NEUTRINOS:

KEY TO NEW PHYSICS

(30 years beyond the Standard Model)

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SEESAW 1979-2004
Fujihara Seminar, February 2004

STANDARD MODEL LEGACIES

- **Agreement with Data**
- Weakly Coupled Gauge Theories
- Gauge Anomaly Cancellations
- Three Families of Fermions
- Three Massless Neutrinos
- Spontaneously Broken Symmetries
- Fundamental Scalar Particle

NEW & OLD PUZZLES

- CP Violation in Strong Interactions
- Bizarre Mass and Mixing Patterns
- Plethora of Parameters
- Baryon Asymmetry and Cosmology
- Gravity and the Cosmological Constant

GRAND UNIFICATION

- Gauge Structures *Unified*
- Quarks & Leptons *Related*
- Anomaly Cancellations *Explained*
- Gauge Couplings *Nearly Unified*
- Baryon and Lepton Numbers *Broken*

GRAND UNIFIED LEGACIES

- Quark & Lepton Masses *Linked*
- Large Energy Scale:

  Hierarchy Problem
- Monopole Surplus:

  Inflationary Cosmology
- Proton Decay
- Baryon Asymmetry
- Tiny Neutrino Masses
- Flavor Riddles *Unresolved*
- Gravity *Ignored*

SUPERSTRINGS

- Gravity & Gauge Forces *Unified*
- Supersymmetry *Required*
- Extra Dimensions *Required*

AT WHAT ENERGY?

Favorite Scenario

As the Universe Cools...

Extra Dimensions Collapse First

Supersymmetry Hangs On

... for a while

SUPERSYMMETRY

- Bosons and Fermions *Linked*
- Gauge Couplings *Truly Unified*
- Fundamental Scalars *Required*
- Gauge Hierarchy *Managed*
- Top Quark Mass *Predicted*
- ElectroWeak Symmetry *Broken*

SUPERSYMMETRY'S LEGACIES

- Supersymmetry Breaking Mechanism
- Acute Flavor Problem
- Origin of the μ-term

TINY NEUTRINO MASSES

ONLY EXPERIMENTAL EVIDENCE

FOR PHYSICS

BEYOND THE STANDARD MODEL

MASS MEASUREMENTS

$$\Delta m^2_{\odot} \; = \; | \; m^2_{\nu_1} - m^2_{\nu_2} \; | \; \sim \; 7. \times 10^{-5} \; \text{eV}^2$$

Homestake, Kam, SuperK, SNO, KamLand

$$\Delta m^2_{\oplus} \; = \; | \; m^2_{\nu_2} - m^2_{\nu_3} \; | \; \sim \; 3. \times 10^{-3} \; \text{eV}^2$$

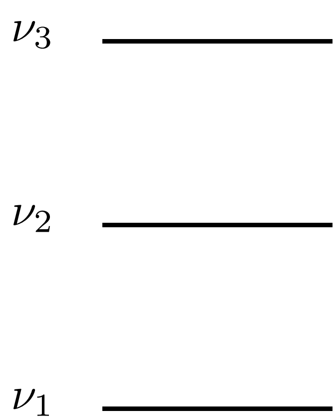
SuperK

$$\sum_i m_{\nu_i} \; < \; .71 \; \text{eV}$$

Wmap

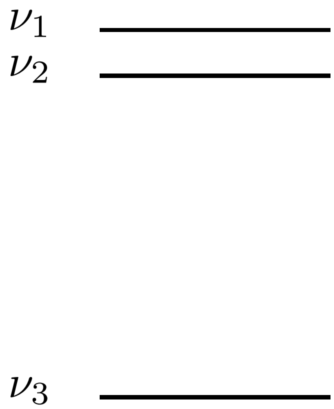
MASS PATTERNS

HIERARCHICAL



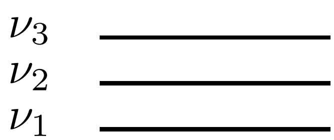
$$|m_{\nu_1}| < |m_{\nu_2}| \ll |m_{\nu_3}|$$

INVERTED



$$|m_{\nu_1}| \simeq |m_{\nu_2}| \gg |m_{\nu_3}|$$

HYPERFINE



$$|m_{\nu_1}| \simeq |m_{\nu_2}| \simeq |m_{\nu_3}|$$

NOVEL MIXING PATTERN

ONE SMALL and TWO LARGE ANGLES

$$\sin^2 2\theta_\oplus \;>\; 0.85$$

SuperK

$$0.30 \;<\; \tan^2\theta_\odot \;<\; 0.65$$

Homestake, Kam, SuperK, SNO, KamLand

$$|\,\epsilon\,|^2 \;<\; 0.005$$

Chooz

$$\mathcal{U}_{MNS} \;=\; \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot & \epsilon \\ -\cos\theta_\oplus\;\sin\theta_\odot & \cos\theta_\oplus\;\cos\theta_\odot & \sin\theta_\oplus \\ \sin\theta_\oplus\;\sin\theta_\odot & -\sin\theta_\oplus\;\cos\theta_\odot & \cos\theta_\oplus \end{pmatrix}$$

Experimental Questions

- Majorana or not Majorana?
- Mass Scale?
- Chooz Angle?
- CP Violation
- Sign of Δm^2?

Theoretical Questions

Right-Handed Neutrinos

- *Brane or Bulk?*
- *How Many?*
- *How Heavy?*
- *How Hierarchical?*
- *Decays: Leptogenesis?*

First Glimpse of Physics

Beyond the Standard Model!

Standard Model Analysis

$\Delta I_{\rm W} = \frac{1}{2}$ *Quark Yukawa Matrices*

$$\mathcal{M}^{(2/3)} = \mathcal{U}_{2/3} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \mathcal{V}^{\dagger}_{2/3}$$

$$\mathcal{M}^{(-1/3)} = \mathcal{U}_{-1/3} \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} \mathcal{V}^{\dagger}_{-1/3}$$

$$\mathcal{U}_{CKM} \equiv \mathcal{U}^{\dagger}_{2/3} \mathcal{U}_{-1/3}$$

$$\mathcal{U}_{CKM} \approx \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(\lambda)$$

Quark Mixings Similar for Charges $2/3$ *and* $-1/3$

(*up to small Cabibbo mixings*)

$\Delta I_{\rm W} = \frac{1}{2}$ *Lepton Yukawa Matrices*

$$\mathcal{M}^{(-1)} = \mathcal{U}_{-1} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \mathcal{V}_{-1}^\dagger$$

one right-handed neutrino per family:

$$\mathcal{M}^{(0)}_{Dirac} = \mathcal{U}_0 \, \mathcal{D}_0 \, \mathcal{V}_0^\dagger = \mathcal{U}_0 \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \mathcal{V}_0^\dagger$$

$$\mathcal{U}_{MNS} \equiv \mathcal{U}_{-1}^\dagger \, \mathcal{U}_0$$

Quark-like mixing patterns?

RIGHT-HANDED NEUTRINO MASSES

$$\mathcal{M}^{(0)}_{Majorana} \sim \Delta I_{\mathrm{W}} = 0$$

Measure the Standard Model Cut-off

UNPROTECTED

(except by lepton number)

Gell-Mann,R., Slansky; Yanagida

$$\frac{\Delta I_{\mathrm{W}} = \frac{1}{2}}{\Delta I_{\mathrm{W}} = 0}$$ **Suppression**

Tiny Neutrino Masses:

Large Scale in the Standard Model

Grand Unification & Supersymmetry?

$$\mathcal{M}^{(0)}_{Seesaw} = \mathcal{M}^{(0)}_{Dirac} \frac{1}{\mathcal{M}^{(0)}_{Majorana}} \mathcal{M}^{(0)\,T}_{Dirac}$$

$$\mathcal{M}^{(0)}_{Seesaw} = \mathcal{U}_0 \left(\mathcal{D}_0 \, \mathcal{V}_0^{\dagger} \frac{1}{\mathcal{M}^{(0)}_{Majorana}} \mathcal{V}_0^{*} \, \mathcal{D}_0 \right) \mathcal{U}_0^T$$

$$\equiv \mathcal{U}_0 \, \mathcal{C} \, \mathcal{U}_0^T$$

$\mathcal{C}$: *Central Matrix*

$$\mathcal{C} \;=\; \mathcal{F}\,\mathcal{D}_\nu\,\mathcal{F}^{\mathcal{T}}$$

$$\mathcal{F}\,\mathcal{F}^{\dagger} \;=\; 1$$

Physical ("1", "2", "3") Neutrino Masses

$$\mathcal{D}_\nu \;=\; \begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_3} \end{pmatrix}$$

Seesaw Lepton Mixing Matrix:

$$\mathcal{U}_{MNS} \;=\; \mathcal{U}_{-1}^{\dagger}\,\mathcal{U}_0\,\mathcal{F}$$

$\mathcal{F}$: *Seesaw* $\Delta I_{\rm W} = 0$ *Addition*

Where are the large angles?

Both in $\mathcal{F}$?	*not generic*
Only one in $\mathcal{F}$?	*generic*

BASICS OF GRAND UNIFICATION

Quark and Lepton $\Delta I_{\rm W} = \frac{1}{2}$ Yukawa Relations:

$$SU(5) \; : \qquad \mathcal{M}^{(-1/3)} \sim \mathcal{M}^{(-1)\,T}$$

$$SO(10) : \qquad \mathcal{M}^{(2/3)} \sim \mathcal{M}^{(0)}_{Dirac}$$

$$\mathcal{U}_{-1/3} \sim \mathcal{V}^{*}_{-1}$$

$$\mathcal{U}_{2/3} \sim \mathcal{U}_{0}$$

$$
\begin{aligned}
\mathcal{U}_{MNS} &= \mathcal{U}^{\dagger}_{-1}\,\mathcal{U}_0\,\mathcal{F} \\
&\sim \mathcal{U}^{\dagger}_{-1}\,\mathcal{U}_{-1/3}\,\mathcal{U}^{\dagger}_{CKM}\,\mathcal{F} \\
&\sim \mathcal{V}^{T}_{-1/3}\,\mathcal{U}_{-1/3}\,\mathcal{U}^{\dagger}_{CKM}\,\mathcal{F}
\end{aligned}
$$

SYMMETRIC $\mathcal{M}_{-1/3}$?

$$\mathcal{U}_{-1/3} \; = \; \mathcal{V}^*_{-1/3}$$

$$\mathcal{U}_{MNS} \; = \; \mathcal{U}^\dagger_{CKM} \, \mathcal{F}$$

$\mathcal{F}$ **contains two large angles!**

NOT GENERIC

Non Abelian Structure for $\mathcal{F}$?

NON-SYMMETRIC $\mathcal{M}_{-1/3}$?

$$\mathcal{U}_{CKM} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\frac{m_s}{m_b} \sim \lambda^2 \qquad \frac{m_d}{m_b} \sim \lambda^4$$

Reconstruct Charge $-\frac{1}{3}$ *matrix:*

$$\mathcal{M}^{(-1/3)} = \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^? & \lambda^2 & \lambda^2 \\ \lambda^? & \lambda^? & 1 \end{pmatrix}$$

$$\mathcal{M}^{(-1/3)} = \begin{pmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^1 & \lambda^0 & 1 \end{pmatrix}$$

$\leftarrow$ $U(1)$ **Charge** $\rightarrow$

Froggatt-Nielsen

$$\mathcal{M}^{(-1/3)} \approx \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & a & b \end{pmatrix} + \mathcal{O}(\lambda)$$

NOT SYMMETRIC!

$$\mathcal{U}_{MNS} \;=\; \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_\oplus & \sin\theta_\oplus \\ 0 & -\sin\theta_\oplus & \cos\theta_\oplus \end{pmatrix} \mathcal{F}$$

$$\tan\theta_\oplus \;=\; \frac{a}{b} \;\sim\; \mathcal{O}(1)$$

$\mathcal{F}$ may contain only one large angle!

GENERIC

CHOOZ Angle as Cabibbo Mixing Effect?

Symmetric Charge $-\frac{1}{3}$ Yukawa Matrix

$$\mathcal{U}_{MNS} = \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot & \lambda^\gamma \\ -\cos\theta_\oplus \, \sin\theta_\odot & \cos\theta_\oplus \, \cos\theta_\odot & \sin\theta_\oplus \\ \sin\theta_\oplus \, \sin\theta_\odot & -\sin\theta_\oplus \, \cos\theta_\odot & \cos\theta_\oplus \end{pmatrix}$$

$$\theta_{13} \sim \begin{cases} \lambda^\gamma \\ \lambda \sin\theta \sim 0.7\,\lambda \end{cases}$$

Asymmetric Charge $-\frac{1}{3}$ Yukawa Matrix

$$\mathcal{U}_{MNS} = \begin{pmatrix} 1 & \lambda^\alpha & \lambda^\beta \\ \lambda^\alpha & \cos\theta_\oplus & \sin\theta_\oplus \\ \lambda^\beta & -\sin\theta_\oplus & \cos\theta_\oplus \end{pmatrix} \begin{pmatrix} \cos\theta_\odot & \sin\theta_\odot & \lambda^\gamma \\ -\sin\theta_\odot & \cos\theta_\odot & \lambda^\delta \\ \lambda^\gamma & \lambda^\delta & 1 \end{pmatrix}$$

$$\theta_{13} \sim \begin{cases} \lambda^\gamma \\ \lambda^{\alpha+\delta} \\ \lambda^\beta \end{cases}$$

Large angles in $\mathcal{F}$?

Dirac Masses in $\mathcal{D}_0$ are Hierarchical

$$\mathcal{C} \; \equiv \; \mathcal{D}_0 \, \mathcal{V}_0^\dagger \, \frac{1}{\mathcal{M}^{(0)}_{Majorana}} \, \mathcal{V}_0^* \, \mathcal{D}_0$$

$\mathbf{2 \times 2}$ case

$$\mathcal{D}_0 \; = \; m \begin{pmatrix} a\,\lambda^\alpha & 0 \\ 0 & 1 \end{pmatrix}$$

M_1 , M_2 : eigenvalues of $\mathcal{M}^{(0)}_{Majorana}$

Large mixing angle if:

$$\mathcal{C}_{11} \sim \mathcal{C}_{22} \sim \mathcal{C}_{12}$$

$$\longrightarrow \qquad \frac{M_1}{M_2} \sim \lambda^{2\beta}$$

Correlated Hierarchy
between the
$\Delta I_{\rm W} = 0$ and $\Delta I_{\rm W} = \frac{1}{2}$ Sectors

Grand Unification?

or if:

$$\mathcal{C}_{11}\,,\,\mathcal{C}_{22}\;\ll\;\mathcal{C}_{12}$$

$$\frac{\lambda^{\alpha}\ m^2}{\sqrt{-M_1 M_2}}\begin{pmatrix}0 & a\\ a & 0\end{pmatrix}$$

MAXIMAL MIXING

Right-Handed Neutrinos are Dirac Partners!

$L_1 - L_2$ **conserved!**

A Wolfenstein expansion for the MNS matrix?

Starting Point

$$\mathcal{U}_{MNS} \sim \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\frac{\sin\alpha}{\sqrt{2}} & \frac{\cos\alpha}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{\sin\alpha}{\sqrt{2}} & -\frac{\cos\alpha}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} + \mathcal{O}(\lambda)$$

Cabibbo effect strongest in $1-2$ mixing; smaller in $2-3$ and $1-3$

$$\alpha = \begin{cases} \frac{\pi}{4} \; ? \, , \\ \frac{\pi}{6} \; ? \end{cases}$$

$$\theta_\odot \sim \frac{\pi}{4} - \theta_c \; ?$$

New Era:

Physics of Right-Handed Neutrinos

Keys to the flavor problem (family symmetries?)

Baryon Asymmetry through Leptogenesis

Their mass patterns are probed by the seesaw

Couple to the Standard Model via $SO(10)$