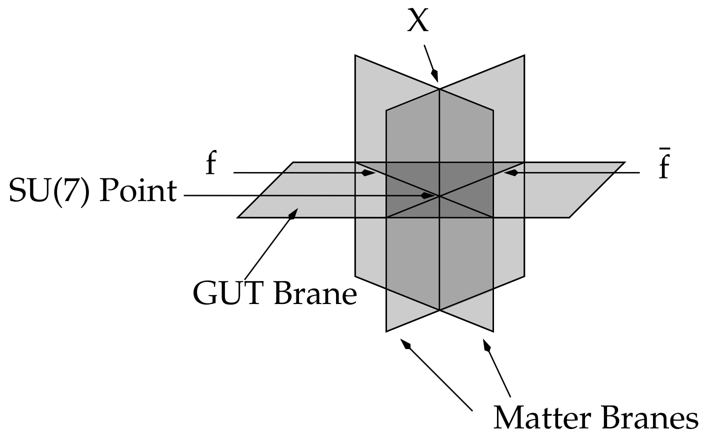
GUT singlet X couples to $\mathbf{5}$ and $\bar{\mathbf{5}}$ messengers by

$$W = \lambda_X X f \bar{f}$$

Linear term for X by instantons:
X localized on $S_f \cap S_{\bar{f}} = \Sigma_{Pol}$

$$W_{\text{inst}} = F_X X$$

Ensure: no extra fermi zero modes are generated. In particular $\mathcal{L}_Y$ restricts trivially here!



Ingredient 2: $W \supset F_X X + \lambda_X X f \bar{f}$

Remains to couple this to the $SU(5)$ GUT and mediate SUSY breaking.

Instantons for other scales 1: μ-term?

$$\mathcal{L} \supset \int d^2\theta \mu H \bar{H}$$

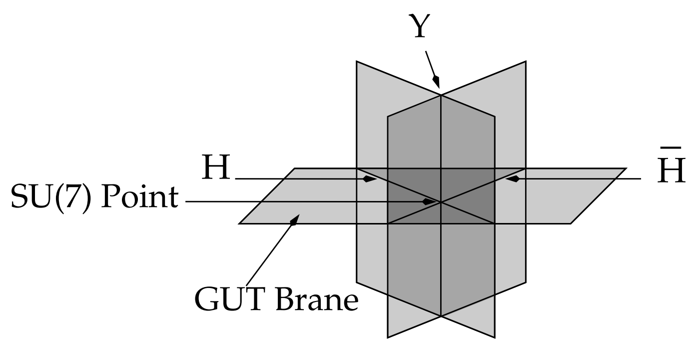
Electro-weak symmetry breaking requires $\mu \sim O(100)$ GeV

"μ-problem": Why is μ so small?

Naively one could anticipate generating by analogy: Y GUT-singlet

$$W \sim Y H \bar{H}$$

$\langle Y \rangle \neq 0 \Rightarrow$ would generate small μ-term.



Doublet-triplet splitting requires: $U(1)_Y$ flux restricts non-trivially

$\Rightarrow$Generates extra zero-modes which cannot be cancelled!

$\Rightarrow$ μ-term CANNOT be generated in these models directly by instantons

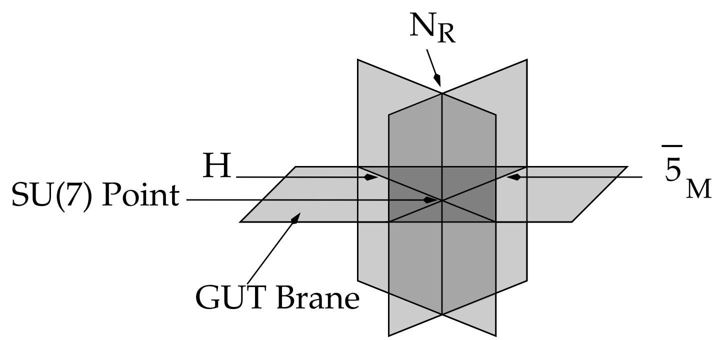
$\Rightarrow$ Will see: μ will be related to other scale, namely SUSY breaking scale, and yield very elegant solution to μ-problem

Instantons for other scales 2: Right-handed neutrino-mass

We can use instantons to generate small mass for right-handed neutrinos:
N_R = GUT-singlet at $SU(7)$ point. Coupling:

$$W \sim N_R H \Phi_{\bar{\mathbf{5}}}$$

Instantons generated $W_{\text{inst}} = \mu_N N_R^2$, $\mu_N \sim e^{-S_{inst}}$.
If N_R = Right-handed neutrino, masses using see-saw mechanism.



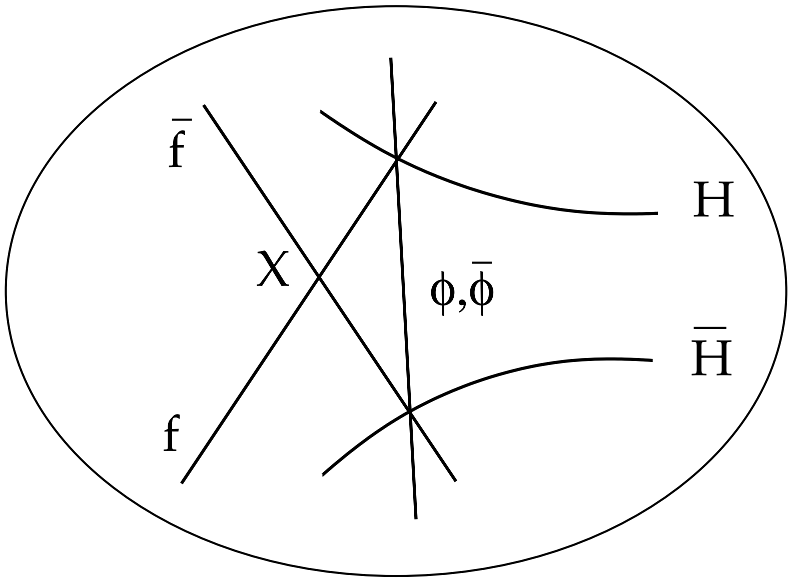
General lesson: D3-instantons

- Introduce scales
- Can construct Polonyi (also O'R and Fayet) model of SUSY breaking
- Right-handed neutrino-masses can be generated
- μ-term CANNOT be generated in $SU(5)$ GUT due to $U(1)_Y$ flux

3. Gauge Mediation

Coupling to Higgs sector [Marsano, Saulina, SSN]

Gauge-mediation of SUSY-breaking most natural in local F-GUTs:



$SO(12)$ point:

$$W \sim \mathbf{5} \times \mathbf{5} \times \overline{\mathbf{10}} + \overline{\mathbf{5}} \times \overline{\mathbf{5}} \times \mathbf{10}$$

10's KK-mode: $M \sim M_{GUT}$

$$W \sim Xf\overline{f} + Hf\overline{\phi} + \overline{H}\overline{f}\phi + M\phi\overline{\phi}$$

Coupling to Higgs sector: $U(1)_{PQ}$

$U(1)$ Peccei-Quinn symmetry under which X is charged $+2$.

$$SO(12) \text{ point :} \qquad W \sim Xf\overline{f} + Hf\overline{\phi} + \overline{H}\bar{f}\phi + M\phi\overline{\phi}$$

respects

	X	f	$\overline{f}$	ϕ	$\overline{\phi}$	H	$\bar{H}$
PQ	2	-1	-1	0	0	1	1

D3-instanton-generated Polonyi term $W_{\text{inst}} = F_X X$ breaks $U(1)_{PQ}$

$U(1)_{PQ}$ forbids μ-term $\mu H\bar{H}$

How do we generate μ?

Generation of μ-term

$U(1)_{PQ}$ prohibits $\mu H\bar{H}$ because $PQ(H) = PQ(\bar{H}) = 1$.

In $SO(12)$ model:

we obtain μ by integrating out KK-modes and generating

$$\frac{1}{M_{GUT}} \int d^4\theta X^\dagger H\bar{H} \quad \Rightarrow \quad \mu \sim \frac{F_X}{M_{GUT}}$$

B_μ term cannot be generated as $X^\dagger X H\bar{H}$ is forbidden by $U(1)_{PQ}$

$\Rightarrow B_\mu = 0$ at messenger scale.

SUSY-breaking vacuum

Polonyi model by itself does not yield SUSY-breaking vacuum. Need to lift flat directions and find non-zero M for $\langle X \rangle = M + \theta^2 F_X$

- Anomalous $U(1)$:
  integrating out massive gauge boson [Arkani-Hamed, Dine, Martin]

$$\delta K_{AHDM} \sim -\frac{c(X^\dagger X)^2}{M^2_{KK,Polonyi}}$$

  $c > 0 \;\Rightarrow$ Favours $M = 0$
  ($c < 0$: instability, roll out of regime of validity)

- Integrating out KK-modes: Leading KK yield O'Raifeartaigh model
  $W = F_X X + \lambda X \tilde{X}_{KK} \Phi_{KK} + M_{KK} X_{KK} \tilde{X}_{KK} + M_{KK} \Phi^2_{KK}$
  Coleman-Weinberg potential lifts flat directions, captured by [Shih]

$$\delta K_{KK} \sim -\frac{a|X|^4}{M^2_{GUT}} + \frac{b|X|^6}{M^4_{GUT}} + \cdots$$

  $a > 0 \;\Rightarrow$ Favours $M = 0$

SUSY-breaking vacuum (cont.)

But M gives mass to messengers via $\lambda_X X f \bar{f}$! Disaster?

In order to generate $M \neq 0$ we have to include coupling to supergravity. Leading corrections to M turns out to be not small, namely $O(M_{GUT}^2/M_{Pl})$. [Kitano]

Additional term from energy density in bulk: $W = F_X X + W_0$

$$\Rightarrow V_{Sugra} \sim \frac{1}{M_{Pl}^2} W_0 F_X X + c.c. + \frac{a|F_X|^2|X|^2}{M_{GUT}^2}$$

This shifts

$$M = 0 \quad \Rightarrow \quad M \sim \frac{|W_0| M_{GUT}^2}{|F_X| M_{Pl}^2}$$

Imposing vanishing vacuum energy, yields in fact $W_0 = F_X M_{Pl}$, so that

$$M \sim \frac{M_{GUT}^2}{M_{Pl}} = O(10^{14})\ \text{GeV}$$

Clearly not negligible!

Complete Model: Sweet-spot SUSY

Ingredient 1: $SU(5)$ GUT, with hypercharge flux to eliminate Higgs **3**'s

Ingredient 2: SUSY-breaking by D3-instanton generated Polonyi model
$W = F_X X + W_0$ with $\langle X \rangle = M + \theta^2 F_X$,

$$M \sim \frac{M_{GUT}^2}{M_{Pl}}\,, \qquad F_X \sim M_{GUT}^2 e^{-t_{\text{inst}}}$$

Ingredient 3: Gauge-mediation $SO(12)$ model, $Xf\bar{f}$ and $U(1)_{PQ}$ symmetry, with couplings (after integrating out KK-modes)

$$\mathcal{L}_{\text{sweet}} \sim \int d^4\theta \left(X^\dagger X - \frac{a(X^\dagger X)^2}{M_{GUT}^2} + \frac{c_\mu X^\dagger H \overline{H}}{M_{GUT}} + \frac{c_H X^\dagger X \left(H H^\dagger + \overline{H}\,\overline{H}^\dagger \right)}{M_{GUT}^2} + \dots \right)$$
$$+ \int d^2\theta \left(F_X X + \lambda_X X f \bar{f} + \dots \right) + \mathcal{L}_{MSSM}$$

This is essentially the effective model of [Ibe, Kitano]'s Sweet-spot SUSY.
Complete realization in local F-theory GUT.

Sweet-spot SUSY phenomenology

The Ibe-Kitano's sweet-spot SUSY model has various appealing features

Input into EFT:

- Order 1 coefficients c_μ, c_H
- $\lambda_X \sim 10^{-2}$: susy breaking vacuum stays stable after coupling to Higgses
- $F_X \sim 10^{19}\mathrm{GeV}^2$
- Gravitino mass $m_{3/2} = \frac{F_X}{M_{Pl}} = 1\ \mathrm{GeV}$

Implies

$$\mu \sim \frac{F_X}{M_{GUT}} = 10^3 GeV$$

$\Rightarrow$ Solves μ-problem.

Features of F-theory Sweet-spot SUSY

More detailed look at parameters and scales from F-theory point of view:

Scales:	$M_{GUT} \sim 10^{16}$ GeV, $M_{Pl} = 10^{19}$ GeV
Couplings:	Tension of branes M_* and τ
GUT coupling constant	$\alpha_{GUT} \sim \frac{M_{GUT}^4}{M_*^4}$
Scales in the model:	$F_X \sim M_{GUT}^2 e^{-t}$
	$M \sim \frac{M_{GUT}^2}{M_{Pl}}$
	$\mu \sim \frac{F_X}{M_{GUT}}$, $B_\mu = 0$ at messenger scale

Important feature as in Ibe-Kitano:

- μ-term is related to SUSY breaking scale.
- Geometrically realized $U(1)_{PQ}$ dictates which couplings are possible.
- $B_\mu = 0$ and gets generated by MSSM RG flow below messenger scale [Babu, Kolda, Wilczek]

To see, whether Sweet-spot model is realizable in this context, assume that these are $O(1)$ constants.

For $m_{3/2} = 1$ GeV, we obtain from

$$m_{3/2} \sim \frac{F_X}{M_{Pl}} \qquad \Rightarrow \qquad F_X \sim 10^{19}\text{GeV}^2$$

In our setup: F_X was related to size of cycle S that is wrapped by D3-instanton: $M_{Pol}^4 = 1/Vol(S)$. Up to O(1) parameter η:

$$M_{Pol} = \eta M_{GUT}$$

and

$$F_X \sim M_{Pol}^2 e^{-\frac{M_*^4}{M_{Pol}^4}}$$

which gives correct order for $\eta \sim 0.68$. Recall: $\alpha_{GUT} \sim M_{GUT}^4 / M_*^4$.

$\Rightarrow$ there is Sweet-spot in F-theory EFT landscape

4. Summary and Outlook

F-theory GUT models are interesting String EFT with realistic GUTs

Our findings:

- D3-instanton effects introduce scales
- SUSY breaking by D3-instanton effects
- Gauge-mediation natural
- μ-term has to be related SUSY breaking scale, cannot be generated by other effects, e.g. instantons; solution to μ-problem
- Complete local model for SU(5) GUT with SUSY breaking

Future directions:

- Compute Yukawa couplings, check hypothesis of $O(1)$ coefficients
- For this: need to find compact models, and conditions on compact geometries
- Moduli stabilization

Thank you