Neutrinos & Strings

TECHNISCHE UNIVERSITÄT MÜNCHEN

Michael Ratz

TUM LMU Excellence Cluster Universe

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Based on:

- W. Buchmüller, K. Hamaguchi, O. Lebedev, S. Ramos–Sánchez, M.R., Phys. Rev. Lett. 99, 021601 (2007)
- O. Lebedev, H.P. Nilles, S. Raby, S. Ramos-Sánchez, M.R., P. Vaudrevange, A. Wingerter, Phys. Rev. D77, 046013 (2008)
- H.M. Lee, S. Raby, G. Ross, M.R., R. Schieren, K. Schmidt–Hoberg & P. Vaudrevange, Phys. Lett. **B** 694, 491-495 (2011)
- R. Kappl, B. Petersen, S. Raby, M.R., R. Schieren & P. Vaudrevange, Nucl. Phys. **B** 847, 325-349 (2011)
- M.–C. Chen, M.R., C. Staudt & P. Vaudrevange, arXiv:1206.5375

Outline

☞ Scales in unified model building:

- Planck scale M_{P}
- String scale M_{string}
- GUT scale M_{GUT}
- See–saw scale $M_{\mathrm{see-saw}}$

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$$\left\{\begin{array}{l} \text{Planck scale } M_{\mathrm{P}} \\ \text{String scale } M_{\mathrm{string}} \\ \text{GUT scale } M_{\mathrm{GUT}} \\ \text{See–saw scale } M_{\mathrm{see-saw}} \end{array}\right.$$

☞ Neutrinos from the top–down:

- what is a neutrino in a string model?
- how to distinguish neutrinos from other SM singlets (moduli etc.)

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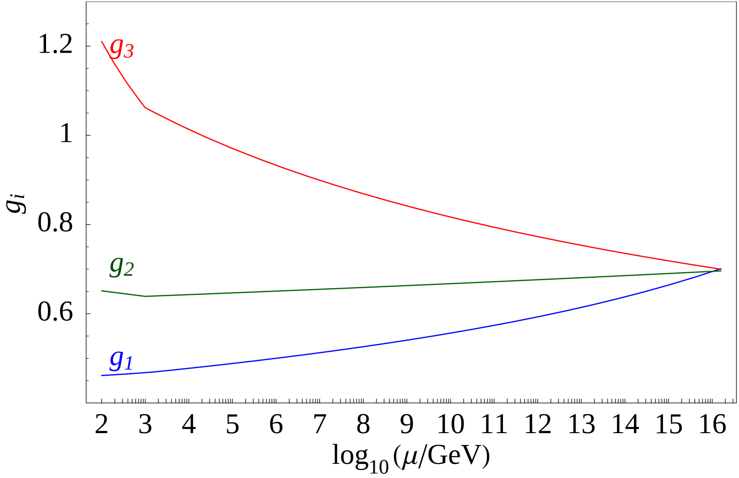
- ☞ Summary

Scales in unified model building

Gauge coupling unification in the MSSM

- Running couplings in the (minimal) supersymmetric standard model (MSSM)

Dimopoulos et al. (1981)



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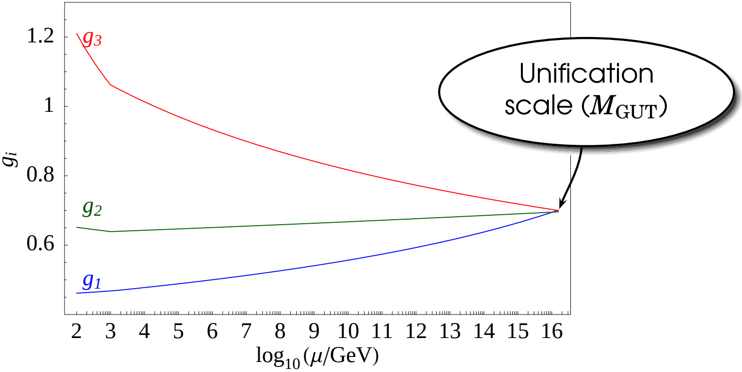

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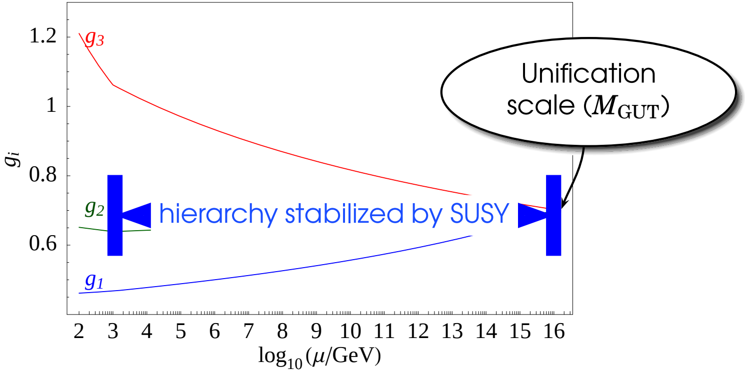

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Neutrino masses in grand unification: see–saw

- allowed coupling: $\overline{\mathbf{126}}\,\mathbf{16}\,\mathbf{16} \;\to\;$ (SM singlets) $\overline{\nu}\,\overline{\nu} + \ldots$

'right-handed' neutrino = SM singlet

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➥ Higgs VEV: $\langle\overline{\mathbf{126}}\rangle$ ↷ mass term $M\,\overline{\nu}\,\overline{\nu}$

☞ expect: $\langle\overline{\mathbf{126}}\rangle \sim M_{\mathrm{GUT}} \simeq 2\cdot 10^{16}\,\mathrm{GeV}$

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'u–type Higgs'

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$$

'lepton doublet'

$$L = \begin{pmatrix} \nu \\ E \end{pmatrix}$$

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Minkowski (1977)
Gell-Mann et al. (1979)
Yanagida (1979)

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- ➥ see–saw mass matrix

$$\mathscr{W}_{\text{see-saw}} \xrightarrow{H_u\to v} (\nu,\overline{\nu})\begin{pmatrix} 0 & y_\nu\,v \\ y_\nu\,v & M \end{pmatrix}\begin{pmatrix} \nu \\ \overline{\nu} \end{pmatrix} \;\simeq\; \frac{y_\nu^2\,v^2}{M}\,\nu\,\nu + M\,\overline{\nu}\,\overline{\nu}$$

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- expectation: $m_\nu \sim (100\,\mathrm{GeV})^2/10^{16}\,\mathrm{GeV} \sim 10^{-3}\,\mathrm{eV}$

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- experiments: $\sqrt{\Delta m^2_{\rm atm}} \simeq 0.04\,{\rm eV}$ & $\sqrt{\Delta m^2_{\rm sol}} \simeq 0.008\,{\rm eV}$
- neutrino masses hint at
  - see–saw
  - GUT structures
- Factor 10–100 discrepancy (. . . would need $M \sim$ few $\cdot\, 10^{14}\,{\rm GeV}$)

GUT vs. string scale

➥ 4D Newton's constant and gauge coupling

$$G_{\mathrm{N}} = \frac{\mathrm{e}^{2\phi}\,(\alpha')^4}{64\pi\,V} \quad \text{and} \quad \alpha_{\mathrm{GUT}} = \frac{\mathrm{e}^{2\phi}\,(\alpha')^3}{16\pi\,V}$$

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- Relation between Newton's constant and gauge coupling

$$G_N = \frac{\alpha_{GUT}\,\alpha'}{4} = \frac{\alpha_{GUT}}{8\pi\,M_{string}^2} \simeq \frac{1}{(24\,M_{string})^2} \stackrel{!}{=} \frac{1}{M_P^2}$$

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- Well–known problem: using $\alpha_{GUT} = g_{GUT}^2/4\pi \simeq 1/25$

$$M_{string} \simeq 9 \cdot 10^{17}\,\text{GeV} \quad \text{and} \quad M_{GUT} \simeq (2-3) \cdot 10^{16}\,\text{GeV}$$

$$\curvearrowright \quad \frac{M_{string}}{M_{GUT}} \sim 30 \ldots 40$$

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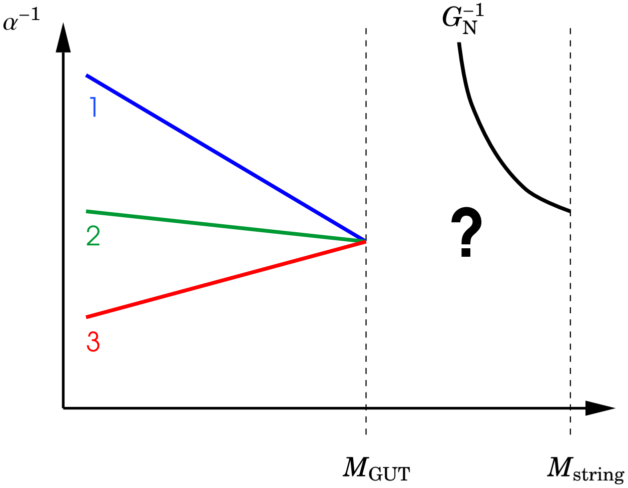
Gauge unification: GUT vs. string scale

cf. Dienes (1997)



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☞ 1–3 can be reconciled in anisotropic compactifications:

$$R_{\mathrm{large}} \sim 1/M_{\mathrm{GUT}} \quad \& \quad R_{\mathrm{small}} \sim 1/M_{\mathrm{string}}$$

R_{large} ↔ SU(5)/SO(10) GUT breaking

R_{small} ↔ E_8 breaking

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☞ Remainder of this talk:
$M_\mathrm{see-saw}$ vs. M_GUT in string models

Neutrinos
in string models

Matter parity or effective R parity from $\mathrm{U}(1)_{B-L}$

- $\mathrm{U}(1)_{B-L} \subset \mathrm{SO}(10)$ yields standard charges for matter

$$
\begin{array}{lcl}
\mathrm{SO}(10) & \to & \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_{\mathrm{Y}}\times\mathrm{U}(1)_{B-L} \\
\mathbf{16} & \to & (\mathbf{3},\mathbf{2})_{1/6,1/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{-2/3,-1/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{1/3,-1/3} \\
 & & \oplus\,(\mathbf{1},\mathbf{1})_{1,1}\oplus(\mathbf{1},\mathbf{2})_{-1/2,-1}\oplus(\mathbf{1},\mathbf{1})_{0,1}
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☞ How to define $B-L \subset \mathrm{E}_8\times\mathrm{E}_8$?

Buchmüller et al. (2007a) ; Lebedev et al. (2007)

1. $q_{B\text{-}L}$(members of **16**-plet) $\overset{!}{=}$ standard
2. spectrum $\overset{!}{=}$ 3 generations + vector–like w.r.t. $G_{\mathrm{SM}}\times\mathrm{U}(1)_{B\text{-}L}$

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in many orbifold MSSM models:

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

➤

Matter parity:

$\mathrm{U}(1)_{B-L} \to \mathbb{Z}_2^R$

Unique $\mathbb{Z}_4^R$ symmetry for the MSSM

Lee et al. (2011) ; Chen et al. (2012)

☞ A simple anomaly–free $\mathbb{Z}_4^R$ symmetry can

- provide a solution to the μ problem
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universal anomaly coefficients
universal charges for matter
forbid μ @ tree–level
allow Yukawa couplings
allow Weinberg operator

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$\mathbb{Z}_4^R$ $\curvearrowright$ {
dim. 4 proton decay operators completely forbidden
dim. 5 proton decay operators highly suppressed
μ appears non–perturbatively

Neutrinos and $\mathbb{Z}_4^R$

☞ $\mathbb{Z}_4^R$: $\begin{cases} \text{matter} & : \quad R \text{ charge } 1 \\ \text{Higgs} & : \quad R \text{ charge } 0 \end{cases}$

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Kappl et al. (2011)

☞ Explicit string models with $\mathbb{Z}_4^R$ and see–saw neutrinos

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Kappl et al. (2011)

- Explicit string models with $\mathbb{Z}_4^R$ and see–saw neutrinos
- However, discuss an older example

An explicit example

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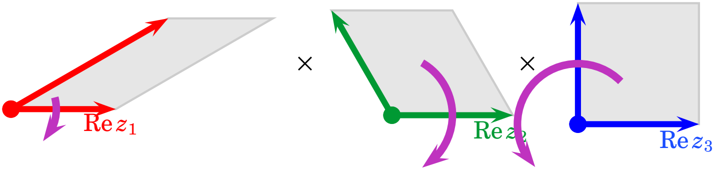
Lebedev et al. (2007)

☞ Input = geometry, shift & Wilson lines



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

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

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

An explicit example

Lebedev et al. (2007)

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

$$\subset \mathrm{SU}(5) \subset \mathrm{SO}(10)$$

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

GUT normalization ➡ gauge coupling unification

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

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

normalization not as in SO(10)

An explicit example

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➥ Gauge group

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

- Spectrum

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

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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
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

#	irrep	label	#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i	3	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(-2/3,-1/3)}$	$\bar{u}_i$
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	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(1/3,-1/3)}$	$\bar{d}_i$	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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
6	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(1/3,2/3)}$	$\bar{\delta}_i$	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	$\left(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1}\right)_{(1/2,1)}$	$\bar{f}_i^+$
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	$\left(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1}\right)_{(-1/6,2/3)}$	$\bar{v}_i$	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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
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						
6					$_{(0,*)}$	
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	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm2)}$	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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i	1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]	$(\ldots)_{(0,*)}$	[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	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
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	$(\mathbf{1},\mathbf{1};\mathbf{1},$ [illegible]	[illegible]		[illegible]	[illegible]	η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},$ [illegible]	[illegible]		[illegible]	[illegible]	ν_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},$ [illegible]	[illegible]		[illegible]	[illegible]	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	[illegible]		[illegible]	[illegible]$_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$				2,0)	ϕ_i
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$				/3,−2/3)	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$				/2,*)	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$				$(0,-1)$	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

crucial:

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

Spectrum in MSSM vacua

- Decoupling of exotics

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

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We have checked that:

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

$$s_i = G_{\text{SM}} \times \text{SU}(4) \text{ singlets with } q_{B\text{-}L} = 0 \text{ or } \pm 2$$

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➥ Have obtained an MSSM vacuum with R parity

What is a (‘right-handed’) neutrino?

- 4D GUTs: $\overline{\nu}$ member of $\mathbf{16}$-plet

$$\begin{aligned} \mathrm{SO}(10) &\rightarrow \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_{\mathrm{Y}}\times\mathrm{U}(1)_{B\text{-}L} \\ \mathbf{16} &\rightarrow (\mathbf{3},\mathbf{2})_{1/6,1/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{-2/3,-1/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{1/3,-1/3} \\ &\quad\oplus(\mathbf{1},\mathbf{1})_{1,1}\oplus(\mathbf{1},\mathbf{2})_{-1/2,-1}\oplus(\mathbf{1},\mathbf{1})_{0,1} \end{aligned}$$

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$$\mathrm{SO}(10) \rightarrow \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y\times\mathrm{U}(1)_{B\text{-}L}$$

$$\mathbf{16} \rightarrow (\mathbf{3},\mathbf{2})_{1/6,1/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{-2/3,-1/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{1/3,-1/3}\oplus(\mathbf{1},\mathbf{1})_{1,1}\oplus(\mathbf{1},\mathbf{2})_{-1/2,-1}\oplus(\mathbf{1},\mathbf{1})_{0,1}$$

Higher-dimensional GUTs/Strings:

$\bar{\nu}$ = G_{SM} singlet which is odd under matter parity

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Higher-dimensional GUTs/Strings:

$\bar{\nu}$ = G_{SM} singlet which is odd under matter parity

- remark: we get 49 neutrinos in the example

$$n_i \;\&\; \bar{n}_i \;=\; (\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{0,\mp1}$$

$$\bar{\eta}_1 = \begin{pmatrix} \bar{n}_{17} \\ n_{18} \end{pmatrix}, \dots \bar{\eta}_5 = \begin{pmatrix} \bar{n}_{25} \\ n_{26} \end{pmatrix} ; \; \eta_1 = \begin{pmatrix} n_{14} \\ n_{15} \end{pmatrix}, \dots \eta_3 = \begin{pmatrix} n_{22} \\ n_{23} \end{pmatrix}$$

$$\{\nu_i\}_{i=1}^{49} \;=\; \{n_i\}_{i=1}^{26} \cup \{\bar{n}_i\}_{i=1}^{23}$$

See–saw couplings

☞ see–saw couplings: $W_{\text{see-saw}} = Y_\nu^{ij}\,\overline{\phi}\,\ell_i\,\overline{\nu}_j + M_{ij}\,\overline{\nu}_i\,\overline{\nu}_j$

See–saw couplings

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singlet

See–saw couplings

- see–saw couplings: $W_{\text{see-saw}} = Y_\nu^{ij}\,\overline{\phi}\,\ell_i\,\overline{\nu}_j + M_{ij}\,\overline{\nu}_i\,\overline{\nu}_j$
- in string models M, $Y_\nu \sim \langle s^n \rangle$
- ↪ see–saw mass matrix

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

See–saw neutrinos from the heterotic string

$$
\mathcal{M}_{nn} = \begin{pmatrix}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&\widetilde{s}^6&\widetilde{s}^6&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{pmatrix}
$$

See–saw neutrinos from the heterotic string

$$
\mathcal{M}_{n\bar{n}} = \left(\begin{array}{cccccccccccccccccccccccccc}
\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{array}\right)
$$

See–saw neutrinos from the heterotic string

$$M_{\overline{n}\overline{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

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

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

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

See–saw neutrinos from the heterotic string

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☞ Note: the zeros get filled in at higher order

See–saw neutrinos from the heterotic string

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

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

See–saw neutrinos from the heterotic string

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- Note: the zeros get filled in at higher order

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

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

Buchmüller et al. (2007b) ; Buchmüller et al. (2007a) ; Lebedev et al. (2007) ; Kappl et al. (2011)

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

Heterotic see–saw

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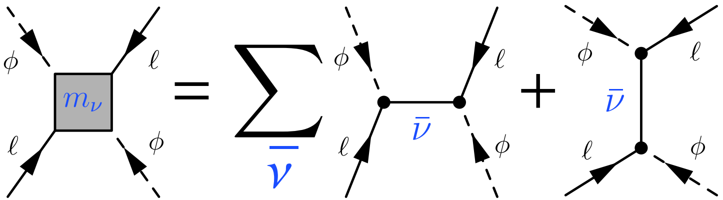
☞ there are $\mathcal{O}(100)$ neutrinos (= R parity odd SM singlets)

➥ $\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator



Heterotic see–saw

Buchmüller et al. (2007b) ; Buchmüller et al. (2007a) ; Lebedev et al. (2007) ; Kappl et al. (2011)

- 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

$$m_\nu \sim \frac{v^2}{M_*}$$

$$M_* \sim \frac{M_{\mathrm{GUT}}}{10\ldots100}$$

... 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

Buchmüller et al. (2007b) ; Buchmüller et al. (2007a) ; Lebedev et al. (2007) ; Kappl et al. (2011)

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

Main conclusion:

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

Heterotic see–saw

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

Main conclusion:

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

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

Giedt et al. (2005)

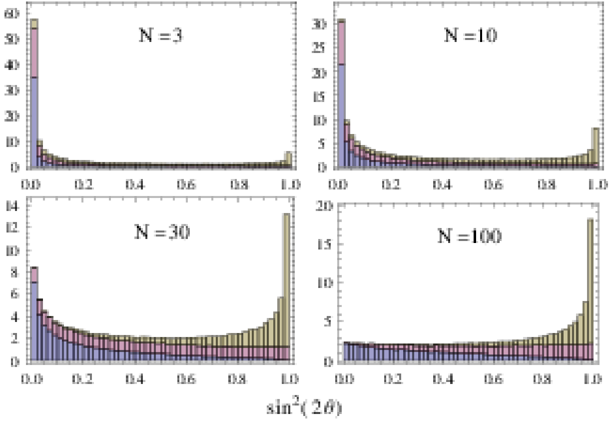
Possible implications

Feldstein and Klemm (2012)

see talks by Altarelli & de Gouvea for discussion on anarchy

☞ Anarchy: statistical preference for

- large mixing angles



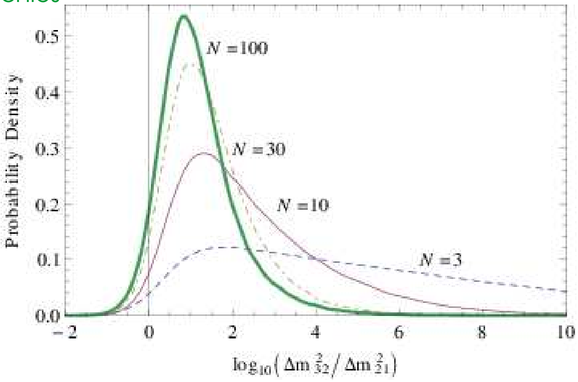
Possible implications

Feldstein and Klemm (2012)

see talks by Altarelli & de Gouvea for discussion on anarchy

☞ Anarchy: statistical preference for

- large mixing angles
- mild hierarchies



Possible implications

Feldstein and Klemm (2012)

see talks by Altarelli & de Gouvea for discussion on anarchy

☞ Anarchy: statistical preference for

- large mixing angles
- mild hierarchies

Eisele (2008) ; Ellis and Lebedev (2007)

☞ Relaxation of leptogenesis constraints: bound on the lighest right–handed neutrino mass gets about one order of magnitude weaker than in the three neutrino case

Summary

Summary

- ☞ See–saw is generic in explicit heterotic MSSM models

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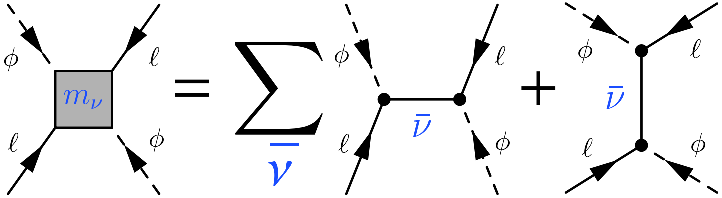
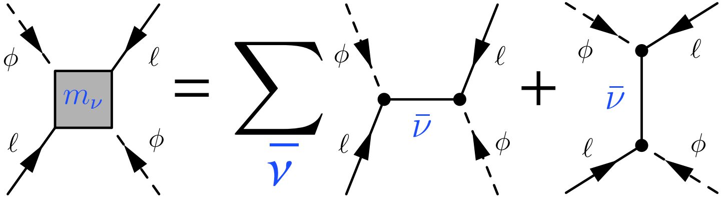
- See–saw is generic in explicit heterotic MSSM models
- Effective suppression of see–saw scale



Summary

- See–saw is generic in explicit heterotic MSSM models
- Effective suppression of see–saw scale



- Possible implications:
  - 'anarchical spectrum' with large mixing angles and small mass hierarchies
  - relaxation of cosmological bounds on mass of lightest right–handed neutrino
  - . . .

Mille grazie!

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