GUTs, Remnants, and the String Landscape

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Outline and Questions

• A smaller unification: GUTs.

• String Remnants.

   What does string theory often give you even if you didn’t order it?

• The Landscape.

   How do you do anything with $10^{500}$ of something?

   New construction! Explicit control, largest set of geometries to date (?),

   strong motivation for gauged, non-abelian dark sectors.
GUTs
Bird’s Eye View from Strings

- Heterotic: Many Concrete Constructions of E6, SO(10), SU(5).
  [many, many references; e.g. Nilles et al for orbifolds, Ovrut et al for smooth CY]
- Type II: Georgi-Glashow SU(5): No top Yukawa
  Flipped SU(5): No bottom Yukawa
  SO(10): No 16 of SO(10)
- F-theory: move away from weak coupling, GUTs work.
  [see e.g. Blumenhagen, Cvetic, Langacker, Shiu review]
  Recent: non-trivial type II always realizes F-GUTs?
- M-theory: examples are expected (Joyce?), but math is harder. (G2 7-mflds)
  [Freidmann, Witten] [Acharya, Kane, Kumar et al] Simons $10m to G2 Math Collaboration

You can’t always get what you want. But sometimes close @ group, spec, W level.
GUT Tuning Costs in F-theory

- SU(5) and SO(10) require tuning.
- “Cost of tuning”

**Here:** average number of scalar fields (7-brane moduli) that must be turned off to engineer gauge symmetry in $O(10^{15})$ geoms.

- $SU(5)$: $I_{5S}$ Kodaira fiber
- $SO(10)$: $I_{1S}^*$ Kodaira fiber

- Costly for low $h^{11}$, better for high.

[J.H., Tian]
See also [Braun, Watari]
String Remnants
String Remnants

Extra DOF often present in string theory.
Not there to solve any problem, necessarily, just along for the ride.

• Moduli: hundreds of uncharged scalars, non-therm cosmo.  
  [Ccoli’s talk]

• Vector-like Quarks, Leptons: often mass-protected by extra symm.
  [many works; e.g. Schellekens et al, also Cvetic, J.H., Langacker]

• Additional U(1)’s: anomalous or non-anomalous, intricate couplings possible  (fam. Non-univ, phobic)

• Axions: hundreds again. Large field inflation, dark matter.  
  [Ccoli’s, Safdi’s talk]
  [many early works] [Svrcek, Witten], [Arvanitaki et al] [review: Marsh]

• Gauged non-abelian dark sectors.
  [many early works] [F-th: Taylor et al, and J.H., Taylor]

• Landscape of metastable vacua.
  [many early works] [Schellekens] [Susskind]  
  Last two: this talk!
String Instantons and Ultralight (10^{-21} eV) Axions

• Instantons in Strings: Not necessarily gauge BPST instantons!
• Can generate $10^{-21} eV$ axion masses for FDM.  \[\text{[Hui, Ostriker, Tremain, Witten]}\]
• Instantons can also generate matter couplings to axions.
  \[\text{[Blumenhagen, Cvetic, Weigand] [Ibanez, Uranga] [Florea, Kachru, McGreevy, Saulina]}\]

• Instanton Motivated Effective Operators: (VL-like zero modes) (n=2k)

  \[V_a = A \frac{(h\dagger h)^n}{\Lambda^{4k-4}} \cos(a/F)}\]
  \[m_a = A^{\frac{1}{2}} \langle h \rangle \left( \frac{\langle h \rangle}{\Lambda} \right)^{n-1} \left( \frac{\Lambda}{F} \right)\]

  For $\Lambda \sim F \sim M_p$ and O(1) A,  \[m_a \approx \Lambda_{ew} \times (\text{hierarchy})^{n-1}\]

  so n=0,1,2,3 gives Planckian, EW, neutrino, ultralight scale axions.
The Landscape

Semi-Precise: A complex scalar potential with a large ensemble of metastable de Sitter vacua.

Some: “This is so complicated and everything is anthropic, so just give up.”
Tao: “It’s not scientific to give up!”

Yes!! But how do we do anything when the numbers are so large?

Coarse grain and / or universality?
“Algorithmic Universality”

- Q: How do you do anything with $10^{500}$ (or more) of something?

- Grandma gives you $100 in bills for your birthday. Universal bill properties? **Open your wallet.** (explore set)

  Q for later: exploration of presented set requires how many grad stud?

- $10^{500}$? Universal bill properties? **Bill counting infeasible, must understand grandma!**

- Algorithmic Universality:

  universality derived from construction algorithm, not constructed ensemble!
Context for Comparison

• Multiplicity of background fluxes on fixed geometry.

Original numbers: $O(10^{500})$  
Current number: $O(10^{272,000})$  

[Ashok, Douglas] [Denef, Douglas]  
[Taylor, Wang]

• Here: large multiplicity of geometries. \textbf{Diversity of extra dimensions}

Previous numbers: $O(0.5 \times 10^9) \times $ Triangs  
Here: first time \# geometries above original flux \#'s?  

[Kreuzer, Skarke], $O(10^{15})$  
[J.H., Tian]  
[Long, Sung]  

• Rel. Advantage: math easier \hspace{1cm} (point counts and combs, not mirror symm.)  
transparent physical data \hspace{1cm} (geometric gauge group)  

→ can do something very concrete (universality & physics) with this large ensemble!
The Sources of Gauge Sectors

• Geometry:  Elliptic CY over B.  B extra six spatial dimensions.

\[ wy^2 = x^3 + f x w^2 + g w^3 \]

Discriminant:  \[ \Delta = 4f^3 + 27g^2 \]

• Sources:  Seven-branes on \( \Delta = 0 \).

• Seven-brane Gauge Sectors:

<table>
<thead>
<tr>
<th>( F_i )</th>
<th>( l_i )</th>
<th>( m_i )</th>
<th>( n_i )</th>
<th>Sing.</th>
<th>( G_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_0 )</td>
<td>( \geq 0 )</td>
<td>( \geq 0 )</td>
<td>0</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>( I_n )</td>
<td>0</td>
<td>0</td>
<td>( n \geq 2 )</td>
<td>( A_{n-1} )</td>
<td>( SU(n) ) or ( Sp([n/2]) )</td>
</tr>
<tr>
<td>( III )</td>
<td>( \geq 1 )</td>
<td>1</td>
<td>2</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>( IV )</td>
<td>( \geq 2 )</td>
<td>2</td>
<td>4</td>
<td>( A_1 )</td>
<td>( SU(2) )</td>
</tr>
<tr>
<td>( I_6 )</td>
<td>( \geq 2 )</td>
<td>( \geq 3 )</td>
<td>6</td>
<td>( D_4 )</td>
<td>( SO(8) ) or ( SO(7) ) or ( G_2 )</td>
</tr>
<tr>
<td>( I_{n}^* )</td>
<td>2</td>
<td>3</td>
<td>( n \geq 7 )</td>
<td>( D_{n-2} )</td>
<td>( SO(2n - 4) ) or ( SO(2n - 5) )</td>
</tr>
<tr>
<td>( IV^* )</td>
<td>( \geq 3 )</td>
<td>4</td>
<td>8</td>
<td>( E_6 )</td>
<td>( E_6 ) or ( F_4 )</td>
</tr>
<tr>
<td>( III^* )</td>
<td>3</td>
<td>( \geq 5 )</td>
<td>9</td>
<td>( E_7 )</td>
<td>( E_7 )</td>
</tr>
<tr>
<td>( II^* )</td>
<td>( \geq 4 )</td>
<td>5</td>
<td>10</td>
<td>( E_8 )</td>
<td>( E_8 )</td>
</tr>
</tbody>
</table>

\[ f = \tilde{f} \prod_i x_i^{l_i} \]

\[ g = \tilde{g} \prod_i x_i^{m_i} \]

\[ \Delta = \tilde{\Delta} \prod_i x_i^{\min(3l_i, 2m_i)} =: \tilde{\Delta} \prod_i x_i^{n_i} \]
Seven-branes for Generic Moduli

• Will see: generic B gives many 7-branes for generic f,g. [many works] with increasing “generic” strength.

• “Non-Higgsable Cluster” (NHC) of “Non-Higgsable 7-branes” (NH7)

  6D: [Morrison, Vafa], [Morrison, Taylor], [Taylor, Johnson], [Taylor, Wang]
  4D: [Grassi, J.H., Shaneson, Taylor], [Morrison, Taylor], [Anderson, Taylor]

• Possible Geometric G on NH7: [Grassi, J.H., Shaneson, Taylor] [Morrison, Taylor]

  \[ G \in \{ E_8, E_7, E_6, F_4, SO(8), SO(7), G_2, SU(3), SU(2) \} \]

• Note well: E6, SU(3) and SU(2) possible, but no SU(5) or SO(10).

  [Grassi, J.H., Shaneson, Taylor]
Systematic Spaces from Topological Transitions
[J.H., Long, Sung]

• Starting point: smooth weak-Fano toric threefold $B_i$, a 6-mfld.

• 1-1 correspondence with certain triangulations of 3d reflexive polytope.

• “Blow-up” transitions give new 6-mflds where 4-mflds emanating from points and Riemann surfaces. (alg curves).
A Simple Dictionary

• Curve blow-up: subdivide edge with verts $v_1, v_2$ by $v_e = v_1 + v_2$.

• Point blow-up: subdivide face with vertices $v_1, v_2, v_3$ by adding $v_e = v_1 + v_2 + v_3$.

• Iterate to produce more manifolds.

• Note: a “tree”-like structure. Non-zero dots are “leaves” labelled by “heights.” (coeff sum)

[J.H., Long, Sung]
Face Trees and Edge Trees

• Face trees encode a sequence of blow-ups beginning with pt.
• Edge trees: beginning with curve.
• Rule: if tree height \( \leq 6 \), geometry is allowed.
• Example: \( h \leq 3 \) face trees and edge trees, 5 and 2. \( (head\ on) \)

\[
\begin{array}{c}
1 & 1 \\
1 & 2 & 1 \\
1 & 3 & 2 & 1 \\
& 132 & 31
\end{array}
\quad \rightarrow 
\begin{array}{c}
1 \\
1 \\
1 & 3 \\
1 & 1 & 1
\end{array}
\]

• Computation: \( @ h \leq 6 \) \#edge trees = 82, \#face trees = 41,439,964

[Caveat!]
New Ensemble of Geometries

[J.H., Long, Sung]

• Construction algorithm:

0) Pick an FRST of a 3d Reflexive Polytope $\Delta^\circ$.
1) For each face in a facet, place a face tree.
2) For each edge in a facet, place an edge tree.

• Cardinality of resulting ensemble $S_{\Delta^\circ}$:

$$|S_{\Delta^\circ}| = \sum_{F} 82 \cdot \#\tilde{E} \text{ on } F (4.2 \times 10^6) \cdot \#\tilde{F} \text{ on } F - \sum_{E} 82 \cdot \#\tilde{E} \text{ on } E$$

• Two polytopes with far larger ensembles than other 4317:

$$|S_{\Delta_1^\circ}| = \frac{1.3998}{3} \times 10^{755} \quad |S_{\Delta_2^\circ}| = 1.3998 \times 10^{755}$$
Deriving Universality: Approach

• Concrete construction algorithm for an enormous ensemble.

Do elements of the ensemble have (near) universal features?

• If $A_i \rightarrow P_i$, then $P(P_i) \geq P(A_i)$.

Goal: find pairs $(A_i, P_i)$ that

1) maximize $P(A_i)$
2) maximize interestingness($P_i$).

• In practice here: $A_i$ geometric, $P_i$ physical. Geometry $\rightarrow$ Physics.
Physics Results

“Enough math overload. Tell me about seven-branes and gauge sectors.”

- You
Universality of Non-Higgsable Clusters

**Theorem:** if there is even a single tree on a facet F, then all interior points to F correspond to 4-mflds with NH 7-branes.

- $A_1$: there is a tree on F.
- $P_1$: there are NH7 on every 4-mfld associated to F interior points.

Immediately gives:

$$P(\text{NHC in } S_{\Delta^0}) \geq 1 - \frac{1}{|S_{\Delta^0}|}$$

$$P(\text{NHC in } S_{\Delta_1^0}) \geq 1 - 2.14 \times 10^{-755}$$

$$P(\text{NHC in } S_{\Delta_2^0}) \geq 1 - .71 \times 10^{-755}.$$  

**Note:** strictly <1, though!

**Punchline:** absolutely expect large networks of gauged non-abelian sectors.
Universal Geometric Gauge Structures  

**Theorem:** A leaf built on $E_8$ roots with height $h = 1, 2, 3, 4, 5, 6$ has Kodaira fiber $F = II^*, IV_{ns}, I_0^*, IV_{ns}, II, -$ and geometric gauge group $G = E_8, F_4, G_2, SU(2), -, -, -$ respectively.

- $A_3 \rightarrow P_3,$ let $H_i$ be $\#$ leaves of height $i$ above $E_8$ roots.

$A_3$: every vertex-containing simplex has a face tree and there is a height $h \geq 5$ face tree somewhere on big facet F.

$$P_3: \quad G \geq E_8^{10} \times F_4^{18} \times U^9 \times F_4^{H_2} \times G_2^{H_3} \times A_1^{H_4}$$

$$rk(G) \geq 160 + 4H_2 + 2H_3 + H_4$$

**Punchline:** the rank of the large gauge sector is large and diverse.
Summary

• GUTs exist in string theory. Easier in Het / M / F than type I/II.
• Remnants:  *DOF that frequently arise, but not to solve a problem.*
  *E.g.* moduli, axions, BSM exotics, Z’, non-abelian hidden sectors.

• Landscape: how do you do anything with $10^{500}$ of something?

  *Here:* $\frac{4}{3} \times 1.3998 \times 10^{755}$ geometries.

  Geometric gauged H.S. with $\text{rk}(G) \geq 157$ arise with prob $\geq .999995$.

• **Algorithmic Universality:**  *universality derived from construction algorithm, not constructed ensemble.*

  **Physics Punchline:** Take gauged non-abelian dark sectors very seriously.

  *e.g.* [Carlson, Hall, Machacek] [Faraggi, Pospelov] [Soni] [J.H., Nelson, Ruehle] [Acharya, Fairbairn, Hardy]
Thanks!