MODULI FIXING IN REALISTIC STRING VACUA

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ELEMENTS OF STRING UNIFICATION

Classically : $g^{\alpha\beta} \longrightarrow \eta^{\alpha\beta}$

Quantum : D=26 (bosonic)

D=10 (fermionic)

Heterotic string -> $D_L = 10$ $D_R = 10$

Real World D = 4

Bosonic -> $4_{L+R} + 22_{L+R}$

Superstring -> $4_{L+R} + 6_{L+R}$

Heterotic−string -> $4_{L+R} + (6_L + 6_R) + 16_R$

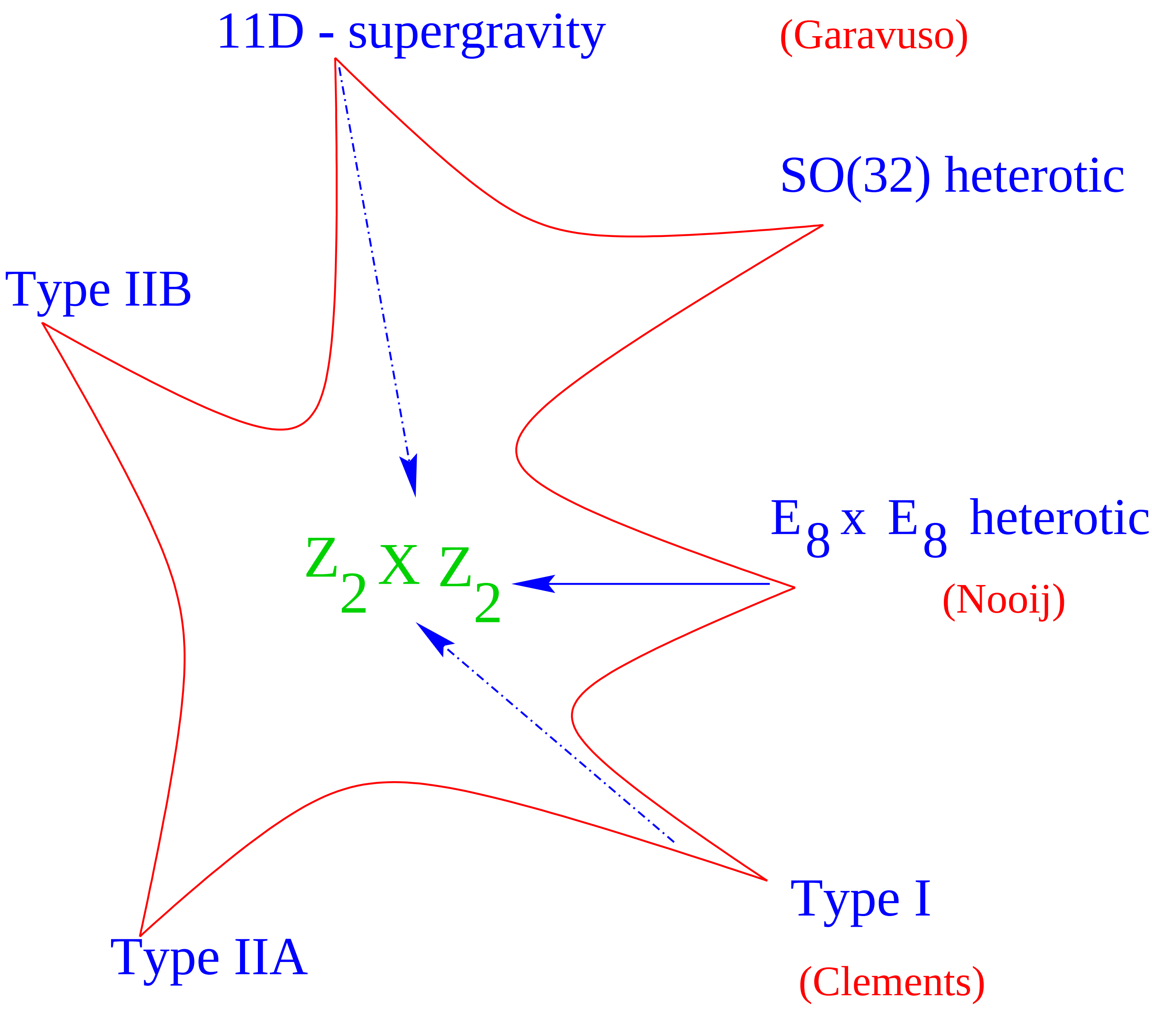
$(6_L + 6_R)$: 6D internal manifold

16_R: 16D lattice $R=\sqrt{2}$

moduli −> size & shape of internal 6D manifold.
Twisted moduli

no known mechanism selects and fixes these moduli

realistic string vacua < − > phenomenological guide?



11D - supergravity
(Garavuso)
SO(32) heterotic
Type IIB
E8 x E8 heterotic
(Nooij)
Z2 X Z2
Type I
Type IIA
(Clements)

DATA $\longrightarrow$ STANDARD MODEL

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

$$\left[\begin{pmatrix} \nu \\ e \end{pmatrix} + D_L^c \right] + \left[U_L^c + \begin{pmatrix} u \\ d \end{pmatrix} + E_L^c \right] + N_L^c$$

$$\bar{5} \quad + \quad 10 \quad \quad 1 \quad \overline{\quad\quad} \; 16$$

STANDARD MODEL -> UNIFICATION

ADDITIONAL EVIDENCE:

Logarithmic running, proton longevity, neutrino masses

PRIMARY GUIDES:

3 generations

SO(10) embedding

REALISTIC STRING MODELS :

heterotic 10D −> heterotic 4D

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

Z_3 Orbifold −> $U(1)_Y \notin SO(10)$

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

=> $\sin^2\Theta_W = 3/8$ at M_{string}

low energy data distinguishes between classes of string compactifications !!!

$Z_2 \times Z_2$ orbifold based models - Gross Structure

Untwisted sector

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

Three twisted sectors $\Longrightarrow$ $1 \quad + \quad 1 \quad + \quad 1$

$16 \quad + \quad 16 \quad + \quad 16$

decomposed under $(3, 2, 1, 1)$

$\oplus$ Hidden sector : $E_8 \quad \rightarrow$ subgroup + matter

$\oplus$ Exotics $- >$ decouple from the low energy spectrum

primarily studied in the free fermionic formulation

Free Fermionic Model Building

Models $\longrightarrow$ set of boundary condition basis vectors

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

$\longrightarrow$ $Z_2 \times Z_2$ orbifold compactification

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

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

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

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

Realistic free fermionic models

Phenomenology of the Standard Model and string unification

1. Top quark mass $\sim 175 - 180$ GeV — PLB 274 (1992) 47

2. Generation mass hierarchy — NPB 407 (1993) 57

3. CKM mixing — NPB 416 (1994) 63
   with Edi Halyo

4. Stringy see–saw mechanism — PLB 307 (1993) 311
   with Edi Halyo

5. Gauge coupling unification — NPB 457 (1995) 409
   with Keith Dienes

6. Proton stability — NPB 428 (1994) 111

7. Squark degeneracy — NPB 526 (1998) 21
   with jogesh Pati

8. Minimal Superstring Standard Model — PLB 455 (1999) 135
   with Cleaver & Nanopoulos

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

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

$R_i \rightarrow$ 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 $\qquad X = \{\bar{\psi}_{1,\cdots,5}, \bar{\eta}^1, \bar{\eta}^2, \bar{\eta}^3\} = 1$

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

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 $SO(16)_H$

This will be important for the twisted moduli.

Moduli?

Untwisted moduli $->$ shape & size of the internal dimensions

Twisted moduli $->$ arise from the twisted sectors

models $$\frac{T^6}{Z_2 \times Z_2}$$

$$T^6 \; : \quad G_{IJ} \quad ; \quad B_{IJ} \qquad I, J \; = \; 1, \cdots, 6 \; .$$

untwisted moduli: coefficients of exactly marginal operators

moduli fields: massless chiral superfields with flat scalar potential
to all orders in string perturbation theory

VEVs are unconstrainted $->$ parametrize connected vacua

Narain construction : Scalar couplings of $N = 4$ SUGRA

$$\underset{\text{internal manifold}}{\frac{SO(6,6)}{SO(6) \times SO(6)}} \quad \times \quad \underset{\text{dilaton}}{\frac{SU(1,1)}{U(1)}}$$

Up to orbifold projections

$$\frac{T^6}{Z_2 \times Z_2} \implies \frac{SO(6,6)}{SO(6) \times SO(6)} \longrightarrow \left(\frac{SO(2,2)}{SO(2) \times SO(2)}\right)^3$$

$\Rightarrow$ 3 complex structures $+$ 3 Kähler moduli

In all symmetric $Z_2 \times Z_2$ orbifolds

We would like to identify these moduli in the fermionic formalism

In symmetric orbifolds:

EMO $\rightarrow$ $\partial X^I \bar{\partial} X^J$

$X^I \quad I = 1, \cdots, 6 \quad \rightarrow \quad T^6$

$$S = \frac{1}{8\pi} \int d^2\sigma \;\; (G_{IJ}\; \partial X^I \bar{\partial} X^J \; + \; B_{IJ}\; \partial X^I \bar{\partial} X^J)$$

In FFF $\partial X_L^I \;\to\; y^i\omega^I$

$i\partial X_L^I \;\to\; U(1)$ current in the Cartan subalgebra

In the fermionic language

$$i\partial X_L^I \;\to\; J_L^I = y^I\omega^I$$

$$\Rightarrow \quad \partial X^I\bar\partial X^J \to J_L^I(z)\bar J_R(\bar z)$$

$\to$ WS Thirring interactions $\quad (R-\frac{1}{R})J_L(z)\bar J(\bar z)$

Thirring interactions vanish at free fermionic point with $R=\frac{1}{R}$

To identify the untwisted moduli in the free fermionic models

$\to$ find the operators of the form

$$J_L^I(z)\bar J_R^J(\bar z)$$

that are allowed by the orbifold (fermionic) symmetry group

Free Fermionic Construction

$$C_L = D \cdot 1 + D \cdot \tfrac{1}{2} + \tfrac{1}{2} N_{f_\ell} - 26 + 11 = 0$$

$$C_R = D \cdot 1 \qquad\qquad + \tfrac{1}{2} N_{f_r} - 26 \qquad\quad = 0$$

$$D = 4 \ \rightarrow \ n_L^f = 18 \quad , \quad n_R^f = 44$$

free fermion world–sheet content in LCG

$$\mathrm{L} \ : \quad \psi^\mu_{1,2} \qquad \chi_i \qquad y^i \quad \omega^i \qquad\qquad i = 1, \cdots, 6$$

$$\mathrm{R} \ : \qquad\qquad\qquad\qquad \bar{y}^i \quad \bar{\omega}^i \qquad\qquad \bar{\psi}^{1\cdots5} \bar{\eta}^1 \bar{\eta}^2 \bar{\eta}^3 \bar{\phi}^{1\cdots8}$$

$$T_F(z) = \psi^\mu \partial X_\mu + \sum \chi^j y^j \omega^j$$

$$f \rightarrow -e^{i\pi\alpha(f)} f \qquad\qquad \alpha(f) = (-1, +1]$$

$$\vec{b} \ = \ (\ b_1^L \ , \ \cdots \ , \ b_{20}^L \ | \ b_{21}^R \ , \ \cdots \ , \ b_{64}^R \ )$$

orbifold twists; Wilson lines $\longrightarrow$ parallel transport phases

$$B \ = \ \{ \ \vec{b}_1 \ , \ \cdots \ , \ \vec{b}_n \ \}$$

1-loop partition function

$$Z = \sum_{\substack{all \;\; spin \\ structures}} c\binom{\vec{\alpha}_i}{\vec{\alpha}_j} \mathcal{Z}\binom{\vec{\alpha}_i}{\vec{\alpha}_j}$$

$$\vec{\alpha}_i = m_1^i \vec{b}_1 + \cdots + m_n^i \vec{b}_n$$

Models $\longrightarrow$ specified by a consistent B and $c\binom{b_i}{b_j}$

Construction of the physical states $\rightarrow$ GSO projection

$$e^{i\pi(\vec{b}_i \cdot \vec{F}_\alpha)} |s\rangle_{\vec{\alpha}} = \delta_\alpha c^* \binom{\vec{\alpha}}{\vec{b}_i} |s\rangle_{\vec{\alpha}}$$

$$\binom{NS}{\vec{b}_i} = \delta_{b_i} = \mathrm{e}^{i\pi b_i(\psi^\mu)}$$

Each complex fermion : $\rightarrow$ $U(1)$ current ff^*

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

Bosonization

$$\xi_i = \sqrt{\frac{1}{2}}(y_i + i\omega_i) = e^{iX_i}, \eta_i = \sqrt{\frac{i}{2}}(y_i - i\omega_i) = ie^{-iX_i}$$

simlarly for the right-movers

Boundary conditions translate to twists and shifts

$$X^I(z, \bar{z}) = X_L^I(z) + X_R^I(\bar{z})$$

Complex internal coordinates

$$Z_k^{\pm} = (X^{2k-1} \pm iX^{2k}), \quad \psi_k^{\pm} = (\chi^{2k-1} \pm i\chi^{2k}) \quad (k = 1, 2, 3)$$

Untwisted moduli

$$S = \int d^2 z h_{ij}(X) J_L^i(z) \bar{J}_R^j(\bar{z})$$

J_L^i $i = 1, \cdots, 6$ are chiral currents of $U(1)_L^6$

J_R^i $i = 1, \cdots, 22$ are chiral currents of $U(1)_R^{22}$

h_{ij} $\rightarrow$ four dimensional scalar fields that are identified with the scalar components of untwisted moduli

$$J_L^i \sim y^i \omega^i \qquad i = 1, \cdots, 6$$
$$J_R^j \sim \bar{\phi}^a \bar{\phi}^{*^a} \qquad a = 1, \cdots, 22$$

some of these operators are projected out in concrete models that are specified by the basis vectors

The basis vectors determine how the WS fermions transform under parallel transport

$\Rightarrow$ some of the EMO may not be invariant

Models

$$\{1, S\} \quad \vec{1} = (\vec{1}_L; \vec{1}_R)$$

$$\vec{S} = (\psi^{\mu}_{1,2}, \chi_{1,\cdots,6} : \vec{0}_R) \equiv 1$$

$N = 4$ $\qquad$ $SO(44)$

$$\frac{SO(6,22)}{SO(6) \times SO(22)} \qquad \text{Moduli space}$$

$\chi^i \otimes \bar{\phi}^a \bar{\phi}^{*^a} |0\rangle$ $\qquad$ moduli fields

6×22 $\qquad$ scalar fields

$Z_2 \times Z_2$ $\qquad$ $\{ 1 , S , \xi_1 , \xi_2 \} + \{ b_1 , b_2 \}$

$SO(12) \times E_8 \times E_8$ $\qquad$ $Z_2 \times Z_2$

$\rightarrow \quad SO(4)^3 \times E_6 \times U(1)^2 \times E_8$

The Thirring interactions that remain invariant are

$$J_L^{1,2} \bar{J}_R^{1,2} \quad ; \quad J_L^{3,4} \bar{J}_R^{3,4} \quad ; \quad J_L^{5,6} \bar{J}_R^{5,6}$$

$$y^{1,2}\omega^{1,2}\bar{y}^{1,2}\bar{\omega}^{1,2} \quad ; \quad y^{3,4}\omega^{3,4}\bar{y}^{3,4}\bar{\omega}^{3,4} \quad ; \quad y^{5,6}\omega^{5,6}\bar{y}^{5,6}\bar{\omega}^{5,6}$$

These moduli are always present in symmetric $Z_2 \times Z_2$ orbifolds