Neutrino Masses from the Top Down

- 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**
  - **E. Witten, Nucl. Phys. B 268, 79 (1986).** (E_6 difficulties.)
  - **C. Coriano and A. E. Faraggi, Phys. Lett. B 581, 99 (2004); A. E. Faraggi and M. Thormeier, Nucl. Phys. B 624, 163 (2002).** (Heterotic inspired. Extended seesaw.)
  - **J. R. Ellis, G. K. Leontaris, S. Lola and D. V. Nanopoulos, Eur. Phys. J. C 9, 389 (1999).** (Flipped $SU(5)$. May be ordinary seesaw, but nonstandard and non-GUT-like Majorana, Dirac matrices.)
  - **L. E. Ibanez, F. Marchesano and R. Rabadan, JHEP 0111, 002 (2001).** (Intersecting brane. L conserved.)
  - **I. Antoniadis, E. Kiritsis, J. Rizos and T. N. Tomaras, Nucl. Phys. B 660, 81 (2003).** (D-brane. L conserved.)
  - **J. Giedt, G. Kane, PL, B. Nelson, in progress.** (Heterotic Z_3 orbifolds. So far, no Majorana.)

- **Key ingredients of most bottom up models forbidden in known constructions (heterotic or intersecting brane)**
  (Due to string symmetries or constraints, not simplicity or elegance)

  - "Right-handed" neutrinos may not be gauge singlets
  - Large representations difficult to achieve (bifundamentals, singlets, or adjoints)
  - GUT Yukawa relations broken
  - String symmetries/constraints forbid couplings, e.g., Majorana masses, or diagonal (same family or same flavor) Majorana
  - Very nonstandard triplet or singlet seesaws (inverted hierarchy for triplet), extended seesaw, or small Dirac masses from HDO.

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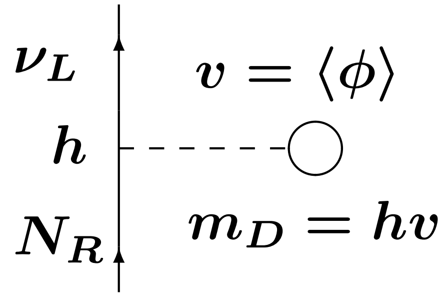
Models and spectra

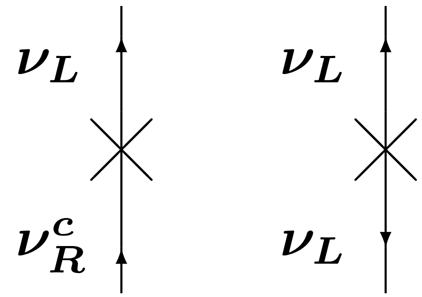
- **Weyl fermion**
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$ by CPT
- **Active Neutrino (a.k.a. ordinary, doublet)**
  - in $SU(2)$ doublet with charged lepton $\rightarrow$ normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$ by CPT
- **Sterile 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., $m_D \bar{\nu}_{eL} \nu^c_{\mu R} \Rightarrow L_e - L_\mu$ conserved; $\Delta I = 1$



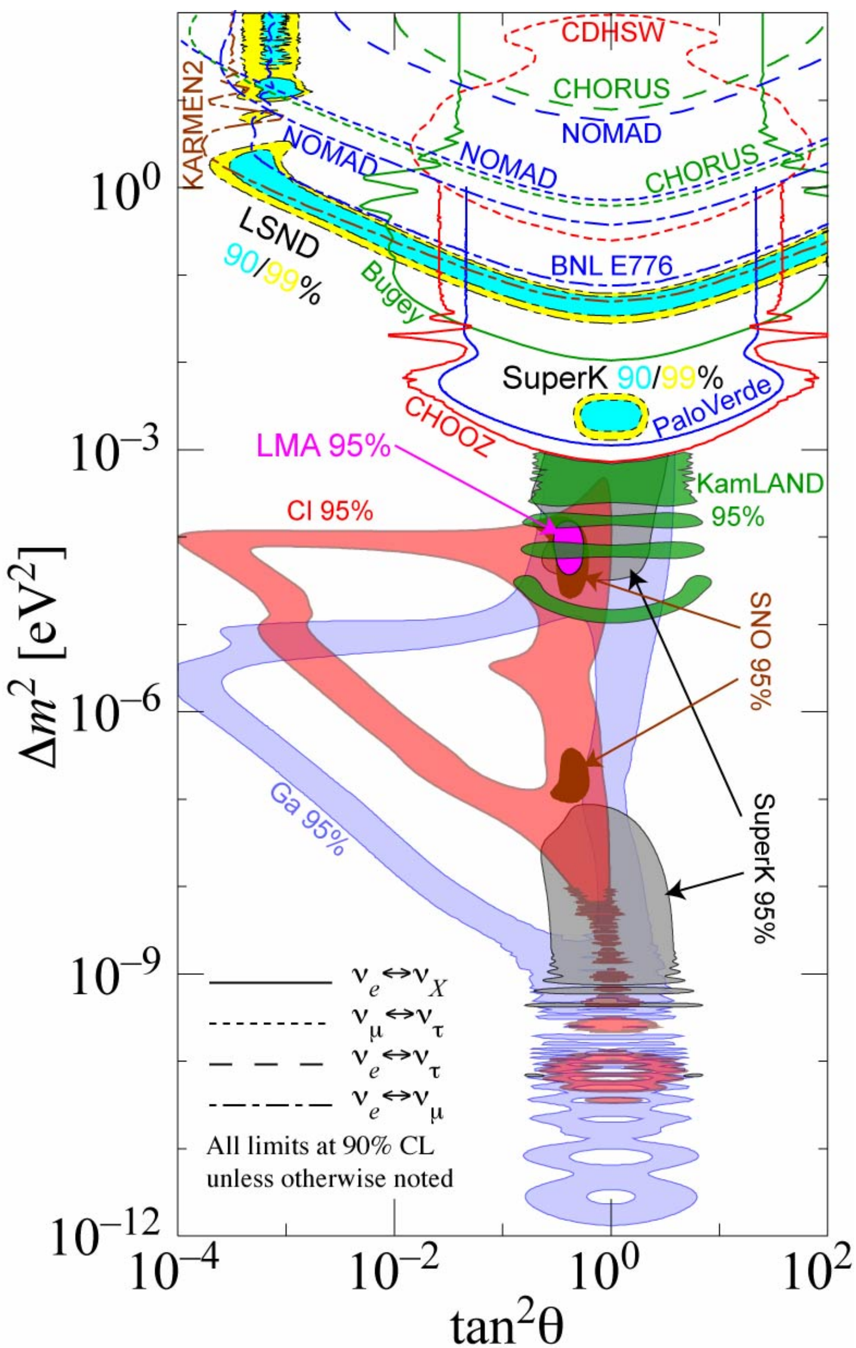
- Majorana Mass
  - Connects Weyl spinor with itself: $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$ (active); $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$ (sterile)
  - 2 components, $\Delta L = \pm 2$
  - Active: $\Delta I = 1 \rightarrow$ triplet or seesaw
  - Sterile: $\Delta I = 0 \rightarrow$ singlet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

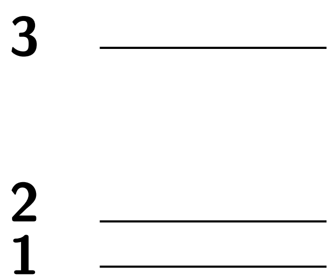
3 ν Patterns

- **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**



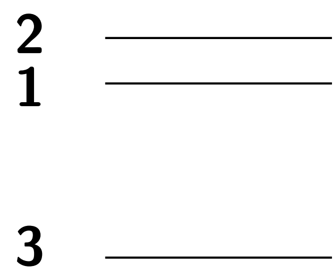
– Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:

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



– Hierarchical pattern

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



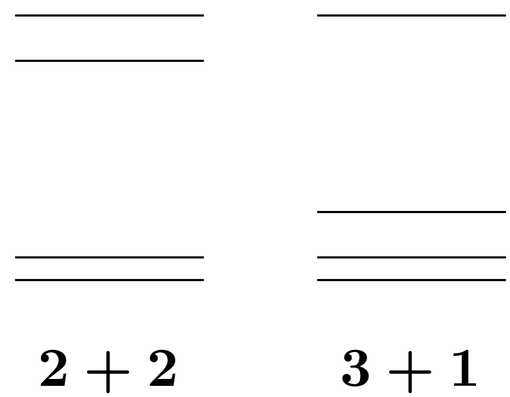
– Inverted quasi-degenerate pattern

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

– Degenerate patterns

* Motivated by CHDM (no longer needed)
* Strong cancellations needed for $\beta\beta_{0\nu}$ if Majorana
* May be radiative unstable

- 4 ν Patterns
  - LSND: $\Delta m^2_{\rm LSND} \sim 1\ eV^2$
  - Z lineshape: $2.986(7)$ active ν's lighter than $M_Z/2 \rightarrow$ fourth sterile ν_S
  - $2+2$ patterns
  - $3+1$ patterns



- Pure $(\nu_\mu - \nu_s)$ excluded for atmospheric by SuperK, MACRO
- Pure $(\nu_e - \nu_s)$ excluded for solar by SNO, SuperK
- More general admixtures possible, but very poor global fits

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
- L may be conserved, or extra $U(1)'$ charge for N_R
- String constraints may forbid couplings allowed by 4d symmetries
- Superpotential terms leading to Majorana masses, or diagonal (same family or same flavor) Majorana 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 (sterile) neutrinos ν_L (N_R) (3 flavors each)

$$L = \frac{1}{2} \left(\bar{\nu}_L \quad \bar{N}^c_L \right) \begin{pmatrix} m_T & m_D \\ m_D^T & m_S \end{pmatrix} \begin{pmatrix} \nu^c_R \\ N_R \end{pmatrix} + \mathrm{hc}$$

  - $m_T = m_T^T =$ 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
  - Can one generate large effective m_S from

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

    consistent with D and F flatness?
  - Can one have such terms simultaneously with Dirac couplings, consistent with flatness and other constraints?
  - Is $c_{ii} = 0$? (Diagonal superpotential rare. Would be very nonstandard.)
  - Are bottom-up model assumptions for relations to quark, charged lepton masses maintained?
- Under investigation for Z_3 orbifold. So far, no examples.
- Flipped $SU(5)$ example? (Non GUT-like) (Ellis, Leontaris, Lola, Nanopoulos)

- **Extended (TeV) Seesaw?**
  - $m_\nu \sim m^{p+1}/m_S^p, \quad p > 1$ (e.g., $m \sim 100$ MeV, $m_S \sim 1$ TeV for $p = 2$)
  - ν_L, N_R, N'_R (3 flavors each)

$$L = \frac{1}{2}\left(\bar{\nu}_L \;\; \bar{N}_L^c \;\; \bar{N'}_L^c\right) \begin{pmatrix} 0 & \mathrm{m}_D & \mathrm{m}_{D'} \\ \mathrm{m}_D^T & 0 & \mathrm{m}_{SS'} \\ \mathrm{m}_{D'}^T & \mathrm{m}_{SS'}^T & 0 \end{pmatrix} \begin{pmatrix} \nu_R^c \\ N_R \\ N'_R \end{pmatrix} + \mathrm{hc}$$

or

$$L = \frac{1}{2}\left(\bar{\nu}_L \;\; \bar{N}_L^c \;\; \bar{N'}_L^c\right) \begin{pmatrix} 0 & \mathrm{m}_D & 0 \\ \mathrm{m}_D^T & 0 & \mathrm{m}_{SS'} \\ 0 & \mathrm{m}_{SS'}^T & m_{S'} \end{pmatrix} \begin{pmatrix} \nu_R^c \\ N_R \\ N'_R \end{pmatrix} + \mathrm{hc}$$

(Faraggi et al.: may occur in specific heterotic model, with dynamical assumptions.)

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 Gelmini-Roncadelli model: $\langle T^0 \rangle \ll$ EW scale with spontaneous L violation
  - Excluded by $Z \rightarrow$ 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