Roaming among free fermion models

Alon E. Faraggi

- Spinor-vector duality
- Free fermion and orbifold partition function

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DATA → STANDARD MODEL

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

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

$$\bar{5} \qquad + \qquad 10 \qquad\qquad 1 \qquad\qquad \frac{}{16}$$

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’

• 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 (1993) 409 (with Dienes)
• Proton stability	NPB 428 (1994) 111
• Squark degeneracy	NPB 526 (1998) 21 (with Pati)
• Minimal Superstring Standard Model	PLB 455 (1999) 135 (with Cleaver & Nanopoulos)
• Moduli fixing	NPB 728 (2005) 83

Free Fermionic Construction

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

Right-Movers

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

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

$$V \longrightarrow V$$

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

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

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

$$N = \quad 4 \quad \rightarrow \quad 2 \qquad\quad 1 \qquad\quad 1 \quad \text{vacua}$$

$Z_2 \times Z_2$ orbifold compactification

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

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

number of generations is reduced to three

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

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

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

Fermion mass hierarchy

Fermion mass terms

$$c g f_i f_j h \left(\frac{\langle\phi\rangle}{M}\right)^{N-3}$$

c - calculable coefficients g - gauge coupling

$f_i,\, f_j \;\in\; b_j \quad j \;=\; 1, 2, 3$

h → light Higgs multiplets

$M \;\sim\; 10^{18}\, GeV$

$\langle\phi\rangle$ generalized VEVs, several sources

Top quark mass prediction

only $\lambda_t = \langle t^c Q_t \bar{h}_1 \rangle = \sqrt{2}g \neq 0$ at $N = 3$

$$W_4 \longrightarrow b^c Q_b h_{\alpha\beta} \Phi_1 + \tau^c L_\tau h_{\alpha\beta} \Phi_1$$

$$\Longrightarrow \quad \lambda_b = \left(c_b \frac{\langle \phi \rangle}{M} \right) \qquad \lambda_\tau = \left(c_\tau \frac{\langle \phi \rangle}{M} \right)$$

$$\longrightarrow \quad \lambda_b = \lambda_\tau = 0.35 g^3 \sim \frac{1}{8} \lambda_t$$

Evolve λ_t , λ_b to low energies

$$m_t = \lambda_t v_1 = \lambda_t \frac{v_0}{\sqrt{2}} \sin\beta \qquad m_b = \lambda_b v_2 = \lambda_b \frac{v_0}{\sqrt{2}} \cos\beta$$

where $v_0 = \dfrac{2m_W}{g_2(M_Z)} = 246\mathrm{GeV}$ and $(v_1^2 + v_2^2) = \dfrac{v_0^2}{2}$

$$m_t = \lambda_t(m_t) \frac{v_0}{\sqrt{2}} \frac{\tan\beta}{(1 + \tan^2\beta)^{\frac{1}{2}}} \Longrightarrow \quad m_t \sim 175\mathrm{GeV} \quad \mathrm{PLB274(1992)47}$$

Cabibbo mixing

PLB 307 (1993) 305

Find anomaly free solution

$$M_d \sim \begin{pmatrix} \epsilon & \frac{V_2 \bar{V}_3 \Phi_{\alpha\beta}}{M^3} & 0 \\ \frac{V_2 \bar{V}_3 \Phi_{\alpha\beta} \xi_1}{M^4} & \frac{\bar{\Phi}_2^- \xi_1}{M^2} & 0 \\ 0 & 0 & \frac{\Phi_1^+ \xi_2}{M^2} \end{pmatrix} v_2,$$

$\epsilon < 10^{-8}$

$$\frac{V_2 \bar{V}_3 \Phi_{\alpha\beta}}{M^3} = \frac{\sqrt{5}\, g^6}{64\, \pi^3} \approx 2 - 3 \times 10^{-4}.$$

$$\Rightarrow \quad |V| \sim \begin{pmatrix} 0.98 & 0.2 & 0 \\ 0.2 & 0.98 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three generation mixing ⟶ NPB 416 (1994) 63 $|J| \sim 10^{-6}$

Correspondence with $Z_2 \times Z_2$ orbifold

PLB 326 (1994) 62

NAHE $\oplus$ $(\xi_2 = \{\bar{\psi}_{1,\cdots,5}, \bar{\eta}^1, \bar{\eta}^2, \bar{\eta}^3\} = 1) \quad \rightarrow \quad \{1, S, \xi_1, \xi_2, b_1, b_2\}$

Gauge group: $SO(4)^3 \times E_6 \times U(1)^2 \times E_8$ and 24 generations.

toroidal compactification $(6_L + 6_R)$ g_{ij}, b_{ij}

$$g_{ij} = \begin{pmatrix} 2 & -1 & 0 & 0 & 0 & 0 \\ -1 & 2 & -1 & 0 & 0 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 2 & -1 & -1 \\ 0 & 0 & 0 & -1 & 2 & 0 \\ 0 & 0 & 0 & -1 & 0 & 2 \end{pmatrix} \qquad b_{ij} = \begin{cases} g_{ij} & i < j \\ 0 & i = j \\ -g_{ij} & i > j \end{cases}$$

$R_i \quad \rightarrow$ the free fermionic point $\rightarrow$G.G. $SO(12) \times E_8 \times E_8$

mod out by a $Z_2 \times Z_2$ with standard embedding

$\Rightarrow SO(4)^3 \times E_6 \times U(1)^2 \times E_8$ with 24 generations

Exact correspondence

In the realistic free fermionic models

replace $X = \{\bar{\psi}^{1,\cdots,5}, \bar{\eta}^1, \bar{\eta}^2, \bar{\eta}^3\} = 1$

with $2\gamma = \{\bar{\psi}^{1,\cdots,5}, \bar{\eta}^1, \bar{\eta}^2, \bar{\eta}^3, \bar{\phi}^{1,\cdots,4}\} = 1$

Then $\{\vec{1}, \vec{S}, \vec{\xi}_1 = \vec{1} + \vec{b}_1 + \vec{b}_2 + \vec{b}_3, 2\gamma\} \rightarrow$ N=4 SUSY and

$SO(12) \times SO(16) \times SO(16)$

apply $b_1 \times b_2 \rightarrow Z_2 \times Z_2 \rightarrow$ N=1 SUSY and

$SO(4)^3 \times SO(10) \times U(1)^3 \times SO(16)$

b_1, b_2, b_3 $\Rightarrow (3 \times 8) \cdot 16$ of $SO(10)_O$

$b_1 + 2\gamma$, $b_2 + 2\gamma$, $b_3 + 2\gamma$ $\Rightarrow (3 \times 8) \cdot 16$ of $SO(16)_H$

Alternatively, $c\binom{\xi_1}{\xi_2} = +1 \rightarrow -1$

$Z_2 \times Z_2$ orbifolds

torus: One complex parameter $Z = Z + n\, e_1 + m\, e_2$

$T^2 \times T^2 \times T^2 \longrightarrow$ Three complex coordinates z_1 , z_2 and z_3

Z_2 orbifold : $Z = - Z + \sum_i m_i e_i \longrightarrow$ 4 fixed points

$$Z = \{ 0 , 1/2\, e_1 , 1/2\, e_2 , 1/2\, (e_1 + e_2) \}$$

$$\frac{T^2 \times T^2 \times T^2}{Z_2 \times Z_2}$$

$$\begin{aligned}
\alpha &: (z1 , z2 , z3) \;\text{->}\; (-z1 , -z2 , +z3) \;\text{->}\; 16 \\
\beta &: (z1 , z2 , z3) \;\text{->}\; (+ z1 , -z2 , -z3) \;\text{->}\; 16 \\
\alpha\beta &: (z1 , z2 , z3) \;\text{->}\; (-z1 , +z2 , -z3) \;\text{->}\; \underline{16}
\end{aligned}$$

$$48$$

$$\downarrow$$

$$\gamma : (z1, z2, z3) \;\text{->}\; (z1+1/2, z2+1/2, z3+1/2) \longrightarrow 24$$

Classification of fermionic $Z_2 \times Z_2$ orbifolds (AEF, Kounnas, Rizos)

Basis vectors: consistent modular blocks 4,8 periodic fermions

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

$N = 4$ Vacua

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

Vector bosons: NS, $z_{1,2}$, $z_1 + z_2$, $x = 1 + s + \sum e_i + z_1 + z_2$

impose: Gauge group $SO(10) \times U(1)^3 \times \text{hidden}$

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

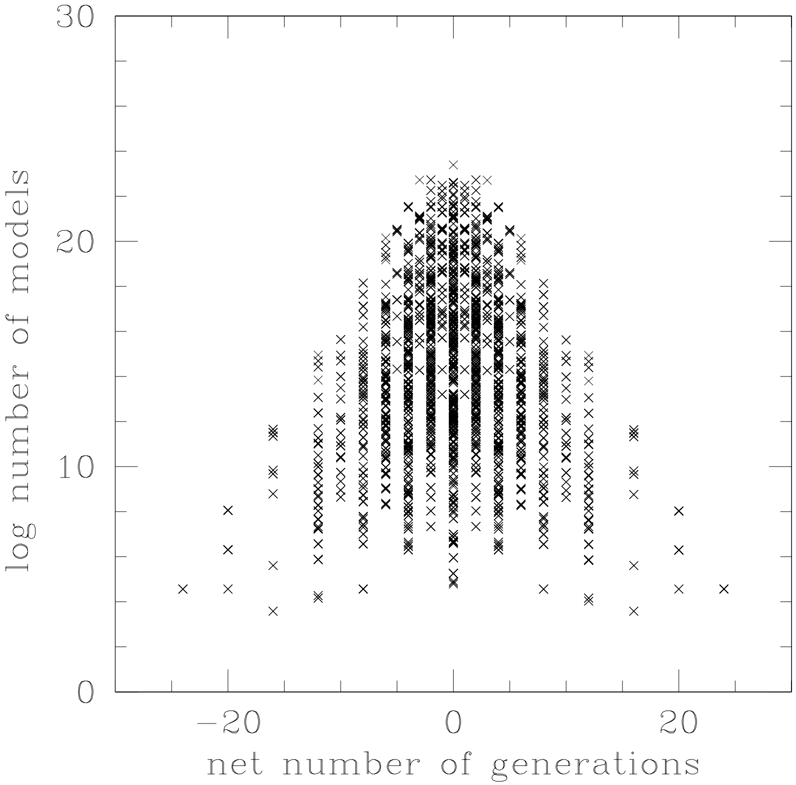
$$
\begin{array}{c|cccccccccccc}
 & 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & z_1 & z_2 & b_1 & b_2 \\
\hline
1 & -1 & -1 & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
S & & & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 \\
e_1 & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_2 & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_3 & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_4 & & & & & & & \pm & \pm & \pm & \pm & \pm & \pm \\
e_5 & & & & & & & & \pm & \pm & \pm & \pm & \pm \\
e_6 & & & & & & & & & \pm & \pm & \pm & \pm \\
z_1 & & & & & & & & & & \pm & \pm & \pm \\
z_2 & & & & & & & & & & & \pm & \pm \\
b_1 & & & & & & & & & & & & \pm \\
b_2 & & & & & & & & & & & &
\end{array}
$$

Apriori 55 independent coefficients → 2^{55} distinct vacua

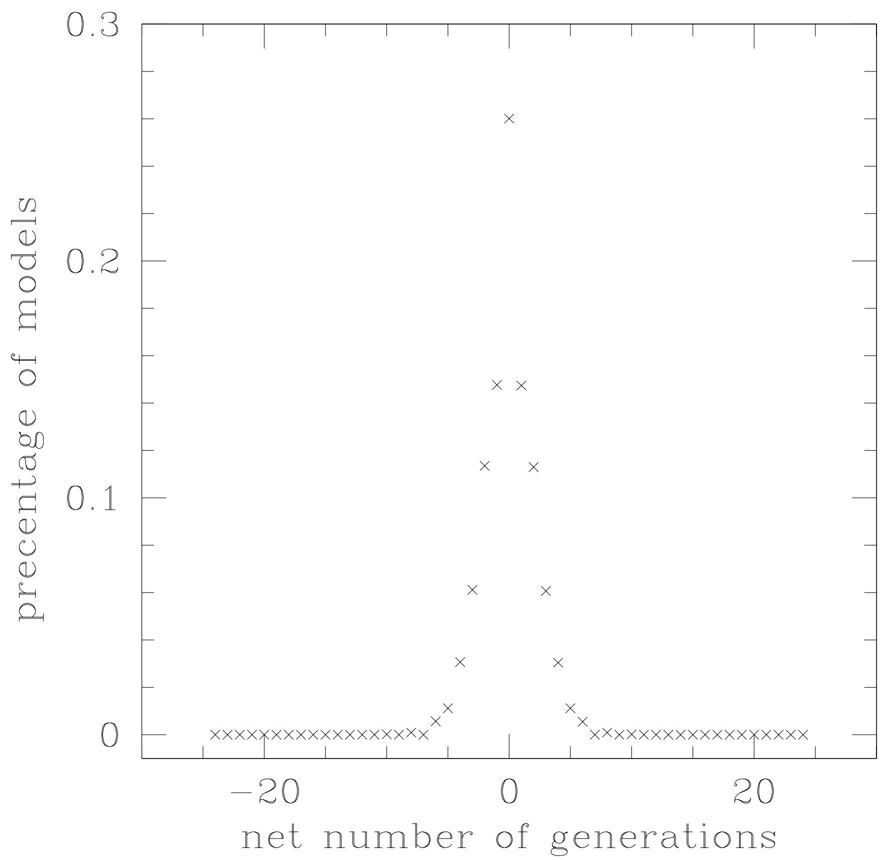
Impose: Gauge group $SO(10) \times U(1)^3 \times SO(8)^2$

→ 40 independent coefficients

RESULTS:



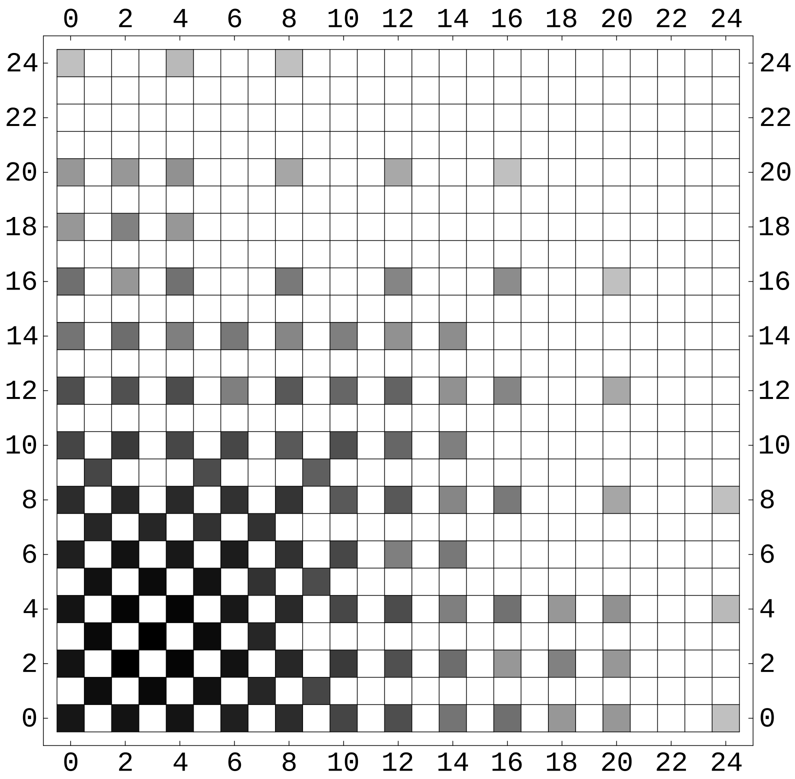
30
20
10
0
−20
0
20
log number of models
net number of generations



7×10^9 models $\sim$ 15% with 3 gen FKRI

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

Progress:

Tristan Catelin-Jullien, AEF, C. Kounnas, J. Rizos, NPB2009 ⟶
Operational understanding in terms of partition function free phases

$$
\begin{aligned}
Z =& \int \frac{d^2\tau}{\tau_2^2}\,\frac{\tau_2^{-1}}{\eta^{12}\bar{\eta}^{24}}\,\frac{1}{2^3}\left(\sum (-)^{a+b+ab}\vartheta\begin{bmatrix}a\\b\end{bmatrix}\vartheta\begin{bmatrix}a+h_1\\b+g_1\end{bmatrix}\vartheta\begin{bmatrix}a+h_2\\b+g_2\end{bmatrix}\vartheta\begin{bmatrix}a+h_3\\b+g_3\end{bmatrix}\right)_{\psi^\mu,}\\
&\times\left(\frac{1}{2}\sum_{\epsilon,\xi}\bar{\vartheta}\begin{bmatrix}\epsilon\\\xi\end{bmatrix}^5\bar{\vartheta}\begin{bmatrix}\epsilon+h_1\\\xi+g_1\end{bmatrix}\bar{\vartheta}\begin{bmatrix}\epsilon+h_2\\\xi+g_2\end{bmatrix}\bar{\vartheta}\begin{bmatrix}\epsilon+h_3\\\xi+g_3\end{bmatrix}\right)_{\bar{\psi}^{1\dots5},\bar{\eta}^{1,2,3}}\\
&\times\left(\frac{1}{2}\sum_{H_1,G_1}\frac{1}{2}\sum_{H_2,G_2}(-)^{H_1G_1+H_2G_2}\bar{\vartheta}\begin{bmatrix}\epsilon+H_1\\\xi+G_1\end{bmatrix}^4\bar{\vartheta}\begin{bmatrix}\epsilon+H_2\\\xi+G_2\end{bmatrix}^4\right)_{\bar{\phi}^{1\dots8}}\\
&\times\left(\sum_{s_i,t_i}\Gamma_{4,4}\Gamma_{2,2}\begin{bmatrix}h_i|s_i\\g_i|t_i\end{bmatrix}\right)_{(y\omega\bar{y}\bar{\omega})^{1\dots6}}\times e^{i\pi\Phi(\gamma,\delta,s_i,t_i,\epsilon,\xi,h_i,g_i,H_1,G_1,H_2,G_2)}
\end{aligned}
$$

- The S or $\overline{S}$ arise when $\epsilon = 1$

- The V representation arise when $\epsilon + h = 1$; $\epsilon = 0$

Four possibilities to couple the lattice characters (t_i, s_i) to (ϵ, ζ), (h, g)

- Inserting 1 → $(2,2)$ $SO(10) \rightarrow E_6$ $[S_t] = [V]$

- Inserting $(-)^{sh+tg}$ → freely acting orbifold $[S_t] = [V] = 0$

- Inserting $(-)^{s\epsilon+t\xi}$ → $(2,0)$ superconformal only V

- Inserting $(-)^{s(\epsilon+h)+t(\xi+g)}$ → $(2,0)$ superconformal only S, $\overline{S}$

X–map $\Longrightarrow$ $\epsilon = 0 \leftrightarrow \epsilon = 1$

$S_t \leftrightarrow V$ – duality : interchange of GGSO discrete phases

Future: Understand in geometrical terms:

NAHE-based partition functions:

w Carlo Angelantonj, Mirian Tsulaia

Question:

$$\frac{T^6}{Z_2 \times Z_2} \rightarrow 48 \text{ fixed points} \qquad \frac{SO(12)}{Z_2 \times Z_2} \rightarrow 24 \text{ fixed points}$$

$$Z_2 \text{ shift } : 48 \longleftrightarrow 24$$

Is this the same model? In general, no.

shift that reproduces the $SO(12)$ lattice at the free fermionic point?

Possible shifts:

$$A_1 \ : \ X_{\rm L,R} \to X_{\rm L,R} + \tfrac{1}{2}\pi R \, ,$$

$$A_2 \ : \ X_{\rm L,R} \to X_{\rm L,R} + \tfrac{1}{2}\left(\pi R \pm \frac{\pi\alpha'}{R}\right) \, ,$$

$$A_3 \ : \ X_{\rm L,R} \to X_{\rm L,R} \pm \tfrac{1}{2}\frac{\pi\alpha'}{R} \, .$$

Using the level-one $\mathrm{SO}(2n)$ characters

$$O_{2n} = \tfrac{1}{2}\left(\frac{\vartheta_3^n}{\eta^n} + \frac{\vartheta_4^n}{\eta^n}\right) \, , \qquad V_{2n} = \tfrac{1}{2}\left(\frac{\vartheta_3^n}{\eta^n} - \frac{\vartheta_4^n}{\eta^n}\right) \, ,$$

$$S_{2n} = \tfrac{1}{2}\left(\frac{\vartheta_2^n}{\eta^n} + i^{-n}\frac{\vartheta_1^n}{\eta^n}\right) \, , \qquad C_{2n} = \tfrac{1}{2}\left(\frac{\vartheta_2^n}{\eta^n} - i^{-n}\frac{\vartheta_1^n}{\eta^n}\right) \, .$$

The partition function of the heterotic string on $SO(12)$ lattice:

$$\mathrm{Z}_{+} = (V_8 - S_8)\left[|O_{12}|^2 + |V_{12}|^2 + |S_{12}|^2 + |C_{12}|^2\right](\bar{O}_{16} + \bar{S}_{16})\,(\bar{O}_{16} + \bar{S}_{16})$$

and

$$\begin{aligned}\mathrm{Z}_{-} \;=\; (V_8 - S_8)\Big[&\left(|O_{12}|^2 + |V_{12}|^2\right)(\bar{O}_{16}\bar{O}_{16} + \bar{C}_{16}\bar{C}_{16})\\ &+ \left(|S_{12}|^2 + |C_{12}|^2\right)(\bar{S}_{16}\bar{S}_{16} + \bar{V}_{16}\bar{V}_{16})\\ &+ (O_{12}\bar{V}_{12} + V_{12}\bar{O}_{12})\,(\bar{S}_{16}\bar{V}_{16} + \bar{V}_{16}\bar{S}_{16})\\ &+ (S_{12}\bar{C}_{12} + C_{12}\bar{S}_{12})\,(\bar{O}_{16}\bar{C}_{16} + \bar{C}_{16}\bar{O}_{16})\Big]\;.\end{aligned}$$

where ± refers to

$$c\binom{\xi_1}{\xi_2} \;=\; \pm 1$$

connected by :
$$\mathrm{Z}_{-} = \mathrm{Z}_{+}/a \otimes b\,,$$

$$a = (-1)^{F_{\mathrm{L}}^{\mathrm{int}} + F_{\xi}^{1}}\,, \qquad\qquad b = (-1)^{F_{\mathrm{L}}^{\mathrm{int}} + F_{\xi}^{2}}\,.$$

Starting from:

$$Z_+ = (V_8 - S_8) \left(\sum_{m,n} \Lambda_{m,n} \right)^{\otimes 6} (\bar{O}_{16} + \bar{S}_{16}) \, (\bar{O}_{16} + \bar{S}_{16}) \ ,$$

where as usual, for each circle,

$$p^i_{\mathrm{L,R}} = \frac{m_i}{R_i} \pm \frac{n_i R_i}{\alpha'} \, ,$$

and

$$\Lambda_{m,n} = \frac{q^{\frac{\alpha'}{4} p^2_{\mathrm{L}}} \, \bar{q}^{\frac{\alpha'}{4} p^2_{\mathrm{R}}}}{|\eta|^2} \, .$$

Add shifts : (A_1, A_1, A_1) , (A_3, A_3, A_3)

($48 \rightarrow 24$ yes)

($SO(12)$? no)

Uniquely:

$$g \ : \ (A_2, A_2, 0)\,,$$

$$h \ : \ (0, A_2, A_2)\,,$$

where each A_2 acts on a complex coordinate

($48 \longrightarrow 24$ yes)

($SO(12)$? yes)

$$R = \sqrt{\alpha'}$$

Uniquely in 10D:

$$c\begin{pmatrix}\xi_1\\ \xi_2\end{pmatrix} = -1 \quad \Longrightarrow \quad N=1 \rightarrow N=0 \ \ \mathrm{SUSY}$$

Question : What is the relation between the $10D$ and $D < 10$ cases?

Answer : Mirian Tsulaia →

Interpolation among SUSY and non–SUSY vacua

Conclusions

Phenomenological string models produce interesting lessons

Spinor–vector duality

relevance of non–standard geometries

Free Fermionic Models $\longrightarrow$ $Z_2 \times Z_2$ orbifold near the self–dual point

Duality & Self–Duality $\Leftrightarrow$ String Vacuum Selection

MINIMAL DOUBLET HIGGS CONTENT (EJPC50)

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

(With Elisa Manno and Cristina Timirgaziu)

SYMMETRIC ↔ ASYMMETRIC

with respect to b_1 & b_2

$h_1,\ \bar{h}_1,\ D_1,\ \bar{D}_1\ ,\ \ h_2,\ \bar{h}_2,\ D_2,\ \bar{D}_2$ are projected out

$h_3,\ \bar{h}_3$ remain in the spectrum

$$\lambda_t Q_3 t^c_3 \bar{h}_3 \ \text{ with } \ \lambda_t\ O(1)$$

No Phenomenologically viable flat directions

Exotics superpotential in FNY model (NPB 335 (1990) 347)

$$W_2 = \frac{1}{\sqrt{2}}\{ \, H_1H_2\phi_4 + H_3H_4\bar\phi_4 + H_5H_6\bar\phi_4 + (H_7H_8 + H_9H_{10})\phi'_4 + (H_{11} + H_{12})(H_{13} + H_{14})\bar\phi'_4 + V_{41}V_{42}\bar\phi_4 + V_{43}V_{44}\bar\phi_4 + V_{45}V_{46}\phi_4 + (V_{47}V_{48} + V_{49}V_{50})\bar\phi'_4 + V_{51}V_{52}\phi'_4\}$$

$\langle \, \bar\phi_4, \bar\phi'_4, \phi_4, \phi'_4 \, \rangle \rightarrow$ massive exotic states at N=3 (PRD46 (1993) 3204)

CFN → Classification of flat directions (PLB 455 (1999) 135)

Example: $\{\phi_{12}, \phi_{23}, \bar\phi_{56}, \phi_4, \phi'_4, \bar\phi_4, \bar\phi'_4, H_{15}, H_{30}, H_{31}, H_{38}\}$

All Standard Model charged states beyond MSSM → $\approx M_{\rm string}$

MINIMAL STANDARD HETEROTIC STRING MODEL

Cleaver, Faraggi, Manno, Timirgaziu, PRD 78 (2008) 046009

Classification of F and D flat directions in EMT reduced Higgs model

No D flat direction which is F-flat up to order eight in the superpotential

no stringent flat directions to all orders

Suggesting no supersymmetric flat directions in this model (class of models)

implying no supersymmetric moduli

only remaining perturbative moduli is the dilaton

quasi–realistic model: SLM; 3 gen; $SO(10)$ embed; Higgs & $\lambda_t \sim 1$; ...

vanishing one–loop partition function, perturbatively broken SUSY

Fixed geometrical, twisted and SUSY moduli

The massless spectrum

Three twisted generations $b_1, \quad b_2, \quad b_3$

Untwisted Higgs doublets

$h_{1_{1,0,0}}$ $\bar{h}_{1_{-1,0,0}}$

$h_{2_{0,1,0}}$ $\bar{h}_{2_{0,-1,0}}$

$h_{3_{0,0,1}}$ $\bar{h}_{3_{0,0,-1}}$

"standard" $SO(10)$ representations

NAHE $+ \{ \alpha , \beta , \gamma \} \rightarrow$ exotic vector–like matter $\rightarrow$ superheavy

$\oplus$ Quasi-realistic phenomenology

A STRINGY DOUBLET-TRIPLET SPLITTING MECHANIS

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

NAHE → $\chi_j\bar{\psi}^{1,\cdots,5}\bar{\eta}_j + c.c. \rightarrow (5+\bar{5})_j = 10_j$ of $SO(10)$

α , β → $SO(10) \rightarrow SO(6)\times SO(4)$

$$\Delta_j = |\alpha_L(T_2^j) - \alpha_R(T_2^j)|$$

$\Delta_j = 0 \rightarrow D_j, \bar{D}_j$ $\Delta_j = 1 \rightarrow h_j, \bar{h}_j$

$h_1,\ \bar{h}_1,\ D_1,\ \bar{D}_1$, $h_2,\ \bar{h}_2,\ D_2,\ \bar{D}_2$ are projected out

$h_3,\ \bar{h}_3$ remain in the spectrum

Model building – Construction of the physical states

$$b_j \quad j = 1, \cdots, N \quad \rightarrow \quad \Xi = \sum_j n_j b_j$$

For $\vec{\alpha} = (\vec{\alpha}_L; \vec{\alpha}_R) \in \Xi \Rightarrow$ H$_{\vec{\alpha}}$

$$M_L^2 = -\frac{1}{2} + \frac{\vec{\alpha}_L \cdot \vec{\alpha}_L}{8} + N_L = -1 + \frac{\vec{\alpha}_R \cdot \vec{\alpha}_R}{8} + N_R = M_R^2 \quad (\equiv \quad 0 \ )$$

GSO projections $\qquad e^{i\pi(\vec{b}_i \cdot \vec{F}_\alpha)} |s\rangle_{\vec{\alpha}} = \delta_\alpha c^* \begin{pmatrix} \vec{\alpha} \\ \vec{b}_i \end{pmatrix} |s\rangle_{\vec{\alpha}}$

$Q(f) = \frac{1}{2}\alpha(f) + F(f) \rightarrow$ U(1) charges

Calculation of Mass Terms

nonvanishing correlators

$$\langle V_1^f V_2^f V_3^b \cdot \cdot \cdot \cdot V_N^b \rangle$$

gauge & string invariant

"anomalous" $U(1)_A$

$$\text{Tr}Q_A \neq 0 \Rightarrow \quad D_A = 0 = A + \sum Q_k^A |\langle \phi_k \rangle|^2$$

$$D_j \ = 0 = \qquad \sum Q_k^j |\langle \phi_k \rangle|^2$$

$$\langle W \rangle = \langle \frac{\partial W_N}{\partial \eta_i} \rangle = 0 \quad N = 3 \cdot \cdot \cdot \cdot$$

Supersymmetric vacuum $\langle F \rangle = \langle D \rangle = 0.$

nonrenormalizable terms → effective renormalizable operators

$$V_1^f V_2^f V_3^b \cdot \cdot \cdot \cdot V_N^b \ \rightarrow \ V_1^f V_2^f V_3^b \frac{\langle V_4^b \cdot \cdot \cdot V_N^b \rangle}{M^{N-3}}$$

in realistic models

$$\{\,1\,,\,S\,,\,\xi_1\,,\,\xi_2\,\}\ \oplus\ \{\,b_1\,,\,b_2\,\}\ \oplus\ \{\,\alpha\,,\,\beta\,,\,\gamma\}$$

$$N=4 \qquad\qquad N=1$$

$$E_8\times E_8 \qquad\qquad Z_2\times Z_2$$

new feature Asymmetric orbifold

the key focus: boundary conditions of the internal fermions

$$\{\,y\,,\,\omega\ \mid\ \bar{y}\,,\,\omega\,\}$$

WS fermions that have same B.C. in all basis vectors are paired

pairing of LR fermions $\longrightarrow$ Ising model $\longrightarrow$ symmetric real fermions

pairing of LL & RR fermions $\longrightarrow$ complex fermions $\longrightarrow$ asymmetric