Sterile neutrinos in string derived models

light sterile neutrinos $\longleftrightarrow$ low–scale $U(1)$ under which they are chiral

- Sterile neutrinos:

  AEF, EPJC78 (2018) 867;

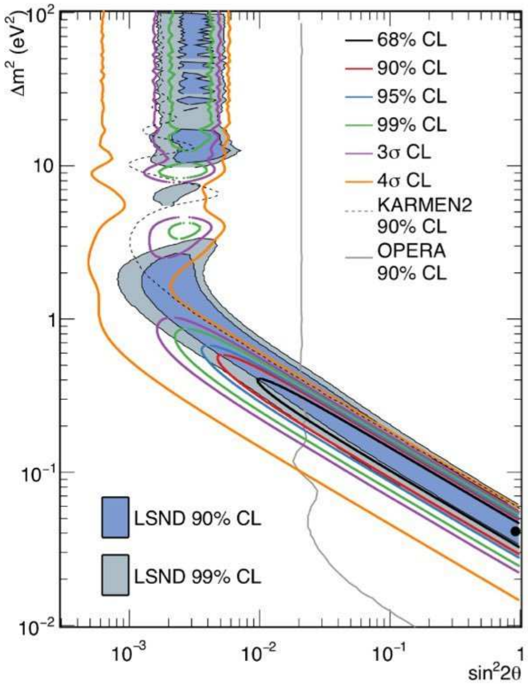
  AEF & Marco Guzzi, EPJC82 (2022) 590;

  Andrew McEntaggart, AEF & Marco Guzzi, EPJC83 (2023) 590;

- String derived Z' model: (hard to construct)

  AEF, & John Rizos, NPB895 (2014) 233;

CERN Neutrino Platform Pheno Week 2023, CERN, 13 March 2023



LSND 1993: Evidence for sterile neutrinos

MiniBooNE 2018: Further evidence for sterile neutrinos

MicroBooNE 2021: No evidence for sterile neutrinos

Sterile neutrinos in string vacua?

Realistic free fermionic GUT models

'Phenomenology of the Standard Model and Unification'

- Minimal Superstring Standard Model — NPB 335 (1990) 347 (with Nanopoulos & Yuan)
- Top quark mass $\sim$ 175–180GeV — PLB 274 (1992) 47
- Generation mass hierarchy — NPB 407 (1993) 57
- CKM mixing — NPB 416 (1994) 63 (with Halyo)
- Stringy seesaw mechanism — PLB 307 (1993) 311 (with Halyo)
- Gauge coupling unification — NPB 457 (1995) 409 (with Dienes)
- Proton stability — NPB 428 (1994) 111
- Squark degeneracy — NPB 526 (1998) 21 (with Pati)
- Moduli fixing — NPB 728 (2005) 83
- Classification & Exophobia — 2003 – $\cdots$ (with Nooij, Assel, Christodoulides, Kounnas, Rizos & Sonmez)

String GUT models in the Free Fermionic Construction:

Left-Movers: $\psi^{\mu}_{1,2}, \quad \chi_i, \quad y_i, \;\; \omega_i \quad (i=1,\cdots,6)$

Right-Movers

$$\bar\phi_{A=1,\cdots,44} = \begin{cases} \bar y_i \;,\; \bar\omega_i & i=1,\cdots,6 \\ & \\ \bar\eta_i & U(1)_i \quad i=1,2,3 \\ \bar\psi_{1,\cdots,5} & SO(10) \\ \bar\phi_{1,\cdots,8} & SO(16) \end{cases}$$

Models $\longleftrightarrow$ Basis vectors $+$ one–loop phases

Free Fermionic Models: $Z_2 \times Z_2$ orbifolds with discrete Wilson lines

Sterile neutrinos in free Fermionic models   Stringy 3GEN $SO(10)$ $\to$ X

Analyse mass terms constributing to the neutrino mass matrix   FN–like

AEF & Edi Halyo, PLB **307** (1993) 311

AEF & Claudio Coriano, PLB **581** (2004) 99

The generic form:

$$\left(\nu_i,\ N_i,\ \phi_i\right)\begin{pmatrix} 0 & (M_D)_{ij} & 0 \\ (M_D)_{ij} & 0 & \langle\overline{\mathcal{N}}\rangle_{ij} \\ 0 & \langle\overline{\mathcal{N}}\rangle_{ij} & \langle\phi\rangle_{ij} \end{pmatrix}\begin{pmatrix} \nu_j \\ N_j \\ \phi_j \end{pmatrix},$$

$$m_{\nu_j} \sim \left(\frac{kM_u^j}{\langle\overline{\mathcal{N}}\rangle}\right)^2 \langle\phi\rangle \quad , \qquad m_{N_j}, m_\phi \sim \langle\overline{\mathcal{N}}\rangle \ .$$

$$\langle\overline{\mathcal{N}}\rangle \quad > \quad 10^{14}\mathrm{GeV}$$

No Light sterile neutrino

Specific example:

	L_3	L_2	L_1	N_3	N_2	N_1	H_{23}	H_{25}	Φ_{13}	Φ_{45}	Φ_2^+	$\bar{\Phi}_2^+$
L_3	0	0	0	0	0	r	0	0	0	0	0	0
L_2	0	0	0	r	0	r	0	0	0	0	0	0
L_1	0	0	0	r	0	v	0	0	0	0	0	0
N_3	0	r	r	0	0	0	0	x	0	0	0	0
N_2	0	0	0	0	0	0	z	0	u	u	z	u
N_1	r	r	v	0	0	0	0	w	0	0	0	0
H_{23}	0	0	0	0	z	0	p	0	x	x	x	x
H_{25}	0	0	0	x	0	w	0	0	0	0	0	0
Φ_{13}	0	0	0	0	u	0	x	0	q	y	0	y
Φ_{45}	0	0	0	0	z	0	p	0	x	x	x	x
Φ_2^+	0	0	0	0	z	0	x	0	0	q	0	x
$\bar{\Phi}_2^+$	0	0	0	0	0	0	x	0	y	q	x	q

mass eigenvalues $\{1.7 \times 10^{13}, ..., 2.4^{-8}\}\mathrm{GeV}$

No Light sterile neutrinos -> non–chiral matter -> heavy

Sterile neutrinos -> Chiral under an extra $U(1)$ symmetry

Low scale Z' in free fermionic models:

- $\frac{3}{2}U(1)_{B-L} - 2U(1)_R \in SO(10)$ @ $1TeV$ MPL A6 (1991) 61

  (with Nanopoulos)

- But $m_t = m_{\nu_\tau}$ & $1TeV$ $Z' \Rightarrow$ $m_{\nu_\tau} \approx 10MeV$ PLB 245 (1990) 435

  $E_6 \to SO(10) \times U(1)_A$ $\Longrightarrow$ $U(1)_A$ is anomalous!

  $\Longrightarrow$ $U(1)_A$ $\notin$ low scale $U(1)_{Z'}$

- 1996-2013, Pati, AEF, Guzzi, Mehta, Athanasopoulos, $U(1) \notin E_6$

- On the other hand ....(AEF, Viraf Mehta, PRD88 (2013) 025006)

$$\sin^2\theta_W(M_Z)\ ,\ \alpha_s(M_Z) \Longrightarrow U(1)_{Z'} \in E_6$$

- Z' string derived model, (with Rizos) NPB 895 (2015) 233

Classification of fermionic $Z_2 \times Z_2$ orbifolds

Basis vectors:

$$1 = \{\psi^\mu,\ \chi^{1,\dots,6}, y^{1,\dots,6}, \omega^{1,\dots,6} \mid \bar{y}^{1,\dots,6}, \bar{\omega}^{1,\dots,6}, \bar{\eta}^{1,2,3}, \bar{\psi}^{1,\dots,5}, \bar{\phi}^{1,\dots,8}\}$$

$$S = \{\psi^\mu, \chi^{1,\dots,6}\},$$

$$z_1 = \{\bar{\phi}^{1,\dots,4}\},$$

$$z_2 = \{\bar{\phi}^{5,\dots,8}\},$$

$$e_i = \{y^i, \omega^i | \bar{y}^i, \bar{\omega}^i\},\ i = 1, \dots, 6,$$ $N = 4$ Vacua

$$b_1 = \{\chi^{34}, \chi^{56}, y^{34}, y^{56} | \bar{y}^{34}, \bar{y}^{56}, \bar{\eta}^1, \bar{\psi}^{1,\dots,5}\},$$ $N = 4 \to N = 2$

$$b_2 = \{\chi^{12}, \chi^{56}, y^{12}, y^{56} | \bar{y}^{12}, \bar{y}^{56}, \bar{\eta}^2, \bar{\psi}^{1,\dots,5}\},$$ $N = 2 \to N = 1$

$$\alpha = \{\bar{\psi}^{4,5}, \bar{\phi}^{1,2}\}$$ & $SO(10) \to SO(6) \times SO(4) \times \cdots$

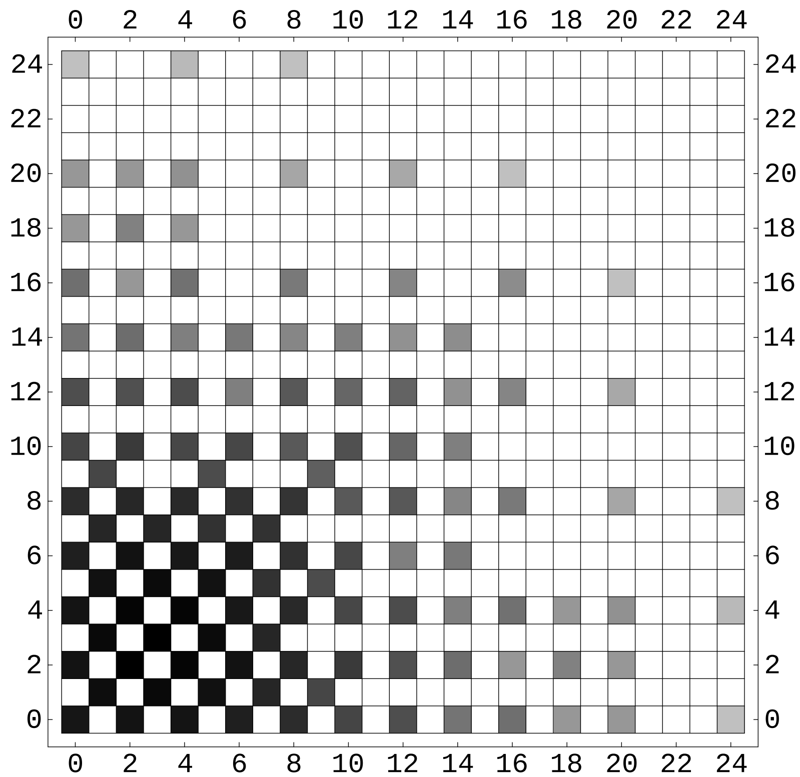
Independent phases $c\begin{bmatrix} v_i \\ v_j \end{bmatrix} = \exp[i\pi(v_i|v_j)]$: upper block

$$
\begin{array}{c|ccccccccccccc}
 & 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & z_1 & z_2 & b_1 & b_2 & \alpha \\
\hline
1 & -1 & -1 & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
S & & & -1 & -1 & -1 & -1 & -1 & -1 & -1 & -1 & 1 & 1 & -1 \\
e_1 & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_2 & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_3 & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_4 & & & & & & & \pm & \pm & \pm & \pm & \pm & \pm & \pm \\
e_5 & & & & & & & & \pm & \pm & \pm & \pm & \pm & \pm \\
e_6 & & & & & & & & & \pm & \pm & \pm & \pm & \pm \\
z_1 & & & & & & & & & & \pm & \pm & \pm & \pm \\
z_2 & & & & & & & & & & & \pm & \pm & \pm \\
b_1 & & & & & & & & & & & & \pm & \pm \\
b_2 & & & & & & & & & & & & -1 & \pm \\
\alpha & & & & & & & & & & & & &
\end{array}
$$

A priori 66 independent coefficients $\rightarrow 2^{66}$ distinct vacua

Spinor–vector duality:

Invariance under exchange of $\#(16+\overline{16}) \;<->\; \#(10)$



Symmetric under exchange of rows and columns

$$E_6 \;:\qquad 27 = 16 + 10 + 1 \qquad \overline{27} = \overline{16} + 10 + 1$$

Self-dual: $\#(16+\overline{16}) \;=\; \#(10)$ without E_6 symmetry

light Z' heterotic–string model $c\left[\begin{matrix} vi \\ v_j \end{matrix}\right] = \exp[i\pi(v_i|v_j)]$:

$$
(v_i|v_j) \;=\; \begin{array}{c} \\ 1 \\ S \\ e_1 \\ e_2 \\ e_3 \\ e_4 \\ e_5 \\ e_6 \\ b_1 \\ b_2 \\ z_1 \\ z_2 \\ \alpha \end{array}
\begin{array}{c}
\begin{array}{ccccccccccccc} 1 & S & e_1 & e_2 & e_3 & e_4 & e_5 & e_6 & b_1 & b_2 & z_1 & z_2 & \alpha \end{array} \\
\left(\begin{array}{ccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 \\
1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{array}\right)
\end{array}
$$

Observable gauge group: $SO(6) \times SO(4) \times U(1)_{1,2,3}$

$U(1)_\zeta = U(1)_1 + U(1)_2 + U(1)_3$ is anomaly free

sector	field	$SU(4)\times SU(2)_L\times SU(2)_R$	$U(1)_1$	$U(1)_2$	$U(1)_3$	$U(1)_\zeta$
$S+b_1$	$\bar{F}_{1R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	1/2	0	0	1/2
$S+b_1+e_3+e_5$	F_{1R}	$(\mathbf{4},\mathbf{1},\mathbf{2})$	1/2	0	0	1/2
$S+b_2$	F_{1L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	1/2	0	1/2
$S+b_2+e_1+e_2+e_5$	F_{2L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	1/2	0	1/2
$S+b_2+e_1$	$\bar{F}_{2R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	1/2	0	1/2
$S+b_2+e_2+e_5$	$\bar{F}_{3R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	1/2	0	1/2
$S+b_3+e_1+e_2$	F_{3L}	$(\mathbf{4},\mathbf{2},\mathbf{1})$	0	0	1/2	1/2
$S+b_3+e_2$	$\bar{F}_{4R}$	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	0	0	1/2	1/2
$S+b_3+x$	h_1	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	$-1/2$	0	-1
$S+b_2+x+e_5$	h_2	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	0	$-1/2$	-1
$S+b_2+x+e_1+e_2$	h_3	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$-1/2$	0	$-1/2$	-1
$S+b_3+x+e_1$	D_4	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	$-1/2$	0	-1
	χ_1^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1/2	1	+2
	χ_1^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1/2	-1	0
	$\zeta_a, a=2,3$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	$-1/2$	0	0
	$\bar{\zeta}_a, a=2,3$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	1/2	0	0
$S+b_2+x+e_1+e_5$	D_5	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	0	$-1/2$	-1
	χ_2^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1	1/2	+2
	χ_2^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	-1	1/2	0
	$\zeta_a, a=4,5$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	0	$-1/2$	0
	$\bar{\zeta}_a, a=4,5$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	0	1/2	0
$S+b_2+x+e_2$	D_6	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$-1/2$	0	$-1/2$	-1
	χ_3^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	1	1/2	+2
	χ_3^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	-1	1/2	0
	$\zeta_a, a=6,7$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	0	$-1/2$	0
	$\bar{\zeta}_a, a=6,7$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	0	1/2	0
$S+b_1+x+e_3$	$\bar{D}_6$	$(\mathbf{6},\mathbf{1},\mathbf{1})$	0	1/2	1/2	+1
	$\bar{\chi}_4^+$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	-1	$-1/2$	$-1/2$	-2
	$\bar{\chi}_4^-$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1	$-1/2$	$-1/2$	0
	$\zeta_a, a=8,9$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	$-1/2$	0
	$\bar{\zeta}_a, a=8,9$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	1/2	0
$S+b_1+x+e_5$	D_7	$(\mathbf{6},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1
	χ_5^+	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1	1/2	1/2	+2
	χ_5^-	$(\mathbf{1},\mathbf{1},\mathbf{1})$	-1	1/2	1/2	0
	$\zeta_a, a=10,11$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	$-1/2$	0
	$\bar{\zeta}_a, a=10,11$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	1/2	0
$S+b_3+x+e_2+e_3$	ζ_1	$(\mathbf{1},\mathbf{1},\mathbf{1})$	1/2	$-1/2$	0	0
	$\bar{\zeta}_1$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$-1/2$	1/2	0	0
$S+b_1+x+e_3+e_4+e_6$	ϕ_1	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	1/2	+1
	$\bar{\phi}_1$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1
$S+b_1+x+e_4+e_5+e_6$	ϕ_2	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	1/2	1/2	+1
	$\bar{\phi}_2$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	0	$-1/2$	$-1/2$	-1

Table 1: *Observable twisted matter spectrum and* $SU(4)\times SU(2)_L\times SU(2)_R\times U(1)^3$ *quantum numbers.*

The chiral spectrum is self–dual under spinor–vector duality

maintains the E_6 embedding $\Rightarrow$ $U(1)_\zeta$ is anomaly free

Exophobic, three generations + heavy and light higgs + $\lambda_t \sim 1$

$$U(1)_{Z'} = \frac{1}{5}\,U(1)_C - \frac{1}{5}\,U(1)_L - U_\zeta$$

$Z' \Rightarrow$ Additional matter at the Z' breaking scale

Z' model at low scales Heavy Higgs $\langle \mathcal{N} \rangle \sim M_{\text{String}} \rightarrow$ high seesaw $\rightarrow$ Z'

Field	$SU(3)_C$	$\times SU(2)_L$	$U(1)_Y$	$U(1)_{Z'}$
Q_L^i	3	2	$+\frac{1}{6}$	$-\frac{2}{5}$
u_L^i	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{2}{5}$
d_L^i	$\bar{3}$	1	$+\frac{1}{3}$	$-\frac{4}{5}$
e_L^i	1	1	$+1$	$-\frac{2}{5}$
L_L^i	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
D^i	3	1	$-\frac{1}{3}$	$+\frac{4}{5}$
$\bar{D}^i$	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{6}{5}$
H^i	1	2	$-\frac{1}{2}$	$+\frac{6}{5}$
$\bar{H}^i$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
S^i	1	1	0	-2
h	1	2	$-\frac{1}{2}$	$-\frac{4}{5}$
$\bar{h}$	1	2	$+\frac{1}{2}$	$+\frac{4}{5}$
ϕ	1	1	0	-1
$\bar{\phi}$	1	1	0	$+1$
ζ^i	1	1	0	0

Additional matter states at $U(1)_{Z'}$ breaking scale

Neutrino mass spectrum a plausible scenario

$$
\begin{array}{c} \\ L_i \\ S_i \\ H_i \\ \overline{H}_i \\ N_i \end{array}
\begin{array}{c} \begin{array}{ccccc} L_i & S_i & H_i & \overline{H}_i & N_i \end{array} \\
\begin{pmatrix}
0 & 0 & 0 & \lambda n & \lambda v \\
0 & 0 & \lambda v_2 & \lambda v_3 & 0 \\
0 & \lambda v_2 & 0 & z' & 0 \\
\lambda n & \lambda v_3 & z' & 0 & 0 \\
\lambda v & 0 & 0 & 0 & \mathcal{N}^2/M
\end{pmatrix} \end{array},
$$

$$\lambda v = 1\text{GeV}; \qquad \lambda n = 5 \times 10^{-4}\text{GeV}; \approx m_e;$$

$$\lambda v_2 = 5 \times 10^{-4}\text{GeV} \approx m_e; \qquad \lambda v_3 = 5 \times 10^{-4}\text{GeV}; \approx m_e;$$

$$z' = 5 \times 10^{4}\text{GeV} = 50\text{TeV}; \qquad \overline{\mathcal{N}} = 5 \times 10^{14}\text{GeV},$$

$m_{1,2} = \{10^{-2}\text{eV}, 10^{-3}\text{eV}\}$ mix of ν_L^i and S_i, with $\sin\theta \approx 0.98$.

$m_{3,4,5} = \{50\text{TeV}, 50\text{TeV}, 2.5 \times 10^{11}\text{GeV}\}$.

$m_5 \leftrightarrow N_i$ $\qquad$ $m_{3,4} \leftrightarrow$ equal mix of H_i and $\bar{H}_i$

Conclusions

- DATA $\longrightarrow$ UNIFICATION
- STRINGS $\longrightarrow$ GAUGE & GRAVITY UNIFICATION
- Free fermionic models $\longrightarrow$ A Fertile Crescent $\longleftrightarrow$ $Z_2 \times Z_2$ orbifolds
- Sterile neutrinos $\longrightarrow$ chiral matter charged under low scale extra $U(1)$
- Low scale Z' $\longrightarrow$ hard to implement in string GUT constructions
- Rich phenomenology at the Z' breaking scale and below