Hidden sector renormalisation in gauge mediation scenario

Shinsuke Kawai

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based on [1001.1509] [1011.3998]
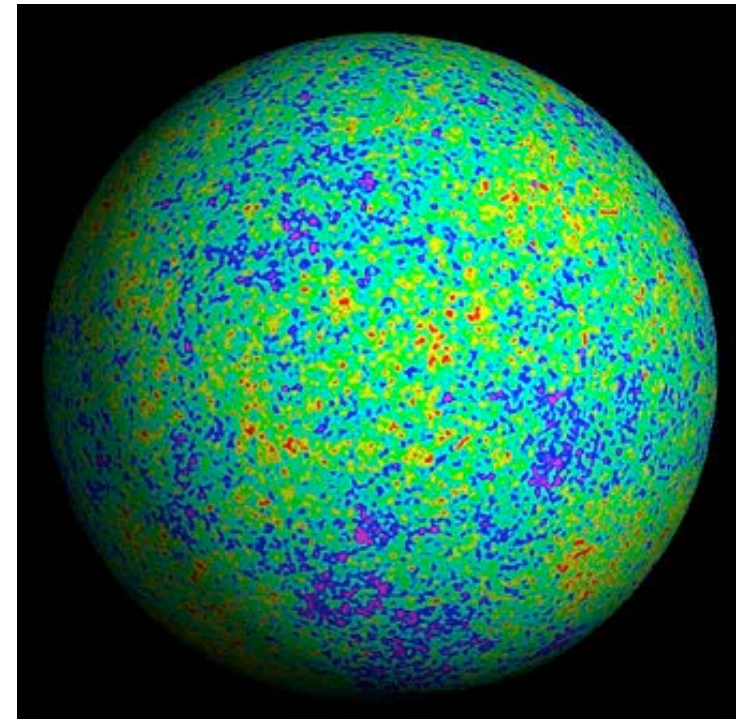with M.Arai and N.Okada

17 March 2011

Particle theory: top-down and bottom-up

☐ Top-down approach

- String-, M- and F-theory cosmology

- Inflation, KKLT, brane configuration

☑ Bottom-up approach

- Low energy spectrum (SM+α)

- SUSY breaking mechanism

LHC: What do we expect to detect?

▸ Higgs: the last piece of SM

▸ Signals beyond the SM

  ▸ Supersymmetry

  ▸ Extra dimensions

  ▸ Hidden local symmetry

  ▸ etc.

This talk is about...

- SUSY $\Longleftarrow$ hierarchy prob, gauge coupling unification, dark matter, ...

- Particle masses: RG flow from high energy

- visible sector + hidden sector

- RG effects from the hidden sector: not seriously considered until recent

  ‣ Hidden sector RG, mass formula; RG study in cMSSM
      [Cohen Roy Schmaltz (2007)]   [Campbell Ellis Maybury (2008)]

  ‣ GMSB, phenomenological implications, more serious hidden sector
      [Arai SK Okada, arXiv:1001.1509]   [Arai SK Okada, arXiv:1011.3998]

      - Gauge mediation scenario in MSSM, to be specific.

Outline of this talk

1. MSSM and GMSB

2. RG equation and the hidden sector

3. Hidden sector effects: a simple toy model **[arXiv:1001.1509]**

4. Hidden sector effects: a strongly coupled model **[arXiv:1011:3998]**

5. Summary and outlook

Supersymmetry

- A solution to the hierarchy problem (cf. technicolour)

- Gauge coupling unification -- Good!!

- LSP: natural candidate of Dark Matter (stable due to R-parity)

- Bottom-up approach: Minimal Supersymmetric Standard Model (MSSM)

MSSM

- Matter supermultiplets

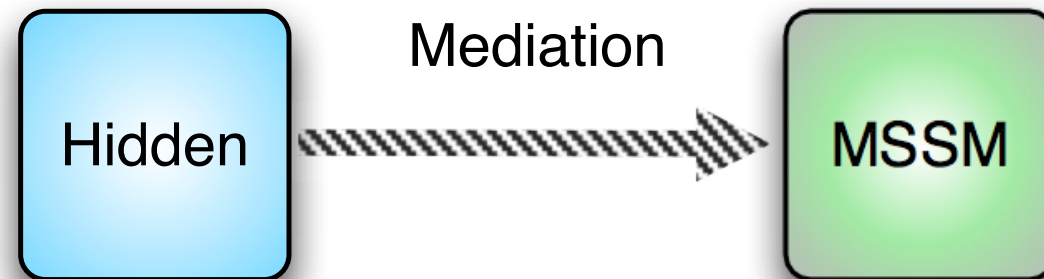| Multiplets		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\mathbf{3},\mathbf{2},\frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\overline{\mathbf{3}},\mathbf{1},-\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\overline{\mathbf{3}},\mathbf{1},\frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1},\mathbf{1},1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\mathbf{1},\mathbf{2},+\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$

- Gauge supermultiplets

Multiplets	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\mathbf{8},\mathbf{1},0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\mathbf{1},\mathbf{3},0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\mathbf{1},\mathbf{1},0)$

Supersymmetry breaking

- Gravity mediation, gauge mediation, extra-dim mediation, anomaly mediation...

	Gravity mediation	Gauge mediation
Coupling	Planck suppressed operators	MSSM gauge
FCNC	Challenging	Naturally suppressed
μ-problem	Simple	Challenging
Dark matter	Neutralino	Gravitino

Gauge-mediated SUSY breaking (GMSB)

- Messengers charged under SU(3)xSU(2)xU(1) gauge interaction of MSSM

- After integrating out the messenger fields, $\quad \mathcal{L} = \mathcal{L}_{\text{MSSM}} + \mathcal{L}_{\text{Hid}} + \mathcal{L}_{\text{int}}$

Hidden sector fields

$$\mathcal{L}_{\text{int}} = k_i \int d^4\theta \frac{XX^\dagger}{M^2} \Phi_i \Phi_i^\dagger + \left(w_a \int d^2\theta \frac{X}{M} W^{a\alpha} W_\alpha^a + h.c. \right)$$

Messenger scale

MSSM fields $\quad \phi_i = \left\{ \tilde{q}, \tilde{u}, \tilde{d}, \tilde{l}, \tilde{e}, H_u, H_d \right\}$

- Gaugino masses arise from 1-loop corrections: $M_a(t=0) = \dfrac{\alpha_a(M)}{4\pi} \Lambda$

- Sfermion masses arise from 2-loop corrections (8 diagrams)

$$\alpha_a = \frac{g_a^2}{4\pi}$$
$$\Lambda = F/M$$
$$t = \ln(\mu/M)$$

$$m_i^2(t=0) = 2\Lambda^2 \sum_{a=1}^{3} C_2^a(R_i) \left(\frac{\alpha_a(M)}{4\pi} \right)^2$$

Boundary conditions of mass RG

Features of typical GMSB models

- LSP: gravitino -- dark matter candidate

- NLSP: neutralino (bino) or slepton (stau)

- Flavour universality -- no FCNC problem

- Structure formation favours **Cold Dark** Matter (CDM)

$$m_{3/2} \sim \frac{M\Lambda}{\sqrt{3}M_P} \gtrsim 100 \text{ keV} \quad \text{(M: messenger scale, Λ: cut off scale)}$$

- High messenger scale GMSB scenario favoured

$$M \gtrsim 9.0 \times 10^9 \text{ GeV}$$

Minimal GMSB

- Keep the successful gauge coupling unification -- messenger in SU(5) reps

- Count the messengers using Dynkin index -- $N_5 = 1$ for $\mathbf{5}$, $N_5 = 3$ for $\mathbf{10}$,

- N_5 cannot be taken too large (diverge before unification)

- $N_5 = 1$ model = minimal GMSB scenario

- In the minimal GMSB, NLSP = neutralino

Renormalization with hidden sector

- RG effects from HS not included so far: non-perturbative -- difficult to analyze

- A toy model for mimicking the RG effects of the hidden sector:

$$\mathcal{L}_{\text{hid}} = \int d^4\theta\, X^\dagger X + \left(\int d^2\theta\, \mathcal{W} + h.c. \right)$$

$$\mathcal{W} = \frac{\lambda}{3} X^3.$$

$$\langle F_X \rangle \neq 0$$

[Cohen Roy Schmaltz (2007)]

[Campbell Ellis Maybury (2008)]

- Couple the hidden sector with MSSM in the standard way:

$$\mathcal{L}_{\text{int}} = k_i \int d^4\theta\, \frac{XX^\dagger}{M^2} \Phi_i \Phi_i^\dagger + \left(w_a \int d^2\theta\, \frac{X}{M} W^{a\alpha} W^a_\alpha + h.c. \right)$$

sfermion masses   messenger scale   gaugino masses

Outline of this talk

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messenger scale

Renormalisation effects from HS

- The hidden-visible interaction term

$$\mathcal{L}_{\text{int}} = k_i \int d^4\theta \frac{XX^\dagger}{M^2} \Phi_i \Phi_i^\dagger + \left(w_a \int d^2\theta \frac{X}{M} W^{a\alpha} W_\alpha^a + h.c. \right)$$

renormalised
(hidden+MSSM gauge)

not renormalised
(non-renormalisation theorem)

- [Cohen Roy Schmaltz (2007)] : Mass sum rules unchanged

- [Campbell Ellis Maybury (2008)]: RG study for constrained MSSM

- We studied the hidden RG effects in GMSB & phenomenological implications

Mass renormalisation with hidden sector

$$8\pi^2 \frac{dm_Q^2}{dt} = \xi_t + \xi_b - \frac{16}{3}g_3^2 M_3^2 - 3g_2^2 M_2^2 - \frac{1}{15}g_1^2 M_1^2 + \frac{1}{5}g_1^2 \xi_1 + 4\lambda^2 m_Q^2,$$

$$8\pi^2 \frac{dm_U^2}{dt} = 2\xi_t - \frac{16}{3}g_3^2 M_3^2 - \frac{16}{15}g_1^2 M_1^2 - \frac{4}{5}g_1^2 \xi_1 + 4\lambda^2 m_U^2,$$

$$8\pi^2 \frac{dm_D^2}{dt} = 2\xi_b - \frac{16}{3}g_3^2 M_3^2 - \frac{4}{15}g_1^2 M_1^2 + \frac{2}{5}g_1^2 \xi_1 + 4\lambda^2 m_D^2,$$

$$8\pi^2 \frac{dm_L^2}{dt} = \xi_\tau - 3g_2^2 M_2^2 - \frac{3}{5}g_1^2 M_1^2 - \frac{3}{5}g_1^2 \xi_1 + 4\lambda^2 m_L^2,$$

$$8\pi^2 \frac{dm_E^2}{dt} = 2\xi_\tau - \frac{12}{5}g_1^2 M_1^2 + \frac{6}{5}g_1^2 \xi_1 + 4\lambda^2 m_E^2,$$

$$8\pi^2 \frac{dm_{H_u}^2}{dt} = 3\xi_t - 3g_2^2 M_2^2 - \frac{3}{5}g_1^2 M_1^2 + \frac{3}{5}g_1^2 \xi_1 + 4\lambda^2 m_{H_u}^2,$$

$$8\pi^2 \frac{dm_{H_d}^2}{dt} = 3\xi_b + \xi_\tau - 3g_2^2 M_2^2 - \frac{3}{5}g_1^2 M_1^2 - \frac{3}{5}g_1^2 \xi_1 + 4\lambda^2 m_{H_d}^2$$

Mass renormalisation with hidden sector --cont.

$$\xi_t = y_t^2(m_{H_u}^2 + m_Q^2 + m_U^2 + A_t^2),$$

$$\xi_b = y_b^2(m_{H_d}^2 + m_Q^2 + m_D^2 + A_b^2),$$

$$\xi_\tau = y_\tau^2(m_{H_d}^2 + m_L^2 + m_E^2 + A_\tau^2),$$

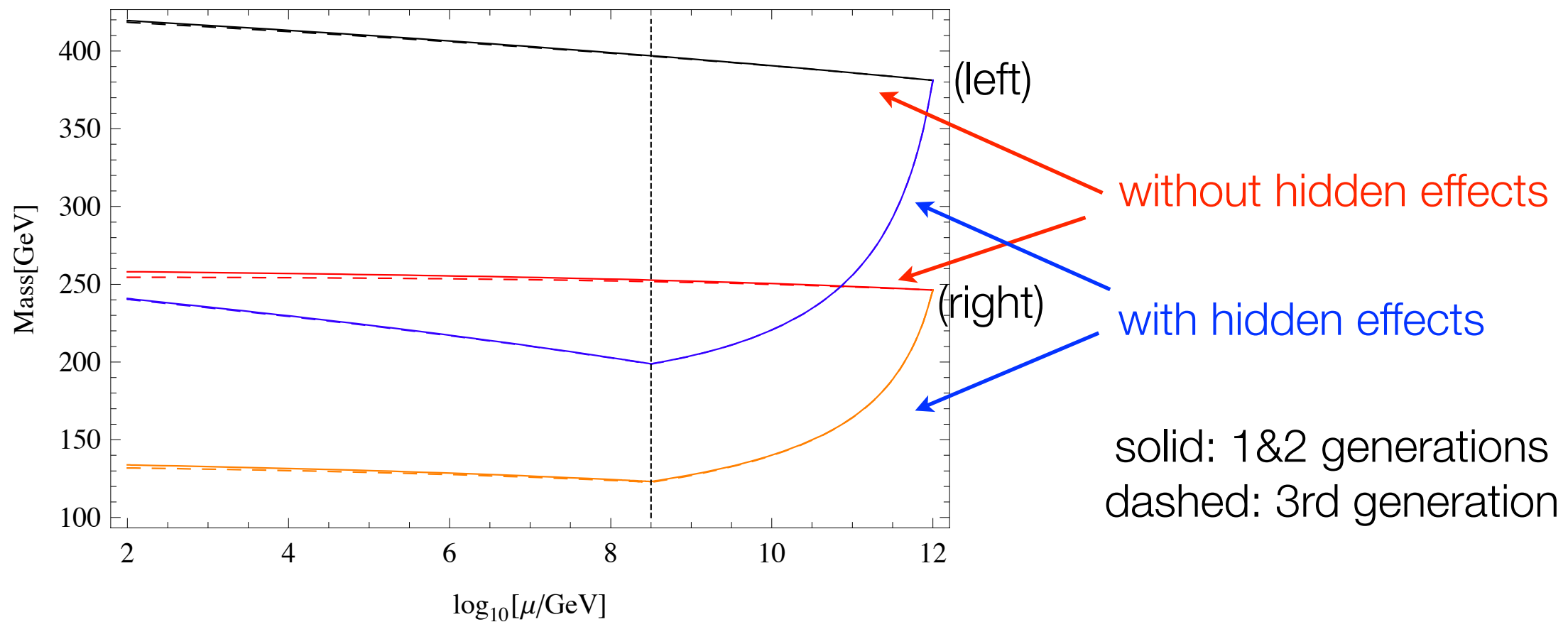$$\xi_1 = \frac{1}{2}\left\{m_{H_u}^2 - m_{H_d}^2 + \text{Tr}(m_Q^2 - 2m_U^2 + m_D^2 + m_E^2 - m_L^2)\right\}$$

RGE for gauge couplings, gaugino masses, Yukawa couplings, A-terms -- unchanged

The GMSB boundary conditions

$$M_a(t=0) = \frac{\alpha_a(M)}{4\pi}\Lambda$$

$$m_i^2(t=0) = 2\Lambda^2 \sum_{a=1}^{3} C_2^a(R_i)\left(\frac{\alpha_a(M)}{4\pi}\right)^2$$

RG flow -- slepton masses

The slepton mass RG flows with and without the hidden sector effects. The upper curves (black and blue) are the left-handed, and the lower curves (red and orange) are the right-handed sleptons. The 1st and the 3rd generations are respectively indicated by the solid and the dashed curves. The curves with sharp decline (blue and orange) above the hidden scale $M_{\mathrm{hid}} = 10^{8.5}$ GeV (indicated by the vertical dotted line) are the flows including the hidden sector effects. The straight lines (black and red) are the flows without the hidden sector effects. We have chosen $M = 10^{12}$ GeV, $\lambda = 3.8$ and $\tan\beta = 10$.

Squark masses

without hidden effects

(left)
(right)

with hidden effects

solid: 1&2 generations
dashed: 3rd generation
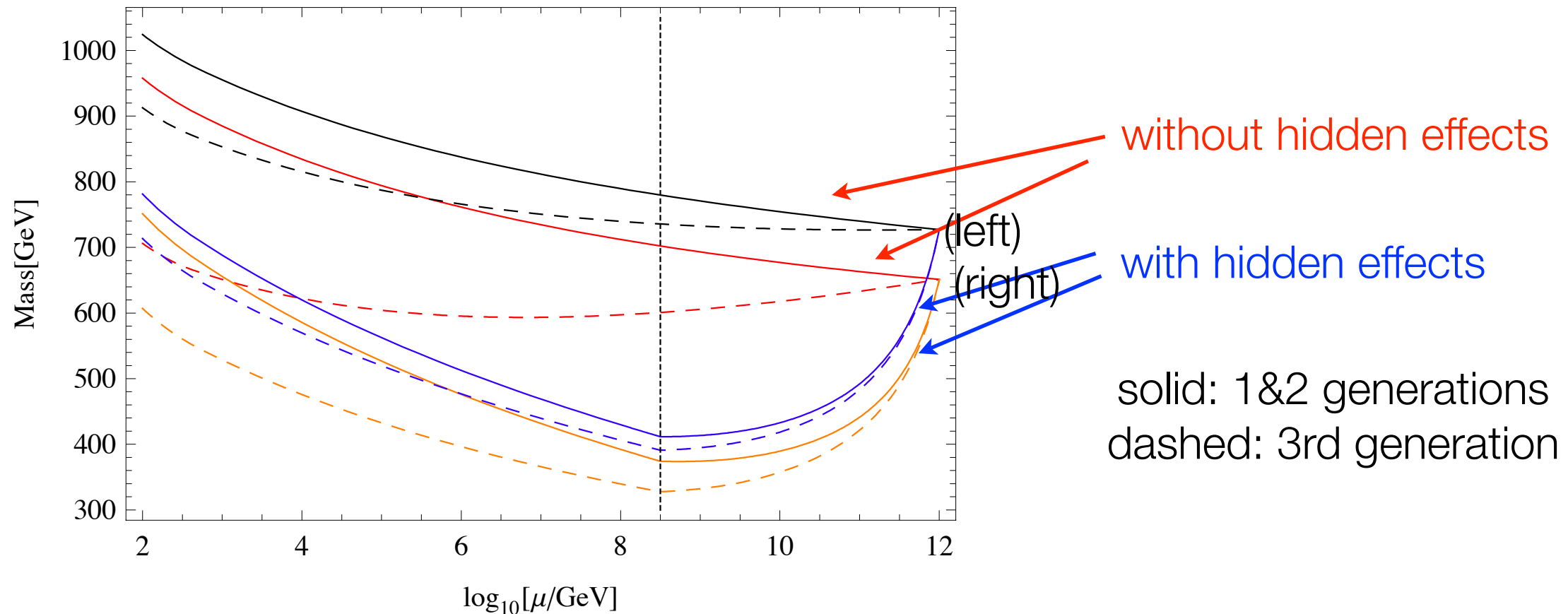
The squark mass RG flows with and without the hidden sector effects. The curves starting from the larger mass at $M = 10^{12}$ GeV are the left-handed squarks, and those starting from the smaller mass are the right-handed up-type squarks. The 1st and the 3rd generations are denoted by the solid and the dashed curves. The blue (left-handed) and orange (right-handed) curves with sharp decline above the hidden scale $M_{\mathrm{hid}} = 10^{8.5}$ GeV (the dotted vertical line) are the flows with the hidden sector effects, whereas the black (left-handed) and red (right-handed) curves show the flows without the hidden sector effects. The parameters are the same as in Fig. **??** ($\lambda = 3.8$ and $\tan\beta = 10$).

RG flow with hidden sector renormalisation

- Only the soft scalar and gravitino become lighter

- Other masses unaffected by the hidden sector

- stau can be lighter than bino -- stau NLSP scenario

- OK with BBN and dark matter constraints

- stau NLSP is interesting in collider physics

stau-neutralino mass ratio
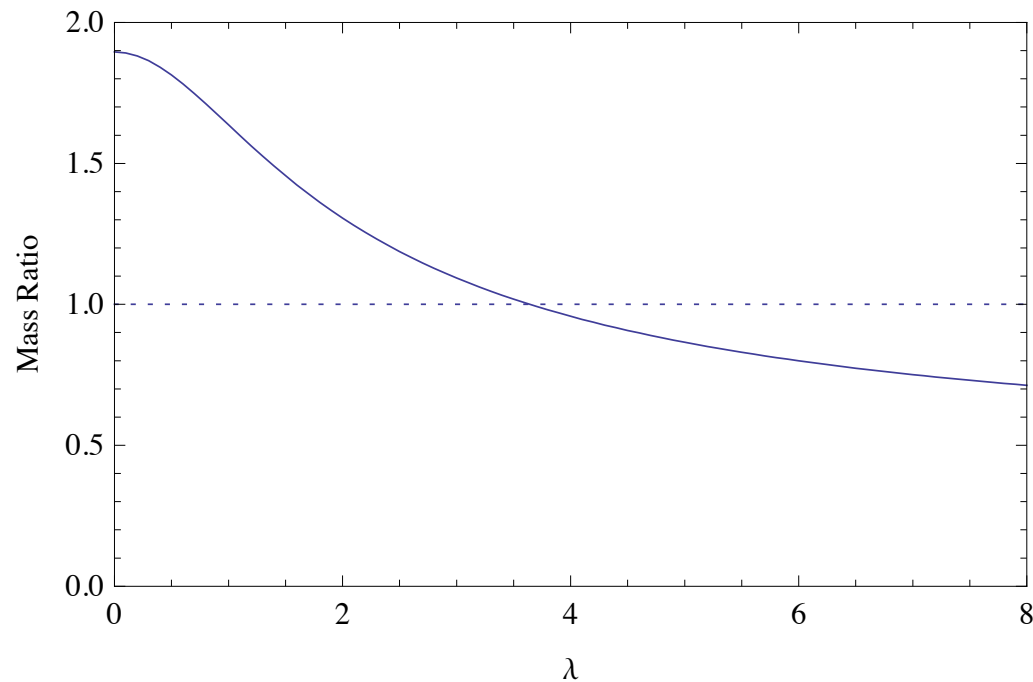
The stau/neutralino mass ratio $m_{\tilde{\tau}}/m_{\tilde{\chi}^0}$ plotted against the hidden sector coupling λ. We used $M = 10^{12}$ GeV and $\tan \beta = 10$.
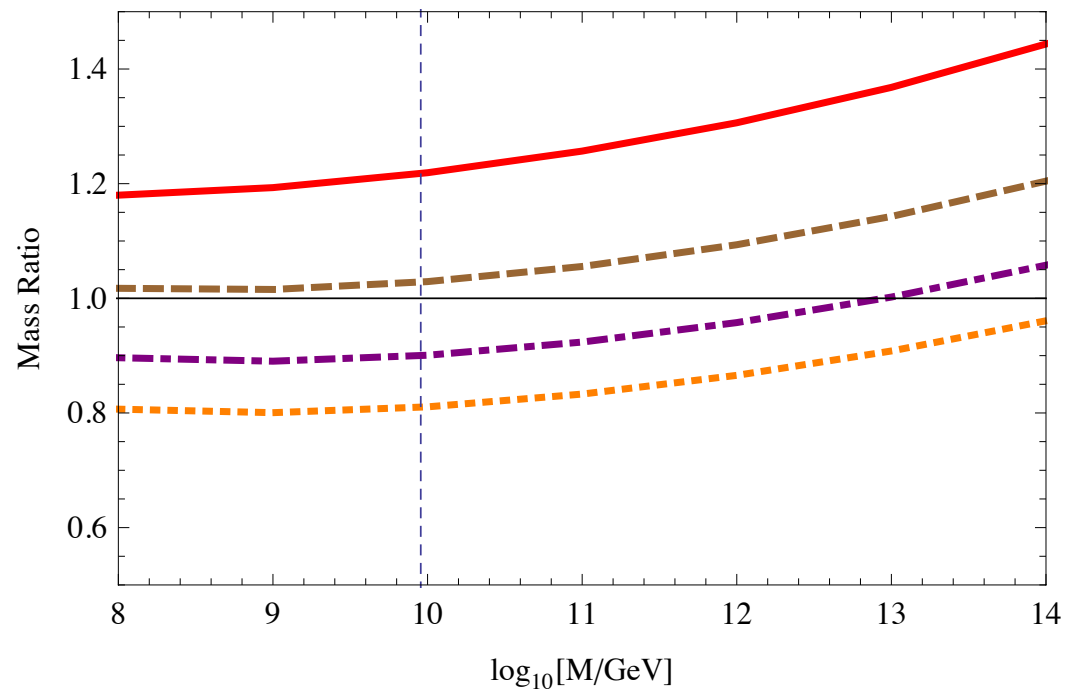
The stau/neutralino mass ratio $m_{\tilde{\tau}}/m_{\tilde{\chi}^0}$ plotted against the messenger scale M, for $\lambda = 2$ (solid red), $\lambda = 3$ (dashed brown), $\lambda = 4$ (dot-dashed purple), $\lambda = 5$ (dotted orange) from above, with $\tan \beta = 10$. The vertical dashed line indicates the minimal messenger scale in our model, $M_* = 9.0 \times 10^9$ GeV. For large enough λ stau becomes lighter than neutralino.

Outline of this talk

1. MSSM and GMSB

2. RG equation and the hidden sector

3. Hidden sector effects: a simple toy model **[arXiv:1001.1509]**

4. Hidden sector effects: a strongly coupled model **[arXiv:1008:????]**

5. Summary and outlook

A model of strongly coupled hidden sector

- Soft SUSY breaking -- expected to be realized dynamically

- Non-renormalization theorem: non-perturbative SUSY breaking mechanism

- RG analysis -- essentially perturbative scheme

- Is it possible to incorporate the strongly coupled hidden sector dynamics into the perturbative RG?

A model of strongly coupled hidden sector

- Soft SUSY breaking -- expected to be realized dynamically

- Non-renormalization theorem: non-perturbative SUSY breaking mechanism

- RG analysis -- essentially perturbative scheme

- Is it possible to incorporate the strongly coupled hidden sector dynamics into the perturbative RG?

YES.
Use duality.

Strongly coupled hidden sector

- N=1 SUSY QCD with meta-stable local vacuum [Intriligator Seiberg Shih 2007]

  - ✦ Kahler potential perturbatively calculable $\quad N_c + 1 \leq N_f < \dfrac{3}{2} N_c$

  - ✦ Phenomenological applications [many]

- N=2 SUSY (perturbed Seiberg-Witten) [Arai Okada 2001] [Ooguri Ookouchi Park 2007] [Pastras 2007] [Arai Montonen Okada Sasaki 2007] [Marsano Ooguri Ookouchi Park 2007]

  - ✦ Kahler potential exactly calculable

  - ✦ Phenomenological applications [our paper]

Our model of strongly coupled hidden sector

- SU(2) x U(1) SQCD with 2 hypermultiplets (fundamental reps)

- The SU(2) and U(1) scales chosen so that the Seiberg-Witten duality persists.

- Perturbed by FI term $\lambda \ll \Lambda^2_{SU(2)} \ll \Lambda^2_{U(1)}$

- U(1) scale -- cut off scale at the Landau pole

- Low energy effective dynamics determined by the duality and holomorphicity

- Couple this to the MSSM via messenger (we use GMSB)

- Analyze the mass renormalization as before.

Dynamics in the Coulomb branch

- SUSY broken in the Coulomb branch

- 2 moduli parameters: u and a1

- Local vacua at singular points

- Meta-stable local vacuum at a1=0
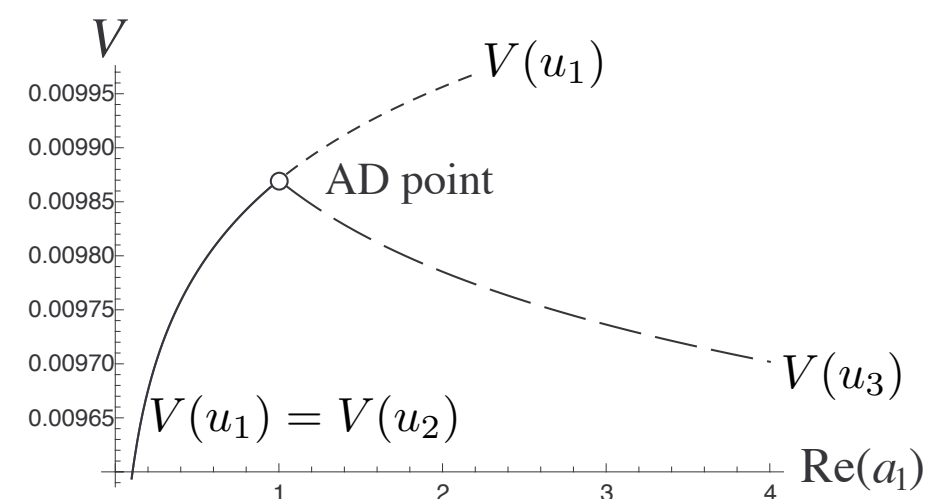
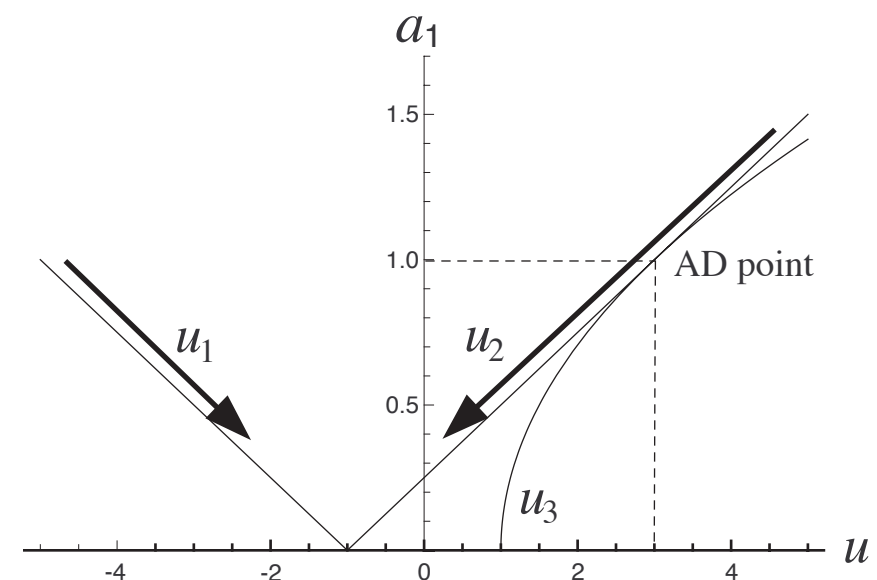$$y^2 = 4(x - e_1)(x - e_2)(x - e_3) \longrightarrow \qquad \text{singular points}$$
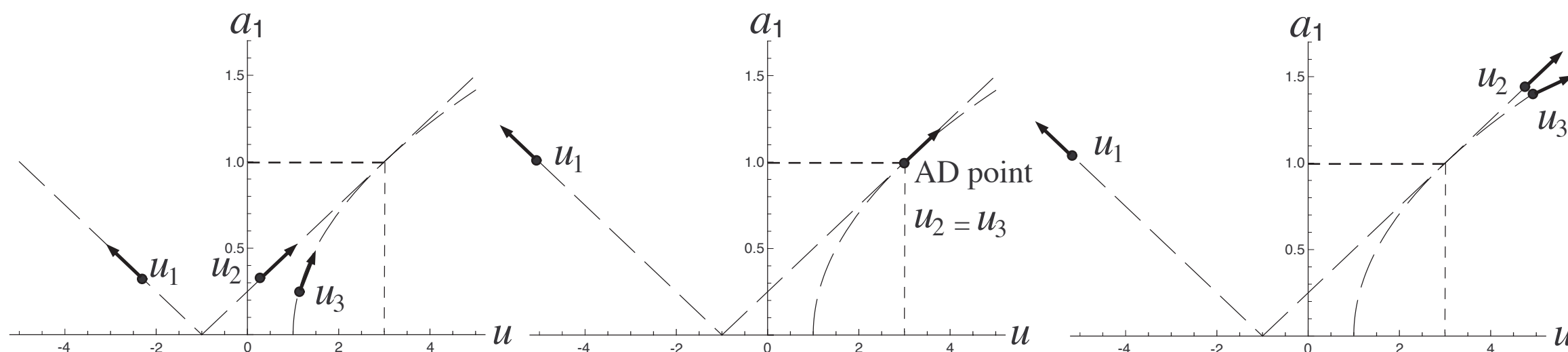
Possible coupling to the messenger fields

- 2 possible RG flows -- u1 and u2

- 2 possible messenger-hidden couplings

  (a) U(1) field $W_{\mathrm{mess}} = A_1 \Psi\tilde\Psi + m_{\mathrm{mess}} \Psi\tilde\Psi$

  (b) SU(2) field $W_{\mathrm{mess}} = \dfrac{u}{\tilde M}\Psi\tilde\Psi + m_{\mathrm{mess}}\Psi\tilde\Psi$

  $$u = \mathrm{Tr}\, A_2^2$$

Mass RG -- (a) U(1) coupled messenger

- • The RG flow: scalars flows modified

- • Smaller masses by the hidden sector effects
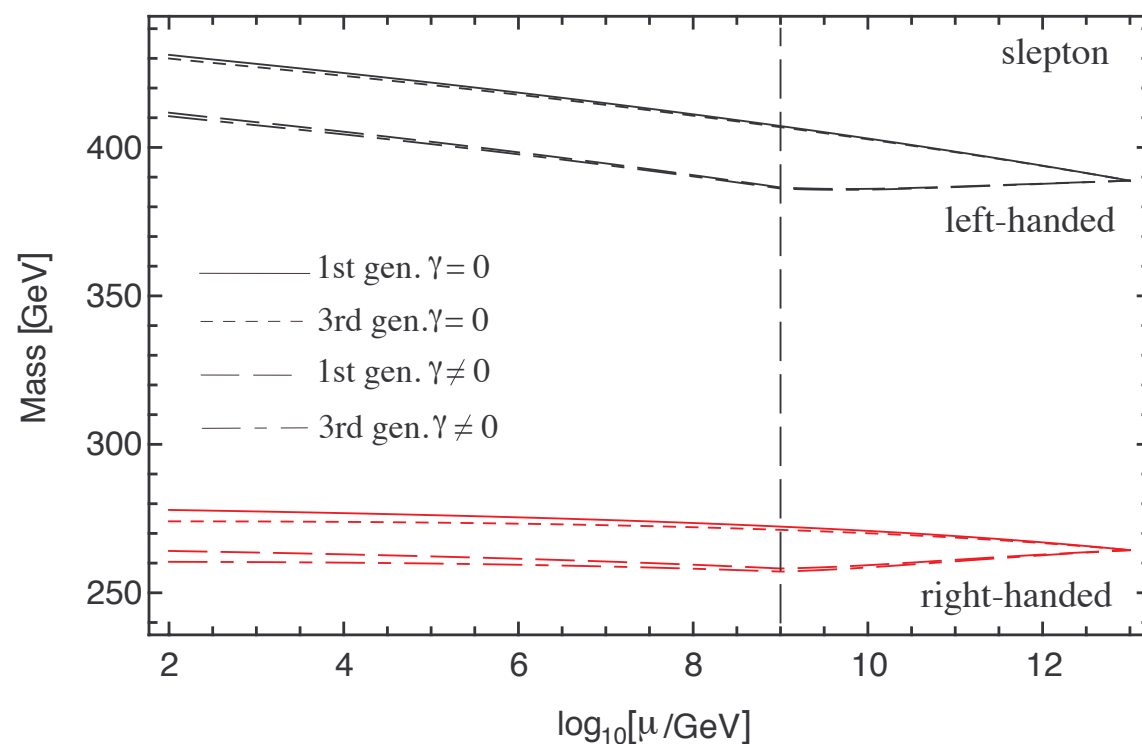
- • For typical parameter values, neutralino NSLP

$$\tan\beta = 10$$
$$M_S = 500\,\mathrm{GeV}$$
$$m_{\mathrm{mess}} = 10^5\,\mathrm{GeV}$$
$$M_{\mathrm{hid}} = 10^9\,\mathrm{GeV}$$
$$M = 10^{13}\,\mathrm{GeV}$$
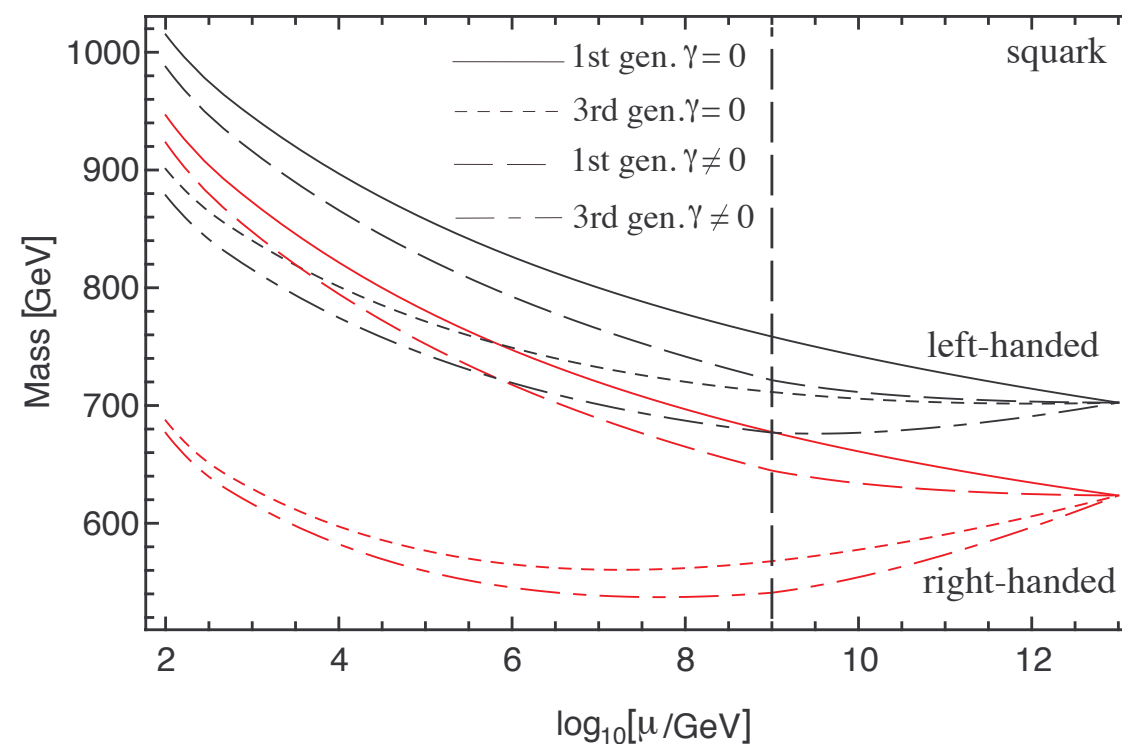
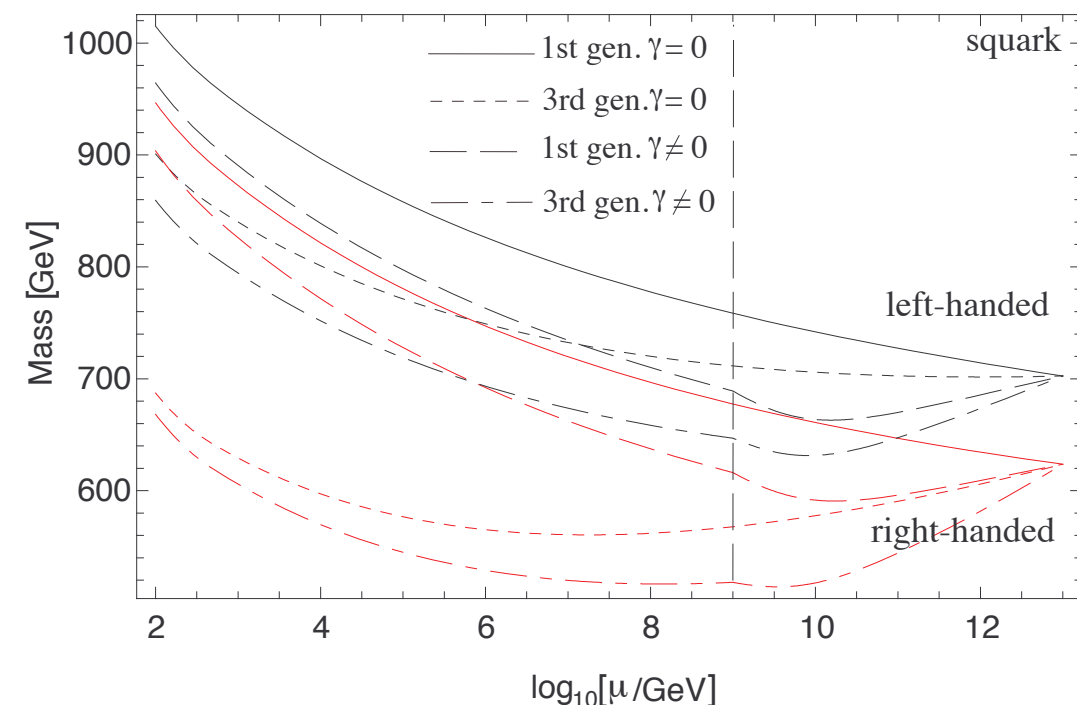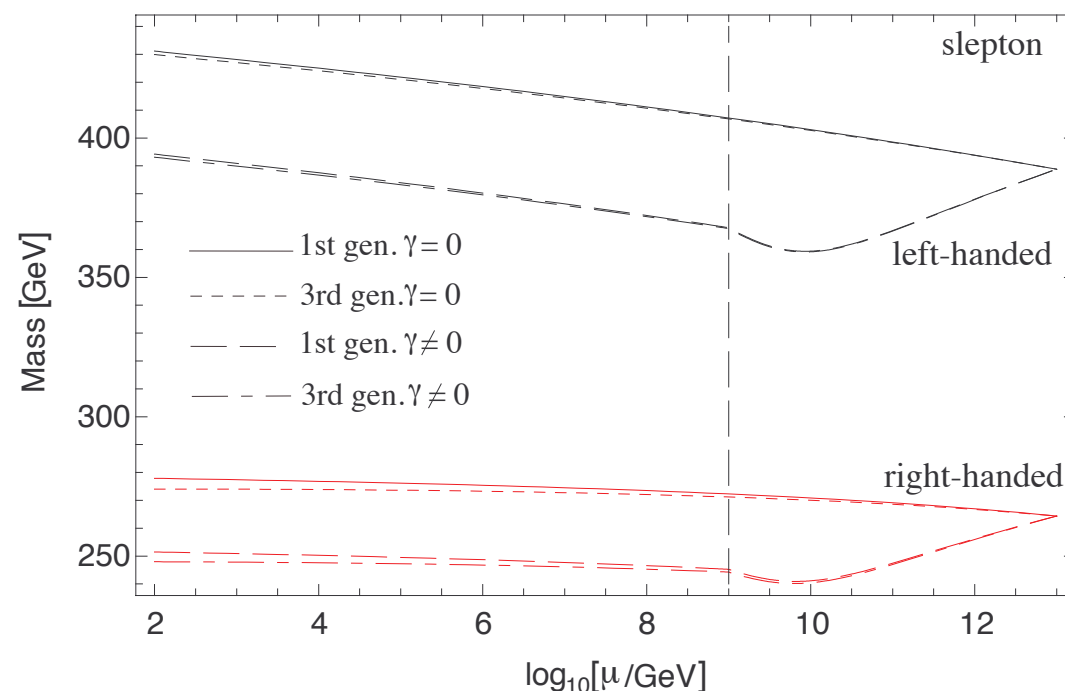# Mass RG -- (b) SU(2) coupled messenger

- The hidden effect is more complicated

$$\frac{dm_i^2}{dt} = \frac{dm_i^2}{dt}\bigg|_{\text{MSSM}} + \gamma(t)m_i^2$$

➡ sensitive to init conditions and flow path

- Examples of larger masses (figures below)

Mass RG -- (b) SU(2) coupled messenger

- The hidden effect is more complicated

$$\frac{dm_i^2}{dt} = \frac{dm_i^2}{dt}\bigg|_{\text{MSSM}} + \gamma(t)m_i^2$$

➡ sensitive to init conditions and flow path

$$\gamma(t) = \frac{\lambda\lambda^\dagger}{2\pi^2} > 0$$

$$\gamma(t) > 0 \quad \text{for} \quad U(1)$$

- Examples of larger masses (figures below)

$$\gamma(t) < 0 \quad \text{possible for} \quad SU(2)$$
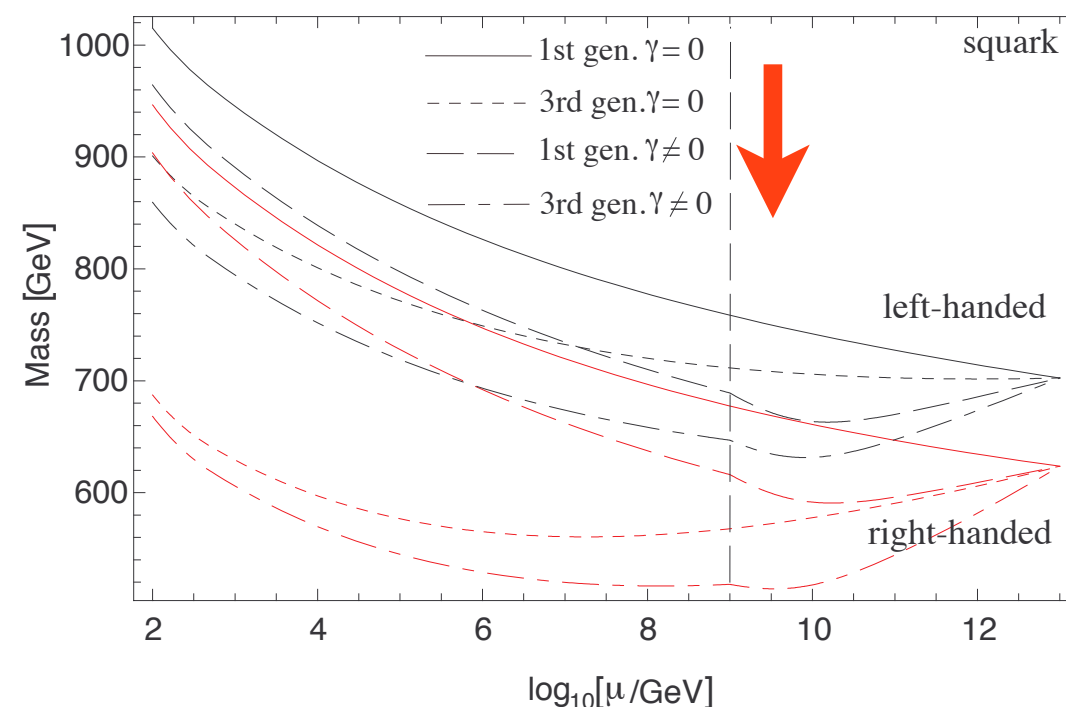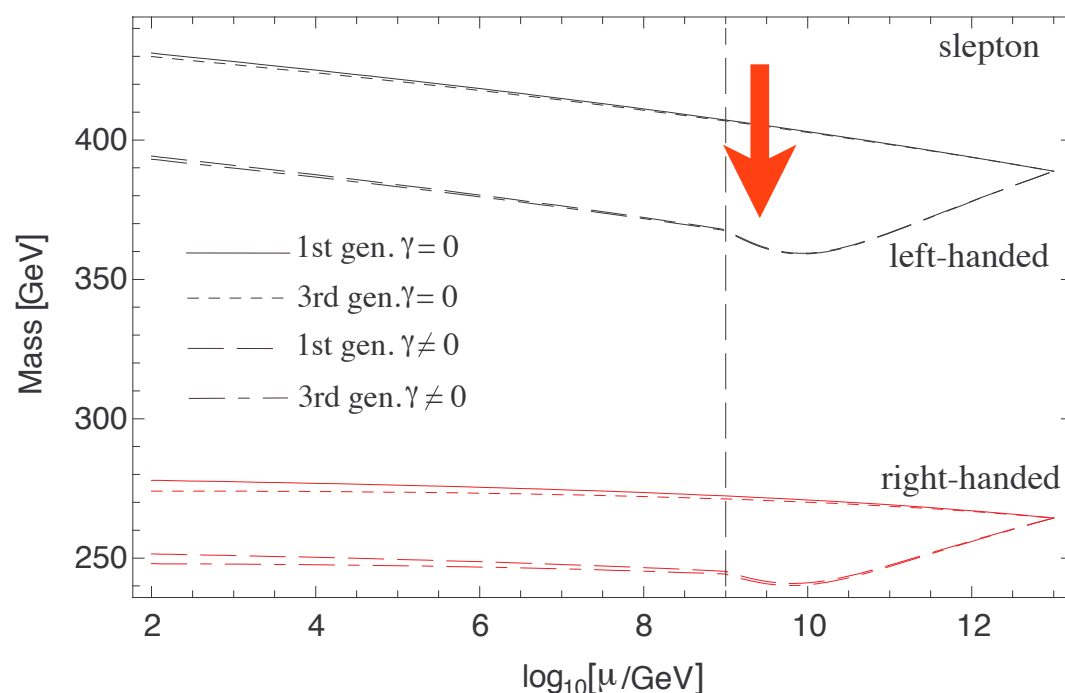
Summary and outlook

- Hidden sector contributes to the mass RG flow.

- Collider experiments in near future are expected to reveal mass spectrum of SUSY particles -- hidden sector physics may be accessible!

- We analyzed two example in GMSB.

- The simple toy model: gravitino LSP (DM) and possible stau NLSP -- interesting collider physics

- The strongly coupled model: the results sensitive to the hidden sector dynamics
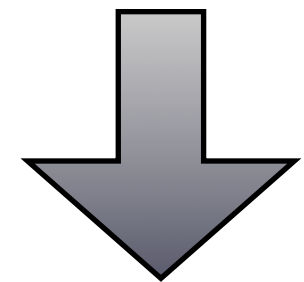
BBN constraints
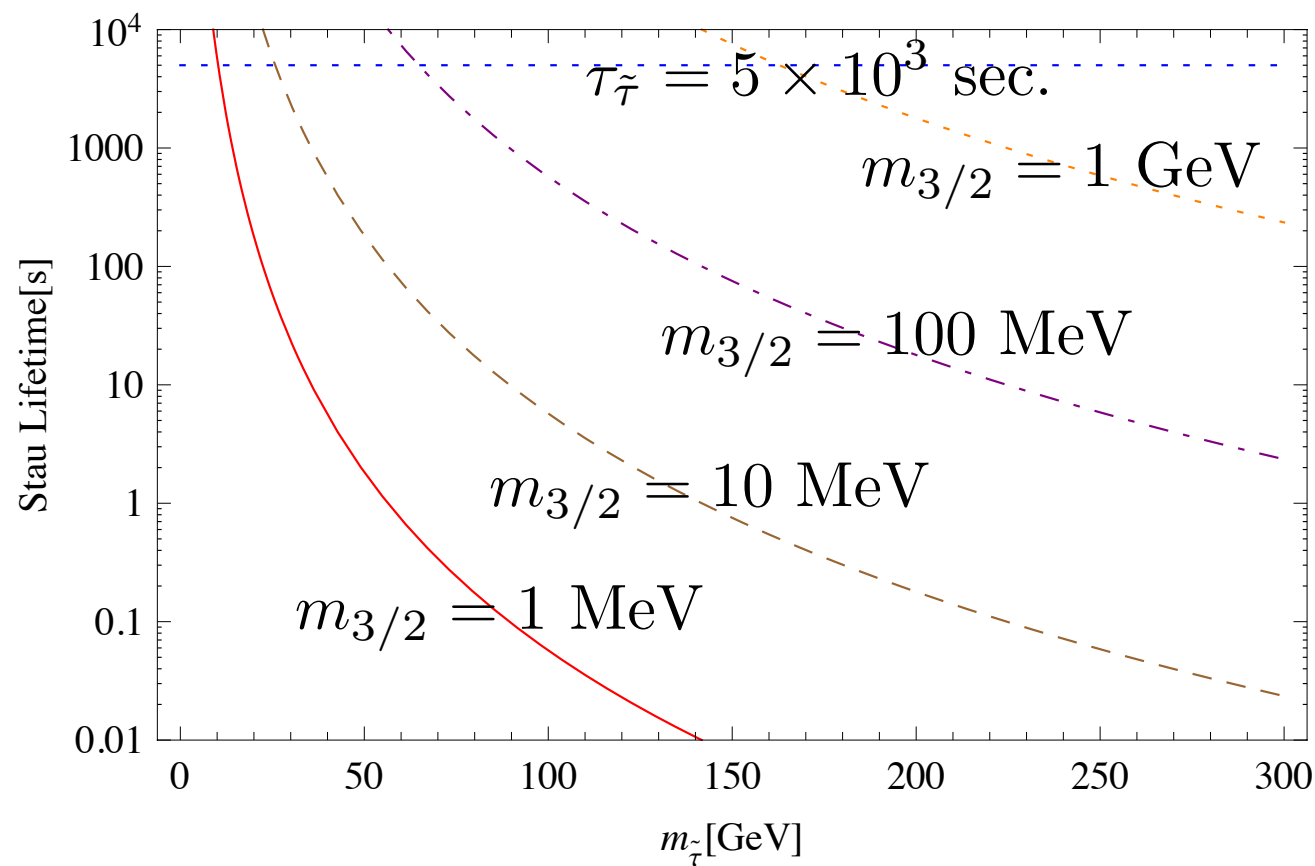
BBN constraints primordial abundance

Catalytic production of $^6\mathrm{Li}$

$$^4\mathrm{He}\ \tilde{\tau}^- + \mathrm{D} \to {}^6\mathrm{Li} + \tilde{\tau}^-$$

giving an upper bound on stau lifetime

$$\tau_{\tilde{\tau}} = \Gamma^{-1}(\tilde{\tau} \to \tau\tilde{G}) \lesssim 5 \times 10^3 \text{ sec.}$$

Cold dark matter

$$0.1 \text{ MeV} \lesssim m_{3/2} \lesssim 0.6 \text{ GeV}$$

upper bound on gravitino mass

Dark matter constraints on gravitino

- The total gravitino abundance

$$\Omega_{\tilde{G}} h^2 = \Omega_{\tilde{G}}^{\mathrm{TP}} h^2 + \Omega_{\tilde{G}}^{\mathrm{NTP}} h^2 \leq \Omega_{CDM} h^2 \simeq 0.1131 \pm 0.0034$$

- Our typical stau mass: $m_{\tilde{\tau}} \approx 130 \text{ GeV}$

$$\left.\begin{array}{l}\\ \\ \end{array}\right\} \quad \Omega_{\tilde{G}}^{\mathrm{NTP}} h^2 \lesssim 10^{-5}$$

- BBN constraints $\quad m_{3/2} \lesssim 0.6 \text{ GeV}$

- Gravitino DM thermally produced -- reheating temperature $T_R \lesssim 10^7 \text{ GeV}$

- No leptogenesis -- Affleck Dine

Implications in collider physics

- Standard story of minimal GMSB: neutralino NLSP

    ➡ Severe BBN constraints (non-thermal production -- heavier than TeV)

- Our story: stau NLSP -- long-lived charged NLSP

    ➡ Less stringent BBN bounds, can be light enough, within LHC

    ➡ Charged -- very distinctive collider signals

    ➡ No missing E_T -- precise measurements of formation/decay processes

stau NLSP scenario

- With λ = 3.8, tanβ=10, M=10^12 GeV, we have the following scenario:

    ‣ Minimal GMSB: very simple, no FCNC

    ‣ Gravitino LSP: 11 MeV -- thermally produced dark matter.

    ‣ Reheating temperature 10^6 GeV

    ‣ stau NLSP: 130 GeV -- detected in LHC soon?

Quark/dyon condensation

- Light particles (dyons) show up in the moduli space

- Quantum trapping by light particles ('Beauty is attractive' [Kofman Linde Liu Maloney McAllister Silverstein hep-th/0403001])

- Local potential minima at singular points
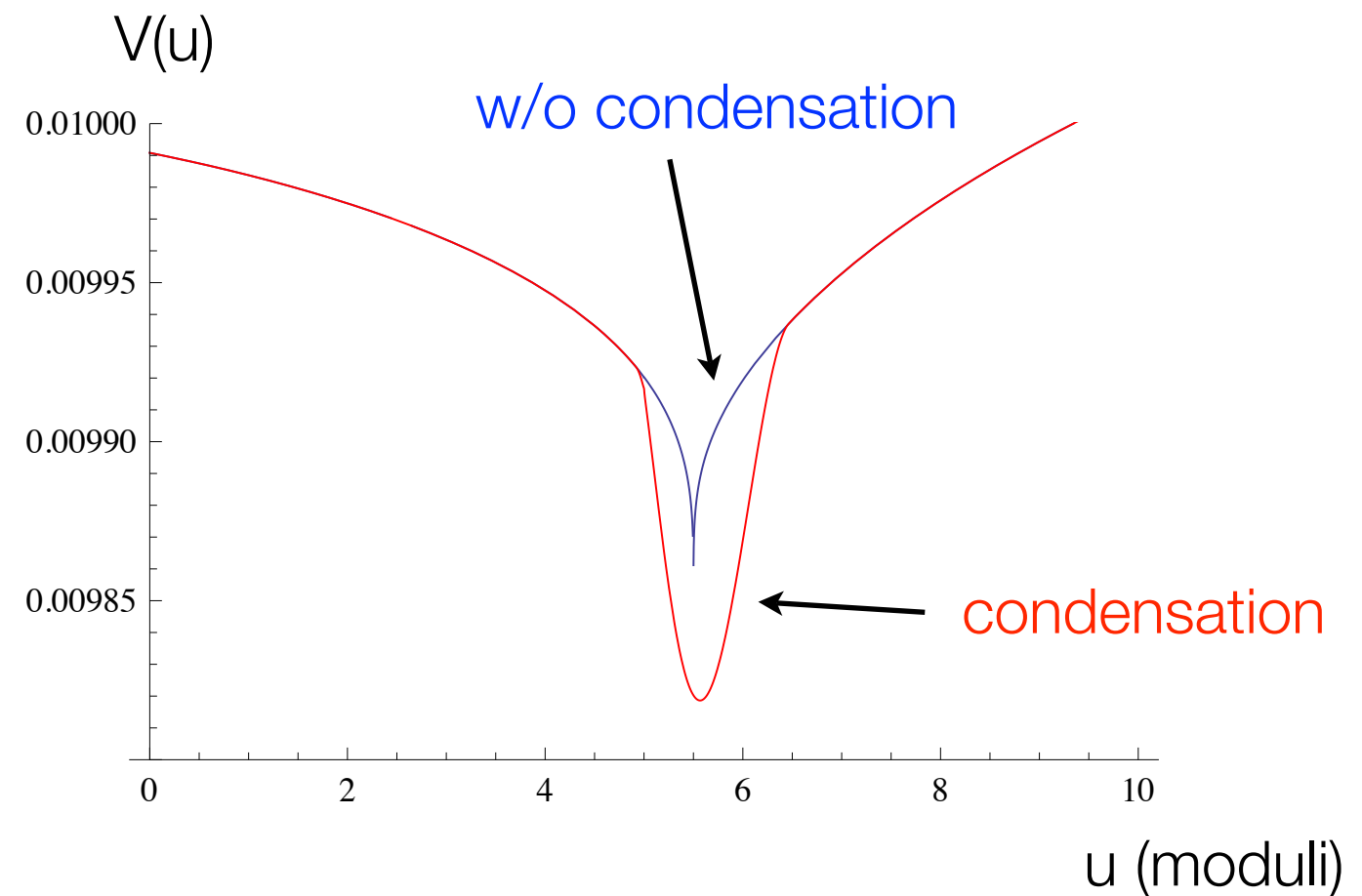
The μ-problem in MSSM

- Why $\mu \ll M_{\mathrm{U}}, M_{\mathrm{str}}, M_{\mathrm{Pl}}$?   or, why μ is close to the SUSY breaking scale?

  (the μ-problem) [Kim Nilles, Phys.Lett.138B(1984)150]

- Solved if small μ is dynamically generated

  ✦ vev of a singlet field S: $\lambda \langle S \rangle H_u H_d \rightarrow \mu H_u H_d$

  ✦ radiative correction

  ✦ non-renormalisable interaction

- Giudice-Masiero mechanism [Giudice Masiero, PLB206(1988)480]

  ✦ successful in gravity mediation, not applicable for gauge mediation

The Bμ-problem in gauge mediation

- **Bμ problem**: $B = \dfrac{B\mu}{\mu} \simeq \dfrac{F}{M} \gg m_s \sim \dfrac{g_{\mathrm{SM}}^2 F}{16\pi^2 M}$

- Remains as a serious problem in gauge mediation scenario

  [Roy Schmaltz 2008] [Murayama Nomura Poland 2008]

- Possible solutions: loop supression/extra singlet field/hidden sector RG

  [Dvali Giudice Pomarol 1996] [Delgado Giudice Slavish 2007] [Roy Schmaltz 2008]

  [Murayama Nomura Poland 2008]

- The hidden sector RG method requires large anomalous dimension γ

- We have seen that γ→∞ near the AD point

- The effective description reliable??