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# Non-Universal Gaugino Mass in the NMSSM

in preparation

Junichiro Kawamura
Keio University (→ Ohio State Univ.)

in collaboration with

Natsumi Nagata (Univ. of Tokyo), Tatsuo Kobayashi (Hokkaido Univ.)

# Outline

1. Introduction
2. Condition for EW vacuum with RG-effect
3. Numerical Analysis
4. Summary

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1. **Introduction**
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# Next-to-MSSM (NMSSM)

- NMSSM = MSSM + singlet $S$

$$W_{NMSSM} = \lambda\, S H_u H_d + \frac{\kappa}{3}\, S^3$$

$$\rightarrow \quad \mu_{eff} = \lambda\, v_s \sim \mathcal{O}(m_{SUSY})$$

- VEV of $S$ induces the higgsino mass
- $v_s$ is determined by the Higgs potential

# Higgs potential in the NMSSM

- Neutral Higgs potential

$$V_{H^0} = \left(m_{H_u}^2 + |\lambda\, S|^2\right)|H_u^0|^2 + \left(m_{H_d}^2 + |\lambda\, S|^2\right)\left|H_d^0\right|^2 + m_S^2|S|^2$$
$$+\left|\lambda H_u^0 H_d^0 - \kappa S^2\right|^2 + \frac{g^2}{4}\left(|H_u^0|^2 - \left|H_d^0\right|^2\right)^2$$
$$+\left(-\lambda A_\lambda H_u^0 H_d^0 + \frac{\kappa}{3} A_\kappa \mathrm{S}^3 + \mathrm{h.c.}\right)$$

# Higgs potential in the NMSSM

- Neutral Higgs potential

$$V_{H^0} = \left(m_{H_u}^2 + |\lambda S|^2\right)|H_u^0|^2 + \left(m_{H_d}^2 + |\lambda S|^2\right)\left|H_d^0\right|^2 + m_S^2|S|^2$$
$$+\left|\lambda H_u^0 H_d^0 - \kappa S^2\right|^2 + \frac{g^2}{4}\left(|H_u^0|^2 - \left|H_d^0\right|^2\right)^2$$
$$+\left(-\lambda A_\lambda H_u^0 H_d^0 + \frac{\kappa}{3} A_\kappa S^3 + \mathrm{h.c.}\right)$$

effective $\mu, B\mu$ term

specific to the NMSSM

- $\mu/B\mu$ terms in the MSSM are induced
- singlet $S$ makes potential complicated

# Higgs potential in the NMSSM

- Minimization condition ($v_s \gg v_u, v_d,\ \tan\beta \gg 1$)

$$m_Z^2 \sim -2m_{H_u}^2 - 2\,\lambda^2 v_s^2 = -2m_{H_u}^2 - 2\,\mu_{eff}^2$$

$$m_S^2 + \kappa A_\kappa v_s + 2\kappa^2 v_s^2 \sim 0$$

→ $\lambda^2\, v_s^2 \sim -m_{H_u}^2\ \ (\gg m_Z^2)$

$$v_s \sim \frac{1}{4\kappa}\left(-A_\kappa \pm \sqrt{A_\kappa^2 - 8m_S^2}\right)$$

→ $\max(A_\kappa^2, -m_S^2) \gtrsim -m_{H_u}^2$ to explain EW scale

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# RG effects for $m_{H_u}^2$

- RGE of $m_{H_u}^2$

$$16\pi^2 \frac{dm_{H_u}^2}{dt} \simeq 6y_t^2 \left(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2\right) - 6g_2^2|M_2|^2 + \cdots$$

- Assume universal soft mass $m_0 = m_S$ and A-term $A_0 = A_\kappa$

$$\lambda = 0.6, \kappa = 0.3, \tan\beta = 20, M_s = 3.0 \text{ TeV}$$

$$m_{H_u}^2 (M_s) \sim +0.20\, M_2^2 - 0.10 M_2 M_3 - 1.14\, M_3^2 + 0.23 M_3 A_0 - 0.12 A_0^2$$

heavy gluino makes large $\left|m_{H_u}^2\right|$ as in MSSM

# RG effects for $A_\kappa, m_S^2$

- RGE of $A_\kappa, m_S^2$

$$X_\lambda = m_{H_u}^2 + m_{H_d}^2 + m_S^2 + A_\lambda^2$$
$$X_\kappa = 3m_S^2 + A_\kappa^2$$

$$16\pi^2 \frac{dA_\kappa}{dt} \simeq 12\lambda^2 A_\lambda + 12\kappa^2 A_\kappa \qquad 16\pi^2 \frac{dm_S^2}{dt} \simeq 4\lambda^2 X_\lambda + 4\kappa^2 X_\kappa$$

no direct gaugino contributions at LO

- If $\lambda, \kappa$ are large, $\lambda = 0.3, \kappa = 0.6$

$$A_\kappa\,(M_s) \sim +0.03\, M_2 - 0.02\, M_3 + 0.07 A_0$$
$$m_S^2\,(M_s) \sim -0.02\, M_2^2 + 0.02\, M_3^2 - 0.03 A_0^2 + 0.08\, m_0^2$$

Initial values diminish through RGE

# Condition for $\max(A_\kappa^2, -m_s^2) \gtrsim -m_{H_u}^2$

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$|m_{H_u}^2| \gg |m_S^2|, A_\kappa^2$ in wide parameter space

- Possible known options

1. preparing large negative $m_S^2 \ll m_0^2$ (conflict with universality cond.)
2. very small $\lambda, \kappa$ and large $A_0$ → $-m_{H_u}^2 < A_\kappa^2$

# Condition for $\max(A_\kappa^2, -m_S^2) \gtrsim -m_{H_u}^2$

- small $\lambda, \kappa$ and large $A_0$

$$A_\kappa\,(M_S) \sim A_0 \quad m_S^2\,(M_S) \sim m_0^2$$

large $A_0$ → $v_s \sim A_\kappa/2\kappa \gtrsim \sqrt{-m_{H_u}^2}$

- CNMSSM has correct EW vacua only for $\kappa^2 < \lambda^2 \ll 1$

9611251 U.Ellwanger, M.Rausch de Traubenberg, C.A.Savoy

- This is the MSSM-limit except singlino
- singlino-like DM : $m_{\tilde{S}} \sim 2\kappa v_s < m_{\tilde{H}} \sim \lambda\, v_s$
- singlino DM tends to be overproduced unless e.g. stau co-ann. works

# Condition for $\max(A_\kappa^2, -m_s^2) \gtrsim -m_{H_u}^2$

Third option is Non-Universal Gaugino Mass (NUGM)

- If $\lambda = 0.3, \kappa = 0.6$

$$m_{H_u}^2\,(M_s) \sim +0.20\,M_2^2 - 0.10 M_2 M_3 - 1.14\,M_3^2 + 0.23 M_3 A_0 - 0.12 A_0^2$$

$$m_S^2\,(M_s) \sim -0.02\,M_2^2 + 0.02\,M_3^2 - 0.03 A_0^2 + 0.08\,m_0^2$$

- $|m_{H_u}^2| \ll M_3^2$ if the wino mass is relatively heavy $M_2 \sim 3\,M_3$
- heavy wino (and A-term) induces negative $m_S^2$

→ $-m_{H_u}^2 < -m_S^2$ can be achieved at a certain ratio $M_2/M_3$

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# Numerical Analysis

- We assume modulus + anomaly type gaugino mass ratio

$$M_a \sim M_{1/2}\left[1 + \frac{b_a}{96\pi}\alpha_m \log\frac{M_p}{m_{3/2}}\right] \qquad b_a = \left(\frac{33}{5}, 1, -3\right)$$

- NMSSMTools

  - NMSSMTools find $m_S^2, \kappa$ satisfying EW condition for a given parameter
  - We search tan$\beta$ that $\left|m_S^2 - m_0^2\right| < (5\ \mathrm{GeV})^2$
  - free-parameters: $M_3, \alpha_m, A_0, \lambda,\ m_0 = 1\ \mathrm{TeV}, \mathrm{sgn}(v_s) = -1$

$M_3 \in [2.0, 12.5]$ TeV $\quad A_0 \in [-10, 0]$ TeV

$\alpha_m \in [0.8, 2.2] \quad \lambda \in [0.25, 0.5]$

# Numerical Analysis

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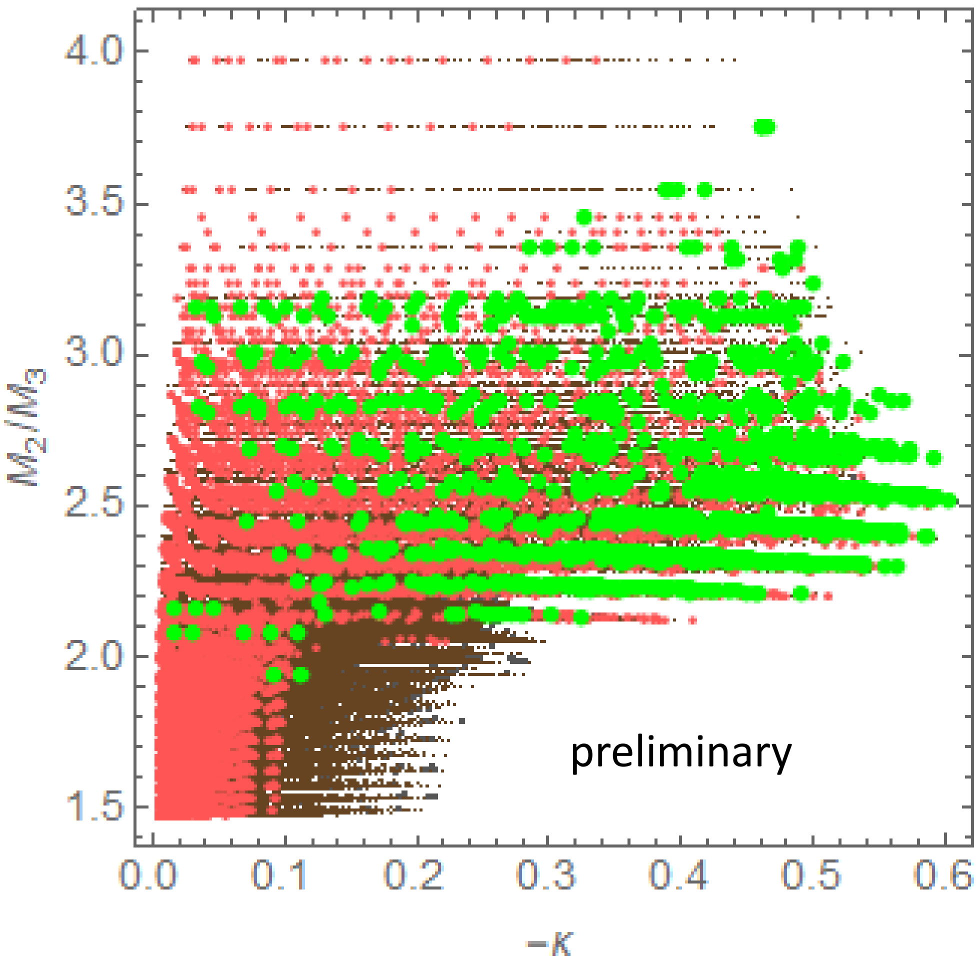
$M_3 \in [2.0, 12.5]$ TeV $\quad A_0 \in [-10, 0]$ TeV $\quad$ for positive singlet scalar masses

$\alpha_m \in [0.8, 2.2] \quad \lambda \in [0.25, 0.5]$

# Result: $M_2/M_3$ vs $\kappa$




Brown: $m_h \notin [122.1, 128.1]$ GeV

Red : $\Omega_{LSP} > \Omega_{obs}$

Green : $\Omega_{LSP} \leq \Omega_{obs}$

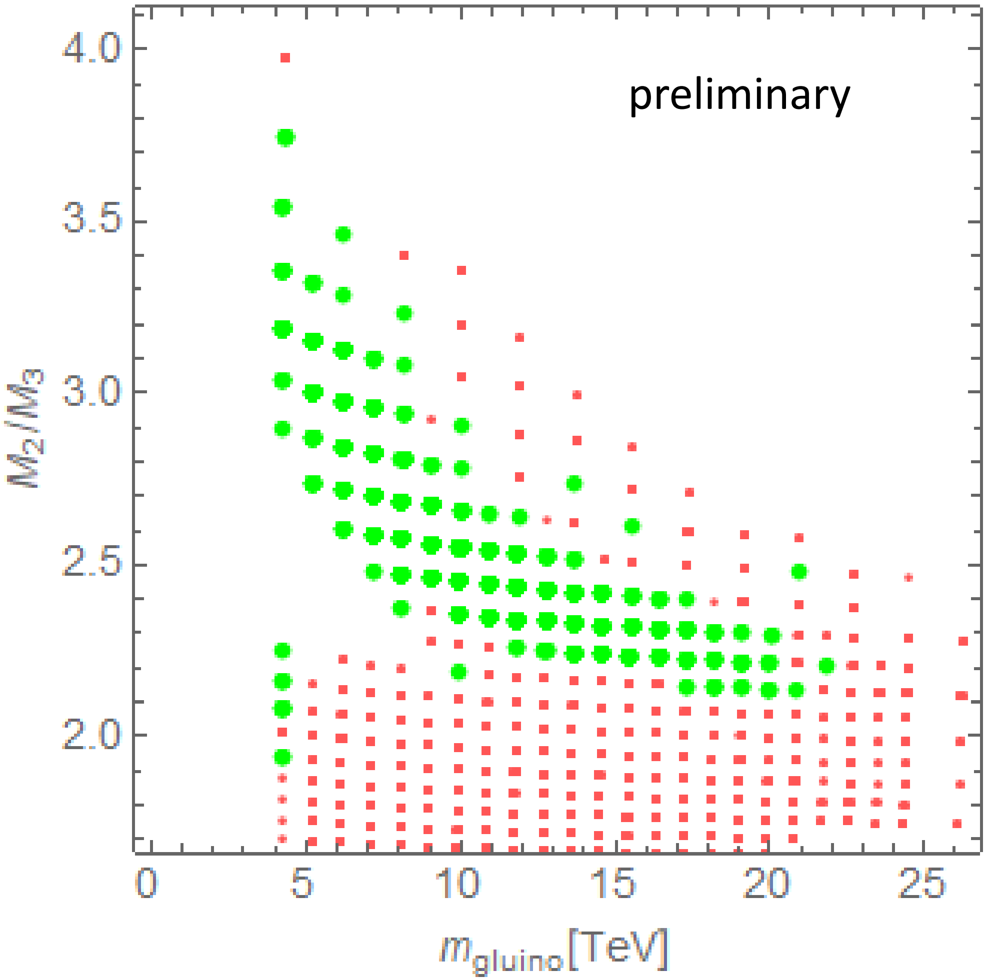
solutions find at $|\lambda| \lesssim |\kappa|$

→ $m_{\tilde{S}} \sim 2\kappa v_s > m_{\tilde{H}} \sim \lambda\, v_s$

$M_2/M_3 \gtrsim 2$

→
- EW vac. w/ large $|\kappa|$
- higgsino DM $\lesssim 1$ TeV

# Result: $M_2/M_3$ vs $m_{gluino}$




Red : $\Omega_{\rm LSP} > \Omega_{obs}$

Green : $\Omega_{LSP} \leq \Omega_{obs}$

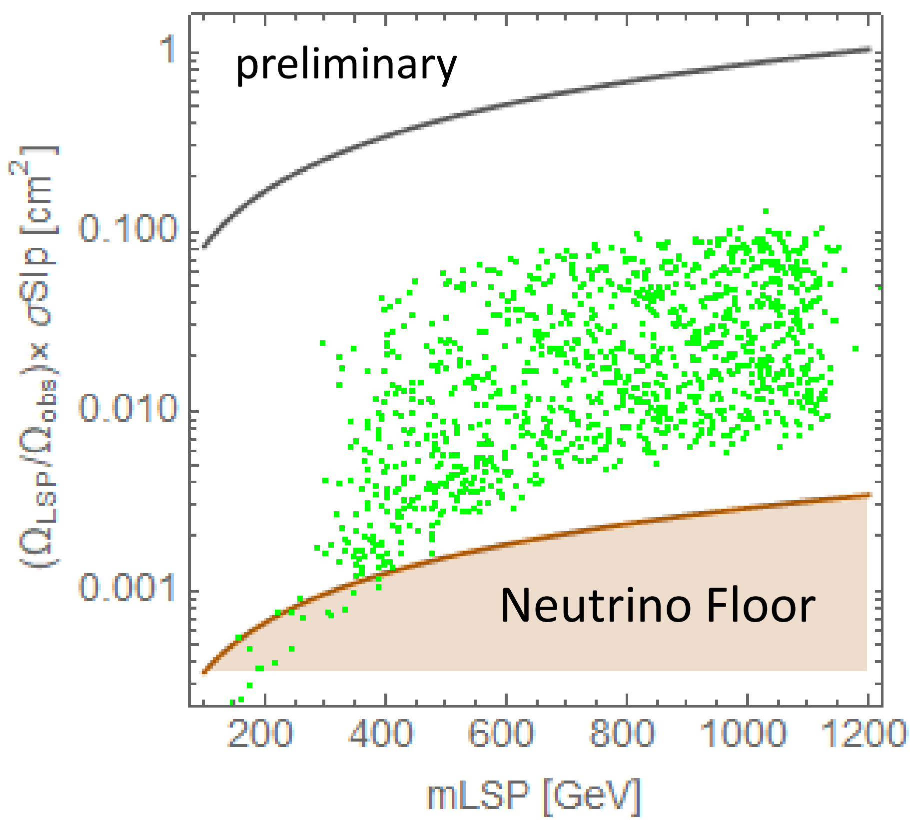
$\Omega_{LSP} \leq \Omega_{obs}$

→

- $m_{\tilde{g}} \lesssim$ 22 TeV
- 100 TeV collider reach: $\lesssim$ 13 TeV

1511.06495 N. Arkani-Hamed, T. Han, M. Mangano, L-T. Wang

# Result: Direct Detection




Current Limit (Xenon1T)

$\sigma_{SI}$ is ON neutrino floor

- There is sizable singlino mixing : c.f. $\mu = \lambda\, v_s$

$$\tilde{\chi}_1 \sim \frac{1}{\sqrt{2}}\,\widetilde{H}_d + \frac{1}{\sqrt{2}}\widetilde{H}_u + \frac{c_\beta + s_\beta}{\sqrt{2}}\left(\frac{s_W m_Z}{M_1 - |\mu|}\tilde{B} - \frac{c_W m_Z}{M_2 - |\mu|}\widetilde{W}\right) + \frac{s_\beta - c_\beta}{\sqrt{2}}\frac{\lambda\, m_Z}{g(2\kappa v_s - |\mu|)}\tilde{S}$$

# Summary

correct EW vacuum is realized by $M_2/M_3 \gtrsim 2$

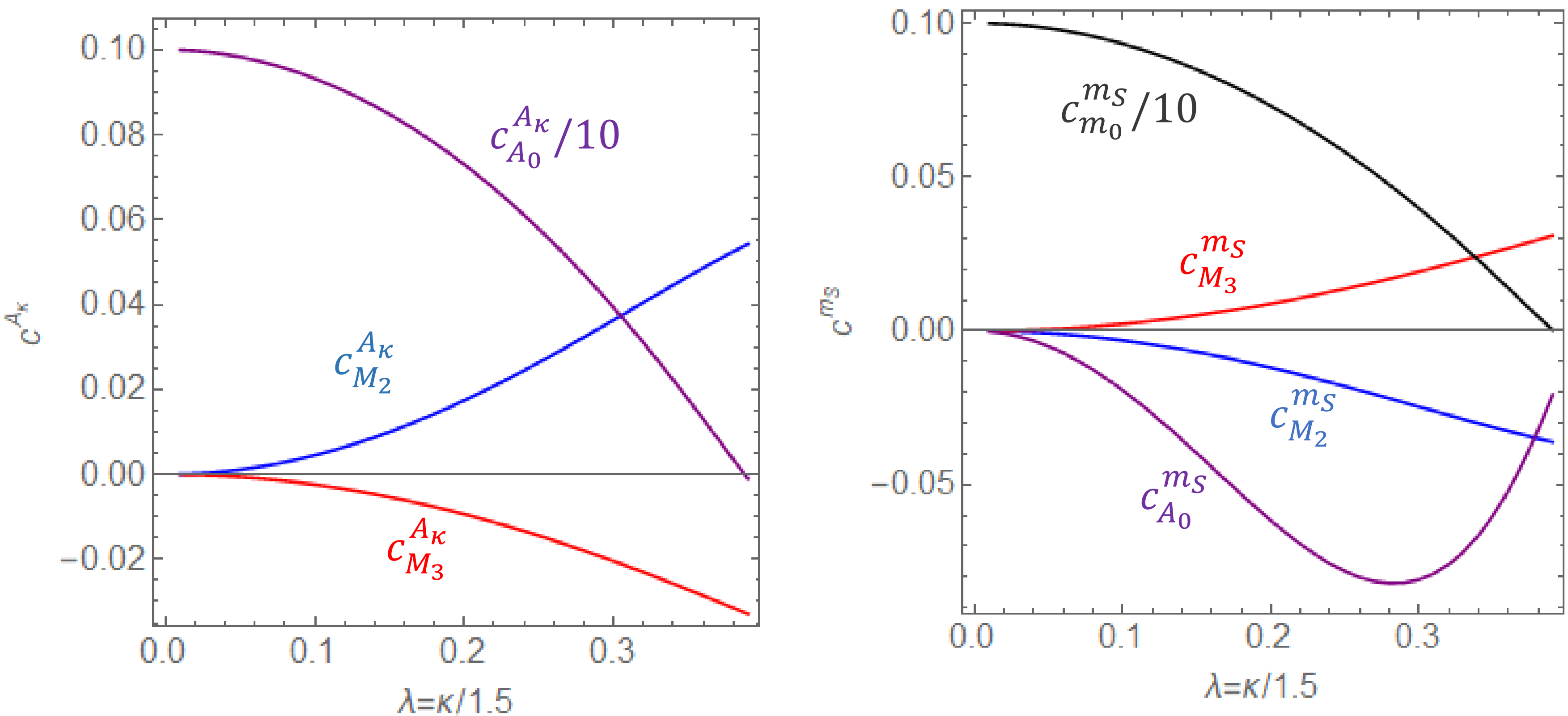
- EW solutions with sizable $\lambda, \kappa$
  - radiative EW symmetry breaking : $m_S^2 > 0 \rightarrow m_S^2 < 0$
  - rich structure of the Higgs potential (EW baryogenesis ?)
- (thermal) higgsino-like DM is realized
  - proper thermal relic density
  - direct detection is promising
  - gluino mass is lighter than about 22 TeV

# back up

# RGE coefficients: $\tan\beta = 20$, $M_S = 3$ TeV

$$A_\kappa(M_s) \sim c_{M_2}^{A_\kappa} M_2 + c_{M_3}^{A_\kappa} M_3 + c_{A_0}^{A_\kappa} A_0 + \cdots$$

$$m_S^2(M_s) \sim c_{M_2}^{m_S} M_2^2 + c_{M_3}^{m_S} M_3^2 + c_{A_0}^{m_S} A_0^2 + c_{m_0}^{m_S} m_0^2 + \cdots$$



# $\lambda \lesssim |\kappa|$ is favored

- $\lambda^4/\kappa^2$ must be small to keep $m_h^2 \sim 125$ GeV

$$m_h^2\Big|_{tree} \sim m_Z^2 \left( \cos^2 2\beta + \frac{\lambda^2}{g^2}\sin^2 2\beta - \frac{4\lambda^2\{2\mu - (A_\lambda + 2\kappa v_s)\sin 2\beta\}^2}{g^2 \mathcal{M}_{33}^2} \right)$$

$$= m_Z^2 \left[ 1 - \frac{4\lambda^2\mu^2}{\kappa v_s (A_\kappa + 4\kappa v_s)} + \mathcal{O}\left(\frac{1}{\tan\beta}\right) \right] \qquad m_{H_d}^2 \gg m_Z^2, v_s^2$$

- higgsino DM is realized and can avoid overproduced singlino

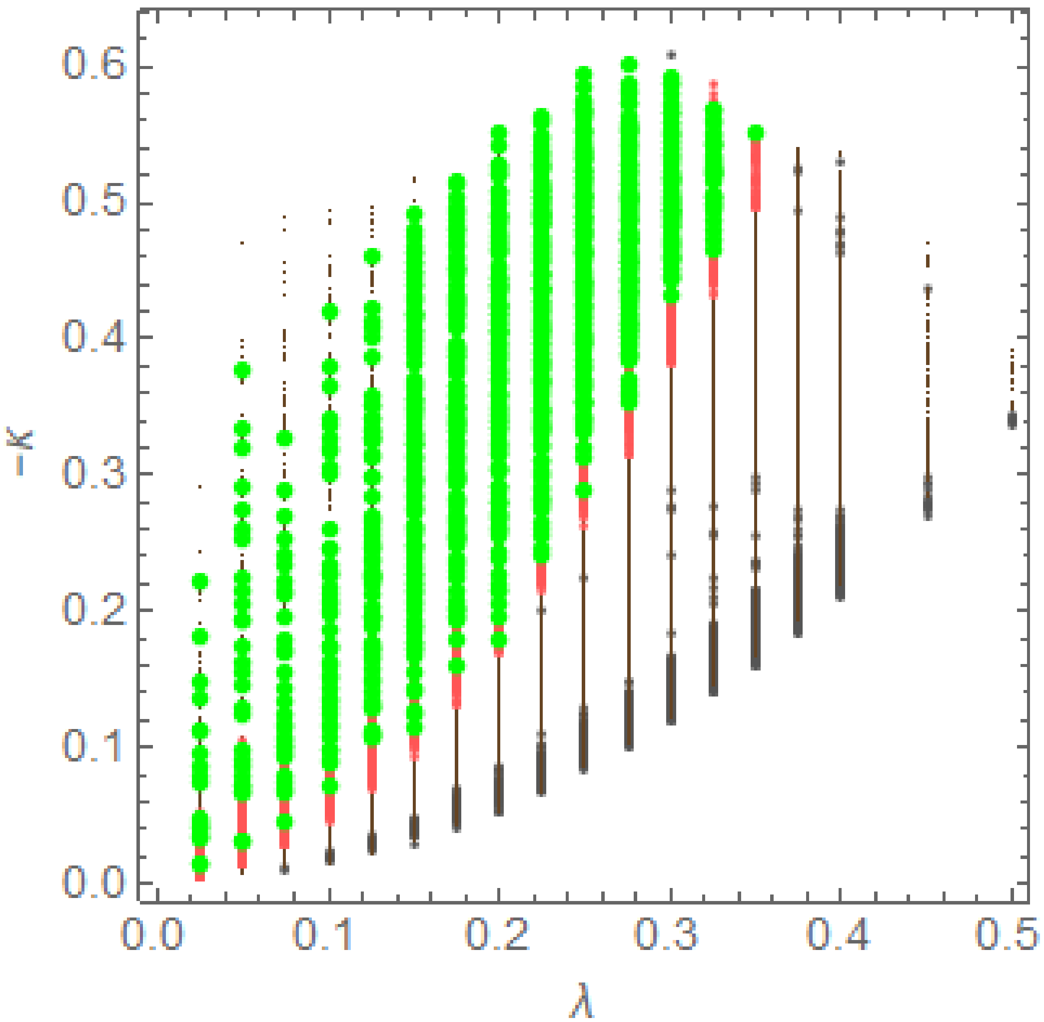
$$m_{\tilde{H}} \sim \lambda\, v_s, m_{\tilde{S}} \sim 2\kappa v_s$$

- $\lambda^2 \lesssim \kappa^2$ is required to avoid the deeper false vacua

1203.4328 T.Kobayashi, T.Shimomura, T.Takahashi

# $\lambda \lesssim |\kappa|$ is favored

- Found Parameters



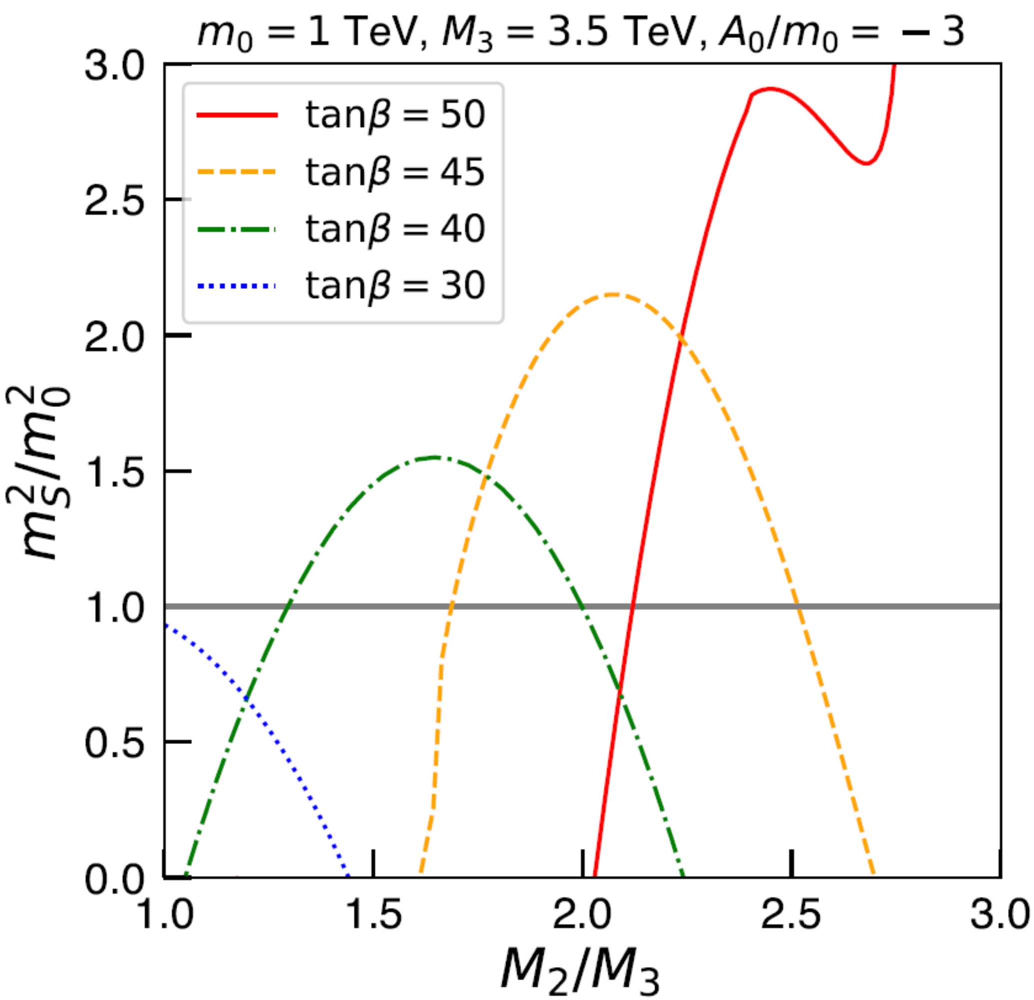

Black: tachyon exist

Brown: $m_h \notin [122.1, 128.1]$ GeV

Red : $\Omega h^2 > 0.1188$

Green : $\Omega h^2 \leq 0.1188$

# $m_S^2/m_0^2$ satisfying EW condition



# Neutralino mass matrix

- Neutralino matrix for $(-i\,\tilde{B}, -i\,\widetilde{W}^3,\ \widetilde{H}_d^0,\ \widetilde{H}_u^0,\ \tilde{S})$

$$M_\chi = \begin{pmatrix} M_1 & 0 & -g_1 v_d/\sqrt{2} & g_1 v_u/\sqrt{2} & 0 \\ 0 & M_2 & g_2 v_d/\sqrt{2} & -g_2 v_u/\sqrt{2} & 0 \\ -g_1 v_d/\sqrt{2} & g_2 v_d/\sqrt{2} & 0 & -\lambda\, v_s & -\lambda\, v_u \\ g_1 v_u/\sqrt{2} & g_2 v_u/\sqrt{2} & -\lambda\, v_s & 0 & -\lambda\, v_d \\ 0 & 0 & -\lambda\, v_u & -\lambda v_d & 2\,\kappa\, v_s \end{pmatrix}$$

→ higgsino/singlino mass is determined by $v_s$

c.f. CNMSSM → $\kappa \ll \lambda \ll 1$ → light singlino LSP

# Condition for viable EW minima

We also consider about

1. the EW solution is a minimum of the potential

→ signs of parameters are constrained

2. there is no deeper minima

D-flat and F-flat directions tend to have deeper min.

$$m_{H_d}^2(M_s) \sim +0.35\, M_2^2 - 0.13\, M_3^2 + 0.78 A_0^2$$

→ these directions are lifted by $m_{H_d}^2$