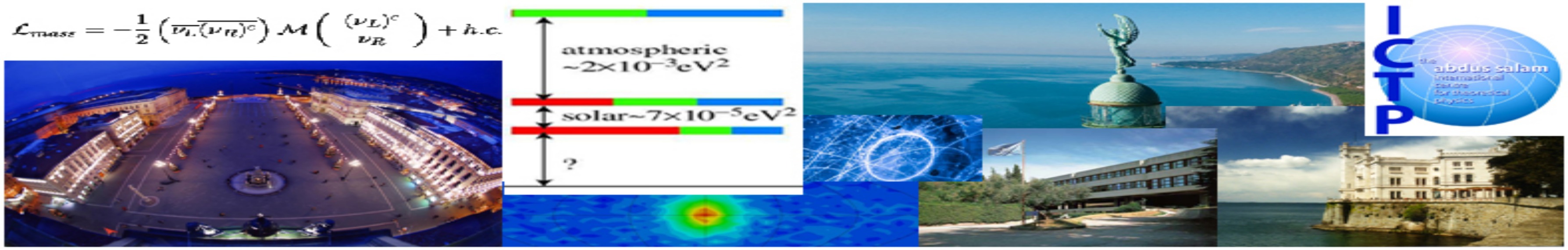


BeNe 2012 'Behind the Neutrino Mass'

Proton decay window to GUT Seesaw

R. N. Mohapatra

UNIVERSITY OF MARYLAND

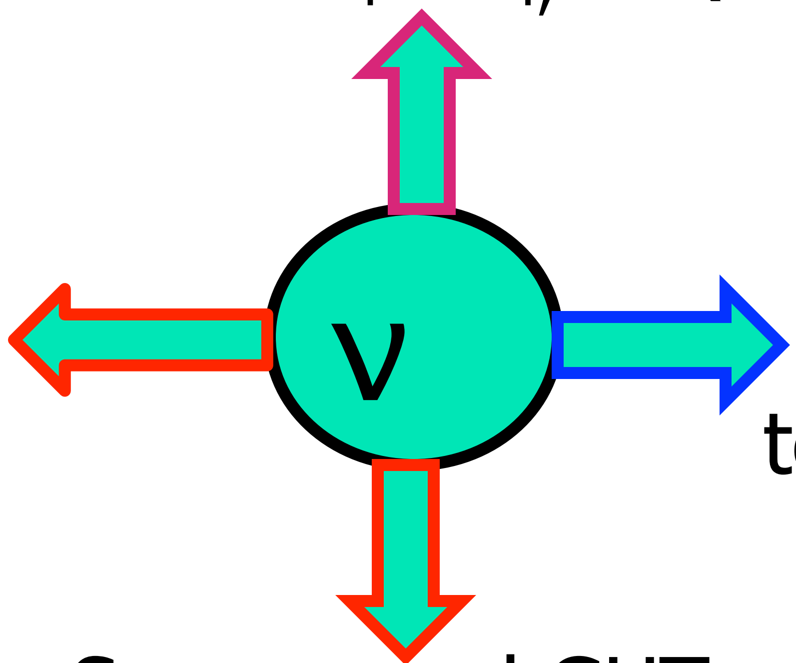
September, 2012

(K. S. Babu and R. N. M., arXiv:1204.5544;PRL: 1206.5701; PLB)

Different Approaches to neutrino masses

Symmetries A_4 , $S_{4,}$ → (TBM)

QLC



Anarchy, texture zeros

Seesaw and GUTs

Seesaw paradigms for small neutrino mass

- Generating the Weinberg operator $\frac{LHLH}{M}$ from UV theories: $M \gg v_{wk}$
- Two UV complete realizations:
- **Type I** SM+ Majorana N $m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}$ $M_R \approx 10^{14} GeV$

(Minkowsk'; Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra, Senjanovic')

- **Type II** SM+ Triplet Higgs $m_\nu \simeq \frac{f v_{wk}^2}{M_\Delta}$ $M_\Delta \simeq 10^{14} GeV$

(Maag, Wetterich; Lazaridis, Shafi, Wetterich; Mohapatra, Senjanovic';Schecter,Valle)

How to test high scale seesaw ?

- Seesaw (I and II) have two features:

  (i) Near GUT seesaw scale

  (ii) B-L=2
- How good a test is $\mu \to e + \gamma$?
- First it needs susy
- Tests “large Dirac Yukawa couplings” but not B-L=2
- Can test Seesaw **only** in GUTs like SUSY SO(10)
- How to probe B-L=2 nature ?What if there is no susy ?
- Nu-less double beta decay (only if inverted or degenerate)

B-Violation and GUT seesaw

- Need more probes of B-L violation to test high scale seesaw

- Main theme of the talk:
- Selection rules in B-violating processes e.g. proton decay and NN-bar oscillation can provide another window to probe seesaw in GUTs
- A new way for GUT scale baryogenesis as an alternative to leptogenesis

Neutrinos and GUTs

- Coupling unification scale ~ 10^{16} GeV ~ seesaw scale

  → Natural theories for neutrino mass are GUTs

- Provide a unified description of quark and lepton flavor : potential to explain curious features of neutrino masses e.g. $m_\odot/m_\oplus \sim \theta_C; \theta_{13} \sim \theta_C$

- Possible GUT embeddings of seesaw:

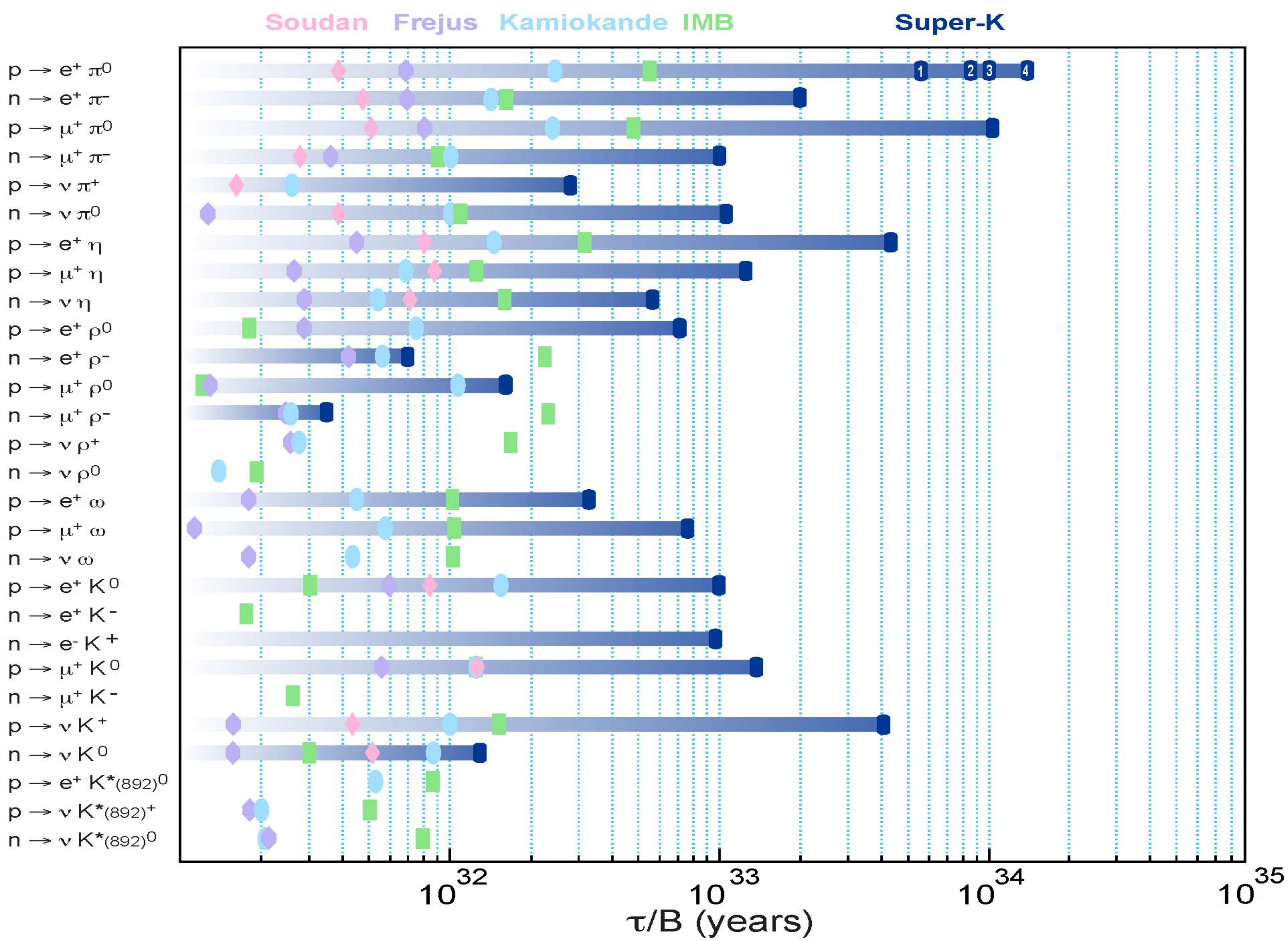
  -SU(5) with Type I, II

  -SO(10) with type I and type II

Proton decay seesaw connection

- B-L is a good symmetry of SM;
- Neutrino mass breaks L-part
- Therefore, if there is B-violation in neutrino mass theories, the neutrino mass specific B-violation must then break B-L symmetry:
- Since GUT-seesaw models naturally lead to proton decay- they are right models for exploring this issue.

Proton decay: Current Status



$n \rightarrow e^- K^+$ $\tau > 10^{33}$ yrs.;

$pp \rightarrow K^+ K^+$ $\tau > 1.7 \times 10^{32}$ yr

S-K (Miura talk, BLV'11)

Selection rules for B-violation

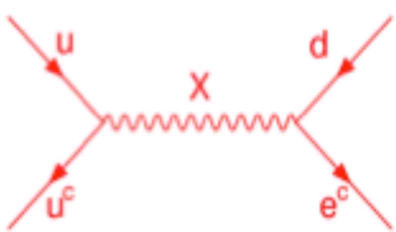
(i) D=6 operators (Weinberg; Wilczek, Zee'79) B-L=0

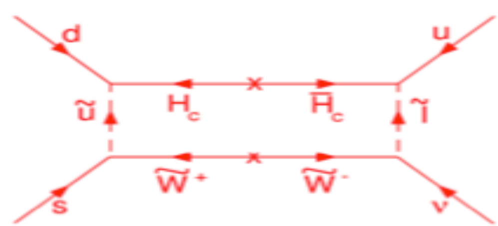
$$\mathcal{O}_1 = (d^c u^c)^* (Q_i L_j)\epsilon_{ij}, \quad \mathcal{O}_2 = (Q_i Q_j)(u^c e^c)^* \epsilon_{ij}, \quad \mathcal{O}_3 = (Q_i Q_j)(Q_k L_l)\epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_4 = (Q_i Q_j)(Q_k L_l)(\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl}, \quad \mathcal{O}_5 = (d^c u^c)^* (u^c e^c)^* .$$

- Leads to $p \to e^+ + \pi^0; p \to K^+ \bar{\nu}$ canonical GUTmodes

$p \to e^+ \pi^0$





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

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

$$\Gamma^{-1}(p \to e^+ \pi^0) = (2.0 \times 10^{35}\ \mathrm{yr}) \times \left(\frac{\alpha_H}{0.01\ \mathrm{GeV}^3}\right)^{-2} \left(\frac{\alpha_G}{1/25}\right)^{-2} \left(\frac{A_R}{2.5}\right)^{-2} \left(\frac{M_X}{10^{16}\ \mathrm{GeV}}\right)^4$$

B-L=2 B-violation

(ii) D=7 : Have B-L=2 (Weinberg; Weldon, Zee'80)

$$\tilde{O}_1 = (d^c u^c)^* (d^c L_i)^* H_j^* \epsilon_{ij}, \qquad \tilde{O}_2 = (d^c d^c)^* (u^c L_i)^* H_j^* \epsilon_{ij},$$

$$\tilde{O}_3 = (Q_i Q_j)(d^c L_k)^* H_l^* \epsilon_{ij} \epsilon_{kl}, \qquad \tilde{O}_4 = (Q_i Q_j)(d^c L_k)^* H_l^* (\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl},$$

$$\tilde{O}_5 = (Q_i e^c)(d^c d^c)^* H_i^*, \qquad \tilde{O}_6 = (d^c d^c)^* (d^c L_i)^* H_i,$$

$$\tilde{O}_7 = (d^c D_\mu d^c)^* (\overline{L}_i \gamma^\mu Q_i), \qquad \tilde{O}_8 = (d^c D_\mu L_i)^* (\overline{d^c} \gamma^\mu Q_i),$$

$$\tilde{O}_9 = (d^c D_\mu d^c)^* (\overline{d^c} \gamma^\mu e^c) .$$

→ $n \to e^- \pi^+$

(iii) D=9: $u^c d^c d^c u^c d^c d^c$ B-L=2 → $n - \bar{n}$

(RNM, Marshak'80; Glashow'80)

- Same property as seesaw →Are they present in GUT theories for neutrinos?

GUT Possibilities: SU(5)

- Minimal renorm. SU(5) –not realistic due to
  $m_s = m_\mu; m_d = m_e$: add 45:
- Type I seesaw: 5+45+ N_R with Majorana mass
  -Why large M_N ?
  -60 parameters; Need symmetries to predict:
  (Altarelli, Feruglio; King, Luhn, Antusch, Spinrath; Chen, Mahanthappa; Smirnov, Schmidt, Hagedorn….)
- Type II alternative: SU(5) +45+15
  - 45 parameters (Joaquim, Rossi, Hambye,Raidal; Nasri, Yu, RNM,…)

SO(10) SUSY GUT –dream picture for neutrinos

- SO(10) unifies all fermions/family (including RH nu) in single rep.

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

(Georgi; Fritzsch, Minkowski)

- Scales : SO(10) → MSSM → SM
- Contains all the ingredients for seesaw
- Minimal renormalizable models with 126-Higgs is **predictive** for nu masses and mixings in terms of quark masses (19 parameters) (Babu,Mohapatra'93)
- (Fukuyama,Okada'02; Bajc, Senjanovic, Vissani'02; Goh, Mohapatra, Ng'03; Babu, Macesanu'05; Aulakh,Bajc,Melfo,Senjanovic, Vissani;Fukuyama,Ilakovic,Meljanac,Kikuchi,Okada; Dutta,Mimura,RNM;Bertolini,Frigerio,Malinsky; Joshipura,Patel'11;Altarelli,Blankenburg'11; Dev, RNM, Severson'11)

Predictive SO(10)-
no symmetries-just minimal

- Quark lepton masses with 10(H)+126 (Δ) Higgs

$$W = h\psi\psi H + f\psi\psi\Delta$$

$$M_u = hv_{u,10} + fv_{u,126}$$
$$M_d = hv_{d,10} + fv_{d,126}$$
$$M_\ell = hv_{d,10} - 3fv_{d,126}$$
$$M_D = hv_{u,10} - 3fv_{u,126}$$

$$M_\nu = fv_L - M_D(fv_R)^{-1}M_D$$

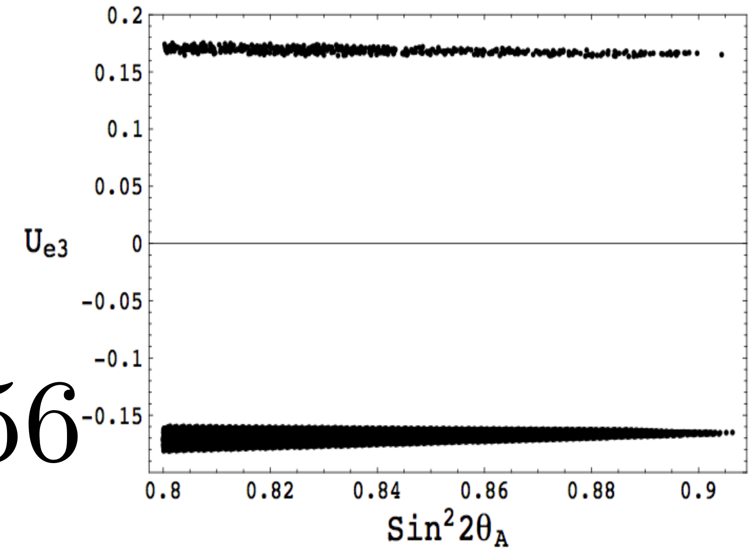
Few parameters→ predictive for neutrinos; (Goh, RNM, Ng; Babu, Macesanu)

Daya Bay value .15 $\theta_{13} \simeq .17$ $m_\odot/m_\oplus \sim \lambda$

Theta_13 prediction of $SO(10)_{126}$ Models

- Type II seesaw case:

Goh, RNM, Ng'03 $\theta_{13} \simeq 0.17$



- Babu and Macesanu'05: $\theta_{13} \simeq 0.156$

- Non-SUSY case (Type I) (Joshipura, Patel, '11; Severson'12)

$$\sin^2\theta_{13} = .024 \qquad \theta_{13} \simeq 0.156$$

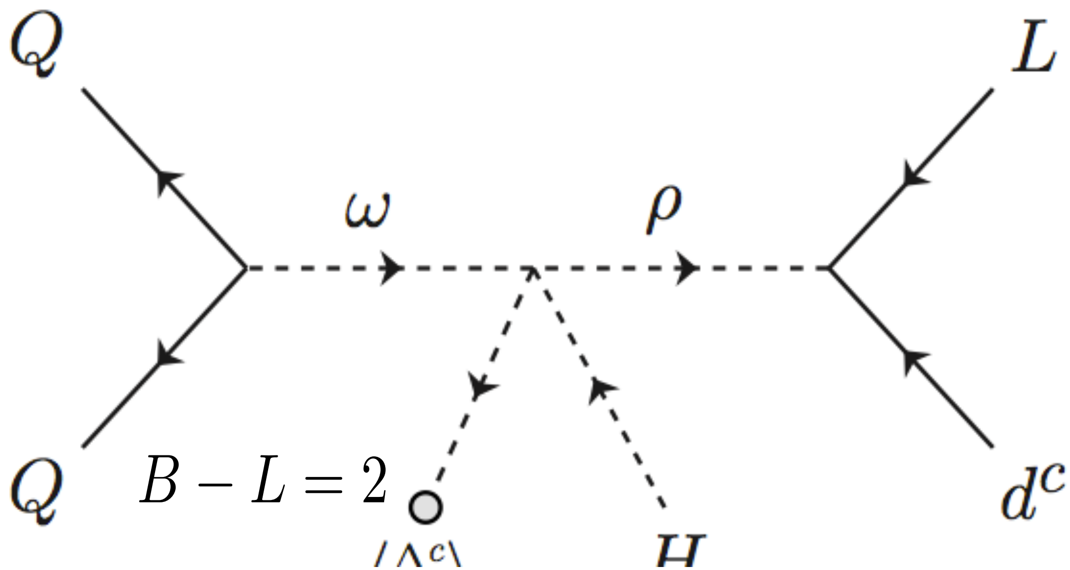
(Daya Bay-RENO-DC value ~0.15)

Testing seesaw via new nucleon decay modes in SO(10)

- Key ingredient of minimal renorm. SO(10) models for nu mass is 126-Higgs field that leads to large Majorana mass for N_R.
- If some of the {126} scalar fields remain at intermediate scale, they can give enhanced B-violation with B-L=2 e.g. $n \to e^- \pi^+$ $n - \bar{n}$ oscillation (Babu, Mohapatra; arXiv:1203:5544; 1206.5701; PRL)
- Can be observable in Hyper-K etc.
- Way to distinguish between SU(5) and SO(10)

Origin of B-L=2 n-decay

- Diagram for neutron-decay: d=7 Operator O_2



$$\tilde{O}_2 = (Q_i Q_j)(d^c L_i)^* H_j^* \epsilon_{ij}\epsilon_{kl},$$

ω in {10, 126};

$\rho(3,2,1/6)$ {126}

$\omega\rho^* H$ in {126}[4]

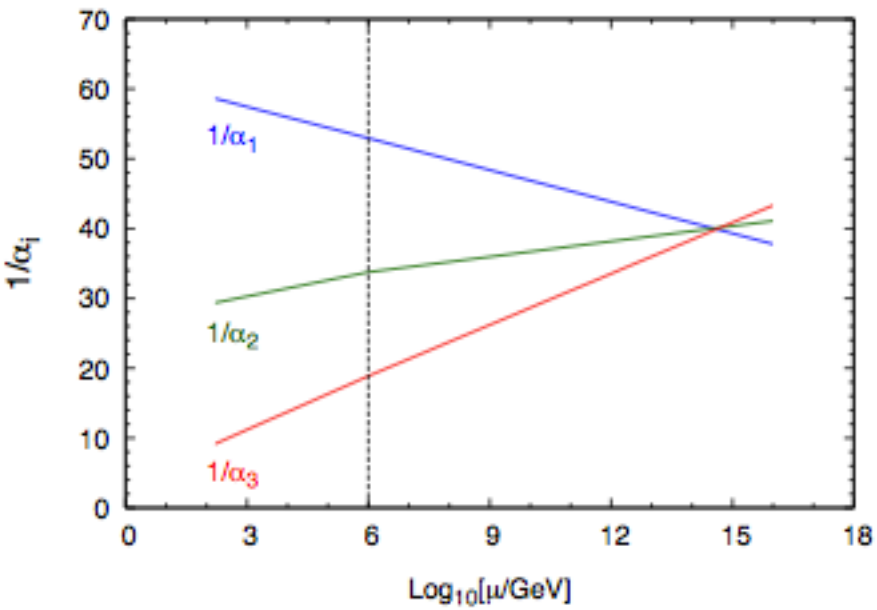
- Leads to $n \to e^- + \pi^+$ decay

Coupling unification and observable proton decay

- $A_{n\rightarrow e^- \pi^+} \sim \frac{f_{126}^2 v_{BL} v_{wk}}{M_\omega^2 M_\rho^2} \sim \frac{10^{-20}}{M_\rho^2}$

Observability→ $M_\rho \sim 10^5 GeV$; is it GUT allowed ?

Yes→



→ $\tau_p \sim 4 \times 10^{33} yrs$

Non-SUSY vs SUSY SO(10)

- Only as lone operator: $d^c\, d^c\, u^c\, L h_u$
- Arises both in {16} and {126} models:

e.g. in 16 models: $\{16\}^2 \{16\}^2_H$, $\{16\}^2 \{10\}$, $\{10\}^2_H \{45\}$

- Distinguishing between SUSY vs non-SUSY

$n \rightarrow e^- K^+$ allowed in non-SUSY but not in SUSY

Alternative SO(10) scenario

- Non-SUSY SO(10) does not unify without low scale particles,
- Coupling unif with

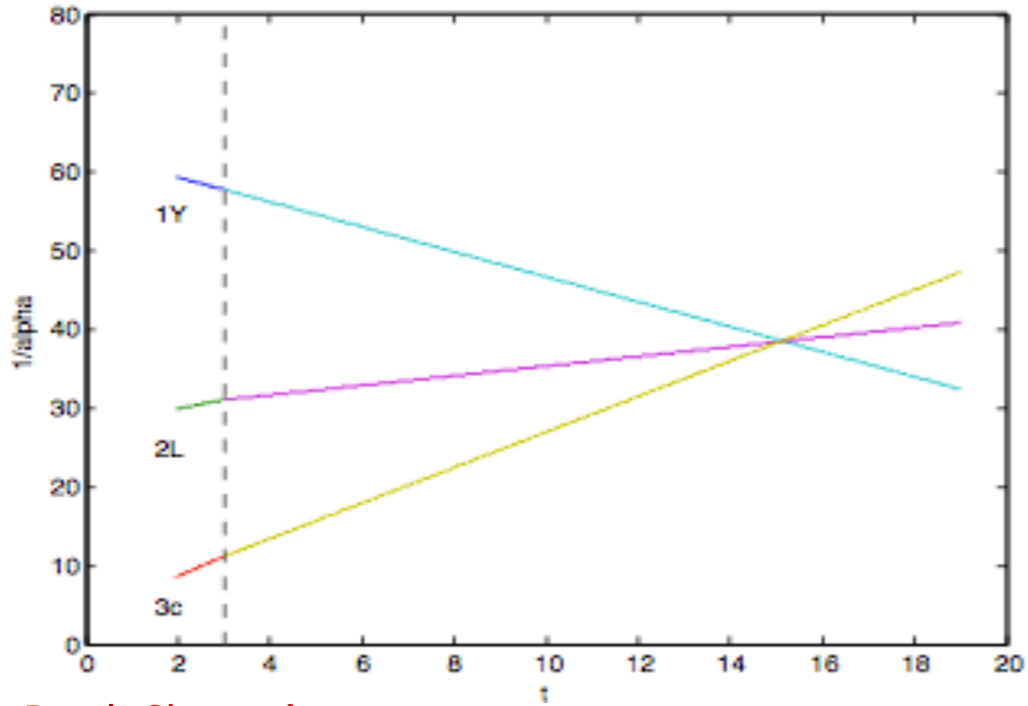
sub-TeV $\Delta_{ud}(6,1,\frac{1}{3})$

+ 2 SM triplets;

- Predicts seesaw scale

near $M_U \sim 10^{16}$ GeV;

- Δ_{ud} mass ~1 TeV GeV



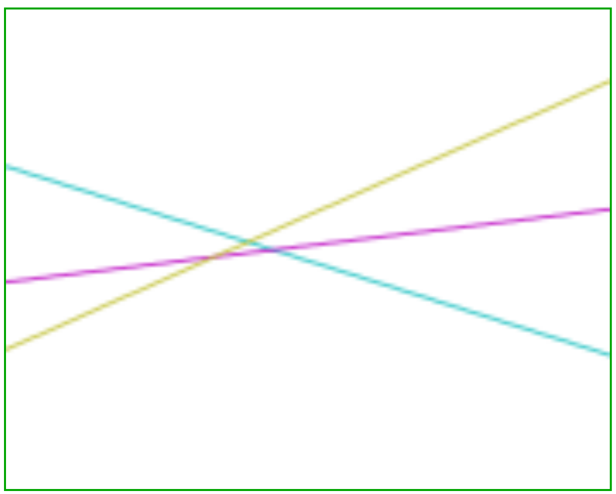
(Babu, Mohapatra, arXiv:1206.5701, PLB; Patel, Sharma)

- B-L violation→GUT scale coupling $v_{BL}\Delta_{ud}\Delta_{ud}\Delta_{dd}$

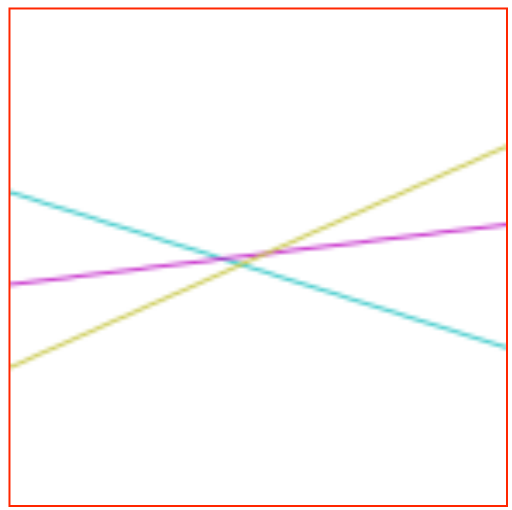
Scale sensitivity-1-loop

- Coupling unification is sensitive to sextet mass

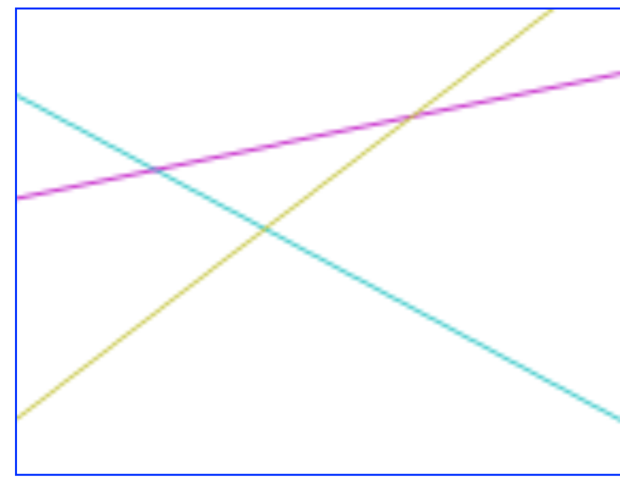
1 TeV



2 TeV

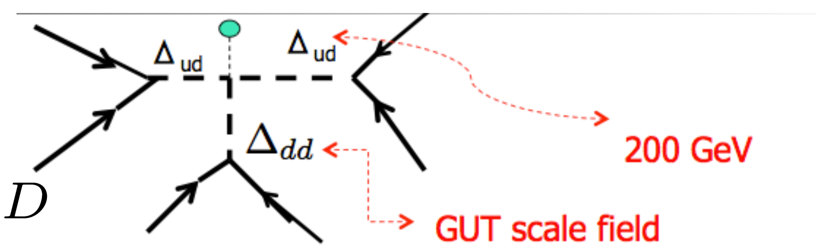


10 TeV



Observable neutron-anti-neutron oscillation

- B-L violation at GUT scale leads to couplings
- $v_{BL}\Delta_{ud}\Delta_{ud}\Delta_{dd}$



- (Babu, Mohapatra'12 PLB)
- → $G_{\text{nn-bar}} = \dfrac{v_{BL} f^3 \eta_{QCD}}{M^4_{\Delta_{ud}} M^2_{\Delta_{dd}}}$
- = 10^{-29} GeV^{-5} → $\tau_{n-\bar{n}} = \dfrac{1}{G_{n-\bar{n}}\Lambda^6_{QCD}} \sim 10^{10} - 10^{11} sec$
- Current bounds: $\tau_{n\bar{n}} \geq 2 \times 10^8 s.$ ILL; SK,SNO
- Observable with available reactor fluxes

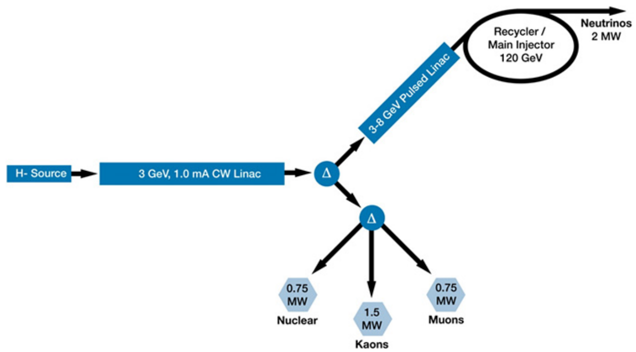
Given this limit on $\tau_{n\bar{n}}$ why are nuclei stable ?

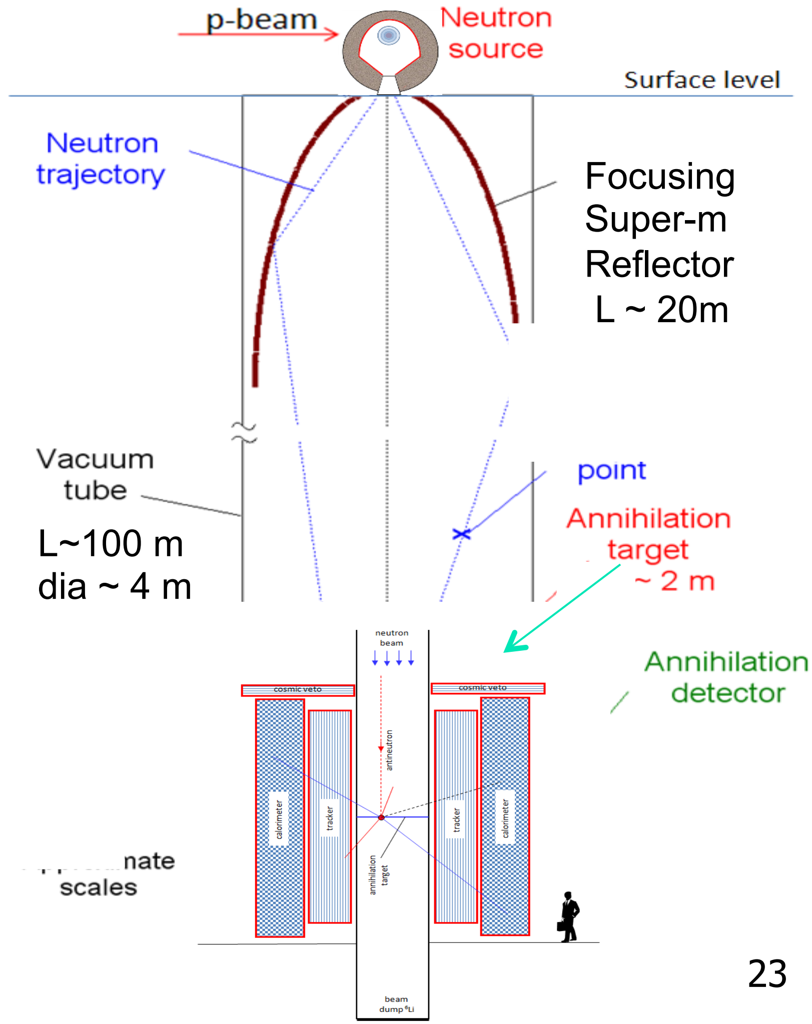
- Oscillation inside nuclei are suppressed by the factor $\left(\frac{\delta m_{n\bar{n}}}{V_n - V_{\bar{n}}}\right)^2 \leq 10^{-62}$
- More detailed calculation: (Dover, Gal, Richard)

$$\tau_{Nuc} = R\tau_{n\bar{n}}^2 \quad R = 0.3\times 10^{23}\ \sec^{-1} \rightarrow \tau_{Nuc} \geq 10^{32} yrs$$

- Super-K search $\tau_{n\bar{n}} > 2.44\text{x}10^8$ sec.

Possible N-Nbar search At Fermilab Project X





Dedicated spallation target optimized for cold neutron production

- "Background free" detector: one event = discovery
- Expected sensitivity > 2,000 ILL units

$$P_{n-\bar{n}} \approx \left(\frac{t}{\tau_{n-\bar{n}}}\right)^2$$

Color sextets Δ_{qq} @LHC

- **TeV scaleColor sextets** Can be searched at LHC:

(I) **Single production**: $ud \longrightarrow \Delta_{ud} \longrightarrow tj$

xsection calculated in **(RNM, Okada, Yu' 07;)** resonance peaks above SM background- decay to tj;

- **Important LHC signature:** $\sigma(tt) > \sigma(\bar{t}\bar{t})$

(II) **Drell-Yan pair production** $q\bar{q} \rightarrow G \rightarrow \Delta_{ud}\bar{\Delta}_{ud}$

- Leads to $tjtj$ final states: **LHC reach < TeV**

(Chen, Rentala, Wang; Berger, Cao, Chen, Shaughnessy, Zhang' 10; Han, Lewis' 09)

Seesaw in SU(5) and B-L nucleon decays

- SU(5) with type I seesaw:
- Recall: exotic Higgs couplings for BLV decay:

$$\omega\rho^* h; \eta^* \rho h; \rho^* \Phi h; \chi^* \eta h$$

- But ρ and η absent in SU(5) nu models with type I or III seesaw.→ hence no B-L p-decays
- **Way to distinguish SU(5) vs SO(10)**
- SU(5) with type II seesaw→ {15}-field
- Leads to observable BVL n-decay but not observable nn-bar

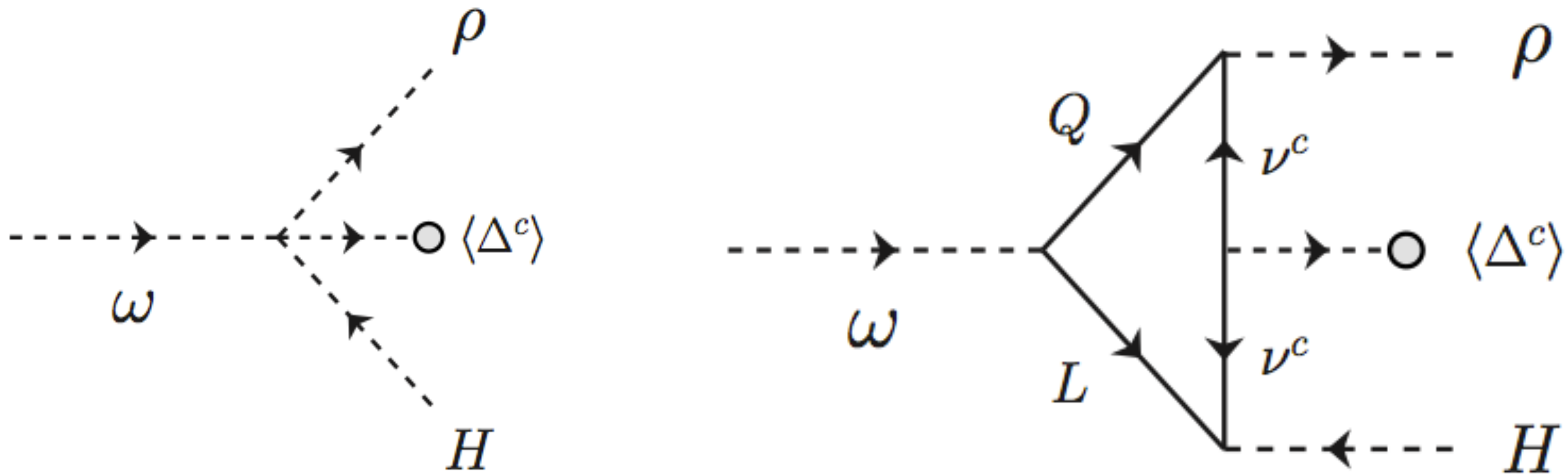
GUT scale baryogenesis: why SU(5) failed

- In SU(5) dominant B-violation conserves B-L;
- Baryon asym, $\Delta B = \Delta(B-L) + \Delta(B+L)$
- B-L conservation→ $\Delta B = \Delta(B+L)$

- But sphalerons violate B+L and therefore erase $\Delta(B+L)$ and hence no asymmetry !
- Things change with the inclusion of {15} because of tiny B-L breaking

B-L=2 Proton decay and baryogenesis in SO(10)

- In our case, p-decay violates B-L
- Decays of $\omega \rightarrow \rho$ H can produce baryon asym.



- Graphs break B-L;
- Sphalerons cannot wash B-L hence leave $\Delta B \neq 0$

Asymmetry related to neutrino mass

- Asymmetry related to ω-couplings that are couplings of {10} and {126} and related to neutrino masses:

$$\epsilon_{B-L}^{(c)} = \frac{1}{\pi} \mathrm{Im} \left[\frac{\mathrm{Tr}\{ Y_{d^c \nu^c \omega} Y^{\dagger}_{d^c L \rho} Y_{\nu^c L H} M_{\nu^c} F_2(M_{\nu^c}) \} \lambda v_R}{|\lambda v_R|^2} \right] \mathrm{Br},$$

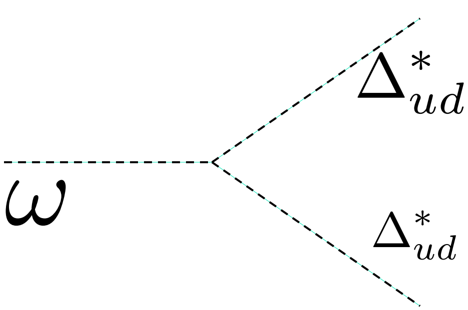
- For the light color sextet case: leptogeneis works.

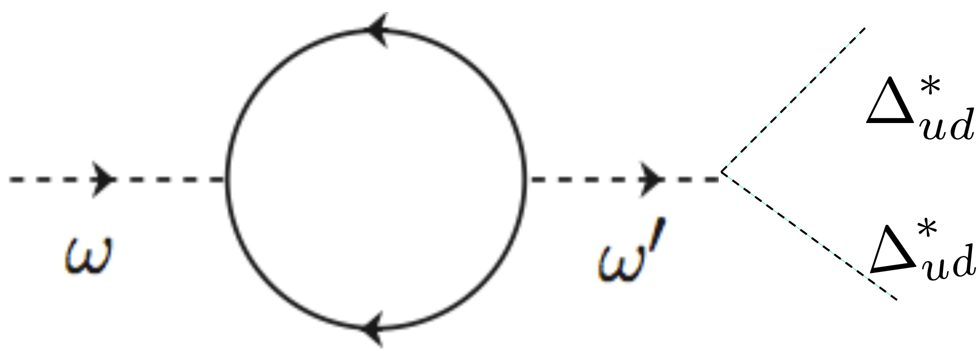
Baryogenesis in the color sextet model

- N-N-bar interactions go out of eq. around 10^{15} GeV;
- Two sources of matter-anti-matter asymmetry:

  (a) Leptogenesis

  (b) B-L violating GUT scale by $\Delta_{dd}(\omega)$ decay



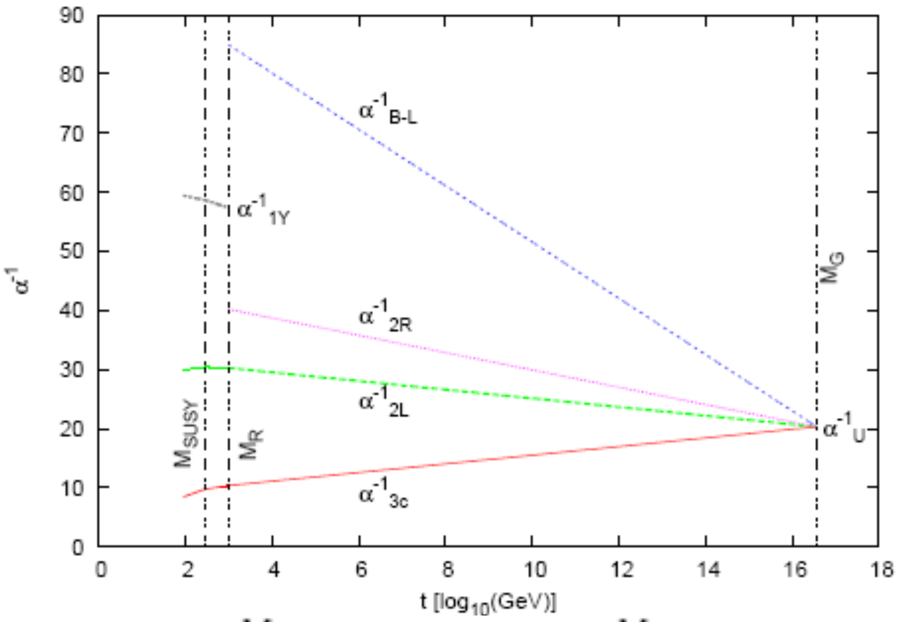


Summary

- Baryon non-conservation are generic to GUTs !
- Observation of B-L conserving modes does not say anything about GUTs for neutrino masses
- Proton decay modes bearing direct seesaw signature (i.e. B-L=2) are $n \to e^- \pi^+$ and $n - \bar{n}$ oscillation !!
- They can be observable in realistic SO(10) models for neutrino masses !!
- Lead to revival of GUT scale baryogenesis

Coupling unification with TeV LR inverse seesaw

- Running plot: Inverse seesaw with TeV WR and Z'



new appeal of inverse seesaw

p-decay OK→ squark mass>TeV

- $SO(10) \xrightarrow{M_G} 3_c 2_L 2_R 1_{B-L} \xrightarrow{M_R} 3_c 2_L 1_Y(\mathrm{MSSM}) \xrightarrow{M_{SUSY}} 3_c 2_L 1_Y(\mathrm{SM}) \xrightarrow{M_Z} 3_c 1_Q$

$$M_U \cong 10^{16}\, GeV; M_{BL,R} \cong TeV$$

(Dev, RNM, 09; PRD; arXiv: 1003:6102);

Current best fit values

- ▪ Schwetz, Tortola, Valle :1108

Curious feature!

	best fit $\pm 1\sigma$	3σ range	prec@3σ	
$\frac{\Delta m^2_{21}}{10^{-5}\text{eV}^2}$	$7.59^{+0.20}_{-0.18}$	7.09–8.19	7%	KamLAND
$\frac{\Delta m^2_{31}}{10^{-3}\text{eV}^2}$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$	$2.14 - 2.76$ $-(2.13 - 2.67)$	12%	MINOS
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.27–0.36	14%	SNO
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06	0.39–0.64	24%	SuperK
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$	0.001–0.035 0.001–0.039	120%	T2K + global data
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$	$0 - 2\pi$	–	

upper: normal hierarchy, lower: inverted hierarchy

$$\frac{\Delta m^2_{\odot}}{\Delta m^2_{\oplus}} \sim \theta^2_{Cabibbo}$$

General SM multiplets responsible for ~~B-L~~ decays

- Multiplets: $h(1,2,+1/2)$, $\overline{h}(1,2,-1/2)$, $\omega(3,1,-1/3)$, $\omega^c(\overline{3},1,1/3)$, $\rho(3,2,1/6)$, $\overline{\rho}(\overline{3},2,-1/6)$, $\eta(3,1,2/3)$, $\overline{\eta}(\overline{3},1,-2/3)$, $\Phi(3,3,-1/3)$, $\overline{\Phi}(\overline{3},3,1/3)$, $\chi(3,2,7/6)$, $\overline{\chi}(\overline{3},2,-7/6)$, $\delta(3,1,-4/3)$, $\overline{\delta}(\overline{3},1,4/3)$.
- Couplings: $\omega\rho^* h; \eta^*\rho h; \rho^*\Phi h; \chi^*\eta h$

  Present in $(126)^4$ coupling in SO(10)

$$\begin{aligned}\mathcal{L}(16_i 16_j 10_H) \;=\; & h_{ij}\left[(u_i^c Q_j + \nu_i^c L_j)\, h - (d_i^c Q_j + e_i^c L_j)\, \overline{h} + \left(\frac{\epsilon}{2} Q_i Q_j + u_i^c e_j^c - d_i^c \nu_j^c\right)\omega \right.\\ & \left. + \left(\epsilon u_i^c d_j^c + Q_i L_j\right)\omega^c\right], \qquad (6)\end{aligned}$$

$$\begin{aligned}\mathcal{L}(16_i 16_j \overline{126}_H) \;=\; & f_{ij}\left[(u_i^c Q_j - 3\nu_i^c L_j)\, h - (d_i^c Q_j - 3 e_i^c L_j)\, \overline{h} \right.\\ & + \sqrt{3}i\left(\frac{\epsilon}{2} Q_i Q_j - u_i^c e_j^c + \nu_i^c d_j^c\right)\omega_1 + \sqrt{3}i(Q_i L_j - \epsilon u_i^c d_j^c)\,\omega_1^c \\ & + \sqrt{6}(d_i^c \nu_j^c + u_i^c e_j^c)\,\omega_2 + 2\sqrt{3}i\, d_i^c L_j\, \rho - 2\sqrt{3}i\, \nu_i^c Q_j\, \overline{\rho} + 2\sqrt{3}\, u_i^c \nu_j^c\, \eta \\ & \left. - 2\sqrt{3}i\, u_i^c L_j\, \chi + 2\sqrt{3}i\, e_i^c Q_j\, \overline{\chi} - 2\sqrt{3}\, d_i^c e_j^c\, \delta + \sqrt{6}i\, Q_i L_j\, \overline{\Phi} + \ldots\right], (7)\end{aligned}$$

Flavor puzzle in particle physics

- quark flavor puzzle: hierarchical pattern
- Neutrino mixngs: $\theta_{23} \sim 45^{0}$; large $\theta_{12} \sim 33^{0}$

+Recent θ_{13} results:

- T2K: $0.03 \leq \sin^2(2\theta_{13}) \leq 0.28$
- MINOS: $0.00 \leq \sin^2(2\theta_{13}) \leq 0.12$
- Double Chooz: $\sin^2(2\theta_{13}) = 0.085 \pm 0.051$
- Daya Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016 \pm 0.005$
- RENO expt. $\sin^2 2\theta_{13} = 0.103 \pm 0.013 \pm 0.011$
- How to have a unified understanding of flavor ?

Type II dominance and mixings

- **II seesaw** $M_\nu \cong c(M_d - M_l)$
- GUT relation $m_b \approx m_\tau + \lambda^2 \rightarrow$ $\lambda \equiv \theta_C = 0.22$

$$M_\nu \propto m_b \begin{pmatrix} \lambda^5 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} - m_\tau \begin{pmatrix} \lambda^6 & \sim\lambda^3 & \\ \lambda^3 & -3\lambda^2 & \lambda^2 \\ & \lambda^2 & 1 \end{pmatrix} \sim \lambda^2 \begin{pmatrix} \lambda^2 & \lambda^2 & \lambda \\ \lambda^2 & 1+\lambda & 1 \\ \lambda & 1 & 1 \end{pmatrix}$$

(Bajc, Senjanovic, Vissani' 02)

- Predicts $\theta_{13} \simeq .17$; $m_\odot / m_\oplus \sim \lambda$ (Goh, RNM, Ng'03)

(Daya Bay central value~.15)

SO(10) with Type I+II

- **Why?**
- How well does the GUT relation $m_b \approx m_\tau + \lambda^2$ work ?
- Quite well for susy SO(10) with large tan β ~50; within 2 sigma for tan $\beta = 10$
- Large tan β values have problem with p-decay
- Non-Susy no $m_b \approx m_\tau$
- More general analysis with I+II+CPV (Babu, Macesanu; Bertolini, Malinsky, Schwetz;'05)
- Large θ_{13} generic of 126 models with susy.