Soft SUSY breaking terms in KKLT flux compactification

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& in preparation

- Motivation & Background
- KKLT flux compactification models
(Kachru, Kallosh, Linde, Trivedi)
  - Couplings & Scales
  - Weak scale SUSY with small C.C
- Pattern of soft terms
- Summary

• Motivation & Background

Moduli stabilisation & SUSY breaking

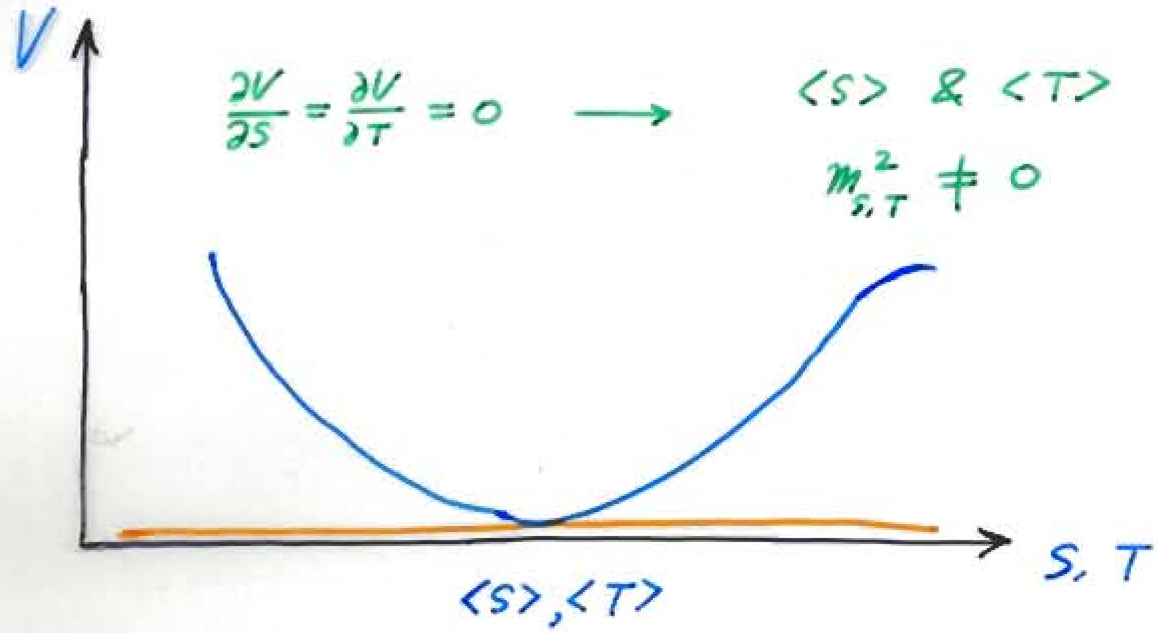
Moduli : 4D scalar fields describing flat directions of supersymmetric string vacua

$S \sim e^{-\phi}$ (dilaton)

$T \sim R^n$ (Volume modulus)

compactification radius

We don't see any (almost) massless scalar, so the vacuum degeneracy should be lifted.



Some moduli can be fixed by nonperturbative dynamics.

(cf: nonrenormalization theorem)

Racetrack (multi gaugino condensation)

Krasnikov;

Casas, Lalak, Munoz & Ross; ...

$$W = \frac{A_1 e^{-a_1 S} + A_2 e^{-a_2 S}}{\eta(T)^6}$$

$$\rightarrow \quad \langle S \rangle \sim \frac{25}{4\pi}, \quad \langle T \rangle \sim \frac{1.2}{4\pi}$$

$$\left(\begin{array}{l} S_{\text{self-dual}} = T_{\text{self-dual}} = \frac{1}{4\pi} \\ S \equiv S + \frac{i}{4\pi}, \quad T \equiv T + \frac{i}{4\pi} \end{array} \right)$$

$$\frac{F^S}{S+\bar{S}} = 0, \quad \frac{F^T}{T+\bar{T}} \sim m_{3/2} \sim 1\ \text{TeV}$$

$\frac{m_{3/2}}{M_{Pl}} \sim e^{-\frac{8\pi^2}{bg^2}}$ is naturally small, however

typically • $\langle V \rangle = -\mathcal{O}(m_{3/2}^2 M_{Pl}^2)$

(AdS vacuum)

• difficult to stabilize all moduli

(including complex structure moduli)

String vacua with fluxes

Flux has been considered at the very early stage of heterotic string compactification

Derendinger, Ibanez, Nilles ; Dine, Rohm, Seiberg, Witten ; Rohm, Witten

$$H_3 = dB - (\omega_3^{YM} + \omega_3^{L})$$

$$\frac{1}{4\pi^2\alpha'}\int_{C_3} dB = n \ , \quad \frac{1}{4\pi^2\alpha'}\int_{C_3} \omega_3^{YM} = m$$

(for flat YM bundle)

It has been realized that NS-flux can be useful for dilaton stabilisation & SUSY breaking, however this was not taken seriously since it generically gives

$$M_{SUSY} \sim M_{st}$$ (Fluxes are quantized !)

But in the presence of many independent fluxes, an extremely small energy gap between different vacua is possible even when each flux has a size of $\mathcal{O}(M_{st})$!

Bousso & Polchinski (2000)

Generic set of fluxes :

$$\frac{1}{4\pi^2\alpha'}\int_{C_k} F_{(k)} = n_k$$

$n_k = 0, \cdots, L \quad (= \mathcal{O}(10^2 \sim 10^3))$

$k = 1, 2, \cdots, N \quad (= \mathcal{O}(10^2))$

Total # of discrete vacua $\quad N_{vac} \sim L^N$

$$N_{vac}(\langle V\rangle \leq \epsilon M_{st}^4) \sim \epsilon L^N$$

$$N_{vac}(\langle W\rangle \leq \tilde{\epsilon} M_{st}^3) \sim \tilde{\epsilon}^2 L^N$$

Ashok & Douglas ; Denef & Douglas (2004)

Type IIB on CY orientifold with NS & RR flux

$$\frac{1}{4\pi^2\alpha'}\int_{C_3} H_3 = n \quad , \quad \frac{1}{4\pi^2\alpha'}\int_{C_3} F_3 = m$$

- Provides a landscape of string vacua which is huge enough ($N_{vac} \sim 100^{100}$) to accomodate a vacuum with $\langle V \rangle \sim (3\times 10^{-3}\, eV)^4$

  (Weinberg's anthropic explanation for small C.C)

- Typically stabilize the dilaton & all complex structure moduli (CSM) :

$$CSM \sim Vol(C_3)$$

SL(2,Z) S-duality ($ad-bc=1$)

$$\begin{pmatrix} H_3 \\ F_3 \end{pmatrix} \longrightarrow \begin{pmatrix} a & b \\ c & d \end{pmatrix}\begin{pmatrix} H_3 \\ F_3 \end{pmatrix}$$

- Can generate warped geometry :

  Giddings, Kachru, Polchinski

$$ds^2_{(10)} = e^{2A(y)}\eta_{\mu\nu}\,dx^\mu dx^\nu + e^{-2A(y)}\tilde{g}_{mn}\,dy^m dy^n$$

$$e^{A_{min}} \sim e^{-4\pi n/(s+\bar{s})m}$$

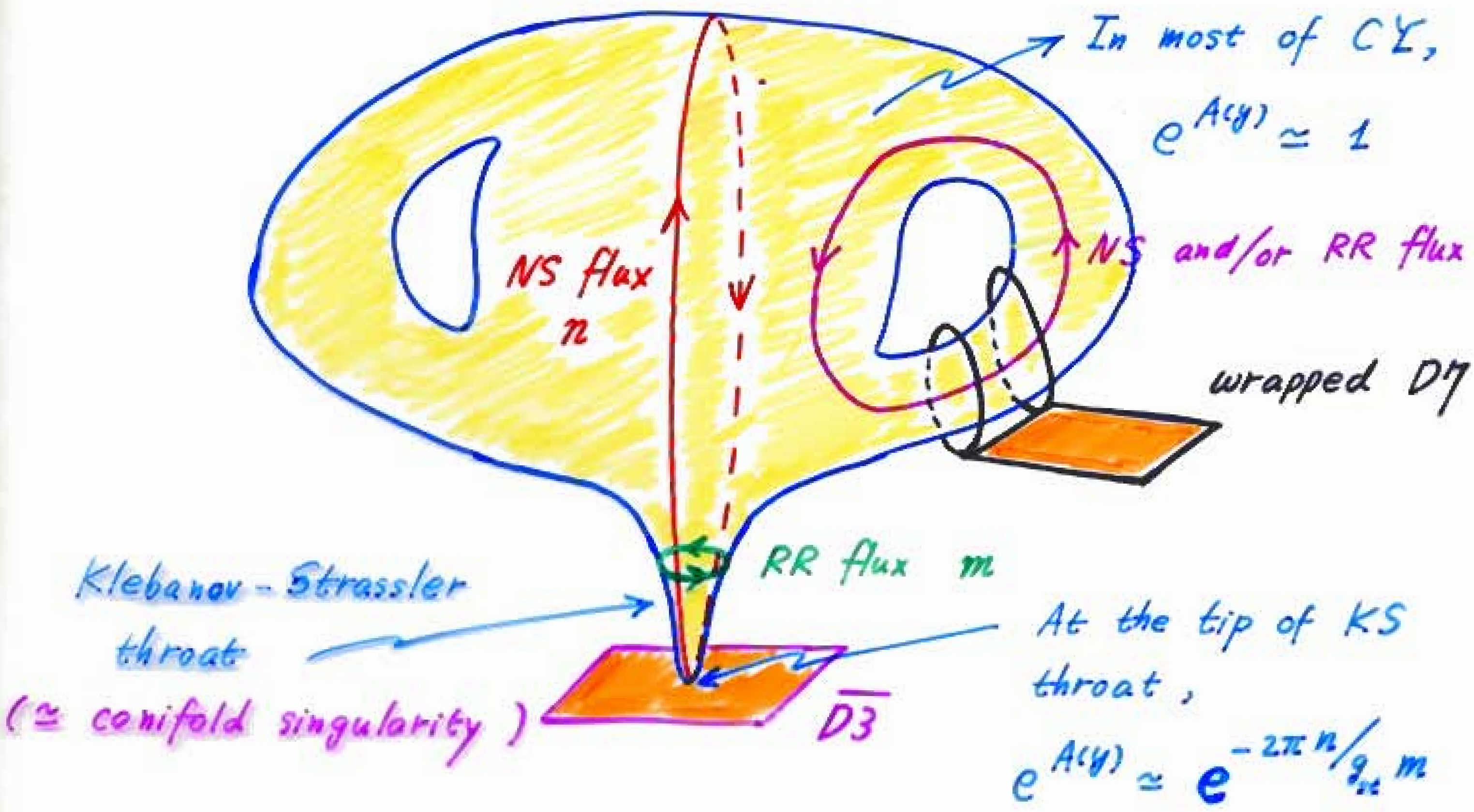
♦ KKLT flux compactification

(with low energy SUSY & almost vanishing vacuum energy density)

Type IIB on CY orientifold with

- NS & RR 3-form fluxes
- D7/D3 → hidden gaugino condensations + visible (MSSM) sector
- $\overline{D3}$

$$ds^2 = e^{2A(y)}(M_{st}R)^{-6}\, \underbrace{g^{(E)}_{\mu\nu}}_{\text{4D Einstein frame metric}}\, dx^\mu dx^\nu + e^{-2A(y)}(M_{st}R)^2\, \underbrace{\tilde{g}_{mn}}_{\int\sqrt{\tilde{g}}\, d^6y \,=\, M_{st}^{-6}}\, dy^m dy^n$$



- Moduli

Bulk : $\overset{\text{dilaton}}{S} = \frac{1}{2\pi} \underbrace{e^{-\phi}}_{g_{st}} + i C_0$

$\overset{\text{Kähler}}{T} = \frac{1}{2\pi} e^{-\phi} (\underbrace{M_{st} R}_{})^4 + i C_4$ ← 4-cycle volume

$\overset{\text{Complex structure}}{Z^\alpha}$

D7/D3 : $\Phi_{7,3}$ $\qquad \overline{D3}$: $\Phi_{\bar{3}}$

- Couplings & Scales

$$M_{Pl}^2 \sim e^{-2\phi} M_{st}^8 R^6 \simeq 4\pi S^{1/2} T^{3/2} M_{st}^2$$

for D7 wrapping 4-cycle

$$\frac{1}{g_7^2} = T \quad , \quad \frac{1}{g_3^2} = S$$

Kähler potential of bulk moduli

$$K = -\ln(S+\bar{S}) - 3\ln(T+\bar{T}) - \ln i \int \Omega \wedge \bar{\Omega}$$

★ Step I : Stabilize S & Z^α

$\boxed{\text{Flux}} \longrightarrow \langle Z^\alpha \rangle$ & $\langle S \rangle \longrightarrow G_3 = i {}^* G_3$ (ISD)

$(G_3 = F_3 - i S H_3)$

$$W_{flux} = \int_{CY} (F_3 - i S H_3) \wedge \Omega = A(Z^\alpha; m) + S B(Z^\alpha; n)$$

Kähler covariant derivative $\partial_Z W_{flux} + (\partial_Z K) W_{flux}$

$$D_Z W_{flux} \Big|_{Z=\langle Z \rangle,\, S=\langle S \rangle} = 0 \longrightarrow \int G_3 \wedge \chi^\alpha = 0$$

$$D_S W_{flux} \Big|_{Z=\langle Z \rangle,\, S=\langle S \rangle} = 0 \longrightarrow \int \bar{G}_3 \wedge \Omega = 0$$

$\longrightarrow$ ISD $G_3 = G_{(2,1)} + G_{(0,3)}$

- Mass scales generated in Step I

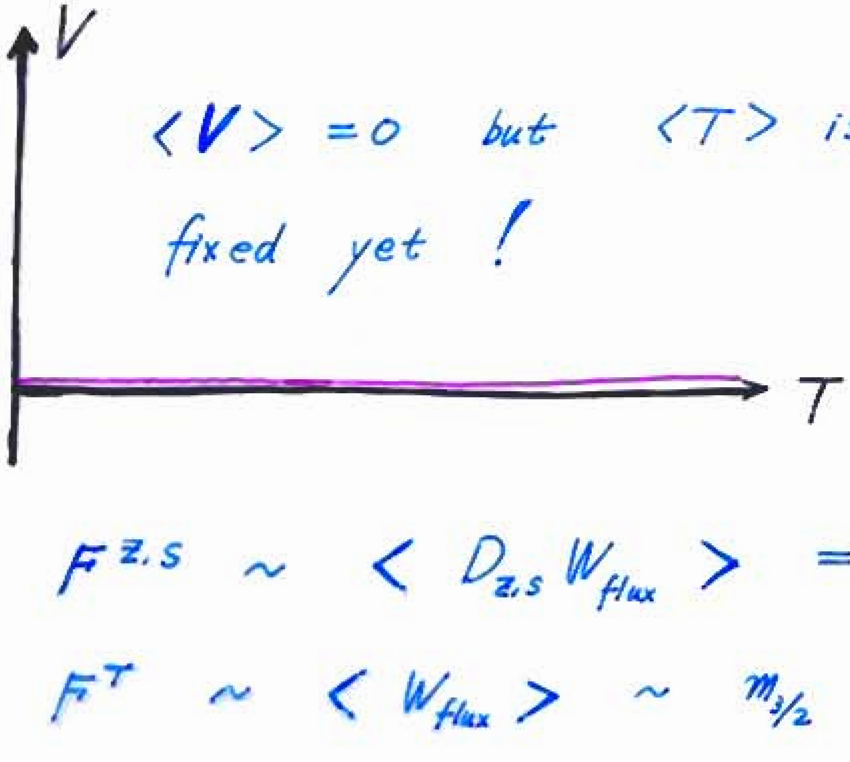
$$m_z \sim M_{pl}\, e^{\frac{K}{2}} \frac{\partial_z^2 W_{flux}}{\partial_z \partial_{\bar z} K} \sim \frac{g_{st} M_{st}}{(M_{st} R)^3}$$

$$(m_{S,\Phi_i} \sim m_z)$$

$$m_{3/2} = M_{pl}\, e^{\frac{K}{2}} W_{flux} \sim \frac{g_{st} M_{st}}{(M_{st} R)^3} \frac{|G_{(0,3)}|}{|G_3|}$$

$$\left(\langle W_{flux} \rangle = \langle \int G_3 \wedge \Omega \rangle = \int G_{(0,3)} \wedge \Omega \right)$$

$m_T = 0$: No scale flat-direction



$$F^{z,s} \sim \langle D_{z,s} W_{flux} \rangle = 0$$

$$F^T \sim \langle W_{flux} \rangle \sim m_{3/2} \;(\propto G_{(0,3)})$$

- Flux configurations should be tuned to yield $G_{(0,3)} \ll G_{(2,1)}$ for low energy SUSY !
- Need additional dynamics depending on the volume of 4-cycle $(\propto T)$ to fix $\langle T \rangle$!

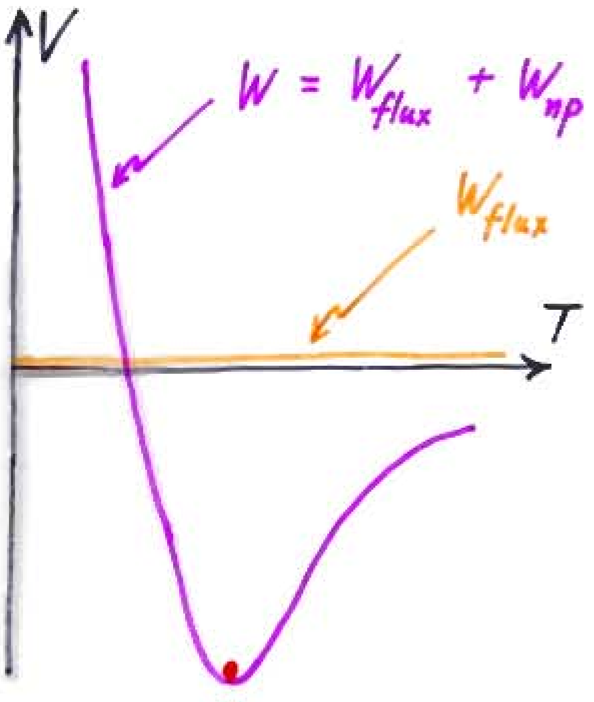
★ Step II : Stabilize T

Nonperturbative dynamics depending on the size of 4-cycle $\longrightarrow$ $W_{np} = C e^{-aT}$ $(C \sim 1)$

D7 gaugino condensation : $aT = \frac{8\pi^2}{N} T$

D3 brane instanton : $aT = 8\pi^2 T$

$\left(m_T \sim \langle aT \rangle m_{3/2} \sim 4\pi^2 m_{3/2} \right)$



$$\langle aT \rangle \simeq \ln \frac{C}{G_{(3,0)}}$$

$$\simeq \ln \frac{M_{pl}}{m_{3/2}} = \mathcal{O}(4\pi^2)$$

$$F^T \sim \langle D_T W \rangle = 0$$

(SUSY is recovered !)

$$\langle W \rangle \sim G_{(3,0)} \neq 0$$

SUSY AdS vacuum :

$$V = e^K \left[K^{I\bar{J}} D_I W (D_J W)^* - 3|W|^2 \right] < 0$$

$$\left(D_S W = D_Z W = D_T W = 0 \quad \& \quad W \neq 0 \right)$$

F^T from $G_{(0,3)}$ is dynamically cancelled by W_{np} :

hidden gaugino on D7

$$\bar{\lambda} \left[G_{(0,3)} + \langle \lambda_h \lambda_h \rangle \right] \lambda = 0$$

visible gaugino on D7

★ Step III : Uplift

Uplifting to SUSY-breaking Minkowski vacuum
(or dS)

- $\overline{D3}$ (KKLT)
- FI D-term (Burgess, Kallosh, Quevedo)
  ↳ D7 magnetic flux

- Most general U(1) FI D-term in 4D SUGRA

GS parameter

$$A_\mu \to A_\mu + \partial_\mu \alpha \,, \quad \Phi \to \Phi + i\,\delta_{GS}\,\alpha(x)$$

$U(1)_R$ charge

$$Q \to e^{iq\alpha(x)} Q \,, \quad W \to e^{-i g_R \alpha(x)} W$$

Anomalous U(1) FI

$$\to \quad D = g_R - \frac{\partial K}{\partial \Phi}\delta_{GS} - \frac{\partial K}{\partial Q} q Q$$

↳ $U(1)_R$ FI

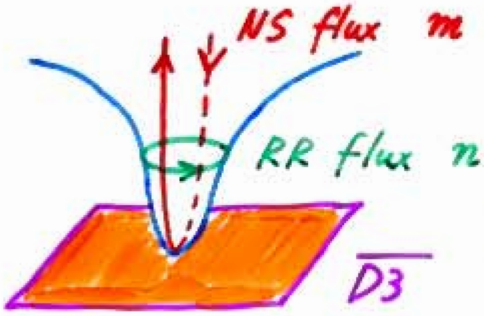
$W \neq 0$

$$= -\frac{1}{W}(D_I W)\frac{\delta \Phi^I}{i\,\delta\alpha(x)} \qquad (\Phi^I = \Phi, Q)$$

$$V = V_F + V_D = e^K\left[K^{I\bar{J}} D_I W (D_J W)^* - 3|W|^2\right] + \boxed{\frac{g^2}{2}\left[\frac{1}{W}(D_I W)\frac{\delta\Phi^I}{i\,\delta\alpha(x)}\right]^2}$$

If V_F gives a SUSY AdS vacuum as in KKLT situation ($D_I W = 0$ & $W \neq 0$), V_D does not affect the vacuum solution at all!

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



$$m_{\Sigma_3} \sim \frac{M_{st}}{(M_{st} R)^3} e^{-2\pi n / g_{st} m}$$

$$V_{\overline{D3}} \sim \Big(\underbrace{e^{-2\pi n / g_{st} m}}_{\simeq\, e^{A(y_{\overline{D3}})}} M_{st} \Big)^4$$

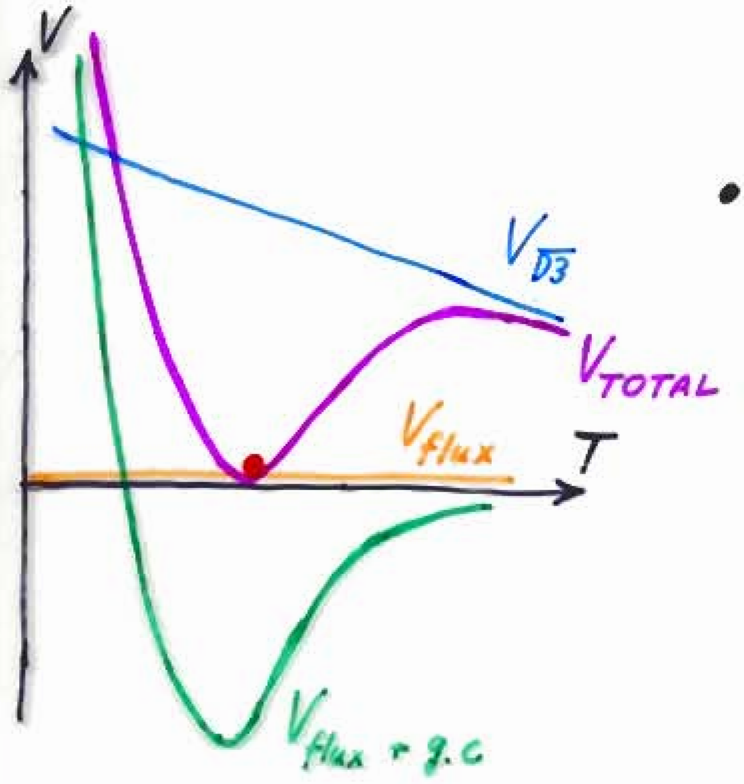
$$V_{TOTAL} = V_{\boxed{flux + g.c}} + V_{\overline{D3}}$$

$\leftarrow$ gaugino condensation

$$\simeq -3 m_{3/2}^2 M_{P\ell}^2 + V_{\overline{D3}} \simeq 0$$

$$\rightarrow \quad e^{A(y_{\overline{D3}})} \sim e^{-2\pi n / g_{st} m} \sim \sqrt{m_{3/2} / M_{P\ell}}$$

$$\left(\sim \sqrt{G_{(0,3)} / G_{(2,1)}} \right)$$



- $\Lambda_{flux} \sim \dfrac{M_{st}}{(M_{st} R)^3} \nearrow 10^{16}\,\mathrm{GeV}$
  (I)

  $\gg \Lambda_{g.c} \sim e^{-\frac{aT}{3}} M_{st} \nearrow 10^{13}\,\mathrm{GeV}$
  (II)

  $\gg \Lambda_{\overline{D3}} \sim e^{-2\pi n / g_{st} m} M_{st}$, $\searrow 10^{11}\,\mathrm{GeV}$
  (III)

so each step can be treated seperately.

Summary of couplings & scales in KKLT

(with weak scale SUSY)

- M_{st} (stringy exitation) $\quad 10^{17}$ GeV
- $\frac{1}{R}$ (KK exitation)
- $m_{Z,S,\Sigma_\eta} \sim \frac{M_{st}}{(M_{st} R)^3}$ (flux) $\quad 10^{16}$ GeV
- $\Lambda_{\overline{D3}} \sim M_{st} \sqrt{m_{3/2}/M_{st}}$ ($\overline{D3}$) $\quad 10^{11}$ GeV
- $m_T \sim m_{3/2} \ln (M_{st}/m_{3/2})$ $\quad 10^{6}$ GeV
- $m_{3/2} \sim \frac{M_{st}}{(M_{st} R)^3} \left(\frac{G_{(0,3)}}{G_{(2,1)}} \right)$ $\quad 10^{4}$ GeV
- $m_{soft} \sim M_{weak} \sim \frac{m_{3/2}}{\ln (M_{st}/m_{3/2})}$ $\quad 10^{2}$ GeV

$$\frac{1}{\alpha_3} \sim e^{-\phi}$$

$$\frac{1}{\alpha_7} \sim e^{-\phi} (M_{st} R)^4$$

$$M_{Pl}^2 \sim \frac{1}{4\pi} \frac{1}{\alpha_3^{1/2} \alpha_7^{3/2}} M_{st}^2$$

- $\Lambda_{g.c} \sim M_{st} \left(m_{3/2} / M_{st} \right)^{1/3}$ $\quad 10^{13}$ GeV

(hidden gaugino condensation)

♦ Pattern of Soft Terms

* 4D effective action of light fields with

$m \ll m_{s,z,\mathcal{I}_7} \sim M_{st}/(M_{st}R)^3$ ($\sim 10^{16}$ GeV):

4D SUGRA + T + D7/D3 matter & gauge + $\overline{D3}$

$$S = \int d^{10}x \, [\mathcal{L}_{IIB} + \delta^2(z-z_7)\mathcal{L}_{D7} + \delta^6(y-y_3)\mathcal{L}_{D3} + \delta^6(y-\bar{y}_3)\mathcal{L}_{\overline{D3}}]$$

$$= S_{N=1}[IIB, D7, D3] + S_{\overline{D3}}$$

$$ds^2 = e^{2A(y)} T^{-1/2} g^{(C)}_{\mu\nu} dx^\mu dx^\nu + e^{-2A(y)} T^{1/2} \tilde{g}_{mn} dy^m dy^n$$

$$S_{N=1} = \int d^4x \sqrt{-g^{(C)}} \Big[\int d^4\theta \, C\bar{C} \left(-3 e^{-\frac{K}{3}} \right)$$

chiral compensator

$$+ \int d^2\theta \left(\tfrac{1}{4} f_a W^{a\alpha} W^a_\alpha + C^3 W \right) + h.c \Big]$$

- Super-Weyl : $C \to e^{-\tau} C$, $g^{(C)}_{\mu\nu} \to e^{(\tau+\bar{\tau})} g^{(C)}_{\mu\nu}$

  $\theta^2 \to e^{(2\bar{\tau}-\tau)}\theta^2$, $W^{a\alpha} \to e^{-\frac{3}{2}\tau} W^{a\alpha}$

- $$-3e^{-\frac{K}{3}} = -3(T+\bar{T}) + (T+\bar{T})\overline{Q}_7 Q_7 + \overline{Q}_3 Q_3$$

  D7 matter

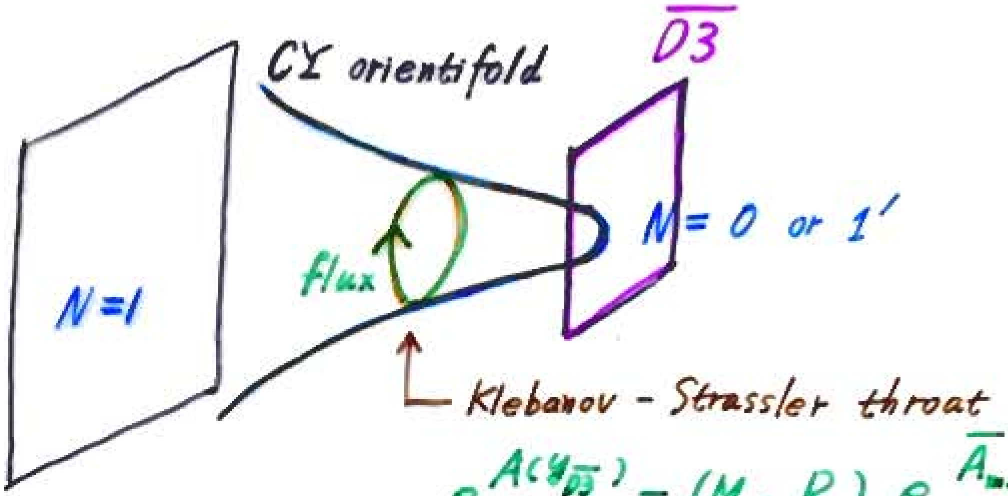
  $K = -3\ln(T+\bar{T}) + \cdots$, $T \sim (M_{st}R)^4$

$$f_7 = T \quad , \quad f_3 = \langle S \rangle = \text{const}$$

D7 gaugino condensation

$$W = W_0 + C e^{-aT} + \tfrac{1}{6}\lambda_3 Q_3 Q_3 Q_3 + \tfrac{1}{6}\lambda_7 Q_7 Q_7 Q_7$$

flux



D7/D3

$$e^{A(y_{\overline{D3}})} = (M_{st} R)\, e^{\overline{A}_{min}} = (M_{st} R)\, e^{-2\pi n / g_{st} m}$$

$\overline{D3}$ breaks explicitly the $N=1$ SUSY preserved by

$S_{N=1}[\text{IIB}, D7/D3]$ (flux + gaugino condensation)

$$S_{\overline{D3}} = \int d^{10}x\, \delta^6(y - \bar{y}_3)\, \mathcal{L}_{\overline{D3}} = \int d^4x \sqrt{-g_{(4)}}\, e^{-\phi}\left[M_{st}^4 + \cdots \right]$$

coupling of $N=1$ SUGRA to a local explicit SUSY

$$= \int d^4x \sqrt{-g^{(c)}} \left[\int d^4\theta \left\{ (C\bar{C})^2 e^{4\overline{A}_{min}} \theta^2 \bar{\theta}^2 \tilde{P}(T,\bar{T}) + C^3 e^{3\overline{A}_{min}} \tilde{F}(T,\bar{T})\, \bar{\theta}^2 + h.c \right\} \right]$$

$\overline{D3}$ may contain a Goldstino ($\lambda_{\overline{D3}}$) with which

$N=1$ SUSY is non-linearly realized on $\overline{D3}$-world volume :

$$\theta^\alpha \longrightarrow \Lambda^\alpha \equiv \theta^\alpha + \frac{1}{\overline{M}^2} \bar{\lambda}^\alpha + \cdots$$

Goldstino superfield

$$\theta^2\bar{\theta}^2 \longrightarrow \Lambda^2 \bar{\Lambda}^2$$

$$\theta^2 \longrightarrow (\bar{\mathcal{D}}^2 - 8R)(\Lambda^2 \bar{\Lambda}^2)$$

$$S_{\overline{D3}} \longrightarrow \text{Samuel-Wess action (1983)}$$

$\overline{D3}$ does not have a direct contact interaction with visible fields on $D7$ (or $D3$).

- $\overline{D3} \longrightarrow F^T$ & $F^C \longrightarrow D7/D3$

(in bulk CY)

In Einstein frame

contribution from $N=0$ $\overline{D3}$

$$m_{3/2} = e^{\frac{K}{2}} (W + e^{3\bar{A}_{min}} \tilde{F})$$

contribution from $N=1$ sector (flux + g.c)

$$\simeq e^{\frac{K}{2}} W$$

$W \sim e^{2\bar{A}_{min}}$, so $\tilde{F}$ is irrelevant!

$$\frac{F^C}{C} = \frac{1}{3}(\partial_I K) F^I + e^{\frac{K}{2}} (W + e^{3\bar{A}_{min}} \tilde{F})$$

$$\simeq \frac{1}{3}(\partial_I K) F^I + e^{\frac{K}{2}} W$$

$$F^I = -e^{\frac{K}{2}} K^{I\bar{J}} \left(D_J (W + e^{3\bar{A}_{min}} \tilde{F})\right)^*$$

$$\simeq -e^{\frac{K}{2}} K^{I\bar{J}} (D_J W)^*$$

$$V = e^K \left[K^{I\bar{J}} D_I (W + e^{3\bar{A}_{min}} \tilde{F}) (D_J (W + e^{3\bar{A}_{min}} \tilde{F}))^* - 3 |W + e^{3\bar{A}_{min}} \tilde{F}|^2 \right] + e^{4\bar{A}_{min}} e^{2K/3} \tilde{P}$$

$$\simeq e^K \left[K^{I\bar{J}} D_I W (D_J W)^* - 3 |W|^2 \right] \equiv V_F$$

$V_{flux+g.c}$

$$+ \boxed{e^{4\bar{A}_{min}} e^{2K/3} \tilde{P}} \longleftarrow V_{\overline{D3}}$$

Matching $\overline{D3}$ tension :

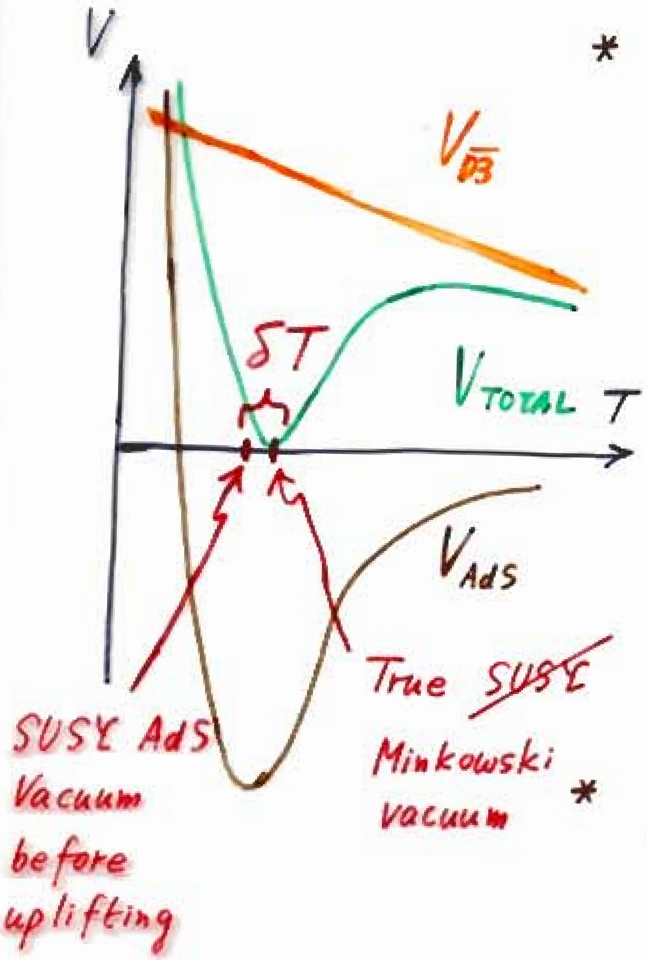
$$\int_{\overline{D3}} d^4x \sqrt{-g_{(st)}}\, M_{st}^4 \overset{\downarrow}{=} \int d^4x \sqrt{-g^{(c)}}\, e^{4A_{min}} (M_{st}R)^{-4} M_{st}^4 \qquad g_{(st)\mu\nu} = e^{2A(y)} (M_{st}R)^{-2} g^{(c)}_{\mu\nu}$$

$$= \int d^4x \sqrt{-g^{(c)}}\, e^{4\bar{A}_{min}} M_{st}^4 \equiv \int d^4x \sqrt{-g^{(c)}}\, e^{4\bar{A}_{min}} \tilde{P}$$

$$e^{A_{min}} = (M_{st}R)\, e^{\bar{A}_{min}} \sim (M_{st}R)\, e^{-2\pi n / g_{st} m}$$

$\Rightarrow \quad \tilde{P} = \text{constant of } \mathcal{O}(M_{st}^4)$

$\Rightarrow \quad V_{\overline{D3}} = e^{2K/3}\, e^{4\bar{A}_{min}} M_{st}^4 \propto \dfrac{1}{(T+\bar{T})^2}$



* $W_0 = \omega + C e^{-aT}$

$$\frac{\delta T}{T} \sim \frac{1}{\langle aT \rangle^2} \sim \frac{1}{\left(\ln (M_{st}/m_{3/2})\right)^2}$$

$$\frac{F^T}{T+\bar{T}} \sim \frac{m_{3/2}}{\langle aT \rangle} \sim \frac{1}{4\pi^2} \frac{F^C}{C}$$

$$\left(\frac{m_{3/2}}{M_{st}} \sim e^{-aT} \sim e^{-4\pi^2} \right)$$

* $W_0 = C_1 e^{-a_1 T} + C_2 e^{-a_2 T}$

$$\frac{F^T}{T+\bar{T}} \sim \frac{m_{3/2}}{\langle aT \rangle^2} \sim \frac{1}{(4\pi^2)^2} \frac{F^C}{C}$$

$\Rightarrow$ Anomaly mediation $\simeq$ Modulus mediation

* Soft terms of visible fields on D7/D3

$$\mathcal{L}_{visible} = \int d^4\theta \left[Y_Q \bar{Q} Q + \frac{1}{16}\left(G_a W^{a\alpha} \frac{D^2}{\partial^2} W^a_\alpha + h.c \right) \right.$$

$$+ \int d^2\theta \; \lambda_Q QQQ + h.c$$

$$G_a = \mathrm{Re}\, f_a - \frac{b_a}{16\pi^2} \ln\left(\frac{CC^*}{\mu^2} \right)$$

$$\ln Y_Q = \ln Y_Q^{tree} - \frac{1}{8\pi^2}\left(\sum_a \frac{T_a(Q)}{\mathrm{Re}\, f_a} - \sum_Q \sum_Q \frac{|\lambda_Q|^2}{Y_Q Y_Q Y_Q} \right)$$

canonical Yukawa coupling

$$y_Q = \frac{\lambda_Q}{\sqrt{Y_Q Y_Q Y_Q}} \quad , \quad \frac{1}{g_a^2} = \langle G_a \rangle$$

$$\mathcal{L}_{soft} = -\left[\frac{1}{2} M_a \lambda^a \lambda^a + y_Q A_Q \tilde{Q}\tilde{Q}\tilde{Q} + \frac{1}{2} m_Q^2 \tilde{Q}\tilde{Q}^* \right]$$

$$+ h.c$$

$$M_a = F^A \partial_A \ln G_a \qquad (A = T, C)$$

$$A_Q = - F^A \partial_A \ln\left(\frac{\lambda_Q}{Y_Q Y_Q Y_Q} \right)$$

$$m_Q^2 = \frac{2}{3}(V_F + V_{\overline{D3}}) - F^A F^{\bar{B}} \partial_A \partial_{\bar{B}} \ln Y_Q$$

$$= \boxed{\frac{2}{3} V_{\overline{D3}}} + \boxed{V_F + \left[m_{3/2}^2 - F^A F^{\bar{B}} \partial_A \partial_{\bar{B}} \ln Z_Q \right]}$$

$$-3 e^{-\frac{K}{3}} = -3 e^{-\frac{1}{3} K_0(T,T^*)} + Y_Q \bar{Q} Q$$

$$K = K_0(T,T^*) + Z_Q \bar{Q} Q$$

Kähler metric of Q

$$M_a \overset{\text{at } M_{GUT} \sim 10^{16}\text{ GeV}}{=} K_a^T \frac{F^T}{T+\bar{T}} + \underbrace{K_a^C \frac{F^C}{C}}$$

$$A_Q = a_Q^T \frac{F^T}{T+\bar{T}} + \underbrace{a_Q^C \frac{F^C}{C}}$$

$$m_Q^2 = h_Q^{TT} \left|\frac{F^T}{T+\bar{T}}\right|^2 + \left(h_Q^{TC} \frac{F^T}{T+\bar{T}}\left(\frac{F^C}{C}\right)^* + h.c \right)$$

$$+ \underbrace{h_Q^{CC} \left|\frac{F^C}{C}\right|^2}$$

UV-sensitive 1-loop threshold

$$K_7^T = 1 + \mathcal{O}\left(\frac{1}{8\pi^2}\right), \quad K_3^T = 0 + \mathcal{O}\left(\frac{1}{8\pi^2}\right)$$

$$K_a^C = \frac{b_a}{8\pi^2}$$: UV-insensitive anomaly-mediation

$$a_7^T = 3 + \mathcal{O}\left(\frac{1}{8\pi^2}\right), \quad a_3^T = 0 + \mathcal{O}\left(\frac{1}{8\pi^2}\right)$$

$$a_Q^C = -\frac{1}{16\pi^2}\left(\gamma_Q + \gamma_Q + \gamma_Q\right)$$

$$\frac{1}{8\pi^2}\gamma_Q = \frac{d\ln Y_Q}{d\ln\mu}$$

$$h_7^{TT} = 1 + \mathcal{O}\left(\frac{1}{8\pi^2}\right), \quad h_3^{TT} = 0 + \mathcal{O}\left(\frac{1}{8\pi^2}\right)$$

$$h_Q^{CC} = -\frac{1}{32\pi^2}\frac{d\gamma_Q}{d\ln\mu} = \mathcal{O}\left(\frac{1}{(8\pi^2)^2}\right)$$

$$h_7^{TC} = -\frac{1}{8\pi^2}\sum_a g_a^2 T_a(Q) + \frac{3}{32\pi^2}\sum_{Q_7}\sum_{Q_7}|y_Q|^2$$

If MSSM lives on D7 branes wrapping a common 4-cycle,

- modulus-mediation $\simeq$ anomaly-mediation
- flavor-independent

$$W_0 = \omega + Ce^{-aT} \quad , \quad C_1 e^{-a_1 T} + C_2 e^{-a_2 T}$$

$\mathrm{Im}(T)$ (axion) $\longrightarrow$ $\dfrac{\omega}{Ce^{-aT}} = \text{real}$

$$\frac{C_1 e^{-a_1 T}}{C_2 e^{-a_2 T}} = \text{real}$$

$\rightarrow$ $\left(\dfrac{F^C}{C}\right) \Big/ \left(\dfrac{F^T}{T+\bar{T}}\right) = \text{real}$

$\rightarrow$ No SUSY CP problem

- Detailed low energy phenomenology

KC & Okumura, in preparation

♦ Summary

KKLT model is a nice example of the following (more generic) scenario :

(I) Some (most) of moduli are stabilized at high scales ($\sim M_{st}$), while preserving (approximate) $N=1$ SUSY ($m_{3/2} \ll M_{st}$) : Flux

(II) Non-perturbative dynamics stabilize the few remained moduli (T), yielding a SUSY AdS vacuum :

Gaugino condensation on D7 : $e^{-\frac{8\pi^2}{Ng^2}} \sim \frac{m_{3/2}}{M_{st}}$

(III) SUSY AdS vacuum is uplifted to a ~~SUSY~~ Minkowski vacuum by additional dynamics : $\overline{D3}$

$$\underbrace{\frac{F^T}{T+\bar{T}}}_{\text{moduls-mediation}} \sim \frac{m_{3/2}}{\ln(M_{st}/m_{3/2})} \sim \underbrace{\frac{1}{4\pi^2}\frac{F^C}{C}}_{\text{anomaly-mediation}}$$

$$M_{1/2},\ A_a = \frac{F^T}{T+\bar{T}} + \frac{1}{4\pi^2}\frac{F^C}{C}$$

$$m_a^2 = \left|\frac{F^T}{T+\bar{T}}\right|^2 + \frac{F^T}{T+\bar{T}}\frac{1}{4\pi^2}\left(\frac{F^C}{C}\right)^* + \left|\frac{1}{4\pi^2}\frac{F^C}{C}\right|^2$$

- Naturally preserves flavor & CP
- Leads to highly predictive sparticle spectrums