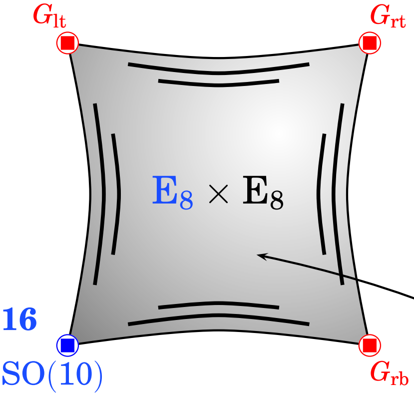
Neutrinos and Strings

Oleg Lebedev
CERN

Based on:

- W. Buchmüller, K. Hamaguchi, O.L., S. Ramos-Sánchez, M. Ratz, Phys.Rev.Lett.99:021601, 2007.
- J. Ellis, O.L., Phys.Lett.B653:411, 2007.

Local grand unification



W. Buchmüller, K. Hamaguchi, O.L., M. Ratz (2004-2006)

'low-energy' ⟶ effective theory

standard model as an intersection of G_{rb}, G_{rt}, G_{lt} & $SO(10)$ in G

SM generation(s):
localized in region with $SO(10)$ symmetry

Higgs doublets:
live in the bulk

Exact MSSM spectra from strings on orbifolds

Guided by the idea of local grand unification we have obtained $\mathcal{O}(100)$ models with the following features:

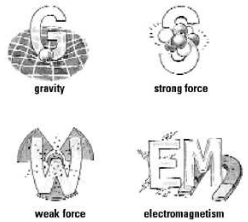
1. $3 \times \mathbf{16}$ + Higgs + nothing

No exotics

Exact MSSM spectra from strings on orbifolds

$\mathcal{O}(100)$ **models with**:

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



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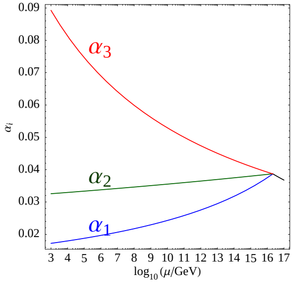
3. unification



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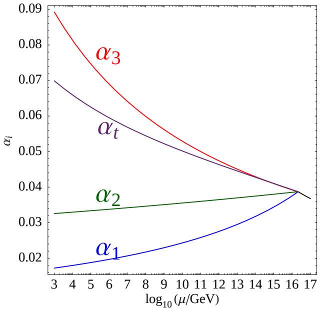
4. $y_t \simeq g$ @ M_{GUT} & qualitatively realistic flavor structures



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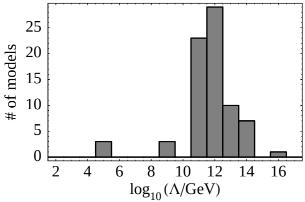
5. hidden sector gaugino condensation

➥ Spontaneously broken SUSY with TeV scale soft masses



$$m_{3/2} \sim \frac{\Lambda^3}{M_{\mathrm{P}}^2}$$

Exact MSSM spectra from strings on orbifolds

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5. TeV scale soft masses
6. R-parity

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

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

Exact MSSM spectra from strings on orbifolds

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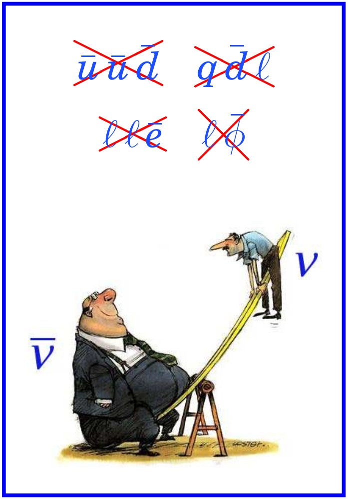
This talk:

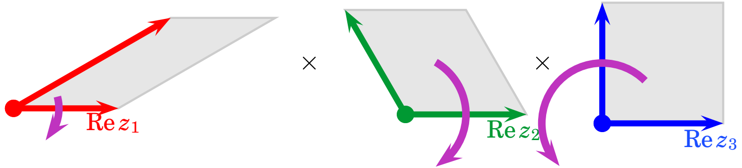
7. See-saw



Z_6 orbifold

O.L., H.P. Nilles, S. Raby, S. Ramos-Sánchez, M. Ratz, P. Vaudrevange, A. Wingerter (2006)

- Input = geometry, shift & Wilson lines



$$
\begin{aligned}
V &= \left(\tfrac{1}{3}, -\tfrac{1}{2}, -\tfrac{1}{2}, 0, 0, 0, 0, 0\right) \left(\tfrac{1}{2}, -\tfrac{1}{6}, -\tfrac{1}{2}, -\tfrac{1}{2}, -\tfrac{1}{2}, -\tfrac{1}{2}, -\tfrac{1}{2}, \tfrac{1}{2}\right) \\
W_2 &= \left(\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, -\tfrac{1}{4}, \tfrac{1}{4}, \tfrac{1}{4}, \tfrac{1}{4}\right) \left(1, -1, -\tfrac{5}{2}, -\tfrac{3}{2}, -\tfrac{1}{2}, -\tfrac{5}{2}, -\tfrac{3}{2}, \tfrac{3}{2}\right) \\
W_3 &= \left(-\tfrac{1}{2}, -\tfrac{1}{2}, \tfrac{1}{6}, \tfrac{1}{6}, \tfrac{1}{6}, \tfrac{1}{6}, \tfrac{1}{6}, \tfrac{1}{6}\right) \left(\tfrac{10}{3}, 0, -6, -\tfrac{7}{3}, -\tfrac{4}{3}, -5, -3, 3\right)
\end{aligned}
$$

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➥ Gauge group

$$G = [\overbrace{\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y}^{\subset\,\mathrm{SU}(5)\,\subset\,\mathrm{SO}(10)}\times\mathrm{U}(1)_{B-L}]\times[\mathrm{SO}(8)\times\mathrm{SU}(2)]\times\mathrm{U}(1)^6$$

GUT normalization ➡ gauge coupling unification

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

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

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	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$				
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		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	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
$1+3$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	ϕ_i		$1+3$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	$\bar{\phi}_i$
$3+12$	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$		12	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		3	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	s_i^-
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$		3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
20	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i		2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(1/2,1)}$	x_i^+		2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(-1/2,-1)}$	x_i^-
2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i		18	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
4	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,*)}$	$\bar{v}_i$		4	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,*)}$	v_i
2	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{(0,-1/2)}$	f_i		2	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{(0,1/2)}$	$\bar{f}_i$
5	$(\mathbf{1},\mathbf{1};\mathbf{8},\mathbf{1})_{(0,0)}$	w_i		4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i

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

$$s_i \;=\; G_{\text{SM}} \times \text{SO}(8) \text{ singlets with } q_{B\text{–}L} = 0 \text{ or } \pm 2$$

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3. there are $\widetilde{s}_i \subset s_i$ configurations where all exotics are massive and there is one pair of massless Higgs (@ order $\widetilde{s}^6$)

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remainder of this talk : neutrino masses

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

What is a (`right-handed') neutrino?

☞ 4D GUTs: $\bar{\nu}$ member of **16**-plet

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

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Higher-dimensional GUTs/Strings:

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

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Higher-dimensional GUTs/Strings:

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☞ remark: we get 39 neutrinos in the example

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

$$\bar{\eta}_1 = \begin{pmatrix} \bar{n}_{16} \\ \bar{n}_{17} \end{pmatrix},\ldots\bar{\eta}_3 = \begin{pmatrix} \bar{n}_{20} \\ \bar{n}_{21} \end{pmatrix};\; \eta_1 = \begin{pmatrix} n_{13} \\ n_{14} \end{pmatrix},\ldots\eta_3 = \begin{pmatrix} n_{17} \\ n_{18} \end{pmatrix}$$

$$\{\nu_i\}_{i=1}^{39} = \{n_i\}_{i=1}^{21}\cup\{\bar{n}_i\}_{i=1}^{18}$$

See-saw couplings

- ☞ see-saw couplings: $W_{\mathrm{see-saw}} = Y_\nu^{ij}\,\bar{\phi}\,\ell_i\,\bar{\nu}_j + \boldsymbol{M}_{ij}\,\bar{\nu}_i\,\bar{\nu}_j$

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singlet

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- ➥ see-saw mass matrix

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

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… suspiciously close to observed values

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

See-saw neutrinos from the heterotic string

W. Buchmüller, K. Hamaguchi, O.L., M. Ratz (2006)
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See-saw is a **generic feature** in heterotic MSSM vacua:

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

$$\mathcal{M}_{nn} = \left(\begin{array}{cccccccccccccccccc}
0&0&0&\widetilde{s^2}&0&\widetilde{s^6}&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&\widetilde{s^6}&0&\widetilde{s^2}&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
\widetilde{s^2}&\widetilde{s^6}&0&\widetilde{s^6}&0&\widetilde{s^6}&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
\widetilde{s^6}&\widetilde{s^2}&0&\widetilde{s^6}&0&\widetilde{s^6}&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{array}\right)$$

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0 & \widetilde{s^3} & 0 & 0 & \widetilde{s^6} & 0 & \widetilde{s^6} & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^2} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 \\
0 & \widetilde{s^6} & 0 & 0 & \widetilde{s^3} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 \\
\widetilde{s^6} & 0 & 0 & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\widetilde{s} & \widetilde{s^2} & \widetilde{s^3} & \widetilde{s^5} & \widetilde{s^4} & \widetilde{s^4} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} \\
\widetilde{s^6} & 0 & 0 & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\widetilde{s^5} & \widetilde{s^4} & \widetilde{s^4} & \widetilde{s} & \widetilde{s^2} & \widetilde{s^3} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} \\
0 & 0 & \widetilde{s^6} & 0 & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & \widetilde{s^3} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 \\
0 & 0 & \widetilde{s^6} & 0 & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & \widetilde{s^3} & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 \\
\widetilde{s^6} & 0 & 0 & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 & \widetilde{s^5} & \widetilde{s^5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\widetilde{s^6} & 0 & 0 & \widetilde{s^6} & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & 0 & \widetilde{s^5} & \widetilde{s^5} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \widetilde{s^3} & 0 & 0 & \widetilde{s^3} & 0 & \widetilde{s^2} & \widetilde{s^6} & \widetilde{s^3} & \widetilde{s^3} & 0 & 0 & \widetilde{s^2} & \widetilde{s^6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \widetilde{s^3} & 0 & 0 & \widetilde{s^3} & 0 & 0 & 0 & 0 & 0 & \widetilde{s^3} & \widetilde{s^3} & 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} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^3} & \widetilde{s^3} & \widetilde{s^3} & \widetilde{s^3} \\
0 & 0 & 0 & 0 & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^6} & 0 & \widetilde{s^6} & \widetilde{s^6} & \widetilde{s^3} & \widetilde{s^3} & \widetilde{s^3} & \widetilde{s^3} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \widetilde{s^6} & \widetilde{s^6} & 0 & 0 & 0 & \widetilde{s^3} & \widetilde{s^3} & 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^3} & \widetilde{s^3} & 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^3} & \widetilde{s^3} & 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^3} & \widetilde{s^3} & 0 & 0 & 0 & 0
\end{array}\right)$$

See-saw neutrinos from the heterotic string

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$$
\mathcal{M}_{\bar{n}\bar{n}} = \left(\begin{array}{ccccccccccccccccccccc}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^3&\widetilde{s}^3&0&0&0&0\\
0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&\widetilde{s}^3&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&\widetilde{s}^3&\widetilde{s}^3&0&0&0&0\\
0&0&0&0&\widetilde{s}^4&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&\widetilde{s}^3&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&\widetilde{s}^3&0&0&\widetilde{s}^3&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&\widetilde{s}^3&0&0&\widetilde{s}^3&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{array}\right)
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$$\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}$$

See-saw neutrinos from the heteretic string

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

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

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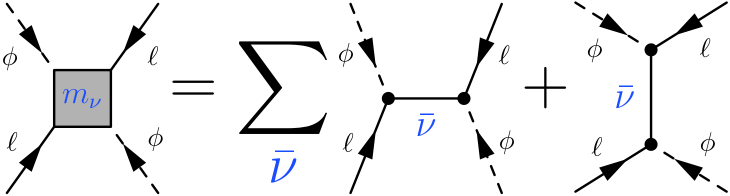

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- ☞ there are $\mathcal{O}(100)$ neutrinos ($=$ R-parity odd SM singlets)
- ➥ $\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator
- ➥ effective suppression of the see-saw scale

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

$$M_* \sim \frac{M_{\mathrm{GUT}}}{10 \dots 100}$$

. . . seems consistent with observation

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

Lepton-Flavor-Violation with many neutrinos

Ellis & O.L. (2007)

☞ Radiative corrections induce FV slepton masses in mSUGRA

$$m^2_{\tilde{\ell}} = \begin{pmatrix} m^2_{\rm L} & m^{2\,\dagger}_{\rm LR} \\ m^2_{\rm LR} & m^2_{\rm R} \end{pmatrix}_{\rm mSUGRA} + \begin{pmatrix} \delta m^2_{\rm L} & \delta m^{2\,\dagger}_{\rm LR} \\ \delta m^2_{\rm LR} & 0 \end{pmatrix}$$

☞ 1–loop effect:

$$\delta m^2 \sim \sum_{\nu} \widetilde{m}^2 \cdot \frac{1}{16\pi^2} (Y^\dagger_\nu)_{iJ} \ln\left(\frac{M_{\rm GUT}}{M_J}\right) (Y_\nu)_{Jk}$$

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- LFV grows as a power law with the multiplicity, can be enhanced by orders of magnitude
- Significant effects even for small Yukawa couplings

Leptogenesis

Ellis & O.L. (2007) (see also Eisele'07)

☞ Casas-Ibarra parametrization affected ($n \times 3$ case)

$$Y_\nu = \frac{1}{v}\,\mathrm{diag}\,\sqrt{M}\,R\;\;\mathrm{diag}\,\sqrt{m}\,U^\dagger_{\mathrm{PMNS}}$$

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- Some algebraic relations relevant to leptogenesis violated

- CP asymmetry (Davidson-Ibarra bound):

$$\epsilon < \frac{3}{8\pi} \frac{M_1}{v^2} (m_3 - m_1) \;\; \rightarrow \;\; \frac{3}{8\pi} \frac{M_1}{v^2} m_3$$

- Relaxes for degenerate neutrinos , T_{reheat} relaxes by an order of magnitude

Leptogenesis

Ellis & O.L. (2007)

- "Out-of-equilibrium decay" condition:

$$\tilde{m}_1 \equiv (Y_\nu Y_\nu^\dagger)_{11} \frac{v^2}{M_1} \leq 5 \times 10^{-3}\ \mathrm{eV}$$

$$m_1 \leq \tilde{m}_1 \ \ (3 \times 3) \ \ , \ \ m_1 \not\leq \tilde{m}_1 \ \ (n \times 3)$$

- This bound on the lightest m_ν disappears

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- **Pheno is affected by many ν's**
  enhanced LFV, lower T_{reh},...