GMSB with hidden sector renormalisation in MSSM

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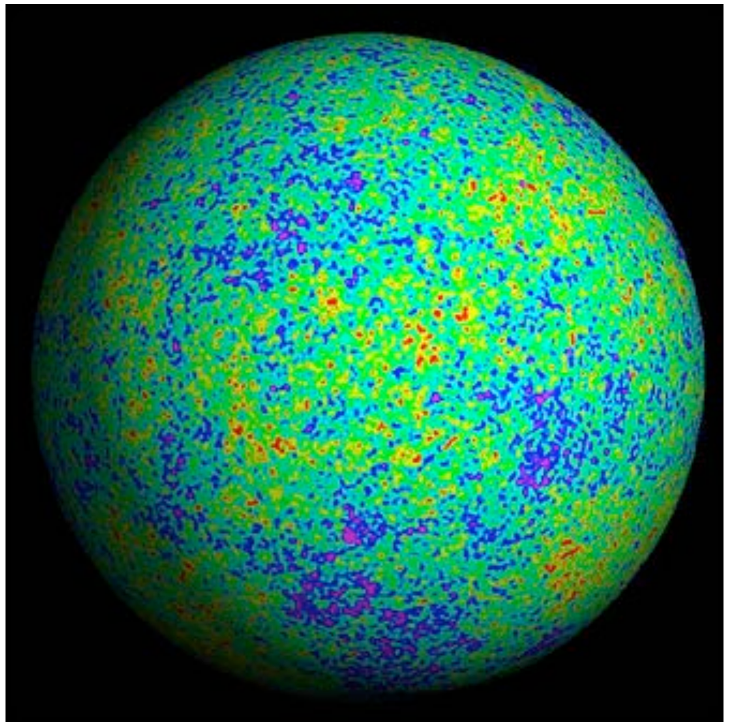
YITP Workshop: 場の理論と超弦理論の最先端

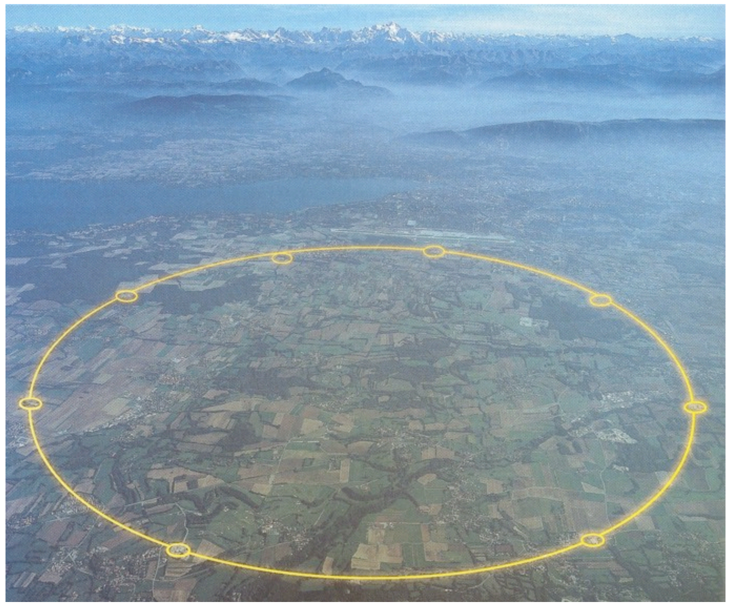
Talk based on [arXiv:1001.1509] and [arXiv:1008:NNNN]

with Masato Arai (Prague) and Nobuchika Okada (Alabama)

Particle theory in the LHC era

- ☐ Top-down approach
  - String-, M- and F-theory cosmology
  - Inflation, KKLT, brane configuration
- ☑ Bottom-up approach
  - Low energy spectrum (SM+α)
  - SUSY breaking mechanism





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

1. MSSM and GMSB

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

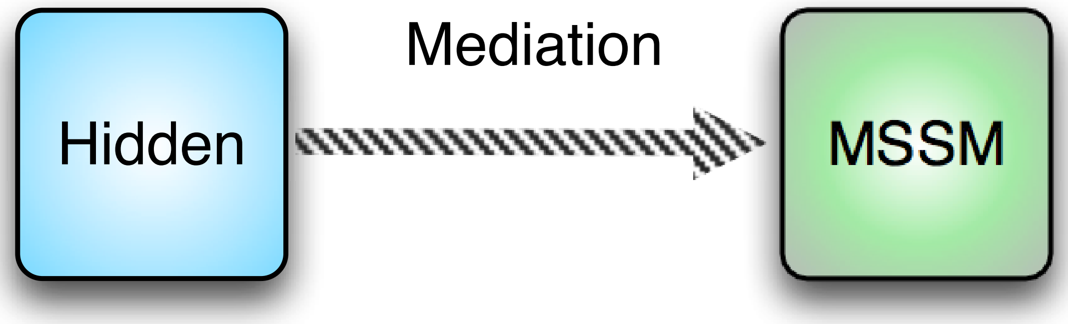
- Matter supermultiplets

Multiplets		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \;\; \widetilde{d}_L)$	$(u_L \;\; d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \;\; \widetilde{e}_L)$	$(\nu \;\; e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
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

1. MSSM and GMSB

Gauge-mediated SUSY breaking (GMSB)

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

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

Hidden sector fields $\phi_i = \{\tilde{q}, \tilde{u}, \tilde{d}, \tilde{l}, \tilde{e}, H_u, H_d\}$

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

MSSM fields

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

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

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

Boundary conditions of mass RG

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

Features of GMSB

- LSP: gravitino -- dark matter candidate
- NLSP: neutralino (bino) or slepton (stau)
- Flavour universality -- no FCNC problem
- Structure formation favors **Cold** **Dark** Matter (CDM)

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

- High messenger scale GMSB scenario favored

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

Minimal GMSB

- Keep the successful gauge coupling unification -- messenger in SU(5) reps
- Count the messengers using Dynkin index -- $N_5 = 1 \text{ for } \mathbf{5}, \ \ N_5 = 3 \text{ for } \mathbf{10},$
- N_5 cannot be taken too large (diverge before unification)
- $N_5 = 1$ model = minimal GMSB scenario
- In the minimal GMSB, NSLP = 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:

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

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

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

[Cohen Roy Schmaltz (2007)]

[Campbell Ellis Maybury (2008)]

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

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

messenger scale

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sfermion masses

messenger scale

gaugino masses

2. RGE and hidden sector

Renormalisation effects from HS

- The hidden-visible interaction term

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

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

$$
\begin{aligned}
8\pi^2 \frac{dm_Q^2}{dt} &= \xi_t + \xi_b - \frac{16}{3} g_3^2 M_3^2 - 3 g_2^2 M_2^2 - \frac{1}{15} g_1^2 M_1^2 + \frac{1}{5} g_1^2 \xi_1 + 4\lambda^2 m_Q^2, \\
8\pi^2 \frac{dm_U^2}{dt} &= 2\xi_t - \frac{16}{3} g_3^2 M_3^2 - \frac{16}{15} g_1^2 M_1^2 - \frac{4}{5} g_1^2 \xi_1 + 4\lambda^2 m_U^2, \\
8\pi^2 \frac{dm_D^2}{dt} &= 2\xi_b - \frac{16}{3} g_3^2 M_3^2 - \frac{4}{15} g_1^2 M_1^2 + \frac{2}{5} g_1^2 \xi_1 + 4\lambda^2 m_D^2, \\
8\pi^2 \frac{dm_L^2}{dt} &= \xi_\tau - 3 g_2^2 M_2^2 - \frac{3}{5} g_1^2 M_1^2 - \frac{3}{5} g_1^2 \xi_1 + 4\lambda^2 m_L^2, \\
8\pi^2 \frac{dm_E^2}{dt} &= 2\xi_\tau - \frac{12}{5} g_1^2 M_1^2 + \frac{6}{5} g_1^2 \xi_1 + 4\lambda^2 m_E^2, \\
8\pi^2 \frac{dm_{H_u}^2}{dt} &= 3\xi_t - 3 g_2^2 M_2^2 - \frac{3}{5} g_1^2 M_1^2 + \frac{3}{5} g_1^2 \xi_1 + 4\lambda^2 m_{H_u}^2, \\
8\pi^2 \frac{dm_{H_d}^2}{dt} &= 3\xi_b + \xi_\tau - 3 g_2^2 M_2^2 - \frac{3}{5} g_1^2 M_1^2 - \frac{3}{5} g_1^2 \xi_1 + 4\lambda^2 m_{H_d}^2
\end{aligned}
$$

3. A simple toy model

Mass renormalisation with hidden sector --cont.

$$\begin{aligned}\xi_t &= y_t^2(m_{H_u}^2 + m_Q^2 + m_U^2 + A_t^2),\\ \xi_b &= y_b^2(m_{H_d}^2 + m_Q^2 + m_D^2 + A_b^2),\\ \xi_\tau &= y_\tau^2(m_{H_d}^2 + m_L^2 + m_E^2 + A_\tau^2),\\ \xi_1 &= \frac{1}{2}\left\{m_{H_u}^2 - m_{H_d}^2 + \mathrm{Tr}(m_Q^2 - 2m_U^2 + m_D^2 + m_E^2 - m_L^2)\right\}\end{aligned}$$

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

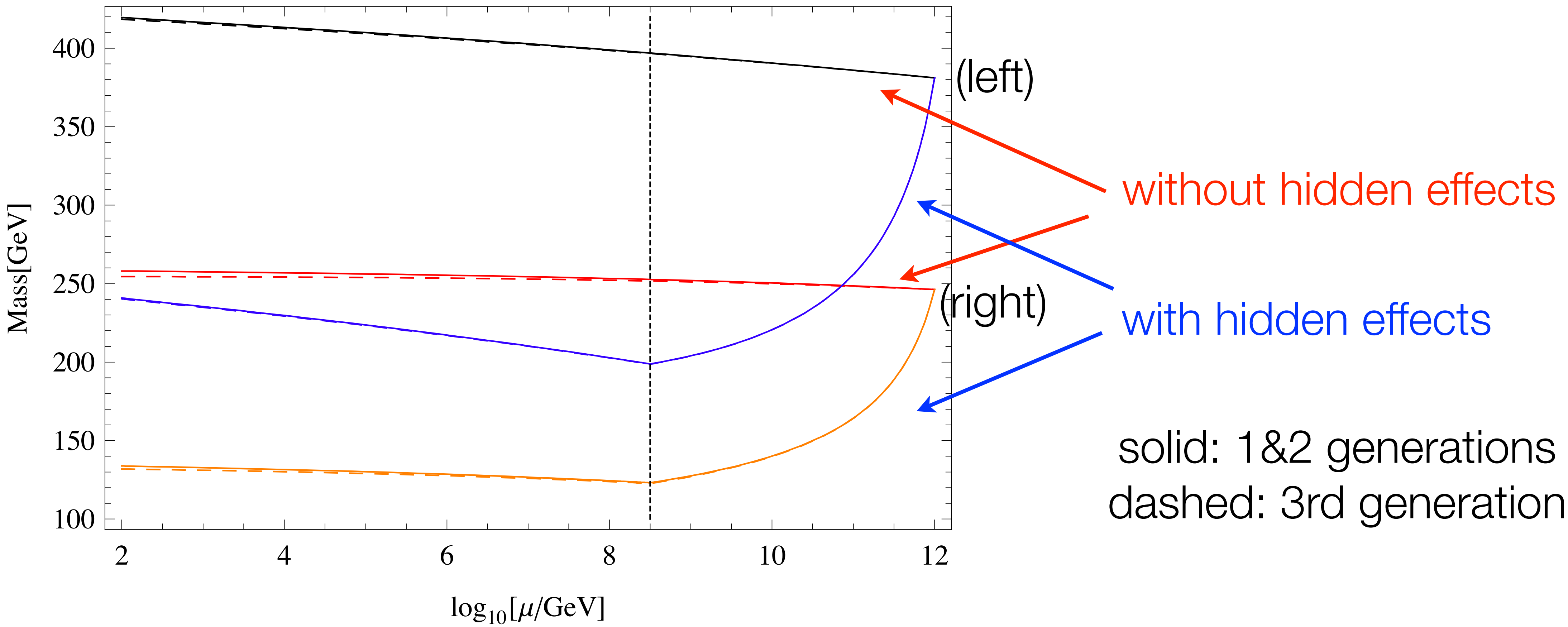
The GMSB boundary conditions

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

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

3. A simple toy model

RG flow -- slepton masses

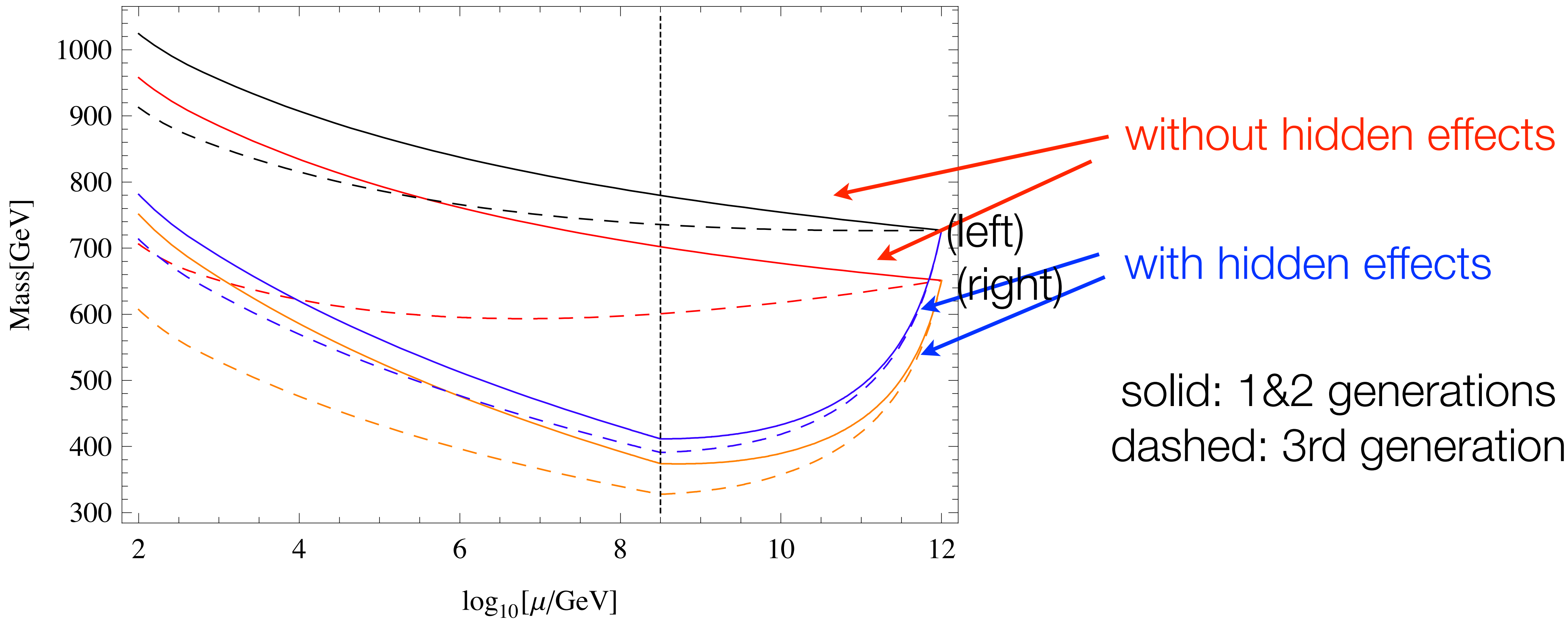


solid: 1&2 generations
dashed: 3rd generation

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 $M_{\rm hid} = 10^{8.5}$ 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 $\tan\beta = 10$.

3. A simple toy model

Squark masses



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 $M_{\text{hid}} = 10^{8.5}$ 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 $\tan\beta = 10$).

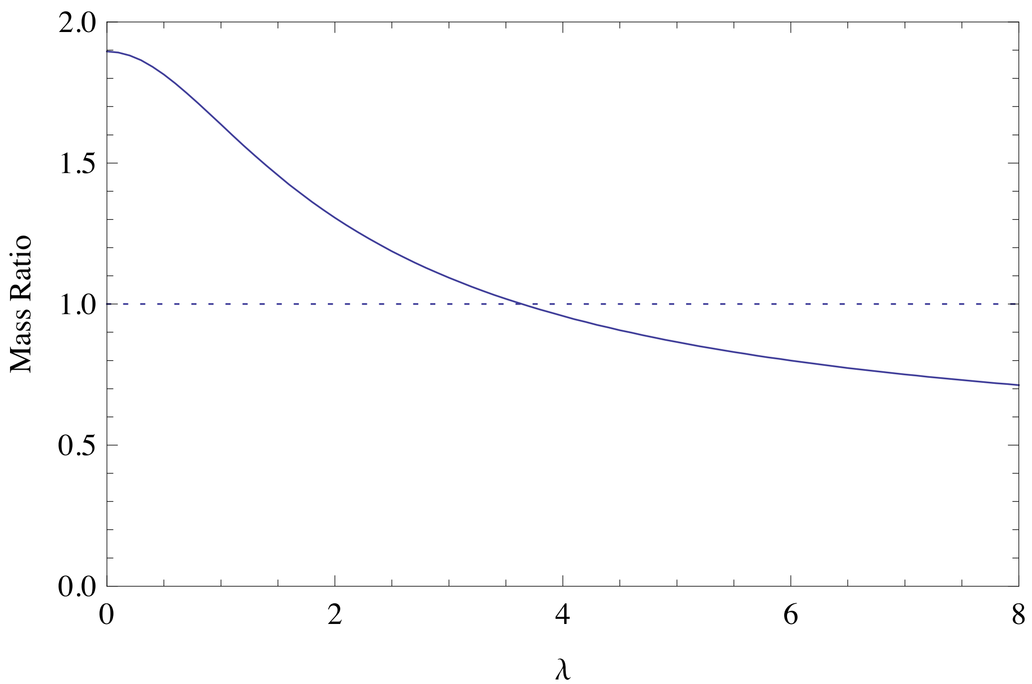
3. A simple toy model

RG flow with hidden sector renormalisation

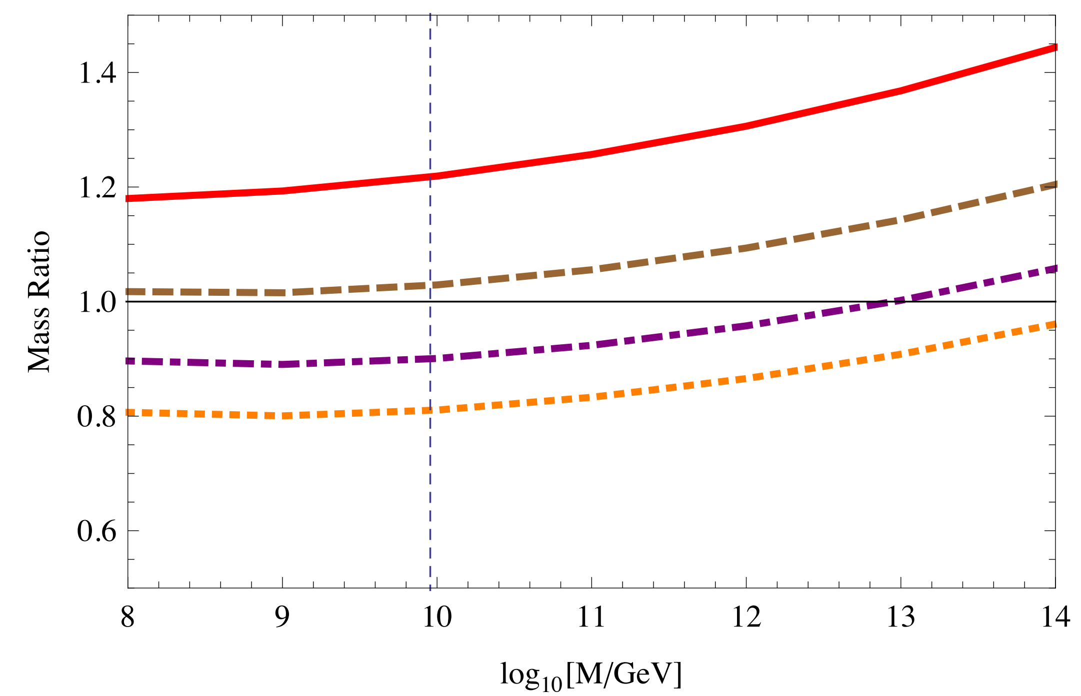
- Only the soft scalar and gravitino become lighter
- Other masses unaffected by the hidden sector
- stau can be lighter than bino -- stau NLSP scenario
- OK with BBN and dark matter constraints
- stau NLSP is interesting in collider physics

3. A simple toy model

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.

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

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- 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 $N_c + 1 \leq N_f < \frac{3}{2} N_c$
  - ✦ Phenomenological applications [many]
- N=2 SUSY (perturbed Seiberg-Witten) [Arai Okada 2001] [Ooguri Ookouchi Park 2007] [Pastras 2007] [Arai Montonen Okada Sasaki] [Marsano Ooguri Ookouchi Park 2007]
  - ✦ Kahler potential exactly calculable
  - ✦ Phenomenological applications [our paper]

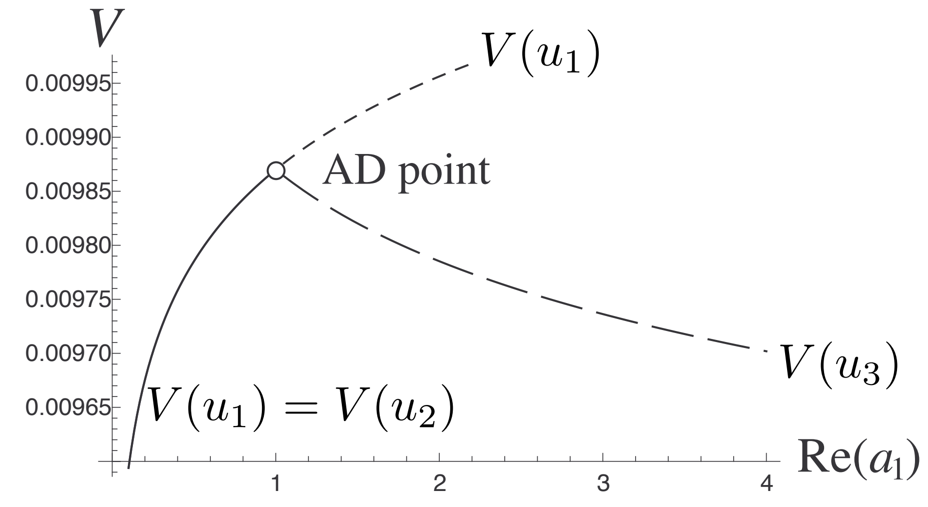
Our model of strongly coupled hidden sector

- 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.

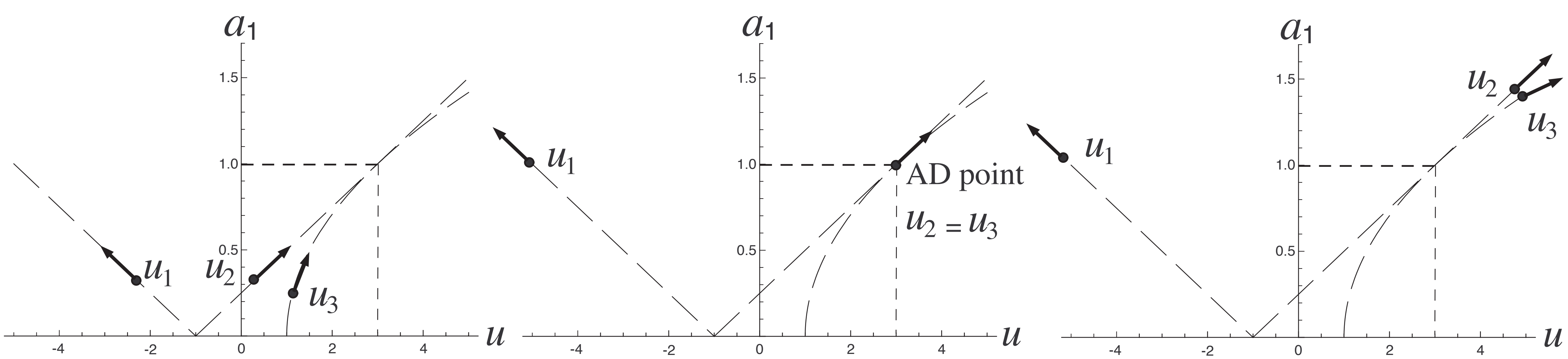
4. A strongly coupled model

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



$$y^2 = 4(x - e_1)(x - e_2)(x - e_3) \longrightarrow \text{singular points}$$



4. A strongly coupled model

Possible coupling to the messenger fields

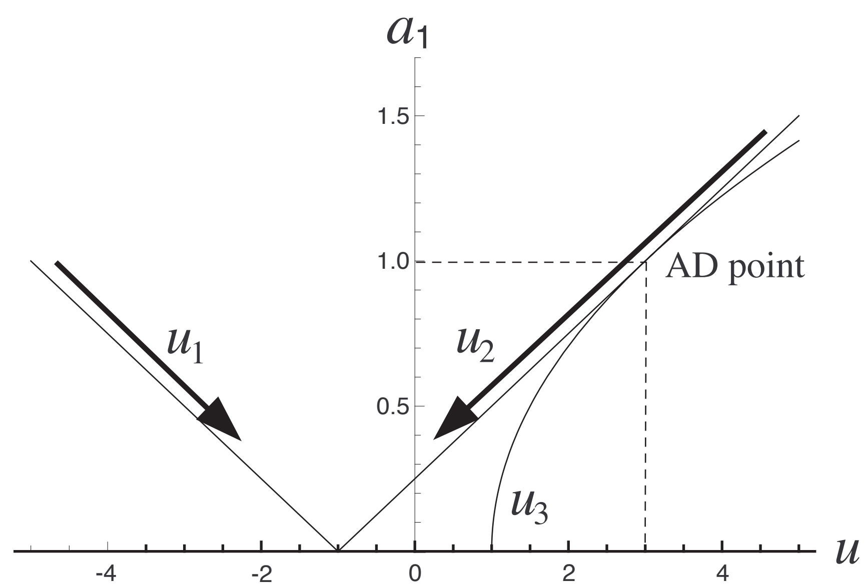
- 2 possible RG flows -- u1 and u2

- 2 possible messenger-hidden couplings

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

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

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

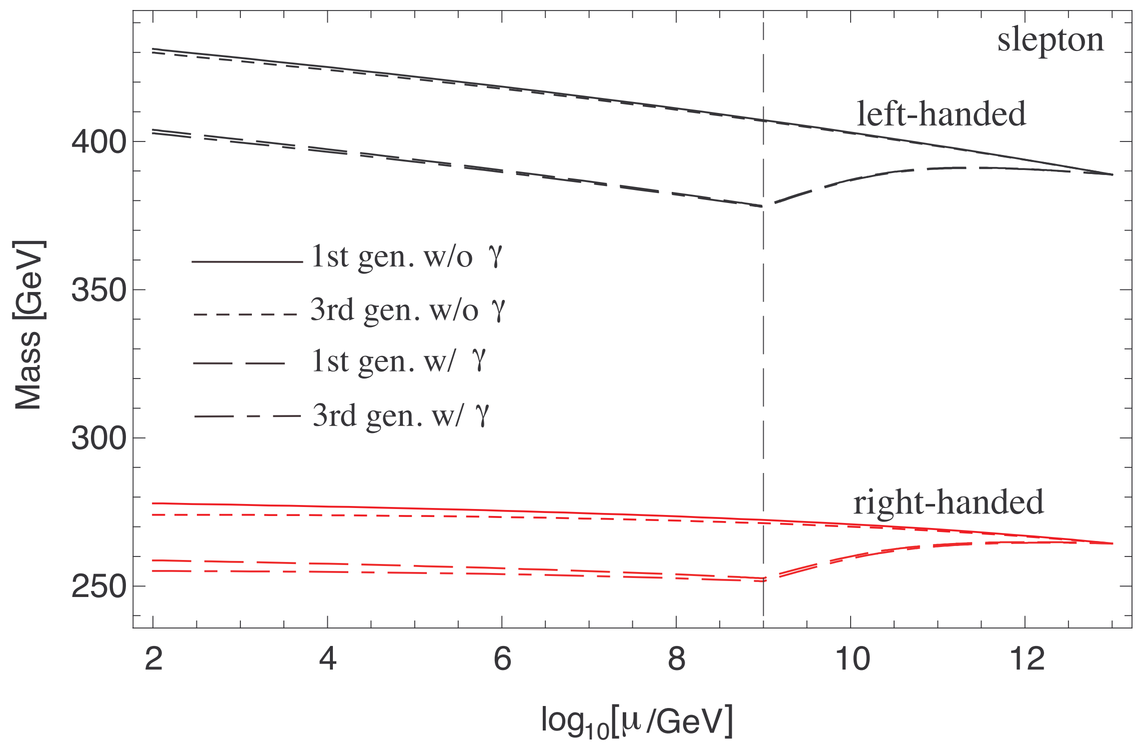


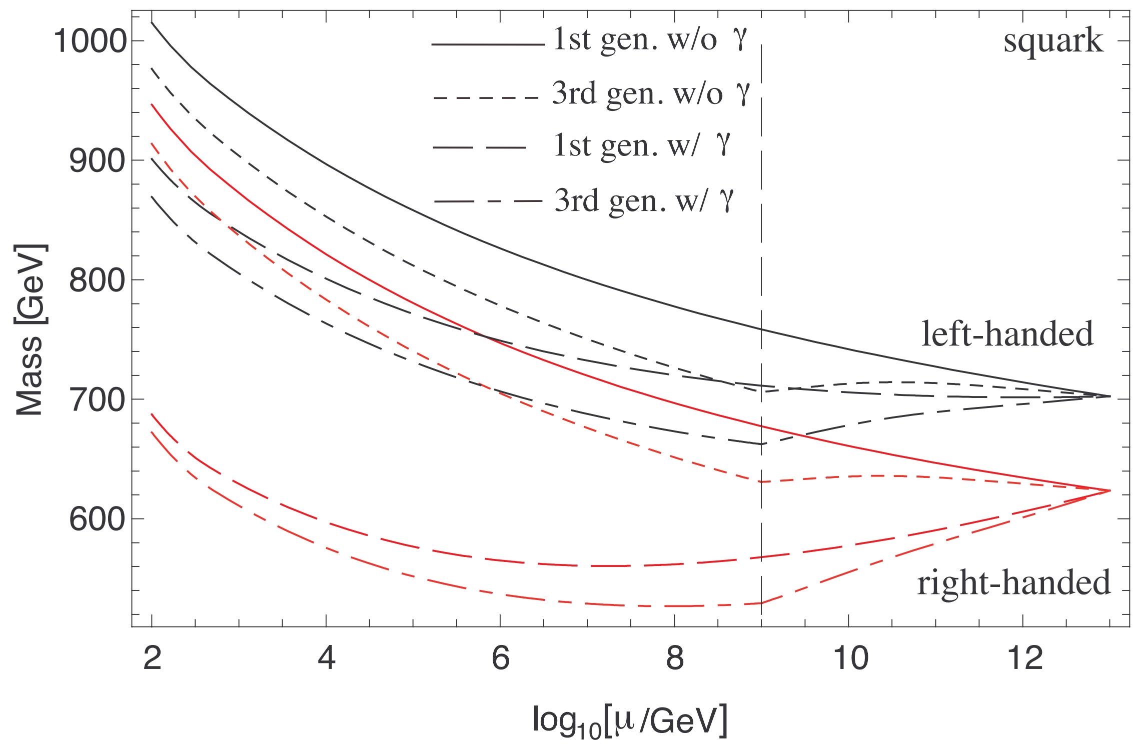
4. A strongly coupled model

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

$$\tan\beta = 10$$
$$M_S = 500\text{GeV}$$
$$m_{\text{mess}} = 10^5\text{GeV}$$
$$M_{\text{hid}} = 10^9\text{GeV}$$
$$M = 10^{13}\text{GeV}$$





4. A strongly coupled model

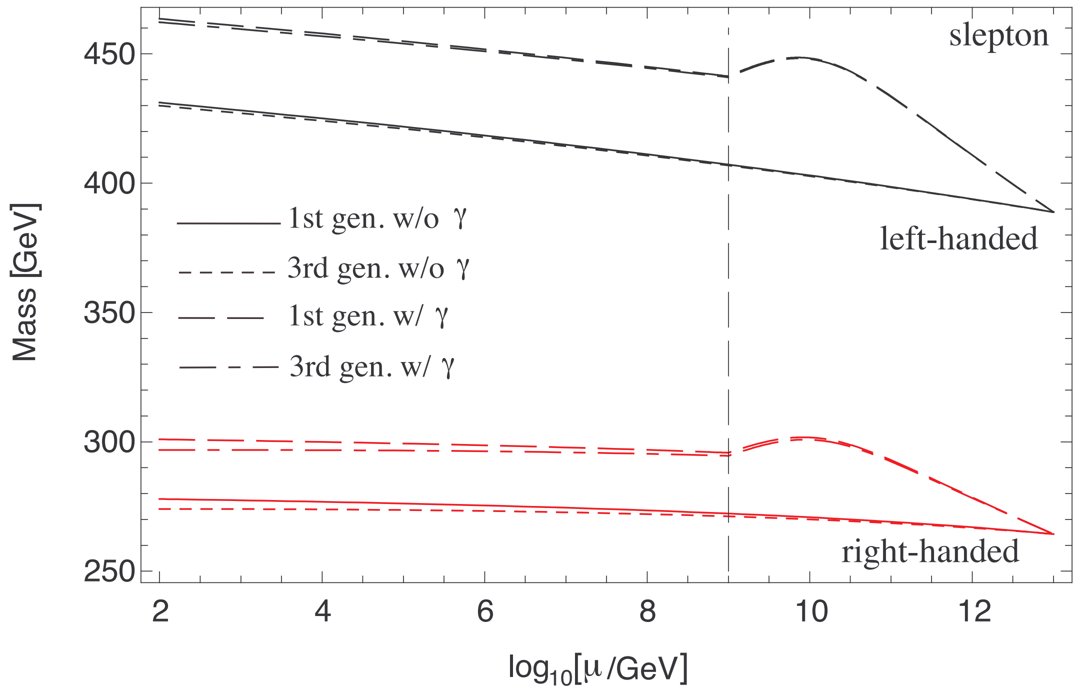
Mass RG -- (b) SU(2) coupled messenger

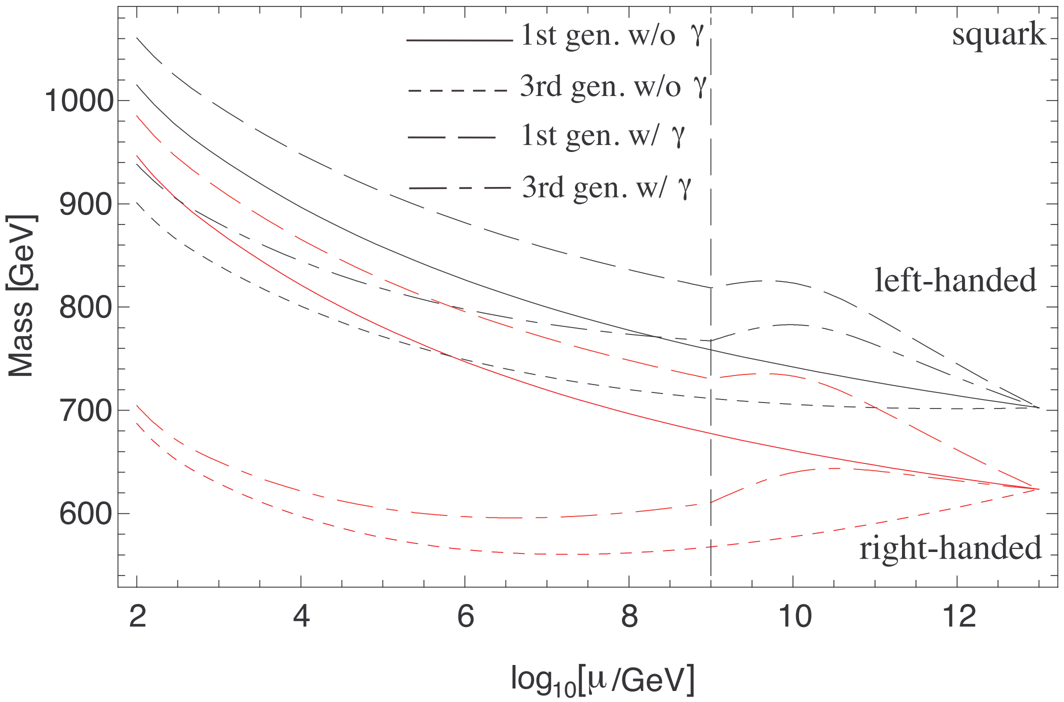
- The hidden effect is more complicated

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

➡ sensitive to init conditions and flow path

- Examples of larger masses (figure below)





4. A strongly coupled model

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

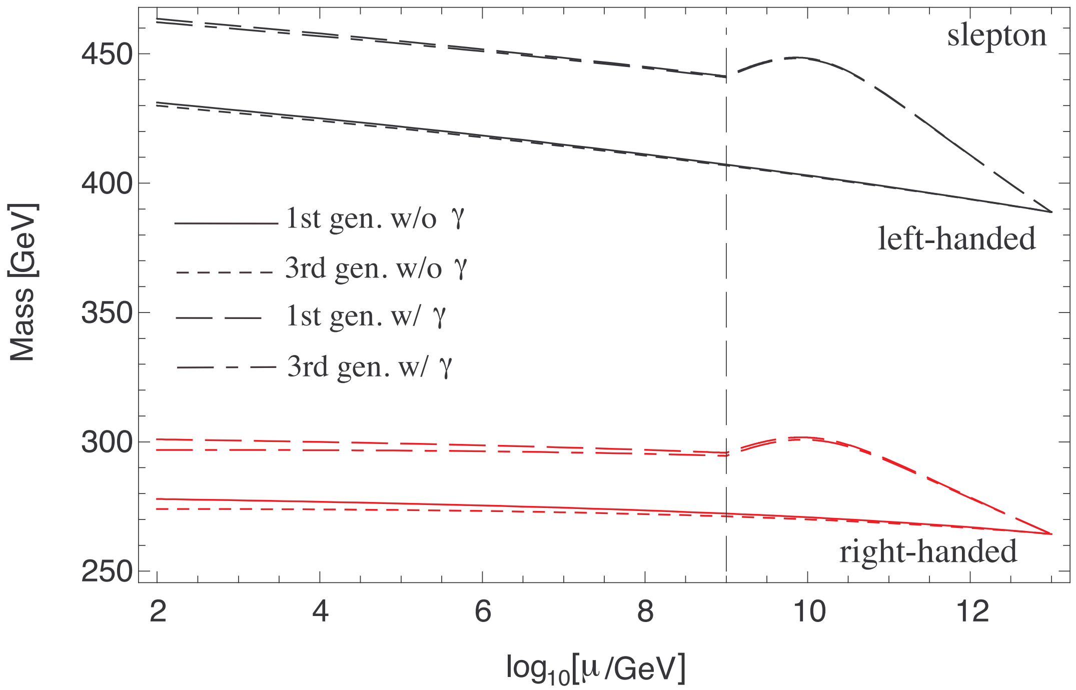
- The hidden effect is more complicated
  - ➡ sensitive to init conditions and flow path
- Examples of larger masses (figures below)

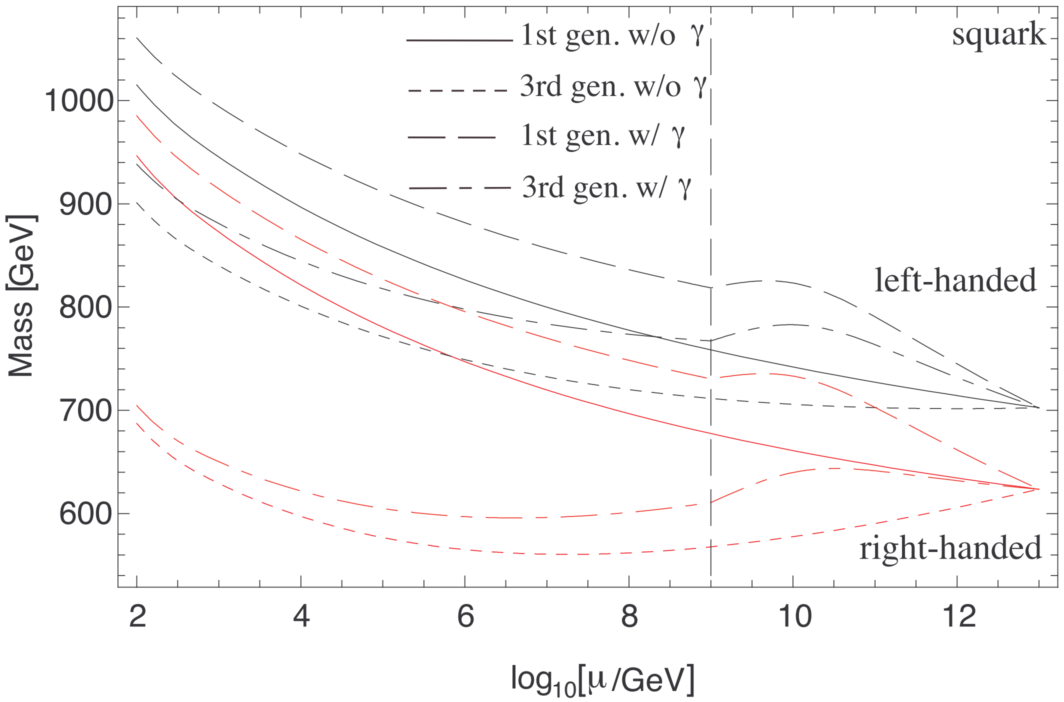
$$\frac{dm_i^2}{dt} = \frac{dm_i^2}{dt}\bigg|_{\rm MSSM} + \gamma(t) m_i^2$$

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

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

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

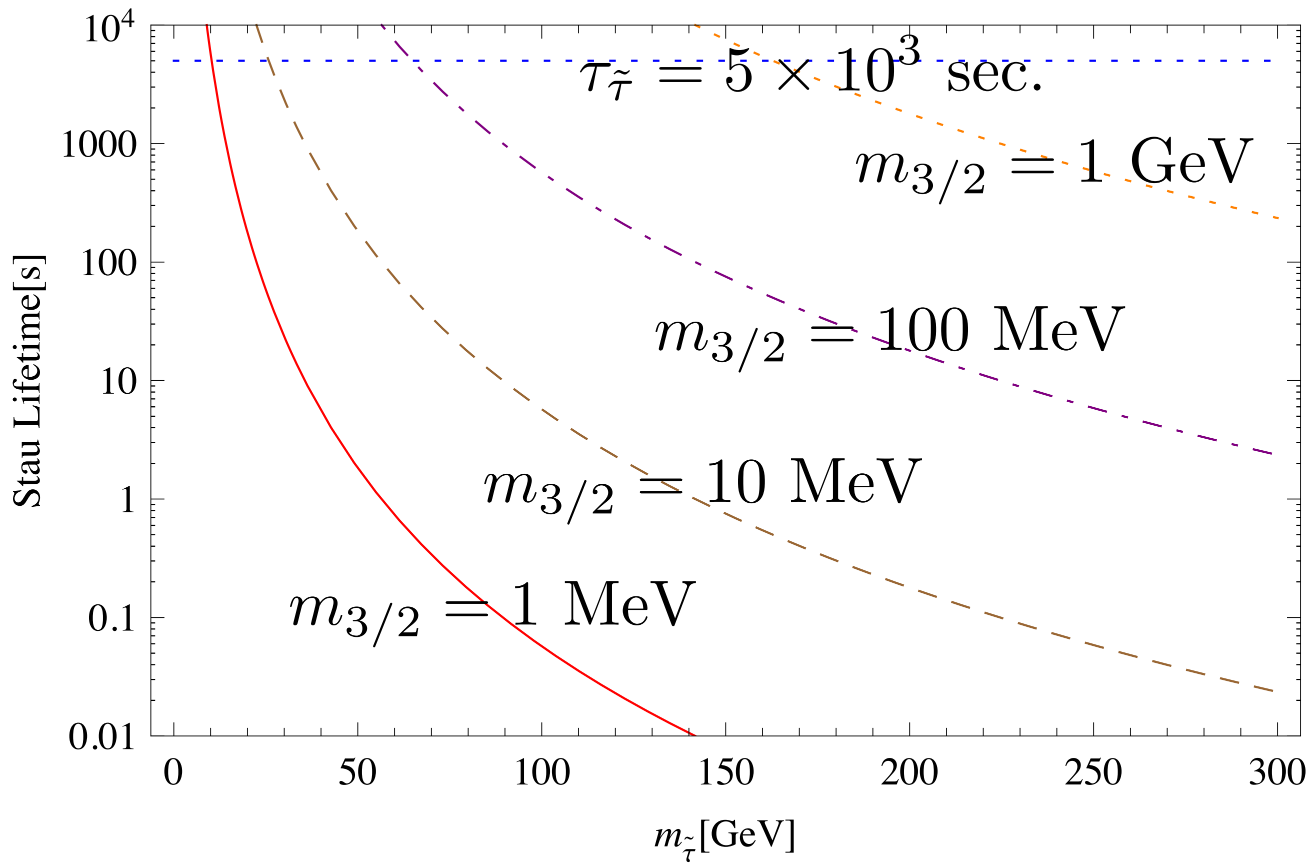




Summary and outlook

- 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

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

upper bound on gravitino mass

Cold dark matter

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

Dark matter constraints on gravitino

- The total gravitino abundance

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

- Our typical stau mass: $m_{\tilde{\tau}} \approx 130 \text{ GeV}$
- BBN constraints $m_{3/2} \lesssim 0.6 \text{ GeV}$

$$\left.\begin{array}{l} m_{\tilde{\tau}} \approx 130 \text{ GeV} \\ m_{3/2} \lesssim 0.6 \text{ GeV} \end{array}\right\} \Omega_{\tilde{G}}^{\rm NTP} h^2 \lesssim 10^{-5}$$

- 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?