Machine learning in $Z_2 \times Z_2$ orbifold classification

or, *What do we need machine learning for?*

- Classification of $Z_2 \times Z_2$ orbifolds 2003 –

  With: Costas Kounnas, John Rizos, Sander Nooij, Ben Assel,

  Kyriakos Christodoulides, Laura Bernard, Ivan Glazer,

  Hasan Sonmez, Glyn Harries, Ben Percival

- Related results:

  Spinor–Vector duality, Exophobia, stringy Z' models, ...

Machine Learning in the String Landscape, ICTP, Trieste, 12 December 2018

String Phenomenology: An answer in search of a question

The Answer : The Standard Model and its BSM extensions

A question : What is the true string vacuum?

A question : Can we identify signatures of classes of string compactifications in the experimental particle data?

In this talk:

Classification of fermionic $Z_2 \times Z_2$ orbifold compactifications

Where can novel computational tools help?

PHENOMENA

DATA $\longrightarrow$ STANDARD MODEL

EWX -> PERTUBATIVE

STANDARD MODEL -> UNIFICATION

EVIDENCE: 16 of SO(10), Log running, proton stability, neutrino masses

+ GRAVITY < - - > STRINGS

PRIMARY GUIDES:

3 generations
SO(10) embedding

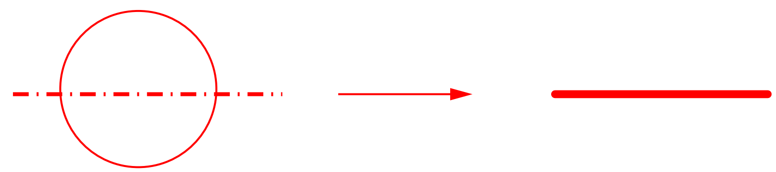
REALISTIC STRING MODELS :

heterotic 10D –> heterotic 4D

6D compactifications $(T^2 \times T^2 \times T^2)$

Orbifold – twists of flat 6D torus

Z_2



FREE FERMIONIC MODELS –

$Z_2 \times Z_2$ Orbifold –> $U(1)_Y \in SO(10)$

$$\frac{6}{2} = 1 + 1 + 1$$

Realistic free fermionic models

'Phenomenology of the Standard Model and Unification'

- Minimal Superstring Standard Model NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Top quark mass $\sim$ 175–180GeV PLB 274 (1992) 47
- Generation mass hierarchy NPB 407 (1993) 57
- CKM mixing NPB 416 (1994) 63 (with Halyo)
- Stringy seesaw mechanism PLB 307 (1993) 311 (with Halyo)
- Gauge coupling unification NPB 457 (1995) 409 (with Dienes)
- Proton stability NPB 428 (1994) 111
- Squark degeneracy NPB 526 (1998) 21 (with Pati)
- Moduli fixing NPB 728 (2005) 83
- Classification & Exophobia 2003 – $\cdots$ (with Nooij, Assel, Christodoulides, Kounnas, Rizos & Sonmez)

Other approaches

Geometrical

Greene, Kirklin, Miron, Ross (1987)
Donagi, Ovrut, Pantev, Waldram (1999)
Blumenhagen, Moster, Reinbacher, Weigand (2006)
Heckman, Vafa (2008)
....

Orbifolds

Ibanez, Nilles, Quevedo (1987)
Bailin, Love, Thomas (1987)
Kobayashi, Raby, Zhang (2004)
Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter (2007)
Blaszczyk, Groot–Nibbelink, Ruehle, Trapletti, Vaudrevange (2010)
....

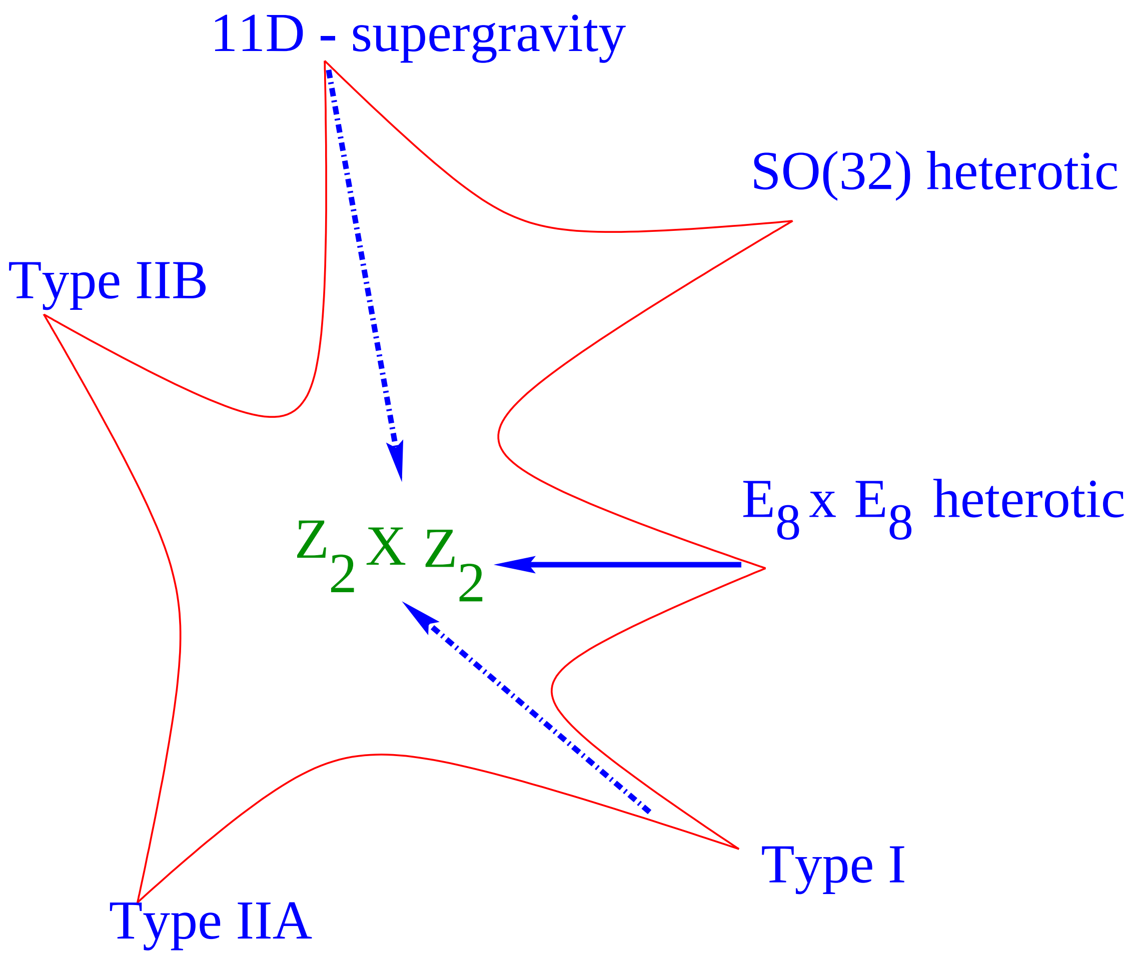
Other CFTs

Gepner (1987)
Schellekens, Yankielowicz (1989)
Gato–Rivera, Schellekens (2009)
....

Orientifolds

Cvetic, Shiu, Uranga (2001)
Ibanez, Marchesano, Rabadan (2001)
Kiristis, Schellekens, Tsulaia (2008)
....

Point, String, Membrane ....



String GUT models in the Free Fermionic Construction:

Left-Movers: $\psi^{\mu}_{1,2}, \quad \chi_i, \quad y_i, \ \omega_i \quad (i = 1, \cdots, 6)$

Right-Movers

$$\bar{\phi}_{A=1,\cdots,44} = \begin{cases} \bar{y}_i \ , \ \bar{\omega}_i & i = 1, \cdots, 6 \\ \\ \bar{\eta}_i & U(1)_i \quad i = 1,2,3 \\ \bar{\psi}_{1,\cdots,5} & SO(10) \\ \bar{\phi}_{1,\cdots,8} & SO(16) \end{cases}$$

Models $\longleftrightarrow$ Basis vectors $+$ one–loop phases

Free Fermionic Models: $Z_2 \times Z_2$ orbifolds with discrete Wilson lines

Old School:

The NAHE set : $\{\ \mathbf{1},\ S\ ,\quad b_1\ ,\quad b_2\ ,\quad b_3\ \}$

$N = \quad 4 \quad \rightarrow \quad 2 \qquad 1 \qquad 1$ vacua

$Z_2 \times Z_2$ orbifold compactification

$\Longrightarrow$ Gauge group $SO(10) \times SO(6)^{1,2,3} \times E_8$

beyond the NAHE set Add $\{\alpha, \beta, \gamma\}$ $e.g.$ FNY model

number of generations is reduced to three

$$SO(10) \quad \longrightarrow \quad SU(3) \times SU(2) \times U(1)_{T_{3_R}} \times U(1)_{B-L}$$

$$U(1)_Y \ = \ \tfrac{1}{2}(B-L) \ + \ T_{3_R} \ \in \ SO(10)\ !$$

$$SO(6)^{1,2,3} \quad \longrightarrow \quad U(1)^{1,2,3} \ \times \ U(1)^{1,2,3}$$

Exotic matter :

In realistic string models

Unifying gauge group $\Rightarrow$ broken by "Wilson lines".

$\Rightarrow$ non–GUT physical states.

$\Rightarrow$ Meta-stable heavy string relics

$\rightarrow$ Dark Mater NPB 477 (1996) 65

(with Coriano and Chang)

Provided that $N^c_L \in 16$, $\overline{N}^c \in \overline{16}$ Exist in the spectrum

Discrete symmetry : $U(1)_{T_{3_R}} \times U(1)_{B-L} \rightarrow U(1)_Y$

FNY model (NPB 335 (1990) 347) $\rightarrow$ no $\overline{N}^c \in \overline{16}$

$\Rightarrow$ Forced to use exotics $\Longleftrightarrow$ No discrete symmetry

Classification of fermionic $Z_2 \times Z_2$ orbifolds (Modern School)

Basis vectors:

$$
\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\}, \\
z_1 &= \{\bar{\phi}^{1,\dots,4}\}, \\
z_2 &= \{\bar{\phi}^{5,\dots,8}\}, \\
e_i &= \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6, \qquad N = 4 \text{ Vacua} \\
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, \qquad N = 4 \to N = 2 \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, \qquad N = 2 \to N = 1 \\
\alpha &= \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\} \qquad \& \quad SO(10) \to SO(6) \times SO(4) \times \cdots \\
\beta &= \{\bar{\psi}^{1,\cdots,5} \equiv \tfrac{1}{2}, \cdots\} \qquad \& \quad SO(10) \to SU(5) \times U(1) \times \cdots
\end{aligned}
$$

Independent phases $c\binom{v_i}{v_j} = \exp[i\pi(v_i|v_j)]$: upper block

$$
\begin{array}{cc}
 & \begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & z_1 & z_2 & b_1 & b_2 & \alpha \end{array} \\
\begin{array}{c} 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ z_1 \\ z_2 \\ b_1 \\ b_2 \\ \alpha \end{array} &
\left(\begin{array}{ccccccccccccc}
-1 & -1 & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\
 & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
 & & & & & & & \pm & \pm & \pm & \pm & \pm & \pm \\
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 & & & & & & & & & \pm & \pm & \pm & \pm \\
 & & & & & & & & & & \pm & \pm & \pm \\
 & & & & & & & & & & & \pm & \pm \\
 & & & & & & & & & & & -1 & \pm \\
 & & & & & & & & & & & &
\end{array}\right)
\end{array}
$$

A priori 66 independent coefficients $\longrightarrow$ 2^{66} distinct vacua

The twisted matter spectrum:

$$B^1_{\ell^1_3\ell^1_4\ell^1_5\ell^1_6} = S + b_1 + \ell^1_3 e_3 + \ell^1_4 e_4 + \ell^1_5 e_5 + \ell^1_6 e_6$$

$$B^2_{\ell^2_1\ell^2_2\ell^2_5\ell^2_6} = S + b_2 + \ell^2_1 e_1 + \ell^2_2 e_2 + \ell^2_5 e_5 + \ell^2_6 e_6$$

$$B^3_{\ell^3_1\ell^3_2\ell^3_3\ell^3_4} = S + b_3 + \ell^3_1 e_1 + \ell^3_2 e_2 + \ell^3_3 e_3 + \ell^3_4 e_4 \qquad l^j_i = 0, 1$$

sectors $B^i_{pqrs} \quad \rightarrow \quad 16$ or $\overline{16}$ of $SO(10)$ with multiplicity $(1, 0, -1)$

$B^i_{pqrs} + x \quad \rightarrow \quad 10$ of $SO(10)$ with multiplicity $(1, 0)$

$x = \{\bar\psi^{1,\cdots,5}, \bar\eta^1, \bar\eta^2, \bar\eta^3\}$ $\qquad x -$ map $\leftrightarrow$ spinor–vector map

Counting: for each B^i_{pqrs}:

Projectors: $$P^{(1)}_{p^1q^1r^1s^1} = \frac{1}{16} \prod \left(1 - c\binom{e_i}{B^{(1)}_{p^1q^1r^1s^1}}\right) \prod \left(1 - c\binom{z_i}{B^{(1)}_{p^1q^1r^1s^1}}\right)$$

$$S^{(i)}_{\pm} = \sum_{pqrs} \frac{1 \pm X^{(i)}_{p^iq^ir^is^i}}{2} P^{(i)}_{p^iq^ir^is^i}\ ,\ i = 1, 2, 3$$ similarly for vectorials

Algebraic formulas for $S = \sum_{i=1}^3 S^{(i)}_+ - S^{(i)}_-$ and $V = \sum_{i=1}^3 V^{(i)}$

Introducing the notation $c\binom{a_i}{a_j} = e^{i\pi(a_i|a_j)}\ ,\ (a_i\,|a_j) = 0,1$

the projectors can be written as system of equations

$$\Delta^{(I)}\,U_{16}^{(I)} = Y_{16}^{(I)} \quad , \quad \Delta^{(I)}\,U_{10}^{(I)} = Y_{10}^{(I)}\ ,\ I = 1,2,3$$

where the unknowns are the fixed point labels

$$U_{16}^{(I)} = \begin{bmatrix} p_{16}^I \\ q_{16}^I \\ r_{16}^I \\ s_{16}^I \end{bmatrix} \quad , \qquad U_{10}^{(I)} = \begin{bmatrix} p_{10}^I \\ q_{10}^I \\ r_{10}^I \\ s_{10}^I \end{bmatrix}$$

and

$$\Delta^{(1)} = \begin{bmatrix} (e_1\,|e_3) & (e_1\,|e_4) & (e_1\,|e_5) & (e_1\,|e_6) \\ (e_2\,|e_3) & (e_2\,|e_4) & (e_2\,|e_5) & (e_2\,|e_6) \\ (z_1\,|e_3) & (z_1\,|e_4) & (z_1\,|e_5) & (z_1\,|e_6) \\ (z_2\,|e_3) & (z_2\,|e_4) & (z_2\,|e_5) & (z_2\,|e_6) \end{bmatrix} \quad ; \quad \Delta^{(2)} \ldots$$

$$Y_{16}^{(1)} = \begin{bmatrix} (e_1 \,|b_1) \\ (e_2 \,|b_1) \\ (z_1 \,|b_1) \\ (z_2 \,|b_2) \end{bmatrix} \quad , \quad Y_{16}^{(2)} = \ldots$$

$$Y_{10}^{(1)} = \begin{bmatrix} (e_1 \,|b_1 + x) \\ (e_2 \,|b_1 + x) \\ (z_1 \,|b_1 + x) \\ (z_2 \,|b_2 + x) \end{bmatrix} \quad , \quad Y_{10}^{(2)} = \ldots$$

The number of solutions per plane

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

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

Spinor–vector duality:

Duality under exchange of spinors and vectors.

First Plane			Second plane			Third Plane			
s	$\bar{s}$	v	s	$\bar{s}$	v	s	$\bar{s}$	v	# of models
2	0	0	0	0	0	0	0	0	1325963712
0	2	0	0	0	0	0	0	0	1340075584
1	1	0	0	0	0	0	0	0	3718991872
0	0	2	0	0	0	0	0	0	6385031168

# of models with $\#(16+\overline{16})$ = # of models with $\#(10)$

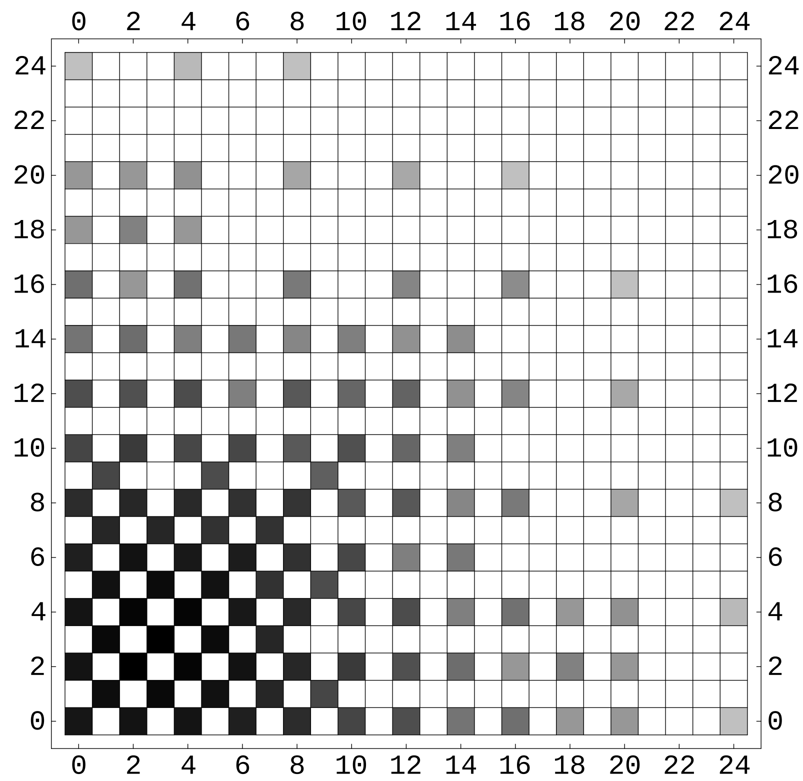
For every model with $\#(16+\overline{16})$ & $\#(10)$

There exist another model in which they are interchanged

Reflects discrete exchange of phases

Spinor–vector duality:

Invariance under exchange of $\#(16+\overline{16}) \;\; <-> \;\; \#(10)$



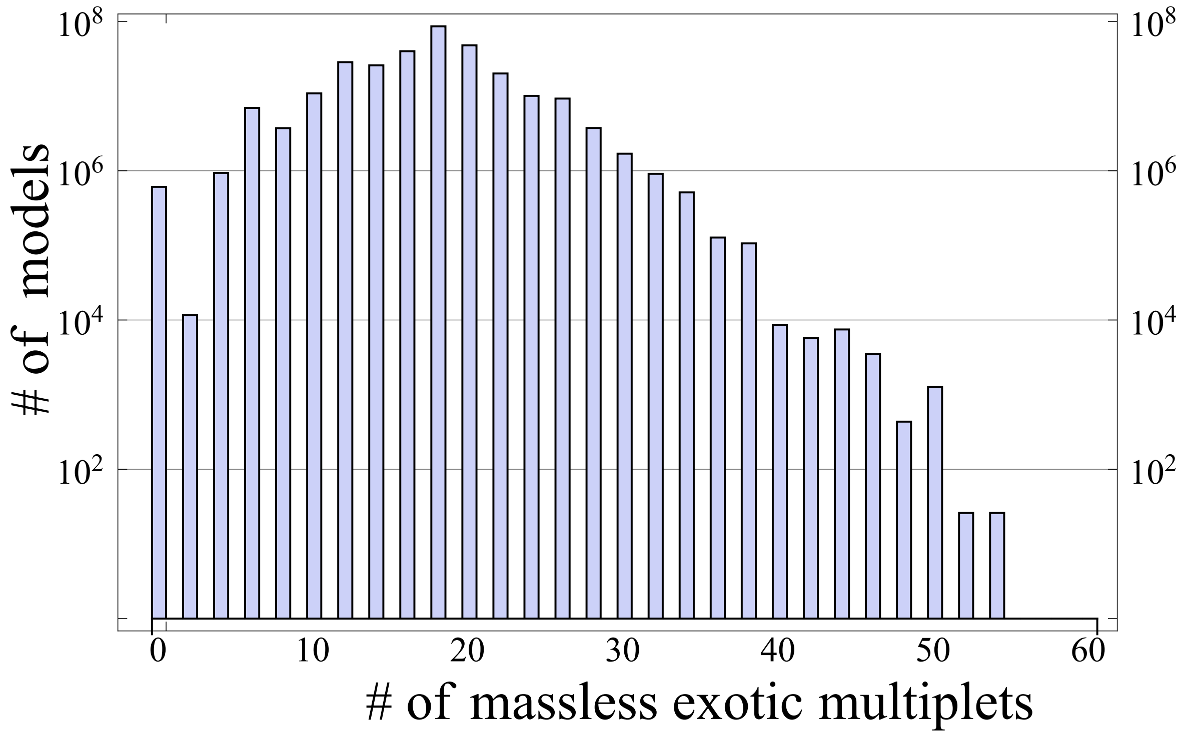
Symmetric under exchange of rows and columns

$$E_6 \;\; : \qquad 27 = 16 + 10 + 1 \qquad \overline{27} = \overline{16} + 10 + 1$$

Self-dual: $\#(16+\overline{16}) \;\; = \;\; \#(10)$ without E_6 symmetry

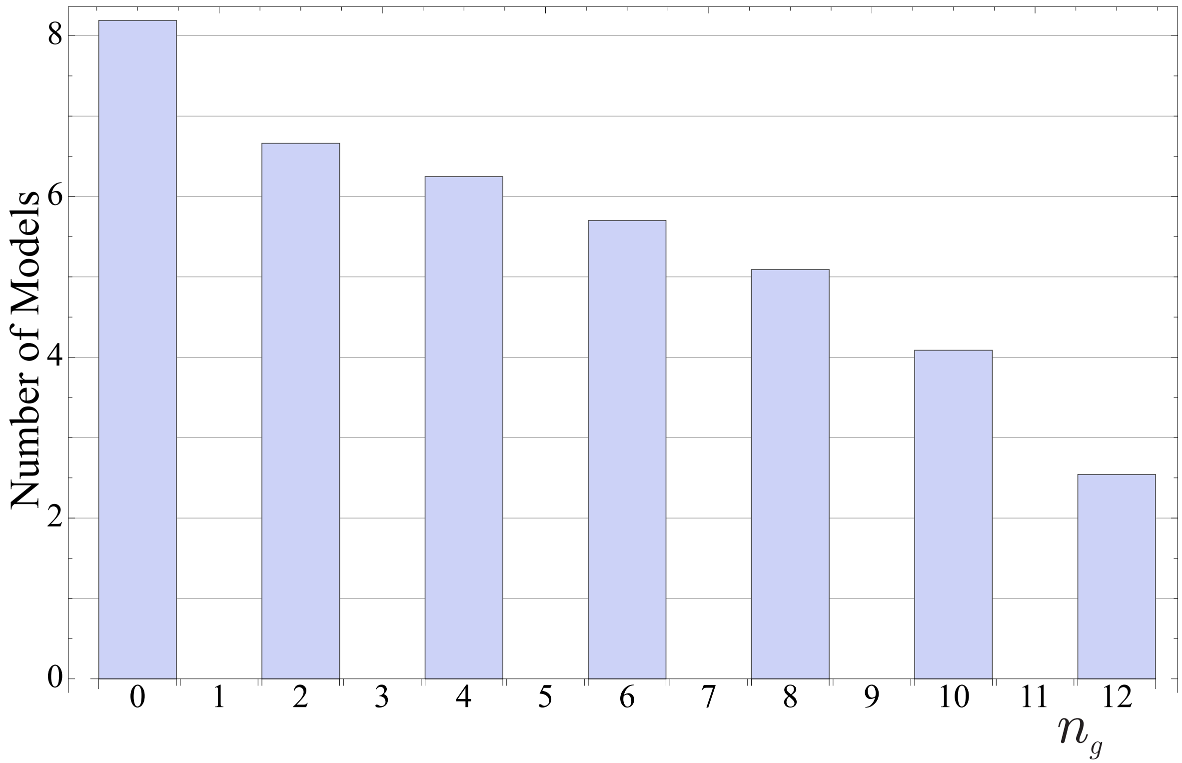
Pati–Salam class: with Assel, Christodoulides, Kounnas, Rizos

RESULTS: of random search of over 10^{11} vacua



Number of 3-generation models versus total number of exotic multiplets flipped $SU(5)$ class: with Sonmez, Rizos

RESULTS: of random search of over 10^{12} vacua



Number of exophobic models versus the number of generations

Low scale Z' in free fermionic models:

- $\frac{3}{2}U(1)_{B-L} - 2U(1)_R \in SO(10)$ @ $1TeV$ MPL A6 (1991) 61

  (with Nanopoulos)

- But $m_t = m_{\nu_\tau}$ & $1TeV\ Z' \Rightarrow\ m_{\nu_\tau} \approx 10MeV$ PLB 245 (1990) 435

  $\underline{E_6 \rightarrow SO(10) \times U(1)_A} \quad \Longrightarrow \quad U(1)_A$ is anomalous!

  $\Longrightarrow \quad U(1)_A \quad \notin$ low scale $U(1)_{Z'}$

- 1996-2013, Pati, AEF, Guzzi, Mehta, Athanasopoulos, $U(1) \notin E_6$

- On the other hand ....(AEF, Viraf Mehta, PRD88 (2013) 025006)

$$\sin^2\theta_W(M_Z)\ ,\ \alpha_s(M_Z) \quad \Longrightarrow \quad U(1)_{Z'}\ \in\ E_6$$

- Z' string derived model, (with Rizos) NPB 895 (2015) 233

light Z' heterotic–string model $c\binom{v_i}{v_j} = \exp[i\pi(v_i|v_j)]$:

$$
(v_i|v_j) \;=\; \begin{array}{c} \\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ b_1 \\ b_2 \\ z_1 \\ z_2 \\ \alpha \end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 & \alpha \end{array} \\
\left(\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{array}\right)
\end{array}
$$

Observable gauge group: $SO(6) \times SO(4) \times U(1)_{1,2,3}$

$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ is anomaly free

sector	field	$SU(4)\times SU(2)_L\times SU(2)_R$	$U(1)_1$	$U(1)_2$	$U(1)_3$	$U(1)_\zeta$
$S+b_1$	$\bar{F}_{1R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	1/2	0	0	1/2
$S+b_1+e_3+e_5$	F_{1R}	$(\mathbf{4},\mathbf{1},\mathbf{2})$	1/2	0	0	1/2
$S+b_2$	F_{1L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	1/2	0	1/2
$S+b_2+e_1+e_2+e_5$	F_{2L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	1/2	0	1/2
$S+b_2+e_1$	$\bar{F}_{2R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	1/2	0	1/2
$S+b_2+e_2+e_5$	$\bar{F}_{3R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	1/2	0	1/2
$S+b_3+e_1+e_2$	F_{3L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	0	1/2	1/2
$S+b_3+e_2$	$\bar{F}_{4R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	0	1/2	1/2
$S+b_3+x$	h_1	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	$-1/2$	0	-1
$S+b_2+x+e_5$	h_2	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	0	$-1/2$	-1
$S+b_2+x+e_1+e_2$	h_3	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	0	$-1/2$	-1
$S+b_3+x+e_1$	D_4	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	$-1/2$	0	-1
	χ_1^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1/2	1	$+2$
	χ_1^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1/2	-1	0
	$\zeta_a, a=2,3$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	$-1/2$	0	0
	$\bar{\zeta}_a, a=2,3$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	1/2	0	0
$S+b_2+x+e_1+e_5$	D_5	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	0	$-1/2$	-1
	χ_2^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1	1/2	$+2$
	χ_2^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	-1	1/2	0
	$\zeta_a, a=4,5$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	0	$-1/2$	0
	$\bar{\zeta}_a, a=4,5$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	0	1/2	0
$S+b_2+x+e_2$	D_6	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	0	$-1/2$	-1
	χ_3^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1	1/2	$+2$
	χ_3^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	-1	1/2	0
	$\zeta_a, a=6,7$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	0	$-1/2$	0
	$\bar{\zeta}_a, a=6,7$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	0	1/2	0
$S+b_1+x+e_3$	$\bar{D}_6$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	0	1/2	1/2	$+1$
	$\bar{\chi}_4^+$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	-1	$-1/2$	$-1/2$	-2
	$\bar{\chi}_4^-$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1	$-1/2$	$-1/2$	0
	$\zeta_a, a=8,9$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	$-1/2$	0
	$\bar{\zeta}_a, a=8,9$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	1/2	0
$S+b_1+x+e_5$	D_7	$(\mathbf{6},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1
	χ_5^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1	1/2	1/2	$+2$
	χ_5^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1/2	1/2	0
	$\zeta_a, a=10,11$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	$-1/2$	0
	$\bar{\zeta}_a, a=10,11$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	1/2	0
$S+b_3+x+e_2+e_3$	ζ_1	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	$-1/2$	0	0
	$\bar{\zeta}_1$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	1/2	0	0
$S+b_1+x+e_3+e_4+e_6$	ϕ_1	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	1/2	$+1$
	$\bar{\phi}_1$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1
$S+b_1+x+e_4+e_5+e_6$	ϕ_2	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	1/2	$+1$
	$\bar{\phi}_2$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1

Table 1: *Observable twisted matter spectrum and* $SU(4)\times SU(2)_L\times SU(2)_R\times U(1)^3$ *quantum numbers.*

The chiral spectrum is self–dual under spinor–vector duality

maintains the E_6 embedding $\quad \Rightarrow \quad U(1)_\zeta$ is anomaly free

Exophobic, three generations $+$ heavy and light higgs $+ \ \lambda_t \sim 1$

$$U(1)_{Z'} \ = \ \frac{1}{5}\,U(1)_C \ - \ \frac{1}{5}\,U(1)_L - U_\zeta$$

$Z' \Rightarrow$ Additional matter at the Z' breaking scale

Exotic $SO(10)$ singlets with non–standard $U(1)_\zeta$ charges

$\Rightarrow$ Natural Wilsonian dark–matter candidates

SLM random classifcation 1z: with Sonmez, Rizos

Total Models		1E+11
		1276526169
Total Realistic Models		3
States		Total
	-8	37
	-6	1047
	-5	756
	-4	34765
	-3	163225
	-2	3036744
	-1	76330452
	0	4505764853
	1	51148185
	2	1357446
	3	28878
	4	5046
	6	22
3 Generation Models		Total
Total Models		1E+11
		1276526169
Constraint		3
Number of 3 Generations		28878
SLM Heavy Higgs Breaking		0
SM Light Higgs Breaking		0
SLM Heavy Higgs Breaking & SM Light Higgs Breaking		0
Triplet Higgs		0
Minimal SLM Heavy Higgs Breaking		0
Minimal SMLight Higgs Breaking		0
Minimal SLM Heavy Higgs & SMLight Higgs Breaking		0
Minimal Higgs Triplet		0

SLM random classifcation 2z: with Sonmez, Rizos

Total Models		1E+11
		1276526169
Total Realistic Models		3
States		Total
	-8	37
	-6	1047
	-5	756
	-4	34765
	-3	163225
	-2	3036744
	-1	76330452
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Minimal SMLight Higgs Breaking		0
Minimal SLM Heavy Higgs & SMLight Higgs Breaking		0
Minimal Higgs Triplet		0

Standard-like Model class: with Sonmez, Rizos NPB 927 (2018) 1

RESULTS: of random search of over 10^{11} vacua

- Adaptation of the methodology:

- Two stage process;

- Random fertile $SO(10)$ models; Fertility conditions

- Complete SLM classification of fertile cores.

10^7 Three generation SLMs with standard light and heavy Higgs spectrum

Fertile 3 generations Standard-like Model classification 10^9 sample

	$n(Q)$	$n(L)$	$n(d^c)$; $n(\nu^c)$	$n(u^c)$;$n(e^c)$	$n(\overline{Q})$	$n(\overline{L})$	$n(\overline{d^c})$; $\mathbf{n}(\overline{\boldsymbol{\nu}^{\mathbf{c}}})$	$n(\overline{u^c})$; $n(\overline{e^c})$	$n(H_u)$; $n(H_d)$	$n(d^{c\prime})$; $n(\overline{d^{c\prime}})$	Multiplicity
1	3	3	3	3	0	0	0	0	1	1	27264
2	3	3	3	3	0	0	0	0	3	3	16896
3	3	3	3	3	0	0	0	0	2	0	7296
4	3	3	3	3	0	0	0	0	2	2	2304
5	3	3	3	3	0	0	0	0	5	1	1536
6	4	3	3	4	1	0	0	1	2	2	768
7	3	4	3	4	0	1	0	1	2	2	768
8	3	3	3	3	0	0	0	0	1	5	640
9	4	4	3	3	1	1	0	0	5	3	512
10	3	3	4	4	0	0	1	1	3	1	384
11	3	3	4	4	0	0	1	1	1	3	384
12	3	3	3	3	0	0	0	0	3	1	256
13	4	4	3	3	1	1	0	0	3	5	256
14	**3**	**3**	**4**	**4**	**0**	**0**	1	**1**	**7**	**1**	**192**
15	4	4	3	3	1	1	0	0	3	1	192
16	3	3	3	5	0	0	0	2	3	1	192
17	3	3	3	5	0	0	0	2	1	3	192
18	3	3	3	3	0	0	0	0	1	3	128
19	3	4	3	4	0	1	0	1	4	4	128
20	3	4	4	3	0	1	1	0	4	4	128
21	4	3	4	3	1	0	1	0	4	4	128
22	4	3	3	4	1	0	0	1	4	4	128
23	3	3	4	4	0	0	1	1	5	3	64
24	3	3	4	4	0	0	1	1	3	5	64
25	3	3	4	4	0	0	1	1	1	7	64

Conclusions

- DATA $\longrightarrow$ UNIFICATION
- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION
- Free fermionic models $\longleftrightarrow$ $Z_2 \times Z_2$ orbifolds $\longrightarrow$ A Fertile Crescent
- From exemplary models $\longrightarrow$ Large classes $\longrightarrow$ too large classes
- Question: Can ML tools be used to identify fertility conditions ?
- Glyn Harries, Ben Percival, (John Rizos)