Classification of Heterotic String Vacua

Left Right Symmetric Models

Glyn Harries

In collaboration with Alon Faraggi & Hasan Sonmez

21/06/2016

Outline

- Introduction to the Free Fermionic Construction
- Aims and method of classification
- Observable gauge groups
- Results of the flipped SU(5) project
- Introduction to the Left-Right symmetric project and the progress so far
- Conclusion

Free Fermions

- The free fermionic construction of string theory offers an interesting way to test the phenomenology of various string models
- To date, the models constructed represent some of the most realistic string models with three chiral generations of matter
- In the free fermionic construction we interpret the extra degrees of freedom as free fermions propagating on the string worldsheet, instead of spacetime dimensions. This allows us to formulate the theory directly in four spacetime dimensions
- We do this by introducing:
- Left moving $c_L = -26 + 11 + D + \frac{D}{2} + N_{f_L} \cdot \frac{1}{2} = 0$
- Right moving $c_R = -26 + D + N_{f_R} \cdot \frac{1}{2} = 0$
- We can then see that to cancel the conformal anomaly, we need:

$$N_{f_L} = 18$$
$$N_{f_R} = 44$$

Free Fermions

- The fermions on the worldsheet are

	Label	Description
Left–moving	X^{μ}	Bosonic coordinates with spacetime index, $\mu = 0, \ldots, 3$
	ψ^{μ}	Majorana–Weyl superpartners of the bosonic coordinates with spacetime index
	$\chi^{1,\ldots,6}$	Majorana–Weyl superpartners to the six compactified dimensions
	$y^{1,\ldots,6}, w^{1,\ldots,6}$	Majorana–Weyl fermions that correspond to the bosons describing the six compactified dimensions in the bosonic formulation
Right–moving	$\overline{X}^{\mu}$	Bosonic coordinates with spacetime index
	$\overline{y}^{1,\ldots,6}, \overline{w}^{1,\ldots,6}$	Majorana–Weyl fermions that correspond to the bosons describing the six compactified dimensions in the orbifold formulation
	$\overline{\psi}^{1,\ldots,5}, \overline{\eta}^{1,2,3}$	Complex fermions that describe the visible gauge sector
	$\overline{\phi}^{1,\ldots,8}$	Complex fermions that describe the hidden gauge sector

Partition Function

- The partition function is the sum over all the massive and massless string states which have to be included when the string propagates around the vacuum to vacuum amplitude
- The total partition function of this is

$$Z = \int \frac{d\tau d\bar{\tau}}{[Im(\tau)]^2} Z_B^2(\tau,\bar{\tau}) \sum_{\text{spin structures}} C\binom{a}{b} Z_{\text{long},3/2}\begin{bmatrix} a_\psi \\ b_\psi \end{bmatrix} \sum_{f=1}^{64} Z_f \begin{bmatrix} \alpha(f) \\ \beta(f) \end{bmatrix}$$

Partition Function

- The relevent information from the one loop fermionic partition function we concern ourself with for model building is then

$$\sum_{\text{spin structures}} C\binom{\vec{\alpha}}{\vec{\beta}}\, Z\binom{\vec{\alpha}}{\vec{\beta}}$$

- This is what we consider in order to build our models

GSO Projection

- The equation for the Generalized GSO projection is

$$e^{i\pi b_j \cdot F_\alpha} \left|s\right\rangle_\alpha = \delta_\alpha \, C\binom{\alpha}{b_j}^* \left|s\right\rangle_\alpha$$

  where α is the sector being considered and b_j is the basis vector
- The states $|s\rangle$ which satisfy this equation are 'kept in' and the states which do not satisfy this equation are 'projected out'.
- By performing the GSO projection on sectors we can break the gauge group and remove any unwanted states from the spectrum

Aims of Classification

The classification of a model then refers finding vacua consistent with our phenomenological constraints, such as

- Three chiral generations of observable matter
- $\mathcal{N} = 1$ SUSY
- No exotic states at the level of the Standard Model
- No observable gauge group enhancements
- Constraints on the number and type of Higgs particles in the spectrum

The classification of the model then refers to enumerating the number of vacua in the model consistent with these constraints

Method of Classification

- A model consisting of a set of basis vectors (defined by the boundary conditions of each of the free fermions) is chosen, with some insight into what model is wanted
- We then derive algebraic expressions for the generalized GSO projections for all the physical states appearing in the sectors generated by the basis vectors
- These algebraic expressions can then be input into a computer code which allows for an analysis of the entire string spectrum
- A statistical analysis of the string spectrum can be performed to check how many string vacua in the model adhere to the phenomenological constraints

Observable Gauge Groups

- The observable sector has a $SO(10)$ GUT symmetry at the string scale
- This is broken directly at the string scale by a choice of basis vectors
- Depending on the basis vectors, the resulting models can have an observable gauge group of
- $SO(6) \times SO(4) \rightarrow$ Pati-Salam
- $SU(5) \times U(1) \rightarrow$ Flipped $SU(5)$
- $SU(3) \times SU(2)_L \times SU(2)_R \times U(1) \rightarrow$ Left-Right Symmetric
- $SU(3) \times SU(2) \times U(1) \times U(1) \rightarrow$ Standard-Like
- $SU(4) \times SU(2)_L \times U(1)_R \rightarrow SU(421)$
- $SU(6) \times SU(2)$

Flipped SU(5) Results

- A previous project involved the classification of a flipped $SU(5)$ model
- The model classified had the basis vectors

$$
\begin{aligned}
S &= \{\psi^{\mu}_{12}, \chi^{12}, \chi^{34}, \chi^{56}\} \\
e_i &= \{y^i, w^i \mid \bar{y}^i, \bar{w}^i\} \\
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} \mid \bar{y}^{34}, \bar{y}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^1\} \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} \mid \bar{y}^{12}, \bar{y}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^2\} \\
z_1 &= \{\bar{\phi}^{1,\dots,4}\} \\
z_2 &= \{\bar{\phi}^{5,\dots,8}\} \\
\alpha &= \{\bar{\psi}^{1,2,3,4,5} = \frac{1}{2}, \bar{\eta}^{1,2,3} = \frac{1}{2}, \bar{\phi}^{1,2} = \frac{1}{2}, \bar{\phi}^{3,4} = \frac{1}{2}, \bar{\phi}^{5} = 1\}
\end{aligned}
$$

- The results from classification are

Flipped SU(5) Results

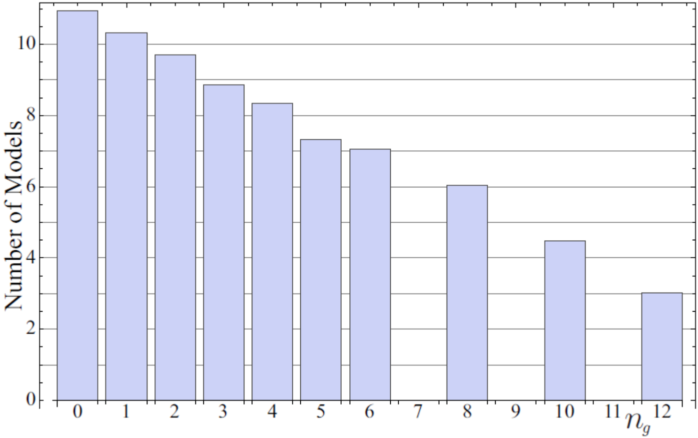

Figure 1: *Logarithm of the number of models against the number of generations* (n_g) *in a random sample of* 10^{12} *flipped* $SU(5)$ *configurations.*

Flipped SU(5) Results

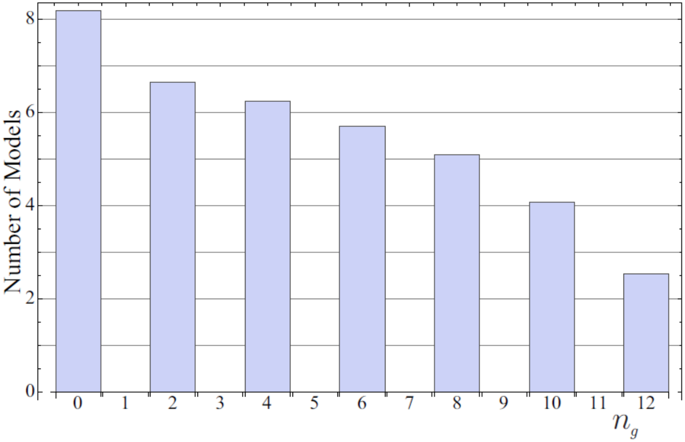

Figure 2: *Logarithm of the number of exophobic models against the number of generations (n_g) in a random sample of 10^{12} flipped $SU(5)$ configurations.*

Flipped SU(5) Results

	Constraints	Total models in sample	Probability	Estimated number of models in class
	No Constraints	1000000000000	1	1.76×10^{13}
(1)	+ No Enhancements	762269298719	7.62×10^{-1}	1.34×10^{13}
(2)	+ Anomaly Free Flipped $SU(5)$	139544182312	1.40×10^{-1}	2.45×10^{12}
(3)	+ 3 Generations	738045321	7.38×10^{-4}	1.30×10^{10}
(4a)	+ SM Light Higgs	706396035	7.06×10^{-4}	1.24×10^{10}
(4b)	+ Flipped $SU(5)$ Heavy Higgs	46470138	4.65×10^{-5}	8.18×10^{8}
(5)	+ SM Light Higgs + & Heavy Higgs	43624911	4.36×10^{-5}	7.67×10^{8}
(6a)	+ Minimal Flipped $SU(5)$ Heavy Higgs	42310396	4.23×10^{-5}	7.44×10^{8}
(6b)	+ Minimal SM Light Higgs	25333216	2.53×10^{-5}	4.46×10^{8}
(7)	+ Minimal Flipped $SU(5)$ Heavy Higgs + & Minimal SM Light Higgs	24636896	2.46×10^{-5}	4.33×10^{8}
(8)	+ Minimal Exotic States	1218684	1.22×10^{-6}	2.14×10^{7}

Statistics for the flipped $SU(5)$ models with respect to phenomenological constraints. Here we note that the results of 4a and 4b have no effect on each other and this also holds for 6a and 6b.

Left-Right Symmetric Models

- The current project is the classification of a left right symmetric model
- This has the basis vectors

$$\mathbb{1} = \{\psi^{\mu}_{12}, \chi^{12}, \chi^{34}, \chi^{56}, y^{12}, y^{34}, y^{56}, w^{12}, w^{34}, w^{56} \mid \bar{y}^{12}, \bar{y}^{34}, \bar{y}^{56}, \bar{w}^{12}, \bar{w}^{34}, \bar{w}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^{1,2,3}, \bar{\phi}^{1,\dots,8}\}$$

$$S = \{\psi^{\mu}_{12}, \chi^{12}, \chi^{34}, \chi^{56}\}$$

$$e_i = \{y^i, w^i \mid \bar{y}^i, \bar{w}^i\}$$

$$b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} \mid \bar{y}^{34}, \bar{y}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^{1}\}$$

$$b_2 = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} \mid \bar{y}^{12}, \bar{y}^{56}, \bar{\psi}^{1,\dots,5}, \bar{\eta}^{2}\}$$

$$z_1 = \{\bar{\phi}^{1,\dots,4}\}$$

$$z_2 = \{\bar{\phi}^{5,\dots,8}\}$$

$$\alpha = \{\bar{\psi}^{1,2,3} = \frac{1}{2}, \bar{\eta}^{1,2,3} = \frac{1}{2}, \bar{\phi}^{1,\dots,6} = \frac{1}{2}, \bar{\phi}^{7}\}$$

Progress of LRS Model

- The observable sectors have been calculated and input into the code
- Currently, the sectors which give gauge group enhancements are being calculated. The spinorial enhancements have been included in the code and the vectorial enhancements are nearing completion
- The sectors giving exotic states have been enumerated and coded so it is known which exotic states are still present in different vacua. This work still needs to be completed by calculating the gauge groups of the states still present after the GSO projections
- Sectors which provide the Higgs then need to be included in the code
- The code then needs to be run in order to perform the statistical analysis of the string vacua associated with the method of classification

Conclusions

- Free fermionic models currently give the most promising phenomenological results from string theory
- By classifying different choices of basis vectors, we can provide a statistical analysis of the quasi-realistic vacua with a number of different observable gauge groups
- The flipped $SU(5)$ results were promising, but did not have exophobic models with three chiral generations of matter
- The Left-Right Symmetric classification is underway and will be presented in a future publication

Thank you for listening

Flipped $SU(5)$ paper:
Alon E. Faraggi , John Rizos & Hasan Sonmez - arXiv: 1403.4107