Mirage Mediation

(Mixed Modulus - Anomaly Mediation)

Kiwoon Choi (KAIST)

DSU 2006 (MADRID)

KC, A. Falkowski, H.P. Nilles, M. Olechowski
NPB 718, 113 (2005)

KC, K.S. Jeong, K.I. Okumura
JHEP 0509, 039 (2005)

KC, K.S. Jeong, T. Kobayashi, K.I. Okumura
PLB 633, 355 (2006)

& also in preparation.

- ## Motivation

Suggested (or predicted) by large class of string compactifications stabilizing moduli at phenomenologically viable dS vacuum.

- ## Characteristic Features

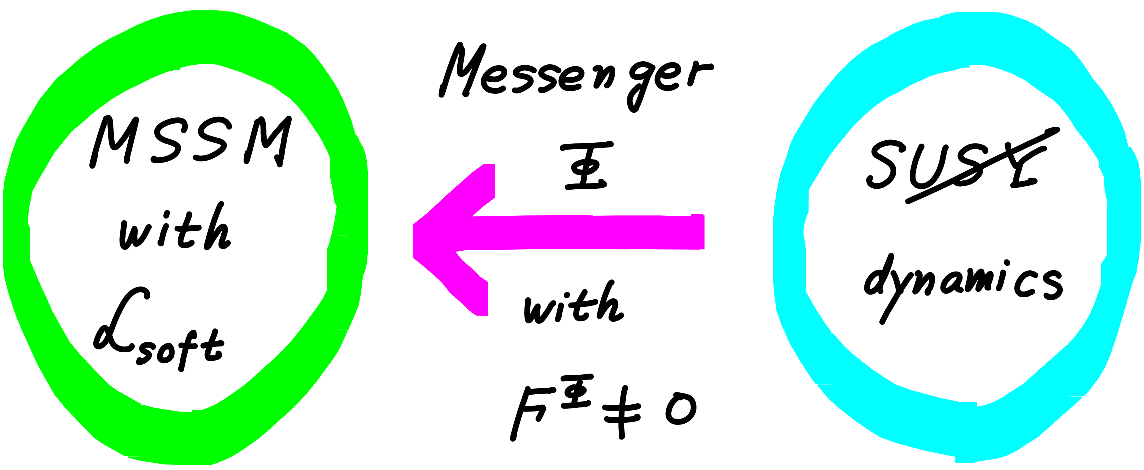
★ Highly distinctive low energy spectrum of superparticles : compressed spectrum

★ Naturally avoid dangerous $\cancel{CP}$ & FCNC & also ameliorate (even avoid) the little fine-tuning for EWSB

★ Various possibilities for LSP DM
(Next talk by K. Okumura)

- Soft ~~SUSY~~ terms in models with low energy SUSY

$$-\frac{1}{2}M_a\lambda^a\lambda^a-\frac{1}{2}m_i^2|\phi^i|^2-\frac{1}{6}A_{ijk}y_{ijk}\phi^i\phi^j\phi^k+h.c$$



The pattern of superparticle masses is closely connected to the mechanism of messenger stabilization which determines $\langle\Phi\rangle$ & $\langle F^{\Phi}\rangle$.

- Plausible messengers of ~~SUSY~~ in compactified string theory

  - 4D SUGRA multiplet $\{ g_{\mu\nu}, M, \cdots \}$

    Chiral compensator $C = 1 + M\theta^2$

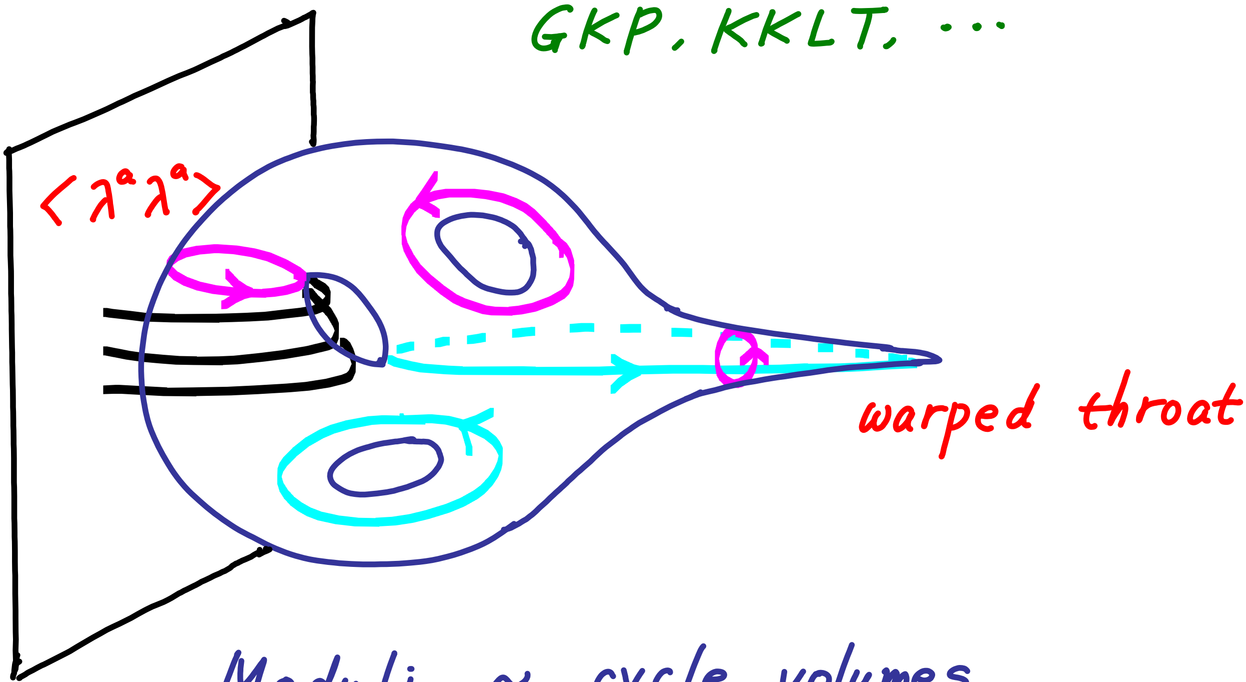
    → Anomaly mediation

  - Moduli / Dilaton multiplet

→ For a reliable computation of m_{soft} in 4D EFT of string theory, one needs to know how the dilaton/moduli are stabilized at a vacuum with nearly vanishing cosmological constant.

♦ Moduli stabilization by flux & NP effects

GKP, KKLT, ⋯



Moduli ~ cycle volumes

- cycles with flux :

  flux density $\propto$ $1/\text{Volume}$

- cycles with wrapping D-branes :

  gaugino condensation $\propto$ $e^{-1/\text{Volume}}$

  (or brane instanton)

→ Fix the cycle volumes ~ moduli

- Generically some fluxes generate warped throat & the warp factor at the end of throat can be exponentially small :

$$e^{A} = \exp\left[-\frac{2\pi \int H_3}{g_{st} \int F_3}\right]$$

- Typically moduli are stabilized at a SUSY AdS vacuum.

$$D_\Phi W(\Phi_0) = 0 \quad , \quad W(\Phi_0) \neq 0$$

$D_\Phi W = 0$ is always a stationary point of $V_{SUGRA} = e^{K}\left[K^{\Phi\bar{\Phi}}|D_\Phi W|^2 - 3|W|^2\right]$.

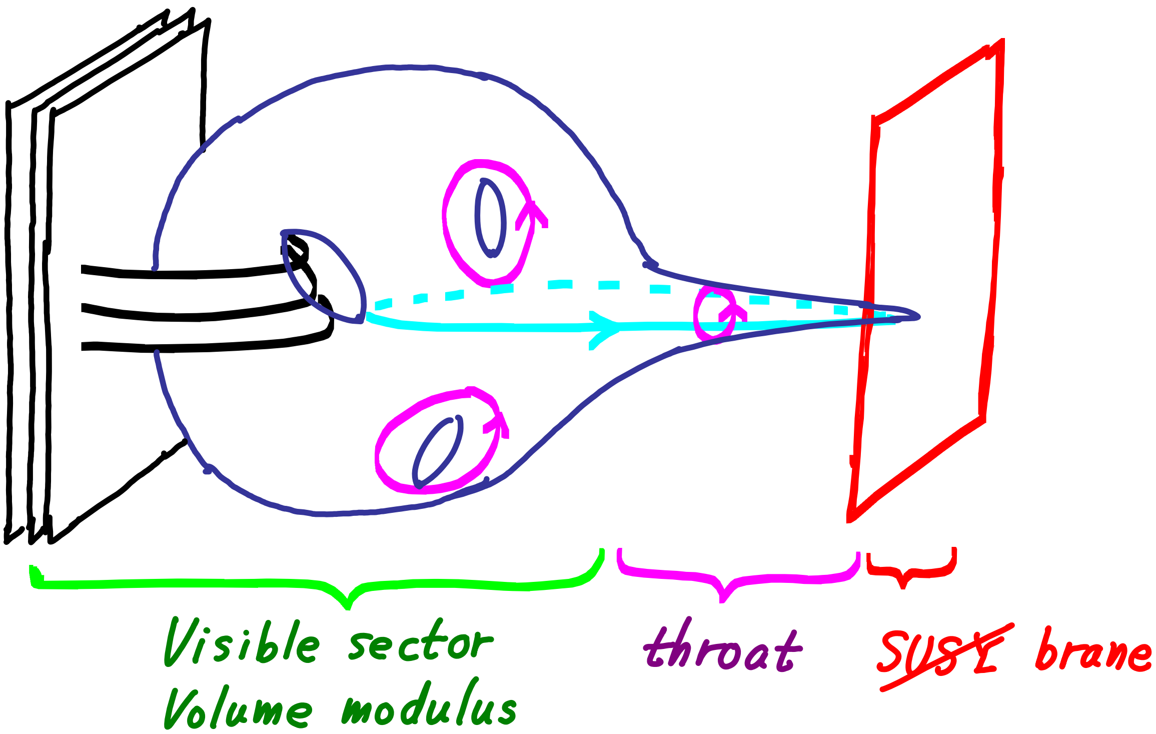
$$\rightarrow \langle V_{SUGRA} \rangle = -3e^{K}|W|^2 = -3\, m_{3/2}^2 M_{Pl}^2 < 0$$

- We need to add ~~SUSY~~ brane with positive energy density.

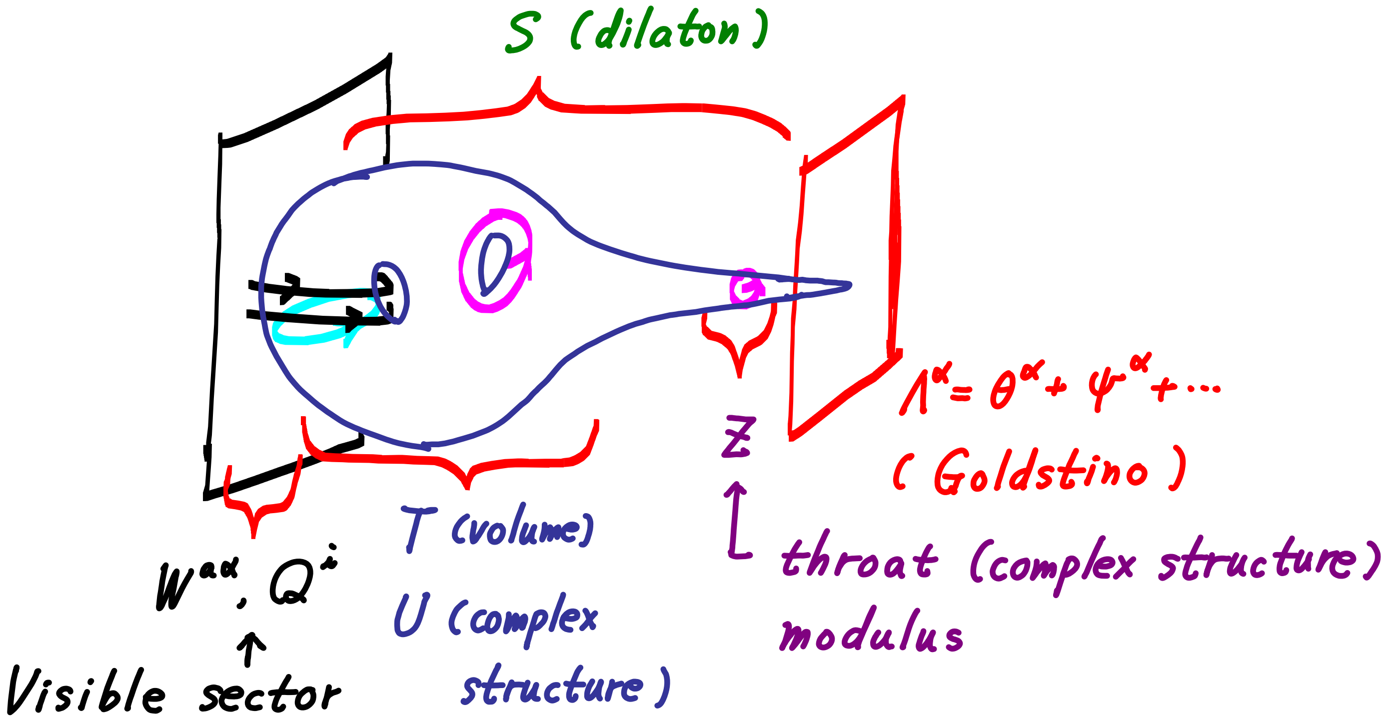
  $\overline{D3}$ (KKLT) or any brane with ~~SUSY~~ dynamics

- It is energetically favored that ~~SUSY~~ brane is stabilized at the end of warped throat.

- On the other hand, visible sector branes should be stabilized at unwarped region to achieved $M_{GUT} \sim 2 \times 10^{16}$ GeV.



♦ Example   KC, Jeong, Kobayashi, Okumura



$$W = W_{flux} + W_{np}$$

$$W_{flux} = \int (F_3 - 2\pi i\, S\, H_3) \wedge \Omega$$

$$= \frac{n}{2\pi i} Z \ln Z - 2\pi i\, m\, S Z + \mathcal{F}(U) - 2\pi i\, S\, \mathcal{H}(U)$$

$$W_{np} = \sum_I A_I\, e^{-8\pi^2 (k_I T + l_I S)} \qquad (A_I \sim 1)$$

$$= A_1 e^{-8\pi^2 S} + A_2\, e^{-8\pi^2 (kT - lS)}$$

(k, l, m, n are rational numbers)

Consider $\mathcal{F}$ & $\mathcal{H}$ with common zero :

$$\mathcal{F}(U_0) = \mathcal{H}(U_0) = 0$$

($\mathcal{F}$ & $\mathcal{H}$ are polynomials with quantized coefficients.)

S, U & Z are stabilized by W_{flux} at

$$\langle Z \rangle \simeq Z_0 \equiv e^{-\left(\frac{4\pi^2 m S_0}{n} + 1\right)}$$

$$\langle U \rangle \simeq U_0 \quad , \quad \langle S \rangle \simeq S_0 \equiv \frac{\mathcal{F}'(U_0)}{2\pi i\, \mathcal{H}'(U_0)}$$

with $\quad m_{S,U,Z} \gg m_T \, , \, m_{3/2}$.

To get low energy SUSY ($m_{3/2} \sim$ TeV) together with vanishing C.C , we need to choose the discrete parameters as

$$m_{3/2}/M_{Pl} \sim e^{-8\pi^2 S_0} \sim 10^{-14}$$

$$Z_0 \sim e^{-4\pi^2 m S_0/n} \overset{m = 3n}{\sim} \left(m_{3/2}/M_{Pl} \right)^{3/2} \sim 10^{-21}$$

(red-shift factor at the end of throat$)^3$

Heavy S, U, Z can be integrate out, yielding an effective SUGRA of $T, \Lambda^\alpha, W^{a\alpha}, Q^i$:

$$\mathcal{L}_{eff} = \int d^4\theta \, C\bar{C} \left[-3 e^{-K/3} + \underbrace{C\bar{C} \, Z_0^{\overbrace{4/3}^{\text{red-shift by warping}}} \theta^2 \bar{\theta}^2}_{\text{uplifting potential from } \cancel{\text{SUSY}} \text{ brane}} \right]$$

$$+ \int d^2\theta \left[\frac{1}{4} f_a W^{a\alpha} W^a_\alpha + C^3 W_{eff} \right]$$

$$K = K_0(T, \bar{T}) + Z_i(T, \bar{T}) Q^i \bar{Q}^i$$

$$f_a = T$$

$$Z_0^{1/3} \sim e^{-4\pi^2 S_0} \sim 10^{-7}$$

$$m_{3/2} \sim e^{-8\pi^2 S_0} \sim 10^{-14}$$

(in the unit with $M_{Pl} = 1$)

$$W_{eff} = e^{-8\pi^2 S_0} + e^{-8\pi^2 (kT - \ell S_0)} + \frac{1}{6} \lambda_{ijk} Q^i Q^j Q^k$$

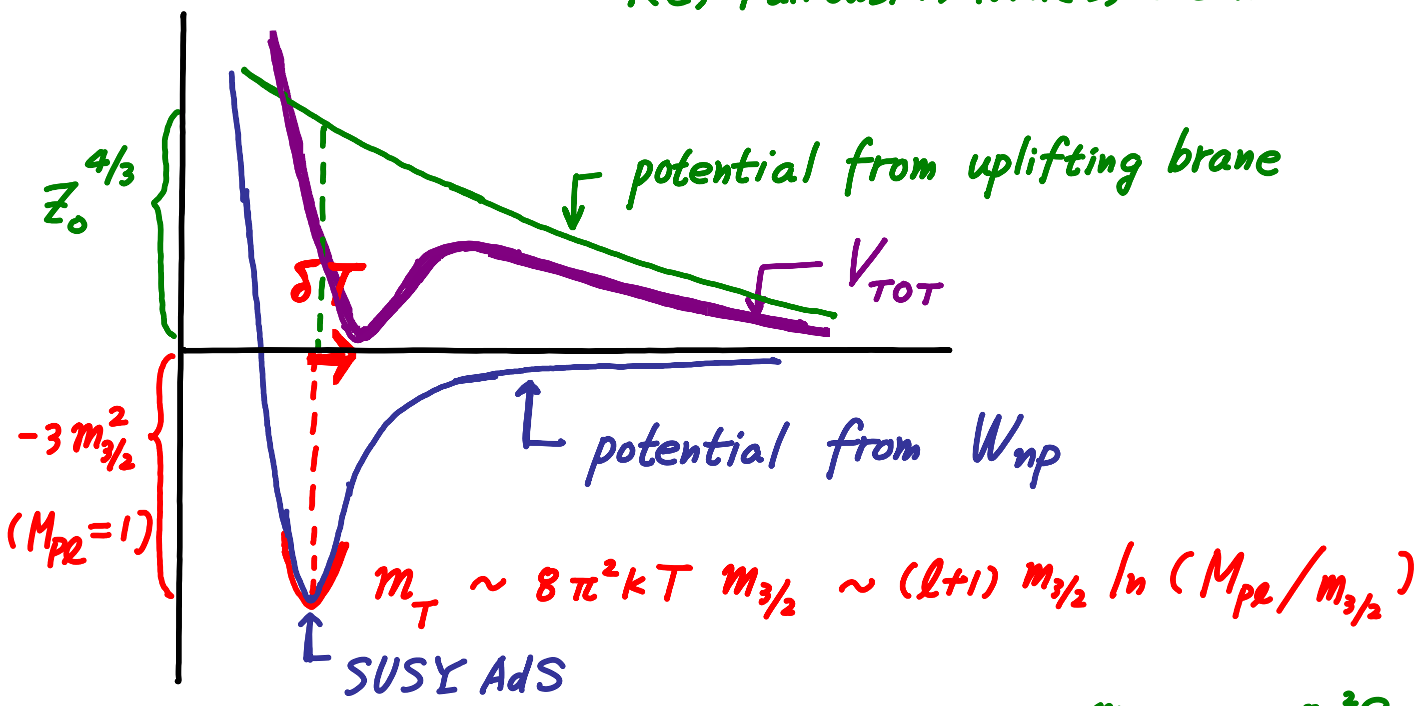
$$= m_{3/2} + m_{3/2}^{-\ell} e^{-8\pi^2 kT} + \frac{1}{6} \lambda_{ijk} Q^i Q^j Q^k$$

The non-perturbative superpotential stabilizing the lightest modulus is directly connected to the weak to Planck scale hierarchy $m_{3/2}/M_{Pl}$:

$$e^{-8\pi^2 kT} \sim \left(m_{3/2}/M_{Pl} \right)^{\ell+1}$$

$\cancel{SUSY}$ by uplifting potential

KC, Falkowski, Nilles, Olechowski



$$\frac{m_{3/2}}{M_{Pl}} \sim e^{-8\pi^2 S_0}$$

For nearly vanishing C.C ,

$$Z_0^{4/3} \sim e^{-16\pi^2 S_0\, m/3n} \sim (m_{3/2}/M_{Pl})^2$$

$\cancel{SUSY}$ shift of T : $\delta T \sim m_{3/2}^2/m_T^2$

modulus mediated gaugino mass

$$\rightarrow \quad \frac{F^T}{T+\bar{T}} \equiv M_0 \sim \frac{m_{3/2}^2}{m_T} \sim \frac{m_{3/2}}{(l+1)\ln(M_{Pl}/m_{3/2})}$$

Big hierarchy $\longrightarrow$ Little hierarchy

$$(M_{Pl}/m_{3/2}) \sim e^{4\pi^2} \qquad\qquad M_0 \sim \frac{m_{3/2}}{8\pi^2} \sim \frac{m_T}{(8\pi^2)^2}$$

◆ Mirage mediation pattern of soft masses

KC, Jeong, Okumura

Stabilization of the lightest set of moduli by W_{np} & uplifting of vacuum by red-shifted ~~SUSY~~ brane

→ $\boxed{\text{Moduli mediation} \sim \text{Anomaly mediation}}$

$$\frac{F^T}{T+\bar{T}} \equiv M_0 \qquad\qquad \frac{m_{3/2}}{8\pi^2}$$

$$M_a(M_{GUT}^{(-)}) = M_0 + \frac{b_a}{8\pi^2} g_{GUT}^2 m_{3/2}$$

$$A_{ijk}(M_{GUT}^{(-)}) = a M_0 - \frac{1}{16\pi^2}(\gamma_i + \gamma_j + \gamma_k) m_{3/2}$$

$$m_i^2(M_{GUT}^{(-)}) = \underbrace{c M_0^2}_{\text{moduli mediation}} + \underbrace{\frac{1}{8\pi^2}\frac{\partial \gamma_i}{\partial \ln T} M_0 m_{3/2}}_{\text{mixed mediation}} - \underbrace{\frac{\dot{\gamma}_i}{16\pi^2} m_{3/2}^2}_{\text{anomaly mediation}}$$

Low energy superparticle masses

$$M_a(\mu) = M_0 \left[1 - \frac{b_a}{4\pi^2} g_a^2(\mu) \ln\left(\frac{M_{mirage}}{\mu}\right) \right]$$

$$m_i^2(\mu) = M_0^2 \left[c + \frac{1}{4\pi^2} \left(\gamma_i - \frac{1}{2}\dot{\gamma}_i\right) \ln\left(\frac{M_{mirage}}{\mu}\right) \times \ln\left(\frac{M_{mirage}}{\mu}\right) \right]$$

1st & 2nd generations

$$M_{mirage} = M_{GUT} \left(m_{3/2} / M_{Pl} \right)^{\alpha/2}$$

$\equiv$ Mirage Messenger Scale

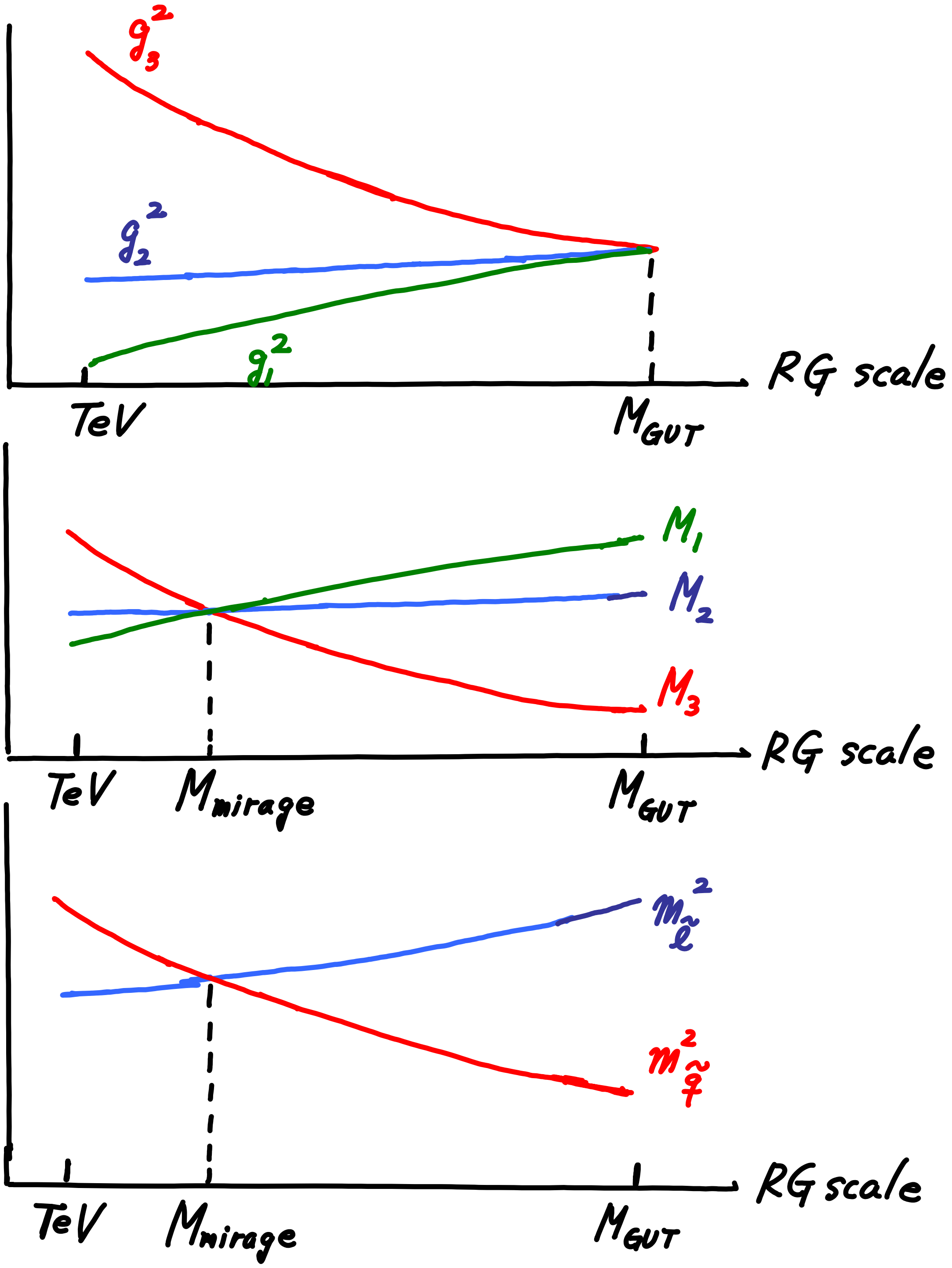
$$\alpha \equiv \frac{m_{3/2}}{M_0 \underbrace{\ln\left(M_{Pl}/m_{3/2}\right)}_{\sim 4\pi^2}} = 1 + \underbrace{\ell}_{\text{model-dependent rational number}}$$

$\alpha = 1 \rightarrow M_{mirage} \sim \sqrt{m_{3/2} M_{Pl}}$

(intermediate mirage scale)

$\alpha = 2 \rightarrow M_{mirage} \sim$ TeV

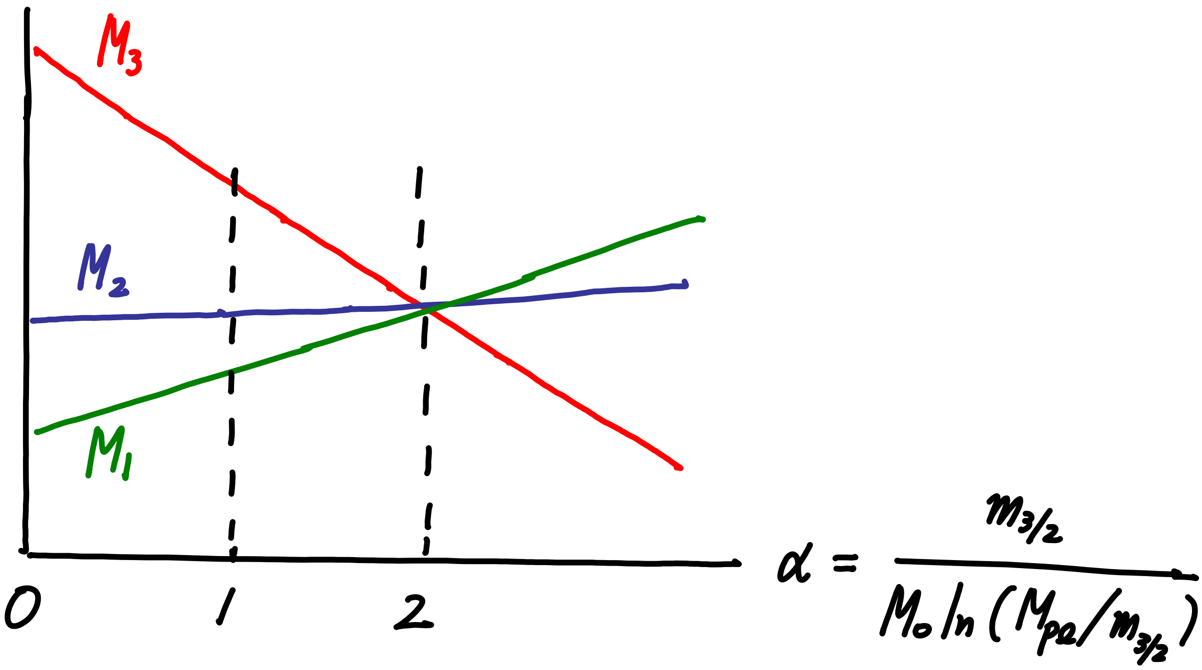
(TeV mirage scale)



Compressed SUSY spectrum at TeV!

KC, Jeong, Okumura ; Endo, Yamaguchi, Yoshioka

Low energy gaugino masses as a ftn of α



	M_1	:	M_2	:	M_3
$\alpha = 0$ (mSUGRA, GMSB)	1	:	2	:	6
$\alpha = 1$ (intermediate scale mirage mediation)	1	:	1.3	:	2.4
$\alpha = 2$ (TeV scale mirage)	1	:	1	:	1
$\alpha = \infty$ (AMSB)	3.3	:	1	:	10

◆ μ & B, EWSB, ~~CP~~, FCNC, Cosmology

- μ & B (KC, Jeong, Okumura)

$\alpha \neq 2 \longrightarrow$ NMSSM

$\alpha = 2 \longrightarrow W_\mu = \kappa\, e^{-8\pi^2(kT - lS_0)} H_u H_d$

- little SUSY fine-tuning

$$\Delta m_{H_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{M_{mirage}}{m_{\tilde{t}}}\right)$$

Mirage mediation generically ameliorates the little fine tuning for $m_h > 114$ GeV.

$\alpha = 2$ ($M_{mirage} \sim$ TeV) is the best scenario for the little fine tuning problem.

(KC, Jeong, Kobayashi, Okumura ; Kitano, Nomura)

- SUSY CP problem

Axionic shift symmetry

$U(1)_T$: $\mathrm{Im}(T) \to \mathrm{Im}(T) + $ real constant

KC (1994)

assures that soft preserve CP :

$$K = K_0(T+\bar{T}) + Z_i(T+\bar{T}) Q^{i*} Q^i$$

$$W = \omega_0 + A e^{-8\pi^2 T} + \kappa S^3 + \lambda S H_u H_d + \cdots$$

$$f_a = k_a T + \text{constant}$$

↑ real constant

- Using $U(1)_T$, $U(1)_R$ & other appropriate field redefinition, one can always make ω_0, A, κ, λ real.
- $U(1)_T$ also assures $\partial_T K$, $\partial_T Z_i$, $\partial_T f_a$, $\cdots$ are all real.

→ All soft parameters are real.

(KC, Falkowski, Nilles, Olechowski ; Endo, Yamaguchi, Yoshioka)

- SUSY flavor problem

Typically $Z_i = \dfrac{1}{(T+\overline{T})^{n_i}}$

(n_i = discrete modular weights)

If n_i are flavor universal, which is a rather natural possibility, soft terms preserve flavor also.

- Moduli & gravitino cosmology & DM

Still we might need a mechanism to eliminate coherent moduli oscillation.

(M. Yamaguchi's talk)

Variety of possibilities for LSP DM.

(K.I. Okumura's talk)

Summary

- String compactification stabilizing moduli at phemomenologically viable dS vacuum with low energy SUSY suggests (or predict) mirage mediation with a mirage messenger scale hierarchically lower than M_{Pl} which appears as a consequence of dynamical cancellation between moduli mediation & anomaly mediation.

- Mirage mediation

i) gives highly distinctive low energy superparticle spectrum :

Compressed spectrum which is clearly distinguishable from mSUGRA, GMSB & AMSB.

ii) naturally avoid dangerous ~~CP~~ & FCNC & also ameliorate (even avoid) the little fine-tuning for EWSB

iii) allowes various types of LSP DM

(Next talk by K. Okumura)