

# Some Features of Soft Terms in Flux Compactification

Kiwoon Choi  
( KAIST )

Based on

KC, Jeong & Okumura , arXiv : 0804.4283

KC & Jeong , hep-th / 0605108

KC, Falkowski, Nilles & Olechowski , hep-th/0503216

- Gaugino masses (Peter's talk)
- Sfermion masses

The most severe phenomenological constraints on weak scale SUSY come from **FCNC & CPV** associated with the structure of sfermion masses.

- ★ How natural is it that sfermion soft parameters in high scale mediation scenarios (*gravity mediation*) preserve flavor & CP in flux compactification?
- ★ Sfermion masses in KKLT flux compactification.

◆ Potentially important origins of sfermion masses  
in flux compactification

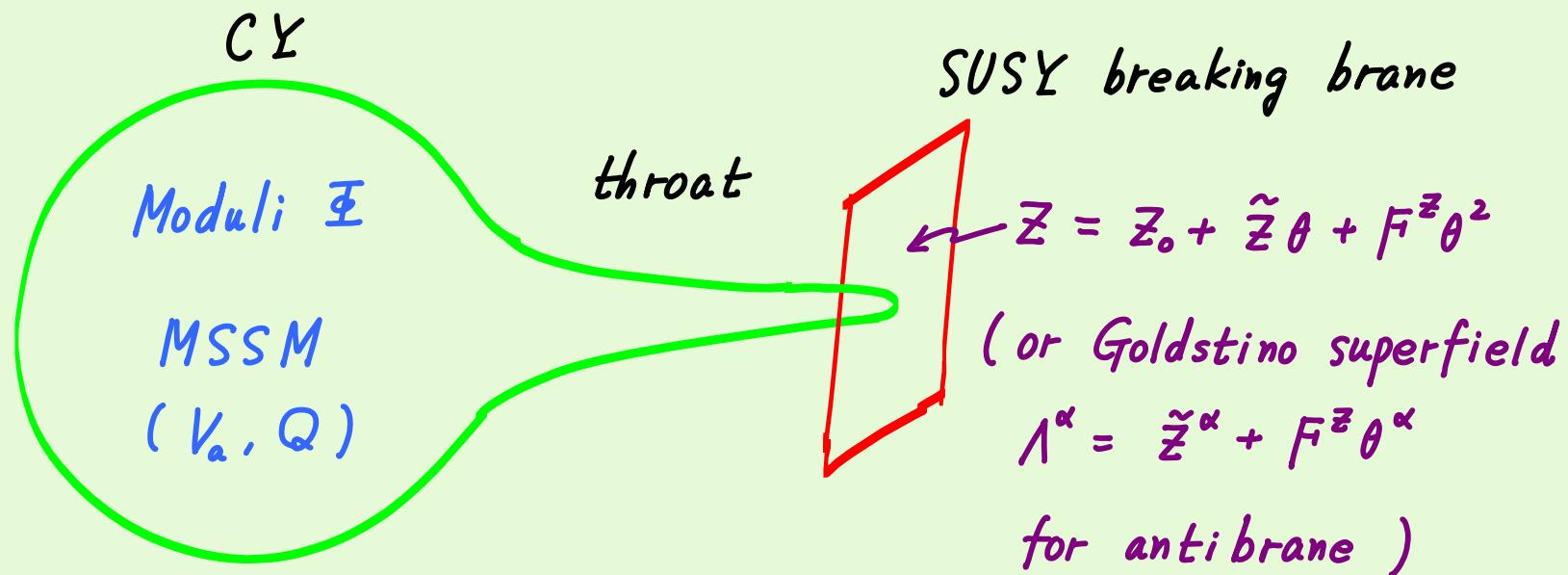
- A) Brane-localized SUSY breaking stabilized at  
the tip of warped throat
- B) Moduli mediation determined by moduli stabilization  
(flux  $\oplus$  NP effects  $\oplus$  perturbative Kähler correction  
 $\oplus$  uplifting  $\oplus \dots$ )
- C) Anomalous U(1) mediation
- D) Anomaly mediation, Gauge mediation, ...

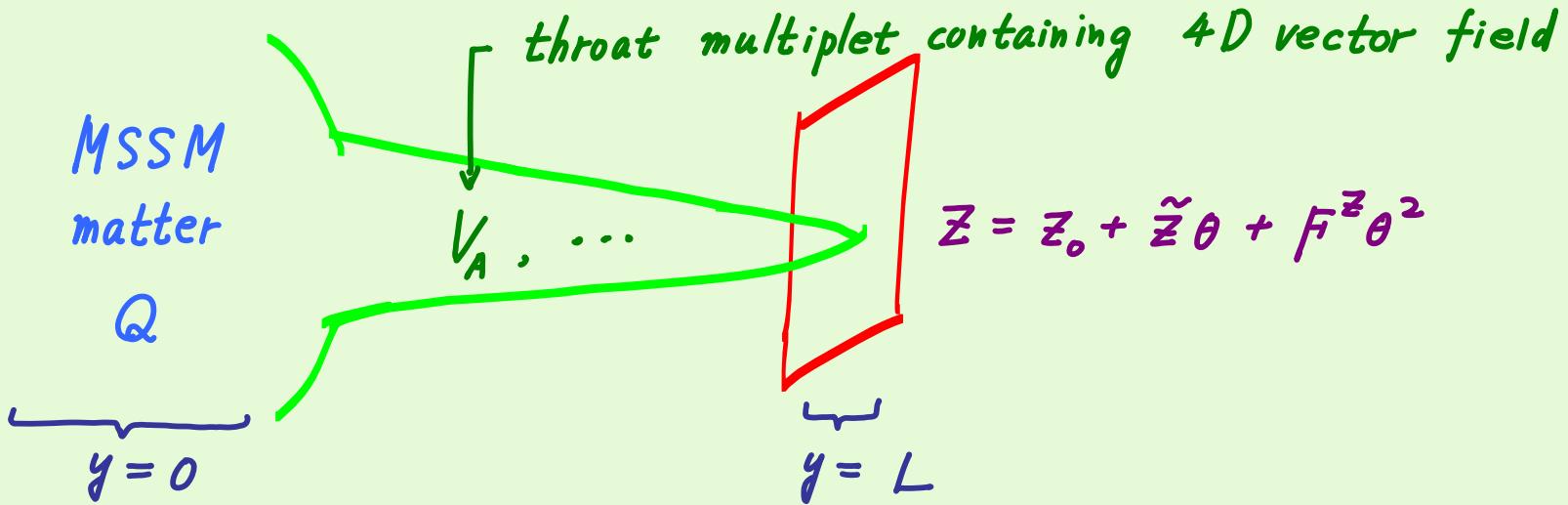
Generically A) & B) do not preserve flavor & CP,  
so should be carefully examined.

## ◆ Sequestering of brane-localized SUSY breaking

GKP, KKLT, ...

In flux compactifications with warped throat , any brane-localized SUSY breaking is stabilized at the IR end of warped throat , while the high scale gauge coupling unification suggests that the visible sector is localized at the UV end of throat :





$$\int d^4\theta \left[ V_A \left( \delta_{cy} Q^+ T_A Q + \delta_{c(y-L)} Z^+ T_A Z \right) \right.$$

generically family-dependent

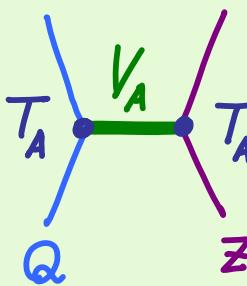
$$+ V_A V_A \left( M_V^2 + M_0^2 \delta_{cy} \right) \left. \right]$$

UV-localized mass  $\sim M_{KK}$  of CY

bulk mass over the throat

Brane-localized SUSY breaking ( $F^Z$ ) might generate generically family-dependent sfermion masses of  $\mathcal{O}(m_{3/2})$  through the exchange of throat vector multiplet.

KC, Jeong ; Brummer, Hebecker, Trapletti

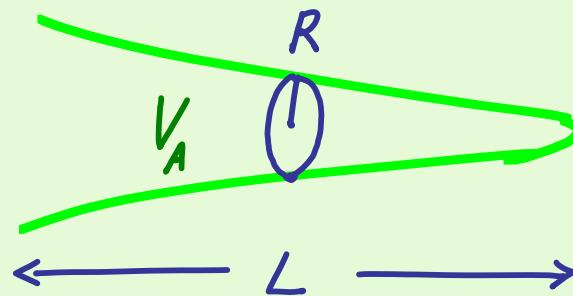


$$\Rightarrow \int d^4\theta \frac{e^{-\pi M_V L}}{M_V^2 + M_0^2} (Q^+ T_A Q) (Z^+ T_A Z)$$

$$\Rightarrow m_{\tilde{Q}}^2 \sim e^{-\pi M_V L} D_A$$

$$(D_A = \frac{1}{M_V^2 + M_0^2} \bar{F}^{\bar{z}} T_A F^z \sim m_{3/2}^2)$$

Only  $V_A$  with  $M_V \lesssim \frac{1}{L}$  can give a sizable  $m_{\tilde{Q}}^2$ .



For  $R \ll L$ , only  $V_A$  associated with the isometry of the transverse 5-d can have  $M_V \lesssim \frac{1}{L}$ .

KC, Jeong ; Brummer, Hebecker, Trapletti ; Kachru, McAllister, Sundrum

If SUSY breaking at the tip preserves (some of) the isometry,  $(D_A)_{\text{isometry}} = 0$  & thus  $m_{\tilde{Q}}^2 = 0$ .

$\overline{D3}$  at the tip of KS throat :

$$SO(4) \rightarrow SO(3) \Rightarrow (D_A)_{SO(4)} = 0$$

Attaching the KS throat at CY slightly breaks  $SO(4)$   
Kachru, McAllister, Sundrum

$$\Rightarrow m_{\tilde{Q}}^2 \sim (m_{3/2}/M_{Pl})^{\sqrt{7}-2} m_{3/2}^2 \sim 10^{-8} m_{3/2}^2$$

$\Rightarrow$  SUSY breaking at the tip of warped throat  
 is well sequestered from the visible sector  
 at the UV end, and thus does not cause  
 dangerous FCNC or CPV.

## ◆ Moduli mediation

$$\int d^4\theta Y_i(\bar{\Xi}, \bar{\Xi}^+) Q_i^+ Q_i + \int d^2\theta \left[ \frac{1}{4} f_a(\bar{\Xi}) W^a W^a + \lambda_{ijk}(\bar{\Xi}) Q_i Q_j Q_k \right]$$

↑ generic moduli
↑ MSSM gauge fields
  
 $\frac{1}{g_{GUT}^2(\bar{\Xi}, \bar{\Xi}^+)} = \text{Re } f_a$ 
↓ moduli Kähler potential
  
 $Y_i = e^{-K_0/3} Z_i$ 
↑ matter Kähler metric
  
 $Y_{ijk}(\bar{\Xi}, \bar{\Xi}^+) = \frac{\lambda_{ijk}(\bar{\Xi})}{\sqrt{Y_i Y_j Y_k}}$ 
↑ canonical Yukawa couplings

Moduli mediated soft parameters

$$M_a = F^{\bar{\Xi}} \partial_{\bar{\Xi}} \ln (\text{Re } f_a)$$

Kaplunovsky, Louis ;  
Brignole, Ibanez, Munoz

$$m_i^2 = - |F^{\bar{\Xi}}|^2 \partial_{\bar{\Xi}} \partial_{\bar{\Xi}^+} \ln (Y_i)$$

$$A_{ijk} = F^{\bar{\Xi}} \partial_{\bar{\Xi}} \ln \left( \frac{\lambda_{ijk}}{Y_i Y_j Y_k} \right)$$

## Perturbative gauge coupling unification

$\Rightarrow f_a = \text{universal} \quad (\text{for } SU(3) \times SU(2) \times U(1))$   
 $= T \quad (= \text{gauge coupling modulus})$

$$Re(T) = \frac{1}{g_{\text{GUT}}^2} \approx 2 \gg \frac{1}{4\pi}$$

- \*  $Re(T)$  is stabilized at a large value, and then the perturbative expansion of  $S_{4D}$  controlled by  $\frac{1}{Re(T)}$  ( $= \frac{1}{T}$ -expansion) provides a good approximation for  $S_{4D}$ .
- \* Axionic shift symmetry :  $Im(T) \rightarrow Im(T) + \text{constant}$  is a good symmetry which might be broken by small nonperturbative effects  $\sim e^{-\Theta(\pi^2/g_{\text{GUT}}^2)}$ .

At leading order in the  $\frac{1}{T}$ -expansion,

$$Y_i = (T + T^*)^{n_i} Y_i(U, U^*) , \quad \lambda_{ijk} = \lambda_{ijk}(U)$$

↑ moduli other than  $T$

If the kinetic terms of  $Q_i$  with same SM gauge charges are generated at the same order in the  $\frac{1}{T}$ -expansion,

$$n_i = \text{family-independent} ,$$

and the  $T$ -mediated soft terms preserve flavor and  $CP$ .

## Hierarchical Yukawa couplings

There should be some moduli  $U$  ( $\equiv$  flavon moduli) which have highly family-dependent couplings to  $Q_i$ :

$$\lambda_{ijk} \sim e^{-k_{ijk} U} \quad \begin{matrix} \text{(wavefunction localization)} \\ \text{instanton, ...} \end{matrix}$$

For flavor conservation, flavon moduli should be decoupled from SUSY breaking ( $F^U = 0$ )

Flux stabilization of flavon moduli naturally leads to such decoupling : KC, Falkowski, Nilles, Olechowski ; Conlon

- \* Fluxes are quantized: Flux-induced  $M_U \sim M_{st} \gg m_{3/2}$
- \* Typically  $T$  &  $U$  have different topological origin, e.g.  $T \sim$  even-cycle volume &  $U \sim$  odd-cycle volume.  
 $\Rightarrow$  Fluxes stabilizing  $U$  do not touch on  $T$ .

## 4 D effective SUGRA action

$$\int d^4\theta \overset{\leftarrow}{CC^*} \Omega(U, U^*, T+T^*, Q, Q^*) \quad \Omega = -3 e^{-K/3}$$

$$+ \int d^2\theta C^3 [ W_{\text{flux}}(U) + A(U) e^{-aT} + \lambda(U) QQQ ]$$

Eq. of motion for  $U$  under background  $C, T & Q$ :

$$\bar{\partial}^2 \left( CC^* \frac{\partial \Omega}{\partial U} \right) + C^3 \frac{\partial}{\partial U} (W_{\text{flux}} + \Delta W) = 0$$

$\downarrow M_{pe} = 1$

$$\left( \Delta W = A(U) e^{-aT} + \lambda(U) QQQ \sim m_{3/2} \right)$$

$$W_{\text{flux}}(U = U_0 + \hat{U}) = W_{\text{flux}}(U_0) + \frac{1}{2} M_U(U_0) \hat{U}^2 + \dots$$

$$\left( \frac{\partial W_{\text{flux}}}{\partial U} \Big|_{U=U_0} = 0, \quad M_U(U_0) = \frac{\partial^2 W_{\text{flux}}}{\partial U^2} \Big|_{U=U_0} \right)$$

$\uparrow$  supersymmetric mass in global SUSY limit

When  $M_U(U_0) \sim M_{st} \gg m_{3/2}$ , the solution for flux-stabilized heavy moduli  $U$  can be expanded as

$$U(C, T, Q) = U_0 - \frac{1}{M_U} \left[ \bar{\partial}^2 \left( \frac{C^*}{C^2} \frac{\partial \Omega(U_0, U_0^*, T+T^*, Q, Q^*)}{\partial U} \right) + \frac{\partial \Delta W(U_0, T, Q)}{\partial U} \right] + \mathcal{O}\left(\frac{1}{M_U^2}\right)$$

$$\left( \bar{\partial}^2 \sim F^C \sim F^T \sim \Delta W \sim m_{3/2} \sim m_T \right)$$

up to the little hierarchy factor  $\sim \ln(M_{Pl}/m_{3/2})$

$$\Rightarrow * F^U = \mathcal{O}\left(m_{3/2}^2/M_U\right) \ll F^C, F^T$$

$$* \mathcal{L}_{eff} = \int d^4\theta CC^* \Omega(U_0, U_0^*, T+T^*, Q, Q^*) \\ + \int d^2\theta C^3 \left( W_{flux}(U_0) + A(U_0) e^{-aT} + \lambda(U_0) QQQ \right) \\ + \text{corrections further suppressed by } \frac{m_{3/2}}{M_U}$$

- \* Non-flux stabilization of the gauge coupling modulus at a large value ( $\text{Re}(T) \approx 2 \gg 1/4\pi$ ) for which the leading order Kähler potential in the  $\frac{1}{T}$ -expansion is a good approximation.
- \* Flux stabilization of flavon moduli, making all flavon moduli decoupled from SUSY breaking.

$\Rightarrow$  Flavor & CP conserving gauge coupling modulus mediation

$$M_a = \frac{F^T}{T + T^*} \left( 1 + \mathcal{O}\left(\frac{\alpha_{GUT}}{4\pi}, \frac{m_{3/2}}{M_U}\right) \right)$$

$$m_i^2 = n_i \left| \frac{F^T}{T + T^*} \right|^2 \left( 1 + \mathcal{O}\left(\frac{\alpha_{GUT}}{4\pi}, \frac{m_{3/2}}{M_U}\right) \right)$$

$$A_{ijk} = (n_i + n_j + n_k) \frac{F^T}{T + T^*} \left( 1 + \mathcal{O}\left(\frac{\alpha_{GUT}}{4\pi}, \frac{m_{3/2}}{M_U}\right) \right)$$

$$(n_i = \text{moduli (or scaling) weight : } e^{-K_0/3} z_i \propto (T + T^*)^{n_i})$$

Modular weights can be determined by simple scaling argument & axionic shift symmetry:  
*Conlon, Cremades, Quevedo*

- \*  $\dim(\text{gauge}) = \dim(\text{matter}) = \dim(\text{Yukawa}) > 4$   
 $\Rightarrow n_i = 1/3$  ( $\Rightarrow$  heterotic dilaton domination)
- \*  $\dim(\text{gauge}) = \dim(\text{matter}) > 4$ ,  $\dim(\text{Yukawa}) = 4$   
 $\Rightarrow n_i = 1$
- \*  $\dim(\text{gauge}) = 8$ ,  $\dim(\text{matter}) = 6$ ,  $\dim(\text{Yukawa}) = 4$   
 $\Rightarrow n_i = 1/2$
- \*  $\dim(\text{gauge}) > 4$ ,  $\dim(\text{matter}) = \dim(\text{Yukawa}) = 4$   
 $\Rightarrow n_i = 0$

## ◆ Anomalous $U(1)$ mediation

Anomalous  $U(1)$ -mediated soft masses severely depend on the Kähler potential of the corresponding GS modulus.

Arkani-Hamed, Dine, Martin

Case that the perturbative Kähler potential of the GS modulus is a good approximation : KC & Jeong

$$-3e^{-K/3} = -3t_\nu^{n_0} + t_\nu^{n_X} X^+ e^{-V} X + t_\nu^{n_i} Q_i^+ e^{\frac{q_i}{\alpha'} V} Q_i$$

$$\left( t_\nu = T + T^* - \delta_{GS} V \text{ with } \delta_{GS} = \mathcal{O}\left(\frac{1}{8\pi^2}\right) \right)$$

$\uparrow$  gauge coupling modulus being the GS modulus

$$\tilde{V} = V - \ln X X^+ : \text{massive vector superfield with } M_V^2 = \delta_{GS} M_{pe}^2$$

$$\tilde{T} = T - \delta_{GS} \ln X : \text{light gauge invariant gauge coupling modulus}$$

Eq. of motion for  $\tilde{V}$

$$\frac{\partial K}{\partial \tilde{V}} = 0 \quad (\text{upon ignoring superspace derivatives})$$

$$\Rightarrow e^{-\tilde{V}} = 3 (\tilde{T} + \tilde{T}^*)^{n_0 - n_x - 1} \times \text{constant}$$

$$(T + T^* - \delta_{GS} V)^{n_i} Q_i^+ e^{q_i V} Q_i \xrightarrow{\text{appropriate field redefinition}} (\tilde{T} + \tilde{T}^*)^{n_i^{\text{eff}}} Q_i^+ Q_i$$

$$\text{with } \underline{n_i^{\text{eff}} = n_i + (n_x + 1 - n_0) q_i}$$

Mediation by the massive anomalous U(1) vector superfield  $\tilde{V} = V - \ln X X^+$  can be included in the light modulus mediation by  $\tilde{T} = T - \delta_{GS} \ln X$  with appropriate change of modular weights, and preserves flavor and CP if  $q_i$  are family independent.

◆ Sfermion masses in KKLT compactification  
 KC, Falkowski, Nilles, Olechowski

- \* Flux stabilization of flavon moduli
- \* Nonperturbative stabilization of gauge coupling modulus
- \* Brane-localized SUSY breaking at the tip of throat

$$\int d^4\theta \quad CC^* \left[ -3(T+T^*)^{n_0} + (T+T^*)^{n_i} Q_i^+ Q_i^- + \Omega_{\text{lift}}(z, z^*) \right] \\ + \int d^2\theta \left[ \frac{1}{4} T W^{\alpha\bar{\alpha}} W_\alpha^\beta + C^3 (w_0 + A e^{-aT} + W_{\text{lift}}(z)) \right]$$

Independently of the detailed form of  $\Omega_{\text{lift}}$  &  $W_{\text{lift}}$ ,

$$* \quad F^T \approx \frac{1}{a} F^C \quad \sim \quad \frac{F^C}{8\pi^2} \quad (a = \frac{8\pi^2}{N})$$

$$* \quad -3 |F^C|^2 + |F^z|^2 \approx 0 \quad (\text{vanishing C.C.})$$

↑ SUGRA AdS vacuum energy

↑ uplifting vacuum energy

- Vacuum energy density :  $-3|F^C|^2 + |F^Z|^2 + \text{subleading}$   
 modulus mediation  $\downarrow$        $\downarrow$  anomaly mediation
  - Soft SUSY breaking masses :  $F^T + \frac{F^C}{8\pi^2} + \text{subleading}$
- ( Modulus mediation  $\sim$  Anomaly mediation )

$\Rightarrow$  Mirage unification of sparticle masses

KC, Jeong, Okumura

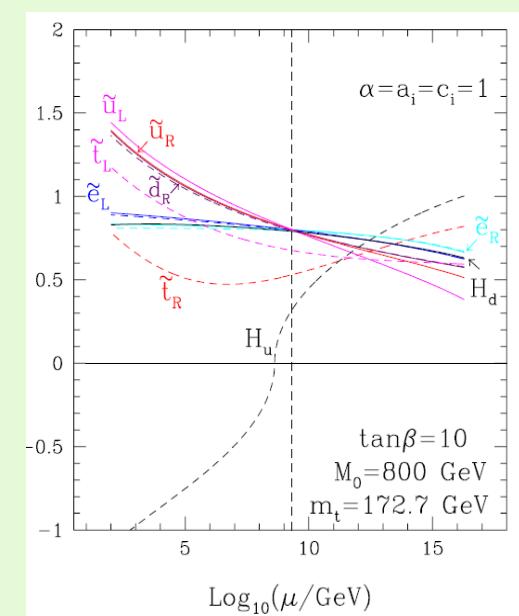
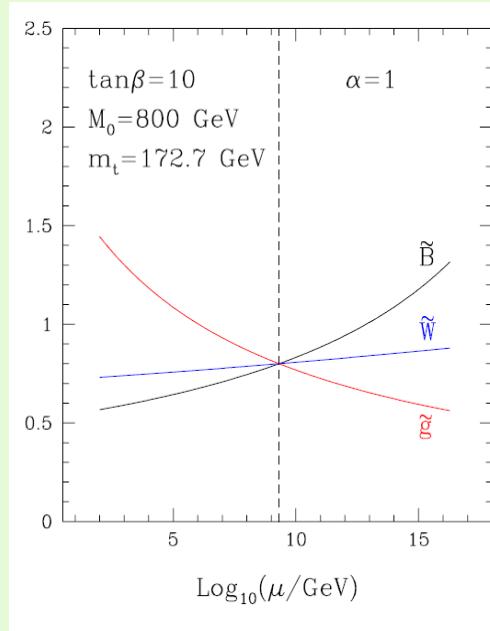
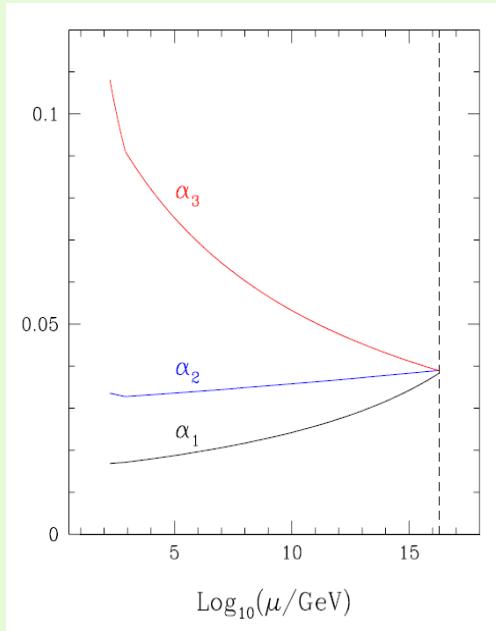
$$M_a(\mu) = M_0 \left[ 1 - \frac{b_a}{8\pi^2} g_a^2(\mu) \ln \left( \frac{M_{\text{mirage}}}{\mu} \right) \right]$$

$$m_i^2(\mu) = M_0^2 \left[ n_i^{\text{eff}} + \left\{ Y_i(\mu) - \frac{g_i(\mu)}{16\pi^2} \ln \left( \frac{M_{\text{mirage}}}{\mu} \right) \right\} \frac{\ln \left( \frac{M_{\text{mirage}}}{\mu} \right)}{4\pi^2} \right]$$

$\uparrow$  1st & 2nd generations with small Yukawa couplings

$$M_{\text{mirage}} \approx \sqrt{m_{3/2} M_{\text{GUT}}} \sim 10^{10} \text{ GeV}$$

# Mirage mediation pattern



For  $SU(5)$  invariant  $n_i^{\text{eff}} = n_i + (n_x + 1 - n_o) \tilde{q}_i$ ,

$$M_{\tilde{B}} : M_{\tilde{W}} : M_{\tilde{g}} : \sqrt{m_{\tilde{q}_L}^2 - m_{\tilde{e}_R}^2} : \sqrt{m_{\tilde{d}_R}^2 - m_{\tilde{l}_L}^2}$$

$$\approx 1 : 1.3 : 2.5 : 2 : 1.7$$

( very different from  $m$ SUGRA, anomaly mediation )  
and gauge mediation

## ◆ Conclusion

- ★ Flux compactification can provide a good framework for flavor & CP conserving gravity mediation.
- ★ Under certain reasonable assumptions , one can have concrete predictions on sparticle masses , which might be tested at the LHC .

( more in Peter's talk )