Spinor–Vector Duality and Sterile Neutrinos in String Derived Models

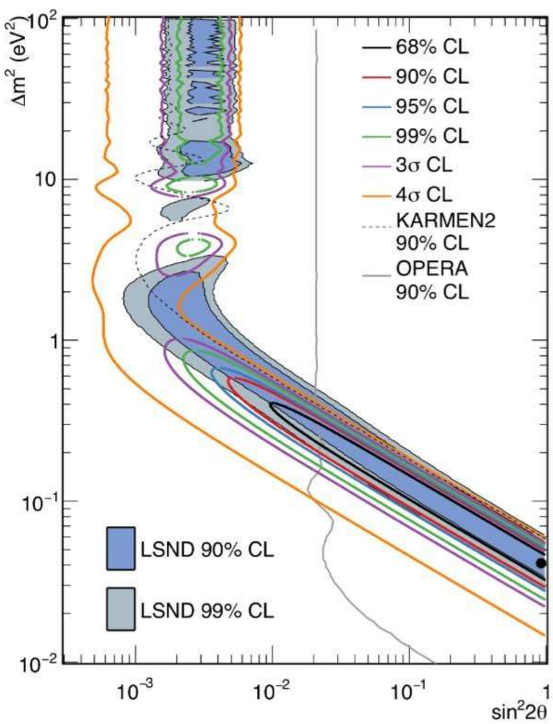
- Spinor–vector duality:

  With: Costas Kounnas, John Rizos, Carlo Angelantonj, Mirian Tsulaia, Ioannis Florakis, Thomas Mohaupt, Panos Athanasopoulos, Doron Gepner

- Sterile neutrinos:

  AEF, European Phys Journal C78 (2018) 867.

DISCRETE2018, Austrian Academy of Sciences, Vienna, 28 December 2018



LSND 1993: Evidence for sterile neutrinos

MiniBooNE 2018: Further evidence for sterile neutrinos

Sterile neutrinos in string vacua?

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:

Light sterile neutrinos in heterotic string vacua require a light Z'

A light Z' is hard to implement in heterotic string constructions

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

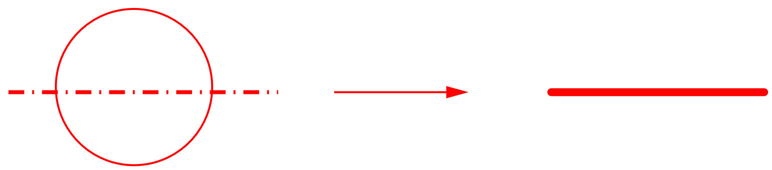
REALISTIC STRING MODELS :

heterotic 10D –> heterotic 4D

6D compactifications $(T^2 \, x \, T^2 \, x \, T^2)$

Orbifold – twists of flat 6D torus

Z_2



FREE FERMIONIC MODELS –

$Z_2 \, X \, Z_2$ 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 – · · ·

  (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)
....

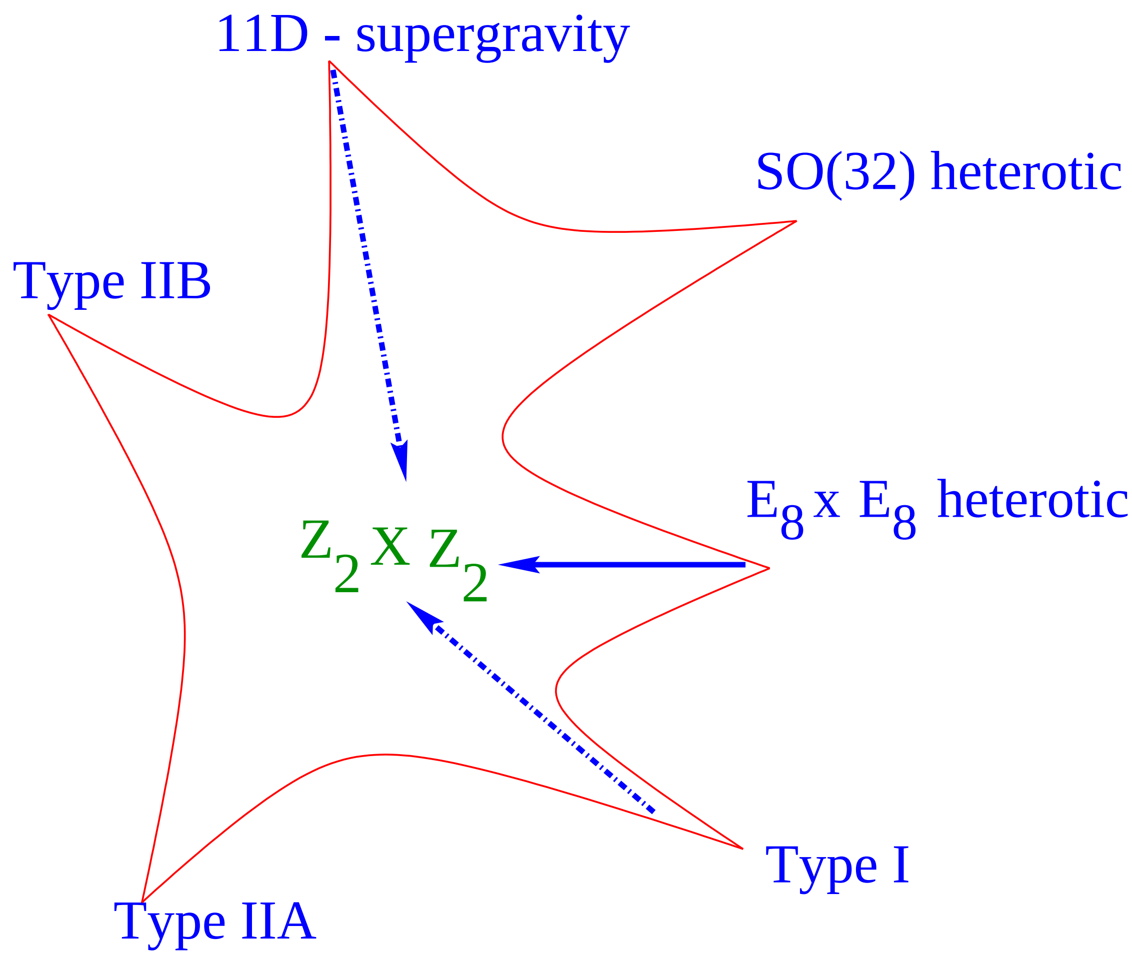
Other CFTs

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

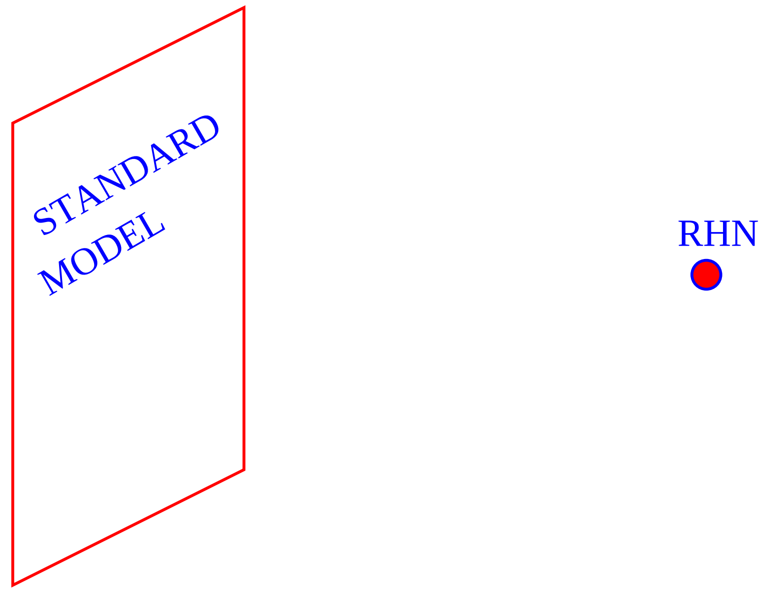
Orientifolds

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

Point, String, Membrane ....



Sterile neutrinos in large volume scenarios



$$\nu_R^{(c)}(x,y) = \sum_n \frac{1}{\sqrt{2\pi r}} \nu_{Rn}^{(c)}(x) e^{iny/r}$$

$$S^{\rm int} = \int d^4x \lambda l(x) h^*(x) \nu_R(x, y=0)$$

$$\lambda_{(4)} = \frac{\lambda}{\sqrt{r^n M_*^n}},$$

plus tower of KK modes $\longrightarrow$ sterile neutrinos

String GUT models in the Free Fermionic Construction:

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

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

Sterile neutrinos in free Fermionic models

Analyse mass terms constributing to the neutrino mass matrix

AEF & Edi Halyo, PLB **307** (1993) 311

AEF & Claudio Coriano, PLB **581** (2004) 99

The generic form:

$$\left(\nu_i,\ N_i,\ \phi_i\right)\begin{pmatrix} 0 & (M_D)_{ij} & 0 \\ (M_D)_{ij} & 0 & \langle\overline{\mathcal{N}}\rangle_{ij} \\ 0 & \langle\overline{\mathcal{N}}\rangle_{ij} & \langle\phi\rangle_{ij} \end{pmatrix}\begin{pmatrix} \nu_j \\ N_j \\ \phi_j \end{pmatrix},$$

$$m_{\nu_j} \sim \left(\frac{kM_u^j}{\langle\overline{\mathcal{N}}\rangle}\right)^2 \langle\phi\rangle \quad , \qquad m_{N_j}, m_\phi \sim \langle\overline{\mathcal{N}}\rangle \ .$$

$$\langle\overline{\mathcal{N}}\rangle \quad > \quad 10^{14}\mathrm{GeV}$$

No Light sterile neutrino

Specific example:

$$
\begin{array}{c|cccccccccccc}
 & L_3 & L_2 & L_1 & N_3 & N_2 & N_1 & H_{23} & H_{25} & \Phi_{13} & \Phi_{45} & \Phi_2^+ & \bar{\Phi}_2^+ \\
\hline
L_3 & 0 & 0 & 0 & 0 & 0 & r & 0 & 0 & 0 & 0 & 0 & 0 \\
L_2 & 0 & 0 & 0 & r & 0 & r & 0 & 0 & 0 & 0 & 0 & 0 \\
L_1 & 0 & 0 & 0 & r & 0 & v & 0 & 0 & 0 & 0 & 0 & 0 \\
N_3 & 0 & r & r & 0 & 0 & 0 & 0 & x & 0 & 0 & 0 & 0 \\
N_2 & 0 & 0 & 0 & 0 & 0 & 0 & z & 0 & u & u & z & u \\
N_1 & r & r & v & 0 & 0 & 0 & 0 & w & 0 & 0 & 0 & 0 \\
H_{23} & 0 & 0 & 0 & 0 & z & 0 & p & 0 & x & x & x & x \\
H_{25} & 0 & 0 & 0 & x & 0 & w & 0 & 0 & 0 & 0 & 0 & 0 \\
\Phi_{13} & 0 & 0 & 0 & 0 & u & 0 & x & 0 & q & y & 0 & y \\
\Phi_{45} & 0 & 0 & 0 & 0 & z & 0 & p & 0 & x & x & x & x \\
\Phi_2^+ & 0 & 0 & 0 & 0 & z & 0 & x & 0 & 0 & q & 0 & x \\
\bar{\Phi}_2^+ & 0 & 0 & 0 & 0 & 0 & 0 & x & 0 & y & q & x & q
\end{array}
$$

mass eigenvalues $\{1.7 \times 10^{13}, ..., 2.4^{-8}\}\mathrm{GeV}$

No Light sterile neutrinos -$>$ non–chiral matter -$>$ heavy

Sterile neutrinos -$>$ Chiral under and extra $U(1)$ symmetry

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

  $E_6 \rightarrow SO(10) \times U(1)_A \implies U(1)_A$ is anomalous!

  $\implies U(1)_A \notin$ 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)

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

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

Classification of fermionic $Z_2 \times Z_2$ orbifolds (PS talk by Ben Percival)

Basis vectors:

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

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

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

Independent phases $c\left[\begin{smallmatrix} v_i \\ v_j \end{smallmatrix}\right] = \exp[i\pi(v_i|v_j)]$: upper block

	1	S	e_1	e_2	e_3	e_4	e_5	e_6	z_1	z_2	b_1	b_2	α
1	-1	-1	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
S			-1	-1	-1	-1	-1	-1	-1	-1	1	1	-1
e_1				$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
e_2					$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
e_3						$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
e_4							$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
e_5								$\pm$	$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
e_6									$\pm$	$\pm$	$\pm$	$\pm$	$\pm$
z_1										$\pm$	$\pm$	$\pm$	$\pm$
z_2											$\pm$	$\pm$	$\pm$
b_1												$\pm$	$\pm$
b_2												-1	$\pm$
α													

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 $B^i_{pqrs} \quad \rightarrow \quad 16$ 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

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

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 $\#(10)$

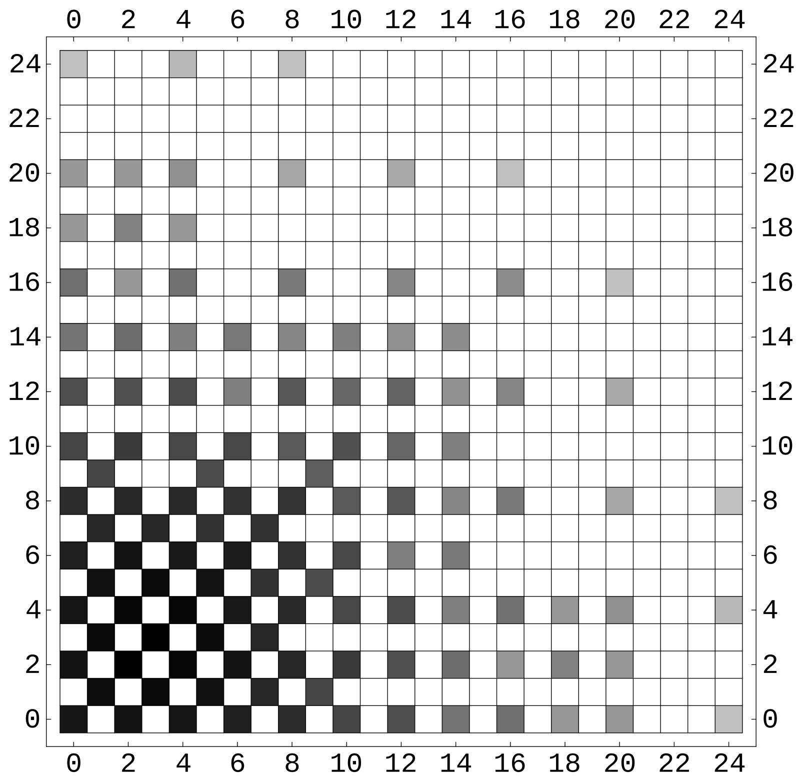
For every model with $\#(16+\overline{16})$ & $\#(10)$

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

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

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

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

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

Z' model at low scales   Heavy Higgs $\langle \mathcal{N} \rangle \sim M_{\rm String} \quad \rightarrow$ high seesaw $\rightarrow$

Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_Y$	$U(1)_{Z'}$
Q_L^i	3	2	$+\frac{1}{6}$	$-\frac{2}{5}$
u_L^i	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{5}$
d_L^i	$\bar{3}$	1	$+\frac{1}{3}$	$-\frac{4}{5}$
e_L^i	1	1	$+1$	$-\frac{2}{5}$
L_L^i	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
D^i	3	1	$-\frac{1}{3}$	$+\frac{4}{5}$
$\bar{D}^i$	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{6}{5}$
H^i	1	2	$-\frac{1}{2}$	$+\frac{6}{5}$
$\bar{H}^i$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
S^i	1	1	0	-2
h	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
$\bar{h}$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
ϕ	1	1	0	-1
$\bar{\phi}$	1	1	0	$+1$
ζ^i	1	1	0	0

Additional matter states at $U(1)_{Z'}$ breaking scale

Neutrino mass spectrum   a plausible scenario

$$\begin{array}{c} \\ L_i \\ S_i \\ H_i \\ \overline{H}_i \\ N_i \end{array} \begin{array}{c} \begin{array}{ccccc} L_i & S_i & H_i & \overline{H}_i & N_i \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & \lambda n & \lambda v \\ 0 & 0 & \lambda v_2 & \lambda v_3 & 0 \\ 0 & \lambda v_2 & 0 & z' & 0 \\ \lambda n & \lambda v_3 & z' & 0 & 0 \\ \lambda v & 0 & 0 & 0 & \mathcal{N}^2/M \end{pmatrix} \end{array},$$

$$\lambda v = 1\text{GeV}; \qquad \lambda n = 5 \times 10^{-4}\text{GeV}; \approx m_e;$$

$$\lambda v_2 = 5 \times 10^{-4}\text{GeV} \approx m_e; \qquad \lambda v_3 = 5 \times 10^{-4}\text{GeV}; \approx m_e;$$

$$z' = 5 \times 10^{4}\text{GeV} = 50\text{TeV}; \qquad \overline{\mathcal{N}} = 5 \times 10^{14}\text{GeV},$$

$m_{1,2} = \{10^{-2}$eV, 10^{-3}eV$\}$ mix of ν_L^i and S_i, with $\sin\theta \approx 0.98$.

$m_{3,4,5} = \{50$TeV, 50TeV, 2.5×10^{11}GeV$\}$.

$m_5 \leftrightarrow N_i$ $m_{3,4} \leftrightarrow$ equal mix of H_i and $\bar{H}_i$

Spinor–Vector Duality from a Novel Basis

$$
\begin{aligned}
S &= \{\psi^\mu, \chi^{1,\dots,6}\},\\
z_1 &= \{\bar\phi^{1,\dots,4}\},\\
z_2 &= \{\bar\phi^{5,\dots,8}\},\\
z_3 &= \{\bar\psi^{1,\dots,4}\},\\
z_4 &= \{\bar\eta^{0,\dots,3}\},\\
e_i &= \{y^i, \omega^i | \bar y^i, \bar\omega^i\},\ i = 1,\dots,6,
\end{aligned}
$$

$\bar\eta^0 \equiv \bar\psi^5$

$N = 4$ Vacua

$$
\begin{aligned}
1 &= S + \sum e_i + z_1 + z_2 + z_3 + z_4\\
b_1 &= \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar y^{34}, \bar y^{56}, \bar\eta^1, \bar\psi^{1,\dots,5}\},
\end{aligned}
$$

$N = 4 \longrightarrow N = 2$

Vector bosons: NS, $z_{1,2,3,4}$, $z_i + z_j$ NS $\rightarrow SO(8)^4$

$SO(12)$–GUT $\longrightarrow$ from enhancement

Duality picture is facilitated

Spinor $\longleftrightarrow$ Vector map $\longrightarrow$ $B \longleftrightarrow B + z_4$

$SO(12)$ enhancement $\longrightarrow$ $B \longleftrightarrow B + z_3$

A convenient basis to study dualities; modular properties

$\longrightarrow 2$D $\longrightarrow$ 24 dimensional lattices

GUT structure is obscured

Conclusions

- DATA $\longrightarrow$ UNIFICATION
- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION
- Free fermionic models $\longrightarrow$ A Fertile Crescent $\longleftrightarrow$ $Z_2 \times Z_2$ orbifolds
- Sterile neutrinos $\longrightarrow$ chiral matter charged under low scale extra $U(1)$
- Low scale Z' $\longrightarrow$ hard to implement in string GUT constructions
- Spinor–vector duality (alternatively: extended GUT embeddings)
- String Phenomenology $\longrightarrow$ Physics of the third millenium

  $e.g.$ Aristarchus to Copernicus