Neutrino Mass and Grand Unification of Flavor

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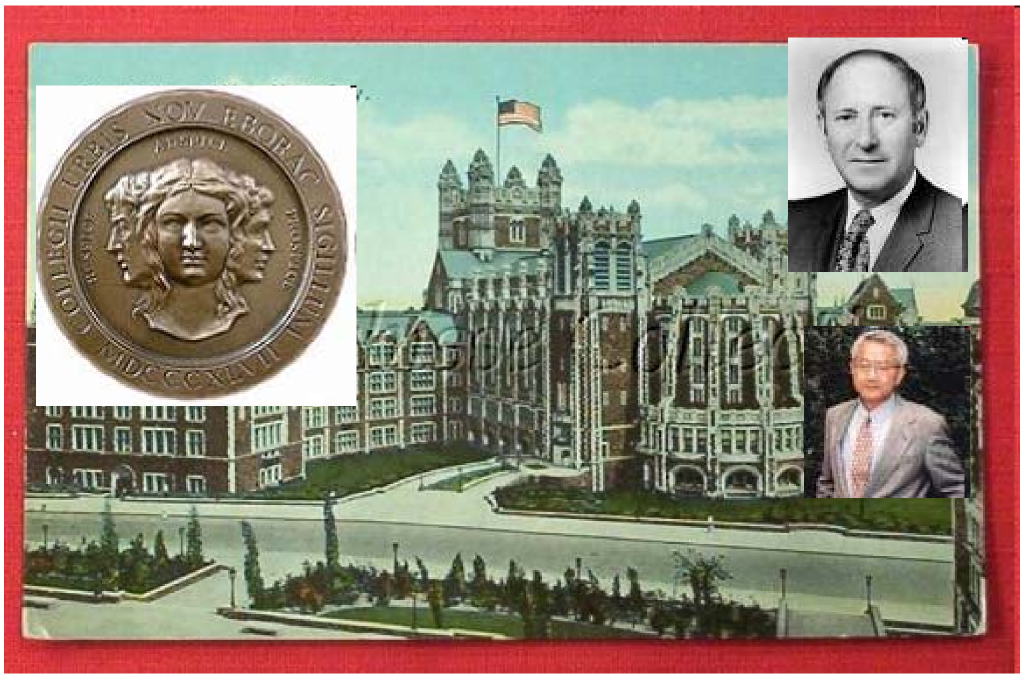
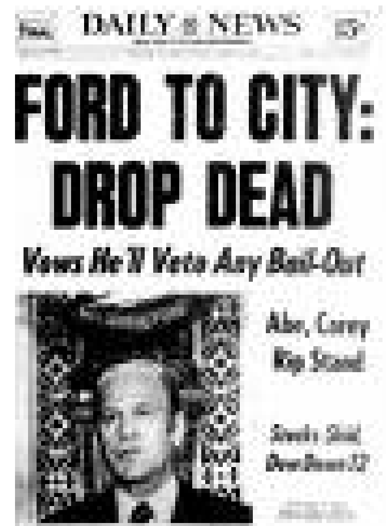
Split.

Brief Remembrances

- CCNY-70's: Turbulent times




DAILY NEWS

FORD TO CITY: DROP DEAD

Vows He'll Veto Any Bail-Out

Abe, Carey Rip Stand

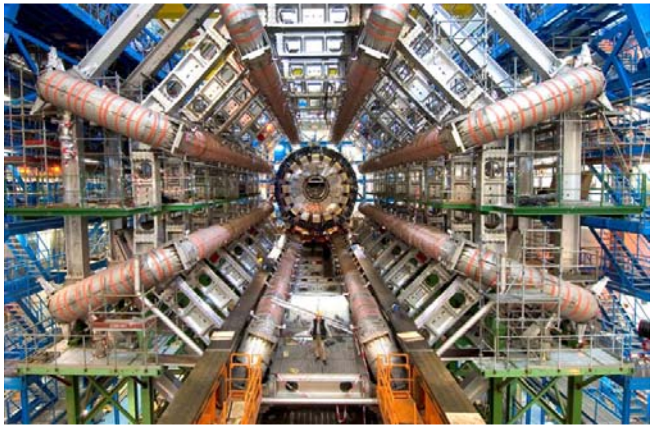
Stocks Skid, Dow Down 12

Look back, Look at, Look ahead

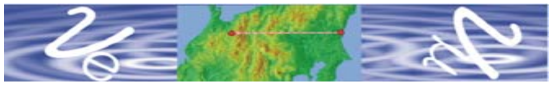
Joy was doing physics…

Two Outstanding Problems in Particle Physics Today

- **Origin of Mass:**
  - --Higgs, SUSY, Extra D
  - --LHC will probe this:



- **Origin of Flavor:** (this talk)
  - -- Many non-collider probes:



Quark, Lepton flavor: Definitions

- **Masses and mixings- two aspects of flavor**

Def. $$L_{mass} = \overline{Q}_L M_{q=u,d} Q_R + \bar{l}_L M_l l_R + \nu^T m_\nu \nu + h.c.$$

- **Mass basis:** $U_L M_{q,l} U_R^+ = M_{q,l}^{diag}$ **and for neutrinos**

$$V_{CKM} = U_u U_d^+ \qquad\qquad U_{PMNS} = U_l U_\nu^+$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad\qquad \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Flavor Puzzle < 1998:

- **Quark masses and mixings (at GUT scale)**
- **Up quarks:** $m_u : m_c : m_t = 0.0008 : 0.2 : 82$
- **Down quarks:** $m_d : m_s : m_b = 0.002 : 0.03 : 1$
- **Mixings:** $V_{us} \approx 0.22; V_{cb} \approx 0.037; V_{ub} \approx 0.003$
- **Leptons:** $m_e : m_\mu : m_\tau = 0.0005 : 0.093 : 1.58$
- **Note:** $m_b \approx m_\tau ; m_\mu \approx 3 m_s$

WHY ?

Attempts to Understand using texture zeros

- **Relation:** $V_{us} \cong \sqrt{\frac{m_d}{m_s}}$ **→d-s mass matrix** $\begin{pmatrix} 0 & a \\ a & b \end{pmatrix}$
- $a << b \rightarrow m_s = b; m_d = -\frac{a^2}{b}; V_{us} = \frac{a}{b} = \sqrt{\frac{m_d}{m_s}}$

  (Weinberg; Wilczek,Zee; Fritzsch)

- **Also GUT scale relations:** $m_b \cong m_\tau$

  and $m_e m_\mu \approx m_d m_s \Rightarrow Det[M^l] = Det[M^d]$
- **Finally at GUT scale,** $m_\mu \approx 3m_s$
- **This implies: M$_d$ =** $\begin{pmatrix} 0 & a \\ a & b \end{pmatrix}$ **whereas M$_l$ =** $\begin{pmatrix} 0 & a \\ a & -3b \end{pmatrix}$

  (Georgi, Jarlskog)

Neutrino mass discovery has added to this puzzle !

- **What we know about neutrino masses ?**
- **Masses:** $\Delta m^2_{sol} \cong 7.67 \times 10^{-5} eV^2$ **;** $\Delta m^2_{Atm} \cong 2.39 \times 10^{-3} eV^2$
- **Mixings:** $\sin^2\theta_{12} \cong .312$; $\sin^2\theta_{23} \cong .466$ $\sin^2\theta_{13} \leq .04$ **;**
- **Overall mass scale:** < .1- 1 eV (roughly)
- **To be determined** (expts in progress or planning)

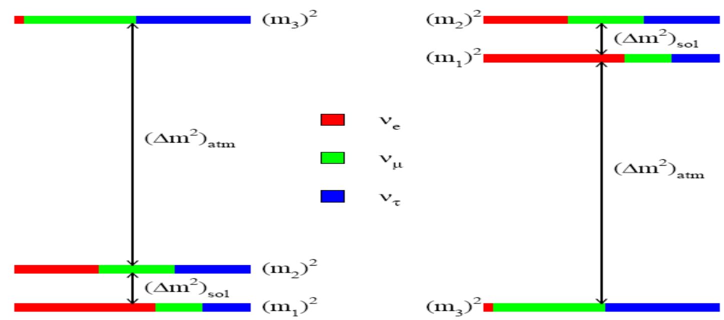
(i) Majorana or Dirac ?

(ii) Mass ordering: normal

or inverted?

(iii) Value of θ_{13}

(iv) Any possible CP violation ?



An Interesting mixing pattern ?

- **Tri-bi-maximal mixing for neutrinos:**

$$U = \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

(Harrison, Perkins, Scott; Xing; He, Zee)

- **Is it exact ? If not how big are corrections ?**

New Challenges posed by neutrino masses

(i) $m_{\nu} << m_{q,l}$ **?**

(ii) Flavor issues :

A. $\frac{m_{sol}}{m_{atm}} \approx \theta_C >> \frac{m_{\mu}}{m_{\tau}}, \frac{m_s}{m_b}$

B. $V^{l}_{23} \approx 0.7 >> V^{CKM}_{23} \approx 0.04$

Quarks and leptons so different- is a unified description of Flavor possible ?

Hints for a strategy for flavor

- Small quark mixings: → $$M_u^0 \propto M_d^0$$
- Mass hierarchy for quarks and charged leptons: suggests: $$M^0{}_{u,d,l} \sim \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_{t,b,\tau} \end{pmatrix}$$
- Large mixings for leptons→ M_l, M_ν unrelated.
- Unifying quark-lepton flavors: GUTs

Basic strategy to unify quark-lepton flavor:

- **Assumption (I):** **Suppose a theory gives:**
- $$M_u = M_0 + \delta_u$$
  $$M_d = rM_0 + \delta_d$$
  $$M_l = rM_0 + \delta_l$$

(Dutta, Mimura, RNM'PRD-09)

$$m_\nu = f v_L$$

$$\delta_{u,d,l} << M_0$$

- **Choose basis so f diagonal.** Then lepton mixings are given by the matrix that diagonalizes**;** M_l .
- **For anarchic M0, quark mixings are small while lepton mixings are large.**

How to see that ?

- **Suppose:** $U_0 M_0 U_0^+ = M^{diag}$
- **Then** $VU_0(rM_0 + \delta_d)' U_0^+ V^+ = M_d^{diag}$
- **Since** $\delta_{u,d,l} << M_0$ **off-diagonal elements of** V **are small.**

$$V_{CKM} = U_0 U_0^+ V^+ = V^+$$

- **On the other hand,** $U_{PMNS} = U_0$ **whose matrix elements are large.**

Rank One mechanism and mass hierarchy

- **Assumption (II):** M_0 **has rank one** i.e.

$$M_0 = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \begin{pmatrix} a & b & c \end{pmatrix}$$

- gives mass to third gen fermions: t, b, tau + $m_b \cong m_\tau$
  others are massless. Turn on $\delta_{u,d,l} << M_0$
  Other fermions c,s,mu pick up mass with
- $m_{c,s,\mu} << m_{t,b,\tau}$ and relates mixings to masses

Illustration for 2-Gen. case

- Suppose $M_0 = \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} c & s \end{pmatrix}$ and $f = diag(\varepsilon_2, \varepsilon_3) \propto \delta_{u,d}$
- $\theta = Atm.$ angle; chosen large; f <<h.
- **Predictions:** $m_\tau \cong m_b$, $\frac{m_s}{m_b} \approx -V_{cb} \tan\theta$ } **consistent with observations:**

Making model predictive

- Key idea: SM sym for massless fermions :**[SU(3)]^5**;
- **Choose subgroup**: Discrete subgroup with 3-d. rep.
- **Replace Yukawa's by scalar fields (flavons);**
- **Minima of the flavon theory→ Yukawas:**
- **GUT theory that realizes the new ansatz for flavor**

What kind of GUT theory ?

- **Recall ansatz:** $M_u = M_0 + \delta_u$ **as** $\delta_{u,d} \to 0, M_u \propto M_d$

  $M_d = rM_0 + \delta_d$

- In SM, u_R d_R singlets- so M**u**, M**d** **unrelated.**
- We need a theory where, $\begin{pmatrix} u_R \\ d_R \end{pmatrix}$ are in a doublet.
- Left-Right symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$ and SO(10) (which contains LR) are precisely such theories.

Neutrino mass and seesaw also suggest LR and SO(10)

- **SM:**

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{matrix} u_R \\ d_R \end{matrix} \qquad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \quad e_R$$

nu mass

Add → ν_R

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \qquad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- Adding RH neutrino for nu mass → left-right sym.unification based on $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$ and SO(10)

SUSY SO(10) Features

- Minimal GUT group with complete fermion unification (per family) is SO(10)-its spinor rep contains **all 16** SM fermions (including RH nu) in single rep.

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

- **Has B-L needed to understand why $M_R << M\_{Pl}$**
- **Theory below GUT scale is MSSM:**
- **B-L needed for naturally stable dark matter.**

From SO(10) down to the Std Model

SO(10) **Nu mass**

$$\downarrow$$

- **LR Sym.** $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_c$ $\begin{pmatrix} 0 & 0 \\ \hline 0 & M \end{pmatrix}$

$$\downarrow \qquad \Delta(B-L) \neq 0$$

- **Standard Model-** $SU(2)_L \times U(1)_Y \times SU(3)_c$

$$\downarrow$$

-> seesaw $\begin{pmatrix} 0 & m \\ \hline m & M \end{pmatrix}$

$$SU(3)_c \times U(1)_{em}$$

SUSY SO(10) and unified understanding of flavor

- **Fermions in {16}:**
  $16_m \times 16_m = \{10\}_H + \{120\}_H + \{126\}_H$
- Only renorm. couplings for fermion masses:
  $$L_Y = h 16 \cdot 16 \cdot 10_H + f 16 \cdot 16 \cdot \overline{126}_H + h' 16 \cdot 16 \cdot [120, 10]_H$$
- **Has SM doublets → contributes to fermion mass**
- **$\{126\}_H$ responsible for both neutrino masses and quark masses:→ helps to connect quark mixings to neutrino mixings: Unifies quark and lepton flavors:** (Babu, Mohapatra, 93)

Fermion mass formulae in renormalizable SO(10)

- **Define** $Y_f = M_f / v_{wk}$
- **The mass formulae:** **Compare with ansatz**

$$
\begin{aligned}
Y_u &= h + r_2 f + r_3 h' \\
Y_d &= r_1(h + f + h') \\
Y_e &= r_1(h - 3f + c_e h') \\
Y_\nu &= h - 3r_2 f + c_\nu h'
\end{aligned}
$$

$$M_u = M_0 + \delta_u$$

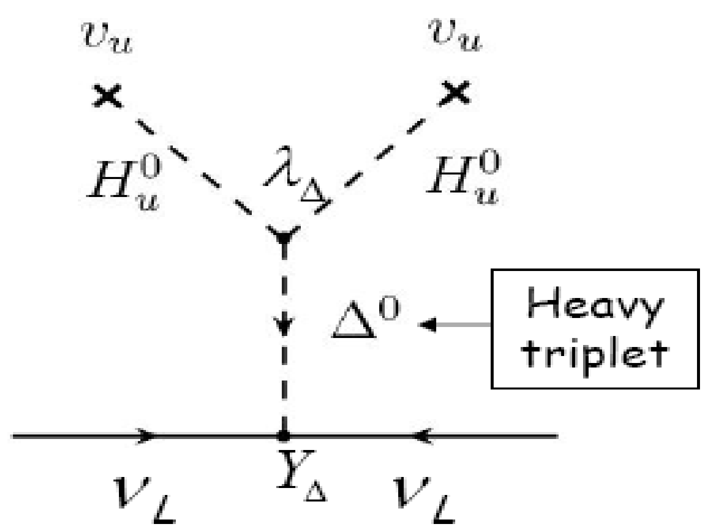
$$M_d = rM_0 + \delta_d$$

$$M_l = rM_0 + \delta_l$$

- **Both sets of formulae identical for** f, h'<< h

Neutrino mass in Renormalizable SO(10):

- {126} has an SU(2)$_L$ triplet with B-L=2:
- New formula for nu-mass:



$$m_\nu = f v_\Delta - M_D \frac{1}{f v_{BL}} M_D^T$$

$$v_\Delta = \lambda_\Delta \mu \frac{v_{wk}^2}{M_\Delta^2}$$

- Type II seesaw: $M_\Delta \approx M_U$ gives naturally small v
- **Two independent parameters:** M_Δ^2, v_R

Lazaridis, Shafi, Wetterich; R.N.M.,Senjanovic; Schecter, Valle'81

Type II dominance:

- If $M_\Delta << f v_{BL}$,first term dominates
- **Then the fermion mass formula become:**

$$
\begin{aligned}
Y_u &= h + r_2 f + r_3 h' \\
Y_d &= r_1(h + f + h') \\
Y_e &= r_1(h - 3f + c_e h') \\
Y_\nu &= h - 3r_2 f + c_\nu h'
\end{aligned}
$$

:

$$m_\nu \cong f v_\Delta$$

(Bajc, Senjanovic,Vissani'02)

(Babu, Mohapatra'92)

- **Neutrino mass and quark and charged lepton masses connected and all ingredients of our ansatz are realized in SO(10) .**

Rank One mechanism for Flavor

- Generic case does not explain mass hierarchies

$$\begin{aligned} Y_u &= h + r_2 f + r_3 h' \\ Y_d &= r_1(h + f + h') \\ Y_e &= r_1(h - 3f + c_e h') \end{aligned}$$

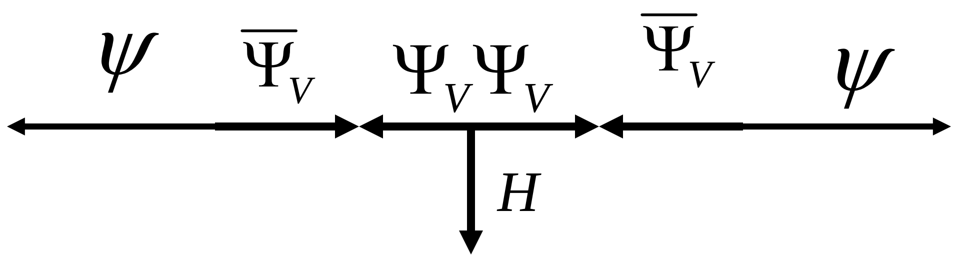
$$m_\nu \cong f v_\Delta$$

- **Assume h is rank 1** $h = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \begin{pmatrix} a & b & c \end{pmatrix}$ **+** $f, h' << h$

- **For f, h'=0, only 3rd gen. pick up mass.**
- **Leads to** $m_{s,d} << m_b ; m_{e,\mu} << m_\tau$ **with f, h'<<h**
- **Gives** $m_\tau \cong m_b$ **and** $m_\mu = -3 m_s$ **;** $\frac{m_{sol}}{m_{atm}} \sim \theta_C$

Origin of Rank one SO(10)

- Rank one model as an effective theory at GUT scale:
- Add one vector like matter $\Psi_V\{16\} + \overline{\Psi}_V\{\overline{1}\overline{6}\}$
  and singlets: ϕ_i
- **Superpotential:** $W = \phi_i \psi_i \overline{\Psi}_V + \overline{\Psi}_V \overline{\Psi}_V H$ **+** $M \overline{\Psi}_V \Psi_V$



- **Flavor texture depends on < ϕ_i >; with symmetries it can be predicted.**

VEV alignment from flat directions in an S4 model

- Examples: S4 triplet flavon case:

$$W = \frac{1}{2}m\phi^2 - \lambda\phi^3 = \frac{1}{2}m(x^2+y^2+z^2) - \lambda xyz.$$

$$\phi = \frac{m}{\lambda}\{(1,1,1) \text{ or } (1,-1,-1) \text{ or } (-1,1,-1) \text{ or } (-1,-1,1)\}.$$

- While fo

$$W = \frac{1}{2}m\phi^2 - \frac{\kappa_1}{M}(\phi^4)_1 - \frac{\kappa_2}{M}(\phi^4)_2$$

$$\vec{a} = (0,0,\pm1),\ (0,\pm1,0),\ (\pm1,0,0),\ \vec{b} = (\pm1,\pm1,\pm1),\ \text{and}\ \vec{c} = (0,\pm1,\pm1),$$

A specific realization with predictive textures:

- Group: SO(10)x**S4** $\supset 3_1 + 3_2 + 2 + 1_1 + 1_2$
- **Consider flavons** $\phi_{1,2,3} \subset 3_{1,2}$ **; matter {16}** $\subset 3_2$
- **Inv effective superpotential at GUT scale:**

$$W = (\phi_1\psi)(\phi_1\psi)H + (\phi_2\psi)(\phi_2\psi)\bar{\Delta} + \phi_3\psi\psi\bar{\Delta} + \phi_2\psi\psi H'$$

- **The flavon vevs align as:** $\phi_1 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad \phi_2 = \begin{pmatrix} 0 \\ -1 \\ 1 \end{pmatrix}, \quad \phi_3 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}.$

- **Leading to f=** $\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix} + \lambda \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix}$ **and h'=** $\begin{pmatrix} 0 & 1 & -1 \\ 1 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}$

- **Gives realistic model for fermion masses and mixings**

Prediction of a specific theory with S4- symmetry

- **Solar mass** $\frac{m_{solar}}{m_{atm}} \cong \lambda \cong \theta_c$
- **Bottom-tau:** $m_b \approx m_\tau$ **and** $m_\mu = -3m_s$
- **Leading order PMNS: U** $= \begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$
- **Testable prediction:** $\theta_{13} = \frac{\theta_c}{3\sqrt{2}} \cong 0.05$

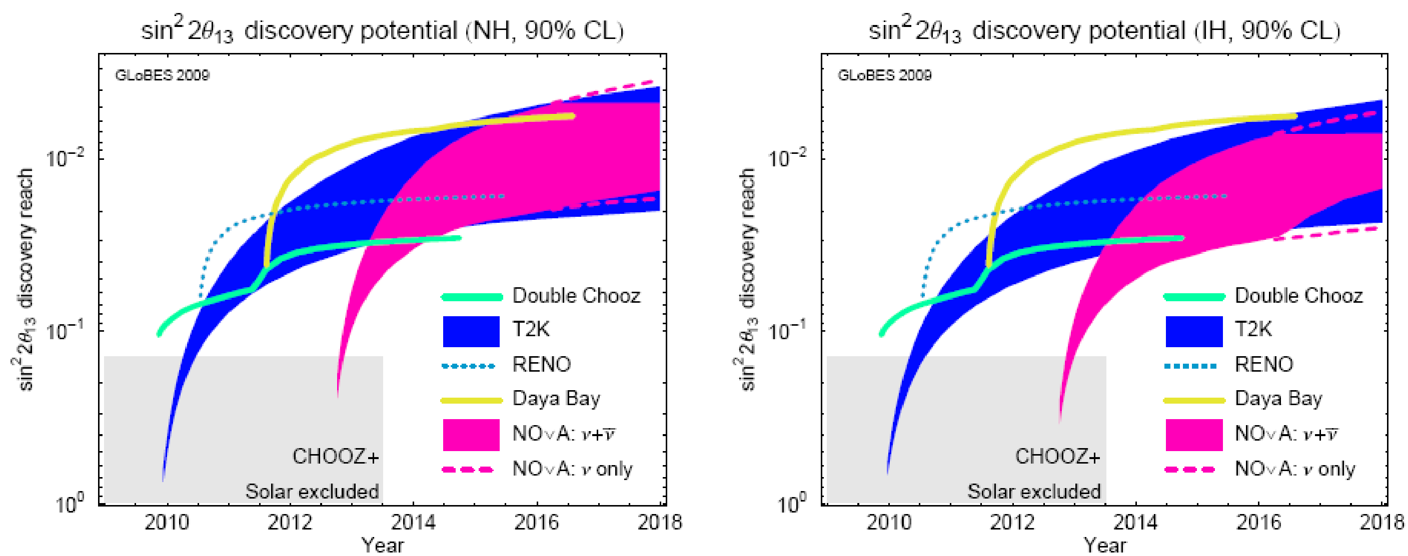
  Bjorken, King,
  Pakvasa Ferrandis (2004-05)
- Double beta mass 3 meV.

Dutta, Mimura, RNM arXiv:0911.2242

Prospects for measuring θ_{13}

- Reactor, Long base line e.g. T2K, NoVA:

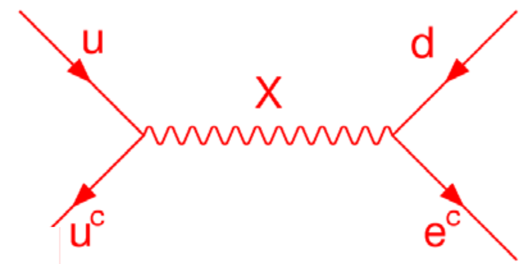
(Lindner, Huber,Schwetz,Winter'09)



Our prediction $\sin^2 2\theta_{13} > 0.01$

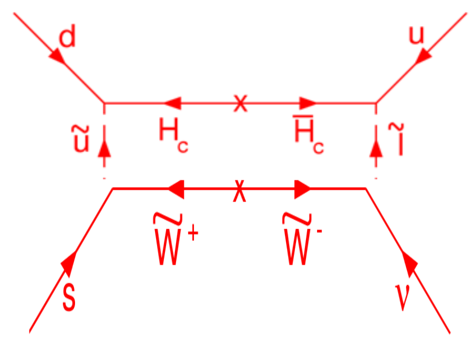
GUTs and Proton decay

- **Proton decay in SUSY GUTs have two generic sources:**
- **(i) Gauge exchange:**



$$p \to e^+\pi^0,\ \tau_p^{-1} \approx \left[\frac{g^2}{M_X^2}\right]^2 m_p^5 \approx [10^{36\pm1} yr]^{-1}$$

- **(ii) Higgsino exchange:**



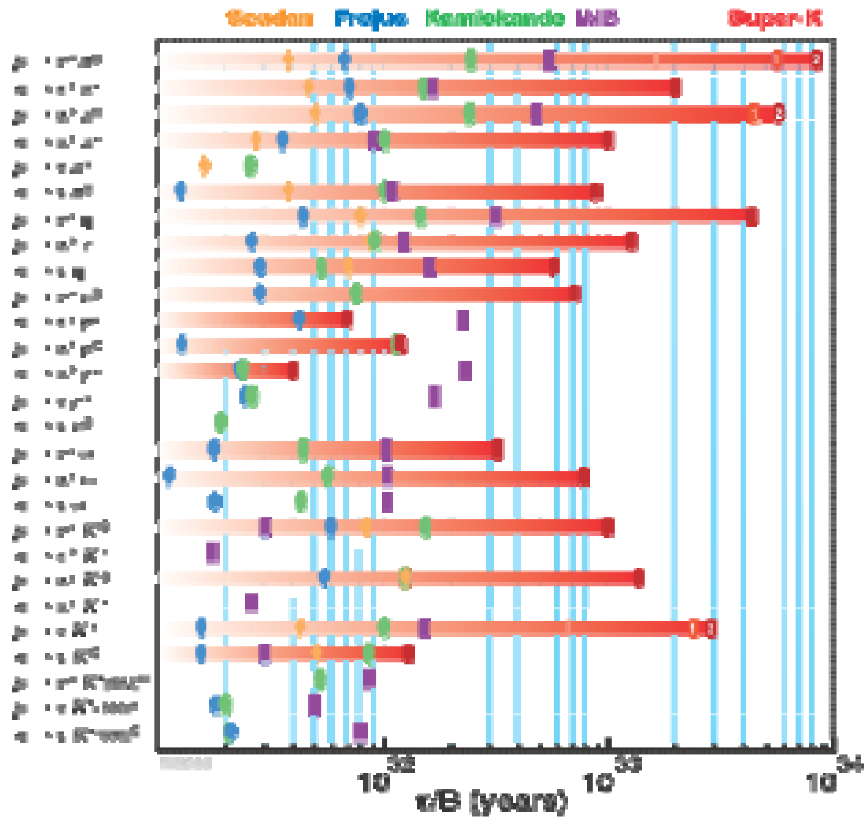
$$p \to \bar{\nu} K^+$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

- **Present limit:** $\tau_{\bar{\nu}K^+} > 2.3 \times 10^{33}\, yrs$

Present experimental limits

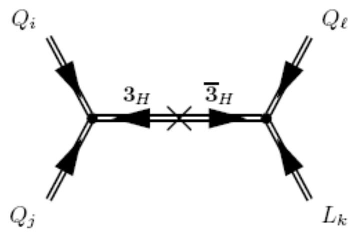
- Super-K, Soudan, IMB, Frejus



Ed Kearns @ LBNV-09

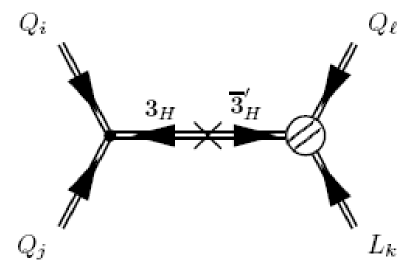
Rank one also solves the proton decay problem

- **Proton decay problem in SU(5): one Higgs pair s**



$$\rightarrow A_p \propto Y_u Y_d$$

- **In SO(10), there are more Higgs fields and if flavor structure is such that triplet Higgs do not connect, no p-decay problem:**



- **Choice flavor structure that does it** (Dutta, Mimura, RNM'05)

$$h_{10} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}; \quad h_{126} = \begin{pmatrix} 0 & 0 & \lambda^3 \\ 0 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix};$$

$$h_{120} = \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ -\lambda^3 & 0 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 0 \end{pmatrix};$$

Conclusion:

(i) New ansatz to unify diverse profiles of quark and lepton flavor patterns.

(ii) SO(10) GUT with type II seesaw provides a natural framework for realization of this ansatz.

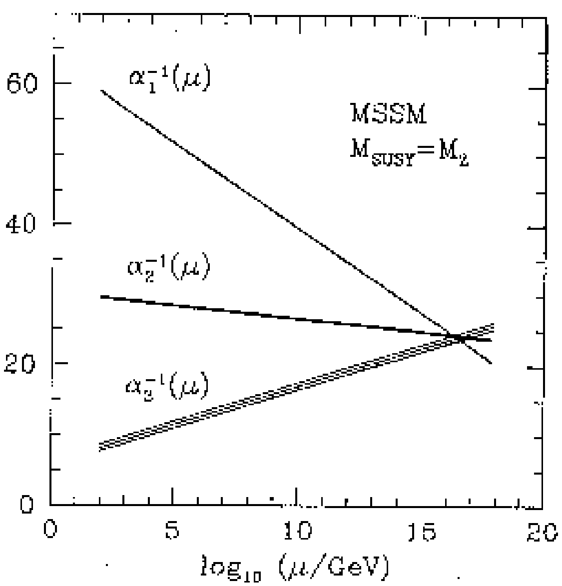
(iii) Predicts measurable θ_{13} and solves proton decay problem of susy GUTs.

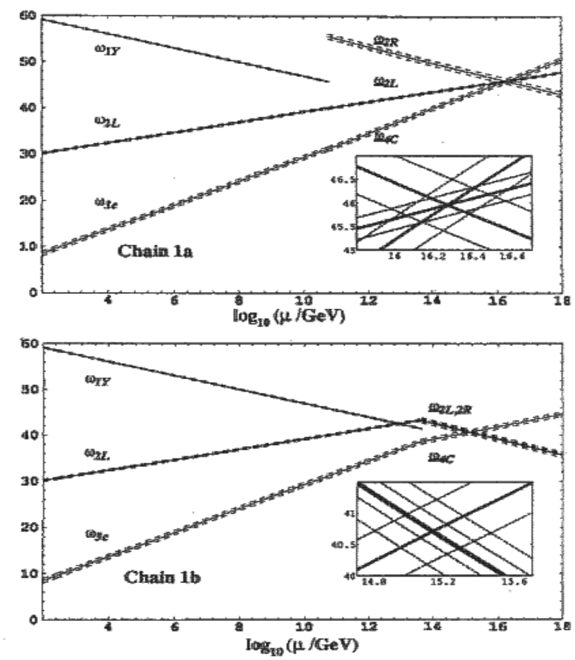
Happy Birthday, Goran !

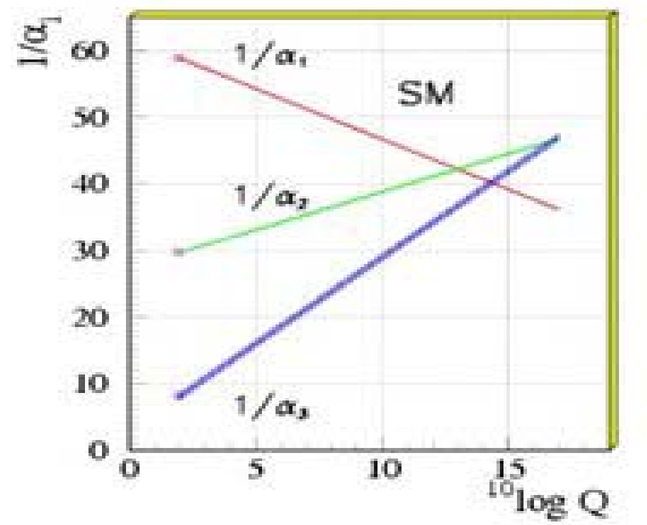
Some examples:

- SUSY Non-SUSY SO(10) SM

with seesaw







Simplest example: SUSY SU(5)

☞ The simplest GUT model (circa 1980s)

➢ Fermions: $5 = \begin{pmatrix} d^c \\ d^c \\ d^c \\ \nu \\ e^- \end{pmatrix}$ and $10 = \begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ & 0 & u_1^c & u_2 & u_3 \\ & & 0 & u_3 & d_3 \\ & & & & e^+ \\ & & & & 0 \end{pmatrix}$

➢ : Higgs $5 \oplus \bar{5} \oplus 24$.

➢ Predicts: at M_U, $m_b = m_\tau$; very good prediction

Also predicts $m_s = m_\mu$; $m_d = m_e$; VERY BAD PREDICTION!!

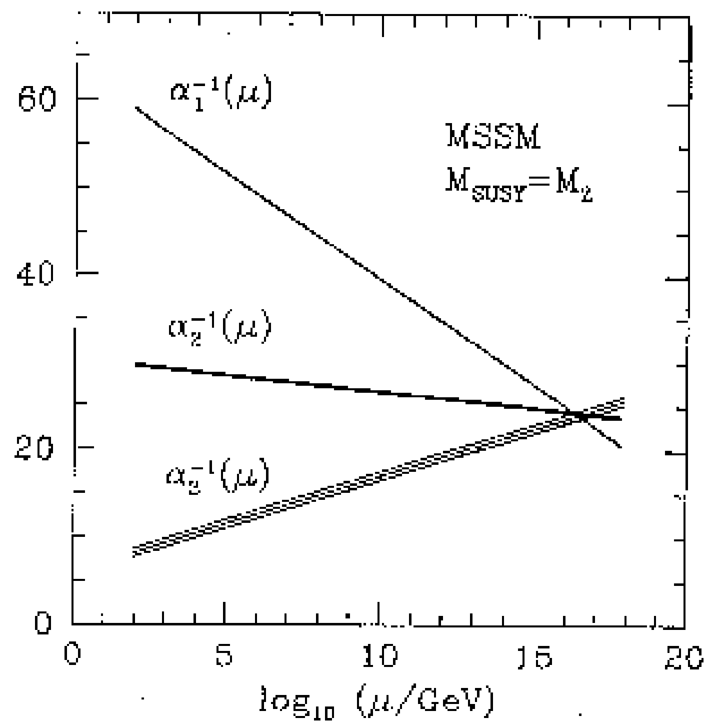
➢ No explanation of neutrino mass:

Why minimal SU(5) not satisfactory

- **Minimal model ruled out by proton decay !**
- **Not predictive for neutrinos- so no advantage of GUTs except scale !**
- **However one nice feature**: $m_b = m_\tau$
- A small piece of the flavor puzzle !!

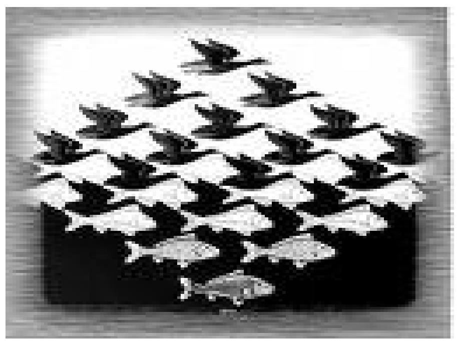
Grand unification hypothesis:

- **All forces and all matter become one at high energies no matter how different they are at low energies.**



Leptons→

quarks→



become same.

What we need to know:

(i) Majorana or Dirac $\beta\beta_{0\nu}$

(Nucl matrix element)

(ii) Absolute mass scale:

(iii) Mass ordering:

(iv) Value of θ_{13}

(v) CP phase

Unified understanding of Flavor in SO(10)

Fermion masses depend on 3 matrices: **h, f, h'**

$$
\begin{aligned}
Y_u &= h + r_2 f + r_3 h' \\
Y_d &= r_1(h + f + h') \\
Y_e &= r_1(h - 3f + c_e h')
\end{aligned}
$$

$$m_\nu \cong f v_\Delta$$

- **Suppose, h >> f and h'=0 and h is anarchic:**
- **Choose basis so** $f = diag(\varepsilon_1, \varepsilon_2, \varepsilon_3)$ **with** $\varepsilon_{1,2} << \varepsilon_3 << h_{ab}$
- **Dominant contributions to V_{CKM} cancel out explaining why CKM angles are small V_{CKM} coming from** $\varepsilon_{1,2,3}$.

→ **large neutrino mixngs come entirely from charged lepton sector;** $U_{PMNS} = U_l^+ U_\nu \equiv U_l^+$ **and hence are large!!**

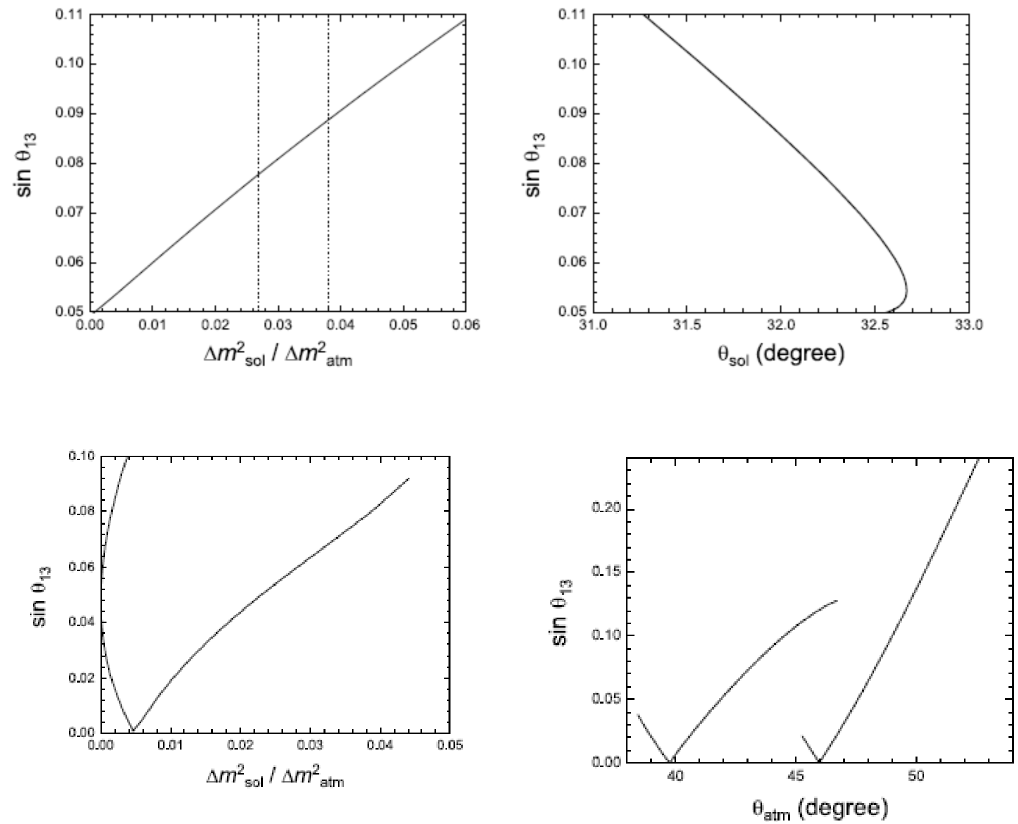
Realistic 3-generation model for Flavor:

- Our proposal after diagonalization of h
- $$h \propto \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$ with appropriately rotated f and h'.

- Different ansatzes for f and h' lead to different realizations of this idea:

More general Rank one model Predictions for θ_{13}:

- Depends on solar and atm masses:



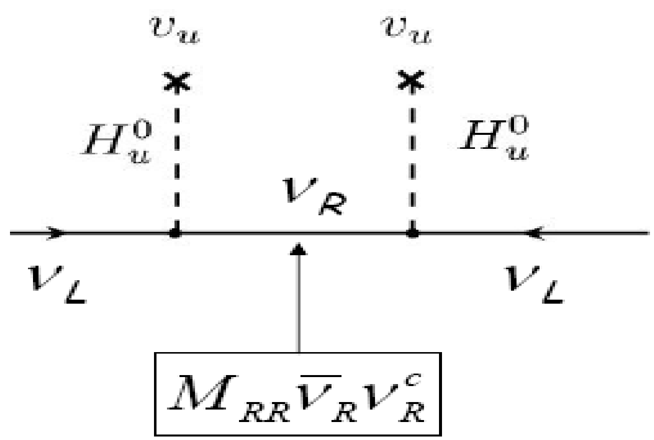
$$\theta_{13} > 0.05$$

Why GUT theory for neutrinos ?

- **Seesaw paradigm to explain** $m_\nu << m_{q,l}$
- **Add right handed neutrinos** N_R **to SM with Majorana mass:**

$$L_Y = h_\nu \overline{L} H N_R + M_R N N$$

- M_R Breaks B-L : New scale and new physics beyond SM.



- After EWSB

$$m_\nu \cong -\frac{h_\nu^{\ 2} v_{wk}^{\ \ 2}}{M_R}$$

-neutrino mass tiny and neutrino Majorana

- **Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Mohapatra, Senjanovic, Glashow**

Seesaw scale

- **Neutrino masses → seesaw scale much lower than Planck scale→ New symmetry (B-L).**
- $m_D \approx m_t$ Type I seesaw + Δm^2_{atm}

  → $M_R \approx 10^{14} GeV$ **GUT scale** 10^{16} GeV-

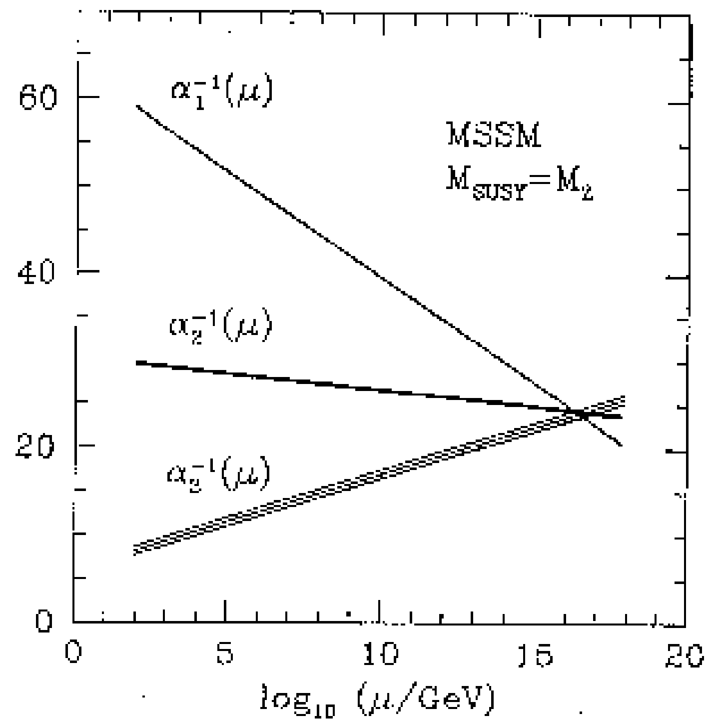
-*Small neutrino mass strong indication for* **SUSYGUT**;

- $m_D \approx m_e$ Seesaw scale is around **TeV**

- **Accessible at LHC, other signals,** $\mu \to e + \gamma$ **,** $\beta\beta_{0\nu}$

Why Supersymmetry ?

- **Simple picture of force Unification:**



- Predicts correct Weinberg angle

- Candidate for Dark matter