Systematic Investigations of the Free Fermionic Heterotic String Landscape

SVP Fall Meeting 2010

Timothy Renner

Baylor University

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Outline

- Free fermionic heterotic string construction.
- Why systematic studies?
- Redundancies and floating correlations.
- The D=10 heterotic string landscape.
- The D=8, D=6 heterotic string landscape.
- The NAHE Set and NAHE Variation.
- Interesting models.
- Future work.

Motivations

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- It allows for "exotic" models to be constructed.
- It details the limits of a particular construction method, which aids searches in other parts of the landscape.
- Fits into the goals of the string vacuum project as a whole : "The mission of the SVP is to bring together experts in string theory and string phenomenology with experts in pure and computational mathematics to concentrate efforts on understanding the systematic features of string vacua."

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- **Order** - the allowable phases the modes can have.
- **Layer** - the number of basis vectors specifying a model.

Basis Vectors

- **Left Movers** - Order 2, obey $SU(2)^6$ WS SUSY current.

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- There are 32 real fermion modes in complex pairs from the D=10 bosonic string, $\bar{\psi}^{1,1^*,\ldots,5,5^*}, \ \bar{\eta}^{1,1^*,\ldots,3,3^*}, \ \bar{\phi}^{1,1^*,\ldots,8,8^*}$.

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- There are 2(10-D) real fermion modes which are bosonic contributions from compactifications, $\bar{y}^{1,\dots,10-D}$, $\bar{w}^{1,\dots,10-D}$.

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  - **Permutations** - Sets of matching boundary conditions can, in some cases, be permuted.
  - $SO(n)$ **Rotations** - Basis vectors with different numbers of periodic modes can produce identical models.

Floating Correlations

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- **floating correlation** - statistical correlations become a function of sample size due to the mapping of the input space to the model space not being one-to-one.
- Studying and reducing the redundancies inherent to the input space is a crucial step towards true random sampling, and can only be completely done with a thorough, systematic study of the landscape.

D=10 Landscape Systematic Search Inputs

- Basis Vector Schematic:
  $(\psi^{1,1^*,\ldots,4,4^*} \mid\mid \bar{\psi}^{1,1*,\ldots,5,5^*}\ \bar{\eta}^{1,1^*,\ldots,3,3^*}\ \bar{\phi}^{1,1^*,\ldots,8,8^*})$
- SUSY basis vector ('S' vector): $(\vec{1}^8 \mid\mid \vec{0}^{32})$.

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- Performed the following searches with an additional S vector: Order 2,4.
- Performed without the S vector: Order 3.

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- All searches were performed first without changing the GSO coefficient matrix.

D=10, Order 2, Layer 1 Landscape

QTY	$SO(4)$	$SO(24)$
1	8	24

N=0 ST SUSY

QTY	$SO(16)$	$SO(16)$
1	128	1
1	1	128

N=0 ST SUSY

D=10, Order 2, Layer 1 Landscape

QTY	$SO(4)$	$SO(24)$
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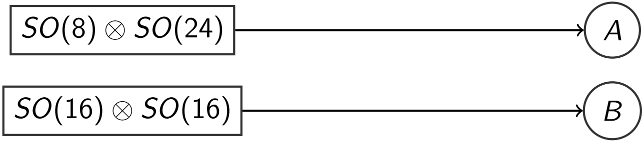
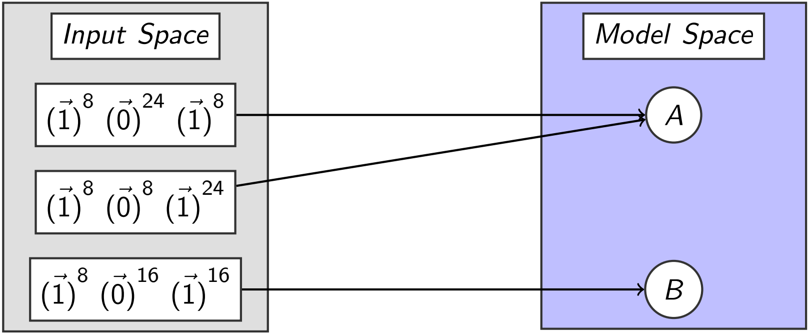
1	1	128

N=0 ST SUSY

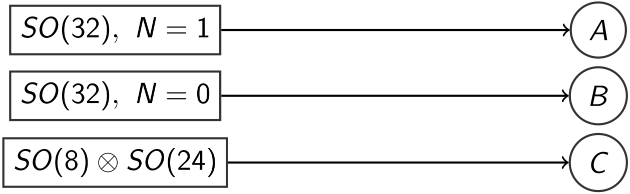
Two unique models, three "distinct" basis vectors.

D=10, Order 2 Landscape Map





D=10, Order 2, 1 Layer GSO Coefficient Mappings



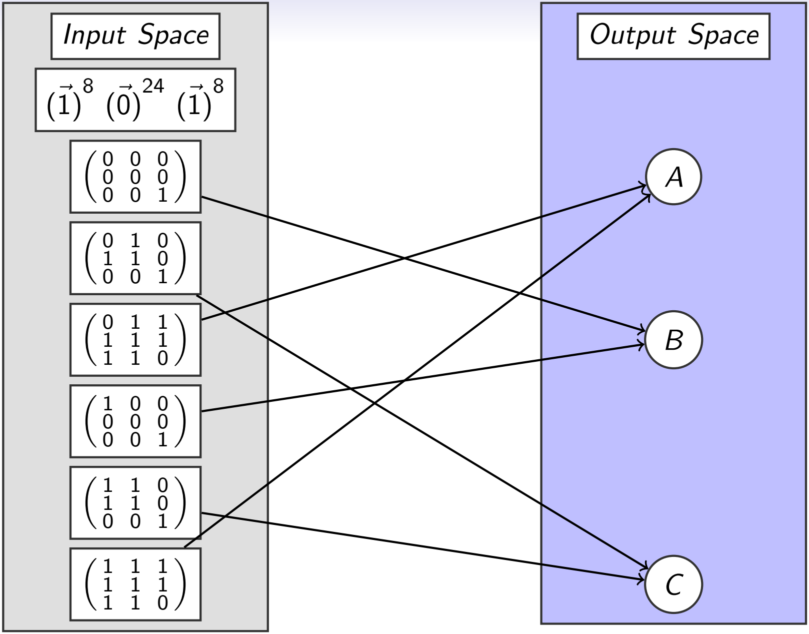
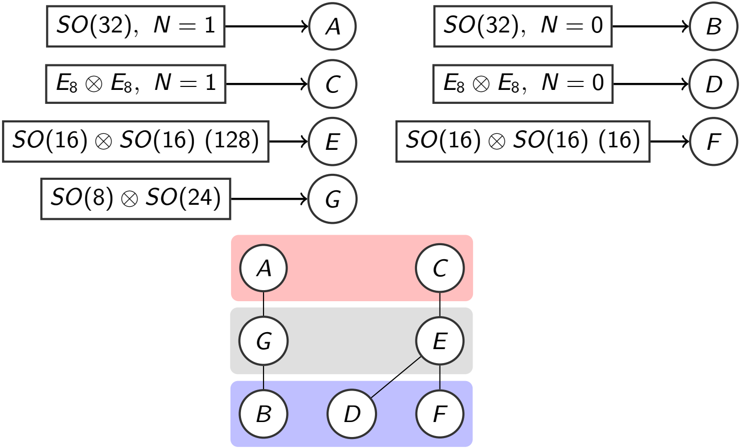

Input Space
$(\vec{1})^8 \ (\vec{0})^{24} \ (\vec{1})^8$
$\begin{pmatrix}0&0&0\\0&0&0\\0&0&1\end{pmatrix}$
$\begin{pmatrix}0&1&0\\1&1&0\\0&0&1\end{pmatrix}$
$\begin{pmatrix}0&1&1\\1&1&1\\1&1&0\end{pmatrix}$
$\begin{pmatrix}1&0&0\\0&0&0\\0&0&1\end{pmatrix}$
$\begin{pmatrix}1&1&0\\1&1&0\\0&0&1\end{pmatrix}$
$\begin{pmatrix}1&1&1\\1&1&1\\1&1&0\end{pmatrix}$
Output Space
A
B
C

Diagram of the D=10, Order 2, 1 Layer Landscape



The D=10, Order 3, 1 Layer Landscape

$SO(32)$, N=0 ST SUSY

$E_8 \otimes E_8$, N=0 ST SUSY

$SO(32)$, N=1 ST SUSY

The D=10, Order 3, 1 Layer Landscape

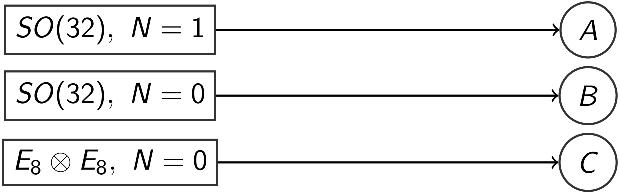
$SO(32)$, N=0 ST SUSY

$E_8 \otimes E_8$, N=0 ST SUSY

$SO(32)$, N=1 ST SUSY

Three unique models, three distinct basis vectors.

Mapping of the D=10, Order 3, Layer 1 Landscape



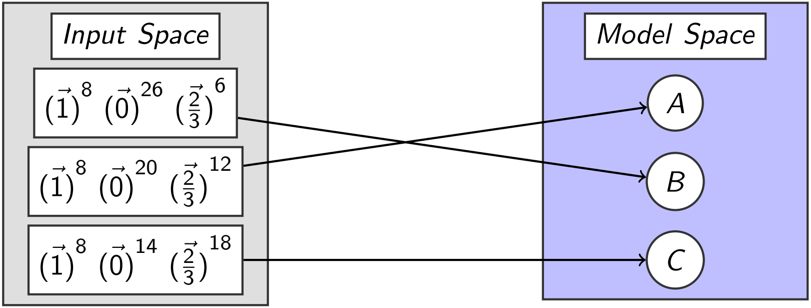
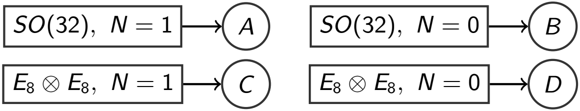


Diagram of the D=10, Order 3, Layer 1 Landscape



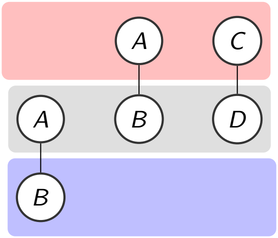
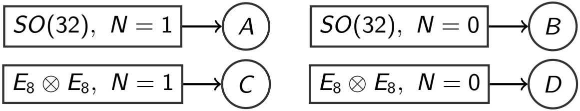
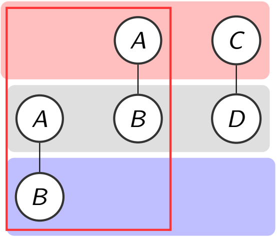


Diagram of the D=10, Order 3, Layer 1 Landscape





D=10, Order 4, Layer 1 Landscape

QTY	$SU(2)$	$SU(2)$	E_7	E_7
1	2	1	1	56
1	1	2	56	1

N=0 ST SUSY

QTY	$SU(16)$
2	120

N=0 ST SUSY

QTY	$SO(8)$	$SO(24)$
1	8	24

N=0 ST SUSY

QTY	$SO(16)$	$SO(16)$
1	128	1
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N=0 ST SUSY

There are 6 distinct models produced by 14 "distinct" basis vectors.

Diagram of the D=10, Order 4, Layer 1 Landscape

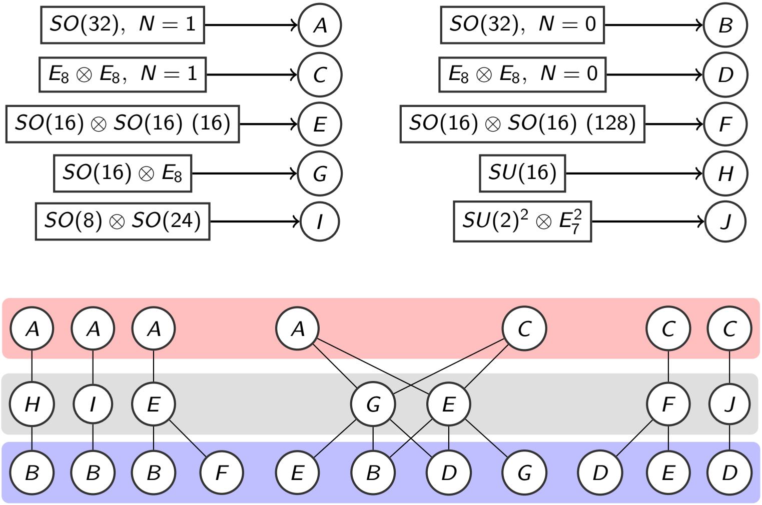
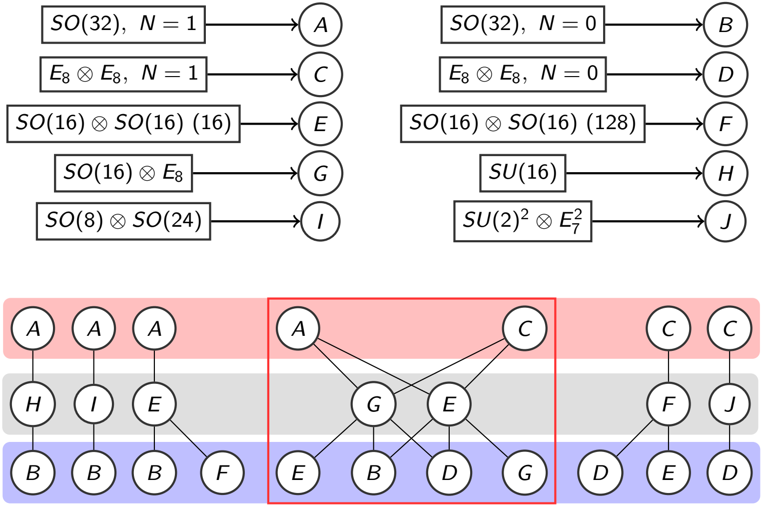


Diagram of the D=10, Order 4, Layer 1 Landscape



D=8 Landscape Systematic Search Inputs

- Basis Vector schematic:
  $(\psi^{1,1^*,\ldots,3,3^*}\ (x\ y\ z\ )^{1,2}\ ||\ \bar{\psi}^{1,1^*,\ldots,5,5^*}\ \bar{\eta}^{1,1^*,\ldots,3,3^*}\ \bar{y}^{1,2}\ \bar{w}^{1,2}\ \bar{\phi}^{1,1^*,\ldots,8,8^*})$
- SUSY basis vector ('S' vector): $(\vec{1}^6\ (1\ 0\ 0)^2\ ||\ \vec{0}^{36})$.

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- Order 2, 4 with S vector.
- Order 3 without S vector.

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- Order 2, 4 with S vector.
- Order 3 without S vector.
- All searches performed without changing the GSO coefficient matrix.

D=8, Order 2, 1 Layer Landscape Statistics

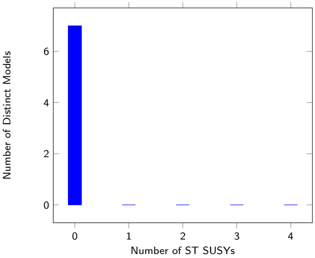
Gauge Group	N	%
$SU(2)$	1	14.3
$SO(8)$	1	14.3
$SO(10)$	1	14.3
$SO(12)$	1	14.3
$SO(16)$	1	14.3
$SO(18)$	1	14.3
$SO(20)$	1	14.3
$SO(24)$	1	14.3
$SO(26)$	1	14.3
$SO(28)$	1	14.3
$SO(32)$	1	14.3
$SO(34)$	1	14.3

Total models: 242

Unique models: 7

Average BVs per unique model: 34.6

Models with N=0 ST SUSY: 7



D=8, Order 3, 1 Layer Landscape Statistics

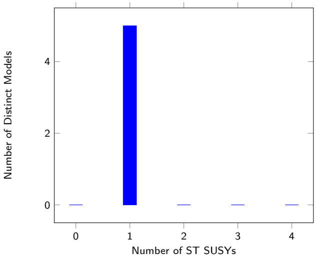
Gauge Group	N	%
$SU(2)$	1	20.0
$SU(4)$	1	20.0
$SU(16)$	1	20.0
$SU(18)$	1	20.0
$SO(12)$	1	20.0
$SO(20)$	1	20.0
$SO(24)$	1	20.0
$SO(36)$	1	20.0
E_8	1	20.0

Total models: 4,049

Unique models: 5

Average BVs per unique model: 809.8

Models with N=1 ST SUSY: 5



D=8, Order 4, 1 Layer Landscape Statistics

Gauge Group	N	%
$SU(2)$	10	27.0
$SU(4)$	10	27.0
$SU(8)$	6	16.2
$SU(12)$	7	18.9
$SU(16)$	4	10.8
$SU(18)$	1	2.7
$SO(8)$	4	10.8
$SO(10)$	6	16.2
$SO(12)$	4	10.8
$SO(14)$	2	5.4
$SO(16)$	5	13.5
$SO(18)$	4	10.8
$SO(20)$	4	10.8
$SO(22)$	1	2.7
$SO(24)$	1	2.7
$SO(26)$	3	8.1
$SO(32)$	1	2.7
$SO(34)$	1	2.7
$SO(36)$	1	2.7
E_6	1	2.7
E_7	3	8.1
E_8	1	2.7

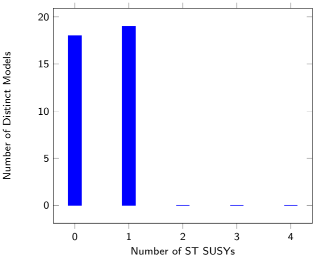
Total models: 11,104

Unique models: 37

Average BVs per unique model: 300.1

Models with

- N=0 ST SUSY: 18
- N=1 ST SUSY: 19



D=6 Landscape Systematic Search Inputs

- Basis vector LM: $(\psi^{1,1^*,2,2^*}\ (x\ y\ z\ )^{1,\ldots,4})$
- Basis vector RM: $(\bar{\psi}^{1,1^*,\ldots,5,5^*}\ \bar{\eta}^{1,1^*,\ldots,3,3^*}\ \bar{y}^{1,\ldots,4}\ \bar{w}^{1,\ldots,4}\ \bar{\phi}^{1,1^*,\ldots,8,8^*})$
- SUSY basis vector ('S' vector): $(\vec{1}^4\ (1\ 0\ 0)^4\ ||\ \vec{0}^{40})$.

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- Order 3 with and without S vector.

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- Orders 2, 4 with S vector.
- Order 3 with and without S vector.
- All searches performed without changing the GSO coefficient matrix.

D=6, Order 2, 1 Layer Landscape Statistics

Gauge Group	N	%
$SU(2)$	1	6.3
$SU(4)$	1	6.3
$SO(8)$	3	18.8
$SO(10)$	1	6.3
$SO(12)$	1	6.3
$SO(14)$	1	6.3
$SO(16)$	3	18.8
$SO(18)$	1	6.3
$SO(20)$	1	6.3
$SO(22)$	1	6.3
$SO(24)$	3	18.8
$SO(26)$	1	6.3
$SO(28)$	1	6.3
$SO(30)$	1	6.3
$SO(32)$	3	18.8
$SO(34)$	1	6.3
$SO(36)$	1	6.3
$SO(38)$	1	6.3
$SO(40)$	2	12.5

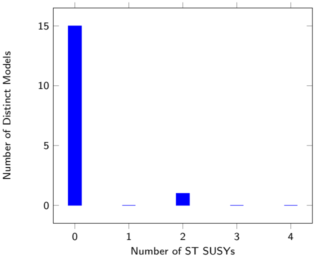
Total models: 3,248

Unique models: 16

Average BVs per unique model: 203

Models with

- N=0 ST SUSY: 15
- N=2 ST SUSY: 1



D=6, Order 3, 1 Layer Landscape Statistics

Gauge Group	N	%
$SU(2)$	5	7.7
$SU(3)$	1	1.5
$SU(4)$	2	3.1
$SU(5)$	1	1.5
$SU(6)$	1	1.5
$SU(7)$	1	1.5
$SU(8)$	1	1.5
$SU(9)$	1	1.5
$SU(10)$	1	1.5
$SU(11)$	1	1.5
$SU(12)$	1	1.5
$SU(13)$	1	1.5
$SU(14)$	1	1.5
$SU(15)$	1	1.5
$SU(16)$	3	4.6
$SU(17)$	1	1.5
$SU(18)$	4	6.2
$SU(19)$	1	1.5

Gauge Group	N	%
$SO(8)$	1	1.5
$SO(10)$	5	7.7
$SO(12)$	1	1.5
$SO(14)$	1	1.5
$SO(16)$	13	20.0
$SO(18)$	2	3.1
$SO(20)$	8	12.3
$SO(22)$	16	24.6
$SO(24)$	6	9.2
$SO(26)$	1	1.5
$SO(28)$	1	1.5
$SO(30)$	1	1.5
$SO(32)$	5	7.7
$SO(34)$	2	3.1
$SO(36)$	13	20.0
$SO(38)$	1	1.5
$SO(40)$	2	3.1
E_8	2	3.1

D=6, Order 3, 1 Layer Landscape Statistics

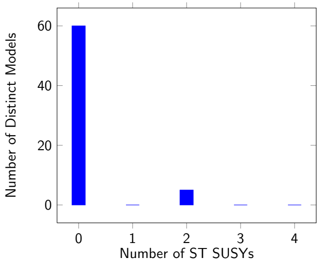
Total models: 81,752

Unique models: 65

Average BVs per unique model: 1,257.7

Models with

- N=0 ST SUSY: 60
- N=2 ST SUSY: 5



The NAHE Set

QTY	$SU(4)$	$SU(4)$	$SU(4)$	$SO(10)$	E_8
2	$\bar{4}$	1	1	16	1
2	1	$\bar{4}$	1	16	1
2	1	1	$\bar{4}$	16	1
2	1	1	4	16	1
1	1	1	6	10	1
2	1	4	1	16	1
1	1	6	1	10	1
1	1	6	6	1	1
2	4	1	1	16	1
1	6	1	1	10	1
1	6	1	6	1	1
1	6	6	1	1	1

Total Matter Representations: 18

Number of ST SUSYs: 1

Exotic Order 3 Model 1

- NAHE extension with S vector.

Exotic Order 3 Model 1

- NAHE extension with S vector.
- LM: $(1,\ 1)\ (0,\ 1,\ 0)^4\ (1,\ 0,\ 0)^2$
- RM:
  - $\bar{\psi},\ \bar{\eta}:\ (\frac{2}{3}^{10})\ (0^2,\ \frac{2}{3}^2,\ 0^2)$
  - $\bar{y},\ \bar{w}:\ (\frac{2}{3},\ 0^3,\ \frac{2}{3}^2)\ (0^2,\ \frac{2}{3}^2,\ 0,\ \frac{2}{3})$
  - $\bar{\phi}:\ (0^4,\ \frac{2}{3}^{12})$

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  - $\bar{y}, \ \bar{w}: \ (\frac{2}{3}, \ 0^3, \ \frac{2}{3}^2) \ (0^2, \ \frac{2}{3}^2, \ 0, \ \frac{2}{3})$
  - $\bar{\phi}: \ (0^4, \ \frac{2}{3}^{12})$
- Gauge groups: $SU(2)^4 \otimes SU(5)^2 \otimes E_6$
- Total matter representations: 36

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    - $\bar{y},\ \bar{w}:\ (\frac{2}{3},\ 0^3,\ \frac{2}{3}^2)\ (0^2,\ \frac{2}{3}^2,\ 0,\ \frac{2}{3})$
    - $\bar{\phi}:\ (0^4,\ \frac{2}{3}^{12})$
- Gauge groups: $SU(2)^4 \otimes SU(5)^2 \otimes E_6$
- Total matter representations: 36
- N=2 ST SUSY

Exotic Order 3 Model 2

- NAHE extension without S vector.

Exotic Order 3 Model 2

- NAHE extension without S vector.
- LM: $(1,\ 1)\ (1,\ 0,\ 0)^6$
- RM:
  - $\bar{\psi},\ \bar{\eta}:\ (\frac{2}{3}^{10})\ (0^2,\ \frac{2}{3}^{4})$
  - $\bar{y},\ \bar{w}:\ (\frac{2}{3}^{2},\ 0^2,\ \frac{2}{3}^{2})\ (\frac{2}{3}^{4},\ \frac{2}{3}^{2})$
  - $\bar{\phi}:\ (0^4,\ \frac{2}{3}^{12})$

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  - $\bar{\phi}:\ (0^4,\ \frac{2}{3}^{12})$
- Gauge groups: $SU(2)^2 \otimes SU(3)^2 \otimes SU(4) \otimes SU(5) \otimes E_6$
- Total matter representations: 44

Exotic Order 3 Model 2

- NAHE extension without S vector.
- LM: $(1,\ 1)\ (1,\ 0,\ 0)^6$
- RM:
  - $\bar{\psi},\ \bar{\eta}:\ (\frac{2}{3}^{10})\ (0^2,\ \frac{2}{3}^{4})$
  - $\bar{y},\ \bar{w}:\ (\frac{2}{3}^{2},\ 0^2,\ \frac{2}{3}^{2})\ (\frac{2}{3}^{4},\ \frac{2}{3}^{2})$
  - $\bar{\phi}:\ (0^4,\ \frac{2}{3}^{12})$
- Gauge groups: $SU(2)^2 \otimes SU(3)^2 \otimes SU(4) \otimes SU(5) \otimes E_6$
- Total matter representations: 44
- N=1 ST SUSY

Exotic Order 3 Model 2

- NAHE extension without S vector.
- LM: $(1,\ 1)\ (1,\ 0,\ 0)^6$
- RM:
  - $\bar{\psi},\ \bar{\eta}:\ (\frac{2}{3}^{10})\ (0^2,\ \frac{2}{3}^4)$
  - $\bar{y},\ \bar{w}:\ (\frac{2}{3}^2,\ 0^2,\ \frac{2}{3}^2)\ (\frac{2}{3}^4,\ \frac{2}{3}^2)$
  - $\bar{\phi}:\ (0^4,\ \frac{2}{3}^{12})$
- Gauge groups: $SU(2)^2 \otimes SU(3)^2 \otimes SU(4) \otimes SU(5) \otimes E_6$
- Total matter representations: 44
- N=1 ST SUSY
- Three U(1)'s make the total rank 22, and make two sets of SM gauge groups.

Differences Between the NAHE Set and NAHE Variation

NAHE Set

$\bar{\eta}^{1,2}$	$\bar{\eta}^{3,4}$	$\bar{\eta}^{5,6}$	$\bar{y}^{1,2}$	$\bar{y}^{3,4}$	$\bar{y}^{5,6}$	$\bar{w}^{1,2}$	$\bar{w}^{3,4}$	$\bar{w}^{5,6}$
1	0	0	0	1	1	0	0	0
0	1	0	1	0	0	0	0	1
0	0	1	0	0	0	1	1	0

NAHE Variation

$\bar{\eta}^{1,2}$	$\bar{\eta}^{3,4}$	$\bar{\eta}^{5,6}$	$\bar{y}^{1,2}$	$\bar{y}^{3,4}$	$\bar{y}^{5,6}$	$\bar{w}^{1,2}$	$\bar{w}^{3,4}$	$\bar{w}^{5,6}$
1	0	0	0	1	1	0	0	0
0	1	0	1	0	1	0	0	0
0	0	1	1	1	0	0	0	0

The NAHE Variation

QTY	$SO(22)$	E_6
15	1	$\overline{27}$
90	1	1
15	1	27
30	22	1

Total Matter Representations: 150

Number of ST SUSYs: 1

Mirror Model 1

QTY	$SO(11)$	$SO(11)$	$SO(10)$
88	1	1	1
12	1	1	10
20	1	1	16
16	1	11	1
2	1	32	1
16	11	1	1
1	11	11	1
2	32	1	1

Total Matter Representations: 157

Number of ST SUSYs: 0

Mirror Model 2

QTY	$SO(10)$	$SO(10)$	$SO(14)$
40	1	1	1
12	1	1	14
14	1	10	1
1	1	10	14
16	1	16	1
14	10	1	1
1	10	1	14
16	16	1	1

Total Matter Representations: 114

Number of ST SUSYs: 0

Future Work

- Speed Optimizations

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- Speed Optimizations
  - Better algorithms
  - Better knowledge of computer systems
  - Parallel processing

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- Additional Phenomenology
- Larger Data Sets
- Systematic NAHE and NAHE Extension Studies

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Citations

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