Natural Standard Model-like theories from E_7 flux breaking in F-theory: features and challenges

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Outline

1. SM-like models from rigid E_7 flux breaking in F-theory

2. Features

3. Issues

Based on work with Shing Yan (Kobe) Li:
2112.03947, 2207.14319, 2401.00040

+ works in progress with Wang/Yu, Jefferson/Li

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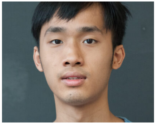

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1. SM-like models from rigid E_7 flux breaking in F-theory

F-theory: Nonperturbative formulation of type IIB string theory

Dictionary for geometry $\leftrightarrow$ physics [Vafa, Morrison-Vafa]

$\sim$ compactification of IIB on compact Kähler (non-CY) space B (e.g. $\mathbb{P}^n$)
B_2 (complex surface) $\rightarrow$ 6D, $B_3 \rightarrow$ 4D.

Defined by Weierstrass model (fiber τ = 10D IIB axiodilaton)

$$y^2 = x^3 + fx + g, \quad f, g \text{ “functions}'' \text{ on } B_2$$

Elliptic fibration: $\pi : X(CY) \rightarrow B$,
$\pi^{-1}(p) \cong T^2$, for general $p \in B$

Fiber singularities $\rightarrow$

Gauge group G (codimension 1 in B)
[Kodaira: resolution $\rightarrow$ affine Dynkin]

Matter (codimension 2 in B)

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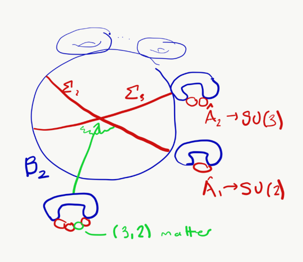

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There are many different ways the standard model may be realized in F-theory

	GUT	$(SU(3) \times SU(2) \times U(1))(/Z_6)$
Tuned G	Tuned GUT (e.g., SU(5))	Direct tuned G_{SM}
Rigid G	Rigid GUT (e.g., E_6, E_7)	Rigid G_{SM}

- Much work: tuned GUT e.g. SU(5) [Beasley/Heckman/Vafa, Donagi-Wijnholt]
- Can tune G_{SM} directly (e.g. "F_{11}" fibers, "quadrillion SM")

[Klevers/Mayorga Peña/Oehlmann/Piragua/Reuter, Cvetič/K/MP/O/R, Raghuram/WT/Turner, Cvetič/Halverson/Lin/(Liu/Tian, Long), Jefferson/WT/Turner]

Tuned models are rare in landscape, however: require tuning many moduli, many bases will not support

- $SU(3) \times SU(2)$ can be rigid/geometrically non-Higgsable in 4D [Grassi/Halverson/Shaneson/WT]; U(1) factor difficult however to integrate

Most natural approach: rigid/non-Higgsable GUT

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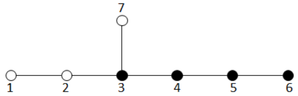
Breaking $E_7 \to G_{\rm SM}$ [Li/WT, arXiv:2112.03947, 2207.14319, 2401.00040]

E_7 arises naturally in many geometries as a rigid gauge group [Morrison/WT]

Can break gauge group with fluxes ϕ:

$$\Theta_{IJ} = \int_{S_{IJ}} G = M_{(IJ)(KL)}\phi^{KL}\,.$$

When $\Theta_{i\alpha} \neq 0$, breaks Cartan generator i; $\sum_i c_i \Theta_{i\alpha} = 0 \forall \alpha$ preserves U(1), etc.



Can choose fluxes to break $i = 3, 4, 5, 6$ for any geometric E_7, leaving $SU(3) \times SU(2)$

Note: this realization of $SU(3) \times SU(2)$ is unique up to E_7 automorphism

Depending on fluxes, preserve different $U(1)$ factors, different spectra

– Many $SU(3) \times SU(2) \times U(1)$ breakings, but most have exotics

Intermediate SU(5) and remainder hypercharge flux breaking

To avoid exotic chiral matter, any appropriate $U(1) \to SU(5)$ enhancement!
(flux vanishes on an additional $\mathbb{P}^1$; equivalent to $\Theta_{3\alpha} = 0$)

Proceed in two steps: 1) Vertical flux breaking $E_7 \to SU(5)$,
2) Remainder flux breaking $SU(5) \to G_{\rm SM}$
($\sim$ [Beasley/Heckman/Vafa, Donagi-Wijnholt, Blumenhagen/Grimm/Jurke/Weigand, Marsano/Saulina/Schafer-Nameki, Grimm/Krause/Weigand, . . .])

Remainder flux:

$$G_4^{\rm rem} = [D_Y|_{C_{\rm rem}}] \, ,$$

where $D_Y = 2D_1 + 4D_2 + 6D_3 + 3D_7$ generates hypercharge.

$C_{\rm rem}$ is a curve on Σ, homologically trivial in B. Such curves exist on some (typical?) non-toric bases [Braun/Collinucci/Valandro]

Matter content with this breaking contains only SM family

$$(\mathbf{3}, \mathbf{2})_{1/6} \, , \quad (\mathbf{3}, \mathbf{1})_{2/3} \, , \quad (\mathbf{3}, \mathbf{1})_{-1/3} \, , \quad (\mathbf{1}, \mathbf{2})_{1/2} \, , \quad (\mathbf{1}, \mathbf{1})_{1} \, ,$$

arising from (non-chiral) E_7 representations **56** and **133**.

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2. Features of $E_6, E_7 \to G_{\text{SM}}$ flux construction

- Explicit examples in papers.
- Natural: many bases have rigid E_7 (more below)
- Flux breaking of GUT E_7 without its own chiral matter
- Higgs sector and chiral matter naturally separated (more below)
- No chiral exotics for certain breaking pattern with intermediate SU(5)
- Chiral multiplicity is naturally small from tadpole/χ.
  (3 arises very naturally as solution of linear Diophantine eqs.)
- Proton decay enabling Yukawa couplings naturally suppressed by broken U(1) factors (more below)

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Feature: Natural separation of Higgs and chiral matter

Σ = 7-brane locus supporting $E_7 \to G_{\text{SM}}$ (**133** of E_7)

$C = C_{\mathbf{56}} = -\Sigma \cdot (4K_B + 3\Sigma)$ = matter curve for **56** of E_7

In principle 3 types of Yukawa couplings: $\Sigma\Sigma\Sigma, \Sigma CC, CCC$

Assume:
– $-K_\Sigma$ effective (e.g. dP Σ; natural for rigid Σ) $\Rightarrow$ no $\Sigma\Sigma\Sigma$ Yukawas (BHV I),
– $C = \mathbb{P}^1$ (technical simplifications)

CCC: W. model has codim. 3 (4, 6) loci. Non-minimal singularities, not usual Yukawa (no singlet in $\mathbf{56}^3$). Extra flux ϕ_{ij} ([Jefferson/Li/WT wip]), likely strongly coupled matter; set $\phi_{ij} = 0$. (cf. [Achmed-Zade/Garcia-Extebarria/Mayrhofer])

Upshot: only ΣCC Yukawa couplings. Want Higgs on Σ, so chiral matter on C

No chiral matter from **133**: constraint on flux parameters n_α

$$\chi^{\mathbf{133}}_{(\mathbf{3},\mathbf{2})_{1/6}} = 2\Sigma \cdot (K_B + \Sigma) \cdot D_\alpha n_\alpha = 0$$

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Feature: Approximate global U(1) symmetries from E_7 suppress proton decay

U(1) charges (Y, b_4, b_5, b_6):

$$\mathbf{56} \to (\mathbf{1},\mathbf{1})_{0,5/2,2,3/2} + (\mathbf{1},\mathbf{1})_{0,5/2,2,1/2} + (\mathbf{1},\mathbf{1})_{0,5/2,1,1/2} + (\mathbf{1},\mathbf{1})_{1,3/2,1,1/2}$$
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$$+ \text{conjugates}\,,$$

[note: 3 types of $\bar{D} = \left(\bar{\mathbf{3}},\mathbf{1}\right)_{1/3}$ and $L = (\mathbf{1},\mathbf{2})_{-1/2}$; similar for **133**]

Yukawa couplings are suppressed unless neutral, e.g.

$$H_u Q \bar{U}: \quad (\mathbf{1},\mathbf{2})_{1/2,-3,-2,-1} \times (\mathbf{3},\mathbf{2})_{1/6,3/2,1,1/2} \times \left(\bar{\mathbf{3}},\mathbf{1}\right)_{-2/3,3/2,1,1/2}$$

Dimension 4 proton decay:

$$W \supset \alpha_1 QL\bar{D} + \alpha_2 LL\bar{E} + \alpha_3 \bar{D}\bar{D}\bar{U}$$

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Proton decay, continued.

Dimension 5 proton decay: standard SUSY GUTs have

$$W \supset \lambda_1 T_u QQ + \lambda_2 T_d QL + M T_u T_d \,,$$

$T_u, T_d =$ triplet Higgs. In E_7 models, last term absent/suppressed, partners T'_u, T'_d give triplets mass;

$$W \supset \lambda_1 T_u QQ + \lambda_2 T_d QL + M T_u T'_d + M T'_u T_d + m T_u T_d + m T'_u T'_d \,,$$

$m \ll M \sim M_{\text{GUT}} \rightarrow (m/M)\; QQQL/M$ probably safe (?)

Dimension 6: depends on mass, wavefunctions of broken gauge bosons, not really under control but plausibly suppressed within experimental bounds (?)

Comment on vector-like exotics

Vector-like exotics a standard issue for GUT models.

Choice of $C = \mathbb{P}^1, -K_\Sigma$ effective simplifies; no vector-like matter from C (**56**); avoids complications of general ($\sim$ root bundle) story
[Bies/Mayrhofer/(Pehle)/Weigand, Bies/Cvetič/Donagi/Liu/Ong + subsets]

Expect vector-like matter is massive at KK/Planck scale, E_7 models give no obvious resolution of μ problem ($\mu H_u H_d$ suppressed like for triplets but similarly (inert) partners can give large masses). So light Higgs is still a puzzle.

For other vector-like exotics, $(\mathbf{3}, \mathbf{2})_{-5/6}$ would be problematic for proton decay, but mild flux tuning can remove (particularly simple if $C^2_{\text{rem}} = -2$).

As shown by BHV, generally impossible to remove all vector-like exotics for SO(10) or bigger groups. But fortunately in this case, remaining exotics are largely inert due to residual U(1) approximate symmetries . . .

Challenge/issue: How natural/ubiquitous are rigid E_7 factors?

To answer this question we need two things:

(A) A global picture of the set of B_3's and/or elliptic CY4's

(B) A measure on that set.

Some progress on (A).

Lessons from 6D:

Pretty good handle on $\{B_2\}$:

65k toric B_2; $> 50\%$ have rigid E_6/E_7 [Morrison/WT]

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Classification of B_3 less clear

[WT/Wang]: MC sampling of toric bases w/o codim 2 (4, 6) or E_8 factors: $\sim 20\%$ of $\sim 10^{50}$ bases have rigid E_7 factors. $\Rightarrow$ many bases have rigid E_7's

However, full number of bases (with triangulation, E_8's, codim 2 (4, 6)) is $> 10^{750}$ by direct construction [Halverson/Long/Sung]

$\sim 10^{3000}$ by Monte Carlo [WT/Wang]

A better measure may be polytopes (no triangulation) [WT/Wang/Yu wip]: $\sim 10^{60}$ from sampling Monte Carlo, but fraction with E_7 seems to decrease rapidly $\rightarrow 10^{-20}$? as $h^{1,1}$ increases.

Including singular bases up to flips/flops may give $\sim 10^{50000}$

Also, for CY4, we need non-toric (dominant?). Is there a systematic way to sample non-toric, even e.g. B_3 = distinct toric hypersurface?

Which measure is more accurate?
–Discrete topologies are finite ([Di Cerbo/Svaldi])
–Does some tameness principle ([Grimm etc.]) lead to finite number of patches somehow, which might constrain distribution?

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No non-perturbative definition of F-theory

- Holomorphy/algebraic geometry gives remarkably strong global picture
- Often defined as limit of M-theory
- IIB supergravity provides some insights, Sen limit perturbative
- Duality to heterotic when B is $\mathbb{P}^1$-fibered
- String junctions give insights [Grassi/Halverson/Long/Shaneson/(Tian|Sung)]
- Special cases τ constant [Behan/Chester/Ferrero]

But despite all this we have no rigorous definition that could in principle enable precise analysis of quantitative features of F-theory, even given arbitrary computational abilities. [cf. Morrison: "What is F-theory, 1" wip]

We need some definition analogous to SFT or even string perturbation theory to compute quantities in a specific compactification to any precision.

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Summary:

Rigid E_7 flux breaking gives a natural way of getting (SUSY) Standard Model-like theories from F-theory. Likely more numerous than any other explicit construction to date (e.g., many more bases with rigid E_7 than weak Fano). Some nice features like automatic suppression of proton decay.

But need better definition of F-theory to compute detailed low-energy physics. Need a better understanding of non-toric bases + measure to be more precise about naturalness.

Thank You!