

Title: Aspects of Moduli in String Compactifications - Lecture 2

Date: Jan 27, 2010 11:00 AM

URL: <http://pirsa.org/10010100>

Abstract:

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln(V_{\text{int}}) - \ln(S \Omega \bar{S}) - \ln(S + \bar{S})$$

$V =$ volume of Calabi-Yau in string units

$$W = \int G_{\text{int}} \Omega + \sum_{\text{KKLT}} A_i e^{-a_i \tau_i}$$

$$V = e^{2\sigma} \int \sqrt{g} = \int J \wedge J \wedge J$$

($W_0 \ll \int G_{\text{int}} \Omega$)

Vacuum energy:

Gravitino mass:

Kahler moduli mass:

Dilaton/complex structure mass:

Susy broken:

Fluxes

$$0$$

$$\frac{H_0}{V}$$

$$0 \text{ (used)}$$

$$-\frac{D^2 W}{V} \sim m_{\text{pl}}$$

Yes, $F^T \neq 0$

(KKLT) Fluxes + non-perturb.

$$-3 m_{\text{pl}}^2 M_{\text{p}}^2$$

$$-\frac{H_0}{V}$$

$$-m_{\text{pl}}^2 \left(\frac{H_0}{M_{\text{pl}}} \right)$$

$$-\frac{D^2 W}{V} \sim m_{\text{pl}}$$

No

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln \left(V \left(\frac{F}{S^2} \right) \right) - \ln(S \Omega \bar{S}) - \ln(S + \bar{S})$$

$$W = \int G_{\alpha\beta} \Omega + \sum_{\text{KKLT}} A_i e^{-a_i \tau_i}$$

V = volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int_G \sqrt{g} = \int J \wedge J \wedge J$$

($W_0 = \langle S G_{\alpha\beta} \Omega \rangle$)

Vacuum energy:

Gravitino mass:

Kahler moduli mass:

Dilaton/complex structure mass:

Susy broken:

Fluxes

0

$\frac{H_0}{V}$

0 (used)

$-\frac{D D \bar{W}}{V} \sim m_{3/2}$

Yes, $F^T \neq 0$

(KKLT)
Fluxes + non-perturb.

$-3 m_{3/2}^2 M_P^2$

$-\frac{H_0}{V}$

$-m_{3/2} h \left(\frac{H_0}{M_{\text{pl}}} \right)$

$-\frac{D D \bar{W}}{V} \sim m_{3/2}$

No

Susy broken:

Yes, $F^T \neq 0$

No

Large volume

→ include α^3 correction to Kähler potential

$$W = \int G_{\text{grav}} \Omega + \sum_{\text{KKLT}} A_i e^{-a_i \tau}$$

(Note $\langle S_{\text{grav}} \rangle$)

Vacuum energy:

Gravitino mass:

Kähler moduli mass:

Dilaton/complex structure mass:

Susy breaking:

KKLT

Fluxes

0

$\frac{H_0}{V}$

0 (unfixed)

$-\frac{DDW}{V} \sim m_{\text{pl}}$

Yes, $F^T \neq 0$

(KKLT)
Flux-minimization

$-3 m_{\text{pl}}^2 M_{\text{pl}}^2$

$-\frac{H_0}{V}$

$-m_{\text{pl}}^2 \left(\frac{H_0}{m_{\text{pl}}} \right)$

$-\frac{DDW}{V} \sim m_{\text{pl}}$

No

in string units

$$V = e^{2\sigma} \int G^2 = \int J \wedge J \wedge J$$

Large Volume

→ include α'^3 correction to Kähler potential

Dilute/complex structure mass: $-\frac{V \cdot V^{\dagger}}{V} = m_{\tilde{H}}$

$-\frac{V \cdot H^{\dagger}}{V} = m_{\tilde{H}_1}$

Susy broken: Yes, $F^{\dagger} \neq 0$

No

Volume

→ include α^3 correction to Kähler potential

Need at least 2 moduli, one 'big', one 'small'

Volume

blow-up

Large volume

→ include α^3 correction to Kähler potential

* Need at least 2 moduli, one 'big', one 'small'

Volume

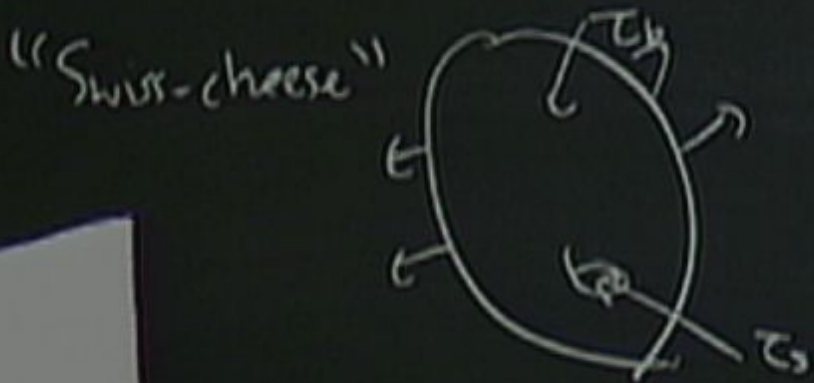
blow-up



LARGE Volume

→ include α'^3 correction to Kähler potential

* Need at least 2 moduli, one 'big', one 'small'



Volume

blow-up

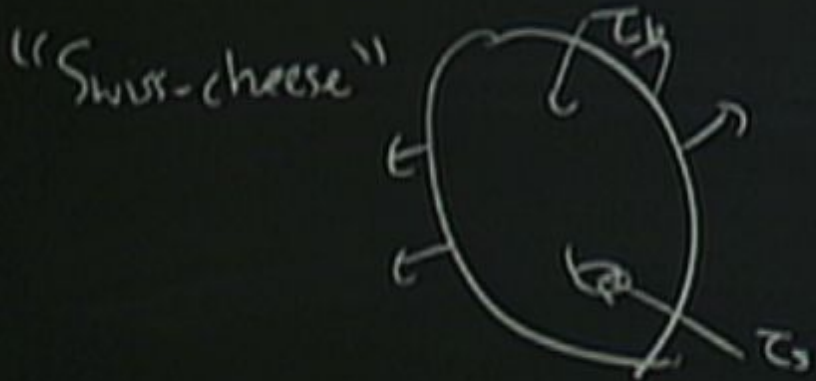
simplest case PP_1
 $(1, 1, 1, 6, 1)$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

Large Volume

→ include α'^3 correction to Kähler potential

* Need at least 2 moduli, one 'big', one 'small'
"Volume" "blow-up"



simplest case $(P^1 \times P^1, 1, 1, 1, 6, 4)$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

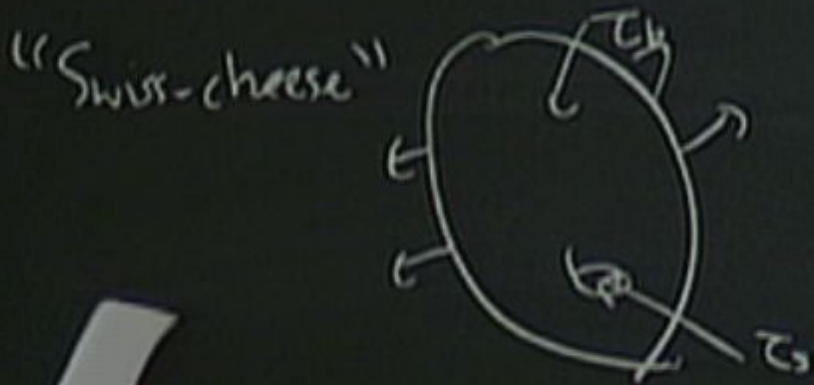
* Fix dilaton + complex structure moduli:

$$D_S W = D_U W = 0$$

Large Volume

→ include α'^3 correction to Kähler potential

* Need at least 2 moduli, one 'big', one 'small'



Volume "blow-up"

simplest case $(P^1 \times P^1, (1,1), (1,1))$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

* Fix dilaton + complex structure moduli:

$$D_S W = D_U W = 0$$

$$K = -2 \ln(V_{(4D)} + \frac{r}{g^2}) - \ln(S \Omega_n \bar{\Omega}) - \ln(S + \bar{r})$$

$$W = \int G_{mn} \Omega^m \Omega^n + \sum_{KKLT} A_{\nu} e^{-a T_{\nu}}$$

$V =$ volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int \Omega^m \Omega^n = \int J \wedge J \wedge J$$

$$\langle W \rangle \ll \int G_{mn} \Omega^m \Omega^n$$

Vacuum energy:

Gravitino mass:

Kähler moduli mass:

Dilaton/complex structure mass:

Susy broken:

Fluxes

$$0$$

$$\frac{H_0}{V}$$

$$0 \text{ (unfixed)}$$

$$-\frac{DDW}{V} \sim m_{\nu}$$

Yes, $F \neq 0$

(KKLT) Flux + non-perturb.

$$-3 m_{\text{pl}}^2 M_{\text{p}}^2$$

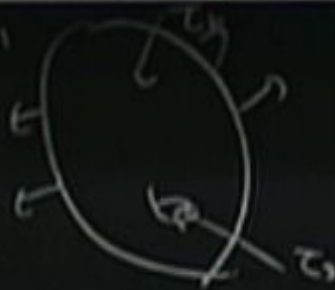
$$-\frac{H_0}{V}$$

$$= m_{\text{pl}} \ln\left(\frac{H_0}{m_{\text{pl}}}\right)$$

$$m_{\text{pl}}$$

$$K_{ij} = \begin{pmatrix} K_{-T} & & \\ & & \\ & & K_{\text{mod}} \end{pmatrix}$$

"Swiss-cheese"



Simple

blow-up

$(2, 1, 1/2, 1/2)$

$$\left(S^2 - \tau^2 \right)^{1/2}$$

* Fix dilaton + complex structure

D

$$K = -2 \ln(V(\frac{1}{g^2}) + \frac{7}{9}) - \ln(S \Omega_n \bar{\Omega}) - \ln(S + \bar{S})$$

$$W = \int G_n \Omega + \sum_{KKLT} A_i e^{-a T_i}$$

$V =$ volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int \Omega^3 = \int J \wedge J \wedge J$$

($W \ll S G_n \Omega$)

Vacuum energy:

Gravitino mass:

Kähler moduli mass:

Dilaton/complex structure mass:

Susy broken:

Fluxes

$$0$$

$$\frac{H_4}{V}$$

$$0 \text{ (unfixed)}$$

(KKLT) Fluxes + nonperturb.

$$-3 m_{3/2}^2 M_P^2$$

$$- \frac{H_4}{V}$$

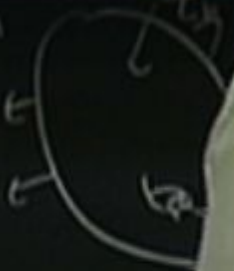
$$= m_{3/2} h \left(\frac{H_4}{m_{3/2} V} \right)$$

$$= \frac{D^2 \sigma}{V} = m_{3/2}$$

No

$$K_{ij} = \begin{pmatrix} K_{T\bar{T}} & 0 \\ 0 & K_{K\bar{K}} \end{pmatrix}$$

"Swiss-cheese"



Volume blow-up

best case $(P^1 \times \mathbb{C}P^1, \mathbb{C}P^1, \mathbb{C}P^1)$

$$V = \frac{1}{9\sqrt{2}} (\tau_6^{3/2} - \tau_5^{3/2})$$

* Fix dilaton + c

$$K = -2 \ln(V(\tau, \sigma) + \frac{1}{9\sqrt{2}}) - \ln(\det g_{\alpha\beta}) - \ln(\det \tau_{\alpha\beta})$$

$$W = \int G_{\alpha\beta} \Omega + \sum_{KKLT} A_i e^{-a_i T_i}$$

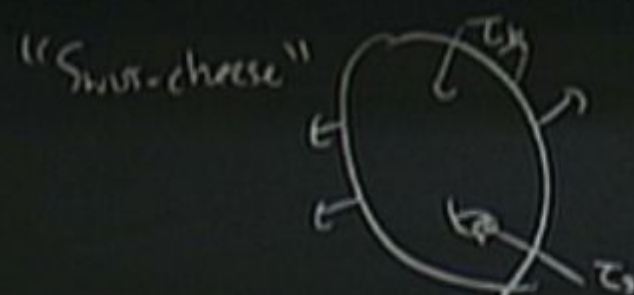
$V =$ volume of Calabi-Yau in string units
 $V = e^{2\sigma} \int \sqrt{g} = \int J \wedge J \wedge J$

$\langle W \rangle = \langle \int G_{\alpha\beta} \Omega \rangle$

	<u>Fluxes</u>	<u>(KKLT) Flux + non-perturb.</u>
Vacuum energy:	0	$-3 m_{pl}^2 M_p^2$
Gravitino mass:	$\frac{H_0}{V}$	$-\frac{H_0}{V}$
Kahler moduli mass:	0 (unfixed)	$-m_{pl} \ln(\frac{H_0}{M_{pl}})$
Dilaton/complex structure mass:	$-\frac{D^2 W}{V} = m_{pl}$	$-\frac{D^2 W}{V} = m_{pl}$
Susy broken:	Yes, $F^i \neq 0$	No

$$K_{ij} = \begin{pmatrix} K_{\tau\tau} & 0 \\ 0 & K_{\sigma\sigma} \end{pmatrix}$$

at least 2 moduli, one 'big', one 'small'
 Volume "blow-up"



simplest case (τ_1, τ_2)

$$V = \frac{1}{9\sqrt{2}} (\tau_1^{3/2} - \tau_2^{3/2})$$

* Fix dilaton + complex structure moduli:
 $D_S W = D_U W = 0$

$$K = -2 \ln \left(\frac{(T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2}}{T_s} \right)$$

$$W = W_0 + A e^{-nT_s}$$

$$K = -2 \ln \left((T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{c}{2} \right)$$

$$W = W_0 + A e^{-a T_s}$$

→ work out scalar potential

$$V = \frac{\sqrt{T_s} A^2 e^{-2a T_s}}{v} - \frac{a T_s A e^{-a T_s} W_0}{v^2} + \frac{c}{v^3} W_0^2$$

* axion

$$K = -2 \ln \left((T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{4}{3} \right)$$

$$W = W_0 + A e^{-a T_s}$$

→ Work out scalar potential

$$V = \frac{\sqrt{T_s} A^2 e^{-2a T_s}}{V} - \frac{a T_s A e^{-a T_s} W_0}{V^2} + \frac{4}{3} \frac{W_0^2}{V^3}$$

* axion part of T_s has been put to its minimum
* other factors left out.

$$K = -2 \ln \left((T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{4}{3} \right)$$

$$W = W_0 + A e^{-a T_s}$$

→ Work out scalar potential

$$V = \frac{\sqrt{T_s} A^2 e^{-2a T_s}}{v} - \frac{a T_s A e^{-a T_s} W_0}{v^2} + \frac{4}{3} \frac{W_0^2}{v^3}$$

- * axion part of T_s has been put to its minimum
- * O(1) factors left out.
- * Large-volume limit:
Terms suppressed by $\frac{1}{v}$ are dropped

$$K = -2 \ln \left((T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{4}{3} \right)$$

$$W = W_0 + A e^{-aT_s} + \underline{A_2 e^{-aT_b}}$$

$$W = \frac{W_0}{1} \underbrace{A e^{-aT_s}}_{\frac{1}{V}}$$

→ Work out scalar potential

$$V = \frac{\sqrt{3} A^2 e^{-2aT_s}}{V} - \frac{a T_s A e^{-aT_s} W_0}{V^2} + \frac{4}{3} \frac{W_0^2}{V^3}$$

- * axion part of T_s has been put to its minimum
- * O(1) factors left out.
- * Large-volume limit:
Terms suppressed by $\frac{1}{V}$ are dropped

$(W_0 < S G_{\text{max}})$

Vacuum energy:

Gravitino mass:

Kahler moduli mass:

Dilaton/complex structure mass:

Susy broken:

KKLT

Fluxes

0

$\frac{W_0}{V}$

0 (unfixed)

$-\frac{DDW}{V} \sim m_{\text{pl}}$

Yes, $F^T \neq 0$

(KKLT) Fluxes + non-perturb.

$-3m_{\text{pl}}^2 M_{\text{pl}}^2$

$\sim \frac{W_0}{V}$

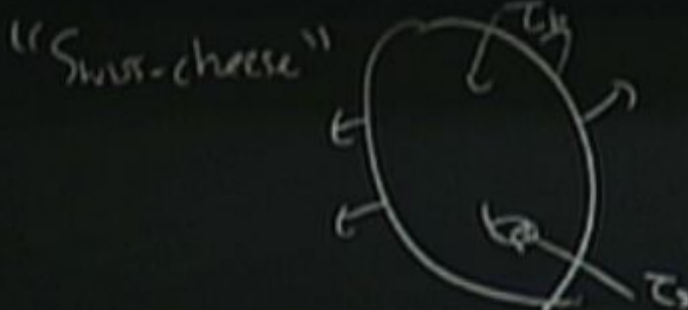
$\sim m_{\text{pl}} h(\frac{M_{\text{pl}}}{m_{\text{pl}}})$

$-\frac{DDW}{V} \sim m_{\text{pl}}$

No

$K_{ij} = \begin{pmatrix} K_{TT} & 0 \\ 0 & K_{ij} \end{pmatrix}$

... at least 2 moduli, one 'big', one 'small'
Volume "blow-up"



simplest case $\mathbb{P}^1 \times \mathbb{P}^1 \times \mathbb{P}^1$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

* Fix dilaton + complex structure moduli

$$D_s W = D_{\tau_i} W = 0$$

$(W_0 \ll S G_{\text{max}}^2)$

Vacuum energy:

Gravitino mass:

Kähler moduli mass:

Dilaton/complex structure mass:

Susy broken:

KKLT

Fluxes

0

$\frac{W_0}{V}$

0 (unfixed)

$-\frac{DDW}{V} \sim m_{\text{pl}}$

Yes, $F^T \neq 0$

(KKLT) Fluxes + non-perturb.

$-3m_{\text{pl}}^2 M_{\text{pl}}^2$

$-\frac{W_0}{V}$

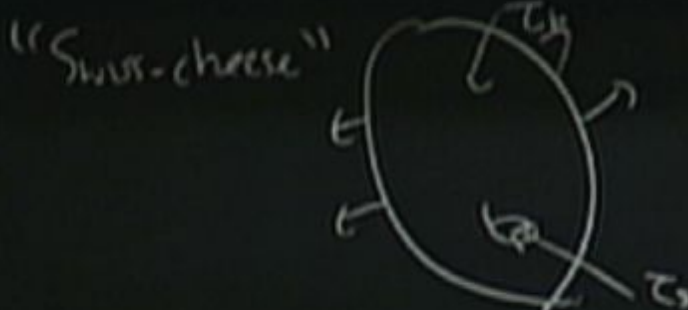
$-m_{\text{KKLTT}}$

$-\frac{DDW}{V} \sim m_{\text{pl}}$

No

$$K_{ij} = \begin{pmatrix} K_{TT} & 0 \\ 0 & K_{ij} \end{pmatrix}$$

... at least 2 moduli, one 'big', one 'small'
Volume "blow-up"



simplest case $P^1 \times (S^1)^2$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

* Fix dilaton + complex structure moduli

$$D_s W = D_{\tau_i} W = 0$$

$$K = -2 \ln \left((T_h + \bar{T}_h)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{W_0}{\sqrt{v}} \right)$$

$$W = W_0 + A e^{-aT_s} + \underline{A_2 e^{-aT_h}}$$

$$W = \frac{W_0}{1} \underbrace{A e^{-aT_s}}_{\frac{1}{\sqrt{v}}}$$

→ Work out scalar potential

$$V = \frac{\sqrt{T_s} A^2 e^{-2aT_s}}{v} - \frac{a T_s A e^{-aT_s} W_0}{v^2} + \frac{W_0^2}{v^3}$$

- * axion part of T_s has been put to its minimum
- * Oscil factors left out.
- * Large-volume limit:
Terms suppressed by $\frac{1}{v}$ are dropped
 e^{2aT_s}

$$K = -2 \ln \left((T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{W_0}{V} \right)$$

$$W = W_0 + A e^{-a T_s} + A_2 e^{-a T_b}$$

$$W = \frac{W_0}{1} \frac{A e^{-a T_s}}{\frac{1}{V}}$$

→ write out scalar potential

$$V = \frac{\sqrt{T_s} A^2 e^{-2a T_s}}{V} - \frac{a T_s A e^{-a T_s} W_0}{V^2} + \frac{W_0^2}{V^3}$$

$$\frac{\partial V}{\partial T_s} = \frac{\partial V}{\partial b} = 0$$

Minimum exists at $T_s = \frac{W_0^{2/3}}{3a}$, $V = W_0 \exp(a T_s)$

- * axion part of T_s has been put to its minimum
- * all factors left out.
- * large-volume limit:
Terms suppressed by $\frac{1}{V}$ are dropped

$$W = W_0 + A e^{-a|z|} + \Lambda_2 e^{-a|z|b}$$

→ Work out scalar potential

$$V = \frac{\sqrt{\tau_3} A^2 e^{-2a\tau_3}}{V} - \frac{a\tau_3 A e^{-a\tau_3} W_0}{V^2} + \frac{c}{V^3} W_0$$

$$\frac{\partial V}{\partial \tau_3} = \frac{\partial V}{\partial c} = 0$$

Minimum exists at $\tau_3 \sim \frac{c}{9a}^{2/3}$, $V \sim W_0 \exp(a\tau_3)$

→ minimum is at exponentially large volume

- * axion part if T_5 has been put to its minimum
- * O(1) factors left out.
- * large-volume limit: terms suppressed by $\frac{1}{V}$ are dropped

→ Werte mit station. part. extrem

$$V = \frac{\sqrt{\tau_s} A e^{-2a\tau_s}}{V} - \frac{a\tau_s A e^{-a\tau_s} W_0}{V^2} + \frac{F W_0}{V^3}$$

$$\frac{\partial V}{\partial \tau_s} = \frac{\partial V}{\partial \tau_s} = 0$$

Minimum exists at $\tau_s \sim \frac{W_0^{2/3}}{2a}$, $V \sim W_0 \exp(a\tau_s)$

→ minimum is at exponentially large volume

* 0th factor left out.
 * large-volume limit.
 Terms suppressed by $\frac{1}{V}$ are dropped
 $e^{2a\tau_s}$ V dropped

$$\frac{\partial V}{\partial \tau_s} = 0$$

$$\frac{\partial V}{\partial \tau_s} = \frac{\partial V}{\partial b} = 0$$

Minimum exists at $\tau_s \sim \frac{W_0^{2/3}}{g_0}$, $V \sim W_0 \exp(a_1 \tau_s)$

→ minimum is at exponentially large volume.

* large term

$$\frac{\partial V}{\partial \tau_s} = 0$$

$V \sim \exp(a_1 \tau_s)$ · integrate out τ_s

$$\frac{\partial V}{\partial \tau_5} = \frac{\partial V}{\partial \tau_6} = 0$$

Minimum exists at $\tau_5 \sim \frac{\mu_5}{g_5}^{2/3}$, $V \sim W_0 \exp(a_5 \tau_5)$

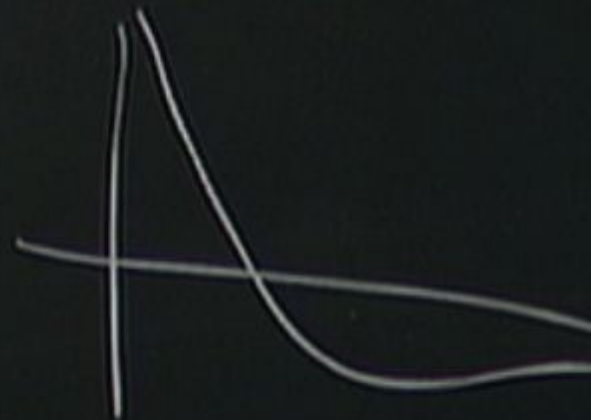
→ minimum is at exponentially large volume.

* large term

$$\frac{\partial V}{\partial \tau_5} = 0$$

$V \sim \exp(a_5 \tau_5)$ · integrate out τ_5

$$-\frac{(\ln V)^{3/2}}{V^3} + \frac{\mu_5}{V^3}$$



(KKLT)
Fluxes + non-perturb.

$$-3 m_{3/2}^2 M_P^2$$

$$\sim \frac{h_a}{V}$$

$$\sim m_{3/2} \ln\left(\frac{M_{Pl}}{m_{3/2}}\right)$$

$$\sim DDW \sim m_{3/2}$$

LV

$$-m_{3/2}^3 M_P$$

cy

(KKLT)
Fluxes + non-perturb.

$$-3 m_{3/2}^2 M_p^2$$

$$\sim \frac{W_0}{V}$$

$$\sim m_{3/2}^2 \ln\left(\frac{M_p}{m_{3/2}}\right)$$

$$\sim \frac{D^2 W}{V} \sim m_{3/2}^2$$

No.

cy

LV

$$-m_{3/2}^3 M_p$$

$$\frac{W_0}{V} \ll M_p$$

Yes, $F^T \neq 0$

'big', one 'small'
" " " " " "
Volume blow-up

(KKLT)
Fluxes + non-perturb.

$$-3 m_{3/2}^2 M_p^2$$

$$\sim \frac{W_0}{V}$$

$$\sim m_{3/2} \ln\left(\frac{M_p}{m_{3/2}}\right)$$

$$\sim \frac{DDW}{V} \sim m_{3/2}$$

LV

$$-m_{3/2}^3 M_p$$

$$\frac{W_0}{V} \ll M_p$$

$$(small) m_{3/2} \ln \frac{M_p}{m_{3/2}} \quad (large) \frac{m_{3/2}^3}{M_p^{3/2}}$$

$$\frac{DDW}{V} \sim m_{3/2}$$

Yes, $F^T \neq 0$

$$\frac{\partial V}{\partial \tau_5} = 0$$

$V = \exp(as\tau_5)$ · integrate out τ_5

$$\frac{-(\ln V)^{3/2}}{V^3} + \frac{y_5}{V^3}$$



$\partial \tau_1 = 0$
 $\partial \tau_2 = 0$
 $\partial \tau_3 = 0$
 $\partial \tau_4 = 0$
 $\partial \tau_5 = 0$

$$K = -2 \ln \left((T_b + \bar{T}_b)^{3/2} - (T_s + \bar{T}_s)^{3/2} + \frac{W_0}{V} \right)$$

$$W = W_0 + A e^{-aT_s} + A_2 e^{-aT_b}$$

$$V = \frac{W_0}{1} \frac{A e^{-aT_s}}{1/V}$$

→ Work out scalar potential

$$V = \frac{\sqrt{T_s} A^2 e^{-2aT_s}}{V} - \frac{a T_s A e^{-aT_s} W_0}{V^2} + \frac{W_0^2}{V^3}$$

$$\frac{dV}{dT_s} = \frac{dV}{dV} = 0$$

Minimum exists at $T_s \sim \frac{W_0^{2/3}}{g_5}$, $V \sim W_0 \exp(a T_s)$

→ minimum is at exponentially large volume

* axion part of T_s has been put to its minimum

* all factors left out.

* large-volume limit:

Terms suppressed by $\frac{1}{V}$ are dropped

→ minimum is at exponentially large volume.

$\partial V = 0$ $V = \exp(as\tau_5)$ · integrate out τ_5

$$\frac{-(\ln V)^{3/2}}{\sqrt{3}} + \frac{\sqrt{5}}{\sqrt{3}}$$



* Addresses the hierarchy problem
: break susy at hierarchically low energy scales

→ minimum is at exponentially large volume.

$\partial V = 0$ $V = \exp(as\tau_5)$ integrate out τ_5

$$\frac{-(\ln V)^{3/2}}{V^3} + \frac{\sqrt{s}}{V^3}$$



* Addresses the hierarchy problem
break susy at hierarchically low energy scales
promising starting point for stringy phenomenology

→ minimum is at exponentially large volume.

$$\frac{\partial V}{\partial \tau_5} = 0 \quad V \sim \exp(as\tau_5) \quad \text{integrate out } \tau_5$$

$$\frac{-(\ln V)^{3/2}}{\sqrt{3}} + \frac{5}{\sqrt{3}}$$



$$\begin{matrix} 0 & \tau_5 = 0 \\ 0 & g_2 = 0 \\ 0 & \tau_5 = 0 \\ 0 & \tau_5 = 0 \end{matrix}$$

- * Address the hierarchy problem
: break susy at hierarchically low energy scales
- * promising starting point for stringy phenomenology

→ minimum is at exponentially large volume.

$$\frac{\partial V}{\partial \tau_5} = 0 \quad V \sim \exp(as\tau_5) \quad \text{integrate out } \tau_5$$

$$\frac{-(\ln V)^{3/2}}{\sqrt{3}} + \frac{5}{\sqrt{3}}$$



$$\begin{matrix} 0 & \tau_5 & 0 \\ 0 & \tau_5 & 0 \\ 0 & \tau_5 & 0 \end{matrix}$$

- * Address the hierarchy problem
: break susy at hierarchically low energy scales
- * promising starting point for stringy phenomenology

$(H_{00} < S_{G_{2n}} \Omega)$

Vacuum energy:

Gravitino mass:

Kähler moduli mass:

Dilaton/complex structure mass:

SUSY broken:

Fluxes

0

$\frac{H_0}{V}$

0 (w/ mod)

$-\frac{DDW}{V} \sim m_{3/2}$

Yes, $F^T \neq 0$

(KKT) Flux transport

$-3m_{3/2}^2 M_p^2$

$-\frac{H_0}{V}$

$-m_{3/2} h(\frac{H_0}{m_{3/2}})$

$-\frac{DDW}{V} \sim m_{3/2}$

No

LV

$-m_{3/2}^2 M_p$

$\frac{H_0}{V} \ll M_p$

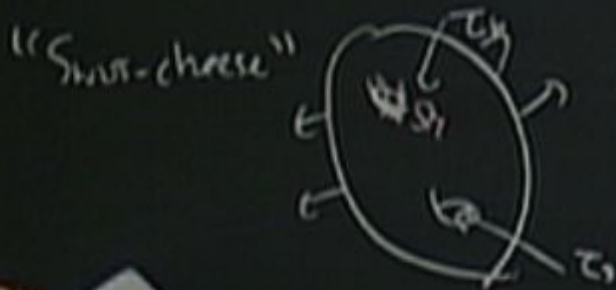
(small) $m_{3/2} h(\frac{H_0}{m_{3/2}})$ (large) $\frac{m_{3/2} h(\frac{H_0}{m_{3/2}})}{m_{3/2}^2 M_p}$

$DDW \sim m_{3/2}$

Yes, $F^T \neq 0$

→ include α'^3 correction to Kähler potential

* Need at least 2 moduli, one 'big', one 'small'



simplest case $P^1 \times C_1 \times C_2 \times C_3$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

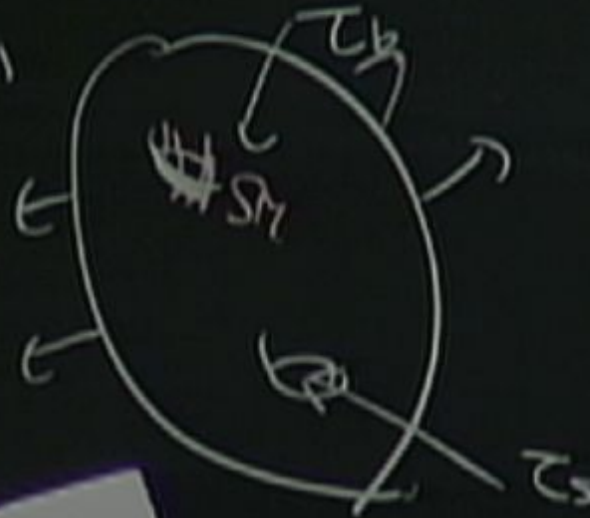
dilaton + complex structure moduli

$$D_s W = D_u W = 0$$

→ include α^3 correction to Kähler

Need at least 2 moduli, one

"muss-cheese"



simplest

con + complex structure moduli

$D_{SW} =$

M

Properties

$$\frac{1}{g_2} = f_a = T_a \quad (\sim 25)$$



$$e^{-a_{st}t_s} = \frac{1}{V}$$

$$\overline{a_{st}t_s} \sim \ln V$$

$$\ln(10^{15}) \\ \approx 30$$

$$m_{3/2} = 1 \text{ TeV}$$

$$V = 10^{15}$$

10D action: $\int \sqrt{g} R + \left(R^4 + G_7^2 R^3 + G_7^4 R^2 + \dots \right)$

10D action: $\int \sqrt{g} R + \left(R^4 + \underline{G_7^2 R^3} + G_7^4 R^2 + \dots \right)$

Fluxes quantised on 3-cycles

$$G_7 \sim \frac{1}{\sqrt{V_{3\text{-cycle}}}}$$

$$\int_{\text{ct.}} \sqrt{g} G_7^2 R^3 \sim \int_{\text{int}} V \times \frac{1}{G_7^2}$$

100 action: $\int \sqrt{g} R + \left(R^4 + \underline{G_7^2 R^3} + G_7^4 R^2 + \dots \right)$

Fluxes quantised on 3-cycles

$$G_7 \sim \frac{1}{\sqrt{V_{3\text{-cycle}}}}$$

$$\int \sqrt{g} G_7^2 R^3 \sim \underbrace{V}_{int} \times \underbrace{\frac{1}{V}}_{G_7^2} \wedge \underbrace{\frac{1}{V}}_{R^3}$$

$$G_7 R^4 \sim$$

100 action $\int \sqrt{g} R + (R^4 + \underline{G_7^2 R^3} + G_7^4 R^4 + \dots)$

Fluctuations on 3-cycles

$\int \frac{1}{\sqrt{V_{3\text{-cycle}}}}$

$\int \sqrt{g} G_7^2 R^3 \sim \underbrace{V}_{int} \times \underbrace{\frac{1}{V}}_{G_7^2} \times \underbrace{\frac{1}{V}}_{R^3}$

$\int \sqrt{g} R^4 \sim V \times \frac{1}{V^{4/3}}$

100 action $\int \sqrt{g} R + (R^4 + \underline{G_7^2 R^3} + G_7^4 R^4 + \dots)$

Fluxes \int over 3-cycles

$$\frac{1}{\sqrt{V_{3\text{-cycle}}}}$$

$$\int \sqrt{g} G_7^2 R^3 \sim \underbrace{V}_{\text{int}} \times \frac{1}{V} \wedge \frac{1}{V}$$

$G_7^2 \quad R^3$

$$\int \sqrt{g} R^4 \sim V \times \frac{1}{V^{4/3}}$$

Other corrections

100 act: $\int \sqrt{g} R + \left(R^4 + \underline{G_7^2 R^3} + G_7^4 R^4 + \dots \right)$

Fl. integrated as 3-cycles

$$G_7 \sim \frac{1}{\sqrt{V_{3\text{-cycle}}}}$$

$$\int \sqrt{g} G_7^2 R^3 \sim \underbrace{V}_{\text{int}} \times \underbrace{\frac{1}{V}}_{G_7^2} \times \underbrace{\frac{1}{V}}_{R^3}$$

$$\int \sqrt{g} R^4 \sim V \times \frac{1}{V^{4/3}}$$

THE CORRECTIONS

10D action: $\int \sqrt{g} R + \left(R^4 + \underline{G_7^2 R^3} + G_7^4 R^4 + \dots \right)$

Fluxes quantised on 3-cycles

$$G_7 \sim \frac{1}{\sqrt{V_{3\text{-cycle}}}}$$

$$\int \sqrt{g} G_7^2 R^3 \sim \underbrace{V}_{\text{int}} \times \underbrace{\frac{1}{V}}_{G_7^2} \times \underbrace{\frac{1}{V}}_{R^3}$$

$$\int \sqrt{g} R^4 \sim V \times \frac{1}{V^{4/3}}$$

10D action: $\int \sqrt{g} R + \left(R^4 + \underline{G_7^2 R^3} + G_7^4 R^2 + \dots \right)$

Fluxes quantised on 3-cycles

$$G_7 \sim \frac{1}{\sqrt{V_{3\text{-cycle}}}}$$

$$\int \sqrt{g} G_7^2 R^3 \sim \underbrace{V}_{\text{int}} \times \frac{1}{\sqrt{G_7^2}} \wedge \frac{1}{\sqrt{R^3}}$$

$$\int \sqrt{g} R^4 \sim V \times \frac{1}{V^{4/3}}$$

$$V = \sqrt{3} M_{pl}^2 e^{-\alpha \tau_1 / M_{pl}} - \frac{\alpha \tau_1 M_{pl}}{\sqrt{3}} \frac{W_0}{V^2} + \frac{1}{\sqrt{3}} \frac{W_0^2}{V^3}$$

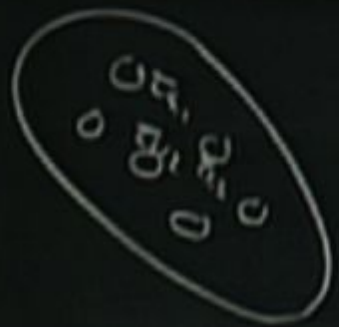
$$\frac{dV}{d\tau_1} = \frac{dV}{d\tau_2} = 0$$

Minimum exists at $\tau_1 = \frac{\sqrt{3}}{g_1} \ln \frac{V}{W_0}, V = W_0 \exp(\alpha \tau_1 / M_{pl})$

→ minimum is at exponentially large volume

* Oscill factors left out.
 * Large-volume limit:
 Terms suppressed by $\frac{1}{V}$ are dropped
 its minimum

$$m_{3,2}^2 \sim \Lambda^2$$



$$\frac{-(\ln V)^{3/2}}{\sqrt{3}}$$

* AdS/CFT problem
 : branes
 * providing point for stringy phenomenology
 hierarchically low energy scales

$$\frac{dV}{d\tau_s} = \frac{dV}{d\tau_b} = 0$$

Minimum exists at $\tau_s \sim \frac{g_0}{g_s} \tau_b^{2/3}$, $V = W_0 \exp(C_1 \tau_s)$

→ minimum is at exponentially large volume

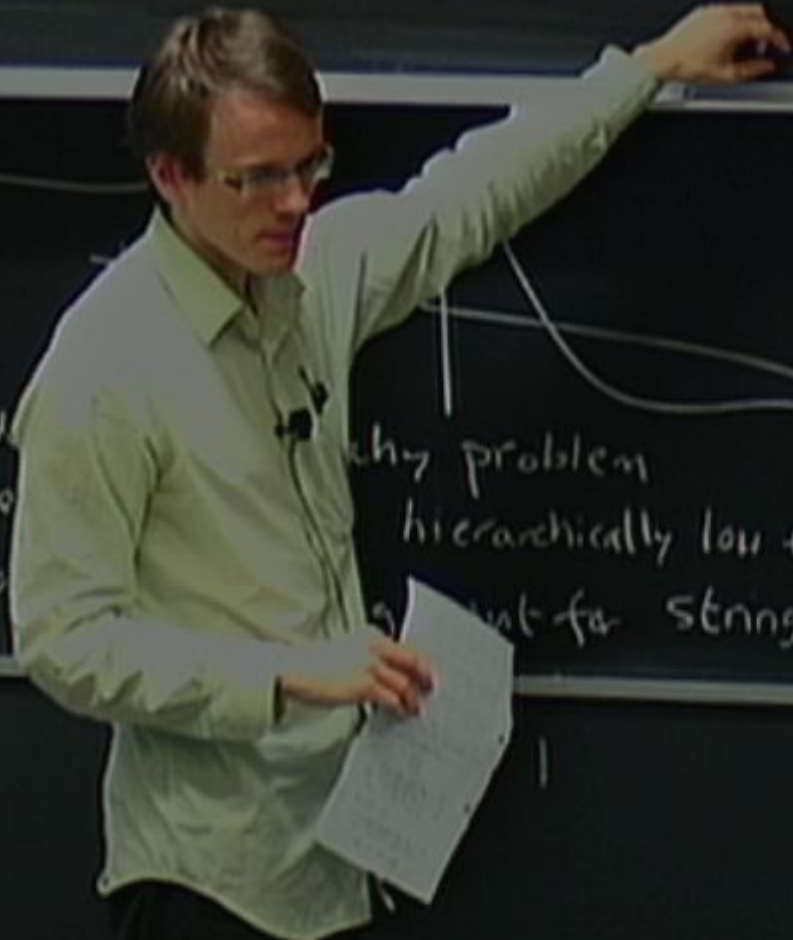
* all factors left out.
 * large-volume limit:
 terms suppressed by $\frac{1}{V}$ are dropped

$$M_{3/2}^2 \sim \frac{\Lambda^2}{M_{\text{KKK/MS}}^2}$$

$0 \leq g_1 \leq g_2 \leq 0$

$$\frac{-(\ln V)^{3/2}}{V^3}$$

* Add ...
 * bro ...
 * pro ...
 why problem
 hierarchically low energy scales
 ... for stringy phenomenology



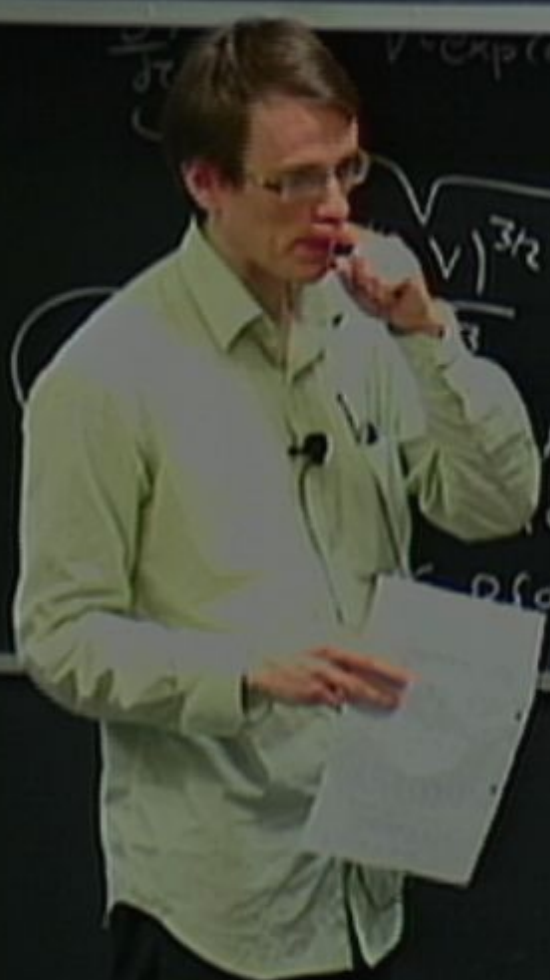
$$\frac{dV}{d\tau_s} = \frac{dV}{d\tau_b} = 0$$

Minimum exists at $\tau_s = \frac{\sqrt{3}}{g} \ln \frac{V}{V_0}$, $V = V_0 \exp(g\tau_s)$

→ minimum is at exponentially large volume

* large-volume limit:
 terms suppressed by $\frac{1}{V}$ are dropped

$$m_{3/2}^2 \sim \frac{\Lambda^2}{M_{\text{KKKK}}^2 m_s}$$



$V = \exp(g\tau_s)$ integrate out τ_s

$$V^{3/2} + \frac{g}{\sqrt{3}}$$



crosses the hierarchy problem
 real susy at hierarchically low energy scales
 promising starting point for stringy phenomenology

→ minimum is at exponentially large volume

$$m_{3/2}^2 \sim \frac{\Lambda^2}{M_{\text{KK}}/M_{\text{Pl}}}$$

$\frac{dV}{d\tau} = 0$ $V \sim \exp(n\tau)$ integrate out τ_3

$$\frac{-(\ln V)^{3/2}}{\sqrt{3}} + \frac{\tau}{\sqrt{3}}$$



0.5, 0.5, 0
0, 0, 0

- * Address the hierarchy problem
: break susy at hierarchically low energy scales
- * promising starting point for string phenomenology

→ Work out scalar potential

$$V = \frac{\sqrt{\tau_3} A^2 e^{-2a\tau_3}}{V} - \frac{a\tau_3 A e^{-a\tau_3} W_0}{V^2} + \frac{F}{V^3} W_0^2$$

$$\frac{dV}{d\tau_3} = \frac{dV}{dcb} = 0$$

Minimum exists at $\tau_3 \sim \frac{W_0^{2/3}}{g_3^{2/3}}$, $V \sim W_0 \exp(a\tau_3)$

→ minimum is at exponentially large volume

→ axion part of T_3 has been put to its minimum
 * O(1) factors left out.
 * charge-volume limit.
 Terms suppressed by $\frac{1}{V}$ are dropped

$$m_{3/2}^2 \sim \frac{\Lambda^2}{M_{\text{KK}} m_{\text{S}}}$$

$\frac{dV}{d\tau_3} = 0$ $V \sim \exp(a\tau_3)$ $\ln V \sim a\tau_3$

$$-\frac{(\ln V)^{3/2}}{V^3} + \frac{F}{V^3}$$

$\frac{dV}{d\tau_3} = 0$
 $\frac{dV}{dcb} = 0$

* Address the problem
 : break
 * promising
 hierarchically low energy scales
 int for strings phenomenology

$$\frac{5 A e^{-a \tau_s} W_0}{V^2} + \frac{c}{5} W_0^2$$

- * axion part of T_s has been put to its minimum
- * O(1) factors left out.
- * large-volume limit:

at $\tau_s \sim \frac{M_{pl}^{2/3}}{g_s}$, $V \sim W_0 \exp(a_s \tau_s)$

essentially large volume.

Terms suppressed by $\frac{1}{V}$ are dropped

$$m_{3/2}^2 \sim \frac{\Lambda^2}{M_{pl}^2 m_s}$$

integrate out τ_s

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln(V(\frac{1}{g_s}) + \frac{F}{g_s^2}) - \ln(S \Omega \bar{S}) - \ln(S + \bar{S})$$

$$W = \int G_3 \wedge \Omega + \sum_{\text{KKLT}} A_i e^{-a_i T_i}$$

V = volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int G_3 \wedge \bar{G}_3 = \int J \wedge J \wedge J$$

($W_0 \ll \int G_3 \wedge \Omega$)

Vacuum energy:

Gravitino mass:

Kähler moduli mass:

Dilaton/complex structure moduli

Susy broken:

Fluxes

0

$\frac{M_p}{M_{\text{pl}}}$

(red)

$\frac{M_p}{M_{\text{pl}}}$

0

(KKLT) Fluxes non-perturb.

$-3 m_{\text{pl}}^2 M_p^2$

$-\frac{M_p}{M_{\text{pl}}}$

$-m_{\text{pl}} \ln(\frac{M_p}{M_{\text{pl}}})$

$-\frac{M_p}{M_{\text{pl}}} m_{\text{pl}}$

No

LV

$-m_{\text{pl}}^2 M_p$

$\frac{M_p}{M_{\text{pl}}} M_p$

(small) $m_{\text{pl}} \ln(\frac{M_p}{M_{\text{pl}}})$

(large) $\frac{M_p}{M_{\text{pl}}}$

DBI = m_{pl}^2

Yes, $F^2 \neq 0$

simplest case $(P^1 \times T^3)$

$$V = \frac{1}{4\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

* Fix dilaton +

structure moduli

$$D_s V = 0$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln(V_{(1,1)} + \frac{\gamma}{g^2}) - \ln(S \Omega_n \bar{\Omega}) - \ln(S + T)$$

$$W = \int G_{n,n} \Omega \sum_{KKLT} A_i e^{-a_i \tau_i}$$

V = volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int g^3 = \int J \wedge J \wedge J$$

($W_0 \ll S G_{n,n}$)

- Vacuum energy
- Gravitino mass
- Kaehler moduli
- Dilaton/complex structure moduli
- SUSY

Fluxes
 0
 $\frac{H_4}{V}$
 0 (w/ mod)
 $-\frac{DDW}{V} \sim m_{3/2}$
 Yes, $F^1 \neq 0$

(KKLT) Fluxes non-perturb.
 $-3 m_{3/2}^2 M_{Pl}^2$
 $-\frac{H_4}{V}$
 $-m_{3/2} h(\frac{H_4}{m_{3/2}})$
 $-\frac{DDW}{V} \sim m_{3/2}$
 No

LV
 $-m_{3/2}^2 M_{Pl}^2$
 $\frac{H_4}{V} \ll M_{Pl}^2$
 (small) $m_{3/2} h(\frac{H_4}{m_{3/2}})$ (large) $\frac{H_4}{m_{3/2}}$
 $DDW \sim m_{3/2}$
 Yes, $F^1 \neq 0$

case IP^1 (1,1,1,1,1)

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

* Fix d... structure moduli

$$D_s W = D_{\tau_i} W = 0$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln \left(\frac{V(\tau, \sigma) + \frac{F}{g_s^2}}{g_s^2} \right) - \ln(S \Omega \alpha') - \ln(S + \frac{F}{g_s^2})$$

$$W = \int G_3 \wedge \Omega + \sum_{\text{KKLT}} A_i e^{-a_i \tau_i}$$

$V =$ volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int g^3 = \int J \wedge J \wedge J$$

($W_0 \ll \int G_3 \wedge \Omega$)

- Vacuum energy:
- Gravitino mass:
- Kaehler moduli:
- Dilaton/complex structure moduli:
- Susy breaking:

Fluxes

- 0
- $\frac{H_0}{V}$
- 0 (w/ mod)
- $-\frac{DDW}{V} = m_{3/2}$
- Yes, $F^T \neq 0$

(KKLT) Fluxes + non-perturb.

- $-3 m_{3/2}^2 M_P^2$
- $-\frac{H_0}{V}$
- $-m_{\text{KKL}} \left(\frac{H_0}{m_{\text{KKL}}} \right)$
- $-\frac{DDW}{V} = m_{3/2}$
- No

LV

- $-m_{3/2}^2 M_P^2$
- $\frac{H_0}{V} \ll M_P$
- (small) $m_{\text{KKL}} \ll m_{3/2}$ (large) $\frac{m_{\text{KKL}}}{M_P} \ll 1$
- $DDW = m_{3/2}$
- Yes, $F^T \neq 0$

Simplest case $(P^1 \times T^3)$

$$V = \frac{1}{4\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

* Fix τ_s moduli:
 $D_s W = D_{\tau_s} W = 0$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln \left(V_{(1,1)} + \frac{F}{9\sqrt{2}} \right) - \ln(S\Omega\sqrt{\alpha}) - \ln(S + \dots)$$

$$W = \int G_3 \wedge \Omega + \sum_{\text{KKLT}} A_i e^{-a_i \tau_i}$$

$V =$ volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int g^3 = \int J \wedge J \wedge J$$

$(W_0 \ll \int G_3 \wedge \Omega)$

Vacuum energy:

Gravitino mass:

Kaehler mod

Dilaton/tau

SUSY

Fluxes

$$0$$

$$\frac{H_0}{V}$$

$$0 \text{ (if red)}$$

$$-\frac{DDW}{V} \sim m_{3/2}$$

Yes, $F^T \neq 0$

(KKLT) Fluxes + non-perturb.

$$-3 m_{3/2}^2 M_P^2$$

$$-\frac{H_0}{V}$$

$$-m_{3/2} \ln \left(\frac{H_0}{m_{3/2}} \right)$$

$$-\frac{DDW}{V} \sim m_{3/2}$$

No

LV

$$-m_{3/2}^2 M_P^2$$

$$\frac{H_0}{V} \ll M_P$$

(small) $m_{3/2} \ll m_{\text{KKL}}$ (large) $\frac{m_{3/2}}{M_P} \ll 1$

$$DDW \sim m_{3/2}$$

Yes, $F^T \neq 0$

simplest case $P^T_{(1,1), (1,1), (1,1)}$

$$V = \frac{1}{9\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

structure moduli

$$D_s W = D_{\tau_i} W = 0$$

Superpotential

$$W = W(\Phi) + \sum_i Y_i h_i(\Phi) (C^i C) C^h$$

(12)



Superpotential

$$W = W(\Phi) + Y_{ijh}(\Phi) C^i C^j C^h$$

(112)

$$T = e^{-d} \int \sqrt{g} + i \int C_4$$

Superpotential

$$W = W(\Phi) + Y_{ij} h(\Phi) C^i C^j$$

(12) $T = \frac{1}{2} \dot{\Phi}^2 + i \int C \dot{C}$

T mod \hbar it appear in pert. superpotential

Superpotential

$$W = W(\Phi) + Y_{ijkl}(\Phi) C^i C^j C^k C^l$$

(112)

$$T = e^{-4\int \sqrt{g}} + i \int C_4$$

T moduli do not appear in pert. superpotential

|| || || || $Y_{ijkl}(\Phi)$

$$W = W(\Phi) + Y_{ijkl}(\Phi) C^i C^j C^k C^l$$

(312)

$$T = e^{-d} \int \sqrt{g} + i \int C_4$$

T moduli do not appear in pert. superpotential

|| || || || $Y_{ijkl}(\Phi)$

IR

$$Y_{ijkl} = Y_{ijkl}(U)$$

* Address the hierarchy problem
: break susy at hierarchically lower

* promising starting point for strings

Superpotential

$$W = W(\Phi) + Y_{ijk}(\Phi) C^i C^j C^k$$

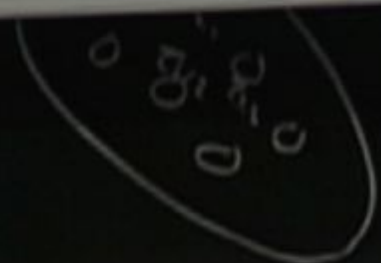
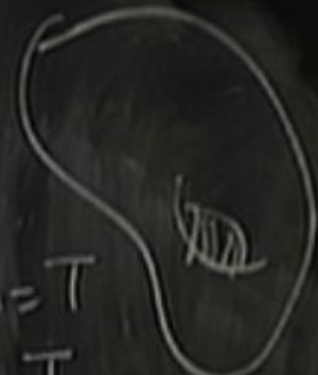
(117) $T = e^{-d} \int \sqrt{g} + i \int C_4$

T moduli do not appear in pert. superpotential

|| || || || $Y_{ijk}(\Phi)$

DB $Y_{ijk} = Y_{ijk}(U)$

$S_n = T$
 $\frac{1}{g^2} = T$



- * Address
- * break
- * promise

problem

hierarchy low energy scales

stringy phenomenology

Superpotential

$$W = W(\Phi) + Y_{ijk}(\Phi) C^i C^j C^k$$

(112)

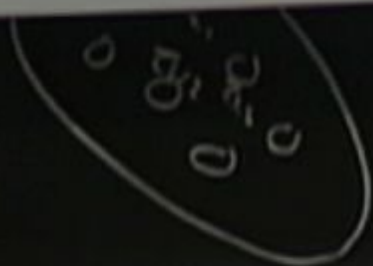
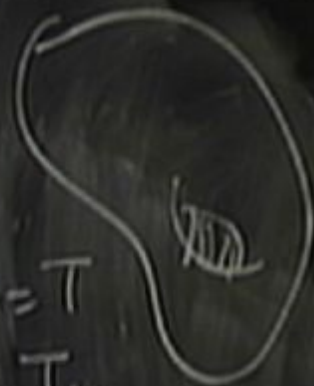
$$T = e^{-d} \int \sqrt{g} + i \int C_4$$

T moduli do not appear in pert. superpotential

$$\parallel \parallel \parallel \parallel Y_{ijk}(\Phi)$$

$$\frac{\partial W}{\partial \Phi} = Y_{ijk}(U)$$

$$\frac{1}{\alpha} = \frac{4\pi}{g^2} = T_{sm}$$



- * Address the hierarchy problem
 - break susy at hierarchically low energy scales
- * promising starting point for stringy phenomenology

$$W = W(\Phi) + Y_{ijk}(\Phi) C^i C^j C^k$$

(18) $T = e^{-d} \int \sqrt{g} + i \int C_4$

T moduli do not appear in pert. superpotential

|| || || || $Y_{ijk}(\Phi)$

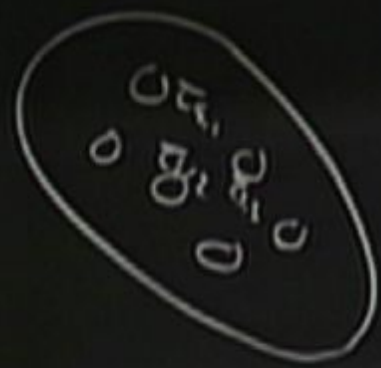
$\frac{\partial}{\partial \Phi} Y_{ijk} = Y_{ijk}(\nu)$

$S_n = T$
 $\frac{1}{\alpha} = \frac{4\pi}{g^2} = T_{sm}$



* Can you get Yukawas as an expansion in α' ?

$$\frac{-(\ln \nu)^{3/2}}{\nu^3} + \frac{\mu}{\nu^3}$$



- * Addresses the hierarchy problem
 - : break susy at hierarchically low energy scales
- * promising starting point for stringy phenomenology

* Can you get turbulence as an expansion in α_{GUT}

Υ_{ijk} -

$$(m_e : m_\mu : m_\tau) \propto \alpha_{GUT}^4 : \alpha_{GUT}^2 : 1$$

* But Υ_{ijk} cannot depend on T and cannot depend on α_{GUT}

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln(V_{(4D)} + \frac{F}{g^2}) - \ln(S \Omega \bar{\Omega}) - \ln(S + \bar{S})$$

$$W = \int G_3 \wedge \Omega + \sum_{KKLT} A_i e^{-a_i \tau_i}$$

$V =$ volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int G^3 = \int J \wedge J \wedge J$$

($W_0 \ll \int G_3 \wedge \Omega$)

Vacuum energy:

Gravitational:

Kahler:

Dilaton/Moduli mass:

Stabilization:

Flores

$$0$$

$$\frac{H_p}{V}$$

0 (up to)

$$-\frac{DDW}{V} \sim m_{pl}$$

Yes, $F^T \neq 0$

(KKLT) Fluxes + non-perturbative

$$-3 m_{pl}^2 M_p^2$$

$$-\frac{H_p}{V}$$

$$-m_{KKLT} \left(\frac{H_p}{m_{pl}} \right)$$

$$-\frac{DDW}{V} \sim m_{KKLT}$$

No

LV

$$-m_{KKLT}^2 M_p^2$$

$$\frac{H_p}{V} \ll M_p$$

(small) $m_{KKLT} \ll m_{pl}$ (large) $\frac{m_{KKLT}}{m_{pl}} \ll 1$

$$-\frac{DDW}{V} \sim m_{KKLT}$$

Yes, $F^T \neq 0$

simplest case $(P^1 \times T^3 / \mathbb{Z}_2)$

$$V = \frac{1}{4\sqrt{2}} (\tau_b^{3/2} - \tau_s^{3/2})$$

complex structure moduli:

$$D_S W = D_U W = 0$$

Ψ_{ijk}

$(m_e : m_c : m_h) \propto_{GUT}^1 : \propto_{GUT}^2 : 1$

* But Ψ_{ijk} cannot depend on T and cannot depend on

$\Psi_{ijk} = e^{R/2} \frac{\Psi_{ijk}}{\sqrt{z_i z_j z_k}}$

* In principle could have family dependence of z_i

Ψ_{ijk}

$$(m_E : m_C : m_H) \propto_{GUT}^1 : \propto_{GUT}^2 : 1$$

• But Ψ_{ijk} cannot depend on T and cannot depend on

$$\Psi_{ijk} = e^{R/2} \frac{\Psi_{ijk}}{\sqrt{z_i z_j z_k}}$$

In principle could have family dependence of z_i

$$\alpha_{GUT}^1 : \alpha_{GUT}^2 : 1$$

k cannot depend on T and cannot depend on α_{GUT}

$$Y_{ijk} = e^{R/2} \psi_{ijk}$$

$$\sqrt{z_i z_j z_k}$$

could have family dependence of z_i

ns & (1) need kinetic terms that $\rightarrow \infty$ in weak coupling limit $T \rightarrow \infty$

Υ_{ijk} -

$$(m_t : m_c : m_u) \propto_{GUT}^1 : \propto_{GUT}^2 : 1$$

* But Υ_{ijk} cannot depend on T and cannot depend on α_{GUT}

$$\Upsilon_{ijk} = e^{R/2} \frac{\Upsilon_{ijk}}{\sqrt{z_i z_j z_k}}$$

* In principle could have family dependence of z_i

Two problems: (1) need kinematic that $\rightarrow \infty$ in IR safe coupling limit $T \rightarrow \infty$
(2) this isn't seen in actual models

Υ_{ijk} -

$$(m_t : m_c : m_u) \propto_{GUT}^1 \propto_{GUT}^2 : 1$$

* But Υ_{ijk} cannot depend on T and cannot depend on α_{GUT}

$$\Upsilon_{ijk} = e^{R/2} \frac{\Upsilon_{ijk}}{\sqrt{z_i z_j z_k}}$$

* In principle could have family dependence of z_i

Two problems: (1) need kinematic that $\rightarrow \infty$ in IR safe coupling limit $T \rightarrow \infty$
(2) this isn't seen in actual models.

* Can you get Yukawas as an expansion in α_{GUT}

$(1,0,0) \rightarrow (1,2)$

$Y_{ijk} \sim (m_t : m_c : m_u) \propto \alpha_{GUT}^1 : \alpha_{GUT}^2 : 1$

* But Y_{ijk} cannot do this

$\Gamma Y_{ijk} = e^{\frac{R}{2}} \frac{Y_{ijk}}{\sqrt{z_i z_j z_k}}$

* In principle could have family dependence of z_i
 (2) this isn't seen in actual mod
 Two problems: (1) need kinematical $z_i \rightarrow \infty$

$$\sum v_i^2 = v^2 \frac{1}{v^{2n}}$$

SUSY-Flavour

$K \bar{K}_0$ mixing, $BR(\mu \rightarrow e \gamma)$

$$(m_{\tilde{a}}^2)_{\alpha\beta} = (m_a^2)_{\alpha\beta}$$

A^T

SUSY - Flavour

$K_0 \bar{K}_0$ mixing, BR($\mu \rightarrow e \gamma$)

$$(m_{\tilde{a}}^2)_{\alpha\bar{\beta}} = (m_{\tilde{a}}^2) \delta_{\alpha\bar{\beta}}$$

$$A_{\alpha\beta\gamma}^I = A^I \Psi_{\alpha\beta\gamma}$$

$$\phi_{M_1} = \phi_{M_2} = \phi_{M_3} = A$$

$\mathcal{L}(\mu \rightarrow e \bar{\nu})$

$$\int d^2\theta d^2\bar{\theta} \left(c_{ij} \frac{X^\dagger X}{M_{Pl}^2} \varphi^i \varphi^j \right)$$

$\delta \alpha \bar{r}$

$\alpha \beta \gamma$

$= A$

$R(\mu \rightarrow e \gamma)$

$$\int d^2\theta d^2\bar{\theta} \frac{C_{ij} X^\dagger X Q^L Q^j}{M_{Pl}^2}$$

$\delta \propto \bar{R}$

C_{ij} is generic \Rightarrow arbitrary flavour violation

$\alpha \beta \gamma$

\downarrow
BAD

$= A$

* Statements about M_{Pl} suppressed couplings should be studied in string theory.

Conditions for flavour universality

①

[The following text on the chalkboard is heavily obscured by large, dark, horizontal brush strokes.]

Conditions for flavour universality

- ① Hidden sector fields divide into 2 kinds, Ψ and χ .
- ② Ψ and χ kinetic terms decouple

$$K_{ij} =$$

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 $f_n(\Psi, \chi) = \sum \lambda_i \Psi_i$

(c) // Matter metric factorises

$$K_{\alpha\beta}(\Psi, \Psi)$$

4 // ^{is} Minkowski metric factorises

$$K_{\alpha\beta}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = \underbrace{h(\Psi + \bar{\Psi})}_{\text{universal}} k_{\alpha\beta}(\chi)$$

4 // ^{is} Matter metric factorises

$$K_{\alpha\bar{\beta}}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = \underbrace{h(\Psi + \bar{\Psi})}_{\text{universal}} \underbrace{k_{\alpha\bar{\beta}}(\chi, \bar{\chi})}_{\text{orbifold}}$$

5 // Ψ brepatic susy and χ preserves it

$$F^{\Psi} \neq 0, F^{\chi} = 0.$$

Susy broken:

Yes, $F \neq 0$

No

Yes, $F \neq 0$

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5 // Ψ breaks susy and χ preserves it

$$F^\Psi \neq 0, F^\chi = 0.$$

$$K_{\text{orb}}(\Psi, \bar{\Psi}, \mathcal{X}, \bar{\mathcal{X}}) = \underbrace{h(\Psi + \bar{\Psi})}_{\text{universal}} \underbrace{k_{\text{orb}}(\mathcal{X}, \bar{\mathcal{X}})}_{\text{orbifold}}$$

5 // Ψ breaks susy and \mathcal{X} preserves it

$$F^\Psi \neq 0, F^{\mathcal{X}} = 0.$$

$\Psi \rightarrow$ Kähler moduli

$\mathcal{X} \rightarrow$ complex structure moduli

* But γ_{ijk} cannot depend on T and cannot depend on vol

$$\gamma_{ijk} = \frac{e^{R/2} \gamma_{ijk}}{\sqrt{z_i z_j z_k}}$$

* In principle could have family dependence of z_i

(2) this isn't seen in actual models
 problems: (1) need kinetic terms that $\rightarrow \infty$ in weak coupling limit

$$K_{\text{orb}}(\Psi, \bar{\Psi}, \mathcal{X}, \bar{\mathcal{X}}) = \underbrace{h(\Psi + \bar{\Psi})}_{\text{universal}} \underbrace{k_{\text{orb}}(\mathcal{X}, \bar{\mathcal{X}})}_{\text{orbifold}}$$

5 // Ψ breaks susy and \mathcal{X} preserves it

$$F^\Psi \neq 0, F^{\mathcal{X}} = 0.$$

$\Psi \rightarrow$ Kähler moduli

$\mathcal{X} \rightarrow$ complex structure moduli

* But Υ_{ijk} cannot depend on T and cannot depend on \mathcal{L}_{orb}

$$\Upsilon_{ijk} = e^{\frac{R/2}{\sqrt{z_i z_j z_k}} \Upsilon_{ijk}}$$

* In principle could have family dependence of z_i

(2) this isn't seen in actual models
 problems: (1) need kinetic terms that $\rightarrow \infty$ in weak coupling limit

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

$$K = -2 \ln \left(\sqrt{V(\mathcal{G}_{10})} + \frac{\gamma}{g^2} \right) - \ln(S \Omega_n \bar{\Omega}) - \ln(S + \dots)$$

$$W = \int G_{10} \Omega + \sum_{\text{KKLT}} A_i e^{-a_i \tau_i}$$

$V =$ volume of Calabi-Yau in string units

$$V = e^{2\sigma} \int G_6 = \int J \wedge J \wedge J$$

(No $\langle S G_{10} \Omega \rangle$)

Vacuum energy:

Gravitino mass:

Kaehler moduli mass:

Dilaton/complex structure mass:

Susy broken:

Fluxes

0

$\frac{H^2}{V}$

(red)

(KKLT) Flux + non-perturb.

$-3 m_{3/2}^2 M_p^2$

$-\frac{H^2}{V}$

$-m_{3/2}^2 \ln \left(\frac{H^2}{m_{3/2}^2} \right)$

$-\frac{D^2 \mu}{V} m_{3/2}$

No

LV

$-m_{3/2}^2 M_p^2$

$\frac{H^2}{V} \ll M_p^2$

(small) $m_{3/2}^2 \ll m_{\text{KKL}}$ (large) $\frac{m_{3/2}^2}{M_p^2}$

$\frac{D^2 \mu}{V} = m_{3/2}$

Yes, $F^T \neq 0$

(3) Sup...

Yukawa

$K_{\alpha\bar{\alpha}}$

$$\langle \Psi, \bar{\Psi} \rangle = Y_{\alpha\beta\gamma}(\tau)$$

* Factorised kinetic terms inherited from $N=2$
hypermultiplets + vector multiplets
have no cross-terms in their kinetic mixing.

	Fluxes	Fluxes + non-perturb.	LV
Vacuum energy:	0	$-3m_{pl}^2 M_p^2$	$-m_{pl}^2 M_p$
Gravitino mass:	$\frac{M_{pl}}{M_p}$	$-\frac{M_{pl}}{M_p}$	$\frac{M_{pl}}{M_p} \ll M_p$
Kahler moduli mass:	0 (unfixed)	$-m_{KK} \sim \left(\frac{M_{pl}}{m_{pl}}\right)$	(small) $m_{KK} \sim \frac{M_{pl}}{M_p}$ (large) $\frac{M_{pl}}{M_p}$
Dilaton/complex structure mass:	$-\frac{DDW}{V} \sim m_{pl}$	$-\frac{DDW}{V} \sim m_{pl}$	$DDW \sim m_{pl}$
Susy broken:	Yes, $F^I \neq 0$	No	Yes, $F^I \neq 0$

Conditions for Standard Universality

① Hidden sector fields divide into 2 kinds, Ψ and χ .

② Ψ and χ kinetic terms decouple

$$K_{ij} = \begin{pmatrix} K_{\Psi\bar{\Psi}} & 0 \\ 0 & K_{\chi\bar{\chi}} \end{pmatrix}$$

③ Superpotential Yukawas depend only on χ

$$Y_{\alpha\beta\gamma}(\Psi, \chi) = Y_{\alpha\beta\gamma}(\chi)$$

$$f_g(\Psi, \chi) = \sum \lambda_i \Psi_i$$

* Factorised kinetic terms inherited from $N=2$
hypermultiplets + vector multiplets
have no cross-terms in their kinetic mixing.

* $T \rightarrow T + i\epsilon$ addresses pt 3

* Factorised kinetic terms inherited from $N=2$

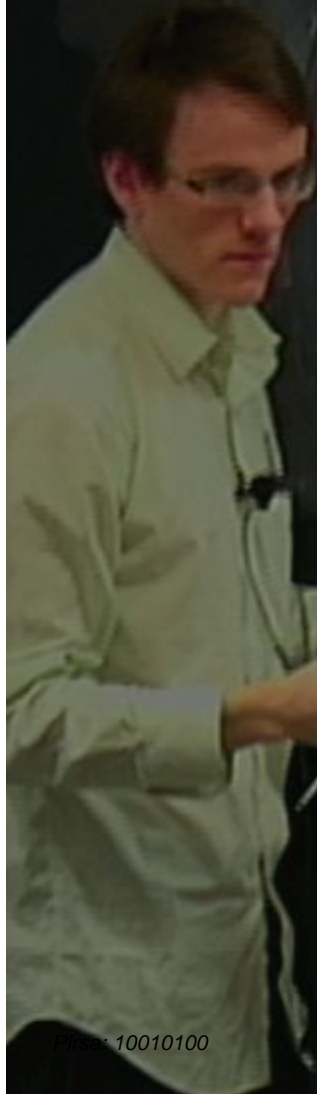
hypermultiplets + vector multiplets

have no cross-terms in their kinetic mixing.

* $T \rightarrow T + i\epsilon$ addresses pt 3

* (S): property of flux compactifications $F^I \neq 0, F^U = 0$

(F) It is true that in compiled examples this factored structure is present.



(F) It is true that in computed examples this factored structure is present.

Toroidal intersection branes

\mathbb{Z}_2

S^1
 IP

ID

(f) It is true that in computed examples this factored structure is present.

Toroidal intersecting branes

Universal T dependence

(D9)



$$\frac{1}{14} \frac{3}{\Gamma(2)}$$

$$\Gamma(1-\phi_{ab}) \Gamma(1-d_{en}) \Gamma(\phi_{ab} + d_{en})$$

$$\Gamma(\phi_{ab}) \Gamma(\phi_{ac}) \Gamma(1-d_{ab} + d_{ac})$$

ip

$\frac{1}{4} \Gamma(2)$

(F) It is true that in computed examples this factorised structure is present.

Toroidal intersecting branes

Universal T dependence

(D9)

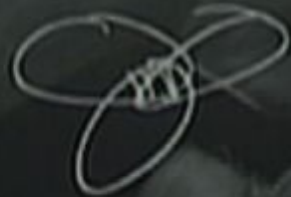
$$\tilde{Y}_{1/2} = \left(\frac{1}{\gamma^{1/4}} \prod_{\alpha} \frac{\Gamma(\dots)}{\Gamma(\dots)} \right)^{1/4}$$

$$(U_r)^{1/4} \mathcal{O} \left[\begin{matrix} \delta_{ij} \\ 0 \end{matrix} \right] \left(\text{or } \sqrt{I_{ab}^r I_{bc}^r I_{ca}^r} \right)$$

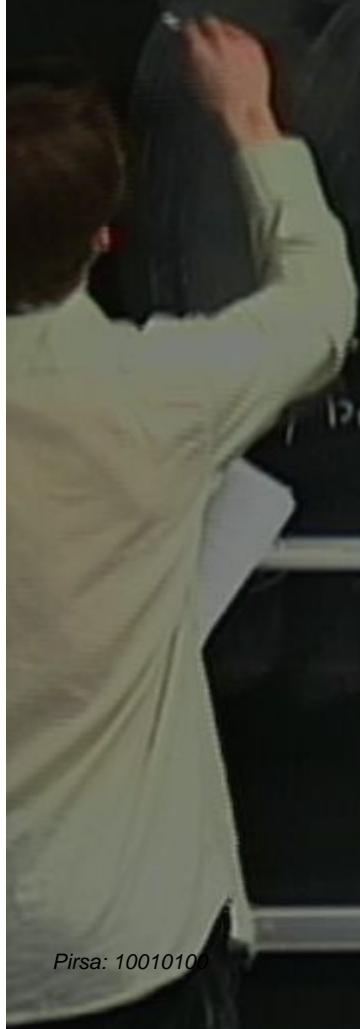
U -dependence

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In D0 setups, flavour comes from wavefunction overlap.
(Kaluza)



$$\sum_j \psi_i^\dagger \psi_j \phi_{ij}$$



mes.
12r0

potential values

depend only on λ

$$Y_{\alpha\beta\gamma}(\Phi, \lambda) = Y_{\alpha\beta\gamma}(\lambda)$$

$$f_{\alpha}(\Phi, \lambda) = \sum_i \lambda_i \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In IIB setups, flavour comes from wavefunction overlap.
(Kaluza)

$$\Psi_{ijh} = e^{iK_{ij} \cdot X} \Psi_{ijh}$$



$$\sum_{ij} \Psi_i^\dagger \Psi_j \phi_{ij}$$



Superpotential terms
depend only on χ

$$Y_{\alpha\beta\gamma}(\Phi, \chi) = Y_{\alpha\beta\gamma}(\chi)$$

$$\int_{\mathcal{M}} \mathcal{L}(\Phi, \chi) = \int_{\mathcal{M}} \delta \chi \cdot \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In DB setups, flavour comes from wavefunction overlap.
(Patz) (Kobayashi)

$$\Psi_{ijk} = e^{i\alpha} \frac{\Psi_{ijk}}{\sqrt{K_i K_j K_k}}$$

constant
depend on
Kähler
moduli



$$\sum_{i,j} \Psi_i^\dagger \Psi_j \phi_{ij}$$



mas

superpotential Yukawas

depend only on α

$$Y_{\alpha\beta\gamma}(\Phi, \alpha) = Y_{\alpha\beta\gamma}(\alpha)$$

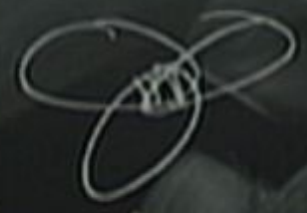
$$\int_{\mathcal{M}} \mathcal{L}(\Phi, \alpha) = \int_{\mathcal{M}} \delta \alpha \cdot \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In DD setups, flavour comes from wavefunction overlap.
(Yukawa)

$$Y_{ij} = e^{k_i} \frac{Y_{ijk}}{\sqrt{K_i K_j K_k}}$$

constant depend on Kähler moduli



$$\sum_{ij} \psi_i^\dagger \psi_j \phi_k$$

k_i tells us how Yukawa under metric rescaling



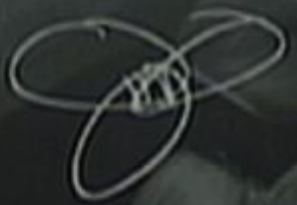
$$Y_{\alpha\beta\gamma}(\Phi, \alpha) = Y_{\alpha\beta\gamma}(\alpha)$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In IIB setups, flavour comes from wavefunction overlap.
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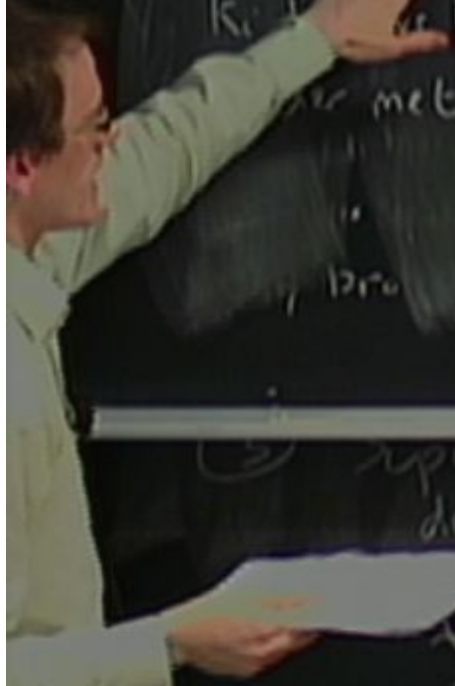
$$\Psi_{ij} = e^{ik_{ij}x} \Psi_{ij}(x)$$

constant depend on
Kähler moduli



$$\sum_{ij} \Psi_i^\dagger \Psi_j \phi_{ij}$$

k_{ij} is how Yukawas scale
under metric rescalings



Superpotential Yukawas
depend only on χ

$$Y_{\alpha\beta\gamma}(\Phi, \chi) = Y_{\alpha\beta\gamma}(\chi)$$

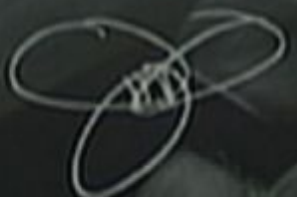
$$\delta_{\mathcal{L}}(\Phi, \chi) = \delta \chi_i \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In IIB setups, flavour comes from wavefunction overlap.
(Katzman)

$$\Psi_{ij} = e^{K_{ij} \Psi_{ij}} \frac{\Psi_{ij}}{\sqrt{K_{ij} K_{ij}}}$$

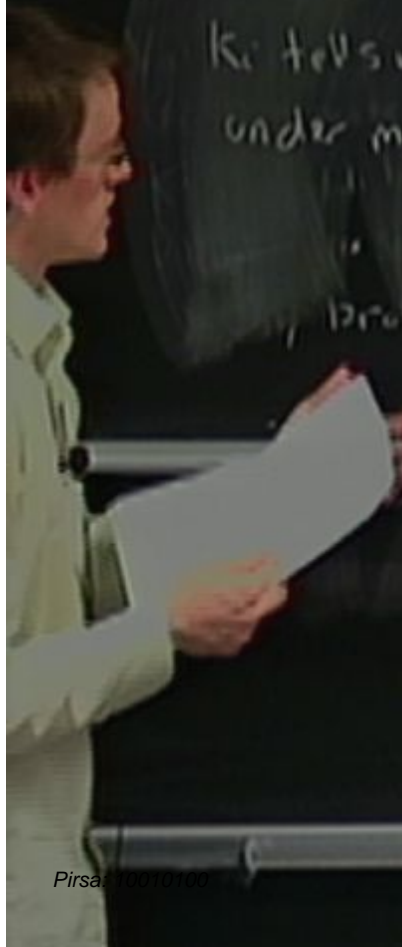
constant depend on Kähler moduli



$$\sum_{ij} \Psi_i^\dagger \Psi_j \phi_{ij}$$



K_i tells us how Yukawas scale under metric rescalings.



superpotential Yukawas depend only on χ

$$Y_{\alpha\beta\gamma}(\Phi, \chi) = Y_{\alpha\beta\gamma}(\chi)$$

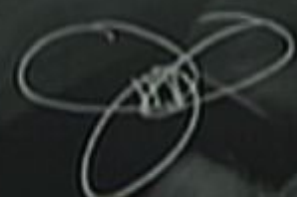
$$f_9(\Phi, \chi) = \sum \lambda_i \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

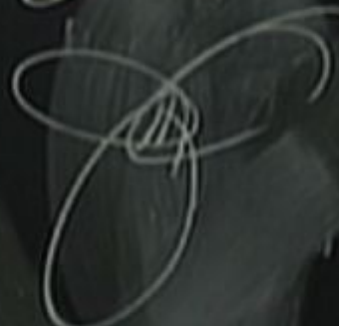
In IIB setups, flavour comes from wave function overlap.
(Kaluza)

$$\Psi_{ij} = e^{i k_i x} \Psi_{ij}(x) e^{i k_j x}$$

cannot depend on Kähler moduli

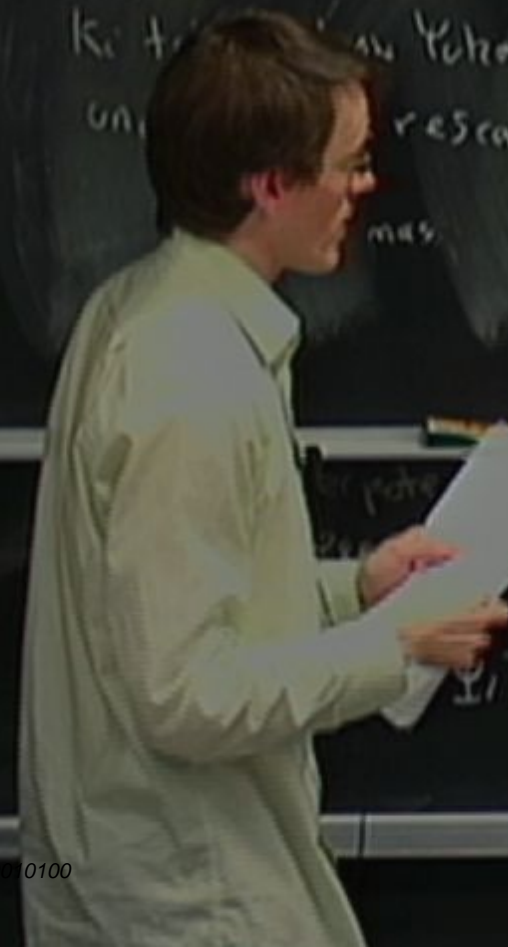


$$\sum \psi_i^\dagger \psi_j \phi_{ij}$$



$$\int_{\mathbb{M}} D_{\mu} \lambda = 0 \rightarrow \text{flavour}$$

k_i + ... Yukawa scale
un... rescalings



$$\Psi_{\alpha\beta\gamma}(\Phi, \lambda) = \Psi_{\alpha\beta\gamma}(\lambda)$$

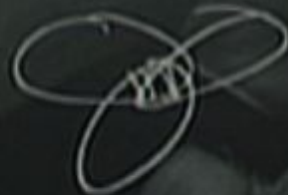
$$\Psi_{\alpha\beta\gamma}(\lambda) = \sum \lambda_i \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In IIB setups, flavour comes from wavefunction overlap
(Yukawa)

$$\Psi_{ij} = e^{K_{ij}} \frac{\Psi_i \Psi_j}{\sqrt{K_{ik} K_{jl}}}$$

constant depends on Kähler moduli



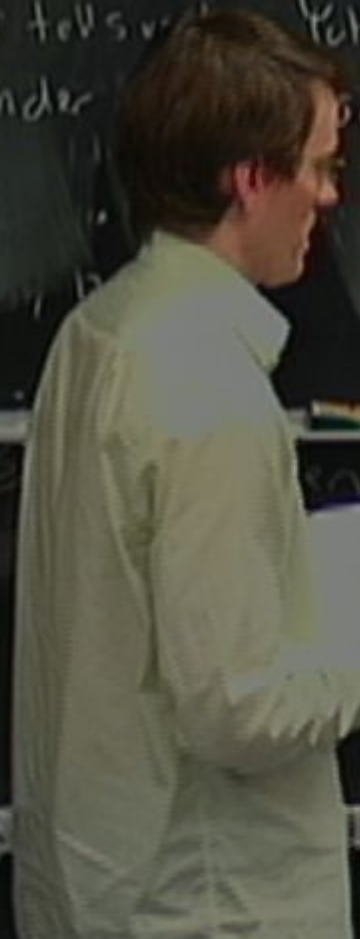
$$\sum_i \Psi_i^\dagger \Psi_j \Phi_{ij}$$



$$\Gamma^m D_m \lambda = 0 \rightarrow \text{flavour}$$

K_i tells you how Yukawas scale under rescalings

Solutions of Dirac eq don't care about metric rescalings



$$\Psi_{\alpha\beta\gamma}(\Phi, \lambda) = \Psi_{\alpha\beta\gamma}(\lambda)$$

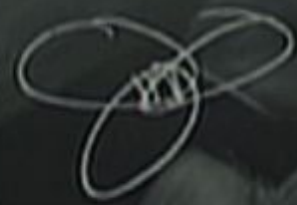
$$\Psi_{\alpha\beta\gamma} = \sum_i \lambda_i \Psi_i$$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS 2

In IIB setups, flavour comes from wavefunction overlap.
(Kobayashi)

$$\Psi_{ij} = e^{K_{ij}} \frac{\Psi_i \Psi_j}{\sqrt{K_{ij} K_{kl}}}$$

cannot depend on Kähler moduli

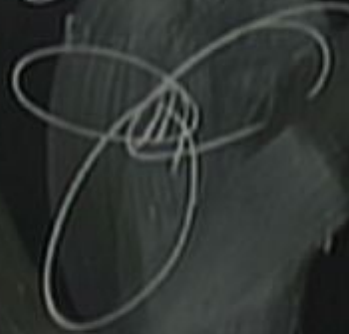


$$\sum_{ij} \Psi_i^\dagger \Psi_j \neq 0$$

$$\sum_{ij} \Psi_i^\dagger \Psi_j = 1$$

K_{ij} how Yukawas scale
metric rescalings

$\int \Gamma^M D_M \lambda = 0 \rightarrow$ flavour
Solutions of Dirac eq
don't care about
metric rescalings



Superpotential Yukawas
depend only on χ

$$Y_{\alpha\beta\gamma}(\Phi, \chi) = Y_{\alpha\beta\gamma}(\chi)$$

$$\int \delta \chi_i \Psi_i$$

In DD setups, flavour comes from wave function overlap.
(Kutruum)

$$\psi_{ij} = e^{iK_{ij}x} \psi_{ij}(x)$$

constant depend on
kähler moduli



$$\sum_i \psi_i^\dagger \psi_j \neq 0$$

$$\sum_i \psi_i^\dagger \psi_i = 1$$

K_i tells us how Yukawas scale under metric rescalings

$$\Gamma^m D_m \lambda = 0 \rightarrow \text{flavour}$$

Solutions of Dirac eq don't care about metric rescalings

Leading order in T , K_i carries almost all info about how solutions scale with metric

$$K_{ij} = \begin{pmatrix} K_{\alpha\bar{\beta}} & 0 \\ 0 & K_{\alpha\bar{\alpha}} \end{pmatrix}$$

Superpotential Yukawas

only on \mathcal{X}

$$Y_{\alpha\beta\gamma}(\Phi, \lambda) = Y_{\alpha\beta\gamma}(\lambda)$$

$$\psi_{\alpha\beta\gamma}(\Phi, \lambda) = \sum_i \lambda_i \psi_i$$