

Neutrino Physics (theory)



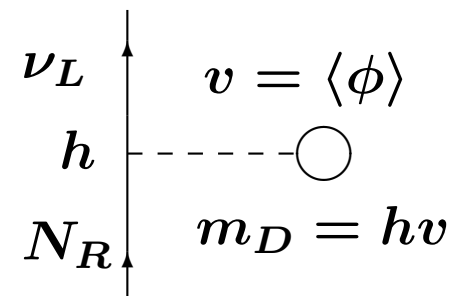
- m_ν : first break with standard model
- Neutrino preliminaries
- Major issues
 - The basic framework
 - Majorana or Dirac
 - Spectrum, mixings, and number
 - Models
 - Implications

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 \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:

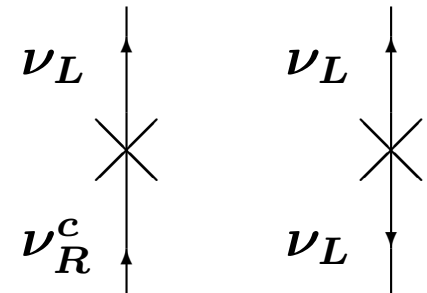
$$\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.) \text{ (active);}$$

$$\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.) \text{ (sterile)}$$

- 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

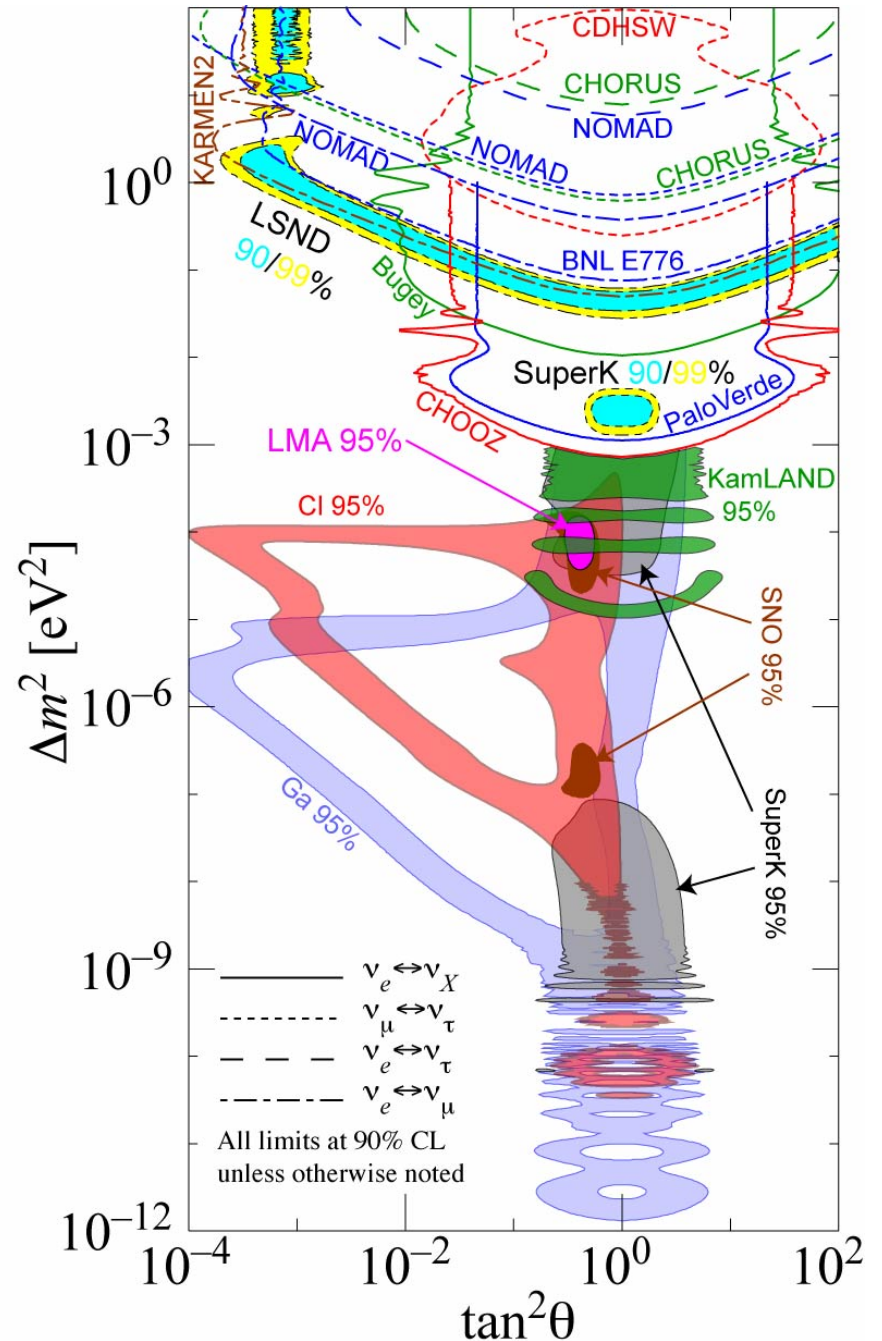
- Majorana and Dirac mass terms

- 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

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

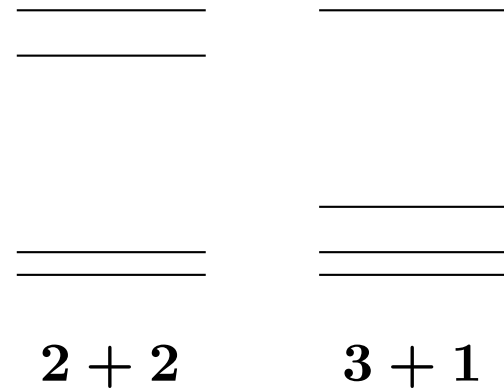
– 4 ν Patterns

* LSND: $\Delta m_{\text{LSND}}^2 \sim 1 \text{ eV}^2$

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

* 2 + 2 patterns

* 3 + 1 patterns



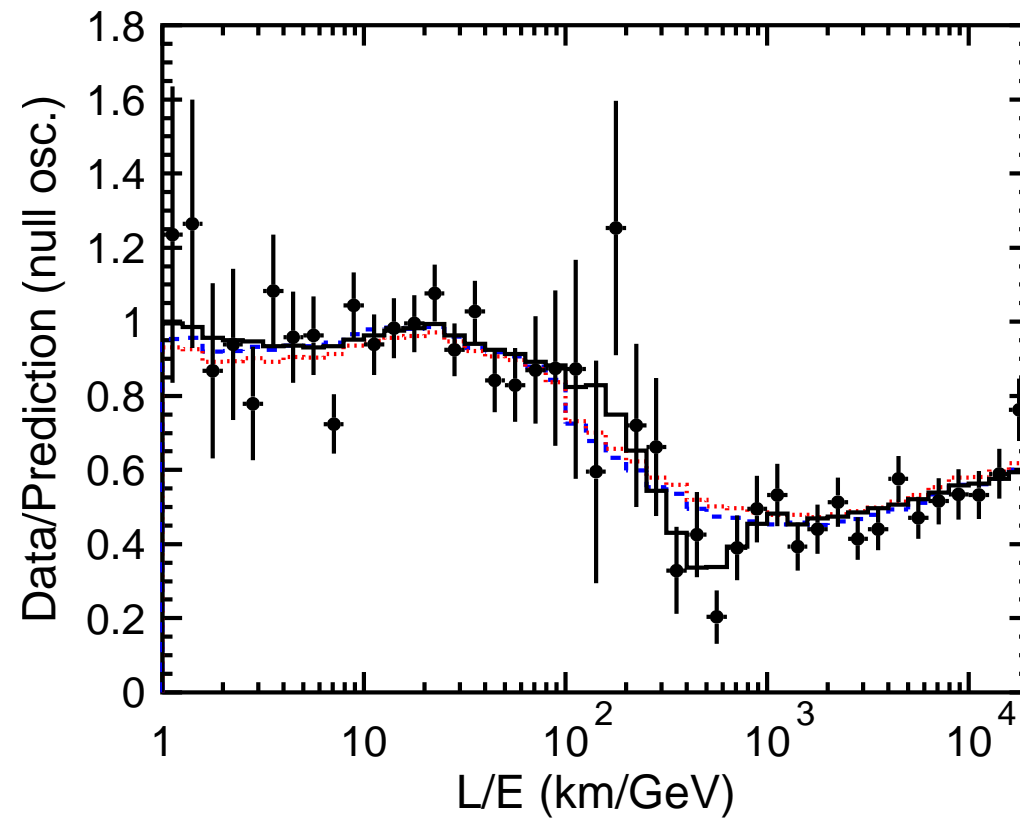
– Pure $(\nu_\mu - \nu_s)$ excluded for atmospheric by SuperK, MACRO

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

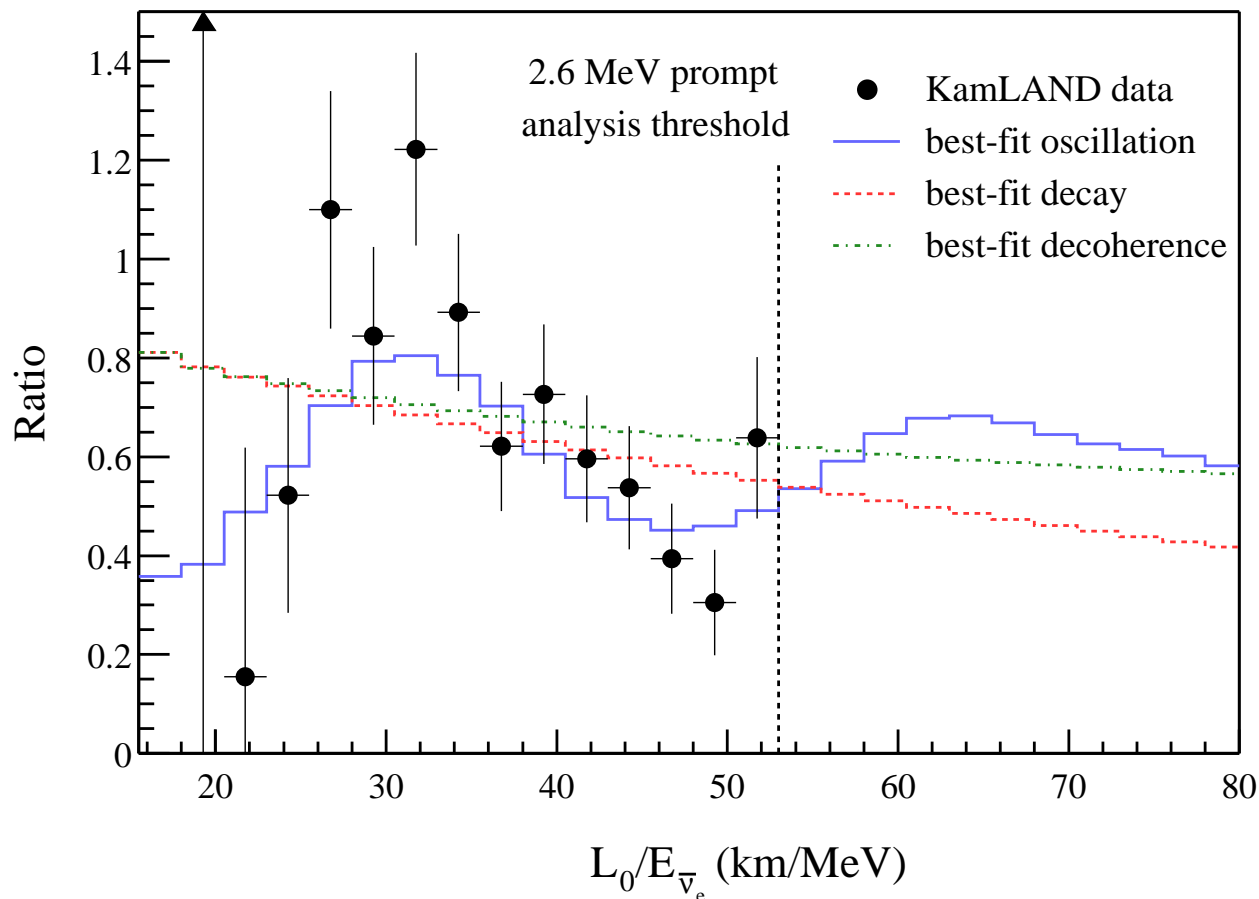
The basic framework

- 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

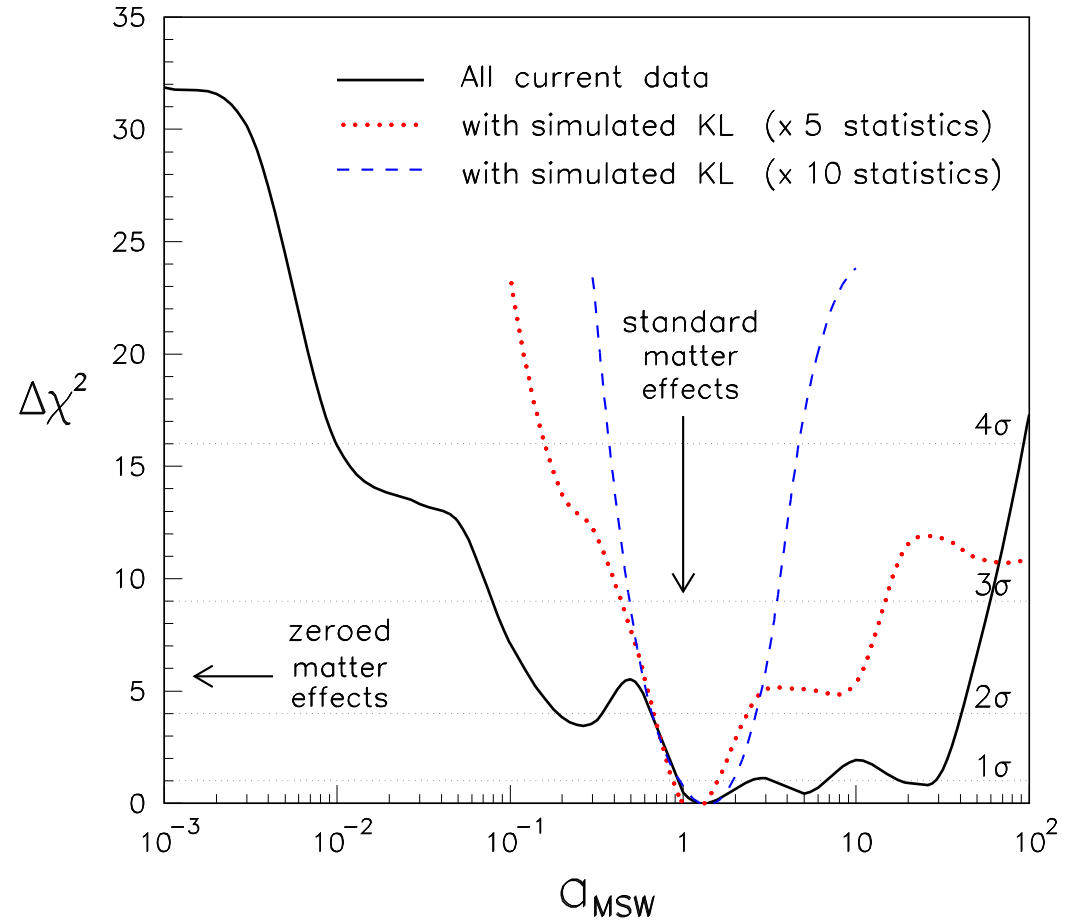


- Solar (before KamLAND): several alternatives to LMA
- Solar (after KamLAND): LMA established and dip observed

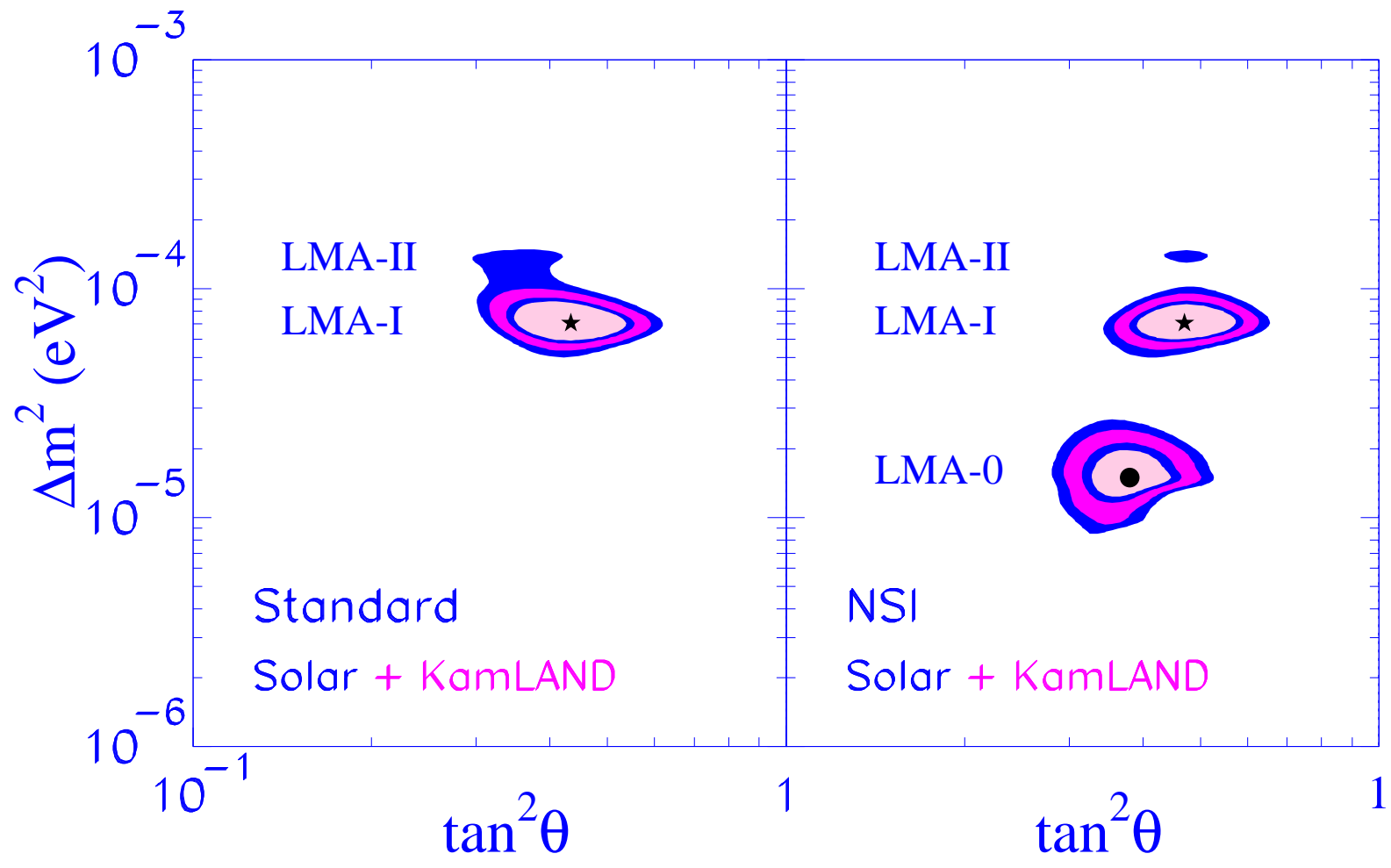


- Clear evidence for MSW (but still need pp experiment) (Fogli, Lisi)
- Detailed theory study (W. Liao talk)

Bounds on a_{MSW} (Solar + CHOOZ + KamLAND)



- 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)



Occam's Razor



through the ages...

*Pluralitas non
est ponenda sine
necessitate.*

*(Plurality should not be
posited without necessity.)*

- William of Ockham

Everything should be
made as simple as
possible, but not
simpler.

- Albert Einstein



KeeP
It
Simple,
Stupid !

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

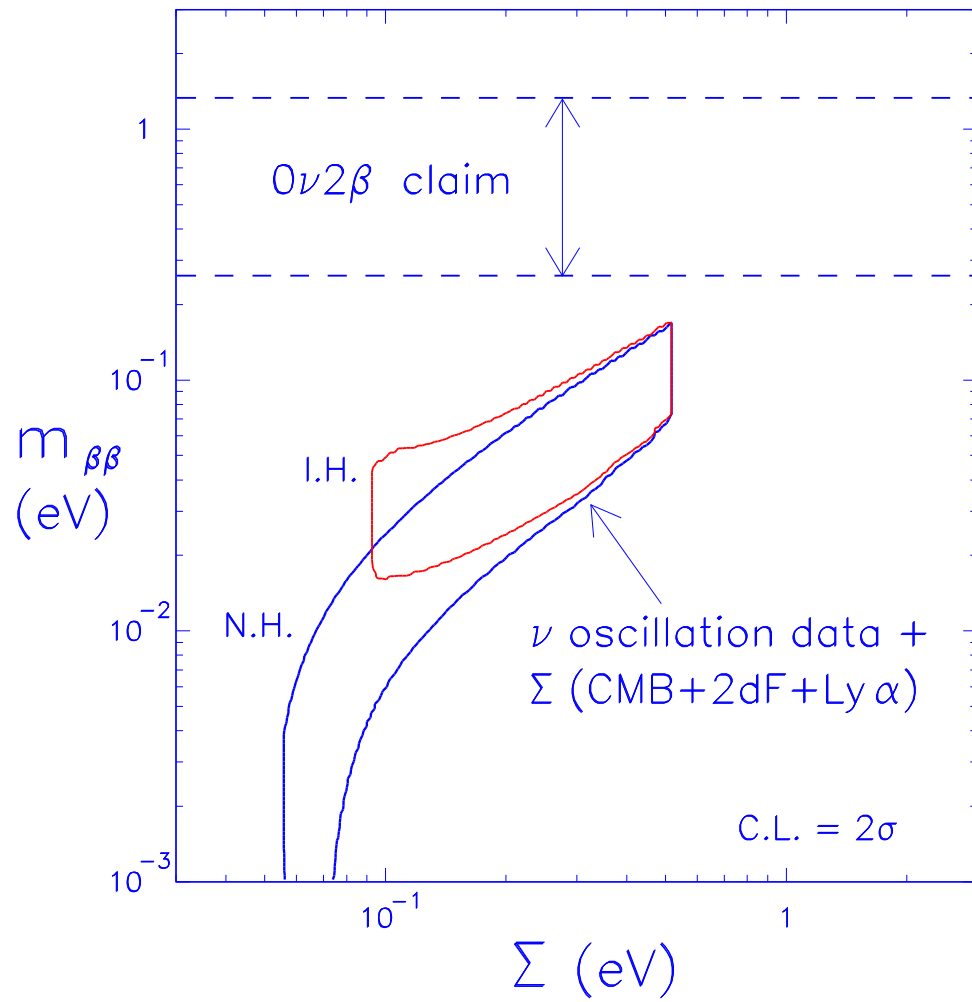
$$\text{beta decay : } m_\beta = \sum_i |U_{ei}|^2 |m_i| \lesssim 2 \text{ eV} \rightarrow \sim 0.2 \text{ eV (KATRIN)}$$

$$\text{cosmology : } \Sigma = \sum_i |m_i| \lesssim 0.42 \text{ eV} \rightarrow (0.05 - 0.1) \text{ eV}$$

$$\beta\beta_{0\nu} : m_{\beta\beta} = \sum_i U_{ei}^2 m_i \rightarrow \sim 0.02 \text{ eV}$$

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

(Fogli et al)



Neutrino mixings

- $U_{PMNS} = U_e^\dagger U_\nu$ very different from U_{CKM}
 - Atmospheric consistent with maximal
 - Solar large but not maximal: $\tan^2 \theta_{12} = 0.40_{-0.07}^{+0.09}$
 - $\sin^2 \theta_{13} < 0.03$ (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)

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

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

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

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

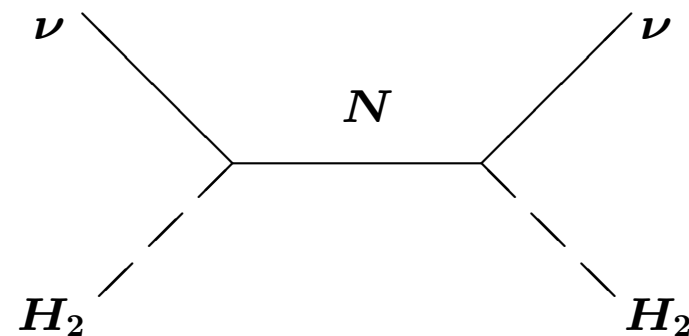
- Active neutrinos ν_L, N_R (3 flavors each)

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

- $m_T = m_T^T =$ 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) $m_S \gg m_D$:

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



- $U_{PMNS} = U_e^\dagger U_\nu$. 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 $SU(5)$)

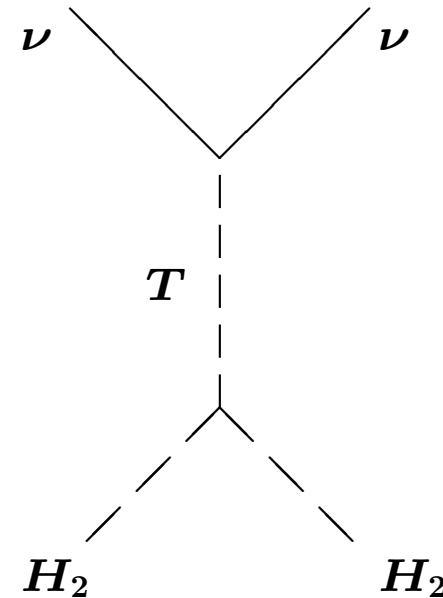
- $SO(10)$ models usually yield ordinary hierarchy

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

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

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

$$\langle T^0 \rangle \sim -\lambda \frac{\langle H_2^0 \rangle^2}{M_T} \Rightarrow m_{\nu ij} = -\lambda_{ij}^T \lambda_2 \frac{v_2^2}{M_T}$$

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

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

- Can one have such terms simultaneously with Dirac couplings, consistent with flatness and other constraints? (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 $\lambda_{ij}^T = 0$ 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.)

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

yields

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

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

- HDO 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})

- $\text{Tr } m_{\nu} = 0$ and $m_{\nu} = m_{\nu}^{\dagger} \Rightarrow m_1 + m_2 + m_3 = 0$
- $|\Delta m_{\text{Atm}}^2| \sim 2 \times 10^{-3} \text{ eV}^2$, $\Delta m_{\odot}^2 \sim 8 \times 10^{-5} \text{ eV}^2 \Rightarrow m_i = 0.046, -0.045, -0.001 \text{ eV}$ ($\sum |m_i| = 0.092 \text{ eV}$ (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 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

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

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

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

Implications

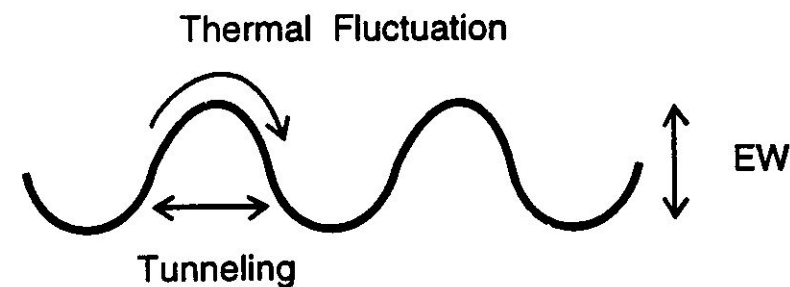
- Lepton flavor nonconservation (LFV), e.g., $\mu \rightarrow e\gamma$, $\mu N \rightarrow eN$, $\mu \rightarrow 3e$
 - Lepton and hadron FCNC expected at some level in most BSM
 - m_ν violates L flavor, but at negligible rate
 - However, LFV generated along with m_ν in specific models (e.g. by $\tilde{\nu}$ 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 $N \rightarrow lH \neq N \rightarrow \bar{l}\bar{H}$
- Partially converted to B asymmetry ($n_B/n_\gamma \sim 6 \times 10^{-10}$) 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