Where in F-theory is the supersymmetric standard model?

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Based in part on papers written in collaboration with various subsets of:

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Challenge: connect string theory $\leftrightarrow$ observable physics

Traditional approach:

— Pick compactification scheme (IIB + flux, heterotic, IBM, F-theory, . . .)

— Assemble ingredients for SU(3) $\times$ SU(2) $\times$ U(1), maybe SU(5) etc.

— Fine tune to get details of standard model

Issues:

1) Generally no global picture for context:
How typical or unusual is SM in space of theories?

2) In most approaches: starting assumption is "blank slate"
Assumes typical vacuum has no gauge fields or matter

F-theory has unique power:

- Holomorphy and complex geometry $\Rightarrow$ global picture of $\{$vacua$\}$
- Generic vacua have nontrivial gauge group G everywhere in moduli space
- Some G natural (e.g. $E_6, E_7, E_8, SU(3) \times SU(2)$), others not (SU(5))
- “Hidden” sectors $\Rightarrow \sim$ dark matter
- Realistic framework for statistical study of $\{$vacua$\}$
  $\longrightarrow$ What G, matter are “natural”
  $\longrightarrow$ How can SM arise? Is it natural or requires extreme tuning?
  [cf. also Halverson, Nelson talks]

Caveat: current story requires/assumes SUSY

Research program goals:

Study global { F-theory vacua } (w/SUSY in 6D, 4D)

- Match with allowed { SUGRA (+ YM, matter) }   (close match in 6D)
- What G, matter are possible?
  What G, matter are typical?
- How can 4D Standard Model arise? Is it natural?

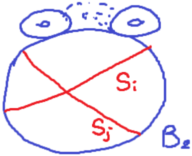
Big questions but surprising progress in last 8 years.

F-theory:

IIB on base B_2 (6D), B_3 (4D)
Axiodilaton $\tau \to$ ell. curve modulus

Physics encoded in Weierstrass model:
$y^2 = x^3 + fx + g$

Codim. 1 singularities (S_i): gauge group,
Codim. 2: matter [cf. Raghuram talk]



To study { F-theory vacua}:

- Classify $B's$: generic fibration typically has non-Higgsable G
  (e.g. -3 curve in $B_2 \to$ SU(3))
- Classify tunings/Weierstrass models

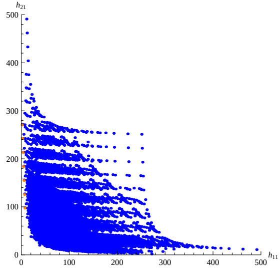
Finite # $B's$, top. distinct CY3, CY4's [rigorous for 6D, pieces for 4D]

Summary of 6D story: [single theory: connected moduli space]

Bases: blow-ups of $\mathbb{P}^2, \mathbb{F}_m (m \leq 12)$, Enriques [Grassi]

Classify bases: 61,539 toric [Morrison/WT];
non-toric: all w/ $h^{2,1}(X) \geq 150$ [WT/Wang]

Classify tunings [Johnson/WT, Huang/WT]



- All known Hodge #'s $\geq 240 \Leftarrow$ EF
- All but 10 (dP) bases $\Rightarrow$ non-Higgsable G
- Typical non-Higgsable G, matter: e.g. $(G_2 \times SU(2))^4 \times F_4 \times E_8^2 \times E_6$
- Max $h^{2,1}$: EF on $\mathbb{F}_{12}$: $(h^{1,1}, h^{2,1}) = (11, 491)$

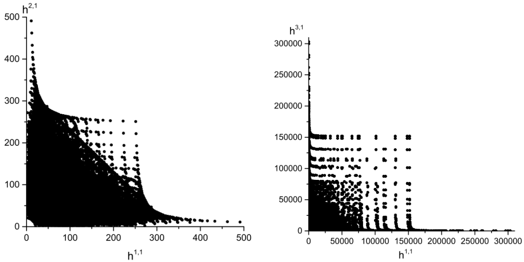
— Good match w/allowed 6D SUGRA, some open issues (U(1)'s, . . .)

— Good global picture of 6D F-theory models: most questions answerable

4D F-theory compactifications: Story parallel in many ways

– Compactify on elliptic Calabi-Yau fourfold, base B_3 = complex threefold
Most known CY4's elliptic (cf. [Gray/Haupt/Lukas, Anderson/Gao/Gray/Lee])

– Empirical data suggest similar structure (though less complete for CY4's)



4D theories significantly more subtle: [cf. eg Grimm talk]

- Minimal models (Mori theory) more subtle
- F-theory $\subset \mathcal{V}_4$ (e.g. heterotic on quintic)
- Fluxes, superpotential, seven-brane dynamics not completely understood

But evidence so far: moduli space of CY4 geometries parallel to CY3 story

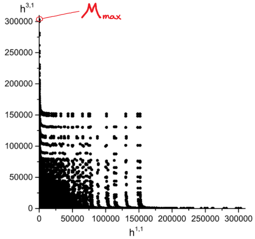
4D F-theory models: Classifying bases [cf. Halverson, Wang talks]

Harder: # B_3 very large

Toric MC (no codim. 2 (4, 6), $E_8, \ldots$)
$\Rightarrow |\{B_3\}| >\sim 10^{50}$ [WT/Wang]

Trees on Fanos (w/ codim. 2 (4, 6))
$\Rightarrow |\{B_3\}| >\sim 10^{750}$ [Halverson/Long]

One-way MC [WT/Wang]
$|\{B_3\}| >\sim 10^{1680}$ (w/ codim. 2 (4, 6))
$|\{B_3\}| >\sim 10^{240}$ (w/o codim. 2 (4, 6))



- Essentially all $B_3 \Rightarrow$ geometrically non-Higgsable G
- Maximum $h^{3,1}$: $\mathcal{M}_{\max}$, $(h^{1,1}; h^{3,1}) = (252; 303, 148)$

4D F-theory geometry: tuning vs. generic G

Non-Higgsable clusters $\sim$ 6D: divisors (surfaces) w/ negative normal bundles
[Anderson/WT, Grassi/Halverson/Shaneson/WT, Morrison/WT]

Geometrically non-Higgsable G:

$\boxed{\text{Factors}: SU(2), SU(3), G_2, SO(7), SO(8), F_4, E_6, E_7, E_8}$ (no $SU(5), SO(10)$)

Local products w/matter:
$G_2 \times SU(2), SO(7) \times SU(2), SU(2) \times SU(2), SU(3) \times SU(2), SU(3) \times SU(3)$

6D: protected by D-terms; 4D, F terms also likely relevant.

NH U(1) factors: possible but rare [6D: Martini/WT, Morrison/Park/WT; 4D: Wang]

Geometrically possible w/tuning: all simple G, U(1) products

Upper bounds on G from geometry

e.g. $\mathbb{P}^3$ (likely max): SU(N), SO(N), $N \leq 32$; Sp(N), $N \leq 16$

Max G: likely $E_8^{2561} \times F_4^{7576} \times G_2^{30168} \times SU(2)^{30200}$ [Candelas/Perevalov/Rajesh]

Caveat: this is geometry; fluxes, superpotential may modify G up or down.

Codimension two: matter [cf. Raghuram talk]

"Generic" matter representations:
Fundamental, antisymmetric, adjoint of SU(N), etc.:
Arise in standard Tate tunings of Weierstrass models.

F-theory appears to strongly limit possible representations of nonabelian G:

SU(N):

3-index antisymmetric representations of SU(6), SU(7), SU(8), similar for Sp
2-index symmetric representation for SU(N)

SU(2): 3-index symmetric representation

Latter representations require non-UFD on singular divisors;
appears no other exotic representations possible without (4, 6) cod. 2

Classifying and constructing possible general U(1) charges: current research

Discrete gauge factors, torsion: even less understood [cf. Cvetic talk]

"Typical" vacua (assume toric base)

Typical toric base has e.g. $E_8^a \times F_4^b \times G_2^c \times SU(2)^d$ [cf. Wang talk]

Toric: $G_2 \times SU(2)$ has matter on $\mathbb{P}^1$ toric curve; no matter w/o fluxes
[cf. Weigand talk]

Flux vacua:

Conventional wisdom (Ashok-Denef-Douglas):
$\Rightarrow$ in regime $h^{1,1} \ll h^{3,1}$, #vacua $N(X) \sim 10^{0.9\ h^{3,1}(X)}$

$\mathcal{M}_{\max}$ is elliptically fibered; B_2 over $\mathbb{P}^1$. Dominates set of flux vacua?
[WT/Wang]

$N(\mathcal{M}_{\max}) \sim 10^{272,000}$ non-Higgsable $G_{\max} = E_8^9 \times F_4^8 \times (G_2 \times SU(2))^8$
Circumstantial evidence: $\sum_{X \neq \mathcal{M}_{\max}} N(X) < 10^{-3000} N(\mathcal{M}_{\max})$

Disconnected non-Higgsable G components $\Rightarrow$ dark matter?

How can we realize the supersymmetric standard model in F-theory?

1. Tune SU(5) GUT (*a la* [Beasley/Heckman/Vafa, Donagi/Wijnholt])
 (or tuning SU(3) $\times$ SU(2) $\times$ U(1) (*e.g.*, [Lin/Weigand]))
- Can't be done on $\mathcal{M}_{\rm max}$
- Requires tuning many moduli [Braun/Watari, Halverson/Tian]
- Flux breaking needs special (*e.g.* non-toric) divisors; Yukawas, ...
 [Heckman/Morrison/Vafa, Marsano/Saulina/Schafer-Nameki]

2. Use non-Higgsable SU(3) $\times$ SU(2) [Grassi/Halverson/Shaneson/WT]
- NHC's fairly natural ($\sim$ 10% of products, $\sim$ 2/base from MC w/Wang)
- Can't be done on $\mathcal{M}_{\rm max}$
- Tuning the U(1) may be expensive ($\sim$ SU(2) on $-K + X_{\rm eff}$, breaking adjoint)

3. GUT breaking through 7-brane flux on non-Higgsable E_6, E_7, E_8
- Doesn't seem to work on $\mathcal{M}_{\rm max}$
 (E_8's all on $D = \mathbb{F}_m$, no Yukawas [Beasley/Heckman/Vafa])
- Need exotic (*e.g.* non-toric) local structure.

Problem: Appears $\mathcal{M}_{\rm max}$ dominates flux vacua but apparently can't give SSM.

How to get around this?

- Non-toric bases? [work w/ Wang, Morrison]

Preliminary analysis suggests possible that $|\{B_3^{\rm non-toric}\}| >\sim 10^{300,000}$.
If so, could dominate landscape, make SSM natural
(currently my favorite solution)

Otherwise, must give something up

- Give up SUSY breaking at sub-Planck scale? [cf. Abel talk]
  Possible, but makes life very hard for string theorists!

- Maybe $10^{300,000}$ vacua from some other approach? G_2? Non-geometric?

Are NHC's so generic that they may also be typical behavior for other vacuum constructions? Without SUSY?

Or: maybe we are thinking about something wrong.

- Perhaps ADD estimate doesn't correctly count F-theory flux vacua?
  (e.g. measure factor, etc.)
- Perhaps nonperturbative effects produce Yukawas for $E_8 \subset G_{\mathcal{M}_{\max}}$?
- Maybe many fluxes naturally force SU(5)
  or a U(1) for non-Higgsable SU(3) $\times$ SU(2)?

If we find a natural SSM solution (e.g. non-toric B_3):

⇒ Can study statistics of vacua

⇒ Likely SSM appears in a peaky statistical ensemble

⇒ Could predict correlated features with high probability

Need better handle on interplay of fluxes, NHC's, 7-brane DOF
[current work w/ Anderson, Gray, Halverson, Long; cf. Wiegand talk]

Conclusions

- We have a good handle on the classification of elliptic Calabi-Yau threefolds
- A plausible “bird’s-eye” picture of the global space of elliptic CY4’s (with much work remaining to be done)
- Significant questions regarding the connection of geometry and physics in 4D
- Several ways of realizing SU(3) $\times$ SU(2) $\times$ U(1) in F-theory
- Some sense of what may be more or less natural in 4D F-theory landscape
- Conventional wisdom seems to make SSM unnatural
  But non-toric geometry has the potential to save the day!