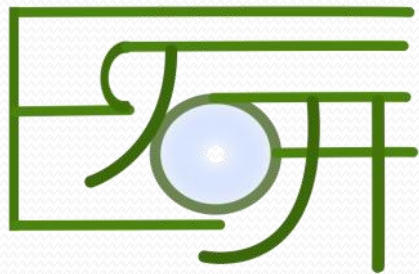


Constraints of chromo-electric dipole moments to natural SUSY type sfermion spectrum

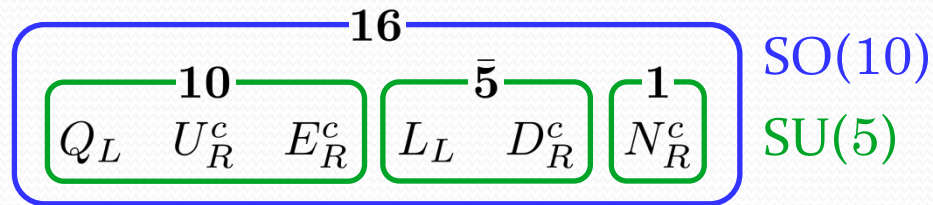
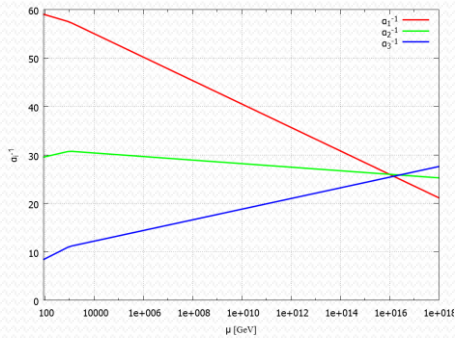


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Introduction

- SUSY GUTは興味深い拡張模型
相互作用の統一 + 物質場の統一



- しかし、解決すべき問題もある
ex) SUSY FCNC、proton decay、SUSY CP problem、...



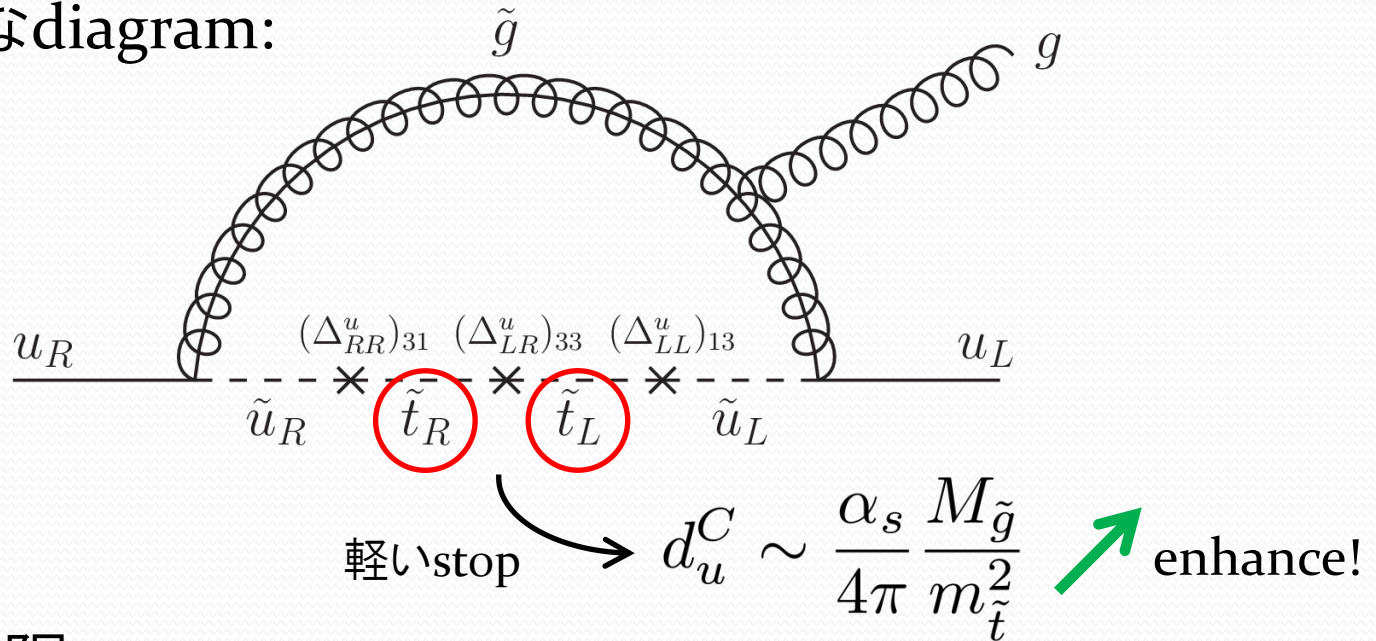
- Natural SUSY type

第3世代のみ軽いmass spectrum: $\tilde{m}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}$

Introduction

- Natural SUSYの問題・・・up quark CEDM

典型的なdiagram:



- 現在の制限:

$$|d_u^C| < 6 \times 10^{-27} \text{ e cm} \Rightarrow$$

- 制限を満たすことができるか?
- どこまで軽いstopが許される?

Introduction

- 今回の研究：
 - GUTスケールでのYukawa couplingの階層性を仮定
 - 様々な値のsfermion massでCEDMを計算
 - 実験からの制限と比較
- これにより、
 - 重いsfermion mass $> 5 \text{ TeV}$
 - stop mass — $> 1 \text{ TeV}$ (real Y^u at GUT scale)
 $> 5 \text{ TeV}$ (complex Y^u at GUT scale)

Contents

- Introduction
- natural SUSY and CEDM
- Set up
- Results
- Summary

Natural SUSY

- 3世代のみ軽いsfermion mass spectrum

Weak scaleの安定化

→ 軽いstop mass

SUSY FCNCの解決

→ (ほぼ)縮退したheavy mass

- 今回の研究では、以下のmass spectrumを採用：

$$m_{10}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} \quad m_{\bar{5}}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} \quad \begin{array}{l} \mathbf{10} \ni Q_L, U_R^c, E_R^c \\ \bar{\mathbf{5}} \ni L_L, D_R^c \end{array}$$

m_0 : heavy, m_3 : light

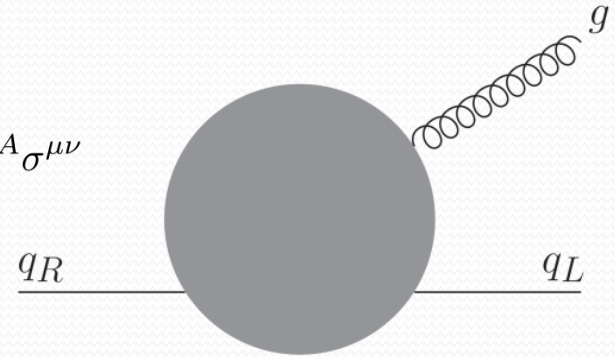
- GUT scaleで仮定するYukawa couplingでは、 $\bar{\mathbf{5}}$ 表現の方がlarge mixing
- $E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT modelでのスペクトラム

CEDM

- 有効ラグランジアン:

$$\mathcal{L}_{\text{CEDM}} = -\frac{i}{2} d_q^C \bar{q} g_s (G \cdot \sigma) \gamma_5 q$$

$$G \cdot \sigma = G_{\mu\nu}^A T^A \sigma^{\mu\nu}$$



$d_q^C \neq 0$ ならばCP対称性の破れが存在する

W. C. Griffith, et. al., PRL **102** (2009), 101601

→ 現在の実験値: $|d_q^C| < 6 \times 10^{-27} e \text{ cm}$ ($q=u,d$)

! SUSY GUT modelにおいて厳しい制限となる

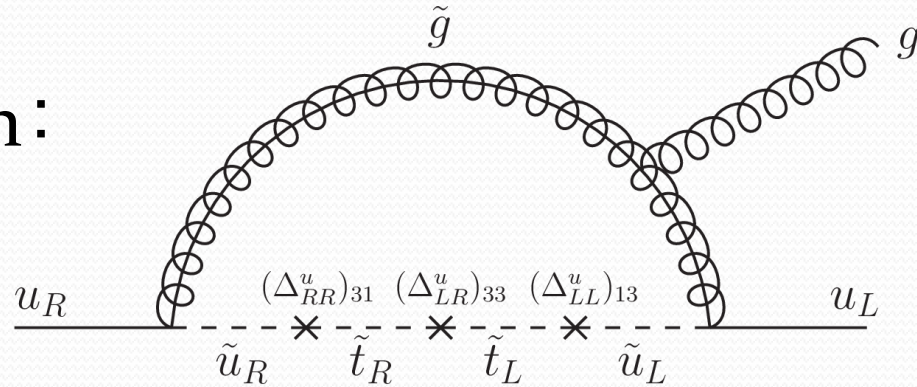
- sfermion mass $\rightarrow \infty$ で小さくなる

naturalnessの観点から、stop $\sim O(1)$ TeV

d_d^C : decouple d_u^C : non-decouple

CEDM

- 典型的なdiagram:



- 1ループの表式 (dominant, gluino contribution)

$$d_u^C \simeq \frac{\alpha_s}{4\pi} \frac{M_{\tilde{g}}}{m_{\tilde{t}}^2} \text{Im} [(\delta_{LL}^u)_{13} (\delta_{LR}^u)_{33} (\delta_{RR}^u)_{31}] \times (\text{loop integral})$$

$$(\delta_{AB}^u)_{ij} = \frac{(\Delta_{AB}^u)_{ij}}{m_{\tilde{u}}^2}, \quad A, B = L \text{ or } R$$

6 × 6 sfermion squared mass matrix element

$$(\Delta_{LL}^u)_{13} \simeq (V_{uL}^\dagger m_{10}^2 V_{uL})_{13} \sim m_0^2 (V_{uL}^*)_{31} (V_{uL})_{33}$$

$$(\Delta_{LR}^u)_{33} \simeq v_u (V_{uL}^\dagger A^u V_{uR}^*)_{33} \sim v_u A_{33}^u (V_{uL}^*)_{33} (V_{uR}^*)_{33} \sim v_u m_{\tilde{t}} \quad \& \quad m_{\tilde{u}_R} \sim m_{\tilde{u}_L} \sim m_0$$

$$(\Delta_{RR}^u)_{31} \simeq (V_{uR}^T m_{10}^2 V_{uR}^*)_{31} \sim m_0^2 (V_{uR})_{13} (V_{uR}^*)_{11}$$

⇒ $m_0 \rightarrow \infty$ としても、この効果は **decoupleしない**

- Yukawa matrices — 以下の階層性を仮定:

$$Y^u = \begin{pmatrix} y_{11}^u \lambda^6 & y_{12}^u \lambda^5 & y_{13}^u \lambda^3 \\ y_{21}^u \lambda^5 & y_{22}^u \lambda^4 & y_{23}^u \lambda^2 \\ y_{31}^u \lambda^3 & y_{32}^u \lambda^2 & y_{33}^u \end{pmatrix} \quad \lambda = 0.22$$

・ 次の3つのタイプで計算

$$\mathcal{O}(1) : y = |y|e^{i\theta_y}, \quad 0.5 < |y| < 1.5, \quad 0 \leq \theta_y \leq 2\pi$$

Complex Y^u type

$$y_{ij}^u, y_{ij}^d, y_{ij}^e : \text{complex } \mathcal{O}(1)$$

Real Y^u type

$$y_{ij}^u : \text{real } \mathcal{O}(1), \quad y_{ij}^d, y_{ij}^e : \text{complex } \mathcal{O}(1)$$

$$Y^e = \begin{pmatrix} y_{11}^e \lambda^6 & y_{12}^e \lambda^5 & y_{13}^e \lambda^3 \\ y_{21}^e \lambda^{5.5} & y_{22}^e \lambda^{4.5} & y_{23}^e \lambda^{2.5} \\ y_{31}^e \lambda^5 & y_{32}^e \lambda^4 & y_{33}^e \lambda^2 \end{pmatrix}$$

E_6 model (with family symm. and spontaneous CP violation)

Real Y^u type + relations:

$$y_{11}^u = y_{13}^u = y_{31}^u = y_{13}^e = y_{21}^e = 0, \quad y_{12}^u = -y_{21}^u = y_{13}^d = \frac{1}{3}d_q,$$

$$y_{23}^u = y_{32}^u, \quad y_{23}^d = y_{32}^e, \quad y_{33}^d = y_{33}^e, \quad y_{12}^e = -y_{31}^e$$

Set up

@GUT scale

- Gaugino masses

$$M_1 = M_2 = M_3 = M_{1/2} \rightarrow \text{Stop mass}$$

- Mass spectrum of sfermion — natural SUSY type

$$m_{10}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} \quad m_{\bar{5}}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix} \quad \begin{array}{l} 10 \ni Q_L, U_R^c, E_R^c \\ \bar{5} \ni L_L, D_R^c \end{array}$$

Heavy sfermion masses

- A-terms — Yukawa matricesと同じ階層性を仮定

$$A^u \sim A_0 Y^u, \quad A^d \sim A_0 Y^d, \quad A^e \sim A_0 Y^e \quad A_0 = -1 \text{ TeV}$$

- Higgs masses and $\tan\beta$

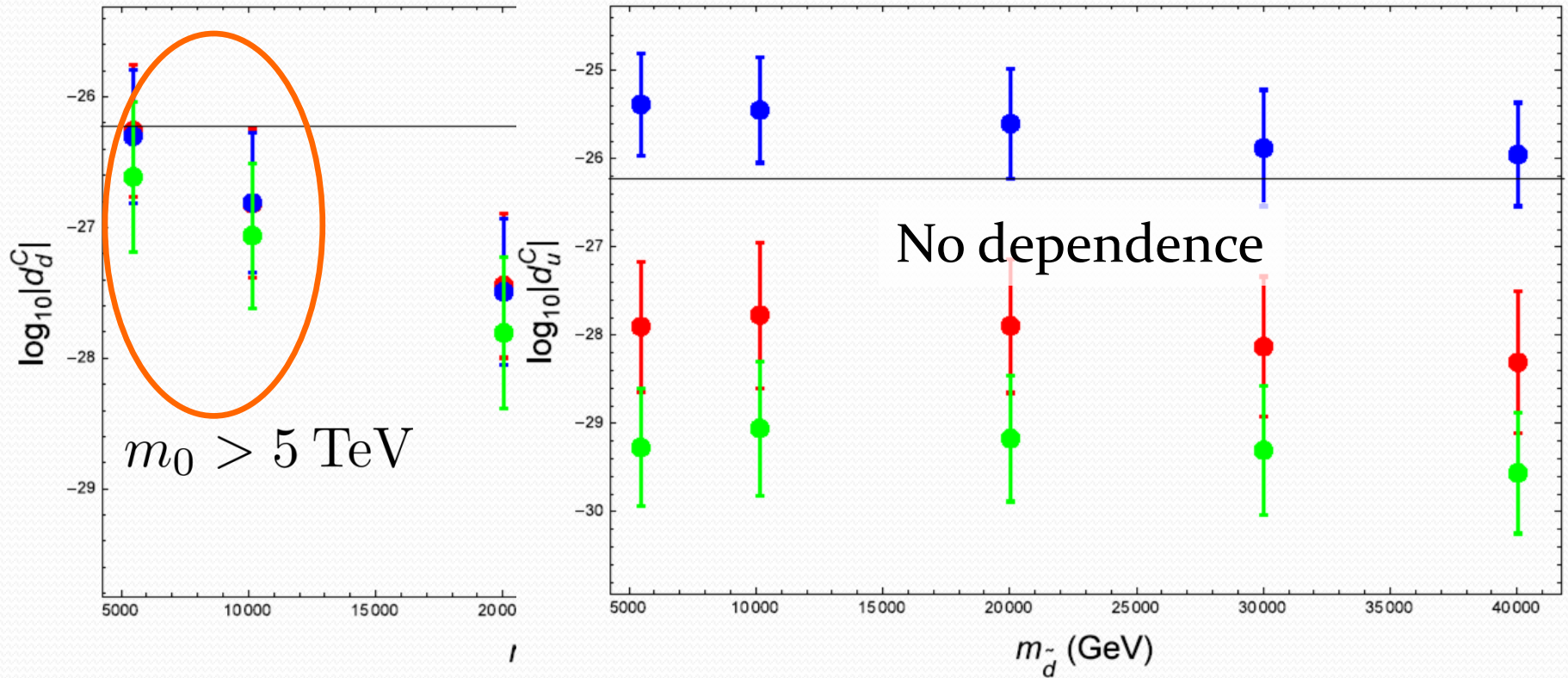
$$m_{H_u}^2 = m_{H_d}^2 = (500 \text{ GeV})^2 \quad \tan\beta = 7$$

✓ GUT scale \rightarrow SUSY scale \cdots MSSMの2-loop RGE

Results

- Heavy sfermion mass dependence

$$m_{\tilde{t}} \sim 2 \text{ TeV}$$



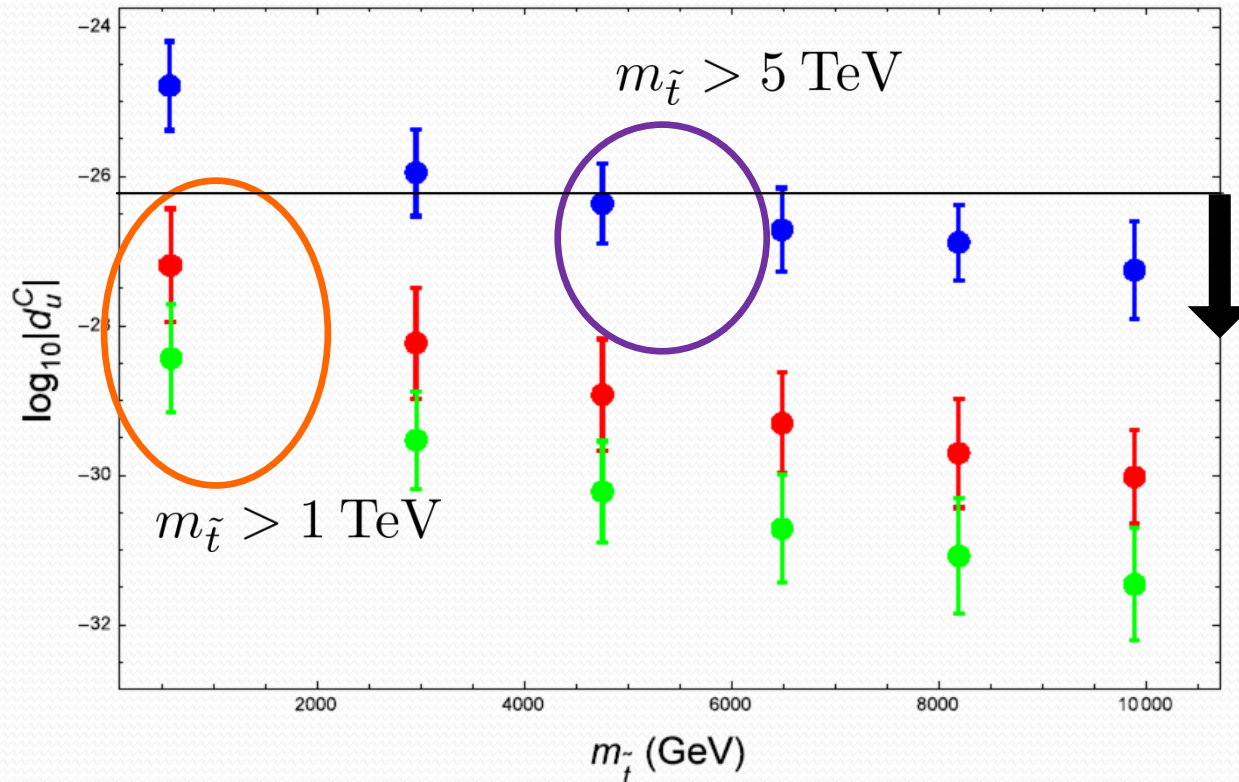
青: complex Y^u type 赤: real Y^u type 緑: E_6 model

Results

青: complex Y^u type 赤: real Y^u type 緑: E_6 model

• Stop mass dependence

$m_0 = 10$ TeV



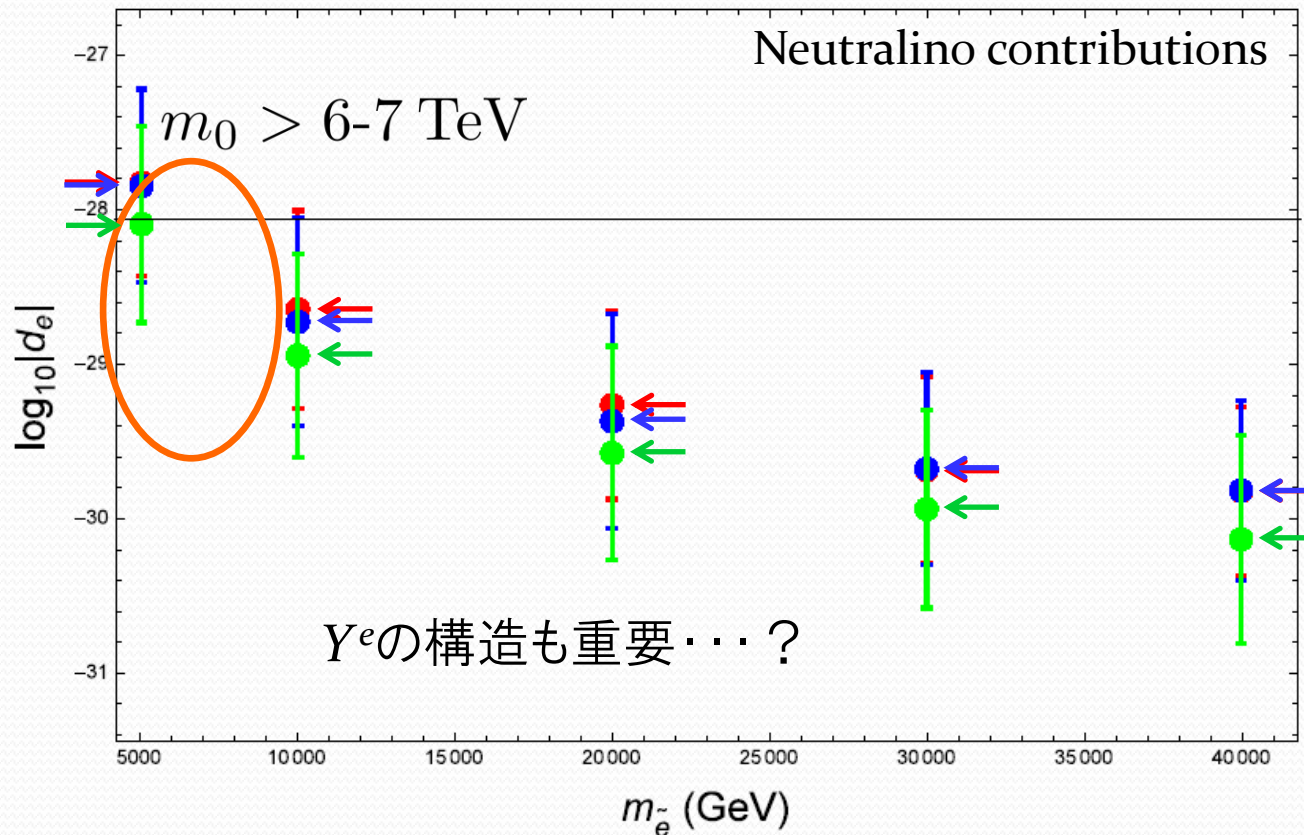
• Y^u が実なら、軽いストップでもCEDMの制限を満たす

• 将来実験でGUTスケールの Y^u の構造が決められる可能性

Comment on electron EDM

- CEDM同様、厳しい制限： $|d_e| < 8.7 \times 10^{-29} e \text{ cm}$

➡ d_e からの制限は？

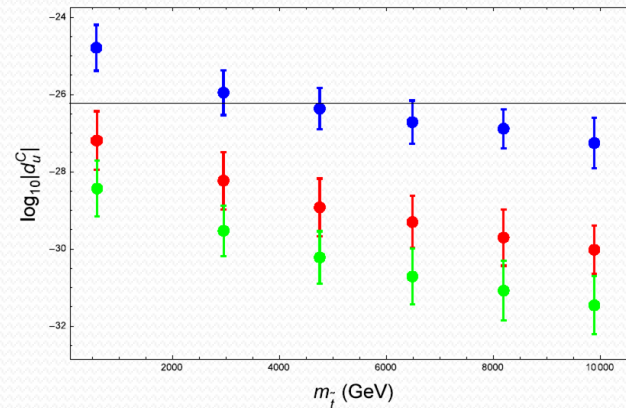
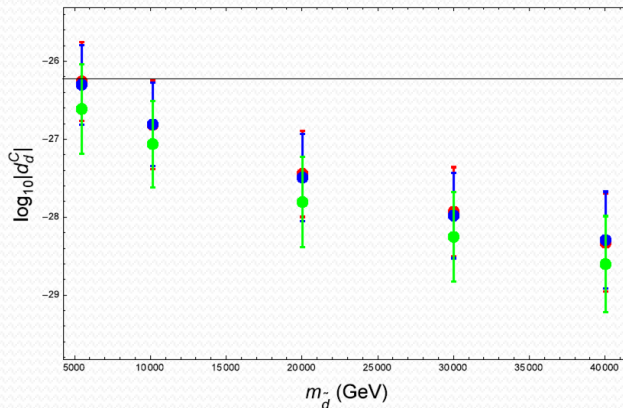


Summary

- Natural SUSY typeを仮定して、CEDMの制限を見た

$$m_{10}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} \quad m_{\frac{5}{5}}^2 = \begin{pmatrix} m_0^2 & 0 & 0 \\ 0 & m_0^2 & 0 \\ 0 & 0 & m_0^2 \end{pmatrix}$$

- Sfermion massに制限



- 将来実験でsfermion mass、Yukawaに何らかの制限

EDM実験、...

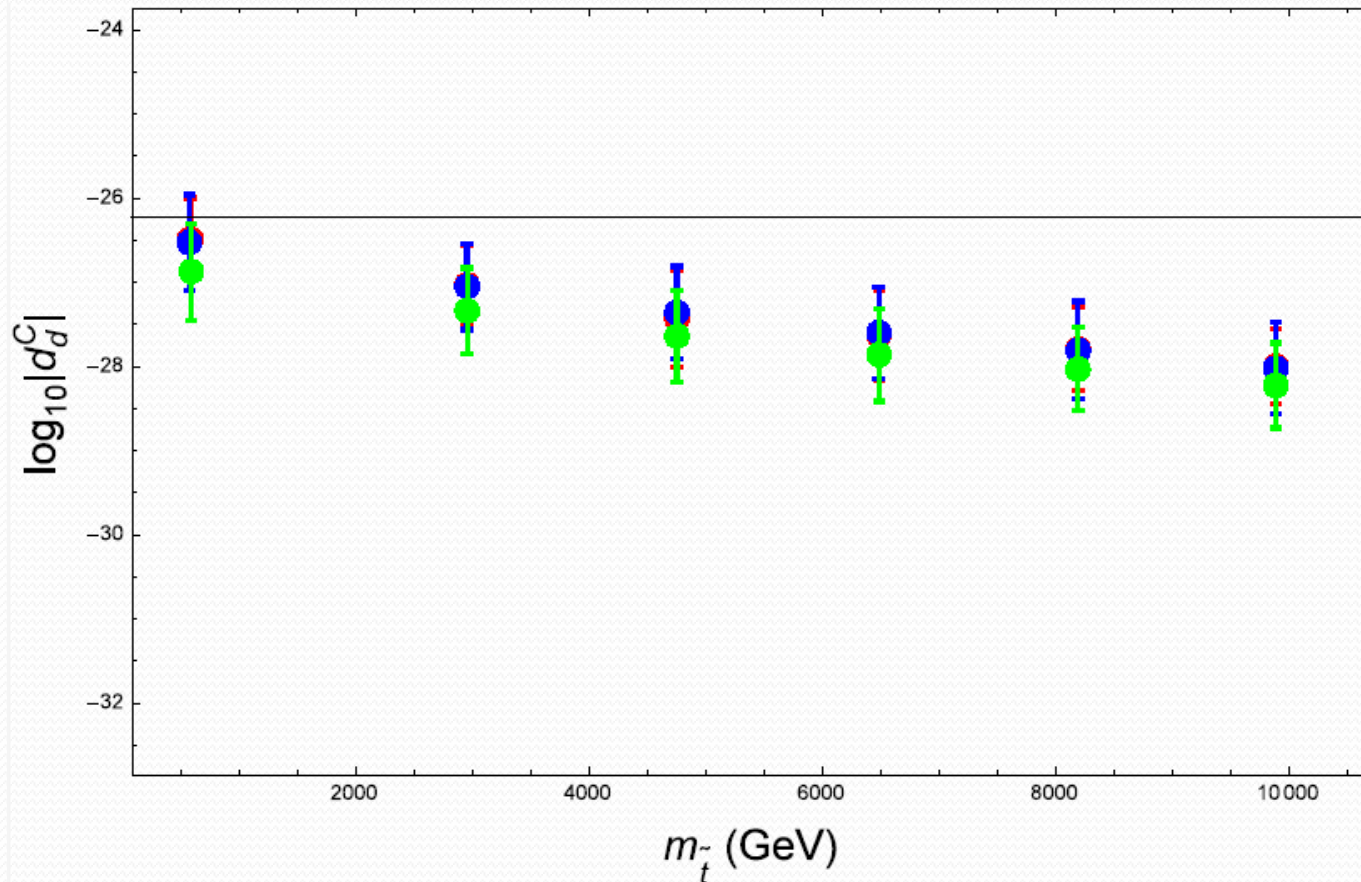
HL-LHC、...



Back up

- Stop mass dependence of d_d^C

$m_0 = 10 \text{ TeV}$



青: complex Y^u type 赤: real Y^u type 緑: E_6 model

CEDM

- 1-loopの表式:

$$d_u^C = c \frac{\alpha_s}{4\pi} \sum_{k=1}^6 \frac{M_{\tilde{g}}}{(\hat{m}_{\tilde{u}}^2)_{kk}} \left\{ \left(-\frac{1}{3} F_1(x_k^u) - 3F_2(x_k^u) \right) \text{Im}[(U_{\tilde{u}}^\dagger)_{1k} (U_{\tilde{u}})_{k4}] \right\}$$

$$d_d^C = c \frac{\alpha_s}{4\pi} \sum_{k=1}^6 \frac{M_{\tilde{g}}}{(\hat{m}_{\tilde{d}}^2)_{kk}} \left\{ \left(-\frac{1}{3} F_1(x_k^d) - 3F_2(x_k^d) \right) \text{Im}[(U_{\tilde{d}}^\dagger)_{1k} (U_{\tilde{d}})_{k4}] \right\}$$

$$d_s^C = c \frac{\alpha_s}{4\pi} \sum_{k=1}^6 \frac{M_{\tilde{g}}}{(\hat{m}_{\tilde{d}}^2)_{kk}} \left\{ \left(-\frac{1}{3} F_1(x_k^d) - 3F_2(x_k^d) \right) \text{Im}[(U_{\tilde{d}}^\dagger)_{2k} (U_{\tilde{d}})_{k5}] \right\}$$

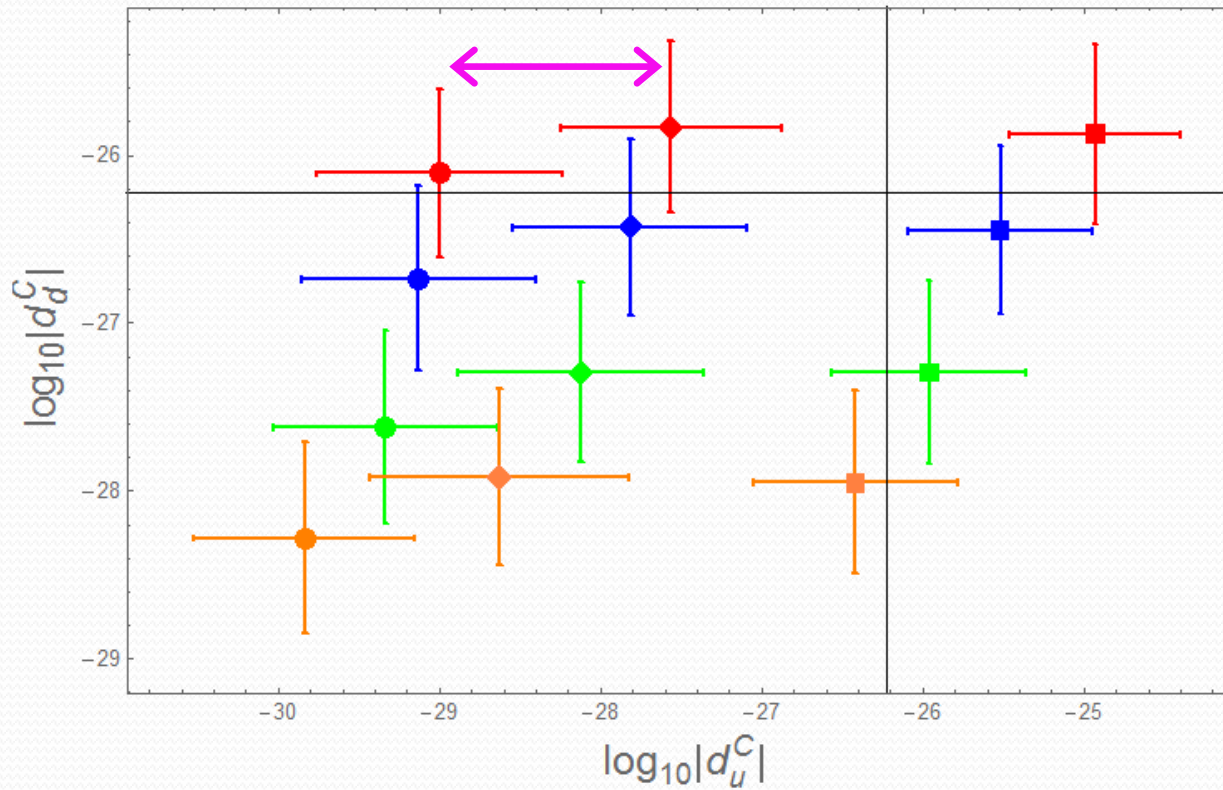
$$U_{\tilde{f}} m_{\tilde{f}}^2 U_{\tilde{f}}^\dagger = \hat{m}_{\tilde{f}}^2, \quad F_1(x) = \frac{x^2 - 1 - 2x \text{Log}[x]}{2(1-x)^3}, \quad F_2(x) = \frac{x^2 - 4x + 3 + 2\text{Log}[x]}{2(1-x)^3}, \quad x_k^f = \frac{M_{\tilde{g}}^2}{(\hat{m}_{\tilde{f}}^2)_{kk}}$$

Results

- d_u^C vs d_d^C

$$Y_u = \begin{pmatrix} 0 & \frac{1}{3}d_q\lambda^5 & 0 \\ -\frac{1}{3}d_q\lambda^5 & c\lambda^4 & b\lambda^2 \\ 0 & b\lambda^2 & a \end{pmatrix}$$

- E_6 model
- real Y_u type
- complex Y_u type



$\tan \beta = 7$

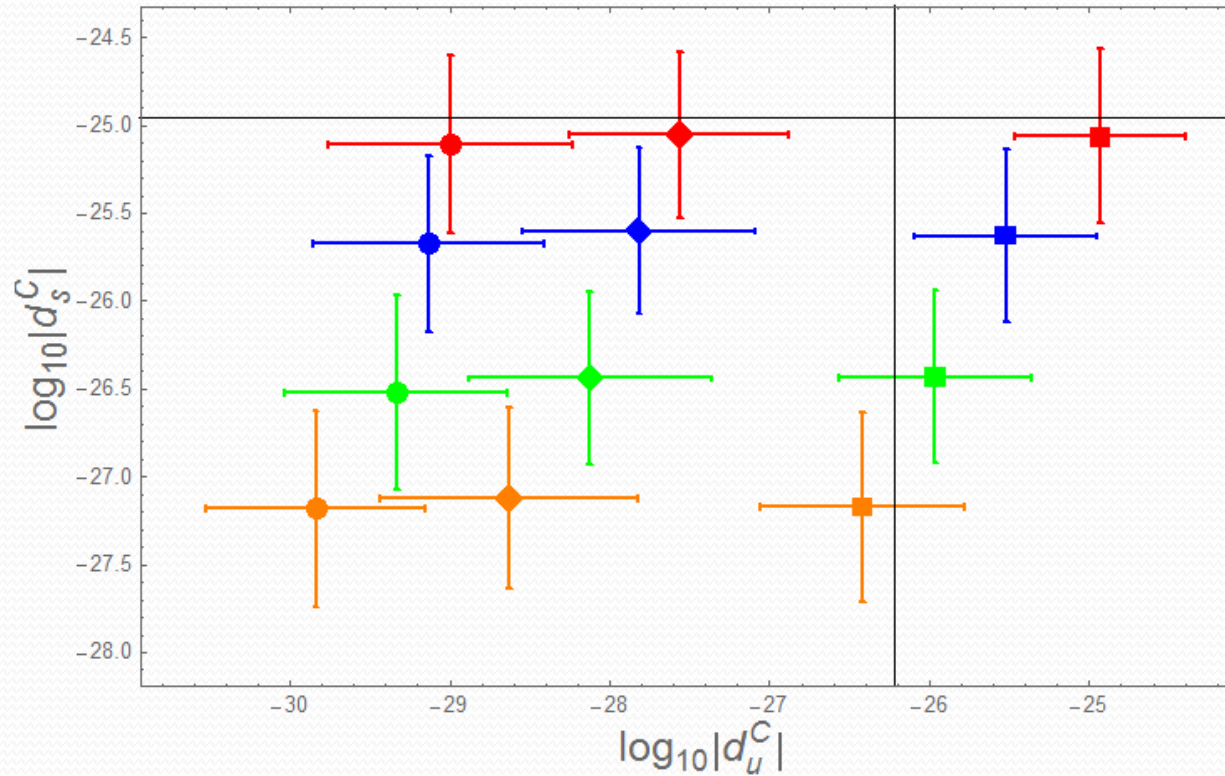
| m_0 | $m_{\tilde{t}}$ |
|--------|-----------------|
| 5 TeV | ~ 2 TeV |
| 10 TeV | ~ 2.3 TeV |
| 20 TeV | ~ 2.6 TeV |
| 40 TeV | ~ 4.2 TeV |

赤 : $m_0 = 5$ TeV、青 : $m_0 = 10$ TeV、緑 : $m_0 = 20$ TeV、橙 : $m_0 = 40$ TeV、

Results

• d_u^C vs d_s^C

◆ : E_6 model
◆ : real Y_u type
■ : complex Y_u type



$\tan \beta = 7$

| m_0 | $m_{\tilde{t}}$ |
|--------|-----------------|
| 5 TeV | ~ 2 TeV |
| 10 TeV | ~ 2.3 TeV |
| 20 TeV | ~ 2.6 TeV |
| 40 TeV | ~ 4.2 TeV |

赤 : $m_0 = 5$ TeV、青 : $m_0 = 10$ TeV、緑 : $m_0 = 20$ TeV、橙 : $m_0 = 40$ TeV、

E_6

- Superpotential

$$W = Y_{ij}^{\Phi} \Psi_i \Psi_j \Phi + Y_{ij}^C \Psi_i \Psi_j C$$

基本階層性

仮定:

$$Y_{ij}^{\Phi} \sim Y_{ij}^C \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}, \quad \frac{\langle C \rangle}{\langle \Phi \rangle} \sim \lambda^{0.5}$$



$$Y^u \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}, \quad Y^d \sim Y^{eT} \sim \begin{pmatrix} \lambda^6 & \lambda^{5.5} & \lambda^5 \\ \lambda^5 & \lambda^{4.5} & \lambda^4 \\ \lambda^3 & \lambda^{2.5} & \lambda^2 \end{pmatrix}$$

現実的な階層性が、1つの基本階層性から得られる

$E_6 \times SU(2)_F$

▶ 基本階層性の導出

$SU(2)_F$ を破る場: F^a, \bar{F}^a

$$\Rightarrow \begin{pmatrix} F^a \Psi_a F^b \Psi_b & F^a \Psi_a \bar{F}^b \Psi_b & F^a \Psi_a \Psi_3 \\ \bar{F}^a \Psi_a F^b \Psi_b & \bar{F}^a \Psi_a \bar{F}^b \Psi_b & \bar{F}^a \Psi_a \Psi_3 \\ \Psi_3 F^a \Psi_a & \Psi_3 \bar{F}^a \Psi_a & \Psi_3 \Psi_3 \end{pmatrix} \Phi \text{ (or } C)$$

仮定: $|\langle F^1 \rangle| = |\langle \bar{F}^2 \rangle| \sim \lambda^2$, F^a には λ が掛かる

$$\Rightarrow Y_{ij}^\Phi \sim Y_{ij}^C \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

基本階層性が導出される

$$E_6 \times SU(2)_F \times U(1)_A$$

● Lagrangian:

| | Ψ_a | Ψ_3 | F_a | \bar{F}^a | Φ | $\bar{\Phi}$ |
|----------|----------|---------------|----------------|----------------|--------|--------------|
| $U(1)_A$ | 4 | $\frac{3}{2}$ | $-\frac{3}{2}$ | $-\frac{5}{2}$ | -3 | 1 |

$$\mathcal{L} \ni \lambda^2 F^a \Psi_a F^b \Psi_b \Phi + \lambda F^a \Psi_a \bar{F}^b \Psi_b \Phi + \lambda F^a \Psi_a \Psi_3 \Phi + \bar{F}^a \Psi_a \bar{F}^b \Psi_b \Phi + \bar{F}^a \Psi_a \Psi_3 \Phi + \Psi_3 \Psi_3 \Phi$$

$$\Rightarrow \begin{pmatrix} F^a \Psi_a F^b \Psi_b & F^a \Psi_a \bar{F}^b \Psi_b & F^a \Psi_a \Psi_3 \\ \bar{F}^a \Psi_a F^b \Psi_b & \bar{F}^a \Psi_a \bar{F}^b \Psi_b & \bar{F}^a \Psi_a \Psi_3 \\ \Psi_3 F^a \Psi_a & \Psi_3 \bar{F}^a \Psi_a & \Psi_3 \Psi_3 \end{pmatrix} \Phi$$

$$\text{Higgs VEVs: } |\langle F^1 \rangle| \sim \lambda^2, \quad |\langle \bar{F}^2 \rangle| \sim \lambda^2, \quad |\langle \Phi \rangle| \sim \lambda$$

$$\Rightarrow Y_{ij}^\Phi \sim \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

電荷の割り当て方で現実的な階層性が導出される

アノマラス $U(1)_A$

- 特徴1: Froggatt-Nielsen機構の実現

- 演算子の係数に $U(1)_A$ 電荷に依存した抑制因子がつく

$U(1)_A$ charge : $\theta = -1$
gauge singlet

$$\mathcal{L} \ni Y_{ij}^u \left(\frac{\Theta}{\Lambda} \right)^{q_i + u_{R_j}^c + h} Q_i U_{R_j}^c H \quad (q_i + u_{R_j}^c + h > 0)$$

Y_{ij}^u : $\mathcal{O}(1)$ coefficients, Θ : FN field, Λ : GUT scale, $q_i, u_{R_j}^c, h$: $U(1)_A$ charges

$$\langle \Theta \rangle \equiv \lambda \Lambda \quad \Rightarrow \quad \mathcal{L} \ni Y_{ij}^u \lambda^{q_i + u_{R_j}^c + h} Q_i U_{R_j}^c H$$

場の $U(1)_A$ 電荷をうまく決めることで、階層的な構造が得られる

アノマラス $U(1)_A$

- 特徴2: SUSY-zero 機構

- SUSYではSuperpotentialの解析性により、 Θ^\dagger が使えない

$$\mathcal{L} \ni Y_{ij}^u \left(\frac{\Theta^\dagger}{\Lambda} \right)^{|q_i + u_{R_j}^c + h|} Q_i U_{R_j}^c H \quad (q_i + u_{R_j}^c + h < 0)$$

Superpotentialでは、このような項は禁止される

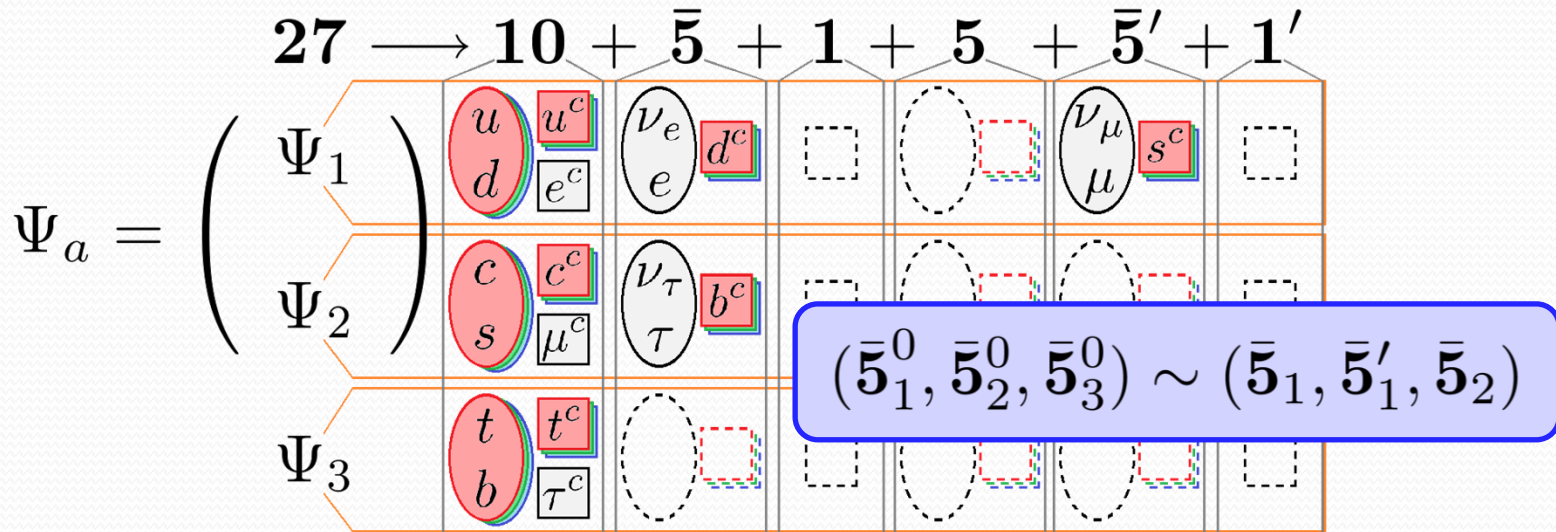
- アノマラス $U(1)_A$ の重要な仮定:

対称性で許される項は、**全て**オーダー-1係数で導入

SUSY-zero 機構により、無限個の相互作用をコントロールすることができる

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- 物質場... E_6 の 27 表現、 Ψ_a 、 Ψ_3



➡ 特徴的な sfermion mass spectrum

$$V_{SB} \ni m_0^2 |\Psi_a|^2 + m_3^2 |\Psi_3|^2$$

$$\tilde{m}_{10}^2 = \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_3^2 \end{pmatrix}, \quad \tilde{m}_{\bar{5}_0}^2 = \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_0^2 \end{pmatrix}$$



- Natural SUSY type
- SUSY FCNC の解決

Modified Universal Sfermion Masses (MUSM)

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- VEV determinationとSUSY zero mechanism

$$\langle O_i \rangle = \begin{cases} 0 & (o_i > 0) \\ \lambda^{-o_i} & (o_i \leq 0) \end{cases} \quad \begin{array}{l} O_i : \text{gauge singlet operator, } o_i : U(1)_A \text{ charge for } O_i, \\ \lambda = \frac{\xi}{\Lambda}, \xi : \text{Fayet-Iliopoulos parameter, } \Lambda : \text{GUT scale} = 1 \end{array}$$

⇒ 相互作用 $XYZ \Rightarrow \begin{cases} 0 & (x + y + z < 0) \\ a \lambda^{x+y+z} XYZ & (x + y + z \geq 0) \end{cases} \quad a : \mathcal{O}(1) \text{係数}$

VEVと相互作用の大きさは、場の $U(1)_A$ 電荷で決まる

- Superpotential

$$W_Y = (a\Psi_3\Psi_3 + b\Psi_3\bar{F}^a\Psi_a + c\bar{F}^a\Psi_a\bar{F}^b\Psi_b) \Phi + d(\Psi_a, \Phi, \bar{\Phi}, A, Z_3, \Theta) + f'\bar{F}^a\Psi_a\epsilon^{bc}F_b\Psi_cC + g'\Psi_3\epsilon^{ab}F_a\Psi_bC$$

$$\begin{array}{l} 27 \times 27 \times 27 \ni 1 \\ 27 \times \bar{27} \ni 1 + 78 \\ 27 \times 78 \ni 27 \\ 78 \times 78 \ni 1 + 78 \end{array}$$

| | Ψ_a | Ψ_3 | F_a | \bar{F}^a | Φ | $\bar{\Phi}$ | C | \bar{C} | A | Z_3 | Θ |
|-----------|----------|---------------|----------------|----------------|--------|--------------|-----|------------|----------------|----------------|----------|
| E_6 | 27 | 27 | 1 | 1 | 27 | $\bar{27}$ | 27 | $\bar{27}$ | 78 | 1 | 1 |
| $SU(2)_F$ | 2 | 1 | 2 | $\bar{2}$ | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| $U(1)_A$ | 4 | $\frac{3}{2}$ | $-\frac{3}{2}$ | $-\frac{5}{2}$ | -3 | 1 | -4 | -1 | $-\frac{1}{2}$ | $-\frac{3}{2}$ | -1 |
| Z_6 | 3 | 3 | 1 | 0 | 0 | 0 | 5 | 0 | 0 | 0 | 0 |

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

$$W_Y = (a\Psi_3\Psi_3 + b\Psi_3\bar{F}^a\Psi_a + c\bar{F}^a\Psi_a\bar{F}^b\Psi_b) \Phi + d(\Psi_a, \Phi, \bar{\Phi}, A, Z_3, \Theta) + f'\bar{F}^a\Psi_a\epsilon^{bc}F_b\Psi_cC + g'\Psi_3\epsilon^{ab}F_a\Psi_bC$$

湯川行列

$$Y^\Phi : \begin{pmatrix} 0 & d(\Psi_a, \Phi, \bar{\Phi}, A, Z_3, \Theta) & 0 \\ d(\Psi_a, \Phi, \bar{\Phi}, A, Z_3, \Theta) & c\bar{F}^a\Psi_a\bar{F}^b\Psi_b & b\bar{F}^a\Psi_a\Psi_3 \\ 0 & b\Psi_3\bar{F}^a\Psi_a & a\Psi_3\Psi_3 \end{pmatrix} \Phi$$

$$Y^C : \begin{pmatrix} 0 & f'F^a\Psi_a\bar{F}^b\Psi_b & g'F^a\Psi_a\Psi_3 \\ f'\bar{F}^a\Psi_aF^b\Psi_b & 0 & 0 \\ g'\Psi_3F^a\Psi_a & 0 & 0 \end{pmatrix} C$$

5と(5', 5)に対する質量行列: $d\Psi^a(A, Z_3, \bar{\Phi}\Phi)\Psi_a \ni \frac{2}{3}d_5\lambda^5\epsilon^{ab}5_a\bar{5}'_b$

Higgs VEVs: $\langle\Phi\rangle \sim \lambda$, $\langle C\rangle \sim \lambda^{2.5}$, $\langle A\rangle \sim \lambda^{0.5}$ $\langle F\rangle \sim \begin{pmatrix} 0 \\ e^{i\rho}\lambda^2 \end{pmatrix}$, $\langle\bar{F}\rangle \sim \begin{pmatrix} 0 \\ \lambda^2 \end{pmatrix}$

$$\left(\begin{array}{ccc|ccc} 0 & \frac{2}{3}\alpha d_5\lambda^5 & 0 & 0 & fe^{i\rho}\lambda^{5.5} & ge^{i\rho}\lambda^{3.5} \\ -\frac{2}{3}\alpha d_5\lambda^5 & c\lambda^4 & b\lambda^2 & fe^{i\rho}\lambda^{5.5} & 0 & 0 \\ 0 & b\lambda^2 & a & ge^{i\rho}\lambda^{3.5} & 0 & 0 \end{array} \right) \langle\Phi\rangle \equiv (M_1 \ M_2)$$

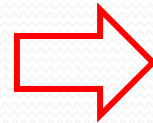
$$\alpha = \begin{cases} 1 & \text{for triplet of } (5, \bar{5}') \\ 0 & \text{for doublet of } (5, \bar{5}') \end{cases} \quad \frac{\lambda^c\langle C\rangle}{\lambda\phi\langle\Phi\rangle} = x\lambda^{0.5} \quad f \equiv xf', \quad g \equiv xg'$$

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

● $\bar{5}$ 場の混合

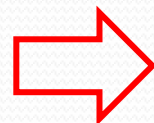
$$\left(\begin{array}{ccc|ccc} 0 & \frac{2}{3}\alpha d_5 \lambda^5 & 0 & 0 & f e^{i\rho} \lambda^{5.5} & g e^{i\rho} \lambda^{3.5} \\ -\frac{2}{3}\alpha d_5 \lambda^5 & c \lambda^4 & b \lambda^2 & f e^{i\rho} \lambda^{5.5} & 0 & 0 \\ 0 & b \lambda^2 & a & g e^{i\rho} \lambda^{3.5} & 0 & 0 \end{array} \right) \langle \Phi \rangle \equiv (M_1 \ M_2)$$

3 × 6行列の対角化: $V^\dagger (M_1 \ M_2) \begin{pmatrix} U_{10}^H & U_{10}^0 \\ U_{16}^H & U_{16}^0 \end{pmatrix} = (M_H^{\text{diag}} \ 0)$

 $M_1 U_{10}^0 + M_2 U_{16}^0 = 0$

$$U_{16}^0 = \begin{pmatrix} 1 & 0 & 0 \\ \mathcal{O}(\lambda^6) & 0 & 1 \\ -\frac{bg-af}{ac-b^2} \frac{\alpha \frac{2}{3} d_5}{g} \lambda^3 & -\frac{\alpha (\frac{2}{3} d_5)^2}{ac-b^2} \frac{a}{g} \lambda^{2.5} e^{-i\rho} & -\frac{f}{g} \lambda^2 \end{pmatrix}$$

$$U_{10}^0 = \begin{pmatrix} -\frac{a\alpha \frac{2}{3} d_5 (bg-af)}{(ac-b^2)^2} \lambda^{2.5} e^{i\rho} & 1 & \mathcal{O}(\lambda^{5.5}) \\ \frac{bg-af}{ac-b^2} \lambda^{1.5} e^{i\rho} & \frac{a\alpha \frac{2}{3} d_5}{ac-b^2} \lambda & \mathcal{O}(\lambda^{4.5}) \\ -\left(\frac{g}{a} + \frac{b}{a} \frac{bg-af}{ac-b^2}\right) \lambda^{3.5} e^{i\rho} & -\frac{b\alpha \frac{2}{3} d_5}{ac-b^2} \lambda^3 & \mathcal{O}(\lambda^{6.5}) \end{pmatrix}$$

 $\bar{\mathbf{5}}_i^0 \equiv (U_{10}^{0\dagger})_{ij} \bar{\mathbf{5}}'_j + (U_{16}^{0\dagger})_{ij} \bar{\mathbf{5}}_j = \begin{pmatrix} \bar{\mathbf{5}}_1 + \cdots \\ \bar{\mathbf{5}}'_1 + \cdots \\ \bar{\mathbf{5}}_2 + \cdots \end{pmatrix}$

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- 対角化行列・・・湯川行列を対角化

$$\text{MSSM Higgs: } \begin{cases} H_u \subset \Phi & \Rightarrow Y_u = Y^\Phi \\ H_d \subset \Phi, C & \Rightarrow Y_{d,e} = Y^\Phi U_{16}^0 + \beta_H e^{-i\delta} \lambda^{0.5} Y^C U_{10}^0 \end{cases}$$

$$Y_u = \begin{pmatrix} 0 & \frac{1}{3}d_q \lambda^5 & 0 \\ -\frac{1}{3}d_q \lambda^5 & c\lambda^4 & b\lambda^2 \\ 0 & b\lambda^2 & a \end{pmatrix}$$

$$Y_d = \begin{pmatrix} -\left(\frac{(bg-af)^2}{ac-b^2} + g^2\right) \frac{\beta_H}{a} e^{i(2\rho-\delta)} \lambda^6 & -\frac{bg-af}{ac-b^2} \frac{2}{3} d_5 \beta_H e^{i(\rho-\delta)} \lambda^{5.5} & \frac{1}{3} d_q \lambda^5 \\ \left(-\frac{1}{3}d_q - \frac{bg-af}{ac-b^2} \frac{b\frac{2}{3}d_5}{g}\right) \lambda^5 & \left(f\beta_H e^{i(\rho-\delta)} - \frac{(\frac{2}{3}d_5)^2}{ac-b^2} \frac{ab}{g} e^{-i\rho}\right) \lambda^{4.5} & \frac{cg-bf}{g} \lambda^4 \\ -\frac{bg-af}{ac-b^2} \frac{a\frac{2}{3}d_5}{g} \lambda^3 & \left(g\beta_H e^{i(\rho-\delta)} - \frac{(\frac{2}{3}d_5)^2}{ac-b^2} \frac{a^2}{g} e^{-i\rho}\right) \lambda^{2.5} & \frac{bg-af}{g} \lambda^2 \end{pmatrix}$$

$$Y_e = \begin{pmatrix} -\left(\frac{(bg-af)^2}{ac-b^2} + g^2\right) \frac{\beta_H}{a} e^{i(2\rho-\delta)} \lambda^6 & d_l \lambda^5 & 0 \\ 0 & f\beta_H e^{i(\rho-\delta)} \lambda^{4.5} & g\beta_H e^{i(\rho-\delta)} \lambda^{2.5} \\ -d_l \lambda^5 & \frac{cg-bf}{g} \lambda^4 & \frac{bg-af}{g} \lambda^2 \end{pmatrix}$$

$a, b, c, d_q, d_l, d_5, g, f, \beta_H : \mathcal{O}(1)$ の実係数 $\rho, \delta : \mathcal{O}(1)$ 位相

 このモデルのパラメータは少ない

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- 対角化行列・・・湯川行列を対角化

$$Y = \begin{pmatrix} y_{11} & y_{12} & y_{13} \\ y_{21} & y_{22} & y_{23} \\ y_{31} & y_{23} & y_{33} \end{pmatrix} \Rightarrow L^T Y R = Y^{\text{diag}} = \begin{pmatrix} y''_{11} & 0 & 0 \\ 0 & y'_{22} & 0 \\ 0 & 0 & y_{33} \end{pmatrix}$$

$$\left\{ \begin{array}{l} L^T \equiv \begin{pmatrix} c_{12}^L & -s_{12}^L & 0 \\ s_{12}^{L*} & c_{12}^L & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13}^L & 0 & -s_{13}^L \\ 0 & 1 & 0 \\ s_{13}^{L*} & 0 & c_{13}^L \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23}^L & -s_{23}^L \\ 0 & s_{23}^{L*} & c_{23}^L \end{pmatrix} \\ R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23}^R & s_{23}^R \\ 0 & -s_{23}^{R*} & c_{23}^R \end{pmatrix} \begin{pmatrix} c_{13}^R & 0 & s_{13}^R \\ 0 & 1 & 0 \\ -s_{13}^{R*} & 0 & c_{13}^R \end{pmatrix} \begin{pmatrix} c_{12}^R & s_{12}^R & 0 \\ -s_{12}^{R*} & c_{12}^R & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array} \right.$$

$$s_{ij}^{L/R} \equiv \sin \theta_{ij}^{L/R} e^{i\chi_{ij}^{L/R}} \ll 1, \quad c_{ij}^{L/R} \equiv \cos \theta_{ij}^{L/R} \simeq 1$$

$$\begin{aligned} y'_{11} &\simeq y_{11} - \frac{y_{13}y_{31}}{y_{33}}, & y''_{11} &\simeq y'_{11} - \frac{y'_{12}y'_{21}}{y'_{22}}, \\ y'_{22} &\simeq y_{22} - \frac{y_{23}y_{32}}{y_{33}}, & y'_{12} &\simeq y_{12} - \frac{y_{13}y_{32}}{y_{33}}, & y'_{21} &\simeq y_{21} - \frac{y_{23}y_{31}}{y_{33}} \end{aligned}$$

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- 対角化行列・・・湯川行列を対角化

$$s_{ij}^{L/R} \equiv \sin \theta_{ij}^{L/R} e^{i\chi_{ij}^{L/R}} \ll 1, \quad c_{ij}^{L/R} \equiv \cos \theta_{ij}^{L/R} \simeq 1$$

$$L^T \simeq \begin{pmatrix} 1 & -s_{12}^L & -s_{13}^L + s_{23}^L s_{12}^L \\ s_{12}^{L*} & 1 & -s_{23}^L \\ s_{13}^{L*} & s_{23}^{L*} & 1 \end{pmatrix}$$

$$R \simeq \begin{pmatrix} 1 & s_{12}^R & s_{13}^R \\ -s_{12}^{R*} & 1 & s_{23}^R \\ -s_{13}^{R*} + s_{23}^{R*} s_{12}^{R*} & -s_{23}^{R*} & 1 \end{pmatrix}$$

$$s_{23}^L \simeq \frac{y_{23}}{y_{33}}, \quad s_{13}^L \simeq \frac{y_{13}}{y_{33}}, \quad s_{12}^L \simeq \frac{y_{12}y_{33} - y_{13}y_{32}}{y_{22}y_{33} - y_{23}y_{32}}$$

$$s_{23}^{R*} \simeq \frac{y_{32}}{y_{33}}, \quad s_{13}^{R*} \simeq \frac{y_{31}}{y_{33}}, \quad s_{12}^{R*} \simeq \frac{y_{21}y_{33} - y_{31}y_{23}}{y_{22}y_{33} - y_{23}y_{32}}$$

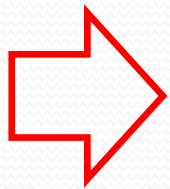
$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- 対角化行列・・・湯川行列を対角化

$$Y_d = \begin{pmatrix} -\left(\frac{(bg-af)^2}{ac-b^2} + g^2\right) \frac{\beta_H}{a} e^{i(2\rho-\delta)} \lambda^6 & -\frac{bg-af}{ac-b^2} \frac{2}{3} d_5 \beta_H e^{i(\rho-\delta)} \lambda^{5.5} & \frac{1}{3} d_q \lambda^5 \\ \left(-\frac{1}{3} d_q - \frac{bg-af}{ac-b^2} \frac{b \frac{2}{3} d_5}{g}\right) \lambda^5 & \left(f \beta_H e^{i(\rho-\delta)} - \frac{(\frac{2}{3} d_5)^2}{ac-b^2} \frac{ab}{g} e^{-i\rho}\right) \lambda^{4.5} & \frac{cg-bf}{g} \lambda^4 \\ -\frac{bg-af}{ac-b^2} \frac{a \frac{2}{3} d_5}{g} \lambda^3 & \left(g \beta_H e^{i(\rho-\delta)} - \frac{(\frac{2}{3} d_5)^2}{ac-b^2} \frac{a^2}{g} e^{-i\rho}\right) \lambda^{2.5} & \frac{bg-af}{g} \lambda^2 \end{pmatrix}$$

$$L_d^T Y_d R_d = Y_d^{\text{diag}} \text{ と対角化}$$

$$L_d \sim \begin{pmatrix} 1 & \left(\frac{2}{3} + i\frac{4}{27}\right)\lambda & \frac{1}{3}\lambda^3 \\ \left(\frac{2}{3} + i\frac{4}{27}\right)\lambda & 1 & \lambda^2 \\ \left(\frac{2}{3} + i\frac{4}{27}\right)\lambda^3 & \lambda^2 & 1 \end{pmatrix}$$



$$R_d \sim \begin{pmatrix} 1 & \frac{2}{3}(1+i)\lambda^{0.5} & \frac{2}{3}\lambda \\ \frac{2}{3}(1+i)\lambda^{0.5} & 1 & (1+i)\lambda^{0.5} \\ \frac{2}{3}(1+i)\lambda & (1+i)\lambda^{0.5} & 1 \end{pmatrix}$$

$E_6 \times SU(2)_F \times U(1)_A$ SUSY GUT model

- この模型における仮定:

対称性で許される相互作用は、**全て** $O(1)$ 係数で導入

- Sfermion mass spectrum: **M**odified **U**niversal **S**fermion **M**asses (**MUSM**)

$$V_{\text{SB}} \ni m_0^2 |\Psi_a|^2 + m_3^2 |\Psi_3|^2 \quad (\bar{5}_1^0, \bar{5}_2^0, \bar{5}_3^0) \sim (\bar{5}_1, \bar{5}'_1, \bar{5}_2)$$

$$\tilde{m}_{10}^2 = \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_3^2 \end{pmatrix}, \quad \tilde{m}_{\bar{5}0}^2 = \begin{pmatrix} m_0^2 & & \\ & m_0^2 & \\ & & m_0^2 \end{pmatrix}$$

$10 : \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}, \tilde{u}_R^c, \tilde{e}_R^c$
 $\bar{5} : \begin{pmatrix} \tilde{\nu}_{eL} \\ \tilde{e}_L \end{pmatrix}, \tilde{d}_R^c$

- ➡ SUSY FCNCの解決に役立つ
- ➡ Natural SUSY type

