The "landscape" of Pati–Salam heterotic superstring vacua

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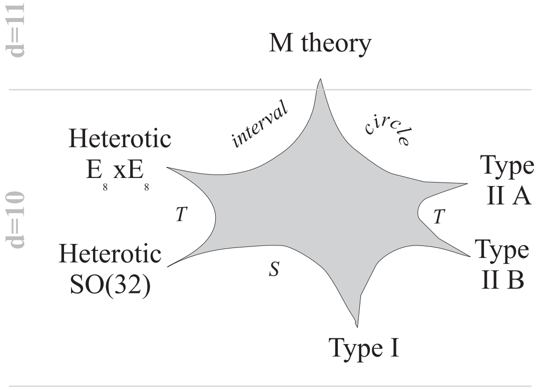
Summary

String Theory

String Theory is our best candidate for a unified theory of all interactions including gravity.



The Standard Model from Strings

String theory, as a theory of all interactions, should reproduce the Standard Model at low energies.
However, String Theory in four dimensions contains a huge number of vacua.
Historically the Heterotic superstring models where explored first.

Heterotic models

Gauge and gravitational interactions, as well as usual matter, correspond to closed strings that propagate in the full 10d space.
Calabi-Yau, Orbifold compactification, fermionic formulation, Gepner models
Basic features:

- String scale related to Planck scale, close to the gauge coupling unification scale $M_{string}^2 \sim \alpha_g M_{Plank}^2$
- No adjoint scalars for level 1 Kac-Moody , gauge groups , $SU(5) \times U(1), SU(4) \times SU(2) \times SU(2), SU(3) \times SU(2) \times U(1)^n$
- Anomalous $U(1)$ broken by the GS mechanism leads to vevs of $M_s/10$ for some singet fields.
- Three generations, hierarchical mass spectra, light neutrinos
- But also fractional charge states (exotics)
- SUSY breaking ?

Study of string vacua

- Statistical approach (landscape) see e.g.
  M. R. Douglas, (2003)
  S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi (2003)
  T. Banks, M. Dine and E. Gorbatov (2003)
- Classification Type II /orientifolds, see eg,
  T.P.T. Dijkstra1 , L. R. Huiszoon2 and A.N. Schellekens (2004)
  P. Anastasopoulos, T. P. T. Dijkstra, E. Kiritsis and A. N. Schellekens,(2006)
  E. Kiritsis, M. Lennek and B. Schellekens (2008),(2009)
- Classification in the context of Heterotic string orbifolds e.g.
  F. Gmeiner, R. Blumenhagen, G. Honecker, D. Lust and T. Weigand (2006)
  O. Lebedev, H. P. Nilles, S. Ramos-Sanchez, M. Ratz and P. K. S. Vaudrevange (2008)
  F. Gmeiner and G. Honecker (2008)

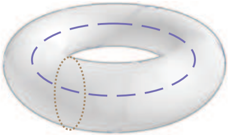
Study of string vacua

- Classification in the context of Heterotic Free Fermionic, e.g.
  A.E. Faraggi , C. Kounnas , S.E.M. Nooij , J. Rizos (2004)
  K. R. Dienes (2006), K. R. Dienes and M. Lennek (2007)
  A. E. Faraggi , C. Kounnas , J. Rizos (2007),(2008), and B. Assel, K. Christodoulides, work in progress

The Free Fermionic Formulation of the heterotic superstring

In the Free Fermionic Formulation of the heterotic superstring we can reduce the critical dimension of the superstring and construct models in $D = 4$ by fermionizing the left movers and introducing non-linear supersymmetry among them.

A model is defined by a set of basis vectors $B = \{v_1, v_2, \dots v_n\}$ and a set of $2^{n(n-1)}$ phases $c\begin{bmatrix} v_i \\ v_j \end{bmatrix}, i > j$.



The basis vectors give rise to a set $\Xi = \{\xi_1 = 0, \xi_2 = 1, \xi_3, \dots, \xi_M\}$ of string sectors and phases are related to the GSO projections.
The basis vectors and phases are subject to constraints due to modular invariance, string amplitude factorization.

$Z_2 \times Z_2$ models

The partition function can be written as

$$Z = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^3} \frac{1}{\eta^2 \bar{\eta}^2} \sum_{\alpha,\beta \epsilon \Xi} c \begin{bmatrix}\alpha \\ \beta\end{bmatrix} \tilde{\zeta} \begin{bmatrix}\alpha \\ \beta\end{bmatrix}$$

where

$$\tilde{\zeta} \begin{bmatrix}\alpha \\ \beta\end{bmatrix} = \frac{1}{2^n} \prod_{i=1}^{n_L} \left(\frac{\theta \begin{bmatrix}\alpha_i \\ \beta_i\end{bmatrix}}{\eta} \right)^{\frac{r_i}{2}} \prod_{i=n_L+1}^{n_R} \left(\frac{\bar{\theta} \begin{bmatrix}\alpha_i \\ \beta_i\end{bmatrix}}{\bar{\eta}} \right)^{\frac{r_i}{2}}$$

where $r_i = 1, 2$ if the i fermion is real or complex respectively and n_L/n_R the number of left/right moving fermions.

Some (semi)realistic models

Using variations of a specific basis set (NAHE set) several $N = 1$ models have been constructed

Flipped $SU(5)$ model $SU(5) \times U(1) \times$ Hidden

Pati-Salam model $SU(4) \times SU(2)_L \times SU(2)_R \times$ Hidden

Standard-like models $SU(3) \times SU(2) \times U(1)^n \times$ Hidden

In simple constructions the gauge group rank r can be reduced by 6 so $r \geq 44/2 - 6 = 16$

Model construction: Gauge group, full massless spectrum, superpotential, flat directions, massless doublets, non-renormalizable interactions, fermions masses, exotic states

Some of the steps have been computerized

Classification strategy

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- Choose a basis set that contains the realistic models
- Fix basis vectors and vary GSO coefficients
- Choose chiral observable gauge group: $SO(10)$ gauge group
- Identify models by few characteristic properties: # of spinorials, # of antispinorials, # of vectorials
- Derive analytic formulas for the above characteristics
- Use a fast computer program to evaluate formulas for all models

The class of $Z_2 \times Z_2$ $SO(10)$ heterotic models

The free fermions in the light-cone gauge in the traditional notation are:

left: $\psi^\mu, \chi^{1,\dots,6}, \quad y^{1,\dots,6}, \omega^{1,\dots,6}$

right: $\bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \quad \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \quad \bar{\phi}^{1,\dots,8}$

The class of models under consideration is generated by a set of 12 basis vectors $B = \{v_1, v_2, \dots, v_{12}\}$ where

$$
\begin{aligned}
v_1 = 1 \quad &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} | \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \\
&\qquad \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\} \\
v_2 = S \quad &= \{\psi^\mu, \chi^{1,\dots,6}\} \\
\text{shifts}: \quad v_{2+i} = e_i \quad &= \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ \ i = 1, \dots, 6 \\
Z_2 \text{ twist}: v_9 = b_1 \quad &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\} \\
Z_2 \text{ twist}: v_{10} = b_2 \quad &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\} \\
v_{11} = z_1 \quad &= \{\bar{\phi}^{1,\dots,4}\} \\
v_{12} = z_2 \quad &= \{\bar{\phi}^{5,\dots,8}\}
\end{aligned}
$$

and a set of $2^{12(12-1)/2}$ phases $c[v_i, v_j] = \pm 1, j < i = 1, \dots, 12$

Massless spectrum

Untwisted sector matter spectrum (universal)
Gauge symmetry (rank 16) $SO(10) \times U(1)^3 \times SO(8)^2$
6 pairs of $SO(10)$ vectorials and a number of $SO(10)$ singlets.
The twisted sectors are generated by $b_1, b_2, b_1 + b_2$ (three $Z_2 \times Z_2$ orbifold planes), they contain

Spinorial $SO(10)$ representations :

$$\begin{aligned}
B^{(1)}_{pqrs} &= S + b_1 + p^1\, e_3 + q^1\, e_4 + r^1\, e_5 + s^1\, e_6 \\
B^{(2)}_{pqrs} &= S + b_2 + p^2\, e_1 + q^2\, e_2 + r^2\, e_5 + s^2\, e_6 \\
B^{(3)}_{pqrs} &= S + b_3 + p^3\, e_1 + q^3\, e_2 + r^3\, e_3 + s^3\, e_4
\end{aligned}$$

where $b_3 = b_1 + b_2 + x$, $p^i, q^i, r^i, s^i = \{0, 1\}$.

Vectorial $SO(10)$ representations

$$V^{(I)}_{pqrs} = B^{(I)}_{pqrs} + x$$

where $x = 1 + S + \sum_{i=1}^{6} e_i + \sum_{i=1}^{2} z_i$

Analytic formulae for # of spinorials/vectorials

$$\#(S^{(I)}) = \begin{cases} 2^{4-\mathrm{rank}\left(\Delta^{(I)}\right)} & \mathrm{rank}\left(\Delta^{(I)}\right) = \mathrm{rank}\left[\Delta^{(I)}, Y_{16}^{(I)}\right] \\ 0 & \mathrm{rank}\left(\Delta^{(I)}\right) < \mathrm{rank}\left[\Delta^{(I)}, Y_{16}^{(I)}\right] \end{cases}$$

$$\#(V^{(I)}) = \begin{cases} 2^{4-\mathrm{rank}\left(\Delta^{(I)}\right)} & \mathrm{rank}\left(\Delta^{(I)}\right) = \mathrm{rank}\left[\Delta^{(I)}, Y_{10}^{(I)}\right] \\ 0 & \mathrm{rank}\left(\Delta^{(I)}\right) < \mathrm{rank}\left[\Delta^{(I)}, Y_{10}^{(I)}\right] \end{cases}$$

$\Delta^{(I)}$, are 4x4 and $Y^{(I)}$ $I = 1, 2, 3$ are 4x1 GSO coefficient matrices

Analytic formulae for spinorial chiralities

The chirality of the surviving spinorials is given by

$$
\begin{aligned}
X^{(1)}_{pqrs} &= c\begin{bmatrix} b_2 + (1-r)e_5 + (1-s)e_6 \\ B^{(1)}_{pqrs} \end{bmatrix} \\
X^{(2)}_{pqrs} &= c\begin{bmatrix} b_1 + (1-r)e_5 + (1-s)e_6 \\ B^{(2)}_{pqrs} \end{bmatrix} \\
X^{(3)}_{pqrs} &= c\begin{bmatrix} b_1 + (1-r)e_3 + (1-s)e_4 \\ B^{(3)}_{pqrs} \end{bmatrix}
\end{aligned}
$$

where $X^i_{pqrs} = +1$ corresponds to a **16** of $SO(10)$($X^i_{pqrs} = -1$ corresponds to a $\overline{\mathbf{16}}$). The net number of families is given by

$$
N_F = \sum_{i=1}^{3} \sum_{p,q,r,s=0}^{1} X^{(i)}_{pqrs} P^{(i)}_{pqrs}
$$

Computer Analysis

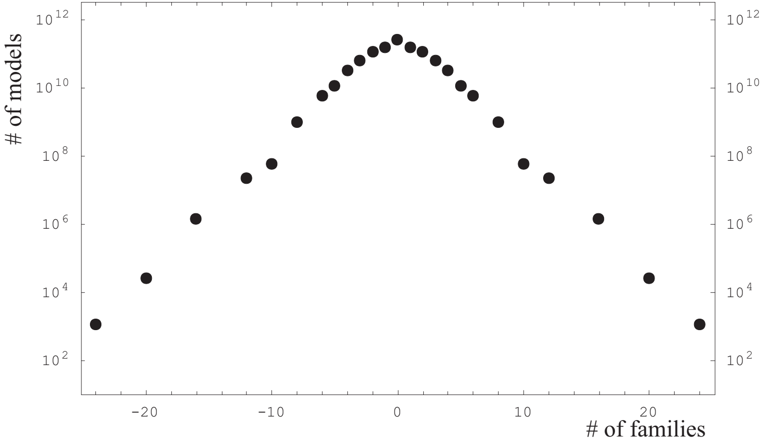
Model characteristics are expressed in term of GSO phase matrices and sums. They can be evaluated for the using a computer program.

1. The program should be fast (at least 10^5 models per second)
2. The program must face the memory and storage problem

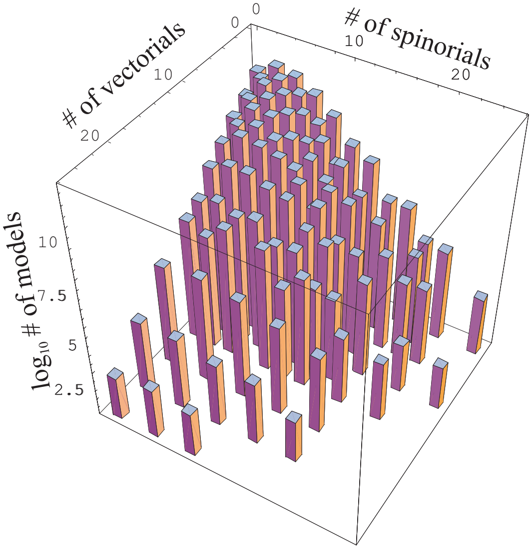
We have constructed such a computer program FORTRAN95. Run on Dual Xeon $\Rightarrow$ full results in 60 days (200.000 models per second).

Results of computer analysis

Total number of models in this class: $1.016.808.865.792 \sim 10^{12}$



Spinorial-Vectorial analysis



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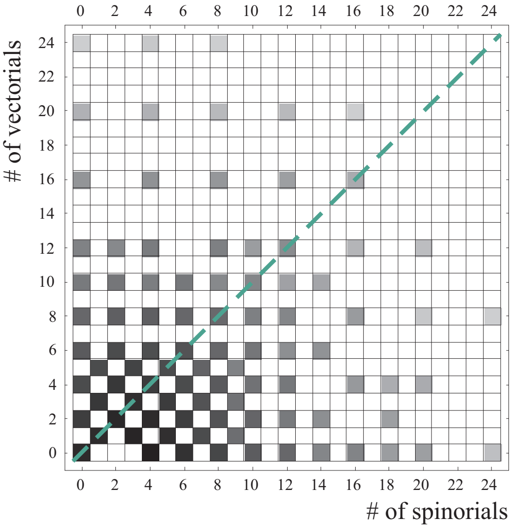

Spinor-Vector Duality

Models in this class appear in pairs related with spinor-vector duality. The map has been derived analytically and holds to each orbifold plane separately.
Self-dual models under this symmetry appear to be anomaly free (no anomalous $U(1)$)
This symmetry appears in each orbifold plane separately.

Towards the Standard Model

The next step in our analysis is to break $SO(10)$ and obtain the Standard Model. The simplest way to realize this is through the Pati-Salam GUT model.

$$SO(10) \to SU(4) \times SU(2)_L \times SU(2)_R \to SU(3) \times SU(2) \times U(1)$$

Motivation for Pati-Salam models

1. Technically easier , can be realized with a single additional vector of real spin structures
2. Models constructed up to now contain additional fractional charge matter (exotics)
3. According to recent results, (see e.g. Lust (2009)) this model has very low statistics in Intersecting D-brane models

The Pati-Salam model

J. Pati and A. Salam, *Lepton number as the fourth color* (1974)
I. Antoniadis and G. Leontaris (1988) (SUSY version)
I. Antoniadis, G. Leontaris and J. Rizos (1990) (heterotic superstring version)

$$SO(10) \supset SU(4) \times SU(2)_L \times SU(2)_R$$

$$\mathbf{16} = (\mathbf{4}, \mathbf{2}, \mathbf{1}) + (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$$

$$\mathbf{10} = (\mathbf{6}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{2}, \mathbf{2})$$

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$$SU(4) \times SU(2)_L \times SU(2)_R \supset SU(3) \times SU(2) \times U(1)$$

$$F_L(\mathbf{4}, \mathbf{2}, \mathbf{1}) \to Q(\mathbf{3}, \mathbf{2}, -\frac{1}{6}) + \ell(\mathbf{1}, \mathbf{2}, \frac{1}{2})$$
$$\bar{F}_R(\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2}) \to u^c(\bar{\mathbf{3}}, \mathbf{1}, \frac{2}{3}) + d^c(\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{3}) + e^c(\mathbf{1}, \mathbf{1}, -1) + \nu^c(\mathbf{1}, \mathbf{1}, 0)$$
$$D(\mathbf{6}, \mathbf{1}, 1) \to D_3(\mathbf{3}, \mathbf{1}, \frac{1}{3}) + \bar{D}_3(\bar{\mathbf{3}}, \mathbf{1}, -\frac{1}{3})$$
$$h(\mathbf{1}, \mathbf{2}, \mathbf{2}) \to h^d(\mathbf{1}, \mathbf{2}, \frac{1}{2}) + h^u(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$$

The Pati-Salam model

Symmetry breaking The PS symmetry can be broken to the Standard Model by $\langle \nu_H^c \rangle$, $\langle \nu_H \rangle$

$$\bar{H}(\bar{\mathbf{4}},\mathbf{1},\mathbf{2}) \to u_H^c(\bar{\mathbf{3}},\mathbf{1},\frac{2}{3}) + d_H^c(\bar{\mathbf{3}},\mathbf{1},-\frac{1}{3}) + \nu_H^c(\mathbf{1},\mathbf{1},0) + e_H^c(\mathbf{1},\mathbf{1},-1)$$

$$H(\mathbf{4},\mathbf{1},\mathbf{2}) \to u_H(\mathbf{3},\mathbf{1},-\frac{2}{3}) + d_H(\mathbf{3},\mathbf{1},\frac{1}{3}) + \nu_H(\mathbf{1},\mathbf{1},0) + e_H(\mathbf{1},\mathbf{1},1)$$

Triplet mass

$$H^2\, D + \bar{H}^2\, D \to d_H\, \bar{D}_3\, \langle \nu_H \rangle + d_H^c\, D_3\, \langle \nu_H^c \rangle$$

We need at least one $(\mathbf{6},\mathbf{1},1)$ to realize this mechanism.

Fermion masses

$$F_L(\mathbf{4},\mathbf{2},\mathbf{1})\bar{F}_R(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})\,\langle h(\mathbf{1},\mathbf{2},\mathbf{2})\rangle \qquad (1)$$

Neutrinos mix with additional heavy singlets

$$\mathcal{M}_{\nu,\nu^c,\varphi} = \begin{pmatrix} 0 & v & 0 \\ v & 0 & M_{GUT} \\ 0 & M_{GUT} & M \end{pmatrix} \to \frac{v^2\, M}{M_{GUT}^2} \qquad (2)$$

Superstring realization of PS gauge symmetry

Add and extra vector to $SO(10)$ basis

$$v_{13} = \alpha = \{\bar{\psi}^{45}\bar{\phi}^{1,2}\}$$

that introduces 12 new GSO projection phases $c[\alpha, v_j], j = 1, \ldots, 12$.

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Gauge Group: $SU(4) \times SU(2)_L \times SU(2)_R \times U(1)^3 \times SU(2)^4 \times SO(8)$

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The α-projection truncates $SO(10)$ multiplets

$$SO(10) \supset SU(4) \times SU(2)_L \times SU(2)_R$$
$$\mathbf{16} = (\mathbf{4}, \mathbf{2}, \mathbf{1}) + (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})$$
$$\overline{\mathbf{16}} = (\bar{\mathbf{4}}, \mathbf{2}, \mathbf{1}) + (\mathbf{4}, \mathbf{1}, \mathbf{2})$$
$$\mathbf{10} = (\mathbf{6}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{2}, \mathbf{2})$$

So we need $2 \times \mathbf{16}$ for each family and one pair of $\mathbf{16}+\overline{\mathbf{16}}$ for the PS breaking Higgs

Superstring realization of PS gauge symmetry

Exotics The presence of fractional charge exotics is generic in these models.
A. N. Schellekens, Electric charge quantization in string theory (1989)

$k = 1$ Kac Moody Algebra
$\sin^2\theta_W = \frac{3}{8}$ at M_s
$\Rightarrow$ fractional charge states in the string spectrum

In all models constructed up to now a lot of these states appear in the massless string spectrum.

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In all models constructed up to now a lot of these states appear in the massless string spectrum.
Some solutions to this problem discussed up to now are:

1. Construct models with higher k (higher $SU(3), SU(2)$ reps)
2. Assume the exotics transform under hidden sector (eg. Flipped $SU(5)$ string model , $SU(4)$ hidden, is this enough ?)
3. Find appropriate flat directions to make them massive at the effective field theory level (usually restricts seriously the vacuum selection)
4. Search for models where these states are vector-like and assume they will get mass to some level (see e.g. Schellekens 2009)

Superstring realization of PS gauge symmetry

Possible exotics in the PS model

$$Q_{em} = \frac{1}{\sqrt{6}} T_{15} + \frac{1}{2} I_{3L} + \frac{1}{2} I_{3R}$$

$$(\mathbf{4},\mathbf{1},\mathbf{1}) + (\bar{\mathbf{4}},\mathbf{1},\mathbf{1}) : \pm \frac{1}{6} \text{ exotic colored particles}$$

$$(\mathbf{1},\mathbf{2},\mathbf{1}) : \pm \frac{1}{2} \text{ leptons}$$

$$(\mathbf{1},\mathbf{1},\mathbf{2}) : \pm \frac{1}{2} \text{ SM singlets}$$

Search strategy

A model is characterized by 9 integers $(n_g, k_L, k_R, n_6, n_h, n_4, n_{\bar{4}}, n_{2L}, n_{2R})$

$$n_{4L} - n_{\bar{4}R} = n_{\bar{4}L} - n_{4R} = n_g = \#\text{ of generations}$$
$$n_{\bar{4}L} = k_L = \#\text{ of non chiral left pairs}$$
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$$n_h = \#\text{ of } (\mathbf{1}, \mathbf{2}, \mathbf{2})$$

$$n_4 = \#\text{ of } (\mathbf{4}, \mathbf{1}, \mathbf{1})\text{ (exotic)}$$

$$n_{\bar{4}} = \#\text{ of } (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{1})\text{ (exotic)}$$

$$n_{2L} = \#\text{ of } (\mathbf{1}, \mathbf{2}, \mathbf{1})\text{ (exotic)}$$

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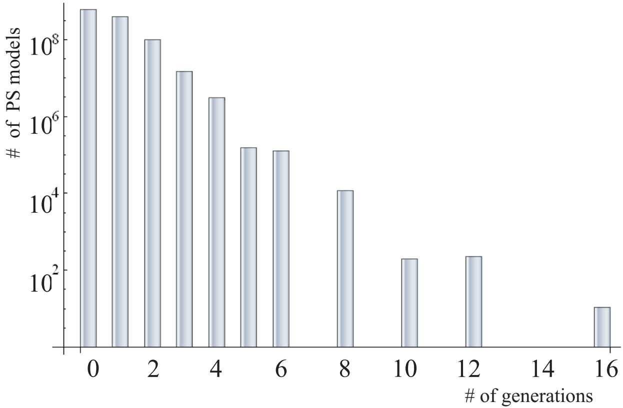
$$n_{2R} = \#\text{ of } (\mathbf{1}, \mathbf{1}, \mathbf{2})\text{ (exotic)}$$

We have derived analytic formulae for all these quantities, similar to the $SO(10)$ case ↰.
It turns out that the depend on 51 GSO phases , that leads to a class of $2^{51} \sim 2 \times 10^{15}$ models.

Generation structure of PS models

Results of a preliminary random search over 5×10^9 out of $2^{51} \sim 2 \times 10^{15}$ PS models



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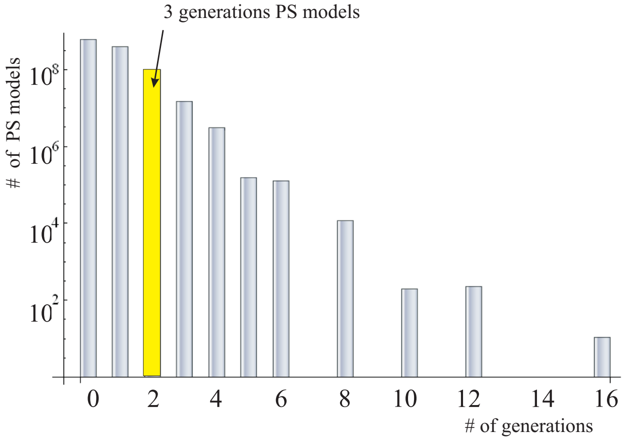

Exotic particle structure of PS models

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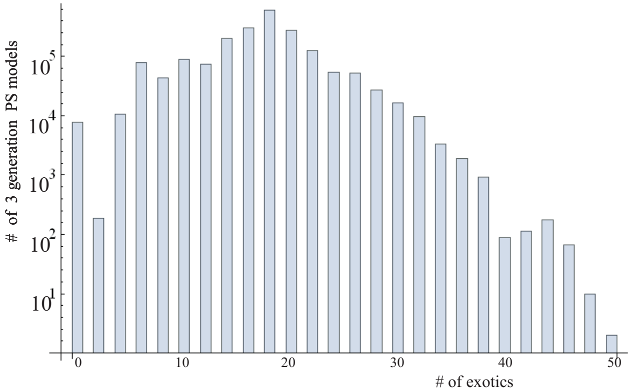

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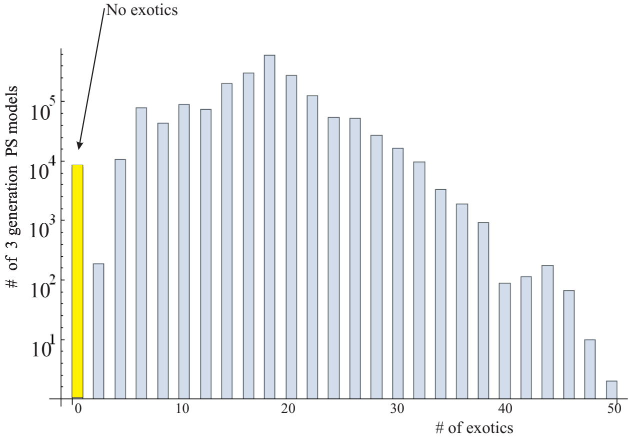

Minimal PS models

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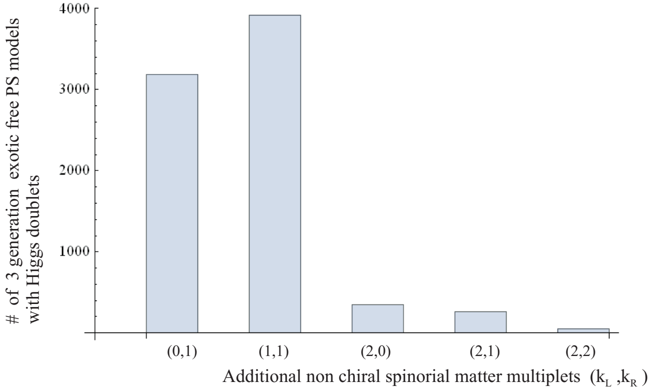
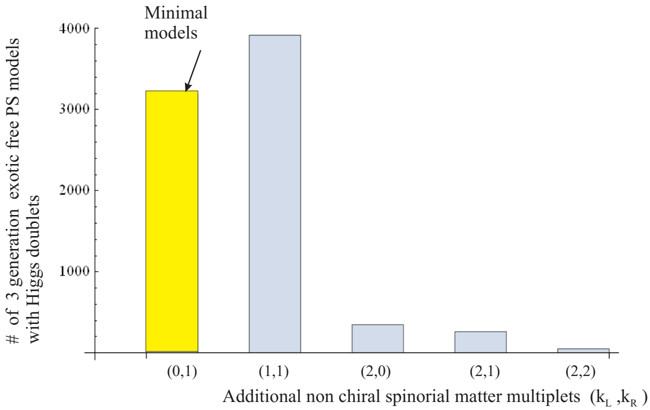


Minimal PS models

Results of a preliminary random search over 5×10^9 out of $2^{51} \sim 2 \times 10^{15}$ PS models



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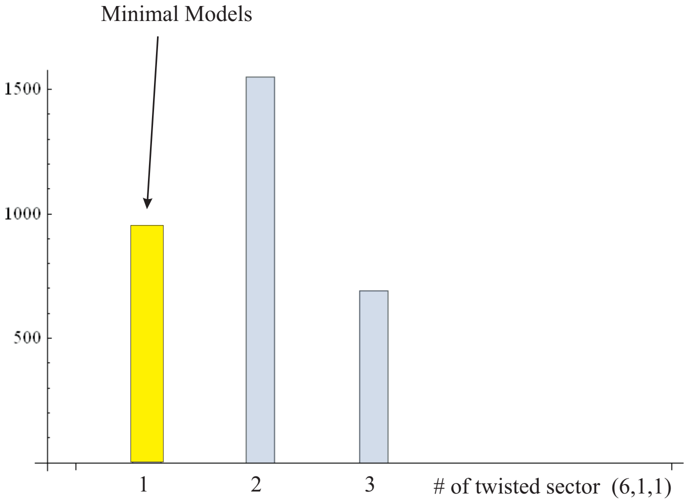

Summary of the Pati–Salam model landscape

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	Constraint	probability	# of models
	No gauge group enhancements	2×10^{-1}	2×10^{14}
$+$	3 generation models	3×10^{-3}	7×10^{12}
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+	Minimal spectrum	2×10^{-7}	4×10^{8}

Conclusions

- We have developed tools that allow the exploration of $2^{51} \sim 10^{15}$ Pati-Salam heterotic $Z_2 \times Z_2$ $N = 1$ vacua
- The heterotic PS vacua seem to be very rich, realistic models (3 generations, PS breaking Higgs, SM breaking Higgs) correspond to 3×10^{-4} of this class
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- Explore the phenomenology of this class of models (Fermion mass matrices).
- Abelian anomaly free models ? (Z')
- Try to explore other models including the SM in this framework.