Neutrino Mass Models

Lisa L. Everett

Neutrinos: Recent Developments and Future Challenges

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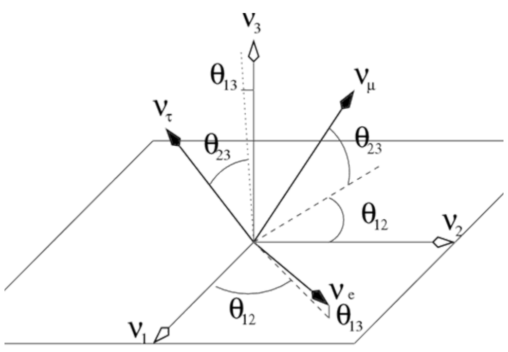
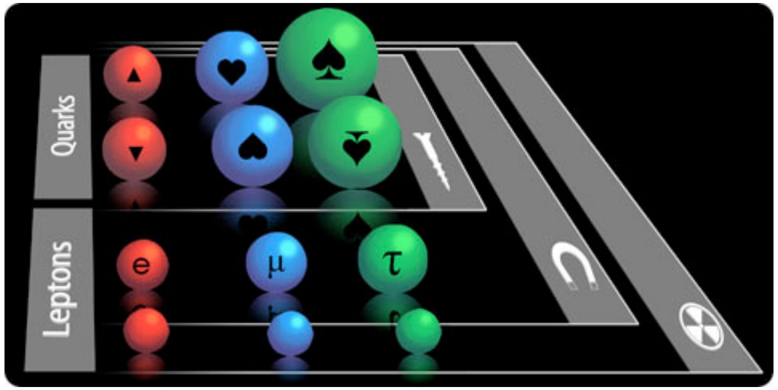
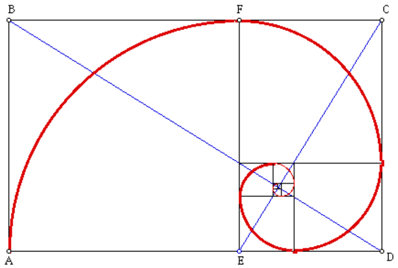
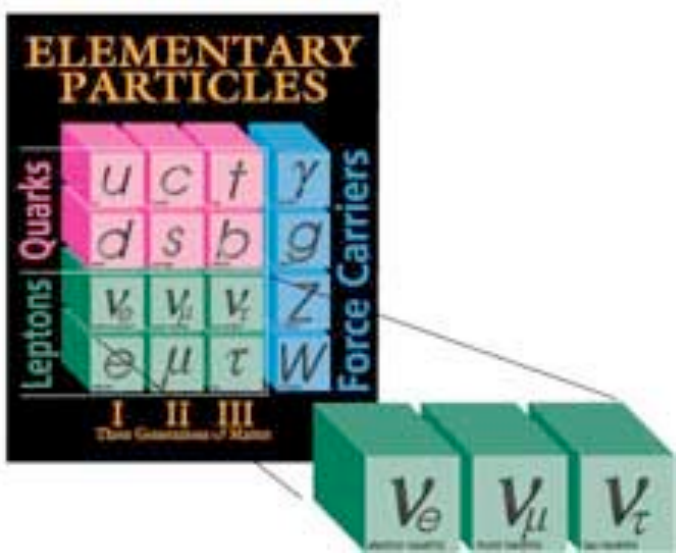






Main Theme



Discovery of Neutrino Oscillations:

$$\mathcal{P}_{\nu_\alpha \to \nu_\beta}(L) = \sum_{ij} \mathcal{U}_{i\alpha}\mathcal{U}^*_{i\beta}\mathcal{U}^*_{j\alpha}\mathcal{U}_{j\beta} e^{-\frac{i\Delta m^2_{ij} L}{2E}}$$

surprises, confusion, excitement for beyond SM physics theory!

3 Neutrino "Reference" Picture:

data (w/exceptions*) consistent with 3ν mixing picture

intriguing pattern of masses, mixings: paradigm shift for SM flavor puzzle

Challenges to this picture:

***LSND, MiniBooNE, reactor anomaly, gallium anomaly: sterile neutrinos?**

Many Questions Remain

- **How many light neutrinos?**

  Anomalies: LSND, MiniBooNE, Gallium, Reactor

  eV-scale sterile neutrinos? But tension still with all oscillation data

  First restrict to 3-family neutrino models only

  SM $\longrightarrow$ νSM

- **Still, many questions:**

  Nature of neutrino mass suppression? Majorana? Dirac?

  Mass hierarchy? Lepton mixing angle pattern? CP violation?

  Implications for BSM paradigms? Connections to other NP?

The Lepton Data

$$\mathcal{U}_{\rm MNSP} = \mathcal{R}_1(\theta_{23})\mathcal{R}_2(\theta_{13}, \delta_{\rm MNSP})\mathcal{R}_3(\theta_{12})\mathcal{P}$$

Pontecorvo
Maki, Nakagawa,
Sakata

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{\rm CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ {\rm eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ {\rm eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

taken from:

Gonzalez-Garcia, Maltoni, Salvado, Schwetz 1409.5439

see also:

Forero, Tortola, Valle 1405.7540

Capozzi, Fogli, Lisi, Marrone, Montanino, Palazzo 1312.2878

2 large angles, 1~Cabibbo-sized ("small")

For Comparison: Quark Mixings

Cabibbo; Kobayashi, Maskawa

$$\mathcal{U}_{\rm CKM} = \mathcal{R}_1(\theta_{23}^{\rm CKM})\mathcal{R}_2(\theta_{13}^{\rm CKM}, \delta_{\rm CKM})\mathcal{R}_3(\theta_{12}^{\rm CKM})$$

Cabibbo angle θ_c

Mixings:

$$\left.\begin{aligned} \theta_{12}^{\rm CKM} &= 13.0^\circ \pm 0.1^\circ \\ \theta_{23}^{\rm CKM} &= 2.4^\circ \pm 0.1^\circ \\ \theta_{13}^{\rm CKM} &= 0.2^\circ \pm 0.1^\circ \end{aligned}\right\}$$

3 small angles

CP violation:

$$J \equiv {\rm Im}(\mathcal{U}_{\alpha i}\mathcal{U}_{\beta j}\mathcal{U}^*_{\beta i}\mathcal{U}^*_{\alpha j})$$

Jarlskog; Dunietz, Greenberg, Wu

$$J_{\rm CP}^{\rm (CKM)} \simeq \sin 2\theta_{12}^{\rm CKM} \sin 2\theta_{23}^{\rm CKM} \sin 2\theta_{13}^{\rm CKM} \sin \delta_{\rm CKM}$$

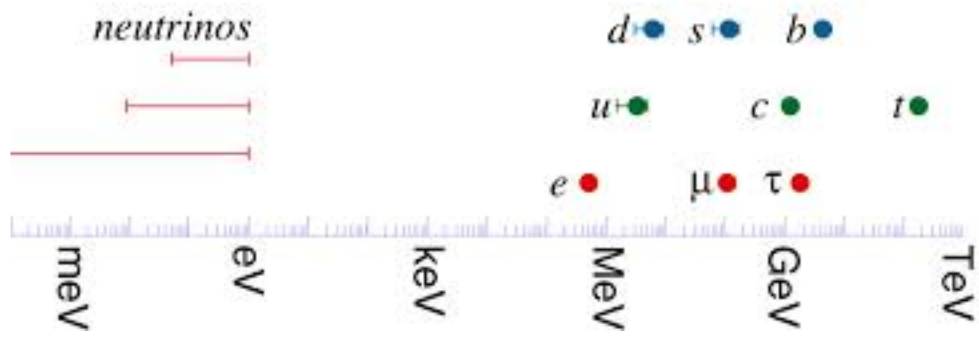
$$J \sim 10^{-5} \qquad \delta_{\rm CKM} = 60^\circ \pm 14^\circ$$

O(1) CP-violating phase

(Broad) Theoretical Implications

Shifts in the paradigm for SM flavor puzzle:

Suppression of neutrino mass scale



Seemingly milder hierarchies for neutrinos

Quark, Lepton Mixing Angles strikingly different

implications for quark-lepton unification?

Mass Generation

Quarks, Charged Leptons

"natural" mass scale tied to electroweak scale

Dirac mass terms, parametrized by Yukawa couplings

$$Y_{ij} H \cdot \bar{\psi}_{Li} \psi_{Rj}$$

top quark: O(1) Yukawa coupling

rest: suppression (flavor symmetry)

Neutrinos

beyond physics of Yukawa couplings!

Options: Dirac

Majorana

Majorana first:

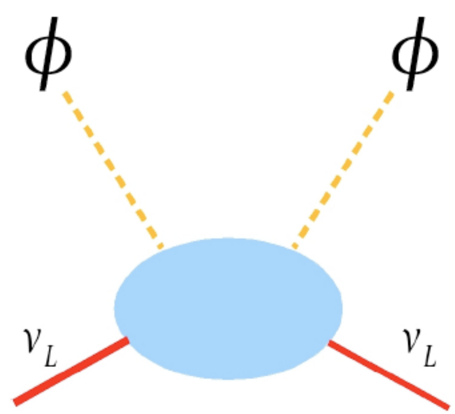
advantages: naturalness, leptogenesis, $0\nu\beta\beta$

SM at NR level: Weinberg dim 5 operator

$$\frac{\lambda_{ij}}{\Lambda} L_i H L_j H$$

(if $\lambda \sim O(1)$ $\quad \Lambda \gg m \sim O(100\,\mathrm{GeV})$ $\quad$ but wide range possible)

Underlying mechanism: examples



Type I seesaw $\quad \nu_R$ (fermion singlet)

Type II seesaw $\quad \Delta$ (scalar triplet)

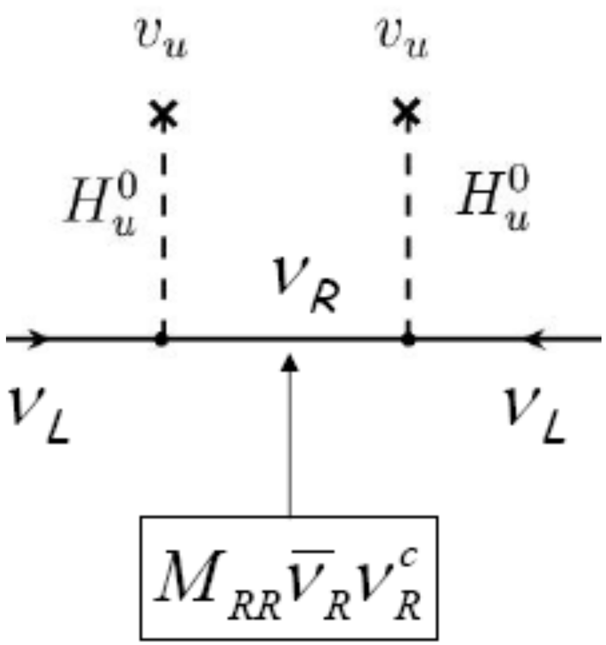
Type III seesaw $\quad \Sigma$ (fermion triplet)

+ variations

Prototype: Type I seesaw

Minkowski; Yanagida;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;…

right-handed neutrinos: $Y_{ij} L_i \nu_{Rj} H + M_{R\,ij} \nu_{Ri} \nu^c_{Rj}$



$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$m \sim \mathcal{O}(100\,\mathrm{GeV})$

$M \gg m$

$$m_1 \sim \frac{m^2}{M} \qquad m_2 \sim M \gg m_1$$

$$\nu_{1,2} \sim \nu_{L,R} + \frac{m}{M} \nu_{R,L}$$

advantages: naturalness, connection to grand unification, leptogenesis,...

disadvantage: testability (even at low scales)

Different in Type II, III: new EW charged states, may be visible at LHC

Many other ideas for Majorana neutrino masses...

more seesaws (double, inverse,...),
loop-induced masses (Babu-Zee, ...),
SUSY with R-parity violation, RS models,
higher-dimensional (>5) operators,...

What about Dirac masses?

Less intuitive, but suppression mechanisms exist…

extra dimensions, extra gauge symms (non-singlet ν_R),SUSY breaking,…

General themes:

Trade-off b/w naturalness and testability.
Much richer than quark and charged lepton sectors.

Lepton (and Quark) Mixing Angle Generation

Standard paradigm: spontaneously broken flavor symmetry

$$Y_{ij} H \cdot \bar{\psi}_{Li} \psi_{Rj} \longrightarrow \left(\frac{\varphi}{M}\right)^{n_{ij}} H \cdot \bar{\psi}_{Li} \psi_{Rj}$$

Froggatt, Nielsen

Quarks:

hierarchical masses, small mixings: continuous family symmetries

CKM matrix: small angles and/or alignment of left-handed mixings

$$\mathcal{U}_{\rm CKM} = \mathcal{U}_u \mathcal{U}_d^\dagger \sim 1 + \mathcal{O}(\lambda)$$

$$\lambda \sim \frac{\varphi}{M}$$

Wolfenstein parametrization: $\lambda \equiv \sin\theta_c = 0.22$

suggests Cabibbo angle (or some power) as a flavor expansion parameter

The Flavor Puzzle, Rejuvenated

Flavor puzzle of SM is notoriously difficult...

Still difficult in νSM, but more interesting --

One primary reason: two large mixing angles!

$$\theta_{23} \simeq 45^\circ \pm 5^\circ \quad \theta_{12} \simeq 34^\circ \pm 1^\circ$$

3-family models: handwave a bit (in diagonal charged lepton basis)

3 small angles	$\longrightarrow$	$\sim$ diagonal $\mathcal{M}_\nu$	("easy")
1 large, 2 small	$\longrightarrow$	$\sim \mathrm{Rank}\mathcal{M}_\nu < 3$	
3 large angles	$\longrightarrow$	anarchical $\mathcal{M}_\nu$	("harder")
2 large, 1 small	$\longrightarrow$	fine-tuning, non-Abelian	

Anarchy vs. Structure

$\longrightarrow$ **The question: is θ_{13} large or small?**

$$\theta_{13} \simeq 9^\circ \pm 1^\circ$$

New case for anarchy: de Gouvea and Murayama, '12

some recent realizations: Bai and Torroba, Altarelli et al., '12

Focus here on structure (symmetry):

Paradigm: discrete non-Abelian family symmetry

(e.g. some subgroup of SO(3) or SU(3), broken to some appropriate coset space)

Main issue/challenge: many theoretical starting points

Role of Small (Cabibbo-sized) Corrections

Quark sector:

$$\mathcal{U}_{\rm CKM} \sim 1 + O(\lambda_C)$$

Cabibbo angle λ_C (or some power) as a flavor expansion parameter

Lepton sector:

$$\mathcal{U}_{\rm MNSP} \sim \mathcal{W} + O(\lambda')$$

"bare" mixing angles $(\theta_{12}^0, \theta_{13}^0, \theta_{23}^0)$ perturbations

choice of bare mixing angles?

Unification paradigm (broad sense): useful to take

$$\lambda' = \lambda_C$$

ideas of quark-lepton complementarity and "Cabibbo haze"

Raidal '04, Minakata+Smirnov, '04, many others...

"haze" terminology from Datta, L.E., Ramond '05

Long before measurement, conjectured that θ_{13} is a Cabibbo effect

$$\theta_{13} \sim \frac{\lambda_C}{\sqrt{2}} \sim \lambda_C \cos\theta_{23}^0$$

Ramond '03,...

(general idea often called "charged lepton corrections") $\mathcal{U}_{\rm MNSP} \sim \mathcal{U}^{\dagger}_{\rm CKM}\mathcal{W}$

good fit to data! but nontrivial to implement...

one reason: now $\sim \lambda_C$ corrections floating around

The Flavor Puzzle in the νSM

Pre-Reactor Meas. most models: $\theta_{23}^0 = 45^\circ \quad \theta_{13}^0 = 0^\circ$

Choices for "bare" solar angle θ_{12}^0:

(i) within $\sim \lambda_C^2$ of exp:

tri-bimaximal mixing $\tan\theta_{12}^0 = \frac{1}{\sqrt{2}} \quad \theta_{12}^0 = 35.26^\circ$

"the beautiful matrix with the ugly name"

Harrison, Perkins, Scott '02

(100s of papers. Key players include Ma, Chen et al., Altarelli et al.,...)

others, such as golden ratio mixing $\phi = (1+\sqrt{5})/2$

$\tan\theta_{12} = \phi^{-1} \quad \theta_{12} = 31.72^\circ$ or $\cos\theta_{12} = \frac{\phi}{2} \quad \theta_{12} = 36^\circ$

Ramond, Kajiyama et al., LE+Stuart (+Ding), Feruglio et al.,...

Rodejohann et al.,...

(ii) within $\sim \lambda_C$ of exp:

Raidal '04, Minakata, Smirnov '04,...)

bimaximal mixing $\tan\theta_{12}^0 = 1$

Approaches:

"top-down": detailed model-building

example: tri-bimaximal mixing

Harrison, Perkins, Scott '02

$$\mathcal{U}_{\rm MNSP}^{\rm (HPS)} = \begin{pmatrix} \sqrt{\frac{2}{3}} & -\frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

(~Clebsch-Gordan coeffs!)

Meshkov; Zee,...

Readily obtained within many discrete subgroups of $SO(3)$, $SU(3)$

$$\mathcal{G}_F = \mathcal{A}_4,\, \mathcal{S}_4,\, \mathcal{T}',\Delta(3n^2),\ldots$$

(100s of papers. Key players include Ma, Chen et al., Altarelli et al.,...)

"bottom-up": residual symmetries

$$\mathcal{G}_F \longrightarrow \mathcal{G}_e \times \mathcal{G}_\nu$$

Lam '07, '08,…

pure group theory argument: e.g. "minimal" group is S_4 for TBM

Post-Reactor Meas.

"top-down": detailed model-building

(1) Keep $\theta_{23}^0 = 45^\circ$ $\theta_{13}^0 = 0^\circ$

(i) within $\sim \lambda_C^2$ of exp: need to control corrections

TBM (or other mixing scenarios) as **leading order framework**

e.g. Lin '09; Ma '12, '13; Chen et al., King and Stuart '12, '13, many others…

(ii) within $\sim \lambda_C$ of exp: resurgence?

(2) Modify $\theta_{23}^0 = 45^\circ$ $\theta_{13}^0 = 0^\circ$

e.g. Hagedorn et al. '12, '13, King and Stuart '12, many others…

θ_{13} numerology?

drop maximal θ_{23} (some hints in data)?

implications for GUT connections?

"bottom-up": residual symmetries

large groups, typically trivial CP violation w/Klein group for $\mathcal{G}_\nu$

Holthausen et al. '12, King et al. '13, Hagedorn et al. '13, many others,…

eV-scale Sterile Neutrinos?

suggested by LSND, MiniBooNE, reactor anomaly, gallium anomaly

n_s **sterile neutrinos:** $3(n_s+1)$ mixing angles

$2n_s+1$ Dirac phases

n_s+2 Majorana phases

Global fits:

$n_s=1$ “2+2” strongly disfavored, “3+1” tension w/cosmology

1+3 (1 at eV scale) better, but no possibility of CP violation in SBL

$n_s=2$ “3+2” tension w/cosmology, “1+3+1” better

allows for CPV in SBL experiments

Kopp, Maltoni, Schwetz ’13
Giunti et al. ’13

but all fits “bad” — tension b/w app and disapp data

Theoretical Implications: Sterile Neutrinos

If eV-scale sterile ν present, many implications:

Impact on $0\nu\beta\beta$ see e.g. Barry, et al. '11, Girardi et al. '13, …

Many interesting implications for model-building!

mass hierarchies? GUT connections?

mixing pattern and residual symmetries

intriguing hint: $n_s = 1$ $\theta_{14} \sim \theta_{13}$ same origin?

recent example: Merle, Morisi, Winter '14,…

back to the drawing board!!

CP Violation

Reactor angle measured: prospects for measuring CP phases

Model-building: spontaneous v. explicit CP violation

generalized CP transformations

CP tmns as automorphisms Grimus, Rebelo '95

for discrete groups: Holthausen et al. '12, Chen et al. '14,…

family symm tmn: $\phi \longrightarrow \rho(g)\phi$

generalized CP tmn: $\phi \longrightarrow U\phi^*$ (not $\phi \longrightarrow \phi^*$)

with consistency condition: $U\rho(g)^* U^{-1} = \rho(g')$

Moral: CP and family symmetries can be inextricably intertwined

Much recent model-building along these lines…

see e.g. Ding et al,. Girardi et al., many others…

Conclusions and Outlook

The SM flavor puzzle is a hard but intriguing problem!

The lepton data $\longrightarrow$ paradigm shift

Bottom Line:

A number of ways to generate masses/mixings, all with advantages/ disadvantages. **Reactor angle** has added new surprises

Still room for **many more surprises** (CP violation, sterile neutrinos…)

Exciting times! Lots of ideas, lots of room for more

Stay tuned!