Predictions from F-theory GUTs

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(including some original work with **James Unwin (Notre Dame)**)

Outline:

- Motivation (Why F-theory GUTs?)
- Proton decay
- Flavor; neutrino masses
- Gauge coupling unification
- SYSY breaking (High vs. low-scale SUSY; proton decay)

Conventional (4d, SUSY-) Grand Unified Theories

Strengths:

- ...many, very well-known...; suffice it to say that they are arguably the most solid piece of BSM theory known to us

Weaknesses:

- Doublet-triplet splitting
- Dimension-5 p-decay tends to be too fast
- Complicated GUT-Higgs sector
- Limited applicability range of effective field theory (gets worse if M_P is replaced by M_{String})

Classic alternative / extension:

Heterotic String Compactifications

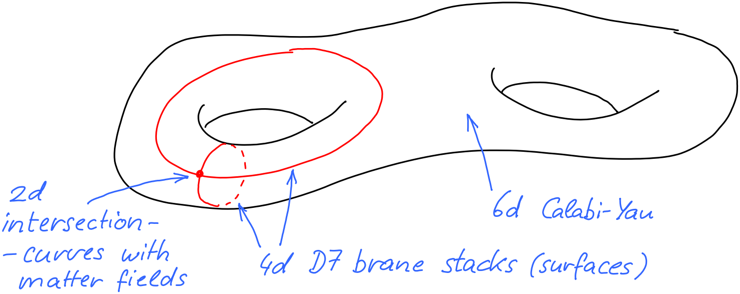
- 10d GUT with gauge group $E_8 \times E_8$
- All of the above issues resolved!

But:

- Complicated technology (gauge bundles on CYs)
- String-scale/GUT-scale problem
- Moduli stabilization not understood

String theory (flux-) landscape

- Fundamental progress in
  moduli stabilization / SUSY-breaking / cosm. const. problem
  GKP, KKLT, $\cdots$ '01$\cdots$'03
- Best-understood in context of type-IIB string theory
- No gauge group in 10d; instead: D7 branes
  (8-dim. submanifolds, N D7's $\Rightarrow$ G =U(N))



Type-IIB GUTs

- However, GUTs in type-IIB are problematic:
  If G =SO(10), there is no **16** available
  If G =SU(5), one has no **10-10-5** Yukawa at leading order

F-theory GUTs

Vafa '96 · · · Beasly/Heckman/Vafa, Donagi/Wijnholt '08

- Type IIB includes non-perturbative objects
  beyond the familiar stacks of D7 branes

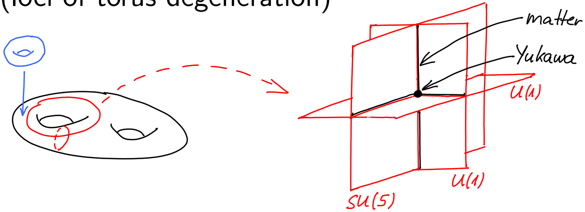
- Such objects carry other gauge groups (e.g. E_8)
  and their intersections allow for other couplings

- In compactifications with such objects, the string coupling g_s
  is not small and in general varies over the compact space

F-theory GUTs

- The variation of g_s and its backreaction on the geometry are described by an ‘auxiliary’ torus fibred non-trivially over the 6d compact space.

- This Calabi-Yau fourfold fully encodes types and locations of branes (loci of torus degeneration)

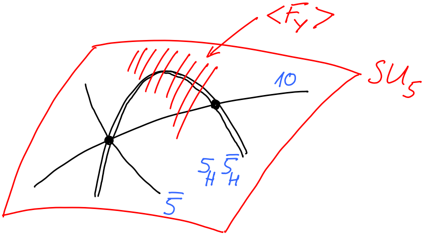


- Key progress of ’08: At least locally, geometries for SU(5) GUTs with 2-3-splitting and leading-order top-Yukawa exist!

- Global models followed soon... Blumenhagen/Grimm/Jurke/Weigand ’09; Cvetic/Garcia-Etxebarria/Halverson ’10

GUT-breaking, Chirality, Higgs curves, ...

- GUT-breaking is induced by flux of $U(1)_Y \subset SU(5)$, i.e. $\langle F_Y \rangle \neq 0$ see, however, Marsano/Clemens/Pantev/Raby/Tseng '12
- Chirality can be induced by extra $U(1)_X$'s, i.e. $\langle F_X \rangle \neq 0$, leading to full chiral generations of $\mathbf{10}$, $\overline{\mathbf{5}}$

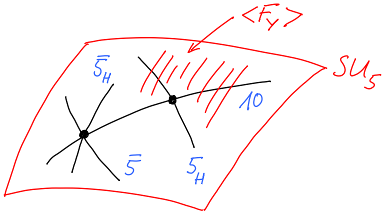


- Technically: $\int_{\mathbf{10},\overline{\mathbf{5}}} F_X \neq 0$ but $\int_{\mathbf{10},\overline{\mathbf{5}}} F_Y = \int_{\mathbf{5_H},\overline{\mathbf{5}}_\mathbf{H}} F_Y = 0$
- Locally, F_Y is nevertheless non-zero on the Higgs curves. This realizes 2-3 splitting.

Chirality, Higgs curves, ...

- However, $\mathbf{3_H}$ and $\overline{\mathbf{3}}_{\mathbf{H}}$ now share a SUSY mass term, leading to dangerous dim-5 p-decay
- This can be avoided by splitting the Higgs curves

  and inducing chirality on them: $\int_{\mathbf{5_H},\overline{\mathbf{5}}_\mathbf{H}} F_Y \neq 0$



- This is a geometric implementation of the missing partner mechanism (as in 'orbifold GUTs', many years ago)

Chirality, Higgs curves, proton decay

- To prevent the dangerous $\mathbf{3_H}$–$\mathbf{\bar{3}_H}$ mass term at intersections of the $\mathbf{5_H}$ and $\mathbf{\bar{5}_H}$ curves, appropriate U(1)-symms. are needed

  see e.g. T. Watari et al. '08-'09
  reviews by J. Heckman, T. Weigand and by S. Schafer-Nameki

  (Forbidding dim.-4 p-decay also requires good control of U(1) symmetries, the geometric understanding of which is an active area of present research...) cf. M. Cvetic' talk

- Thus, as a first prediction*, one can relatively easily suppress/forbid dim.-4/5 p-decay.

  The expected signal is then the classical 'non-SUSY' signal of X, Y-induced dim.-6 p-decay

  *Keeping in mind all the problematic aspects of 'predictions' in the string theory landscape.....

Split matter multiplets

- Going further beyond standard 4d GUTs, one can allow for $\int_{\mathbf{10},\bar{\mathbf{5}}} F_Y \neq 0$
- Generically, this gives non-GUT chiral matter. The observation of 'full-SU(5) matter generations' is then accidental.

  (But gauge coupling unification isn't, see below....)
- Moreover, anomaly cancellation actually 'predicts' SU(5)-matter at the 30% probability level even without GUT

  Foot, Lew, Volkas, Joshi '89
  Knochel, Wetterich '11; AH, Unwin '14
- A phenomenological survey in this most general F-theory-GUT setting has recently appeared:

  Krippendorf, Schafer-Nameki, Wong '1507...

Split matter multiplets:

U(1)'s, p-decay, flavor

- In particular, a partial classification of U(1)-symmetries has been provided in this general setting
- Being in general 'non-GUT', these symmetries are powerful enough to totally rule out dim.-4/5 p-decay
- They are also a useful tool for Froggatt-Nielsen-type flavor model building, see next....

Flavor

- LO-prediction in simplest models ('E_8 point'):
  rank-1 Yukawa matrices; i.e. just the top is massive

- Various subleading effects can be responsible for bottom/light-generation masses:
  non-commutative/bulk fluxes,
  hidden-sector gaugino condensates, T-branes/gluing branes

  see e.g. Cecotti/Cheng/Heckman/Vafa '09
  Marchesano/Martucci '09
  Cecotti/Cordova/Heckman/Vafa '10, Donagi/Wijnholt '11

- Problem: Need to understand geometry (not just topology)

- Alternative: Split generations over different curves
  $\Rightarrow$ several extra U(1)'s can be present
  $\Rightarrow$ Froggat-Nielsen mechanism can be implemented

see e.g. Dudas/Palti '09, $\cdots$,
Krippendorf/Schafer-Nameki/Wong '15

ν-masses

- Standard seesaw approach: $y\,\bar{\mathbf{5}}\,\mathbf{5}_H\,N + M\,N^2$
- Need $M \lesssim M_{GUT}$; at least three options:

(1) N are KK-modes of non-GUT matter field
(Hierarchy is reduced compared to zero-mode sector;
Early prediction of $\theta_{13} \sim 0.2$)

Bouchard, Heckman, Seo, Vafa '09

(2) N is a complex-structure modulus
(M is induced by 3-form flux, hence it scales as $1/R^3$
as opposed to the $1/R$ of KK-modes)

Tatar, Tsuchiya, Watari '09

(3) N is the zero-mode of a non-GUT matter field
M arises from VEV of further zero mode;
Familiar U(1)/Froggatt-Nielsen technology can be used;
Standard ν-textures are implemented....

Krippendorf, Schäfer-Nameki, Wong '15

Quantifying gauge coupling unification

Donagi/Wijnholt; Blumenhagen '08

- Start with the 7-brane DBI action:

$$S_{DBI} \quad \sim \quad \frac{1}{l_s^8} \int d^8x \, \mathrm{tr} \sqrt{\det(g + l_s^2 F)}$$

- After compactification of 4 dimensions at radius R:

$$S_{YM} \quad \sim \quad \int d^4x \, \mathrm{tr} \left((R/l_s)^4 \, F^2 + R^4 \, F^4 + \cdots \right)$$

- And with the SU(5)-breaking VEV $\langle F_Y \rangle \sim 1/R^2$:

$$S_{YM} \quad \sim \quad \int d^4x \sum_{i=1}^{3} \left(\frac{1}{g^2} F_i^2 + \mathcal{O}(1)_i F_i^2 + \cdots \right)$$

F-theory corrections to unification

- We see: This correction behaves like a conventional GUT-scale threshold effect
- A mildly log-enhanced running correction from above the GUT scale has also been argued to be present
- There has been some debate about 'which of the two effects should absorb the other one'

  Donagi/Wijnholt '08
  Blumenhagen '08
  Dolan/Marsano/Schäfer-Nameki '11
- We gave string-theoretic arguments for keeping both as independent contributions

  AH, Unwin '14

The phenomenological analysis is then based on

$$\boxed{\alpha_i^{-1}(m_Z) = \alpha_{\rm GUT}^{-1} + \frac{1}{2\pi} b_i^{\rm MSSM} \log\left(\frac{M_{\rm KK}}{m_Z}\right) + \delta_i^{\rm MSSM} + \delta_i^{\rm tree} + \delta_i^{\rm loop}}$$

where

$$\delta_i^{\rm MSSM} = \frac{1}{2\pi}\left(b_i^{\rm SM} - b_i^{\rm MSSM}\right)\log\left(\frac{M_{\rm SUSY}}{m_Z}\right)$$

$$\delta_i^{\rm loop} = \frac{1}{2\pi} b_i^{5/6} \log\left(\frac{\Lambda}{M_{\rm KK}}\right)$$

see also
Conlon; Conlon/Palti '09

$$\delta_i^{\rm tree} = \frac{b_i^H}{g_s}\int_S \left[f_Y \wedge i^* B_- - \frac{1}{10} f_Y \wedge f_Y - f_Y \wedge f_X\right] \equiv \frac{b_i^H}{g_s}\gamma$$

Mayrhofer/Palti/Weigand '13

Results for precision unification

- In general $\delta_i^{\rm loop} \ll \delta_i^{\rm tree}$, making the theoretically unsettled issue of Λ less pressing
- One has the the freedom/uncertainty of the model-dependent $\mathcal{O}(1)$ number γ
- For low-scale SUSY ($\delta_i^{\rm MSSM}$=0), this can be used to achieve a perfect 'prediction' for α_3.
- Alternatively, it is also easily possible to accommodate, say, $M_{SUSY} \sim 100$ TeV or even higher....

SUSY breaking

- Early suggestion in F-theory-GUT context: Gauge mediation

  see e.g. Heckman, Vafa '08

  (With its well-known phenomenological advantages)

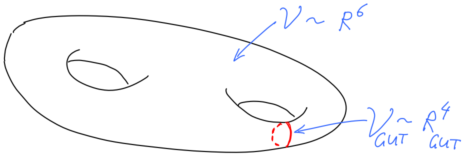
- Problem: In the best-understood moduli-stabilization schemes (KKLT, LVS) one finds dominant gravity mediation effects

  [large F-terms of Kahler moduli]

- In fact, it is hard to get low-scale SUSY at all

- To understand this, note how the string-scale/GUT-scale problem is solved in F-theory...

SUSY breaking (continued)



- $M_P \gg M_{GUT}$ implies $R \gg R_{GUT}$;
  With R_{GUT} fixed by α_{GUT}, this gives $\mathcal{V} \simeq 10^4$
- Easy in LVS, but then moduli too light;
  Hard in KKLT and related settings ($m_{3/2}$ too light)
- In spite of my own efforts to resolve these issues,
  a very personal (too pessimistic?) statement:
- High-scale SUSY may be a 'prediction' of F-theory GUTs

ongoing work with Braun, Krippendorf, Valandro

F-theory GUTs with high-scale SUSY

- First guess: Easy to keep unification while raising SUSY scale (see above)

- Well-known: M_{GUT} goes down, dim-6 p-decay goes up

- Idea: Prevent this by localizing zero modes of X, Y-bosons

  Ibanez/Marchesano/Regalado/Valenzuela, '12
  see also Watari; Marchesano; Hamada/Kobayashi '12

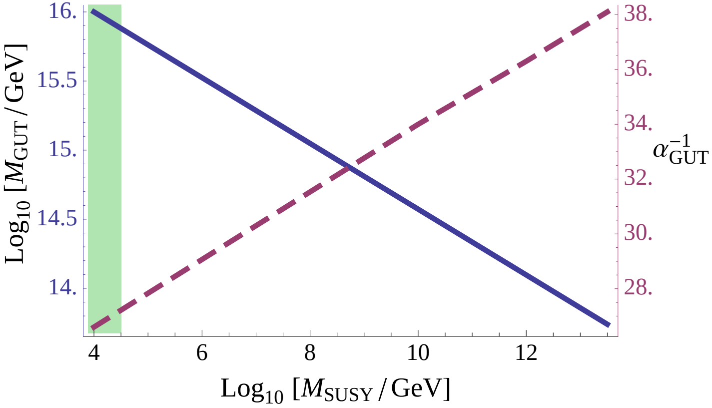
- We find: Problematic, since higher-KK-modes (Landau-levels) of X, Ys don't localize

  AH, Unwin '14

- $\Rightarrow$ Predict (relatively) low-scale SUSY idependently of hierarchy problem;
  hence possibly $e^+\pi^0$ and $K^+\overline{\nu}$ p-decay with same rate

Running/proton-decay constraints

$$M_{\rm GUT} \simeq 4.25 \times 10^{15}\ {\rm GeV} \left(\frac{10^5\ {\rm GeV}}{M_{\rm SUSY}}\right)^{2/9} \left(\frac{3.3}{\Lambda/M_{\rm KK}}\right)^{1/3}$$



Summary/Conclusions

- Together with heterotic string-GUTs, F-theory GUTs are the modern stringy implementation of the higher-dimensional GUT idea
- Due to moduli stabilization, they are the potentially most complete framework
- Dim-5 p-decay can be avoided; dim.-6 p-decay tends to be high ($\rightarrow$ 'prediction')
- Specific neutrino mass textures can be argued for...
- There may be a (stringy) theory bias for $M_{SUSY} \gg m_{EW}$
- On the other hand, there are strong arguments (GUT paradigm + proton decay) to expect SUSY at $\lesssim$ 100 TeV