A heterotic benchmark model

Michael Ratz

Based on:
O. Lebedev, H.P. Nilles, S. Raby, S. Ramos-Sánchez, M. R. P. Vaudrevange & A. Wingerter Phys. Rev. D 77, 046013 (2008)
& work in preparation

Outline

1. Motivation
2. A very brief review of local grand unification
3. Main part: a 'heterotic benchmark model'
4. Discussion

Challenges in top–down model building

- longstanding task: find '**the**' (or 'a'?) realistic string compactification

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  Huge number of string theory vacua

  Lerche, Lüst & Schellekens (1987)
  Bousso & Polchinski (2000)

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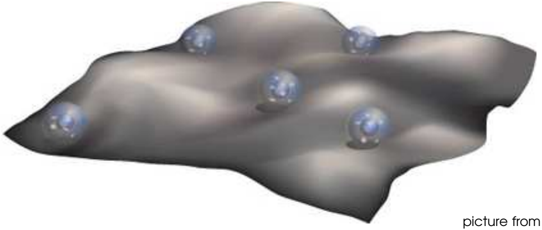
➥ String theory landscape

Susskind (2003)



picture from www.nature.com

Challenges in top–down model building

- longstanding task: find '**the**' (or 'a'?) realistic string compactification
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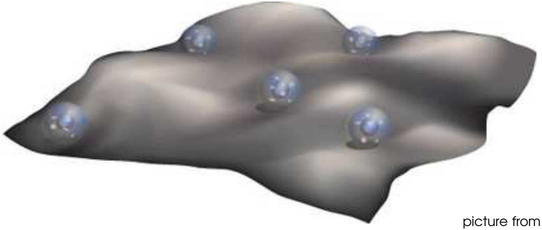

picture from www.nature.com

- SM vacuum a priori as good as many others

The search for realistic string vacua

"Finding a realistic vacuum is similarly difficult as finding a golf ball in the Alps"

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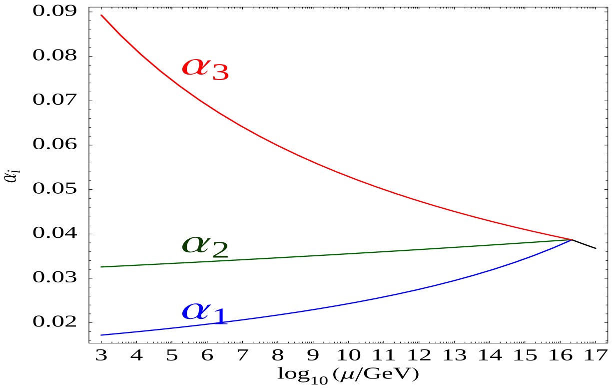
☞ **Our approach:**
"First search for golf courses, and then for golf balls"

Search strategy: 'local GUTs'

☺ MSSM gauge coupling unification @ $M_{\text{GUT}} \sim 10^{16}\,\text{GeV}$



Search strategy: `local GUTs'

- ☺ MSSM gauge coupling unification
- ☺ One generation of observed matter fits into $\mathbf{16}$ of $\mathrm{SO}(10)$

$$
\begin{aligned}
\mathrm{SO}(10) &\to \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_\mathrm{Y} = G_\mathrm{SM} \\
\mathbf{16} &\to (\mathbf{3},\mathbf{2})_{1/6}\oplus(\overline{\mathbf{3}},\mathbf{1})_{-2/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{1/3} \\
&\quad \oplus(\mathbf{1},\mathbf{1})_{1}\oplus(\mathbf{1},\mathbf{2})_{-1/2}\oplus(\mathbf{1},\mathbf{1})_{0}
\end{aligned}
$$

Search strategy: ‘local GUTs’

- ☺ MSSM gauge coupling unification
- ☺ $\mathbf{16}$ of $\mathrm{SO}(10)$
- ☹ However: Higgs only as doublet(s)

$$\mathbf{10} \to (\mathbf{1},\mathbf{2})_{1/2} \oplus (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{3},\mathbf{1})_{-1/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3}$$

doublets: needed

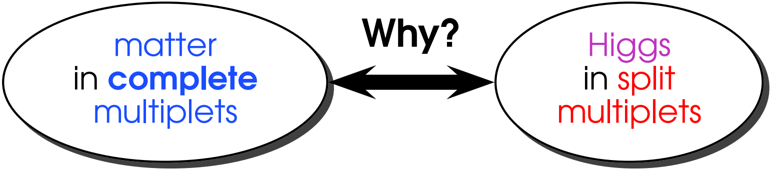
triplets: excluded

Search strategy: ‘local GUTs’

- MSSM gauge coupling unification
- **16** of SO(10)

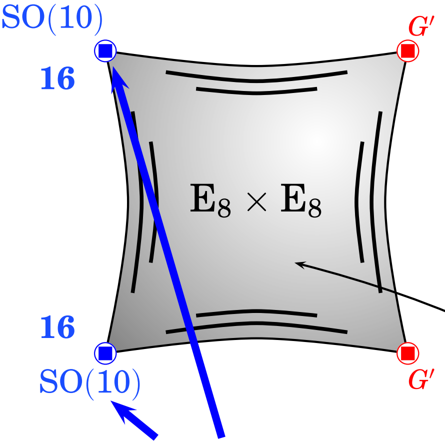
} . . . we take these hints seriously

- However: Higgs only as doublet(s)



convincing answer:
‘localized gauge groups’

Local grand unification (a specific realization)



Buchmüller, Hamaguchi, Lebedev, M.R. (2004-2006)
Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006-2007)

'low-energy' effective theory $\longrightarrow$ standard model as an intersection of $\mathrm{SO}(10)$, G' ... in $\mathrm{E}_8 \times \mathrm{E}_8$

2 SM generation(s):
localized in region with $\mathrm{SO}(10)$ symmetry

Higgs doublets:
live in the 'bulk'

Higher-dimensional GUTs vs. heterotic orbifolds

top-down
→ Orbifold compactifications of the heterotic string

Dixon, Harvey, Vafa, Witten (1985-86)
Ibáñez, Nilles, Quevedo (1987)
Ibáñez, Kim, Nilles, Quevedo (1987)
Font, Ibáñez, Nilles, Quevedo (1988)
Font, Ibáñez, Quevedo, Sierra (1990)
Katsuki, Kawamura, Kobayashi, Ohtsubo, Ono, Tanioka (1990)
...

- has UV completion
- automatically consistent
- explain representations

bottom-up
→ Orbifold GUTs

Kawamura (1999-2001)
Altarelli, Feruglio (2001)
Hall, Nomura (2001)
Hebecker, March-Russell (2001)
Asaka, Buchmüller, Covi (2001)
Hall, Nomura, Okui, Smith (2001)
...

- simple geometrical interpretation
- shares many features with 4D GUTs

combine both approaches

implement field-theoretic GUTs in non-prime orbifold compactifications of the heterotic string

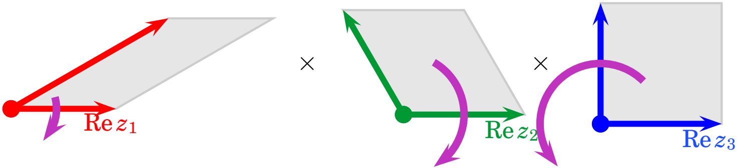
Kobayashi, Raby, Zhang (2004)
Förste, Nilles, Vaudrevange, Wingerter (2004)
Hebecker, Trapletti (2004)
Buchmüller, Hamaguchi, Lebedev, M.R. (2004-2006)
Faraggi, Förste, Timirgaziu (2006)
Kim, Kyae (2006)
Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006-7)

A heterotic
‘benchmark’ model

Model definition and spectrum

O. Lebedev, H.P. Nilles, S. Raby, S. Ramos-Sánchez, M.R., P. Vaudrevange, A. Wingerter (2007)

- Input = geometry, shift & Wilson lines



$$V = \left(\frac{1}{3},-\frac{1}{2},-\frac{1}{2},0,0,0,0,0\right)\left(\frac{1}{2},-\frac{1}{6},-\frac{1}{2},-\frac{1}{2},-\frac{1}{2},-\frac{1}{2},-\frac{1}{2},\frac{1}{2}\right)$$

$$W_2 = \left(0,-\frac{1}{2},-\frac{1}{2},-\frac{1}{2},\frac{1}{2},0,0,0\right)\left(4,-3,-\frac{7}{2},-4,-3,-\frac{7}{2},-\frac{9}{2},\frac{7}{2}\right)$$

$$W_3 = \left(-\frac{1}{2},-\frac{1}{2},\frac{1}{6},\frac{1}{6},\frac{1}{6},\frac{1}{6},\frac{1}{6},\frac{1}{6}\right)\left(\frac{1}{3},0,0,\frac{2}{3},0,\frac{5}{3},-2,0\right)$$

Model definition and spectrum

O. Lebedev, H.P. Nilles, S. Raby, S. Ramos-Sánchez, M.R., P. Vaudrevange, A. Wingerter (2007)

- Input = geometry, shift & Wilson lines
- Gauge group

$$G = [\overbrace{\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y}^{\subset\,\mathrm{SU}(5)\,\subset\,\mathrm{SO}(10)}\times\mathrm{U}(1)_{B-L}]\times[\mathrm{SU}(4)\times\mathrm{SU}(2)']\times\mathrm{U}(1)^7$$

GUT normalization ➡ gauge coupling unification

$$\mathsf{t}_Y = \left(0,0,0,\tfrac{1}{2},\tfrac{1}{2},-\tfrac{1}{3},-\tfrac{1}{3},-\tfrac{1}{3}\right)\left(0,0,0,0,0,0,0,0\right)$$

$$\mathsf{t}_{B-L} = \left(0,0,0,0,0,-\tfrac{2}{3},-\tfrac{2}{3},-\tfrac{2}{3}\right)\left(0,0,0,0,0,2,0,0\right)$$

normalization not as in $\mathrm{SO}(10)$

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- Spectrum

$$\text{spectrum} = 3 \times \text{generation} + \text{vector-like w.r.t. } G_{\mathrm{SM}} \times \mathrm{U}(1)_{B-L}$$

Spectrum @ orbifold point

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	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	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

Spectrum @ orbifold point

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3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,\ast)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,\ast)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,\ast)}$	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	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]		[illegible]	[illegible] $_{(0,\ast)}$	[illegible]
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

spectrum = 3 generations + vector-like

Spectrum @ orbifold point

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
3 + 1	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
3 + 1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	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	(					
6	(				$(0,*)$	
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\bar{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

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Spectrum @ orbifold point

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3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
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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	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
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2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
4	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,+2)}$	χ_i		32	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
2	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

spectrum = 3 generations + vector-like

Spectrum @ orbifold point

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$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$	1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$	6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
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5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})$				η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})$				y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})$				$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	[illegible]	2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$	2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

$B-L$ allows to discriminate

- between lepton and Higgs fields
- between neutrinos and other singlets

Spectrum @ orbifold point

#	irrep	label	#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i	3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$	8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$	1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	[illegible]	[illegible]	… $/2,0)$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	[illegible]	[illegible]	… $1/3,-2/3)$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	[illegible]	[illegible]	… $1/2,*)$	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	[illegible]	[illegible]	… $_{(0,-1)}$	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	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-	2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$	2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

crucial:

existence of SM singlets with $q_{B-L}=\pm 2$

Decoupling of exotics vs. μ term

- Decoupling of exotics

$$X_i \overline{X}_j \quad \underbrace{s_{i_1} \dots s_{i_n}}_{\text{vev}\rightarrow\text{mass term}}$$

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We have checked that:

1. exotics' mass matrices have **full rank** with

$s_i \;=\; G_{\mathrm{SM}} \times \mathrm{SU}(4)$ singlets with $q_{B\text{–}L} = 0$ or ± 2

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Questions:

- ☞ Is there a reason why the Higgs doublets' mass is much smaller than the exotic's masses?
- ☞ Is there a reason why the Higgs mass is of the order of the weak scale?

A stringy solution to the μ problem

☞ The pair h_u-h_d are the only fields from U_3

A stringy solution to the μ problem

- The pair h_u-h_d are the only fields from U_3
- $h_u\,h_d$ is 'neutral' w.r.t. to the selection rules:
  - gauge invariant
  - correspond to space group element $(\mathbb{1}, 0)$
  - total R-charges are $(0, 0, -2) = (0, 0, 0) \mod (6, 3, 2)$

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- As a consequence: for any monomial $\mathscr{M} = s_{i_1} \dots s_{i_N}$

$$\mathscr{M}\,h_u\,h_d \in \mathscr{W} \quad \curvearrowright \quad \mathscr{M} \in \mathscr{W}$$

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- We find (empirically, at order s^6)

$$F_i = 0 \quad \curvearrowright \quad \langle \mathscr{M} \rangle = 0 \quad \forall \text{ monomials } \mathscr{M} \in \mathscr{W}$$

Note: at first glance, the conditions

$$F_i \stackrel{!}{=} 0 \quad \wedge \quad \mathscr{W} = 0$$

appear to be 'overconstraining'.
However, the superpotential $\mathscr{W}$ has to respect many symmetries ('discrete string selection rules').
$\curvearrowright$ $\mathscr{W}$ is not a generic (gauge invariant) polynomial of the fields.

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$$\langle \mathscr{W} \rangle = 0 \quad \text{and} \quad \mu = \frac{\partial^2 \mathscr{W}}{\partial h_u\, \partial h_d} = 0$$

...and all exotics are massive $\left(m_{\text{exotics}} \sim \sqrt{\text{FI-term}} \sim M_{\text{GUT}} \right)$

A stringy solution to the μ problem

Note: these features are not 'put in by hand', but just happen to arise in vacua with unbroken standard model gauge symmetry and R-parity

there are several comparable models in the Mini-Landscape

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Stringy solutions to the μ problem - literature

- There exist proposals for precisely this situation

Stringy solutions to the μ problem - literature

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❶ μ from $\mathscr{W}$

Casas, Muñoz (1993)

…the relation $\mathscr{W} \supset \mathscr{W}_0\, h_u\, h_d$ has been assumed

↷ the b (or $B\,\mu$) term is $2\mu\, m_{3/2}$

where b is the coefficient of $h_u\, h_d$, i.e.

$$\mathscr{L} \supset -(|\mu|^2 + m_{h_u}^2)\,|h_u|^2 - (|\mu|^2 + m_{h_d}^2)\,|h_d|^2 - b\,(h_u\, h_d + \text{c.c.})$$

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❷ μ from K

Antoniadis, Gava, Narain, Taylor (1994)

Brignole, Ibáñez, Muñoz (1995-1997)

see also the recent similar discussion by Hebecker, March-Russell, Ziegler

$$K \supset -\log\left[\left(T_3+\overline{T_3}\right)\left(Z_3+\overline{Z_3}\right)-\left(h_u+\overline{h_d}\right)\left(\overline{h_u}+h_d\right)\right]$$

Kähler modulus

complex structure modulus

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- ☞ Model allows to use both mechanisms (simultaneously!)
- ☞ 'Combinationtion' of both mechanisms appears phenomenologically viable

  Brümmer et al. (in preparation)

Gauge-Top unification

☞ Untwisted sector (=internal components of the gauge bosons)

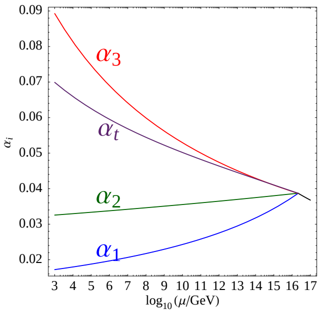
	field-theoretic description	state
U_1	$\sim A_5 + \mathrm{i}A_6$	$\overline{u}_1 + \dots$
U_2	$\sim A_7 + \mathrm{i}A_8$	$q_1 + \dots$
U_3	$\sim A_9 + \mathrm{i}A_{10}$	$h_u + \dots$

Renormalizable coupling

$$y_t \, u_1 \, q_1 \, h_u$$

$y_t \simeq g$ @ M_{comp}

☞ all other Yukawa couplings are suppressed (i.e. appear at higher order)



See-saw couplings

- see-saw couplings: $W_{\mathrm{see-saw}} = Y_\nu^{ij}\, h_u\, \ell_i\, \bar\nu_j + M_{ij}\, \bar\nu_i\, \bar\nu_j$

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singlet

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- see-saw mass matrix

$$W_{\text{see}-\text{saw}} \xrightarrow{h_u \to v} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_\nu\, v \\ y_\nu\, v & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \simeq \frac{y_\nu^2\, v^2}{M}\, \nu\, \nu + M\, \bar{\nu}\, \bar{\nu}$$

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... suspiciously close to observed values

$$\sqrt{\Delta m^2_{\text{atm}}} \simeq 0.04\,\mathrm{eV} \quad \& \quad \sqrt{\Delta m^2_{\text{sol}}} \simeq 0.008\,\mathrm{eV}$$

See-saw neutrinos from the heterotic string

$$
\mathcal{M}_{nn} = \left(\begin{array}{ccccccccccccccccccccccc}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{array}\right)
$$

See-saw neutrinos from the heterotic string

$$\mathcal{M}_{n\bar{n}} = \begin{pmatrix}
\tilde{s}^{6} & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{4} & \tilde{s}^{6} & 0 & 0 & 0 & 0 & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
\tilde{s}^{6} & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{4} & 0 & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} \\
0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & \tilde{s}^{3} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} \\
0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
\tilde{s}^{6} & \tilde{s}^{5} & 0 & \tilde{s}^{6} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
\tilde{s}^{6} & \tilde{s}^{5} & 0 & \tilde{s}^{6} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 \\
\tilde{s}^{5} & \tilde{s}^{4} & 0 & \tilde{s}^{4} & 0 & \tilde{s}^{4} & \tilde{s}^{4} & 0 & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{4} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{4} & \tilde{s}^{4} & \tilde{s}^{4} & \tilde{s}^{4} \\
\tilde{s}^{4} & \tilde{s}^{3} & 0 & 0 & 0 & \tilde{s}^{2} & \tilde{s}^{2} & \tilde{s}^{6} & 0 & 0 & 0 & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{2} & \tilde{s}^{2} & \tilde{s}^{2} & \tilde{s}^{2} \\
\tilde{s}^{4} & \tilde{s}^{3} & 0 & 0 & 0 & \tilde{s}^{2} & \tilde{s}^{2} & \tilde{s}^{6} & 0 & 0 & 0 & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{2} & \tilde{s}^{2} & \tilde{s}^{2} & \tilde{s}^{2} \\
0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} \\
0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} \\
\tilde{s}^{4} & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{2} & 0 & 0 & 0 & \tilde{s}^{3} & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} \\
\tilde{s}^{4} & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{2} & 0 & 0 & 0 & \tilde{s}^{3} & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} & \tilde{s}^{5} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & 0 & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & 0 & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & 0 & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{3} & 0 & \tilde{s}^{5} & \tilde{s}^{5} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{6} & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} \\
0 & 0 & 0 & 0 & 0 & \tilde{s}^{5} & \tilde{s}^{6} & 0 & \tilde{s}^{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & \tilde{s}^{3} & 0 & 0 & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6} & \tilde{s}^{6}
\end{pmatrix}$$

See-saw neutrinos from the heterotic string

$$\mathcal{M}_{\bar{n}\bar{n}} = \left(\begin{array}{cccccccccccccccccccccccccc}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5\\
0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5\\
0&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0\\
0&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&\widetilde{s}^4&0&0&\widetilde{s}^4&0&0&0&0&0&0&\widetilde{s}^4&\widetilde{s}^4&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^4&0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&\widetilde{s}^4&0&0&\widetilde{s}^4&0&0&0&0&0&0&\widetilde{s}^4&\widetilde{s}^4&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^4&0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^4&0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^4&0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0\\
0&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0\\
0&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0\\
0&0&0&\widetilde{s}^5&\widetilde{s}^5&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0
\end{array}\right)$$

See-saw neutrinos from the heterotic string

$$\mathcal{M}_{\bar{\nu}\bar{\nu}} = \begin{pmatrix} \mathcal{M}_{\bar{n}\bar{n}} & \mathcal{M}_{n\bar{n}}^T \\ \mathcal{M}_{n\bar{n}} & \mathcal{M}_{nn} \end{pmatrix}$$

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$$\mathcal{M}_{\bar{\nu}\bar{\nu}} = \begin{pmatrix} \mathcal{M}_{\bar{n}\bar{n}} & \mathcal{M}^T_{n\bar{n}} \\ \mathcal{M}_{n\bar{n}} & \mathcal{M}_{nn} \end{pmatrix}$$

$$Y_n = \begin{pmatrix} 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&\widetilde{s}^3&\widetilde{s}^3&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4&0&0 \\ 0&0&\widetilde{s}^3&\widetilde{s}^3&0&0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4&0&0 \end{pmatrix}$$

$$Y_{\bar{n}} = \begin{pmatrix} \widetilde{s}^6&\widetilde{s}^5&\widetilde{s}^5&0&0&\widetilde{s}^4&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4 \\ \widetilde{s}^6&\widetilde{s}^5&\widetilde{s}^5&0&0&\widetilde{s}^4&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4&\widetilde{s}^4 \\ 0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^5&\widetilde{s}^5&1&0&\widetilde{s}^6&\widetilde{s}^2&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^3&\widetilde{s}^3&\widetilde{s}^3&\widetilde{s}^3&0&0&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5 \\ 0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^6&0&0&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^2&0&\widetilde{s}^6&1&0&\widetilde{s}^6&\widetilde{s}^6&\widetilde{s}^3&\widetilde{s}^3&\widetilde{s}^3&\widetilde{s}^3&0&0&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5&\widetilde{s}^5 \end{pmatrix}$$

See-saw neutrinos from the heterotic string

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$$Y_\nu = (Y_{\bar{n}}, Y_\nu)$$

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$$Y_\nu = (Y_{\bar{n}}, Y_\nu)$$

bottom-line:

Y_ν and M exist with M & $m_\nu = v^2\, Y_\nu^T\, M^{-1}\, Y_\nu$ having full rank

Heterotic see-saw

W. Buchmüller, K. Hamaguchi, O. Lebedev, M.R. (2006)

W. Buchmüller, K. Hamaguchi, O. Lebedev, S. Ramos-Sánchez, M.R. (2007)

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☞ there are $\mathcal{O}(100)$ neutrinos ($=$ R-parity odd SM singlets)

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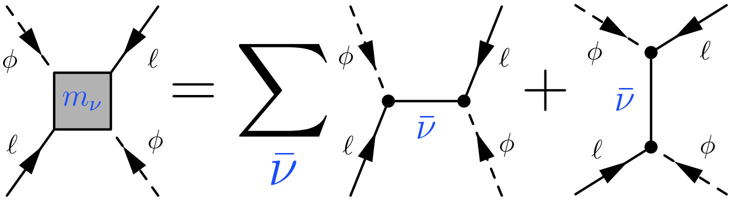

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- there are $\mathcal{O}(100)$ neutrinos ($=$ R-parity odd SM singlets)
- ➥ $\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator
- ➥ effective suppression of the see-saw scale

$$m_\nu \sim \frac{v^2}{M_*} \qquad M_* \sim \frac{M_{\mathrm{GUT}}}{10\dots 100}$$

... seems consistent with observation
$\left(\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.04\,\mathrm{eV}\ \&\ \sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.008\,\mathrm{eV}\right)$

Heterotic see-saw

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Main conclusion:

See-saw is a **generic feature** in heterotic MSSM vacua

Heterotic see-saw

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Main conclusion:

See-saw is a **generic feature** in heterotic MSSM vacua

- Note: in $\mathbb{Z}_3$ orbifolds one arrives at a different conclusion

cf. Giedt, Kane, Langacker, Nelson (2005)

Summary of search strategy

- We started analyzing the heterotic orbifold landscape

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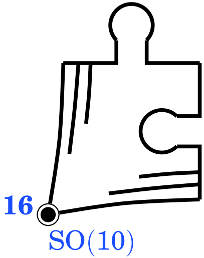


- The concept of 'local grand unification' has lead us to beautiful spots

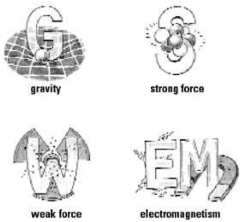
Summary of features

1. $3 \times \mathbf{16}$ + Higgs + nothing

No exotics

Summary of features

1. $3 \times \mathbf{16} + \text{Higgs} + \text{nothing}$
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$



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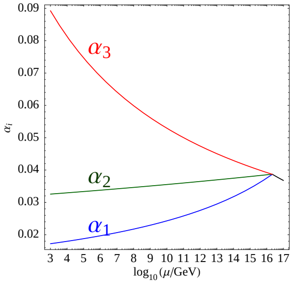
3. unification



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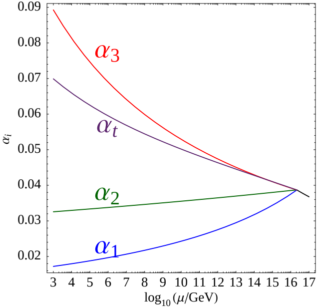

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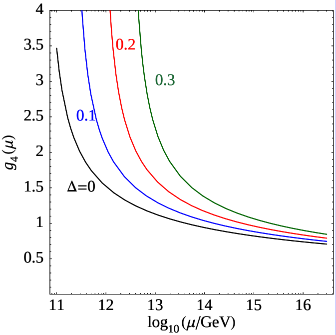
5. hidden sector gaugino condensation

➥ spontaneously broken SUSY with TeV scale soft masses



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6. R-parity

$\xcancel{\bar{u}\,\bar{u}\,\bar{d}}$ $\xcancel{q\,\bar{d}\,\ell}$

$\xcancel{\ell\,\ell\,\bar{e}}$ $\xcancel{\ell\,\bar{\phi}}$

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6. R-parity
7. solution to the μ-problem

   i.e. well-known solutions to the μ-problem are automatically realized in explicit models

$$\mu \sim \langle \mathscr{W} \rangle$$

Summary of features

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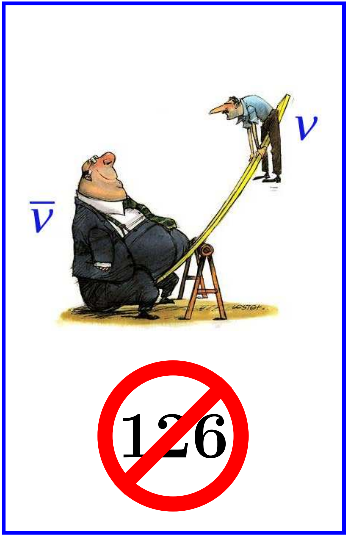
5. hidden sector gaugino condensation
6. R-parity
7. solution to the μ-problem
8. see-saw



Thank you very much!