Neutrino Physics (theory)

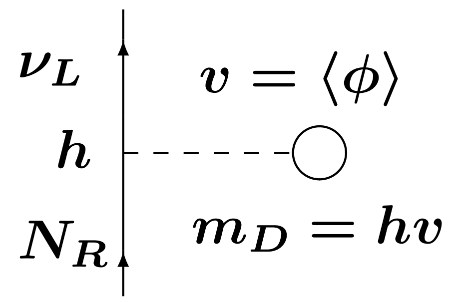
- m_ν: first break with standard model
- Neutrino preliminaries
- Major issues
  - The basic framework
  - Majorana or Dirac
  - Spectrum, mixings, and number
  - Models
  - Implications

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?

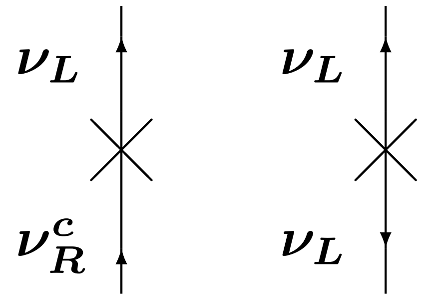
- **Dirac Mass**

  - 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

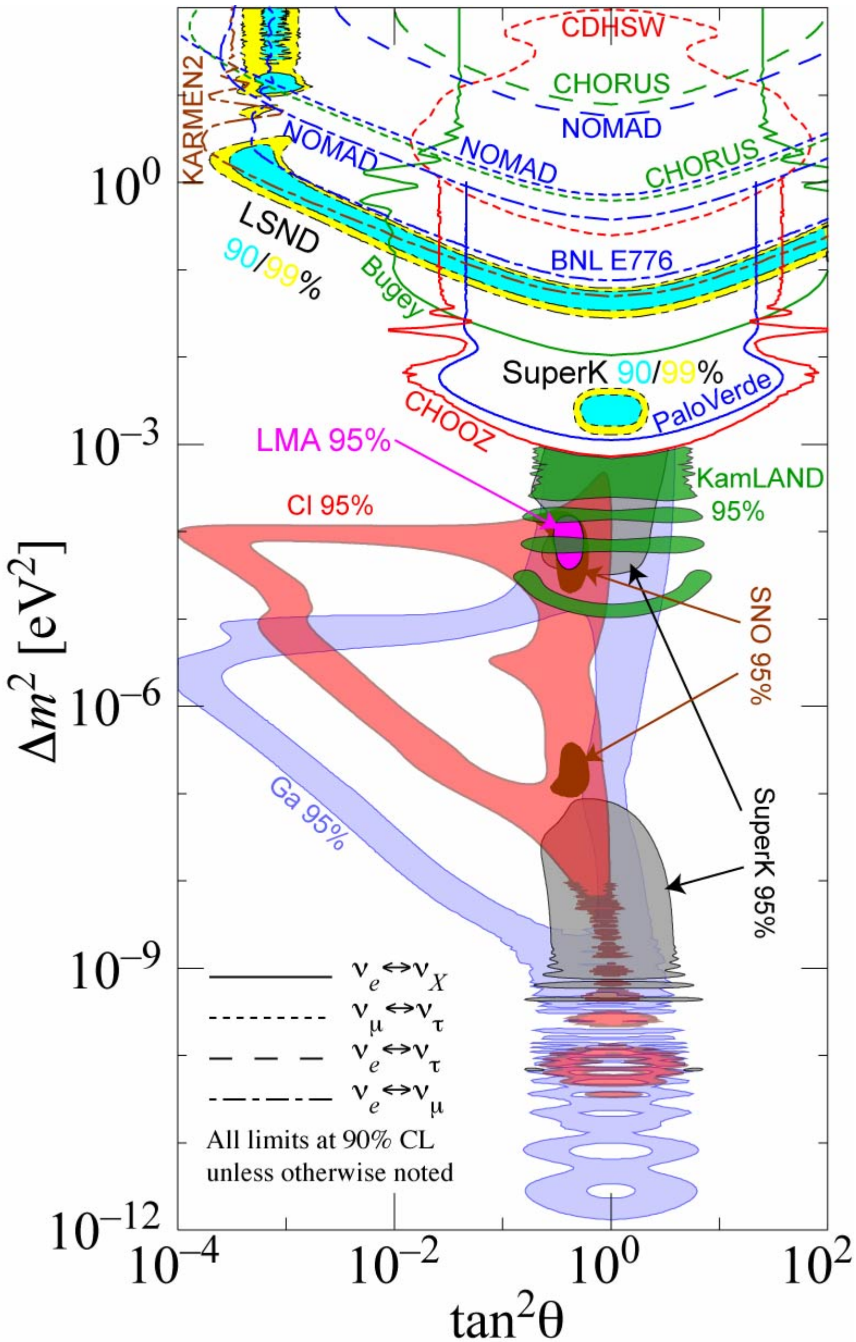


- **Mixed Masses**

  - 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))

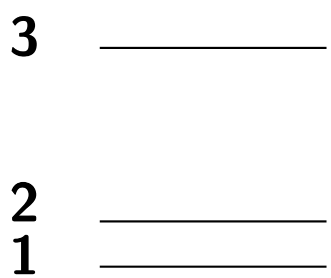
3 ν Patterns

- 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



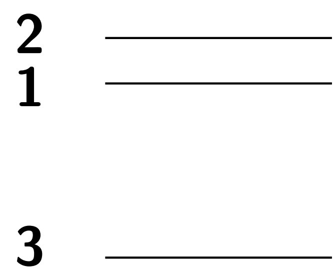
– **Mixings: let $\nu_\pm \equiv \frac{1}{\sqrt{2}}(\nu_\mu \pm \nu_\tau)$:**

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



– **Hierarchical pattern**

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



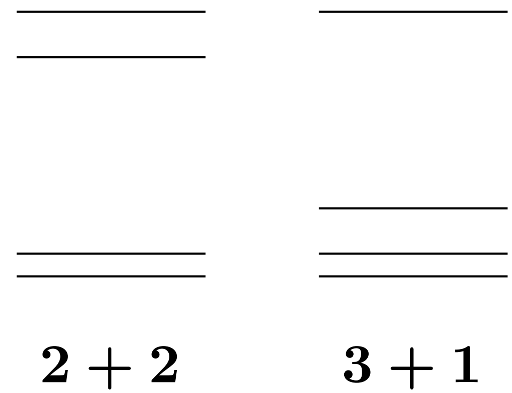
– **Inverted quasi-degenerate pattern**

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

– **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: $2.9841(83)$ active ν's lighter than $M_Z/2 \rightarrow$ fourth sterile ν_S



* 2 + 2 patterns
* 3 + 1 patterns

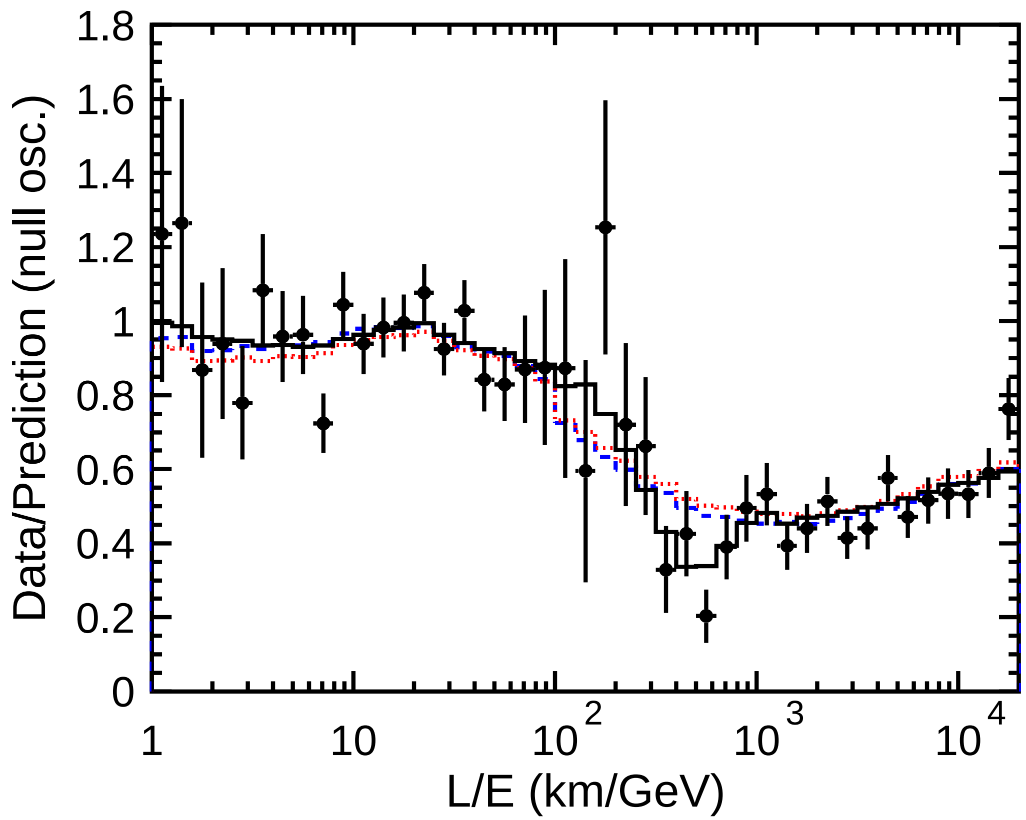
– Pure $(\nu_\mu - \nu_s)$ excluded for atmospheric by SuperK, MACRO

– Pure $(\nu_e - \nu_s)$ excluded for solar by SNO, SuperK

The basic framework

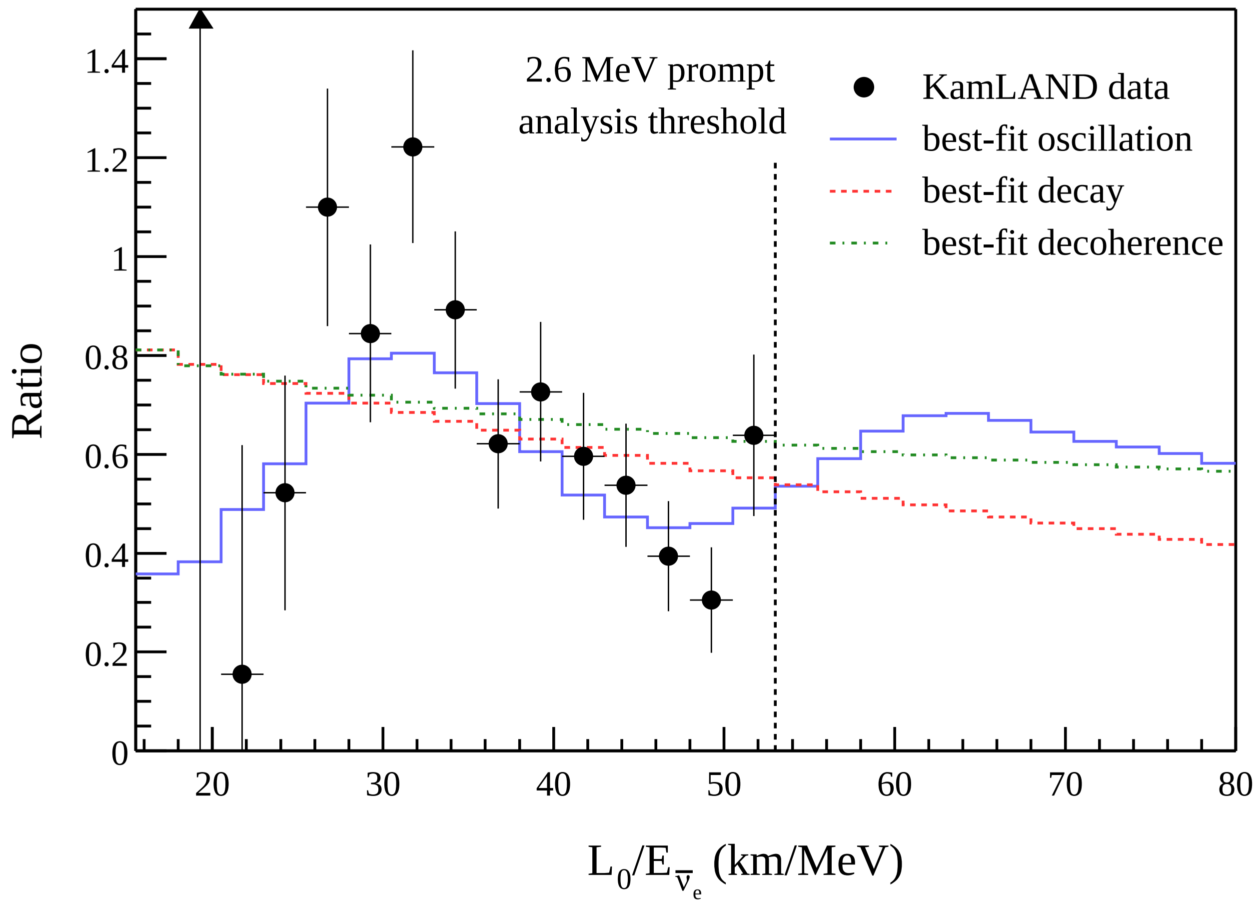
- **Many ideas once considered alternatives to oscillations amongst the 3 active neutrinos**
  - **Atmospheric neutrinos: many alternatives could describe the (lower energy) contained events, but most excluded by (higher energy) upward throughgoing.**
    (Often depend on LE or L rather than L/E.)

– **New SuperK dip further excludes**



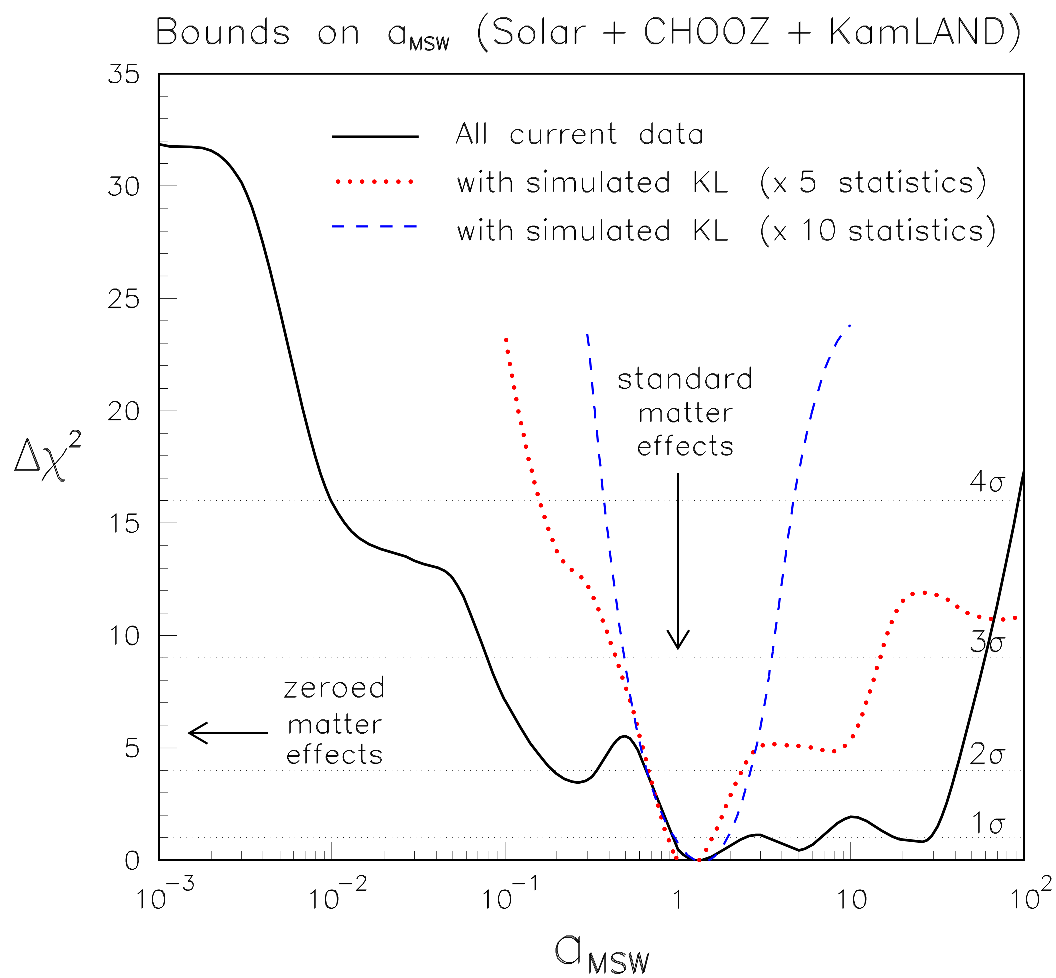
– **Solar (before KamLAND): several alternatives to LMA**

– **Solar (after KamLAND): LMA established and dip observed**



– **Clear evidence for MSW (but still need pp experiment)**
(Fogli, Lisi)

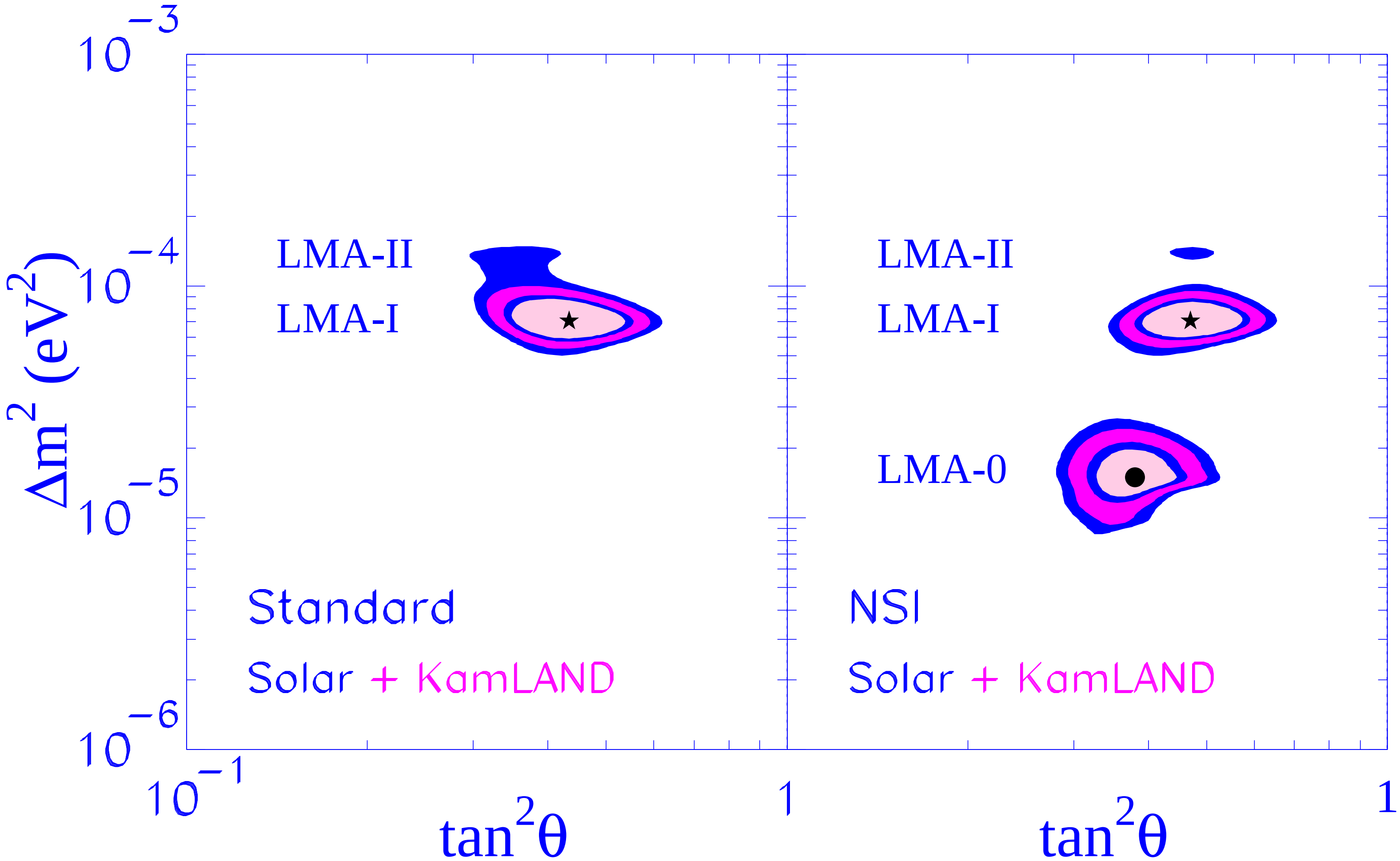
– **Detailed theory study** **(W. Liao talk)**



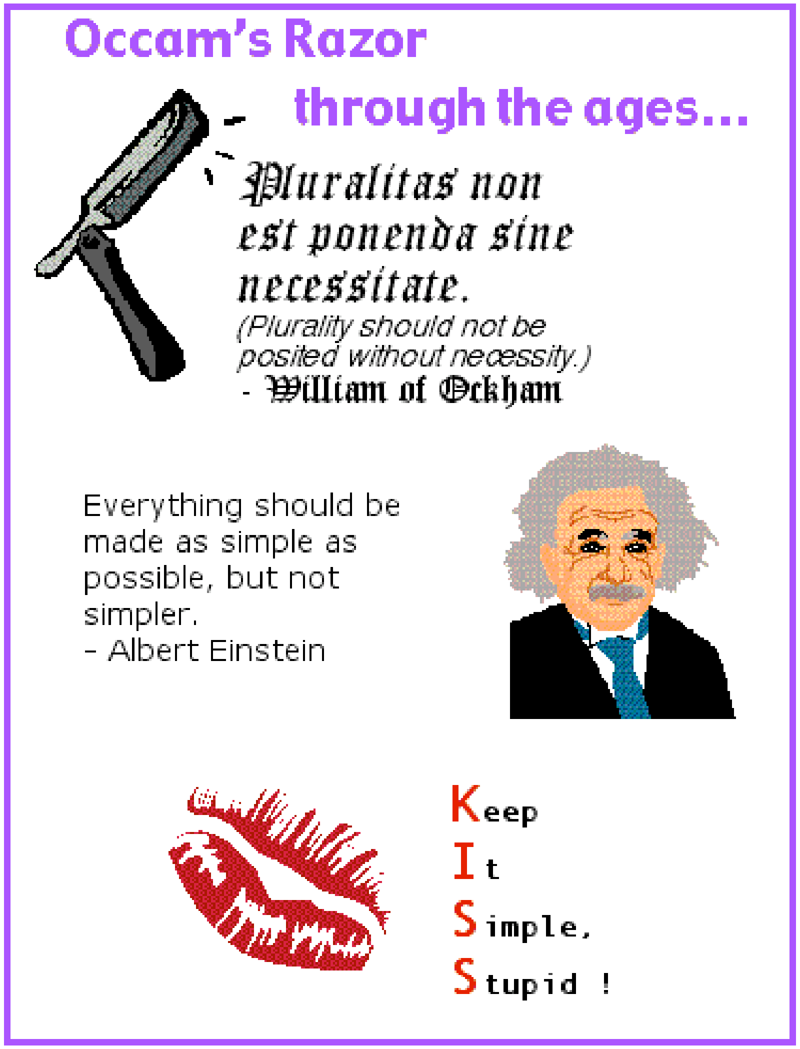
- Can still consider new physics mechanisms as perturbations on dominant 3-flavor oscillations.

  - Sterile neutrinos (will consider later)
  - Neutrino decay
  - Decoherence
  - Large magnetic moments and RSFP (but stellar cooling limits). (S. K. Kang talk)
  - Lorentz, CPT, equivalence principle violation (S. Uma Sankar)
  - New FCNC interactions

    (Friedland, Lunardini, Pena-Garay; Guzzo, Holanda, Peres)



10^{-3}
10^{-4}
10^{-5}
10^{-6}
Δm^2 (eV^2)
LMA-II
LMA-I
Standard
Solar + KamLAND
LMA-II
LMA-I
LMA-0
NSI
Solar + KamLAND
10^{-1}
1
$\tan^2\theta$
1
$\tan^2\theta$



But be careful!

Majorana or Dirac?

- "Neutrinos must be Majorana"
  - No standard model gauge symmetry forbids Majorana mass
  - Nonperturbative electroweak processes (sphalerons), black holes violate L
  - Standard GUTS violate L
- But there could be additional symmetries to forbid or strongly suppress L violation (cf. proton decay)
  - New gauge symmetries (e.g. Z') in 4d field theory
  - Constraints in string construction (extremely restrictive)
- $\Rightarrow$ Dirac or pseudo-Dirac are serious possibilities

The spectrum

- Ordinary hierarchy, inverted hierarchy, or degenerate? (Sensitive to model)

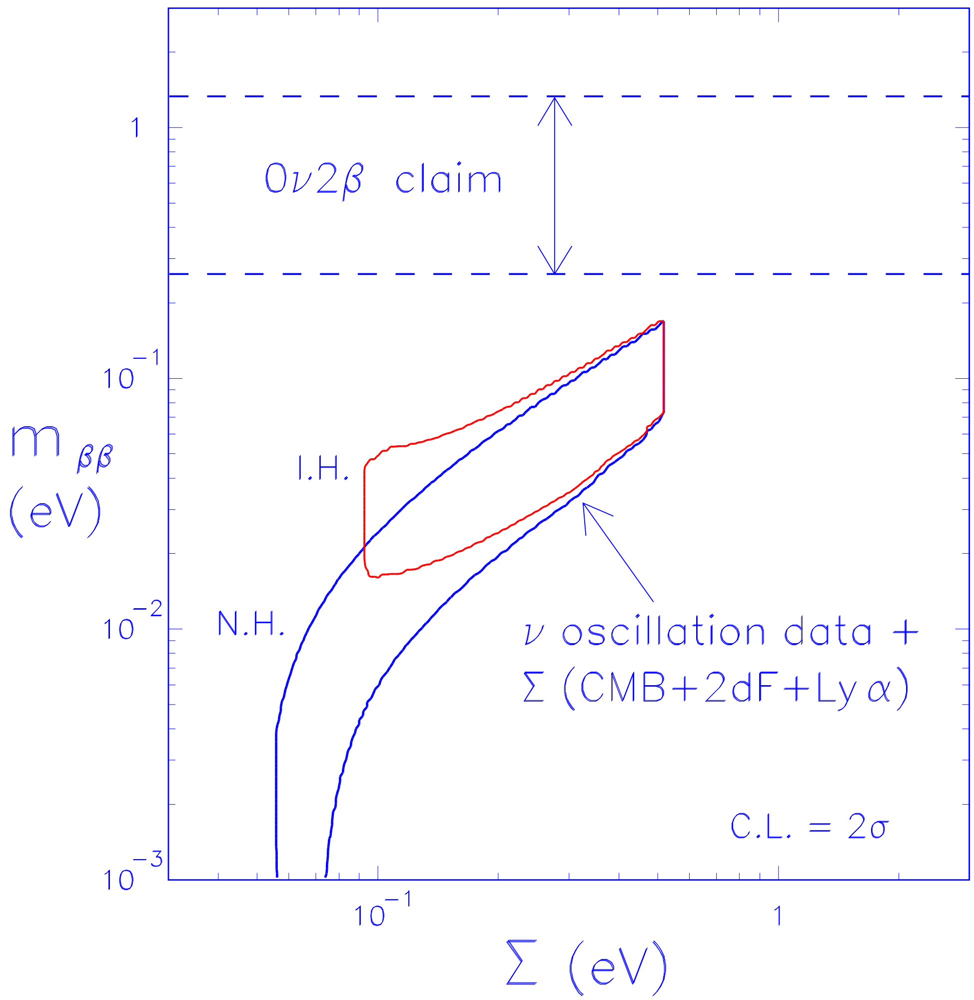
- Ordinary/inverted from long baseline, $\beta\beta_{0\nu}$ (if observed), supernova spectrum

- Scale from

$$\begin{aligned} \text{beta decay} : m_\beta &= \Sigma_i |U_{ei}|^2 |m_i| \lesssim 2 \text{ eV} \rightarrow \sim 0.2 \text{ eV (KATRIN)} \\ \text{cosmology} : \Sigma &= \Sigma_i |m_i| \lesssim 0.42 \text{ eV} \rightarrow (0.05 - 0.1) \text{ eV} \\ \beta\beta_{0\nu} : m_{\beta\beta} &= \Sigma_i U_{ei}^2 m_i \rightarrow \sim 0.02 \text{ eV} \end{aligned}$$

- Claimed observation: $0.17 < m_{\beta\beta} < 2.0$ eV

(Fogli et al)



1
$0\nu 2\beta$ claim
10^{-1}
$m_{\beta\beta}$ (eV)
I.H.
10^{-2}
N.H.
ν oscillation data +
Σ (CMB+2dF+Ly α)
C.L. = 2σ
10^{-3}
10^{-1}
1
Σ (eV)

Neutrino mixings

- $U_{PMNS} = U_e^\dagger U_\nu$ very different from U_{CKM}
  - Atmospheric consistent with maximal
  - Solar large but not maximal: $\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$
  - $\sin^2\theta_{13} < 0.03$ (90%) (need nonzero for CP violation in oscillations)
- Critical test of models (especially θ_{13}; deviation from maximal)
- Bimaximal mixing, $\theta_{23} = \theta_{12} = \frac{\pi}{4}$ easier to obtain than observed
- Most models assume either $U_e \sim I$ or $U_\nu \sim I$
- Several recent papers: bimaximal U_ν with small deviations from U_e $[\theta_{12} + \theta_{\text{Cabibbo}} \sim \frac{\pi}{4}]$ (W. Rodejohann talk)
- Radiative enhancement or instabilities (mainly for $m_i = m_j$)

The number of neutrinos

- Invisible Z width: $N_\nu = 2.9841(83)$
  - Active with $m_\nu < M_Z/2$
  - Other invisible, e.g. triplet Higgs with spontaneous L violation $\Rightarrow N_\nu = 5$

- Big Bang Nucleosynthesis (BBN) - competition between weak and expansion rates: $N'_\nu < 3.1 - 3.3$
  - Active, $m_\nu \lesssim 1$ MeV
  - Sterile, for interesting ranges of masses and mixings with active
  - *Not* N_R for light Dirac unless new BSM interactions

- **If LSND is confirmed by MiniBooNE:**
  - **Suggests 1 or more sterile ν's**
  - **Present in most models, but active-sterile mixing requires Dirac *and* Majorana masses tiny and comparable**
  - **Solar and atmospheric *not* dominantly into sterile**
  - **2+2 and 3+1 schemes excluded by solar, Kamland, atmospheric** (Schwetz, Fargion)
  - **3+2 better** (Sorel, Conrad, Shaevitz)
  - ***But* BBN constraints severe (and possibly large scale structure (LSS))**
  - **Other implications: r-process nucleosynthesis, pulsar kicks**

– Alternatives/ways out (aka long shots)

  * Large ν asymmetries to suppress or compensate steriles
  * Late time phase transitions to suppress masses and sterile mixings until after decoupling ($T < 1$ MeV) (Chacko, Hall, Oliver, Perelstein)
  * Time varying masses (coupling to special scalar fields) $\Rightarrow$sterile too massive to produce cosmologically (possible implications for matter effects and for dark energy) (Fardon, Nelson, Weiner, Kaplan, Zurek; Gu, Wang, Zhang)
  * CPT violation as alternative to sterile
    · CPT violating differences in masses excluded by Solar, Kamland, atmospheric (Schwetz, Strumia)
    · CPT violation *plus* sterile OK (Barger, Marfatia, Whisnant)
    · CPT *plus* decoherence (Barenboim, Mavromatos)

Models: textures

- Specific guesses about form of 3×3 mass (or seesaw) matrices
- Often done in connection with models also involving quarks and charged leptons (e.g. GUTS, family symmetries, left-right symmetry) (C. Low talk)

$$\text{Normal hierarchy}: m_\nu = m \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}, \ \epsilon \ll 1$$

$$\text{Inverted hierarchy}: m_\nu = m \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} + \text{ small}$$

$$\text{Degenerate}: m_\nu = mI + \text{ small}$$

Models

- Small Majorana:
  - Ordinary (type I) seesaw
  - Higgs triplets (type II seesaw)
  - TeV (extended) seesaw, $m_\nu \sim m^{p+1}/M^p$
  - Loops
  - R_p violation
  - Kähler potential
  - anarchy (random)
  - Large extra dimensions ($+$ one of the above?)

- **Small Dirac:**
  - **Higher dimensional operators (HDO) in intermediate scale models (e.g. $U(1)'$)**
  - **Large extra dimensions (LED) from volume suppression if N_R in bulk**
- **Variant ordinary and triplet seesaws motivated by string constructions**

Dirac masses

- Can achieve small Dirac masses (neutrino or other) by higher dimensional operators, or by large intersection areas in intersecting brane constructions

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

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

- 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, or from SUSY-breaking scale)

The ordinary seesaw

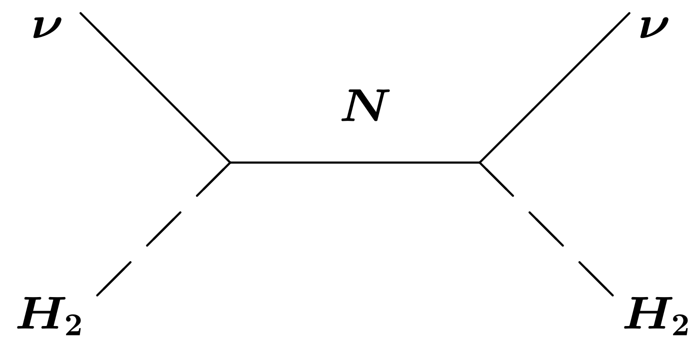
- Active neutrinos ν_L, N_R (3 flavors each)

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

  - $m_T = m_T^T =$ 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, $\mathbf{126}$ of $SO(10)$

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

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



- $U_{PMNS} = U_e^\dagger U_\nu$. Most models assume either
  - $U_e \sim I$ in basis with manifest symmetries for $m_{D,S} \Rightarrow$ large mixings in U_ν (m_D, m_S conspiracy)
  - Large U_e mixings from lopsided m_e in basis with $m_{D,S} \sim$ diagonal (harder to achieve in $SO(10)$ than $SU(5)$)

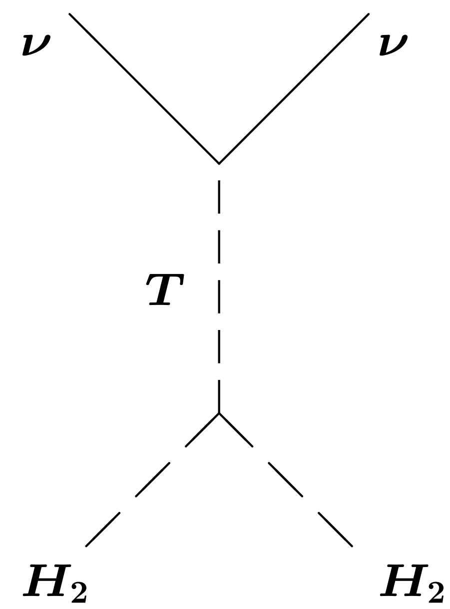
- $SO(10)$ models usually yield ordinary hierarchy

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

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 spontaneous 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



- 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

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

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

$$\langle T^0 \rangle \sim -\lambda \frac{\langle H_2^0 \rangle^2}{M_T} \;\Rightarrow\; \mathrm{m}_{\nu ij} = -\lambda^T_{ij} \lambda_2 \frac{v_2^2}{M_T}$$

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)**

The seesaw in string constructions

- 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? (Not for Z_3 orbifold: Giedt, Kane, PL, Nelson)

- $c_{ii} = 0$ in all known examples (independent of existence of Dirac) $\Rightarrow$

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

- **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)**

- **$\Rightarrow$Consider Dirac masses (OK) or triplet seesaw**

Triplet model in 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 can give $m_{\nu 23} \neq 0$ (but small)** (or $SU(2) \subset SU(2) \times SU(2) \times SU(2)$)

- **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** $m_\nu = m_\nu^\dagger \Rightarrow m_1 + m_2 + m_3 = 0$

- $|\Delta m^2_{\mathrm{Atm}}| \sim 2 \times 10^{-3}$ **eV**^{2}, $\Delta m^2_\odot \sim 8 \times 10^{-5}$ **eV**^{2} $\Rightarrow m_i = 0.046,\ -0.045,\ -0.001$ **eV** ($\sum |m_i| = 0.092$ **eV (cosmology))**

- **Well known phenomenological texture (Rodejohann talk):**

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

- **Inverted hierarchy**
- **Bimaximal mixing for $U_e = I$**

- **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

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

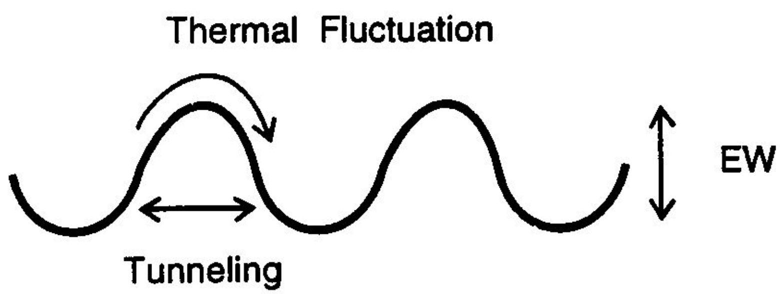
Implications

- Lepton flavor nonconservation (LFV), e.g., $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, $\mu \rightarrow 3e$
  - Lepton and hadron FCNC expected at some level in most BSM
  - m_ν violates L flavor, but at negligible rate
  - However, LFV generated along with m_ν in specific models (e.g. by $\tilde{\nu}$ exchange)
- Large magnetic moments (astrophysical limits)
- Neutrino decay (high energy, supernova, cosmological ν's)
- Majorana phases in $\beta\beta_{0\nu}$ (hard to observe because of nuclear uncertainties)

- **Equilibration of lepton asymmetries**
- **High energy ν's from violent astrophysical events (AGNs, GRBs)**
  - $\nu_e/\nu_\mu/\nu_\tau$ **ratio sensitive to oscillations, decays**
  - Z**-burst (relic ν's)**

- Leptogenesis with heavy Majorana N
  - L asymmetry from $N \to lH \neq N \to \bar{l}\bar{H}$
  - Partially converted to B asymmetry ($n_B/n_\gamma \sim 6\times10^{-10}$) by electroweak sphalerons
  - Severe constraints from gravitino production after reheating (Kawasaki, Kohri, Moroi)
  - Thermal vs non-thermal
  - New seesaw phases not directly measurable at low energy

- Alternatives: electroweak baryogenesis, Affleck-Dine, ...



Conclusions

- m_ν may be first break with standard model
- Spectacularly successful experimental program
- May be GUT/Planck scale physics
- Many possibilities
  - Dirac or Majorana
  - Many models, not just canonical seesaw
  - String constructions unlikely to yield standard GUT or left/right motivated models; may yield highly nonstandard seesaw or nonstandard triplet with inverse hierarchy