Spinor–Vector Duality and Light Z' in heterotic string models

Motivation - vector bosons exist; proton stability; μ–parameter

Constraints

Constructions

With: John Rizos, NPB 895 (2015) 233

Costas Kounnas, Carlo Angelantonj, Ioannis Florakis

Viraf Mehta, Panos Athanasopolos, Hasan Sonmez

PLANCK 2015, Ioannina, 24-30 May 2015

DATA $\longrightarrow$ STANDARD MODEL

$$SU(3) \times SU(2) \times U(1)_Y \longrightarrow SU(5) \longrightarrow SO(10)$$

$$\left[\begin{pmatrix} \nu \\ e \end{pmatrix} + D^c_L \right] + \left[U^c_L + \begin{pmatrix} u \\ d \end{pmatrix} + E^c_L \right] + N^c_L$$

$$\bar{5} \quad + \quad 10 \quad 1 \qquad \underline{} \quad 16$$

STANDARD MODEL -> UNIFICATION

ADDITIONAL EVIDENCE:

Logarithmic running, proton longevity, neutrino masses

PRIMARY GUIDES:

3 generations

SO(10) embedding

Realistic free fermionic models

'Phenomenology of the Standard Model and string 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)
....

Some references on: 'Z' in free fermionic models'

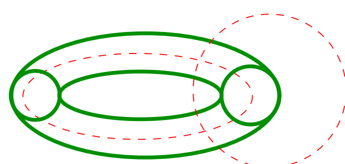
- $\frac{3}{2}U(1)_{B-L} - 2U(1)_R \in SO(10)$ @ $1TeV$ — MPL A6 (1991) 61 (with Nanopoulos)
- But $m_t = m_{\nu_\tau}$ & $1TeV\ Z' \Rightarrow\ m_{\nu_\tau} \approx 10MeV$ — PLB 245 (1990) 435
- Pati – 1996 $U(1)s \notin SO(10)\ \rightarrow\ \tau_{\rm P}$ & M_{ν_L} — PLB 388 (1996) 532
- Pati's $U(1)$s broken at $M_{\rm string}$ — PLB 499 (2001) 147
- String derived anomaly free Z' — PLB EPJC 53 (2008) 421 (with Coriano & Guzzi)
- String inspired collider Z' — PRD 78 (2008) 015012 (with Coriano & Guzzi)
- String inspired anomaly free model — PRD 84 (2011) 086006 (with Mehta)
- Gauge coupling constraints ... — (with Mehta)
- Z' string derived model ... — (with Rizos)

Free Fermionic Construction

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

Right-Movers

$$\bar{\phi}_{A=1,\cdots,44} = \begin{cases} \bar{y}_i \;,\; \bar{\omega}_i & i = 1, \cdots, 6 \\ & \\ \bar{\eta}_i & i = 1, 2, 3 \\ \bar{\psi}_{1,\cdots,5} & \\ \bar{\phi}_{1,\cdots,8} & \end{cases}$$



$$V \longrightarrow V \qquad\qquad f \longrightarrow -e^{i\pi\alpha(f)} f$$

$$Z = \sum_{\substack{all\ spin \\ structures}} c\binom{\vec{\alpha}}{\vec{\beta}} \, Z\binom{\vec{\alpha}}{\vec{\beta}}$$

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

Away from the free fermionic point: $Z_2 \times Z_2$ orbifolds

$$Z = \int \frac{d^2\tau}{\tau_2^2} \frac{\tau_2^{-1}}{\eta^{12}\bar\eta^{24}} \frac{1}{2^3} \left(\sum (-)^{a+b+ab} \vartheta\begin{bmatrix}a\\b\end{bmatrix} \vartheta\begin{bmatrix}a+h_1\\b+g_1\end{bmatrix} \vartheta\begin{bmatrix}a+h_2\\b+g_2\end{bmatrix} \vartheta\begin{bmatrix}a+h_3\\b+g_3\end{bmatrix} \right)_{\psi^\mu,}$$

$$\times \left(\frac{1}{2} \sum_{\epsilon,\xi} \bar\vartheta\begin{bmatrix}\epsilon\\\xi\end{bmatrix}^5 \bar\vartheta\begin{bmatrix}\epsilon+h_1\\\xi+g_1\end{bmatrix} \bar\vartheta\begin{bmatrix}\epsilon+h_2\\\xi+g_2\end{bmatrix} \bar\vartheta\begin{bmatrix}\epsilon+h_3\\\xi+g_3\end{bmatrix} \right)_{\bar\psi^{1\dots5},\bar\eta^{1,2,3}}$$

$$\times \left(\frac{1}{2} \sum_{H_1,G_1} \frac{1}{2} \sum_{H_2,G_2} (-)^{H_1G_1+H_2G_2} \bar\vartheta\begin{bmatrix}\epsilon+H_1\\\xi+G_1\end{bmatrix}^4 \bar\vartheta\begin{bmatrix}\epsilon+H_2\\\xi+G_2\end{bmatrix}^4 \right)_{\bar\phi^{1\dots8}}$$

$$\times \left(\sum_{s_i,t_i} \Gamma_{6,6}\begin{bmatrix}h_i|s_i\\g_i|t_i\end{bmatrix} \right)_{(y\omega\bar y\bar\omega)^{1\dots6}} \times e^{i\pi\Phi(\gamma,\delta,s_i,t_i,\epsilon,\xi,h_i,g_i,H_1,G_1,H_2,G_2)}$$

$$\Gamma_{1,1}[{}^h_g] = \frac{R}{\sqrt{\tau_2}} \sum_{\tilde m,n} \exp\left[-\frac{\pi R^2}{\tau_2} \left|(2\tilde m + g) + (2n+h)\,\tau\right|^2 \right]$$

The NAHE set:

$$1 \;=\; \{\psi^\mu,\; \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}$$

$$S \;=\; \{\psi^\mu, \chi^{1,\dots,6}\}, \qquad N=4 \text{ Vacua}$$

$$b_1 \;=\; \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, \qquad N=4 \rightarrow N=2$$

$$b_2 \;=\; \{\chi^{12}, \chi^{56}, y^{12}, \omega^{56} | \bar{y}^{12}, \bar{\omega}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, \qquad N=2 \rightarrow N=1$$

$$b_3 \;=\; \{\chi^{12}, \chi^{34}, \omega^{12}, \omega^{34} | \bar{\omega}^{12}, \bar{\omega}^{34}, \bar{\eta}^3, \bar{\psi}^{1,\dots,5}\}, \qquad N=2 \rightarrow N=1$$

$Z_2 \times Z_2$ orbifold compactification

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

beyond the NAHE set   Add $\{\alpha, \beta, \gamma\}$

number of generations is reduced to three

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

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

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

Towards String Predictions

1. Low energy supersymmetry

   Specific SUSY breaking patterns $\longrightarrow$ Collider implications

2. Additional gauge bosons

   Proton Stability and low–scale Z' $\longrightarrow$ Collider signatures

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 ; UHECR candidates

Patterns of $SO(10)$ symmetry breaking

The $SO(10) \rightarrow \mathrm{subgroup} \quad b(\bar\psi^{1\cdots5}_{\frac{1}{2}})$:

1. $b\{\bar\psi^{1\cdots5}_{\frac{1}{2}}\ \bar\eta^1\ \bar\eta^2\ \bar\eta^3\} = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \Rightarrow \ SU(5)\times U(1)\ \ U(1)\ U(1)\ U(1)$
2. $b\{\bar\psi^{1\cdots5}_{\frac{1}{2}}\ \bar\eta^1\ \bar\eta^2\ \bar\eta^3\} = \{\ 11100\ 000\ \} \Rightarrow SO(6)\times SO(4)\ U(1)\ U(1)\ U(1)$

$$(1. + 2.) \ \Rightarrow \ SO(10) \ \ \rightarrow SU(3)_C \times SU(2)_L \times U(1)_C \times U(1)_L$$

$$SO(10) \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

2. $b\{\bar\psi^{1\cdots5}_{\frac{1}{2}}\bar\eta^1\ \bar\eta^2\ \bar\eta^3\} = \{\ 11100000\ \} \Rightarrow SO(6)\times SO(4)\ U(1)\ U(1)\ U(1)$
3. $b\{\bar\psi^{1\cdots5}_{\frac{1}{2}}\ \bar\eta^1\ \bar\eta^2\ \bar\eta^3\} = \{\frac{1}{2}\frac{1}{2}\frac{1}{2}00\frac{1}{2}\frac{1}{2}\frac{1}{2}\} \Rightarrow$

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

$U(1)$ matter charges

in cases 1. 2.

$$\Longrightarrow \qquad Q_{U(1)_j}(16 = \{Q, L, U, D, E, N\}) \; = \; +\frac{1}{2}$$

$\Longrightarrow$ the $U(1)_{1,2,3}$ & $U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ are anomalous

In the LRS model of case 3.

$$\Longrightarrow \qquad Q_{U(1)_j}(Q_L, L_L) \; = \; -\frac{1}{2}$$

$$Q_{U(1)_j}(Q_R = \{U, D\}, L_R = \{E, N\}) \; = \; +\frac{1}{2}$$

$\Longrightarrow$ the $U(1)_{1,2,3}$ are anomaly free

STRING DERIVED LEFT-RIGHT SYMMETRIC MODEL

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	$y^{3,\dots,6}$	$\bar{y}^{3,\dots,6}$	$y^{1,2},\omega^{5,6}$	$\bar{y}^{1,2},\bar{\omega}^{5,6}$	$\omega^{1,\dots,4}$	$\bar{\omega}^{1,\dots,4}$	$\bar{\psi}^{1,\dots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,\dots,8}$
1	1	1	1	1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1,...,1	1	1	1	1,...,1
S	1	1	1	1	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0,...,0	0	0	0	0,...,0
b_1	1	1	0	0	1,...,1	1,...,1	0,...,0	0,...,0	0,...,0	0,...,0	1,...,1	1	0	0	0,...,0
b_2	1	0	1	0	0,...,0	0,...,0	1,...,1	1,...,1	0,...,0	0,...,0	1,...,1	0	1	0	0,...,0
b_3	1	0	0	1	0,...,0	0,...,0	0,...,0	0,...,0	1,...,1	1,...,1	1,...,1	0	0	1	0,...,0

	ψ^μ	χ^{12}	χ^{34}	χ^{56}	y^3y^6	$y^4\bar{y}^4$	$y^5\bar{y}^5$	$\bar{y}^3\bar{y}^6$	$y^1\omega^5$	$y^2\bar{y}^2$	$\omega^6\bar{\omega}^6$	$\bar{y}^1\bar{\omega}^5$	$\omega^2\omega^4$	$\omega^1\bar{\omega}^1$	$\omega^3\bar{\omega}^3$	$\bar{\omega}^2\bar{\omega}^4$	$\bar{\psi}^{1,\dots,5}$	$\bar{\eta}^1$	$\bar{\eta}^2$	$\bar{\eta}^3$	$\bar{\phi}^{1,\dots}$
α	0	0	0	0	1	0	0	0	0	0	1	1	0	0	1	1	1 1 1 0 0	0	0	0	1 1 1 1
β	0	0	0	0	0	0	1	1	1	0	0	0	0	1	0	1	1 1 1 0 0	0	0	0	1 1 0 0
γ	0	0	0	0	0	1	0	1	0	1	0	1	1	0	0	0	$\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ 0 0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1 $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

Gerald Cleaver, AEF and Christopher Savage, PRD 63:066001,2001.

3 generations;

3 untwisted Higgs bi–doublets;

Fermion mass terms arise from $N = 3$ and $N = 5$ superpotential terms

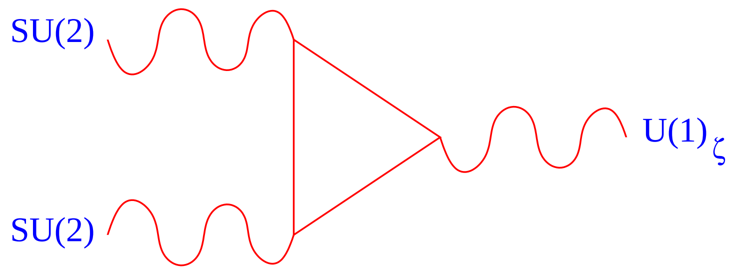
.

.

.

String inspired Z' model (with Viraf Mehta, PRD88 (2013) 02500

- String scale: $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_C \times U(1)_\zeta$
- Chiral matter states: $Q_L,\ Q_R = U + D,\ L_L,\ L_R = E + N$



- $\longrightarrow$ Add $SU(2)_{L/R}$ doublets to cancel gauge anomalies
- Gauge coupling unification $\rightarrow$ add triplets
- $\alpha_s(M_Z) \approx 0.1 \ \ \& \ \ \sin^2\theta(M_Z) \approx 0.231$

$$M_{SUSY} \approx 1\text{TeV};\ \ M_{Z'} > 10^8\text{GeV};\ \ M_D > 10^{12}\text{GeV};\ \ M_R \approx M_{string}$$

$E_6SSM \rightarrow M_{Z'} \approx 10\text{TeV} \quad \longrightarrow \quad$ Anomaly free $U(1)_\zeta$?

Classification of fermionic $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$
\begin{aligned}
1 &= \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\} \\
S &= \{\psi^\mu, \chi^{1,\dots,6}\}, \\
z_1 &= \{\bar{\phi}^{1,\dots,4}\}, \\
z_2 &= \{\bar{\phi}^{5,\dots,8}\}, \\
e_i &= \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6,
\end{aligned}
$$

$N = 4$ Vacua

$$
\begin{aligned}
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\}, & N = 4 \to N = 2 \\
b_2 &= \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\}, & N = 2 \to N = 1
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\} & \& \quad SO(10) \to SO(6) \times SO(4) \times \cdots \\
\beta &= \{\bar{\psi}^{1,\cdots,5} \equiv \tfrac{1}{2}, \cdots\} & \& \quad SO(10) \to SU(5) \times U(1) \times \cdots
\end{aligned}
$$

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

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

A priori 66 independent coefficients $\rightarrow$ 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} $\quad\longrightarrow\quad$ 16 or $\overline{16}$ of $SO(10)$ with multiplicity $(1,0,-1)$

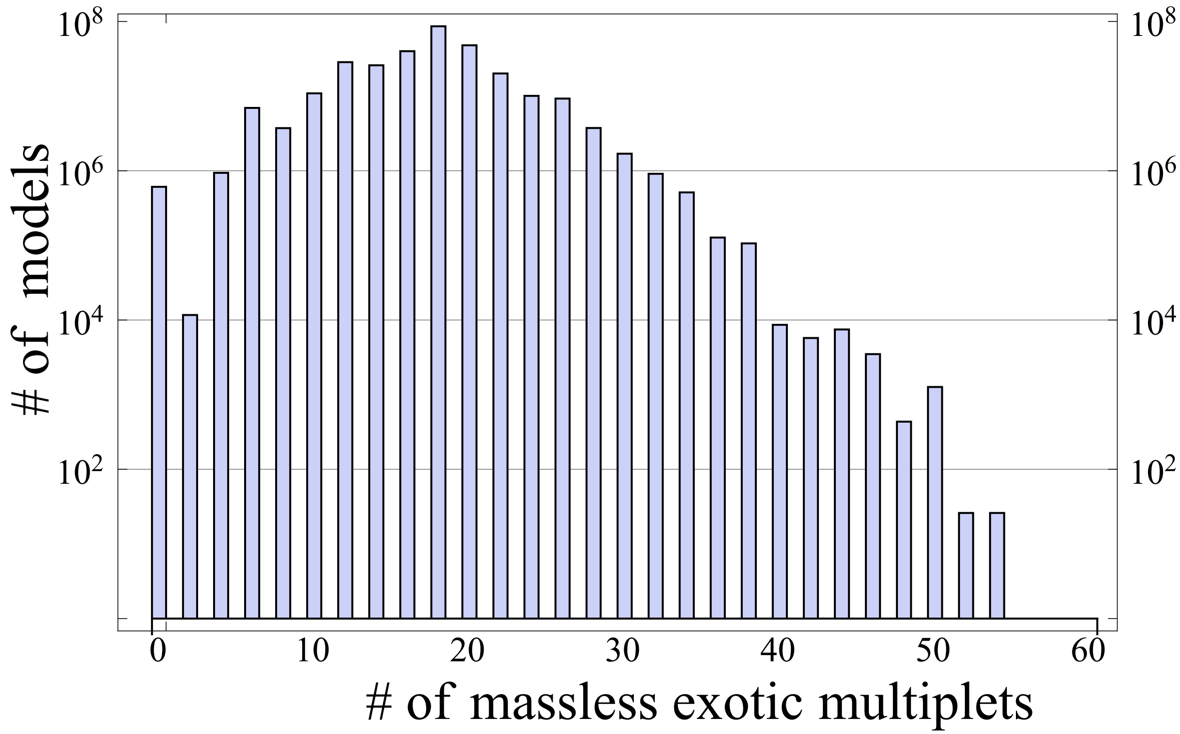
$B^i_{pqrs}+x \quad\longrightarrow\quad 10$ of $SO(10)$ with multiplicity $(1,0)$

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

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

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

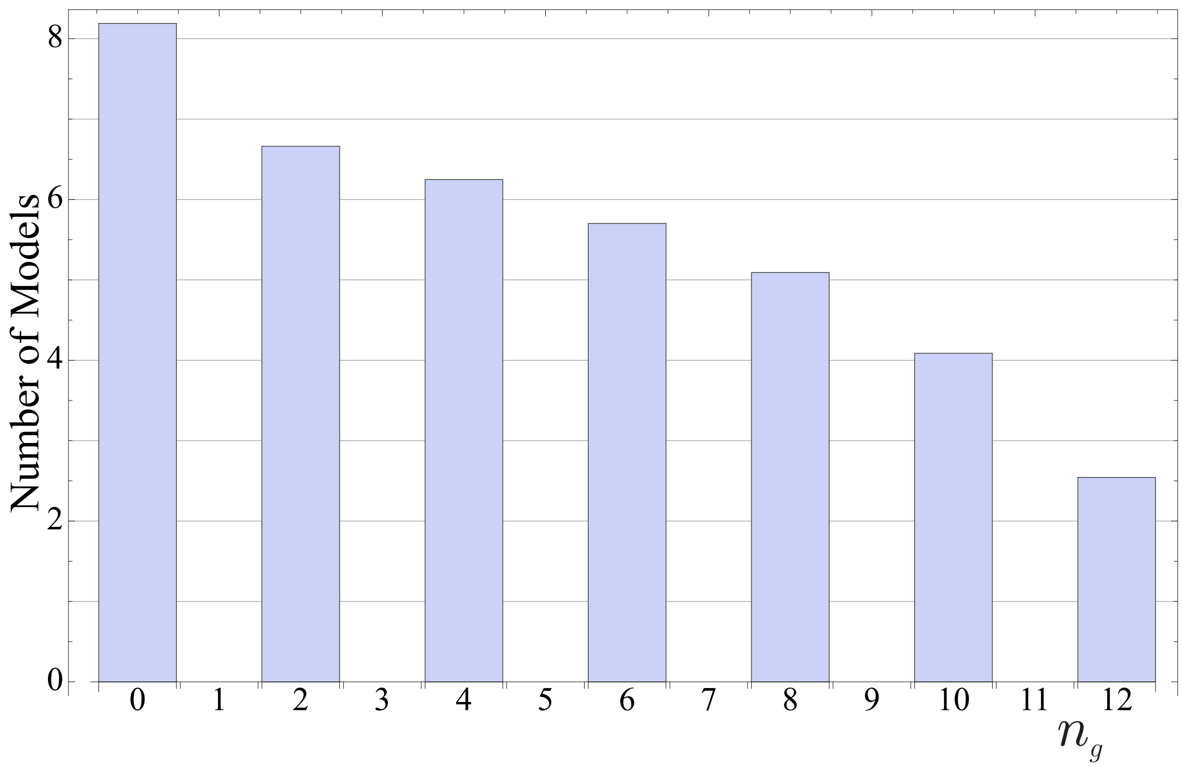
RESULTS: of random search of over 10^{11} vacua



Number of 3-generation models versus total number of exotic multiplets

flipped $SU(5)$ class: with Sonmez, Rizos

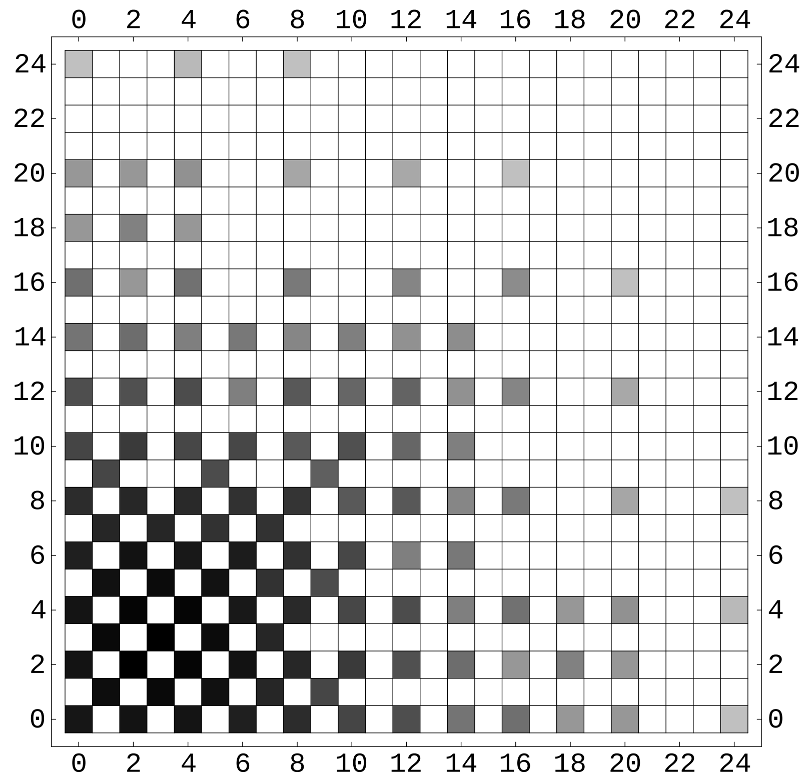
RESULTS: of random search of over 10^{12} vacua



Number of exophobic models versus the number of generations

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

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

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

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

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

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

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

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

$\Rightarrow$ Natural Wilsonian dark–matter candidates

Conclusions

- DATA $\longrightarrow$ HIGH SCALE UNIFICATION

- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION

- STRING CONSISTENCY REQUIRES EXTRA $U(1)$s
- EXPERIMENTAL PREDICTIONS ? Light Z' ?

motivated by proton stability; μ–term ...

Hard to implement $M_{Z'} \sim \mathrm{TeV}$ in heterotic string constructions ...

- $\Rightarrow$ Additional matter, dark matter candidates ...