Flavor violating Z' in $SO(10)$ SUSY GUT

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はじめにーGUTって素晴らしい

標準模型

3つの力＝3つのgauge group

gauge theory

粒子＝gauge groupの表現

大統一理論（GUT）

1つのgauge groupで力（相互作用）を記述
＝力の統一、同時に粒子の統一

本当に統一できるの？

加えて－SUSYも素晴らしい

	boson	fermion
物質	squark, slepton	quark, lepton
gauge	gluon, W, B gauge boson	gluino, wino, bino gaugino
Higgs	Higgs	Higgsino

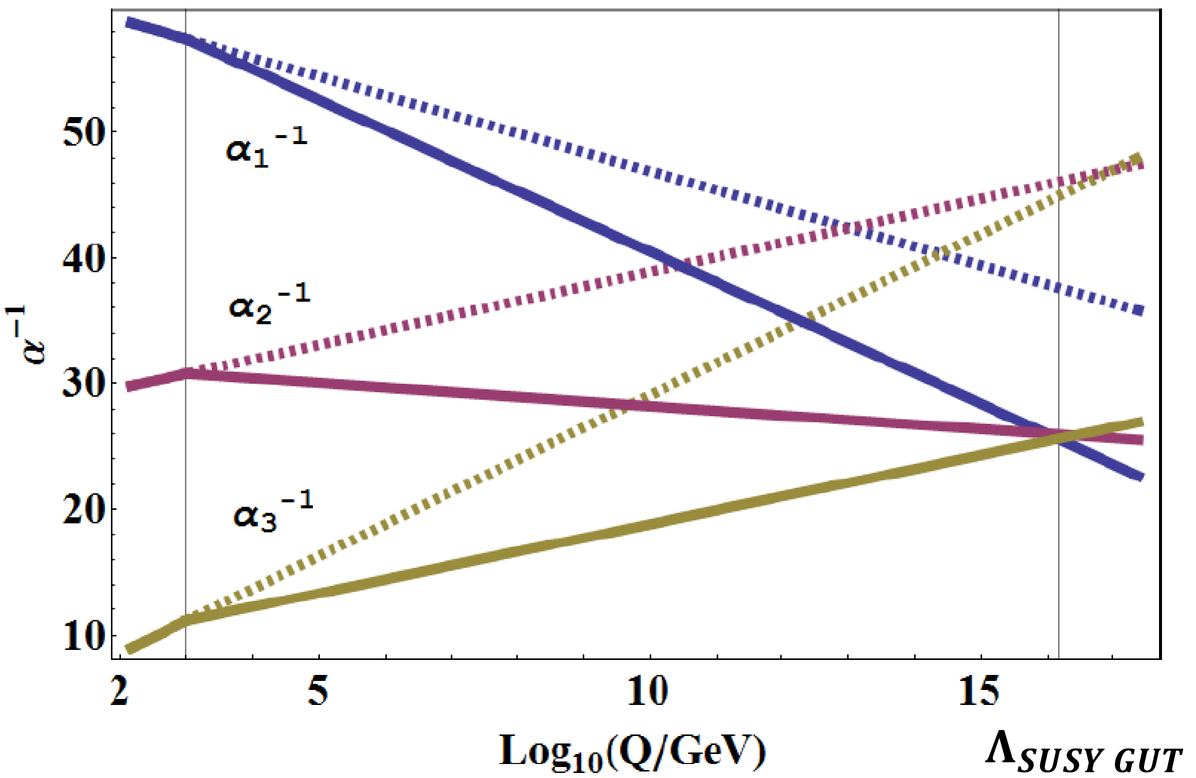
見つかっていない・・・

gauginoさえ質量TeVなら
motivationあり

- SUSY flavorの未観測
- 重いHiggs

→ squark, sleptonは
重い？

gauge coupling unification



$$m_{SUSY} = 1\ \text{TeV}$$

concept of this model

一般にZ' gauge boson from

- $U(1)'$ by hand

  tree level flavor violation

- $U(1)'$ included in GUT group

  no flavor violation

今回

GUTの問題解決mechanism

→flavor violating Z' gauge boson

$SO(10)$ GUT
+
high scale, split SUSY

⇒

flavor physicsが
modelのprobe

$\boldsymbol{Z'}$ gauge boson ($\boldsymbol{U(1)'}$)とは

GUT group, large extra dimensionなどから出る

様々なmotivation

- μ term problemの解
- DM candidate (singlet extension)
- electroweak baryogenesis (singlet extension)

など

tree level flavor violation through Z' exchange

- 手で入れた$U(1)'$ gauge symmetry

  anomaly cancelのため世代ごとに異なるcharge

$$g_{Z'} Z'_\mu \gamma^\mu \begin{pmatrix} \overline{\psi}_1 & \overline{\psi}_2 & \overline{\psi}_3 \end{pmatrix} \begin{pmatrix} a & & \\ & b & \\ & & c \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}$$

$$\longrightarrow \; g_{Z'} Z'_\mu \gamma^\mu \overline{\psi'}_i A^\psi_{ij} \psi'_j$$

$$\text{flavor eigenstate} \rightarrow \text{mass eigenstate } \psi_i \rightarrow \psi'_i = V^\dagger_{ij} \psi_j$$

- GUT gauge symmetry groupに含まれる$U(1)'$

  anomaly問題がないため世代universal charge

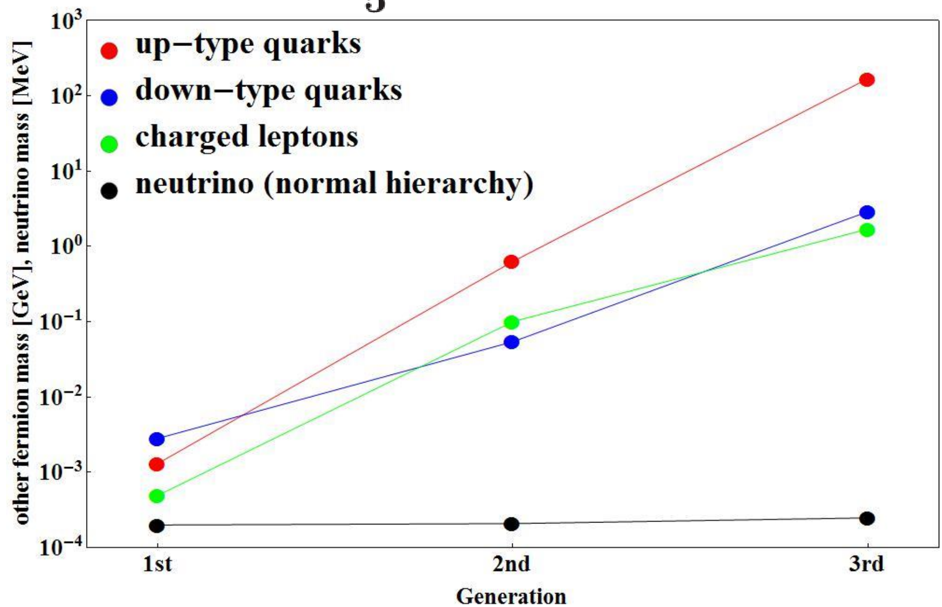
$SO(10)$ GUT modelの問題点

$$16 \to \underbrace{q_L(\mathbf{3},\mathbf{2})_{\frac{1}{6}} + u_R^c(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}} + e_R^c(\mathbf{1},\mathbf{1})_1}_{\mathbf{10}} + \underbrace{d_R^c(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} + l_L(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}}_{\bar{\mathbf{5}}} + \underbrace{\nu_R^c(\mathbf{1},\mathbf{1})_0}_{\mathbf{1}}$$

$$Y_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H$$

⬇

$$Y_u = Y_d = Y_e \equiv Y$$



- quark, (lepton)-mixing
- 豊富なflavorごとの階層構造　が出ない

解決mechanism

- matter sector拡張 ⇒ 今回はこちら
- Higgs sector拡張　　など

$\boldsymbol{SO(10)}$ GUT model + $\mathbf{10}$ matter

$$SO(10) \supset SU(5) \times U(1)_X$$

$$\mathbf{16} \to \mathbf{10}_{-1} + \bar{\mathbf{5}}_3 + \mathbf{1}_{-5}$$

$$\mathbf{10} \to \bar{\mathbf{5}}'_{-2} + \mathbf{5}_2$$

$$\begin{pmatrix} \bar{\mathbf{5}} \\ \bar{\mathbf{5}}' \end{pmatrix}_i = U_{ij} \begin{pmatrix} \bar{\mathbf{5}}^{\mathbf{0}} \\ \bar{\mathbf{5}}^{\mathbf{h}} \end{pmatrix}_j$$

例えば $\begin{pmatrix} \bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{1}} & \bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{2}} & \bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{3}} \end{pmatrix} = \begin{pmatrix} \bar{\mathbf{5}}_{\mathbf{1}} & \bar{\mathbf{5}}'_{\mathbf{1}} & \bar{\mathbf{5}}_{\mathbf{2}} \end{pmatrix}$

$$g_{Z'} Z'_\mu \gamma^\mu \begin{pmatrix} \overline{\psi}_{\bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{1}}} & \overline{\psi}_{\bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{2}}} & \overline{\psi}_{\bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{3}}} \end{pmatrix} \begin{pmatrix} 3 & & \\ & -2 & \\ & & 3 \end{pmatrix} \begin{pmatrix} \psi_{\bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{1}}} \\ \psi_{\bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{2}}} \\ \psi_{\bar{\mathbf{5}}^{\mathbf{0}}_{\mathbf{3}}} \end{pmatrix}$$

tree level FVが生じる　　　　FVに特徴がある

注　正確には

$$\begin{aligned} SO(10) &\to SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\ &\to G_{SM} \end{aligned}$$

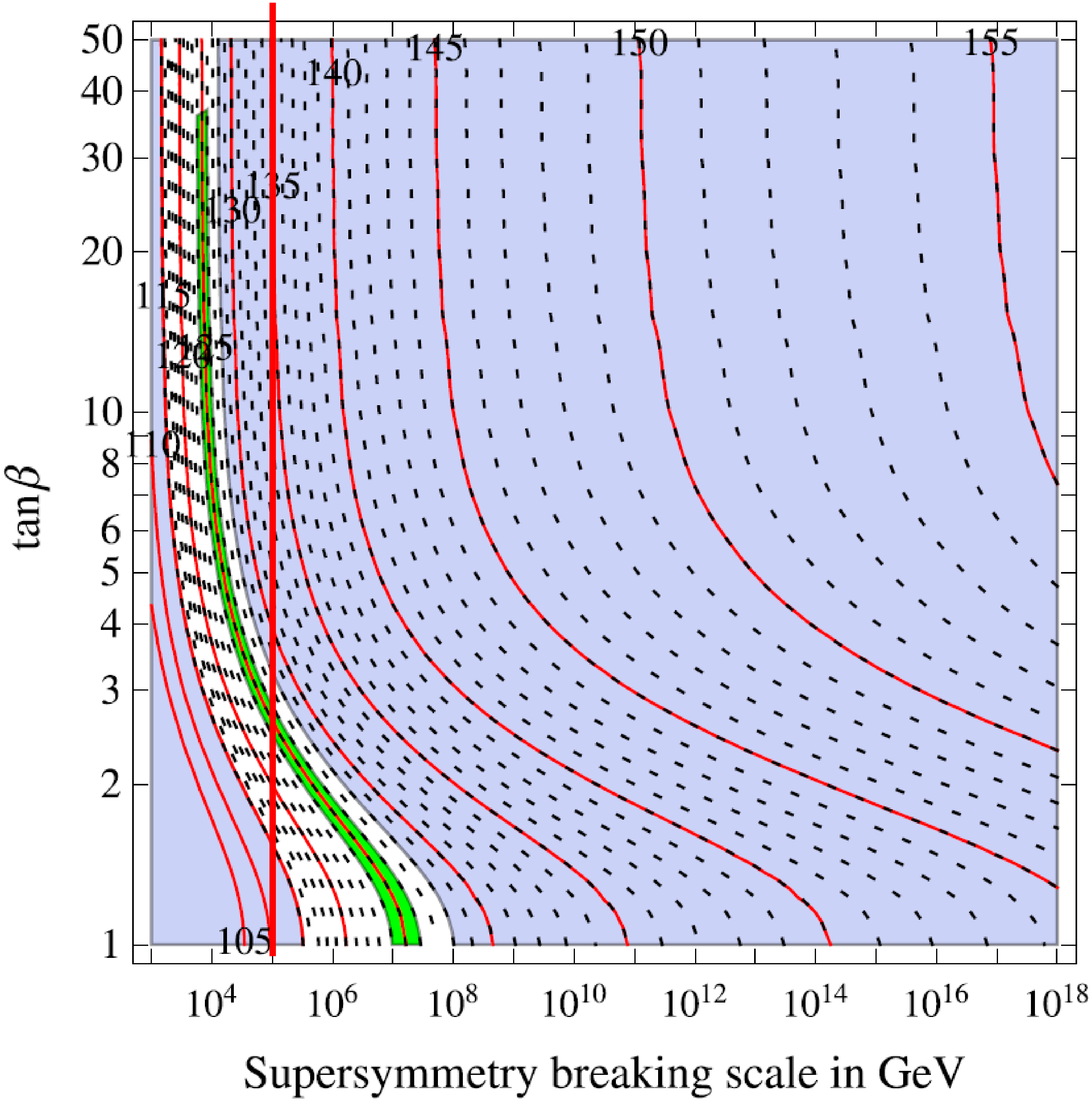
$\boldsymbol{SO(10)}$ SUSY GUT model

$SO(10)$ symmetry中の一部のsymmetryを保つ

high scale (split) SUSY $\qquad$ $O(100)$ TeV SUSY breaking

- $O(100)$ TeV $M_{Z'}$
- SUSYからのFV contributionなし
- gaugino mass $\sim O(1)$ TeVならgauge coupling unification
- $\tan\beta$が小さい

$$\tan\beta = \frac{\langle \phi_{H_u} \rangle}{\langle \phi_{H_d} \rangle}$$



Giudice, Strumia (2012)

concept of this model（繰り返し）

一般にZ' gauge boson from

- $U(1)'$ by hand

  tree level flavor violation

- $U(1)'$ included in GUT group

  no flavor violation

今回

GUTの問題解決mechanism

→flavor violating Z' gauge boson

$SO(10)$ GUT

＋

high scale, split SUSY

➡

flavor physicsが

modelのprobe

FV計算のためのparameter

- $\bar{\mathbf{5}}$表現混合行列：U

$$\left(\begin{array}{c}\bar{\mathbf{5}}\\ \bar{\mathbf{5}}'\end{array}\right)_i = U_{ij}\left(\begin{array}{c}\bar{\mathbf{5}}^{\mathbf{0}}\\ \bar{\mathbf{5}}^{\mathbf{h}}\end{array}\right)_j \equiv \left(\begin{array}{cc}\hat{U}_Y & \hat{U}_h\\ \hat{U}'_Y & \hat{U}'_h\end{array}\right)_{ij}\left(\begin{array}{c}\bar{\mathbf{5}}^{\mathbf{0}}\\ \bar{\mathbf{5}}^{\mathbf{h}}\end{array}\right)_j$$

- flavor mixing matrix：V

$$\psi_i \rightarrow \psi'_i = V^\dagger_{ij}\psi_j$$

- $U(1)'$ gauge coupling：$g_{Z'}$
- $U(1)'$ gauge boson mass：$M_{Z'}$

とりあえず今回は$M_{Z'} = 100$ TeV

parameterの決定

$$\psi_{Q_L i} Y_{u ij} \psi_{u^c_R j} \phi_{H_u} + \psi_{Q_L i} \underline{[(Y_u + \epsilon')\hat{U}_Y]_{ij}} \psi_{d^c_R j} \phi_{H_d}$$

$$\Rightarrow \quad Y_d = (Y_u + \epsilon')\hat{U}_Y$$

$$\Rightarrow \quad \hat{U}_Y V_{d^c_R} = \frac{\tan\beta}{m_u^D + \epsilon v \sin\beta} V^*_{CKM} m_d^D$$

今回は $\tan\beta = 3$

$$\epsilon = \begin{pmatrix} \epsilon & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} \epsilon & \epsilon & 0 \\ \epsilon & \epsilon & 0 \\ 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & \epsilon & \epsilon \\ \epsilon & \epsilon & \epsilon \end{pmatrix}$$ とした

charged lepton sectorは$SU(5)$ limitで

FV coupling A_{ij}^{ψ}の定義

$$\mathcal{L}_{Z'FV} = \sum_{\psi=d_R^c, e_L} -ig_{Z'} A_{ij}^{\psi} \bar{\psi}_i Z'_\mu \gamma^\mu \psi_j$$

$$A_{ij}^{d_R^c} = \sqrt{\frac{3}{8}}(-(V_{d_R^c}^\dagger \hat{U}_Y^\dagger \hat{U}_Y V_{d_R^c})_{ij} + \frac{2}{3}\delta_{ij})$$

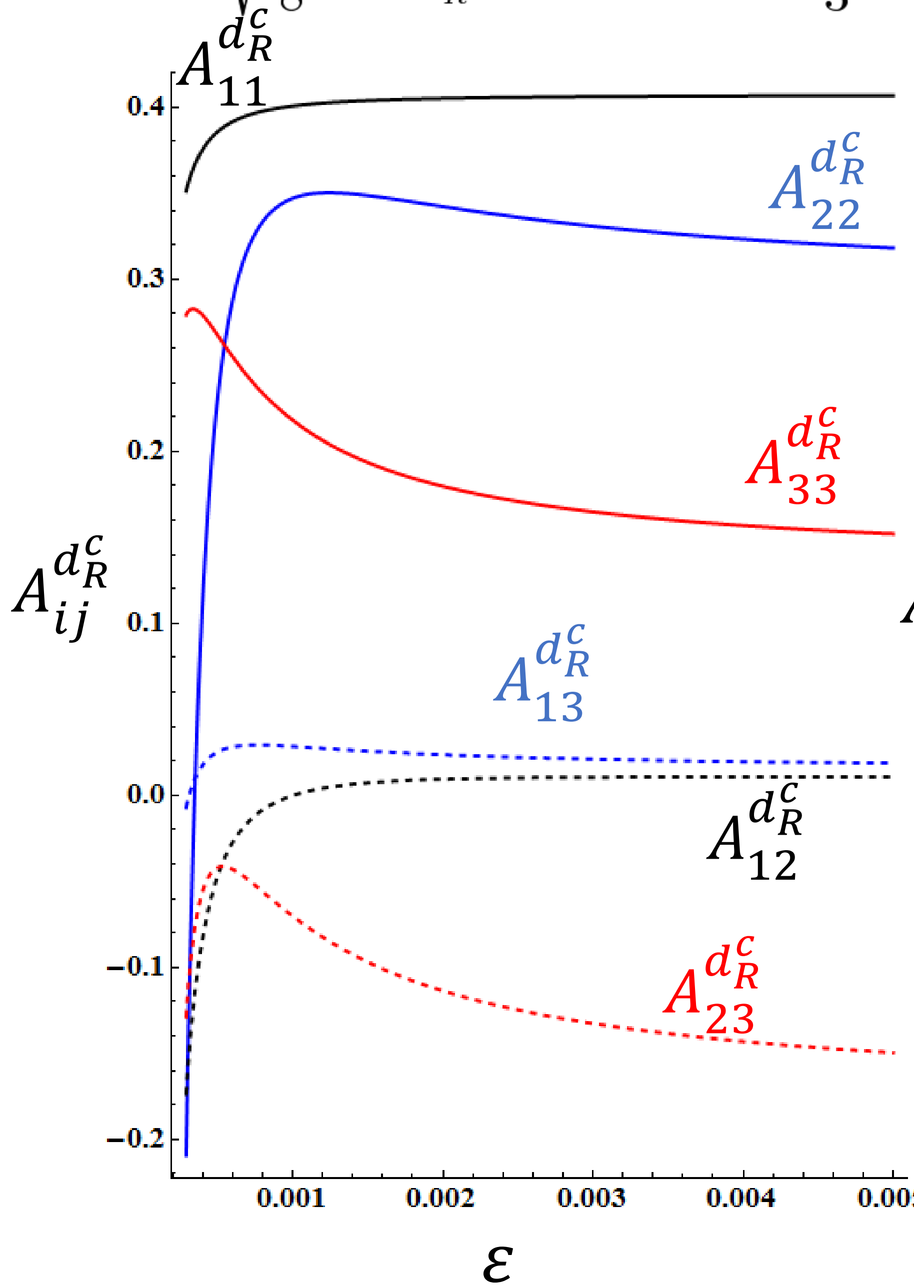
$$-1 = -\frac{1}{3} - \frac{2}{3}$$

$$A_{ij}^{e_L} = -\sqrt{\frac{3}{8}}(V_{e_L}^\dagger \hat{U}_Y^\dagger \hat{U}_Y V_{e_L})_{ij}$$

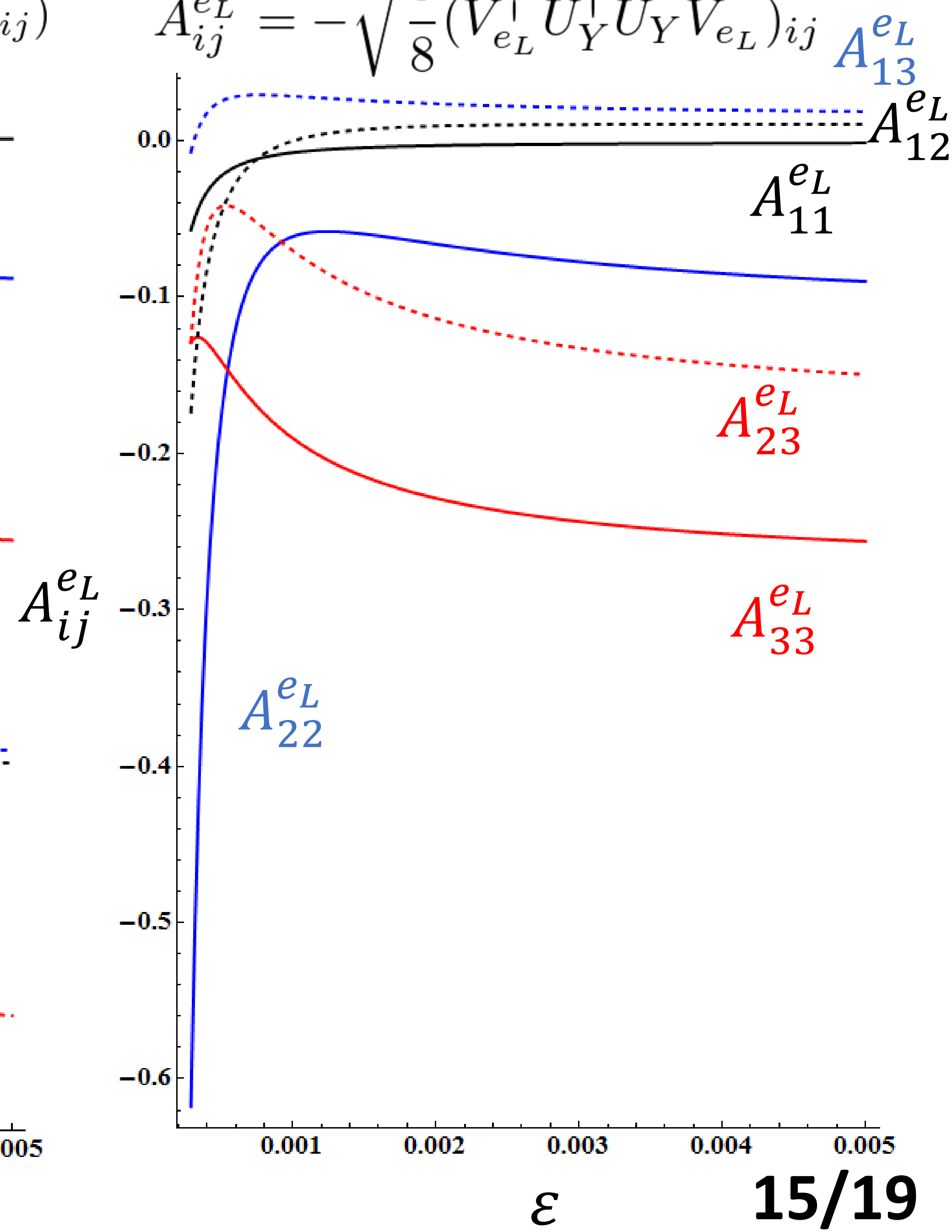
$$\mathbf{10} \to H_T(\mathbf{3},\mathbf{1},\mathbf{1})_{-\frac{2}{3}} + \bar{H}_T(\bar{\mathbf{3}},\mathbf{1},\mathbf{1})_{+\frac{2}{3}} + H_D(\mathbf{1},\mathbf{2},\mathbf{2})_0$$

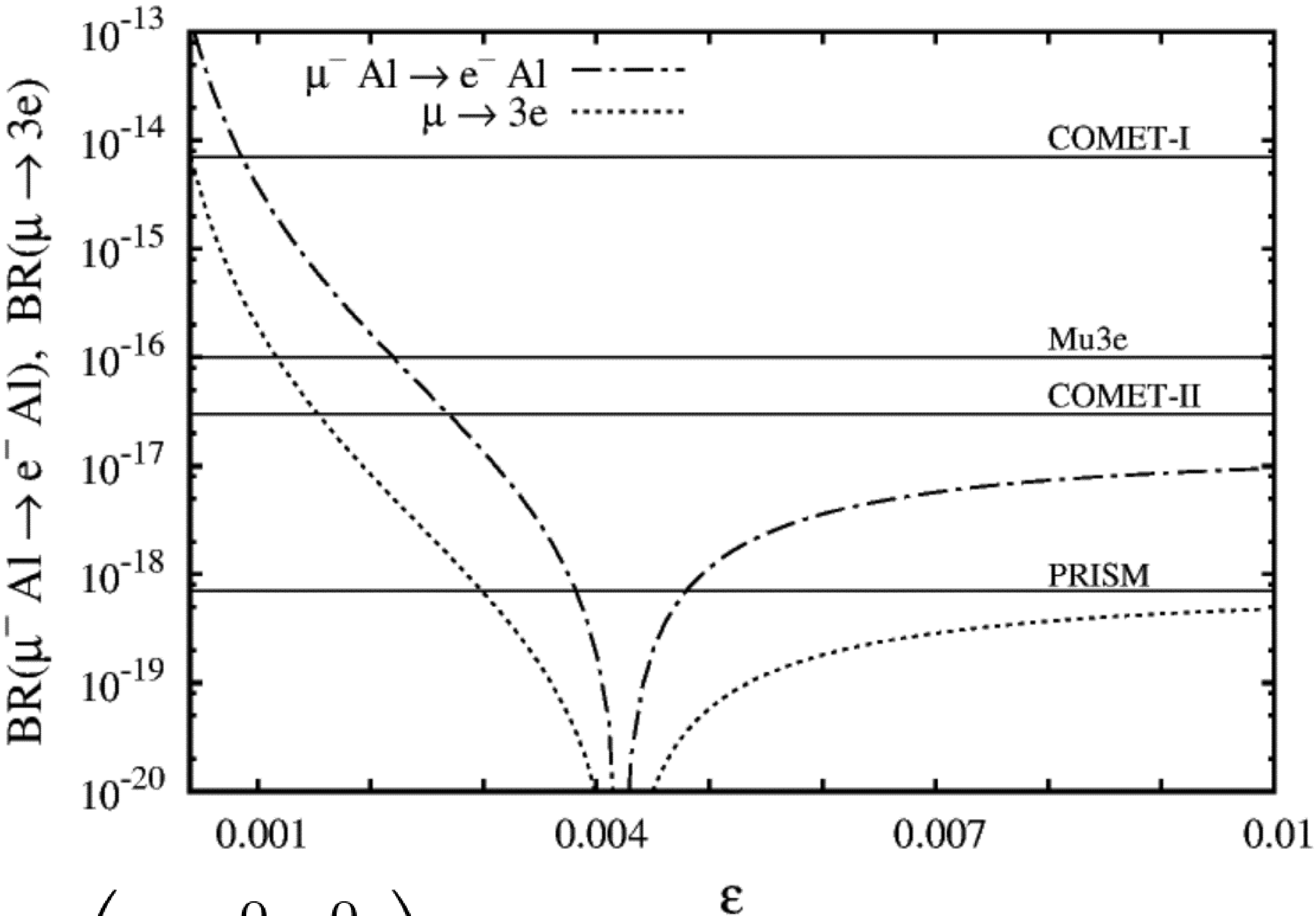
$$\mathbf{16} \to Q_L(\mathbf{3},\mathbf{2},\mathbf{1})_{+\frac{1}{3}} + Q_R(\bar{\mathbf{3}},\mathbf{1},\mathbf{2})_{-\frac{1}{3}} + L_L(\mathbf{1},\mathbf{2},\mathbf{1})_{-1} + L_R(\mathbf{1},\mathbf{1},\mathbf{2})_{+1}$$

$$A_{ij}^{d_R^c} = \sqrt{\frac{3}{8}}\left(-(V_{d_R^c}^\dagger \hat{U}_Y^\dagger \hat{U}_Y V_{d_R^c})_{ij} + \frac{2}{3}\delta_{ij}\right)$$



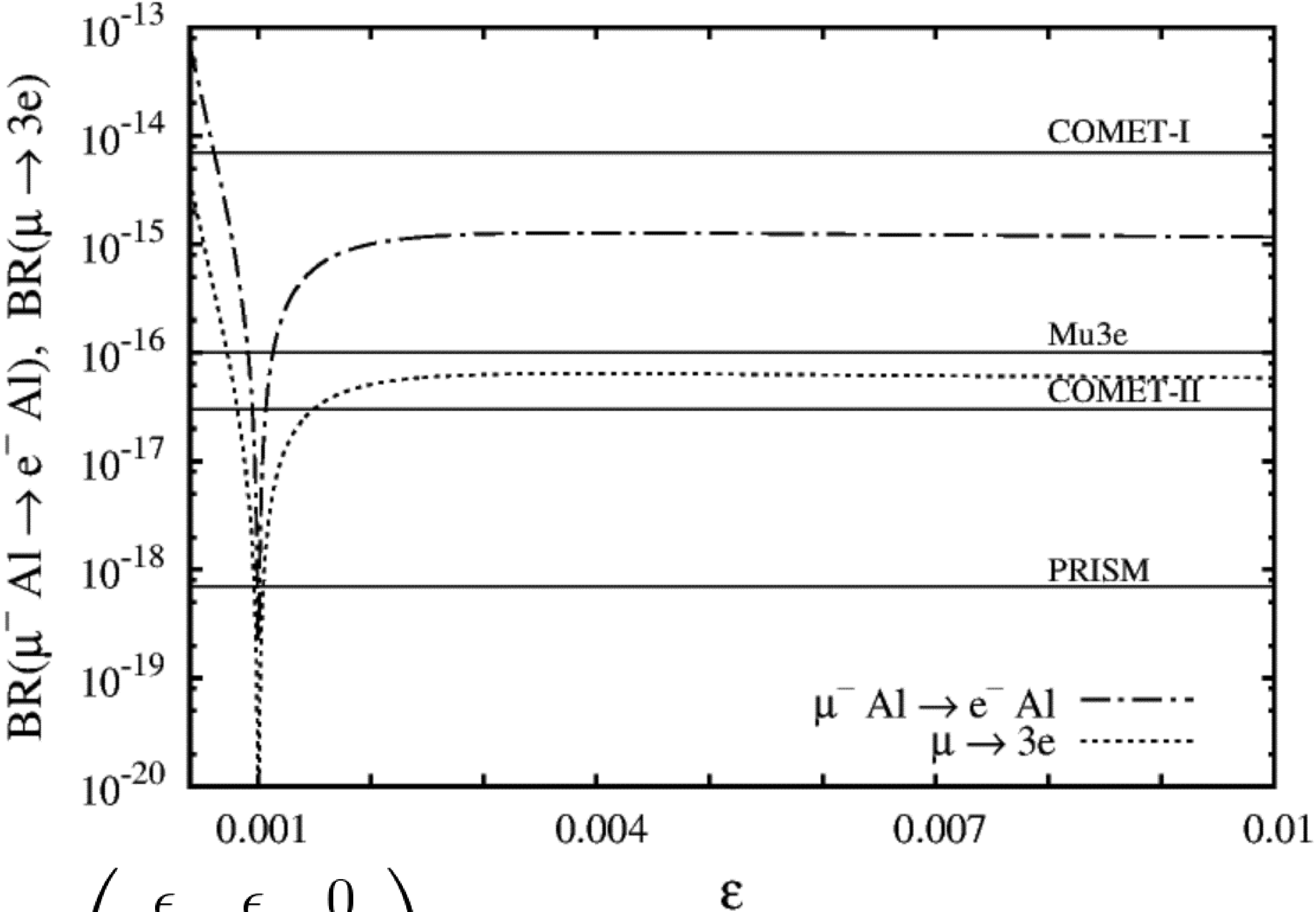
$$A_{ij}^{e_L} = -\sqrt{\frac{3}{8}}(V_{e_L}^\dagger \hat{U}_Y^\dagger \hat{U}_Y V_{e_L})_{ij}$$





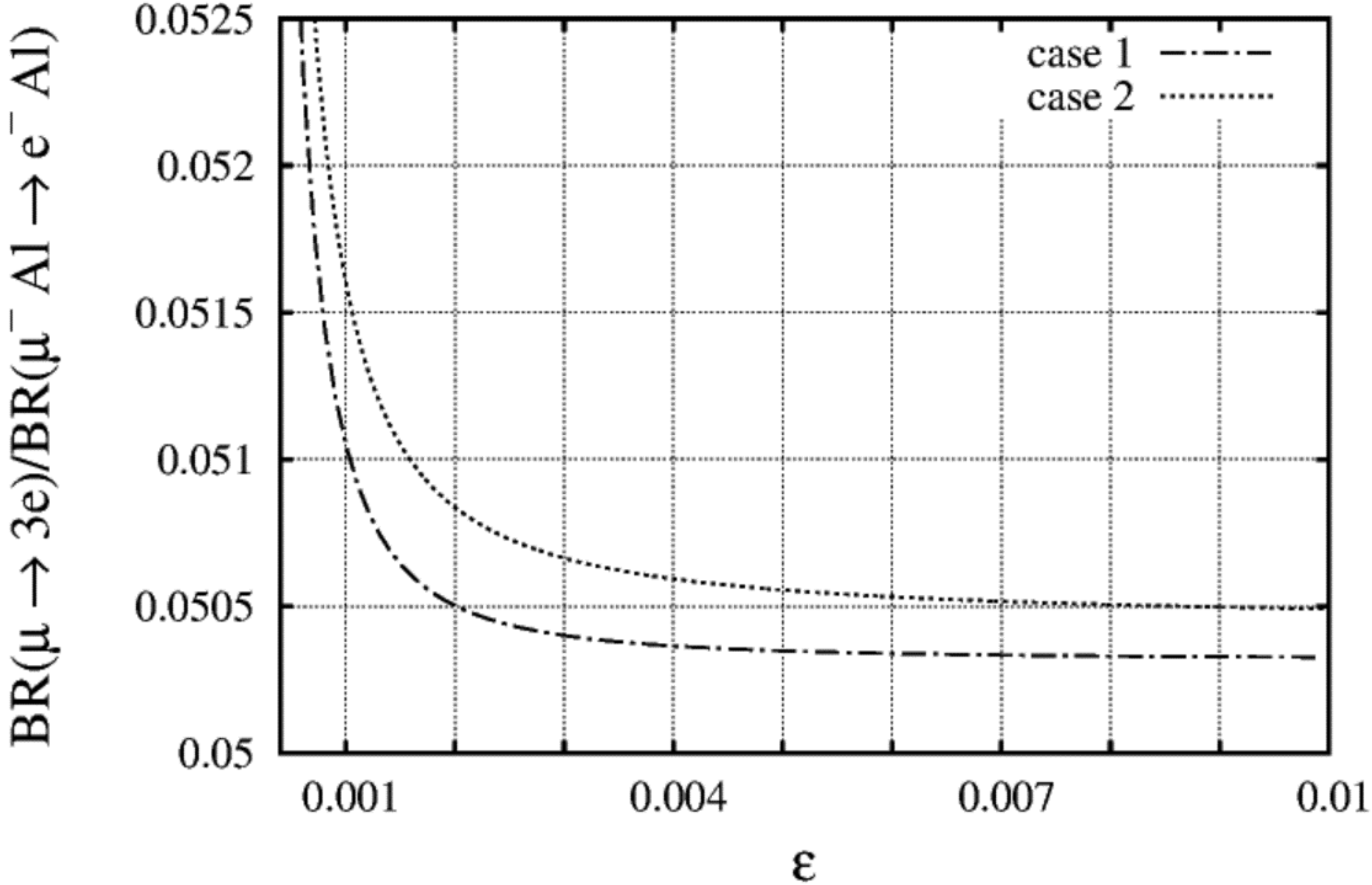
$$\epsilon = \begin{pmatrix} \epsilon & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$M_{Z'} = 100$ TeV



$$\epsilon = \begin{pmatrix} \epsilon & \epsilon & 0 \\ \epsilon & \epsilon & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$M_{Z'} = 100$ TeV



$$\epsilon = \begin{pmatrix} \epsilon & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \; \begin{pmatrix} \epsilon & \epsilon & 0 \\ \epsilon & \epsilon & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

case 1 case 2

$$A^{d^c_R}_{ij} = \sqrt{\frac{3}{8}}(-(V^\dagger_{d^c_R}\hat{U}^\dagger_Y\hat{U}_Y V_{d^c_R})_{ij} + \frac{2}{3}\delta_{ij}) \qquad A^{e_L}_{ij} = -\sqrt{\frac{3}{8}}(V^\dagger_{e_L}\hat{U}^\dagger_Y\hat{U}_Y V_{e_L})_{ij}$$

まとめ

- flavor physicsをprobeとするSUSY GUT model
- GUT modelの持つ問題解決がflavor violationを引き起こす
- 生じるflavor violationに特徴あり

to do

- 現象の解析を進める
- SUSY sectorの模型の詳細


ご静聴ありがとうございます。

Back up

neutrino mass – inverse seesaw

seesaw mechanism in GUT model

成功はGUT scaleが10^{16} GeVとしていることから

今回は

$\underline{M_{Z'} \sim O(100)\mathrm{TeV}}$ ➡ $M_{\nu_R} \sim 10^{-8}\mathrm{GeV}$

GUT symmetryの一つが破れるscale

⬇

いわゆるtype-Ⅰ seesawは働かない

inverse seesaw

元々

Mohapatra (1986)

$$W_Y = \underline{h_{ij}\mathbf{16}_i\mathbf{16}_j\mathbf{10}_H} + \underline{f_{ij}\mathbf{16}_i\mathbf{1}_j\overline{\mathbf{16}}_H} + \mu_{ij}\mathbf{1}_i\mathbf{1}_j$$

$$M_D = h\left\langle\mathbf{10}_H\right\rangle = hv_u \qquad M_N = f\left\langle\overline{\mathbf{16}}_H\right\rangle$$

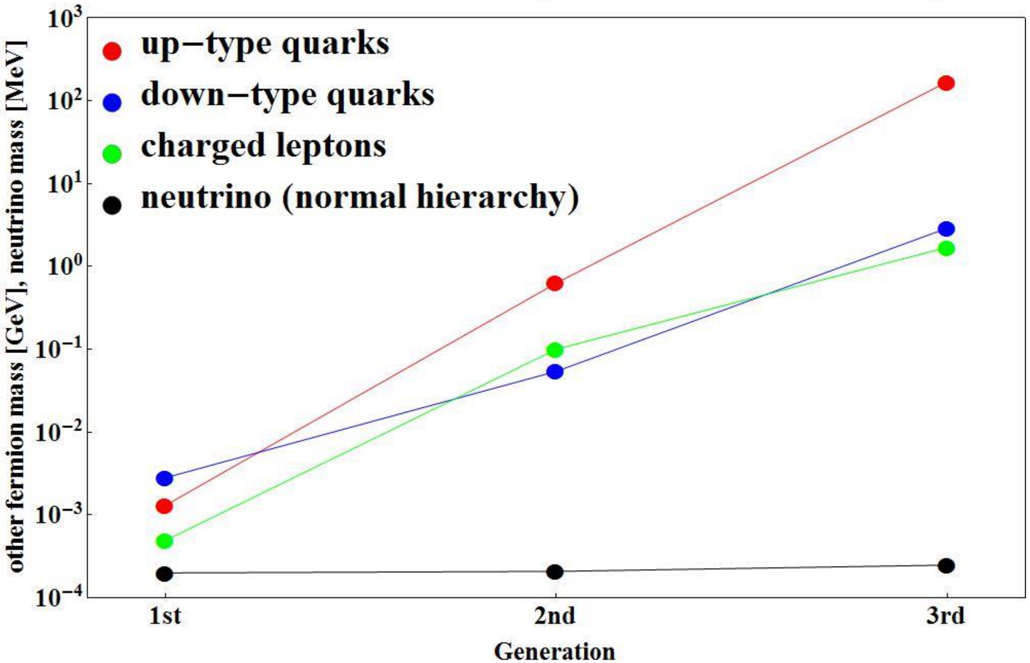
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_N \\ 0 & M_N^T & \mu \end{pmatrix}$$

$\left\langle\overline{\mathbf{16}}_H\right\rangle \sim O(100)\mathrm{T}eV$ より

$$(m_\nu)_{ij} = \left(\frac{\left(hf^{-1}\mu f^{-1}h\right)_{ij}}{1\ \mathrm{M}eV}\right)\left(\frac{100\ \mathrm{T}eV}{\left\langle\overline{\mathbf{16}}_H\right\rangle}\right)^2\left(\frac{\left\langle\mathbf{10}_H\right\rangle}{100\ \mathrm{G}eV}\right)^2 \mathrm{e}V$$

これを拡張する

ii. Realistic quark and lepton masses and mixings



$$|U_{CKM}| = \begin{pmatrix} 0.97 & 0.23 & 0.0035 \\ 0.23 & 0.97 & 0.041 \\ 0.0086 & 0.040 & 1.0 \end{pmatrix},$$

$$\mathrm{U}_{MNS} = \begin{pmatrix} 0.83 & 0.54 & 0.15 \\ -0.48 & 0.53 & 0.70 \\ 0.30 & -0.65 & 0.70 \end{pmatrix}$$

CKM matrix and MNS matrix PDG (2012)
complex phase of MNS matrix is 0.

Quark and charged lepton mass @ m_Z Antusch, Maurer (2013)
Neutrino mass PDG (2012)
Neutrino mass is upper bound of neutrino mass Riemer-Sorensen et al. (2012)

mass
- M_u ⇒ strong
- M_d, M_e ⇒ middle
- M_ν ⇒ weak

} hierarchy

mixing
- U_{CKM} ⇒ small mixing
- U_{MNS} ⇒ large mixing

Realistic quark and lepton masses and mixings in $SU(5)$ GUT model

$$Y_u \mathbf{10}\cdot\mathbf{10}\cdot\mathbf{5_H} + Y_d \mathbf{10}\cdot\bar{\mathbf{5}}\cdot\bar{\mathbf{5}}_{\mathbf{H}} + Y_\nu' \bar{\mathbf{5}}\cdot\mathbf{1}\cdot\mathbf{5_H} + M_{\nu_R}\mathbf{1}\cdot\mathbf{1}$$

$Y_u \mathbf{10}\cdot\mathbf{10}\cdot\mathbf{5_H} \rightarrow M_u$

$Y_d \mathbf{10}\cdot\bar{\mathbf{5}}\cdot\bar{\mathbf{5}}_{\mathbf{H}} \rightarrow M_d, M_e$

seesaw mechanism: $Y_\nu' \bar{\mathbf{5}}\cdot\mathbf{1}\cdot\mathbf{5_H} + M_{\nu_R}\mathbf{1}\cdot\mathbf{1} \rightarrow Y_\nu \bar{\mathbf{5}}\cdot\bar{\mathbf{5}}\cdot\mathbf{5_H}\cdot\mathbf{5_H} \rightarrow M_\nu$

The $\mathbf{10}$ quark and lepton induces stronger hierarchies for Yukawa coupling than the $\bar{\mathbf{5}}$ quark and lepton.

$$\begin{pmatrix}\mathbf{10_1}\\ \mathbf{10_2}\\ \mathbf{10_3}\end{pmatrix} \rightarrow \begin{pmatrix}\lambda^3\\ \lambda^2\\ 1\end{pmatrix} \qquad \begin{pmatrix}\bar{\mathbf{5}}_\mathbf{1}\\ \bar{\mathbf{5}}_\mathbf{2}\\ \bar{\mathbf{5}}_\mathbf{3}\end{pmatrix} \rightarrow \begin{pmatrix}\lambda^3\\ \lambda^{2.5}\\ \lambda^2\end{pmatrix}$$

Quark and lepton masses and mixings can be realized if $\lambda = 0.22$.

$$Y_u \mathbf{10}\cdot\mathbf{10}\cdot\mathbf{5_H} + Y_d \mathbf{10}\cdot\bar{\mathbf{5}}\cdot\bar{\mathbf{5}}_\mathbf{H} + Y_\nu' \bar{\mathbf{5}}\cdot\mathbf{1}\cdot\mathbf{5_H} + M_{\nu_R}\mathbf{1}\cdot\mathbf{1}$$

$$\to M_u \qquad \to M_d, M_e \qquad \to Y_\nu \bar{\mathbf{5}}\cdot\bar{\mathbf{5}}\cdot\mathbf{5_H}\cdot\mathbf{5_H} \to M_\nu$$

$$M_u = \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \langle H_u \rangle$$

$$M_{u\,diag} \sim \begin{pmatrix} \lambda^6 & & \\ & \lambda^4 & \\ & & 1 \end{pmatrix} \langle H_u \rangle$$

$$L_u \sim R_u \sim U_{CKM-type}$$

→ strong hierarchy

→ middle hierarchy

$$M_d = M_e^t = \lambda^2 \begin{pmatrix} \lambda^4 & \lambda^{3.5} & \lambda^3 \\ \lambda^3 & \lambda^{2.5} & \lambda^2 \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \langle H_d \rangle$$

$$M_{d\,diag} = M_{e\,diag} \sim \lambda^2 \begin{pmatrix} \lambda^4 & & \\ & \lambda^{2.5} & \\ & & 1 \end{pmatrix} \langle H_d \rangle$$

$$L_d \sim R_e \sim U_{CKM-type}, R_d \sim L_e \sim U_{MNS-type}$$

$$M_\nu = \frac{\lambda^{-5}}{\Lambda} \begin{pmatrix} \lambda^2 & \lambda^{1.5} & \lambda \\ \lambda^{1.5} & \lambda & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix} \langle H_u \rangle^2$$

$$M_{\nu\,diag} \sim \frac{\lambda^{-5}}{\Lambda} \begin{pmatrix} \lambda^2 & & \\ & \lambda & \\ & & 1 \end{pmatrix} \langle H_u \rangle^2$$

$$L_\nu \sim U_{MNS-type}$$

→ weak hierarchy

$$U_{CKM-type} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad U_{MNS-type} \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

$$U_{CKM} = L_u^\dagger L_d \sim U_{CKM-type}$$

$$U_{CKM-type} \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

→ small mixing

$$U_{MNS} = L_\nu^\dagger L_e \sim U_{MNS-type}$$

$$U_{MNS-type} \sim \begin{pmatrix} 1 & \lambda^{0.5} & \lambda \\ \lambda^{0.5} & 1 & \lambda^{0.5} \\ \lambda & \lambda^{0.5} & 1 \end{pmatrix}$$

→ large mixing

as a result of above assumption,

$$\underline{L_u \sim L_d \sim R_u \sim R_e} \sim U_{CKM-type}$$

→ diagonalizing matrix for **10** of $SU(5)$

$$\underline{L_e \sim L_\nu \sim R_d} \sim U_{MNS-type}$$

→ diagonalizing matrix for $\overline{\mathbf{5}}$ of $SU(5)$

Quark and lepton masses and mixings can be realized if $\lambda = 0.22$.

Realistic quark and lepton masses and mixings in $SO(10)$ GUT model

$$\mathbf{16} \to \underbrace{q_L(\mathbf{3},\mathbf{2})_{\frac{1}{6}} + u_R^c(\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3}} + e_R^c(\mathbf{1},\mathbf{1})_1}_{\mathbf{10}} + \underbrace{d_R^c(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} + l_L(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}}_{\bar{\mathbf{5}}} + \underbrace{\nu_R^c(\mathbf{1},\mathbf{1})_0}_{\mathbf{1}}$$

In $SO(10)$ GUT model, $\mathbf{10}$ and $\bar{\mathbf{5}}$ quark and lepton induce similar hierarchy because of unification into $\mathbf{16}$ rep.

It is hard to realize realistic quark and lepton masses and mixings.

$$Y\,\mathbf{16}\cdot\mathbf{16}\cdot\mathbf{10_H}$$

↓

$$Y_u = Y_d = Y_e$$

add **10** rep. as SM quarks and leptons

$$\mathbf{10} \rightarrow \underbrace{D_R^c(\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3}} + L_L(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}}_{\bar{\mathbf{5}}'} + \underbrace{\overline{D_R^c}(\mathbf{3},\mathbf{1})_{-\frac{1}{3}} + \overline{L_L}(\mathbf{1},\mathbf{2})_{\frac{1}{2}}}_{\mathbf{5}}$$