Spontaneous SUSY breaking in natural SO(10) GUT

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1. **Introduction**
2. **Natural (anomalous U(1)) GUT**
3. **Sp. SUSY breaking in natural GUT**
4. **Predictions**
5. **Summary**

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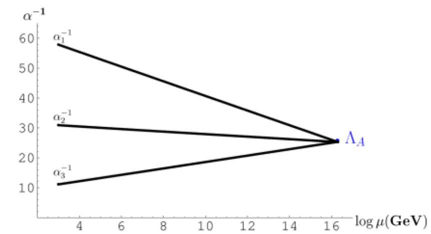
Grand unified theories

- 2 unifications and evidences for both unifs.

  Gauge interactions

  $\mathrm{SO}(10) \supset SU(5) \supset \mathrm{SU}(3)_C \times SU(2)_L \times U(1)_Y$



  Matters

  $\mathbf{10}(Q + U_R^c + E_R^c) + \bar{\mathbf{5}}(D_R^c + L) + \mathbf{1}(N_R^c) = \mathbf{16}$

  $\mathbf{10}$ induces stronger hierarchy than $\bar{\mathbf{5}}$.

  $\Longrightarrow$ Observed quark and lepton masses and mixings

- 2 problems

  Doublet-triplet splitting problem ($m_{H_T} \gg m_{H_D}$)

  Unrealistic GUT Yukawa relations($Y_d = Y_e^t (= Y_u = Y_{\nu_D})$)

Natural GUT (Anomalous U(1) GUT)

N.M.01
N.M.&Yamashita,02

1. **Doublet-triplet splitting and realistic quark and lepton masses and mixings are realized under natural assumption.**
   Geneneric interactions (incl. higher dim. Interactions) are introduced with O(1) coefficients. (No $U(1)_R$.)
   Once we fix the symmetry of the model, we can predict everything except O(1) coefficients.

2. **Natural gauge coupling unification.**
   Natural GUT gives a new explanation for the success of gauge coupling unification in MSSM.
   The cutoff scale should be taken to be the usual GUT scale.

$$\Lambda \sim \Lambda_{GUT}$$

Natural SO(10) GUT

- Natural SO(10) GUT(Anomalous U(1) gauge symmetry)

Symmetry: $SO(10) \times U(1)_A \times Z_2$

$SO(10)$	$negative$	$positive$	$matter$
45	$A(a=-1,-)$	$A'(a'=3,-)$	
16	$C(c=-4,+)$	$C'(c'=3,-)$	$\Psi_a(\psi_1=\frac{9}{2},\psi_2=\frac{7}{2},\psi_3=\frac{3}{2},+)$
$\overline{16}$	$\bar{C}(\bar{c}=-1,+)$	$\bar{C}'(\bar{c}'=6,-)$	
10	$H(h=-3,+)$	$H'(h'=4,-)$	$T(t=\frac{5}{2},+)$
1	$Z,\bar{Z}(Z=\bar{z}=-2,-),$	$Z'(z'=5,+)$	
	Non zero VEV	Vanishing VEV	

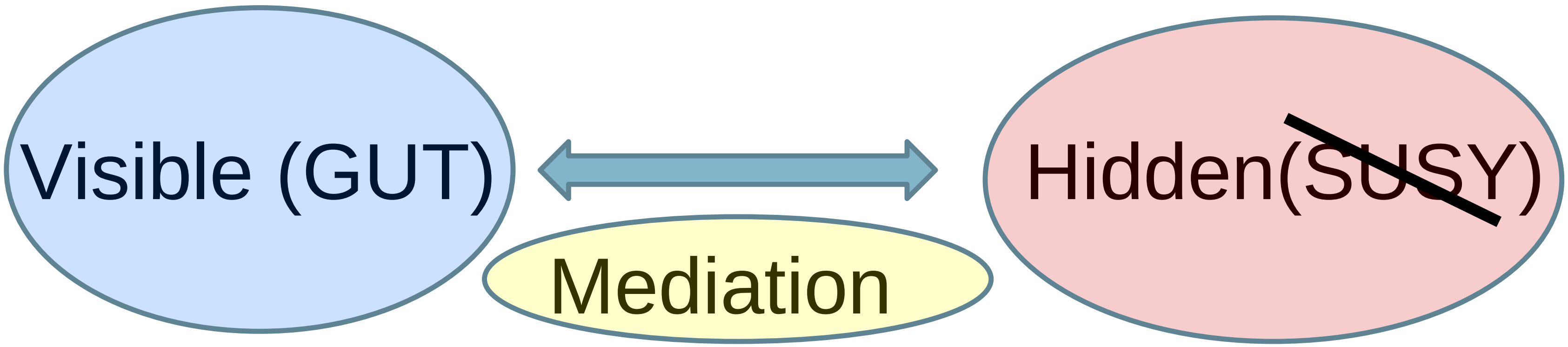
The doublet triplet splitting problem can be solved.

Realistic quark and lepton masses and mixings are obtained just by introducing all terms which are allowed by symmetry with O(1) coefficients.

SUSY breaking?

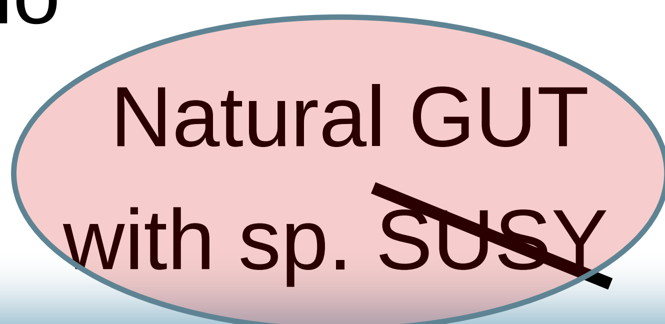
SUSY breaking

- Usual SUSY breaking scenario



to suppress FCNC (and ~~CP~~) processes

- New scenario



High scale SUSY suppresses FCNC and ~~CP~~.

Natural SO(10) GUT

- Natural SO(10) GUT(Anomalous U(1) gauge symmetry)

$SO(10)$	$negative$	$positive$	$matter$
45	$A(a=-1,-)$	$A'(a'=3,-)$	
16	$C(c=-4,+)$	$C'(c'=3,-)$	$\Psi_a(\psi_1=\frac{9}{2},\psi_2=\frac{7}{2},\psi_3=\frac{3}{2},+)$
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1	$Z,\bar{Z}(Z=\bar{z}=-2,-),$	$Z'(z'=5,+)$	

Non zero VEVs   F=0

Variables   Constraints

Constraints(positive fields) are balanced with variables(negative fields)

Sp. SUSY breaking in natural GUT

- Natural SO(10) GUT

$SO(10)$	$negative$	$positive$	$matter$
45	$A(a=-1,-)$	$A'(a'=3,-)$	
16	$C(c=-4,+)$	$C'(c'=3,-)$	$\Psi_a(\psi_1=\frac{9}{2},\psi_2=\frac{7}{2},\psi_3=\frac{3}{2},+)$
$\overline{16}$	$\bar{C}(\bar{c}=-1,+)$	$\bar{C}'(\bar{c}'=6,-)$	
10	$H(h=-3,+)$	$H'(h'=4,-)$	$T(t=\frac{5}{2},+)$
1	$Z,\bar{Z}(Z=\bar{z}=-2,-)$,	$Z'(z'=5,+)$	

- Let us decrease one negatively charged field.
- One of $F_{C'}$ & $F_{\bar{C}'}$ is not vanishing. $W_{C'}=\bar{C}(A+Z)C',\ \ W_{\bar{C}'}=\bar{C}'(A+Z)C$

  Barr-Raby 97

  For alignment by Barr-Raby mechanism is sufficient if $F_{C'}=0$.

$$\frac{\partial W_{\bar{C}'}}{\partial \bar{C}'}=(A+Z)C\sim\lambda^{\bar{c}'+\frac{1}{2}(c-\overline{c})}=\lambda^{\frac{9}{2}}\sim(2\times10^{13}\mathrm{GeV})$$ too large

- SUSY breaking scale can be smaller by choosing larger $\bar{c}'$.

Gauge messenger gives sizable gaugino mass?

- Massive vector multiplets do not respect SUSY $(F_{\bar{C}'} \neq 0)$

  Generically they induce $m_{1/2} \sim c_i \frac{\alpha_i}{4\pi} \frac{F_{\bar{C}'}}{\Lambda} \sim 10^{-2} m_0$(gauge messenger)

- Unfortunately, induced gaugino masses are quite small.

  because of approximate $U(1)_R$ symmetry.

$SO(10)$	$negative$	$positive$	
45	$A(a=-1,-)$	$A'(a'=3,-)$	$\langle A \rangle \neq 0$
16	$C(c=-4,+)$	$C'(c'=3,-)$	$\langle F_{C'} \rangle \neq 0$
$\overline{16}$	$\bar{C}(\bar{c}=-1,+)$	$\bar{C}'(\bar{c}'=6,-)$	
10	$H(h=-3,+)$	$H'(h'=4,-)$	massive chiral multiplets do not
1	$Z(Z=-2,-)$,	$Z'(z'=5,+)$	respect SUSY but $m_{1/2} \sim m_0^2/\Lambda$
$U(1)_R$	0	$2(F_{C'}:0)$	Very small $\langle Z' \rangle, \langle F_Z \rangle$

Very small $U(1)_R$ breaking like $\lambda^{c'+\bar{c}'} \bar{C}' C'$ must be picked up for gaugino mass.

Anomaly mediation gives $m_{1/2} \sim 10^{-2} m_{3/2} \sim 10^{-5} m_0 . (m_{3/2} \sim F_{\bar{C}'}/M_{Pl} \sim 10^{-3} m_0$

Ten years ago, we gave up to build model because of too small gaugino mass.

SUGRA effects induce $m_{1/2} \sim m_{3/2}$

N.M.-Omura-Shigekami-Yoshida17

- R symmetry breaking $\langle W \rangle$ gives larger contribution to gaugino masses
- SUSY breaking spectrum becomes

$\bar{c}'$	$F_{\bar{c}'}/\Lambda$	$m_{1/2} \sim m_{3/2}$	$m_0 \sim \sqrt{D_A}$	
18	200 TeV	2TeV	2000TeV	
19	40 TeV	400 GeV	400TeV	

- High scale SUSY is predicted. (D_A dominates)

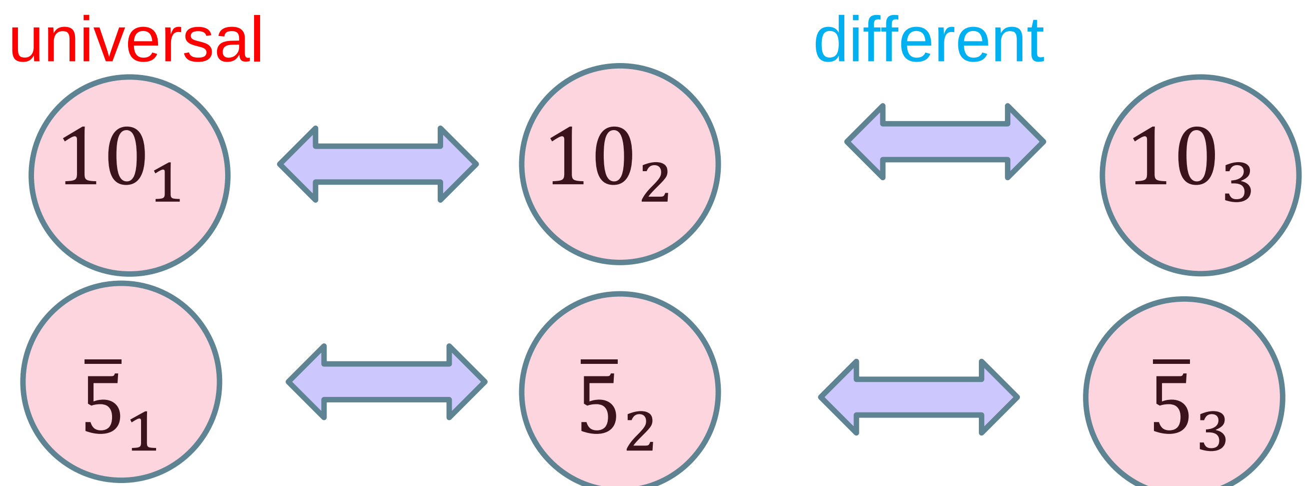
  Roughly $m_{1/2} \sim 1$ TeV, $m_0 \sim (100-)1000$ TeV
- No SUSY flavor and CP problem, although weak scale is destabilized.

"Direct" signature for GUT

- D term dominates sfermion masses.

$$\tilde{m}^2_{10} \sim \left(\frac{9}{2}, \frac{7}{2}, \frac{3}{2}\right) g_A D_A + \frac{1}{5} g_{10} D_V \qquad SO(10) \supset SU(5) \times U(1)_V$$

$$\tilde{m}^2_{\bar{5}} \sim \left(\frac{9}{2}, \frac{5}{2}, \frac{7}{2}\right) g_A D_A + \left(-\frac{3}{5}, \frac{2}{5}, -\frac{3}{5}\right) g_{10} D_V$$



- Sfermion masses respect SU(5) unification!

They can be a direct signature of unification of matter in SU(5) GUT.

- Sfermion masses are fixed by $g_A D_A$ and $g_{10} D_V (= 2 g_A D_A / 3)$.

Predictions from E_6 GUT

- $E_6 \supset SO(10) \times U(1)_{V'}$, has 3 D terms

Bando-N.M.01
N.M.-Yamashita 02

$$\tilde{m}_{10}^2 \sim \left(\frac{9}{2},\frac{7}{2},\frac{3}{2}\right) g_A D_A + \frac{1}{4} g_6 D_{V'} + \frac{1}{5} g_{10} D_V$$

$$\tilde{m}_{\bar{5}}^2 \sim \left(\frac{9}{2},\frac{9}{2},\frac{7}{2}\right) g_A D_A + \left(\frac{1}{4},-\frac{1}{2},\frac{1}{4}\right) g_6 D_{V'} + \left(-\frac{3}{5},\frac{2}{5},-\frac{3}{5}\right) g_{10} D_V$$

- $E_6 \times SU(2)_F$ has 4 D terms

N.M.02
Ishiduki-Kim-N.M.-Sakurai 09
N.M.-Muramatsu-Shigekami 14

$$\tilde{m}_{10}^2 \sim \left(4,4,\frac{3}{2}\right) g_A D_A + \frac{1}{4} g_6 D_{V'} + \frac{1}{5} g_{10} D_V + (1,-1,0) g_F D_F$$

$$\tilde{m}_{\bar{5}}^2 \sim (4,4,4) g_A D_A + \left(\frac{1}{4},-\frac{1}{2},\frac{1}{4}\right) g_6 D_{V'} + \left(-\frac{3}{5},\frac{2}{5},-\frac{3}{5}\right) g_{10} D_V + (1,1,-1) g_F D_F$$

$$g_6 D_{V'} = g_A D_A, \quad g_{10} D_V = \frac{5}{4} g_A D_A, g_F D_F = \frac{1}{2} g_A D_A$$

- The sfermion mass scale is much smaller than the GUT scale, although it is too large to reach by experiments in near future.
- Various GUT can be tested.

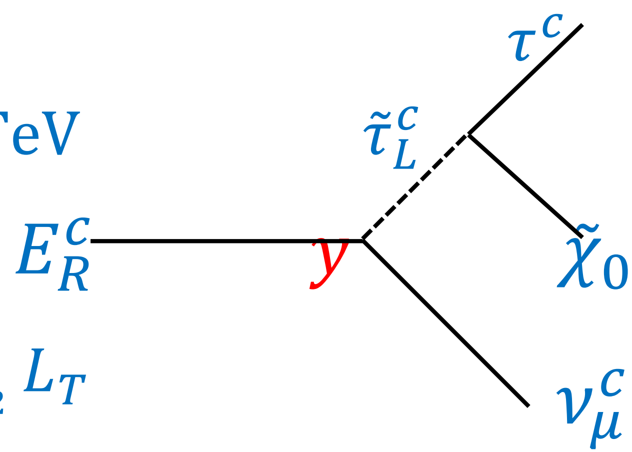
An interesting prediction(preliminary)

- Long-lived heavy electron(R-parity odd)

Lightest particle in Higgs sector is $E_R^c + \overline{E_R^c}$ in $16_{C'} + \overline{16}_{\bar{C}'}$

Roughly we take

$m_0 \sim 1000\text{TeV}, m_{1/2} \sim 1\text{TeV},\ m_{E_R^c} \sim 1\text{TeV}$



- Decay mode is $\tau^c \nu_\mu^c \tilde{\chi}_0$ or $\mu^c \nu_\tau^c \tilde{\chi}_0$

$y = \lambda^{c'+\psi_2+t}$, $\quad 16_{C'} 16_{\psi_2} 10_T \to E_R^c L_{\psi_2} L_T$

- $\tau_{E_R^c} \sim O(1)\text{sec} \left(\frac{10^{-6}}{y}\right)^2 \left(\frac{m_0}{1000\text{TeV}}\right)^4 \left(\frac{1\text{TeV}}{m_{E_R^c}}\right)^5$ sec

$\tau < 1$ is needed for BBN.

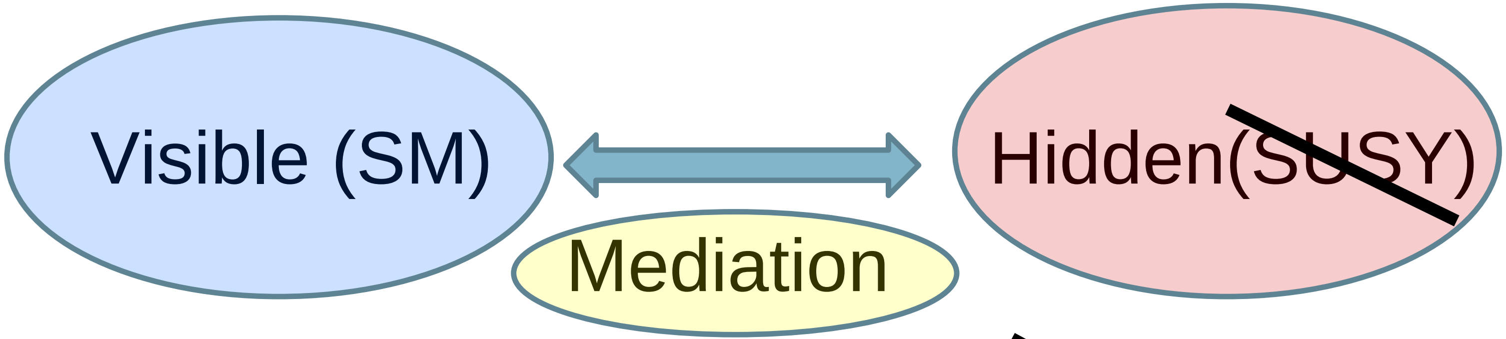
- LHC gives a constraint for long-lived charged particle.

$m_{E_R^c} > 574$ GeV (CMS 1305)

- LHC may find this particle.

Summary and in future

- Usual SUSY breaking scenario



to suppress FCNC and ~~CP~~ processes

- Our scenario

High scale SUSY suppresses FCNC and ~~CP~~

- In future

$E_6 \times SU(2)_F \rightarrow$ Natural SUSY and suppresses FCNC and ~~CP~~ even with low scale SUSY

Summary and discussions

Good points

- SUSY and GUT breaking in a model (just by decreasing a singlet).
- No R-axion. Constant superpotential is allowed by symmetry. (No $U(1)_R$.)
- It produces gaugino mass by gravity mediation. High scale SUSY!

  $m_{1/2} \sim m_{3/2} \sim$ 1TeV, $m_0 \sim 1000$TeV.
- Interesting phenomenology.

  Long lived charged lepton appears.

$$\tau_{E_R^c} \sim O(10^{-2})\ \mathrm{sec}\left(\frac{m_0}{1000\mathrm{TeV}}\right)^4\left(\frac{1\mathrm{TeV}}{m_{E_R^c}}\right)^5$$

  LHC may discover it.
- “Direct” signatures of GUT in sfermion mass spectrum

Bad points

- High scale SUSY needs finetuning. It is caused by $\Lambda \sim \Lambda_G \ll M_{Pl}$, which is required to explain the success of RGE gauge couplings.
- Artificial discrete symmetry and singlets are introduced to obtain lower SUSY scale. (E6 GUT may avoid this issue.) Artificially large $U(1)_A$ charge.
- Gravitino problem
- Bino DM (overproduction?)

The upper 2 bad points are based on the assumption of O(1) coefficients. Suppression factors from extra dimension may avoid these.

Bino overproduction problem

Why is bino LSP?

- D term dominates $\frac{F_{\bar{C}'}}{\Lambda}$ contribution.
- μ must be large to cancel the D term contribution to Higgs.
- $m_{1/2} \sim m_{3/2} \sim 1\text{TeV},\ m_0 \sim 1000\text{TeV}$.
- Interesting phenomenology.

  Long lived charged lepton appears.

$$\tau_{E_R^c} \sim O(1)\ \sec\left(\frac{m_0}{1000\text{TeV}}\right)^4 \left(\frac{1\text{TeV}}{m_{E_R^c}}\right)^5$$

  LHC may discover it.

- "Direct" signatures of GUT in sfermion mass spectrum.
- D term domination is a result of a simple model. This may change in more realistic and complex model.)

Higgsino LSP(DM)

- $\sqrt{D} \sim \frac{F_{\bar{C}'}}{\Lambda}$.
- μ can be small since D can be cancelled by $\frac{F_{\bar{C}'}}{\Lambda}$.
- $m_{1/2} \sim m_{3/2} \sim 1\text{TeV},\ m_0 \sim 100\text{TeV}$.

  Finetuning is improved!

- Interesting phenomenology.

  Long lived charged lepton appears.

$$\tau_{E_R^c} \sim O(0.1)\ \sec\left(\frac{m_0}{100\text{TeV}}\right)^4 \left(\frac{1\text{TeV}}{m_{E_R^c}}\right)^5$$

  Yukawa suppression is compensated by smaller m_0.

  LHC may discover it.

- "Direct" signatures of GUT in sfermion mass spectrum. D-term observation becomes indirect.