Neutrino masses and mixings as an evidence of GUT, and the impact to (flavor changing) nucleon decay

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1. **Introduction&Summary**
2. **Neutrino can be a signature of (SU(5)) GUT!**

   An assumption can explain the various hierarchies in quark and lepton masses and mixings.

3. **E_6 GUT is attractive** $U_{e3} \sim \sin\theta_c$, $\delta_L \sim O(1)$

   The assumption can be derived.

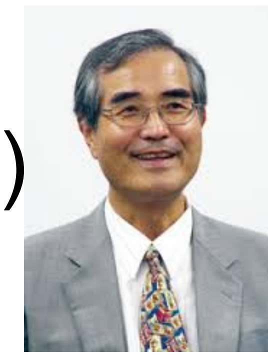
4. **Nucleon decay is important!**

   Branching ratios identify the unification group.

5. **Summary**

Congratulations!

- On Nobel prize on physics in 2015
- To all researchers who are (and/or were) working on neutrino physics.



- Neutrino masses and mixings are important to understand the signature of SU(5) GUT.

The total quark and lepton masses and mixings can be an experimental signature for unification of matters in SU(5) GUT!

Introduction

Grand Unified Theories

2 Unifications

- Gauge Interactions

$$SU(5) \supset SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$SO(10) \supset SU(5)$$

- Matter

$$\boxed{Q \quad U_R^c \quad E_R^c} \; \boxed{D_R^c \quad L} \quad \boxed{N_R^c}$$

$$\mathbf{10} \quad + \quad \bar{\mathbf{5}} + \mathbf{1} \quad = \quad \mathbf{16}$$

Experimental supports for both unifications

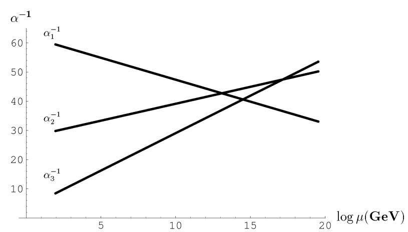
→ GUT is promising

Grand Unified Theories

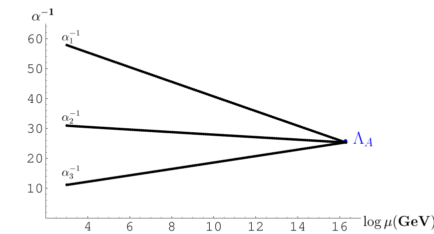
- Unification of gauge interactions

  quantitative evidence:

Non SUSY



SUSY GUT



- Unification of matters

$$(Y_u)_{ij}\mathbf{10}_i\mathbf{10}_j 5_H + (Y_d)_{ij}\mathbf{10}_i\bar{5}_j\bar{5}_H + (Y_\nu)_{ij}\bar{5}_i\bar{5}_j 5_H 5_H$$

  qualitative evidence:

$\mathbf{10}_i(Q_i)$ have stronger hierarchy than $\bar{\mathbf{5}}_i(L)$

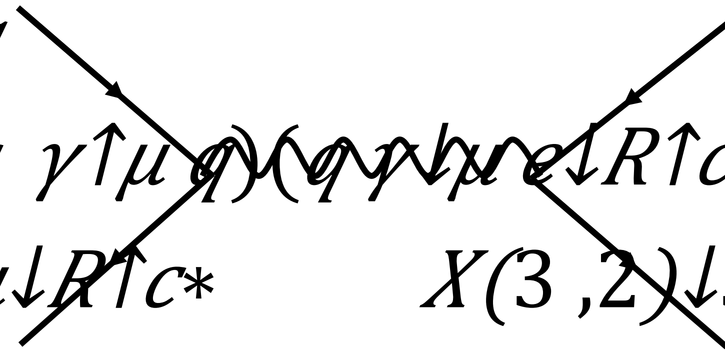
hierarchies of masses and mixings

lepton >>quark (in hierarchies for mixings)

ups >> downs, electrons >> neutrinos (in mass hierarchies)

Nucleon decay($P \to e^+ + \pi^0$)

- Superheavy gauge exchange(dimension 6)

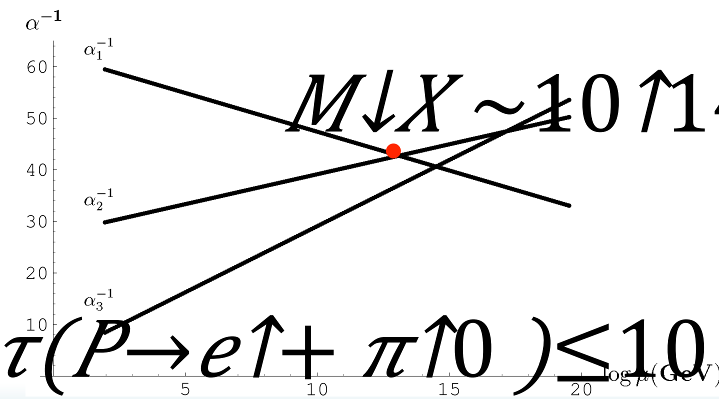


q e_R^{c}

$$\frac{g^2}{M_X^2}\left(u_R^c\, \gamma^\mu\, q\right)\left(q\, \gamma_\mu\, e_R^c\right)$$

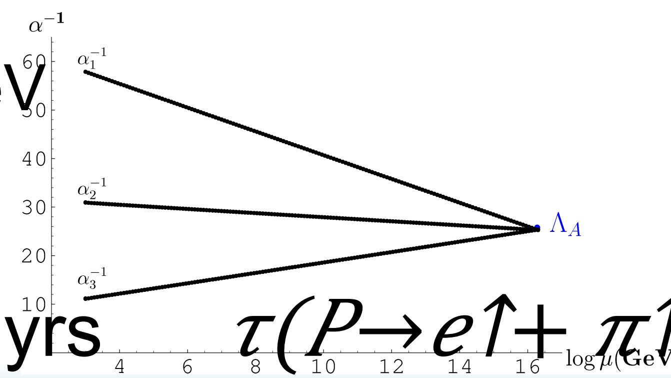
u_R^{c*} $X(3,2)_{5/6}$

$M_X \sim 2\times 10^{16}$



$M_X \sim 10^{14}$ GeV

$\tau(P\to e^+ + \pi^0) \leq 10^{29}$ yrs

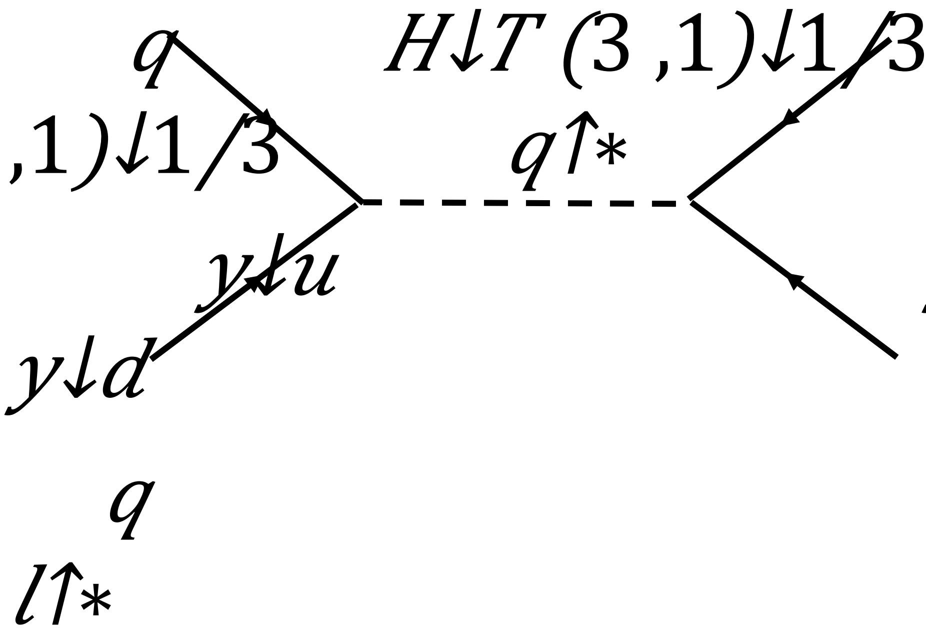


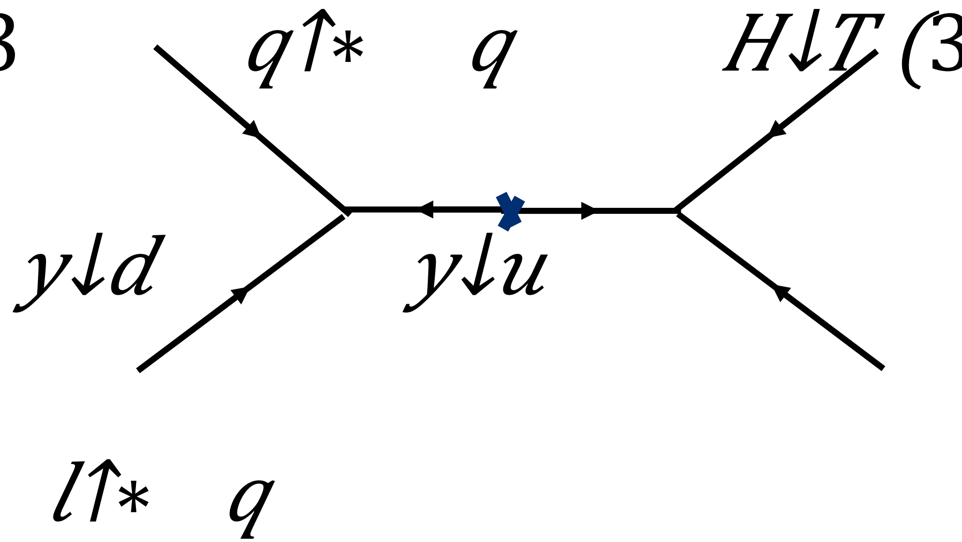
$\tau(P\to e^+ + \pi^0) \sim 10$

$\tau_{exp}(P\to e^+ + \pi^0) > 10^{34}$ yrs

Nucleon decay $(P \rightarrow \nu K^+)$

- Triplet Higgs exchange



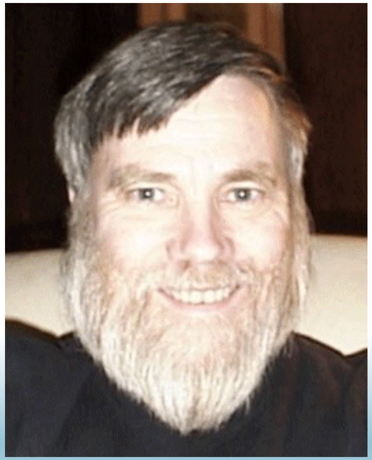


$$y_u y_d / M_{H_T}^2 \; q^c q q^c l \rightarrow$$
$$d^2\theta \; y_u y_d / M_{H_T} \; qqql$$

$M_{H_T} > 10^{12}$ GeV $\rightarrow$ $M_{H_T} > 10^{17}$ GeV

GUT predicts nucleon decay

- No signal for proton decay in (Super)K
  - " I killed GUT" by Koshiba
  - "I gave up GUT" by Georgi



GUT predicts nucleon decay

- No signal for proton decay in (Super)K

  " I killed GUT" by Koshiba

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- Neutrino masses and mixings

The total quark and lepton masses and mixings can be an experimental signature for unification of matters in SU(5) GUT!

2 events in signal region ($P \to \mu^{+} \pi^{0}$

They are consistent with BG expected to be 0.9 events

Results of $p \to \mu^+ \pi^0$

NNN15 by Ikeda

dimension 6!

(analysis proceeds as with $e^+\pi^0$ with additional requirement of 1 Michel-e)

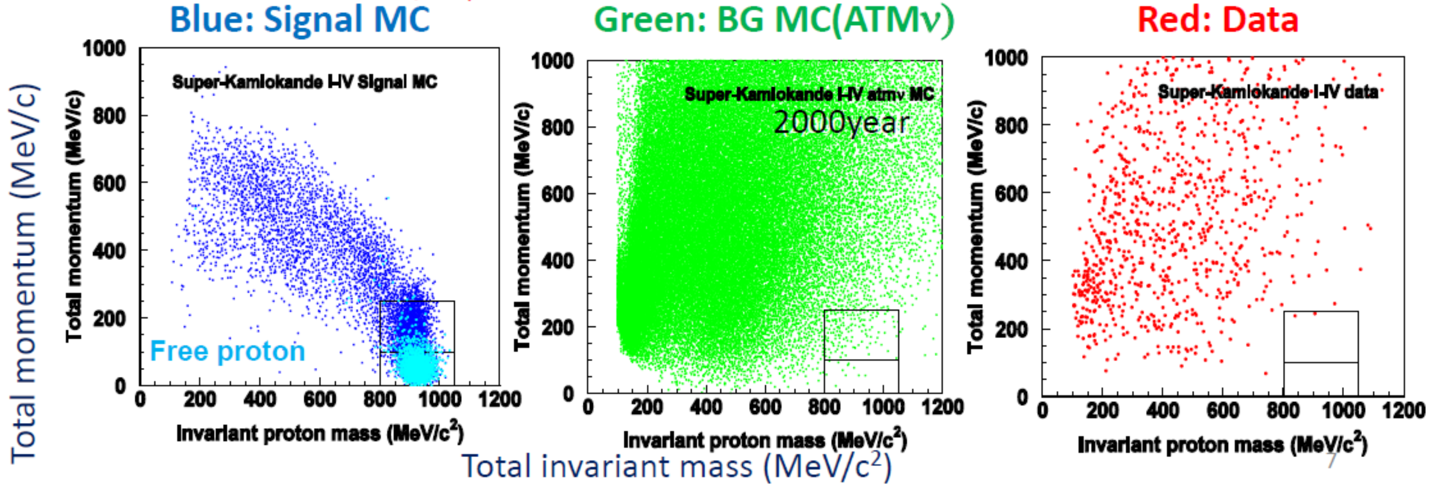
- 306.3 kton·yrs (SKI-IV) (220kt·yrs in PRD)
- signal ε(P_{tot}<250MeV/c): 30-40%
- total expected #BKG:
  - P_{tot}<100: ~0.05, 100≤P_{tot}<250: ~0.82
- no significant data excess

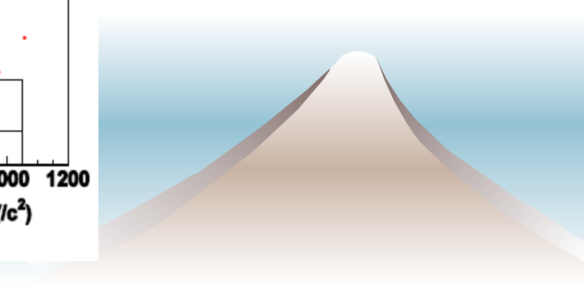
$\tau/B_{p\to\mu\pi^0} > 7.78 \times 10^{33}$ years (90% CL)

$\tau(P \to \mu^{+} \pi^{0}) \sim 10^{34}$ yrs

$\tau_{SUSY} (P \to e^{+} \pi^{0}) \sim 10^{36}$ y

no $P \to e^{+} \pi^{0}$





Summary in part

- Flavor changing nucleon decay($P\rightarrow\mu^{+}+\pi^{0}$)

  1, consistent with observed large neutrino mixings

  2, It suggests higher rank unification group $SO(10)$, E_{6}

- Enhanced nucleon decay via dim. 6 op., while suppressed via dim. 5 op.

  This situation is predicted in natural GUT

  (anomalous U(1) GUT) in 2001. N.M. hep-ph/0110276

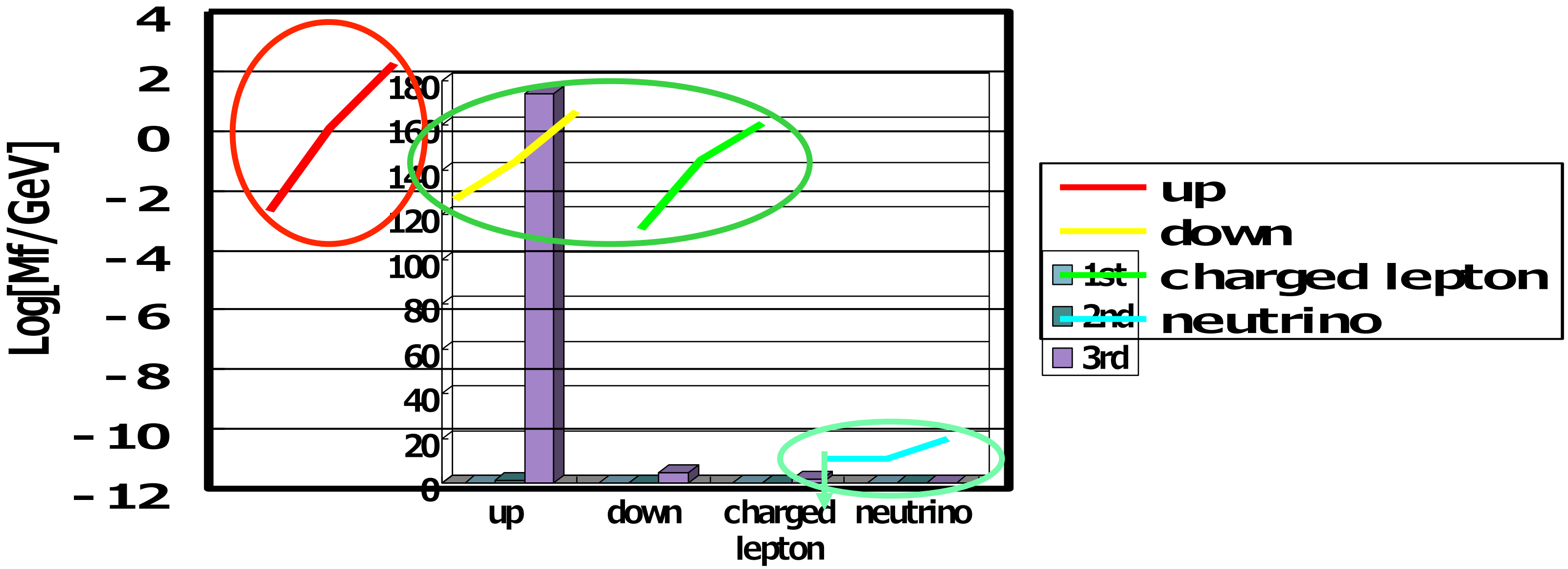
  N.M.- T.Yamashita hep-ph/0209217

  We had studied nucleon decay via dim. 6 op.

Neutrino can be a signature of (SU(5)) GUT!

An assumption can explain the various hierarchies in quark and lepton masses and mixings.

Masses & Mixings and GUT



u, c, t Strongest

Neutrinos Weakest

CKM small mixings

e, μ, τ Middle

MNS large mixings

d, s, b Middle

These can be naturally realized in SU(5) GUT!!

SU(5) SUSY GUT

$$\mathbf{10} = (q, u_R^c, e_R^c) \quad \bar{\mathbf{5}} = (d_R^c, l) \quad \mathbf{1} = \nu_R^c$$

$$Y_u \mathbf{10_i} \mathbf{10_j} \mathbf{5}_H + Y_{(d,e)} \mathbf{10_i} \bar{\mathbf{5}}_\mathbf{j} \bar{\mathbf{5}}_{\bar{H}} + \underbrace{Y_{\nu_D} \bar{\mathbf{5}}_\mathbf{i} \mathbf{1_j} \mathbf{5}_H + M_{\nu_R} \mathbf{1_i} \mathbf{1_j}}_{\frac{Y_\nu}{M} \bar{\mathbf{5}}_\mathbf{i} \bar{\mathbf{5}}_\mathbf{j} \mathbf{5}_H \mathbf{5}_H}$$

$$u \gg d, e \gg \nu$$

⇨ $\mathbf{10_i}$ have stronger hierarchy than $\bar{\mathbf{5}}_\mathbf{i}$

Stronger hierarchy leads to smaller mixings

⇨ Quark mixings(CKM) $\ll$ Lepton mixing(MNS)

$\mathbf{10}_i(q_i)$ $\bar{\mathbf{5}}_i(l_i)$

Mass hierarchy and mixings

- Stronger hierarchy leads to smaller mixings

$$\begin{pmatrix} (\epsilon^2) & \epsilon \\ \epsilon & 1 \end{pmatrix} \to 1, \epsilon^2$$

$$\begin{pmatrix} 1 & \epsilon \\ -\epsilon & 1 \end{pmatrix}$$

Stronger hierarchy $\Longleftrightarrow$ Smaller mixings

SU(5) SUSY GUT

$$\mathbf{10} = (q, u_R^c, e_R^c) \quad \bar{\mathbf{5}} = (d_R^c, l) \quad \mathbf{1} = \nu_R^c$$

$$Y_u \mathbf{10_i 10_j 5}_H + Y_{(d,e)} \mathbf{10_i \bar{5}_j \bar{5}}_{\bar{H}} + \underbrace{Y_{\nu_D} \mathbf{5_i 1_j 5}_H + M_{\nu_R} \mathbf{1_i 1_j}}_{\frac{Y_\nu}{M} \mathbf{\bar{5}_i \bar{5}_j 5}_H \mathbf{5}_H}$$

$$\boxed{u \gg d, e \gg \nu}$$

$\mathbf{10_i}$ have stronger hierarchy than $\bar{\mathbf{5}}_\mathbf{i}$

Stronger hierarchy leads to smaller mixings

Quark mixings(CKM) $\ll$ Lepton mixing(MNS)

$\mathbf{10}_i(q_i)$ $\qquad$ $\bar{\mathbf{5}}_i(l_i)$

Good agreement with masses & mixings

E_6 Grand Unified Theory

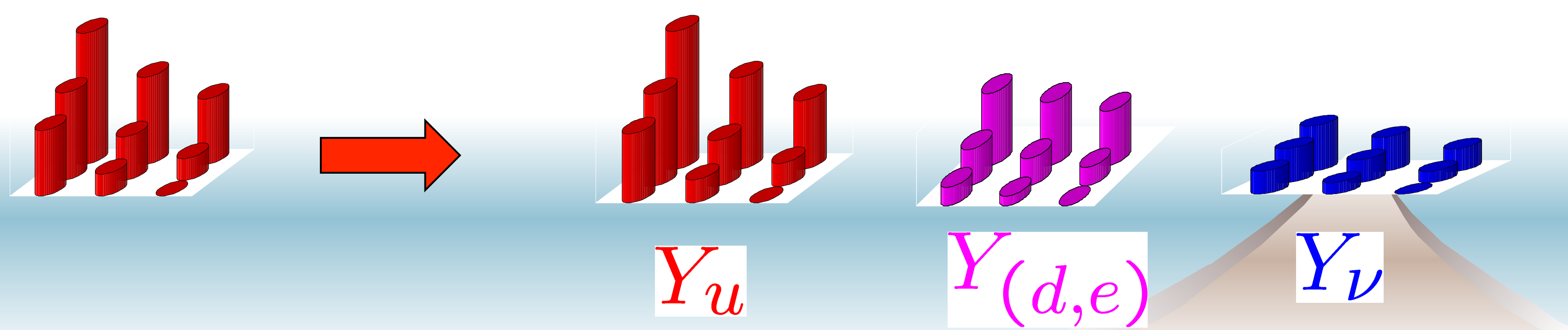
Bando-N.M. 0109
N.M, T. Yamashita 0202

The assumption in SU(5) GUT

10_i have stronger hierarchy than 5_i

can be derived.

Various Yukawa hierarchies can be induced from one Yukawa hierarchy in E_6 GUT.



Guisey-Ramond-Sikivie, Aichiman-Stech, Shafi, Barbieri-Nanopoulos, Bando-Kugo,…

E_6 Unification

$$\mathbf{27}_i = \mathbf{16}_i[\mathbf{10}_i + \underbrace{\bar{\mathbf{5}}_i + \mathbf{1}_i] + \mathbf{10}_i[}_{\langle \mathbf{16}_C \rangle}\underbrace{\mathbf{5}_i + \bar{\mathbf{5}}_i}_{\langle \mathbf{1}_H \rangle}] + \mathbf{1}_i[\mathbf{1}_i]$$

$(i = 1, 2, 3)$

Three of six $\bar{\mathbf{5}}$ become superheavy after the breaking

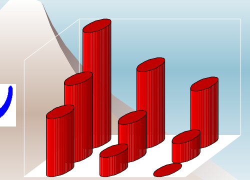
$$E_6 \xrightarrow[\langle \mathbf{1}_H \rangle]{} SO(10) \xrightarrow[\langle \mathbf{16}_C \rangle]{} SU(5)$$

$27^3 \to 16 \cdot 16 \cdot 10 + 10 \cdot 10 \cdot 1$

$\langle \mathbf{1}_H \rangle \geq \langle \mathbf{16}_C \rangle$

$$W = Y^H \mathbf{27}_i \mathbf{27}_j \langle \mathbf{27}_H \rangle + Y^C \mathbf{27}_i \mathbf{27}_j \langle \mathbf{27}_C \rangle$$

Once we fix $Y^H, Y^C, \langle \mathbf{27}_H \rangle, \langle \mathbf{27}_C \rangle$,
three light modes of six $\bar{\mathbf{5}}$ are determined.

We assume all Yukawa matrices $\sim$ 

Milder hierarchy for $\bar{\mathbf{5}}_i(l)$

Bando-N.M. 0109
N.M, T. Yamashita 0202

- $\bar{\mathbf{5}}$ fields from $\mathbf{27}_3$ become superheavy.

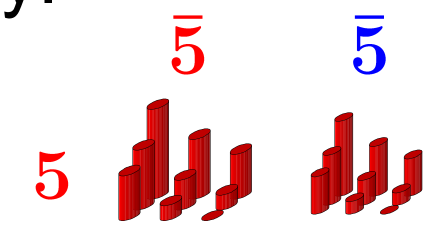
$\bar{\mathbf{5}}_3 \quad \bar{\mathbf{5}}_3$

$\bar{\mathbf{5}}_2 \quad \bar{\mathbf{5}}_2$

$\bar{\mathbf{5}}_1 \quad \bar{\mathbf{5}}_1$

Superheavy

unless $\langle \mathbf{27}_H \rangle >> \langle \mathbf{27}_C \rangle$



- Light modes $(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2)$ have smaller Yukawa couplings and milder hierarchy than $(\mathbf{10}_1, \mathbf{10}_2, \mathbf{10}_3)$

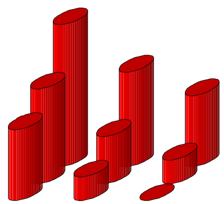
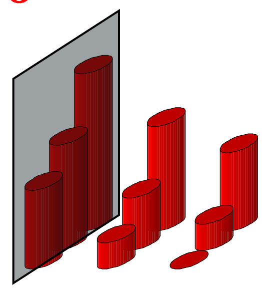
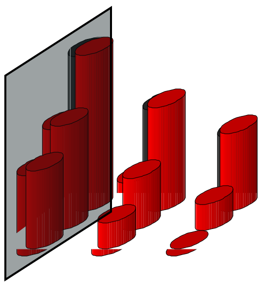
$$Y_{\nu_D}, Y_d << Y_u$$

•Larger mixings in lepton sector than in quark sector.
•Small $\tan\beta$
•Small neutrino Dirac masses

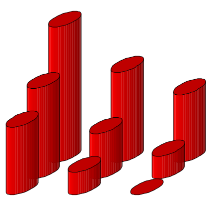
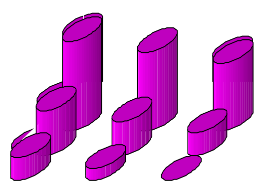
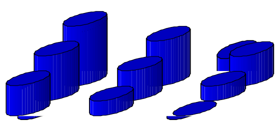
} Suppressed radiative LFV

How to obtain various Yukawas?

$$Y_u \mathbf{10_i 10_j 5}_H + Y_{(d,e)} \mathbf{10_i \bar{5}_j \bar{5}}_{\bar{H}} + Y_\nu \mathbf{\bar{5}_i \bar{5}_j 5}_H \mathbf{5}_H$$

$Y_u \sim$  $Y_{(d,e)} \sim$  $Y_\nu \sim$ 

$$(\mathbf{\bar{5}_1}, \mathbf{\bar{5}_2}, \mathbf{\bar{5}_3}) \rightarrow (\mathbf{\bar{5}_1}, \mathbf{\bar{5}'_1}, \mathbf{\bar{5}_2})$$

SO(10) GUT relations

$$Y_d = Y_e^T = Y_u = Y_{\nu_D}$$

$$Y_u \sim \begin{array}{c c} & \begin{array}{ccc} \mathbf{10}_1 & \mathbf{10}_2 & \mathbf{10}_3 \end{array} \\ \begin{array}{c} \mathbf{10}_1 \\ \mathbf{10}_2 \\ \mathbf{10}_3 \end{array} & \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \end{array} \begin{array}{l} \}\lambda \\ \}\lambda^2 \end{array}$$

$$Y_{\nu_D} \sim \begin{array}{c c} & \begin{array}{ccc} \mathbf{1}_1 & \mathbf{1}_2 & \mathbf{1}_3 \end{array} \\ \begin{array}{c} \bar{\mathbf{5}}_1 \\ \bar{\mathbf{5}}_1 \\ \bar{\mathbf{5}}_2 \end{array} & \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^{5.5} & \lambda^{4.5} & \lambda^{2.5} \\ \lambda^5 & \lambda^4 & \lambda^2 \end{pmatrix} \end{array} \begin{array}{l} \}\lambda^{0.5} \\ \}\lambda^{0.5} \end{array}$$

$$(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2)$$

$$\bar{\mathbf{5}}_1 + \lambda^{\Delta}\bar{\mathbf{5}}_3 \ (\Delta = 3 - r)$$

$$Y_d \sim Y_e^T \sim \begin{array}{c c} & \begin{array}{ccc} \bar{\mathbf{5}}_1 & \bar{\mathbf{5}}_1 & \bar{\mathbf{5}}_3 \end{array} \\ \begin{array}{c} \mathbf{10}_1 \\ \mathbf{10}_2 \\ \mathbf{10}_3 \end{array} & \begin{pmatrix} \lambda^6 & \lambda^{5.5} & \boxed{\lambda^3} \\ \lambda^5 & \lambda^{4.5} & \boxed{\lambda^2} \\ \lambda^3 & \lambda^{2.5} & \boxed{1} \end{pmatrix} \end{array} \begin{array}{l} \}\lambda \\ \}\lambda^2 \end{array}$$

$$\underbrace{\quad\quad}_{\lambda^{0.5}}\underbrace{\quad\quad}_{\lambda^{0.5}}$$

$$\lambda^r \equiv \frac{\langle \mathbf{27}_C \rangle}{\langle \mathbf{27}_\Phi \rangle} \sim \lambda^{0.5}$$

Small $\tan\beta$

Small Y_{ν_D}

Large $U_{e3} \sim \lambda$ Confirmed in 2012!

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$V_{MNS} \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

Right-handed neutrinos

$$W = \frac{Y^{XY}}{\Lambda} \mathbf{27}_i \mathbf{27}_j \langle \overline{27}_X \rangle \langle \overline{27}_Y \rangle$$

$$X, Y = \bar{H}, \bar{C}$$

$$\Rightarrow \quad M_R = Y^{XY} \frac{\langle \overline{27}_X \rangle \langle \overline{27}_Y \rangle}{\Lambda}$$

- The same hierarchy $Y^{XY} \sim Y^H \sim Y^C$

$$M_\nu = Y_{\nu_D} M_R^{-1} Y_{\nu_D}^T \sim \begin{pmatrix} \lambda^2 & \lambda^{1.5} & \lambda \\ \lambda^{1.5} & \lambda & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \frac{\langle H_u \rangle^2 \Lambda}{\langle \mathbf{1}_H \rangle^2}$$

$$\frac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \sim \frac{m^2_{\nu_\mu}}{m^2_{\nu_\tau}} \sim \lambda^2$$

LMA for solar neutrino problem

1st Summary

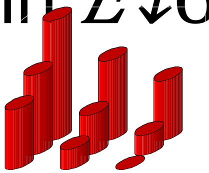
1, Quark and lepton masses and mixings can be a qualitative evidence of GUT.

“$\mathbf{10}_i$ induce stronger hierarchy in Yukawa than 5_i ”

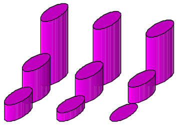
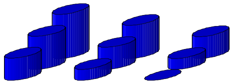
2 , Diagonalising matrices are fixed as

$$V_{10} \sim V_{CKM}, \quad V_5 \sim V_{MNS}$$

3, The assumption in SU(5) can be derived in E_6 .

One basic Yukawa hierarchy $Y \sim Y_u$ 

The other Yukawa hierarchies

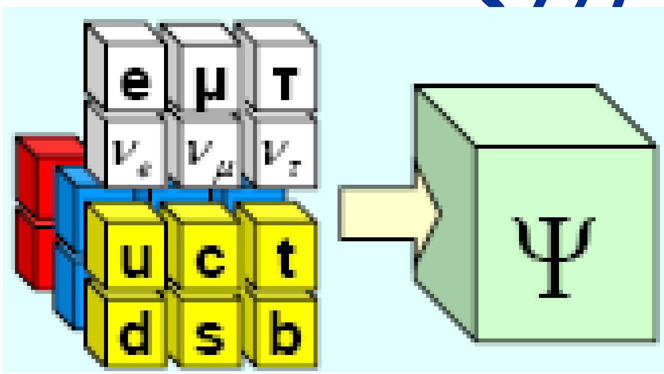
$Y_u \sim$  $Y_{(d,e)} \sim$  $Y_\nu \sim$ 

4, $(\bar{\mathbf{5}}_1, \bar{\mathbf{5}}_1, \bar{\mathbf{5}}_2)$ is important.

5, Large $U_{e3} \sim \lambda$ $U_{e3}^{\exp} \sim 0.15$ by T2K, DayaBay, RENO

6, Large $\delta_L \sim O(1)$

Family symmetry $SU(3)_F$ ($SU(2)_F$)



N.M. 0212, 0402
Ishiduki-Kim-N.M.-Sakurai 0901, 0910
Kawase-N.M. 1005
N.M.-Takayama 1202

E_6 GUT can obtain realistic Yukawa structures so naturally that we can obtain an E_6 GUT in which all three generation quark and leptons can be unified into a single (or two) field(s) by introducing family symmetry.

By breaking the family symmetry, realistic quark and lepton masses and mixings can be obtained.

Spontaneous CP violation solves SUSY CP problem with O(1) KM phase and O(1) neutrino phase(thermal leptogenesis is possible)

Peculiar sfermion mass spectrum is predicted. $m_3 = m_{\tau_R} = m_{t_R} = m_{q_3}$

$m_{10}^2 = \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m_3^2 \end{pmatrix}$, $m_{\bar{5}}^2 = \begin{pmatrix} m^2 & & \\ & m^2 & \\ & & m^2 \end{pmatrix}$

$\Psi_a\ (27,2) \ni 10_1, 10_2, \bar{5}_1, \bar{5}_2, \bar{5}_3$

$\Psi_3\ (27,1) \ni 10_3$

Effective (Natural) SUSY type mass spectrum if $m_3 \ll m$.

Nucleon decay

Nucleon decay($\Lambda_G \sim 2\times 10^{16}$ GeV)

- $g_U^2/M_X^2\ \ qqql$(dim. 6 op.） gauge int.（X,Y)

  main decay mode $\tau_{exp}\ (p\to e\pi)>10^{34}$ years

  → $M_X>10^{15-16}$ GeV

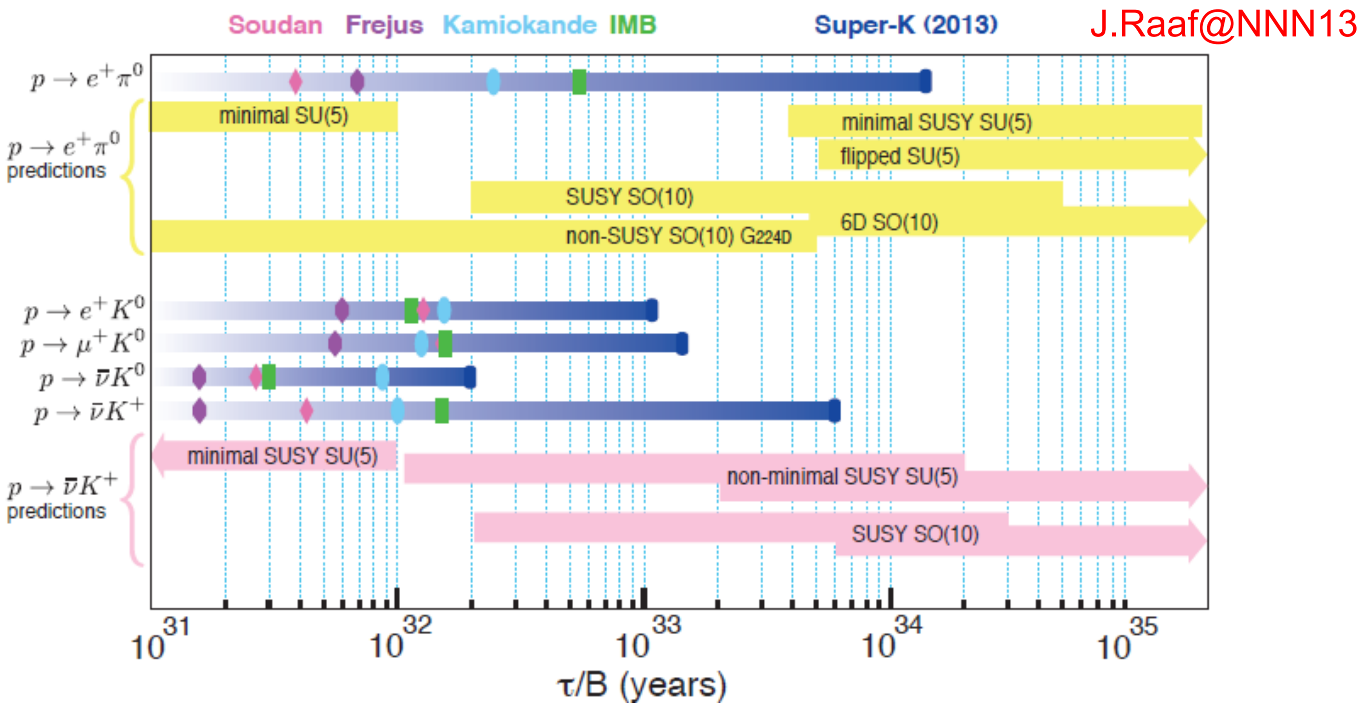
- $y^2/M_{H_T}\ \ qqq\,l$(dim. 5 op.） Yukawa int.(H_T)

main decay mode $\tau_{exp}\ (p\to K\nu)>6\times 10^{33}$ years

→ $M_{H_T}>10^{16-17}$ GeV（minimal

Why nucleon decay via dim. 6 operators?

- Nucleon decay via dim. 5 operators depends on models strongly (and on solutions for finetuning problem in Higgs)



- In Natural (Anomalous U(1)) GUT, nucleon decay via dim. 5 op. is suppressed, but that via dim. 6 op. is enhanced.

Typically $\tau(P\to e\pi)<10↑35$ years

Nucleon decay via dim. 6（gauge int.)

- Predictions depends on Yukawa couplings.

  Decay via weak force depends on CKM mixings.

  CKM mixings can be fixed by Yukawa couplings.

  Predictions depends on explicit models.

- We have reached to a picture for Yukawas.

"10_i induce stronger Yukawa hierarchy than 5_i"

$V_{10} \sim V_{CKM}$, $V_5 \sim V_{MNS}$ →Predictions are possible

In E_6, light modes $(5_1, 5_1, 5_2)$

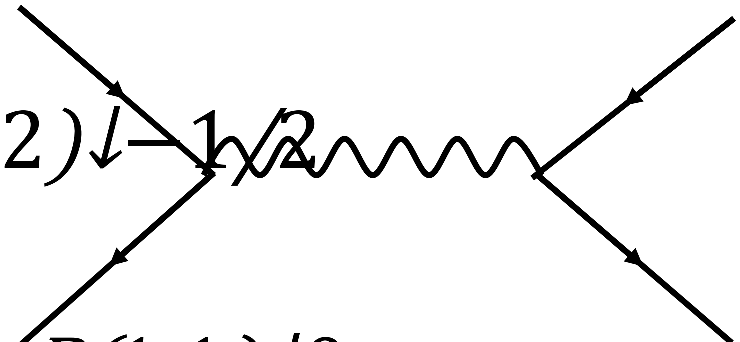
$16_i = 10_i + 5_i + 1_i$ $\quad$ $10_i = 5_i + 5_i$

Nucleon decay via dim. 6 op. $qqql$.

- Quantum # of superheavy gauge boson?

$\mathbf{10} = q(3,2)_{1/6} + u_R^c(3,1)_{-2/3} + e_R^c(1,1)_1$

$\mathbf{5} = d_R^c(3,1)_{1/3} + l(1,2)_{-1/2}$



q

$\mathbf{24} = G(8,1)_0 + W(1,3)_0 + B(1,1)_0$

$\quad + X(3,2)_{5/6} + X(3,2)_{-5/6}$

u_R^{c*} $\quad X(3,2)_{5/6}$

$\mathbf{45} = \mathbf{24} + \mathbf{10} + \mathbf{10} + 1$ $\quad d_R^{c*}$ $\quad X'$

$(3,2)_{-1/6}$

$\mathbf{78} = \mathbf{45} + \mathbf{16} + \mathbf{16} + 1$ $\quad$ **45**$\ni X'$ $\quad \mathbf{10}_{i} 1$

GUT model identification by nucleon decay

N.M.-Muramatsu 13

two important ratios of partial decay widths to identify GUT model

$$R_1 \equiv \frac{\Gamma_{n\to\pi^0+\nu^c}}{\Gamma_{p\to\pi^0+e^c}}$$

to identify grand unification group

$$R_2 \equiv \frac{\Gamma_{p\to K^0+\mu^c}}{\Gamma_{p\to\pi^0+e^c}}$$

to identify Yukawa structure at GUT scale

Small letter（**16**）、Large letter（**10**）

$$\begin{aligned}
\mathcal{L}_{eff} &= \frac{g_{GUT}^2}{M_{X_{SU(5)}}^2}\Big\{(\overline{e^c_{R_i}}u_{Rj})(\overline{u^c_{L_j}}d_{Li}) + (\overline{e^c_{R_i}}u_{Rj})(\overline{u^c_{L_i}}d_{Lj}) \\
&\quad + (\overline{e^c_{L_i}}u_{Lj})(\overline{u^c_{R_j}}d_{Ri}) + (\overline{E^c_{L_i}}u_{Lj})(\overline{u^c_{R_j}}D_{Ri}) \\
&\quad - (\overline{\nu^c_{L_i}}d_{Lj})(\overline{u^c_{R_j}}d_{Ri}) - (\overline{N^c_{L_i}}d_{Lj})(\overline{u^c_{R_j}}D_{Ri})\Big\} \\
&\quad + \frac{g_{GUT}^2}{M_{X_{SO(10)}}^2}\Big\{(\overline{e^c_{L_i}}u_{Lj})(\overline{u^c_{R_i}}d_{Rj}) - (\overline{\nu^c_{L_i}}d_{Lj})(\overline{u^c_{R_i}}d_{Rj})\Big\} \\
&\quad + \frac{g_{GUT}^2}{M_{X_{E_6}}^2}\Big\{(\overline{E^c_{L_i}}u_{Lj})(\overline{u^c_{R_i}}D_{Rj}) - (\overline{N^c_{L_i}}d_{Lj})(\overline{u^c_{R_i}}D_{Rj})\Big\}
\end{aligned}$$

$SU(5)$ GUT

$SO(10)$ GUT

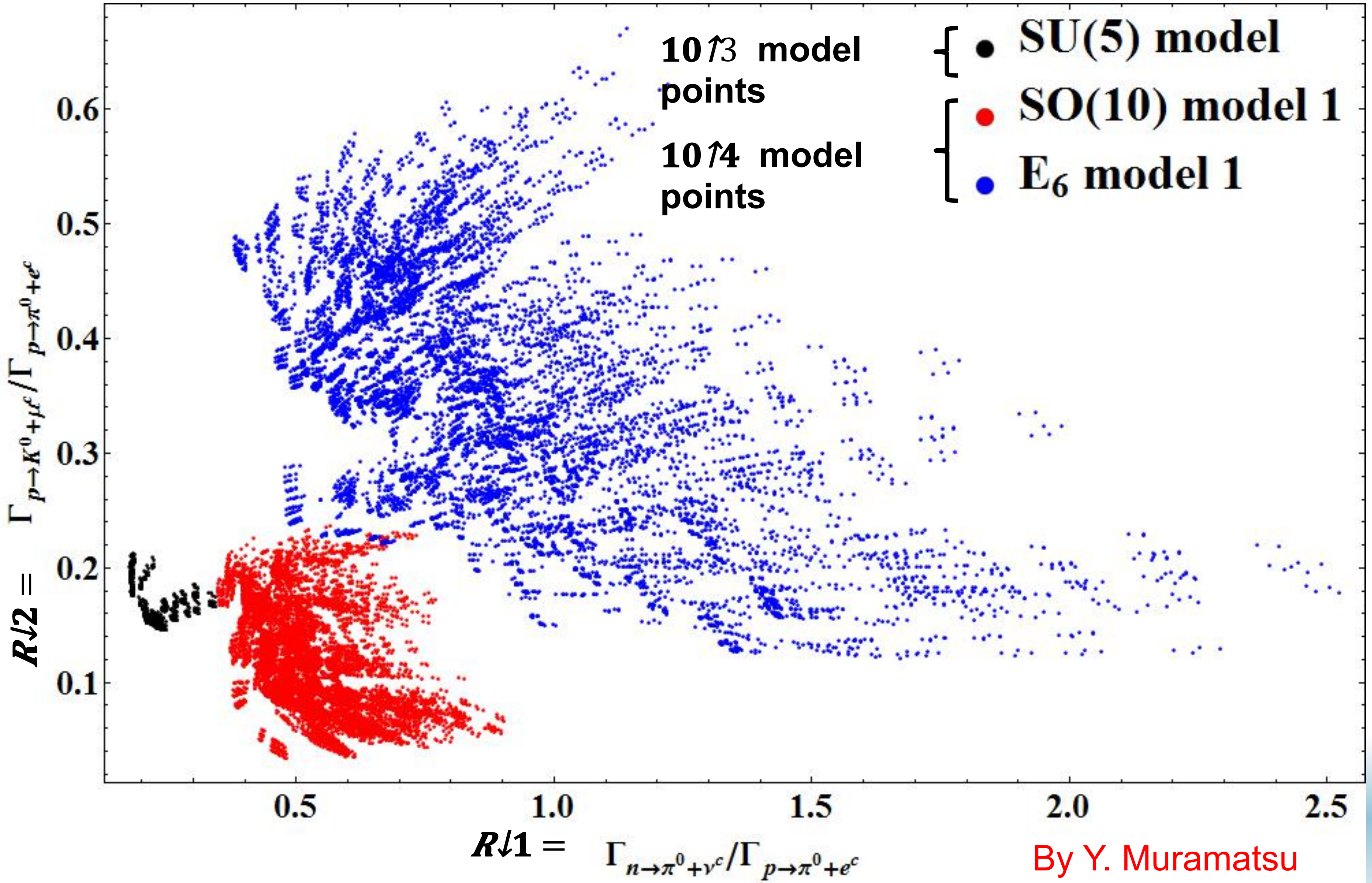
E_6 GUT

: dimension-6 operators which have anti electron in final state

: dimension-6 operators which have anti neutrino in final state

Muramatsu's slide

N.M.-Muramatsu 1307



By Y. Muramatsu

Flavor changing neucleon decay

N.M.-Muramatsu 1601

- Other modes for identification of group.

  $V_{10} \sim V_{CKM}, \; V_{5} \sim V_{MNS} \rightarrow$ FCND

- FCND occurrs easier in larger rank group.

  $P \rightarrow \mu\pi, \, eK, \, etc.$

$(10 \!\uparrow\!+ \cdot 10)\!\uparrow\! 2$

$(5 \!\uparrow\!+ \cdot 5)(10 \!\uparrow\!+ \cdot 10)\!\uparrow$

$$
\begin{aligned}
\mathcal{L}_{eff} = \; & \frac{g^2_{GUT}}{M^2_{X_{SU(5)}}} \{ (\overline{e^c_{Ri}} u_{Rj})(\overline{u^c_{Lj}} d_{Li}) + (\overline{e^c_{Ri}} u_{Rj})(\overline{u^c_{Li}} d_{Lj}) \\
& + (e^c_{Li} u_{Lj})(u^c_{Rj} d_{Ri}) + (E^c_{Li} u_{Lj})(u^c_{Rj} D_{Ri}) \\
& - (\nu^c_{Li} d_{Lj})(u^c_{Rj} d_{Ri}) - (N^c_{Li} d_{Lj})(u^c_{Rj} D_{Ri}) \} \\
& + \frac{g^2_{GUT}}{M^2_{X_{SO(10)}}} \{ (\overline{e^c_{Li}} u_{Lj})(\overline{u^c_{Ri}} d_{Rj}) - (\overline{\nu^c_{Li}} d_{Lj})(\overline{u^c_{Ri}} d_{Rj}) \} \\
& + \frac{g^2_{GUT}}{M^2_{X_{E_6}}} \{ (\overline{E^c_{Li}} u_{Lj})(\overline{u^c_{Ri}} D_{Rj}) - (\overline{N^c_{Li}} d_{Lj})(\overline{u^c_{Ri}} D_{Rj}) \}
\end{aligned}
$$

$SU(5)$ GUT

$SO(10)$ GUT

E_6 GUT

2 events in signal region ($P \rightarrow \mu\pi$)

They are consistent with BG expected to be 0.9 events

NNN15 by Ikeda

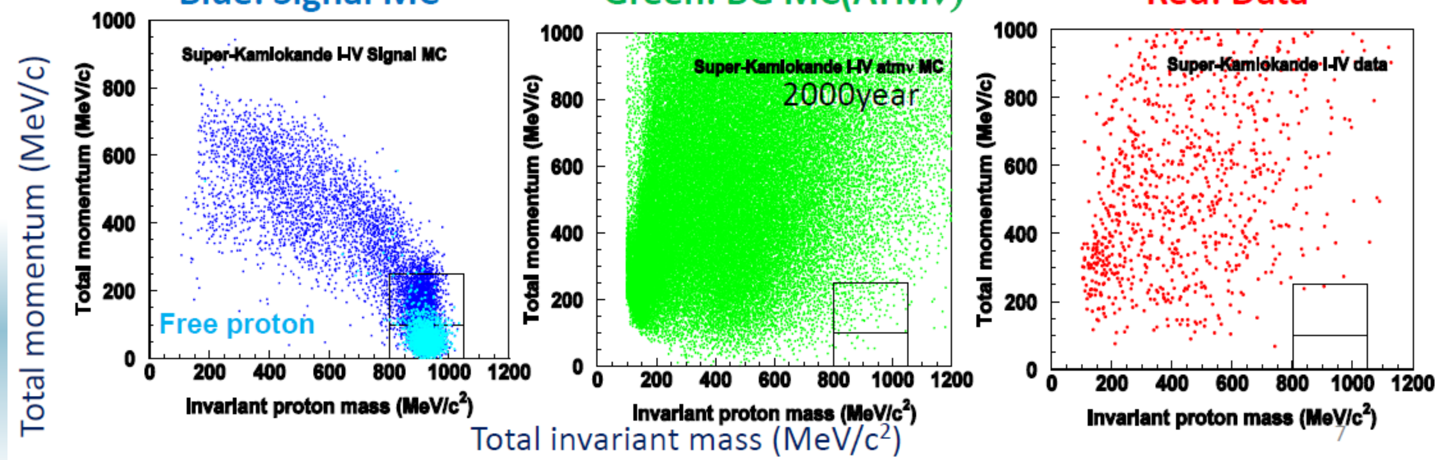
Results of $p \rightarrow \mu^+\pi^0$

(analysis proceeds as with $e^+\pi^0$ with additional requirement of 1 Michel-e)

- 306.3 kton·yrs (SKI-IV) (220kt·yrs in PRD)
- signal ε(P_{tot}<250MeV/c): 30-40%
- total expected #BKG:
  - P_{tot}<100: ~0.05, 100≤P_{tot}<250: ~0.82
- no significant data excess

$$\tau/B_{p\rightarrow\mu\pi 0} > 7.78 \times 10^{33} \text{ years (90\% CL)}$$

Blue: Signal MC Green: BG MC(ATMν) Red: Data



Can $P \to \mu\pi$ be main decay mode?

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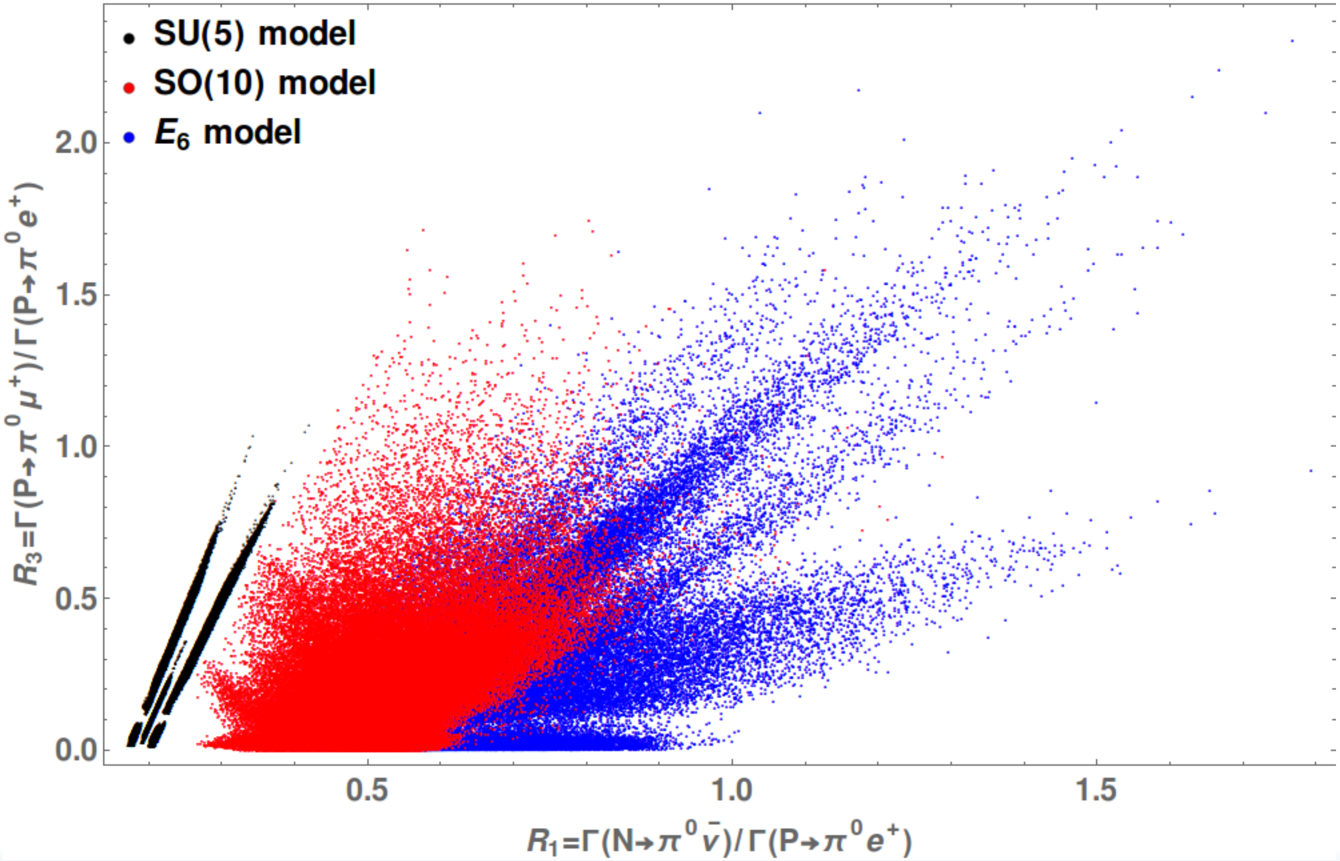
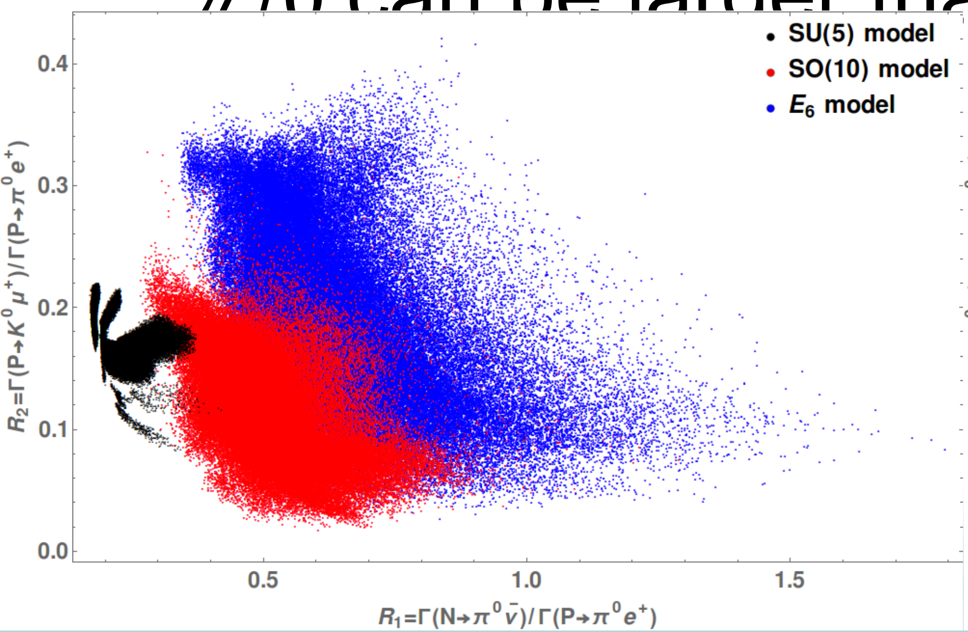


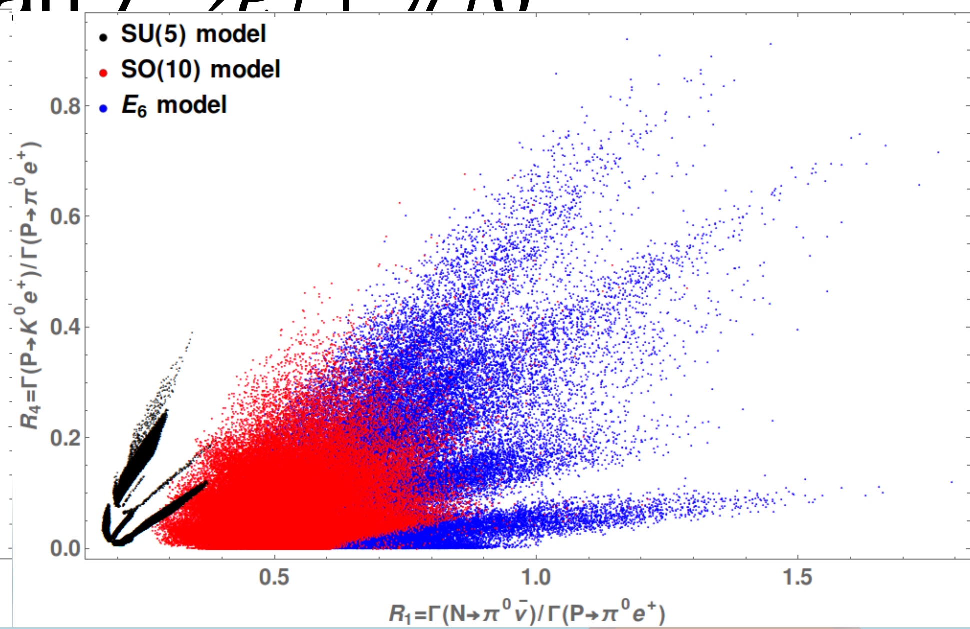
If the events are real signal,
larger rank unification group is preferable!
Larger $\Gamma(P \to \mu^+ \pi^0)$ leads to larger $\Gamma(N \to \nu \pi^0)$.

Which mode is discovered next?

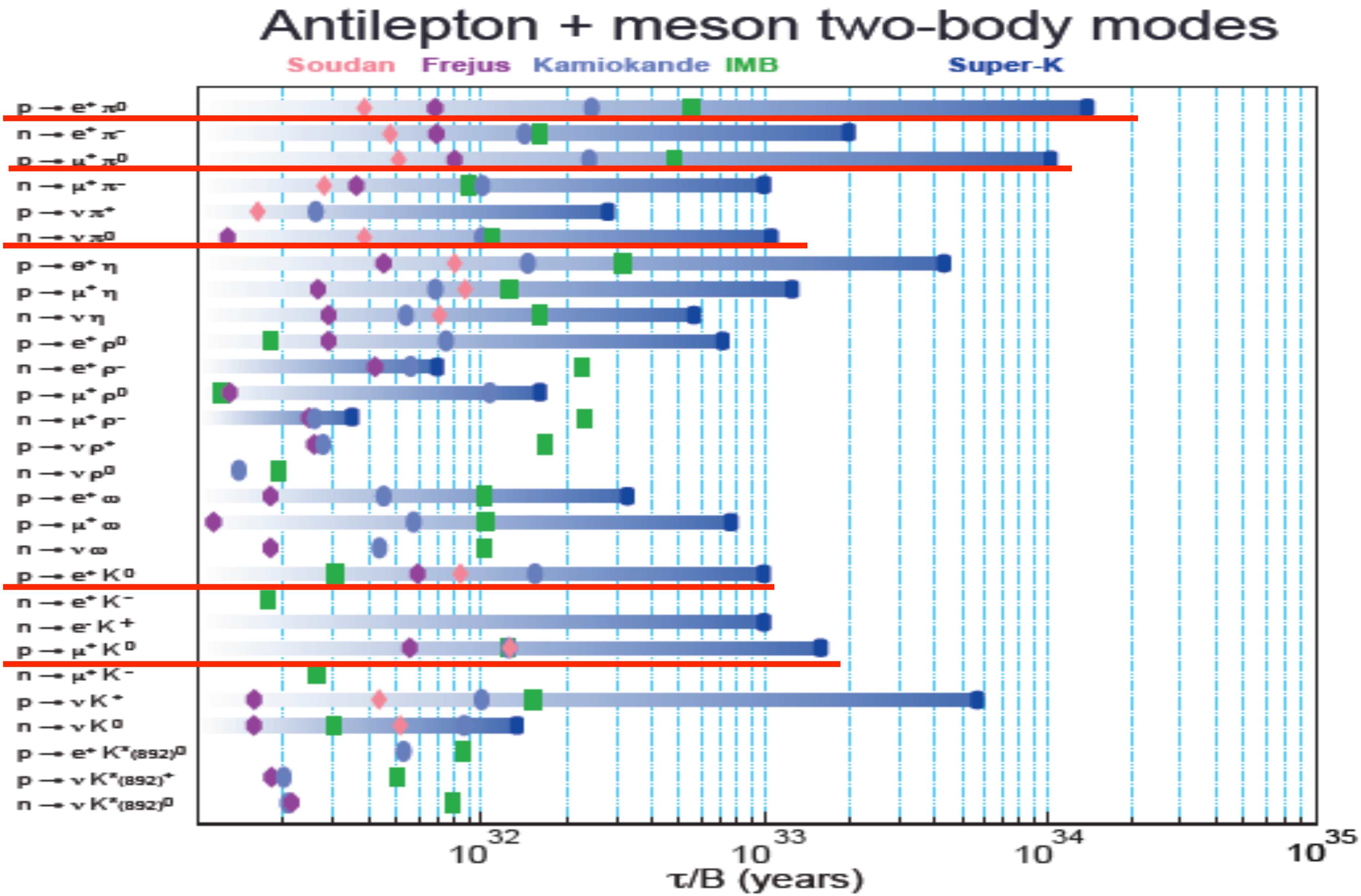
N.M.-Muramatsu 1601

- $P \to e^{+} \pi^{0}$, $N \to \nu \pi^{0}$, $P \to e^{+} K^{0}$, $P \to \mu^{+} K^{0}$
- $P \to e^{+} \pi^{0}$ must be next, although $N \to \nu \pi^{0}$ can be larger than $P \to e^{+} \pi^{0}$



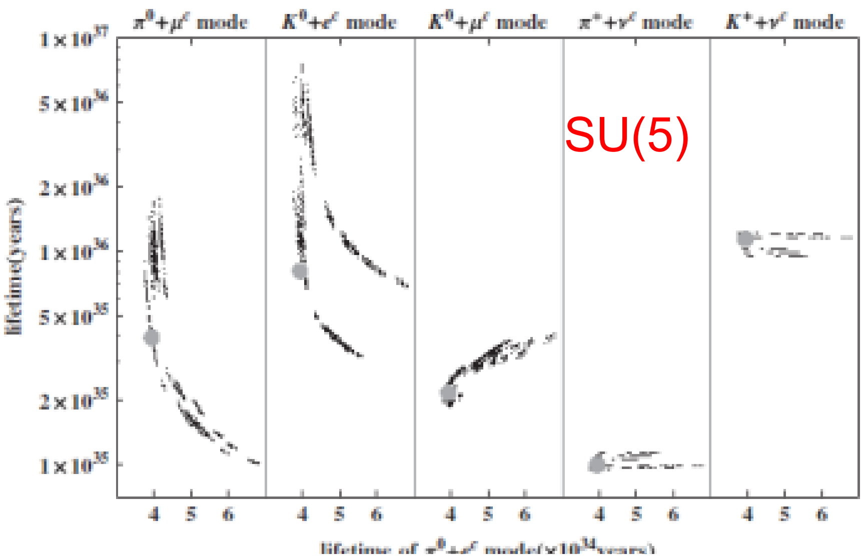


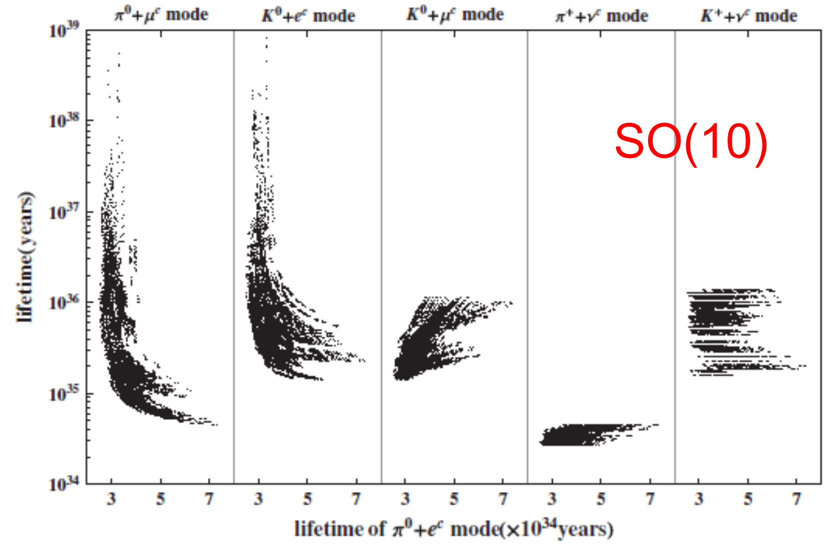
J.Raaf@NNN13

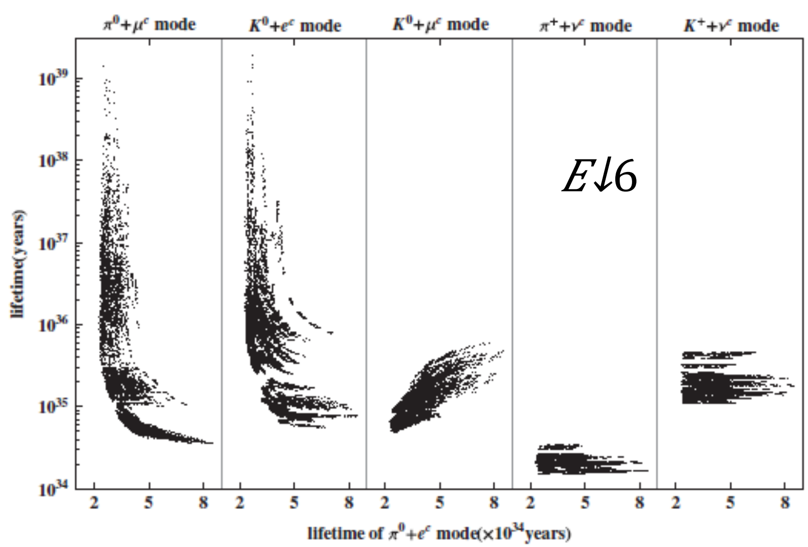

Antilepton + meson two-body modes
Soudan
Frejus
Kamiokande
IMB
Super-K
p → e⁺ π⁰
n → e⁺ π⁻
p → μ⁺ π⁰
n → μ⁺ π⁻
p → ν π⁺
n → ν π⁰
p → e⁺ η
p → μ⁺ η
n → ν η
p → e⁺ ρ⁰
n → e⁺ ρ⁻
p → μ⁺ ρ⁰
n → μ⁺ ρ⁻
p → ν ρ⁺
n → ν ρ⁰
p → e⁺ ω
p → μ⁺ ω
n → ν ω
p → e⁺ K⁰
n → e⁺ K⁻
n → e⁻ K⁺
p → μ⁺ K⁰
n → μ⁺ K⁻
p → ν K⁺
n → ν K⁰
p → e⁺ K*(892)⁰
p → ν K*(892)⁺
n → ν K*(892)⁰
10^{32}
10^{33}
10^{34}
10^{35}
τ/B (years)

We should know FCND before signal!

N.M.-Muramatsu 1307







We should have commented on FCND though most of model points predict larger $\Gamma(P\to e^+ + \pi^0)$ than $\Gamma(P\to \mu^+ + \pi^0)$.

We should consider the difference of efficiencies between $P\to\mu^+ + \pi^0$ and $P\to\nu\pi$

Summary

Quark and lepton masses and mixings can be a qualitative signature for unification of matters in SU(5)

An assumption "10_i induce stronger hierarchy than 5_i"

(Neutrino experiments play an important role)

E_6 GUT explains assumption large $U_{e3} \sim \lambda \leftrightarrow 0.15$, $\delta_L \sim O(1)$

$$(5_1, 5_1, 5_2) \quad 16_i = 10_i + 5_i + 1_i \quad 10_i = 5_i + 5_i$$

$$(10_1, 10_2, 10_3)$$

Possible in $SO(10)$ if 10 matter is included

We understand Yukawa couplings in SU(5), SO(10), E_6 GUT

Diagonalizing matrices are fixed as $V_{10} \sim V_{CKM}$, $V_5 \sim V_{MNS}$

Summary

"10_i induce stronger hierarchy than $\bar{5}_i$"

An assumption in SU(5)

A result in E6 (or SO(10))

E_6 GUT explains assumption large $U_{e3} \sim \lambda \leftrightarrow 0.15$, $\delta_L \sim O(1)$

$(\bar{5}_1, \bar{5}'_1, \bar{5}_2)$ $16_i = 10_i + \bar{5}_i + 1_i$ $10_i = 5_i + \bar{5}_i$

$(10_1, 10_2, 10_3)$ Possible in $SO(10)$ if 10 matter is included

Diagonalizing matrices are fixed as $V_{10} \sim V_{CKM}$, $V_{\bar{5}} \sim V_{MNS}$

It reduces the ambiguities for prediction of nucleon decay.

We calculated various partial decay widths for nucleon decay

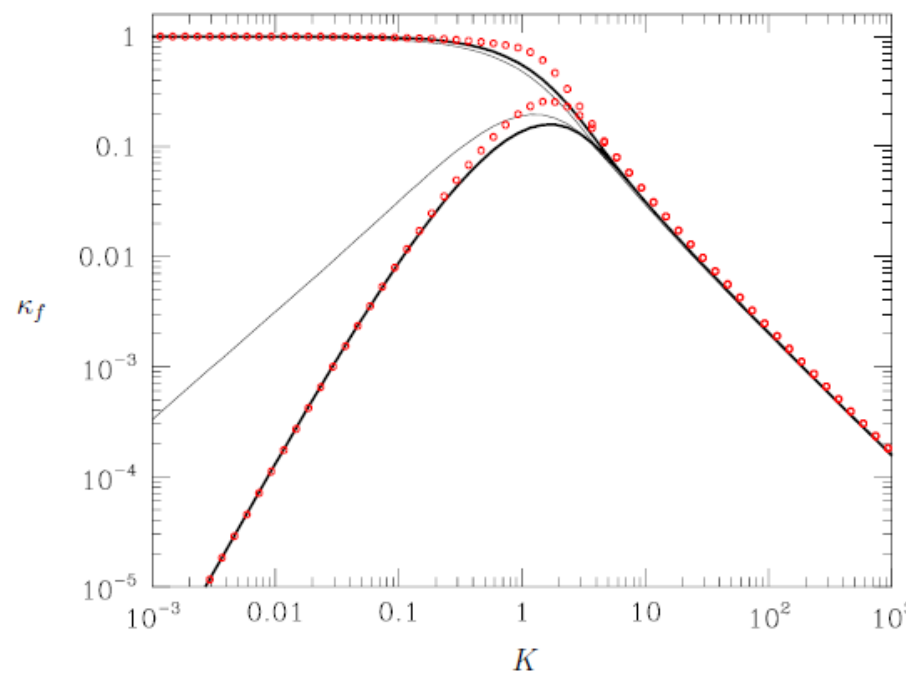
Thermal leptogenesis

- Right-handed neutrino decay produces lepton number
- Basically the abundance is fixed by

$$K = \Gamma_D / H \qquad \epsilon = \Gamma(N_1 \to l + H_u) - \Gamma(N_1 \to l + H_u^{+}) / \Gamma(N_1 \to l + H_u) - \Gamma(N_1 \to l + H_u^{+})$$

- For sufficient leptogenesis

$$K \sim 1 \qquad \epsilon \sim 10^{-7}$$



Thermal leptogenesis in E_6 GUT

Ishihara-N.M.-Takegawa-Yamanaka 1508

- Y_{ν_D} , M_{ν_R} are determined by the symmetry in natural GUT.

($M_1 \sim 6\times 10^{7}$ GeV This is below the Ibarra's lower bound)

$\Rightarrow K \sim 40,\ \epsilon \sim 5\times 10^{-9}$ too small baryon #

($K \sim 1,\ \epsilon \sim 10^{-7}$ is needed

	Ψ_1	Ψ_2	Ψ_3	H	$\bar{H}$	C	$\bar{C}$	A
E_6	**27**	**27**	**27**	**27**	$\overline{\mathbf{27}}$	**27**	$\overline{\mathbf{27}}$	**78**
$U(1)_A$	$\frac{9}{2}$	$\frac{7}{2}$	$\frac{3}{2}$	-3	1	-4	-1	-1

- Three important observations

1, $K \propto M_1^{-1}$, $\epsilon \propto M_1$

$\Rightarrow$ Enhancement of M_1 may improve it.

2, The enhancement can be expected.

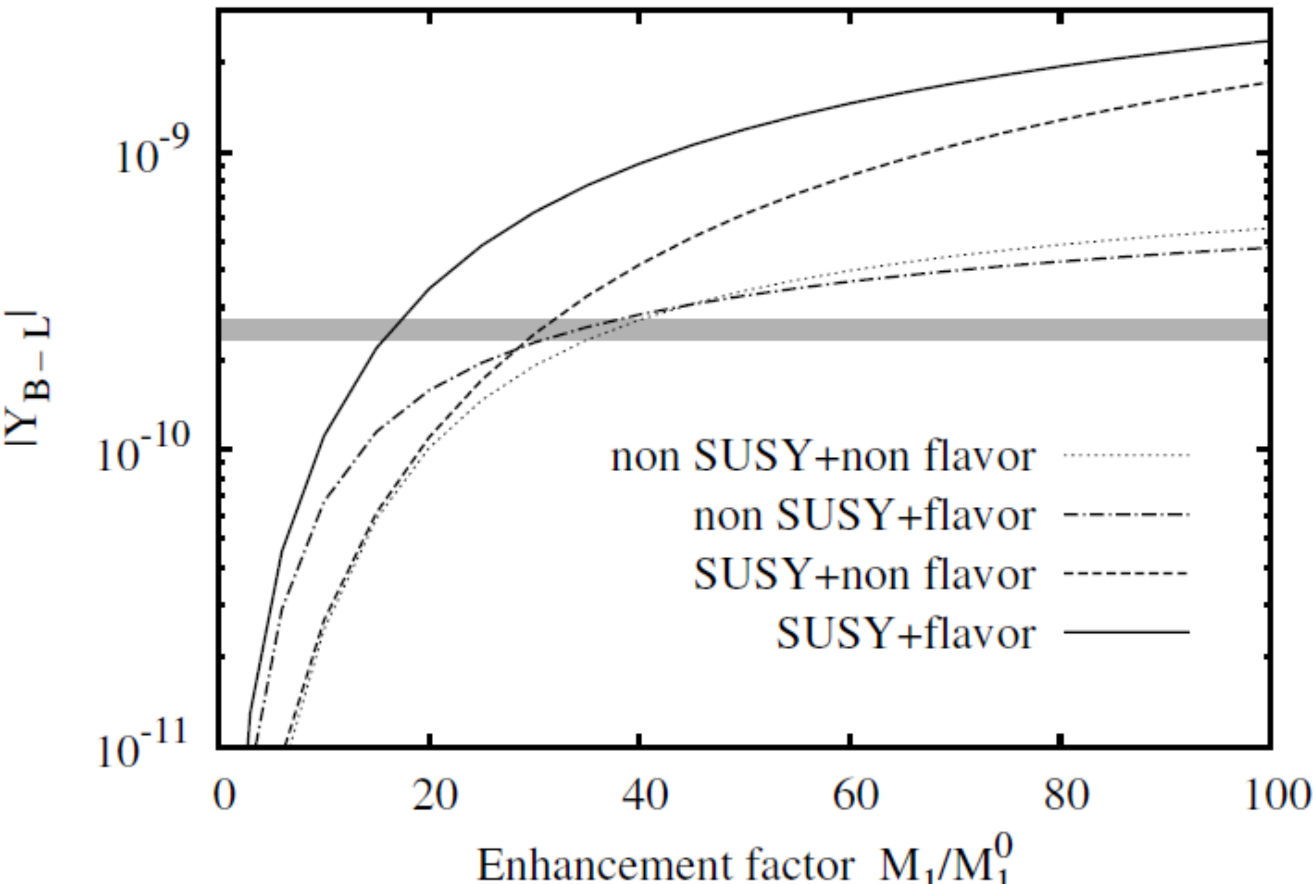
We have a plenty of RH neutrino mass terms which are fixed by the symmetry. (N terms lead to $\sqrt{N}$ enhancement)

3, The enhancement does not change the predictions on

How large enhancement?

Ishihara-N.M.-Takegawa-Yamanaka 1508

- e flavor effects are important when $K \geq 1$.
- SUSY effects are important when $K \leq 1$.
- Bolzmann eq. (Fong-Gonzalez-Garcia-Nardi-Racker 1009)



$M{\downarrow}1\ /M{\downarrow}1{\uparrow}0$

sufficient

$N\sim 300$ mass terms are reasonabley expected in