

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.**

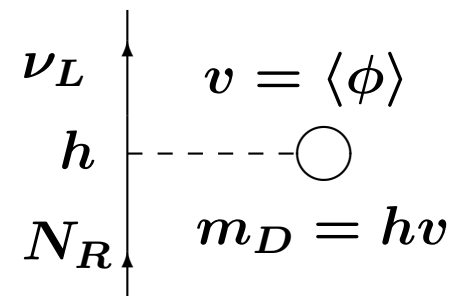
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Models and spectra

- **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 \rightarrow 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?

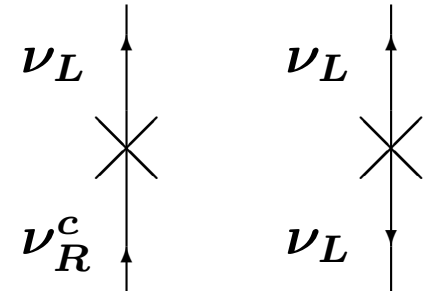
- Dirac Mass

- 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., $m_D \bar{\nu}_{eL} \nu_{\mu R}^c \Rightarrow L_e - L_\mu$ 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

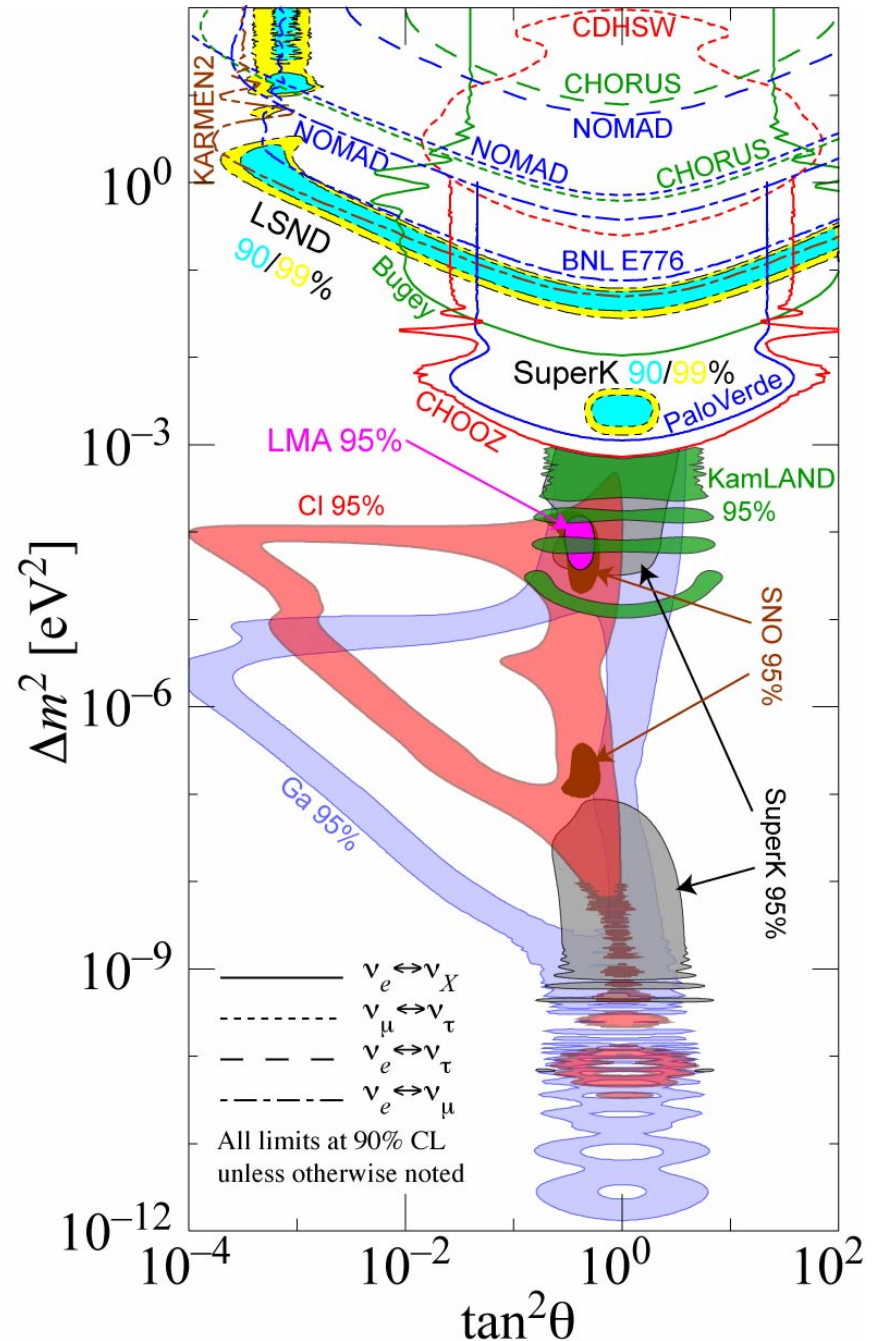


- Mixed Masses

- 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)
- $\Delta m_{\odot}^2 \sim 8 \times 10^{-5} \text{ eV}^2$, nonmaximal
- Atmospheric: $|\Delta m_{\text{Atm}}^2| \sim 2 \times 10^{-3} \text{ eV}^2$, near-maximal mixing
- Reactor: U_{e3} small



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

$$\nu_3 \sim \nu_+$$

$$\nu_2 \sim \cos \theta_{\odot} \nu_- - \sin \theta_{\odot} \nu_e$$

$$\nu_1 \sim \sin \theta_{\odot} \nu_- + \cos \theta_{\odot} \nu_e$$

3 _____

2 _____
1 _____

2 _____
1 _____

3 _____

– 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 accommodate 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)

$$L = \frac{1}{2} (\bar{\nu}_L \quad \bar{N}_L^c) \begin{pmatrix} m_T & m_D \\ m_D^T & m_S \end{pmatrix} \begin{pmatrix} \nu_R^c \\ N_R \end{pmatrix} + \text{hc}$$

- $m_T = m_T^T =$ 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

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

- 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 $L_\nu = \lambda_{ij}^T L_i T L_j$ if $\langle T^0 \rangle \neq 0$
- Old Gelmini-Roncadelli model: $\langle T^0 \rangle \ll \text{EW scale}$ with spontaneous L violation
 - Excluded by $Z \rightarrow \text{Majoron} + \text{scalar}$ (equivalent to $\Delta N_\nu = 2$)
- Modern triplet models (type II seesaw) break L explicitly 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

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

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

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

$$m_{ij}^\nu = -\lambda_{ij}^T \lambda_2 \frac{v_2^2}{M_T}$$

String constructions

- Expect $\lambda_{ij}^T = 0$ for $i = j$ (off-diagonal) $\Rightarrow m_{ii}^\nu = 0$
- 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.)

$$W \sim \lambda_{1j}^T L_1(2, 1) T(2, 2) L_j(1, 2), \quad j = 2, 3$$

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 $m_{23}^\nu \neq 0$

- 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)

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

- $|\Delta m_{\text{Atm}}^2| \sim 2 \times 10^{-3} \text{ eV}^2$, $\Delta m_{\odot}^2 \sim 8 \times 10^{-5} \text{ eV}^2 \Rightarrow$ two solutions

- For $\Delta m_{\odot}^2 = 0$

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

- (b) $m_i \propto 1, -1, 0$ (inverted)

- With $\Delta m_{\odot}^2 \neq 0$

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

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

$$m_a^\nu \sim \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \quad m_b^\nu \sim \begin{pmatrix} 0 & a & b \\ a & 0 & 0 \\ b & 0 & 0 \end{pmatrix}$$

- (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: $\tan \theta_{\text{Atm}} = b/a \Rightarrow$ need $|b| = |a|$ for maximal**
- **$\tan^2 \theta_\odot = 1$ (maximal) (experiment $\tan^2 \theta_\odot = 0.40_{-0.07}^{+0.09}$)**

- 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 Δm_{\odot}^2 and $\frac{\pi}{4} - \theta_{\odot} \sim \theta_C \sim 0.23$ without fine-tuning between terms, e.g.,

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

- However, $U_e \neq I$ with small angles (comparable to CKM) can 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

$$\theta_\odot \sim \frac{\pi}{4} - \frac{s_{12}^e}{\sqrt{2}} = 0.56_{-0.04}^{+0.05}$$

$$|U_{e3}|^2 \sim \frac{(s_{12}^e)^2}{2} \sim (0.023 - 0.081), \quad 90\% \text{ (exp : } < 0.03)$$

$$m_{\beta\beta} \sim m_2(\cos^2 \theta_\odot - \sin^2 \theta_\odot) \sim 0.020 \text{ eV}$$

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