Moduli Stabilization

and

the Pattern of Soft ~~SUSY~~ Terms

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(Goa , 2007)

KC, Falkowski, Nilles, Olechowski, NPB (2005)
[hep-th/0503216]

KC, Jeong, Okumura, JHEP (2005)
[hep-ph/0504037]

KC, Jeong, Kobayashi, Okumura, PLB (2006)
[hep-ph/0508029]

KC & Jeong, hep-th/0611279

- For phenomenology observable at LHC, the mechanism of SUSY breakdown itself is not of direct concern.
  What is important is how SUSY breakdown is transmitted to the SSM sector.

- The mediation mechanism of SUSY breakdown should (approximately) preserve flavor and CP.

	Gaugino masses at TeV		
mSUGRA	1	2	6
Gauge mediation	1	2	6
Anomaly mediation	3.3	1	9
Mirage mediation (Mixed Moduli-Anomaly)	1	1.2	2.5
	$\tilde{B}$	$\tilde{W}$	$\tilde{g}$

Gaugino mass pattern is a robust prediction of the scenario. Similar prediction can be made for the pattern of squark/slepton masses under the assumption of simplest realization of the scenario, however it can be significantly modified by possible additional ingredient, e.g D-term contribution, extra matter & interactions (even in hidden sector) at scales above TeV, e.t.c.

Cohen, Roy, Schmaltz ; Kane et. al.

Mediation scheme based on string theory

$\longleftrightarrow$ Moduli stabilization

$$f_a = X = \text{dilaton / moduli}$$

$$\left(\frac{1}{g_a^2(\Lambda)} = \langle f_a \rangle \right)$$

$\rightarrow$ Two model-independent contributions to M_a:

$$M_a = F^X + \frac{b_a}{16\pi^2} F^C$$

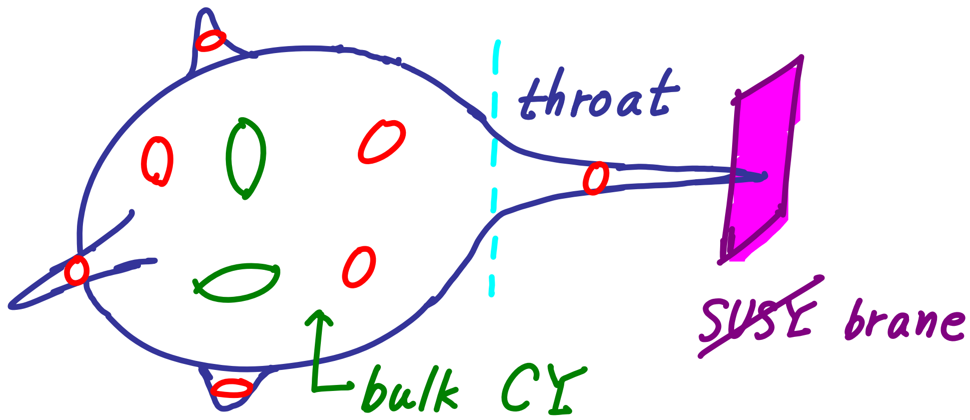
$$(C = \text{SUGRA compensator})$$

F^X & F^C are determined by the mechanism of moduli stabilization!

Outline

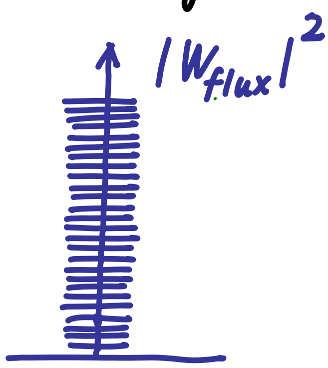
- Some features of GKP and KKLT relevant for us
- Patterns of soft terms (gaugino masses) resulting from 4 different schemes of moduli stabilization scenarios realized in Type IIB theory
- Mirage mediation (Mixed moduli-anomaly mediation) pattern of soft terms
  - + Natural flavor & CP conservation
  - + Mirage unification

- Some features of GKP & KKLT



i) Many 3-cycles supporting 3-form fluxes

→ Huge landscape of discrete flux vacua



flux-induced superpotential

uniform distribution of $|W_{flux}|^2$

with extremely small level spacing

ii) Flux-induced warped throat

Brane-localized source of $\cancel{\text{SUSY}}$, e.g $\overline{D3}$ of KKLT, is stabilized at the IR end :

$$M_{\cancel{SUSY}} \sim e^{A} M_{Pl}$$

small warp factor

$\Rightarrow$ * Hierarchically low ~~SUSY~~ scale

* Busso-Polchinski mechanism to tune C.C $\simeq 0$ following the anthropic selection rule

$$V_{vacuum} = e^{4A} M_{Pl}^4 - \frac{3 e^K |W_{flux}|^2}{M_{Pl}^2} = 0$$

Anthropic selection rule picks up

$$\frac{W_{flux}}{M_{Pl}^3} \sim \frac{m_{3/2}}{M_{Pl}} \sim e^{2A} \ll 1$$

among the uniformly distributed values of $|W_{flux}|^2$ with a level spacing $\frac{\Delta |W_{flux}|^2}{M_{Pl}^6} \lesssim e^{4A}$.

iii) Dilaton (S) & complex structure moduli (Z_i) are stabilized by flux at the SUSY-preserving solution of

$$D_S W_{flux} = D_{Z_i} W_{flux} = 0$$

with m_{S,Z_i} hierarchically heavier than $m_{3/2}$.

Cf : Complex structure modulus Z describing the collapsing 3-cycle of the throat with ~~SUSY~~-brane at IR end developes $D_Z W \neq 0$, but Z is sequestered from the visible sector which is assumed to live on D-branes at the bulk CY.

iv) Kähler moduli (T_α) describing the volume of 4-cycles can not be fixed by 3-form flux, so are light.

Furthermore, T_α live mostly on the bulk CY, so are sequestered from the ~~SUSY~~ brane stabilized at the IR end of throat.

(Giddings & Maharana)

v) Visible sector lives on D7's wrapping the 4-cycles of CY (or D3 stabilized somewhere on CY) over which the warping is negligible.

$\Rightarrow$ Conventional high scale of gauge coupling unification is possible.

- Patterns of soft terms from Type IIB moduli stabilization :

- Effective SUGRA of T_α & visible sector

SUGRA compensator $\quad$ visible matter

$$\int d^4\theta\, CC^* \Big[-3\, e^{-\frac{1}{3}K_0} + Y_i\, Q^{*i} Q^i - \underbrace{C\bar{C}\, e^{4A} P_0\, \Lambda^2 \Lambda^{*2}}_{\text{Volkov-Akulov}} \Big]$$

$$+ \Big[\int d^2\theta \Big(\tfrac{1}{4} f_a\, W^{a\alpha} W^a_\alpha + W_0 + \tfrac{1}{6}\lambda_{ijk}\, Q^i Q^j Q^k \Big) + h.c \Big]$$

visible gauge

$$T_\alpha = e^{-\phi}\frac{R^4}{\alpha'^2} + i\, C_{4\alpha} \qquad (\, S = e^{-\phi} + i\, C_0\,)$$

Λ = Goldstino superfield = θ in unitary gauge

* Axionic shift symmetry :

$$T_\alpha \to T_\alpha + i\,\beta_\alpha\,, \qquad S \to S + i\,\beta$$

$$\Rightarrow \begin{cases} f_{3a} = S_0 & \big(\, (D_S W_{flux})_{S=S_0} = 0 \,\big) \\ f_{\eta a} = \sum_\alpha \underbrace{k_{a\alpha}}_{\text{real \& quantized}} T_\alpha + \underbrace{h_a S_0}_{\mathcal{O}(\alpha'^2)} \end{cases}$$

$$K_0 = K_0(T_\alpha + T_\alpha^*)$$

$$Y_i = Y_i(T_\alpha + T_\alpha^*)$$

$$W_0 = \omega_0 + \sum_\alpha A_\alpha e^{-\underbrace{a_\alpha}_{\text{real \& quantized}} T_\alpha}$$

* At leading order the α'-expansion, K_0 & Y_i have a definite scaling property :

$$K_0(e^\lambda(T_\alpha + T_\alpha^*)) = K_0(T_\alpha + T_\alpha^*) - 3\lambda$$

(no-scale form)

$$Y_i(e^\lambda(T_\alpha + T_\alpha^*)) = e^{n_i \lambda} Y_i$$

n_i = rational number determined by the dimensions of the subspace of the D-brane world volume on which Q^i are confined & also the subspace over which Yukawa couplings are defined

* <u>Sequestering</u>

$$\frac{\partial}{\partial T_\alpha}\left(e^{4A} P_0\right) = 0$$

* Independently of the details of ~~SUSY~~ dynamics at the IR end of throat, the counting of the powers of warp factor for generic SUSY-breaking operators ensures that the low energy consequence of ~~SUSY~~ brane can be described well by single operator, i.e the Volkov-Akukov operator, giving the uplifting potential.

$\Rightarrow$ Warping guarantees the calculability!

A) KKLT

$$K_0 = -3 \ln (T+T^*) \quad , \quad W_0 = w_0 + A e^{-aT}$$

$$e^{4A} \rho_0 = \text{constant}$$

$$V_{TOT} = \overbrace{e^{K_0}\left[K_0^{T\bar{T}} |D_T W_0|^2 - 3 |W_0|^2 \right]}^{V_F} + \overbrace{e^{2K_0/3} e^{4A} \rho_0}^{V_{lift}} \,.$$

V_F gives a SUSY AdS vacuum :

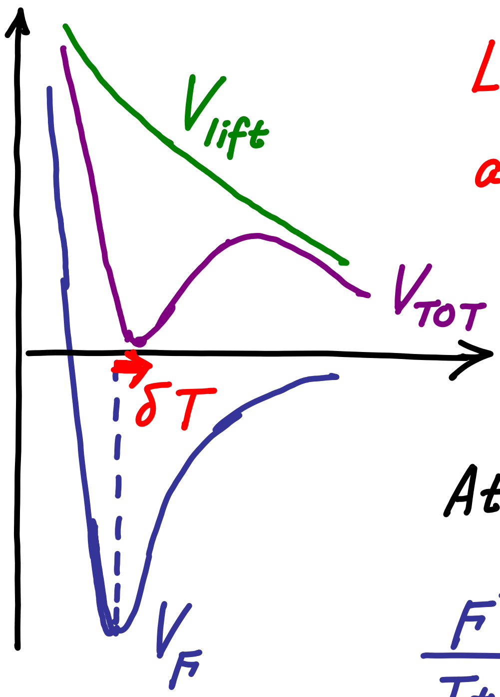
$$a \langle T \rangle \simeq \ln \left(A/w_0 \right) \simeq \ln \left(M_{Pl}/m_{3/2} \right)$$

$$m_T \simeq 2a \langle T \rangle m_{3/2} \simeq 2\, m_{3/2} \ln \left(M_{Pl}/m_{3/2} \right)$$

$$F^T = 0 \quad , \quad \langle V_F \rangle = -3\, m_{3/2}^2 M_{Pl}^2$$

$V_{lift} \simeq 3\, m_{3/2}^2 M_{Pl}^2$ slightly shifts the modulus vacuum value :

$$\delta T \sim \frac{m_{3/2}^2}{m_T^2} \sim \frac{1}{\left[\ln \left(M_{Pl}/m_{3/2} \right) \right]^2}$$



Little hierarchy structure allows a perturbative expansion in

$$\frac{1}{\ln(M_{pl}/m_{3/2})} \simeq \frac{1}{4\pi^2} \;!$$

At leading order in this expansion

$$\frac{F^T}{T+T^*} = \frac{m_{3/2}}{\ln(M_{pl}/m_{3/2})}$$

$$F^C = m_{3/2}$$

$\Rightarrow$ Modulus mediation ~ Anomaly mediation

$$\frac{M_a}{g_a^2} \simeq \frac{M_0}{g_{GUT}^2}\left[1 + \frac{\ln(M_{pl}/m_{3/2})}{16\pi^2}\, g_{GUT}^2\, b_a\, \alpha\right]$$

$$\left(\alpha \equiv \frac{\text{Anomaly}}{\text{Modulus}} \equiv \frac{m_{3/2}}{M_0 \ln(M_{pl}/m_{3/2})} \simeq 1\right)$$

$\Rightarrow$ Mirage pattern $M_1 : M_2 : M_3 \simeq 1 : 1.2 : 2.5$

Gersdorff, Hebecker ; Berg, Haack, Kors

B) Perturbative stabilization

$$K_0 = -3\ln(T+T^*) + \frac{\xi_1}{(T+T^*)^{3/2}} - \frac{\xi_2}{(T+T^*)^2} \quad (\xi_1, \xi_2 > 0)$$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \uparrow \mathcal{O}(\alpha'^3) \quad\quad \uparrow \mathcal{O}(g_{st}^2 \alpha'^4)$

$$W = \omega_0 \quad , \quad f_a = T$$

$$e^{4A} \rho_0 = \text{constant}$$

$$\Rightarrow \quad m_T \simeq \frac{\sqrt{\xi_1}}{(T+T^*)^{3/4}} m_{3/2} \ll m_{3/2}$$

$$\frac{F^T}{(T+T^*)} \simeq m_{3/2}$$

$$F^C \simeq \frac{\xi_1}{2(T+T^*)^{3/2}} m_{3/2} \ll m_{3/2}$$

Approximately no-scale pattern

$\Rightarrow$ Modulus domination leading to the mSUGRA pattern $M_1 : M_2 : M_3 \simeq 1 : 2 : 6$

However $\xi_1 > 0$ requires $\chi > 0 \rightarrow h_{1,1} \gg 1$. Then Kähler moduli other than the overall volume modulus can not be stabilized by this mechanism.

Conlon, Quevedo, Suruliz

C) Exponentially large volume compactification

$$K_0 = -2\ln\left[(T_1+T_1^*)^{3/2} - (T_2+T_2^*)^{3/2} + \xi\right]$$

ξ ← $\mathcal{O}(\alpha'^3)$

$$W_0 = \omega_0 + A e^{-aT_2}$$

$$e^{4A}\rho_0 = \text{constant}, \quad f_a = T_2$$

CY volume in string unit

$$\Rightarrow \quad \mathcal{V}_{CY} \sim (T_1+T_1^*)^{3/2} \sim e^{aT_2} \sim 10^{14}$$

$$\frac{F^{T_1}}{T_1+T_1^*} \simeq m_{3/2}, \quad \frac{F^{T_2}}{T_2+T_2^*} \simeq \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})}$$

$$F^C \simeq \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})} \quad \left(\frac{m_{3/2}}{M_{Pl}} \sim (T_1+T_1^*)^{-3/2}\right)$$

$\Rightarrow$ M_a are dominated by F^{T_2} leading to

$$M_1 : M_2 : M_3 \simeq 1 : 2 : 6$$

But this large volume solution exists in the limit where the α'-expansion breaks down :

$$1 - \frac{\xi}{(T_2+T_2^*)^{3/2}} = \frac{1}{aT_2} + \mathcal{O}\left(\frac{1}{(aT_2)^2}\right)$$

D) Partial KKLT

KC & Jeong

$$K_0 = -2\ln\left[(T_1+T_1^*)^{3/2} - (T_2+T_2^*)^{3/2} - (T_3+T_3^*)^{3/2}\right]$$

$$W_0 = \omega_0 + A_1 e^{-a_1 T_1} + A_2 e^{-a_2(T_2+T_3)}$$

$$e^{4A}\mathcal{P}_0 = \text{constant}, \quad f_a = \sum_\alpha k_{a\alpha} T_\alpha$$

$\mathrm{Im}(T_2 - T_3)$ can be the QCD axion solving the strong CP problem.

$$\Rightarrow \quad m_{T_1} \simeq m_{T_2+T_3} \simeq 2\, m_{3/2} \ln(M_{Pl}/m_{3/2}),$$

$$\underbrace{m_{\mathrm{Re}(T_2-T_3)}}_{\text{saxion}} \simeq \sqrt{2}\, m_{3/2},$$

$$\text{but} \quad \frac{F^{T_1}}{T_1+T_1^*} = \frac{F^{T_2}}{T_2+T_2^*} = \frac{F^{T_3}}{T_3+T_3^*} = \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})}$$

$$\& \quad F^C = m_{3/2}$$

$\Rightarrow$ Mirage pattern

$$M_1 : M_2 : M_3 \simeq 1 : 1.2 : 2.5$$

- Generic Partial KKLT KC & Jeong

$$K_0 = K_0(T_I + T_I^*) \qquad (T_I = \{T_\alpha, T_p\})$$

$$Y_i = Y_i(T_I + T_I^*)$$

$$W_0 = \omega_0 + \sum_\alpha A_\alpha e^{-a_\alpha T_\alpha}$$

$$f_a = \sum_I k_{aI} T_I$$

$$e^{4A} \rho_0 = \text{constant}$$

Axionic shift symmetries : $T_I \to T_I + i\beta_I$

- k_{aI} & a_α are discrete real numbers.
- ω_0 & A_α can be made real.

Scaling properties : $T_I \to e^\lambda T_I$

$$K_0 \to K_0 - 3\lambda, \quad Y_i \to e^{n_i \lambda} Y_i$$

(n_i are flavor universal.)

$$\Rightarrow \quad \frac{F^{T_I}}{T_I + T_I^*} = \frac{m_{3/2}}{\ln(M_{Pl}/m_{3/2})} \equiv M_0$$

(universal at leading order in $\frac{1}{\ln(M_{Pl}/m_{3/2})}$)

$$F^C = m_{3/2}$$

$\Rightarrow$ Flavor & CP-conserving Mirage Mediation with a QCD axion :

* $\partial_I K_0$, $\partial_I Y_i$, $\partial_I f_a$, $\underbrace{\omega_0, A_\alpha, a_\alpha}^{W_0}$, $\partial_I V_{lift}$ are all real $\Rightarrow$ CP-conserving soft terms

* At M_{GUT},

$$M_a = M_0 + \frac{m_{3/2}}{16\pi^2} b_a g_{GUT}^2 + \mathcal{O}\left(\frac{M_0}{8\pi^2}\right)$$

$$A_{ijk} = (n_i + n_j + n_k) M_0 - \frac{m_{3/2}}{16\pi^2}(\gamma_i + \gamma_j + \gamma_k) + \mathcal{O}\left(\frac{M_0}{8\pi^2}\right)$$

$$m_i^2 = n_i M_0^2 - \frac{m_{3/2}}{4\pi^2} M_0 \left(\sum_a g_{GUT}^2 C_2^a(Q^i) - \frac{1}{4}\sum_{jk} |y_{ijk}|^2 (n_i + n_j + n_k) \right) - \frac{m_{3/2}^2}{32\pi^2} \frac{d\gamma_i}{d\ln\mu} + \mathcal{O}\left(\frac{M_0^2}{8\pi^2}\right)$$

Subsequent RG running KC, Jeong, Okumura

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

$$A_{ijk}(\mu) = M_0 \left[(n_i + n_j + n_k) + \frac{1}{8\pi^2}\left(\gamma_i(\mu) + \gamma_j(\mu) + \gamma_k(\mu)\right) \ln\left(\frac{M_{mir}}{\mu}\right) \right]$$

$$m_i^2 = M_0^2 \left[n_i + \frac{1}{4\pi^2}\left\{ \gamma_i(\mu) - \frac{1}{2}\dot{\gamma}_i(\mu) \ln\left(\frac{M_{mir}}{\mu}\right)\right\} \times \ln\left(\frac{M_{mir}}{\mu}\right) \right] \leftarrow y_{ijk} \ll 1$$

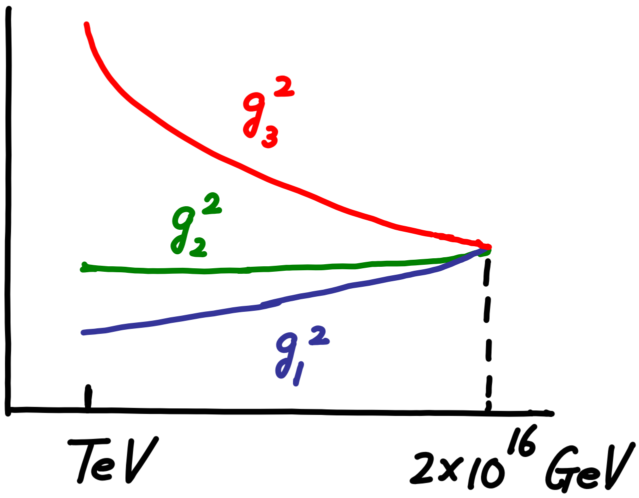
$\Rightarrow$ Mirage moduli mediation with messenger scale

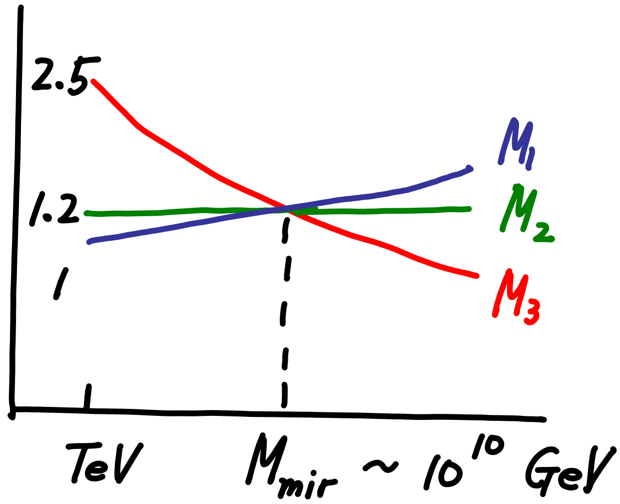
$$M_{mir} = M_{GUT} \left(m_{3/2} / M_{Pl} \right)^{\alpha/2}$$

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

* KKLT & Partial KKLT predict $\alpha \simeq 1$.

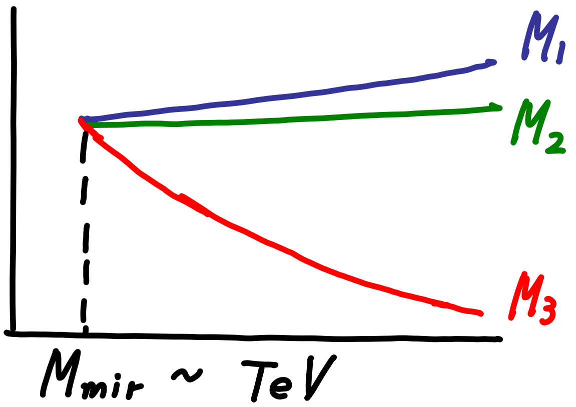
$\Rightarrow$ Intermediate scale mirage mediation.





* TeV scale mirage mediation ($\alpha \simeq 2$)

KC, Jeong, Kobayashi, Okumura ; Kitano, Nomura



This scheme significantly reduces the fine-tuning for the EWSB in MSSM.