Moduli Stabilization & the Pattern of Soft Terms

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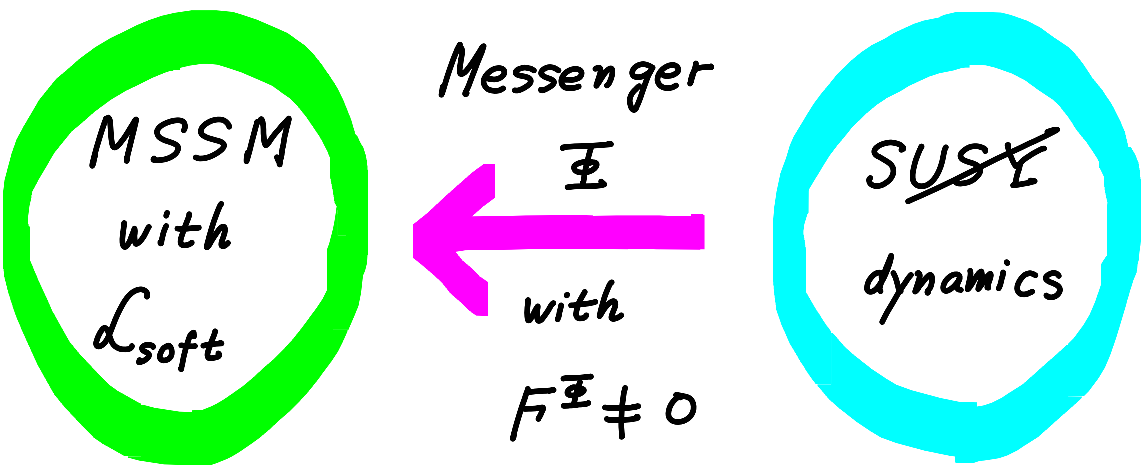
KC, A. Falkowski, H.P. Nilles, M. Olechowski
NPB 718, 113 (2005)

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

KC, K.S. Jeong, hep-th/0605108

- 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 $C = 1 + M\theta^2$)
  - Moduli / Dilaton superfield Φ

Moduli potential $V(\Phi)$

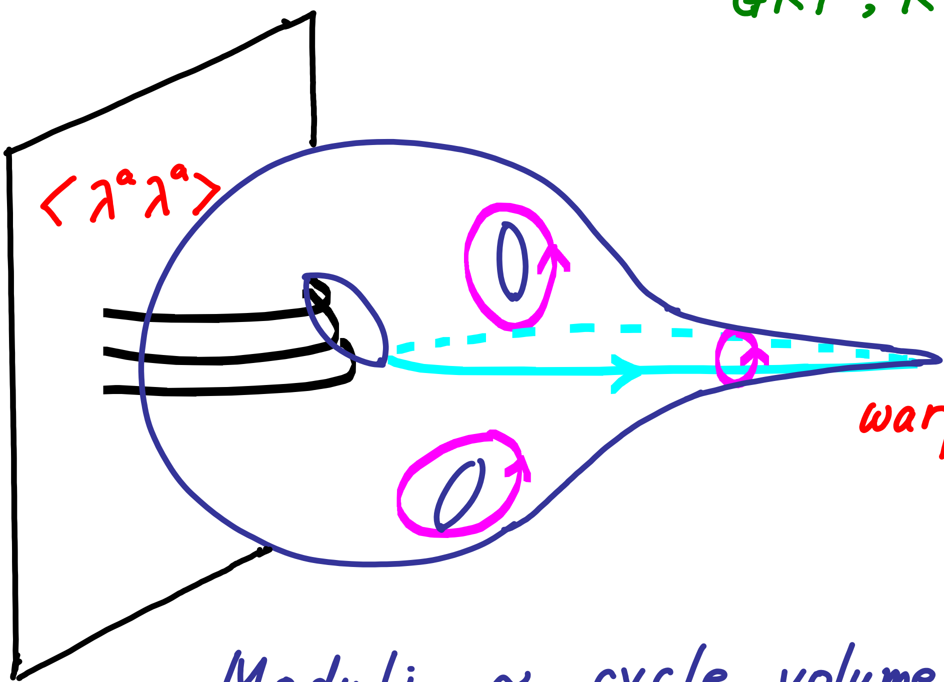
$$\rightarrow \begin{cases} \dfrac{\partial V}{\partial \Phi} = 0 \\ R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N g_{\mu\nu} \langle V \rangle \end{cases}$$

$$\rightarrow \langle \Phi \rangle, \langle g_{\mu\nu} \rangle, \langle F^{\Phi} \rangle, \langle F^C \rangle \equiv \langle M \rangle$$

For a reliable computation of m_{soft}, we need to know how to stabilize Φ & how to get $\langle V \rangle = 0$.

♦ 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

- Typically moduli are stabilized at a SUSY AdS vacuum.

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

$$\rightarrow \langle V_{SUGRA} \rangle = -3\, m_{3/2}^2 M_{Planck}^2$$

KKLT :

$$\Phi = \{ \overset{\text{IIB dilaton}}{S} , \underset{\text{complex structure}}{Z} , \overset{\text{Kähler}}{T} \}$$

$$m_{S,Z} \underset{\text{flux}}{\sim} \frac{M_{com}^3}{M_{st}^2} \quad , \quad m_T \underset{\text{gaugino condensation}}{\sim} m_{3/2} \ln (M_{st} / m_{3/2})$$

- Generically fluxes generate warped throat.

Warp factor at the end of throat :

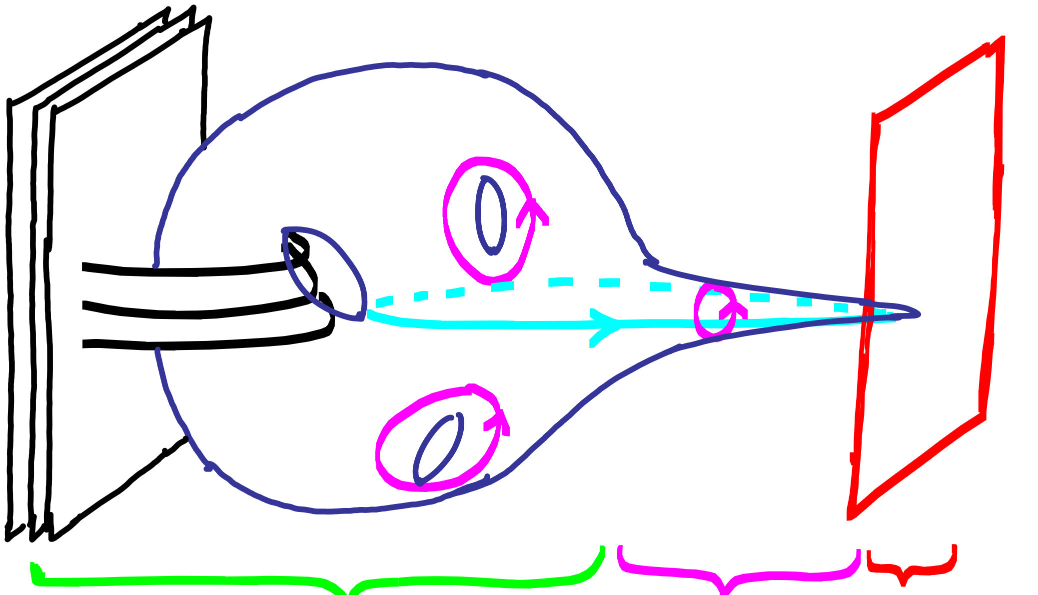
$$e^A \sim \exp \left[- \frac{2\pi \int H_3}{g_{st} \int F_3} \right]$$

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

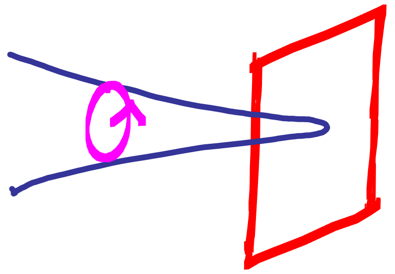
  $\overline{D3}$ (KKLT) or any brane with ~~SUSY~~ dynamics

- 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.



♦ Red-shifted ~~SUSY~~ brane



$$ds^2_{y=\bar{y}} = e^{2A} g_{\mu\nu}\, dx^\mu dx^\nu + \dots$$

- ~~SUSY~~ spurion operators :

$$\delta(y-\bar{y}) \int d^2\Theta\, 2\mathcal{E} \Big[(\bar{\mathcal{D}}^2 - 8R) \Big(\underbrace{e^{4A}\Theta^2\bar{\Theta}^2}_{D\text{-type}} + \underbrace{e^{3A}\bar{\Theta}^2 \Big) + e^{4A}\Theta^2}_{F\text{-type}} \Big]$$

- Uplifting condition :

$$e^{4A} M_{Pl}^4 \sim m_{3/2}^2 M_{Pl}^2 \rightarrow e^A \sim \sqrt{m_{3/2}/M_{Pl}}$$

- F-type spurions

anomaly mediation

$$\rightarrow m_{soft} \sim e^{3A} M_{Pl} \ll \frac{m_{3/2}}{8\pi^2}$$

- D-type spurions

moduli mediation

$$\rightarrow m_{soft} \sim \frac{m_{3/2}^2}{m_\Phi} + \frac{m_{3/2}}{8\pi^2}$$

→ ~~SUSY~~ is dominated by D-type spurion.

(KC, Falkowski, Nilles, Olechowski)

♦ 4D effective action

$$\int d^2\Theta\, 2\mathcal{E}\left[\frac{1}{8}(\bar{\mathcal{D}}^2-8R)\left(3e^{-K/3}+\underline{e^{4A}\Lambda^2\bar{\Lambda}^2\mathcal{P}}\right)+\frac{1}{4}f_a W^{a\alpha}W^a_\alpha+W\right]+\text{h.c}$$

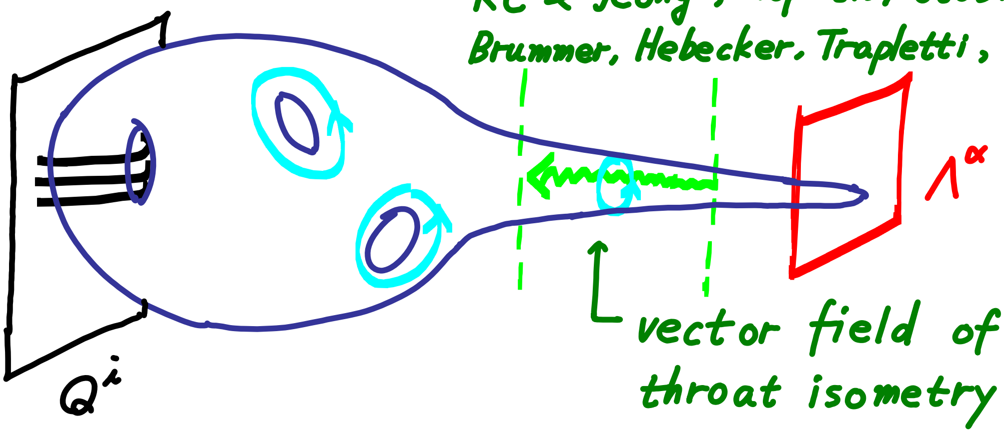
(Λ^α = Goldstino superfield = Θ^α + Goldstino + $\cdots$)

$$K = K_0(\Phi,\Phi^*) + Z_i(\Phi,\Phi^*)\,Q^{i*}Q^i$$

$$W = W_0(\Phi) + \frac{1}{6}\lambda_{ijk}(\Phi)\,Q^iQ^jQ^k$$

$$\mathcal{P} = \underbrace{\mathcal{P}_0(\Phi,\Phi^*)}_{\text{up-lifting}} + \underbrace{Y_i(\Phi,\Phi^*)\,Q^{i*}Q^i}_{\text{brane-to-brane mediation}}$$

KC & Jeong, hep-th/0605108
Brummer, Hebecker, Trapletti, hep-th/0605232



Y_i is suppressed by the exponential damping of the throat vector fields over the region where isometry is broken, however it is hard to estimate the amount of suppression.

Much of observable physics is independent of the precise value of Y_i, e.g M_a & A_{ijk} are totally independent of Y_i.

- Moduli stabilizing dynamics

$$\rightarrow \quad V_{SUGRA} = -3\, m_{3/2}^2 M_{Pl}^2 + m_\Phi^2 |\delta\Phi|^2 + \cdots$$

SUSY AdS

$$(\delta\Phi = \Phi - \Phi_0)$$

- Red-shifted ~~SUSY~~ brane

$$\rightarrow \quad V_{lift} = e^{4A} e^{2K/3} P_0$$

$$\rightarrow \quad \frac{\delta\Phi}{\Phi_0} \sim \frac{m_{3/2}^2}{m_\Phi^2}, \qquad \frac{F^\Phi}{\Phi_0} \sim \frac{m_{3/2}}{m_\Phi} \qquad (m_\Phi \gtrsim m_{3/2})$$

$$\rightarrow \left\{ \begin{array}{lll} m_\Phi \gg 8\pi^2 m_{3/2} & \rightarrow & \dfrac{F^\Phi}{\Phi} \ll \dfrac{m_{3/2}}{8\pi^2} \\ \uparrow \text{lightest modulus mass} & & \text{(Anomaly mediation)} \\ m_\Phi \sim 8\pi^2 m_{3/2} & \rightarrow & \dfrac{F^\Phi}{\Phi} \sim \dfrac{m_{3/2}}{8\pi^2} \\ & & \text{(Mirage mediation)} \\ m_\Phi \lesssim m_{3/2} & \rightarrow & \dfrac{F^\Phi}{\Phi} \sim m_{3/2} \\ & & \text{(Modulus mediation)} \end{array} \right.$$

If the lightest modulus T is stabilized by NP effects, typically $m_T \sim 8\pi^2 m_{3/2}$.

KC, Falkowski, Nilles, Olechowski

$\rightarrow$ Mirage mediation

◆ Model

constant depending on heavy moduli VEV

$$f_a = k T + \Delta f \quad , \quad f_H = k_H T + \Delta f_H$$

$SU(3) \times SU(2) \times U(1)$ hidden $SU(N_c)$

$$K = - n_0 \ln(T+T^*) + \frac{Q^{i*} Q^i}{(T+T^*)^{n_i}}$$

$$W = \omega_0 + N_c e^{-8\pi^2 f_H / N_c} + \frac{1}{6} \lambda_{ijk} Q^i Q^j Q^k$$

$$P_0 = \frac{\text{constant}}{(T+T^*)^{n_p}}$$

$$\alpha \equiv \frac{\text{Anomaly mediation}}{\text{Modulus mediation}} = \frac{m_{3/2}}{M_0 \ln(M_{Pl}/m_{3/2})}$$

(M_0 = modulus mediated gaugino mass at M_{GUT})

$$= \frac{2n_0}{2n_0 + 3n_p} \left(1 + \frac{8\pi^2 (k_H \Delta f - k \Delta f_H)}{k N_c \ln(M_{Pl}/m_{3/2})} \right) = \mathcal{O}(1)$$

- KKLT

$$n_P = \Delta f = \Delta f_H = 0 \;\rightarrow\; \alpha_{KKLT} = 1$$

- At scales just below M_{GUT},

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

$$m_i^2 = \tilde{m}_i^2 - \frac{\gamma_i}{8\pi^2} M_0 m_{3/2} - \frac{\dot{\gamma}_i}{32\pi^2} m_{3/2}^2$$

(1st & 2nd generations)

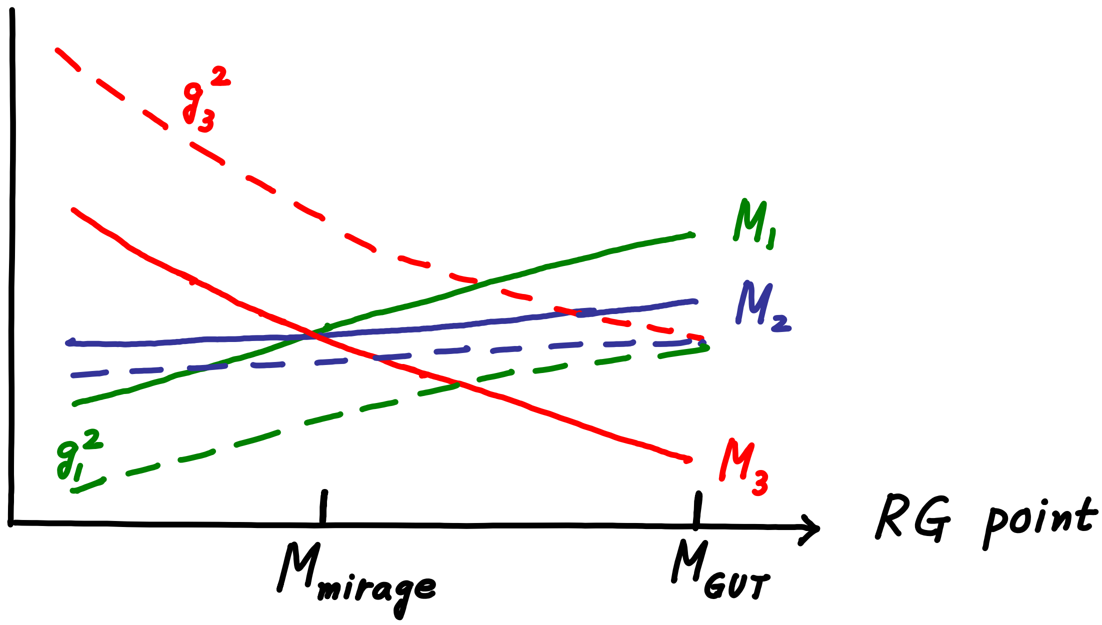
modulus mediation + brane-to-brane mediation

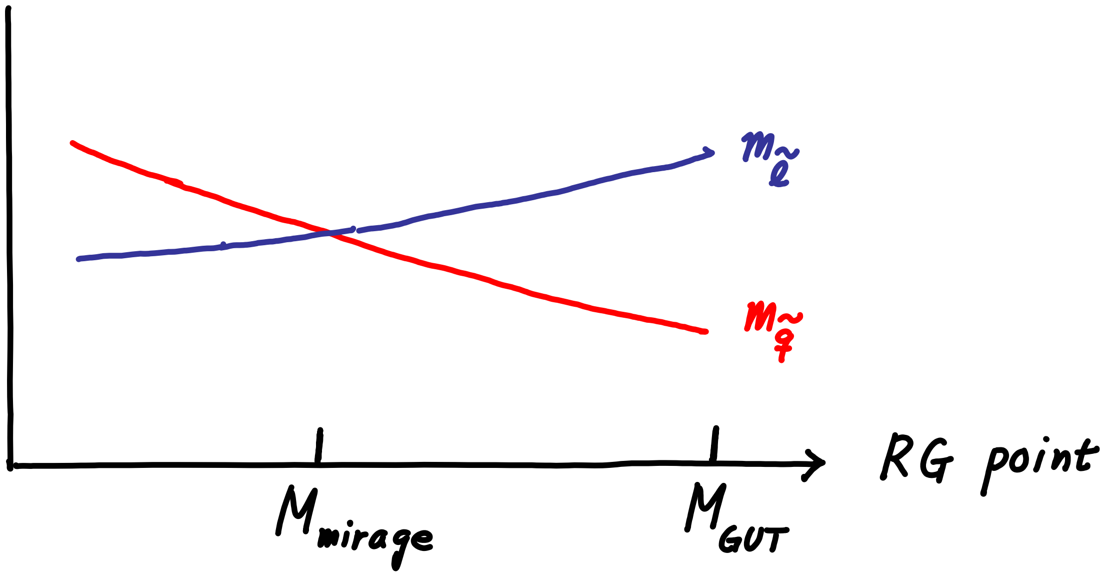
$$\rightarrow \begin{cases} M_a(\mu) = M_0 \left[1 - \frac{1}{4\pi^2} b_a g_a^2(\mu) \ln\left(\frac{M_{GUT}}{(M_{Pl}/m_{3/2})^{\alpha/2}\mu}\right)\right] \\ m_i^2(\mu) = \tilde{m}_i^2 + \frac{M_0^2}{4\pi^2}\left\{\gamma_i(\mu) - \frac{\dot{\gamma}_i(\mu)}{2} \ln\left(\frac{M_{GUT}}{(M_{Pl}/m_{3/2})^{\alpha/2}\mu}\right)\right\} \\ \qquad\qquad \times \ln\left(\frac{M_{GUT}}{(M_{Pl}/m_{3/2})^{\alpha/2}\mu}\right) \end{cases}$$

$\rightarrow$ Mirage messenger scale

KC, Jeong, Okumura

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





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

(Intermediate scale mirage mediation)

$\alpha = 2 \rightarrow \quad M_{mirage} \sim m_{3/2}$

(TeV scale mirage mediation)

♦ Interesting features

- Compared to other mediation scenarios (mSUGRA, AMSB, GMSB), mirage mediation give more compact superparticle spectrum at TeV.

- For $\alpha \simeq 2$, the little fine-tuning for EWSB is significantly ameliorated.

(KC, Jeong, Okumura, Kobayashi ; Kitano, Nomura ; Lebedev, Nilles, Ratz)

- The non-linear PQ symmetry : $T \to T + i\beta$ assures that soft terms are CP conserving.

- $m_\Phi \sim 8\pi^2 m_{3/2} \sim (8\pi^2)^2 m_{soft}$, so moduli cosmology and gravitino cosmology are quite different.

(Endo, Hamaguchi, Takahashi ; Nakamura, Yamaguchi)

⋮

♦ Summary

- The pattern of superparticle spectrum in 4D effective theory of string theory is closely related to the mechanism of moduli stabilization.

- Moduli stabilization by flux and nonperturbative effects leads to mirage mediation pattern of low energy superparticle masses which is clearly distinguishable from the mass patterns predicted by other mediation scenarios such as mSUGRA, AMSB, GMSB.