Unification of SUSY breaking and GUT breaking

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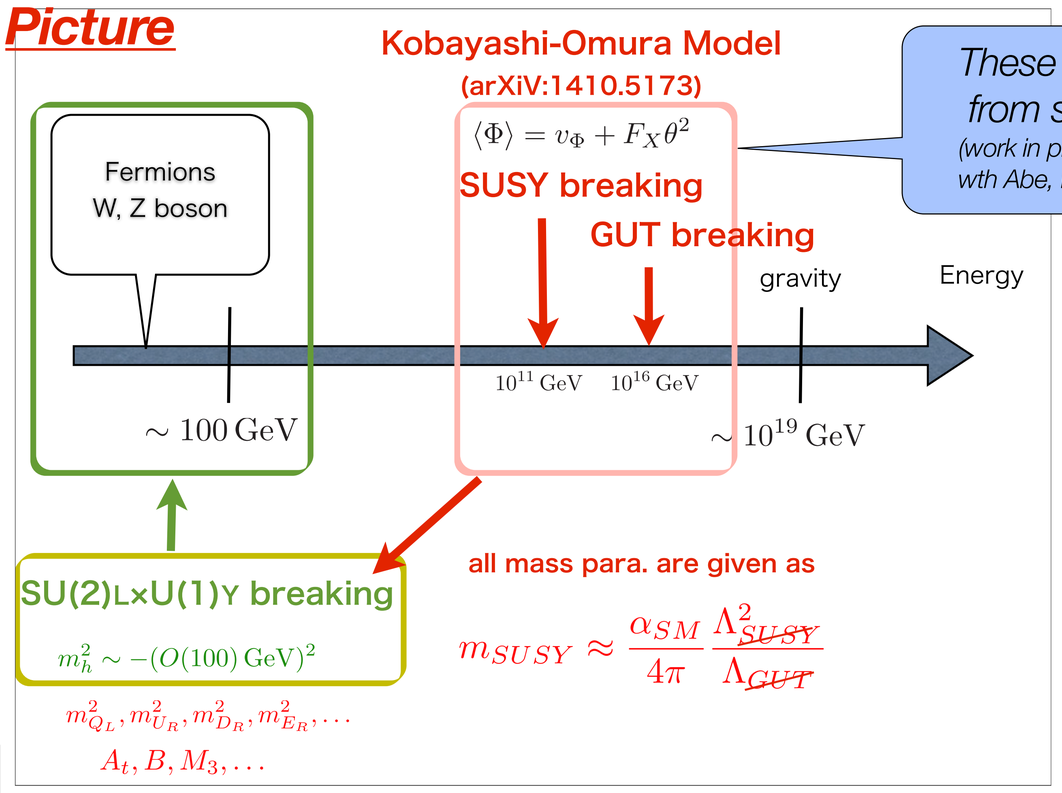
Motivation and Interests

Why Higgs mass so small?
→ SUSY (given by SUSY and GUT breaking scales)
What is origin of hyper-charges?
→ SU(5)
How realize 125GeV Higgs in SUSY?
→ large A-term by Gauge messenger
(large B-term helpful to EW breaking, too)

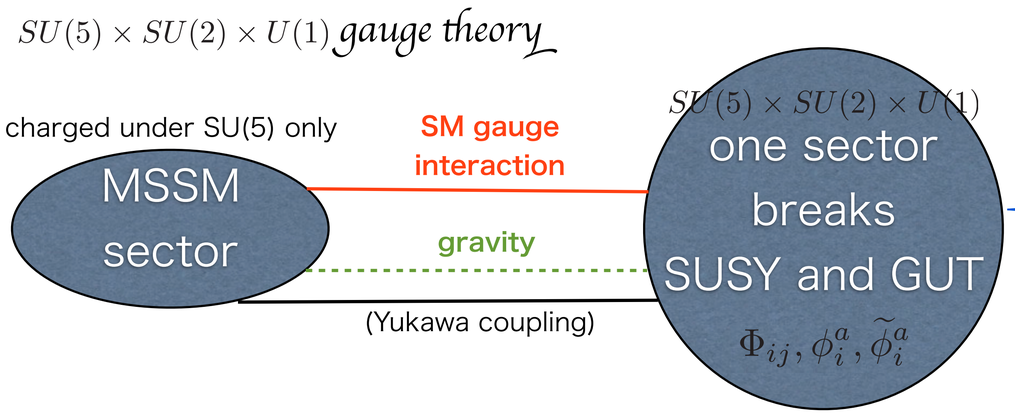
Here is very simple and explicit SUSY GUT model!

Picture



Kobayashi-Omura Model

$SU(5)\times SU(2)\times U(1)$ gauge theory



matter fields (Georgi, Glashow)

	10_I	$\overline{5}_I$	H	$\overline{H}$
$SU(5)$	**10**	$\overline{\mathbf{5}}$	**5**	$\overline{\mathbf{5}}$
$SU(2)$	**1**	**1**	**1**	**1**
$U(1)_\phi$	0	0	0	0

SUSY breaking and GUT breaking sector (Intriligator, Seiberg, Shih)

	ϕ	$\tilde{\phi}$	Φ
$SU(5)$	**5**	$\overline{\mathbf{5}}$	$\mathbf{adj}_5+\mathbf{1}$
$SU(2)$	$\overline{\mathbf{2}}$	**2**	**1**
$U(1)_\phi$	Q_ϕ	$-Q_\phi$	0

superpotential

$$W_{vis} = \hat{y}^u_{IJ} H \mathbf{10}^I \mathbf{10}^J + \hat{y}^d_{IJ}\overline{H}\overline{\mathbf{5}}^I\mathbf{10}^J + \mu\overline{H}H + \lambda_H \overline{H}\Phi H$$

to achieve heavy colored Higgs

(Abe, Kobayashi, YO, 0708.3148, 0712.2519)

$$W_{SB} = -hTr_2(\tilde{\phi}\Phi\phi) + h\Lambda^2_{SB}\mathrm{Tr}_5(\Phi) + m_\phi Tr_2(\tilde{\phi}\phi) + c$$

explicitly R-symmetry breaking

dynamics of SUSY and GUT breaking

The stationary conditions lead

$$\partial_\phi V = \partial_{\tilde{\phi}} V = \partial_\Phi V = 0 \quad \Leftrightarrow \quad \begin{cases} W_{\tilde{\phi}_{11}} = -h\Phi_{11}v_\chi + m_\phi v_\chi = 0 \\ W_{\Phi_{11}} = -hv_\chi^2 + h\Lambda_{SB} = 0 \end{cases}$$

$$\langle\phi\rangle = \langle\phi\rangle^T = \begin{pmatrix} \Lambda_{SB} & 0 \\ 0 & \Lambda_{SB} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \qquad (\langle\Phi_{ij}\rangle) = \begin{pmatrix} \frac{m_\phi}{h} & 0 & 0 & 0 & 0 \\ 0 & \frac{m_\phi}{h} & 0 & 0 & 0 \\ 0 & 0 & v_X & 0 & 0 \\ 0 & 0 & 0 & v_X & 0 \\ 0 & 0 & 0 & 0 & v_X \end{pmatrix}$$

vx is flat in global SUSY.
(loop and gravity correction fix vx)

"SUSY condition" for Φ (If $\partial_{\Phi_{ij}} W_{SB} = 0$, SUSY conserved)

$$(\partial_{\Phi_{ij}} W_{SB}) = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & h\Lambda^2_{SB} & 0 & 0 \\ 0 & 0 & 0 & h\Lambda^2_{SB} & 0 \\ 0 & 0 & 0 & 0 & h\Lambda^2_{SB} \end{pmatrix}$$

breaks SUSY!

after symmetry breaking

What happen in matter fields?

symmetry breaking

$$SU(5)\times SU(2)\times U(1)_\phi \xrightarrow{1} SU(3)_c\times SU(2)_F\times U(1)_F\times SU(2)\times U(1)_\phi \xrightarrow{2} SU(3)_c\times SU(2)_L\times U(1)_Y$$

ex) 1

$$\overline{5}: \begin{pmatrix} d_R^{c1} \\ d_R^{c2} \\ d_R^{c3} \\ l_L^1 \\ l_L^2 \end{pmatrix} \rightarrow (g_F G^{(3)}_\mu + g_F W^{F(2)}_\mu - \frac{1}{3}\sqrt{\frac{3}{5}} g_F B^F_\mu) d_R$$

$$\rightarrow (g_F W^{F(2)}_\mu - \frac{1}{2}\sqrt{\frac{3}{5}} g_F B^F_\mu) l_L$$

2

$$\rightarrow (g_F G^{(3)}_\mu + g_F \cos\theta W^{SM(2)}_\mu - \frac{1}{3}\sqrt{\frac{3}{5}} g_F \cos\theta_Y B^{SM}_\mu) d_R$$

$$(g_F \cos\theta W^{SM(2)}_\mu - \frac{1}{2}\sqrt{\frac{3}{5}} g_F \cos\theta_Y B^{SM}_\mu) l_L$$

SM gauge couplings
charge assignment fixed by SU(5)!

fields from symmetry breaking sector

Expanding around the VEVs,

$$\Phi = \begin{pmatrix} \left(v_Y + \frac{1}{\sqrt{2}}Y_0\right)\mathbf{1}_2 + Y & \tilde{Z} \\ Z & \left(v_X + \frac{1}{\sqrt{3}}X_0\right)\mathbf{1}_3 + X \end{pmatrix}$$

$$\phi = \begin{pmatrix} \left(v_\chi + \frac{1}{\sqrt{2}}\chi_0\right)\mathbf{1}_2 + \chi \\ \rho \end{pmatrix}, \tilde{\phi}^T = \begin{pmatrix} \left(v_\chi + \frac{1}{\sqrt{2}}\tilde{\chi}_0\right)\mathbf{1}_2 + \tilde{\chi}^T \\ \tilde{\rho}^T \end{pmatrix}$$

charge assignment under the SM gauge group

mass scale: Λ_{GUT} | $h\times\Lambda_{GUT}$ | $h\times\Lambda_{SB}, \Lambda_{SB}$ | 0 @ tree-level

	Z	$\tilde{Z}$	ρ	$\tilde{\rho}$	Y	χ	$\tilde{\chi}$	X
$SU(2)_L$	**2**	**2**	**2**	**2**	$\mathbf{adj}_2$	$\mathbf{adj}_2$	$\mathbf{adj}_2$	**1**
$SU(3)_c$	**3**	**3**	**3**	$\overline{\mathbf{3}}$	**1**	**1**	**1**	$\mathbf{adj}_3$
$U(1)_Y$	$\frac{5}{6}$	$\frac{-5}{6}$	$\frac{5}{6}$	$\frac{-5}{6}$	0	0	0	0

gauge messenger (one eaten by SU(5)-boson)
(one eaten by W')
typical messenger $\tilde{\rho}X\rho$

How about gauge symmetry breaking?

stationary conditions for the fields leads

$$(\langle\Phi_{ij}\rangle) = \begin{pmatrix} \frac{m_\phi}{h} & 0 & 0 & 0 & 0 \\ 0 & \frac{m_\phi}{h} & 0 & 0 & 0 \\ 0 & 0 & v_X & 0 & 0 \\ 0 & 0 & 0 & v_X & 0 \\ 0 & 0 & 0 & 0 & v_X \end{pmatrix} \Leftrightarrow \begin{matrix} SU(5)\to SU(3)_c\times SU(2)_F\times U(1)_F \\ SU(2)\times U(1)_\phi \text{ is not broken if } v_\chi = 0. \end{matrix}$$

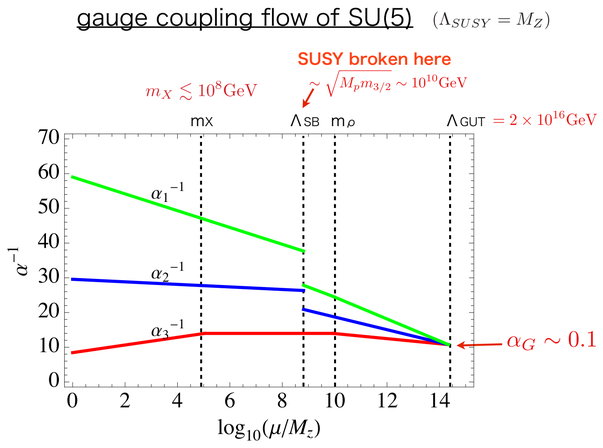
vx is flat in global SUSY.
(loop and gravity correction fix vx)

$$v_\chi = \Lambda_{SB} \quad \Leftrightarrow \quad \begin{matrix} SU(2)\times SU(2)_F \to SU(2)_L \\ U(1)\times U(1)_\phi \to U(1)_Y \end{matrix}$$

Eventually, when <Φ> >> v χ (<ϕ>), there are 2 steps

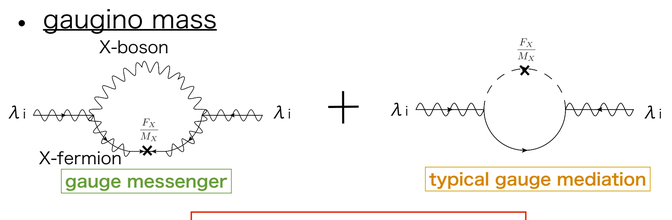
$$SU(5)\times SU(2)\times U(1)_\phi \to SU(3)_c\times SU(2)_F\times U(1)_F\times SU(2)\times U(1)_\phi$$
$$\to SU(3)_c\times SU(2)_L\times U(1)_Y$$

gauge coupling flow of SU(5) $(\Lambda_{SUSY} = M_Z)$



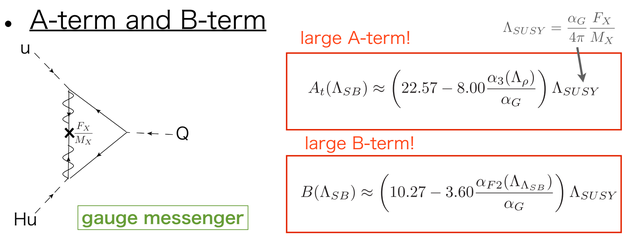
soft SUSY breaking terms

- gaugino mass



$$M_1 : M_2 : M_3 = 7\alpha_1 : 3\alpha_2 : 1\alpha_3$$
$$M_1(M_Z) : M_2(M_Z) : M_3(M_Z) \approx 1.00 : 0.86 : 1$$

- A-term and B-term



$$\Lambda_{SUSY} = \frac{\alpha_G}{4\pi}\frac{F_X}{M_X}$$

$$A_t(\Lambda_{SB}) \approx \left(22.57 - 8.00\frac{\alpha_3(\Lambda_\rho)}{\alpha_G}\right)\Lambda_{SUSY}$$

$$B(\Lambda_{SB}) \approx \left(10.27 - 3.60\frac{\alpha_{F2}(\Lambda_{\Lambda_{SB}})}{\alpha_G}\right)\Lambda_{SUSY}$$

- But, **A-term is too big!** (gluino is too small!)

A-term vs. gluino mass in gauge mediation

$$A_t(\Lambda_{SB}) \approx \left(22.57 - 8.00\frac{\alpha_3(\Lambda_\rho)}{\alpha_G}\right)\Lambda_{SUSY} \gg M_3(\Lambda_{SB}) = \frac{\alpha_3(\Lambda_{SB})}{\alpha_G}\Lambda_{SUSY}$$

running correction easily makes squarks tachyonic....

$$\Delta m_U^2(M_Z) = -0.08A_t(\Lambda_{SB})^2 + 1.54M_3(\Lambda_{SB})^2 - 0.15A_t(\Lambda_{SB})M_3(\Lambda_{SB})\ldots$$

Let me introduce an extra term,

$$W_{extra} = Tr_5(\Phi W_5 W_5) \xrightarrow{\text{shift only gluino}} \Delta M_3 \widetilde{G^a}\widetilde{G^a}$$

ΔM_3 definition

$$M_3(\Lambda_{SB}) = (1 - N_{eff})\frac{\alpha_3(\Lambda_{SB})}{\alpha_G}\Lambda_{SUSY}$$

Neff : extra messenger and gravity effect

benchmarks

	$N_{eff}=6$	$N_{eff}=6$	$N_{eff}=6.97$	$N_{eff}=7.83$
$m_{3/2}$	588.84 GeV	741.31 GeV	495.79 GeV	245.02 GeV
T_ρ	2.39×10^{11} GeV	5.76×10^{12} GeV	5.66×10^{12} GeV	2.74×10^{10} GeV
T_X	1.00×10^7 GeV	1.00×10^7 GeV	1.00×10^7 GeV	1.00×10^7 GeV
$\tan\beta$	3.69	3.93	3.43	4.04
m_h	126.20 GeV	125.89 GeV	124.65 GeV	124.03 GeV
m_{stop}	3.05 TeV	3.61 TeV	2.93 TeV	1.90 TeV
X_t	$3.43\times m_{stop}$	$3.41\times m_{stop}$	$2.98\times m_{stop}$	$2.39\times m_{stop}$
$\lvert\mu\rvert$	3.72 TeV	4.38 TeV	3.27 TeV	1.93 TeV
$\lvert B\rvert$	4.21 TeV	4.72 TeV	3.22 TeV	1.97 TeV
$\lvert B_{EW}/B\rvert$	0.92	1.00	0.91	0.5
$\lvert M_3\rvert$	$5.73\times m_{3/2}$	$5.73\times m_{3/2}$	$6.85\times m_{3/2}$	$0.78\times m_{3/2}$
$\lvert M_2\rvert$	$0.98\times m_{3/2}$	$0.98\times m_{3/2}$	$0.98\times m_{3/2}$	$0.98\times m_{3/2}$
$\lvert M_1\rvert$	$0.75\times m_{3/2}$	$0.75\times m_{3/2}$	$0.69\times m_{3/2}$	$0.64\times m_{3/2}$
$m_{\tilde{t}_1}$	3.52 TeV	4.12 TeV	3.31 TeV	2.15 TeV
$m_{\tilde{t}_2}$	2.62 TeV	3.17 TeV	2.57 TeV	1.65 TeV
$m^2_{\tilde{Q}_L}$	11.72 TeV^2	16.56 TeV^2	10.36 TeV^2	4.24 TeV^2
$m^2_{\tilde{d}_R}$	15.97 TeV^2	22.52 TeV^2	13.60 TeV^2	5.40 TeV^2
$m^2_{\tilde{l}_L}$	0.78 TeV^2	0.93 TeV^2	0.44 TeV^2	0.18 TeV^2
$m^2_{\tilde{e}_R}$	1.42 TeV^2	1.75 TeV^2	0.81 TeV^2	0.31 TeV^2

Higgs mass and EW conditions

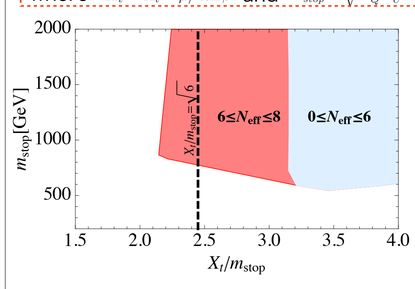
Higgs mass in maximal mixing scenario

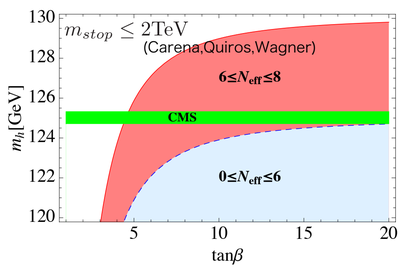
upper bound on Higgs mass

$$m_h^2 \lesssim M_Z^2\cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left\{\ln\frac{m^2_{stop}}{m_t^2} + \frac{X_t^2}{m^2_{stop}}\left(1 - \frac{X_t^2}{12m^2_{stop}}\right)\right\}$$

where $X_t = A_t - \mu/\tan\beta$ and $m^2_{stop} = \sqrt{m^2_Q m^2_{\tilde{U}}}$.

$\Lambda_{GUT} = 2\times10^{16}$GeV
$m_X = 10^7$GeV.
$100\text{GeV} \le m_{3/2} \le 10\text{TeV}$
$1 \le \tan\beta \le 20$

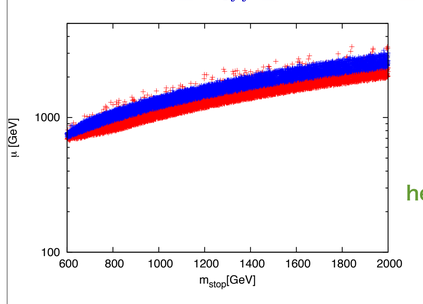


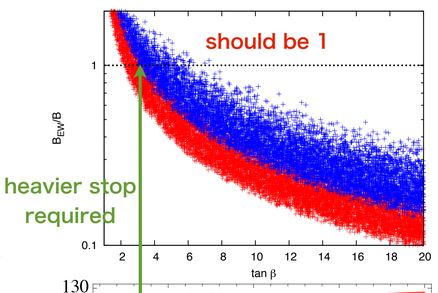


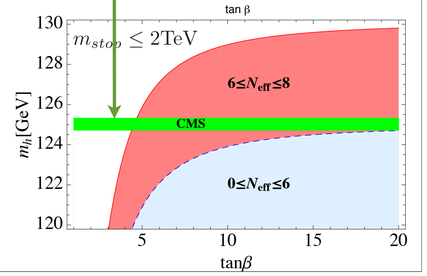
light stop and small tanβ consistent with 125 GeV Higgs, allowing large Neff.

μ and B term

(consistency with EW symmetry breaking)
blue: $0 \le N_{eff} \le 6$ red: $6 \le N_{eff} \le 8$







There is no cancellation in μ:
small stop mass corresponds to small μ

at least 1 % fine-tuning of μ para. required
if stop mass > 1 TeV.

issues

1. doublet-triplet splitting
2. little hierarchy problem
3. origin of Neff
4. origin of the breaking scales
5. suppression of gravity mediation
6. How about other GUT?
7. *Can we unify 3 gauge groups?*

(work in progress wth Abe, Kobayashi, Watanabe)