String Phenomenology

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$E_8 \times E_8$

$d=11$ SUGRA

$\text{IIA}$

$I$

$\text{IIB}$

$\text{E}_8 \times \text{E}_8$

$\text{SO}(32)$

???
Outline

- A (very) basic introduction to string theory
- String theory and the “real world”? 
- Recent work
- Conclusion
String theory
String theory

Warm-up: world-line of a relativistic particle
String theory

Warm-up: world-line of a relativistic particle

$X^\mu = X^\mu(\tau)$
String theory

Warm-up: world-line of a relativistic particle

\[ X^\mu = X^\mu(\tau) \]

World-line action:

\[ S = -m \int d\tau \sqrt{- \frac{dX^\mu}{d\tau} \frac{dX^\nu}{d\tau} \eta_{\mu\nu}} \rightarrow \frac{d^2 X^\mu}{d\tau^2} = 0 \]
World-sheet of free relativistic string
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\[ X^\mu = X^\mu(\tau, \sigma) \]

open string  closed string
World-sheet of free relativistic string

\[ X^\mu = X^\mu(\tau, \sigma) \]

open string \hspace{1cm} closed string

World-sheet action:

\[ S = -\frac{1}{2\pi l_s^2} \int d^2\sigma \sqrt{-\det \left( \frac{\partial X^\mu}{\partial \sigma^\alpha} \frac{\partial X^\nu}{\partial \sigma^\beta} \eta_{\mu\nu} \right)} \]
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string tension, \( l_S \) string length
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Spectrum:
\[ l_S^2 M = \sum_n N_n (+\bar{N}_n) \]
World-sheet of free relativistic string

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open string \hspace{2cm} closed string

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\[ l_S^2 M = \sum_n N_n (+\bar{N}_n) \in \mathbb{Z} \text{ where } N_n = \alpha^\mu_{-n} \alpha^\mu_n \]
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closed string
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string tension, \( l_S \) string length

closed string

Spectrum:

\[
l_S^2 M = \sum_n N_n (+\bar{N}_n) = \begin{cases} 
0 & \rightarrow \text{observed} \\ 
\geq 1 & \rightarrow \text{massive} 
\end{cases}
\]
Lowest string states
Lowest string states

Open string: \( \alpha_{-1}^{\mu} |0 \rangle \rightarrow A^{\mu} \)
Lowest string states

open string: \( \alpha_{-1}^\mu |0 \rangle \rightarrow A^\mu \rightarrow \int d^D x \sqrt{-g} \text{tr} (F_{\mu \nu} F^{\mu \nu}) \)
Lowest string states

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open strings lead to gauge fields (and matter)
Lowest string states

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  \( \alpha^\mu_{-1} \bar{\alpha}^\nu_{-1} |0 \rangle \rightarrow g^{\mu\nu}, \ldots \)
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\( \alpha_{-1}^\mu \bar{\alpha}_{-1}^\nu |0 > \rightarrow g^{\mu \nu}, \ldots \rightarrow \int d^D x \sqrt{-g} R + \ldots \)
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closed strings leads to gravity (and gravity-like physics)
On closer examination:
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And there are more surprises...
T-duality
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Modes of a string on a circle with radius $R$:
T-duality

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**momentum states:**

$$M^2 = \frac{m^2}{R^2} \quad m \in \mathbb{Z}$$

**winding states:**

$$M^2 = \frac{w^2 R^2}{l_s^4} \quad w \in \mathbb{Z}$$

**full spectrum:**

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String theory has minimal length $l_s = \sqrt{\alpha'}$
Branes

String theory contains not just strings but extended objects (p-branes) of all dimensions!
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$N \,(D)p$-brane(s) : U(N) gauge theory

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N (D)p-brane(s) : U(N) gauge theory

\[ d=10/11 \text{ bulk gravity} \]

p-branes are charged under (p+1) forms \( A_{\mu_1...\mu_{p+1}} \) with field strength \( F = dA \).
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bulk $\rightarrow$ gravity (closed strings)
brane $\rightarrow$ gauge theories (open strings)
M-theory and branes
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All five string theories are related and part of a single “theory”: M-theory
M-theory and branes

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All five string theories are related and part of a single “theory”: M-theory

M-theory is a patchwork of the constituent theories plus many “rules”. It seems unclear, at present, what its fundamental degrees of freedom are.
String theory and the “real world” (?)
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Need to compactify six or seven dimensions to obtain $d=4$ theory:
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- **d=10/11 string/M-theory**
  - on d=6/7 dimensional space $X$

- **d=4 theory**
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Need to compactify six or seven dimensions to obtain d=4 theory:

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Two-fold degeneracy in space X: continuous one in size and shape (moduli), discrete one topology
String theory and the “real world” (?)

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- on $d=6/7$ dimensional space $X$
- $d=4$ theory

Two-fold degeneracy in space $X$: continuous one in size and shape (moduli), discrete one topology

But $d=4$ theory depends on space $X$ ...
The enemy
The enemy

different moduli:
The enemy
different moduli:
different topology:
The enemy
different moduli:

different topology:

topology: determines structure of d=4 theory
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- topology: determines structure of d=4 theory
- moduli: determine values of coupling constants in d=4
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different topology:

topology: determines structure of d=4 theory

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-> string theory does impose constraint on compactifications, however, there are still many choices -> many four-dimensional theories with moduli appearing as scalar fields.
The enemy

different moduli:

- different topology:

- topology: determines structure of $d=4$ theory
- moduli: determine values of coupling constants in $d=4$

$\rightarrow$ string theory does impose constraint on compactifications, however, there are still many choices $\rightarrow$ many four-dimensional theories with moduli appearing as scalar fields.

in simplest model and perturbatively: no $D=4$ potential for moduli
The world according to string/M-theory
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d=6/7 internal space X
The world according to string/M-theory

\[ d = 6/7 \text{ internal space } X \]

3 external dimensions

6-brane
The world according to string/M-theory

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3 external dimensions

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The world according to string/M-theory

d=6/7 internal space $X$

3 external dimensions

6-brane 6-brane 8-brane
The world according to string/M-theory

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3 external dimensions

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The world according to string/M-theory

3 external dimensions

$\text{d}=6/7$ internal space $X$

matter

6-brane  6-brane  8-brane  3-brane
The world according to string/M-theory

3 external dimensions

6-brane 6-brane 8-brane 3-brane

d=6/7 internal space X

matter

matter
The world according to string/M-theory

- d=6/7 internal space $X$
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- (S)SM
- Matter
The world according to string/M-theory

$\text{d}=6/7$ internal space $X$

3 external dimensions

6-brane 6-brane 8-brane 3-brane

(S)SM ???
The world according to string/M-theory

$d=6/7$ internal space $X$

3 external dimensions

6-brane 6-brane 8-brane 3-brane

matter
The world according to string/M-theory

3 external dimensions

$\text{d=6/7 internal space } X$

matter

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The world according to string/M-theory

\[ \text{d}=6/7 \text{ internal space } X \]

3 external dimensions

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\((S)\text{SM}\)

matter
The world according to string/M-theory

3 external dimensions

6-brane 6-brane 8-brane 3-brane

(d=6/7 internal space X)

matter

(S)SM
The world according to string/M-theory

And this is not just pictures...
Let us consider in $D=10/11$.
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$$ S_D = \frac{1}{l_S^{D-2}} \int d^D x \sqrt{-g} R + \ldots $$

gravity...
Let us consider in D=10/11:

\[ S_D = \frac{1}{l_s^{D-2}} \int d^D x \sqrt{-g} \, R + \ldots + \frac{1}{l_s^{p-3}} \int d^{p+1} x \sqrt{-\gamma} \, tr (F_{\alpha\beta} F^{\alpha\beta}) + \ldots \]

...and a p-brane

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...and a p-brane compactification on:

$d=6,7$ space $X$, volume $V$
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(p-3) cycle with volume $v$.

p-brane on (p-3) cycle.
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...and a $p$-brane

compactly on:

$D=6,7$ space $X$, volume $V$

...and a $p$-brane on $(p-3)$ cycle

in $D=4$:

$$S_4 = \int d^4 x \frac{V}{l_S^{D-2}} \sqrt{-g_4} \, R_4 + \ldots$$

$(p-3)$ cycle with volume $v$
Let us consider

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compactification on :

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(p-3) cycle with volume $v$

in $D=4$ :

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compactification on:

(p-3) cycle with volume v

D=6,7 space X; volume V

p-brane on (p-3) cycle

in D=4:

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\[ \frac{1}{16 \pi G_N} = \frac{V}{l_D^{D-2}} \]
Let us consider

in $D=10/11$:

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in $D=4$:

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$$\frac{1}{16\pi G_N} = \frac{V}{l_S^{D-2}}$$

$$\frac{1}{16\pi g_{YM}^2} = \frac{v}{l_S^{p-3}}$$
For large volume, the string scale can be smaller than the Planck scale (but one has to find a stabilising potential for \( V \)).
it follows:

- For large volume, the string scale can be smaller than the Planck scale (but one has to find a stabilising potential for $V$).

- On a single stack of branes, the gauge coupling is universal and depends on the volume of the cycle wrapped.
One stack versus several stacks

Two phenomenological facts:
One stack versus several stacks

Two phenomenological facts:

- Gauge couplings unify in MSSM
One stack versus several stacks

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- matter fields descend from higher-dim. gauge theory with large gauge group
One stack versus several stacks

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For example:

$$248_{E_8} \rightarrow [(45, 1) + (1, 15) + (16, 4) + (1\bar{6}, \bar{4}) + (10, 6)]_{SO(10) \times SU(4)}$$
One stack versus several stacks

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One standard model family
Moduli stabilisation and flux

What is flux?
Moduli stabilisation and flux

What is flux? A: Non-zero form field strengths, $F \neq 0$, on the internal space.
Moduli stabilisation and flux

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Moduli types: T (size of X), Z (shape of X),...
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Without flux, perturbatively: $W_{\text{moduli}} = 0 \rightarrow V_{\text{moduli}} = 0$
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Flux and non-pert.: \( W_{\text{moduli}} = P(Z) + e^{-T} \)

Fixes all moduli, cosmological constant needs tuning.
There appears to be a huge number of such stable models \(10^{500}\) and it seems string theory does not discriminate between them. Is this a problem?
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What needs to be done to find a SSM from string theory?
- Need to construct large numbers of models.
- Need to combine this with moduli stabilisation.
Recent Work
Model building for $E_8 \times E_8$ heterotic string/M-theory
Recent Work

Model building for $E_8 \times E_8$ heterotic string/M-theory

(Lara Anderson, Yang-Hui He, A.L.)
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Calabi-Yau manifold $X$

holomorphic vector bundle $V_1$

MSSM?

hidden sector

hidden sector

9-brane

5-brane

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SUSY at $M_S$

$m_{3/2} \sim \frac{M_S^2}{M_{Pl}}$

9-brane

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Recent Work

Model building for $E_8 \times E_8$ heterotic string/M-theory

Calabi-Yau manifold $X$

holomorphic vector bundle $V_1$

holomorphic vector bundle $V_2$

holomorphic curve $W$

Data describing model: CY $X$, bundles $V_1, V_2$ and curve $W$. 

MSSM?

hidden sector

hidden sector

SUSY at $M_S$
Consistency condition: \( c_2(TX) - c_2(V_1) - c_2(V_2) = [W] \)
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For SUSY: $[W] \geq 0$ and $V_1, V_2$ stable bundles (hard to prove).
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How do we construct bundles $V$ on $X$?

Monads

$$0 \to V \to \bigoplus_{i=1}^{r_B} O_X(b_i) \to \bigoplus_{j=1}^{r_C} O_X(c_j) \to 0$$
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For a start we produced a list of \(\sim 5000\) CY manifolds and computed their properties, such as \(c_2(TX)\).
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Goal: Construct all stable (SU(3),SU(4),SU(5)) monad bundles \(V\) on these CYs, such that \(c_2(TX) - c_2(V) \geq 0\) and the number of generations is a multiple of three. Compute the complete spectrum.
Consistency condition: \[ c_2(TX) - c_2(V_1) - c_2(V_2) = [W] \]

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leading to E6, SO(10), SU(5) GUTs
We decided to start with the 5 simplest of the 5000 CYs.
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20 $E_6$ models

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Table 9: The particle content for the $E_6$-GUT theories arising from our classification of stable, positive SU(3) monad bundles $V$ on the Calabi-Yau threefold $X$. The number $n_{27}$ of anti-generations vanishes.
We decided to start with the 5 simplest of the 5000 CYs. Results: 37 models, no anti-generations...

20 $E_6$ models

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<tr>
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</table>

| [52 4]| (2, 2, 1, 1, 1)                  | (4, 3)     | 96       | 206   |
|       | (1, 1, 1, 1, 1)                  | (2, 2, 2)  | 24       | 64    |
|       | (2, 2, 2, 1, 1, 1)               | (3, 3, 3)  | 72       | 154   |

| [53 4]| (1, 1, 1, 1)                     | (4)        | 90       | 200   |
|       | (1, 1, 1, 1, 1)                  | (3, 2)     | 45       | 103   |
|       | (2, 1, 1, 1, 1)                  | (3, 3)     | 63       | 136   |
|       | (1, 1, 1, 1, 1)                  | (2, 2, 2)  | 27       | 64    |
|       | (2, 2, 2, 1, 1, 1)               | (3, 3, 3)  | 81       | 163   |

| [62 3]| (1, 1, 1, 1, 1)                  | (3, 2)     | 60       | 132   |
|       | (2, 1, 1, 1, 1)                  | (3, 3)     | 84       | 174   |
|       | (1, 1, 1, 1, 1, 1)               | (2, 2, 2)  | 36       | 82    |

| [72 2 2 2]| (1, 1, 1, 1, 1)              | (2, 2, 2)  | 48       | 100   |

Table 10: The particle content for the SO(10)-GUT theories arising from our classification of stable, positive, SU(4) monad bundles $V$ on the Calabi-Yau threefold $X$. The number $n_{27}$ of anti-generations vanishes. The number $n_1$ vanishes for generic choices of the map $g$ in the monad sequence (18), but can be made non-vanishing with particular choices of $g$.

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|      | (1, 1, 1, 1, 1)                     | (2, 2, 2)          | 24       | 64    |
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| [5|3|3] | (1, 1, 1, 1)                        | (4)                | 90       | 200   |
|      | (1, 1, 1, 1)                        | (3, 2)             | 45       | 103   |
|      | (2, 1, 1, 1)                        | (3, 3)             | 63       | 136   |
|      | (1, 1, 1, 1, 1)                     | (2, 2, 2)          | 27       | 64    |
|      | (2, 2, 2, 1, 1, 1)                  | (3, 3, 3)          | 81       | 163   |

| [6|2|3] | (1, 1, 1, 1, 1)                     | (3, 2)             | 60       | 132   |
|      | (2, 1, 1, 1, 1)                     | (3, 3)             | 84       | 174   |
|      | (1, 1, 1, 1, 1)                     | (2, 2, 2)          | 36       | 82    |
|      | (1, 1, 1, 1, 1)                     | (2, 2, 2)          | 48       | 100   |

| [7|2|2|2] | (1, 1, 1, 1, 1)                     | (2, 2, 2)          | 48       | 100   |

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10 $SO(10)$ models

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Table 10: The particle content for the $SO(10)$-GUT theories arising from our classification of stable, positive, $SU(4)$ monad bundles $V$ on the Calabi-Yau threefold $X$. The number $n_{16}$ of anti-generations vanishes. The number $n_1$ vanishes for generic choices of the map $g$ in the monad sequence (18), but can be made non-vanishing with particular choices of $g$.

7 $SU(5)$ models

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Table 11: The particle content for the $SU(5)$-GUT theories arising from our classification of stable, positive, $SU(5)$ monad bundles $V$ on the Calabi-Yau threefold $X$. The number of anti-generations, $n_{10}$, vanishes. Further, $n_2 = n_{10}$. Moreover, $n_5 = 0$ for generic choices of the map $g$ in Eq. (18), and can be made non-vanishing in special regions of moduli space.
We decided to start with the 5 simplest of the 5000 CYs. Results: 37 models, no anti-generations...

20 $E_6$ models

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<td>154</td>
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| [5][2][4]  | (2, 2, 1, 1, 1)       | (4, 3)     | 96       | 206   |
|            | (1, 1, 1, 1, 1)       | (2, 2, 2)  | 24       | 64    |
|            | (2, 2, 2, 1, 1, 1)    | (3, 3, 3)  | 72       | 154   |

| [5][3][3]  | (1, 1, 1, 1)          | (4)        | 90       | 200   |
|            | (1, 1, 1, 1, 1)       | (3, 2)     | 45       | 103   |
|            | (2, 1, 1, 1, 1)       | (3, 3)     | 63       | 136   |
|            | (1, 1, 1, 1, 1)       | (2, 2, 2)  | 27       | 64    |
|            | (2, 2, 2, 1, 1, 1)    | (3, 3, 3)  | 81       | 163   |

| [6][2][3]  | (1, 1, 1, 1, 1)       | (3, 2)     | 60       | 132   |
|            | (2, 1, 1, 1, 1)       | (3, 3)     | 84       | 174   |
|            | (1, 1, 1, 1, 1)       | (2, 2, 2)  | 36       | 82    |
| [7][2][2][2]| (1, 1, 1, 1, 1, 1)    | (2, 2, 2)  | 48       | 100   |

Table 9: The particle content for the $E_6$-GUT theories arising from our classification of stable, positive $SU(3)$ monad bundles $V$ on the Calabi-Yau threefold $X$. The number $n_{27}$ of anti-generations vanishes.

10 SO(10) models

<table>
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<tr>
<th>$X$</th>
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<th>${c_i}$</th>
<th>$n_{16}$</th>
<th>$n_1$</th>
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Table 10: The particle content for the SO(10)-GUT theories arising from our classification of stable, positive $SU(4)$ monad bundles $V$ on the Calabi-Yau threefold $X$. The number $n_{16}$ of anti-generations vanishes. The number $n_{16}$ vanishes for generic choices of the map $g$ in the monad sequence (18), but can be made non-vanishing with particular choices of $g$.

7 SU(5) models

<table>
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<tr>
<th>$X$</th>
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<th>${c_i}$</th>
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<td>(2, 2, 2, 2)</td>
<td>60</td>
<td>226</td>
</tr>
</tbody>
</table>

Table 11: The particle content for the SU(5)-GUT theories arising from our classification of stable, positive $SU(5)$ monad bundles $V$ on the Calabi-Yau threefold $X$. The number of anti-generations, $n_{10}$, vanishes. Further, $n_5 = n_{10}$. Moreover, $n_5 = 0$ for generic choices of the map $g$ in Eq. (18), and can be made non-vanishing in special regions of moduli space.

We are currently extending this to all 5000 CYs
Conclusion

String theory realises gravity and gauge theories through closed and open strings (bulk and brane) and has all the right generic ingredients to make contact with particle physics.
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Most ideas for BSM physics are either motivated by string theory or contained in string theory.
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There appears to be a huge number of consistent string vacua. Given the fundamental formulation of the theory is not known one should be careful about jumping to conclusions.
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One can construct standard-like models, but there is not a single standard model from string theory.

The ability to stabilise all moduli has opened up new possibilities for string phenomenology. E.g. the computation of Yukawa couplings for given models seems now feasible, although it is technically hard.
Deriving a SSM with the right particle content and couplings from string theory would be a major success.
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Should the LHC discover physics which points towards string theory (SUSY, KK modes,...) string phenomenology will get a substantial boost.
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Thanks!