Unification & B-L in String Theory

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Phenomenology

- charge quantization
- gauge coupling unification
- Yukawa unification
- neutrino masses

$$q=\begin{pmatrix} u & u & u \\ d & d & d \end{pmatrix} \qquad \bar{u}=\begin{pmatrix} \bar{u} & \bar{u} & \bar{u} \end{pmatrix} \qquad \bar{d}=\begin{pmatrix} \bar{d} & \bar{d} & \bar{d} \end{pmatrix}$$

$$l=\begin{pmatrix} \nu \\ e \end{pmatrix} \qquad \bar{e}$$

$$Q_{EM}=T_L^3+Y/2$$

$$Q=\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix} \qquad \bar{Q}=\begin{pmatrix} \bar{u} & \bar{u} & \bar{u} & \bar{\nu} \\ \bar{d} & \bar{d} & \bar{d} & \bar{e} \end{pmatrix}$$

$$Q_{EM} = T_L^3+T_R^3+(B-L)/2$$

Pati-Salam $SU(4)_C \times SU(2)_L \times SU(2)_R$

$$\begin{tikzcd} & SU(5)\times U(1) \\ SO(10) \arrow[ur] \arrow[dr] & \\ & SU(4)_C\times SU(2)_L\times SU(2)_R \end{tikzcd}$$

$$\begin{tikzcd} & 10_1+\bar{5}_{-3}+1_5 \\ 16 \arrow[ur] \arrow[dr] & \\ & \mathrm{Q}+\overline{\mathrm{Q}} \end{tikzcd}$$

Charge quantization

State	Y $= \frac{2}{3}\Sigma(C) - \Sigma(W)$	Color C spins	Weak W spins
$\overline{\nu}$	0	$+++$	$++$
$\overline{e}$	2	$+++$	$--$
u_r		$-++$	$+-$
d_r		$-++$	$-+$
u_b	$\frac{1}{3}$	$+-+$	$+-$
d_b		$+-+$	$-+$
u_y		$++-$	$+-$
d_y		$++-$	$-+$
$\overline{u}_r$		$+--$	$++$
$\overline{u}_b$	$-\frac{4}{3}$	$-+-$	$++$
$\overline{u}_y$		$--+$	$++$
$\overline{d}_r$		$+--$	$--$
$\overline{d}_b$	$\frac{2}{3}$	$-+-$	$--$
$\overline{d}_y$		$--+$	$--$
ν	-1	$---$	$+-$
e		$---$	$-+$

spinor repsn.
of SO(10)

Phenomenology

- charge quantization
- <u>gauge coupling unification</u>
- Yukawa unification
- neutrino masses

Gauge coupling unification

$$M_G \approx 3\times10^{16} \quad \mathrm{GeV}$$

Phenomenology

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Phenomenology

- charge quantization
- gauge coupling unification
- Yukawa unification
- neutrino masses $M_{See\text{-}Saw} \sim (.01 - .1)\, M_G$

⇒ **SO(10) SUSY GUT w/ L.E. SUSY**

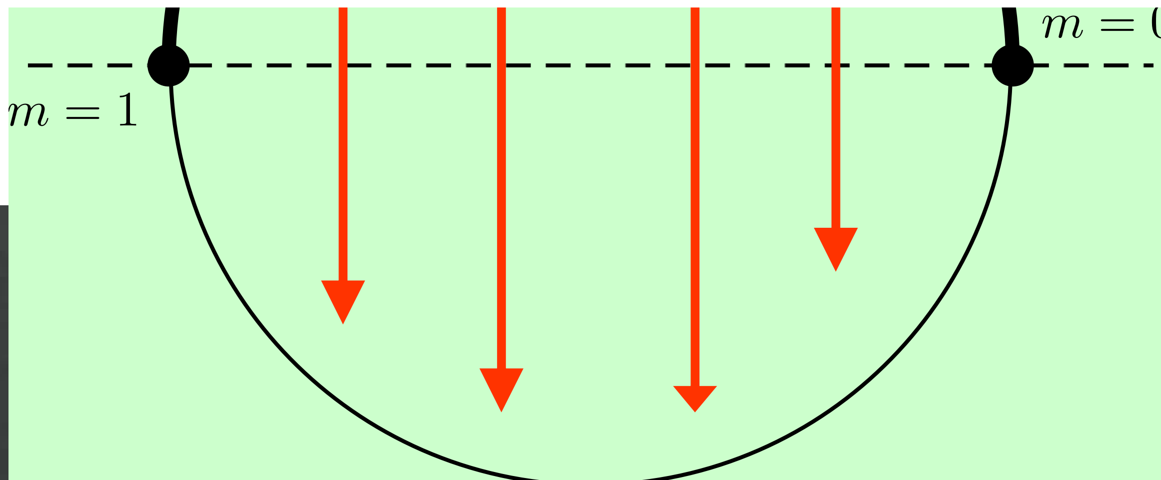
4 D GUT problems

GUT symmetry breaking

Higgs doublet - triplet splitting

Solution ?

Orbifold GUTs



P & P' parity affect boundary conditions
at fixed points

All this first observed in heterotic string in 10D hep-th/0611095, hep-th/0611203

- Road to the MSSM w/ R-parity

LNR^{3}VW 0708.2691 (hep-th)

$E_8 \times E_8$ heterotic string

Constructing MSSM / Caveats

SUSY solution at M_s

100's moduli (geometric & more)

gauge & Yukawa couplings fcns. of moduli

tune to desired values

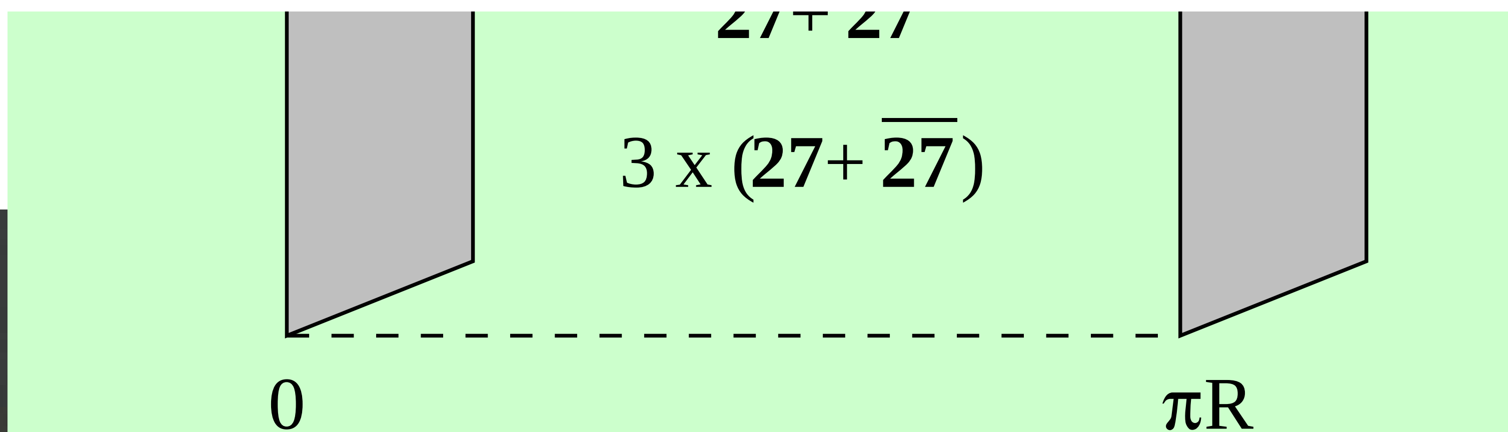
moduli stabilization & SUSY breaking ??

save for later

Add Wilson lines

Z_6 embedded in $E_8 \times E_8$ gauge lattice

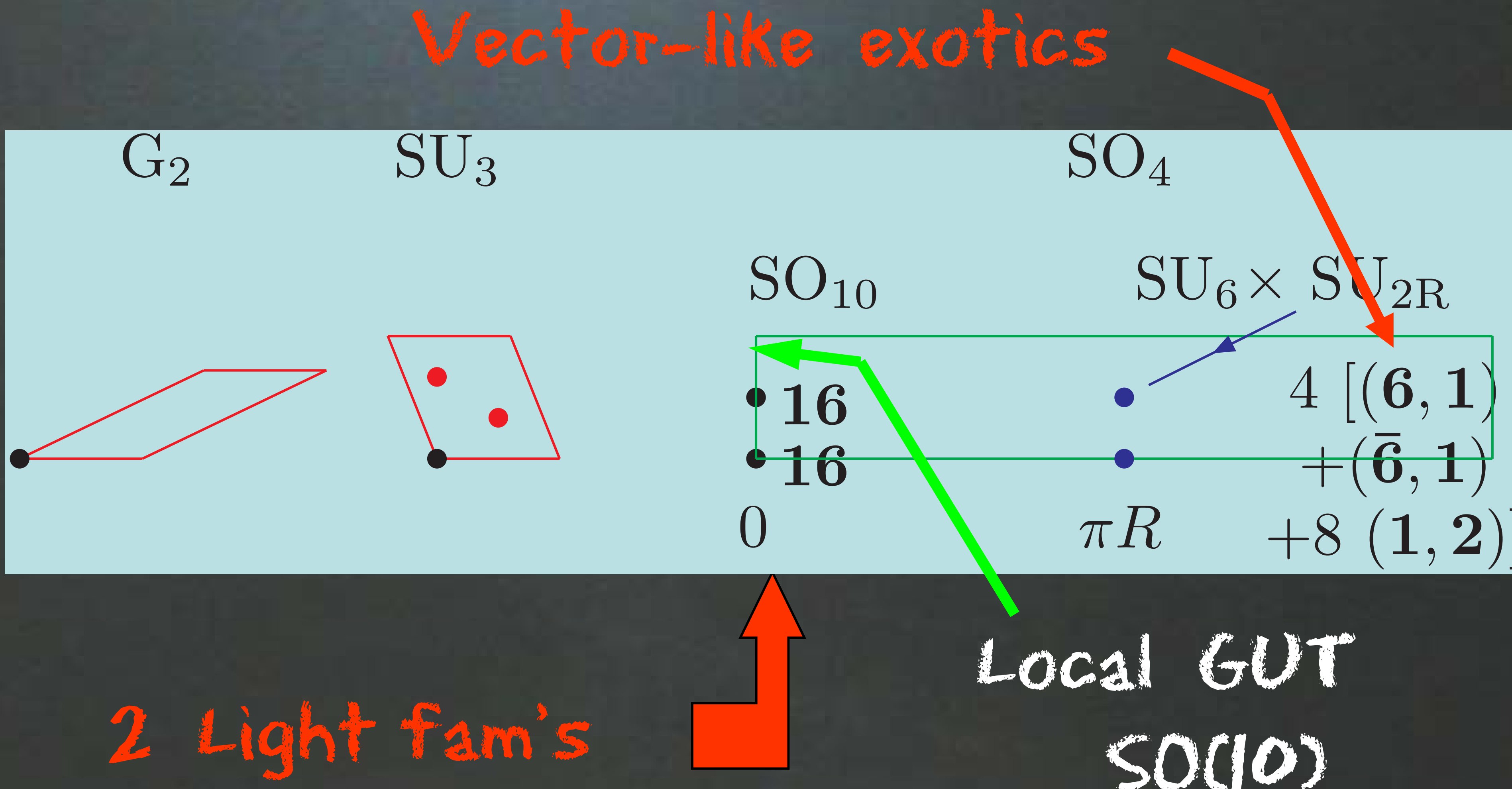
as shift V_6 : consistent with mod. inv. !

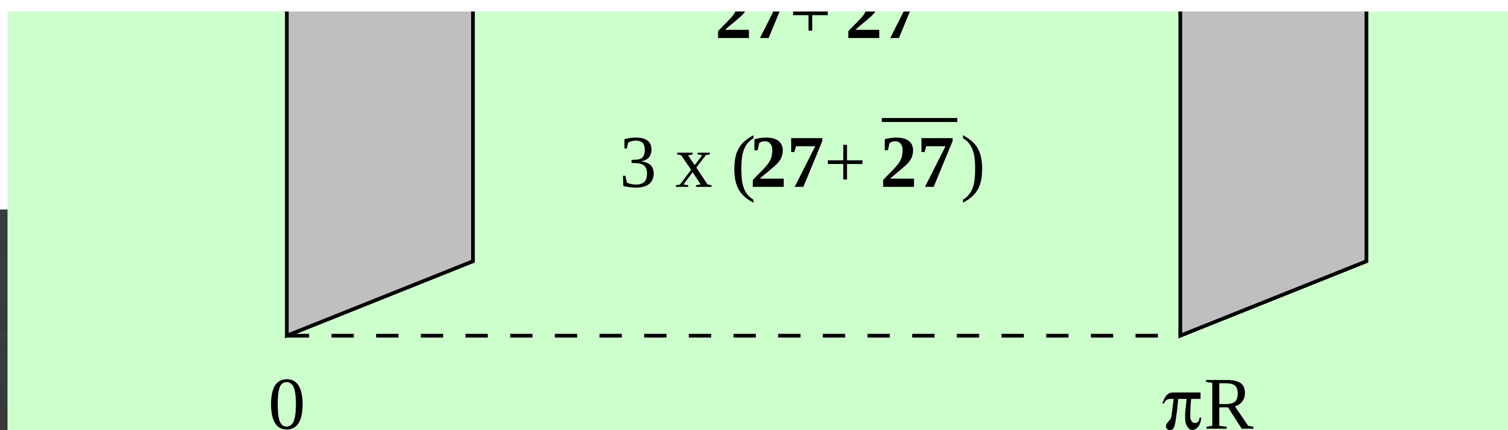

3 x (27+ $\overline{27}$)
0
πR

$E_6 \Rightarrow SO(10) \Rightarrow SU(4) \times SU(2)_L \times SU(2)_R$

$F_3 = (4,2,1), \quad F_3^c = (4^c,1,2), \quad H = (1,2,2)$

T_1 twisted sector




3 x ($\mathbf{27}$+ $\overline{\mathbf{27}}$)
0
πR

string scale

Mini-Landscape search

hep-th/0611095

Lebedev, Nilles, SR, Ramos-Sanchez, Ratz, Vaudrevange & Wingerter

Search for MSSM Spectra in heterotic orbifolds

Buchmuller, Hamaguchi, Lebedev & Ratz

Z_6-II orbifold

hep-ph/0511035, hep-ph/0512326

Looked for and found

SM gauge group in 4D with

3 families and vector-like exotics

Mini-Landscape search Z_6-II orbifold

1. V_6 breaks to SO(10) (or E(6))
2. 2 families (16 (or 27)) in T_1 twisted sect.
3. Generate 2 Wilson lines W_3, W_2
4. Identify 'inequivalent' models
5. Select models with $G_{SM} \subset SU(5) \subset SO(10)$
6. Select models with 3 net (3,2)
7. Select models with non-anom. $U_1(Y) \subset SU(5)$
8. Select models with 3 SM families + Higgses + vector-like exotics

Mini-Landscape search
LNRRRVW

criterion	$V^{\mathrm{SO(10)},1}$	$V^{\mathrm{SO(10)},2}$	$V^{\mathrm{E}_6,1}$	$V^{\mathrm{E}_6,2}$
(4) inequivalent models with 2 Wilson lines	$22,000$	$7,800$	680	$1,700$
(5) SM gauge group $\subset$ SU(5) $\subset$ SO(10) ($\subset \mathrm{E}_6$)	3563	1163	27	63
(6) 3 net $(\mathbf{3},\mathbf{2})$	1170	492	3	32
(7) non–anomalous $\mathrm{U}(1)_Y \subset$ SU(5)	528	234	3	22
(8) spectrum = 3 generations + vector-like	128	90	3	2

Table 1: Statistics of $\mathbb{Z}_6$-II orbifolds based on the shifts $V^{\mathrm{SO(10)},1}, V^{\mathrm{SO(10)},2}, V^{\mathrm{E}_6,1}, V^{\mathrm{E}_6,2}$ with two Wilson lines.

Mini-Landscape search
LNRRRVW

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$	$V^{\mathrm{E}_6,1}$	$V^{\mathrm{E}_6,2}$
(9) heavy top	72	37	3	2
(10) exotics decouple at order 8	56	32	3	2

Table 1: A subset of the MSSM candidates.

93 MSSM-like models or probability ~ 1/300

"Fertile patch" in heterotic landscape !!

Road to the MSSM w/ R-parity

LNRRRVW 0708.2691 (hep-th)

1. Check R parity
2. Check for D = 0 directions
3. Check all exotics get large mass
4. Check light Higgs
5. Check charged fermion masses
6. Check neutrino masses
7. Check dimension 5 B & L violating ops.

R parity

	q	l	H_u	H_d	$\bar{U}\bar{D}\bar{D}$	$Q\bar{D}L$	$LL\bar{E}$	LH_u
B-L	1/3	-1	0	0	-1	-1	-1	-1
$\tilde{R}$	$e^{i\alpha\pi/3}$	$e^{-i\alpha\pi}$	1	1	$e^{-i\alpha\pi}$	$e^{-i\alpha\pi}$	$e^{-i\alpha\pi}$	$e^{-i\alpha\pi}$

$$\widetilde{R} = e^{i\alpha\pi(B-L)} \qquad (B\text{-}L)\langle\tilde{S}\rangle = f\,\langle\tilde{S}\rangle \quad \Rightarrow \quad \alpha = 2/f$$

Forbid Dim 2 & 3 operators $\Rightarrow$ $\boxed{\alpha \neq 2Z}$

$\alpha = \pm 3$

Family Reflection symmetry or Matter parity $\Rightarrow$ $f = \pm\frac{2}{3}$

Generalized matter parity Z_2

Allow right-handed neutrino masses

$$\bar{\nu}\,\bar{\nu}\,\tilde{S}^n \quad \Rightarrow \; \alpha(2+n\,f)=2\mathbf{Z}$$

$$\& \;\; \alpha=2/f \neq 2\mathbf{Z} \;\; \Rightarrow f=2/(2\mathbf{Z}+1)$$

Identify "suitable" B-L

- standard for SM particles
- vector-like on exotics
- maximal no. SM singlets w/

$$\pm f = 0,\, 2,\, 2/3,\, 2/5,\, 4/5,\, 2/7,\, 4/7,\, \ldots.$$

Results

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$	total
(6) spectrum = 3 generations + vector-like	128	90	218
(7) heavy top	72	37	109
(8) exotics decouple at order 8 (arbitrary vevs)	56	32	88

Consider one "Benchmark" Model

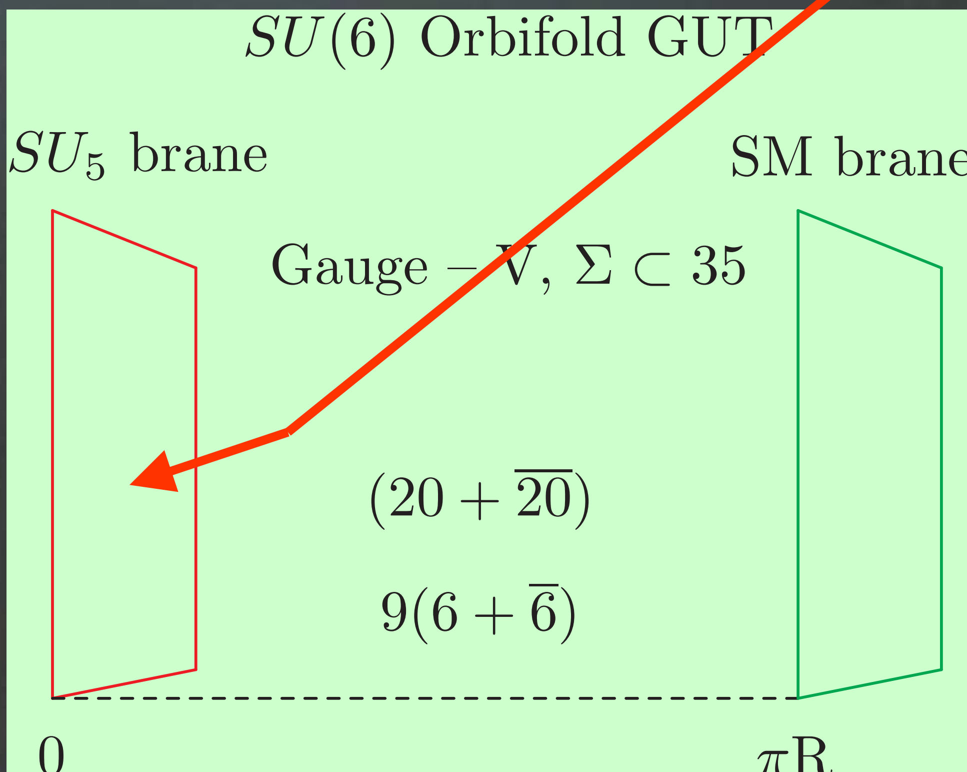
$G = SU(3) \times SU(2) \times [SU(4) \times SU(2)'] \times U(1)^9$

1. Spectrum
2. μ term
3. Yukawa couplings
4. Neutrino masses
5. Dim. 5 ops.

$$V_6 = \tfrac{1}{6}\begin{pmatrix}2 & -3 & -3 & 0 & 0 & 0 & 0 & 0\end{pmatrix}(\cdots)$$

$$W_3 = \tfrac{1}{3}\begin{pmatrix}-\tfrac{3}{2} & -\tfrac{3}{2} & \tfrac{1}{2} & \tfrac{1}{2} & \tfrac{1}{2} & \tfrac{1}{2} & \tfrac{1}{2} & \tfrac{1}{2}\end{pmatrix}(\cdots)$$

- Orbifold GUT – SU(6)
- Local GUT – SO(10) x SO(4)



Spectrum

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/3,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-4/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(2,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(2/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,1/3)}$	d_i
4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1,0)}$	ϕ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1,0)}$	$\bar{\phi}_i$
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(2/3,2/3)}$	δ_i		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-2/3)}$	$\bar{\delta}_i$
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,*)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1,*)}$	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$		13	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$		5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i		2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(0,*)}$	f_i		6	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(0,*)}$	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1,1)}$	$\bar{f}_i^+$
4	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i		32	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
2	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-2/3)}$	v_i

$\widetilde{S}$

Table 1: Spectrum. The quantum numbers under $SU(3)\times SU(2)\times[SU(4)\times SU(2)']$ are shown, hypercharge and B-L charge appear as subscript.

μ term

$$\left\langle \widetilde{S} \right\rangle^{n} \left(\phi_1 \overline{\phi_1} \right) \qquad \mu \sim M_Z$$

Yukawa couplings

Not realistic – YET

Dimension 5 operators –

suppressed ~ $\left\langle \tilde{S} \right\rangle^{6}$

BUT generated again when integrating out δ states – problem ??

Neutrino masses via See-Saw

YES !!

Proton decay

✓ IF families at local GUT fixed points

⟹ Dimension 6 ops. fixed by $1/M_C^2$

Expect $M_C < M_G$ ⟹ τ_p ↘

✓ Dimension 5 ops. unsuppressed -

Unless find symmetry

✓ R-parity forbids

Dimension 3 & 4 B & L violation

Conclusions

Important to test string theory

We find MSSM in "fertile patch" of E(8)xE(8) heterotic string

Almost realistic "Benchmark" models !!!

w/ Caveat

SUSY breaking and lifting flat directions ??

MSSM $\longleftrightarrow$ Orbifold & Local GUT