

SUSY Unification 2001

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1. 序論: 概観
2. SUSY と SUSY Breaking
3. Sparticle Masses から何がわかるか.

最近見つけた文献

H.E. Haber, hep-ph/0103095 and references therein.

1. 序論: 概観

1970年代 素粒子の標準模型の確立:

- ・電弱セクターの精密測定
- ・トップクォークの発見

標準模型における質量を与えるメカニズム:

Higgs Sectorの理解が急務。

Higgsの質量と Naturalnessの問題

Higgs massの量子補正

$$+ \sim \frac{g^2}{(4\pi)^2} \Lambda^2$$

$$m_{\text{phys}}^2 = m_0^2 + \frac{g^2}{(4\pi)^2} \Lambda^2$$

Λ : $\left\{ \begin{array}{l} \cdot E \leq \Lambda \text{で SM の} \\ \text{記述が OK.} \\ \cdot \text{SM の cut-off} \\ \text{scale.} \end{array} \right.$

・ m_0^2 と Λ^2 項の不自然な cancellation を考えないとす
ると.

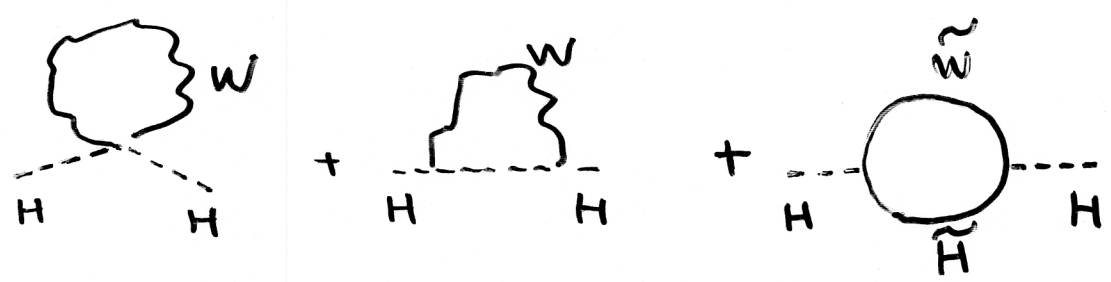
$$\Lambda \lesssim (1) \text{TeV}$$

これ以下のスケールに
新しい物理がある!

色々な可能性

- SUPER SYMMETRY
- dynamical Higgs mechanism (e.g. technicolor)
- large extra dimensions / warped extra dim.

SUSYの場合: 2次発散($\propto \Lambda^2$)の相殺.



$\sim \frac{g^2}{(4\pi)^2} \cdot m_{SUSY}^2$ $\therefore m_{SUSY} \lesssim O(1) \text{ TeV}$

- SUSY mass is $O(1) \text{ TeV}$ ^{scale} 以下
- 理論の cut-off そのものは、大きくてもよい。
 - \Rightarrow 大統一理論 $\sim 10^{16} \text{ GeV}$
 - 量子重力 $\sim 10^{19} \text{ GeV}$

SUSYが注目される理由.

- Gauge Coupling Unification in MSSM

- Higgs Mass from EW global fit.

$$m_h \approx 200 \text{ GeV} \quad (\text{cf. SUSY } m_h \approx 130 \text{ GeV})$$

- Dark Matter.

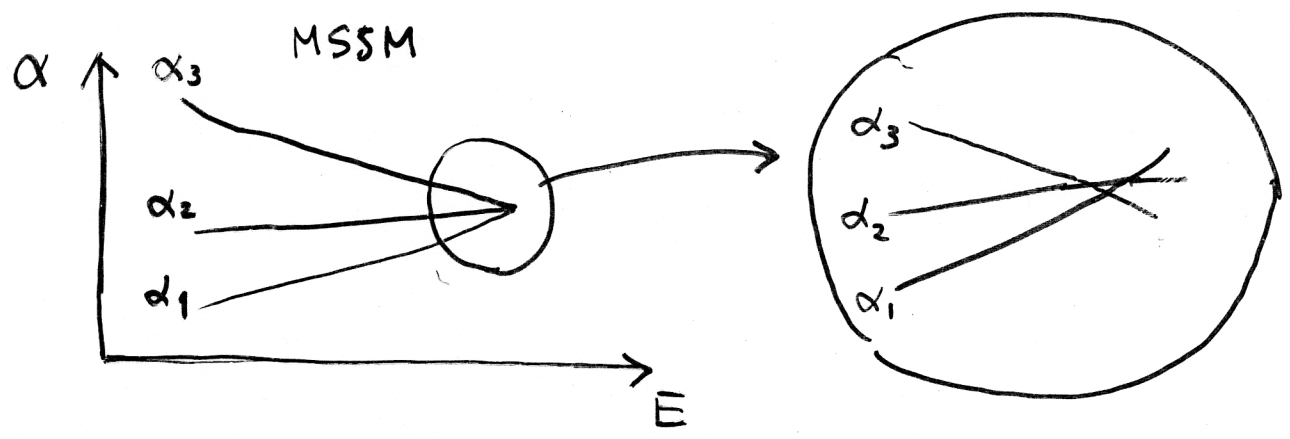
Lightest Superparticle (LSP):

(Cold) Dark Matterの有力候補

- Muonのg-2.

SUSY interpretation O.K.

Gauge Coupling Unification について: どの位あわないか?



- g_1 と g_2 が一致するスケールに M_{GUT} とする.
- ずれを表す量.

$$\epsilon \equiv \frac{g_3(M_{GUT}) - g_1(M_{GUT})}{g_1(M_{GUT})}$$

mSUGRA での weak scale での SUSY threshold 取り直し.

$$\Rightarrow \epsilon \simeq -1\% \sim -2\%.$$

1, 2% のずれ!

Serious?

No!

このずれは簡単に説明できる。例えば。

① GUT scale での threshold 効果

(GUT scale で粒子の mass がバラけている効果)

$$\text{e.g. } G_{H_3} \sim 0.3 \frac{\alpha_G}{\pi} \ln(M_{H_3}/M_{\text{GUT}}).$$

$$M_{H_3} \sim \star \times 10^{15} \text{ GeV なら. OK.}$$

(minimal SU(5))

② Planck suppressed op. の影響

Recall

$$\langle \Sigma \rangle \sim M_{\text{GUT}} \sim 10^{16} \text{ GeV}^{2x}$$

$$M_{\text{Pl}} \equiv \frac{M_{\text{Pl}}}{\sqrt{8\pi}} \sim \sqrt[2x]{10^{18} \text{ GeV}}$$

$$\frac{\Sigma}{M_{\text{Pl}}} \sim 10^{-2}.$$

Muon の $g-2$ について.

E821 Exp. @ Brookhaven

2001. Feb. 8

$$a_{\mu} \equiv \frac{(g-2)_{\mu}}{2} \quad \text{異常磁気能率}$$

$$= 11659202(14)(6) \times 10^{-10}$$

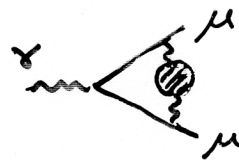
2.6 σ away from SM prediction!

$$a_{\mu}(\text{E821}) - a_{\mu}(\text{SM}) = 43(16) \times 10^{-10}$$

原因?

- 統計のゆらぎ (\rightarrow wait next data)
- SM の予言?

$$a_{\mu}(\text{had}) = 673.9(6.7) \times 10^{-10}$$



~~~~~? Davier & Höcker  
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- NEW Physics
  - SUSY interpretation

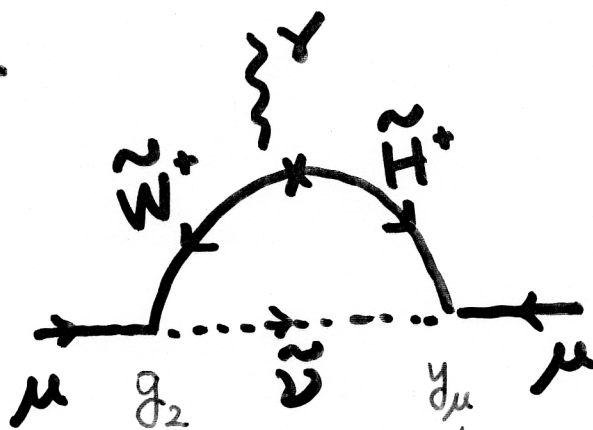
Since the announcement of the E821 experiment, many papers on SUSY interpretation appeared....

Czarnecki & Marciano / Everett, Kane,  
Rigolin & Wang / Feng & Matchev / Baltz  
& Gondolo / Chattopadhyay & Path /  
Komine, Moroi & MY / Ellis, Nanopoulos,  
Olive / Hisano & Tobe / Choi, Hwang, Kang,  
Lee & Song / Kim, Kyae, Lee / Martin & Wells

.....



In SUSY, dominant contributions (mostly) comes from chargino-sneutrino loop.



$$y_\mu = \frac{m_\mu}{\sqrt{2}V} \cdot \frac{1}{\cos\beta} \propto \tan\beta \text{ enhancement.}$$

- $\tan\beta$  enhancement from  $\mu$  Yukawa.
- $a_\mu(\text{SUSY})$ 's sign is sensitive to the sign of  $M_2\mu$ .  
( $M_2\mu > 0$  is preferred.)

We give upper bounds on Sparticle Masses. in (Unconstrained) MSSM, by requiring

$$a_\mu(\text{SUSY}) > 11 \times 10^{-10} \quad (2\sigma)$$

# Upper Bounds on Sparticle Masses.

( $\alpha_\mu(\text{SUSY}) \approx 11 \times 10^{-10}$ )

FIGURES

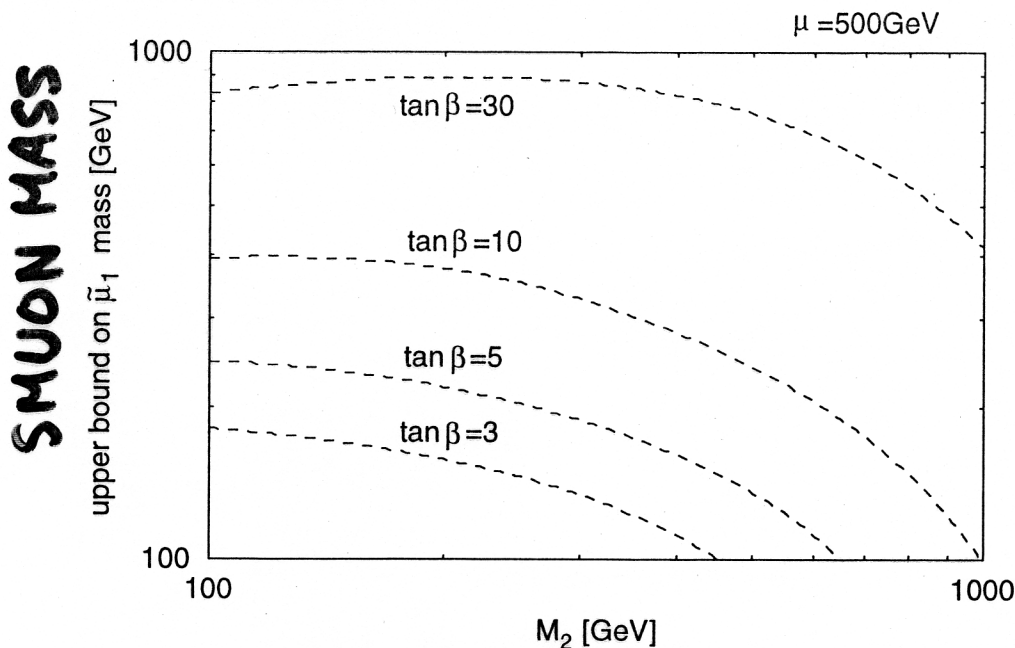


FIG. 1. The upper bounds on the lighter smuon mass  $m_{\tilde{\mu}_1}$ . The horizontal line is the Wino mass parameter  $M_2$ , and we take  $\mu = 500 \text{ GeV}$  and  $A_\mu = 0$ . Here,  $\tan \beta$  is taken to be 3, 5, 10, and 30 from below.

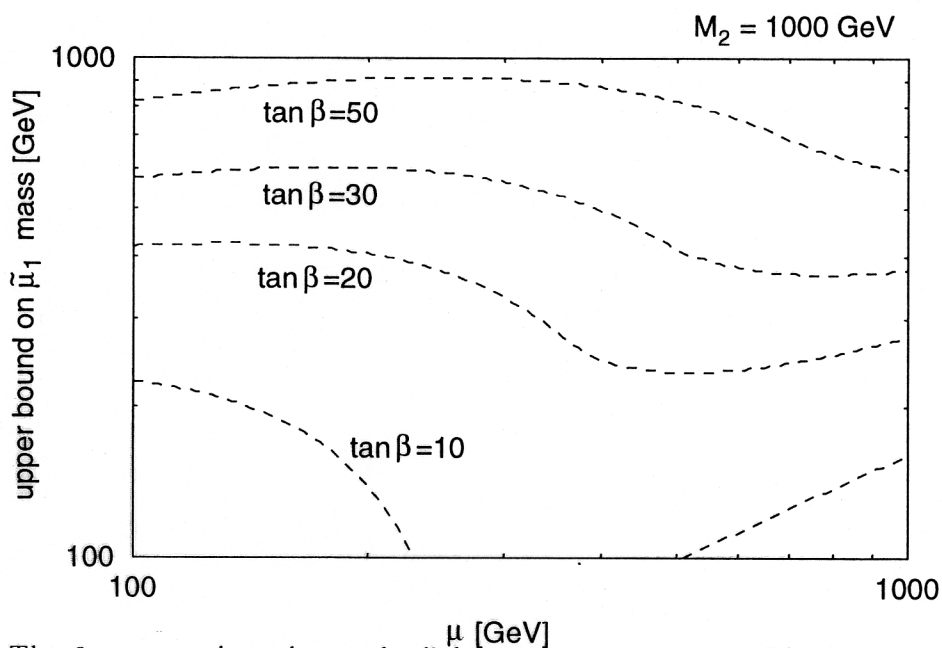


FIG. 2. The  $2\text{-}\sigma$  upper bounds on the lighter smuon mass  $m_{\tilde{\mu}_1}$ . The horizontal line is the Higgsino mass parameter  $\mu$ , and we take  $M_2 = 1 \text{ TeV}$ ,  $A_\mu = 0$ , and  $\tan \beta = 10, 20, 30, 50$ .

# mSUGRA.

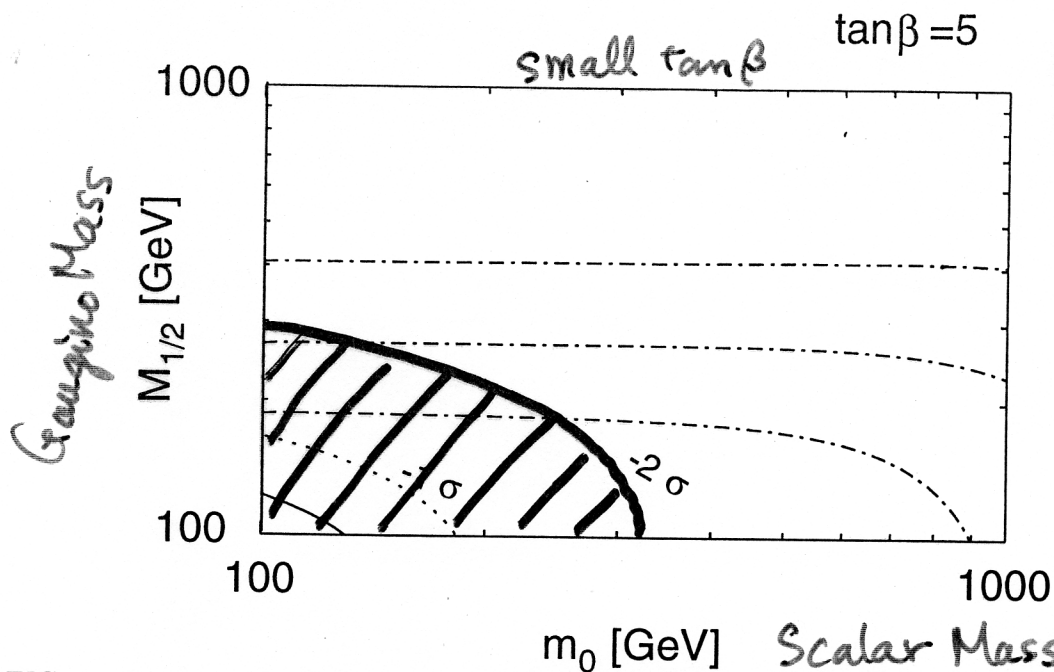


FIG. 3. Contours of the constant  $a_\mu(\text{SUSY})$  on  $m_0$  vs.  $M_{1/2}$  plane in the minimal supergravity model. The solid (dotted, dashed) line is for the center ( $\pm 1\sigma$ ,  $\pm 2\sigma$ ) value of  $a_\mu(\text{SUSY})$ . We take  $A_\mu = 0$  and  $\tan\beta = 5$ . We also plot the constant  $m_h$  contours in the dash-dotted lines ( $m_h = 110, 115,$  and  $120$  GeV from below).

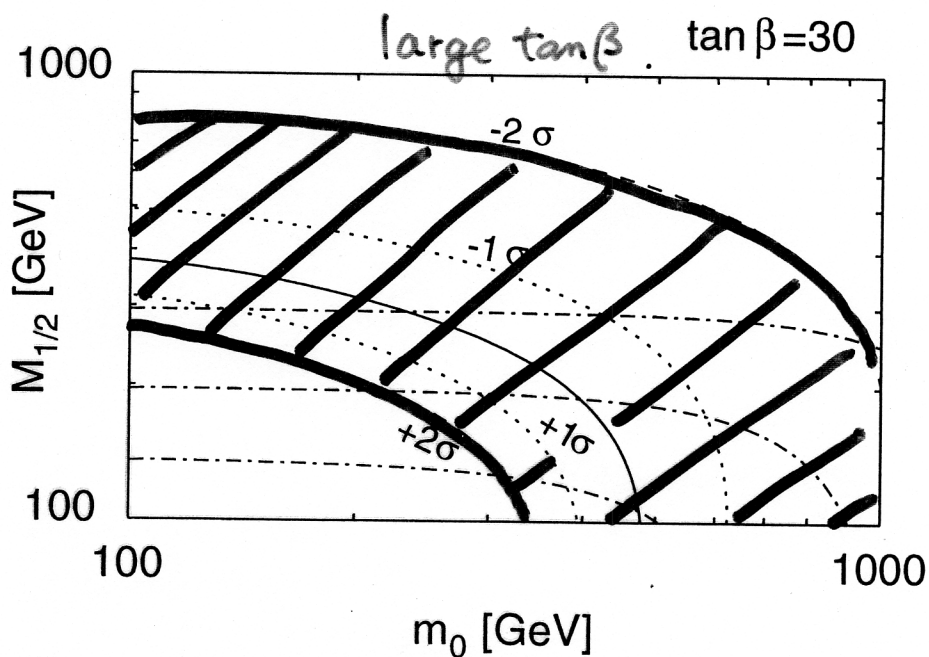


FIG. 4. Same as Fig. 3, except  $\tan\beta = 30$ .

# SUSY (Unification) Scenario

## 直接的検証

Collider で 直接 superparticle を作る!

SUSY breaking  $\rightarrow$  Superparticle が重くなる.

~~SUSY~~ の様子: Collider での signal を考えよ上で重要.

逆に

(将来の) 実験データ  $\rightarrow$  ~~SUSY~~ の様子.

e.g.) ~~SUSY~~ の伝中番 (mediation) の仕方.

• high energy scale での 対称性  
(GUT ...)

## 2. SUSY & SUSY breaking

SUSY

boson  $\leftrightarrow$  fermion

★ quark/lepton/Higgs ... chiral multiplet

|                     |                            |          |
|---------------------|----------------------------|----------|
| $(\phi, \psi_L, F)$ | $\phi$ : complex<br>scalar | 自由度<br>2 |
|                     | $\psi_L$ : Weyl spinor     | 4        |
|                     | $F$ : auxiliary field      | 2        |

$$\mathcal{L}_K = \partial_\mu \phi^* \partial^\mu \phi + i \bar{\psi}_L \gamma^\mu \partial_\mu \psi_L + F^* F$$

### SUSY 变换

$$\delta_{\bar{\zeta}} \phi = \sqrt{2} \bar{\zeta} \psi_L$$

$$\delta_{\bar{\zeta}} \psi_L = \sqrt{2} \bar{\zeta} F + \sqrt{2} i \sigma^\mu \bar{\zeta} \partial_\mu \phi$$

$$\delta_{\bar{\zeta}} F = \sqrt{2} i \bar{\zeta} \sigma^\mu \partial_\mu \psi_L$$

physical な  
\*粒子 :  $\phi$  と  $\psi_L$

∴ SM に比べて 粒子の数が "2倍" になる.

SM に現れる粒子 = particle.  
 ・その SUSY の相棒 = superpartner,  
 superparticle  
 sparticle  
 と呼ぶ。

# (Minimal) SUSY Standard Model

|                                   |         |
|-----------------------------------|---------|
| (squark)                          | (quark) |
| $\tilde{q}_L$                     | $q_L$   |
| $\tilde{u}_R^c (= \tilde{u}_R^*)$ | $u_R^c$ |
| $\tilde{d}_R^c$                   | $d_R^c$ |

|                 |          |
|-----------------|----------|
| (slepton)       | (lepton) |
| $\tilde{l}_L$   | $l_L$    |
| $\tilde{e}_R^c$ | $e_R^c$  |

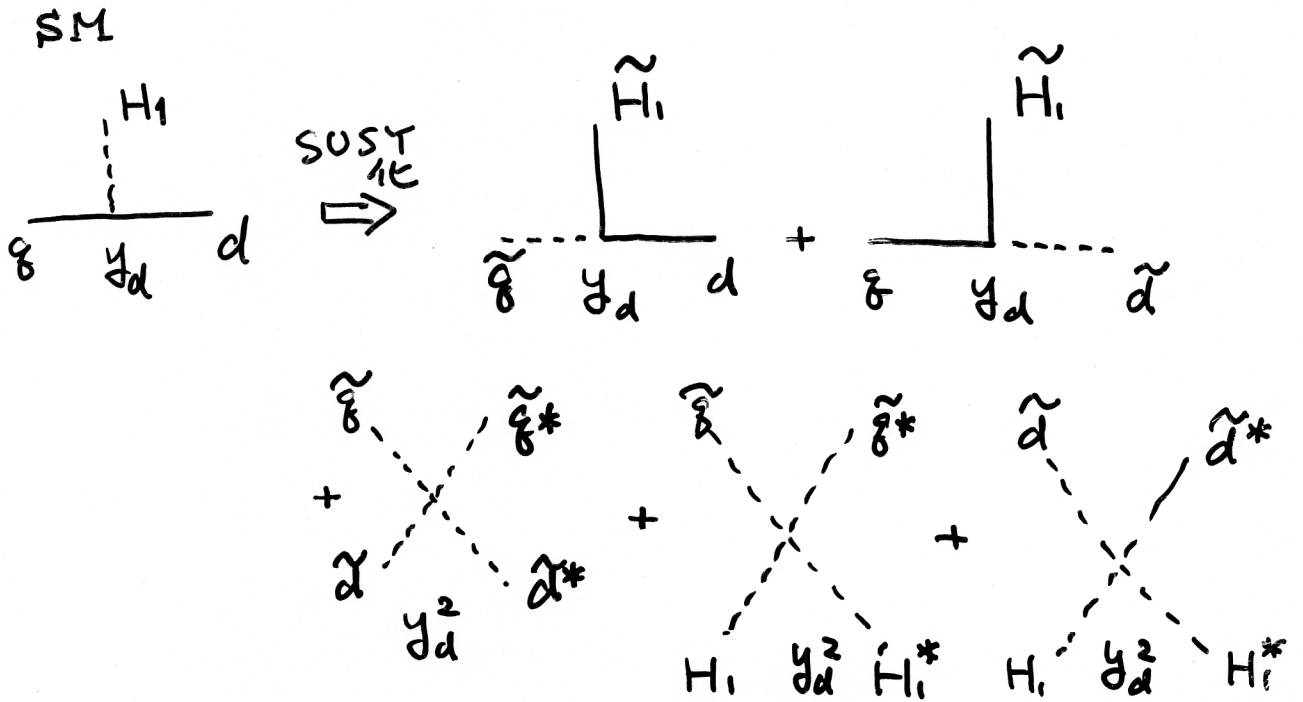
|         |               |
|---------|---------------|
| (Higgs) | (higgsino)    |
| $H_1$   | $\tilde{H}_1$ |
| $H_2$   | $\tilde{H}_2$ |

- 2 Higgs doublet ☺
  - ①  $H_1 \rightarrow d, l_1 = \text{mass}$   
 $H_2 \rightarrow u, l_2 = \text{mass}$
  - ② anomaly cancellation

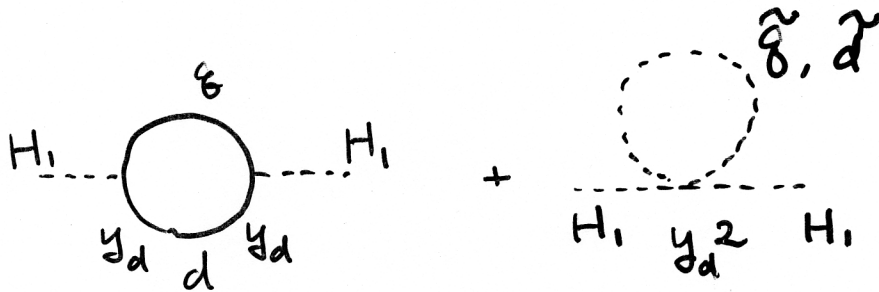
# Particle & Superpartner

SUSY が exact なら

- mass が等しい.
- coupling が等しい.



Scalar Mass : 2次発散の cancellation



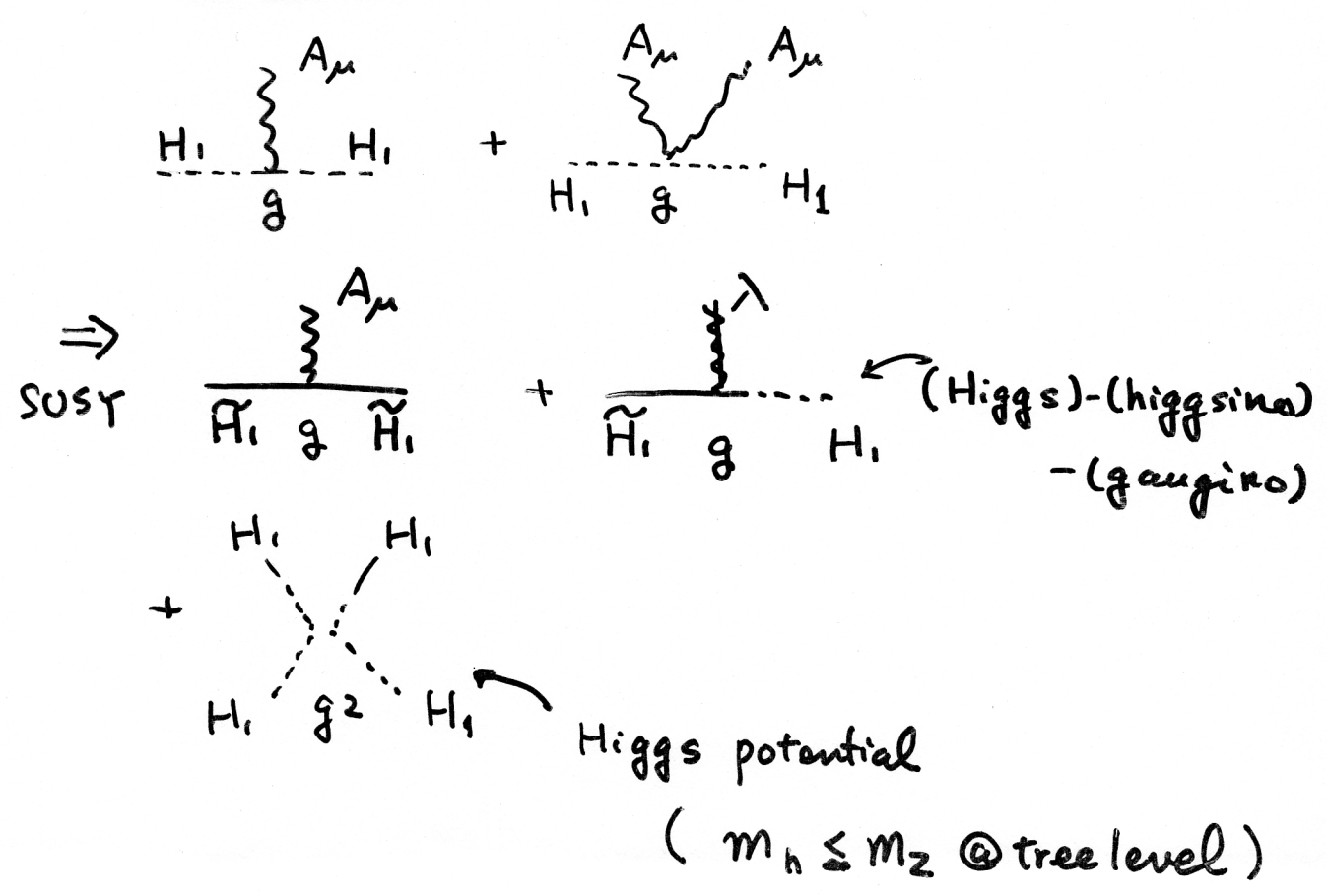
★ gauge boson .... vector multiplet

$(A_\mu, \lambda, D)$        $A_\mu$ : ゲージ場  
 $\lambda$ : gaugino  
 $(D$ : auxiliary field.)

### MSSM (???)

|           |                  |                              |          |
|-----------|------------------|------------------------------|----------|
|           | (gauge boson)    | (gaugino)                    |          |
| $SU(3)_C$ | $g_\mu$          | $\tilde{g}$                  | (gluino) |
| $SU(2)_L$ | $W_\mu^{\pm, 0}$ | $\tilde{W}^\pm, \tilde{W}^0$ | (wino)   |
| $U(1)_Y$  | $B_\mu$          | $\tilde{B}$                  | (bino)   |

### 相互作用





# SUSYの破れ

- SUSYの破れによって、superparticles が重くなる (とよろしい).

## Soft SUSY Breaking Masses.

- scalar mass に 2次発散を生じさせない  
好ましい SUSY mass.

分類

|              |                          |                           |
|--------------|--------------------------|---------------------------|
| scalar mass  | $m^2 \phi^* \phi$        | → squark/slepton<br>Higgs |
| A term       | $B \mu H_1 H_2$          |                           |
| B term.      | $A \phi_1 \phi_2 \phi_3$ |                           |
| gaugino mass | $M \lambda \lambda$      | → gaugino                 |

Soft mass によって superparticle &  
全て重くできる!

Superparticles:

- coupling : SUSYで"control"されている
- mass : ~~SUSY~~を感じ"massive".

### SUSY @ Tevatron & LHC

Superparticle を直接生成/崩壊.

⇒ ~~SUSY~~ の情報が重要.

と3が、

# PARAMETERの数

|      | real | phase | total |
|------|------|-------|-------|
| SM   | 17   | 2     | 19    |
| MSSM | 79   | 45    | 124   |

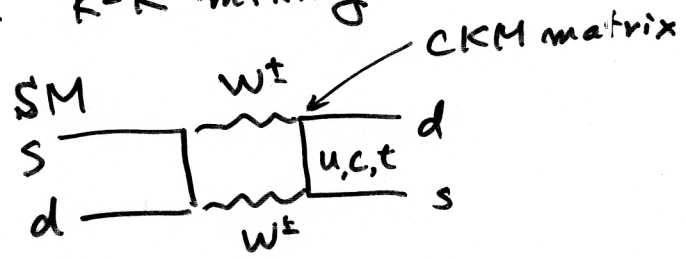
100以上の Soft Mass parameters ?!

さらに

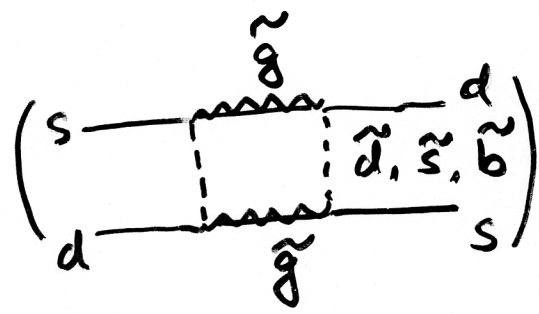
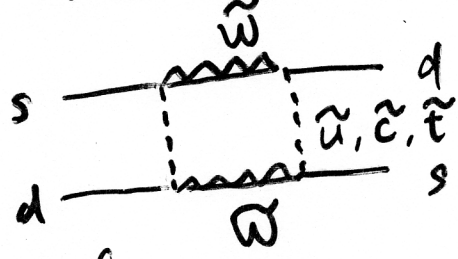
## SUSY FCNC問題

Generic Soft Masses  $\rightarrow$  too large FCNC

(4.1) K-K $\bar{K}$  mixing



SUSY化



$$\frac{g^2}{(4\pi)^2} \cdot \frac{(m_{\tilde{d}}^2 - m_{\tilde{u}}^2)^2 \sin^2 \tilde{\theta}_c \cos^2 \tilde{\theta}_c}{m_{\tilde{g}}^6} \cdot \mathcal{O}_{DS=2}$$

これが小さくないと困る。

# Solns to SUSY FLAVOR PROBLEM

- 1)  $m_{\tilde{g}} \sim m_{\tilde{u}} \gg m_W$  "decoupling"
- 2)  $|m_{\tilde{g}} - m_{\tilde{u}}| \ll m_{\text{SUSY}}$  "degenerate"
- 3)  $\sin \tilde{\theta}_c \approx 0$  "alignment".

~~SUSY~~ と ~~SUSY~~ の伝播の mechanism は, 上を  
みたすような "特殊" なものであるべし!

この mechanism を 実験的, 理論的に 解明  
することが重要.

通常 2) の approach が考えられる. 7ヶリ,  
「同じ ゲージ量子数をもった squark/slepton は, 世代に  
よらず縮退すべし」

$$\begin{aligned} \tilde{u}_R &\leftrightarrow \tilde{c}_R \leftrightarrow \tilde{t}_R \\ \tilde{d}_R &\leftrightarrow \tilde{s}_R \leftrightarrow \tilde{b}_R \\ \tilde{u}_L &\leftrightarrow \tilde{c}_L \leftrightarrow \tilde{t}_L \\ \tilde{d}_L &\leftrightarrow \tilde{s}_L \leftrightarrow \tilde{b}_L \end{aligned}$$

$$\begin{aligned} \tilde{e}_R &\leftrightarrow \tilde{\mu}_R \leftrightarrow \tilde{\tau}_R \\ \tilde{e}_L &\leftrightarrow \tilde{\mu}_L \leftrightarrow \tilde{\tau}_L \\ \tilde{\nu}_e &\leftrightarrow \tilde{\nu}_\mu \leftrightarrow \tilde{\nu}_\tau \end{aligned}$$

実現する例)  $m$  SUGRA, gauge mediation.

# Spontaneous SUSY Breaking.

“真空が SUSY を破る!”

$$Q_{SUSY} |0\rangle \neq 0$$

$Q_{SUSY}$ : SUSY 変換の生成子

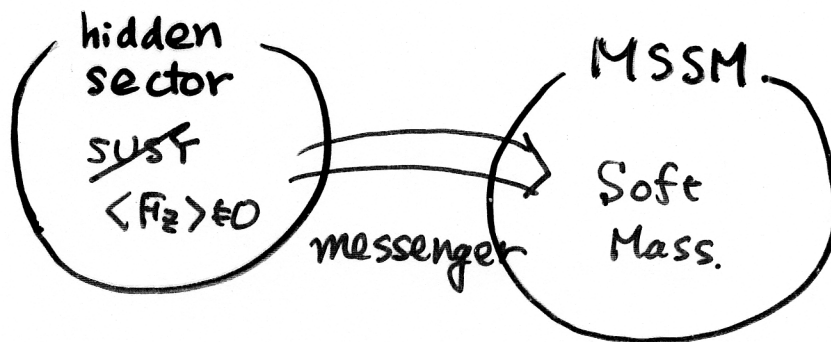
$$\rightarrow \langle 0 | \{ Q_{SUSY}^2, Q_{SUSY} \} |0\rangle \neq 0$$

$$\parallel \langle 0 | F |0\rangle$$

つまり.

Spontaneous SUSY  $\Leftrightarrow$  <sup>ある</sup> 補助場  $F$  の condensate  
i.e.  $\langle F \rangle \neq 0$ .

## Soft Mass の生成



何か messenger か?

## SUGRA Scenario

messenger :  $1/m_{pl}$  で suppress する相互作用

gravity 系に組み入れらる必要あり

→ supergravity (SUGRA)

SUSY mass は 次の 3つ で決まる.

1) gauge kinetic ~~term~~ <sup>function</sup> → gaugino mass

2) Kähler potential → scalar mass

3) superpotential → A, B terms.

1) gauge kinetic function

$f_{ab}(\Phi)$   $\Phi$  (chiral multiplet) の関数.

$$\begin{aligned} & \text{Re } f_{ab}(\phi) F_{\mu\nu}^a F^{\mu\nu b} + \text{Im } f_{ab}(\phi) F_{\mu\nu}^a \tilde{F}^{b\mu\nu} \\ & + \text{Re } f_{ab}(\phi) \bar{\lambda}^a \gamma_\mu \partial_\mu \lambda^b + \sum_i \frac{\partial f_{ab}}{\partial \phi_i} F_{\phi_i} \lambda^a \lambda^b + \text{h.c.} \end{aligned}$$

$\langle \text{Re } f_{ab} \rangle \rightarrow \frac{1}{g^2}$  : gauge coupling

$\langle \frac{\partial f_{ab}}{\partial \phi} F_\phi \rangle \rightarrow$  gaugino mass.

Note: gauge coupling & gaugino mass は 同い origin.

## 2) Kähler potential

$$K(\Phi, \Phi^\dagger)$$

• kinetic term. は次の形式に与えられる.

$$\frac{\partial^2 K}{\partial \phi_i \partial \phi_j^*} \partial_\mu \phi_i \partial^\mu \phi_j^* + \dots$$

• Scalar の Soft Mass

$$K = \hat{K}(z, z^*) + Z_{ij}(z, z^*) \phi_i^* \phi_j$$

$$(\langle Z_{ij} \rangle = \delta_{ij})$$

$$m^2_{ij} = m_{3/2}^2 \delta_{ij} + |F_z|^2 \left\{ \frac{\partial^2 Z_{ij}}{\partial z \partial z^*} - \frac{\partial Z_{ik}}{\partial z} \frac{\partial Z_{kj}}{\partial z^*} \right\}$$

① Gravity

②  $1/m_{pl} z^n$  suppresses

non-renormalizable int.

① universal contribution (flavor blind)

② non-renormalizable int. からの寄与

- 一般に flavor dependent  
→ FCNC ?!
- Kähler pot. は radiative corr. 受ける.

• ここが頭のいたところ!

• P.T.P の出しどころ.

# Minimal SUPERGRAVITY (mSUGRA)

12.

- $K = \sum_i \phi_i^* \phi_i + \hat{K}(z, \bar{z}^*)$  ( $Z_{ij}(z, \bar{z}^*) = \delta_{ij}$ )  
を仮定

$$\Rightarrow m_0^2 = m_{3/2}^2 \quad (\text{universal scalar mass})$$

- $f_{ab}(z) = f(z) \delta_{ab}$ .

$\Rightarrow$  gaugino mass

$$M_{ab} = \underbrace{\frac{\partial f}{\partial z} F_z}_{M_{1/2}} \cdot \delta_{ab} \quad (\text{universal gaugino mass})$$

その他 A-term は

$$\forall A \phi_1 \phi_2 \phi_3 \text{ 型.} \quad (\text{universal A-term})$$

パラメータ

$$m_0, M_{1/2}, A, B, (\mu)$$

↑  
higgsino mass parameter.

cf. MSSM 1241097-9.



m SUGRA

- very simple Soft Masses
  - easy to analyse.
- ⇒ Good Bench Mark!

Q. 100% mSUGRAを信じるか?

A. ????? (no....)

- Kähler potential が 特殊. 理論的な正当化?!

# Flavor Symmetry (horizontal symmetry)

$$U_R \leftrightarrow C_R \leftrightarrow t_R$$

$$d_R \leftrightarrow s_R \leftrightarrow b_R$$

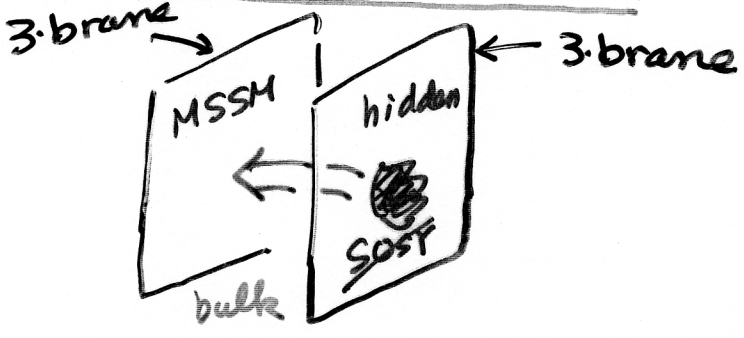
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \leftrightarrow \begin{pmatrix} c_L \\ s_L \end{pmatrix} \leftrightarrow \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

$$K = \sum^{(\delta_L)}_{(z, z^*)} \tilde{\varphi}_{Li}^* \tilde{\varphi}_{Li} + \sum^{(U_R)}_{(z, z^*)} \tilde{U}_{Ri}^* \tilde{U}_{Ri} + \dots$$

$\Rightarrow m_0^2 =$  (generation indep.) + [ flavor 対称性 の破壊 ]

$\Downarrow$   
FCNC o.k.

## Use of Brane World



Horava & Witten  
Randall & Sundrum

- MSSM と hidden sector が異なる brane に住んでいる
- bulk 中の messenger が SUSY と flavor blind に伝える。  $\rightarrow$  FCNC o.k.

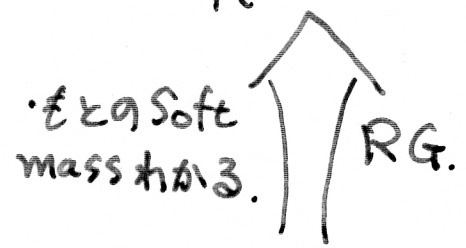
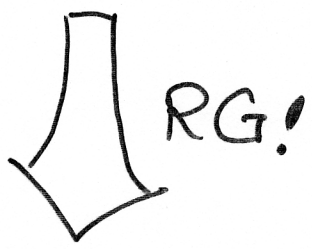
- e.g. anomaly mediation
- gaugino mediation.

① Soft Masses  $\sim O(m_{3/2})$

(1~277の違いはありうる)

② くりこみ群 (renormalization group)

・高いエネルギースケールでの Soft mass  $\leftarrow$  SUGRA  
( $E \sim m_{GUT} - m_{Pl}$ )

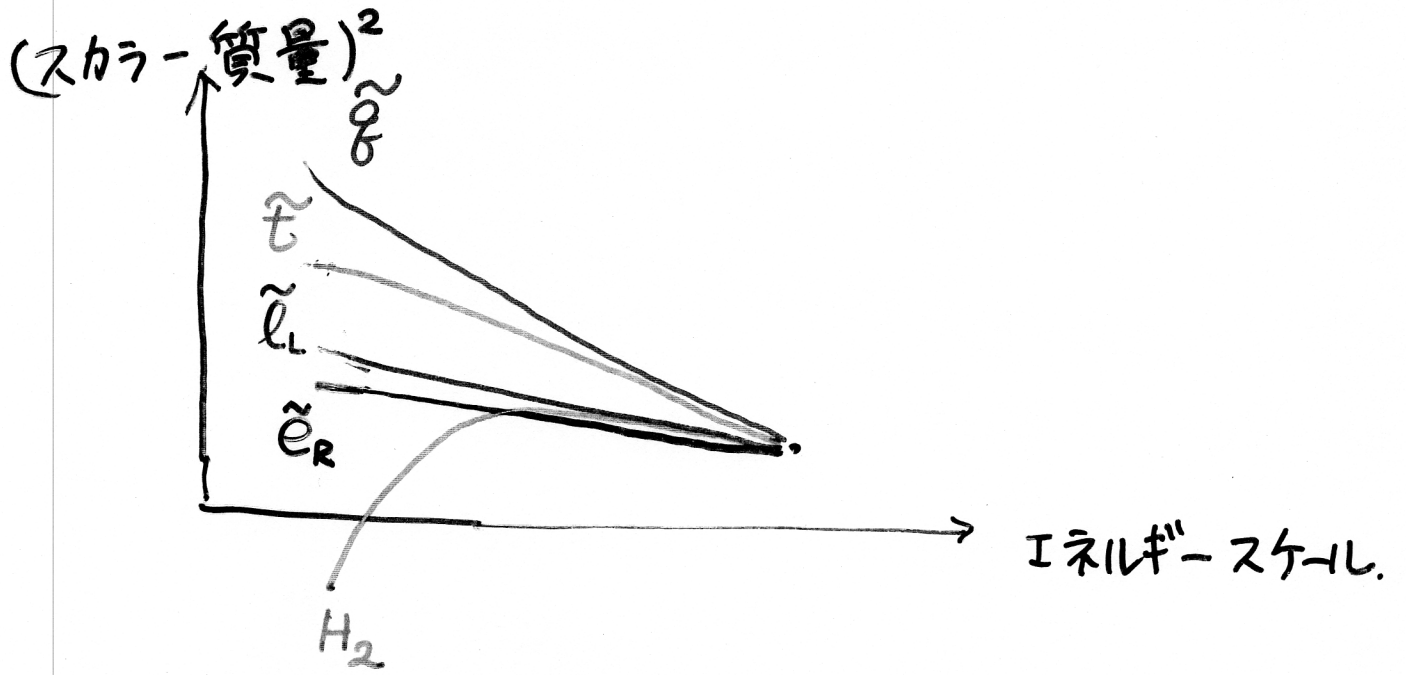
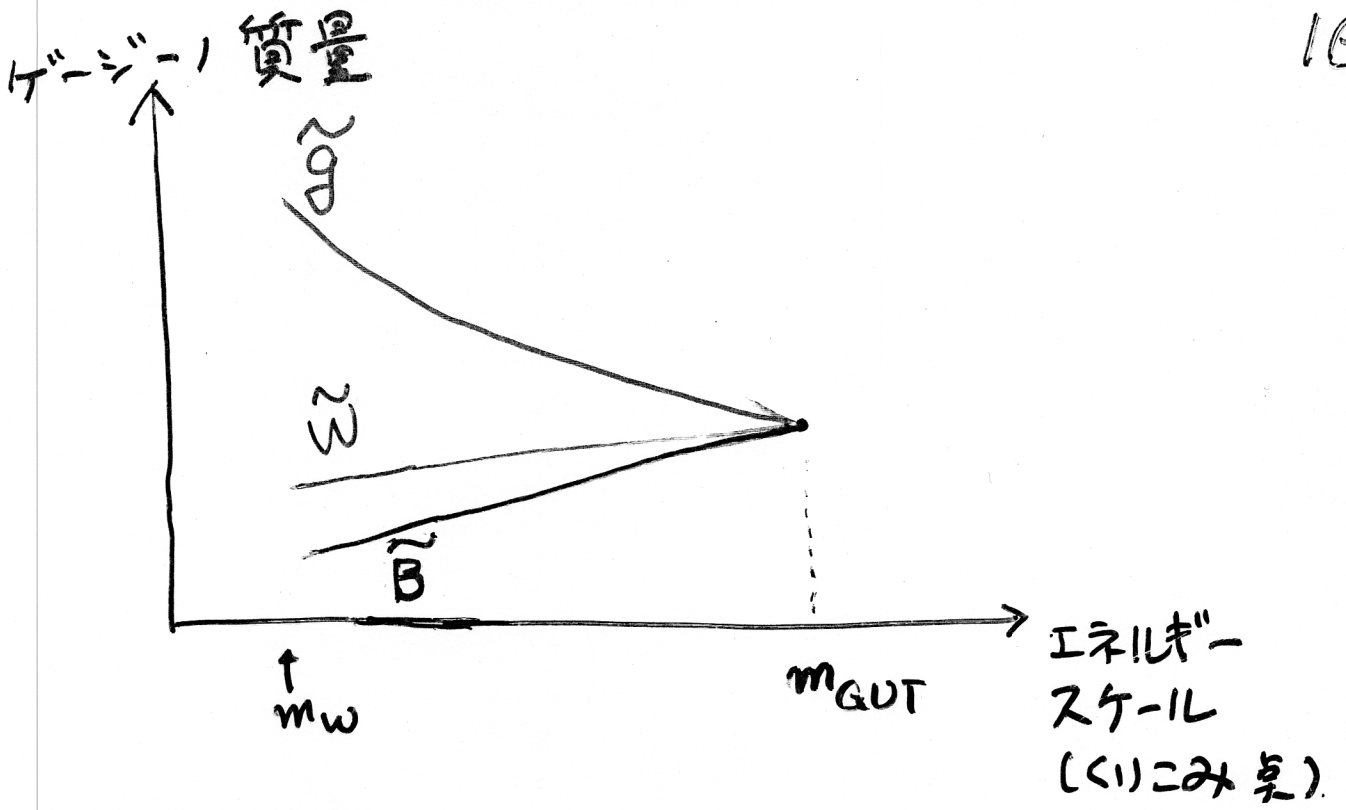


・weak scaleでの Soft mass.  $\rightarrow$  実験.

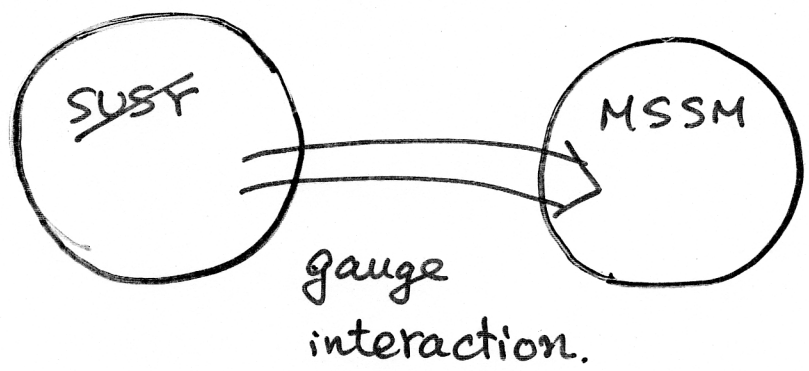
特徴.

・color をもっているものは重くなる.  
(squark / gluino)

・Yukawa  $\rightarrow$  mass<sup>2</sup> 下げ  
3世代は1, 2世代より軽くなる.  
(stop / sbottom / stau)

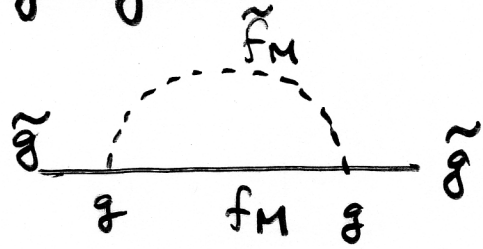


# Gauge Mediation



e.g.

gaugino mass



$$m_\lambda \propto \frac{\alpha}{4\pi} \cdot \frac{F_M}{M_M}$$

Soft masses

• gauge 相互作用 "control"

⇒ • flavor blind → FCNC o.k

• colored sparticle 重<た。.

## Gravitino mass in gauge mediation

$$m_{3/2} \sim \frac{(\sqrt{F})^2}{M_{\text{pl}}}$$

$$\left( \rightarrow m_{\text{soft}} \sim \frac{(\sqrt{F})^2}{M} \quad M \ll M_{\text{pl}} \right)$$

$$\therefore m_{3/2} \ll m_{\text{soft}}$$

→ light gravitino.

$$\sqrt{F} ? \quad \sqrt{F} \sim 10^5 - 10^{10} \text{ GeV}$$

(highly model dependent)

$$\therefore m_{3/2} \sim 10 \text{ eV} - 1 \text{ GeV}$$

(wide range!)

# Lightest superparticle (LSP).

R-parity が保存しているとき

$$R = \begin{cases} +1 & \text{for particle} \\ -1 & \text{for sparticle} \end{cases}$$

- sparticle は 対生成
- sparticle は LSP まで (cascade) decay
- LSP は 安定

何が LSP なのか, 重要.

1) colored sparticle の可能性?  
 RG で 重くなるので LSP にならない

2) charged sparticle? CHAMP  
 海水中の水素の heavy isotope search

exp.  $\frac{n_x}{n_H} |_{\text{Earth}} \lesssim 10^{-28} - 10^{-29}$   
 ( $m_x \lesssim 1 \text{ TeV}$ )

→ charged sparticle LSP (eg.  $\tilde{c}$ ) は  
 排除される.

⇒ colorless, charge neutral LSP.

- neutralino ( $\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0$ )
- $\tilde{\nu}$
- gravitino.

- (minimal) SUGRA  $\rightarrow$  neutralino LSP
- gauge mediation  $\rightarrow$  gravitino.

- ③  $\tilde{\nu}$
- DM search で DM と LSP の  $\tilde{\nu}$  LSP は rule out
  - RG 効果で  $\tilde{\nu}$  は  $\tilde{\beta}$  より重くなりがち.

## Exotics

- 他の LSP 候補

e.g. axino (mass is model dependent)

- decaying LSP.

R-parity violation

- LSP decay

- sparticle single production  
の可能性.