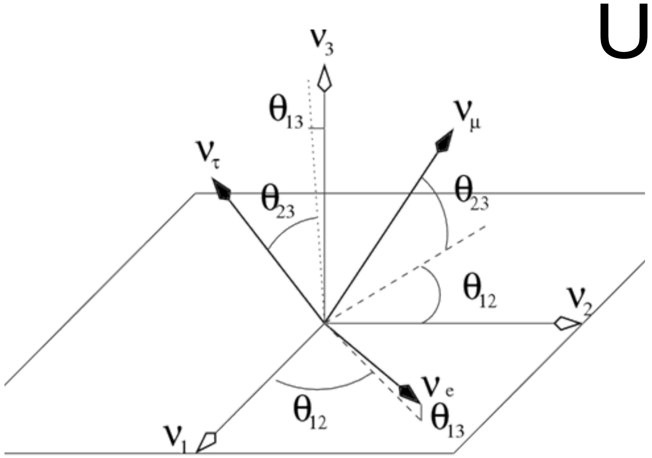
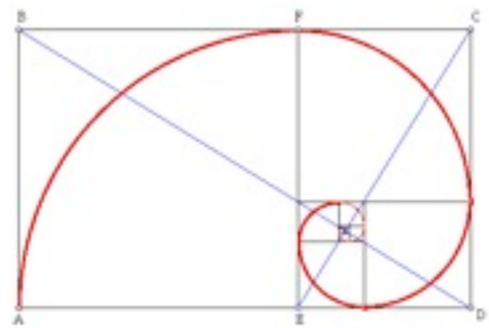
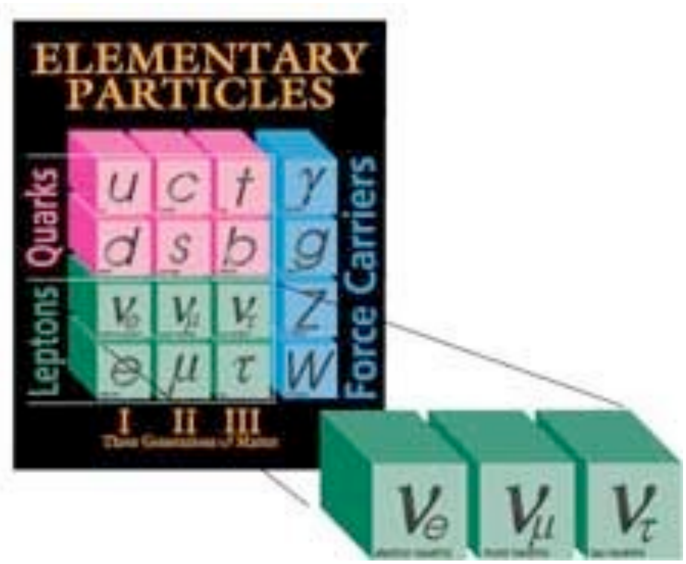
# Neutrinos From Particle Physics, Theory Overview

Lisa L. Everett
U. Wisconsin, Madison



# 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!

## "Standard Picture" (my terminology)

data (except LSND) consistent with $3\nu$ mixing picture

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

## Challenges to the Standard Picture: LSND anomaly revisited

Recent results (updates announced June 2010) from MINOS, MiniBooNE:

differences b/w $\nu, \overline{\nu}$ modes! If robust, potentially profound implications...

fits: Schwetz, Tortola, Valle '08

# The Standard Picture: Neutrino Masses

Homestake, Kam, SuperK, KamLAND, SNO, SuperK, MINOS, MiniBooNE,...

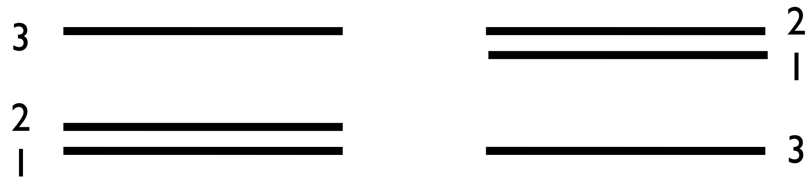
Assume: 3 neutrino mixing (no LSND)

Solar: $\Delta m^2_\odot = |\Delta m^2_{12}| = 7.65^{+0.23}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$

(best fit $\pm 1\sigma$)

Atmospheric: $\Delta m^2_{31} = \pm 2.4^{+0.12}_{-0.11} \times 10^{-3}\,\mathrm{eV}^2$

Normal Hierarchy | Inverted Hierarchy




Cosmology (WMAP): $\sum_i m_i < 0.7\,\mathrm{eV}$

fit: Schwetz, Tortola, Valle '08

# The Standard Picture: Lepton Mixing

Homestake, Kam, SuperK, KamLAND, SNO, SuperK, Palo Verde, CHOOZ, MINOS...

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

Maki, Nakagawa, Sakata
Pontecorvo

$$|\mathcal{U}_{\rm MNSP}| \simeq \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot & \epsilon \\ -\cos\theta_\oplus \sin\theta_\odot & \cos\theta_\oplus \cos\theta_\odot & \sin\theta_\oplus \\ \sin\theta_\oplus \sin\theta_\odot & -\sin\theta_\oplus \cos\theta_\odot & \cos\theta_\oplus \end{pmatrix}$$

(best fit $\pm 1\sigma$)

Solar: $\theta_\odot = \theta_{12} = 33.4^\circ \pm 1.4^\circ$

Atmospheric: $\theta_\oplus = \theta_{23} = 45.0^\circ\,{}^{+4.0}_{-3.4}$

Reactor: $\epsilon = \sin\theta_{13}, \quad \theta_{13} = 5.7^\circ\,{}^{+3.5}_{-5.7}$

2 large

1 small

(~$2\sigma$ claim from other fits for nonzero $\theta_{13}$ near upper bound) Fogli et al., '09

No constraints on CP violation

# For Comparison: Quark Mixing

Cabibbo; Kobayashi, Maskawa

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

**Mixing Angles:** $\theta_{12}^{\text{CKM}} = 13.0^\circ \pm 0.1^\circ$ ⟷ Cabibbo angle $\theta_c$

$$\theta_{23}^{\text{CKM}} = 2.4^\circ \pm 0.1^\circ$$

$$\theta_{13}^{\text{CKM}} = 0.2^\circ \pm 0.1^\circ$$

3 small angles

**CP violation:** $J \equiv \text{Im}(\mathcal{U}_{\alpha i}\mathcal{U}_{\beta j}\mathcal{U}_{\beta i}^*\mathcal{U}_{\alpha j}^*)$

Jarlskog
Dunietz, Greenberg, Wu

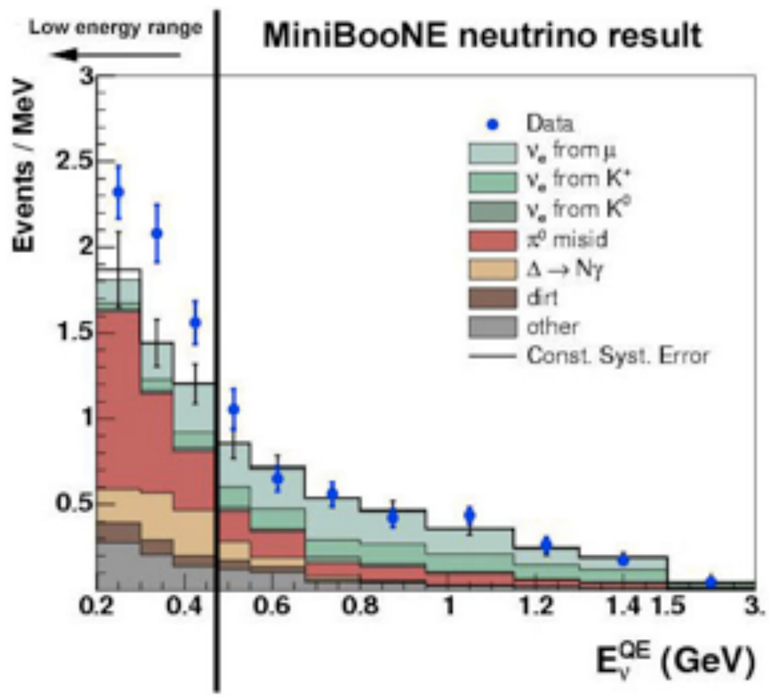
$$J_{\text{CP}}^{(\text{CKM})} \simeq \sin 2\theta_{12}^{\text{CKM}} \sin 2\theta_{23}^{\text{CKM}} \sin 2\theta_{13}^{\text{CKM}} \sin \delta_{\text{CKM}}$$

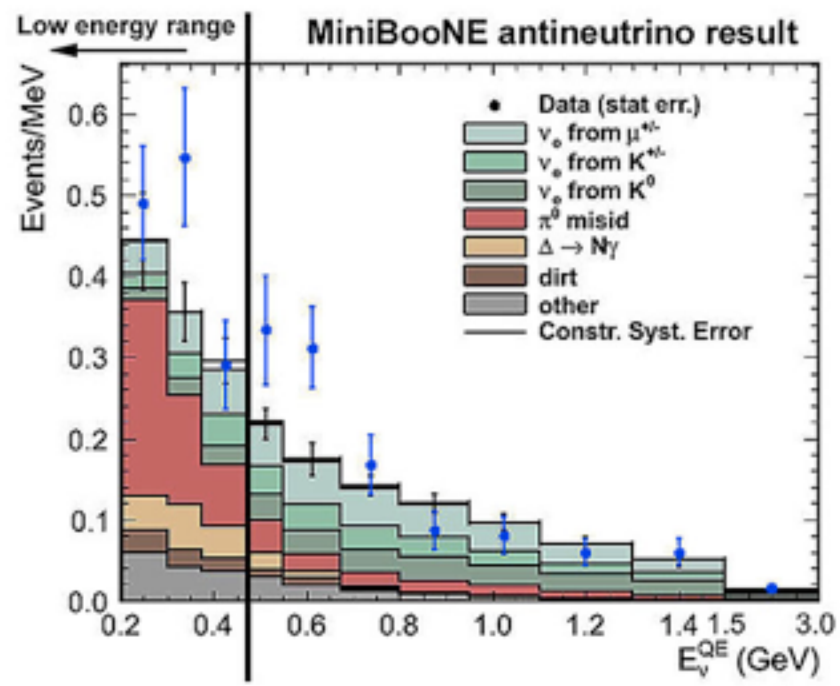
$$J \sim 10^{-5} \qquad \delta_{\text{CKM}} = 60^\circ \pm 14^\circ$$

O(1) CP-violating phase

# Challenge to the Standard Picture: MiniBooNE

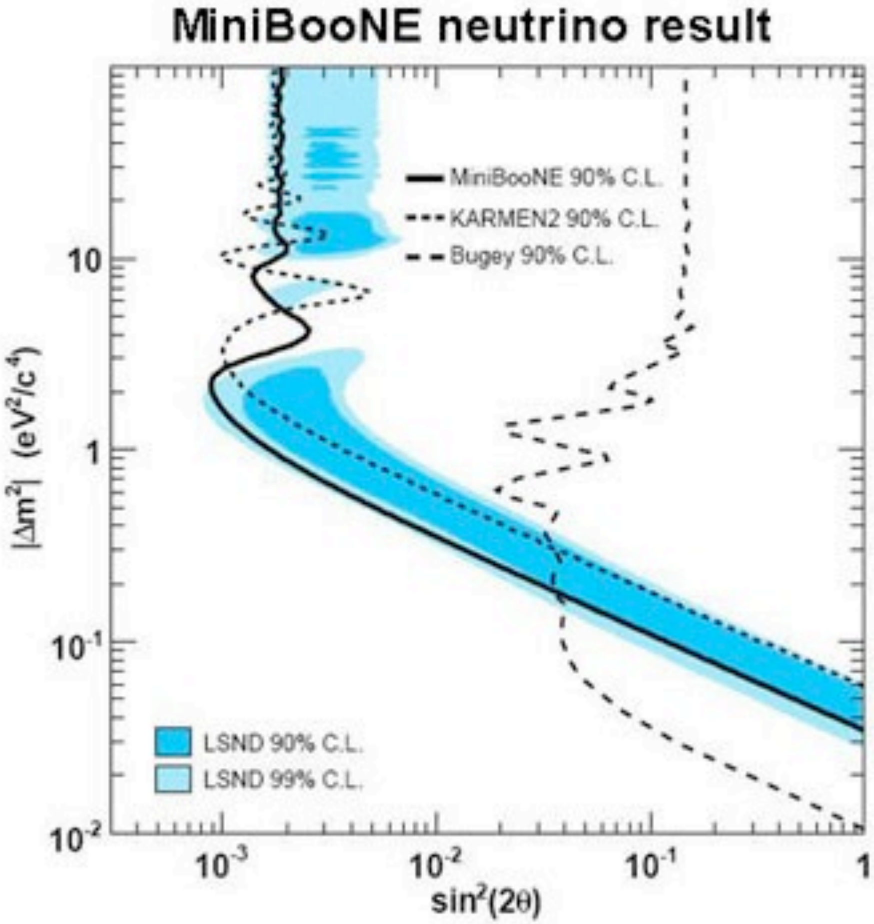
Discrepancy between neutrino and antineutrino modes!



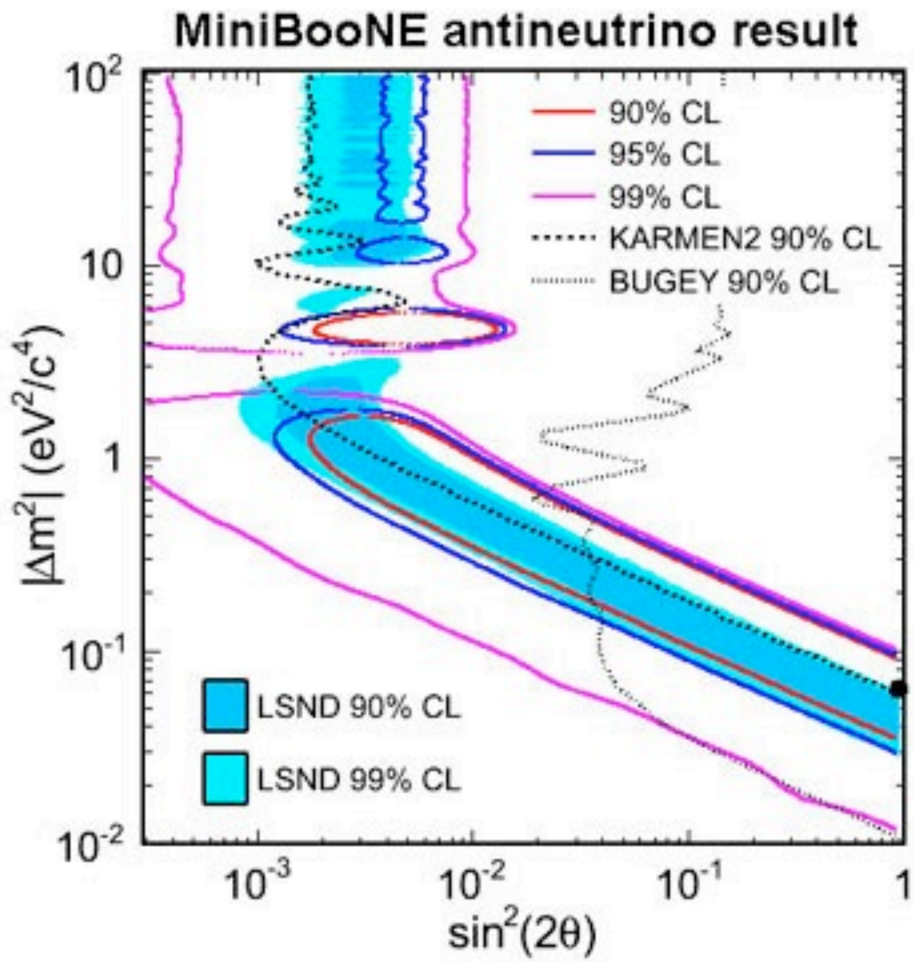




Updated results announced at Neutrino 2010 (talk by Van de Water)

# Possible consistency with LSND?

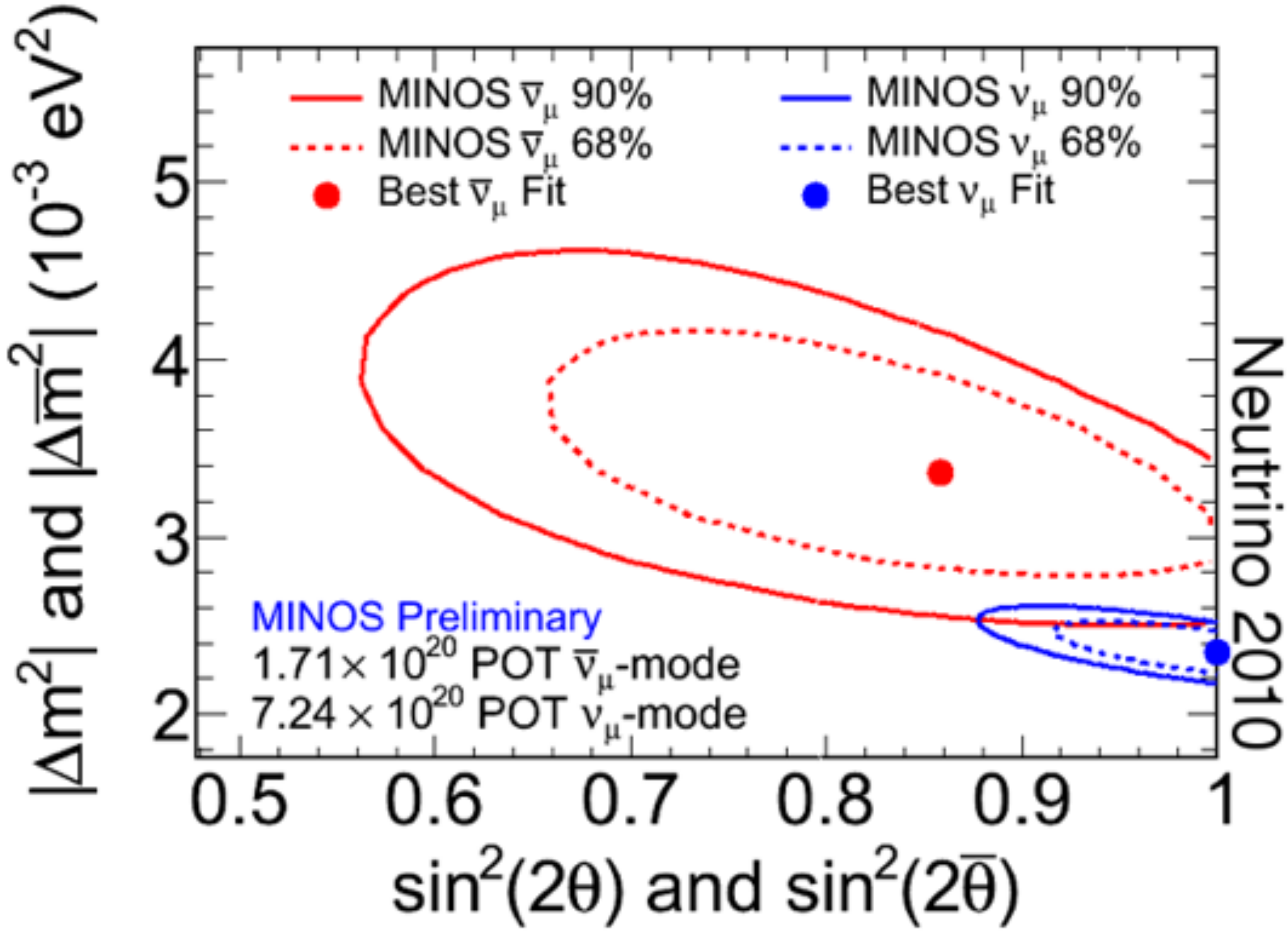



(exclusion region)




(MiniBooNE allowed regions)

# Challenge to the Standard Picture: MINOS

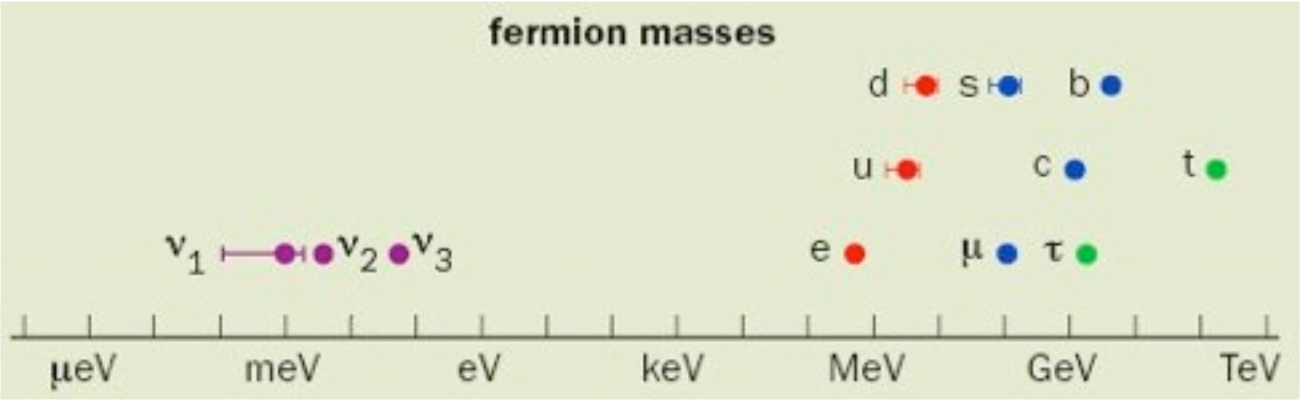



Recent results announced at Neutrino 2010 (see talk by Vahle)

# Theoretical Implications: Standard Picture

Shifts in the paradigm for addressing SM flavor puzzle:

- Suppression of neutrino mass scale




- Mixing Angles    quarks small, leptons 2 large, 1 small

Strikingly different flavor patterns for quarks and leptons!

implications for quark-lepton unification?

# Mass Generation

## Quarks, Charged Leptons

"natural" mass scale tied to electroweak scale

Dirac mass terms, parametrized by Yukawa couplings

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

t quark: O(1) Yukawa coupling

rest: suppression (flavor symmetry)

## Neutrinos

beyond physics of Yukawa couplings!

Options: Dirac

or Majorana

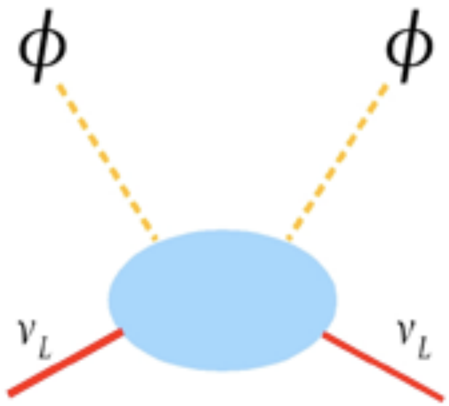
# Majorana first: (naturalness)

SM at NR level: Weinberg dim 5 operator

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

(if $\lambda \sim O(1)$ $\Lambda \gg m \sim O(100\,\mathrm{GeV})$ ... but a priori unknown)

## Underlying mechanism: examples




Type I seesaw $\nu_R$ (fermion singlet)

Type II seesaw $\Delta$ (scalar triplet)

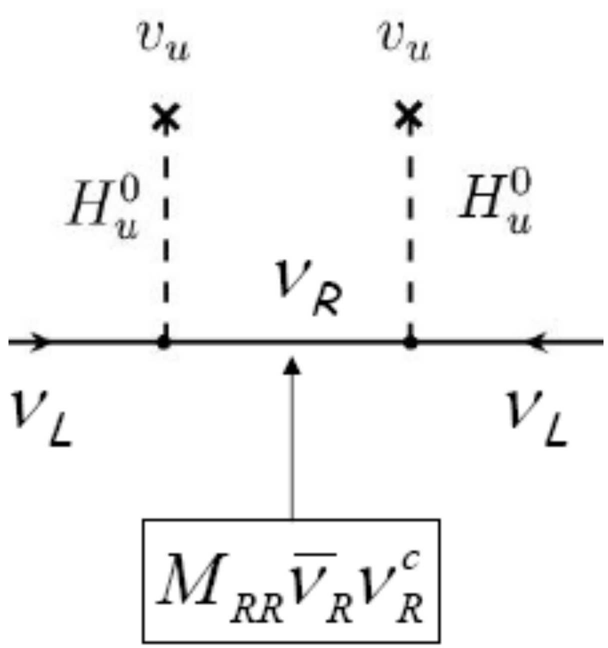
Type III seesaw $\Sigma$ (fermion triplet)

+ variations

## Prototype: Type I seesaw

Minkowski; Yanagida;
Gell-Mann, Ramond, Slansky;...

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

disadvantage: testability (even at low scales)

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

see e.g. Fileviez Perez, Han et al., '08

# Many other ideas for Majorana neutrino masses...

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

# What about Dirac masses?

more difficult in general,
but suppression mechanisms exist.

e.g. extra dimensions, extra gauge symms (non-singlet $\nu_R$), SUSY breaking,...

# General themes:

Trade-off b/w naturalness and testability. Much richer than quark and charged lepton sectors. Everyone has a favorite scenario.

# 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

## First, the quarks:

hierarchical masses, small mixings: continuous family symmetries

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

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

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

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

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

## Now for the leptons:

$$\mathcal{U}_{\rm MNSP} = \mathcal{U}_e \mathcal{U}_\nu^\dagger$$

First comment: observed lepton mixing angle pattern is "non-generic" (for 3-family mixing)

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

Also suggests new focus: discrete (non-Abelian) family symmetries

good for lepton sector, not ideal for quarks...

Proceed by noting that in some limit of flavor symmetry:

$$\mathcal{U}_{\mathrm{MNSP}} = \mathcal{U}_e \mathcal{U}_\nu^\dagger \sim \mathcal{W} + \mathcal{O}(\lambda')$$

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

Main theme: many theoretical starting points!

Perturbations: useful (and well-motivated in many scenarios) to take

$$\lambda' = \lambda \equiv \sin\theta_c$$

ideas of "Cabibbo haze" and quark-lepton complementarity (more shortly)

within the framework of quark-lepton unification, Cabibbo-sized effects will "leak" into lepton sector

So in the lepton sector, classify models by $\mathcal{W}(\theta_{12}^0, \theta_{13}^0, \theta_{23}^0)$

Choose: $\theta_{23}^0 = 45^\circ \quad \theta_{13}^0 = 0^\circ$ (reasonable)

Choices for "bare" solar angle $\theta_{12}^0$ (historical ordering)

"bimaximal" mixing:

requires large perturbations
$\theta_{12} = \theta_{12}^0 + \mathcal{O}(\lambda)$

"tri-bimaximal" mixing:

"hexagonal" mixing

"golden ratio" mixing

need moderate perturbations
$\theta_{12} = \theta_{12}^0 + \mathcal{O}(\lambda^2)$

All can be obtained from discrete non-Abelian family symmetries

Recent overview: Albright, Dueck, Rodejohann 1004.2798 (ADR)

# Bimaximal Mixing

"bare" solar angle $\theta^0_{12} = 45^\circ$ $\tan\theta^0_{12} = 1$

$$\mathcal{U}^{(\mathrm{BM})}_{\mathrm{MNSP}} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\theta_{12} = \theta^0_{12} + \mathcal{O}(\lambda) \sim \frac{\pi}{4} - \theta_c$$

"quark-lepton complementarity"

Raidal; Minakata, Smirnov; Frampton, Mohapatra; Xing; Ferrandis, Pakvasa; King; Ramond; Rodejohann, many, many others...

# Tri-bimaximal (HPS) Mixing

"bare" solar angle $\tan\theta^0_{12} = \frac{1}{\sqrt{2}}$ $\theta^0_{12} = 35.26^\circ$

Harrison, Perkins, Scott '02

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

(~Clebsch-Gordan coeffs!)

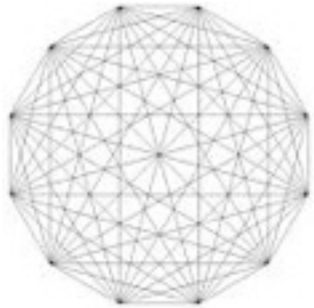
Meshkov; Zee,...

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

$\mathcal{A}_4,\ \mathcal{S}_4,\ \mathcal{T}',\Delta(3n^2),\ldots$ (100s of papers. Some key players: Ma, Altarelli and Feruglio, King,...)

Most popular scenario by far!!

# Hexagonal Mixing



"bare" solar angle $\tan\theta_{12}^{0} = \frac{1}{\sqrt{3}}$ $\theta_{12}^{0} = \pi/6$

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

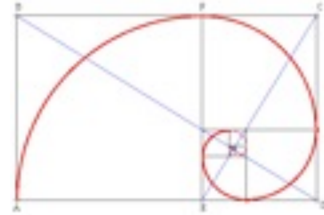
Implementation: dihedral flavor symmetry $\mathcal{D}_{12}$ $\mathcal{D}_{6}$

(bare solar angle as exterior angle of dodecagon)

ADR '10

# Golden Ratio Mixing

$\phi = (1+\sqrt{5})/2$



**Case 1.** $\tan\theta_{12} = \frac{1}{\phi} \qquad \theta_{12} = 31.72^\circ$

$$\mathcal{U}_{\rm MNSP}^{\rm (GR1)} = \begin{pmatrix} \sqrt{\frac{\phi}{\sqrt{5}}} & -\sqrt{\frac{1}{\sqrt{5}\phi}} & 0 \\ \frac{1}{\sqrt{2}}\sqrt{\frac{1}{\sqrt{5}\phi}} & \frac{1}{\sqrt{2}}\sqrt{\frac{\phi}{\sqrt{5}}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}\sqrt{\frac{1}{\sqrt{5}\phi}} & \frac{1}{\sqrt{2}}\sqrt{\frac{\phi}{\sqrt{5}}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Ramond '04 (footnote)

Kajiyama, Raidal, Strumia '07

L.E., Stuart '08, 1007.xxxx

$\mathcal{I}\ (\mathcal{A}_5)$ Example.

**Case 2.** $\cos\theta_{12} = \frac{\phi}{2} \qquad \theta_{12} = 36^\circ$

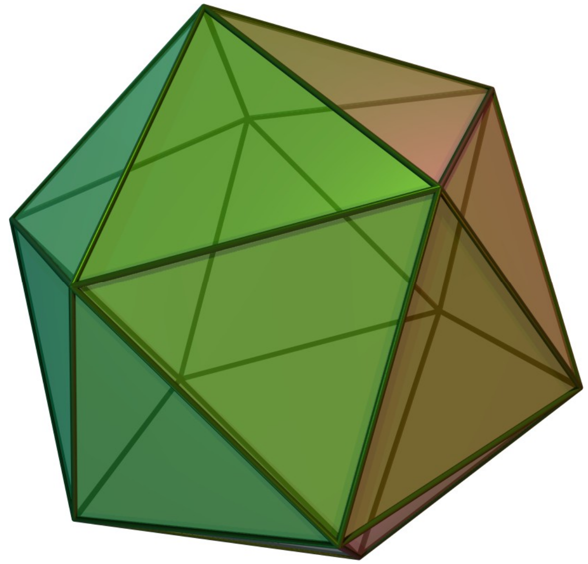
$$\mathcal{U}_{\rm MNSP}^{\rm (GR2)} = \begin{pmatrix} \frac{\phi}{2} & -\frac{1}{2}\sqrt{\frac{\sqrt{5}}{\phi}} & 0 \\ \frac{1}{2}\sqrt{\frac{5}{2\phi}} & \frac{\phi}{2\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2}\sqrt{\frac{5}{2\phi}} & \frac{\phi}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

Adulpravitchai, Blum, Rodejohann '09

$\mathcal{D}_{10}$

# Example: The (Rotational) Icosahedral Group, *I* ~ A5

## Properties of the icosahedron:



20 faces (equilateral triangles)

30 edges (3 sides/triangle, 2 triangles/edge)

12 vertices (3 vertices/triangle, 5 vertices/edge)

## Group elements:

Rotations which take vertices to vertices, i.e., by $0,\ \frac{2\pi}{5},\ \frac{4\pi}{5},\ \frac{2\pi}{3},\ \pi$

Rotation by each angle forms a conjugacy class:

$$e,\ 12C_5,\ 12C_5^2,\ 20C_3,\ 15C_2$$

(Schoenflies: $C_n^k = \frac{2\pi k}{n}$ rotation)

order=number of elements: $1 + 12 + 12 + 15 + 20 = 60$

# The (Rotational) Icosahedral Group, *I* ~ A5

Theorem: group order = sum of squares of irred. reps

$$1 + 12 + 12 + 15 + 20 = 60 = 1^2 + 3^2 + 3^2 + 4^2 + 5^2.$$

(two triplets!)

Conjugacy classes: characterized by trace (character)

## Character Table

| $\mathcal{I}$ | $\mathbf{1}$ | $\mathbf{3}$ | $\mathbf{3}'$ | $\mathbf{4}$ | $\mathbf{5}$ |
|---|---|---|---|---|---|
| $e$ | 1 | 3 | 3 | 4 | 5 |
| $12C_5$ | 1 | $\phi$ | $1-\phi$ | -1 | 0 |
| $12C_5^2$ | 1 | $1-\phi$ | $\phi$ | -1 | 0 |
| $20C_3$ | 1 | 0 | 0 | 1 | -1 |
| $15C_2$ | 1 | -1 | -1 | 0 | 1 |

# The (Rotational) Icosahedral Group, *I* ~ A5

From character table, deduce tensor product decomposition:

$$3 \otimes 3 = 1 \oplus 3 \oplus 5$$
$$3' \otimes 3' = 1 \oplus 3' \oplus 5$$
$$3 \otimes 3' = 4 \oplus 5$$
$$3 \otimes 4 = 3' \oplus 4 \oplus 5$$
$$3' \otimes 4 = 3 \oplus 4 \oplus 5$$
$$3 \otimes 5 = 3 \oplus 3' \oplus 4 \oplus 5$$
$$3' \otimes 5 = 3 \oplus 3' \oplus 4 \oplus 5$$
$$4 \otimes 4 = 1 \oplus 3 \oplus 3' \oplus 4 \oplus 5$$
$$4 \otimes 5 = 3 \oplus 3' \oplus 4 \oplus 5 \oplus 5$$
$$5 \otimes 5 = 1 \oplus 3 \oplus 3' \oplus 4 \oplus 4 \oplus 5 \oplus 5$$

Not enough for flavor model building. Need explicit representations!

*I* not a crystallographic point group, so there was work to be done...

# Lepton Flavor Model Building with A5

Assume: effective LL coupling. (Future: seesaw implementation)

Mass terms: $$-\mathcal{L}_m = \frac{a_{ij}}{M} L_i H L_j H + Y^{(e)}_{ij} L_i \bar{e}_j H$$

Charge assignments: natural to have $L, \ \bar{e}$ triplets under *I*

our choice: $$L \to 3, \qquad \bar{e} \to 3'$$

$$LL : 3 \otimes 3 = 1 \oplus \not{3} \oplus 5, \qquad L\bar{e} : 3 \otimes 3' = 4 \oplus 5$$

(symmetry)

leading order: no charged lepton masses, degenerate neutrinos
fixed at higher order from flavor symmetry breaking

# Lepton Flavor Model Building with A5 (II)

## Toy example (bottom-up approach):

$$-\mathcal{L}_{mass} = \frac{\alpha_{ijk}}{M^2} L_i H L_j H \xi_k + \frac{\beta_{ijk}}{M} L_i \bar{e}_j H \psi_k + \frac{\gamma_{ijl}}{M} L_i \bar{e}_j H \chi_l$$

$$(\alpha, \beta, \gamma \sim O(1))$$

with "minimal" choice of "flavon" fields:

$$\xi \rightarrow 5 \qquad\qquad \psi \rightarrow 5, \;\; \chi \rightarrow 4$$

$$LL \qquad\qquad\qquad L\bar{e}$$

With assumed flavon vevs, can obtain realistic neutrino masses and prediction for neutrinoless double beta decay

Challenge: dynamics of flavon sector, how to incorporate quarks

# Beyond the "Standard Picture"

Question: theoretical implications of distinct oscillation patterns for $\nu$, $\overline{\nu}$?

## Ideas proposed in previous contexts:

CPT violation (CPTV), Lorentz violation (LV) — Barger et al. '03, Kostelecky et al '06,...

effective CPTV (weakly coupled B-L gauge boson) — Nelson, Walsh '07

effective LV (extra dimensions) — Pas, Pakvasa, Weiler '05

decaying sterile neutrino — Palomares-Ruiz, Pascoli, Schwetz '05

Significant challenge to incorporate these signals w/rest of data

Challenges in fits: tension b/w appearance/disappearance, $\nu$, $\overline{\nu}$, . . .

Stay tuned!

# Conclusions

Neutrino data has taken beyond SM physics theory on a wild ride, with no signs of stopping (if anything, may be getting wilder!)

## Bottom Line:

A number of ways to generate masses/mixings, all with advantages/disadvantages. "Favorites" are not the only options.

Anticipated improvements in the data (especially for the reactor angle) will greatly aid these efforts.

The LSND anomaly may throw a wrench in the whole business, which would be tremendously exciting!

Thank you!