

Title: Aspects of Moduli in String Compactifications - Lecture 1

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URL: <http://pirsa.org/10010099>

Abstract:

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

50c
onion

1. What are moduli?

Why are they important?

Moduli effective actions

Moduli stabilisation + supersymmetry breaking

Moduli couplings / axions / cosmology

3. Moduli and threshold corrections

Local models and Kaplunovsky-Louis

Supergravity and string analysis

Application to local GUTs

2. Moduli and Flavour

Holomorphy constraints on Yukawa couplings

Moduli and susy Flavour universality

Moduli and cosmology

Non-renormalisable operators

Moduli effective actions
Moduli stabilisation + supersymmetry breaking
Moduli couplings / axions / cosmology

Moduli and SUSY
Moduli and flavour universality
Moduli and cosmology
Non-renormalisable operators

3. Moduli and threshold corrections
Local models and Kaplunovsky-Louis
Supergravity and string analysis
Application to local GUTs

What are moduli?

* Compactify string theory from 10d \rightarrow 4d



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Supersymmetry and string analysis
Application to local GUTs

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10d \rightarrow 4d \times 6d

Supergravity and string analyses
Application to local GUTs

What are moduli?

* Compactify string theory from 10d \rightarrow 4d

$$10d \rightarrow 4d \times 6d = CY$$

⑤

$10d \rightarrow 4d \times 6d = CY \leftarrow$ low energy supersymmetry
6

$\rightarrow 4d \times 6d = CY \leftarrow$ low energy supersymmetry

⑥

deformations of extra-dimensional geometry \rightarrow scalar fields in 4d.

$10d \rightarrow 4d \times 6d = CY \leftarrow$ low energy supersymmetry

⑥

- * Deformations of extra-dimensional geometry \rightarrow scalar fields in 4d.
- * Massless deformations \rightarrow 'massless' scalar fields: moduli.
'zero mode'

10d \rightarrow $G_d = CY$ \leftarrow low energy supersymmetry

(6)

- * Deformations of extra-dimensional geometry \rightarrow scalar fields in 4d.
- * Metric deformations \rightarrow 'massless' scalar fields: moduli.
- * Solves the equations of motion
- * Ricci-flat Kähler manifold of vanishing 1st Chern Class

$10d \rightarrow 4d \times 6d = CY. \leftarrow$ low energy supersymmetry

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Ricci-flat metric exists and is unique up to

- (1) choice of Kähler form
- (2) choice of complex structure

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Ricci metric exists and is unique up to (1) choice of Kähler form

Kähler moduli $J = \sum_{i=1}^{h^{1,1}} t^i e_i$ (2) choice of complex structure
 e_i \leftarrow basis of (1,1) form
Kähler moduli

$10d \rightarrow 4d \times 6d = CY \leftarrow$ low energy supersymmetry

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Kähler moduli

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(2) choice of complex structure

$\delta g_{ij} \rightarrow$ zero modes
Cliff forms

Kähler moduli

\leftarrow basis of (1,1) form

$10d \rightarrow 4d \times 6d = CY \leftarrow$ low energy supersymmetry

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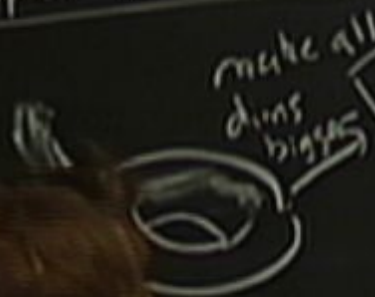
Complex structure moduli

$\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$

$\delta g_{ij} \Omega^j_{\bar{k}\bar{l}}$
 \uparrow
holomorphic
(3,0) forms

(2,1)
(1,2) forms

Complex structure moduli



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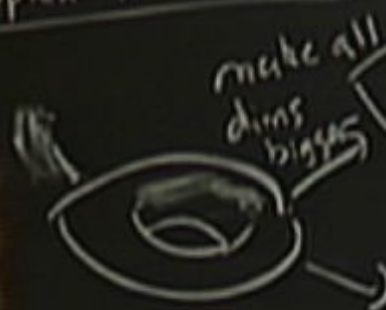
(2,1)
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Complex structure moduli

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$(2,1)$ forms
 $(1,2)$



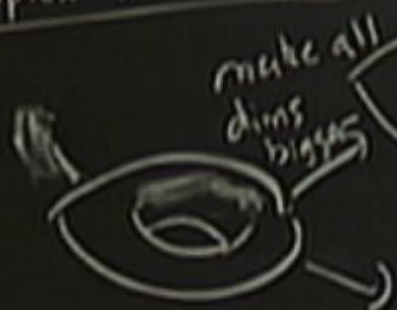
Kähler
deformation

holomorphic
 $(3,0)$ forms



Complex structure
deformation

Complex structure moduli



make all
dims
bigger

$\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$



'size'
Kähler
deformation



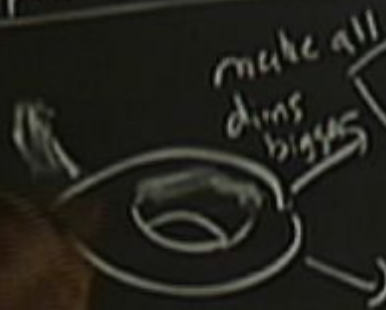
'shape'
Complex structure
deformation

$\delta g_{ij} \Omega^j_{\bar{k}\bar{l}}$

\uparrow
holomorphic
(3,0) form

(2,1) forms
(1,2)

Complex structure moduli



$\delta g_{ij}, \delta g_{i\bar{j}}$



'size'
Kähler
deformation



(shape)
Complex structure
deformation

$\delta g_{ij} \Omega^j \bar{h}^i$

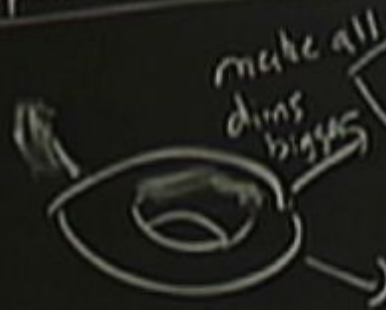
\uparrow
holomorphic
(3,0) form

(2,1) forms
(1,2)

* complexified by Spin fields

$J + iB$

Complex structure moduli



make all
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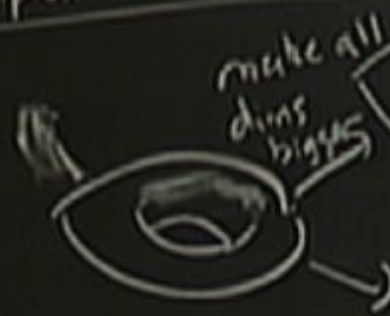
(2,1) forms
(1,2)

* Modul. complexified by Spin fields

$J + iB$

\uparrow
2-form

Complex structure moduli



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Complex structure
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$\delta g_{ij}, \Omega^j_{\bar{i}\bar{j}}$

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holomorphic
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(2,1) forms
(1,2)

* Moduli complexified by Spin fields

$$J + iB \leftarrow \int_{\Sigma} \omega$$

\uparrow Vol 2-cycle \uparrow 2-form

Complex structure moduli

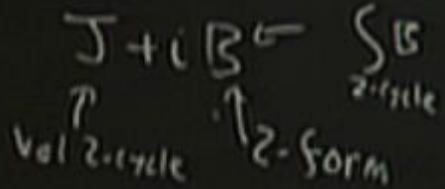


δg $\Omega^j \bar{\Omega}^{\bar{i}}$ $(2,1)$ forms $(1,2)$ forms

\uparrow

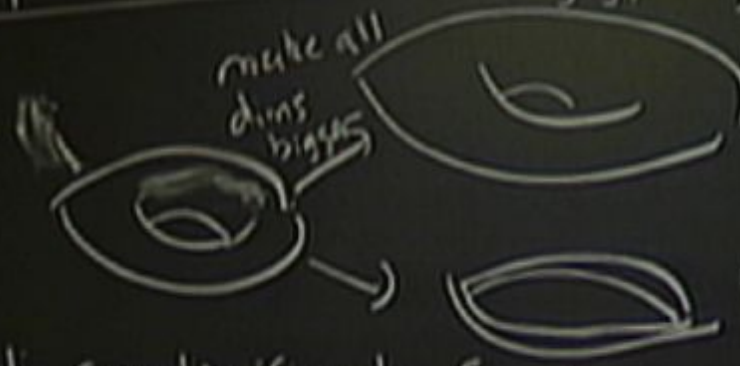
holomorphic $(3,0)$ form

* Modul. complexified by Spin fields



Dilaton : string coupling g_s

Complex structure moduli



$\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$

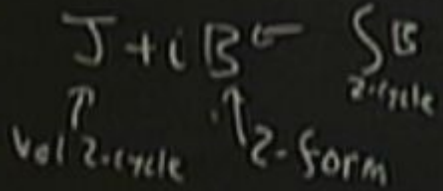
'size' Kähler deformation
(shape) complex structure deformation

δg

$\Omega^j \bar{h}_i$
↑
holomorphic (3,0) form

(2,1) forms
(1,2) forms

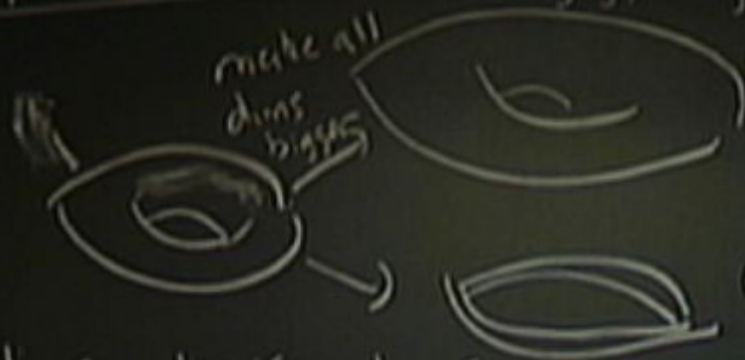
* Moduli complexified by Spin fields



Dilaton : string coupling $g_s + iC_0$

Complex structure moduli

$g_{ij}, g_{\bar{i}\bar{j}}$



'size'
Kähler deformation
(shape)
Complex structure deformation

holomorphic
(3,0) form

* Modul. complexified by Spin fields

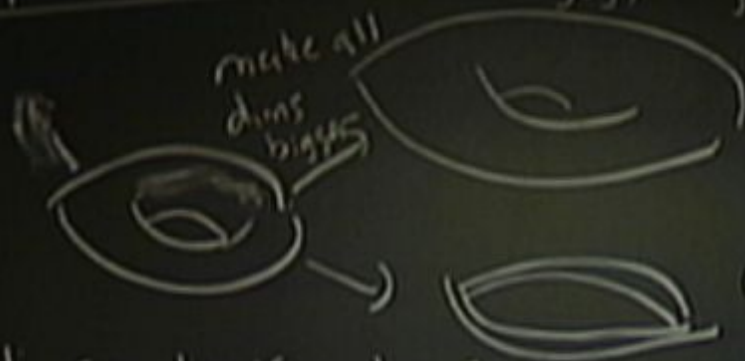
$$J + iB \leftarrow \int_{\Sigma^2} \omega$$

\uparrow vol 2-cycle \uparrow 2-form

Dilaton : string coupling $g_s + iC_0$

Other moduli : bundle moduli, brane moduli

Complex structure



size
Kähler
deformation
(shape)
Complex structure
deformation

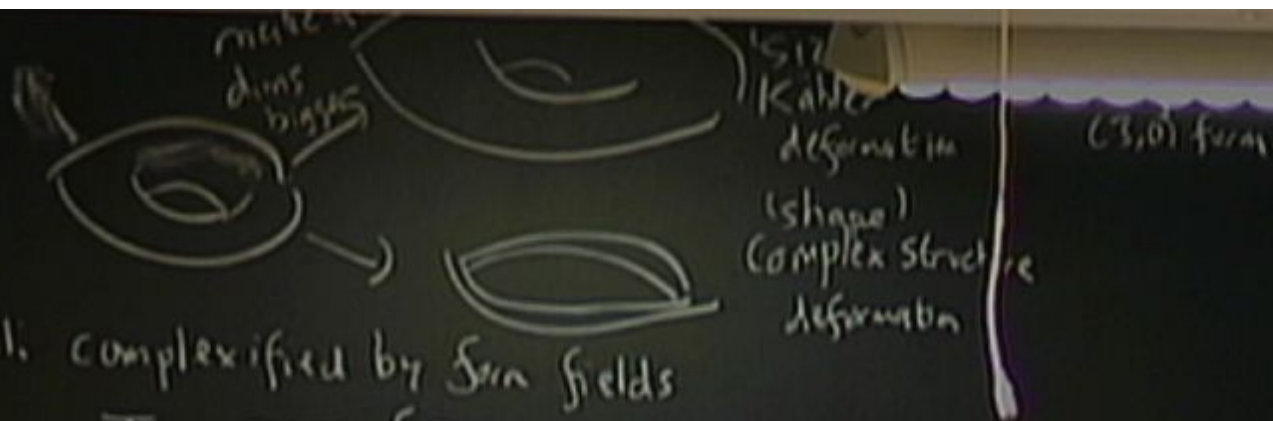
holomorphic
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$$\begin{array}{ccc}
 J + iB & \leftarrow & \int B \\
 \uparrow & & \uparrow \\
 \text{Vol 2-cycle} & & \text{2-form}
 \end{array}$$

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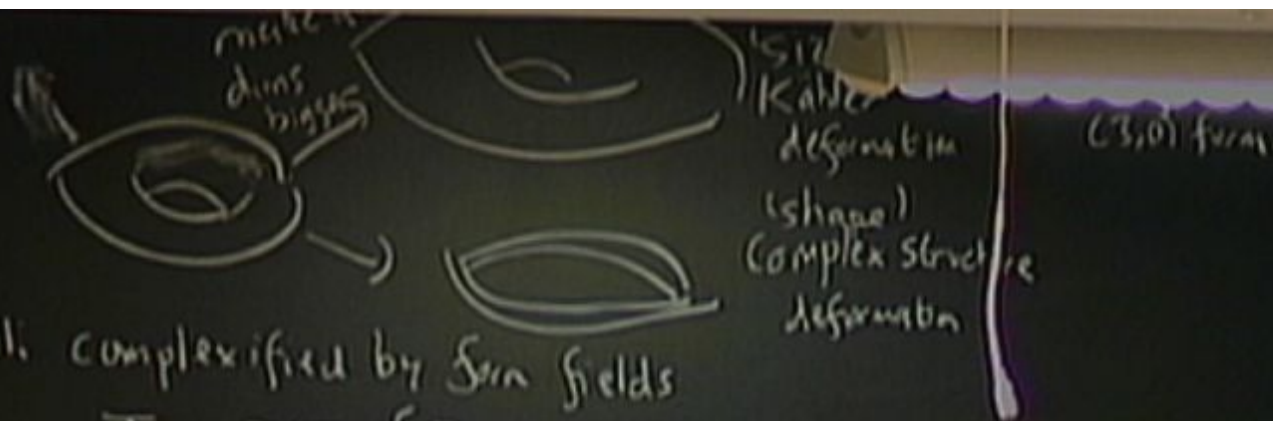
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↑ ↑
Vol 2-cycle 2-form

Dilaton : string coupling $g_s + iC_0$ RR 0-form from the closed string RR sector.

Other moduli : bundle moduli, brane moduli (not going to talk about)



* Moduli complexified by form fields

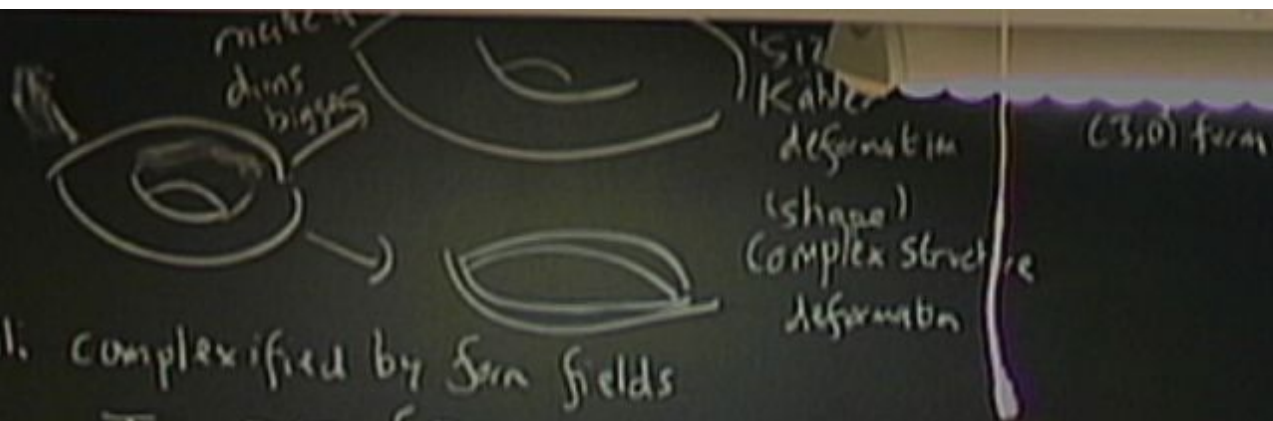
$$J + iB \leftarrow \int_{\Sigma} \omega$$

↑
vol 2-cycle

↑
2-form

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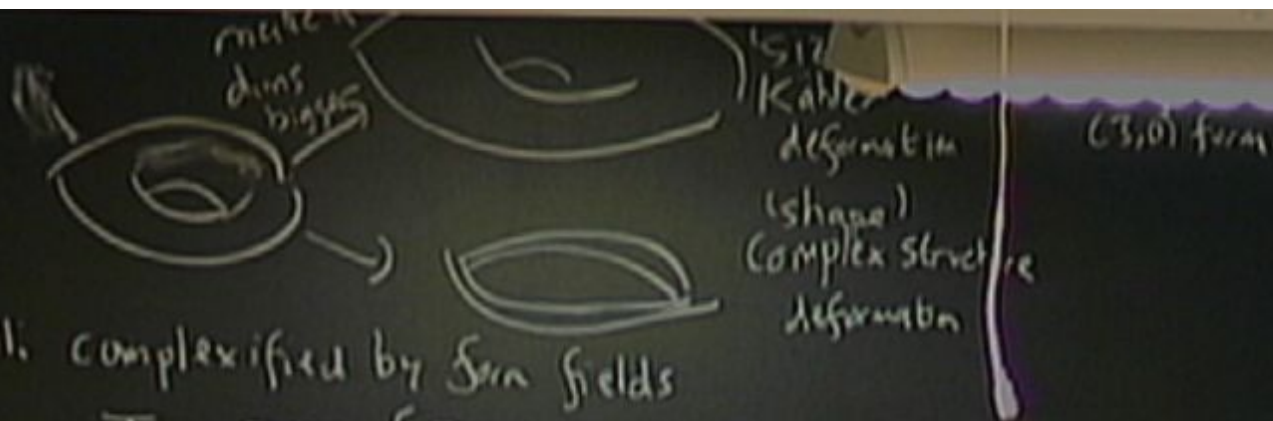
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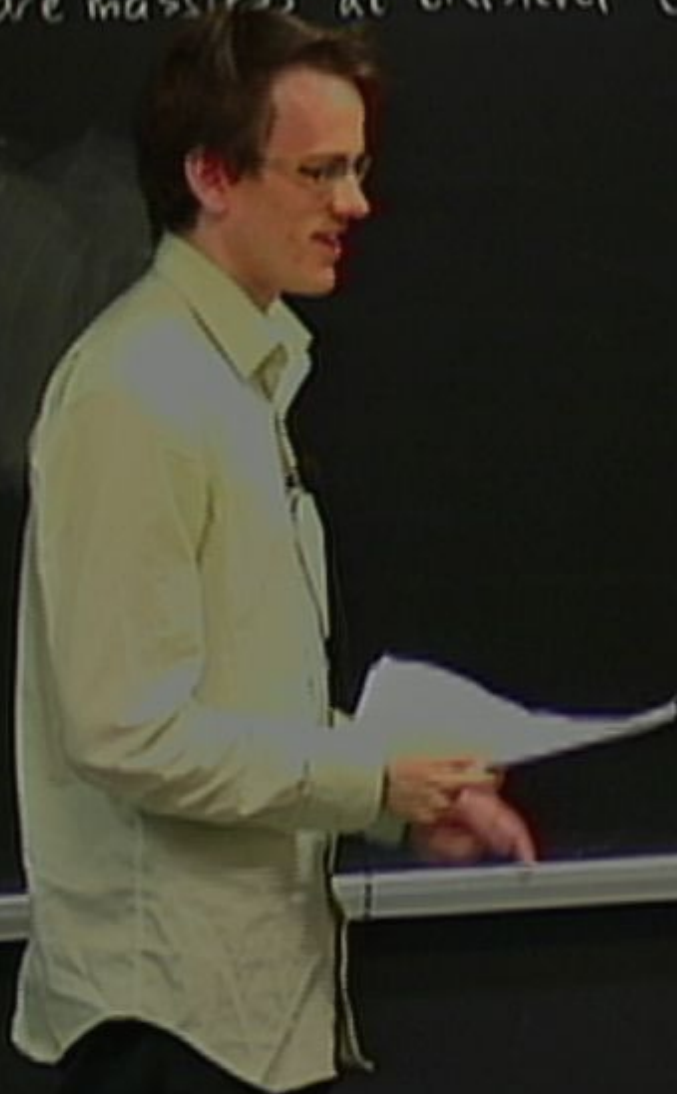


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Moduli are massless at tree-level (5^{th} forces) and so must be stabilised.

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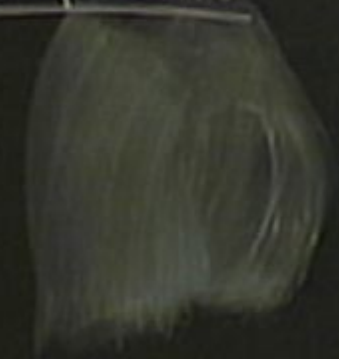
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and will get masses at $1/m_{\text{pl}}^2$



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and will get masses at 1 string

Why important?



Other moduli: bundle moduli, brane moduli (not going to talk about)

Moduli are massless at tree-level (5^{th} forces) and so must be stabilised. ^{Stringy suggests would}
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Why important?

* Moduli are generic.

Other moduli: bundle moduli, brane moduli (not going to talk about)

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Why important?

* Moduli are generic.

* Moduli sector takes some basic form for all CYs.

Other moduli: bundle moduli, brane moduli (not going to talk about)

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portant?

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- * Moduli sector takes some basic form for all CYs
- * Anti-landscape: if any universal results of string compactifications, they will come from the moduli sector.

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1. * Moduli are generic.
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In particular:
* inflation
* cosmology

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In particular, * $SU(3)$ * inflation
* flavor * cosmology
* axions

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2. Moduli enter crucially into all BSM questions in string theory

In particular, * SUSY * inflation

* flavor * cosmology

* axions

3. * Added value of strings: systematic violation of 'naive' EFT expectation

Modul: definitions

Moduli definitions

2 main types of ^{geometric} moduli, Kähler and complex structure

Kähler \rightarrow 2d cycles in CY

2 main types of moduli, Kähler and complex structure

Kähler \rightarrow 2nd cycles in CY

Complex structure \rightarrow 3 cycles

Moduli definitions

2 main types of ^{geometric} moduli, Kähler and complex structure

Kähler \rightarrow 2,4 cycles in CY

Complex structure \rightarrow 3 cycles

specialise

Moduli
2 main types of ^{geometric} moduli, Kähler and complex structure

Kähler \rightarrow 2,4 cycles in CY

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

II B

2 main types of ^{geometric} moduli, Kähler and complex structure

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Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

$$K_0 = e^{-\phi} \sum_{S_4} \sqrt{g} + i \sum_{S_4} C_4$$

2 main types of ^{geometric} moduli, Kähler and complex structure

Kähler \rightarrow 214 cycles in CY

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kähler: $T_{\mathbb{F}} = e^{-\phi} \sum_{2n,i} \sigma_i g + i \sum_{2n,i} C_n$

Kähler \rightarrow 2,4 cycles in CY

Complex structure \rightarrow 3 cycles

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Complex structure U_i

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* Specialise to $N=1$ compactifications

IIB D3/D7

$$\text{Kähler: } T_F = e^{-\phi} \sum_{2,4,i} \sqrt{g} + i \sum_{2,4,i} C_4$$

$$\text{Complex structure } U_i = \sum_{2,3,1} \Omega$$

$$\text{Dilaton } S = e^{-\phi} + i C_0$$

Kähler \rightarrow 2 cycles in U_1

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

$$\text{Kähler: } T_{\tilde{F}} = e^{-\phi} \left(\sum_{\Sigma_{4,i}} \sqrt{g} + i \sum_{\Sigma_{4,i}} C_4 \right) (S E_3)$$

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Complex structure $U_1 = \sum_{\Sigma_{3,i}} \Omega$

$$\text{Dilaton } S = e^{-\phi} + i C_0 \quad (SO_{-1})$$

2 main types of ^{geometric} moduli, Kähler

Kähler \rightarrow 2,4 cycles in CY

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kähler: $T_i = e^{-\phi} \int_{\Sigma_{2,i}} \sqrt{g} + i \int_{\Sigma_{2,i}} C_4$ (SE3)

Complex structure $U_i = \int_{\Sigma_{2,i}} \Omega$

Dilaton $S = e^{-\phi} + i c_0$ (SO-1)

IIA D6/06

$T = \int_{\Sigma_2} \sqrt{g} + i \int_{\Sigma_2} B$

$U = \int_{\Sigma_3} e^{-\phi} \sqrt{g} + i \int_{\Sigma_3} C_3$

$S = \int e^{-\phi} \sqrt{g} + i \int C_3$

2 main types of moduli, Kähler

Kähler \rightarrow 2,4 cycles in CY

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIB D5/D7

$$\text{Kähler: } T_{\tilde{r}} = e^{-\phi} \sum_{\Sigma_{4,i}} \sqrt{g} + i \sum_{\Sigma_{4,i}} C_4 \quad (SE_3)$$

$$\text{Complex structure } U_i = \sum_{\Sigma_{3,i}} \Omega$$

$$\text{Dilaton } S = e^{-\phi} + i C_0 \quad (SO_{d-1})$$

IIA D6/D0

$$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} B \quad (\text{4d/11 sheet instanton})$$

$$U = \sum_{\Sigma_3} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_3} C_3 \quad (E_2)$$

$$S = \sum e^{-\phi} \sqrt{g} + i C_0$$

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

$$\text{Kahler: } T_{\text{I}} = e^{-\phi} \sum_{\Sigma_{4,i}} \sqrt{g} + i \sum_{\Sigma_{4,i}} C_4 \quad (SO_{3,1})$$

$$\text{Complex structure } U_i = \sum_{\Sigma_{3,i}} \Omega$$

$$\text{Dilaton } S = e^{-\phi} + i c_0 \quad (SO_{2,1})$$

IIA D6/D0

$$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} B \quad (\text{world sheet instanton})$$

$$U = \sum_{\Sigma_3} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_3} C_3 \quad (E2)$$

$$S = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_2} C_2$$

Kähler \Rightarrow 2-d cycles in E_7

Complex structure \Rightarrow 3 cycles

* Specialise to $N=1$ compactifications

III D6/D7

$$\text{Kähler: } T = e^{-\phi} \sum_{\alpha_1, i} \sqrt{g} + i \sum_{\alpha_1, i} C_4 (S_{\alpha_1})$$

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$$\text{Dilaton } S = e^{-\phi} + i C_0 (S_{\alpha_1})$$

III A D6/D6

$$T = \sum_{\alpha_1, i} \sqrt{g} + i \sum_{\alpha_1, i} C_4 \quad (\text{hold spinors invariant})$$

$$U = \sum_{\alpha_1, i} e^{-\phi} \sqrt{g} + i \sum_{\alpha_1, i} C_3 (C_{\alpha_1})$$

$$S = \sum_{\alpha_1, i} e^{-\phi} \sqrt{g} + i \sum_{\alpha_1, i} C_3$$

Moduli definitions


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$$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} C_2 \quad (\text{world sheet instanton})$$

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* Specialise to $N=1$ compactifications

IIA D3/D7

Kähler: $T_F = e^{-\phi} \int_{\Sigma_{2n,i}} \sqrt{g} + i \int_{\Sigma_{2n,i}} C_n$ (SE1)

Complex structure $U_i = \int_{\Sigma_{2n,i}} \Omega$

Dilaton $S = e^{-\phi} + i c_0$ ($S_{O(1)}$)

IIA D6/D0

$T = \int_{\Sigma_2} \sqrt{g} + i \int_{\Sigma_2} B$ (Worldsheet instanton)

$U = \int_{\Sigma_3} e^{-\phi} \sqrt{g} + i \int_{\Sigma_3} C_3$ (C2)

$S = \int_{\Sigma_3} e^{-\phi} \sqrt{g} + i \int_{\Sigma_3} C_3$

Heterotic

$\int \sqrt{g} + i B_2$ (Worldsheet instanton)

$\int_{\Sigma_3} \Omega$

Kähler \rightarrow 2-d. cycles in CY

Complex structure \rightarrow 3 cycles

\rightarrow Specialise to $N=1$ compactifications

IIB D3/D7

$$\text{Kähler: } T_F = e^{-\phi} \left(\sum_{\Sigma_{4,i}} \sqrt{g} + i \sum_{\Sigma_{4,i}} C_4 \right) (S_{E3})$$

$$\text{Complex structure } U_i = \sum_{\Sigma_{3,i}} \Omega$$

$$\text{Dilaton } S = e^{-\phi} + i c_0 \quad (S_{O(2)})$$

IIA D6/D0

$$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} B \quad (\text{world sheet instanton})$$

$$U = \sum_{\Sigma_3} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_3} C_3 \quad (C2)$$

$$S = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_2} C_2$$

Heterotic

$$\sum_{\Sigma_3} \sqrt{g} + i B_2 \quad (\text{Worldsheet instanton})$$

$$\sum_{\Sigma_3} \Omega$$

$$S = \sum_{\Sigma_2} e^{-\phi} \sqrt{g}$$



Complex structure \rightarrow 3 cycles

\rightarrow Specialise to $N=1$ compactifications

IIB D3/D7

$$\text{Kahler: } T_F = e^{-\phi} \left(\sum_{\Sigma_{2,1}} \sqrt{g} + i \sum_{\Sigma_{2,1}} C_2 \right) (S_{E3})$$

$$\text{Complex structure } U_i = \sum_{\Sigma_{2,1}} \Omega$$

$$\text{Dilaton } S = e^{-\phi} + i c_0 \quad (S_{O(1)})$$

IIA D6/D0

$$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} B \quad (\text{worldsheet instanton})$$

$$U = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_2} C_3 \quad (C2)$$

$$S = \sum e^{-\phi} \sqrt{g} + i \int C_3$$

Heterotic

$$\int \sqrt{g} + i B_2 \quad (\text{worldsheet instanton})$$

$$\int_{\Sigma_2} \Omega$$

$$S = \int_{C_4} e^{-2\phi} \sqrt{g} + i B_{\mu\nu}$$

Shift symmetries

06

Shift symmetries

III $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)

Shift symmetries

$$\text{IIB: } T \rightarrow T + i\epsilon$$

$$\text{IIA: } U \rightarrow U + i\epsilon$$

(good to all orders in
string perturbation
theory)

//

Shift symmetries

$$\text{IIb } T \rightarrow T + i\epsilon \quad (\text{good to all orders in string perturbation theory})$$

$$\text{IIa } U \rightarrow U + i\epsilon \quad //$$

$$\text{IIb} \leftrightarrow \text{IIa} \quad (\text{mirror symmetry})$$

$$T \leftrightarrow U$$

Shift symmetries

$$\text{II B } T \rightarrow T + \epsilon \quad (\text{good to all orders in string perturbation theory})$$

$$\text{II A } U \rightarrow U + \epsilon \quad //$$

$$\text{II B} \leftrightarrow \text{II A} \quad (\text{mirror symmetry})$$

$$T \leftrightarrow U$$

Shift symmetries

$$\text{IIb } T \rightarrow T + i\epsilon \quad (\text{good to all orders in string perturbation theory})$$

$$\text{IIa } U \rightarrow U + i\epsilon \quad //$$

$$\text{IIb} \leftrightarrow \text{IIa} \quad (\text{mirror symmetry})$$

$$T \leftrightarrow U$$

* focus on $D3/D7$ here.
IIb

Kähler \rightarrow 2d. cycles in CY

Complex structure \rightarrow 3 cycles

\rightarrow Specialise to $N=1$ compactifications

II B D3/D7

Kähler: $T_F = e^{-\phi} \sum_{S_{2,i}} \sqrt{g} + i \sum_{C_{2,i}} (S_{2,i})$

Complex structure $U_i = \sum_{S_{2,i}} \Omega$

Dilaton $S = e^{-\phi} + i c_0$ ($S_{0,i}$)

II A D6/D0

$T = \sum_{S_{2,i}} \sqrt{g} + 6 \sum_{S_{2,i}} B$ (4d. gauge instanton)

$U = \sum_{S_{2,i}} e^{-\phi} \sqrt{g} + 6 \sum_{C_{2,i}} (C_{2,i})$

$S = \sum_{S_{2,i}} e^{-\phi} \sqrt{g} + 6 \sum_{C_{2,i}} C_{2,i}$

Heterotic

$\int \sqrt{g} + i B_2$ (Weyl sheet (instanton))

$\int \Omega$

$S = \sum_{C_{2,i}} e^{2\phi} \sqrt{g} + 6 B_{2,i}$

II A: $U \rightarrow U + ic$

II B \leftrightarrow II A (mirror symmet)

$T \leftrightarrow U$

* focus on D3/D7 here
II B

String perturbation theory

Kähler \rightarrow 2-d. cycles in CY

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

II B D3/D7

Kähler: $T_F = e^{-\phi} \left(\int_{\Sigma_{2,i}} \sqrt{g} + i \int_{\Sigma_{2,i}} C_2 \right) (S^1)$

Complex structure $U_i = \int_{\Sigma_{2,i}} \Omega$

Dilaton $S = e^{-\phi} + i c_0 (S^1)$

II A D6/D0

$T = \int_{\Sigma_2} \sqrt{g} + i \int_{\Sigma_2} B$ (worldsheet instanton)

$U = \int_{\Sigma_2} e^{-\phi} \sqrt{g} + i \int_{\Sigma_2} C_3$ (C2)

$S = \int_{\Sigma_2} e^{-\phi} \sqrt{g} + i \int C_3$

Heterotic

$\int \sqrt{g} + i B_2$ (worldsheet instanton)

$\int_{\Sigma_3} \Omega$

$S = \int_{CY_6} e^{-2\phi} \sqrt{g} + i B_{p,q}$

II A: $U \rightarrow U + i c$

II B \leftrightarrow II A (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7
II B

String perturbation theory

Kähler \rightarrow 2-d. cycles in CY

Complex structure \rightarrow 3 cycles

Specialise to $N=1$ compactifications

IIA D3/D7 orientifold 03107

Kähler: $T_F = e^{-\phi} \left(\sum_{\Sigma_{2,i}} \sqrt{g} + i \sum_{\Sigma_{2,i}} C_2 \right) (SO_{2,1})$

Complex structure $U_i = \sum_{\Sigma_{3,i}} \Omega$

Dilaton $S = e^{-\phi} + i C_0 (SO_{3,1})$

IIA D6/D0

$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} C_2$ (Kahler moduli + integral)

$U = \sum_{\Sigma_3} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_3} C_3$ (CS)

$S = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_2} C_2$

Heterotic

$\int \sqrt{g} + i B_2$ (Weyl sheet structure)

$\sum_{\Sigma_3} \Omega$

$S = \sum_{CY_6} e^{-\phi} \sqrt{g} + i B_{FUV}$

IIA: $U \rightarrow U + i e$

II B \leftrightarrow IIA (mirror S)

$T \leftrightarrow U$

* focus on D3/D7 here
II B

String perturbation theory

* Specialise to $N=1$ compactifications

II B D3/D7 orientifold 03107

Kähler: $T = e^{-\phi} \int_{\Sigma_{2,1}} \sqrt{g} + i \int_{\Sigma_{2,1}} C_2$ (SE3)

Complex structure $U = \int_{\Sigma_{2,1}} \Omega$

Dilaton $S = e^{-\phi} + i c_0$ ($SO_{2,1}$)

$T = \int_{\Sigma_2} \sqrt{g} + i \int_{\Sigma_2} B$ (worldsheet instanton)

$U = \int_{\Sigma_2} e^{-\phi} \sqrt{g} + i \int_{\Sigma_2} C_3$ (C2)

$S = \int_{\Sigma_2} e^{-\phi} \sqrt{g} + i \int_{\Sigma_2} C_3$

$\int \sqrt{g} + i B_2$ (Worldsheet instanton)

$\int_{\Sigma_2} \Omega$

$S = \int_{CY_6} e^{-2\phi} \sqrt{g} + i \int_{CY_6} B_{p,q}$

Shift symmetries

II B $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)

II A: $U \rightarrow U + i\epsilon$ //

II B \leftrightarrow II A (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here
II B

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

Joe Conlon

Effective action * Want Kähler potential and superpotential as a function of the moduli

$$K = -\ln(\mathcal{V}) + \mathcal{Z}_{ij}$$



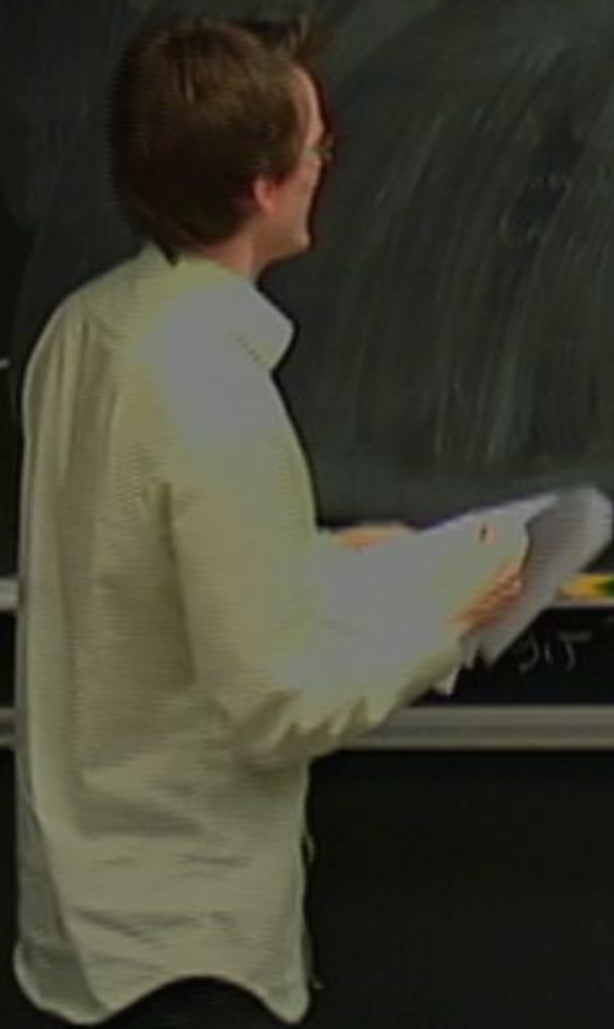
ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

Joe Conlon

Effective action * Want Kähler potential and superpotential as a function of the moduli.

$$K = K(\Phi, \bar{\Phi}) + \mathcal{Z}_{ij}(\Phi, \bar{\Phi})$$

[Large area of the chalkboard is heavily scribbled out with dark grey chalk.]



[Faint handwritten notes at the bottom of the chalkboard:]
 ... a basis of (1,1) form ...
 ... Kähler moduli ...

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

Joe Conlon

Effective action

* Want Kähler potential

and superpotential as a function of the moduli

$$K = K(\Phi, \bar{\Phi}) + Z_{ij}(\Phi, \bar{\Phi}) C^i \bar{C}^j$$

$$W = W(\Phi)$$

digit $\in \mathbb{Z}$ modes

Chl forms

→ a basis of Chl form

Kähler moduli

structure

Complex structure $U(1) = \sum_{2,1}^{2,0}$
 Dilatn $S = e^{-\phi} + i\epsilon_0 (SO_{2,1})$

$$S = \int e^{-\phi} \sqrt{g} + i \int G_3$$

$$S = \int_{CY_6} e^{2\phi} \sqrt{g} + i \int B_{p,q}$$

Shift symmetries

$II_B \quad T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)
 $II_A \quad U \rightarrow U + i\epsilon$ //

$II_B \leftrightarrow II_A$ (mirror symmetry)

$T \leftrightarrow U$

* focus on $D3/D7$ here
 II_B



Complex structure $U(1) = \int_{\Sigma_1} \omega$
 Dilaton $S = e^{-\phi} + i\epsilon_0 (S_{\text{odd}})$

$$S = \int_{\Sigma_1} e^{-\phi} \sqrt{g} + i \int_{\Sigma_1} G_3$$

$$S = \int_{CY_6} e^{2\phi} \sqrt{g} + i \int_{CY_6} B_{\mu\nu}$$

Shift symmetries

II B $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)
 II A $U \rightarrow U + i\epsilon$ //

II B \leftrightarrow II A (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here
 II B



$$\text{Kahler: } T = e^{-\phi} \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_4} C_4 \quad (S^2 \times S^2)$$

$$T = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} B$$

$$\text{Complex structure: } \sum_{\Sigma_3} \Omega$$

$$U = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i \sum_{\Sigma_2} C_2$$

$$V = \sum_{\Sigma_2} \sqrt{g} + i \sum_{\Sigma_2} B$$

$$\text{Dilaton: } \sum_{\Sigma_3} \Omega + i C_0 \quad (S^2 \times S^2)$$

$$S = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i C_2$$

$$S = \sum_{\Sigma_2} e^{-\phi} \sqrt{g} + i B_{\mu\nu}$$

$\text{IIA: } U \rightarrow U + ic$

String perturbation theory

$\text{IIB} \leftrightarrow \text{IIA} \quad (\text{mirror symmetry})$

$T \leftrightarrow U$

focus on D3/D7 here

IIB

Complex structure \rightarrow 3 cycles

* Specialise to $N=1$ compactifications

IIb D3/D7 orientifold

Kahler: $T = e^{-\phi} \int_{\Sigma_{2,1}} \sqrt{g} + i \int_{\Sigma_{2,1}} C_4$ (SO₂)

Complex structure: $U = \int_{\Sigma_{2,1}} \Omega$

Dilaton: $S = e^{-\phi} + i C_0$ (SO₂)

IIA D6/D0

$T = \int_{\Sigma_2} \sqrt{g} + i \int_{\Sigma_2} B$ (Worldsheet instanton)

$U = \int_{\Sigma_2} e^{-\phi} \sqrt{g} + i \int_{\Sigma_2} C_3$ (C2)

$S = \int_{\Sigma_2} e^{-\phi} \sqrt{g} + i \int_{\Sigma_2} C_3$

Heterotic

$\int \sqrt{g} + i B_2$ (Wald instanton)

$\int_{\Sigma_3} \Omega$

$S = \int_{CY_6} e^{-2\phi} \sqrt{g} + i B_{7,6}$

IIb $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)
IIA $U \rightarrow U + i\epsilon$ "

IIb \leftrightarrow IIA (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here
IIb



II B D4D7 orientifold

Kahler: $T = e^{-\phi} \sum_{2,1} \sqrt{g} + i \sum_{2,1} C_4$ (SE3)

Complex structure $U_i = \sum_{2,3,1} \Omega$

Dilaton $S = e^{-\phi} + i c_0$ (SO(2))

II A D6D6

$T = \sum_{2,2} \sqrt{g} + i \sum_{2,2} B_2$ (world sheet instanton)

$U = \sum_{2,2} e^{-\phi} \sqrt{g} + i \sum_{2,2} C_3$ (C2)

$S = \sum_{2,2} e^{-\phi} \sqrt{g} + i \sum_{2,2} C_3$

$\sum_{2,2} \sqrt{g} + i B_2$ (world sheet instanton)

$\sum_{2,3} \Omega$

$S = \sum_{2,4,6} e^{-2\phi} \sqrt{g} + i B_{p,q}$

Shift symmetries

II B $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)

II A $U \rightarrow U + i\epsilon$ //

II B \leftrightarrow II A (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here
II B



IIb D3/D7 orientifold 0310+

Kahler: $T = e^{-\phi} \sum_{2,1} \sqrt{g} + i \sum_{2,1} C_4$ (SO(3))

Complex structure $U = \sum_{2,1} \Omega$

Dilatn $S = e^{-\phi} + i c_0$ (SO(2))

$T = \sum_{2,2} \sqrt{g} + i \sum_{2,2} B$ (hold 2,1,1,1 instanton)

$U = \sum_{2,2} e^{-\phi} \sqrt{g} + i \sum_{2,2} C_3$ (SU(2))

$S = \sum_{2,2} e^{-\phi} \sqrt{g} + i \sum_{2,2} C_3$

$\sum_{2,2} \sqrt{g} + i B_2$ (instanton)

$\sum_{2,2} \Omega$

$S = \sum_{2,2} e^{2\phi} \sqrt{g} + i B_{2,1,0}$

Shift symmetries

IIb $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)

IIa $U \rightarrow U + i\epsilon$ //

IIb \leftrightarrow IIa (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here
IIb



Vilain $S = e^{-1} + (G_0 + \dots) \rightarrow (e^{-1} g + \dots)$ (CY6)

Shift symmetries

$\text{IIb } T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)
 $\text{IIA } U \rightarrow U + i\epsilon$ //

$\text{IIb} \leftrightarrow \text{IIA}$ (mirror symmetry)

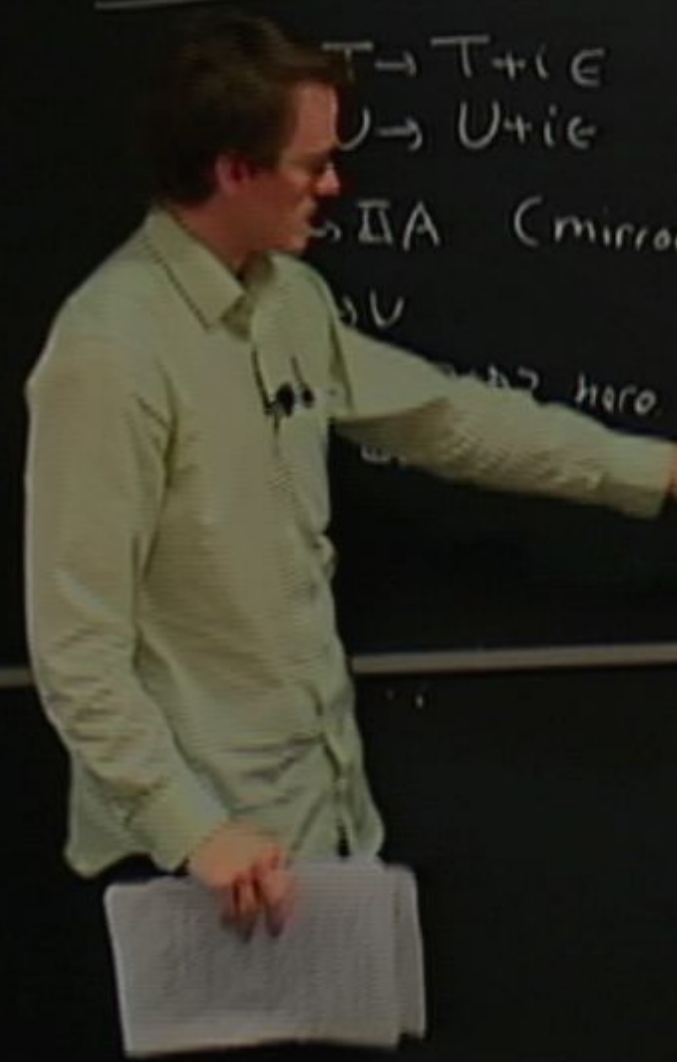
$T \leftrightarrow U$
on $D3/D7$ here
 IIb



Vilain $S = e^{-1} + (G_0 + G_1) \rightarrow S = e^{-1} + (G_0 + G_1)$ (46)

Shift symmetries

$T \rightarrow T + \epsilon$ (good to all orders in string perturbation theory)
 $U \rightarrow U + i\epsilon$ "
 $\rightarrow \Delta A$ (mirror symmetry)



Vilain $S = e^{-1} + i\epsilon_0 (S_{\text{odd}}) + S \rightarrow S(e^{-1} g + \epsilon_0 g)$ (46)

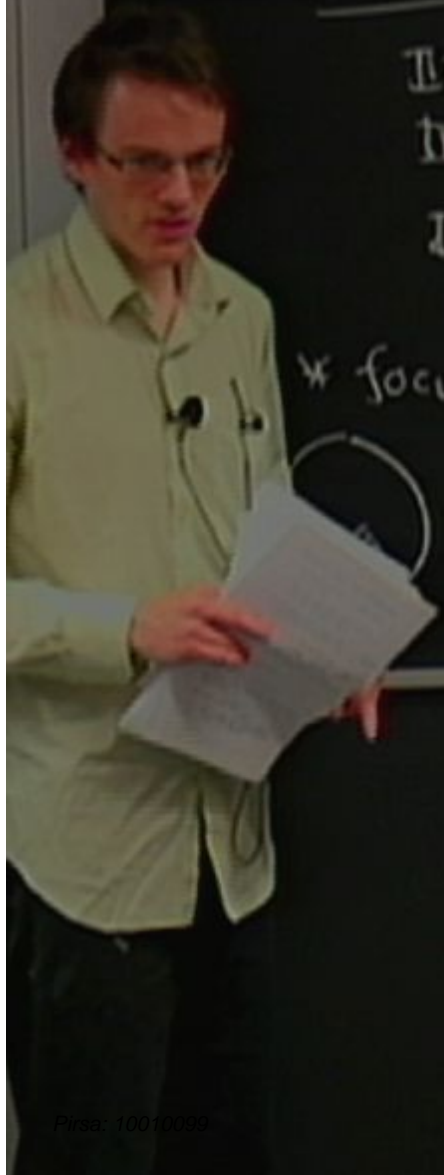
Shift symmetries

IIb $T \rightarrow T + i\epsilon$ (good to all orders in string perturbation theory)
IIA $U \rightarrow U + i\epsilon$ //

IIb \leftrightarrow IIA (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here
IIb



ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

of Conlon

Effective action * want Kähler potential and superpotential as a function of the moduli

$$K = K(\Phi, \bar{\Phi}) + Z_{ij}(\Phi, \bar{\Phi}) C^i C^{\bar{j}}$$

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



→ (1,1) forms
 (1,1) forms
 Kähler moduli
 basis of (1,1) form
 structure

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

Joe Conlon

Effective action * want Kähler potential and superpotential as a function of the moduli

$$K = \underbrace{K(\Phi, \bar{\Phi})}_{\substack{\text{moduli stab.} \\ \text{soft}}} + \sum_{ij} Z_{ij}(\Phi, \bar{\Phi}) (c^i c^j) + \sum_{ijkl} Y_{ijkl}(\Phi) (c^i c^j c^k c^l)$$

$\delta g_{ij} \rightarrow$ (Krommer) Kähler moduli
 c^i basis of (1,1) form structure

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

oc
Conlon

Effective action

* Want Kähler potential and superpotential as a function of the moduli

$$K = \underbrace{K(\Phi, \bar{\Phi})}_{\text{stab.}} + \underbrace{Z_{ij}(\Phi, \bar{\Phi}) C^i C^j}_{\text{flavour physics}}$$

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

stab.
of γ

flavour physics

$\gamma \in \text{chromides}$ $\gamma \in \text{basis of } (1,1) \text{ form}$ structure
 $\gamma \in \text{Kähler moduli}$

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

OC
Conlon

Effective action

* Want Kahler potential

and superpotential as a function of the moduli

$$K = K(\Phi, \bar{\Phi}) + Z_{ij}(\Phi, \bar{\Phi}) C^i C^j$$

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

moduli stab.
soft

flavour physics
soft terms

→ (chromons) & basis of (1,1) form structure
BUT chiral forms Kahler moduli.

MODELS OF MODULI IN STRING COMPACTIFICATIONS

Effective action

want Kähler potential

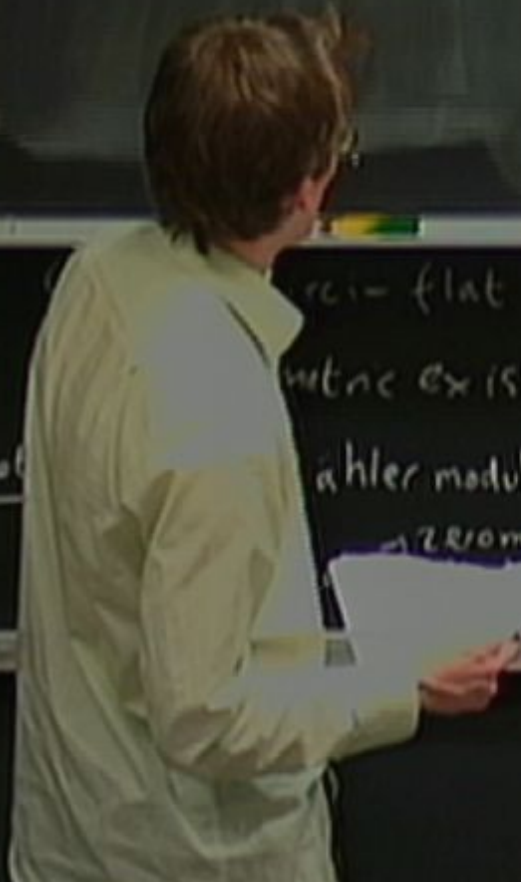
and superpotential as a function of the moduli

$$K = K(\mathbb{I}, \bar{\mathbb{I}}) + \sum_i \gamma_i(\mathbb{I}, \bar{\mathbb{I}}) e^{-c_i \mathbb{I}^i}$$

$$W = W(\mathbb{I}) + \sum_i \gamma_i(\mathbb{I}) e^{-c_i \mathbb{I}^i}$$

Moduli stabil.
= soft

flavour physics
Soft terms



Calabi-Yau manifold of vanishing 1st Chern Class

Metric exists and is unique up to (1) choice of Kähler form

Geomet

Kähler moduli

$$J = \sum_{i=1}^{h^{1,1}} t^i e_i$$

(2) choice of complex structure

e_i basis of $(1,1)$ form
Kähler moduli.

Moduli potential

$$V = e^k (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$
$$= \sum |F^i|^2 - 3m_{3/2}^2$$

Moduli potential

$$V = e^k (K^{L\bar{J}} D_L \bar{W} - 3|W|^2)$$

$$= \sum |F^L|^2$$

$$F^L = e^{K/2} (D_L W - \frac{1}{2} g_{L\bar{M}} \partial_{\bar{M}} K) W$$

$$D_J W = \partial_J W + \partial_{J\bar{K}} K W$$

Moduli potential

$$V = e^k (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$

$$= \sum |F^i|^2 - 3m_{3/2}^2$$

$$F^i = e^{k/2} K^{i\bar{j}} D_{\bar{j}} W, \quad D_{\bar{j}} W = \partial_{\bar{j}} W + \partial_{\bar{j}} k W$$

$$W = W(\phi) + W(\psi)$$

Moduli stab.
+ soft

flavour physics
Soft terms

Moduli potential

$$V = e^k (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$

$$= \sum |F^i|^2 - 3m_{3/2}^2$$

$$F^i = e^{k/2} K^{i\bar{j}} D_{\bar{j}} W, \quad D_{\bar{j}} W = \partial_{\bar{j}} W + \partial_{\bar{j}} K W$$

Moduli potential

$$V = e^k (K^{L\bar{J}} D_L W D_{\bar{J}} \bar{W} - 3|W|^2)$$

$$= \sum |F^L|^2 - 3m_{3/2}^2$$

$$F^L = e^{k/2} K^{L\bar{J}} D_{\bar{J}} W, \quad D_{\bar{J}} W = \partial_{\bar{J}} W + \partial_{\bar{J}} K W$$

Moduli: must be stabilised \rightarrow non-zero WCF

Modul. potential

$$m_{3/2}^2 = e^{K/2} W$$

$$V = e^K (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$

$$= \sum |F^i|^2 - 3m_{3/2}^2 \approx m_{3/2}^2$$

$$F^i = e^{K/2} K^{i\bar{j}} D_{\bar{j}} W, \quad D_{\bar{j}} W = \partial_{\bar{j}} W + \partial_{\bar{j}} K W$$

Modul: must be stabilised \rightarrow non-zero WCF

Moduli potential

$$m_{3/2}^2 = e^{K/2} W$$

$$V = e^K (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$

$$= \sum |F^i|^2 - 3m_{3/2}^2 \approx m_{3/2}^2$$

$$F^i = e^{K/2} K^{i\bar{j}} D_{\bar{j}} W, \quad D_{\bar{j}} W = \partial_{\bar{j}} W + \partial_{\bar{j}} K W$$

must be stabilised \rightarrow non-zero $W(\Phi)$

potential in general breaks supersymmetry ($F^i \neq 0$)
and almost always gives a non-zero gravitino mass ($m_{3/2} \neq 0$)

Moduli potential

$$m_{3/2}^2 = e^{K/2} W$$

$$V = e^K (K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2)$$

$$= \sum |F^i|^2 - 3m_{3/2}^2 \approx m_{3/2}^2$$

$$F^i = e^{K/2} K^{i\bar{j}} D_{\bar{j}} W, \quad D_{\bar{j}} W = \partial_{\bar{j}} W + \partial_{\bar{j}} K W$$

Moduli: must be stabilised \rightarrow non-zero $W(\Phi)$

Moduli potential in general breaks supersymmetry ($F^i \neq 0$)
and almost always gives a non-zero gravitino mass ($m_{3/2} \neq 0$)

String hierarchy problem

(7)



of strings systematic distinction of expectation

Susy hierarchy problem why is $m_{3/2}$ small? (7.2)

Gauge mediated $m_{3/2} \ll 1 \text{ TeV}$

Gravity " $m_{3/2} \sim 10^4 \text{ TeV}$

Even

potential violation of supersymmetry expectation

Susy hierarchy problem: why is $m_{3/2}$ small? (T)

Gauge mediated $m_{3/2} \ll 1 \text{ TeV}$

Gravity "

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

$\ll 10^{16} \text{ GeV} = M_p$

→ Single contribution to $H(\mathbb{R}^3)$ from any sector $> 10^{-15}$
destroys all standard approaches to SUSY

Even

→ λ tuned value of strings: systematic violation of λ expectation

Susy hierarchy problem: why is m_{H_u} small?

Gauge mediated: $m_{H_u} \ll 1 \text{ TeV}$

Gravity "

$m_{H_u} \ll 1 \text{ TeV}$

$\ll 10^{16} \text{ GeV} = M_p$

↳ Circle contribution to $H(\Phi)$ from any sector $> 10^{-15}$
destroys all standard approaches to SUSY

ideal value ... systematic violation of ... expectation

Susy hierarchy problem why is m_{H_u} small? (T)

Gauge mediated $m_{H_u} \ll 1 \text{ TeV}$

Gravity "

$m_{H_u} \ll 1 \text{ MeV}$

$\ll 10^{16} \text{ GeV} = M_p$

↳ Single contribution to $H(\Phi)$ from any sector $> 10^{-15}$
destroys all standard approaches to SUSY

Even

↳ Added value of strings systematic violation of naive expectation

Susy hierarchy problem why is $m_{3/2}$ small?

Gauge mediated $m_{3/2} \ll 1 \text{ TeV}$

Gravity " $m_{3/2} \sim 10^4 \text{ GeV}$

$\ll 10^{16} \text{ GeV} = M_p$

→ Single contribution to $W(\Phi)$ from any sector $> 10^{-15}$
destroys all standard approaches to susy

$$W(\Phi) = (M_p^3)$$

→ Δ fixed value of strings systematic violation of naive expectation

Gravity " max in 11TeV \ll 110

* Single contribution to $W(\Phi)$ from any sector $> 10^{-15}$
destroys all standard approaches to su $\overline{2}$

$$W(\Phi) = (M_{Pl}^3)$$

*

enter crucially into all BSM questions in string theory

- * su $\overline{2}$
- * inflation
- * flavor
- * cosmology
- * axions

of strings. systematic violation of 'naive' EFT expectation

Gravity \approx $m_{3/2} \approx 10^{11} \text{ eV}$

* Single contribution to $W(\Phi)$ from any sector $> 10^{-15}$
destroys all standard approaches to susy

$$W(\Phi) = (M_{\text{Pl}})^3$$

* 2 Basic ways to address the susy hierarchy

$$m_{3/2} = e^{K/2} W$$

(a) Make $e^{K/2}$ small

(b) Make W small

do enter crucially into all BSM questions in string theory

In particular,

* susy

* inflation

* flavor

* cosmology

* axions

fixed value of strings. systematic violation of 'naive' EFT expectation

Gravity $m_{3/2} \sim 10^{11} \text{ TeV}$

* Single contribution to $\langle W(\Phi) \rangle$ from any sector $> 10^{-15}$
destroys all standard approaches to susy

$$W(\Phi) \sim (M_p)^3$$

* 2 Basic ways to address the susy hierarchy

$$m_{3/2} = e^{K/2} W$$

(a) Make $e^{K/2}$ small \rightarrow lower all scales in the problem $M_{\text{sec}} \ll M_p$

(b) Make W small \rightarrow maintain a high string scale

Moduli enter crucially into all BSM questions in string theory

In particular,

* susy

* inflation

* flavor

* cosmology

* axions

and value of strings. systematic violation of 'naive' EFT expectation

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale

requires some basic form for all CYs
 if any universal results of string
 they will come from the moduli sector.
 into all BSM questions in string theory

- * inflation
- * cosmology

flavor mixing, systematic violation of 'naive' EFT expectation

3.

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale.

Models of moduli stabilisation

x Flux compactification

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale

Models of moduli stabilisation

* Flux compactification

$$K = -2 \ln V(\tau, \bar{\tau}) - \ln(S\Omega\Lambda\bar{\tau}) - \ln(S+\bar{S})$$

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale

Models of moduli stabilisation

* Flux compactification

$$K = -2 \ln V(\tau, \bar{\tau}) - \ln(S\Omega\sqrt{\alpha}) - \ln(S + \bar{S})$$

$$W = \int G_{-2n} \Omega(S, U)$$

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale

Models of moduli stabilisation

* Flux compactification

$$K = -2 \ln V(\tau + \bar{\tau}) - \ln(S\Omega\sqrt{\alpha}) - \ln(S + \bar{S}) \quad (\text{factors})$$

$$W = \int G_{-2,n} \Omega \quad (S, U)$$

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale.

Models of moduli stabilisation

Large compactification

$$K = -\frac{1}{2} \ln V(T, \bar{T}) - \ln(S\Omega, \bar{S}) - \ln(S + \bar{S}) \quad (\text{factors})$$

$$W = S G_{-2, \Omega} (S, U)$$

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale.

Models of moduli stabilisation

* Flux compactification

$$K = -2 \ln V(\tau, \bar{\tau}) - \ln(S\Omega\sqrt{\alpha}) - \ln(S + \bar{S}) \quad (\text{factors})$$

$$W = \int G_{2n} \wedge \Omega(C, U)$$

*

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale.

Models of moduli stabilisation

* Flux compactification

$$K = -2 \ln V(\tau, \bar{\tau}) - \ln(S\Omega, \bar{S}) - \ln(S + \bar{S}) \quad (\text{factors})$$

$$W = \int G_{-2n} \Omega(C, U)$$

$$* e^{-ax} \left(1 + \frac{1}{\sqrt{4\pi}} \right)$$

- (a) Make e^{-2} small \rightarrow lower all scales in the problem
- (b) Make W small \rightarrow maintain a high string scale.

2.1.10 Compactification

$$K = -2 \ln \sqrt{G_{T+\bar{T}}} - \ln(S\Omega\sqrt{\alpha}) - \ln(S+\bar{S}) \quad (\text{factorises})$$

$$W = \int G_{-2,2} \Omega(S,U)$$

$$* e^{-ax} \left(1 + \frac{1}{\sqrt{4z}} \right)$$

$$V = e^K \sum_{i,j} K^{ij} D_i W D_j \bar{W} - 3m_{3/2}^2$$

$$= \sum_{i,j} K^{ij} D_i W D_j \bar{W} \rightarrow \text{minimum at } D_i W = D_j \bar{W} = 0$$

Kähler moduli mass C

Dilaton/U mass: $\sim \frac{DDW}{v} \sim M_{pl}^2$

Susy broken: $F_T \neq 0$

M_{pl}^2

$\partial_{jH} + \partial_{jK} W$

symmetry $(F^{\pm} z^0)$

non-zero gravitino mass

K KLT

$$K = -2 \ln V - \ln(\sum_i \Omega_i) - h(\epsilon, T)$$

$$W = \sum_i G_i \Omega_i \sum_j A_j e^{-\alpha_j T}$$

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:

KKT

$$K = -2 \ln V - \ln(\Sigma \Omega \pi) - h c s r s$$

$$\Sigma G_{\tau} \Omega_{\tau} \quad \Sigma A_i e^{-a_i T_i}$$

→ AAS minimum at $D_r W = D_s W = D_U W = 0$

$$\text{Vac energy} = -3 \pi^2 M_p^2$$

$$\text{Grav mass} = \frac{W_s}{V}$$

→ unbroken

K KLT

$$K = -2 \ln V - \ln(\Sigma \Omega \pi) - h c s r s$$

$$W = \int G_{\mu\nu} \Sigma T^{\mu\nu} \Sigma A_i e^{-a T_i}$$

∫ Susy AAS minimum at $D_\mu W = D_5 W = D U W = 0$

$$\text{Vac energy} = -3 m_{3/2}^2 M_{\text{pl}}^2$$

$$\text{Grav mass} = \frac{W_0}{V}$$

Susy unbroken

KLT

$$K = -2 \ln V - \ln(\Sigma \Omega \pi) - h c s s)$$

$$W = \int G_{\mu\nu} \Sigma A_i e^{-a T_i}$$

\exists susy AAS minimum at $D_\mu W = D_5 W = D U W = 0$

$W \sim \text{Re}(T)^{3/4}$
 $\sim 1/a$

$$\text{Vac energy} = -3 m_{3/2}^2 M_p^2$$

$$\text{Grav mass} = \frac{W_0}{V}$$

Susy unbroken

K KLT

$$K = -2 \ln V - \ln(\sum_i m_i^2) - h c s^{-1}$$

$$W = \int G_{\mu\nu} \Sigma^\mu \Sigma^\nu \sum A_i e^{-a T_i}$$

\exists susy, AAS minimum at $D_\mu W = D_5 W = D_{UV} W = 0$

$$V \sim e^{\frac{2d}{3}} (Re T)^{\frac{3d}{2}}$$
$$R^6 \sim g_s^{\frac{3d}{2}} \ln W_0$$

Vac energy = $-3 m_{3/2}^2 M_p^2$

Grav mass = $\frac{W_0}{V}$

Susy unbroken

KLT

$$K = -2 \ln V - \ln(\sum_i m_i^2) - h c s s)$$

$$W = \int G_{\mu\nu} \Sigma_{\tau}^{\mu\nu} \Sigma A_i e^{-a T_i}$$

\exists Susy ADS minimum at $D_\mu W = D_5 W = D U W = 0$

$$V \sim e^{\frac{2d}{3}} (Re T)^{\frac{3d}{4}}$$

$$R^6 \sim g_s^{\frac{2d}{3}} \ln W_0$$

$$\text{Vac energy} = -3 m_{3/2}^2 M_p^2$$

$$\text{Grav mass} = \frac{W_0}{V}$$

Susy unbroken

$$\int \sqrt{g} R$$

K KLT

$$K = -2 \ln V - \ln(\sum_i A_i^2) - h(\phi, \psi)$$

$$W = \int G_{\mu\nu} \Sigma^\mu \tau^\nu + \left(\sum_i A_i e^{-a T_i} \right)$$

Susy AAS minimum at $D_\mu W = D_\nu W = D_\mu W = 0$

$$\text{Vac energy} = -3 m_{\text{Pl}}^2 M_{\text{p}}^2$$

$$\text{Grav mass} = \frac{W_0}{V}$$

Susy unbroken

$$V \sim e^{2\sigma}$$
$$R^6 \sim e^{6\sigma}$$

$$W_0$$

$\sum \sqrt{g} R$

K KLT

$$K = -2 \ln V - \ln(\sum_i a_i \tau_i) - h(\phi, \psi)$$

$$W = \sum_i G_i \tau_i + \sum_i A_i e^{-a_i \tau_i}$$

\exists Susy ADS minimum at $D_\mu W = D_\psi W = D_U W = 0$

$$V \sim e^{\frac{2d}{4}} (Re T)^{\frac{3d}{4}}$$
$$R^6 \sim g_s^{\frac{3d}{4}} \ln W_0$$

$$\text{Vac energy} = -3 m_{\text{Pl}}^2 M_p^2$$

$$\text{Grav mass} = \frac{W_0}{V}$$

Susy unbroken

2.1.10x Compactification

$$K = -2 \ln \sqrt{(\tau + \bar{\tau})} - \ln(S \Omega \Lambda \bar{\Lambda}) - \ln(S + \bar{S}) \quad (\text{factors})$$

$$W = \int G_{\tau\lambda} \Omega (S, U)$$

$$* e^{-\alpha\phi} \left(1 + \frac{1}{\sqrt{2} \Lambda^2}\right)$$

$$V = e^K \sum_{i,j} K^{ij} D_i W D_j \bar{W} - 3 \frac{m_{\text{Pl}}^2}{2} |W|^2$$

$$= \sum_{i,j} K^{ij} D_i W D_j \bar{W} \rightarrow \text{minimum at } D_i W = D_j \bar{W} = 0$$

* prior compactification

$$K = -2 \ln \sqrt{(\tau + \bar{\tau})} - \ln(S \Omega \Lambda \bar{\Lambda}) - \ln(S + \bar{S}) \quad (\text{factors})$$

$$W = \int G_{\tau\lambda} \Omega (S, U)$$

$$* e^{-\alpha\lambda} \left(1 + \frac{1}{\sqrt{2} \lambda}\right)$$

$$V = e^K \sum_{i,j} K^{ij} D_i W D_j \bar{W} - 3 \frac{m^2}{M_{pl}^2}$$

$$= \sum_{i,j} K^{ij} D_i W D_j \bar{W} \rightarrow \text{minimum at } D_i W = D_j \bar{W} = 0$$

Susy broken: $F^T \neq 0$

$\sum \sqrt{g} R$

KKLT

$$K = -2 \ln(\sum_i A_i e^{-a_i T_i}) - h c s^2$$

$$W = \sum_i A_i e^{-a_i T_i}$$

Susy AAS minimum at $D_i W = D_{\bar{i}} W = D_U W = 0$

$$\text{Vac energy} = -3 m_{\text{Pl}}^2 M_p^2$$

$$\text{Grav mass} = \frac{h c s}{V}$$

Susy unbroken

$$V \sim e^{2d}$$

$$R^6 \sim$$