Title: Aspects of Moduli in String Compactifications - Lecture 1

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Abstract:

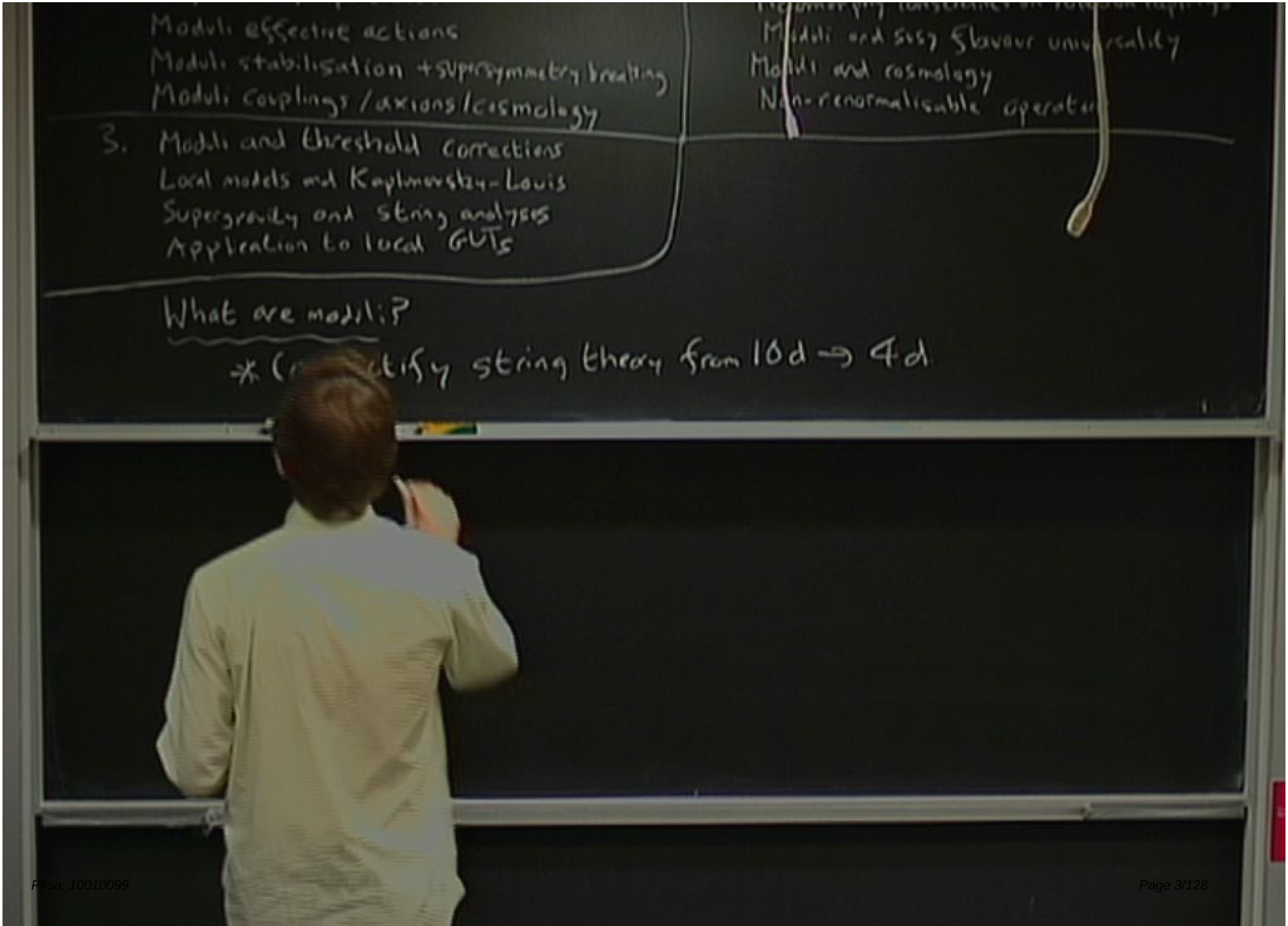
ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

Joe Conlon

1. What are moduli?
   Why are they important?
   Moduli effective actions
   Moduli stabilisation + supersymmetry breaking
   Moduli couplings / axions / cosmology

2. Moduli and flavour
   Holomorphy constraints on Yukawa couplings
   Moduli and susy flavour universality
   Moduli and cosmology
   Non-renormalisable operators

3. Moduli and threshold corrections
   Local models and Kaplunovsky-Louis
   Supergravity and string analyses
   Application to local GUTs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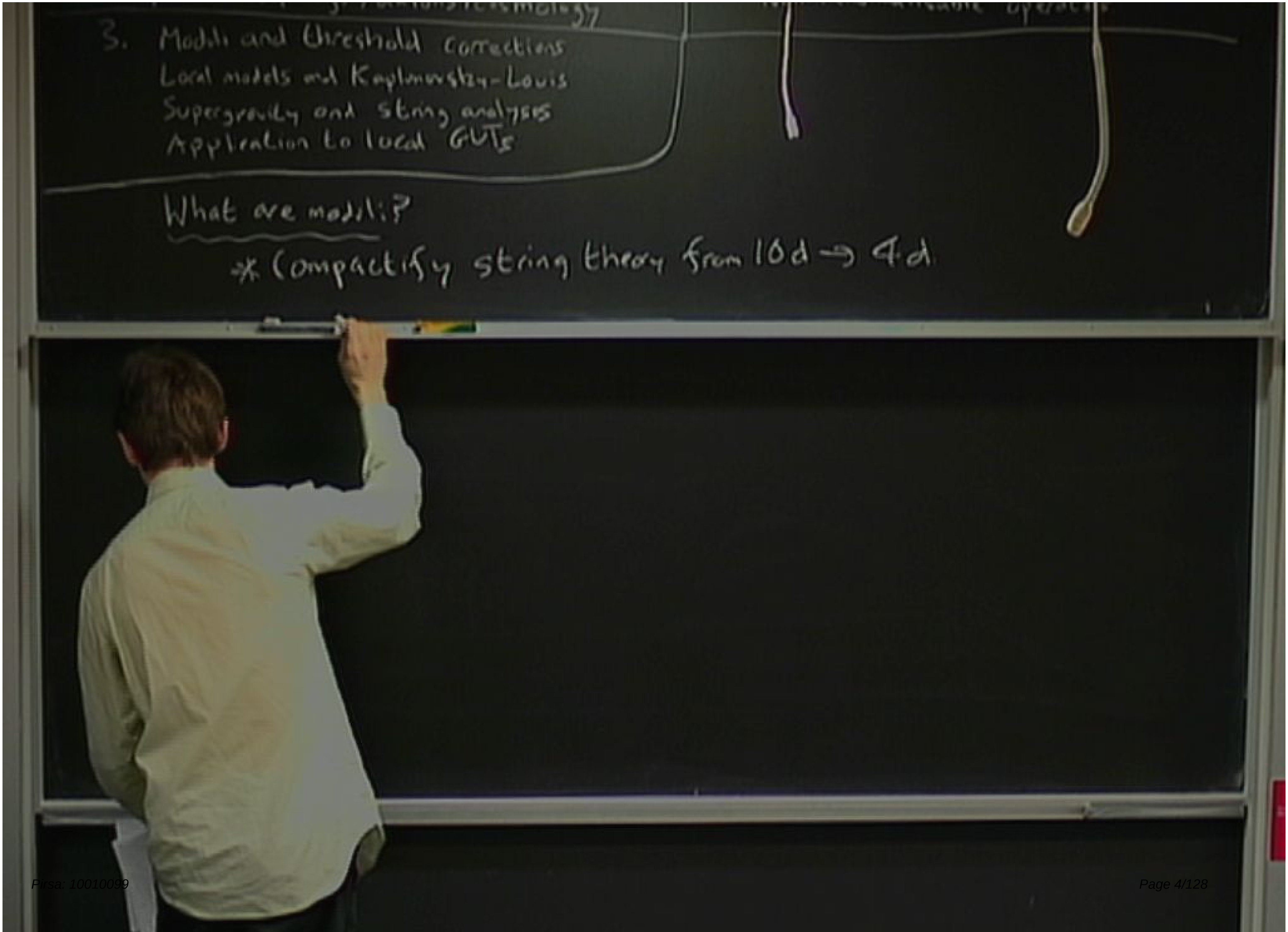
What are moduli?
string theory from 10d → 4d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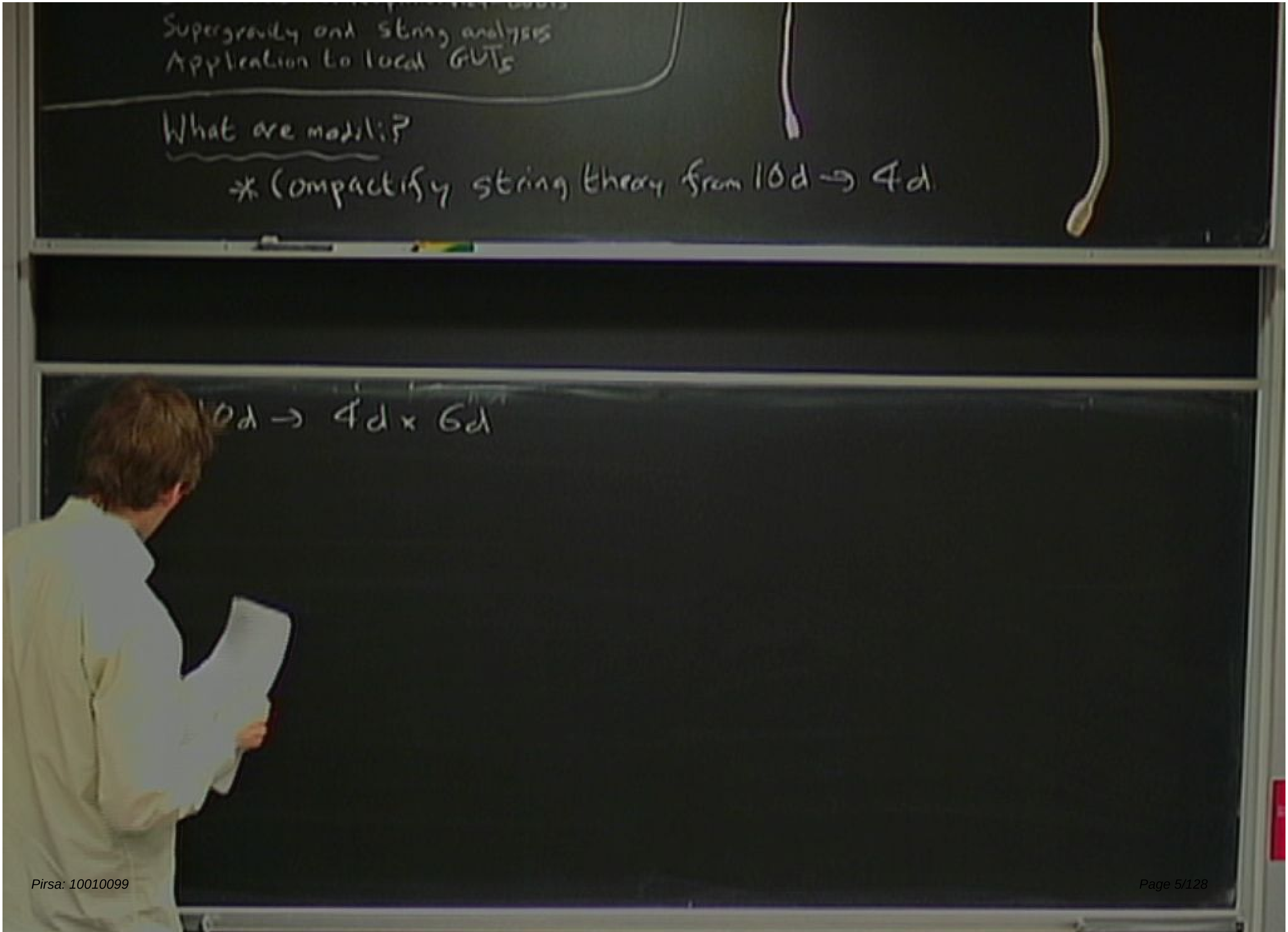
What are moduli?
* Compactify string theory from 10d → 4d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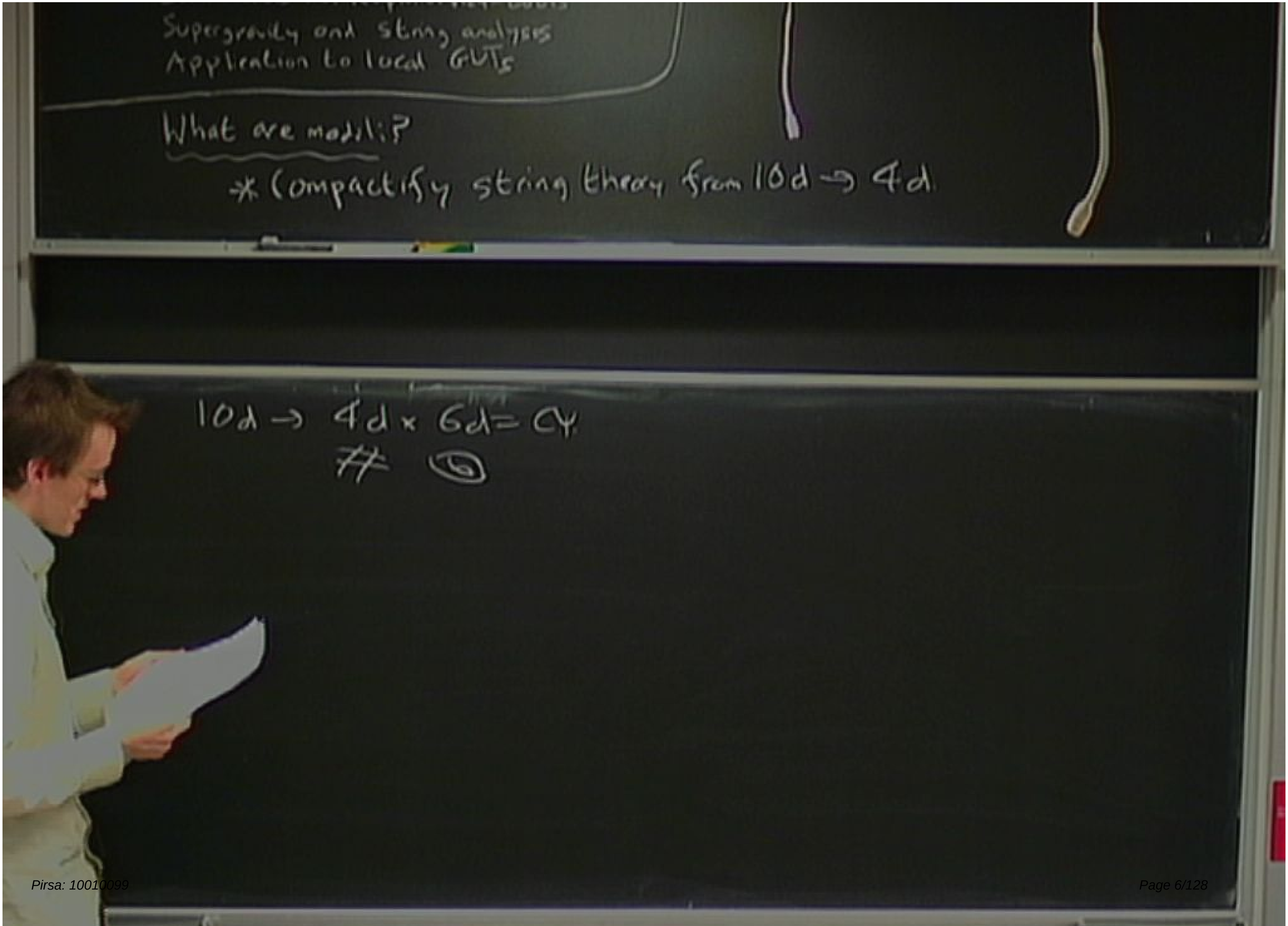
* Compactify string theory from 10d → 4d
0d → 4d × 6d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What are moduli?
* Compactify string theory from 10d → 4d
10d → 4d × 6d = CY
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$10d \to 4d \times 6d = CY \leftarrow$ low energy supersymmetry

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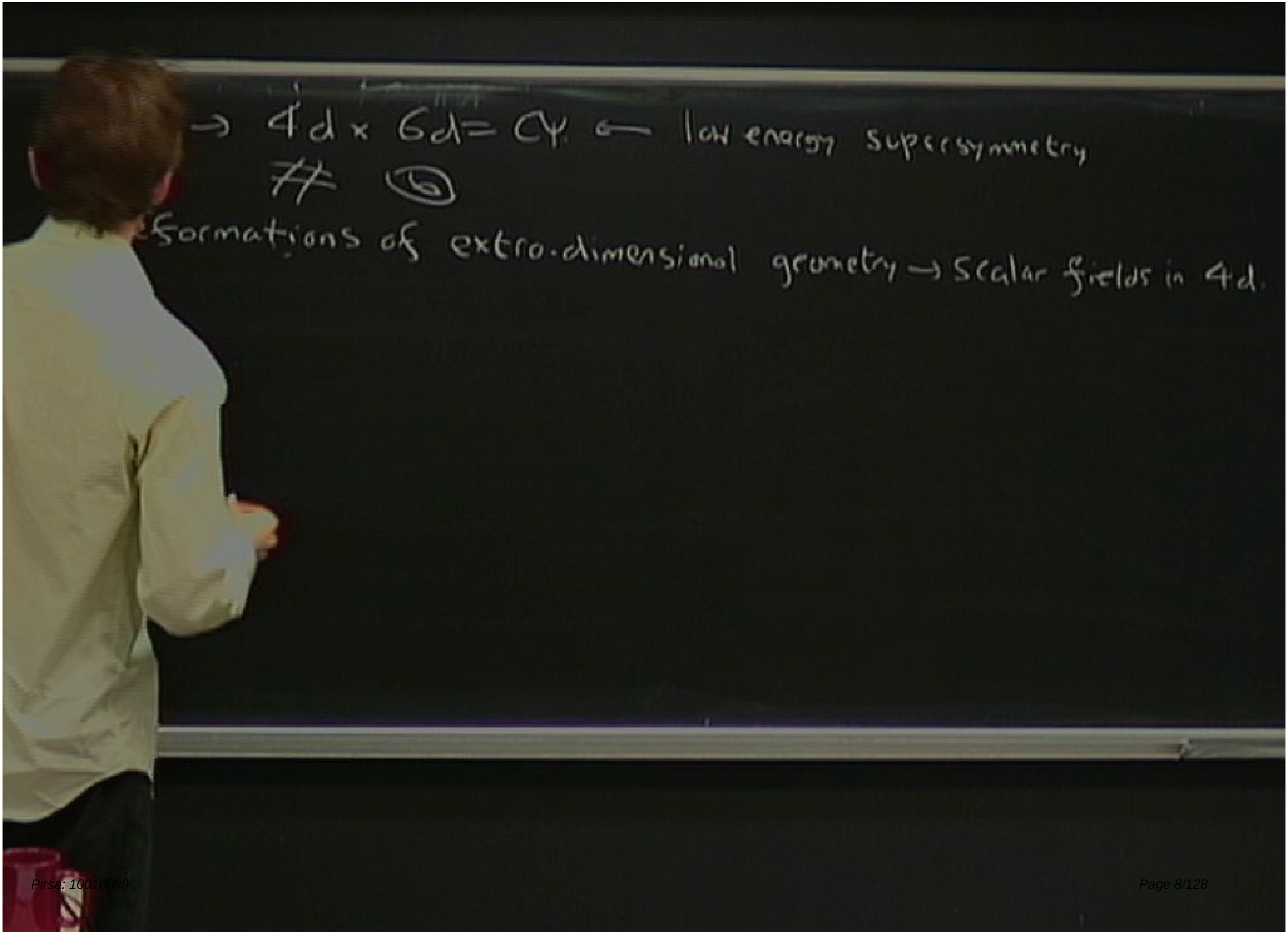
→ 4d × 6d = CY ← low energy supersymmetry
formations of extra-dimensional geometry → scalar fields in 4d.

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

* Deformations of extra-dimensional geometry $\to$ scalar fields in $4d$.

* Massless deformations $\to$ 'massless' scalar fields : <u>moduli</u>.
'zero mode'

$10d \to$ … $\times$ $6d = CY$ ← low energy supersymmetry

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* … olves the equations of motion
… icci-flat Kähler manifold of vanishing 1^{st} Chern Class

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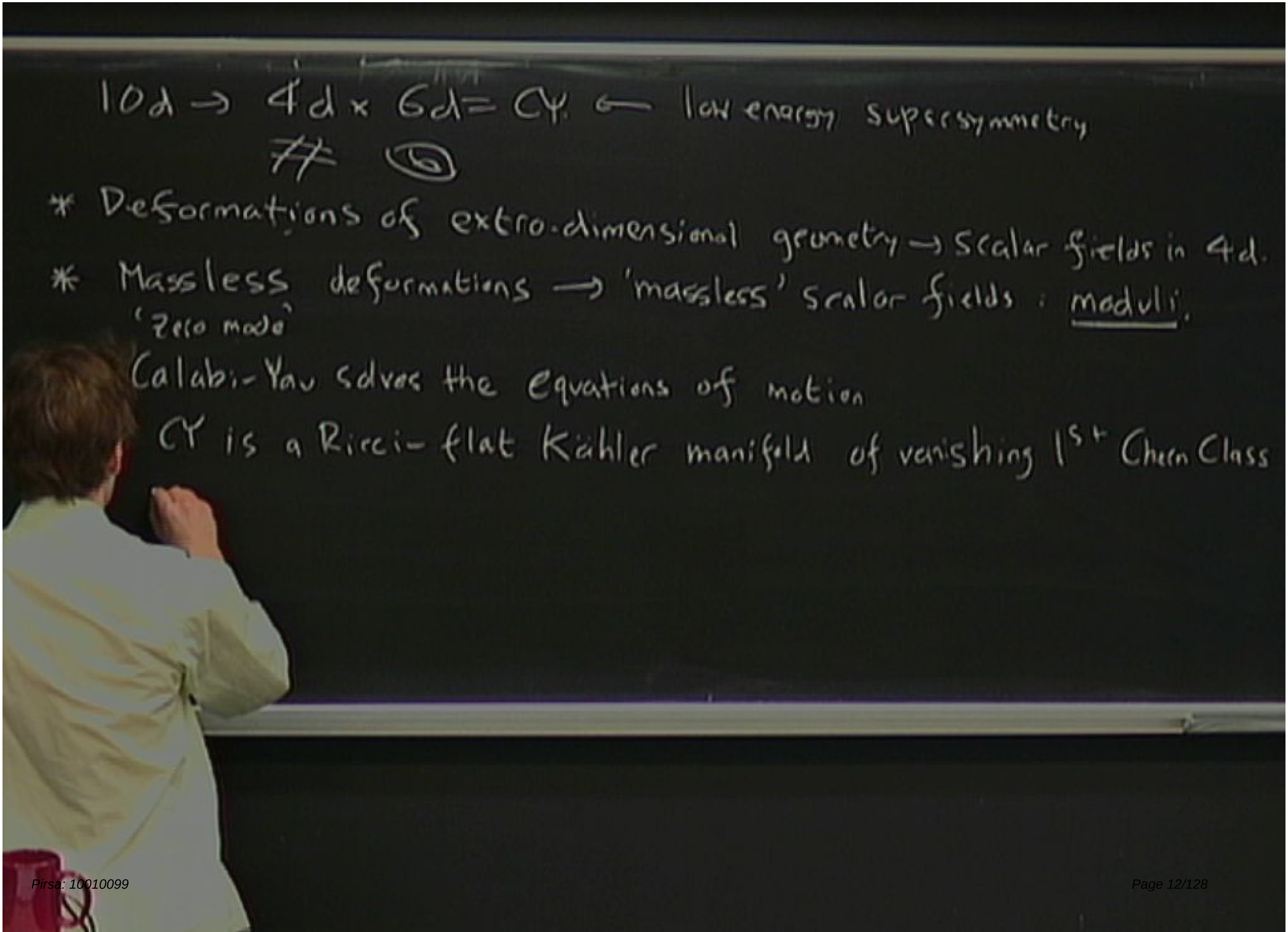
Ricci-flat Kähler manifold of vanishing 1^{st} Chern Class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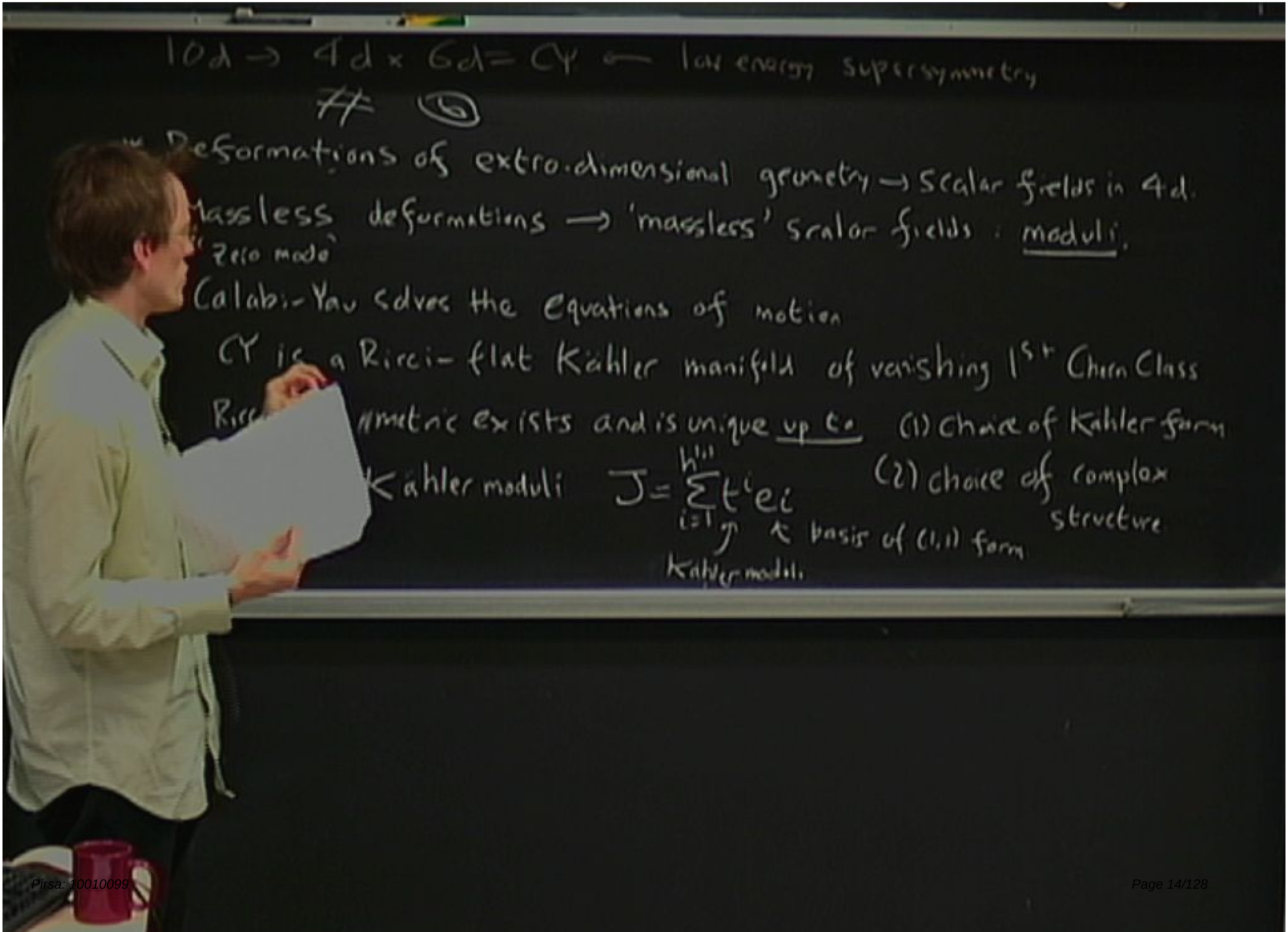
[illegible]at metric exists and is unique <u>up to</u> (1) Choice of Kähler form

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

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

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<u>Geometric moduli</u> Kähler moduli $J = \sum_{i=1}^{h^{1,1}} t^i e_i$ (2) choice of complex structure

t^i : Kähler moduli; e_i : basis of (1,1) form

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\# ⑥

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$\delta g_{i\bar{j}} \to$ zeromodes (1,1) forms   Kähler moduli   basis of (1,1) form

$10d \to 4d \times 6d = CY$ ← low energy supersymmetry

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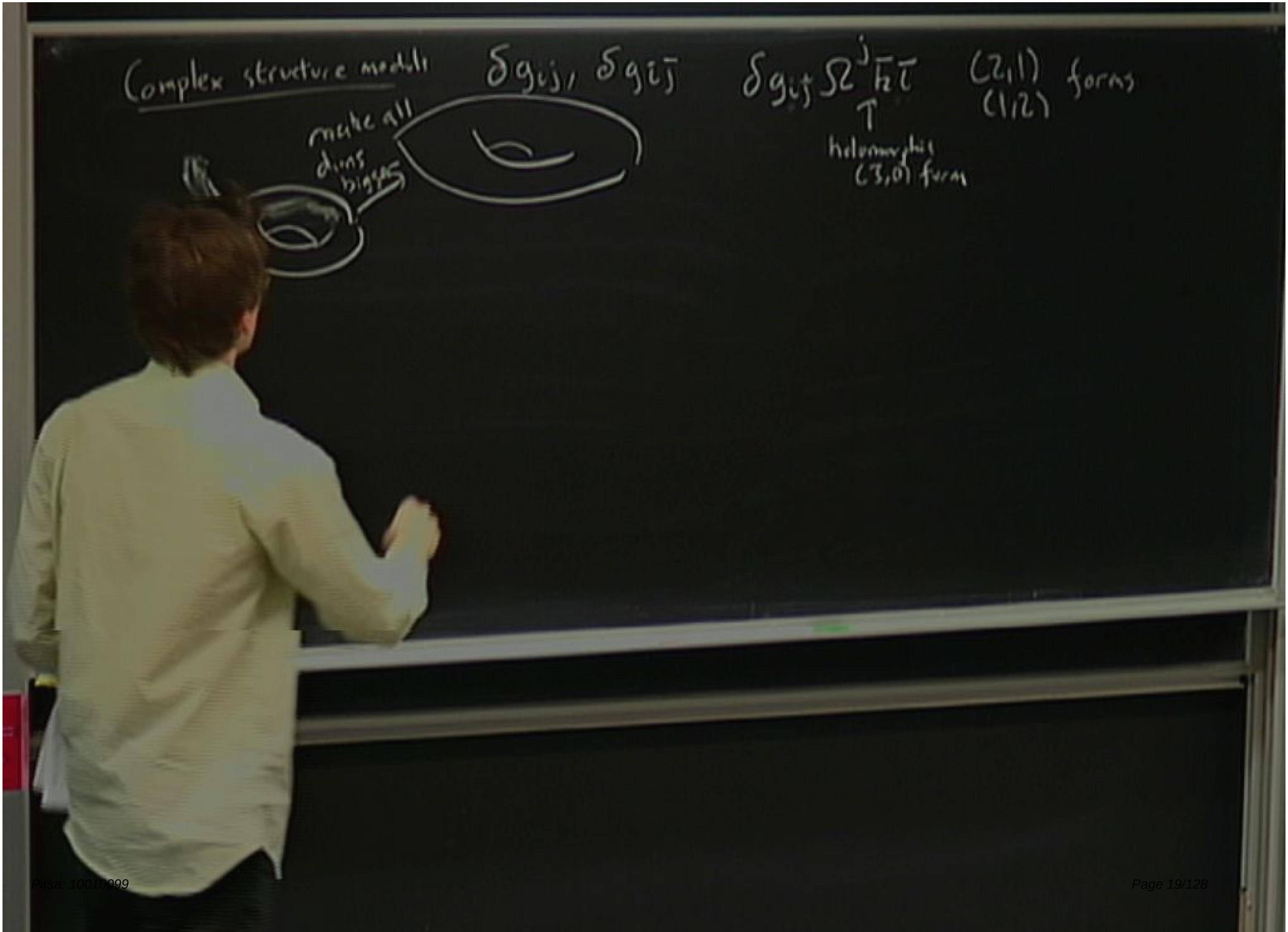
Geometric moduli   Kähler moduli $J = \sum_{i=1}^{h^{1,1}} t^i e_i$ ← basis of (1,1) form

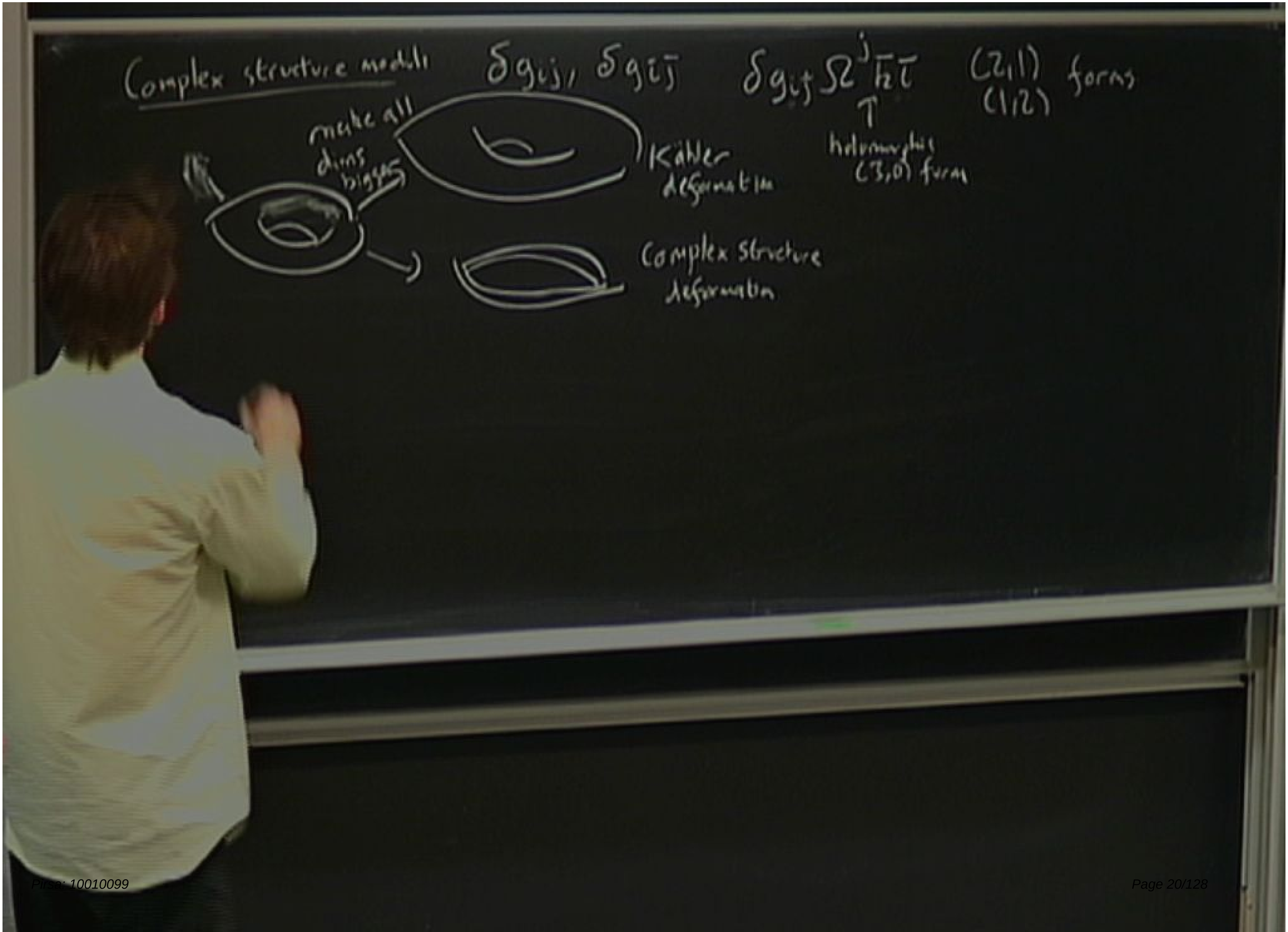
t^i: Kähler moduli

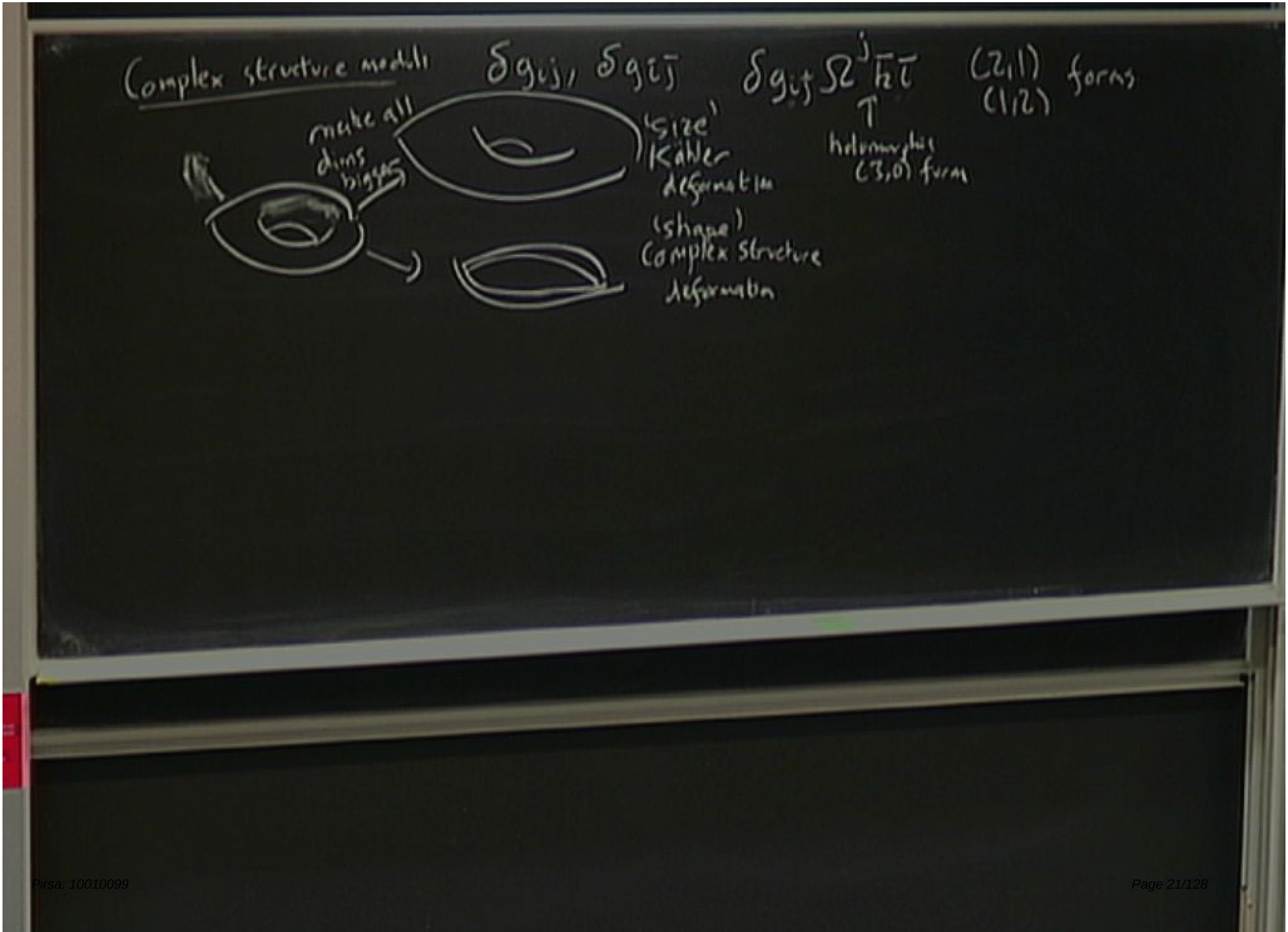
$\delta g_{i\bar{j}}$ → zeromodes (1,1) forms

Complex structure moduli $\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$ $\delta g_{i\bar{j}} \Omega^{j}{}_{\bar{k}\bar{l}}$ $(2,1)$ forms $(1,2)$

holomorphic $(3,0)$ form


Complex structure moduli
$\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$
$\delta g_{i\bar{j}} \Omega^{j}{}_{\bar{k}\bar{l}}$
holomorphic (3,0) form
(2,1)
(1,2) forms
make all dims bigger


Complex structure moduli
δg_ij, δg_iј̄
δg_iј̄ Ω^j_k̄l̄
(2,1)
(1,2)
forms
make all dims bigger
Kähler deformation
holomorphic (3,0) form
Complex structure deformation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$\delta g_{ij}, \delta g_{i\bar{j}}$
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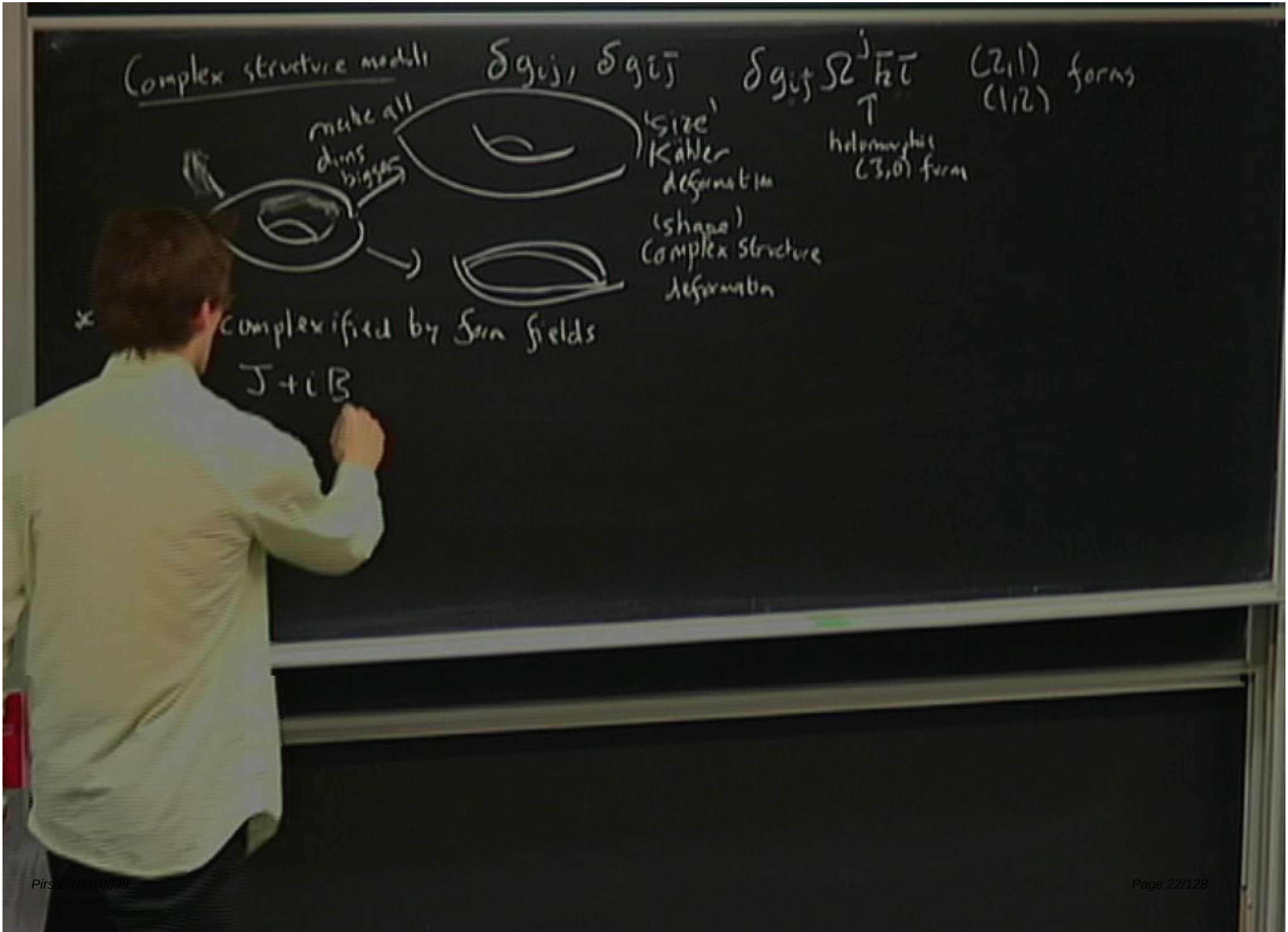
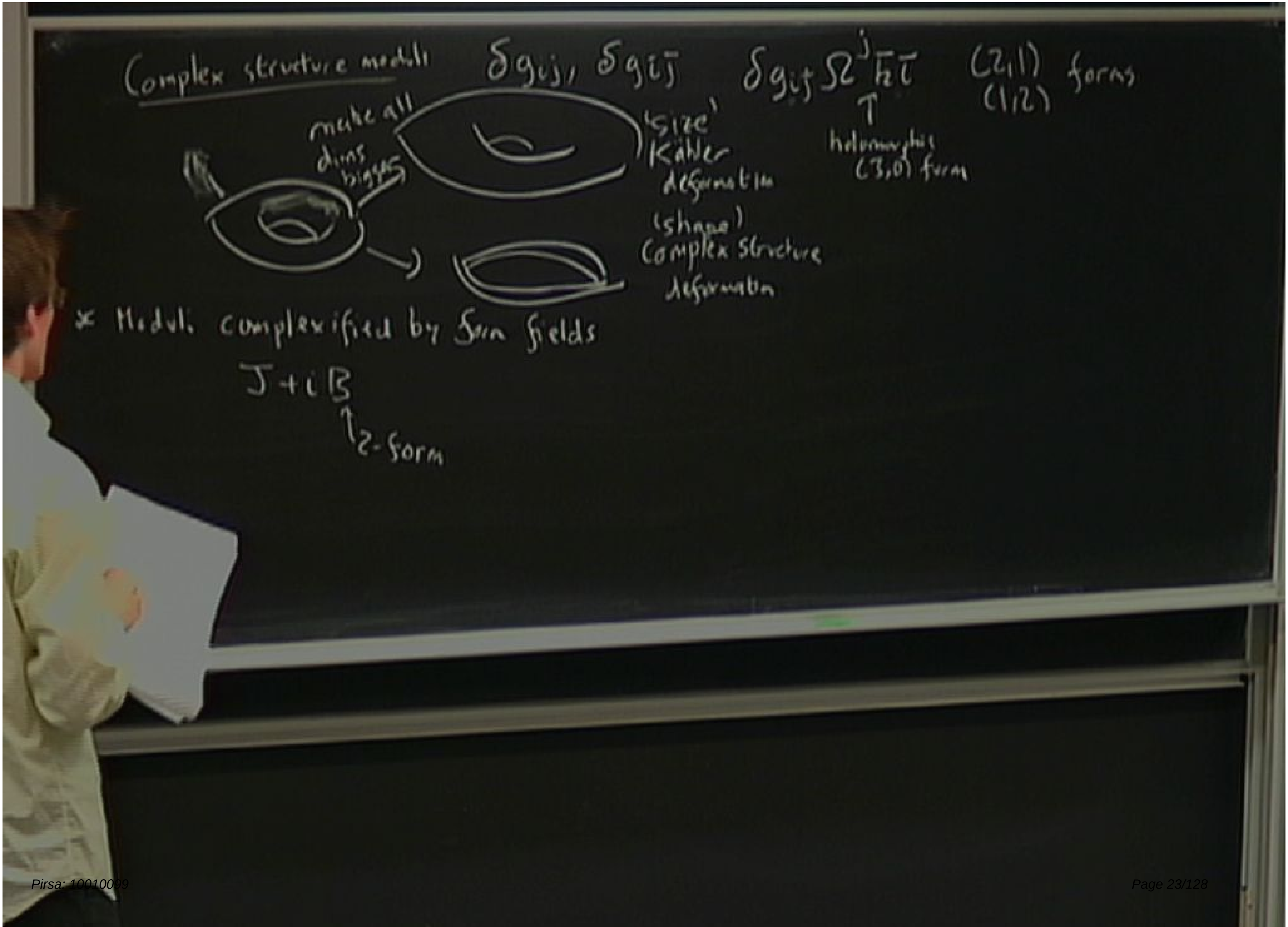
holomorphic (3,0) form
(2,1) (1,2) forms
make all dims bigger
'size' Kähler deformation
'shape' complex structure deformation


Complex structure moduli
(2,1) forms
(1,2)
make all
'size'
Kähler
deformation
holomorphic
(3,0) form
'shape'
Complex structure
deformation
*
complexified by
fields
J + i B


Complex structure moduli
$\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$
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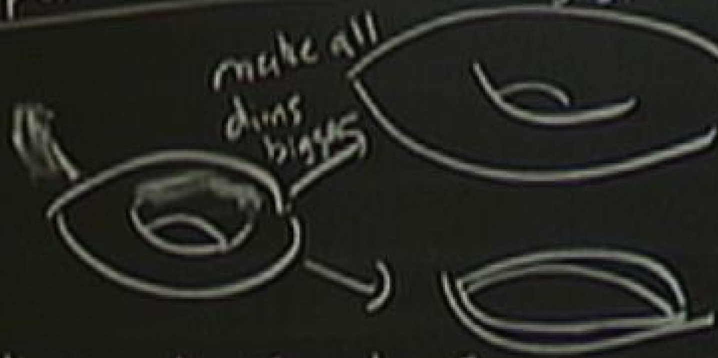
holomorphic (3,0) form
(2,1) forms
(1,2)
make all dims bigger
'size'
Kähler deformation
(shape)
Complex Structure deformation
* Moduli complexified by form fields
J + i B
2-form

Complex structure moduli $\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$ $\delta g_{i\bar{j}}\,\Omega^{j}{}_{\bar{k}\bar{l}}$ (2,1) (1,2) forms

$\uparrow$ holomorphic (3,0) form



'size' Kähler deformation

(shape) Complex structure deformation

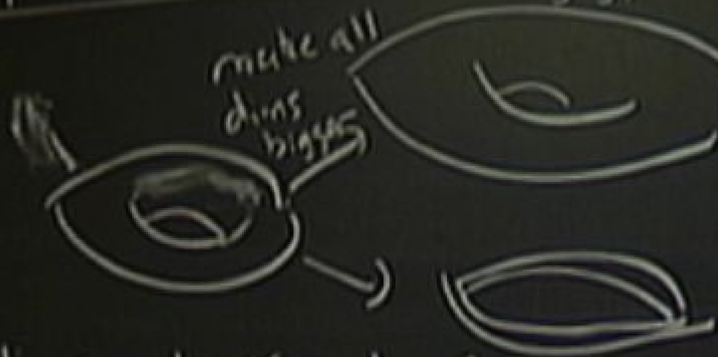
* Moduli complexified by form fields

$$J + iB \leftarrow \int_{2\text{-cycle}} B$$

$\uparrow$ vol 2-cycle $\quad \uparrow$ 2-form

Complex structure moduli $\delta g_{ij}, \delta g_{\bar i \bar j}$ $\delta g_{\bar i \bar j} \; \Omega^{j}{}_{\bar k \bar l}$ $(2,1)$ $(1,2)$ forms

holomorphic $(3,0)$ form



'size'
Kähler
deformation

'shape'
Complex Structure
deformation

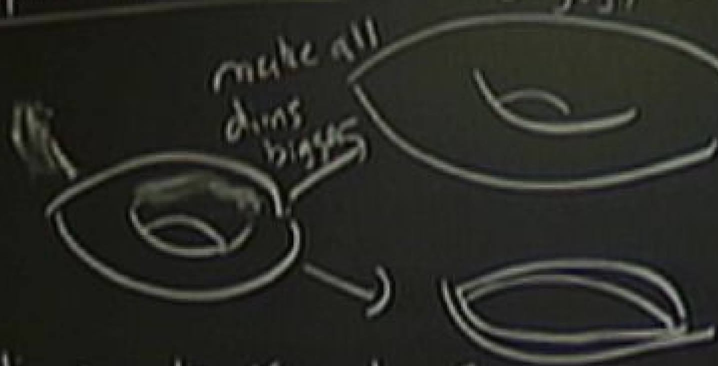
* Moduli complexified by form fields

$$\underset{\text{vol 2-cycle}}{J} + i \underset{\text{2-form}}{B} \leftarrow \int_{\text{2-cycle}} B$$

Dilaton : String coupling g_s

Complex structure moduli $\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$ $\quad \delta g_{\bar{i}\bar{j}}\, \Omega^{j}{}_{\bar{k}\bar{l}}$ $\quad$ (2,1) (1,2) forms

holomorphic (3,0) form



'size' Kähler deformation

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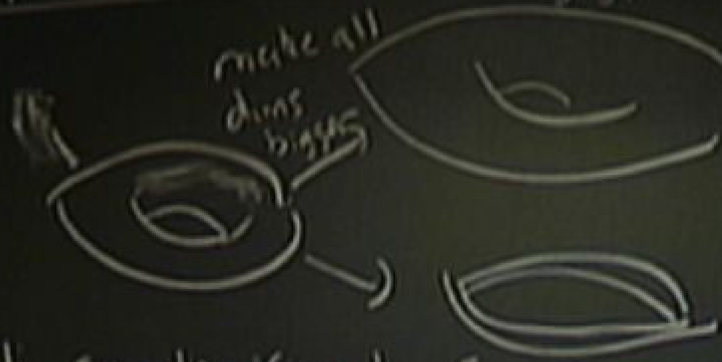
vol 2-cycle $\quad$ 2-form

Dilaton : string coupling $g_s + iC_0$

Complex structure moduli $\delta g_{ij}, \delta g_{\bar{i}\bar{j}}$



'size'
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holomorphic (3,0) form

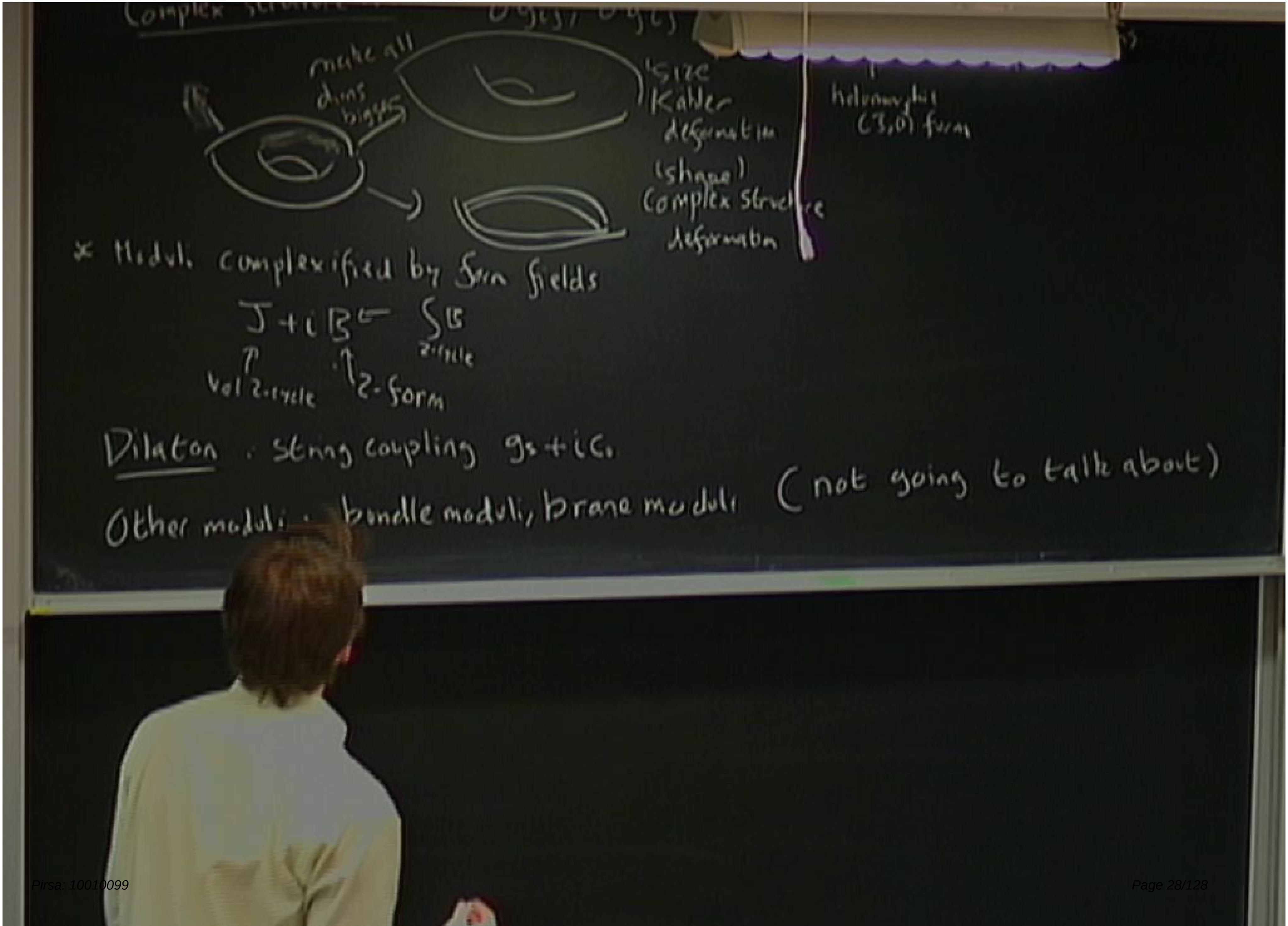
* Moduli complexified by form fields

$$J + iB \leftarrow \int_{\text{2-cycle}} B$$

vol 2-cycle ↑ J, ↑ 2-form B

Dilaton : string coupling $g_s + iC_0$

Other moduli : bundle moduli, brane moduli


Complex structure
make all dims bigger
size
Kähler deformation
(shape)
Complex structure deformation
holomorphic (3,0) form
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J + i B ← ∫B
2-cycle
vol 2-cycle
2-form
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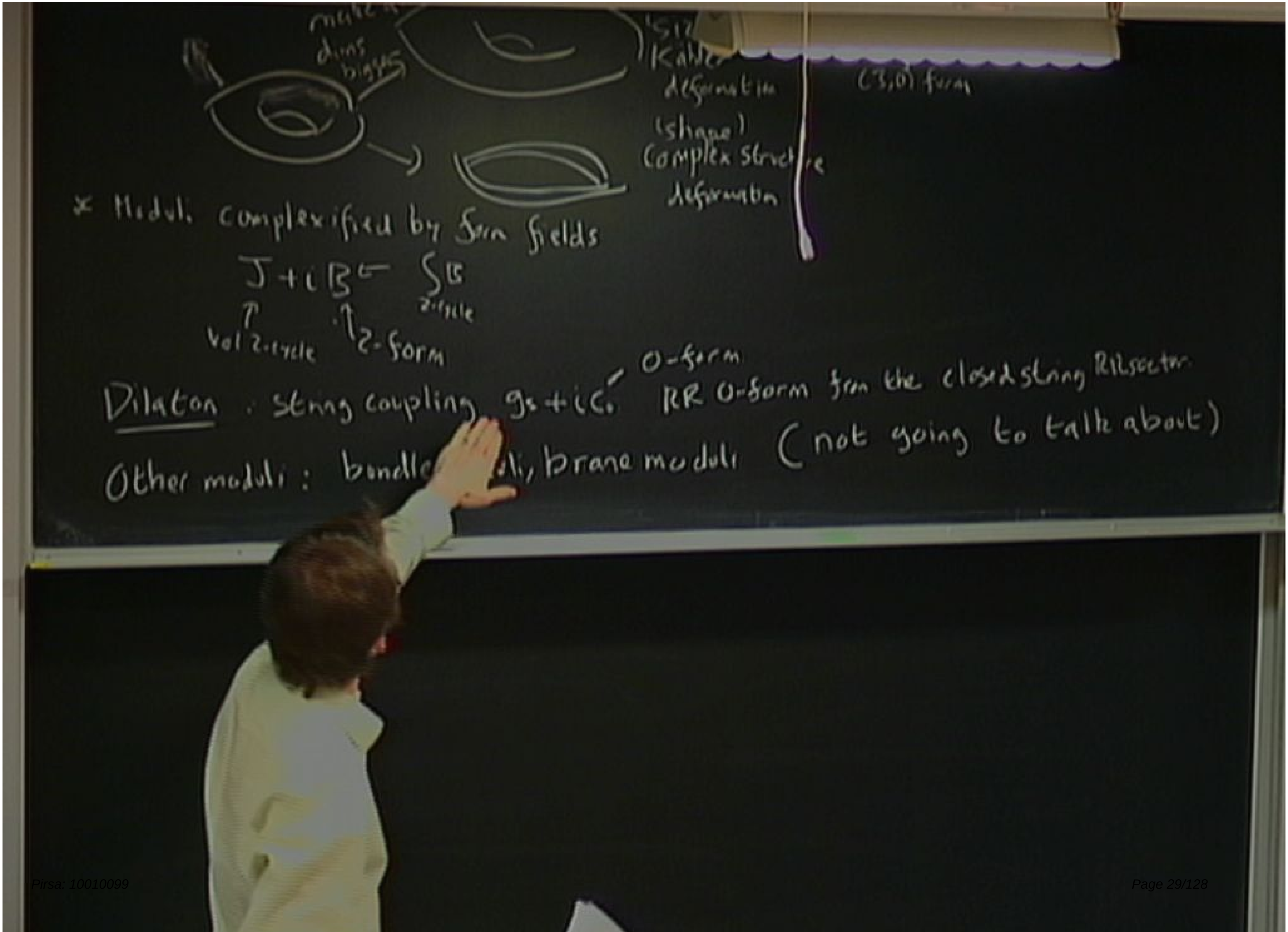
Kähler deformation
(3,0) form
(shape)
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* Moduli complexified by form fields
J + iB ← ∫B
2-cycle
vol 2-cycle
2-form
0-form
Dilaton : string coupling gs + iC0 RR 0-form from the closed string RR sector
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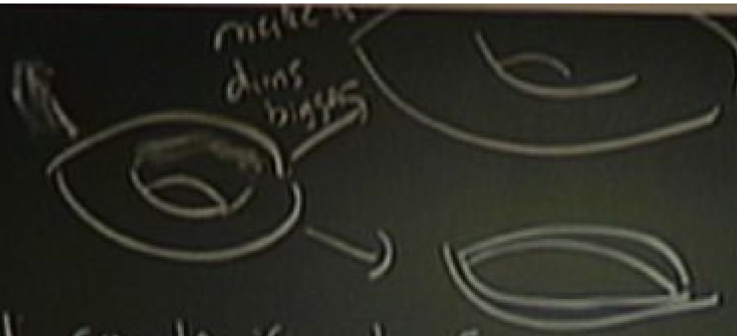


size
Kahler deformation

(3,0) form

(shape)
complex structure deformation

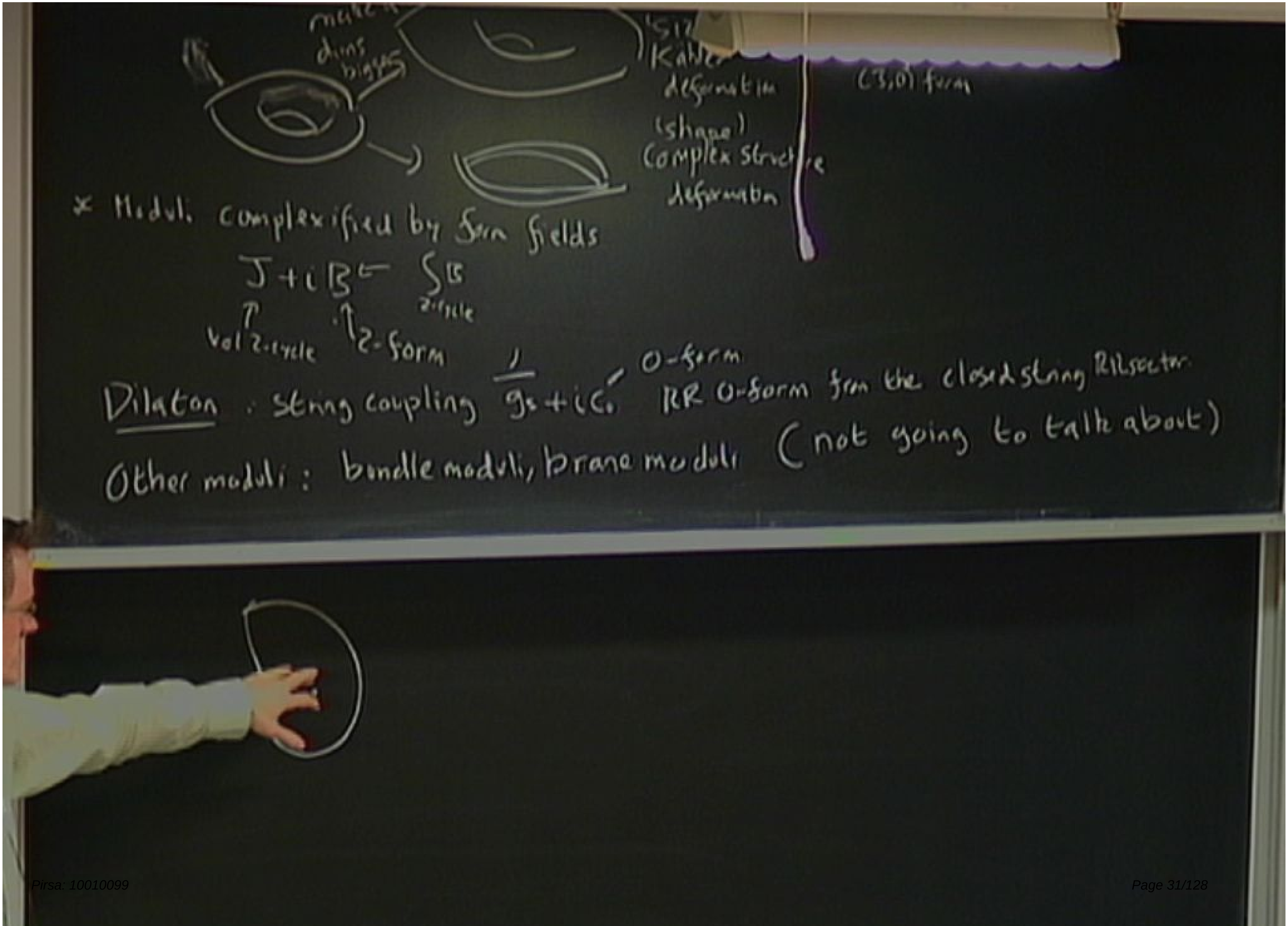
* Moduli complexified by form fields

$$J + iB \leftarrow \int_{2\text{-cycle}} B$$

vol 2-cycle — 2-form

Dilaton: string coupling $\frac{1}{g_s} + iC_0$ ← 0-form RR 0-form from the closed string RR sector

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


dims
higgs
Kahler
deformation
(shape)
Complex Structure
deformation
(3,0) form
* Moduli complexified by form fields
J + i B ← ∫B
2-cycle
vol 2-cycle
2-form
0-form
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* Moduli complexified by form fields

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vol 2-cycle, 2-form

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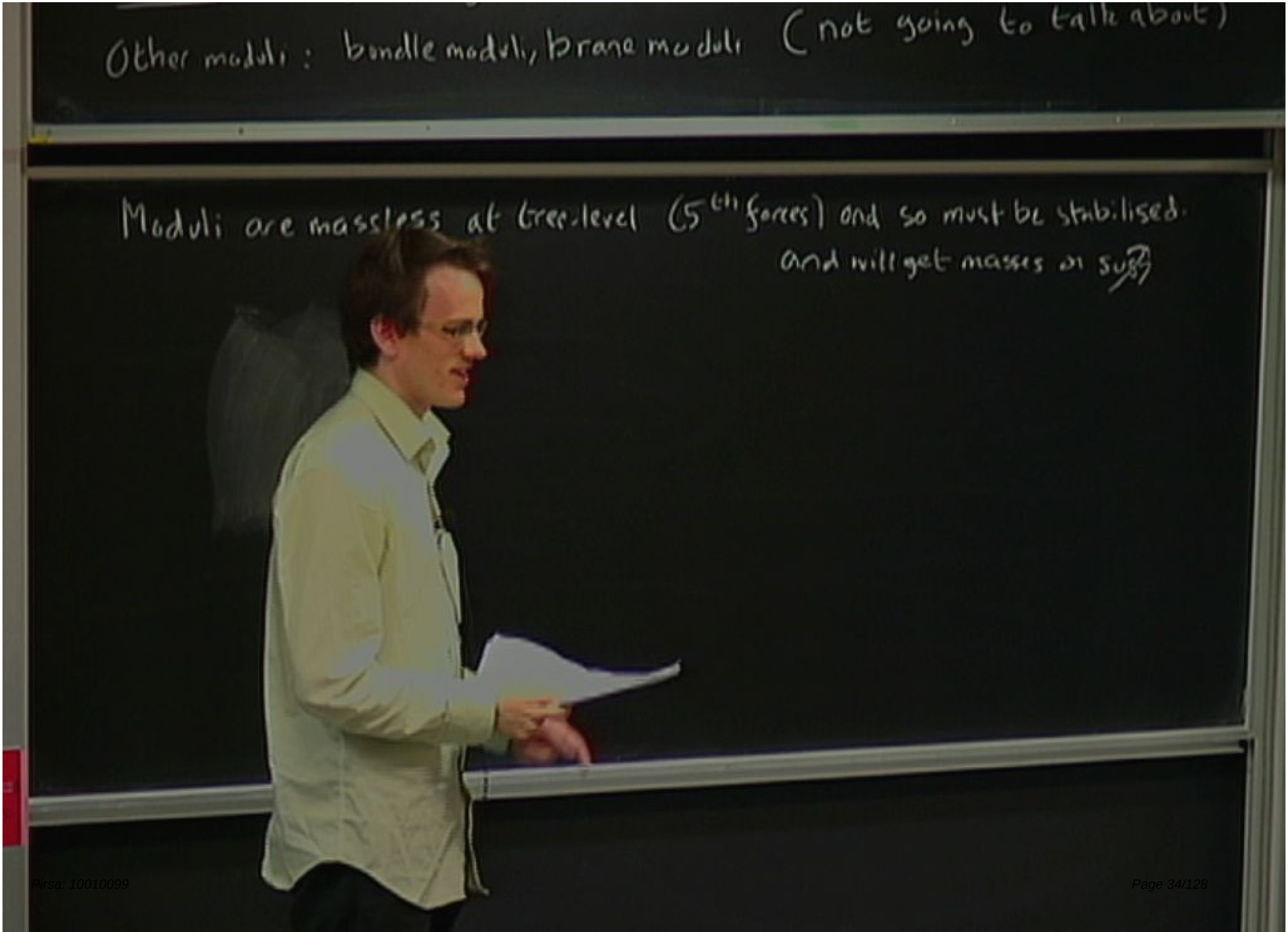
Moduli are massless at tree-level (5^{th} forces) and so must be stabilised.



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and will get masses at SUSY

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Why important?

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

Moduli are massless at tree-level (5th forces) and so must be stabilised.
Strongly suggests they will get masses on SUSY

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

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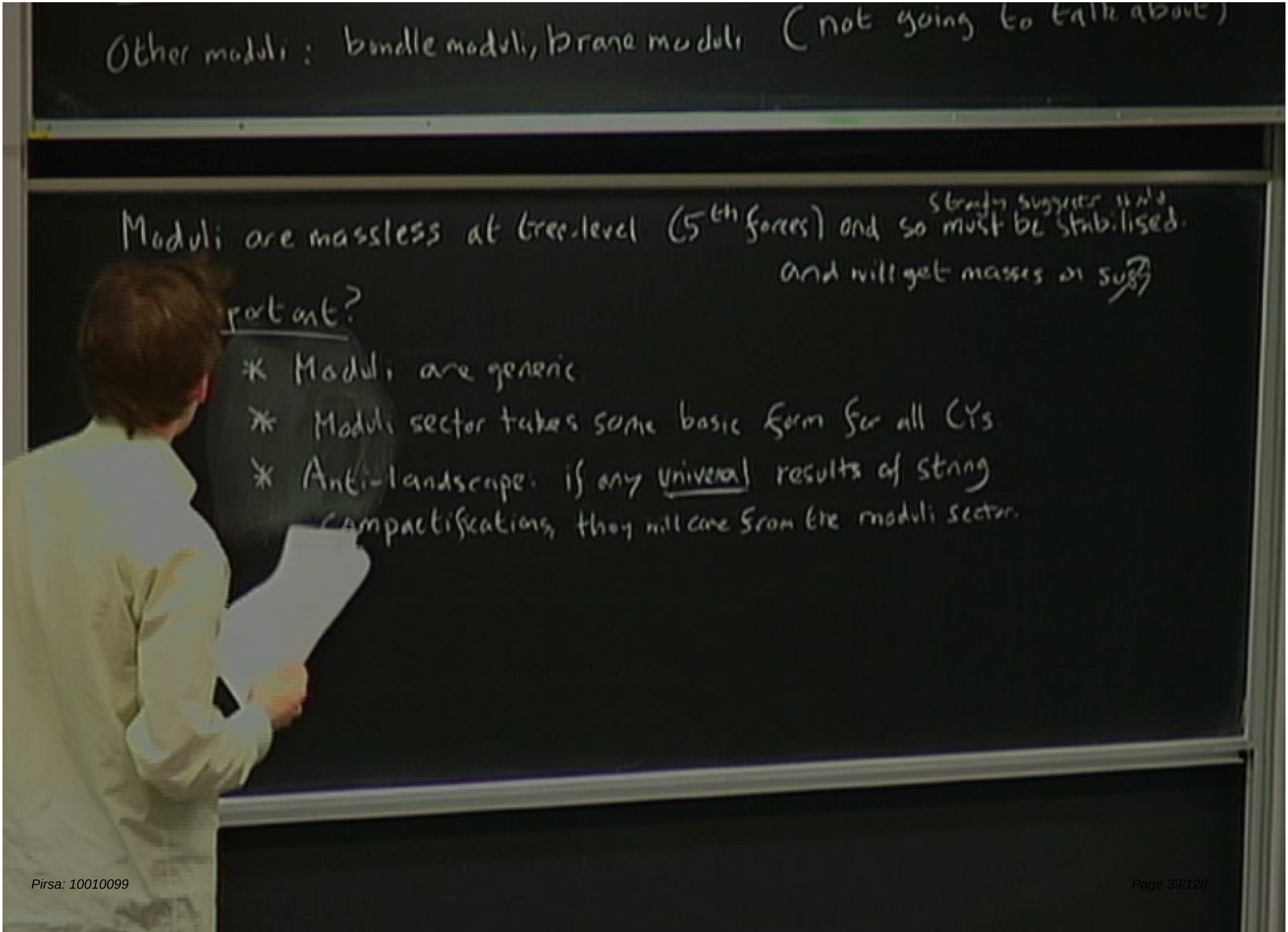
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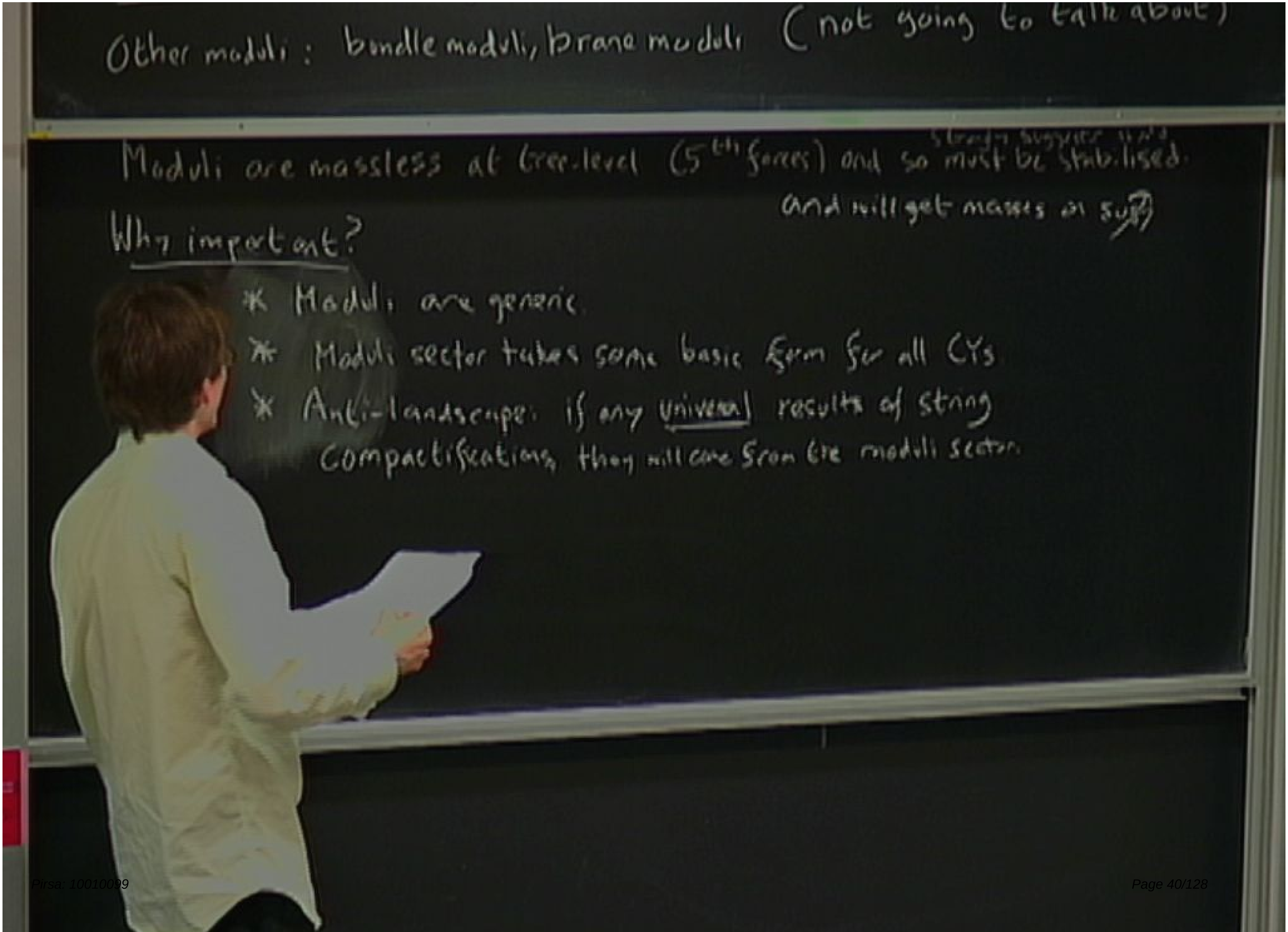
* Anti-landscape: if any universal results of string
compactifications, they will come from the moduli sector.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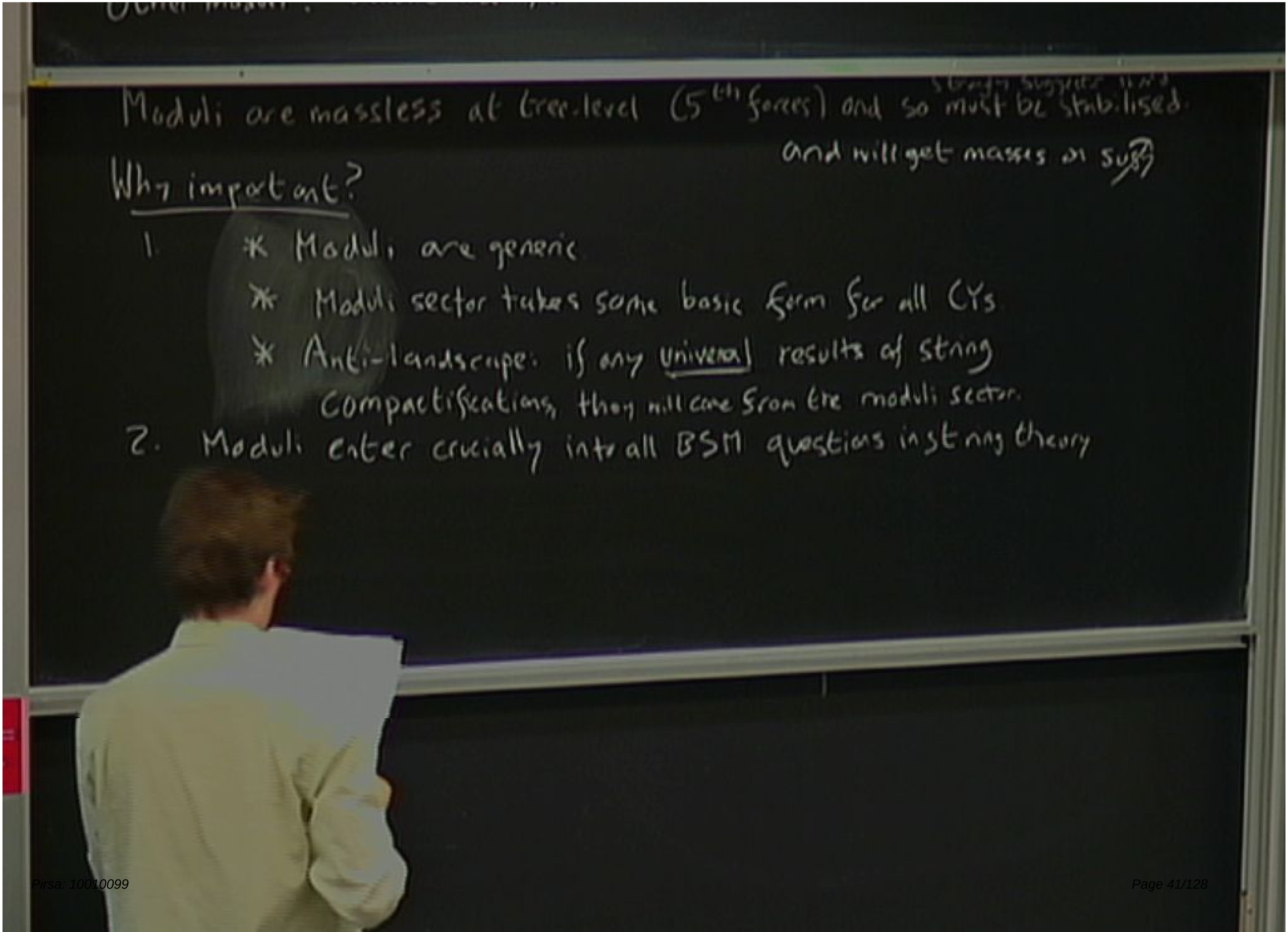
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Why important?
1. * Moduli are generic
* Moduli sector takes same basic form for all CYs.
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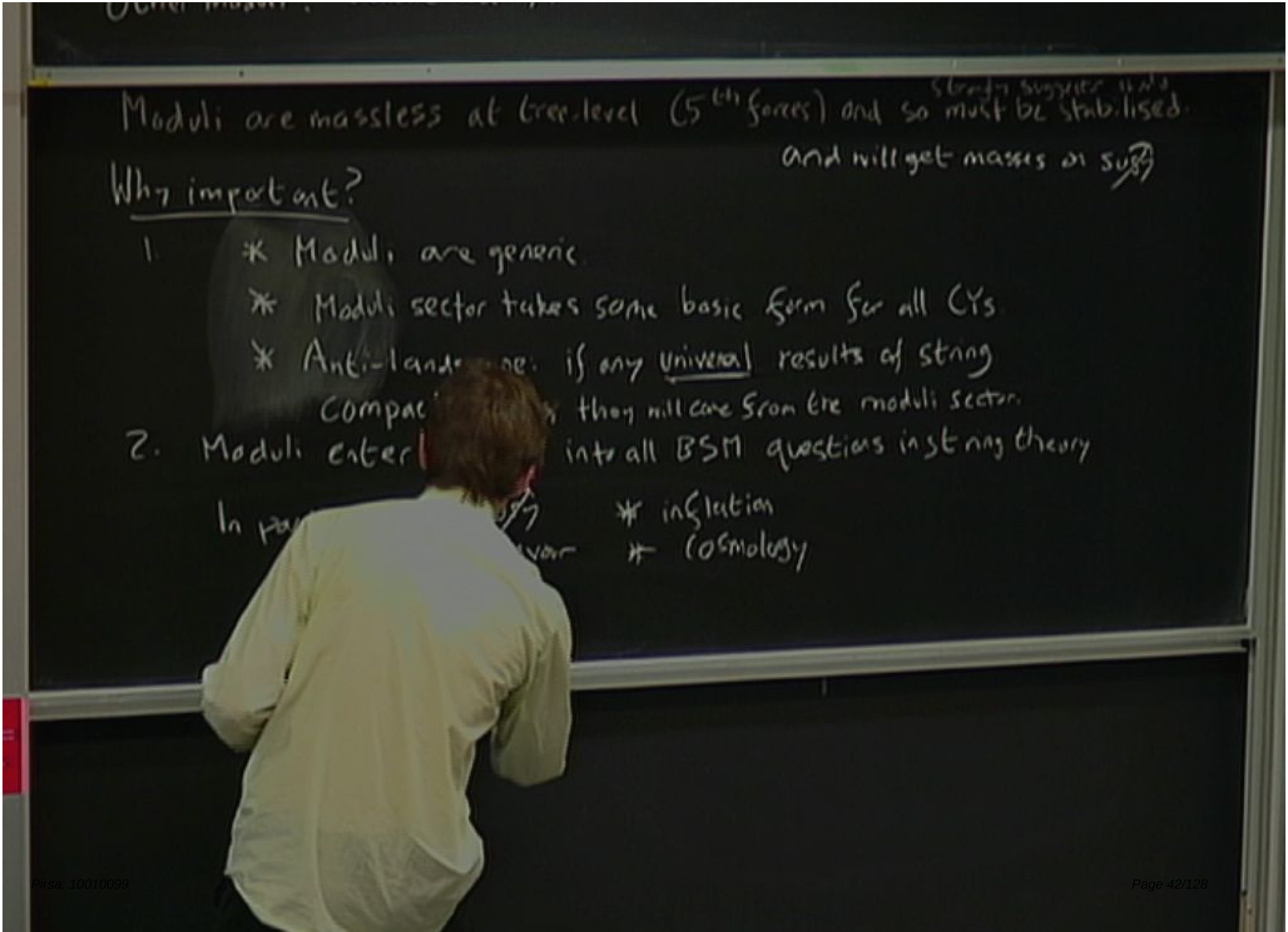
2. Moduli enter crucially into all BSM questions in string theory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* inflation
* cosmology

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Strongly suggests they
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Why important?

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In particular, * SUSY * inflation
* flavor * cosmology
* axions

1 * Moduli are generic

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

In particular, * SUSY * inflation
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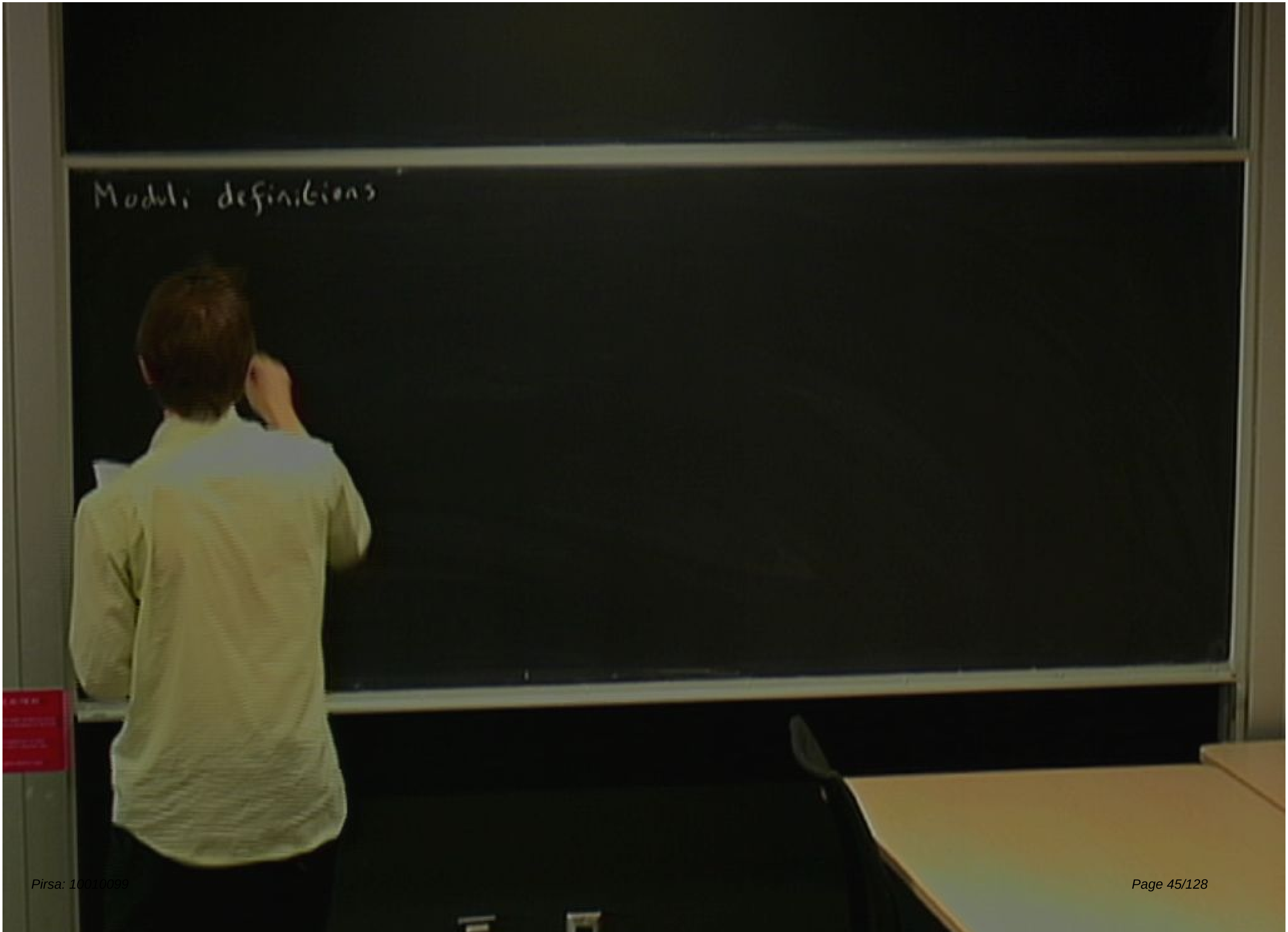
3. * Added value of strings: systematic violation of 'naive' EFT expectation


Moduli definitions

Moduli definitions

2 main types of geometric moduli, Kähler and complex structure

Kähler $\rightarrow$ 2,4 cycles in CY

2 main types of (moduli) Kähler and complex structure

Kähler $\rightarrow$ 2,4 cycles in CY

Complex structure $\Rightarrow$ 3 cycles

Moduli definitions

2 main types of (geometric) moduli, Kähler and complex structure

Kähler → 2,4 cycles in CY

Complex structure → 3 cycles

specialise

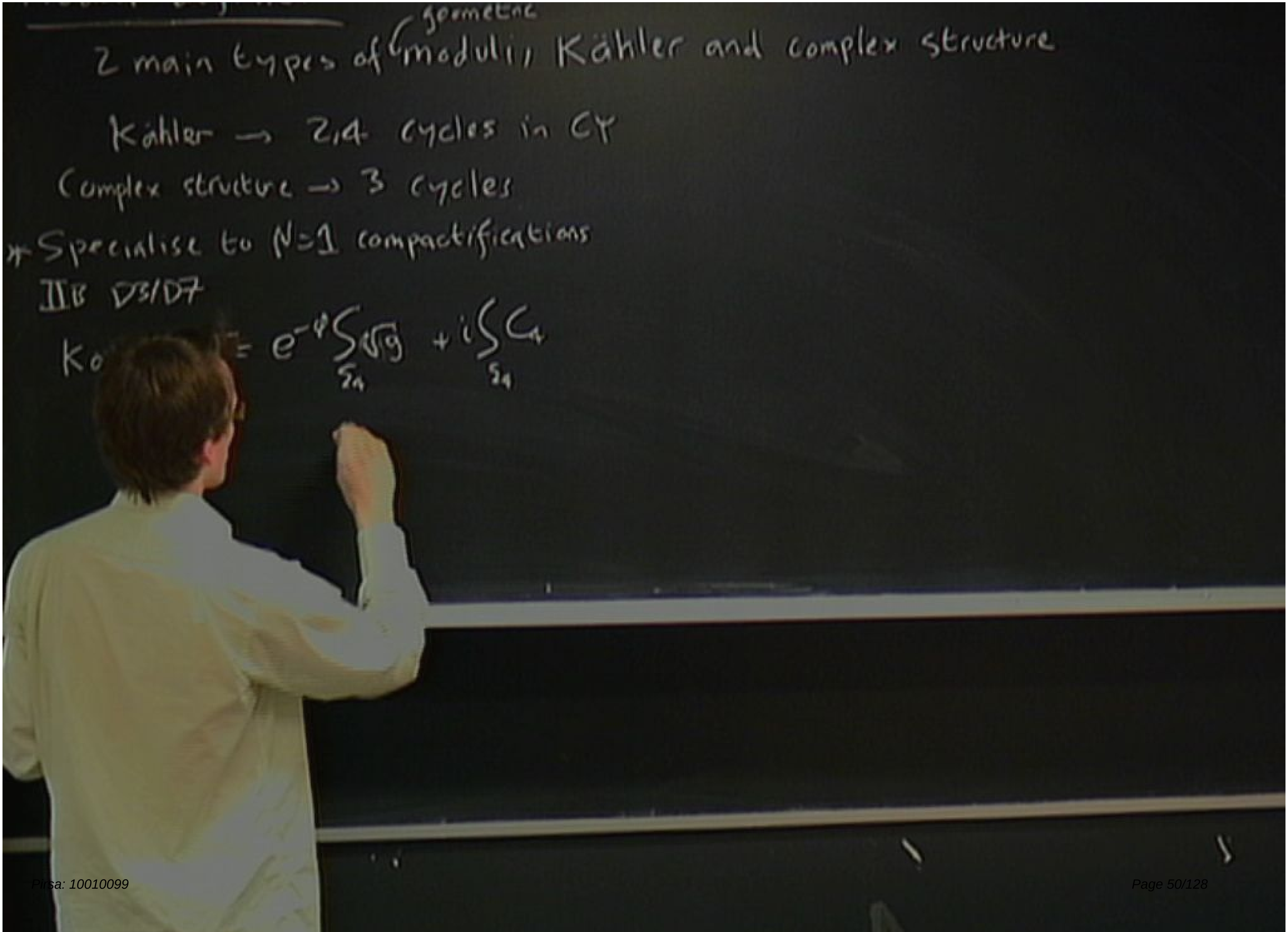
geometric
2 main types of moduli, Kähler and complex structure

Kähler $\rightarrow$ 2,4 cycles in CY

Complex structure $\rightarrow$ 3 cycles

* Specialise to $\mathcal{N}=1$ compactifications

IIB


geometric
2 main types of moduli, Kähler and complex structure
Kähler → 2,4 cycles in CY
Complex structure → 3 cycles
* Specialise to N=1 compactifications
IIB D3/D7
$= e^{-\phi}\int_{\Sigma_4}\sqrt{g} + i\int_{\Sigma_4} C_4$

2 main types of geometric moduli, Kähler and complex structure

Kähler → 2,4 cycles in CY

Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kähler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$

Kähler → 2,4 cycles in CY

Complex structure → 3 cycles

* Specialise to $\mathcal{N}=1$ compactifications

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Kähler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}} \sqrt{g} + i\int_{\Sigma_{4,i}} C_4$

plex structure U_i

Kähler → 2,4 cycles in CY

Complex structure → 3 cycles

* Specialise to $\mathcal{N}=1$ compactifications

IIB D3/D7

Kähler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$

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

Dilaton $S = e^{-\phi} + iC_0$

Kahler → 2,4 cycles in CY

Complex structure → 3 cycles

* Specialise to $\mathcal{N}=1$ compactifications

IIB D3/D7

Kahler: $T_i = e^{-\phi} \int_{\Sigma_{4,i}} \sqrt{g} + i \int_{\Sigma_{4,i}} C_4$

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

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Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kahler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})

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

Dilaton $S = e^{-\phi} + iC_0$ (S_{D-1})

2 main types of (geometric) moduli, Kä[illegible]

Kähler → 2,4 cycles in CY

Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kähler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})

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

Dilaton $S = e^{-\phi} + i C_0$ (S_{D-1})

IIA D6/O6

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

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

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

2 main types of moduli, K

Kähler → 2,4 cycles in CY

Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kahler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})

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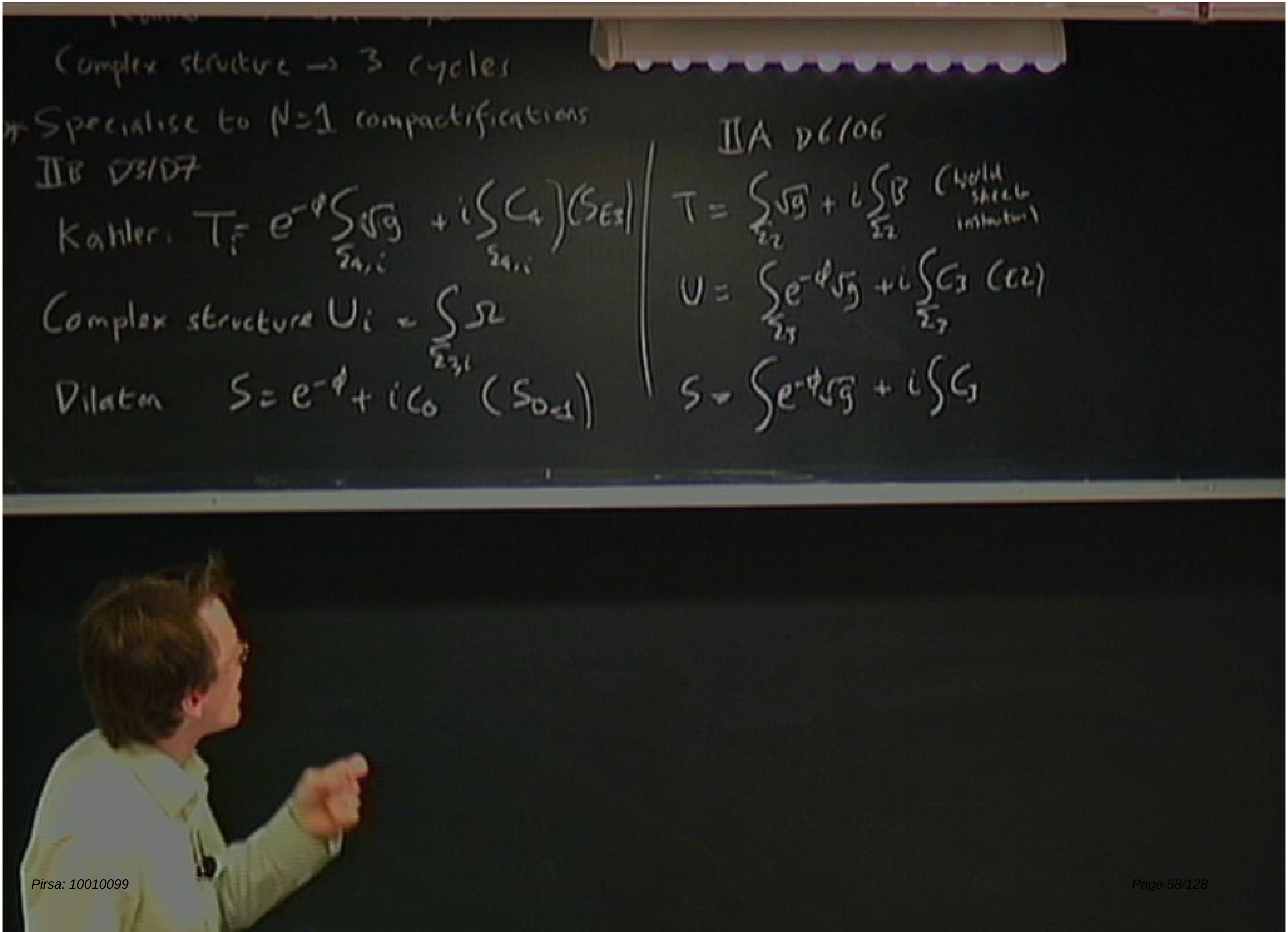
Dilaton $S = e^{-\phi} + iC_0$ (S_{D-1})

IIA D6/O6

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

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

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


Complex structure → 3 cycles
* Specialise to $N=1$ compactifications
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Kahler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})
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Kahler → 2,4 cycles in C_Y

Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7

Kahler: $T = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})

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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 to $N=1$ compactifications

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

Heterotic

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

$\int_{\Sigma_3} \Omega$

Kähler → 2,4 cycles in CY

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IIB D3/D7

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

Heterotic

$\int\sqrt{g} + iB_2$ (worldsheet instanton)

$\int_{\Sigma_3}\Omega$

$S = \int_{CY_6} e^{-2\phi}\sqrt{g}$

Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

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Kahler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})

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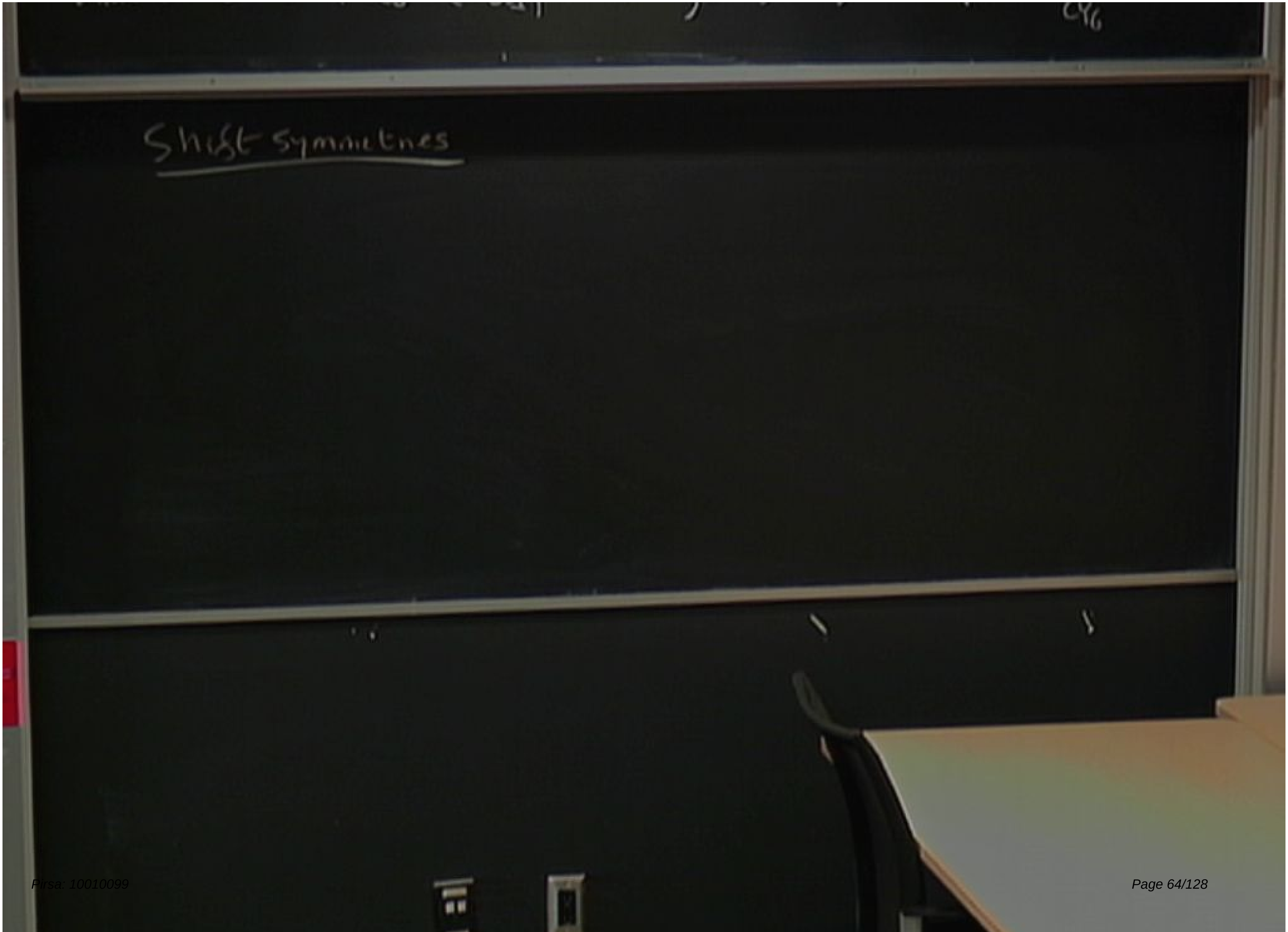
Shift symmetries

Shift symmetries

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

Shift symmetries

IIB $T \to T + i\epsilon$ (good to all orders in string perturbation thy)

IIA. $U \to U + i\epsilon$ "

Shift symmetries

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

IIA. $U \to U + i\epsilon$ "

IIB $\leftrightarrow$ IIA (mirror symmetry)

$T \leftrightarrow U$

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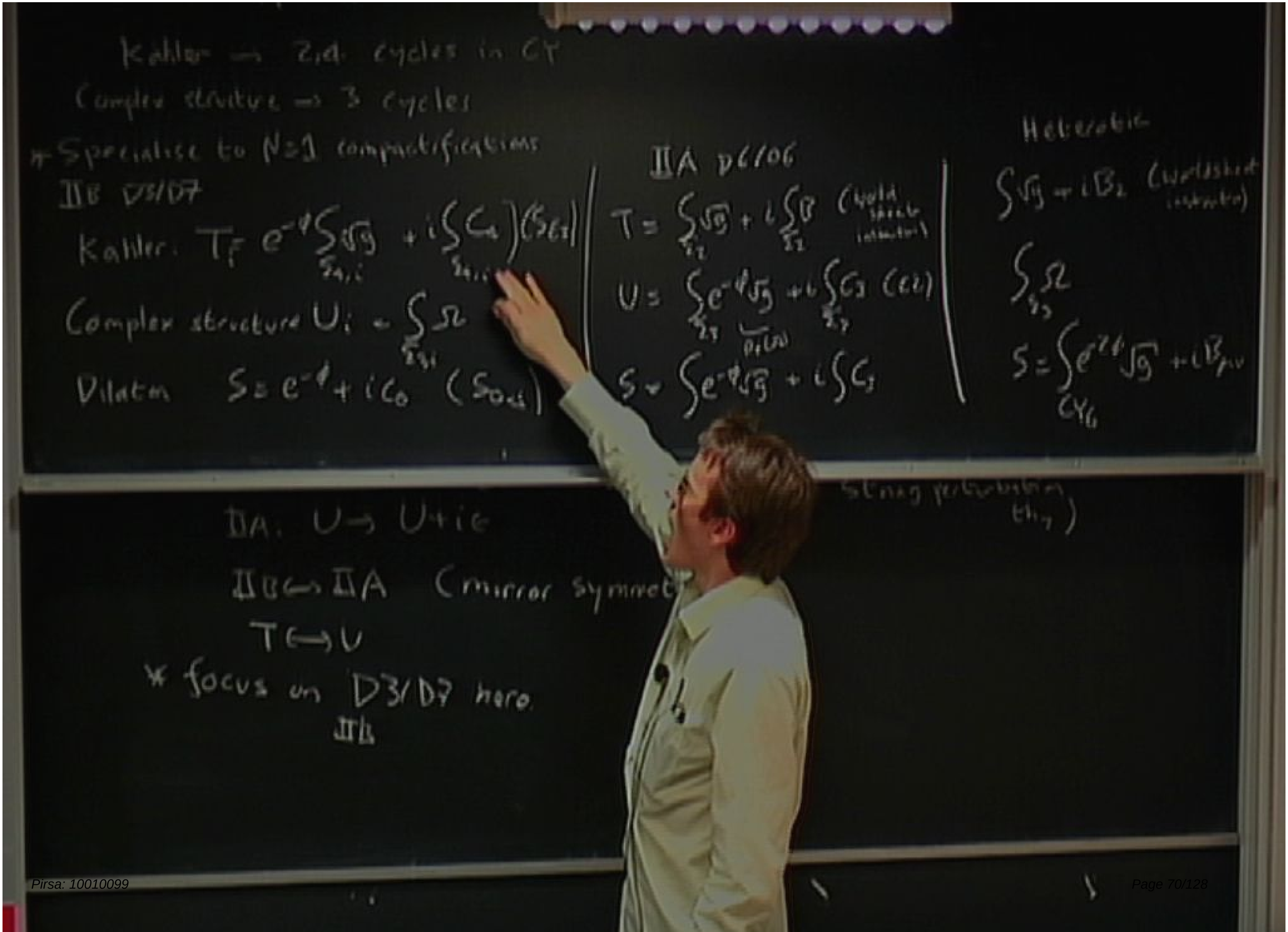
* focus on D3/D7 here.
IIB


Kähler → 2,4 cycles in CY
Complex structure → 3 cycles
* Specialise to N=1 compactifications
IIB D3/D7
Kähler. $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (B_{E3})
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IIA D6/O6
$T = \int_{\Sigma_2}\sqrt{g} + i\int_{\Sigma_2} B$ (world sheet instanton)
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$S = \int e^{-\phi}\sqrt{g} + i\int C_3$
Heterotic
$\int\sqrt{g} + iB_2$ (worldsheet instanton)
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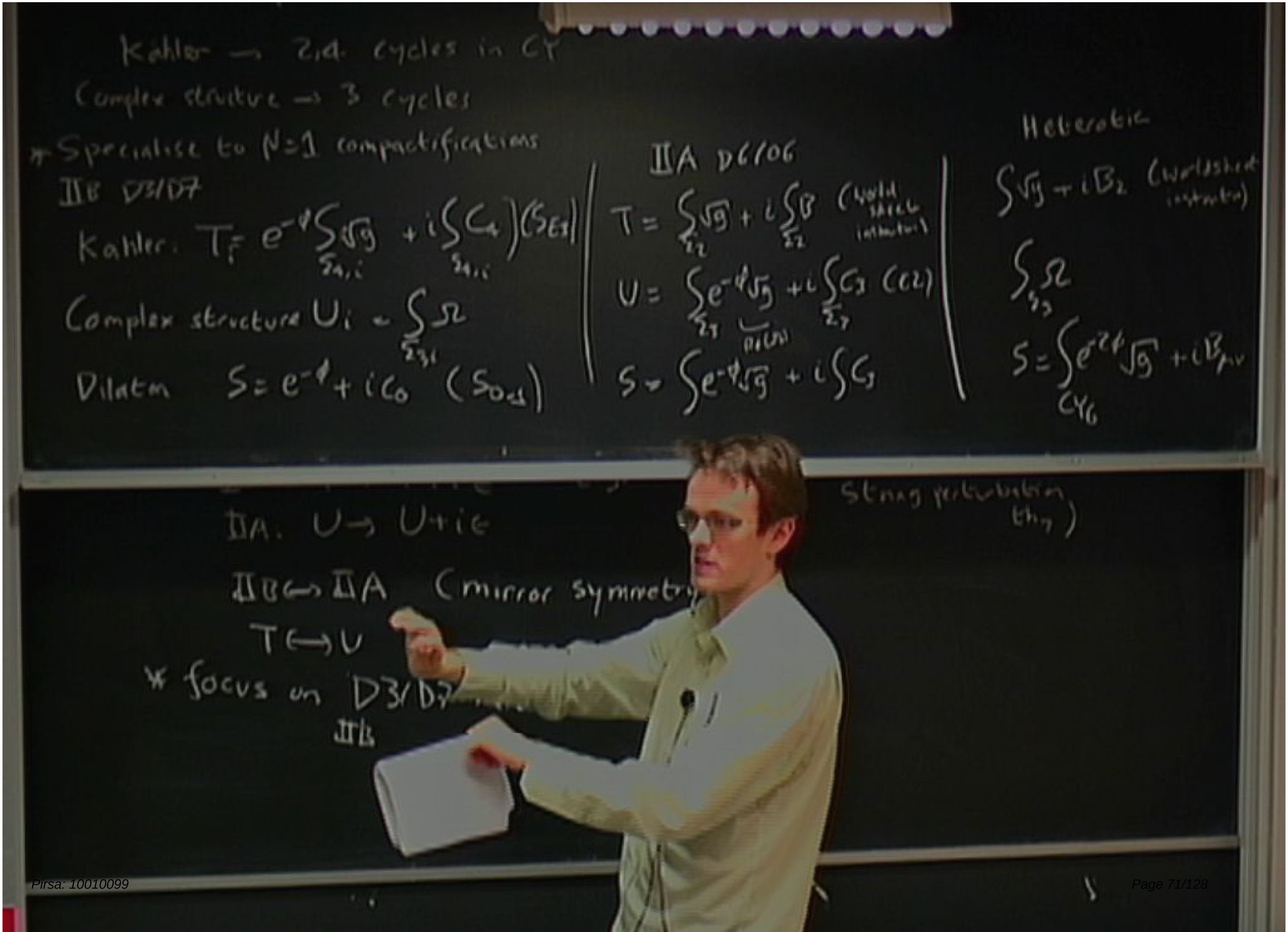
string perturbation theory)
IIA: $U \to U + ic$
IIB ↔ IIA (mirror symmetry
$T \leftrightarrow U$
* focus on D3/D7 here
IIB


Kähler → 2,4 cycles in CY
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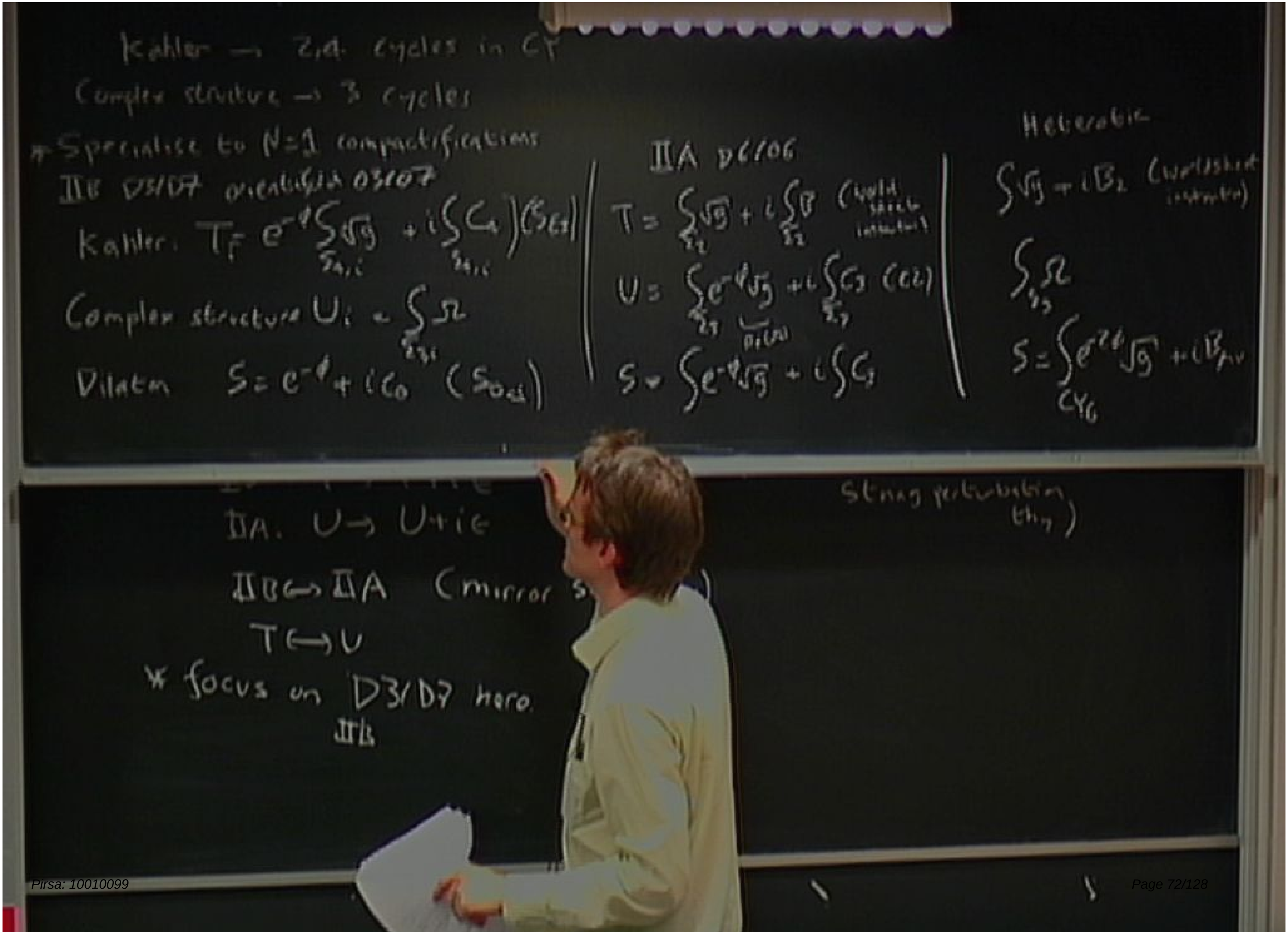
String perturbation thy)
IIA: $U \to U + i\epsilon$
IIB ⟷ IIA (mirror symmetry
$T \longleftrightarrow U$
* focus on D3/D7
IIB


Kähler → 2,4 cycles in CY
Complex structure → 3 cycles
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IIB D3/D7 orientifold O3/O7
Kahler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})
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IIA D6/O6
$T = \int_{\Sigma_2}\sqrt{g} + i\int_{\Sigma_2} B$ (world sheet instanton)
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Heterotic
$\int\sqrt{g} + iB_2$ (worldsheet instanton)
$\int_{\Sigma_3}\Omega$
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IIA: U → U + ic
IIB ↔ IIA (mirror s...)
T ↔ U
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IIB
String perturbation theory)

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IIB D3/D7 orientifolds O3/O7

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

$U = \int_{\Sigma_3} \underbrace{e^{-\phi}\sqrt{g}}_{D6(D)} + i\int_{\Sigma_3} C_3$ (E2)

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

$\int\sqrt{g} + iB_2$ (worldsheet instanton)

$\int_{\Sigma_3}\Omega$

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Shift symmetries

IIB $T \to T + i\epsilon$ (good to all orders in string perturbation thy)

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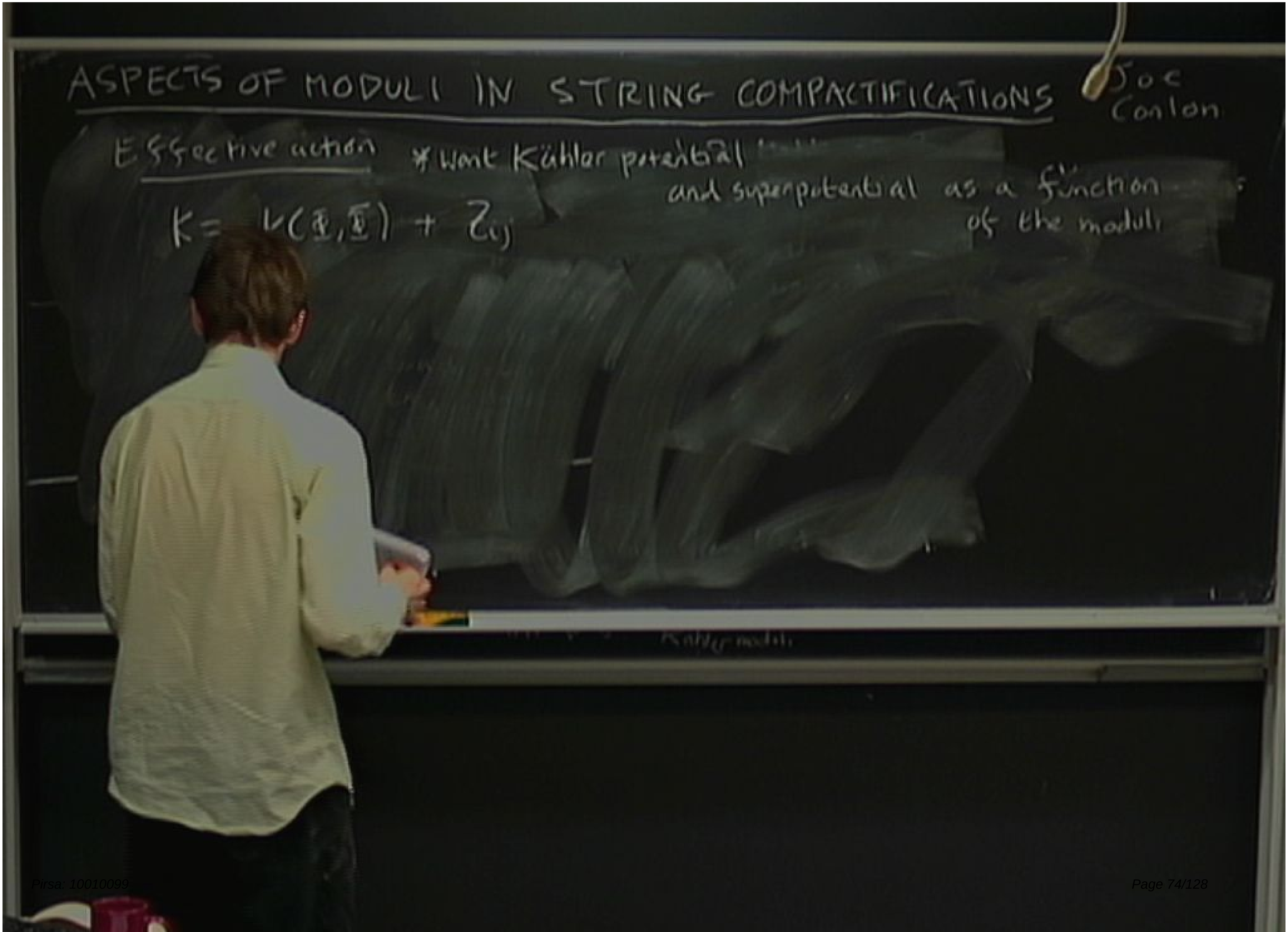
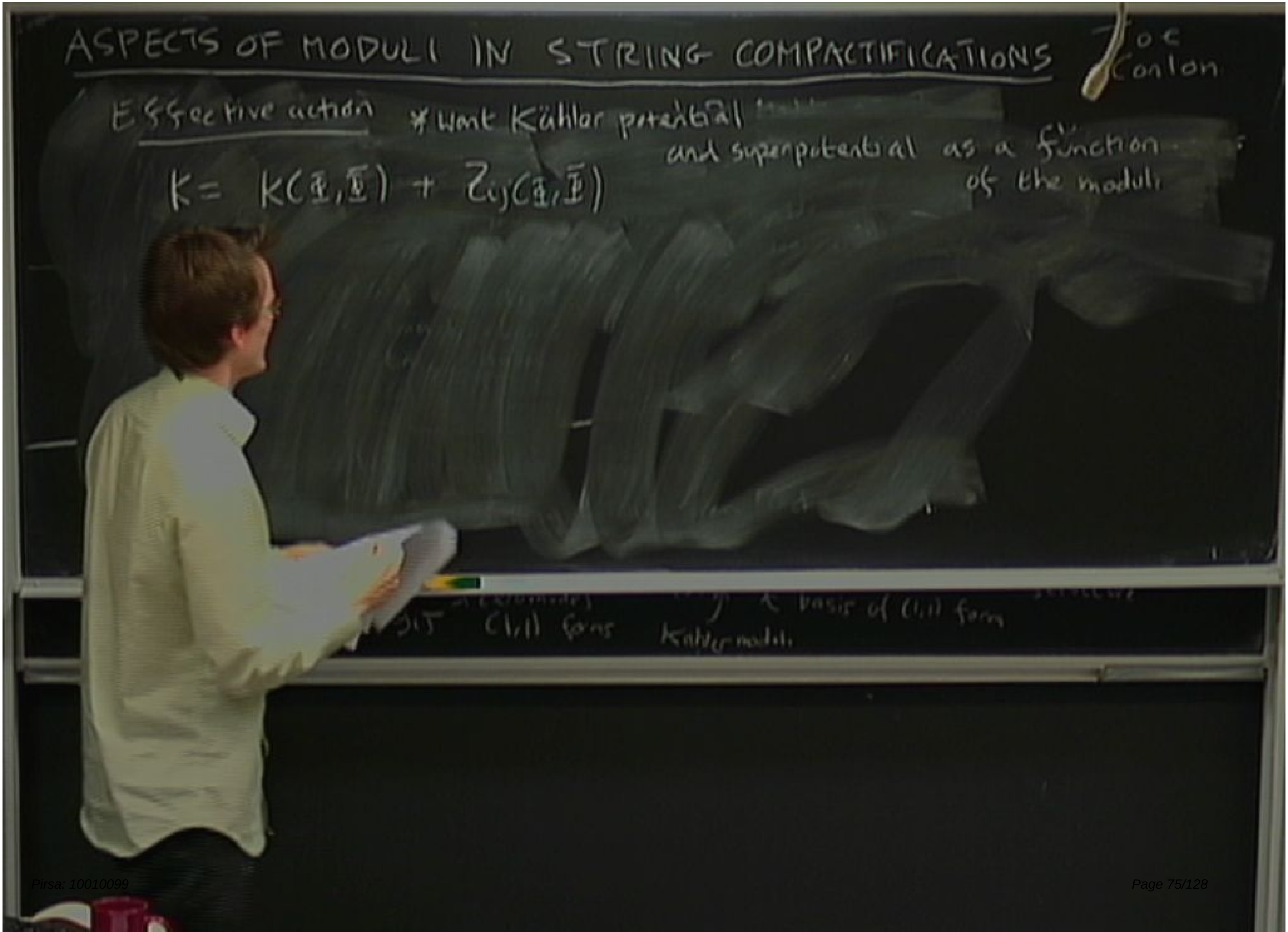
IIB


ASPECTS OF MODULI IN STRING COMPACTIFICATIONS
Joe Conlon
Effective action
* Want Kähler potential
and superpotential as a function
of the moduli
$K = K(\Phi, \bar{\Phi}) + Z_{ij}$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(1,1) forms
Kähler moduli
basis of (1,1) form

ASPECTS OF MODULI IN STRING COMPACTIFICATIONS

Joe Conlon

Effective action

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

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

$$W = W(\Phi)$$

$\delta g_{i\bar{j}}$ (1,1) forms — a basis of (1,1) form — Kähler moduli

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

Dilaton $S = e^{-\phi} + i C_0$ (S_{0-1}) | $S = \int e^{-\phi}\sqrt{g} + i \int C_3$ | $S = \int_{CY_6} e^{-2\phi}\sqrt{g} + i B_{\mu\nu}$

Shift symmetries

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

IIA. $U \to U + i\epsilon$ "

IIB $\leftrightarrow$ IIA (mirror symmetry)

$T \leftrightarrow U$

* focus on D3/D7 here

IIB

Complex structure $U_i = \int_{\Sigma_{3i}}$

Dilaton $S = e^{-\phi} + iC_0$ (S_{odd}) | $S = \int e^{-\phi}\sqrt{g} + i\int C_3$ | $S = \int_{CY_6} e^{-2\phi}\sqrt{g} + iB_{\mu\nu}$

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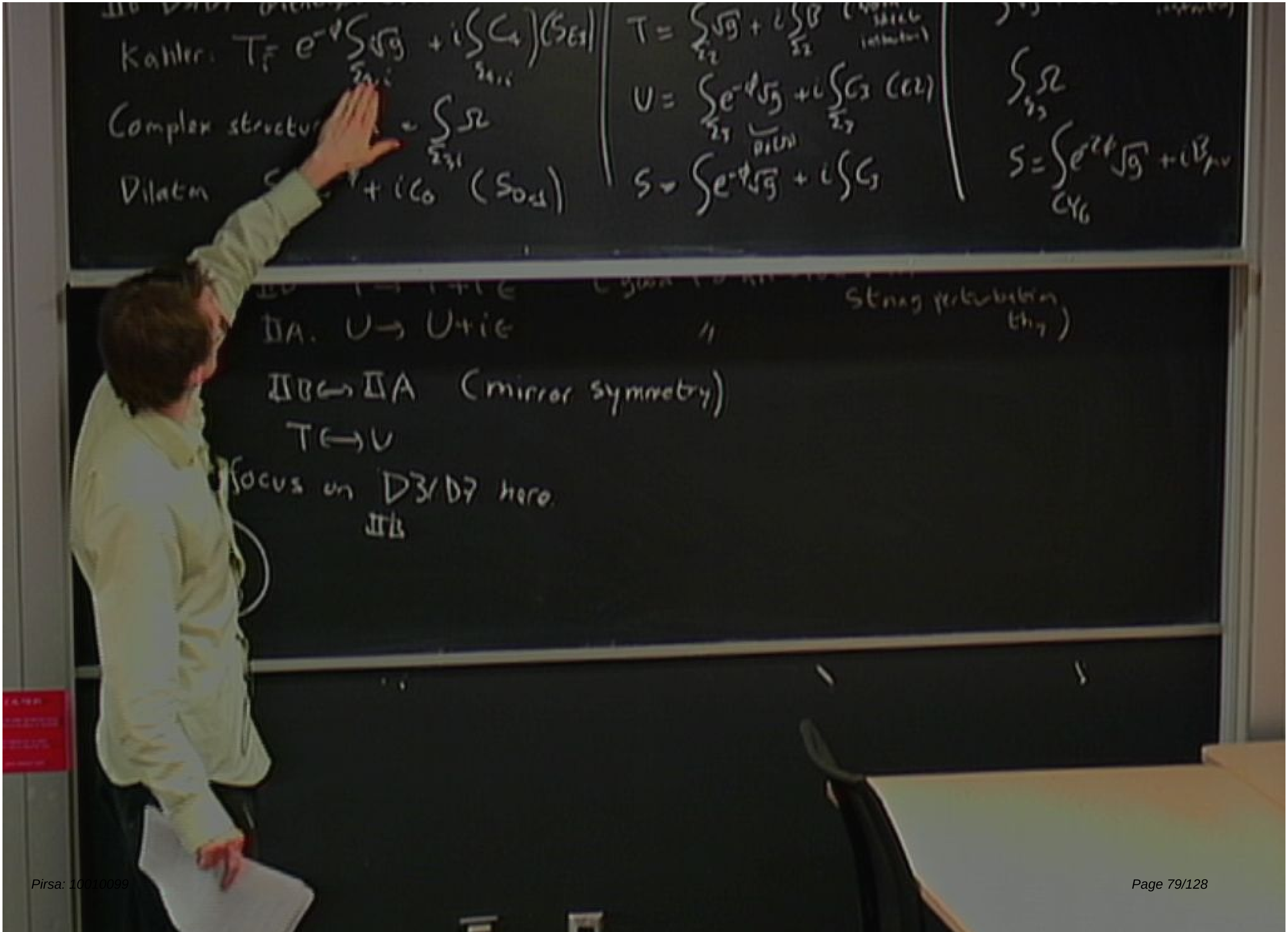
Kahler:
Complex structure
Dilaton
IIA. U → U+iε
IIB ↔ IIA (mirror symmetry)
T ↔ U
focus on D3/D7 here.
IIB
String perturbation thy)

Complex structure → 3 cycles

* Specialise to $N=1$ compactifications

IIB D3/D7 orientifold O3/O7

Kahler: $T_i = e^{-\phi}\int_{\Sigma_{4,i}}\sqrt{g} + i\int_{\Sigma_{4,i}} C_4$ (S_{E3})

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IIA D6/O6

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

$U = \int_{\Sigma_3} \underbrace{e^{-\phi}\sqrt{g}}_{D6/E2} + i\int_{\Sigma_3} C_3$ (E2)

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

Heterotic

$\int\sqrt{g} + iB_2$ (worldsheet instanton)

$\int_{\Sigma_3}\Omega$

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

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IIB ⟷ IIA (mirror symmetry)

$T \longleftrightarrow U$

* focus on D3/D7 here.

IIB

* Specialise to ... compactifications

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IIA D6/O6

$T = \int_{\Sigma_2}\sqrt{g} + i\int_{\Sigma_2} B$ (world sheet instantons)

$U = \underbrace{\int_{\Sigma_3} e^{-\phi}\sqrt{g}}_{\mathrm{Re}(U)} + i\int_{\Sigma_3} C_3$ (E2)

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

$\int\sqrt{g} + iB_2$ (worldsheet instantons)

$\int_{\Sigma_3}\Omega$

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

Shift symmetries

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

$\int\sqrt{g} + iB_2$ (WS instanton)

$\int_{\Sigma_3}\Omega$

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

Shift symmetries

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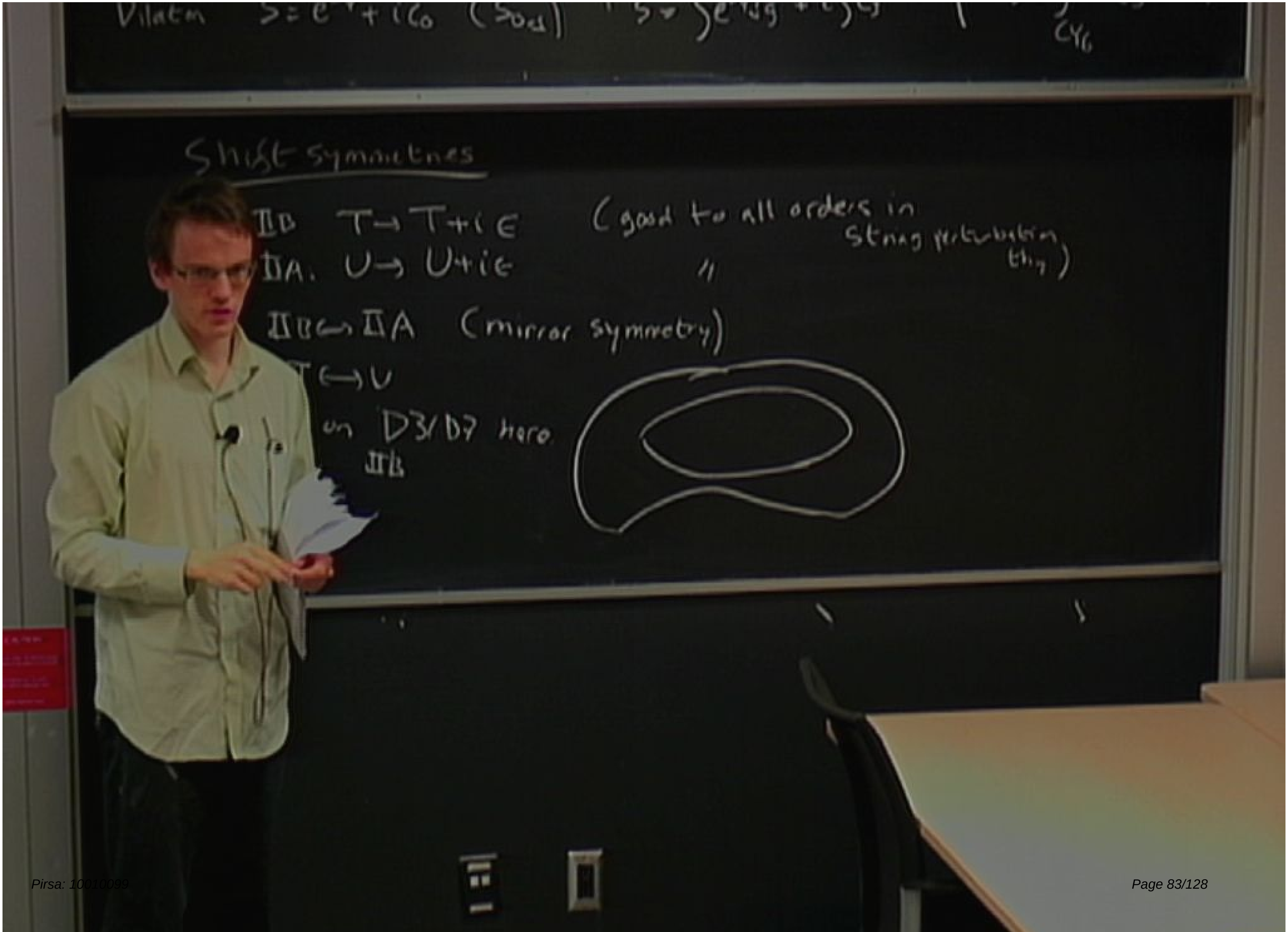
IIB


Shift symmetries
IIB T → T+iε (good to all orders in string perturbation thy)
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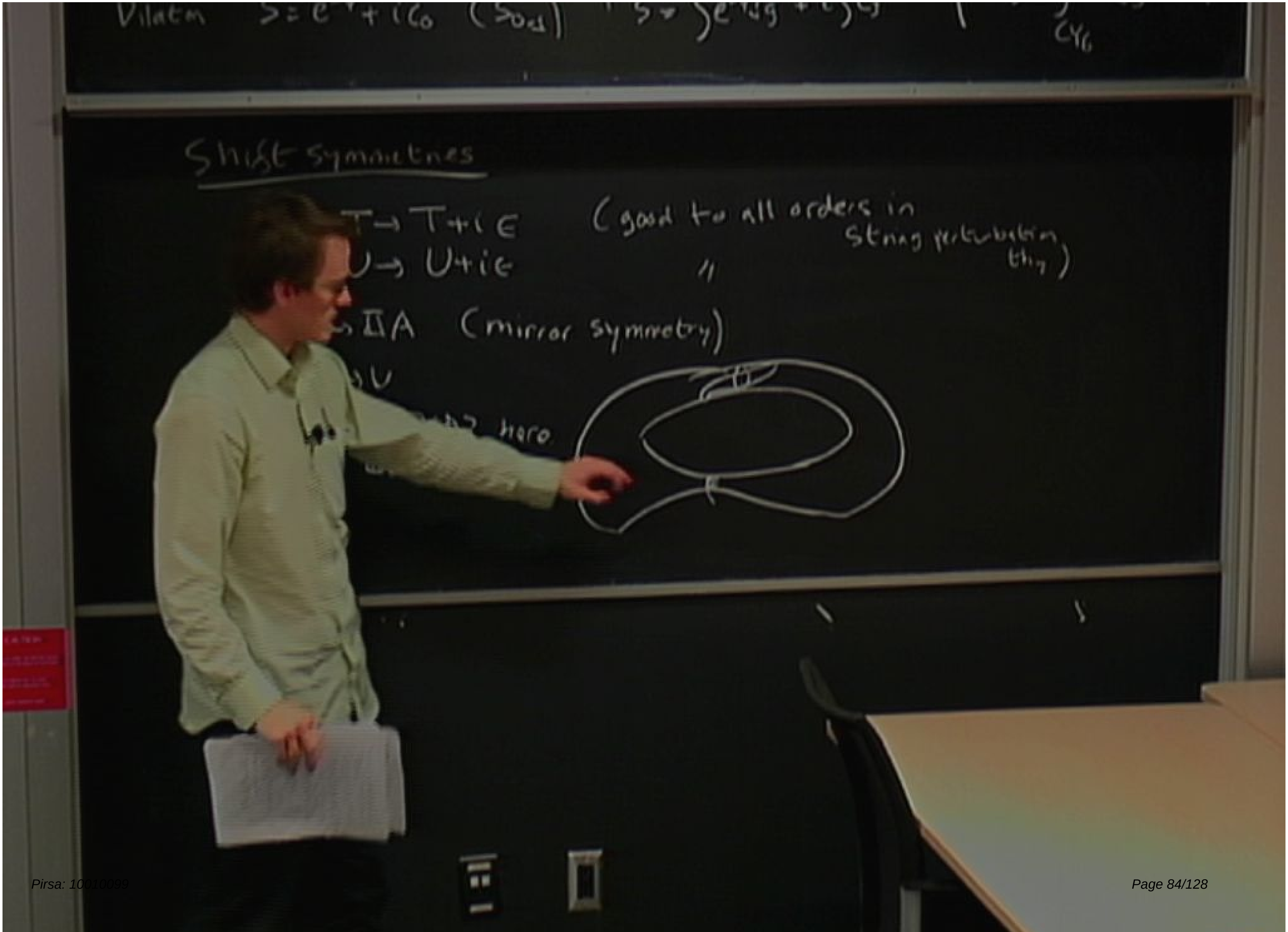
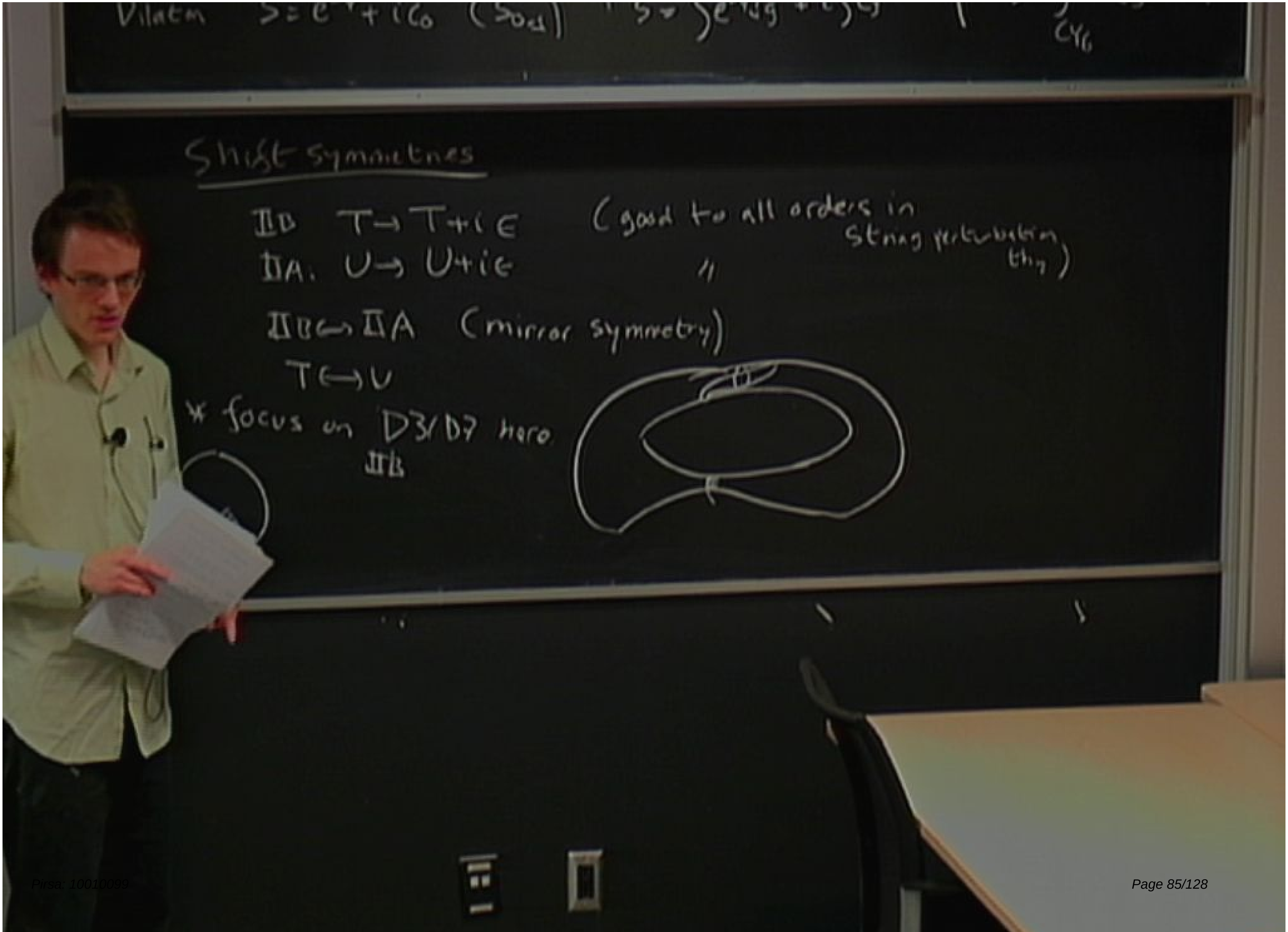
IIB ↔ IIA (mirror symmetry)
T ↔ U
on D3/D7 here.
IIB


Shift symmetries
T → T+iε
(good to all orders in string perturbation thy)
U → U+iε
IIA (mirror symmetry)
here.
CY6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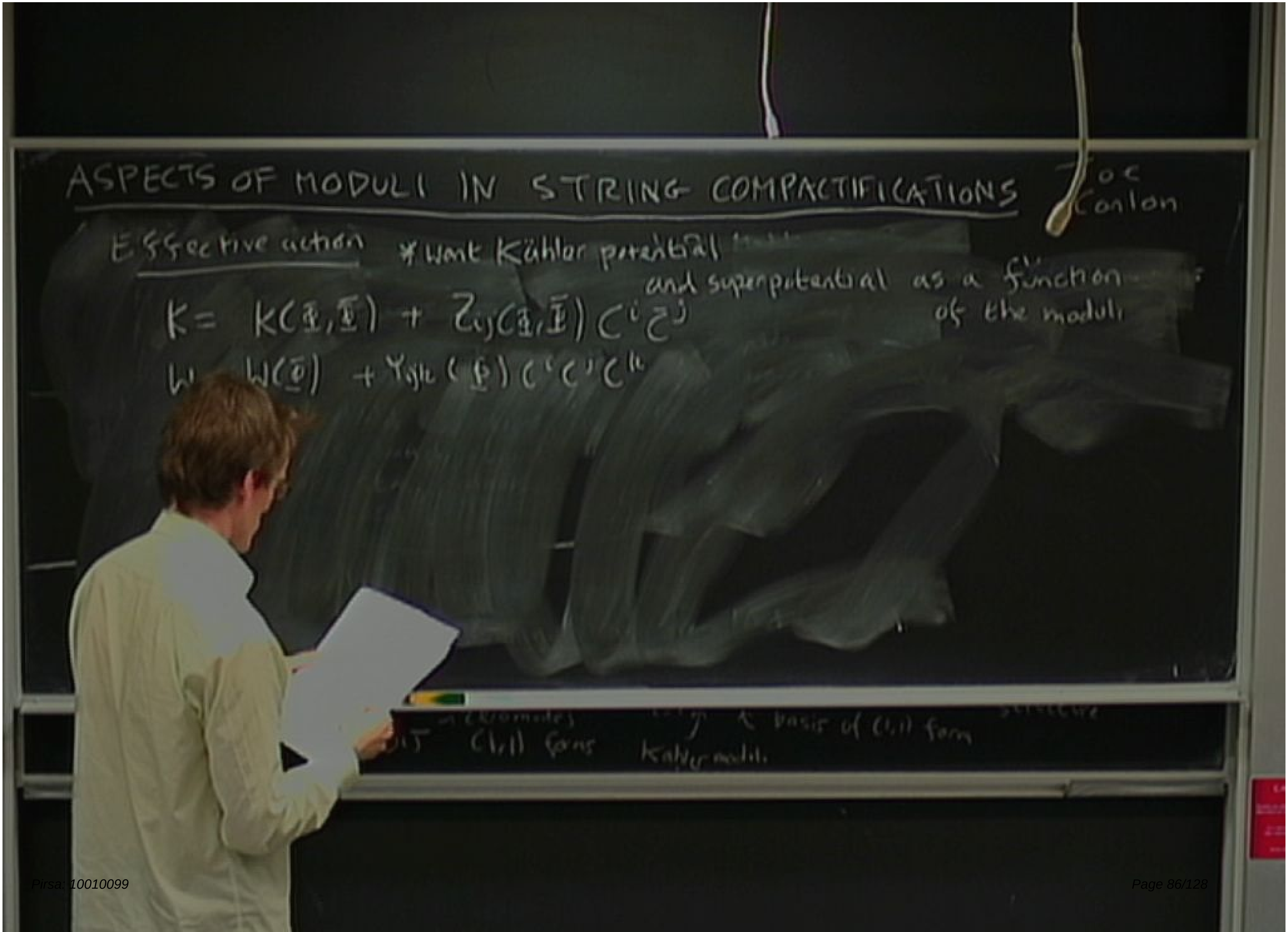
IIB
CY6


ASPECTS OF MODULI IN STRING COMPACTIFICATIONS
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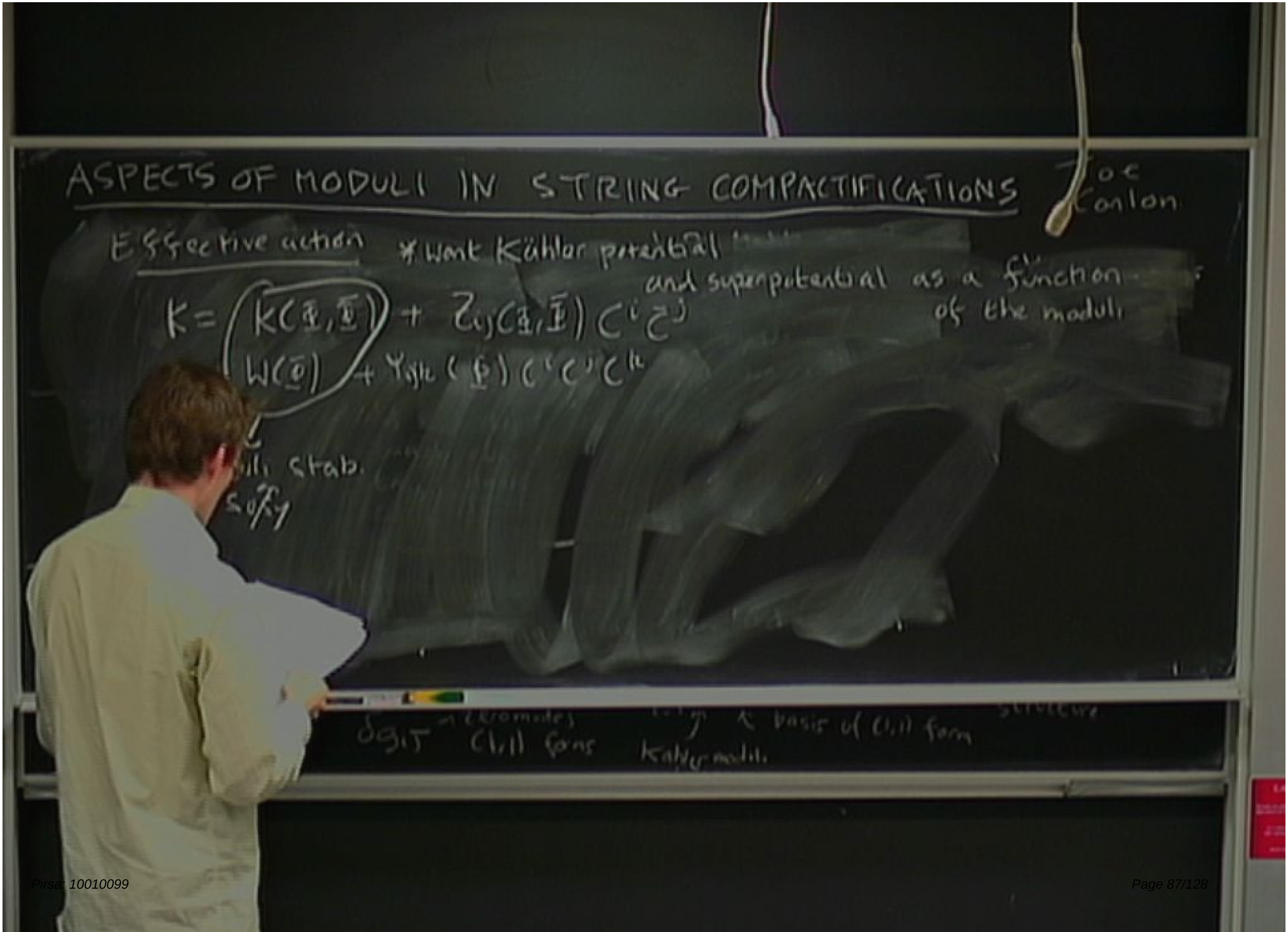
Effective action
* want Kähler potential
and superpotential as a function
of the moduli
K = K(Φ, Φ̄) + Z_ij(Φ, Φ̄) C^i C̄^j
W = W(Φ) + Y_ijk(Φ) C^i C^j C^k
(1,1) forms
basis of (1,1) form
Kähler moduli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K = K(Φ, Φ̄) + Z_ij(Φ, Φ̄) C^i C̄^j
W(Φ) + Y_ijk(Φ) C^i C^j C^k
moduli stab.
SUSY
(1,1) forms
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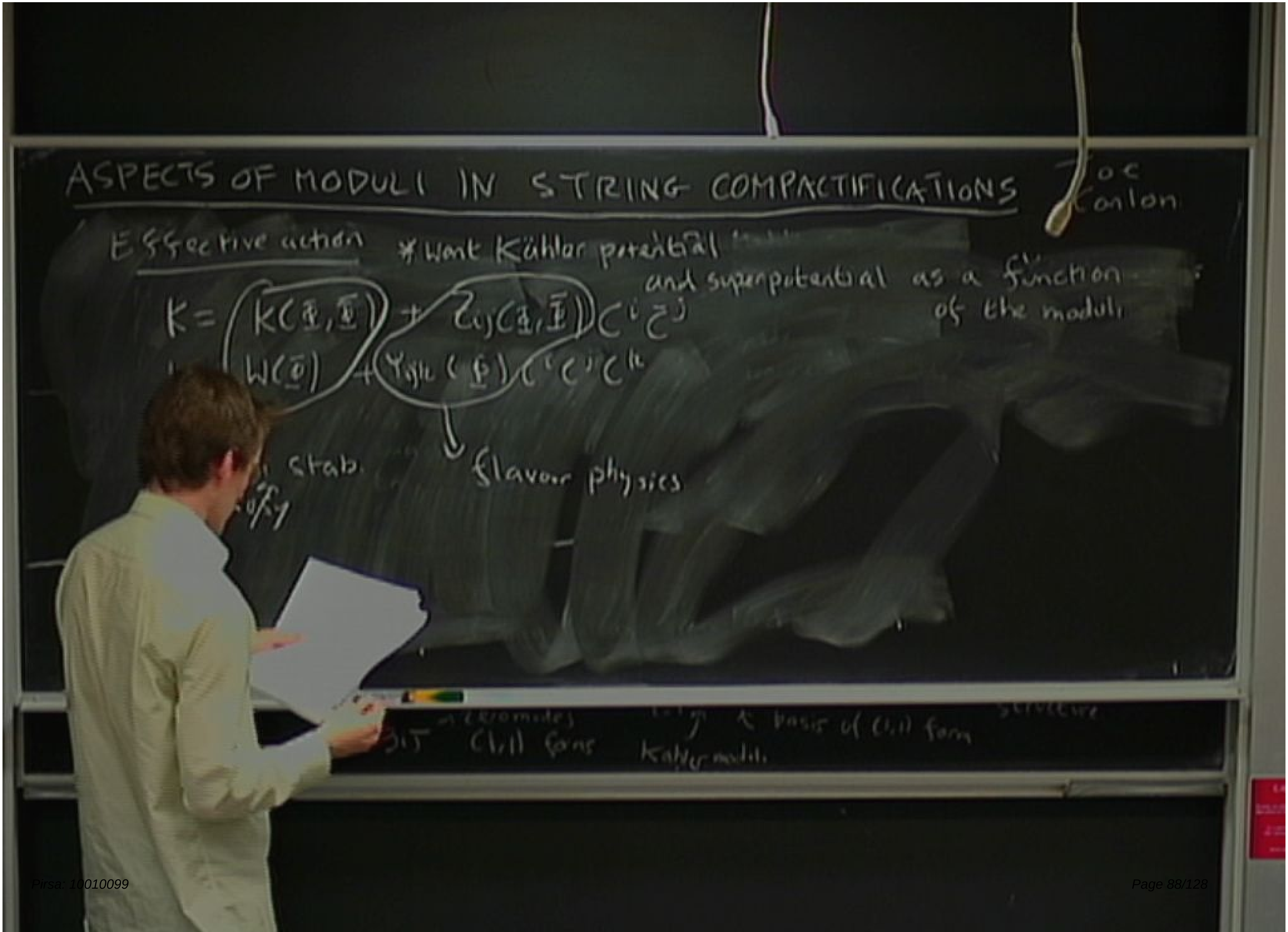
Kähler moduli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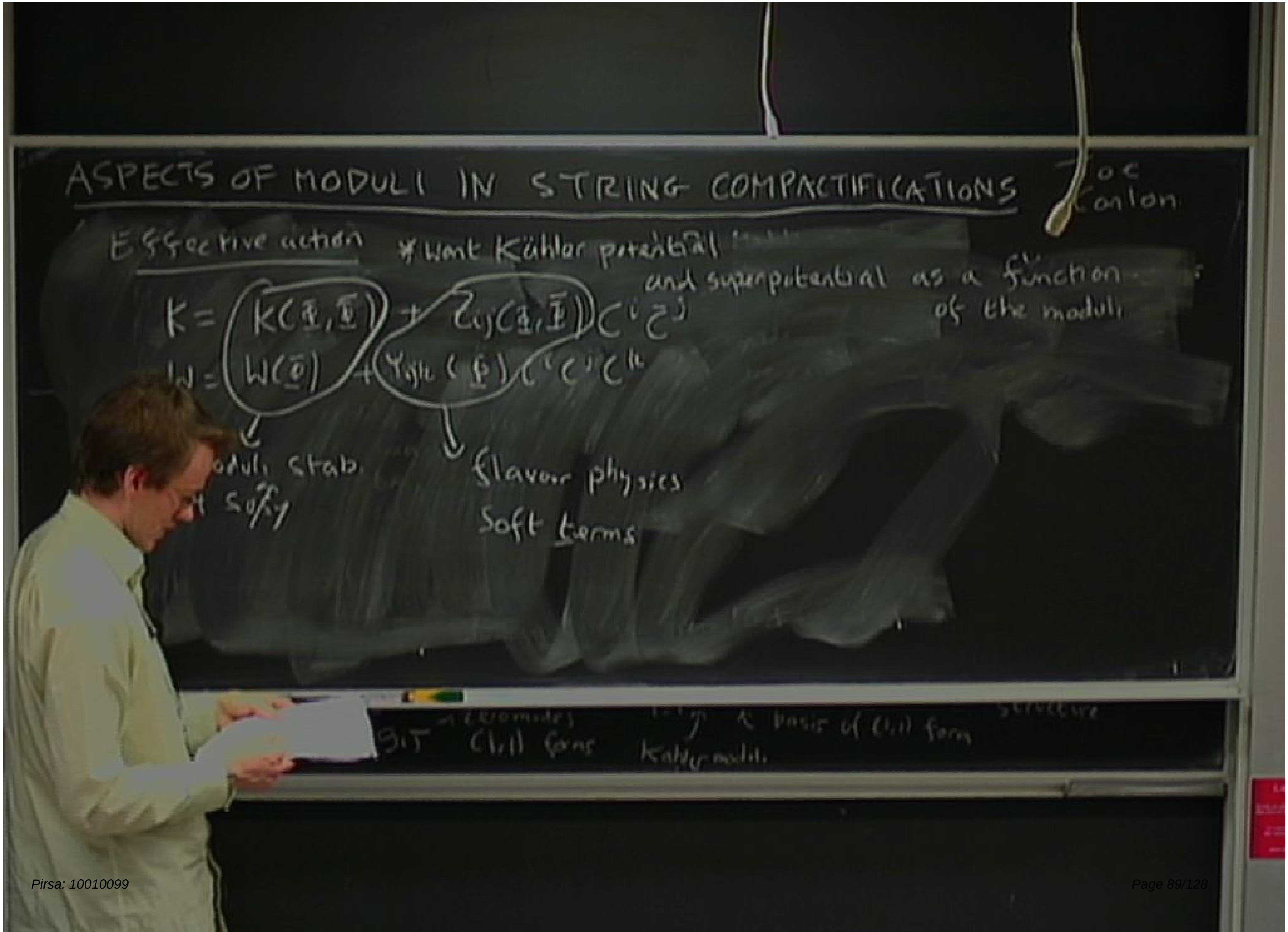
$K = K(\Phi, \bar{\Phi}) + \tilde{Z}_{ij}(\Phi, \bar{\Phi}) C^i \bar{C}^j$
$W(\Phi) + Y_{ijk}(\Phi) C^i C^j C^k$
stab.
flavor physics
(1,1) form
basis of (1,1) form
Kahler moduli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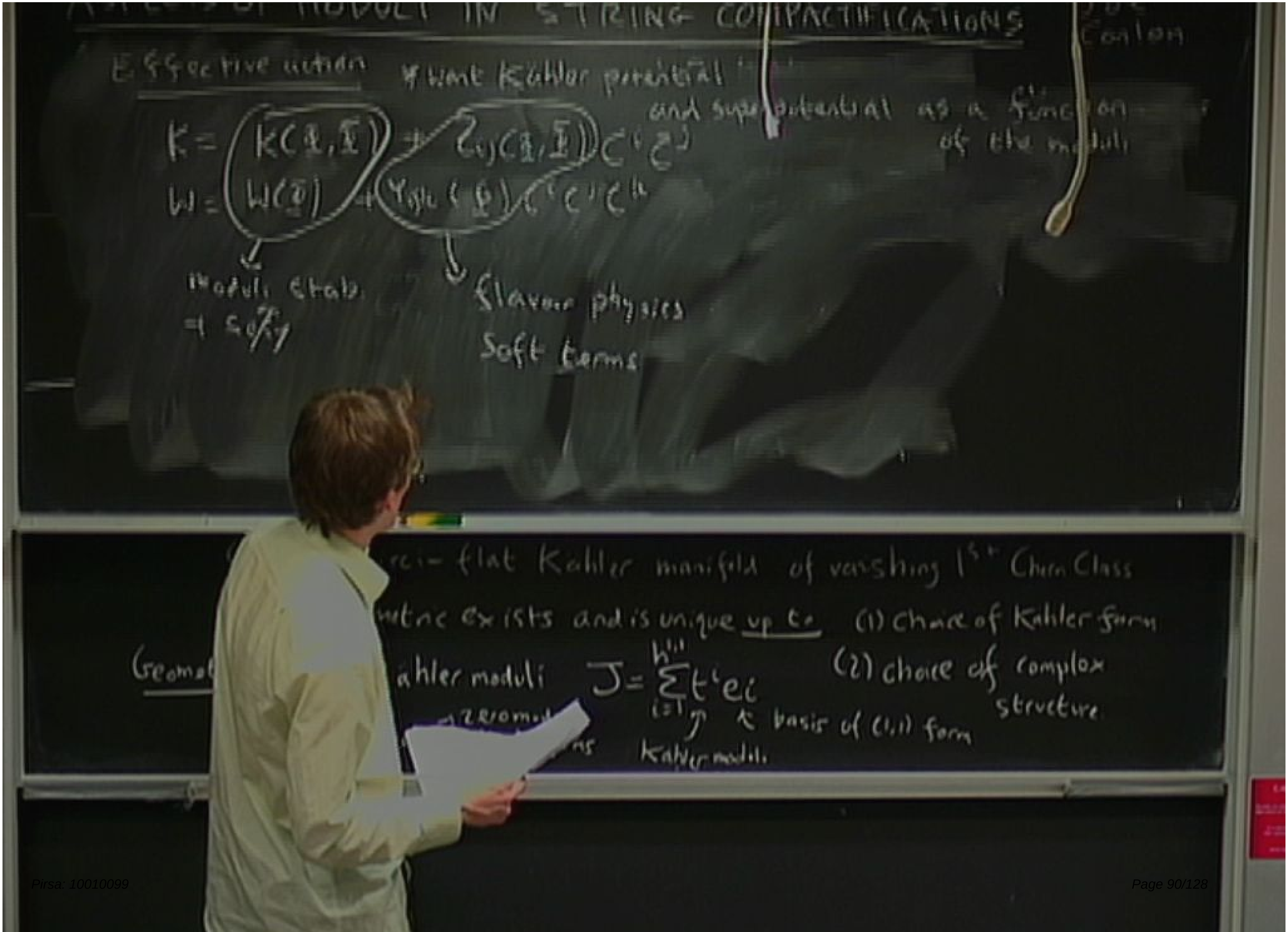
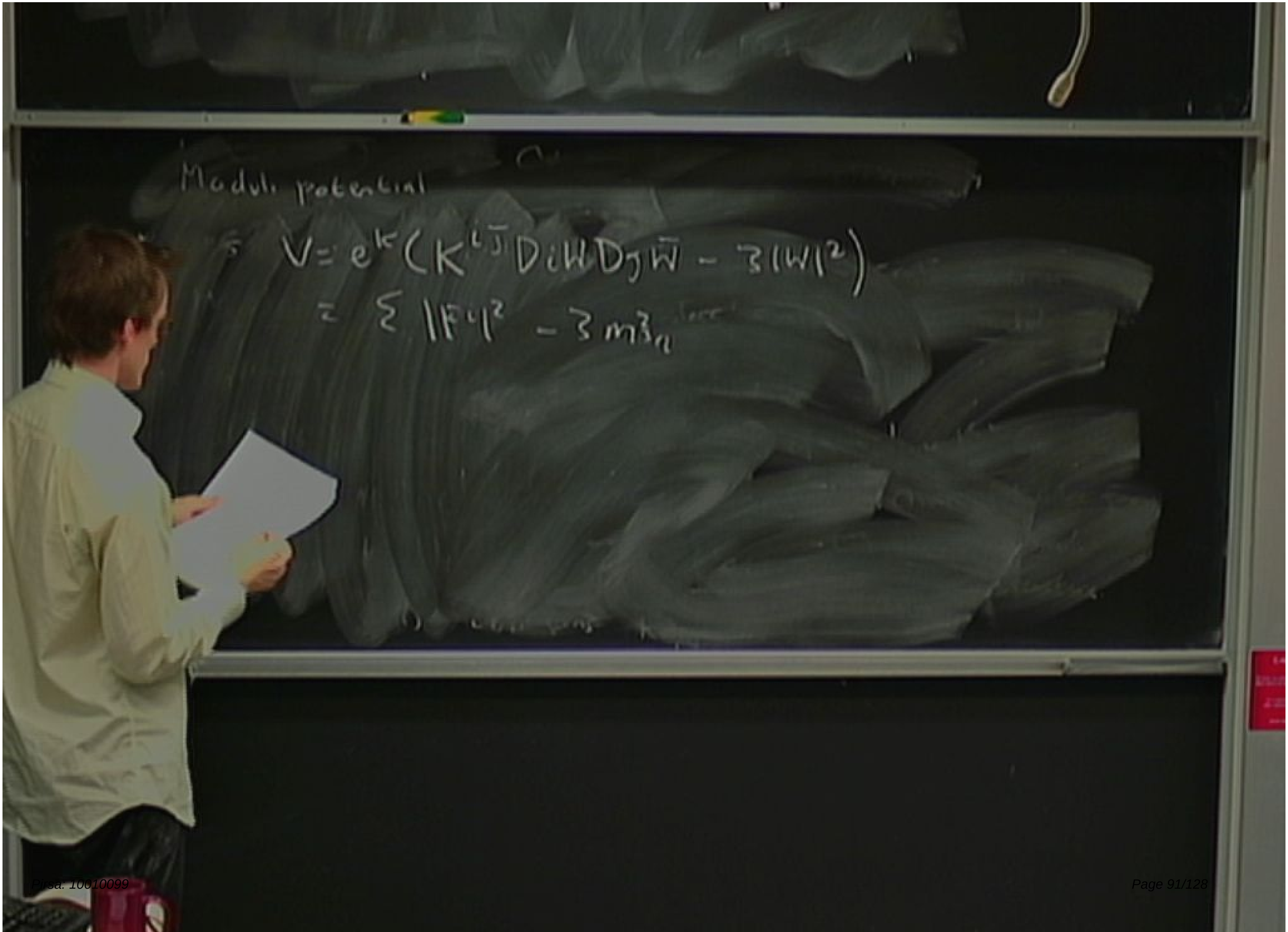
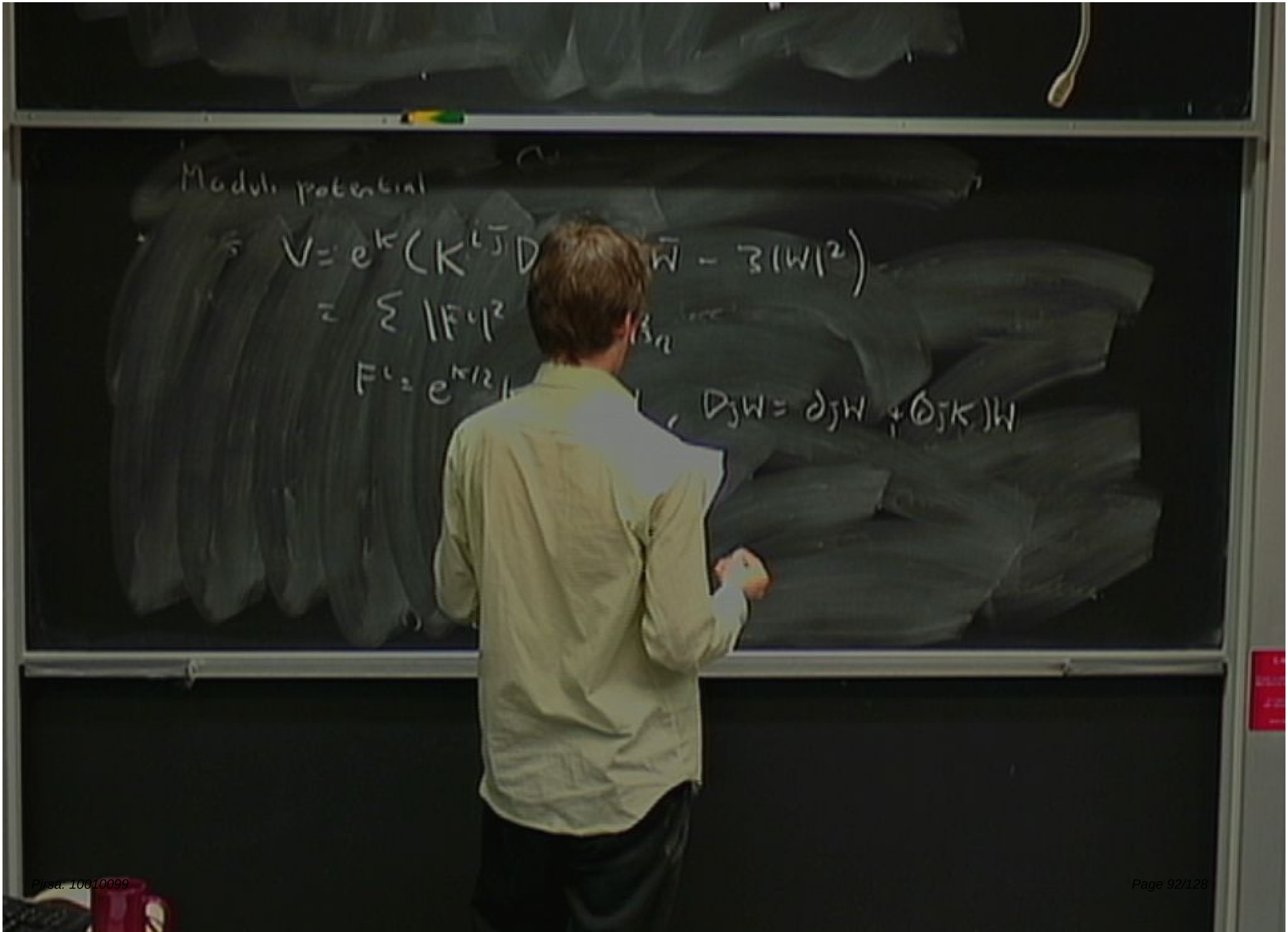
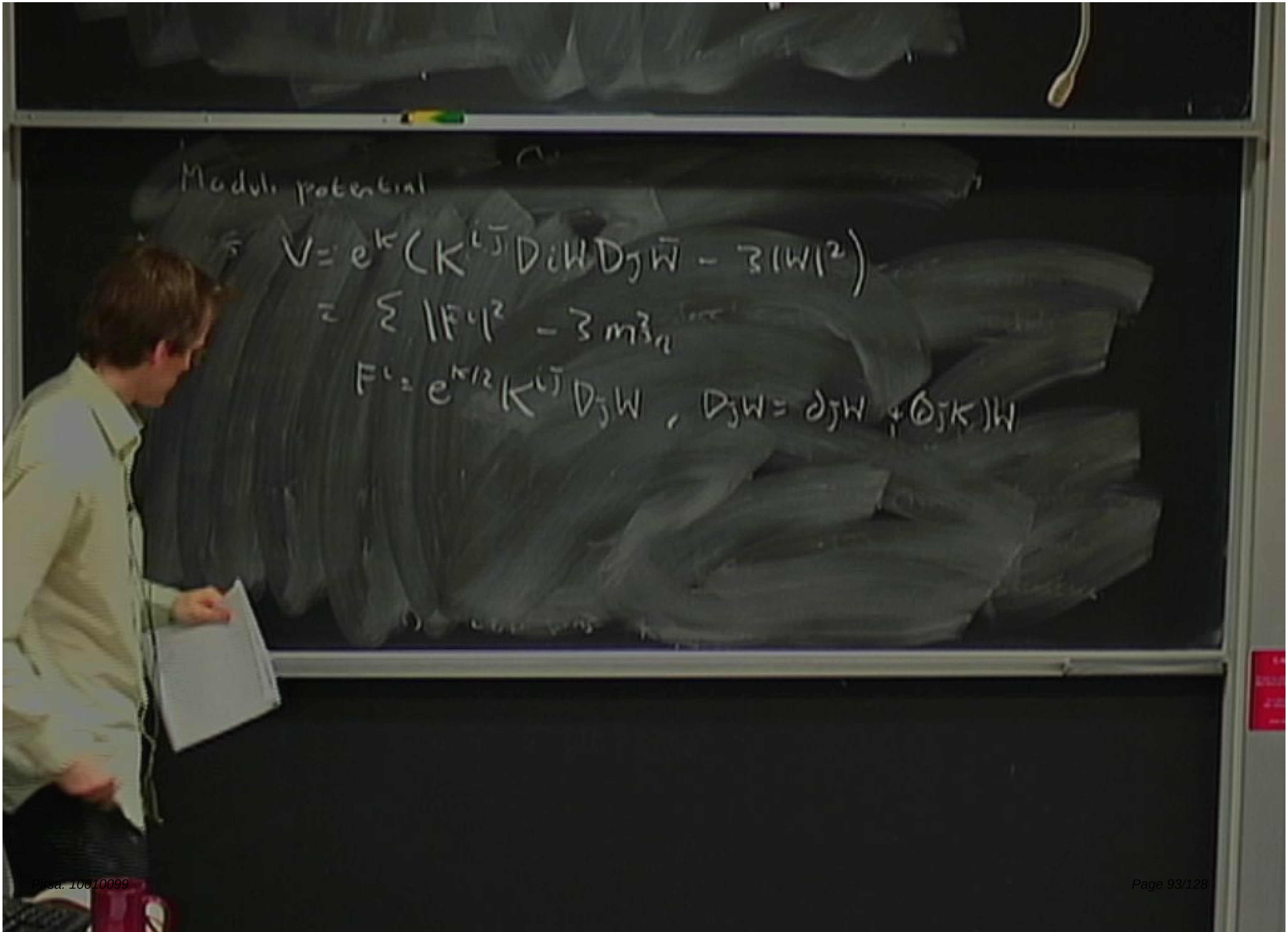
W = W(Φ) + Y_ijk(Φ) C^i C^j C^k
flavor physics
Soft terms
(1,1) forms
Kähler moduli
a basis of (1,1) form


STRING COMPACTIFICATIONS
Effective action
want Kähler potential and superpotential as a function of the moduli
K = K(Φ, Φ̄) + Z_ij(Φ, Φ̄) C^i C̄^j
W = W(Φ) + Y_ijk(Φ) C^i C^j C^k
moduli stab.
+ SUSY
flavour physics
Soft terms
Ricci-flat Kähler manifold of vanishing 1st Chern Class
metric exists and is unique up to (1) Choice of Kähler form
(2) choice of complex structure
Kähler moduli
J = Σ_{i=1}^{h^{1,1}} t^i e_i
basis of (1,1) form
Kähler moduli


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


Moduli potential
$D_j W = \partial_j W + (\partial_j K) W$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moduli stab.
+ susy

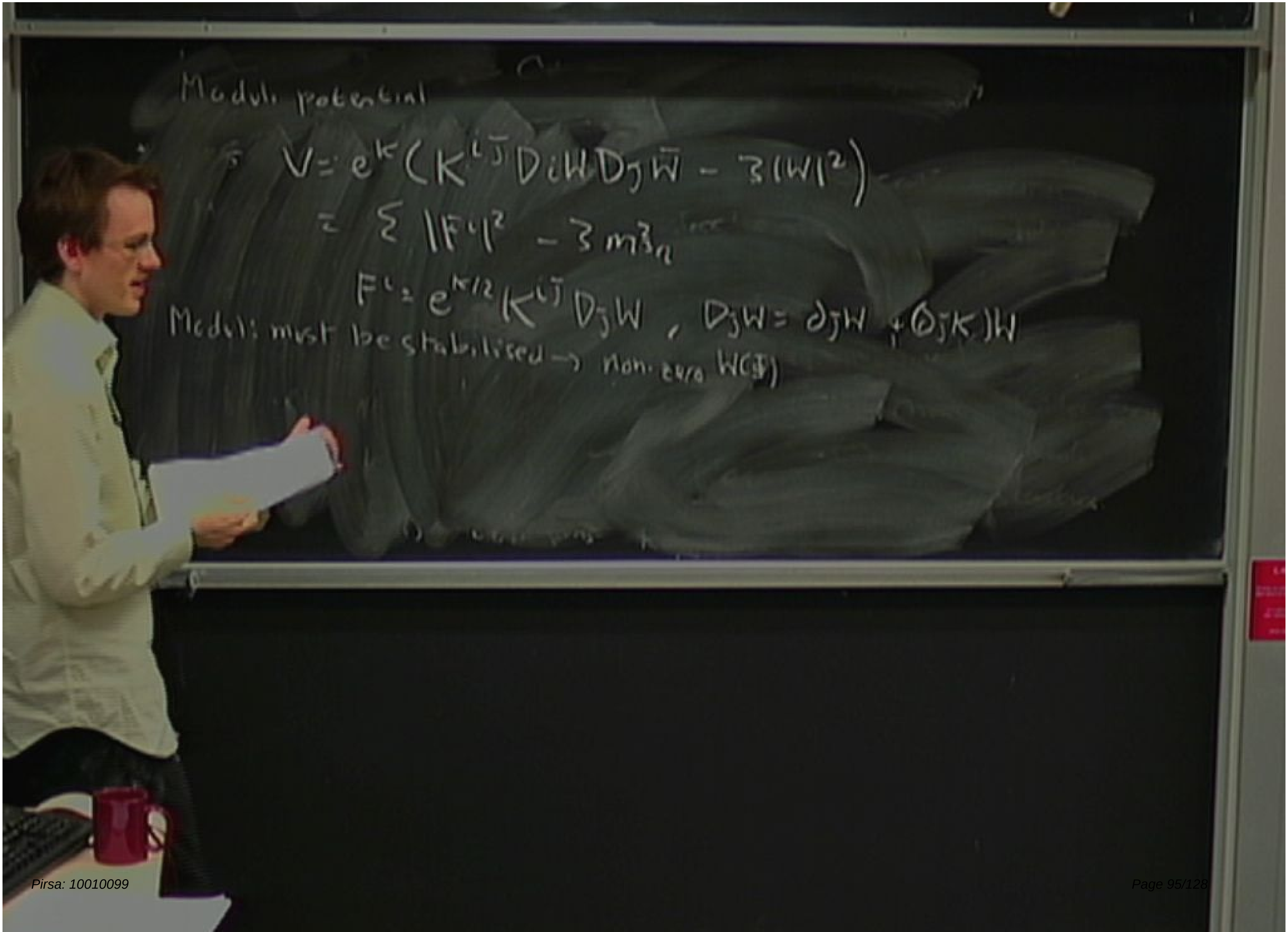
flavor physics
Soft terms

Moduli potential

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

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

$$F^i = e^{K/2} K^{i\bar{j}} D_{\bar{j}} W \ , \quad D_j W = \partial_j W + (\partial_j K) W$$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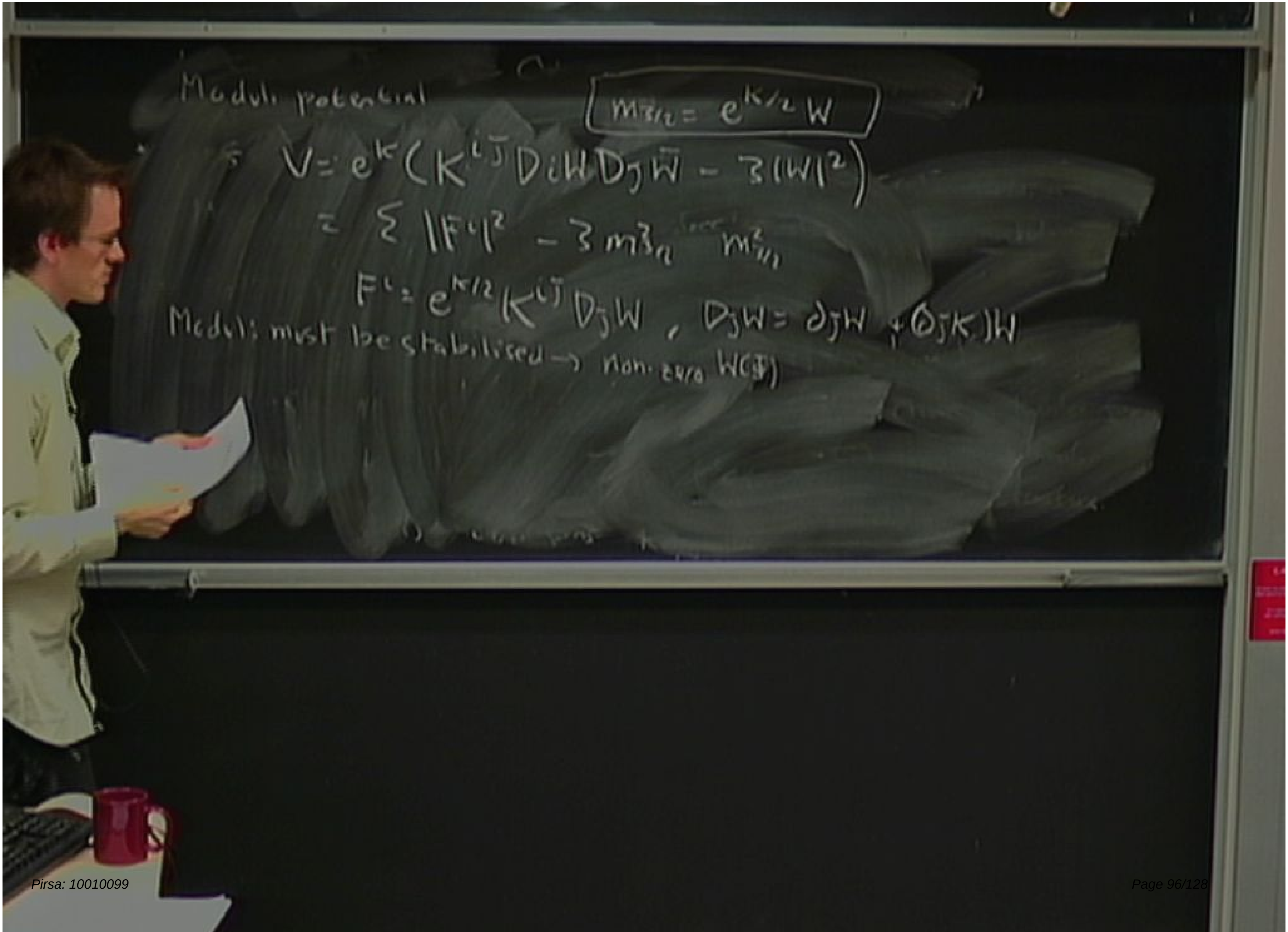
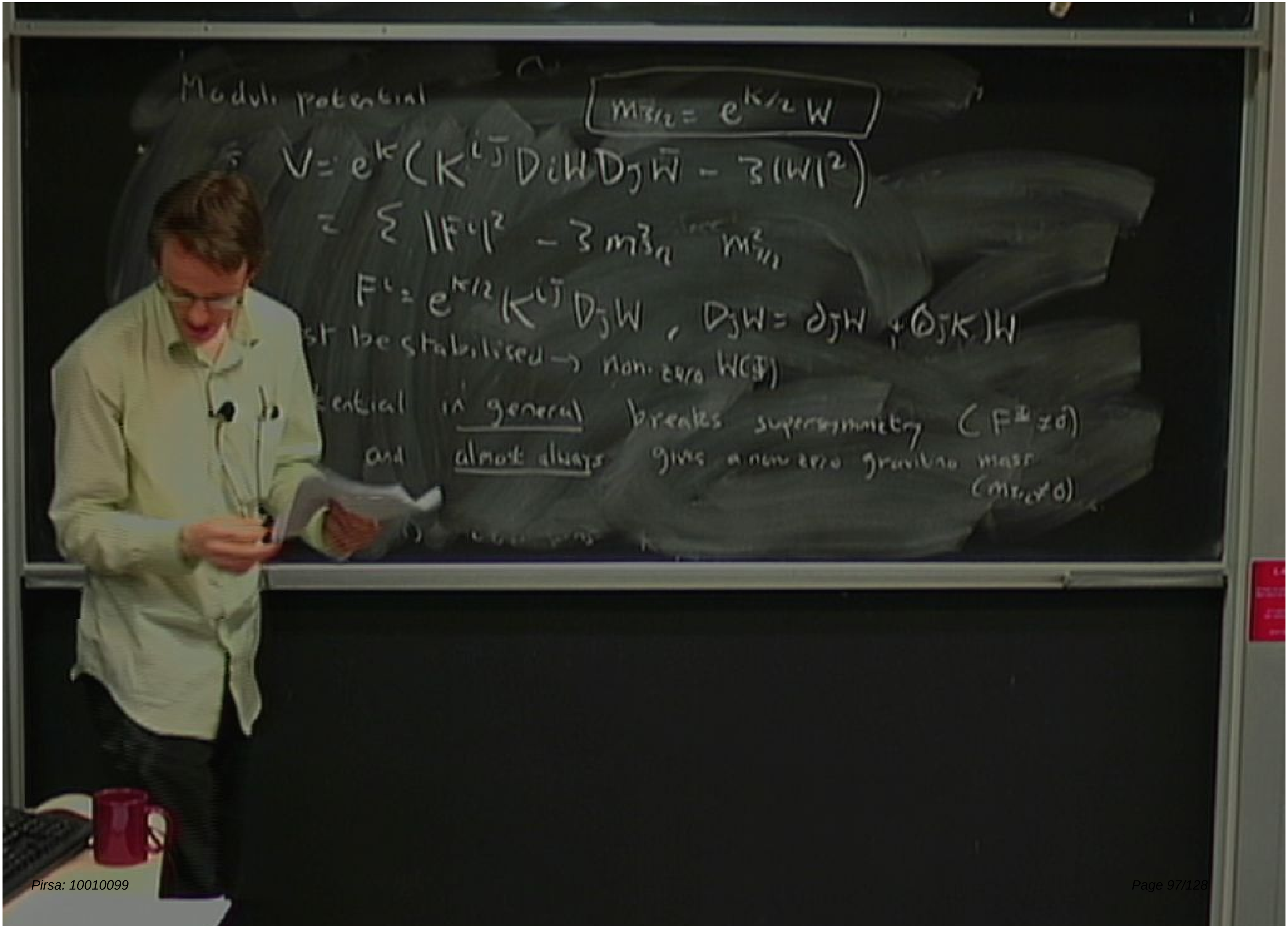
Moduli must be stabilised → non-zero $W(\Phi)$


Moduli potential
m3/2 = e^{K/2} W
V = e^K (K^{ij̄} D_i W D_j̄ W̄ − 3|W|²)
= Σ |F^i|² − 3 m²3/2
F^i = e^{K/2} K^{ij̄} D_j̄ W , D_j W = ∂_j W + (∂_j K) W
Moduli must be stabilised → non-zero W(Φ)


Moduli potential
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Moduli potential $\boxed{m_{3/2} = e^{K/2} W}$

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

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$$F^i = e^{K/2} K^{i\bar{j}} D_{\bar{j}} W \,, \quad D_j W = \partial_j W + (\partial_j K) W$$

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

Moduli potential in <u>general</u> breaks supersymmetry ($F^i \neq 0$)

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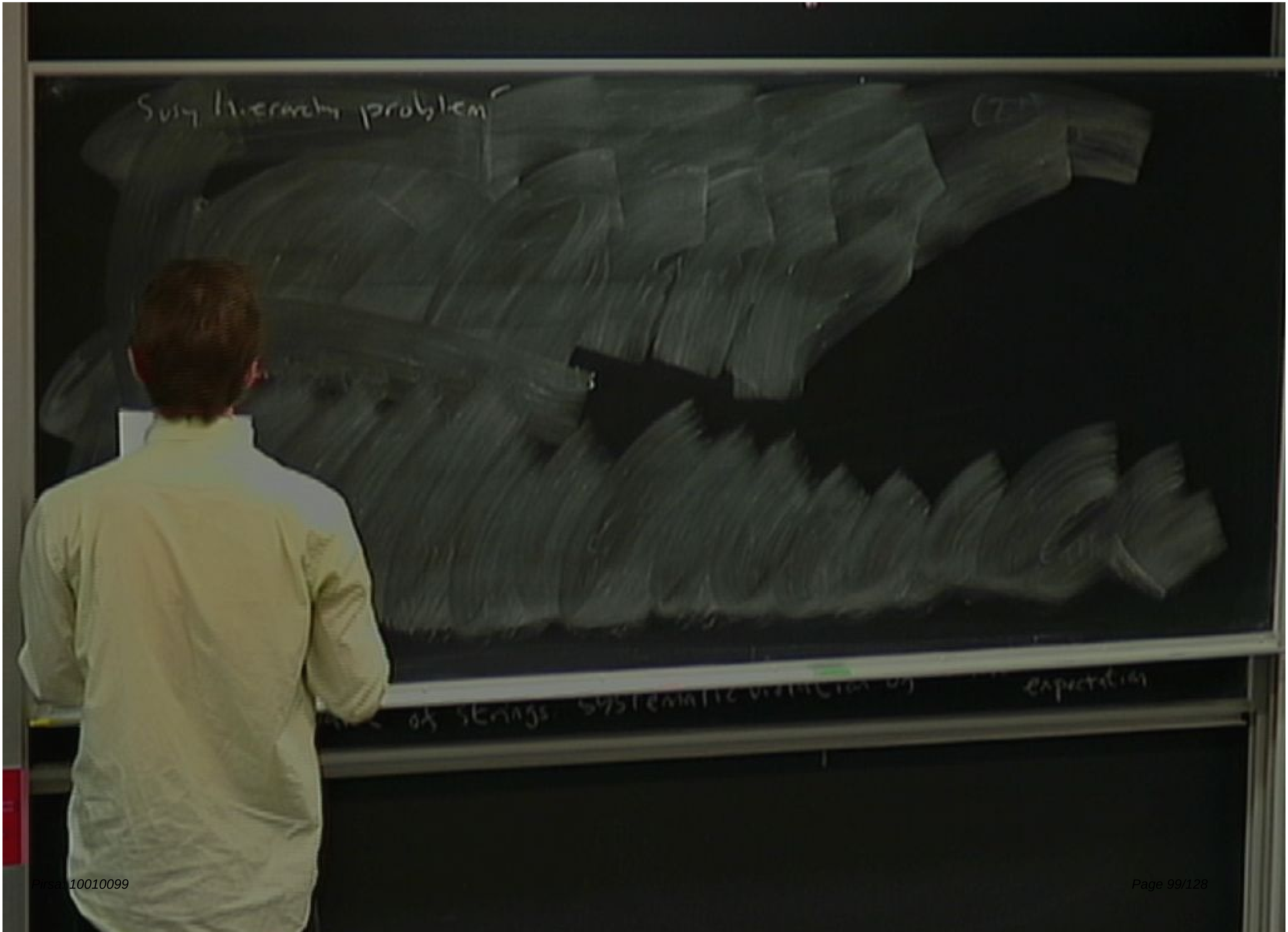
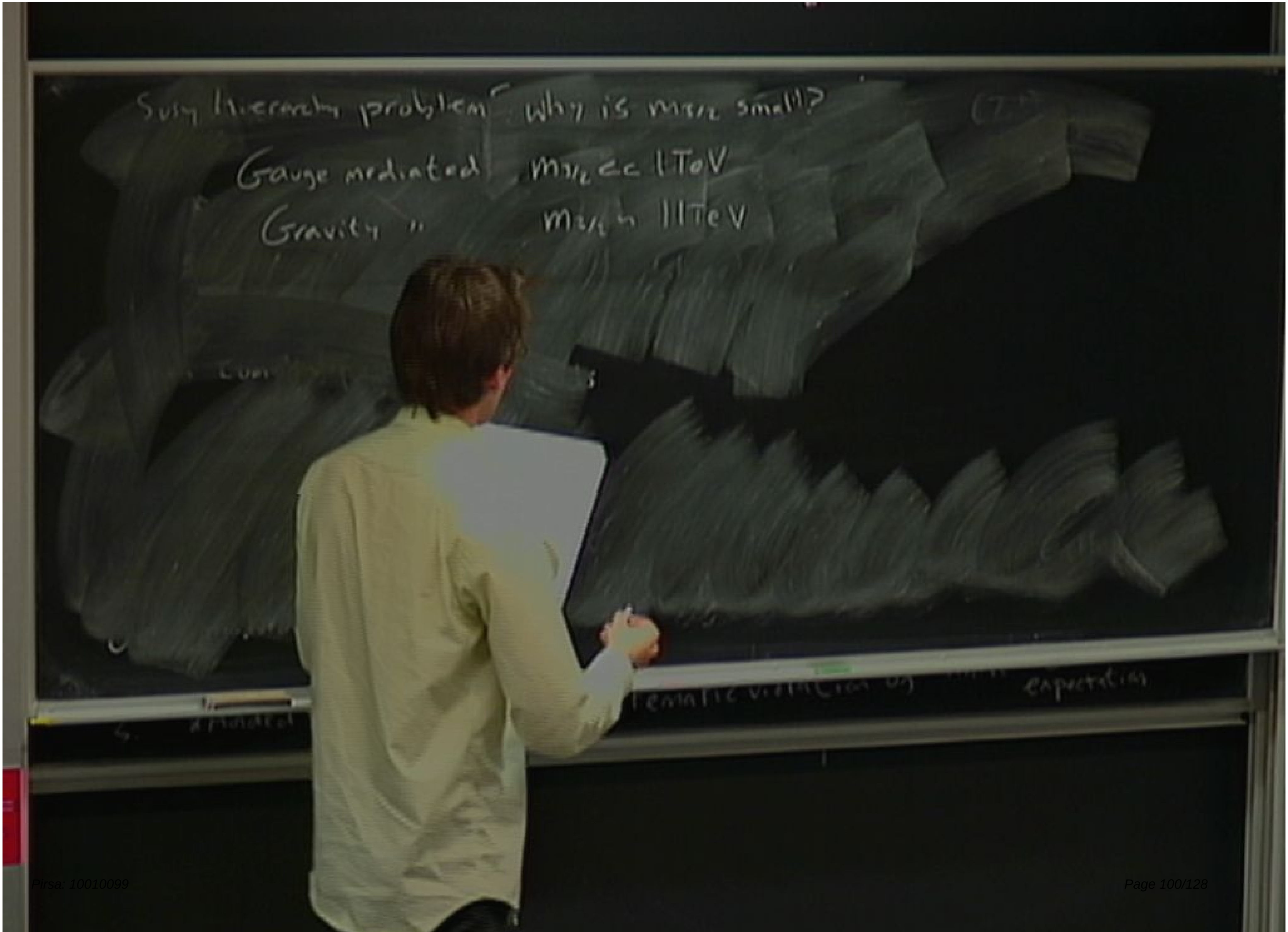

Susy hierarchy problem
of strings
systematic
expectation


Susy hierarchy problem: why is m3/2 small?
Gauge mediated m3/2 << 1TeV
Gravity " m3/2 ~ 1TeV

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

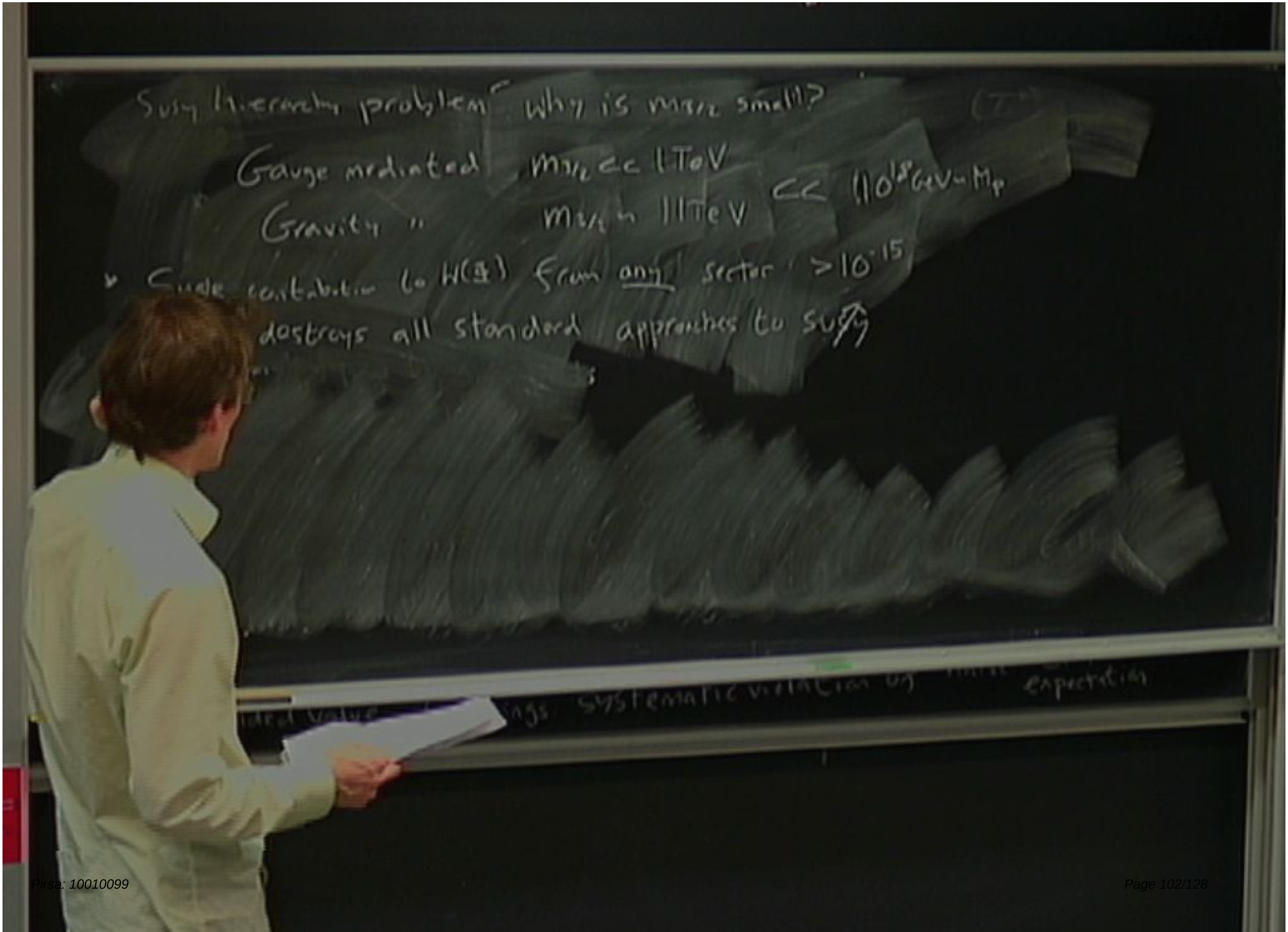
Gauge mediated $m_{3/2} << 1\,\mathrm{TeV}$

Gravity " $m_{3/2} \sim 1\,\mathrm{TeV} << 10^{18}\,\mathrm{GeV} \sim M_p$

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

expectation

5. added value of strings: systematic violation of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Susy hierarchy problem: why is $m_{3/2}$ small??

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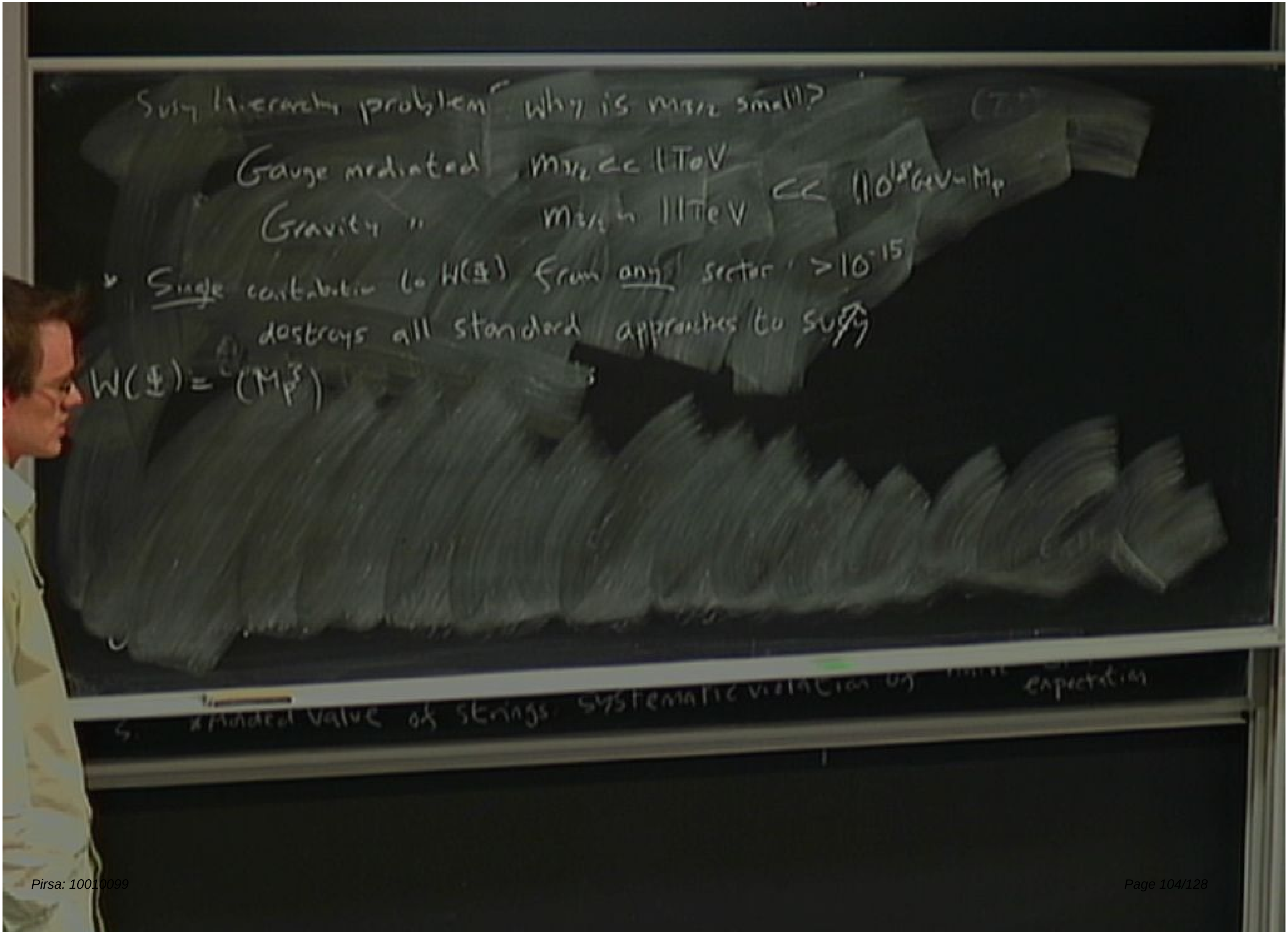
Susy hierarchy problem: Why is m3/2 small??
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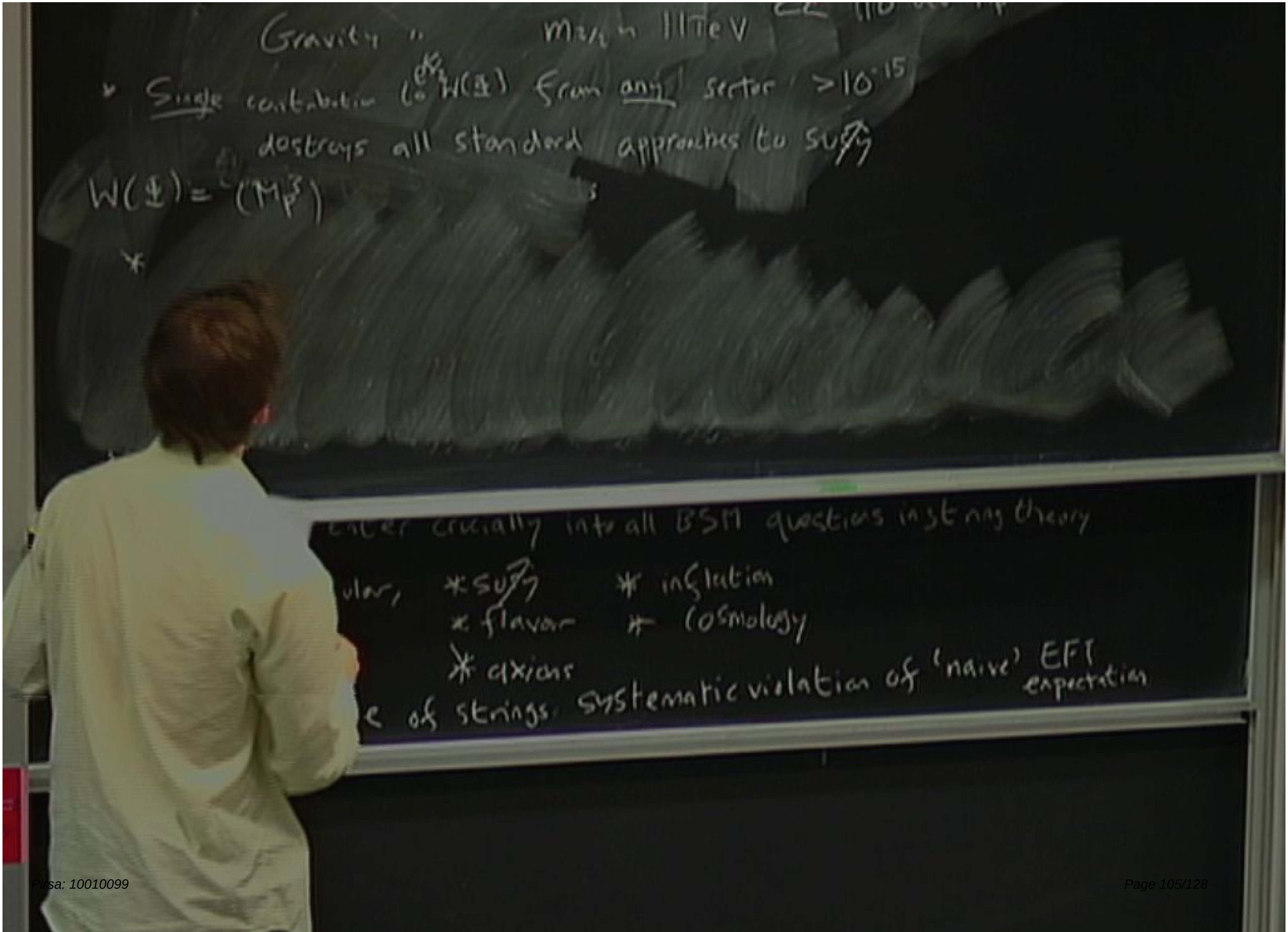
W(Φ) = (Mp^3)
expectation
standard value of strings systematic violation of


Gravity
Single contribution to W(Φ) from any sector >10^-15
destroys all standard approaches to susy
enter crucially into all BSM questions in string theory
* susy
* inflation
* flavor
* cosmology
* axions
of strings. systematic violation of 'naive' EFT expectation

Gravity " $m_{3/2} \sim$ 1 TeV

* Single contribution to $e^{K/2} W(\Phi)$ from any sector $> 10^{-15}$
  destroys all standard approaches to $\cancel{\text{susy}}$

$W(\Phi) = \mathcal{O}(M_P^3)$

* 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

duli enter crucially into all BSM questions in string theory

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* Single contribution to $e^{K/2} W(\Phi)$ from any sector $> 10^{-15}$
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$W(\Phi) = (M_p^3)$

* 2 Basic ways to address the susy hierarchy

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

(a) Make $e^{K/2}$ small $\longrightarrow$ lower all scales in the problem $M_s \ll M_p$

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

Moduli enter crucially into all BSM questions in string theory

In particular, * susy * inflation
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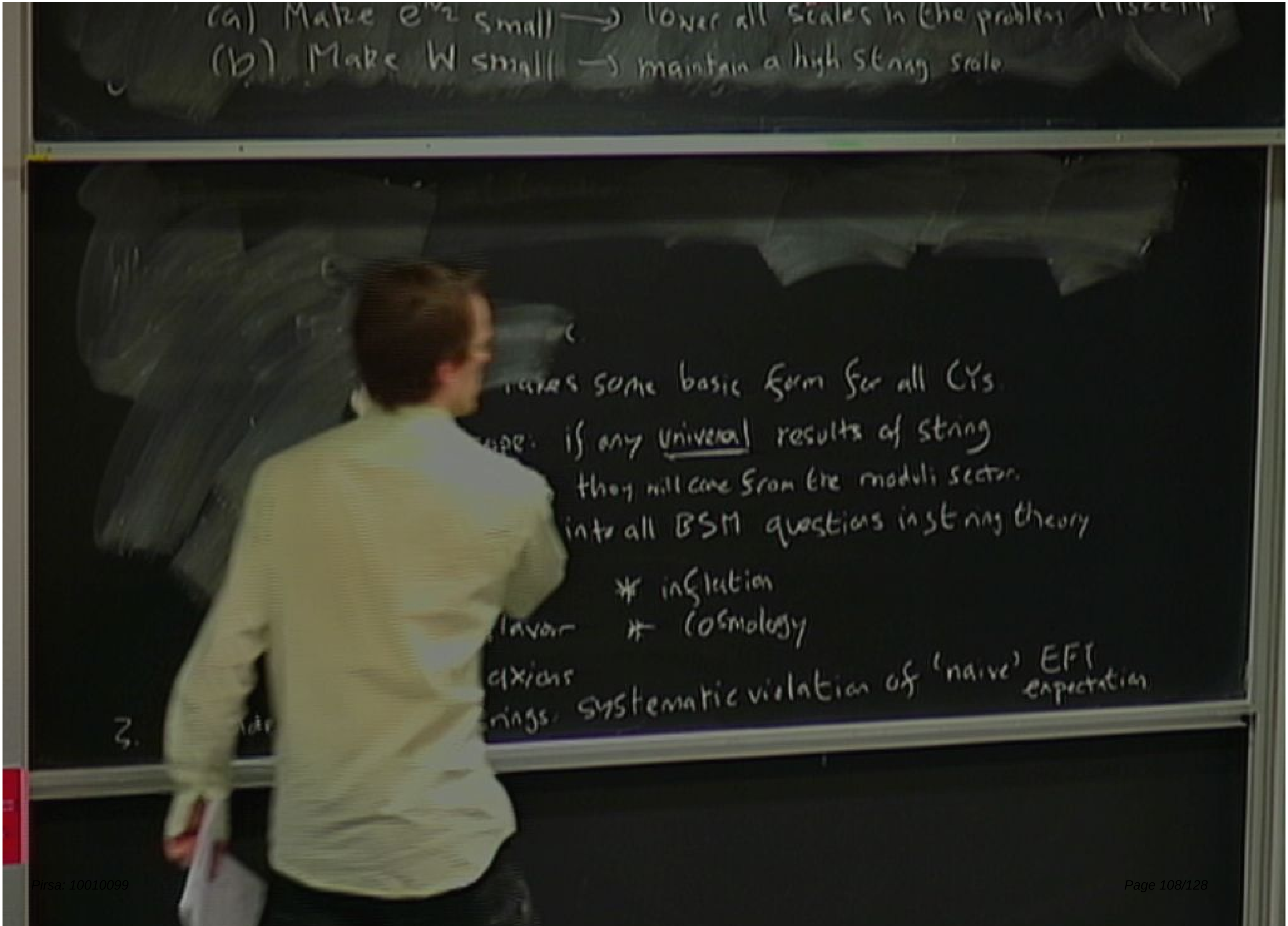
...d value of strings: systematic violation of 'naive' EFT expectation


(a) Make $e^{K/2}$ small → lower all scales in the problem
(b) Make W small → maintain a high string scale
takes same 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
axions
systematic violation of 'naive' EFT expectation

(a) Make $e^{\phi/2}$ small $\longrightarrow$ lower all scales in the problem

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

Models of moduli Stabilisation

* Flux compactification

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Models of moduli stabilisation

* Flux compactification

$$K = -2\ln \mathcal{V}(T+\bar{T}) - \ln\left(\int \Omega\wedge\bar{\Omega}\right) - \ln(S+\bar{S})$$

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$$K = -2\ln \mathcal{V}(T+\bar{T}) - \ln\left(\int \Omega \wedge \bar{\Omega}\right) - \ln(S+\bar{S})$$

$$W = \int G_3 \wedge \Omega \quad (S, U)$$

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Models of moduli stabilisation

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* $e^{-ax} \sim 1 + \frac{1}{\mathcal{V}^{2/3}}$

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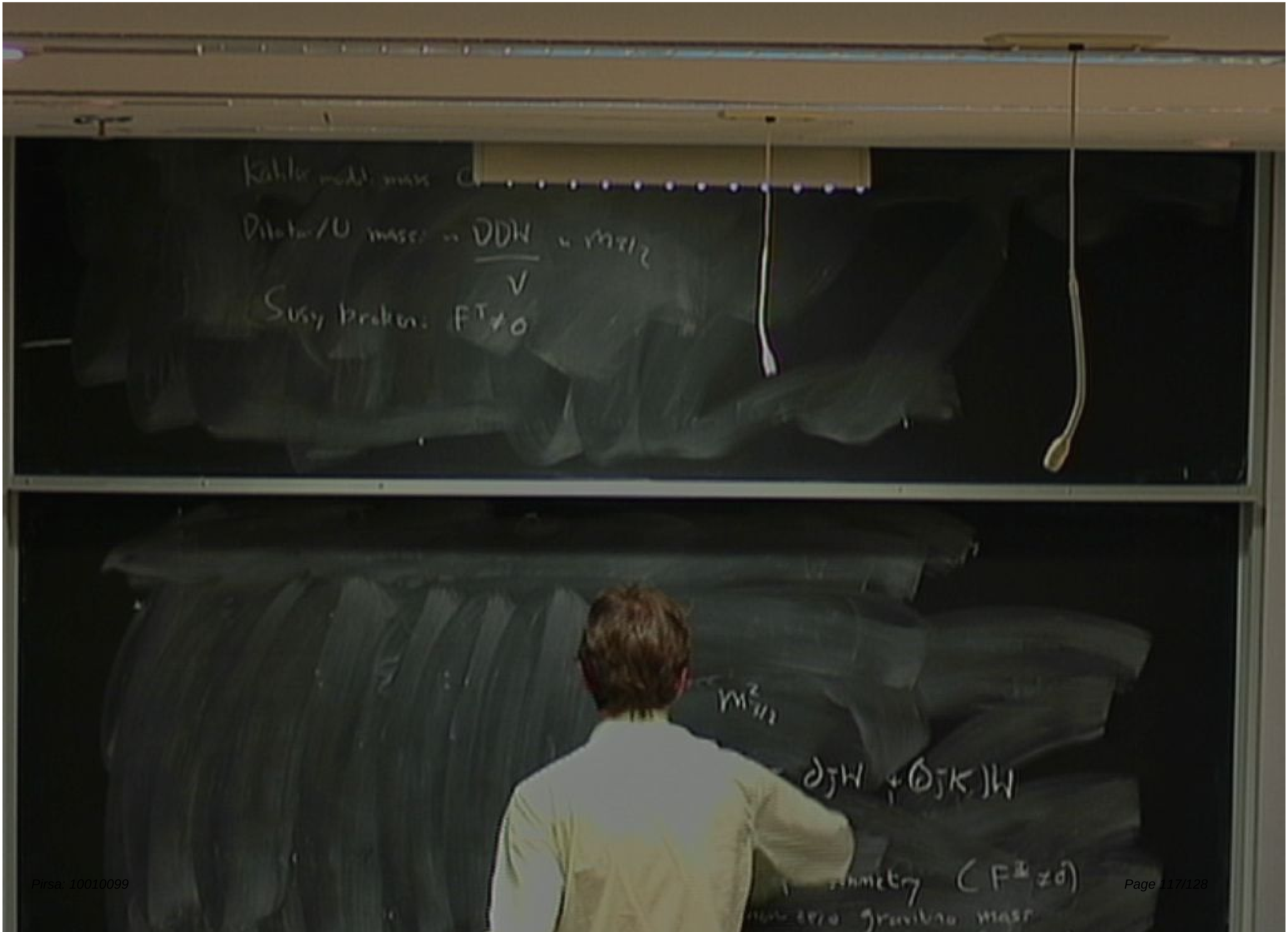
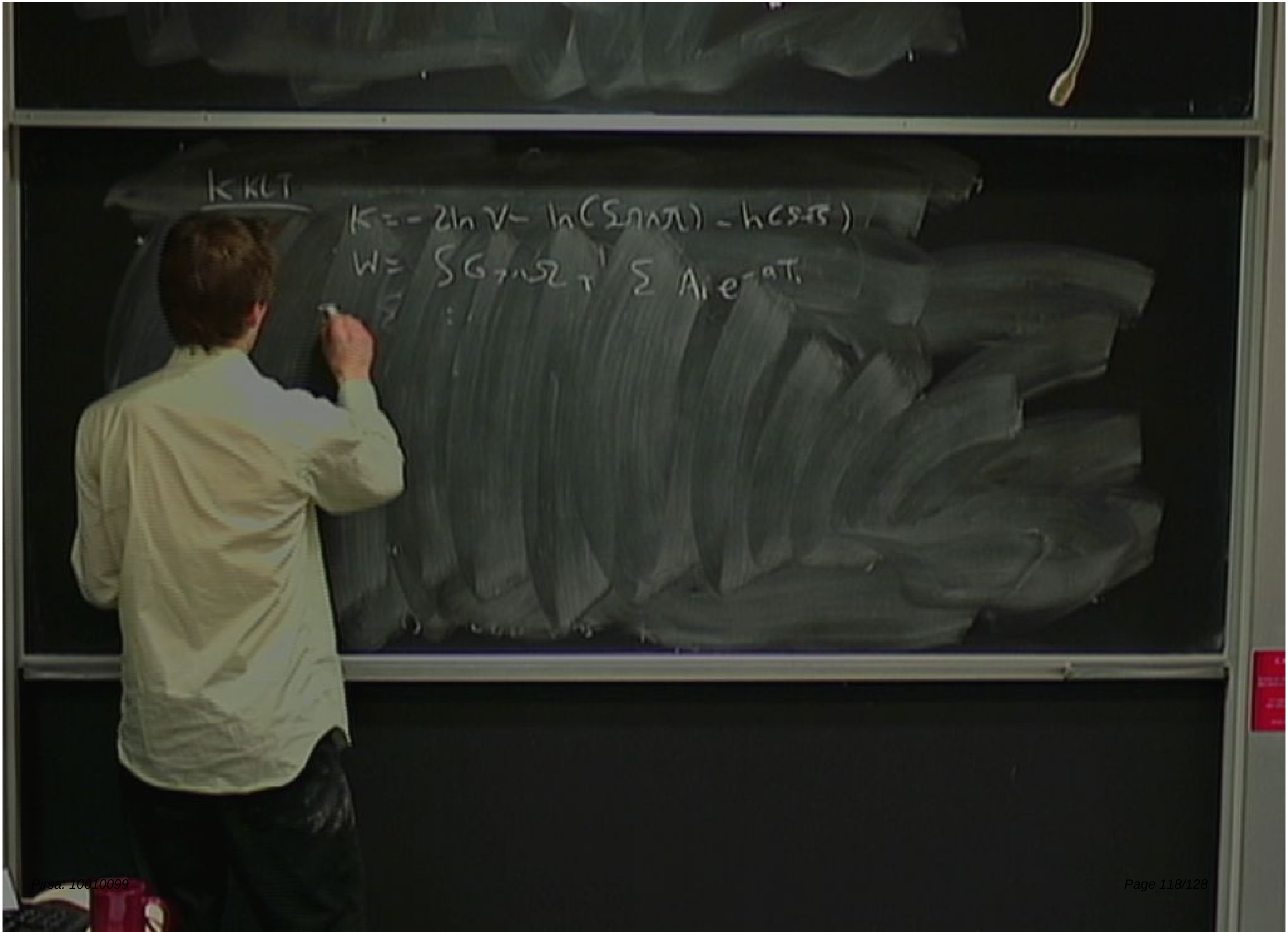
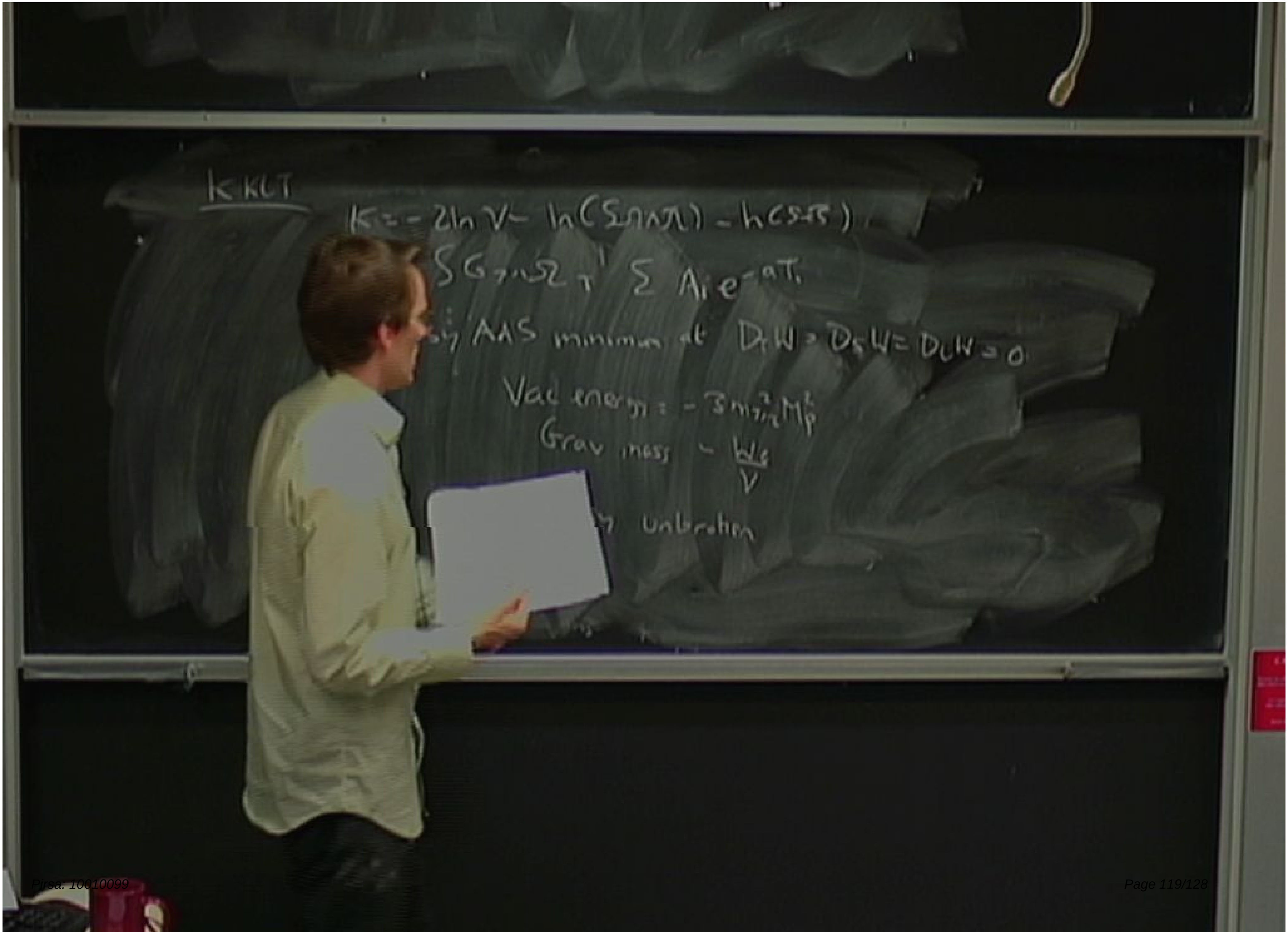
$$* \quad e^{-aT} \sim 1 + \frac{1}{\mathcal{V}^{2/3}}$$

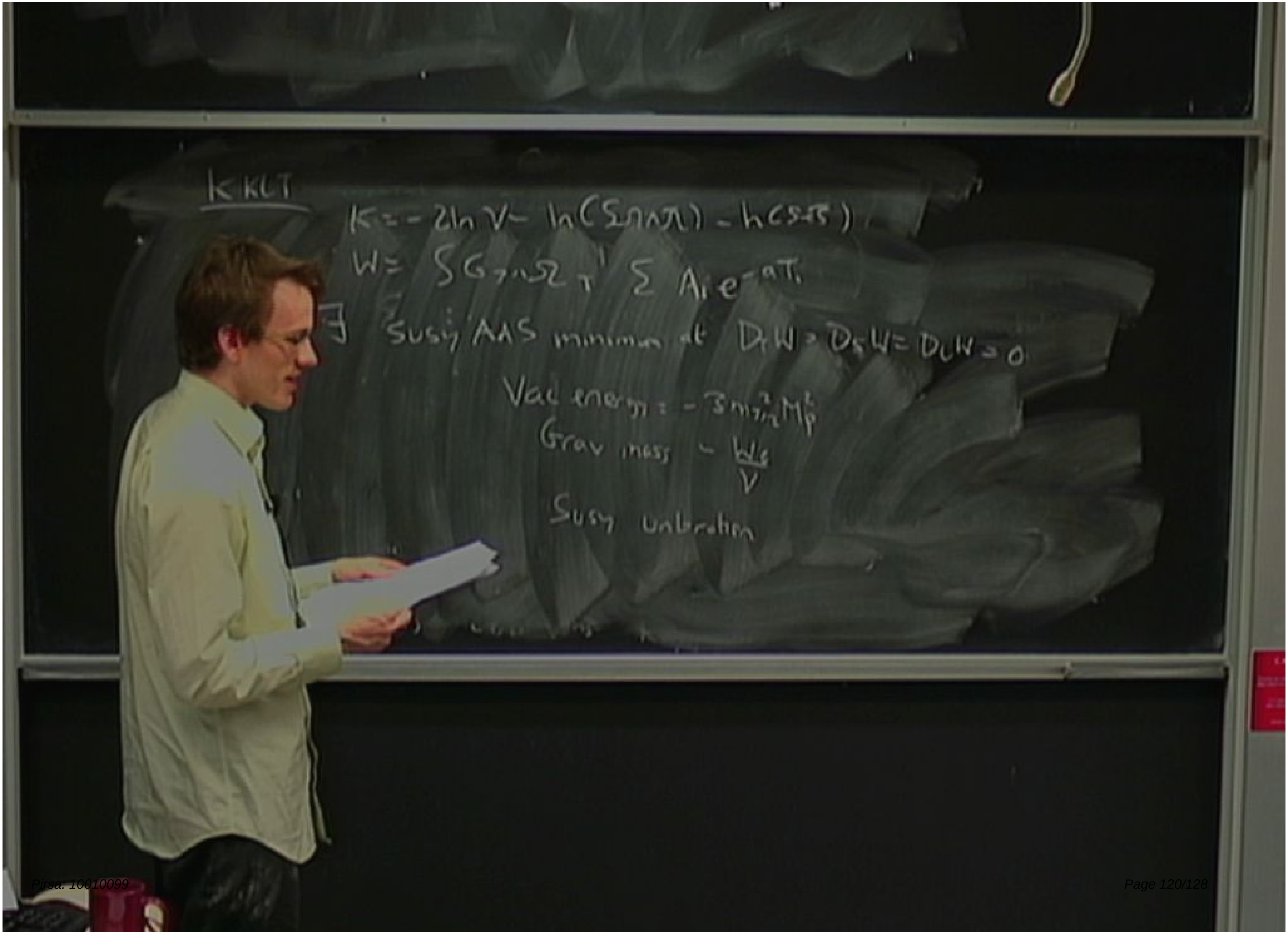
$$V = e^K \sum_{T,S,U} K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3 m_{3/2}^2$$

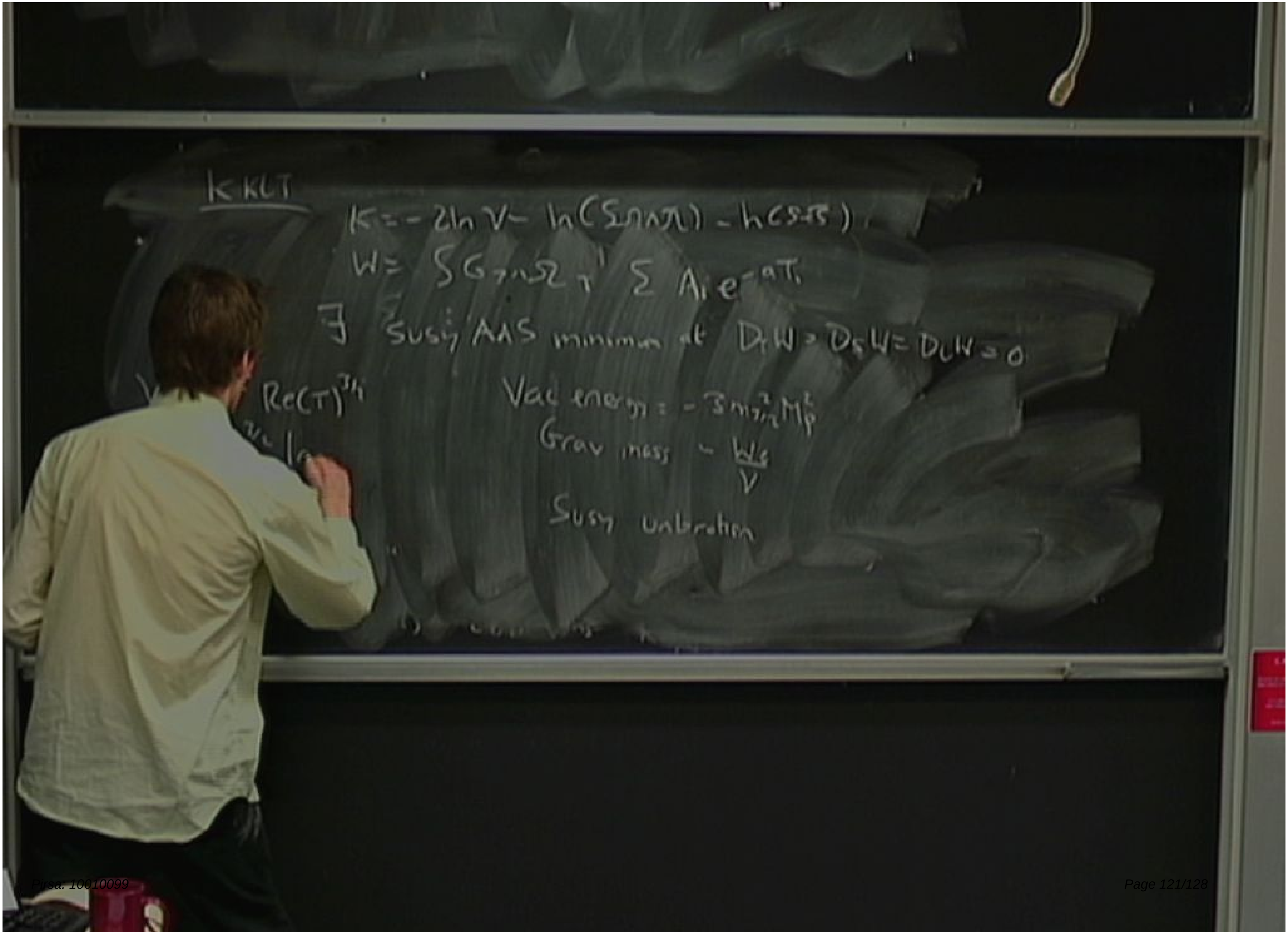
$$= \sum_{U,S} K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} \longrightarrow \text{minimum at } D_U W = D_S W = 0$$


Dilaton/U mass: ~ DDW/V ~ m3/2
Susy broken: F^T ≠ 0
m^2 3/2
∂jW + (∂jK)W
(F^i ≠ 0)
gravitino mass


KKLT
K = -2ln V - ln(∫Ω∧Ω̄) - ln(S+S̄)
W = ∫G∧Ω + Σ A_i e^{-aT_i}


KKLT
Vac energy = - 3 m3/2 Mp
Grav mass ~ W0 / V
unbroken


KKLT
Susy AdS minimum at
Vac energy
Grav mass
Susy unbroken


KKLT
K = -2ln V - ln(∫Ω∧Ω̄) - ln(S+S̄)
W = ∫G∧Ω + Σ Ai e^-aTi
∃ Susy AdS minimum at DTW = DSW = DUW = 0
Re(T)^3/2
Vac energy = -3 m3/2² Mp²
Grav mass ~ W0 / V
Susy unbroken

KKLT

$K = -2\ln \mathcal{V} - \ln\left(\int \Omega \wedge \bar{\Omega}\right) - \ln(S + \bar{S})$

$W = \int G_3 \wedge \Omega + \sum A_i e^{-aT_i}$

$\exists$ Susy AdS minimum at $D_T W = D_S W = D_U W = 0$

$\mathcal{V} \sim e^{\frac{3a}{2}\,} \mathrm{Re}(T)^{3/2}$

$R^6 = g_s^{3/2} \ln W_0$

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

Grav mass $\sim \frac{W_0}{\mathcal{V}}$

Susy unbroken

KKLT

$$K = -2\ln \mathcal{V} - \ln\left(\int \Omega\wedge\bar{\Omega}\right) - \ln(S+\bar{S})$$

$$W = \int G_3 \wedge \Omega + \sum A_i e^{-aT_i}$$

$\exists$ SUSY AdS minimum at $D_T W = D_S W = D_U W = 0$

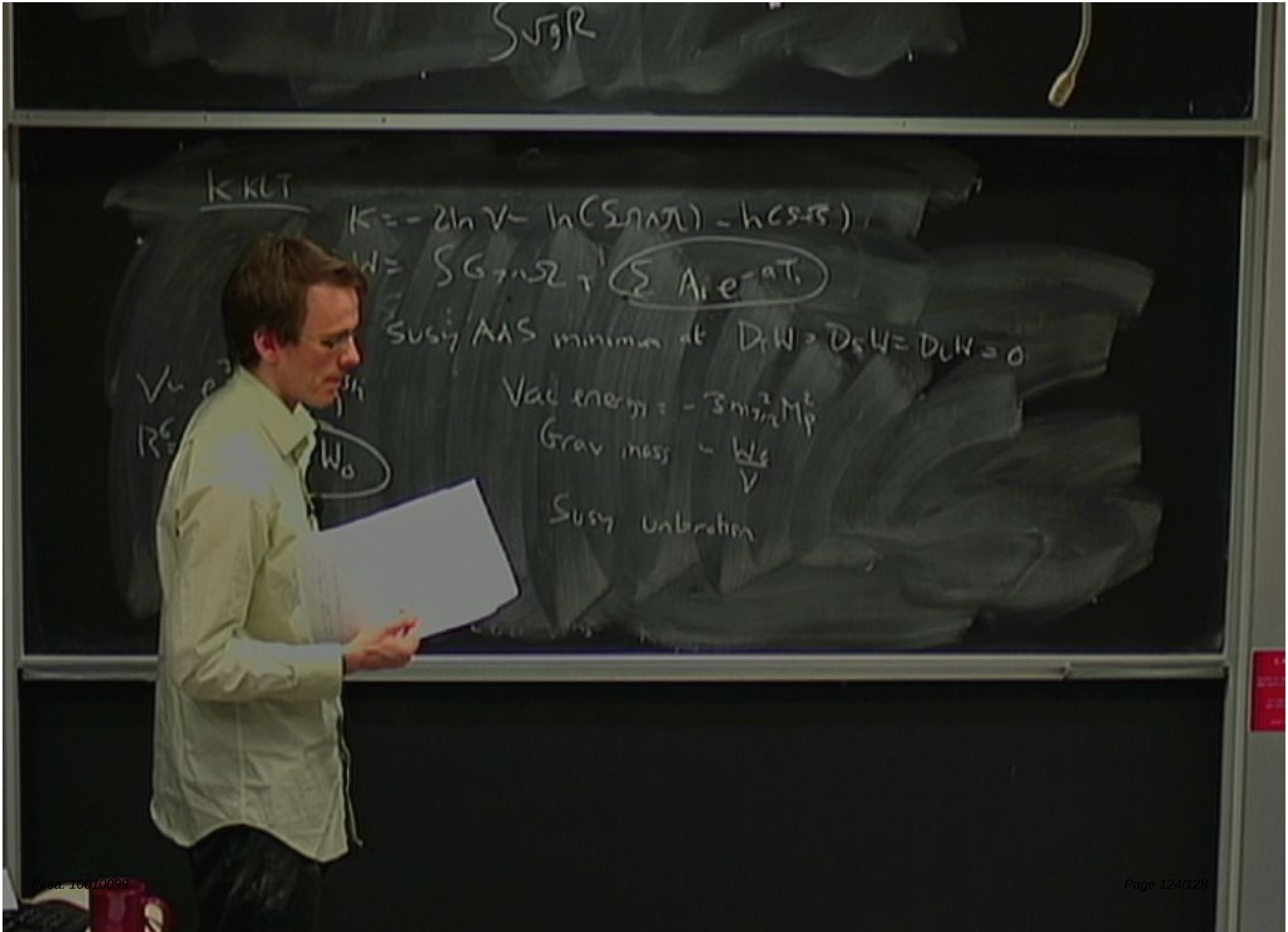
$$\mathcal{V} \sim e^{3\phi/2}\, \mathrm{Re}(T)^{3/2}$$

$$R^6 = g_s^{3/2} \ln W_0$$

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

Grav mass $\sim \frac{W_0}{\mathcal{V}}$

Susy unbroken


KKLT
Susy AdS minimum at $D_T W = D_S W = D_U W = 0$
Vac energy $= -3 m_{3/2}^2 M_p^2$
Grav mass
Susy unbroken

$\int \sqrt{g} R$

KKLT

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

$W = \int G_3 \wedge \Omega + \sum A_i e^{-aT_i}$

$\exists$ SUSY AdS minimum at $D_T W = D_S W = D_U W = 0$

$V \sim e^{\frac{3\phi}{2}} \mathrm{Re}(T)^{3/2}$

$R^6 = g_s^{3/2} \ln W_0$

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

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

Susy unbroken

* ... compactification

$$K = -2\ln \mathcal{V}(T+\bar{T}) - \ln\left(S\,\Omega\wedge\bar{\Omega}\right) - \ln(S+\bar{S}) \quad \text{(factorises)}$$

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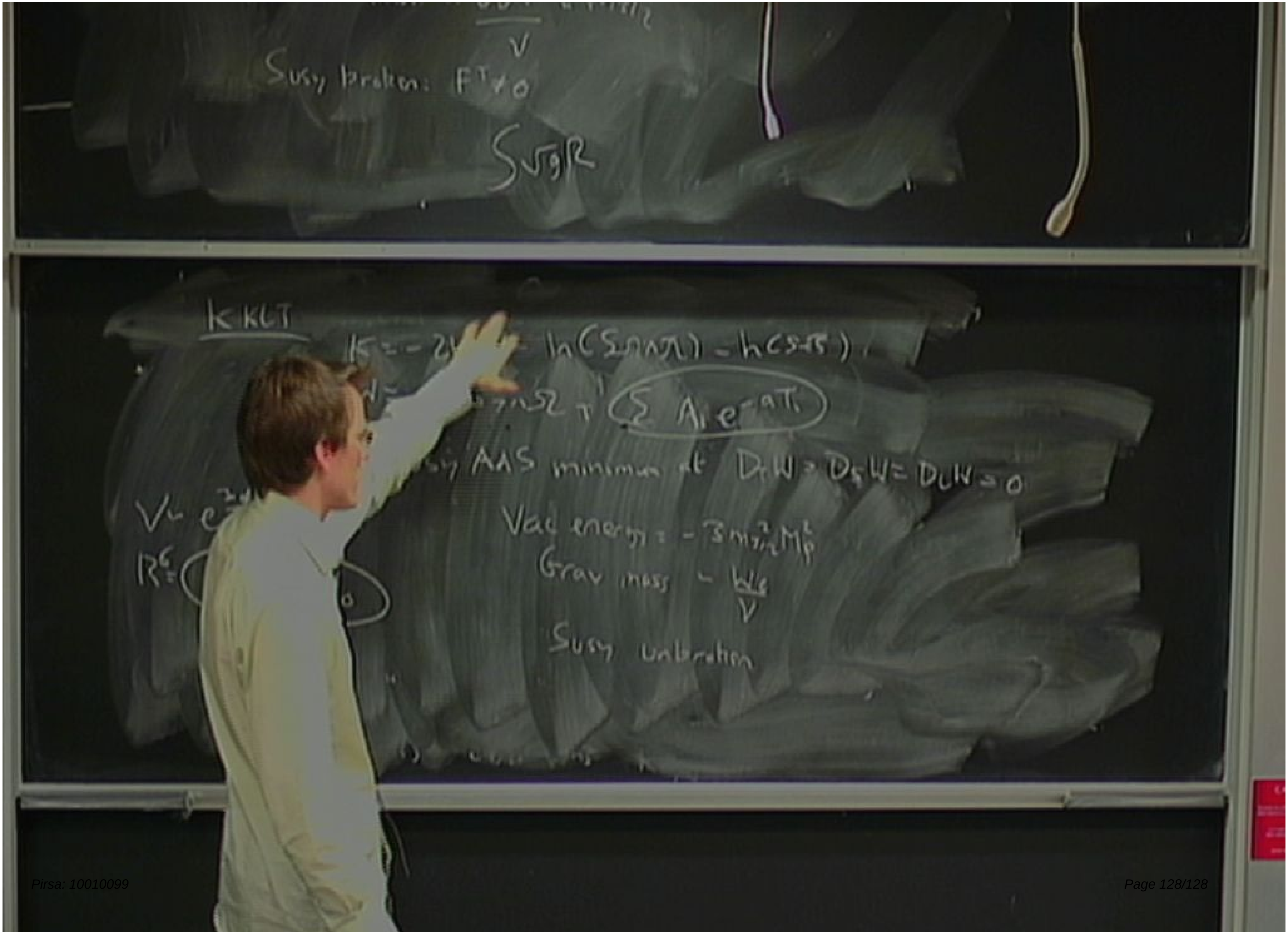

Susy broken: F^T ≠ 0
∫√g R
KKLT
Σ A_i e^{-aT_i}
AdS minimum at D_T W = D_S W = D_U W = 0
Vac energy = -3 m_{3/2}^2 M_p^2
Grav mass ~ W_0 / V
Susy unbroken