Neutrino masses respecting string constraints

- Introduction
- Neutrino preliminaries
- The GUT seesaw
- Neutrinos in string constructions
- The triplet model

(Work in progress, in collaboration with J. Giedt, G. Kane, B. Nelson.)

Neutrino mass

- Nonzero mass may be first break with standard model
- Enormous theoretical effort: GUT, family symmetries, bottom up
  - Majorana masses may be favored because not forbidden by SM gauge symmetries
  - GUT seesaw (heavy Majorana singlet). Usually ordinary hierarchy.
  - Higgs triplets ("type II seesaw"), often assuming GUT, Left-Right relations

- Very little work from string constructions, even though probably Planck scale
  - Key ingredients of most bottom up models forbidden in known constructions (heterotic or intersecting brane)
  - Large representations difficult to achieve (bifundamentals, singlets, or adjoints)
  - String symmetries/constraints restrict couplings, e.g., diagonal Majorana masses
  - Very nonstandard triplet or singlet seesaws, favoring inverted hierarchy, extended seesaw, or small Dirac masses from HDO.

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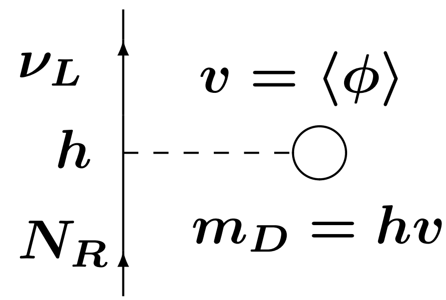
Models and spectra

- **Weyl fermion**
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$ by CPT

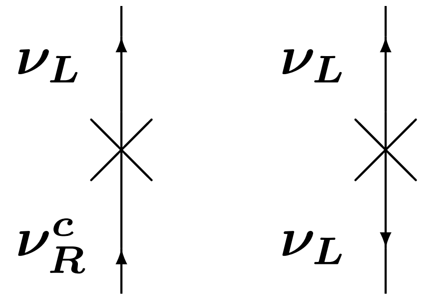
- **Active Neutrino (a.k.a. ordinary, doublet)**
  - in $SU(2)$ doublet with charged lepton $\longrightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CPT

- **Sterile Neutrino (a.k.a. singlet, right-handed)**
  - $SU(2)$ singlet; no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N_L^c$ by CPT
  - Almost always present: Are they light? Do they mix?

- **Dirac Mass**
  - Connects distinct Weyl spinors (usually active to sterile): $(m_D \bar{\nu}_L N_R + h.c.)$
  - 4 components, $\Delta L = 0$
  - $\Delta I = \frac{1}{2} \rightarrow$ Higgs doublet
  - Why small? LED? HDO?
  - Variant: couple active to anti-active, e.g., $m_D \bar{\nu}_{eL} \nu^c_{\mu R} \Rightarrow L_e - L_\mu$ conserved; $\Delta I = 1$



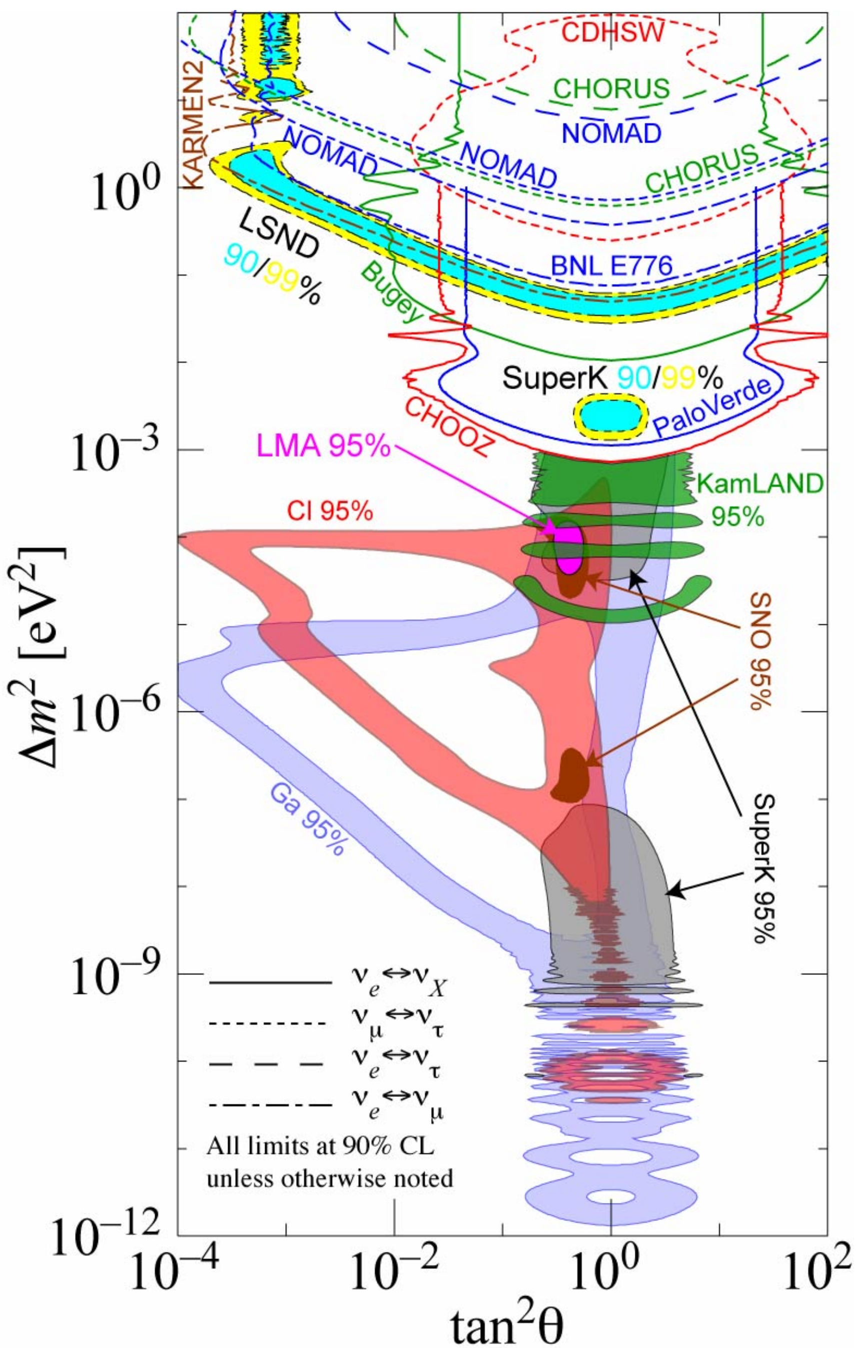
- **Majorana Mass**
  - Connects Weyl spinor with itself: $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ (active); $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ (sterile)
  - 2 components, $\Delta L = \pm 2$
  - Active: $\Delta I = 1 \rightarrow$ triplet or seesaw
  - Sterile: $\Delta I = 0 \rightarrow$ singlet or bare mass



- **Mixed Masses**
  - Majorana and Dirac mass terms
  - Seesaw for $m_S \gg m_D$
  - Ordinary-sterile mixing for m_S and m_D both small and comparable (or $m_S \ll m_d$ (pseudo-Dirac))

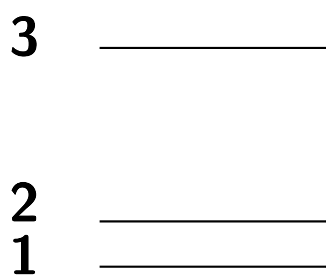
3 ν Patterns

- Solar: LMA (SNO, Kamland)
- $\Delta m^2_\odot \sim 8\times10^{-5}$ eV^2, nonmaximal
- Atmospheric: $|\Delta m^2_{\rm Atm}| \sim 2\times10^{-3}$ eV^2, near-maximal mixing
- Reactor: U_{e3} small



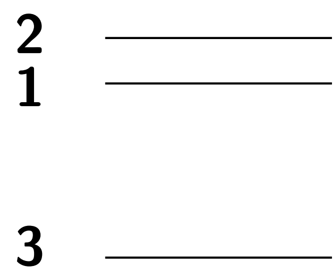
– **Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:**

$$
\begin{aligned}
\nu_3 &\sim \nu_+ \\
\nu_2 &\sim \cos\theta_\odot\ \nu_- - \sin\theta_\odot\ \nu_e \\
\nu_1 &\sim \sin\theta_\odot\ \nu_- + \cos\theta_\odot\ \nu_e
\end{aligned}
$$



– **Hierarchical pattern**

* **Analogous to quarks, charged leptons**
* **$\beta\beta_{0\nu}$ rate very small**



– **Inverted quasi-degenerate pattern**

* **$\beta\beta_{0\nu}$ if Majorana**
* **SN1987A energetics (if $U_{e3} \neq 0$)?**
* **May be radiative unstable**

The GUT Seesaw

- Elegant mechanism for small Majorana masses
- Leptogenesis
- Expect small mixings in simplest versions (can evade by lopsided e/d, Majorana textures, etc.)
- Large Majorana often forbidden, e.g., by extra $U(1)$'s
- Direct Majorana masses and large scales forbidden in some string constructions
- GUTs, adjoint Higgs, large Higgs hard to accomodate in simplest heterotic constructions

- **LSND: active-sterile difficult in simple versions**

- **Therefore, explore alternatives, e.g., with small Dirac and/or Majorana masses**

  - **Small Majorana from loops, R_p violation, TeV seesaw, or triplet**

  - **Small Dirac from large extra dimension or by higher dimensional operators in intermediate scale models (e.g. $U(1)'$)**

  - **Variant ordinary and triplet seesaws motivated by string constructions**

Neutrinos in string constructions

Key ingredients of most GUT/bottom up models forbidden or different in known constructions (heterotic or intersecting brane)

- **Bifundamentals, singlets, or adjoints; not large representations**
- **String symmetries/constraints may forbid couplings allowed by 4d symmetries**
- **Diagonal superpotential terms (e.g., diagonal Majorana masses) usually absent**
- **GUT Yukawa relations broken**
- **Non-zero superpotential terms may be equal (gauge couplings)**
- **Hierarchies from HDO (heterotic), intersection triangles (intersecting brane)**

Dirac masses

- Can achieve small Dirac masses (neutrino or other) by higher dimensional operators or by large intersection areas

$$L_\nu \sim \left(\frac{S}{M_{Pl}}\right)^p L N_L^c H_2, \quad \langle S \rangle \ll M_{Pl}$$

$$\Rightarrow m_D \sim \left(\frac{\langle S \rangle}{M_{Pl}}\right)^p \langle H_2 \rangle$$

- Large $p \Rightarrow \langle S \rangle$ close to M_{Pl} (e.g., anomalous $U(1)'$)
- Small $p \Rightarrow$ intermediate scale $\ll M_{Pl}$

– **Intermediate scale in (non-anomalous) $U(1)'$ from D and (almost) F flat direction:**

Two SM singlets charged under $U(1)'$. If no F terms,

$$V(S_1, S_2) = m_1^2|S_1^2| + m_2^2|S_2^2| + \frac{g'^2 Q'^2}{2}(|S_1^2| - |S_2^2|)^2$$

Break at EW scale for $m_1^2 + m_2^2 > 0$, at intermediate scale for $m_1^2 + m_2^2 < 0$ (stabilized by loops or HDO)

The ordinary seesaw

- Active neutrinos ν_L, N_R (3 flavors each)

$$L = \frac{1}{2} \left(\bar{\nu}_L \quad \bar{N}_L^c \right) \begin{pmatrix} \mathrm{m}_T & \mathrm{m}_D \\ \mathrm{m}_D^T & \mathrm{m}_S \end{pmatrix} \begin{pmatrix} \nu_R^c \\ N_R \end{pmatrix} + \mathrm{hc}$$

  - $m_T = m_T^T =$ triplet Majorana mass matrix (Higgs triplet)
  - $m_D =$ Dirac mass matrix (Higgs doublet)
  - $m_S = m_S^T =$ singlet Majorana mass matrix (Higgs singlet); eg, 126 of $SO(10)$

- **Ordinary (type I) seesaw: $m_T = 0$ and (eigenvalues) $m_S \gg m_D$:**

$$m_\nu^{\text{eff}} = -m_D m_S^{-1} m_D^T$$

with

$$U_{PMNS} = U_e^\dagger U_\nu$$

- **Most models assume either**
  - **$U_e \sim I$ in basis with manifest symmetries for $m_{D,S} \Rightarrow$ large mixings in U_ν**
  - **Large U_e mixings from lopsided m_e in basis with $m_{D,S} \sim$ diagonal (harder to achieve in $SO(10)$ than $SU(5)$)**
- **$SO(10)$ models usually yield ordinary hierarchy**

- String constructions: may be able to generate large effective m_S from

$$W_\nu \sim c_{ij} \frac{S^{q+1}}{M_{Pl}^q} N_i N_j \quad \Rightarrow (m_S)_{ij} \sim c_{ij} \frac{\langle S \rangle^{q+1}}{M_{Pl}^q}$$

- Can one have such terms simultaneously with Dirac couplings, consistent with flatness and other constraints? (Under investigation for Z_3 orbifold.)

- $c_{ii} = 0$ in all known examples $\Rightarrow$

$$m_S = \begin{pmatrix} 0 & m_{12} & m_{13} \\ m_{12} & 0 & m_{23} \\ m_{13} & m_{23} & 0 \end{pmatrix}$$

- **Very different from standard seesaw textures**
  - **Case with three large eigenvalues requires complicated m_D and/or m_e**
  - **2×2 case could resemble special pseudo-Dirac *inverse hierarchy* model found for triplets**
  - **Extended seesaw with greater than 3 N fields?** (Coriano, Faraggi; F., Thormeier)

Triplet models

- Introduce Higgs triplet $T = (T^{++}\ T^{+}\ T^{0})^{T}$ with weak hypercharge $Y = 1$
- Majorana masses m_T generated from $L_\nu = \lambda^T_{ij} L_i T L_j$ if $\langle T^0 \rangle \neq 0$
- Old Roncadelli-Gelmini model: $\langle T^0 \rangle \ll$ EW scale with explicit L violation
  - Excluded by $Z \to$ Majoron $+$ scalar (equivalent to $\Delta N_\nu = 2$)
- Modern triplet models (type II seesaw) break L explicity by THH couplings, giving large Majoron mass (Lazarides, Shafi, Wetterich, Mohapatra, Senjanovic, Schechter, Valle, Ma, Hambye, Sarkar, Rossi, ...)
- Often considered in $SO(10)$ or LR context, with both ordinary and triplet mechanisms competing and with related parameters, but can consider independently.

- **General SUSY case**

$$W_\nu = \lambda^T_{ij} L_i T L_j + \lambda_1 H_1 T H_1 + \lambda_2 H_2 \bar{T} H_2 + M_T T\bar{T} + \mu H_1 H_2$$

T, $\bar{T}$ are triplets with $Y = \pm 1$, $M_T \sim 10^{12} - 10^{14}$ GeV. Typically,

$$\langle T^0 \rangle \sim -\lambda \langle H_2^0 \rangle^2 / m_T \quad \Rightarrow$$

$$\mathrm{m}^\nu_{ij} = -\lambda^T_{ij} \lambda_2 \frac{v_2^2}{M_T}$$

String constructions

- Expect $\lambda^T_{ij} = 0$ for $i = j$ (off-diagonal) $\Rightarrow m^\nu_{ii} = 0$
- Also, need multiple Higgs doublets $H_{1,2}$ with $\lambda_{1,2}$ off diagonal
- Partial explanation: $SU(2)$ triplet with $Y \neq 0$ requires higher level embedding, e.g., of $SU(2) \subset SU(2) \times SU(2)$ (Have Z_3 constructions with some but not all of the features.)

$$W \sim \lambda^T_{1j} L_1(2,1) T(2,2) L_j(1,2), \;\; j = 2, 3$$

yields

$$m^\nu = \begin{pmatrix} 0 & a & b \\ a & 0 & 0 \\ b & 0 & 0 \end{pmatrix}$$

- Typical string case: $|a| = |b|$

- HDO (or $SU(2) \subset SU(2) \times SU(2) \times SU(2)$) can give $m^\nu_{23} \neq 0$

- For

$$m^\nu = \begin{pmatrix} 0 & a & b \\ a & 0 & c \\ b & c & 0 \end{pmatrix}$$

can take a, b, c real w.l.o.g. by redefinition of fields (not true for general m^ν)

- $\mathrm{Tr}\ m^\nu = 0$ and $m^\nu = m^{\nu\dagger} \Rightarrow m_1 + m_2 + m_3 = 0$

- $|\Delta m^2_{\rm Atm}| \sim 2\times 10^{-3}$ eV^2, $\Delta m^2_\odot \sim 8\times 10^{-5}$ eV^2 $\Rightarrow$ two solutions
  - For $\Delta m^2_\odot$ =0

    (a) $m_i \propto 1,\ -\frac{1}{2},\ -\frac{1}{2}$ (ordinary, with shifted masses)

    (b) $m_i \propto 1,\ -1,\ 0$ (inverted)
  - With $\Delta m^2_\odot \neq 0$

    (a) $m_i = 0.054,\ -0.026,\ -0.026$ eV ($\sum |m_i| = 0.107$ eV (cosmology))

    (b) $m_i = 0.046,\ -0.045,\ -0.001$ eV ($\sum |m_i| = 0.092$ eV (cosmology))

$$m^\nu_a \sim \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \qquad m^\nu_b \sim \begin{pmatrix} 0 & a & b \\ a & 0 & 0 \\ b & 0 & 0 \end{pmatrix}$$

  - (a) leads to unrealistic mixing matrix $\Rightarrow$ consider (b)

A special texture

- **The $L_e - L_\mu - L_\tau$ conserving texture**

$$m^\nu \sim \begin{pmatrix} 0 & a & b \\ a & 0 & 0 \\ b & 0 & 0 \end{pmatrix}$$

has been considered phenomenologically by *many* authors (Zee; Barbieri, Hall, Smith, Strumia, Weiner; King, Singh; Ohlsson; Barbieri, Hambye, Romanino; Lebed, Martin; Babu, Mohapatra; Lavignac, Masina, Savoy; Feruglio, Strumia, Vissani; Altarelli, Feruglio, Masina)

$$m^{\nu} \sim \begin{pmatrix} 0 & a & b \\ a & 0 & 0 \\ b & 0 & 0 \end{pmatrix}$$

- **New aspects**
  - **Strong string motivation**
  - **Motivation for special case $|a| = |b|$**
  - **Most likely perturbation in 23 element from HOT**
- **Diagonalization:** $\tan\theta_{\rm Atm} = b/a \Rightarrow$ **need $|b| = |a|$ for maximal**
- $\tan^2\theta_{\odot} = 1$ **(maximal)** (experiment $\tan^2\theta_{\odot} = 0.40^{+0.09}_{-0.07}$)

- **Majorana mass matrix**

$$m^\nu \sim \begin{pmatrix} 0 & 1 & -1 \\ 1 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}$$

- **Inverted hierarchy**

- **Bimaximal mixing for $U_e = I$:**

$$U_\nu \sim \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- **Perturbations on m^ν cannot give both $\Delta m^2_\odot$ and $\frac{\pi}{4} - \theta_\odot \sim \theta_C \sim 0.23$ without fine-tuning between terms, e.g.,**

$$\frac{1}{4\sqrt{2}} \frac{\Delta m^2_\odot}{\Delta m^2_{\rm Atm}} = -\frac{\epsilon_{23}}{4} \sim 0.007 \neq \frac{\pi}{4} - \theta_\odot \sim 0.23$$

- **However, $U_e \neq I$ with small angles (comparable to CKM) can can give agreement with experiment** (Frampton, Petcov, Rodejohann; Romanino; Altarelli, Feruglio, Masina)

$$U_e^\dagger \sim \begin{pmatrix} 1 & -s_{12}^e & 0 \\ s_{12}^e & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

yields

$$\begin{aligned} \theta_\odot &\sim \frac{\pi}{4} - \frac{s_{12}^e}{\sqrt{2}} = 0.56^{+0.05}_{-0.04} \\ |U_{e3}|^2 &\sim \frac{(s_{12}^e)^2}{2} \sim (0.023 - 0.081),\ 90\%\ (\mathrm{exp} : < 0.03) \\ m_{\beta\beta} &\sim m_2(\cos^2\theta_\odot - \sin^2\theta_\odot) \sim 0.020\ \mathrm{eV} \end{aligned}$$

In progress

- Detailed Z_3 constructions for higher level embeddings (triplets) and for heavy Majorana neutrinos
- Implications for m_e, m_q
- Implications of additional Higgs
- RGE effects
- Leptogenesis

Conclusions

- Neutrino mass likely due to large or Planck scale effects, but little work in string context
- Specific orbifold string constructions (heterotic, intersecting brane) not consistent with common GUT and bottom up assumptions for m_ν
- Preliminary conclusion: inverted hierarchy (pseudo Dirac), extended seesaw, or small Dirac favored
- Inverted hierarchy (e.g., from triplet) very predictive