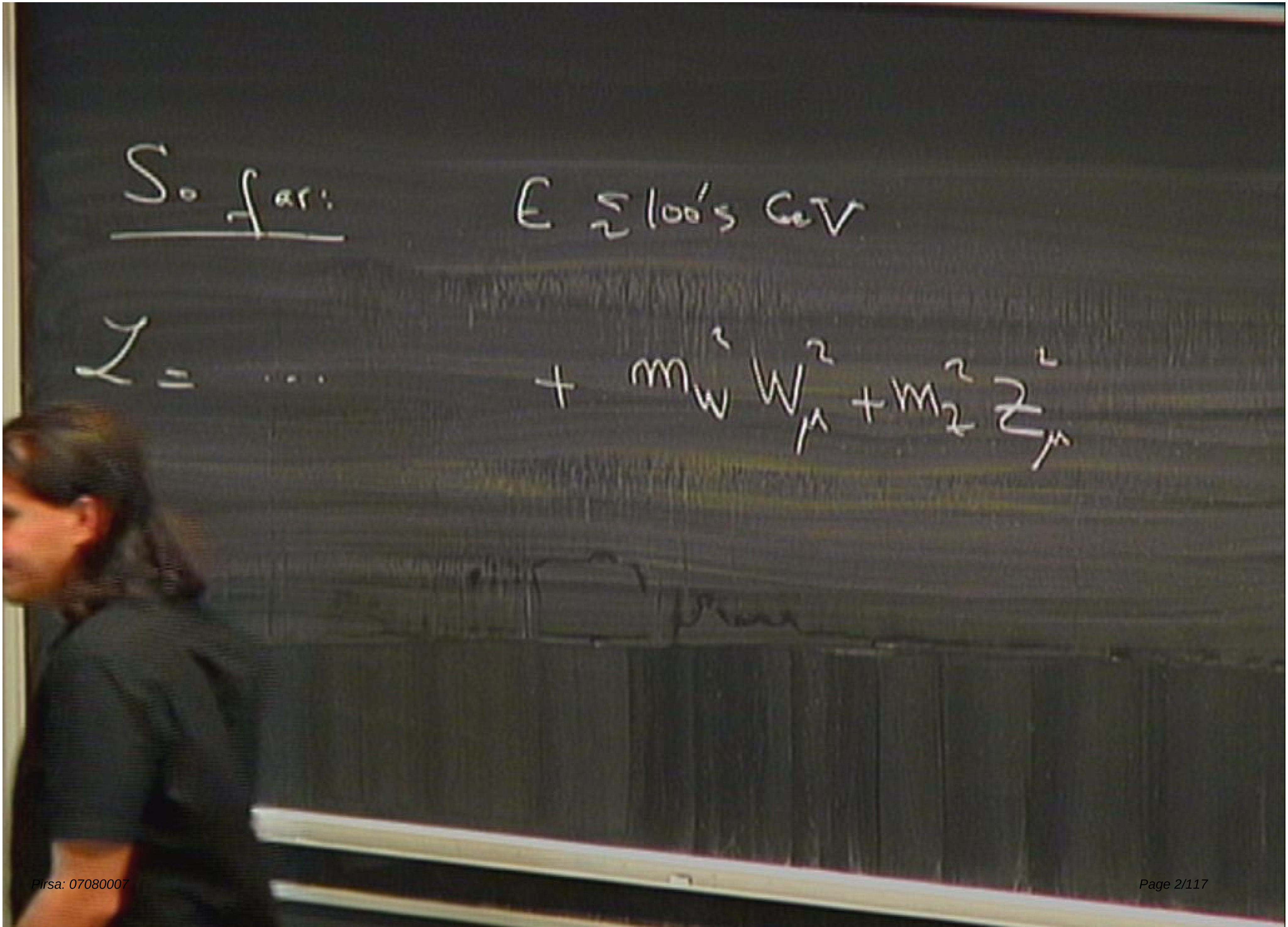
Title: Introduction to Low Energy Supersymmetry

Date: Aug 08, 2007 09:00 AM

URL: http://pirsa.org/07080007

Abstract:


So far:
$E \lesssim 100\text{'s GeV}$
$\mathcal{L} = \ldots + m_W^2 W_\mu^2 + m_Z^2 Z_\mu^2$

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$$\mathcal{L} = \cdots + m_W^2 W_\mu^2 + m_Z^2 Z_\mu^2$$

Global SU(2) symmetry W_μ^a.

$$\mathcal{L} = -\frac{1}{4} \mathrm{tr}\, F_{\mu\nu}^2 + m^2 W_\mu^a W^{\mu a}.$$

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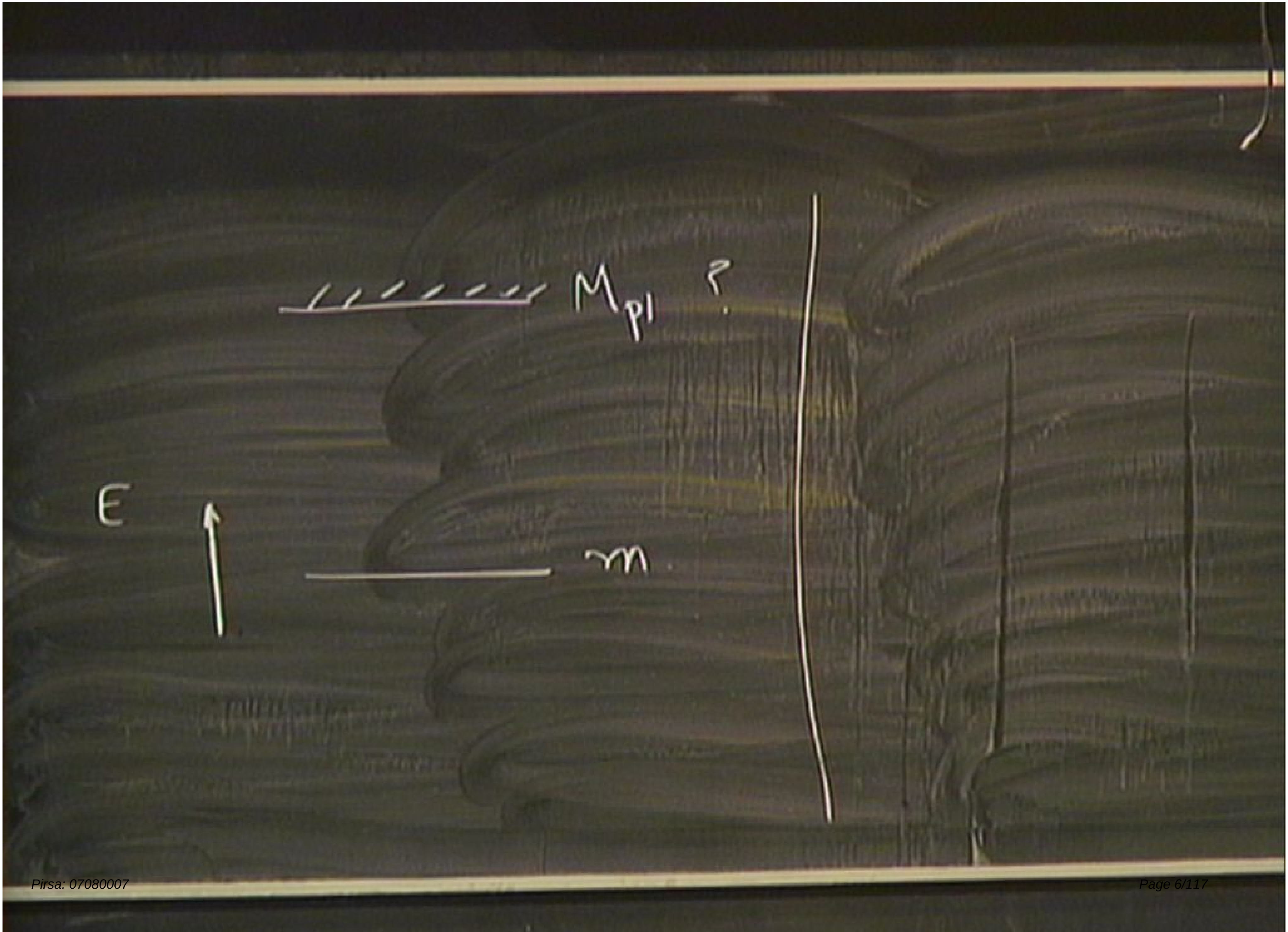
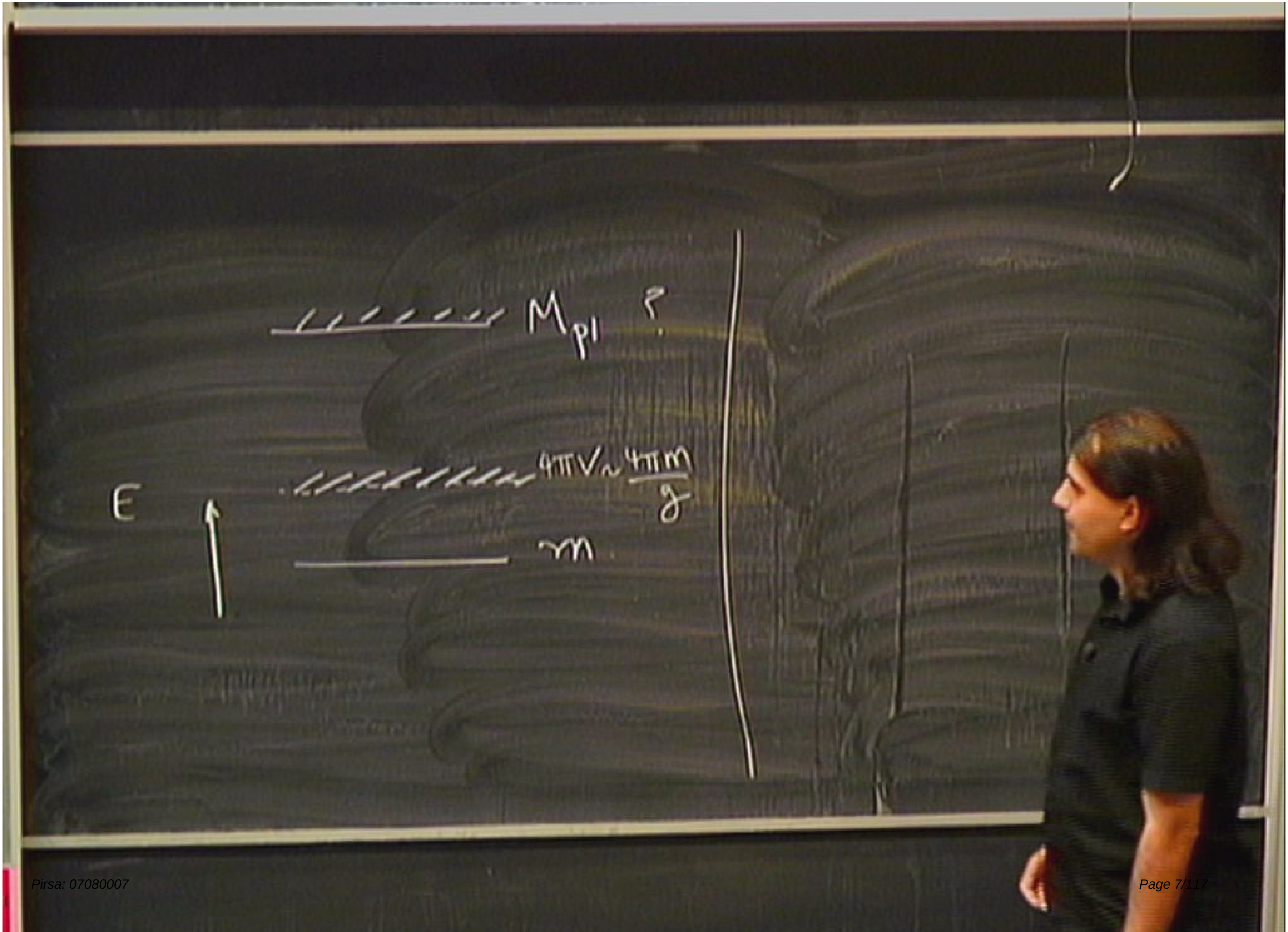
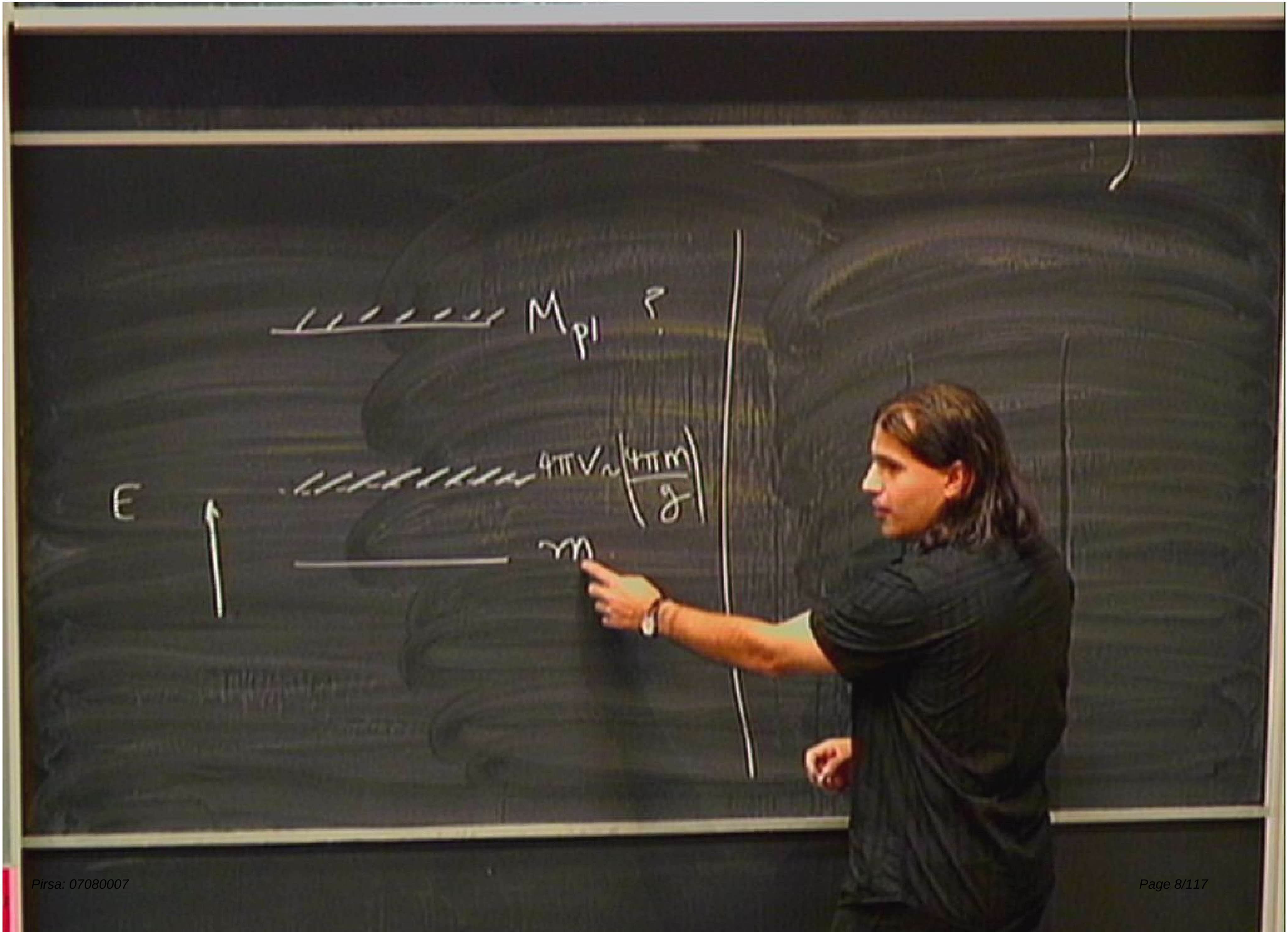
$$\mathcal{L} = -\frac{1}{4} \mathrm{tr}\, F_{\mu\nu}^2 + m^2 W_\mu^a W^{\mu a} + \ldots$$

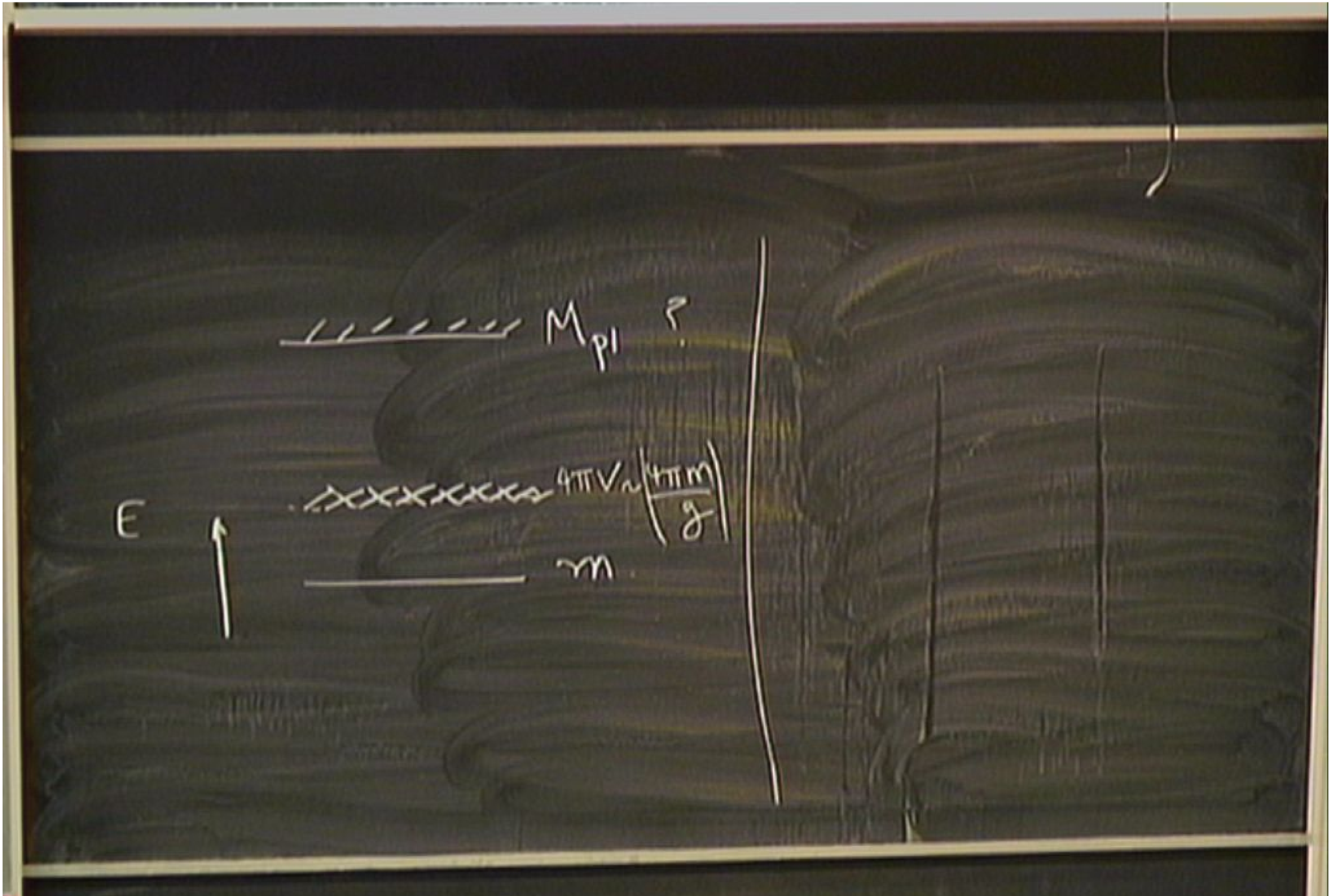

M_pl ?
E
m



Mpl ?
4πV ~ 4πm/g
E
m



E
M_pl ?
4πV~(4πm/g)
m


M_pl ?
4πV_n (4πm/g)
E
m

Global SU(2) symmetry W_μ^a.

$m^2 = g^2 v^2$.

$$\mathcal{L} = -\frac{1}{4g^2} \mathrm{tr}\, F_{\mu\nu}^2 + v^2 W_\mu^a W^{\mu a} + \dots$$

massless A_μ

2 pol

ε_μ

$(p^\mu \varepsilon_\mu) = 0$

$4 - 1 = 3$

$+ \; m_W^2 W_\mu^2 + \frac{1}{2}$

massless A_μ

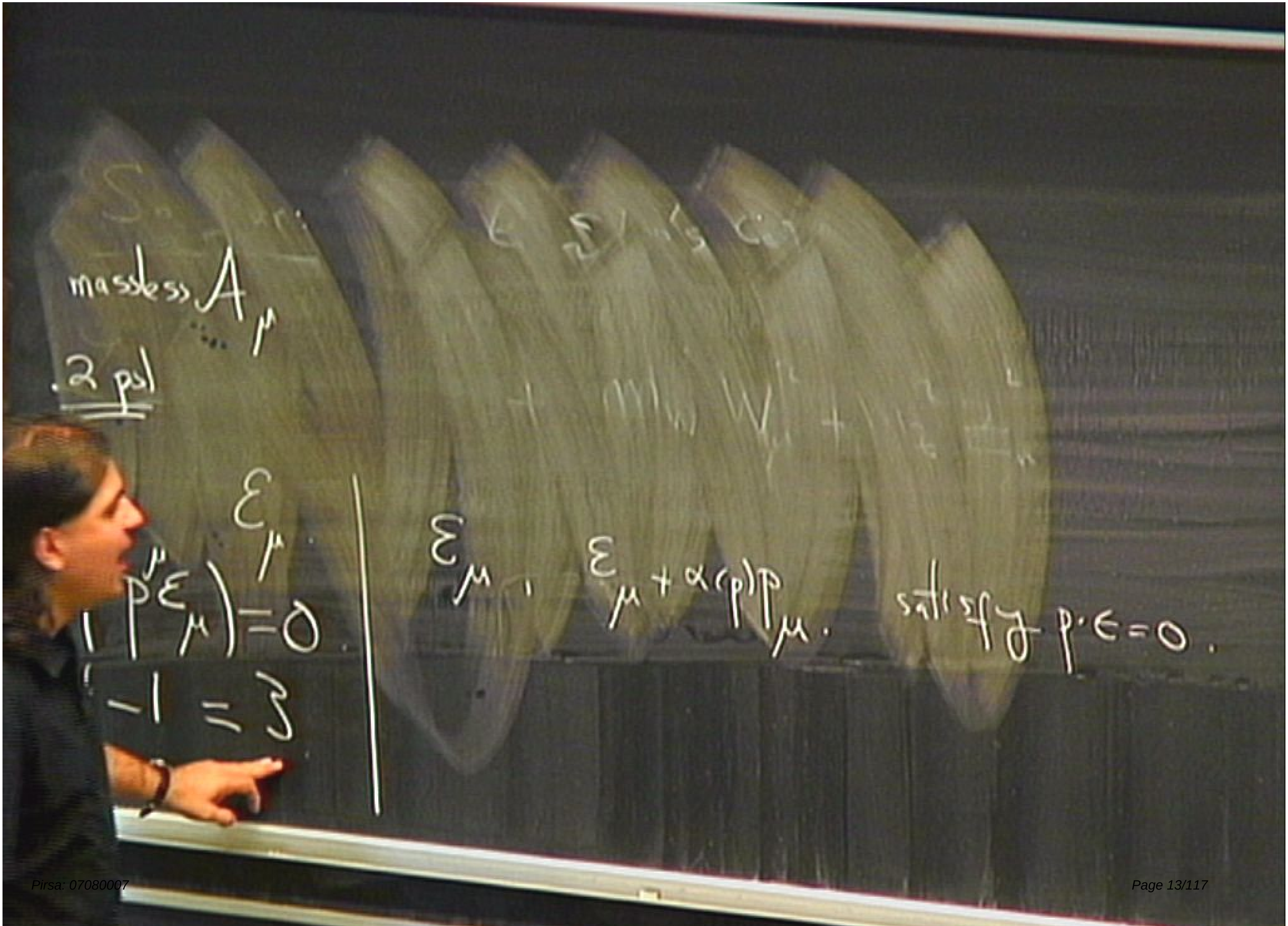
2 pol

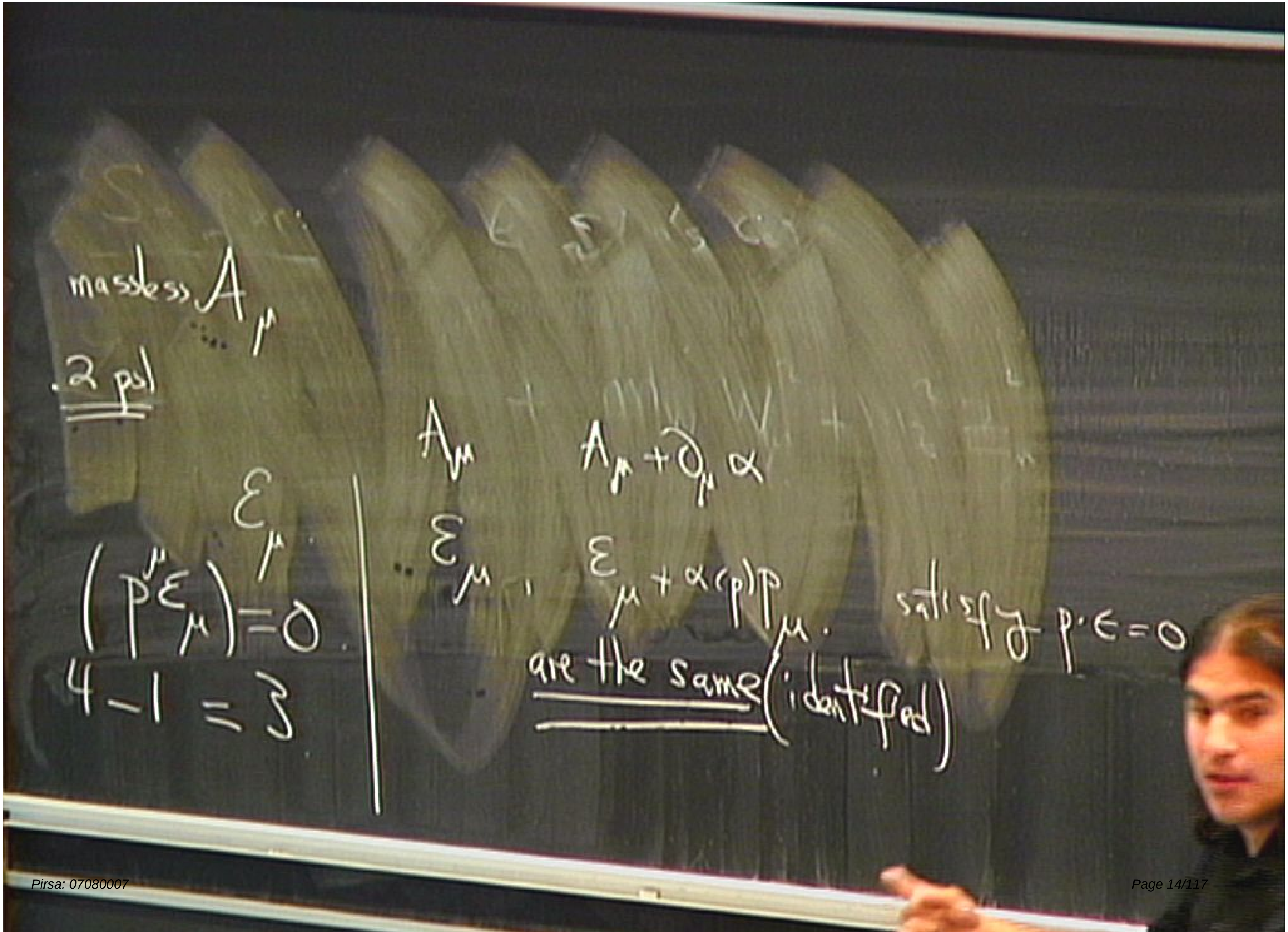
ε_μ

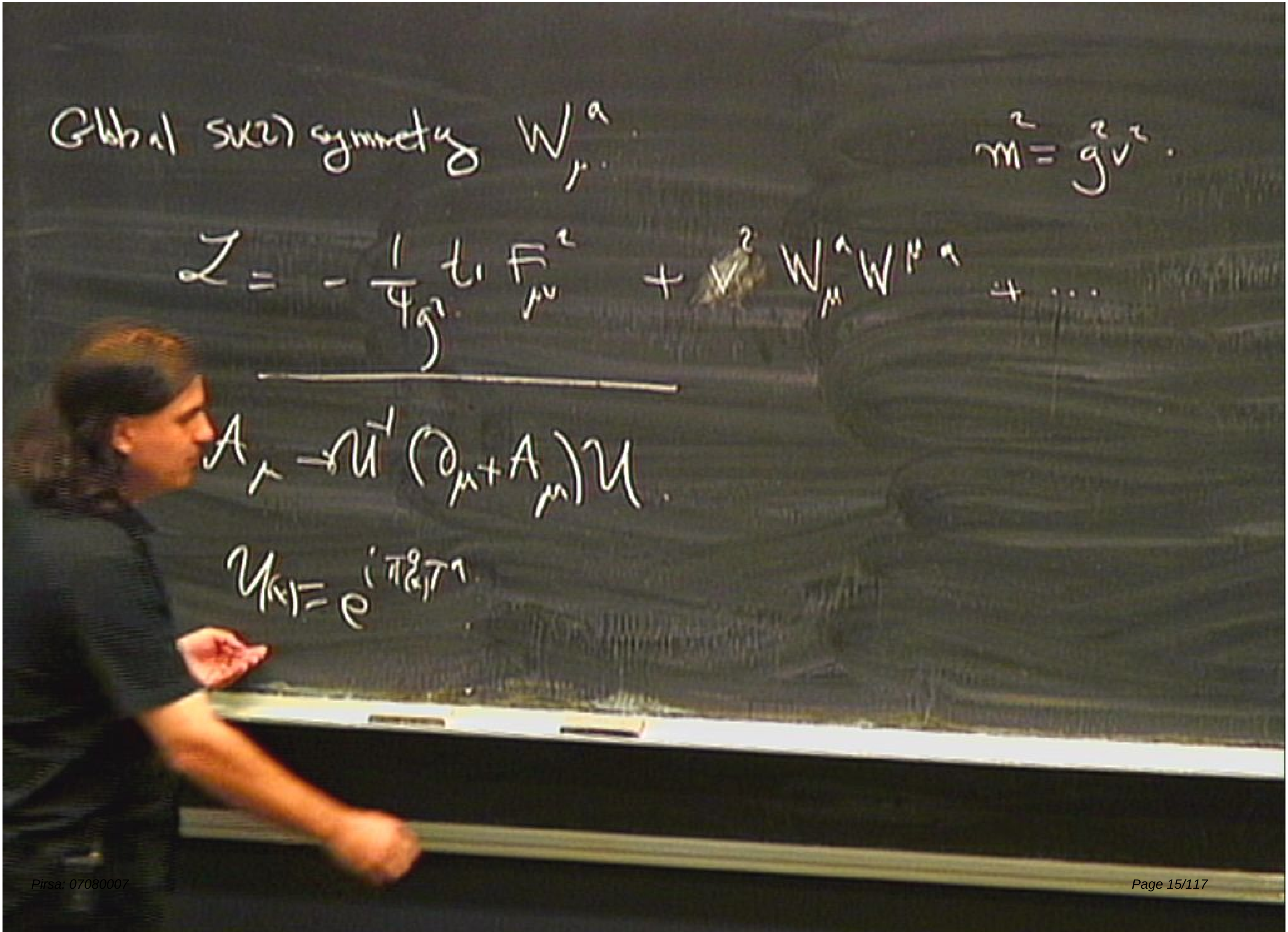
$(p^\mu \varepsilon_\mu) = 0$

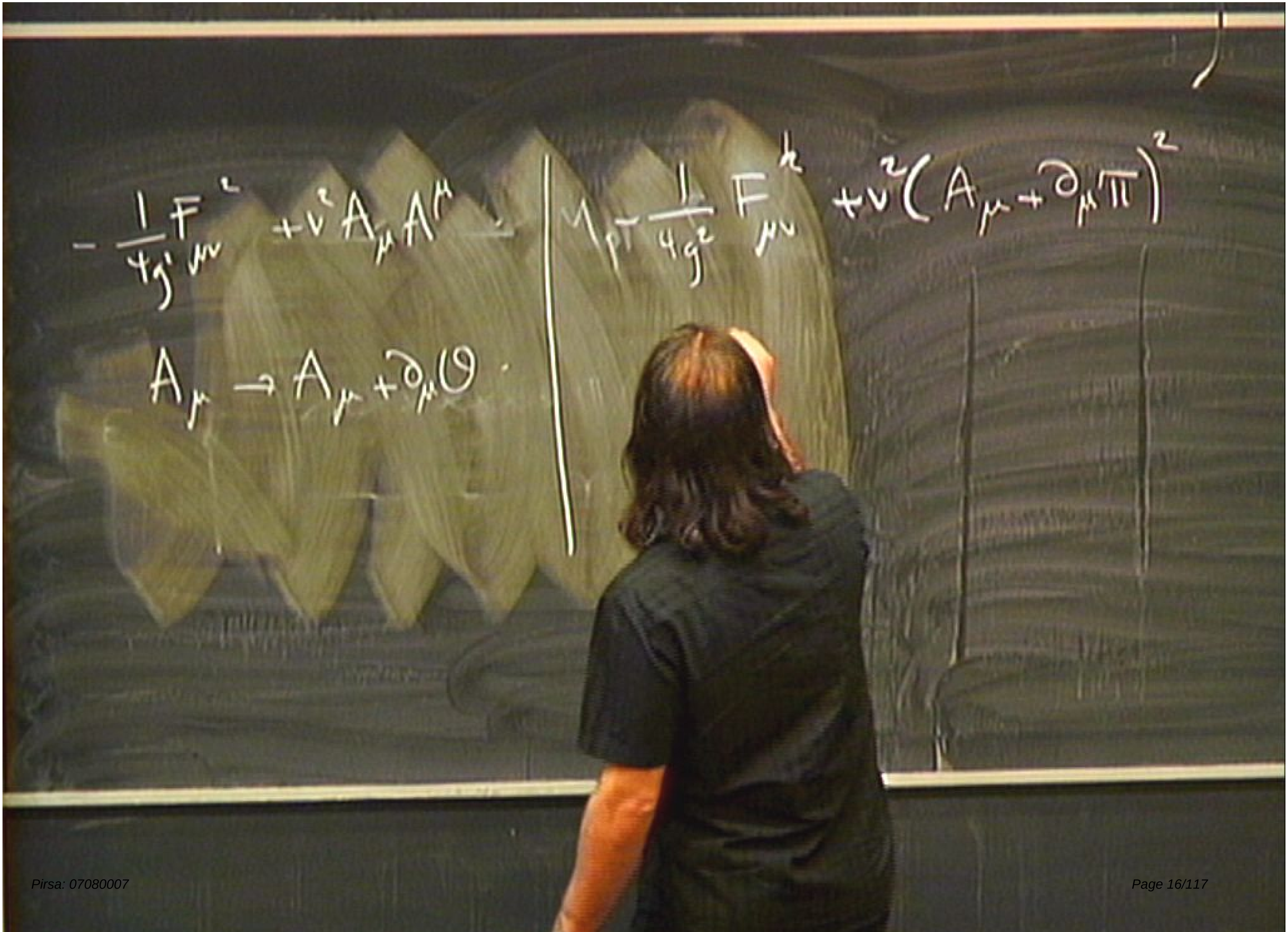
$4 - 1 = 3$

$\varepsilon_\mu \to \varepsilon_\mu + \alpha(p)\, p_\mu$.


massless Aμ
2 pol
εμ
pμεμ = 0
−1 = 3
εμ
εμ + α(p)pμ.
satisfy p·ε = 0.


massless A_μ
2 pol
ε_μ
(p^μ ε_μ) = 0
4 − 1 = 3
A_μ
A_μ + ∂_μ α
ε_μ ,
ε_μ + α(p) p_μ .
satisfy p·ε = 0
are the same (identified)


Global SU(2) symmetry W_μ^a
m² = g²v²
ℒ = - 1/(4g²) tr F_μν² + v² W_μ^a W^μa + ...
A_μ → U⁻¹(∂_μ + A_μ)U


-1/4g² F_μν² + v² A_μ A^μ
A_μ → A_μ + ∂_μ θ
-1/4g² F_μν² + v²(A_μ + ∂_μ π)²

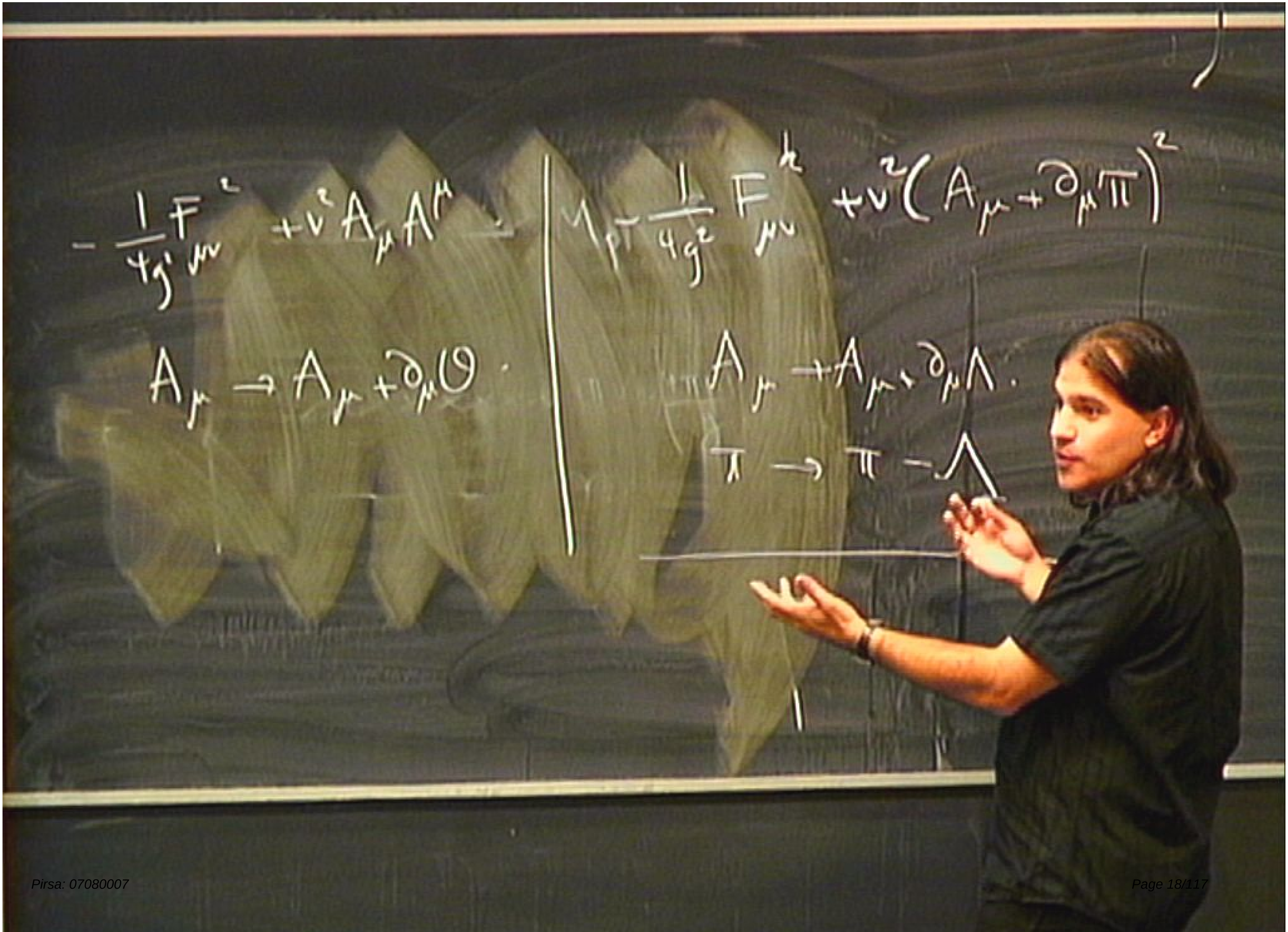
$$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2 A_\mu A^\mu$$

$$A_\mu \to A_\mu + \partial_\mu \theta$$

$$\mathcal{L}_{pr} = -\frac{1}{4g^2}F_{\mu\nu}^2 + v^2\left(A_\mu + \partial_\mu \pi\right)^2$$

$$A_\mu \to A_\mu + \partial_\mu \Lambda$$

$$\pi \to \pi - \Lambda$$


$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2 A_\mu A^\mu$
$A_\mu \to A_\mu + \partial_\mu \theta$
$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2(A_\mu + \partial_\mu \pi)^2$
$A_\mu \to A_\mu + \partial_\mu \Lambda$
$\pi \to \pi - \Lambda$

$$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2 A_\mu A^\mu$$

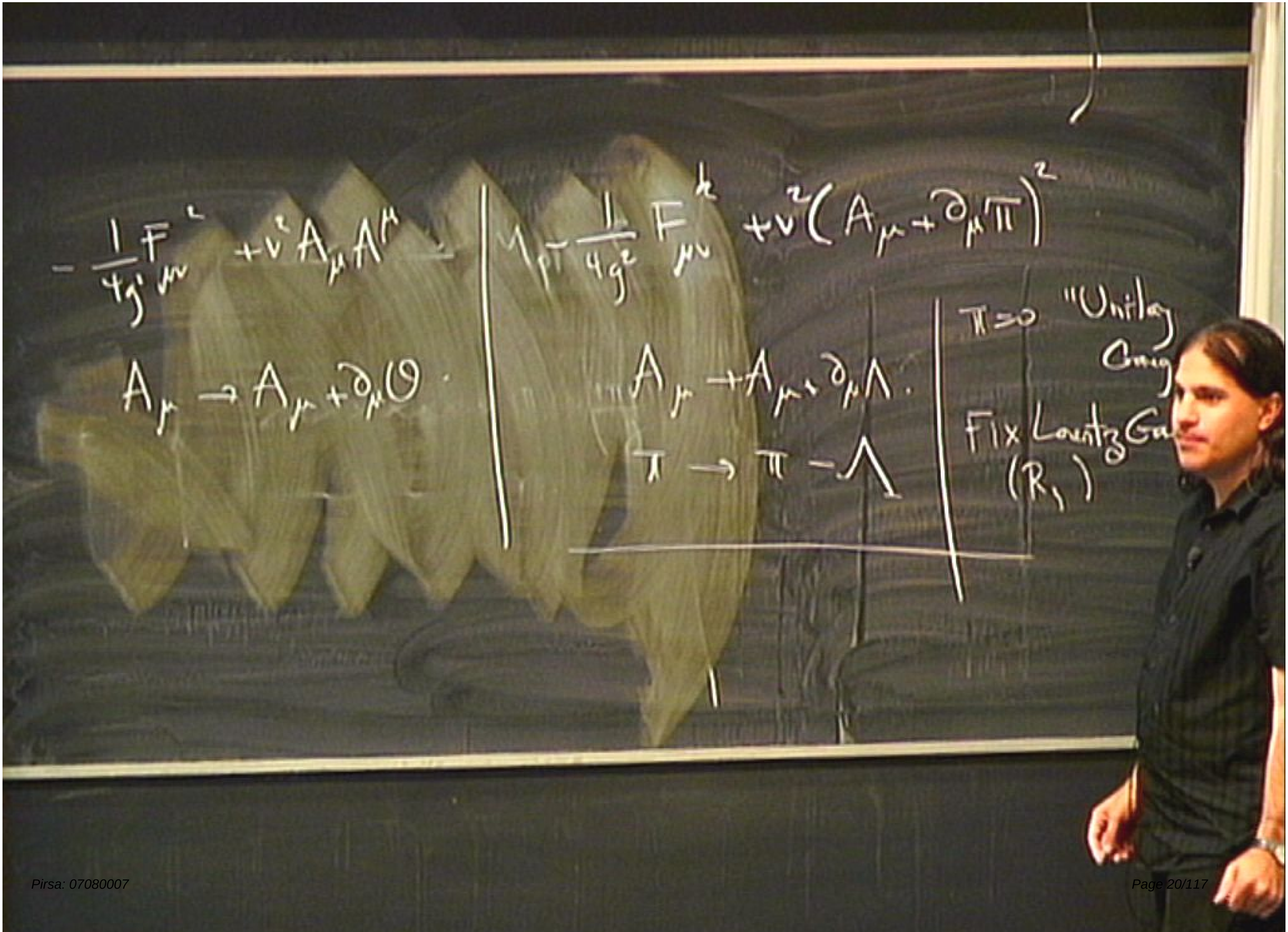
$$A_\mu \to A_\mu + \partial_\mu \theta$$

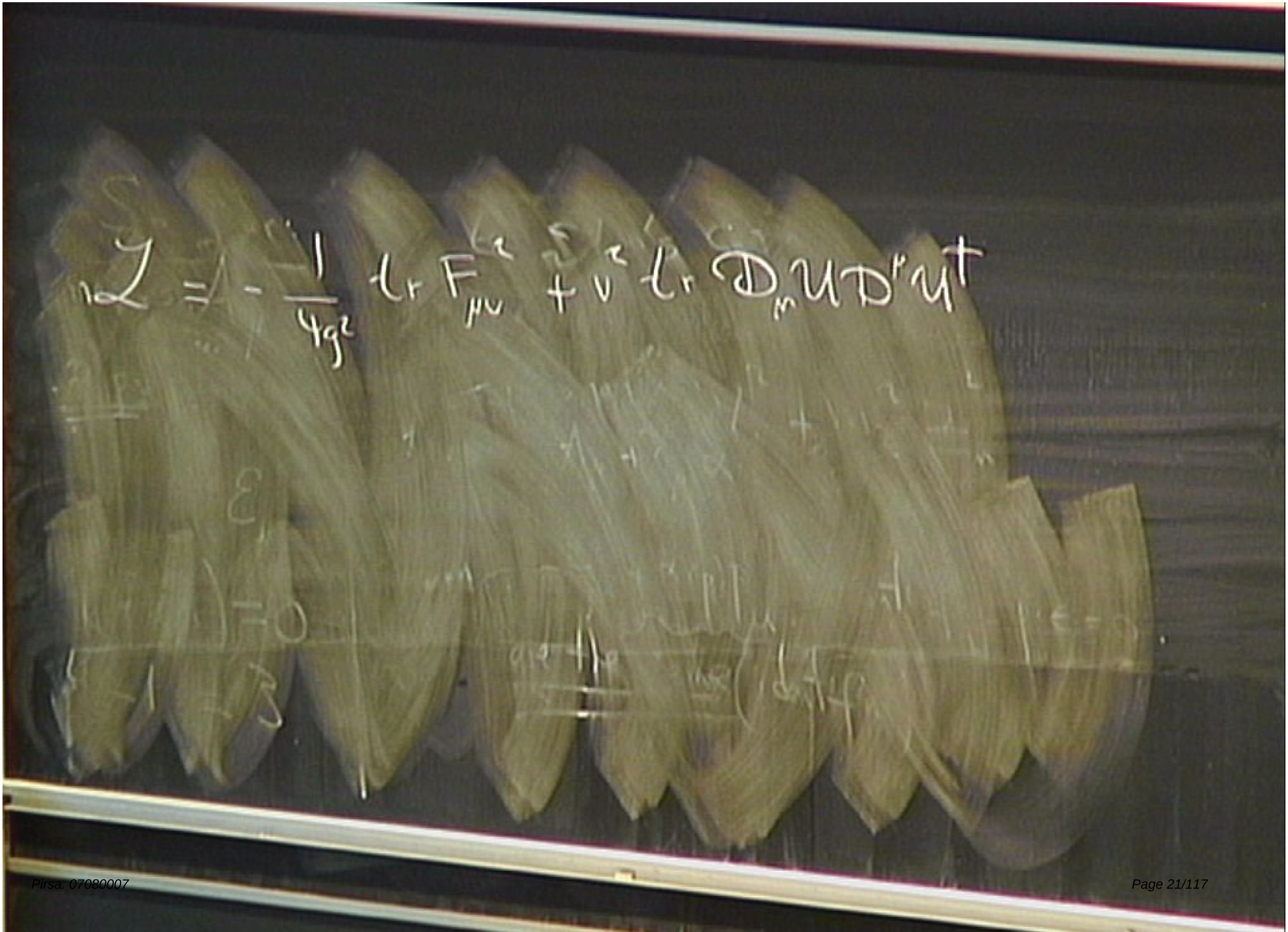
$$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2 (A_\mu + \partial_\mu \pi)^2$$

$$A_\mu \to A_\mu + \partial_\mu \Lambda$$

$$\pi \to \pi - \Lambda$$

$\pi = 0$ "Unitary Gauge"


$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2 A_\mu A^\mu$
$A_\mu \to A_\mu + \partial_\mu \theta$
$-\frac{1}{4g^2}F_{\mu\nu}^2 + v^2 (A_\mu + \partial_\mu \pi)^2$
$A_\mu \to A_\mu + \partial_\mu \Lambda$
$\pi \to \pi - \Lambda$
$\pi = 0$
Fix Lorentz


$\mathcal{L} = -\frac{1}{4g^2}\,\mathrm{tr}\,F_{\mu\nu}^2 + v^2\,\mathrm{tr}\,D_\mu U D^\mu U^\dagger$

$$\mathcal{L} = -\frac{1}{4g^2}\,\mathrm{tr}\,F_{\mu\nu}^2 + v^2\,\mathrm{tr}\,D_\mu U D^\mu U^\dagger$$

Just long components $U = e^{i\pi^a T^a}$

$$\mathcal{L} = \Lambda - \frac{1}{4g^2} \mathrm{tr}\, F_{\mu\nu}^2 + v^2 \mathrm{tr}\, D_\mu U D^\mu U^\dagger$$

Just long components $U = e^{i \pi^a T^a}$

$$U \to U g \qquad \pi^a \to \pi^a + c^a + \dots$$

$$\mathcal{L} = -\frac{1}{4g^2}\,\mathrm{tr}\,F_{\mu\nu}^2 + v^2\,\mathrm{tr}\,D_\mu U D^\mu U^\dagger$$

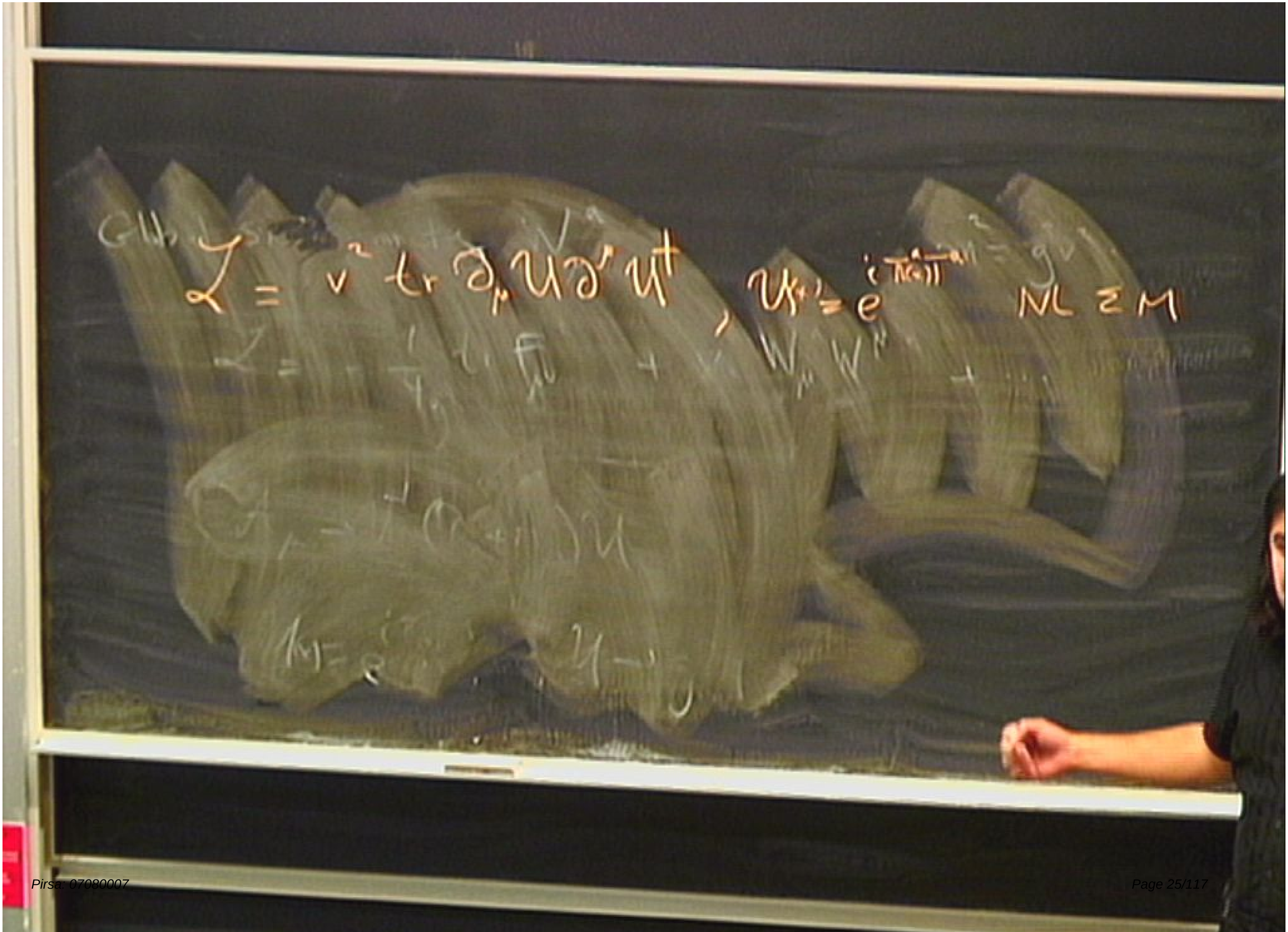
$g \to 0$, $v = \left(\frac{m}{g}\right)$ fixed

Just long components $U = e^{i\frac{\pi^a}{v}T^a}$

$$\boxed{\mathcal{L}_\pi = v^2\,\mathrm{tr}\,\partial_\mu U \partial^\mu U^\dagger}$$

$U \to U g$

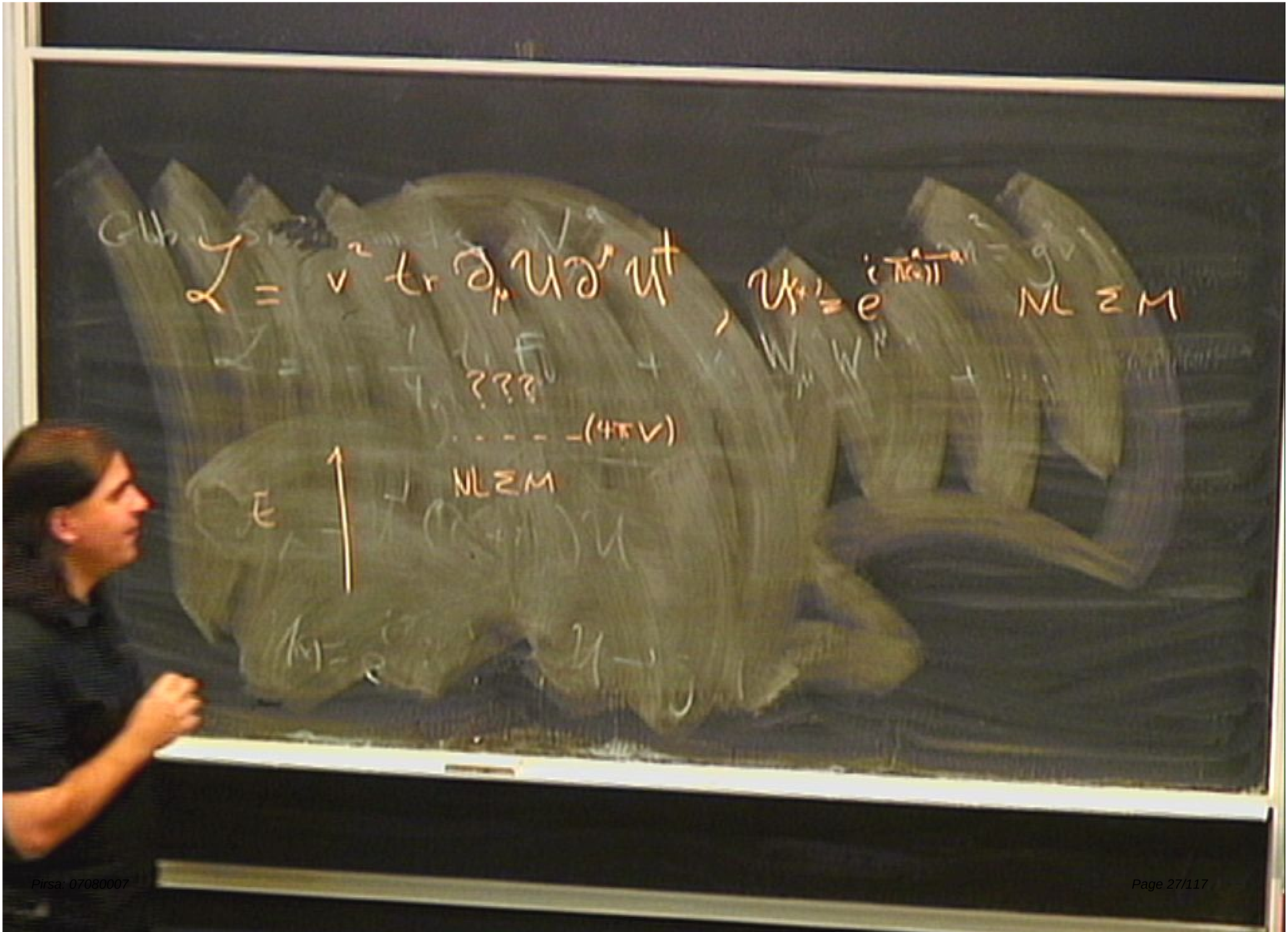
$\pi^a \to \pi^a + c^a + \ldots$

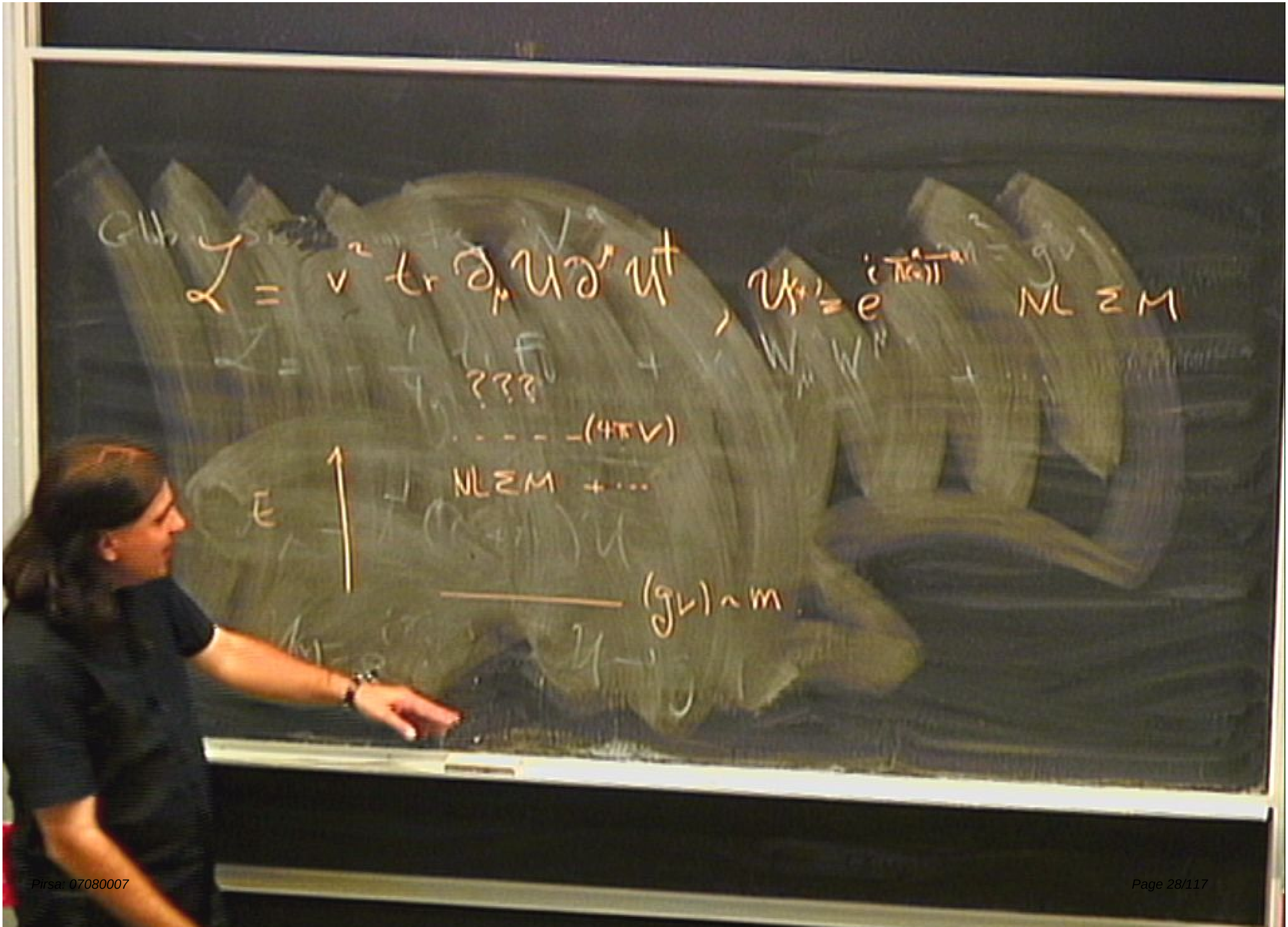

L = v² tr ∂μU∂μU† , U(x) = e^{iπ^aT^a/v}
NL ≥ M

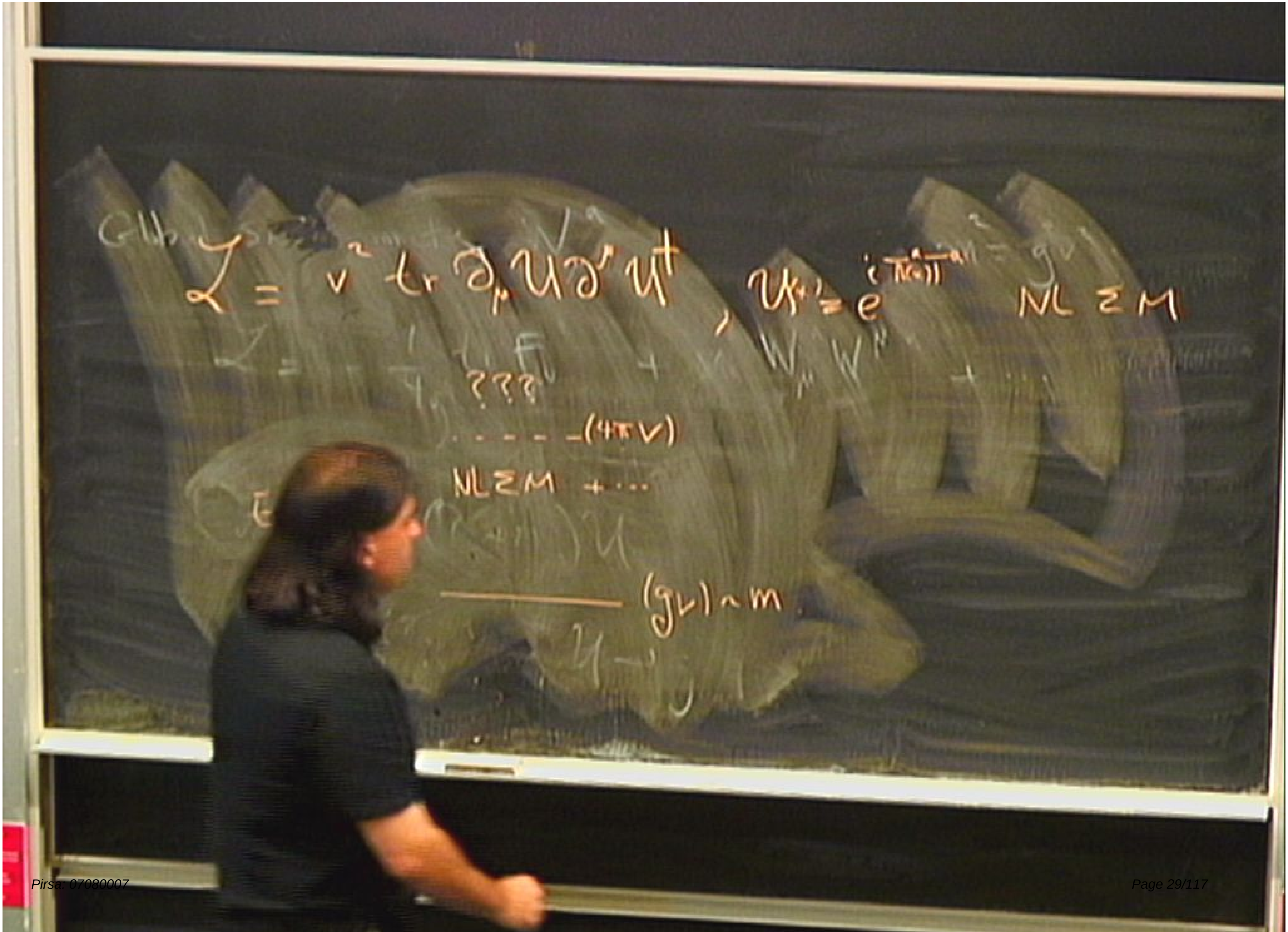
$$\mathcal{L} = v^2 \, \mathrm{tr}\, \partial_\mu U \partial^\mu U^\dagger \,, \quad U(x) = e^{i \pi^a(x) T^a / v}$$

NLΣM

$4\pi v$


NLΣM
???
(4πV)
NLΣM


NLΣM
???
(4πv)
NLΣM + ...
E
(gv) ~ m


NLΣM
???
(4πV)
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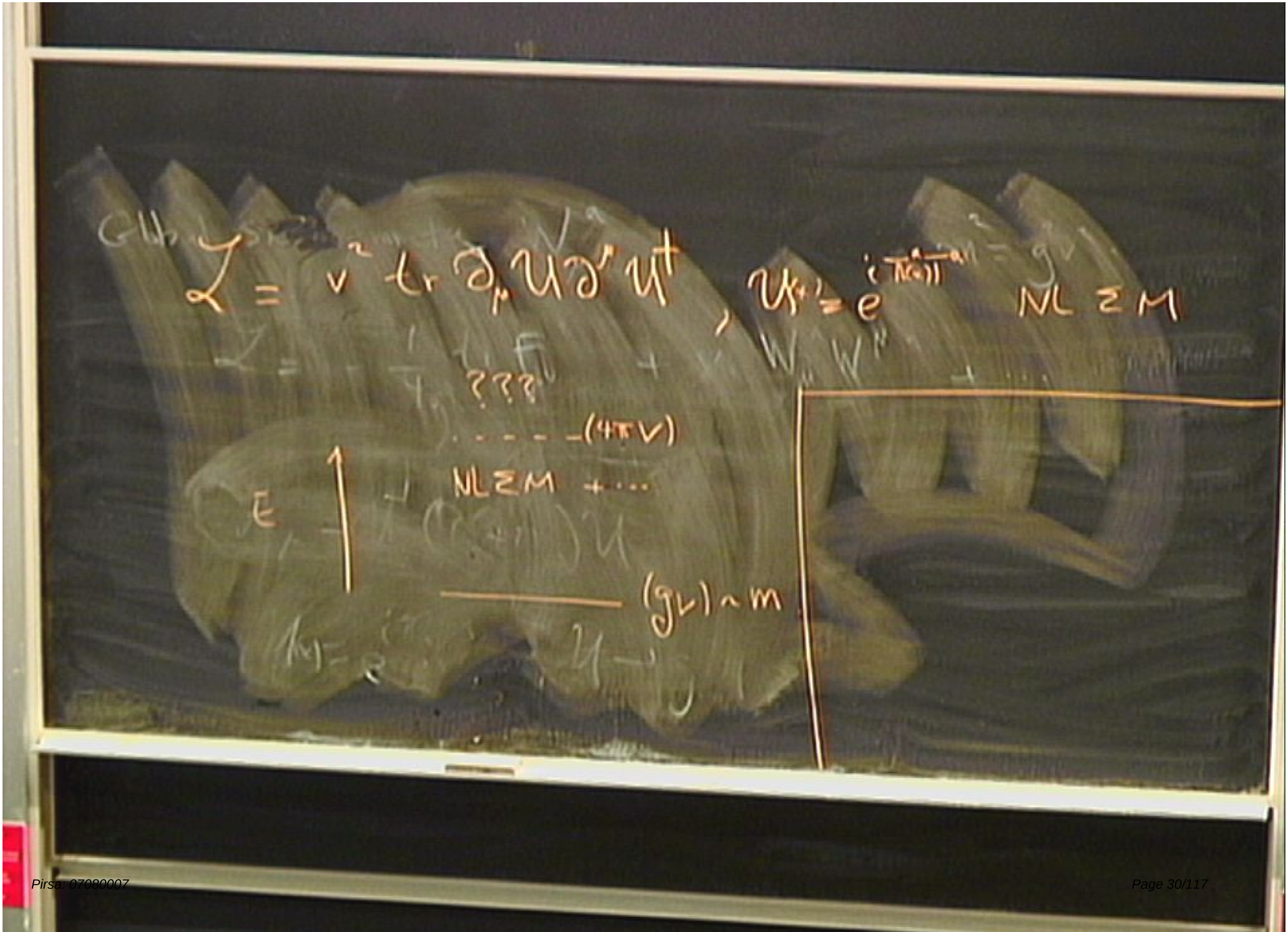
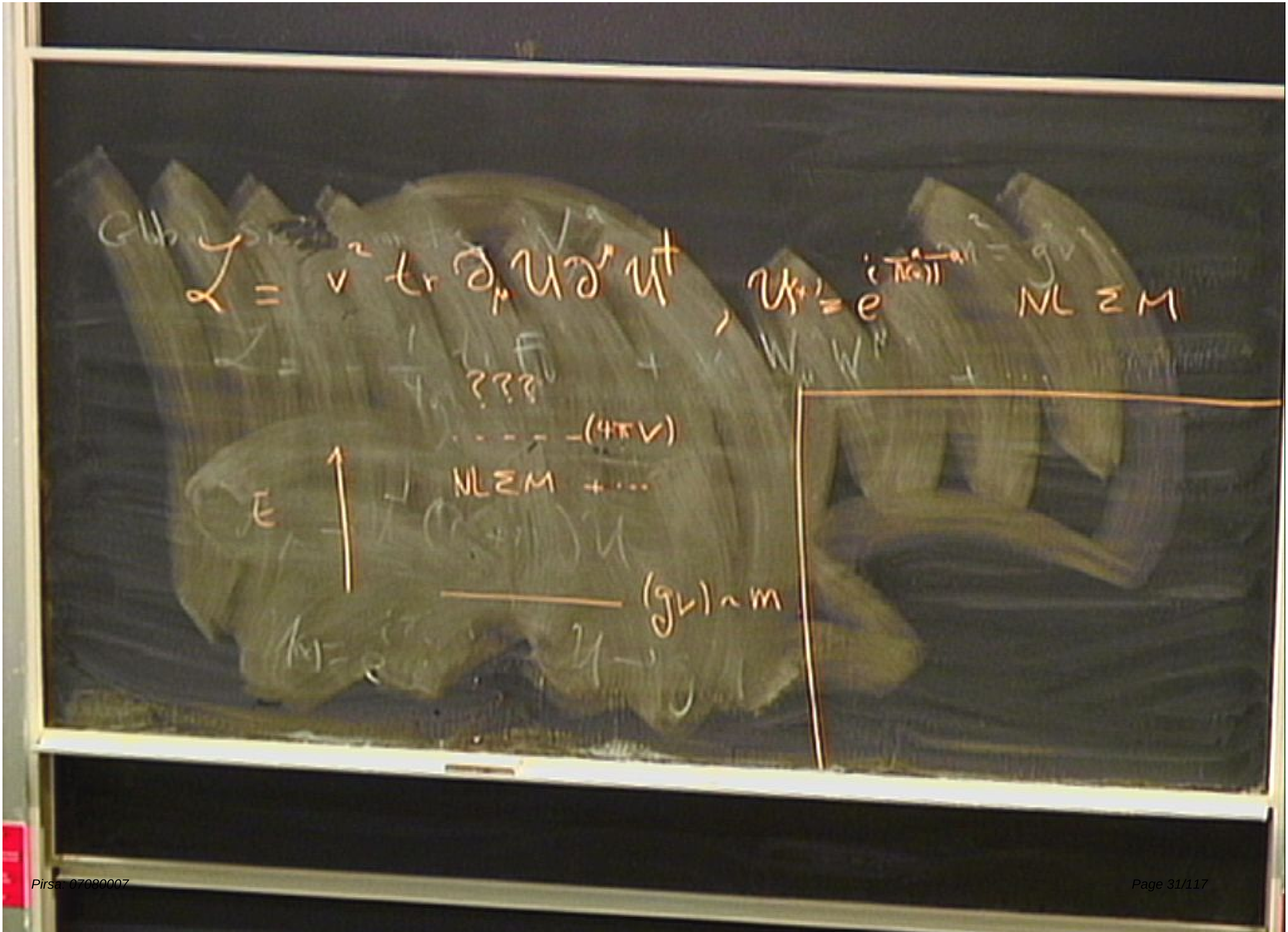


L = v² tr ∂μU∂μU†, U(x) = e^{iπ(x)T/v}
NLΣM
???
(4πv)
E
NLΣM + ...
(gv) ~ m



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NLΣM
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(4πv)
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NLΣM + ...
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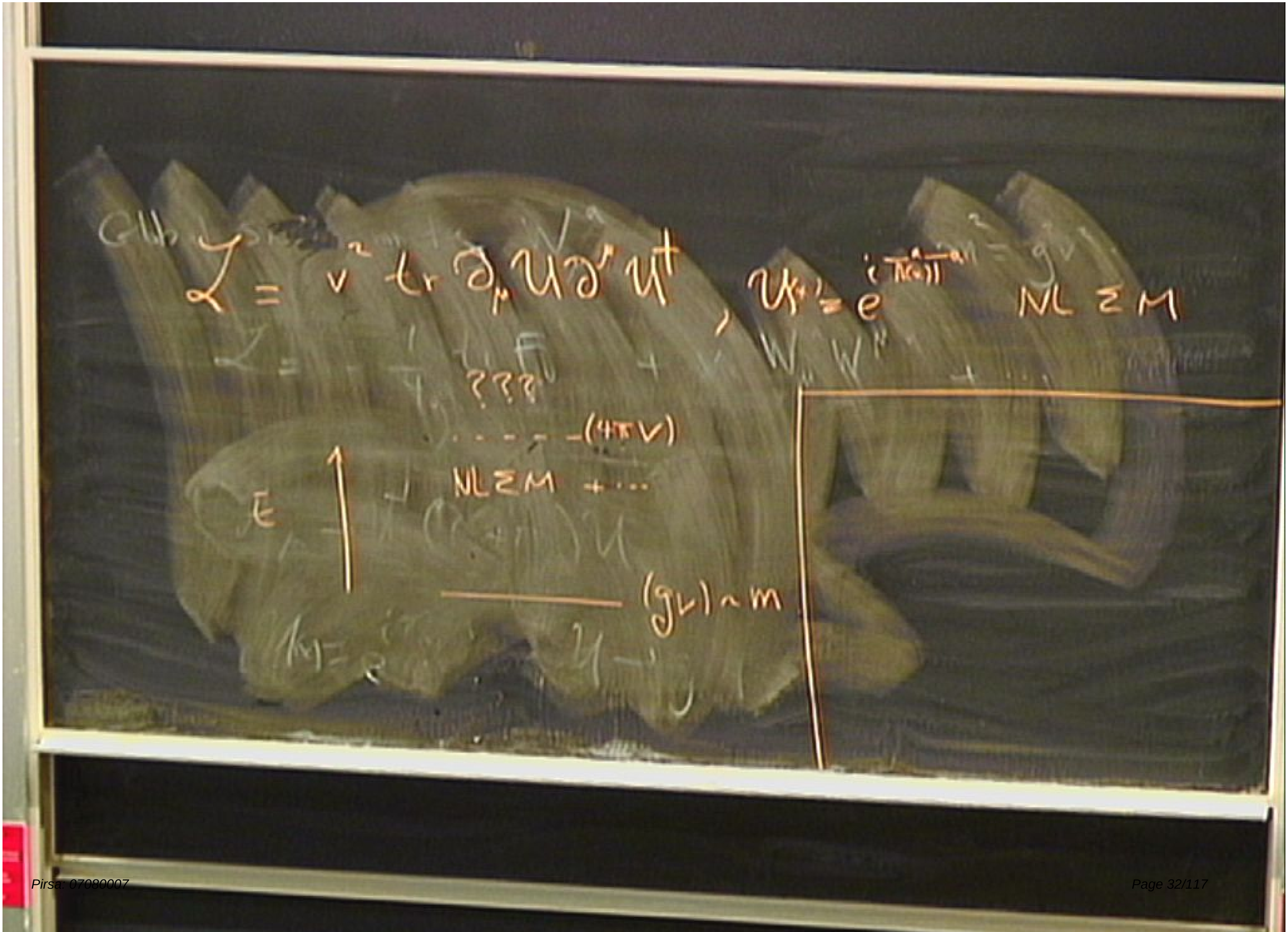
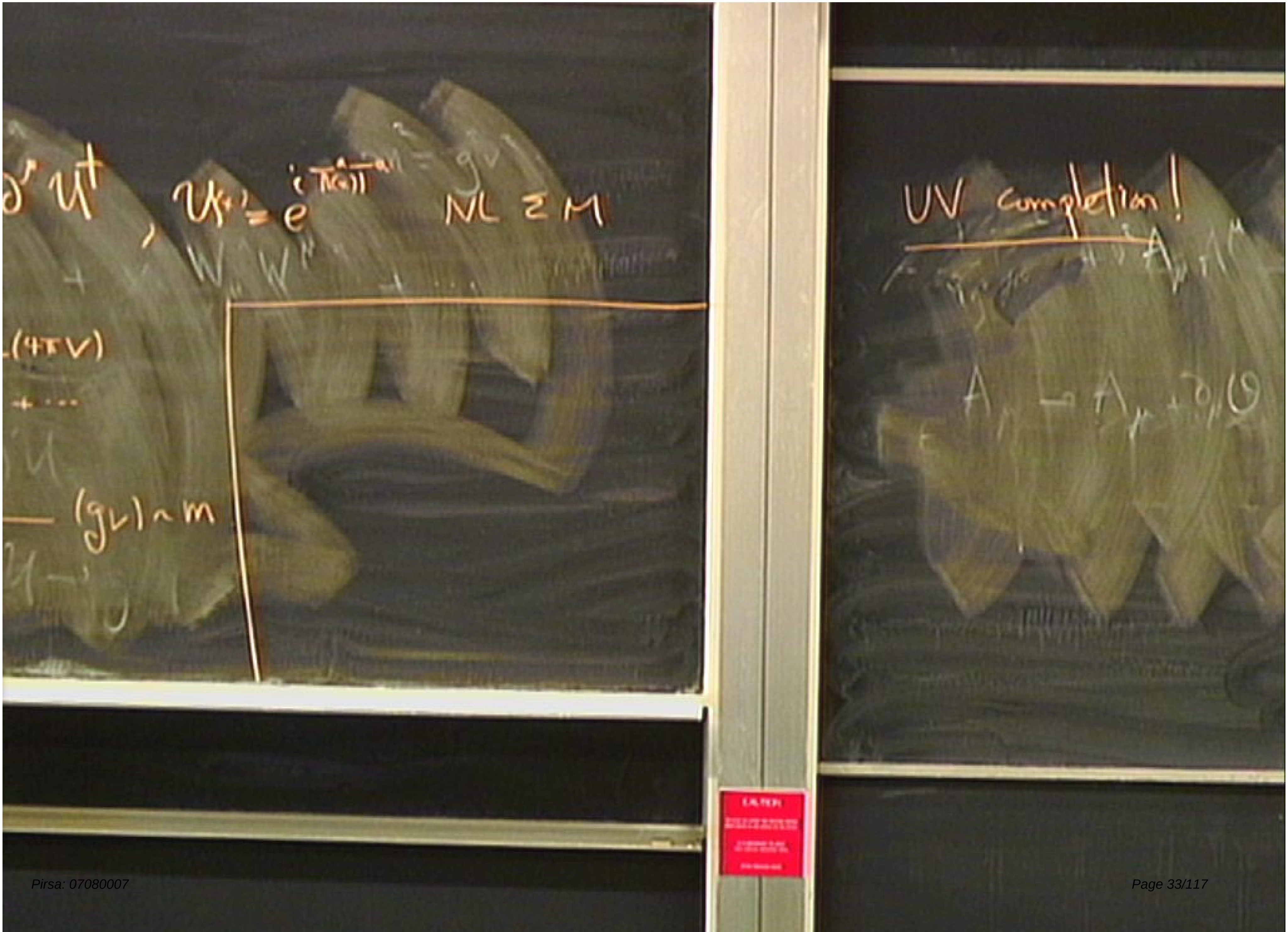
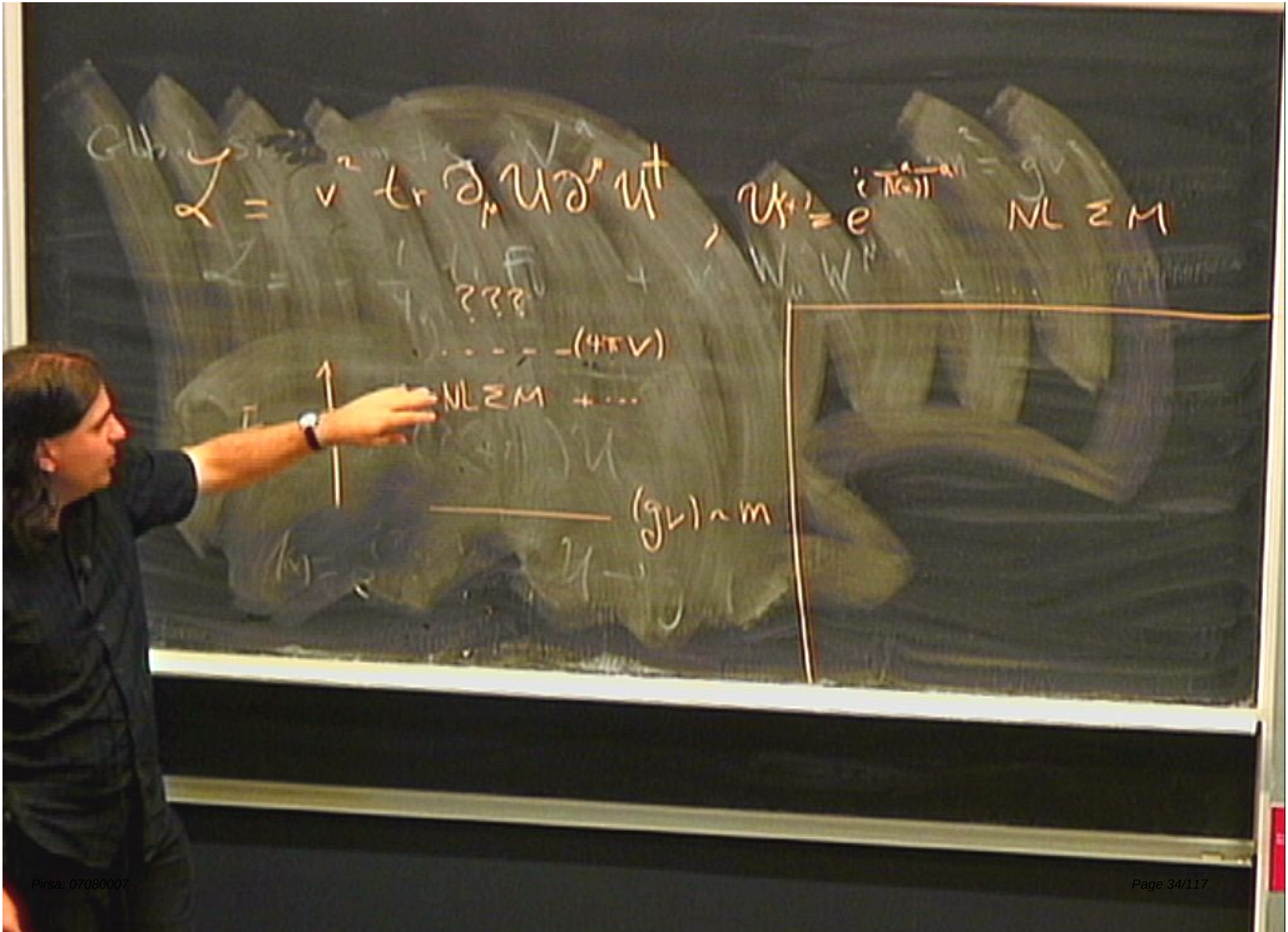
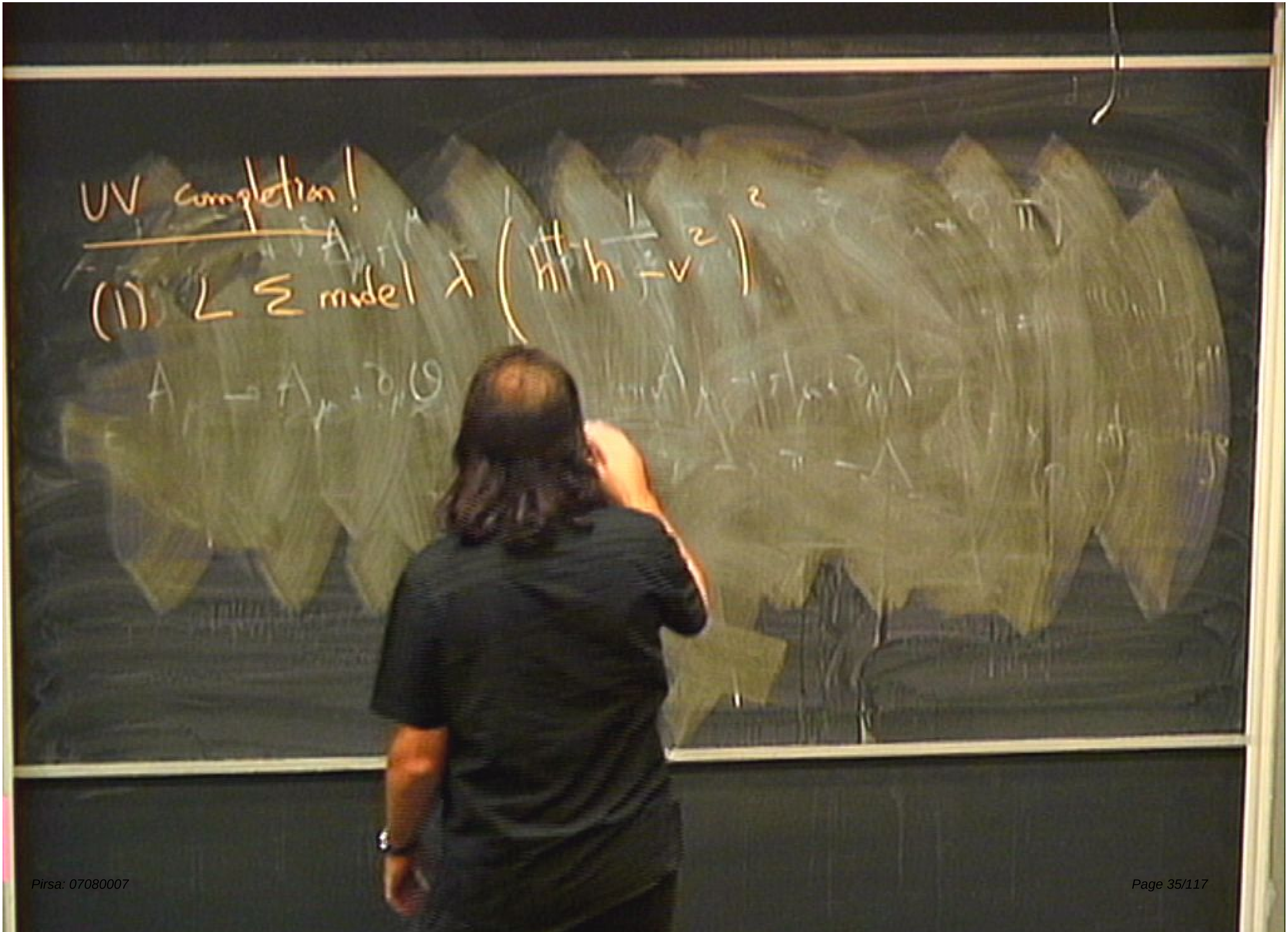
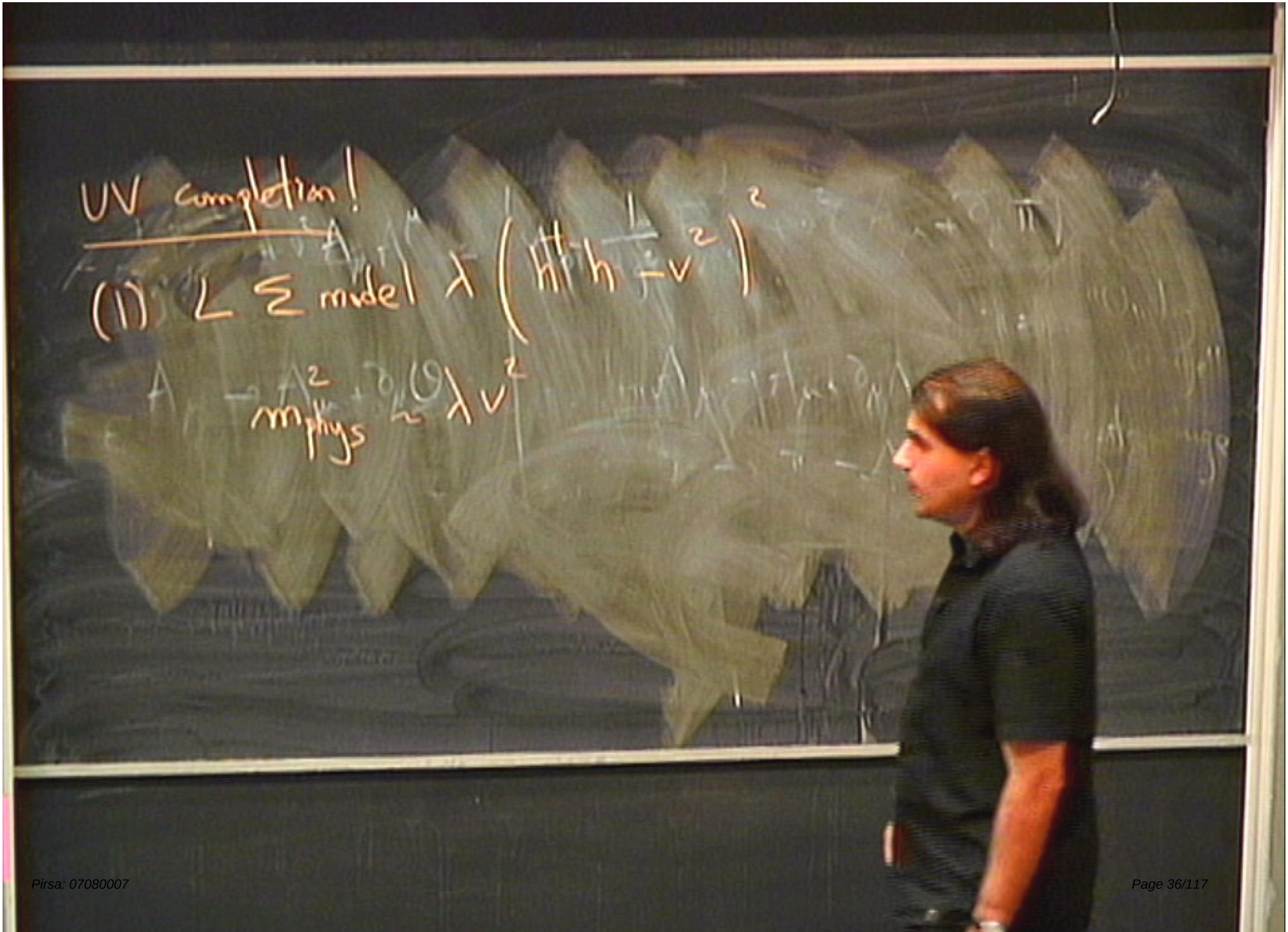
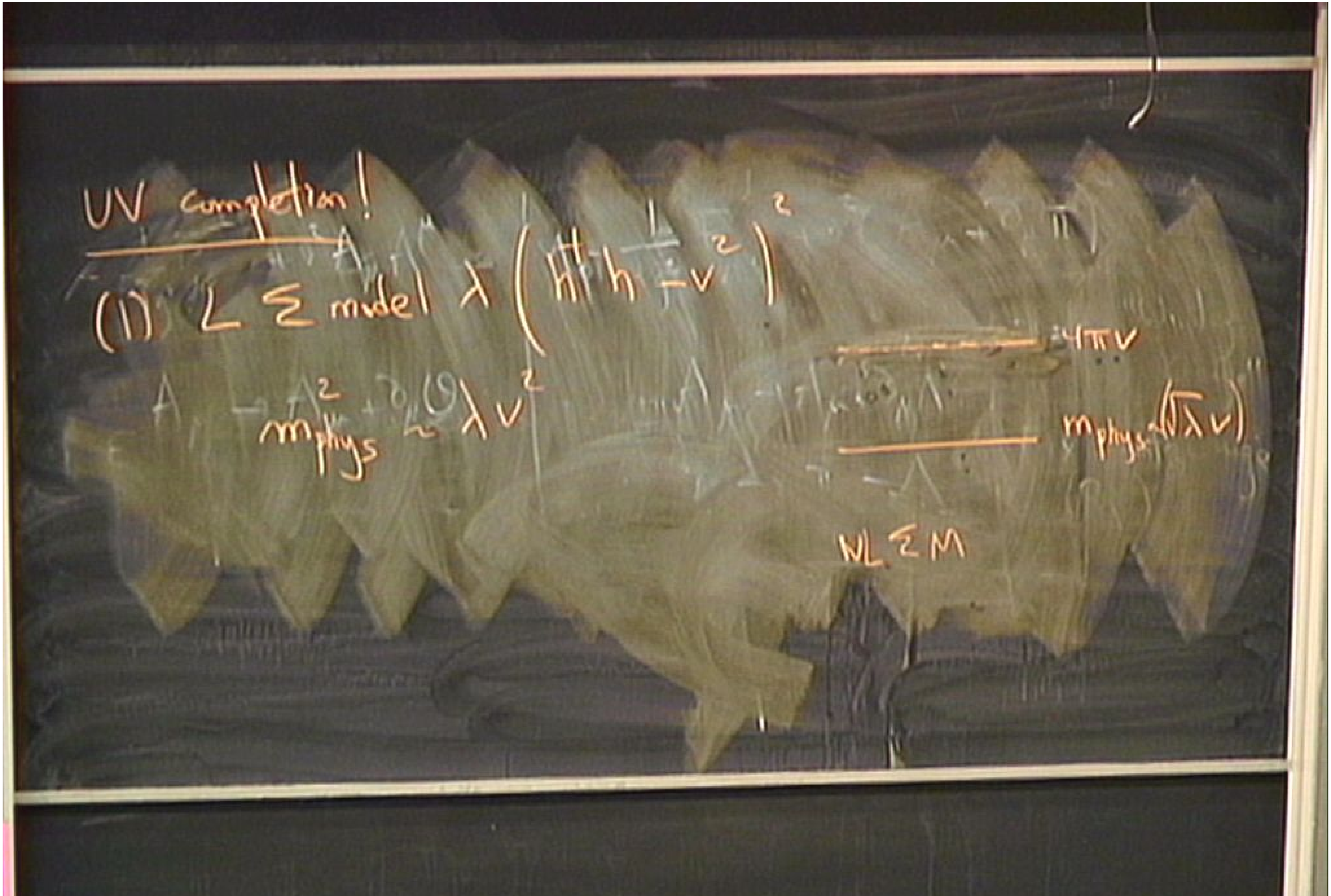

ℒ = v² tr ∂μ U ∂μ U†
U(x) = e^{iπ(x)T}
NL Σ M
???
(4πv)
E
NL Σ M + ...
(gv) ~ m

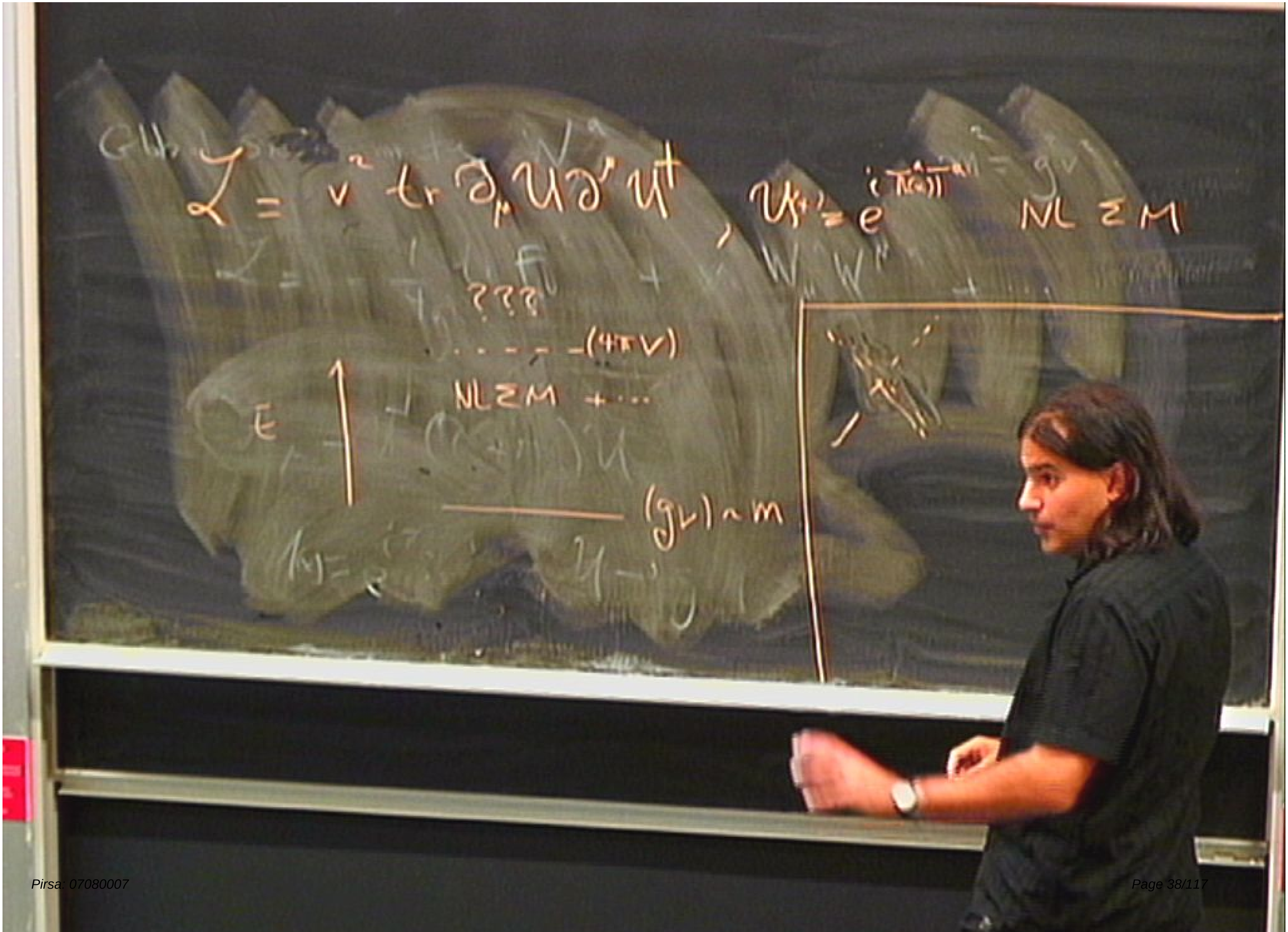

UV completion!

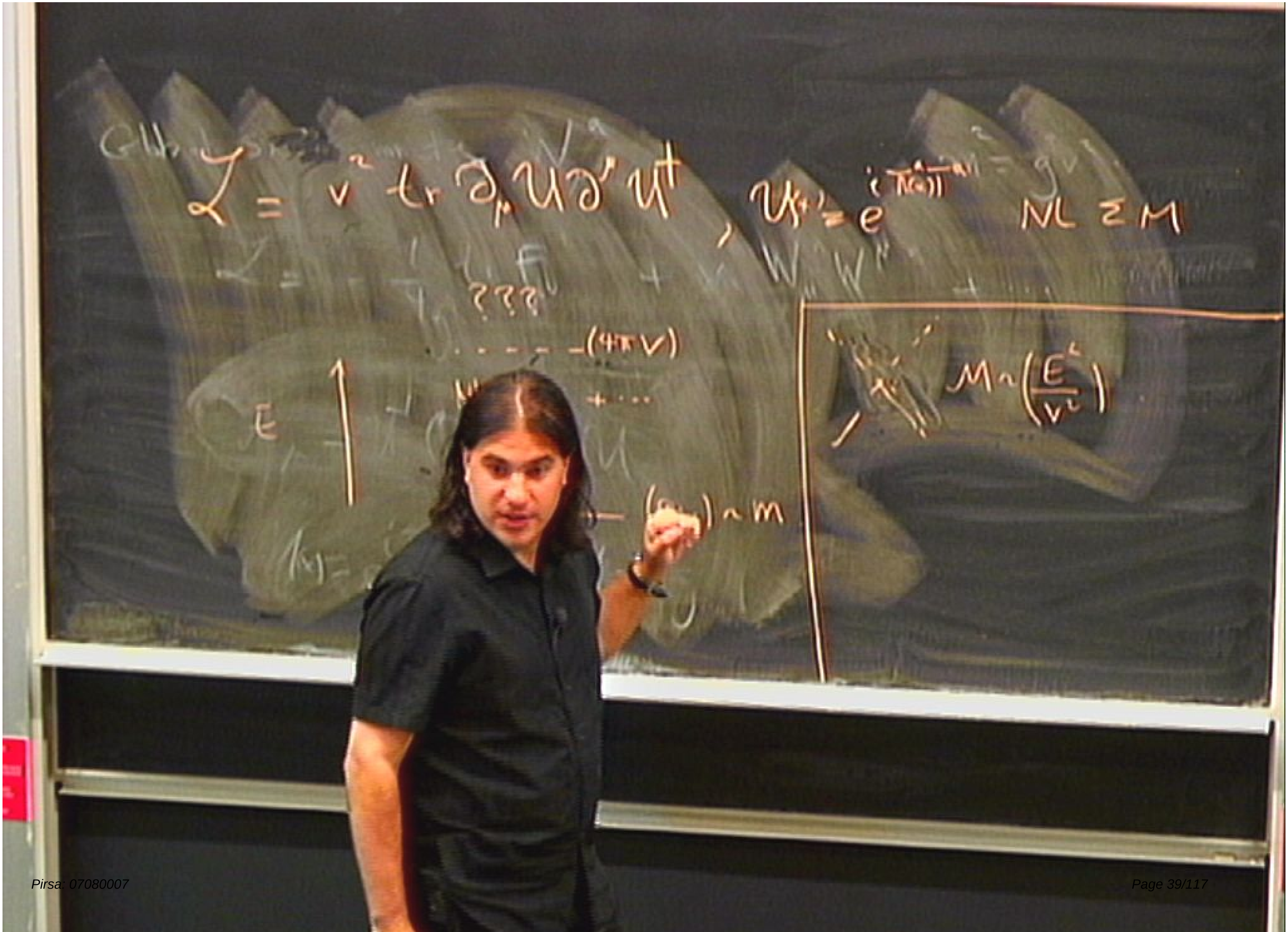

NL Σ M
???
(4πv)
NL Σ M + ...
(gv) ~ m

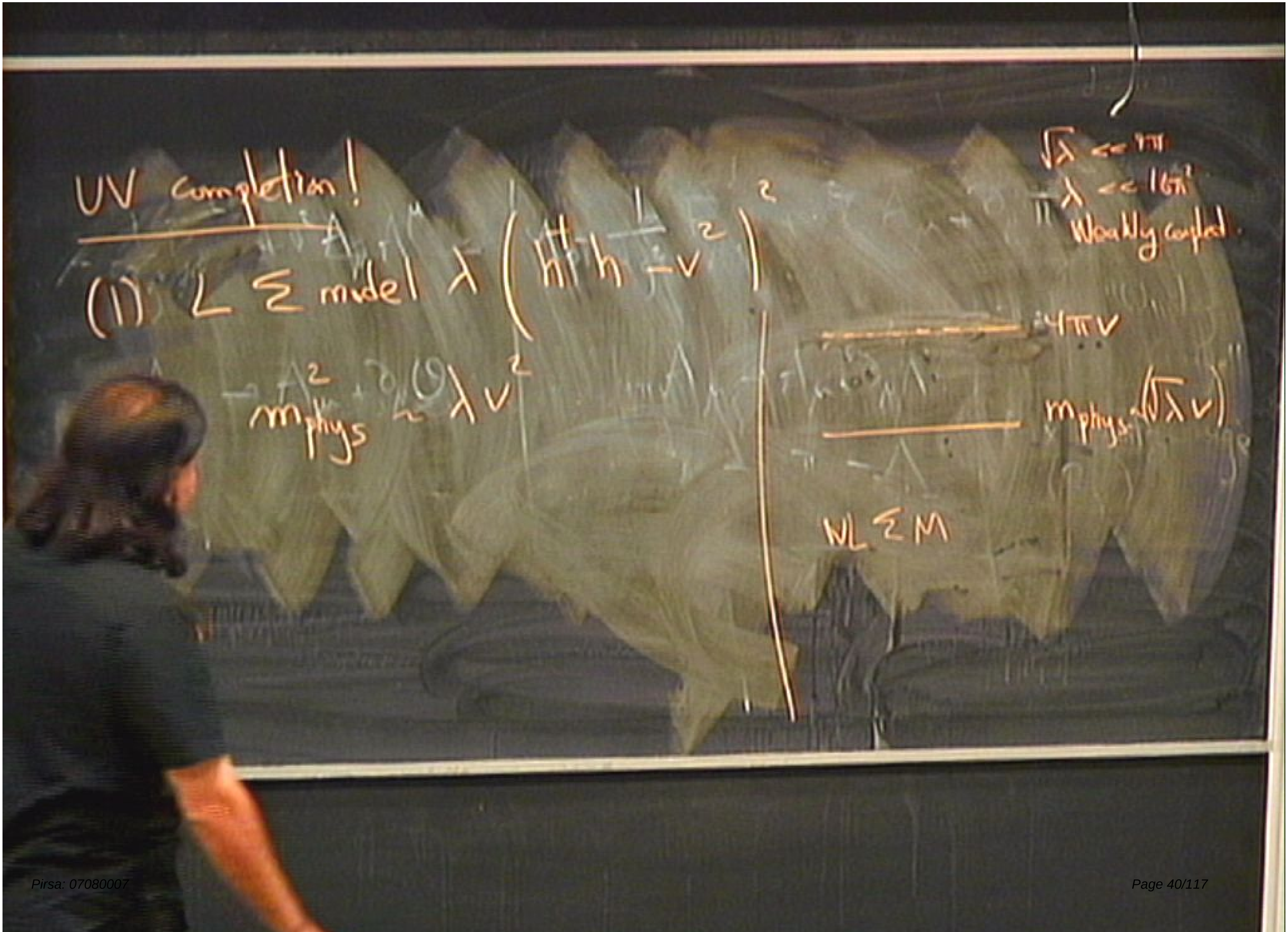

UV completion!
(I) L Σ model λ

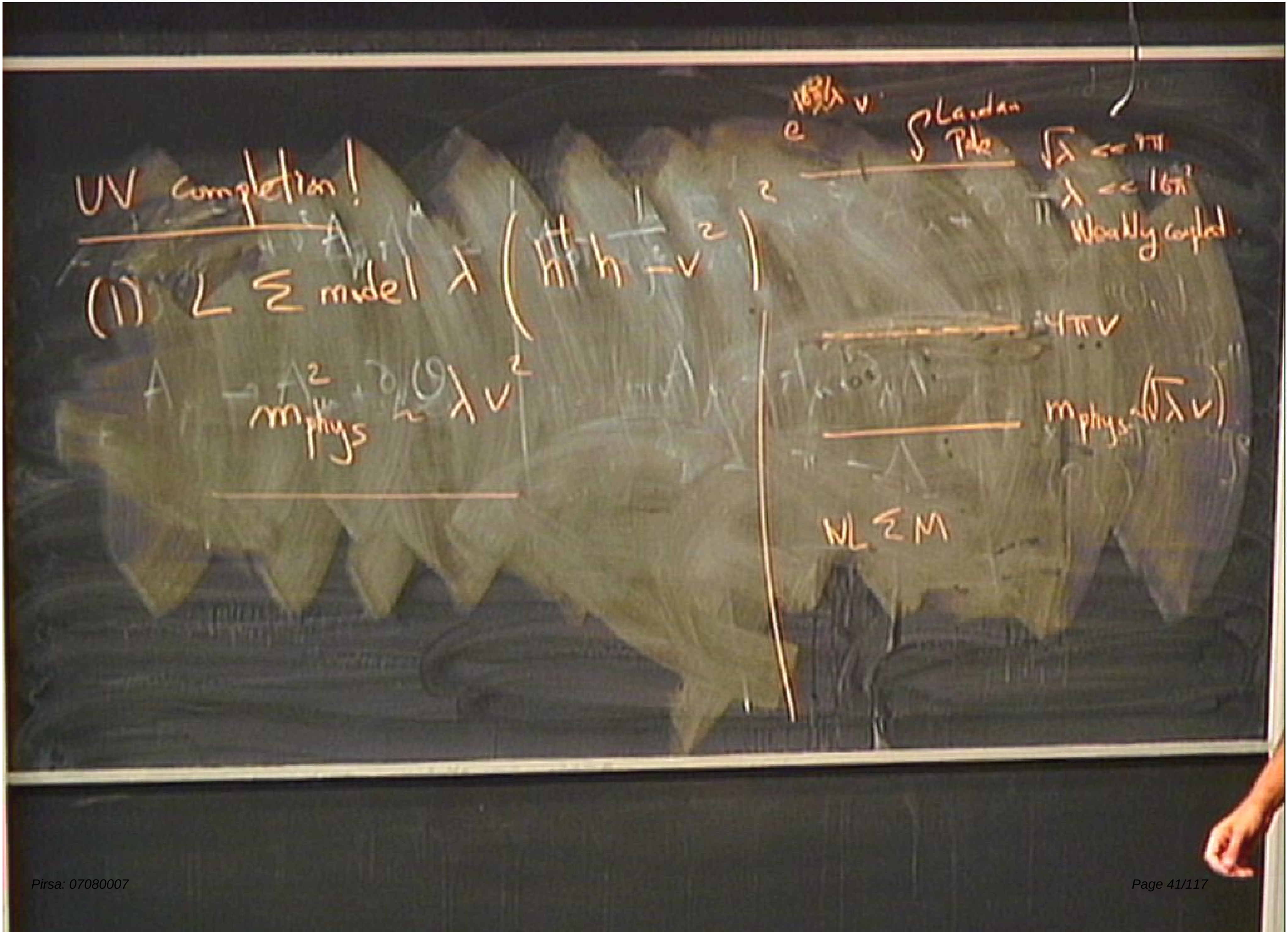

UV completion!
(II) L Σ model λ (H†h − v²)²
m²phys ≃ λ v²

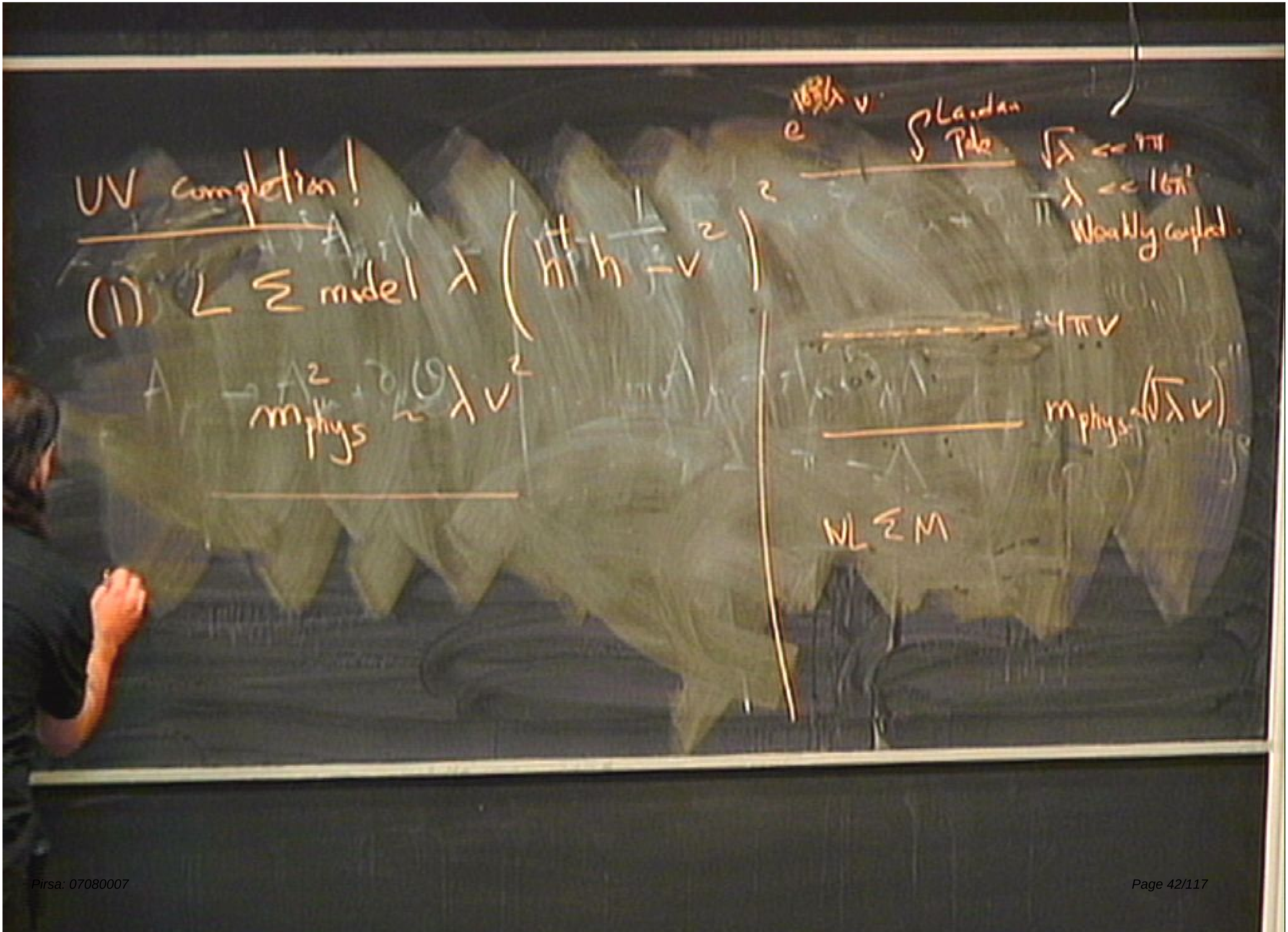

UV completion!
(II) L Σ model λ(H†h − v²)²
m²phys ~ λv²
4πv
mphys ~ (√λ v)
NLΣM


NLΣM
???
(4πv)
E
NLΣM + ...
(gv) ~ m


???
(4πv)
NL ≥ M


UV completion!
(1) L Σ model λ(H†H − ½v²)²
mphys ~ λv²
√λ << 4π
λ << 16π²
Weakly coupled.
4πv
mphys ~ (√λ v)
WLΣM


UV completion!
(II) L Σ model λ(H†h − v²)²
m phys ~ λv²
e v
Landau Pole
√λ << 4π
λ << 16π²
Weakly coupled
4πv
m phys ~ (√λ v)
WLΣM


UV completion!
(I) L Σ model λ(H†h − v²)²
m_phys ~ λv²
Landau Pole
√λ << 4π
λ << 16π²
Weakly coupled.
4πv
m_phys ~ (√λ v)
WLΣM

UV completion!

(1) L Σ model $\lambda\left(H^\dagger h - v^2\right)^2$

$m_{phys} \sim \lambda v^2$

$\mathcal{M} \sim \frac{\epsilon^2}{v^2} \sim \frac{m_{phys}^2}{v^2} \sim \lambda$

$e^{16\pi^2/\lambda}\, v$ — Landau Pole

$\sqrt{\lambda} \ll 4\pi$

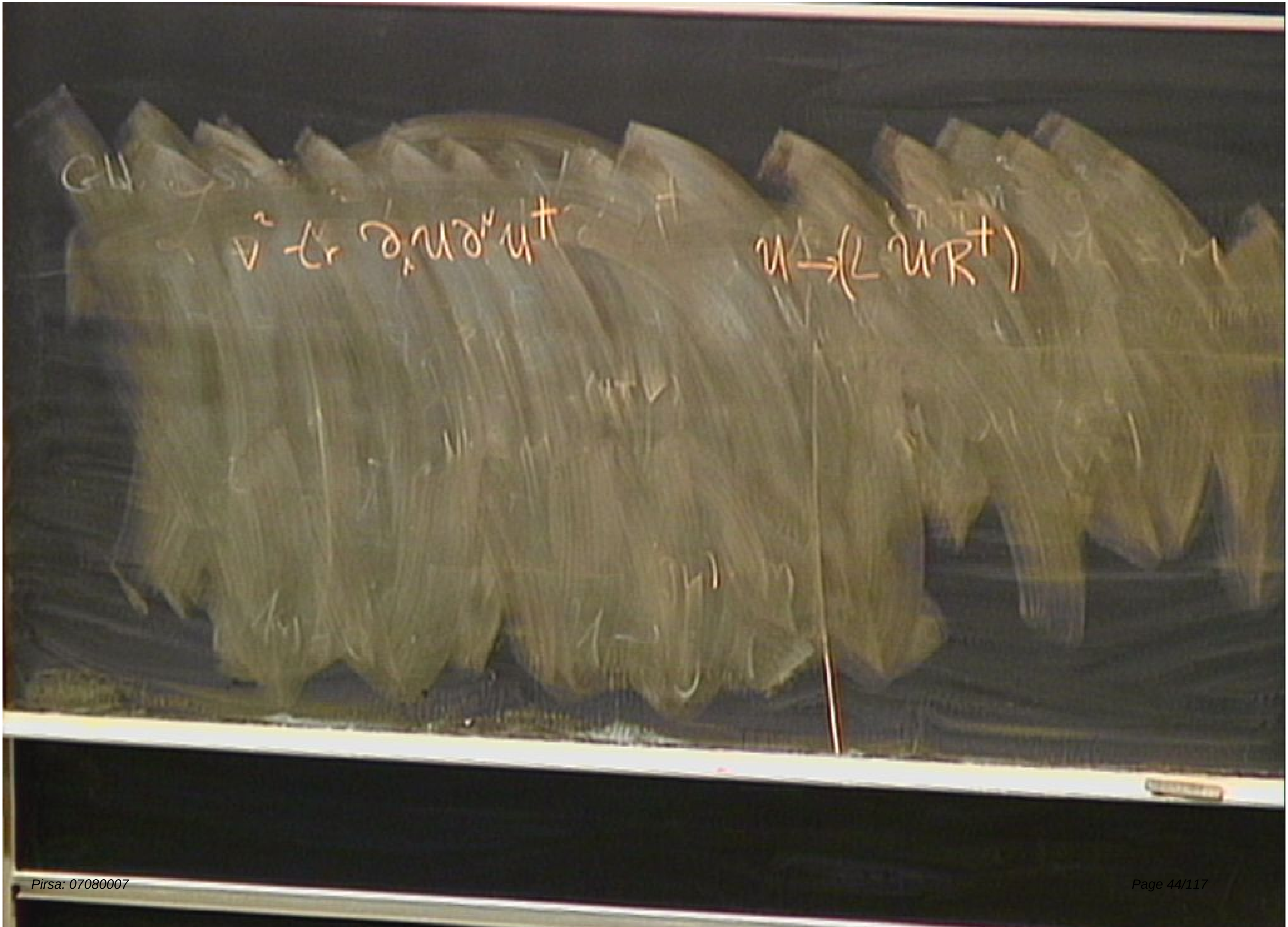
$\lambda \ll 16\pi^2$

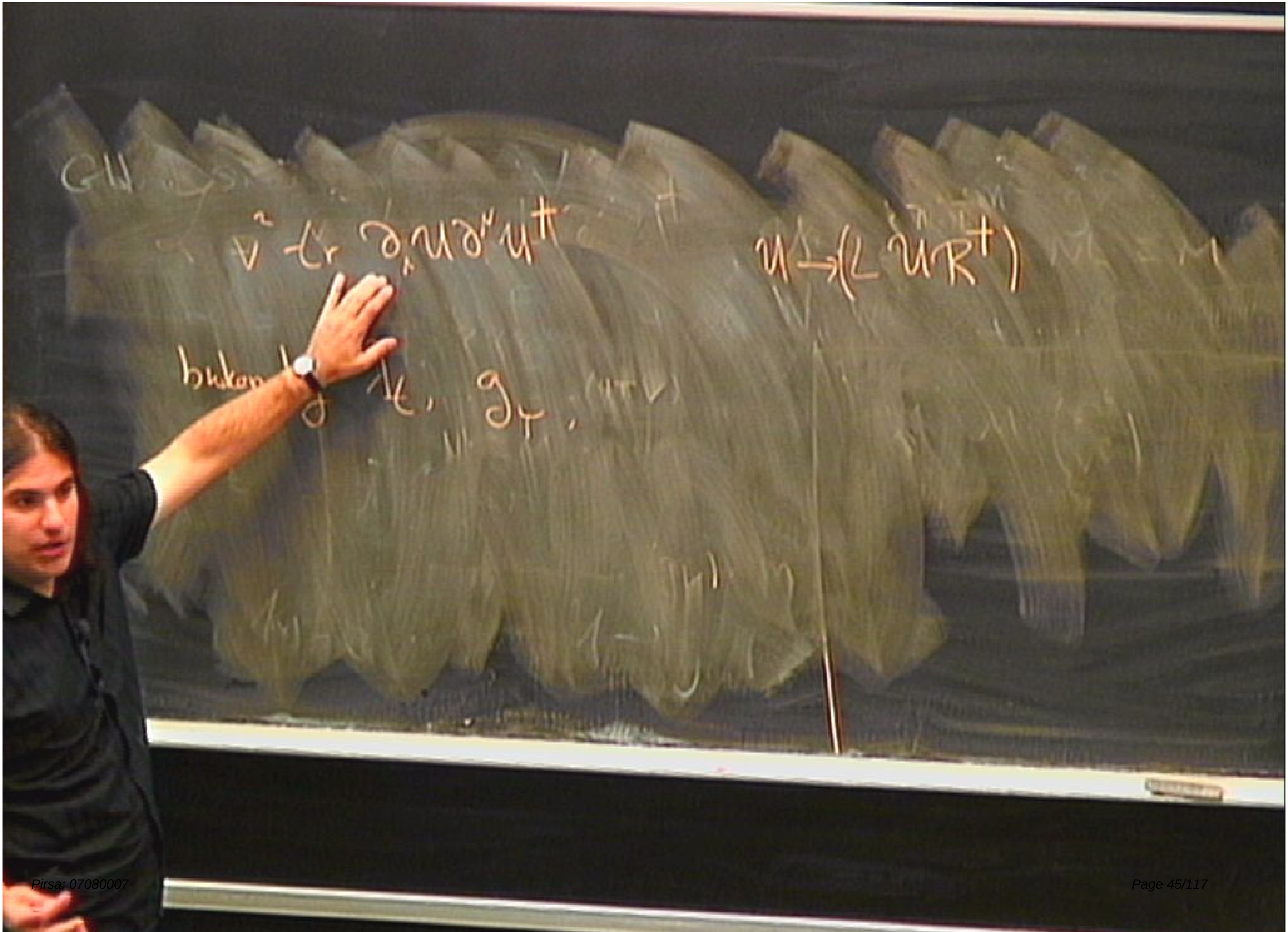
Weakly coupled.

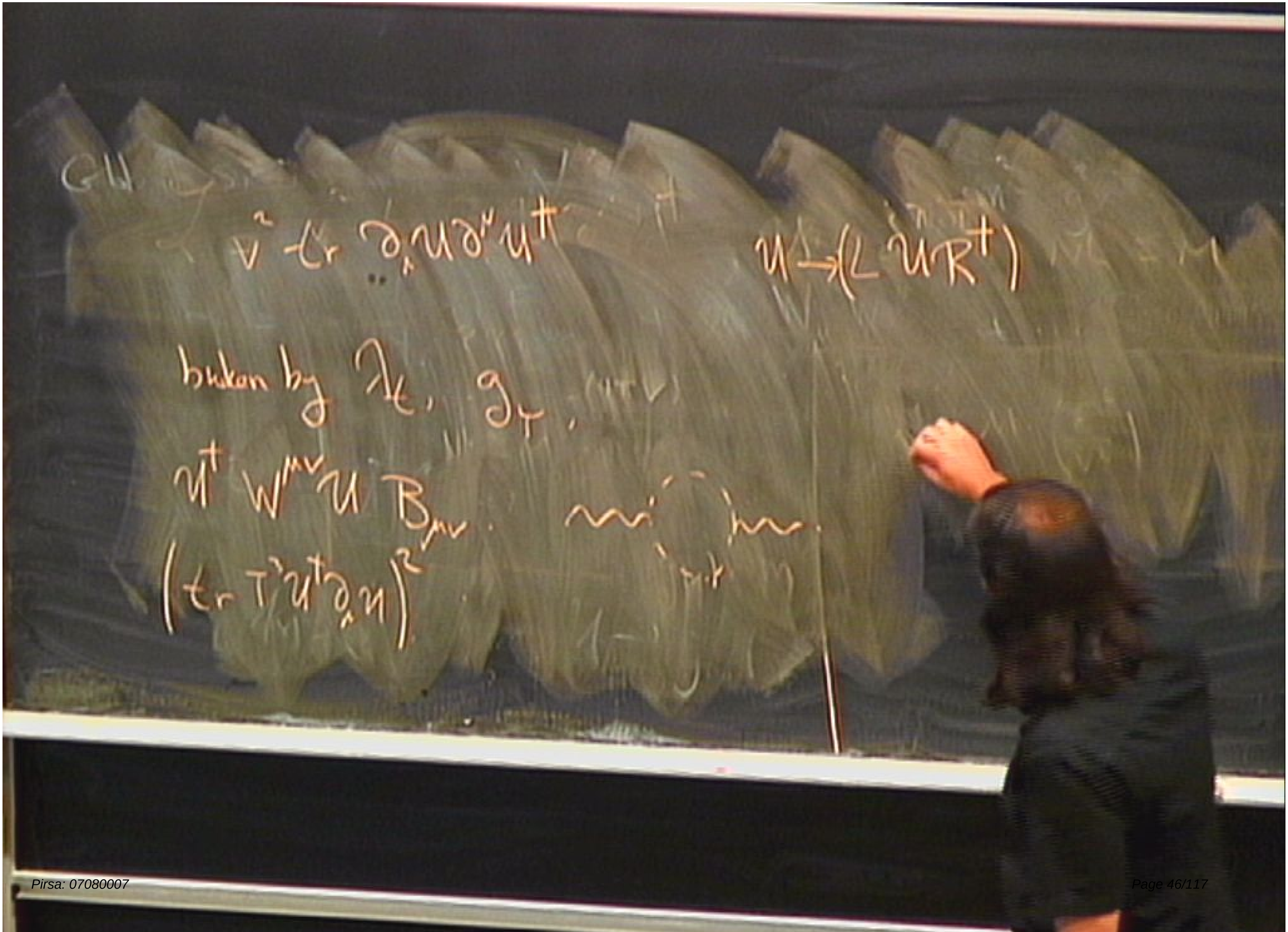
$4\pi v$

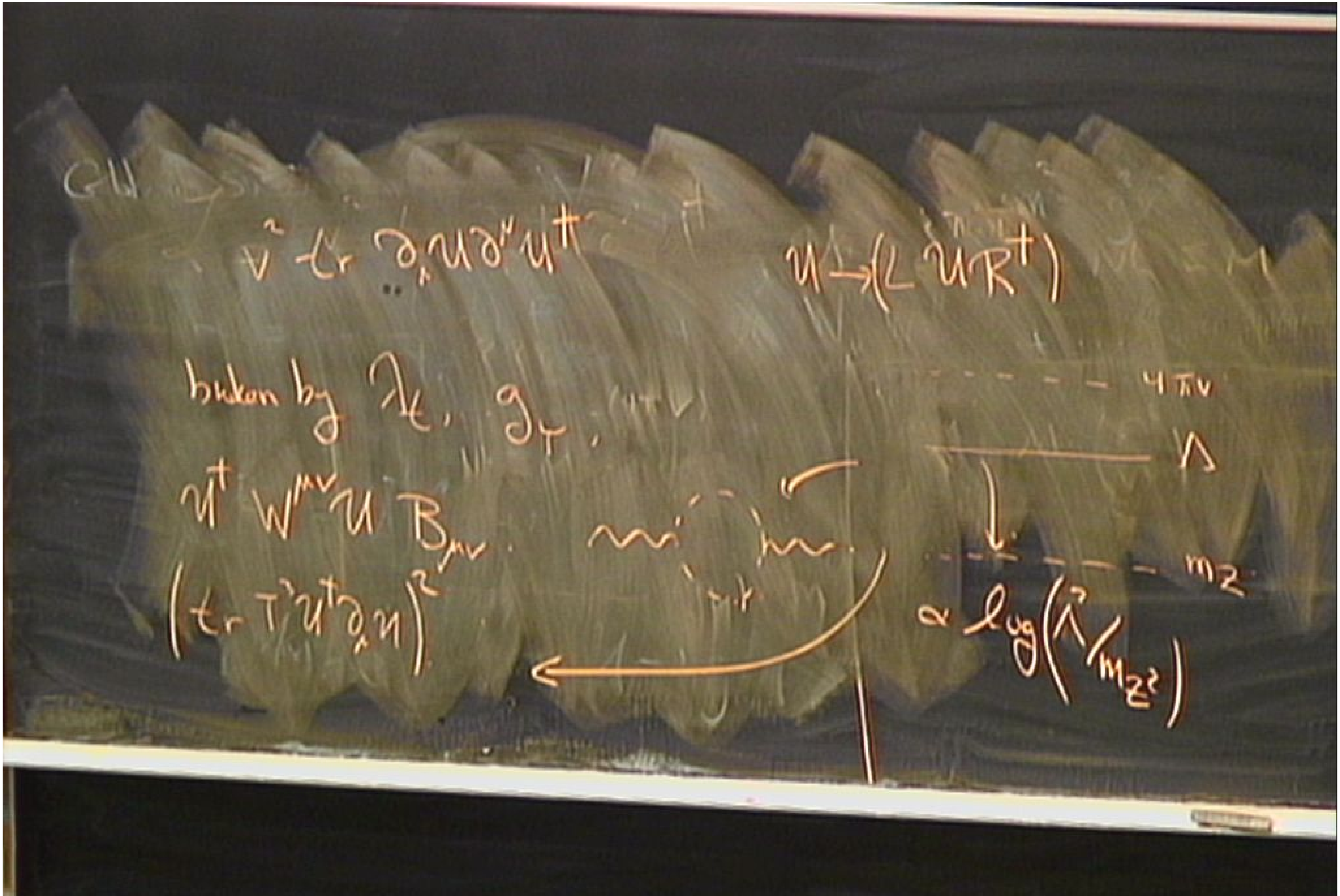
$m_{phys} \sim (\sqrt{\lambda}\, v)$

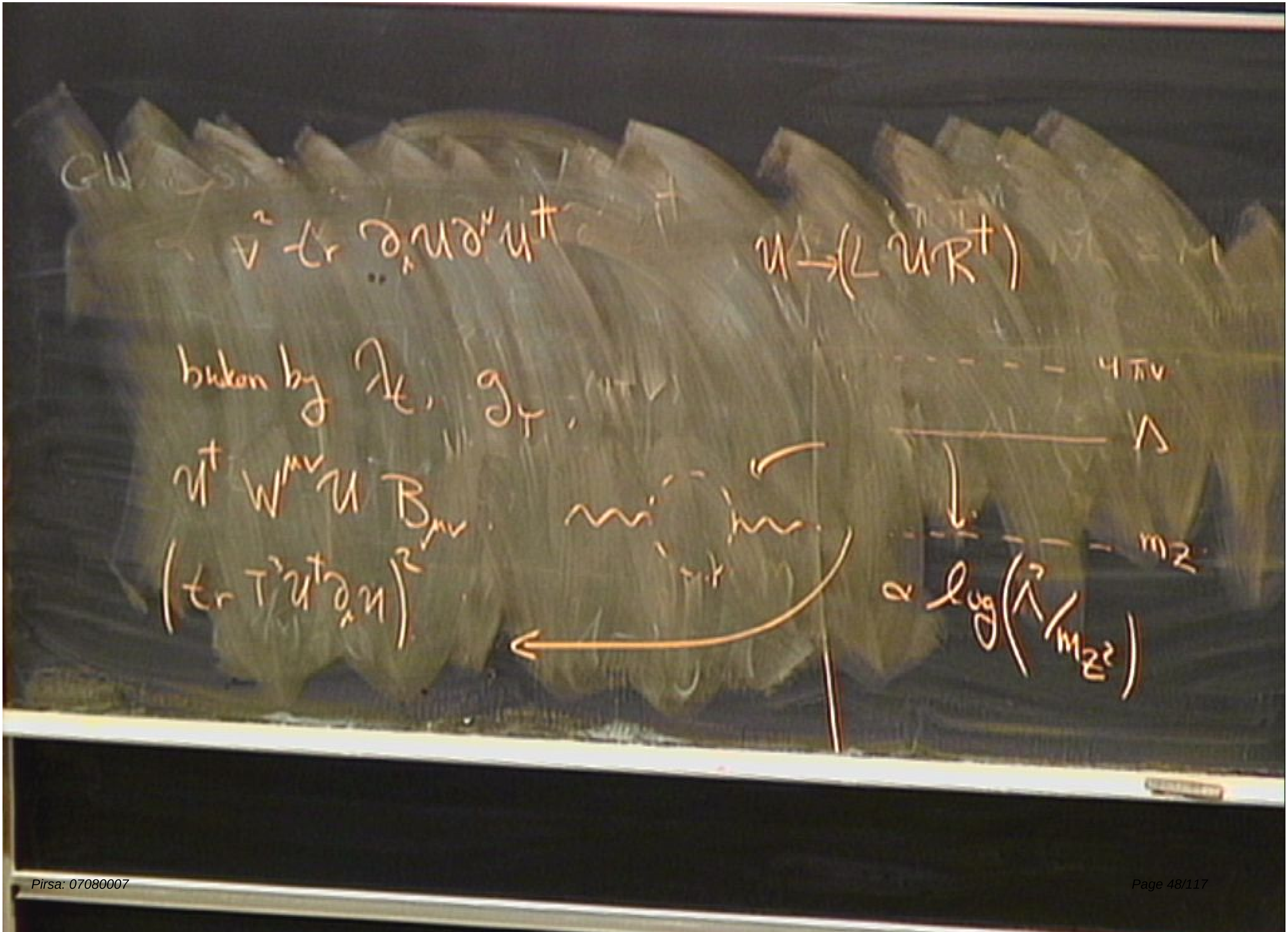
WLΣM

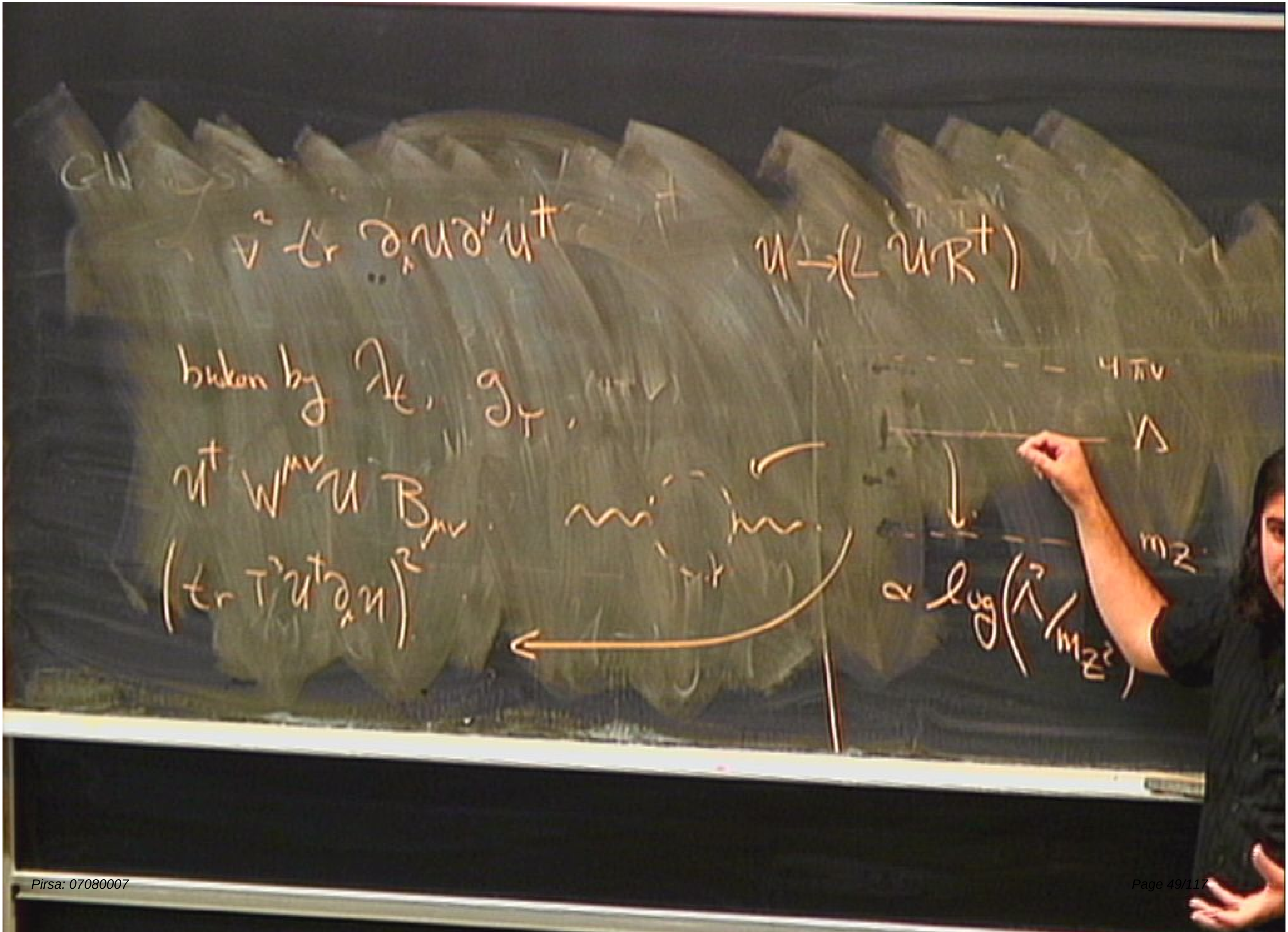

v² tr ∂μU∂μU†
U → (L U R†)

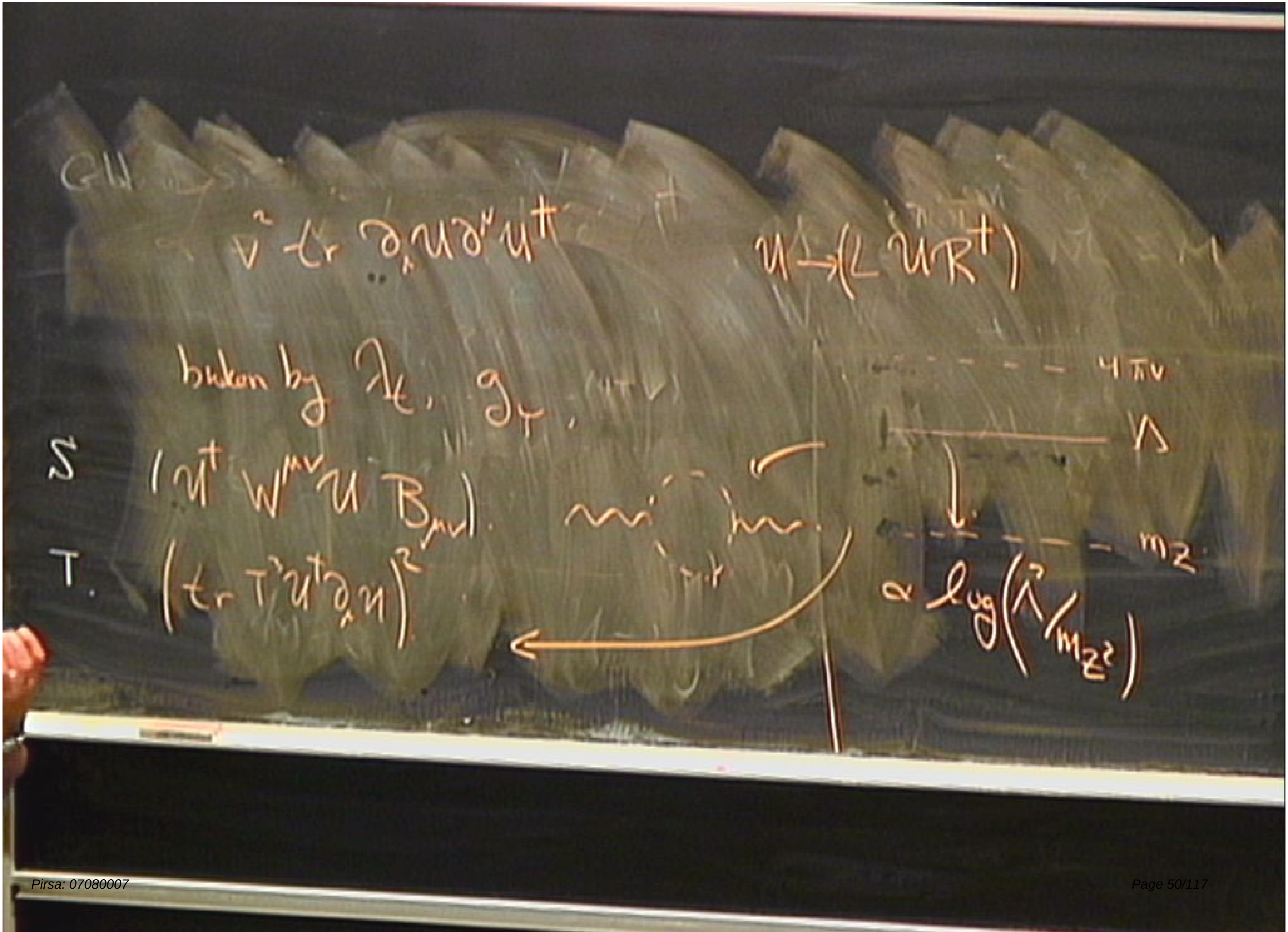



v² tr ∂μU∂^μU†
U → L U R†
broken by λt, gY
U† W^μν U B_μν
(tr T³U†∂μU)²


v² tr ∂μ U ∂^μ U†
U → (L U R†)
broken by λt, gY
U† W^μν U Bμν
(tr T³ U† ∂μ U)²
4πv
Λ
mZ
∝ log(Λ²/mZ²)


v² tr ∂μU∂^μU†
U → L U R†
broken by λt, gY
U† W^μν U Bμν
(tr T³ U† ∂μ U)²
4πv
Λ
mZ
∝ log(Λ²/mZ²)


v² tr ∂μU∂μU†
U → (L U R†)
broken by λt, gY
4πv
Λ
U† Wμν U Bμν
(tr T³U†∂μU)²
mZ
∝ log(Λ²/mZ²)


v² tr ∂μU∂μU†
U → L U R†
broken by λt, gY
S (U† Wμν U Bμν)
T. (tr T³ U† ∂μ U)²
4πv
Λ
mZ
∝ log(Λ²/mZ²)

$U \in$

$v^2 \, \mathrm{tr}\, \partial_\mu U \partial^\mu U^\dagger$ $\quad$ $U \to L U R^\dagger$

$W_3^{\mu\nu} B_{\mu\nu}$

$M_W^2 \ (\propto M_Z^2)$ broken by λ_t, g_Y.

S $\quad (U^\dagger W^{\mu\nu} U B_{\mu\nu})$.

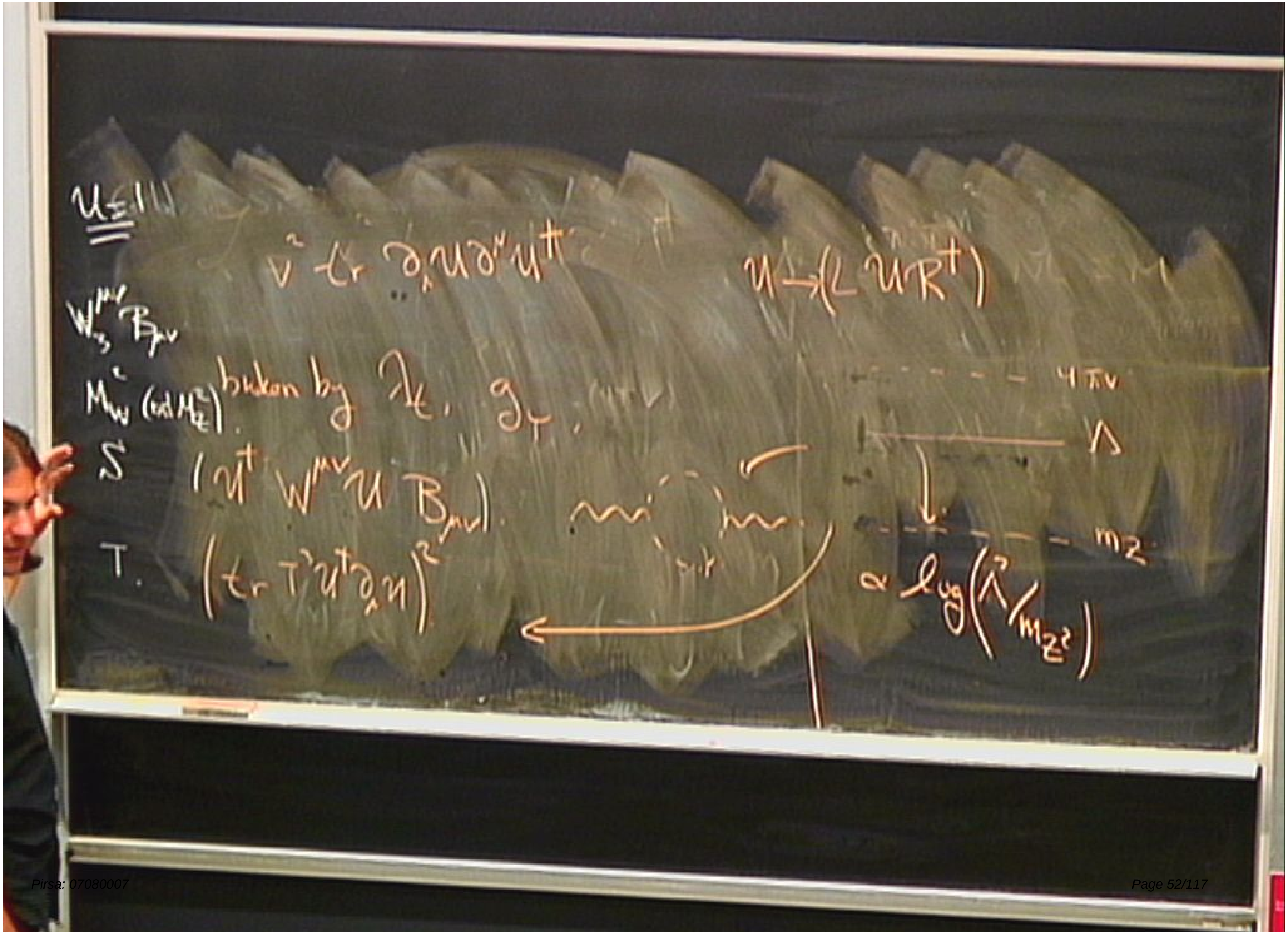
T. $\quad (\mathrm{tr}\, T^3 U^\dagger \partial_\mu U)^2$

$4\pi v$

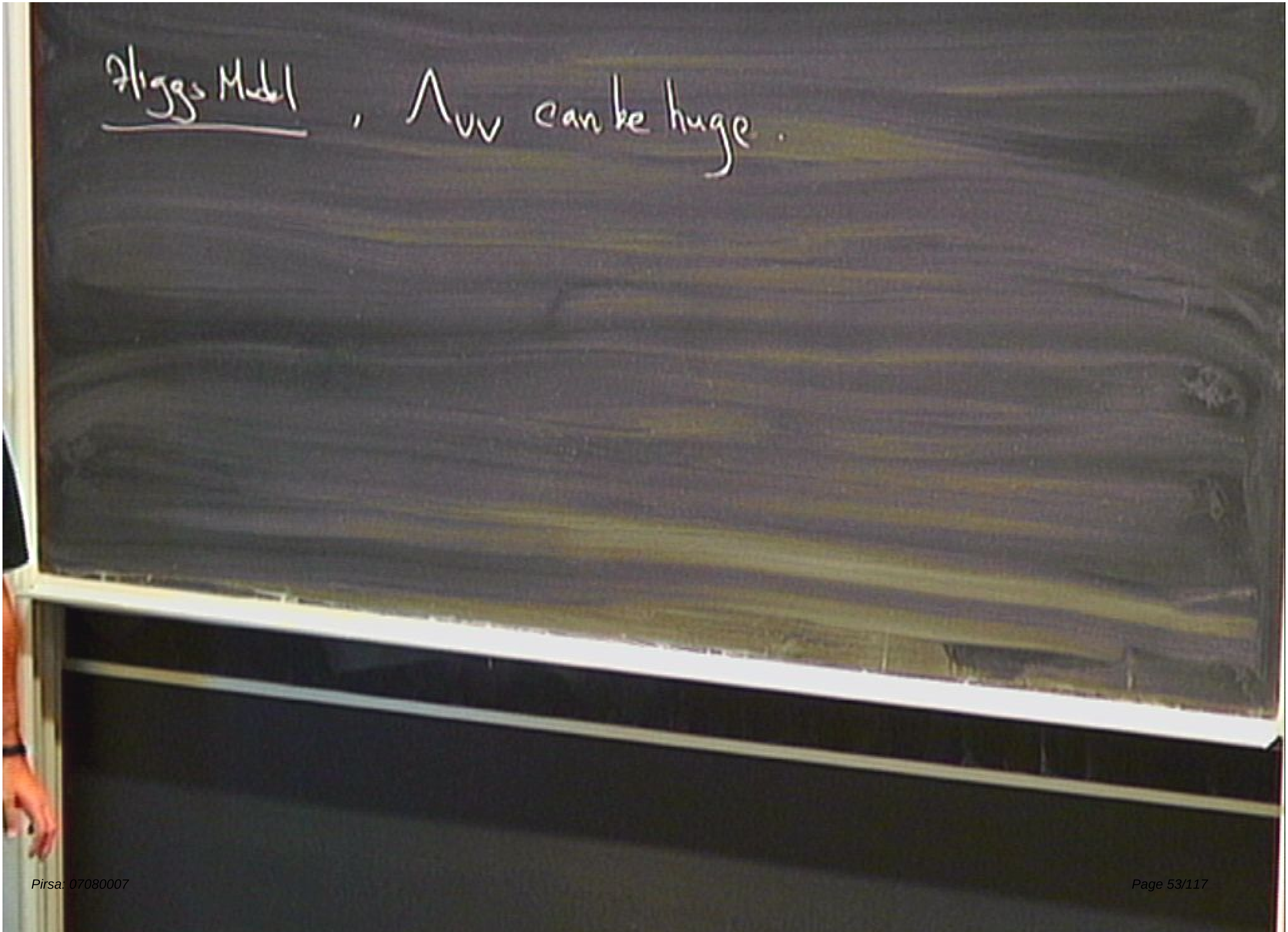
Λ

m_Z

$\propto \log(\Lambda^2 / m_Z^2)$



$v^2 \, tr \, \partial_\mu U \partial^\mu U^\dagger$
$U \to (L U R^\dagger)$
$W_3^{\mu\nu} B_{\mu\nu}$
M_W^2 (rel M_Z^2) broken by λ_t, g_Y
S
$(U^\dagger W^{\mu\nu} U B_{\mu\nu})$
T.
$(tr \, T^3 U^\dagger \partial_\mu U)^2$
$4\pi v$
Λ
m_Z
$\propto \log(\Lambda^2 / m_Z^2)$


Higgs Model , Λ_{UV} can be huge .

Higgs Model, Λ_{UV} can be huge.

B, L; CP, Flavor, ... —— Λ_{UV}

(ren +) $\frac{1}{\Lambda_{UV}}$ + ...

↑ accidental symmetries

Higgs Model, Λ_{UV} can be huge.

B, L; CP, Flavor, ... —— Λ_{UV}

$\frac{(qqq)\ell}{M^2}$. $\not{B}$ (p-decay)

$\frac{\ell h \ell h}{M}$

ren + $\frac{1}{\Lambda_{UV}}$ + ...

accidental symmetries

Higgs Model, Λ_{UV} can be huge.

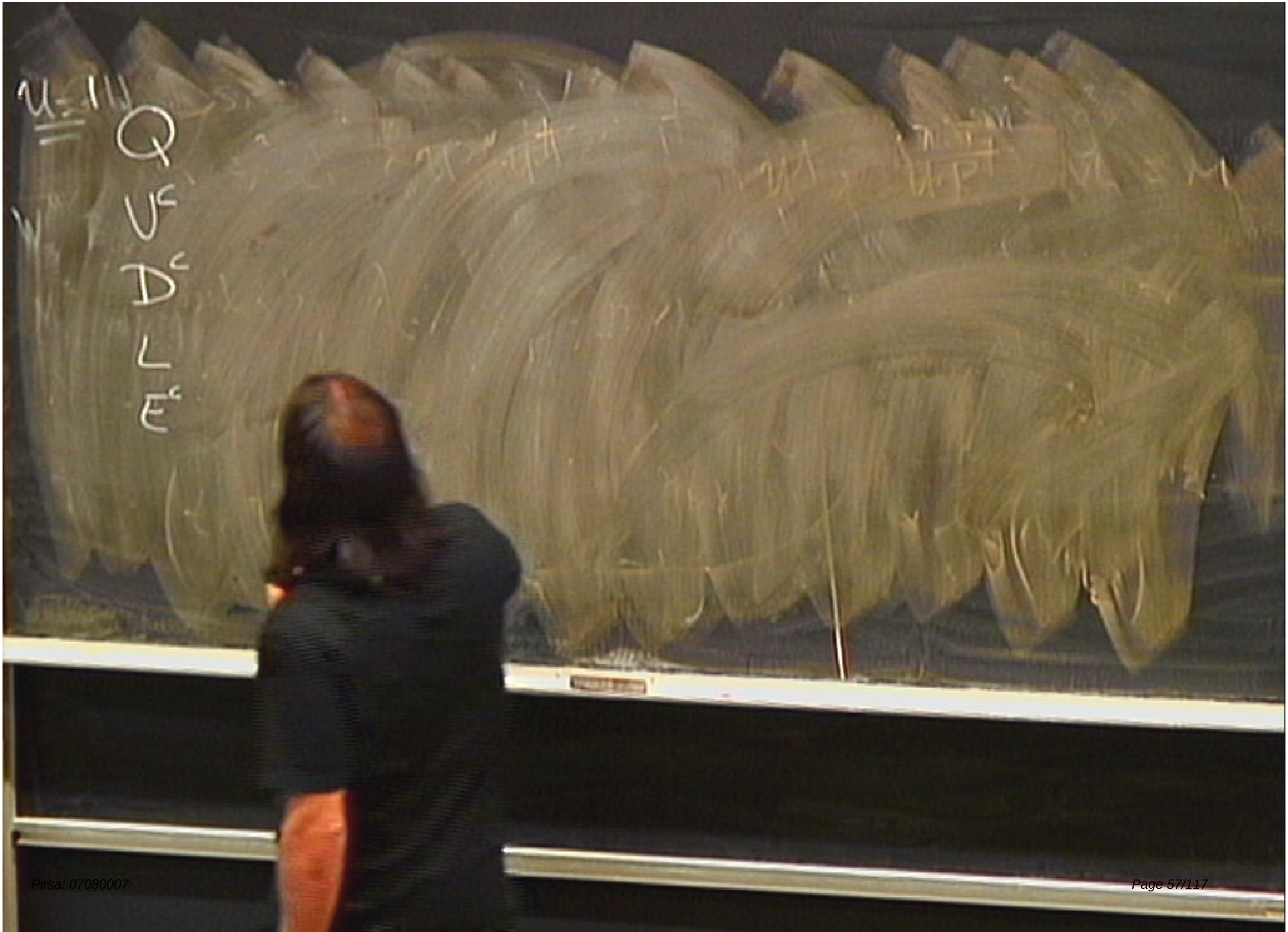
B, L; CP, Flavor, ... —— Λ_{UV}

$\frac{(qqq)\ell}{M^2}$. $\not{B}$ (p-decay)

$\frac{(\ell h)(\ell h)}{M}$. $m_\nu \sim \frac{v^2}{M}$.

(ren +) $\frac{1}{\Lambda_{UV}} + \cdots$

accidental symmetries


Q
U^c
D^c
L^c
E^c

$\mathcal{N}=1$

Q

U^c

D^c

L

E^c

$$Q \lambda_U h^* U^c + Q \lambda_D h D^c + L \lambda_E h E^c$$

$$\lambda_{U,D,E} \to 0 \qquad U(3)_Q \times U(3)_{U^c} \times U(3)_{D^c} \times U(3)_{E^c} \times U(3)_L$$

$$U(3)^5$$

Q

U^c

D^c

L

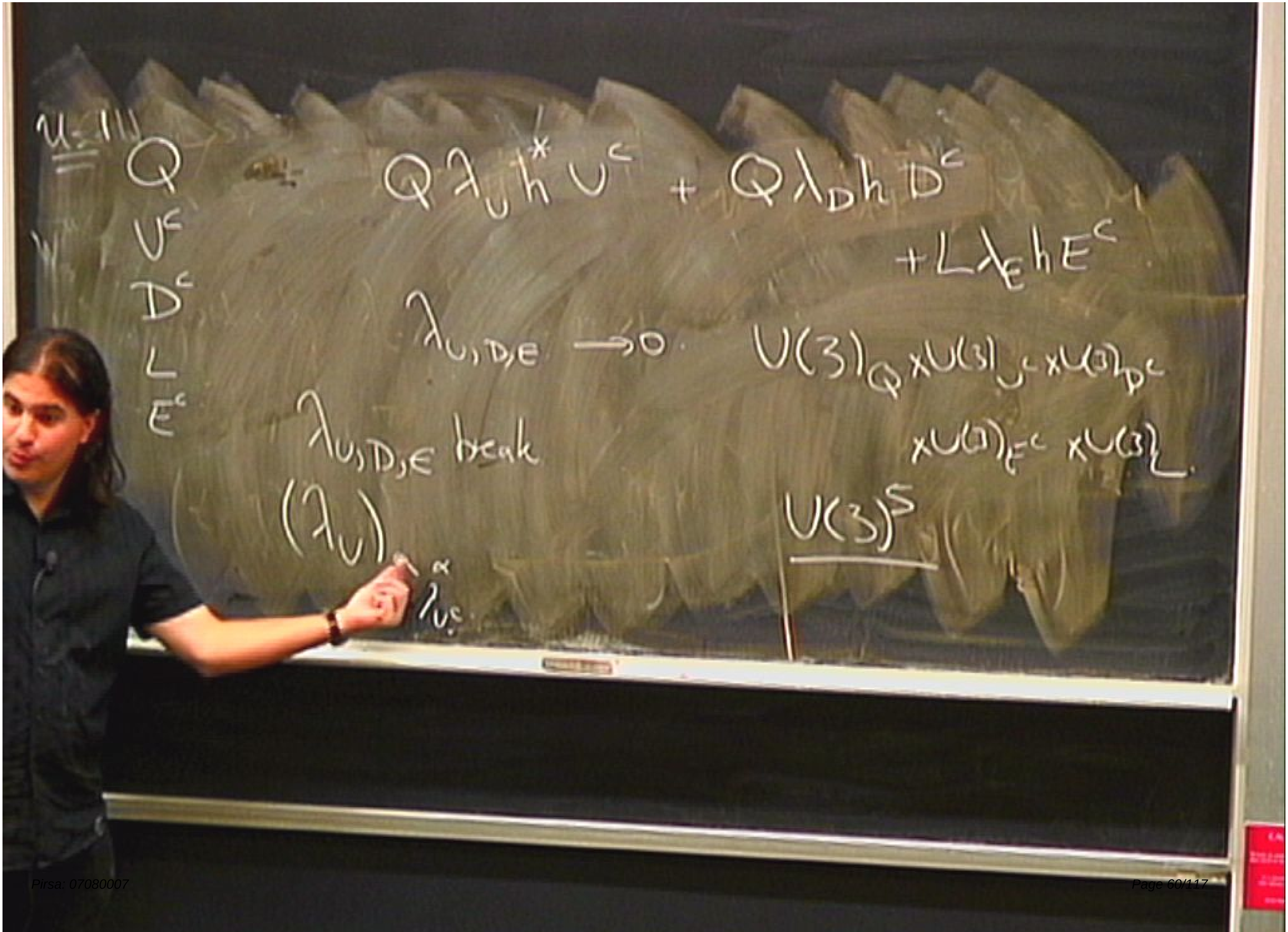
E^c

$$Q \lambda_U h^* U^c + Q \lambda_D h D^c + L \lambda_E h E^c$$

$\lambda_{U,D,E} \to 0$ $\quad U(3)_Q \times U(3)_{U^c} \times U(3)_{D^c} \times U(3)_{E^c} \times U(3)_L$

$\lambda_{U,D,E}$ break

$U(3)^5$


Q
U^c
D^c
L
E^c
Q λ_U h* U^c + Q λ_D h D^c
+ L λ_E h E^c
λ_U,D,E → 0
U(3)_Q x U(3)_U^c x U(3)_D^c
x U(3)_E^c x U(3)_L
λ_U,D,E break
(λ_U)
U(3)^5

Q

U^c

D^c

L

E^c

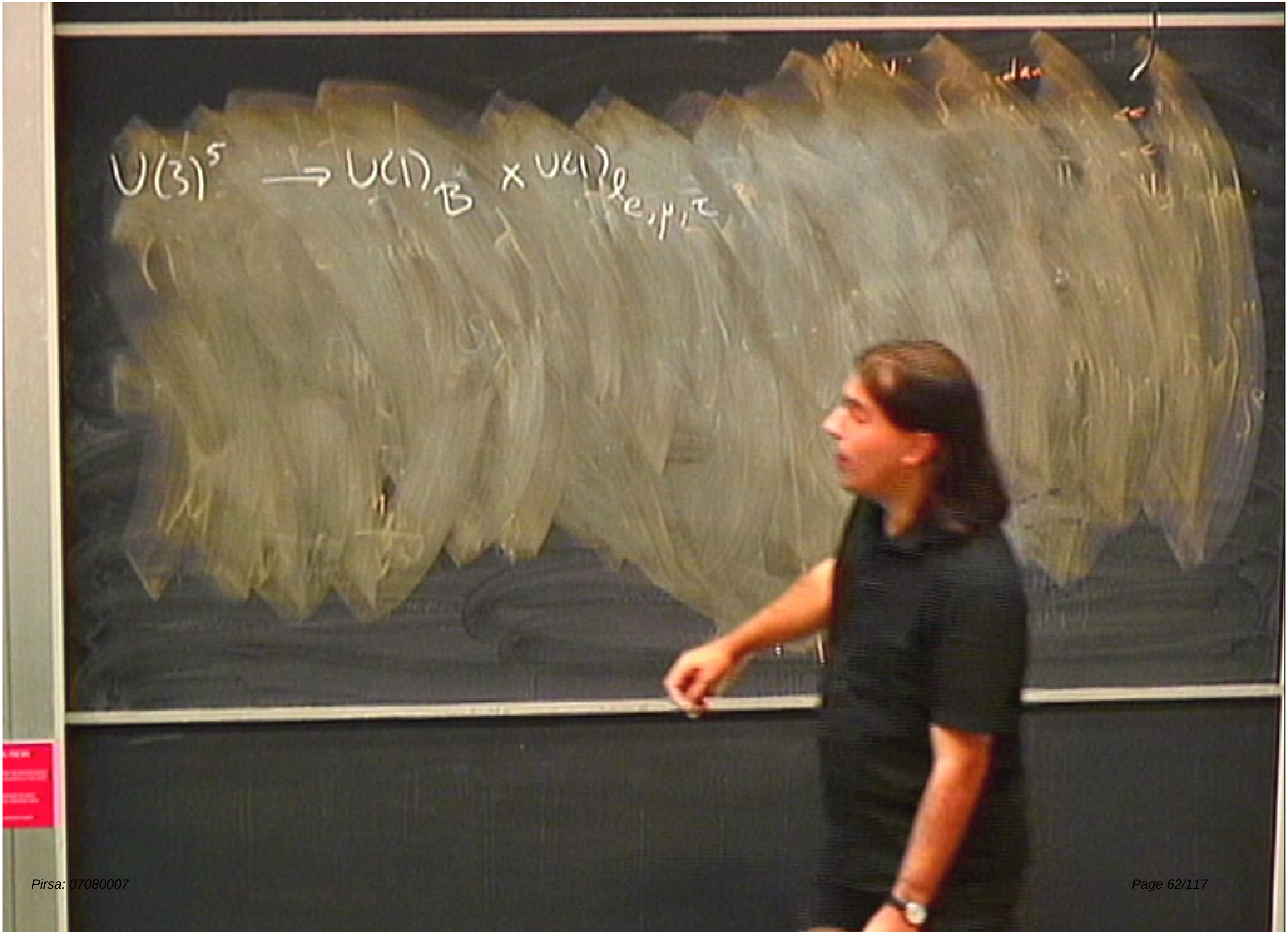
$$Q\lambda_U h^* U^c + Q\lambda_D h D^c + L\lambda_E h E^c$$

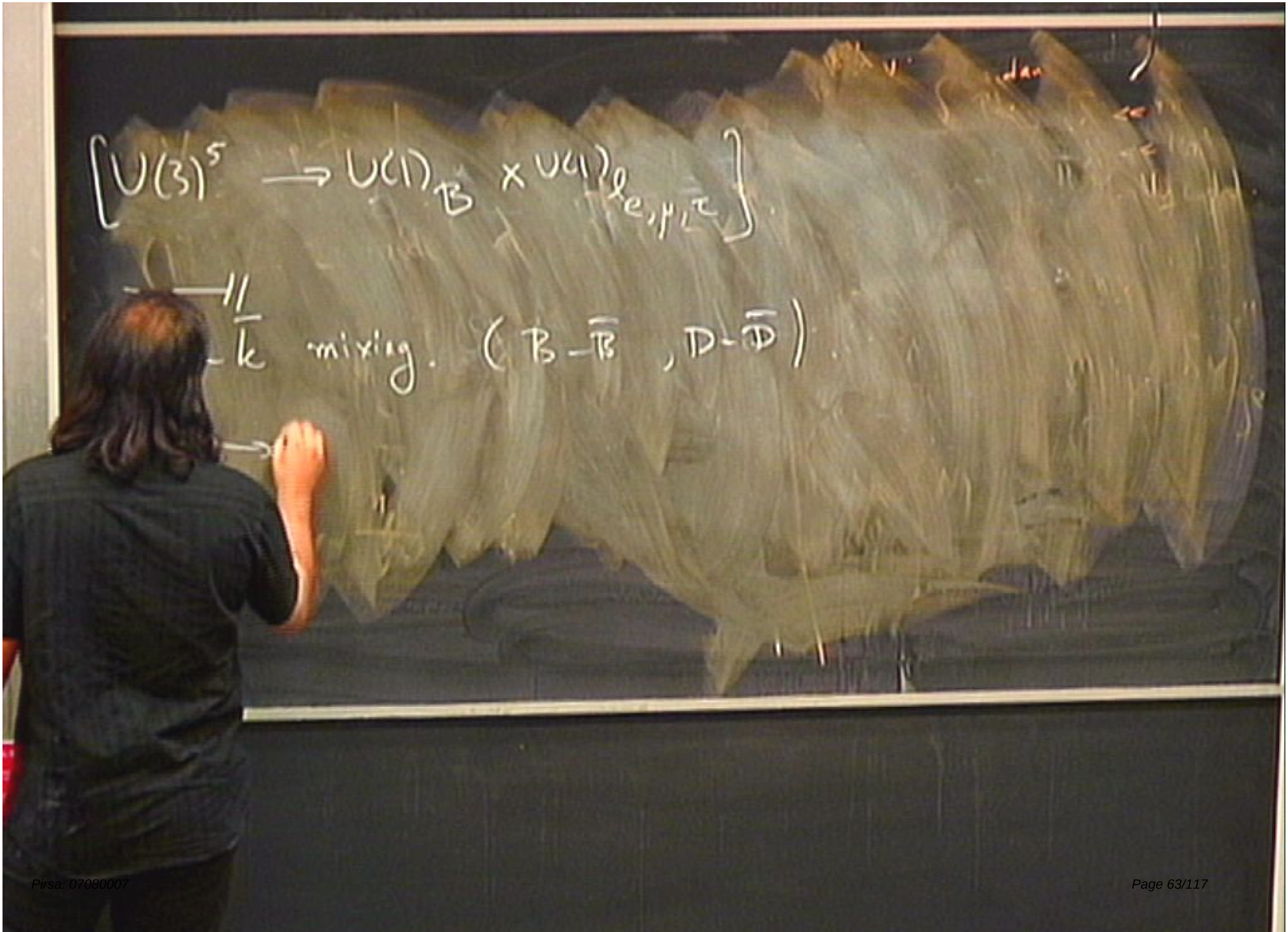
$$\lambda_{U,D,E} \to 0 \qquad U(3)_Q \times U(3)_{U^c} \times U(3)_{D^c} \times U(3)_{E^c} \times U(3)_L$$

$\lambda_{U,D,E}$ break

$$(\lambda_U)_{a\alpha} \quad \underline{U(3)^5}$$

$Q \quad U^c$


U(3)^5 → U(1)_B × U(1)_{e,μ,τ}

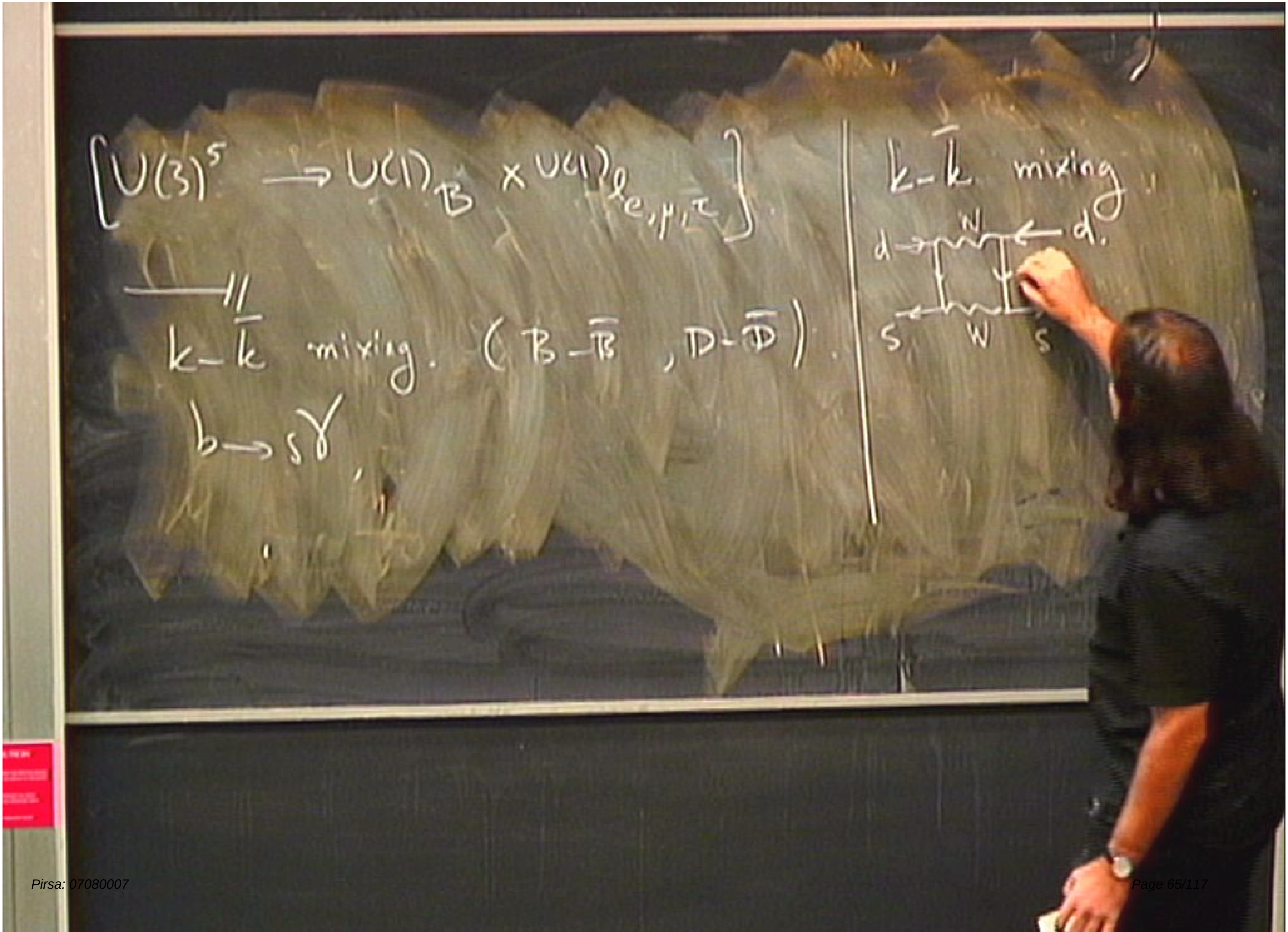

[U(3)^5 → U(1)_B × U(1)_e,μ,τ]
k mixing. (B - B̄ , D - D̄)

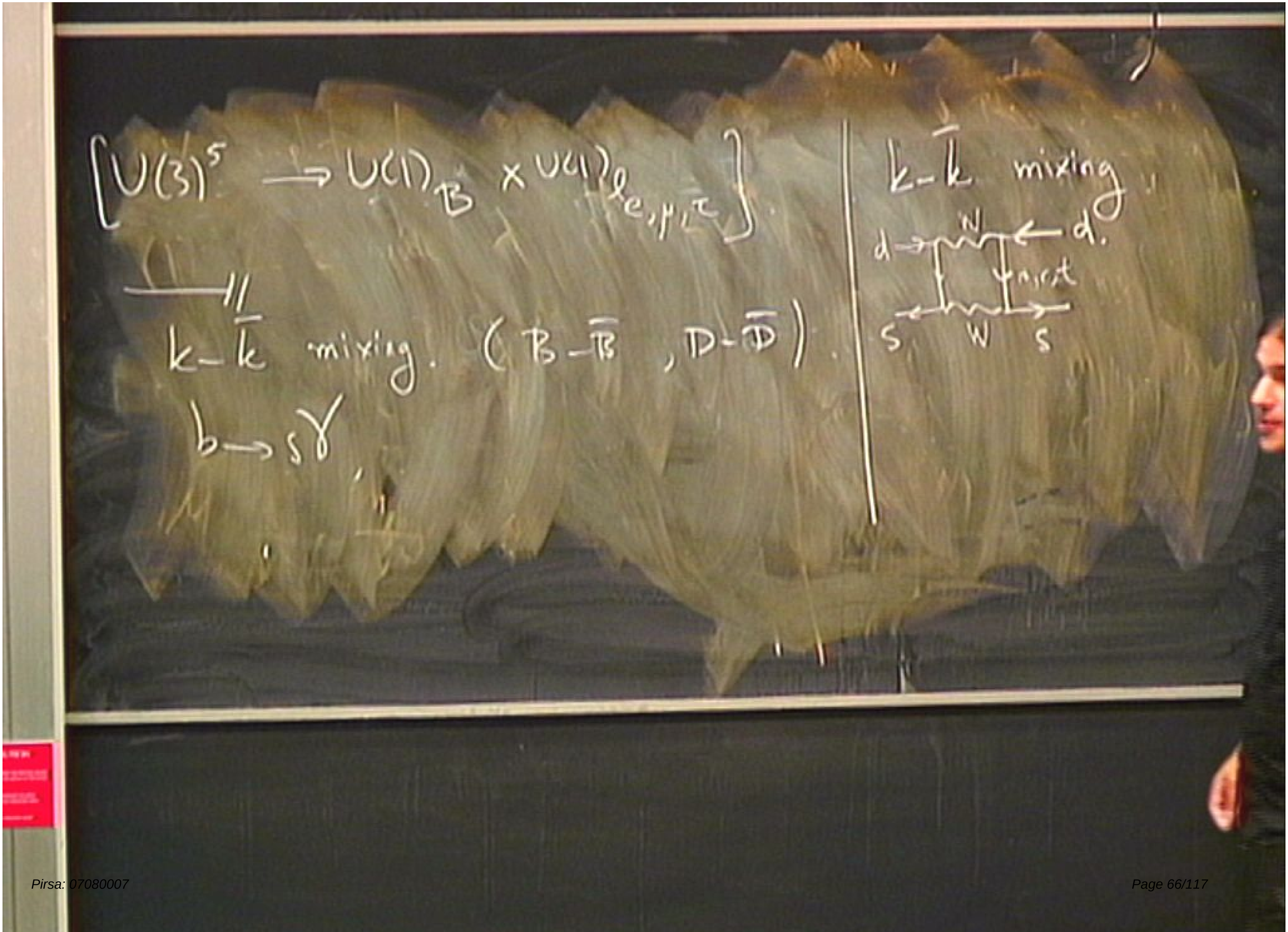
$$\left[U(3)^5 \longrightarrow U(1)_B \times U(1)_{e,\mu,\tau}\right]$$

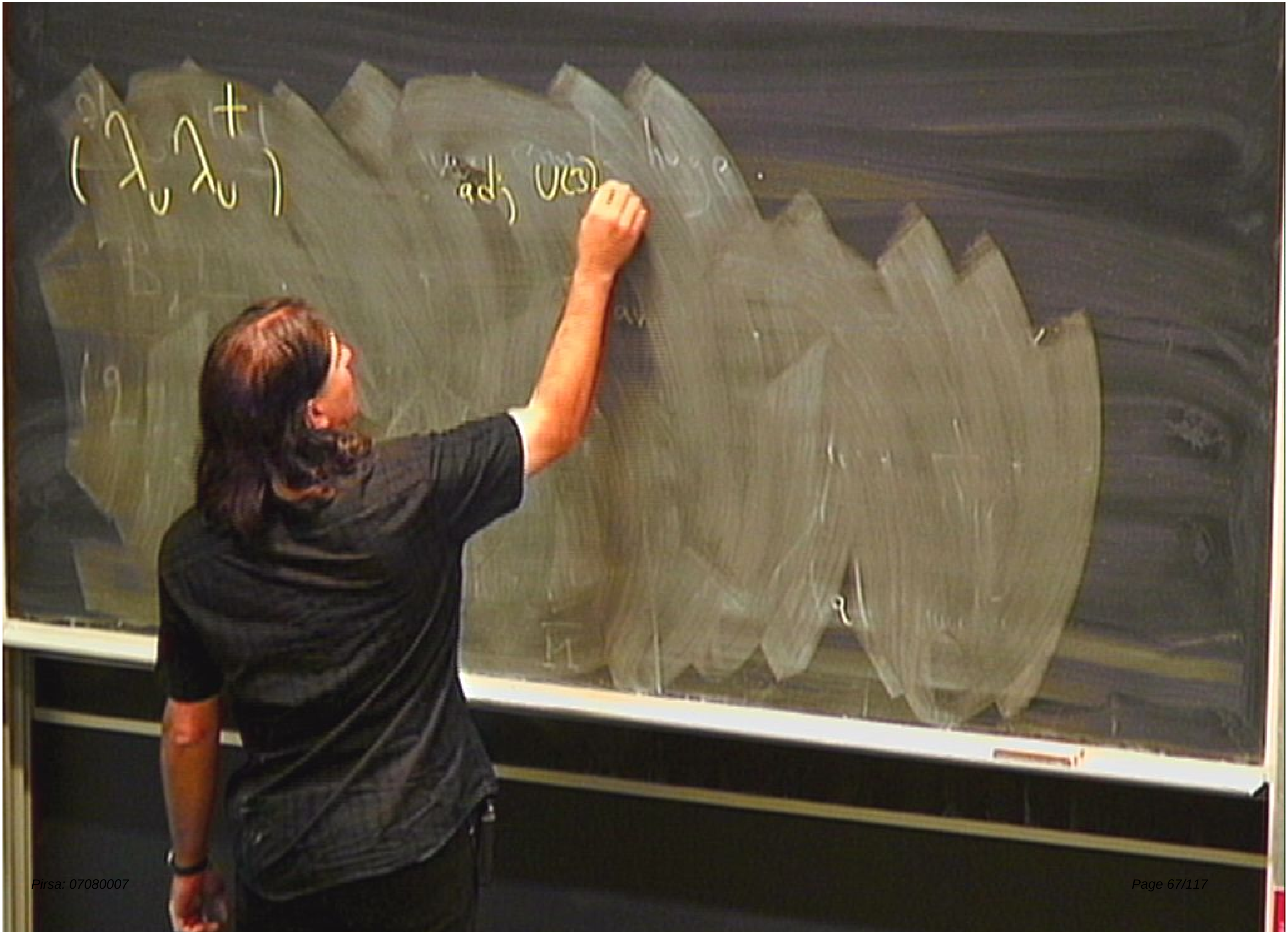
$\longrightarrow\!\!\!/\!/$

$K-\bar{K}$ mixing. $(B-\bar{B}\ ,\ D-\bar{D})$

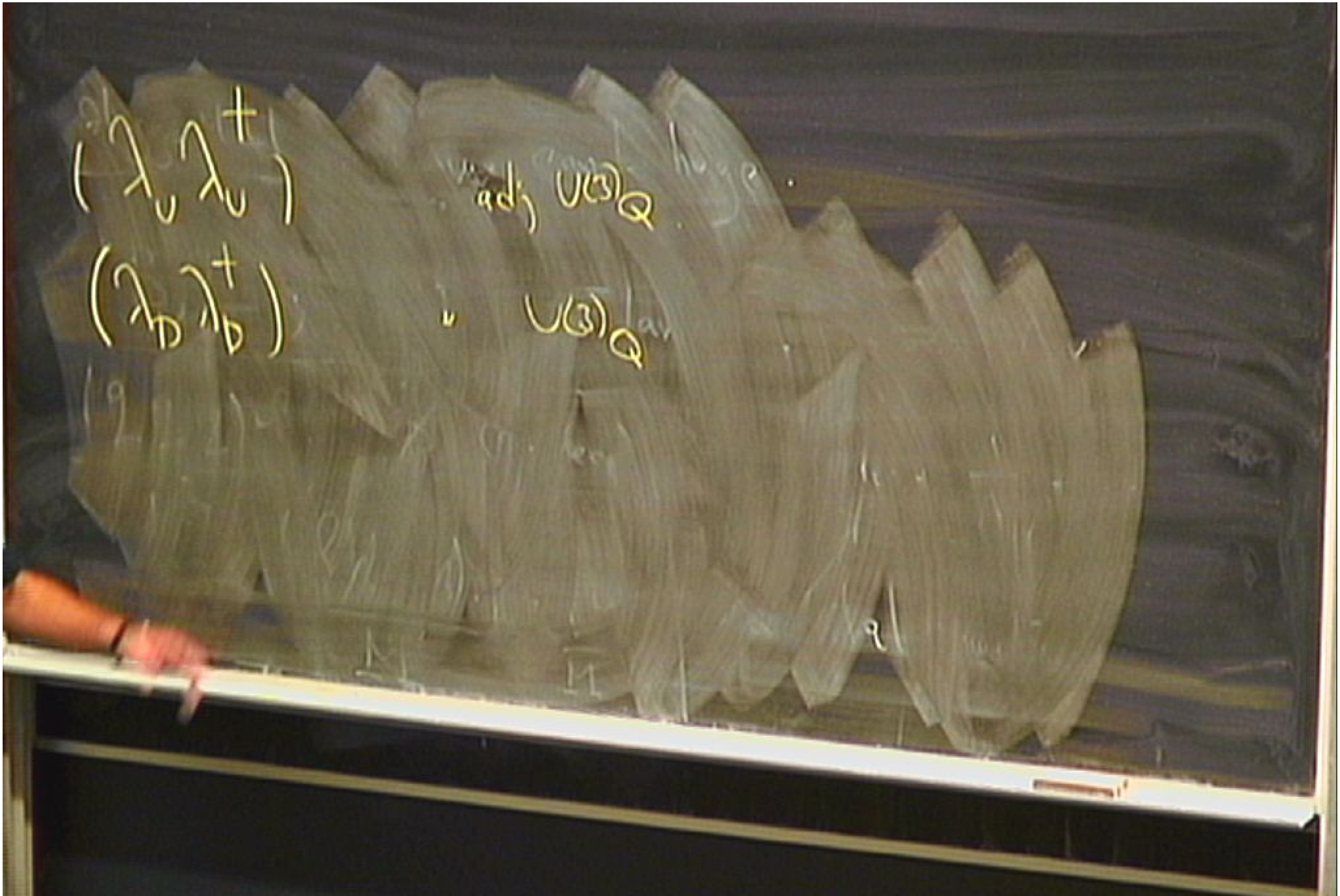
$b \to s\gamma$

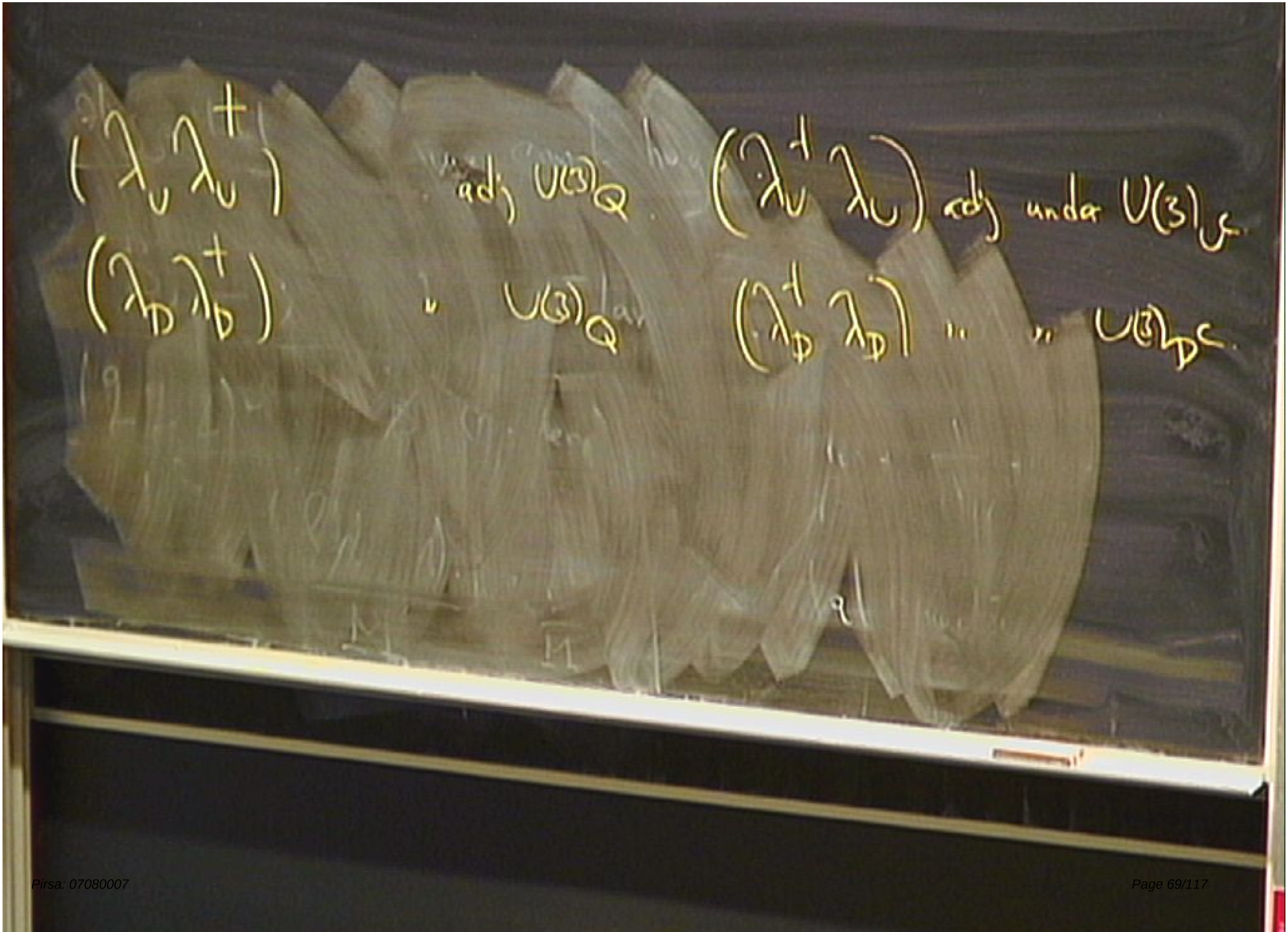

[U(3)^5 → U(1)_B × U(1)_{e,μ,τ}]
K–K̄ mixing. (B–B̄, D–D̄)
b → sγ
K–K̄ mixing
d → W ← d
s ← W s

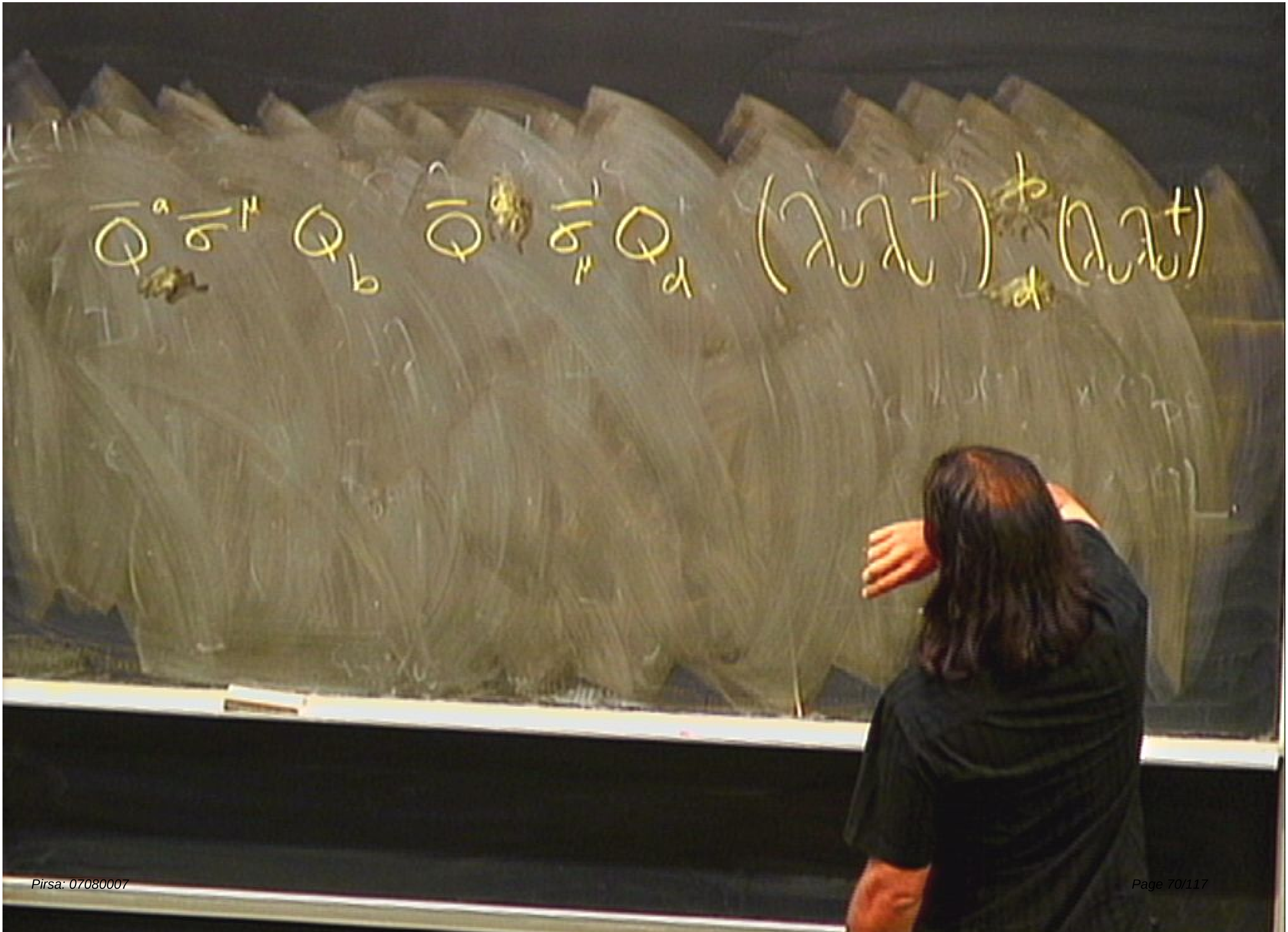

[U(3)^5 → U(1)_B × U(1)_{e,μ,τ}]
k – k̄ mixing. (B – B̄ , D – D̄)
b → sγ
k – k̄ mixing
d → W ← d
u,c,t
s ← W → s



(λν λν†)
adj U(3)

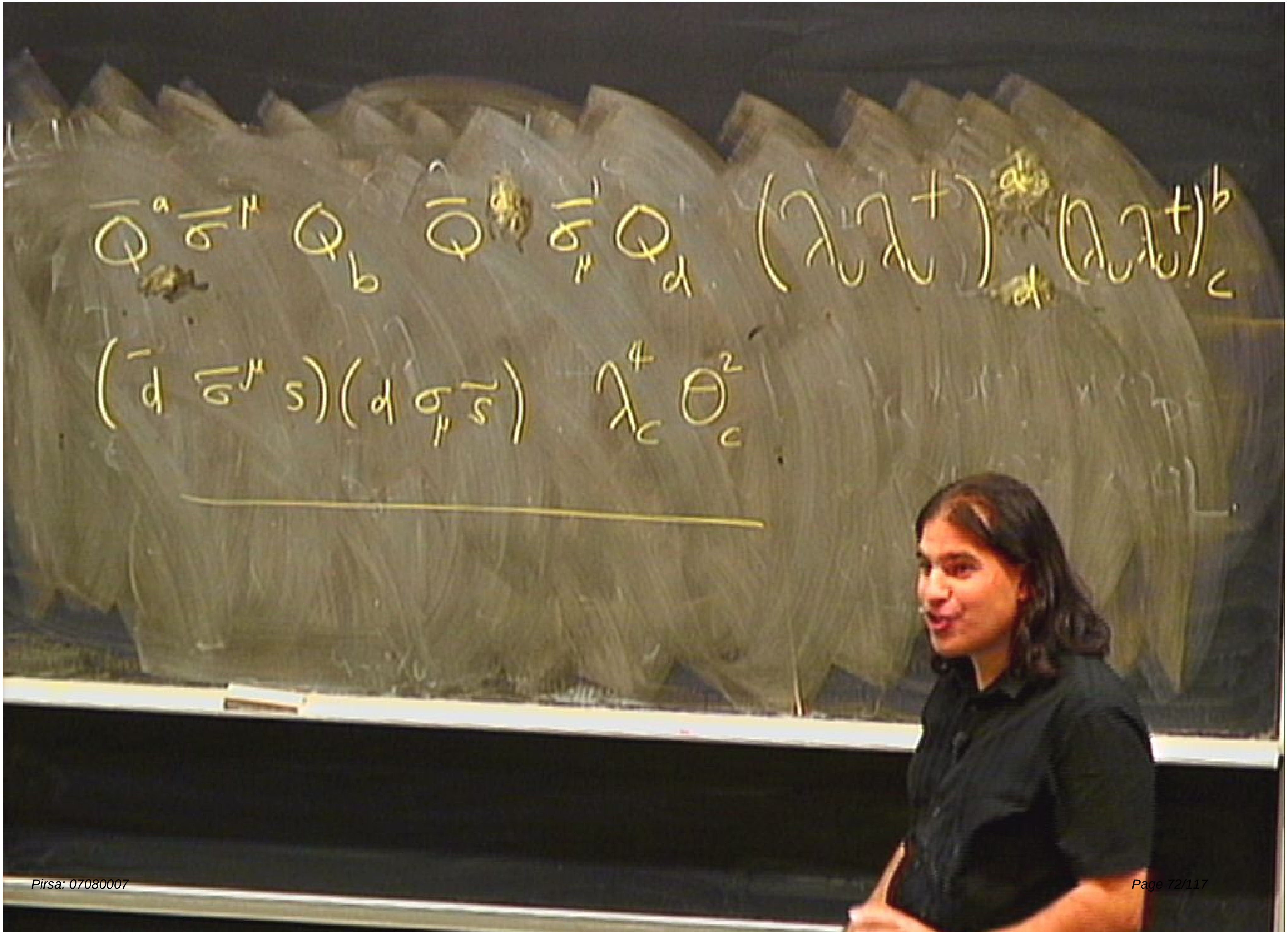

$(\lambda_U \lambda_U^\dagger)$ adj $U(3)_Q$
$(\lambda_D \lambda_D^\dagger)$ " $U(3)_Q$

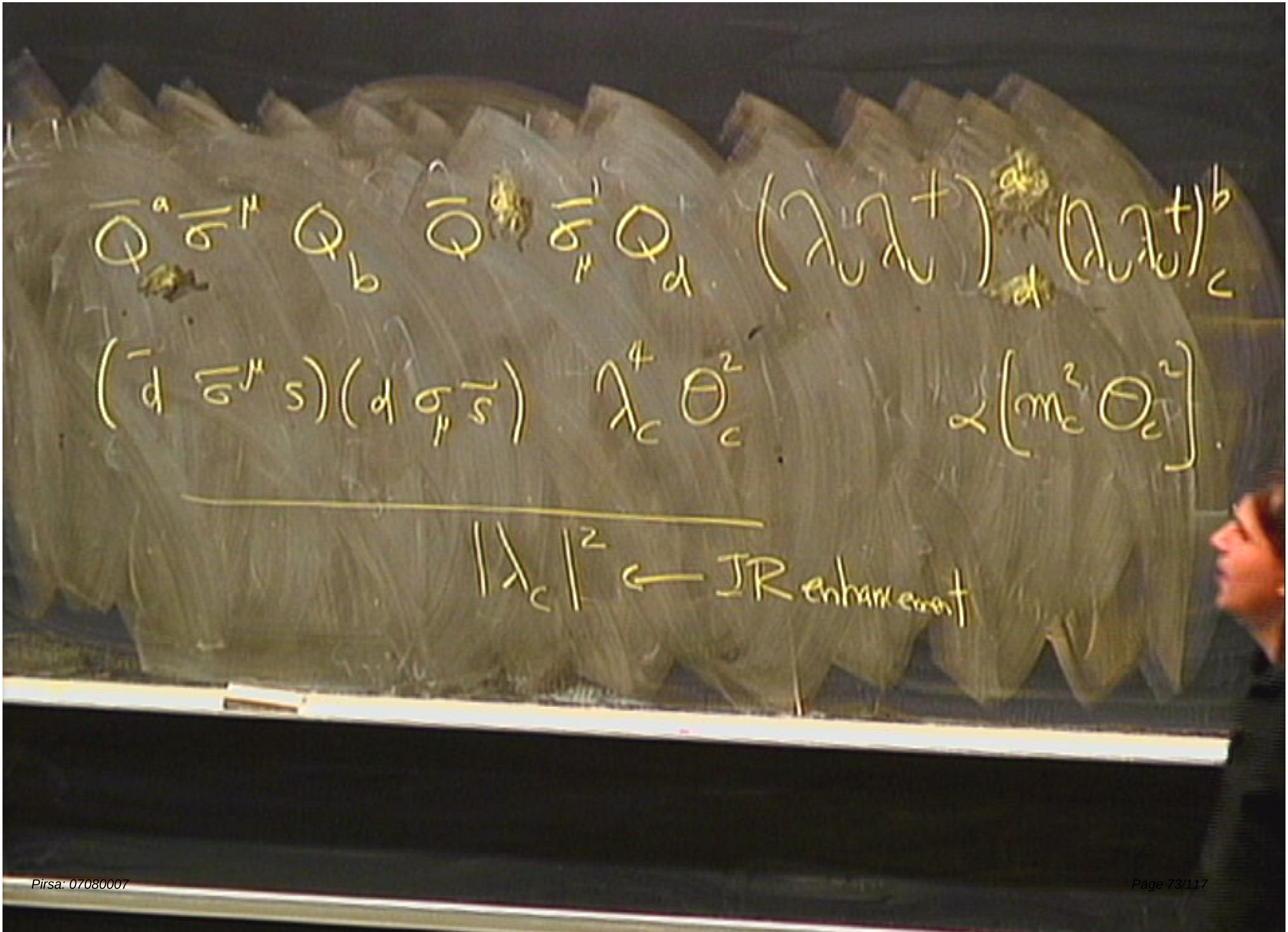

$(\lambda_U \lambda_U^\dagger)$ adj $U(3)_Q$
$(\lambda_U^\dagger \lambda_U)$ adj under $U(3)_{U^c}$
$(\lambda_D \lambda_D^\dagger)$ " $U(3)_Q$
$(\lambda_D^\dagger \lambda_D)$ " " $U(3)_{D^c}$

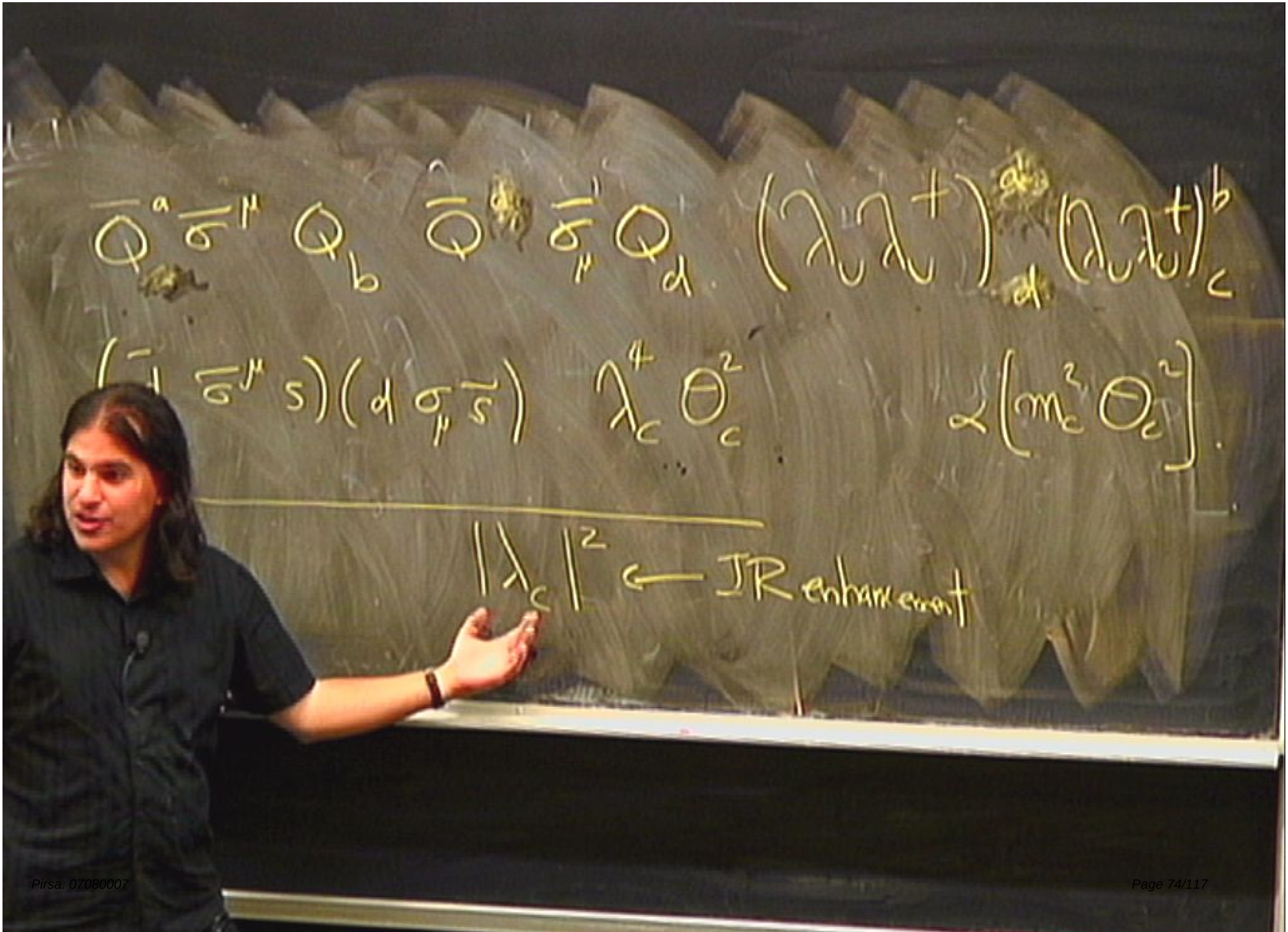

$\bar{Q}^a \bar{\sigma}^\mu Q_b \; \bar{Q} \bar{\sigma}_\mu Q_d \; (\lambda\lambda^\dagger) (\lambda\lambda^\dagger)$

$$\bar{Q}^a \bar{\sigma}^\mu Q_b \quad \bar{Q} \bar{\sigma}_\mu Q_d \quad (\lambda_u \lambda^\dagger) \, (\lambda_u \lambda^\dagger)^b_c$$

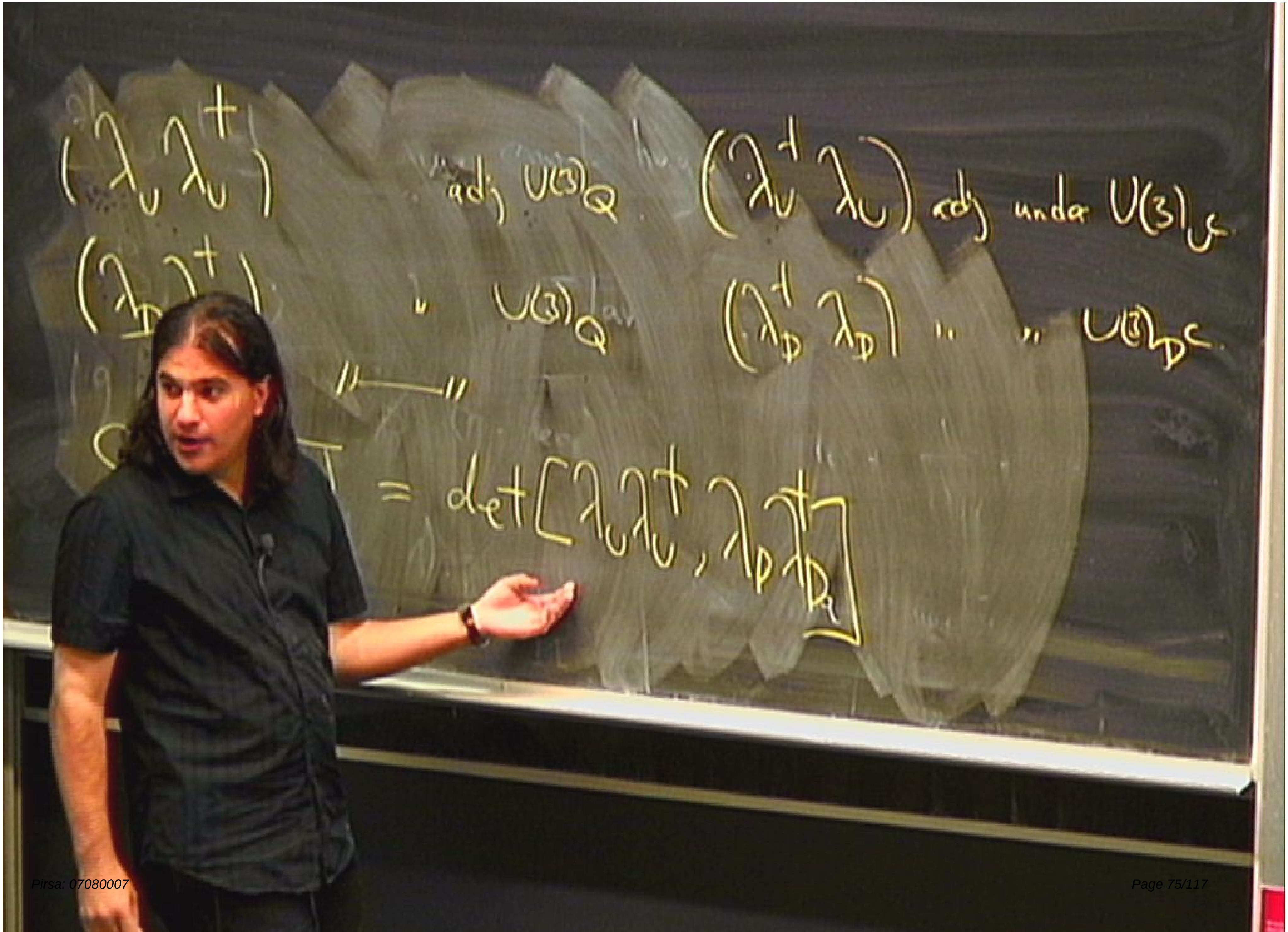
$$(\bar{d} \, \bar{\sigma}^\mu s)(d \, \sigma_\mu \bar{s}) \qquad \lambda_c^4 \, \theta_c^2$$


$\bar{Q}^a \bar{\sigma}^\mu Q_b \; \bar{Q}^d \bar{\sigma}_\mu Q_d \; (\lambda\lambda^\dagger)_a^d (\lambda\lambda^\dagger)_c^b$
$(\bar{d}\, \bar{\sigma}^\mu s)(d\, \sigma_\mu \bar{s}) \quad \lambda_c^4 \theta_c^2$


$\bar{Q}^a \bar{\sigma}^\mu Q_b \, \bar{Q}^d \bar{\sigma}_\mu Q_d \, (\lambda_u \lambda_u^\dagger)_a^d (\lambda_u \lambda_u^\dagger)_c^b$
$(\bar{d} \bar{\sigma}^\mu s)(d \sigma_\mu \bar{s}) \quad \lambda_c^4 \theta_c^2 \quad \propto \left[m_c^2 \theta_c^2 \right].$
$|\lambda_c|^2 \leftarrow$ IR enhancement



$\bar{Q}^a \bar{\sigma}^\mu Q_b \; \bar{Q} \bar{\sigma}_\mu Q_d \; (\lambda_u \lambda_u^\dagger) (\lambda_u \lambda_u^\dagger)^b_c$
$(\bar{d} \bar{\sigma}^\mu s)(d \sigma_\mu \bar{s}) \; \lambda_c^4 \theta_c^2 \; \alpha [m_c^2 \theta_c^2]$.
$|\lambda_c|^2$ ← IR enhancement



$(\lambda_U \lambda_U^\dagger)$ adj $U(3)_Q$
$(\lambda_U^\dagger \lambda_U)$ adj under $U(3)_{U^c}$
$(\lambda_D \lambda_D^\dagger)$ " $U(3)_Q$
$(\lambda_D^\dagger \lambda_D)$ " " $U(3)_{D^c}$
$= \det[\lambda_U \lambda_U^\dagger, \lambda_D \lambda_D^\dagger]$

$(\lambda_U \lambda_U^\dagger)$ adj $U(3)_Q$ $\qquad$ $(\lambda_U^\dagger \lambda_U)$ adj under $U(3)_{U^c}$

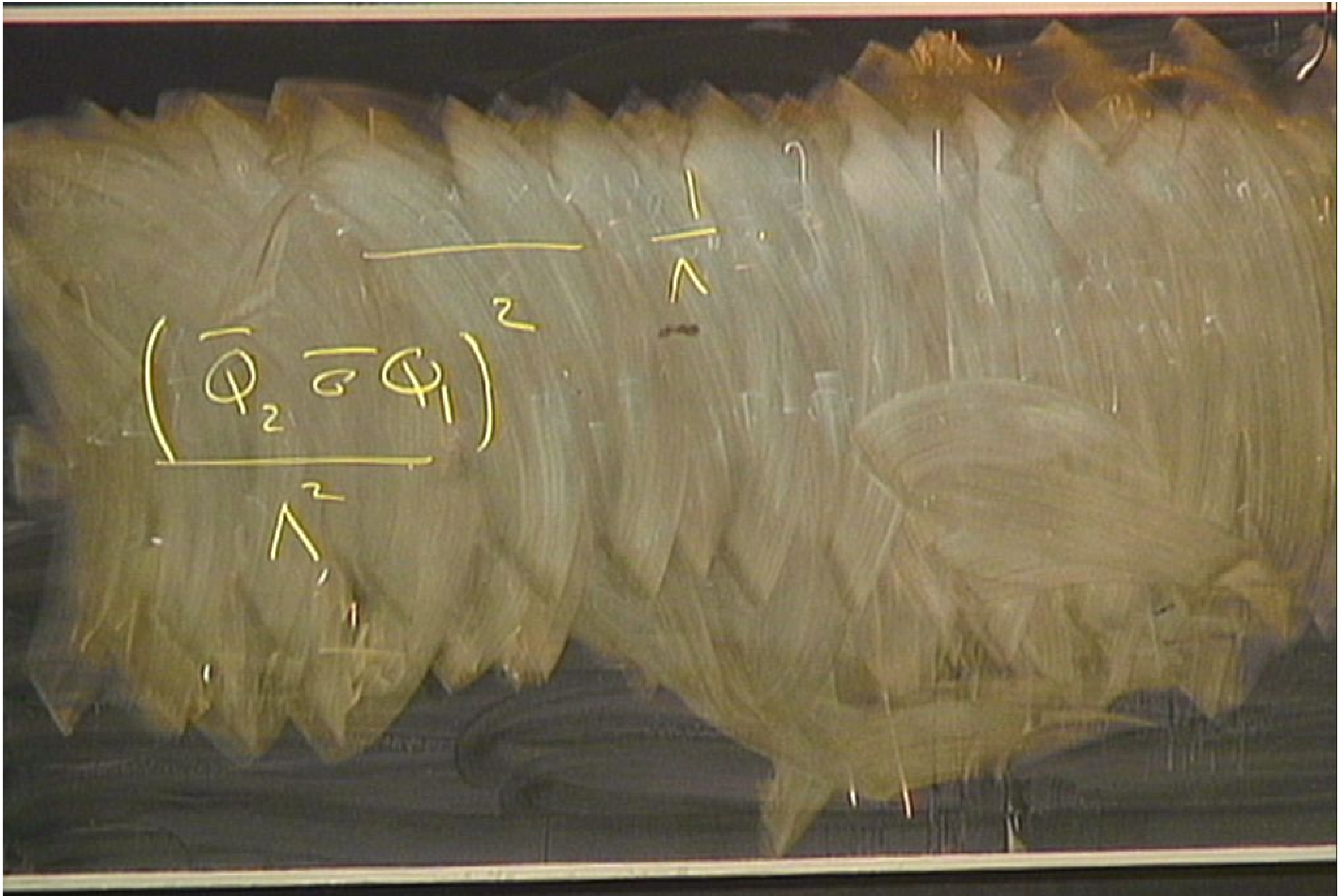
$(\lambda_D \lambda_D^\dagger)$ " $U(3)_Q$ $\qquad$ $(\lambda_D^\dagger \lambda_D)$ " " $U(3)_{D^c}$

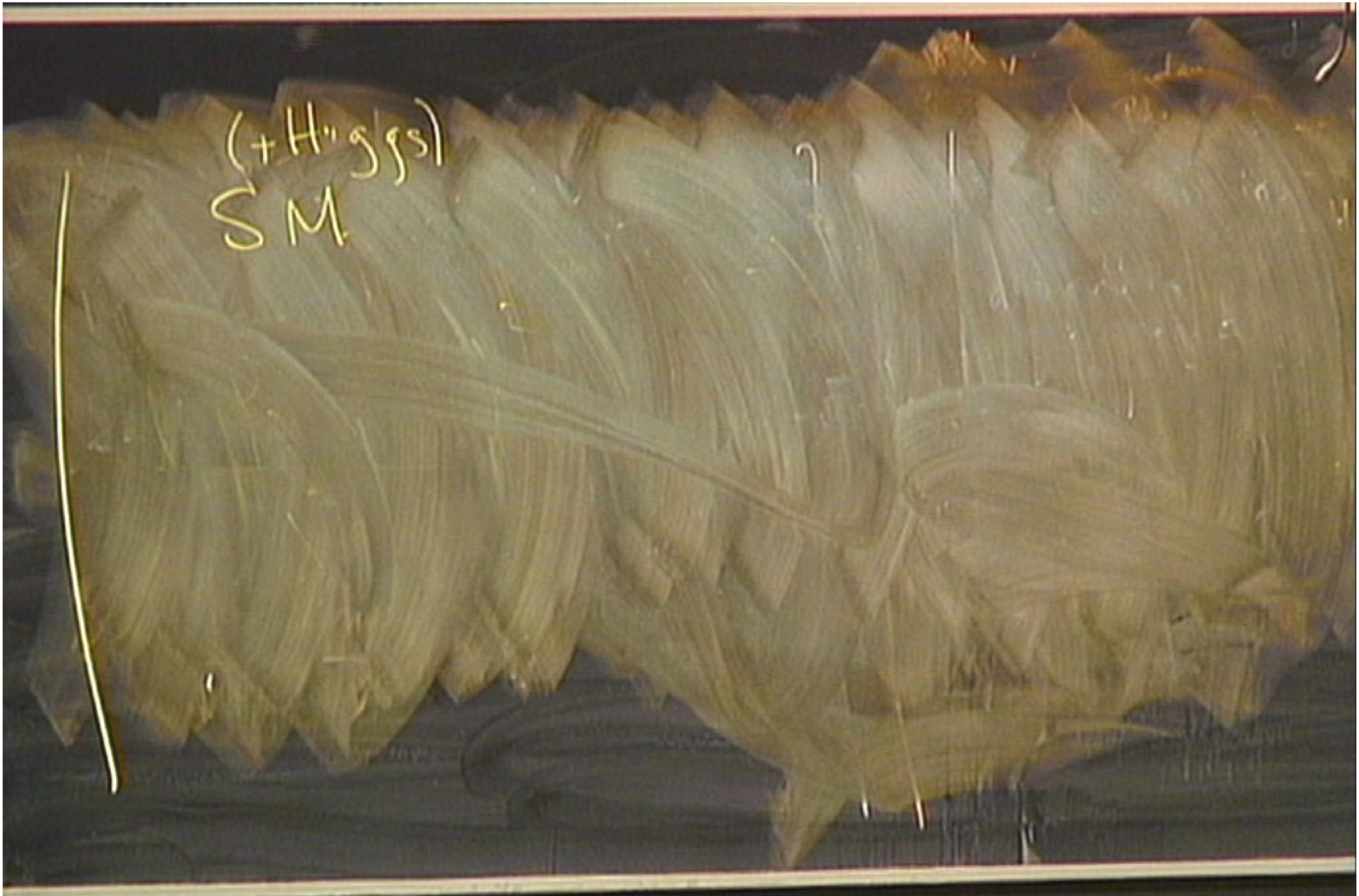
$\not{CP}$ $\qquad$ $J = \mathrm{Im}\,\det[\lambda_U \lambda_U^\dagger, \lambda_D \lambda_D^\dagger]$

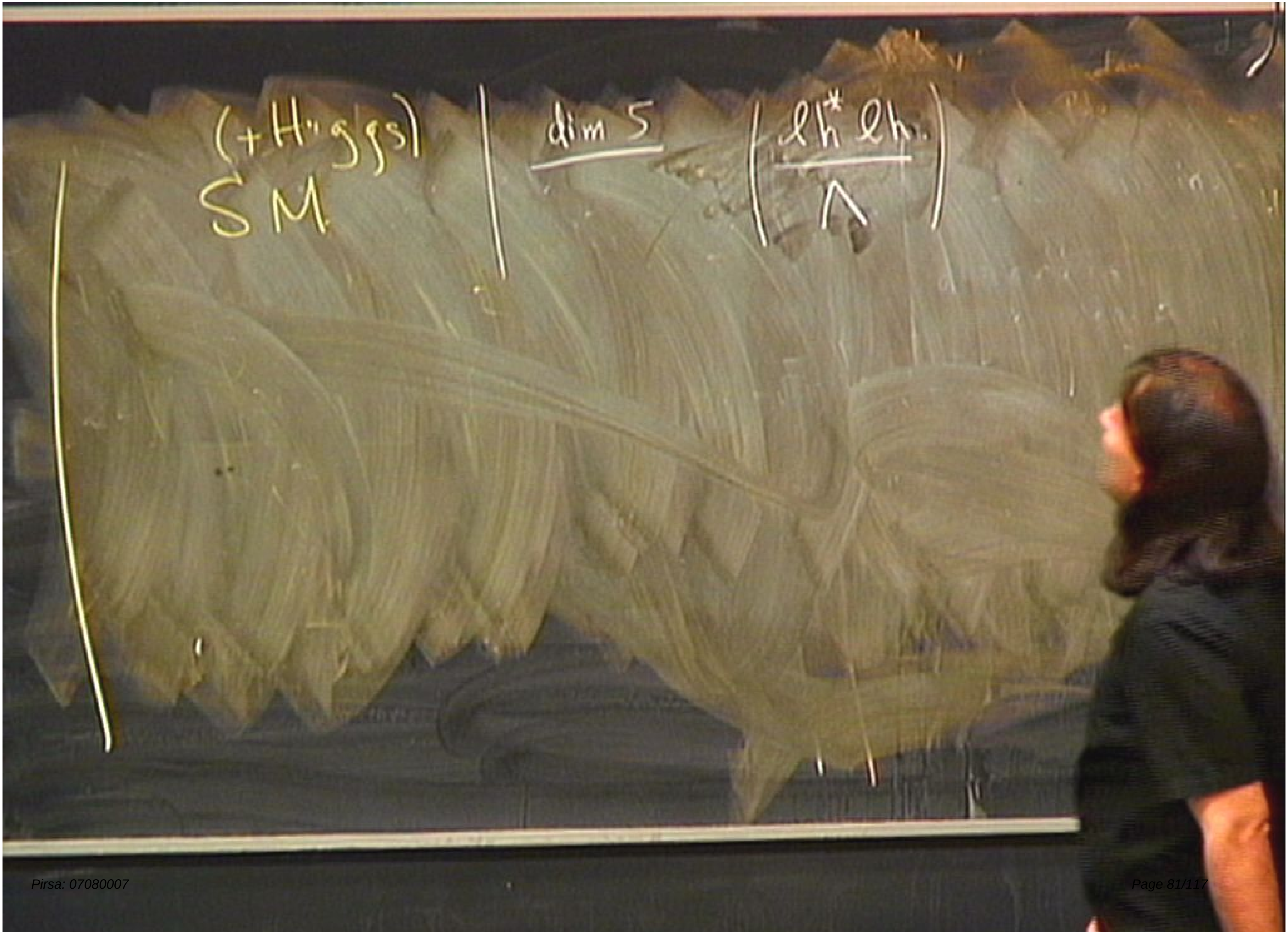
Jarlskog Inv.

$$\frac{\left(\bar{\Phi}_2 \bar{\sigma} \Phi_1\right)^2}{\Lambda^2}$$

$$\frac{1}{\Lambda}$$


$\frac{1}{\Lambda}$
$\frac{(\bar{\Phi}_2 \bar{\sigma} \Phi_1)^2}{\Lambda^2}$

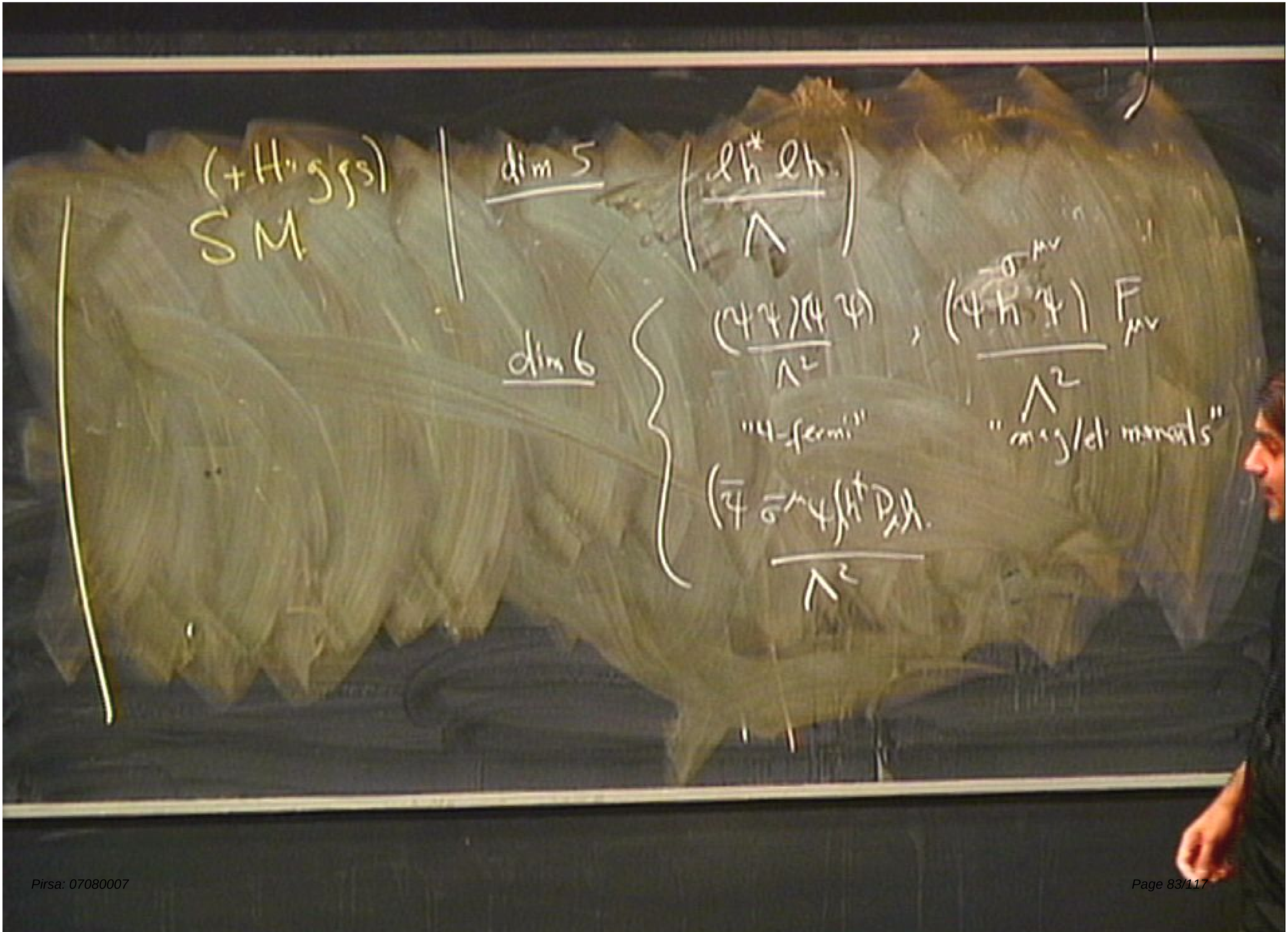

(+Higgs)
SM

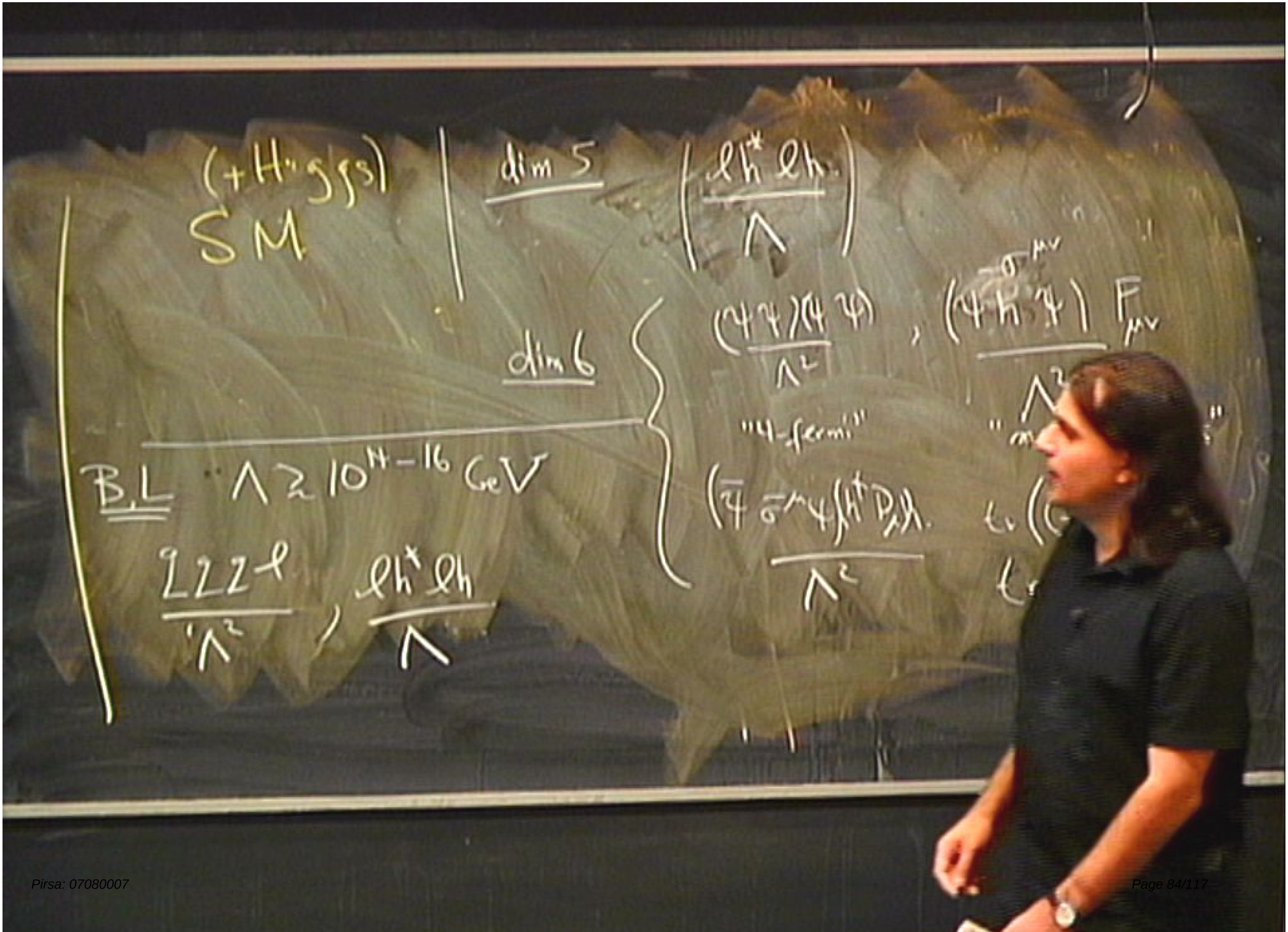

(+Higgs)
SM
dim 5
$\left(\frac{\ell h^* \ell h}{\Lambda}\right)$

SM (+Higgs)

dim 5 $\left(\frac{l h^* l h}{\Lambda} \right)$

dim 6 $\left\{ \frac{(\bar\psi \psi)(\bar\psi \psi)}{\Lambda^2}, \quad \frac{(\bar\psi \sigma^{\mu\nu} \psi) F_{\mu\nu}}{\Lambda^2} \right.$


(+Higgs)
SM
dim 5
(lh* lh / Λ)
dim 6
(ψ̄ψ)(ψ̄ψ) / Λ²
(ψ̄ σ^μν h ψ) F_μν / Λ²
"4-fermi"
"mag/el moments"
(ψ̄ σ^μ ψ)(h† D_μ h) / Λ²


(+Higgs)
SM
dim 5
dim 6
"4-fermi"
B, L
Λ ≳ 10^(14–16) GeV

(+ Higgs)
SM

dim 5 $\left(\frac{\ell h^* \ell h}{\Lambda}\right)$

dim 6 $\frac{(\bar\psi\psi)(\bar\psi\psi)}{\Lambda^2}$, $\frac{(\bar\psi h \sigma^{\mu\nu} \psi) F_{\mu\nu}}{\Lambda^2}$

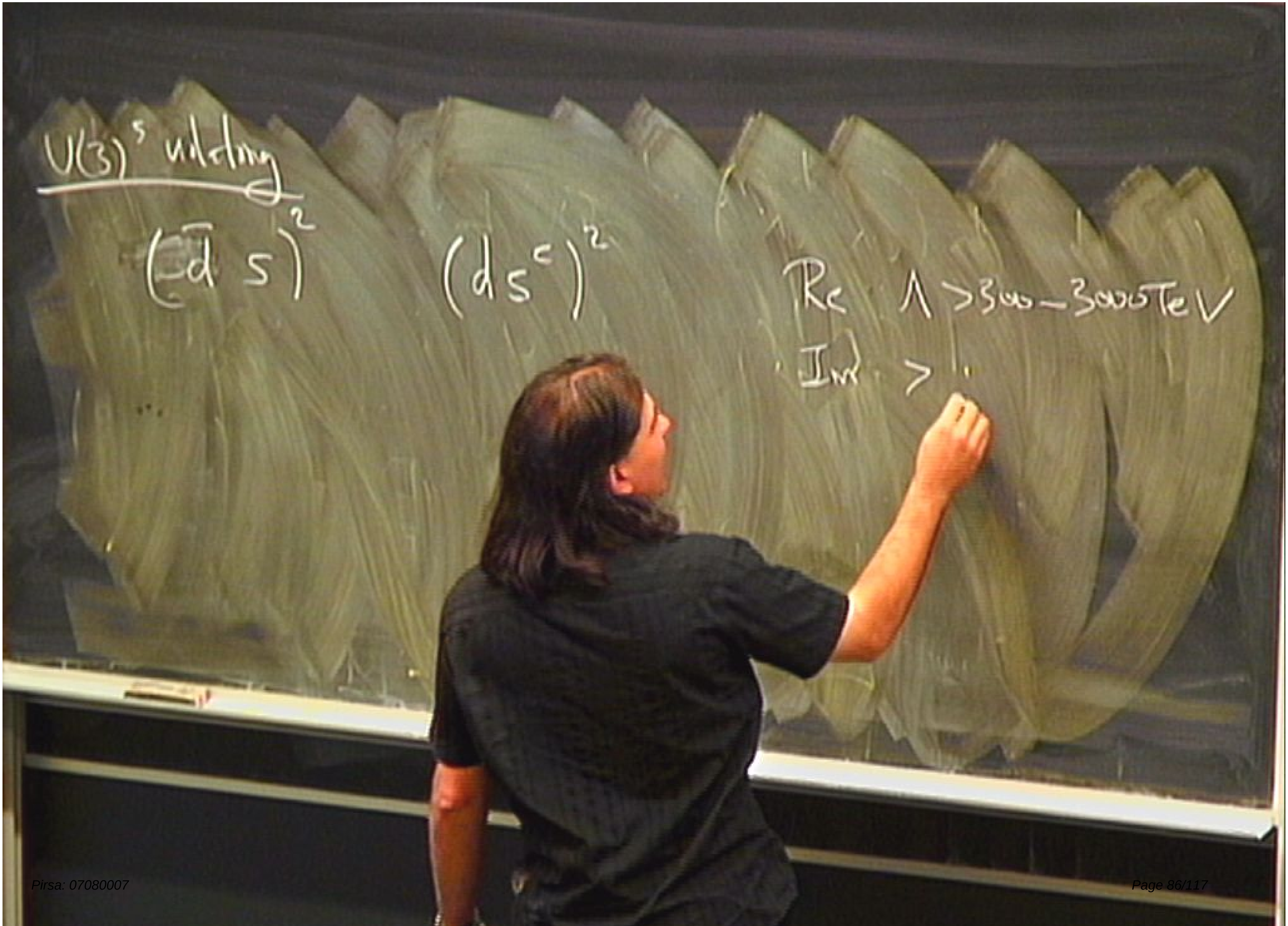
"4-fermi" "mag/el. moments"

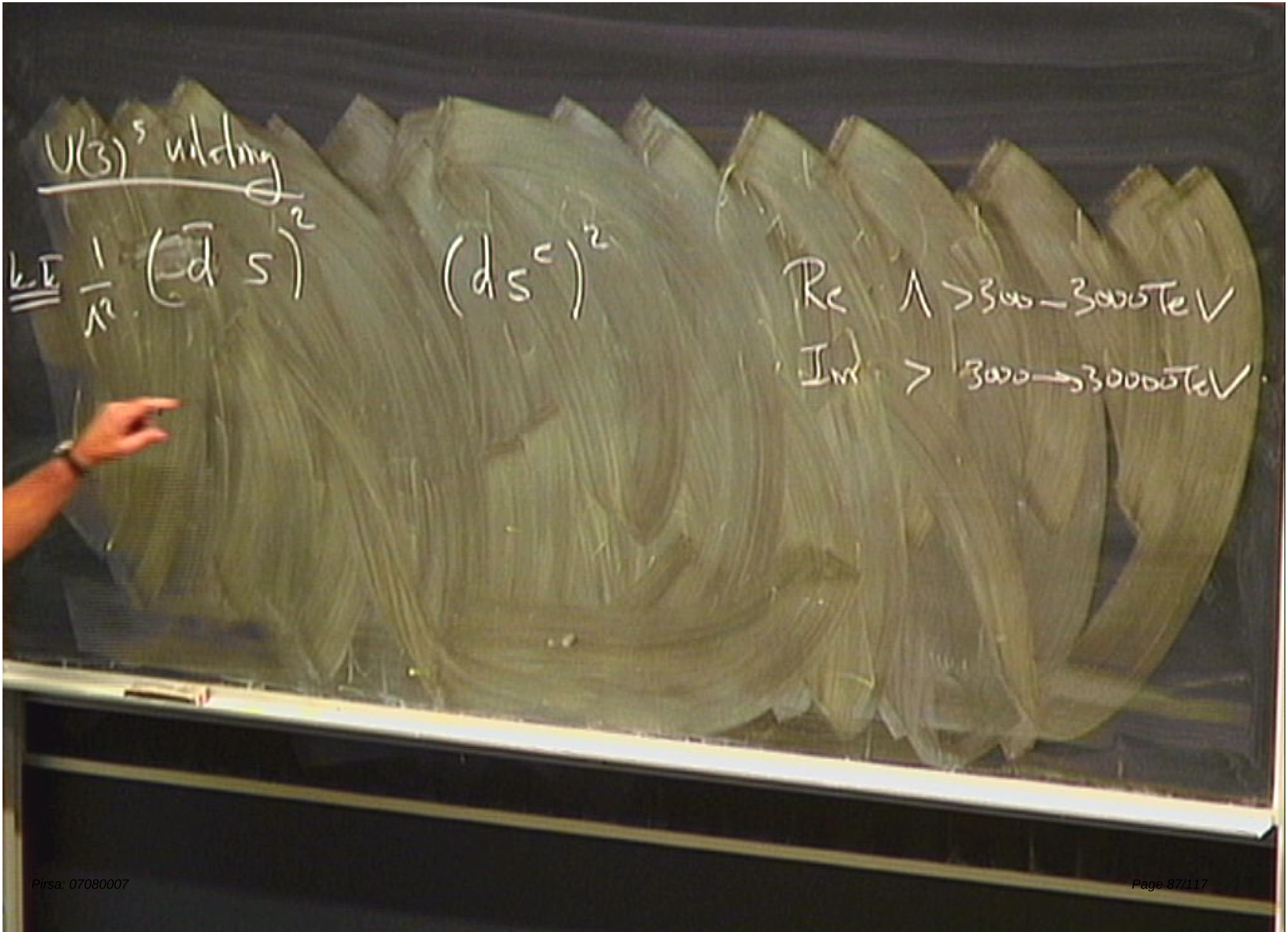
$\frac{(\bar\psi \bar\sigma^\mu \psi)(h^\dagger D_\mu h)}{\Lambda^2}$ $\mathrm{tr}(G^3)$

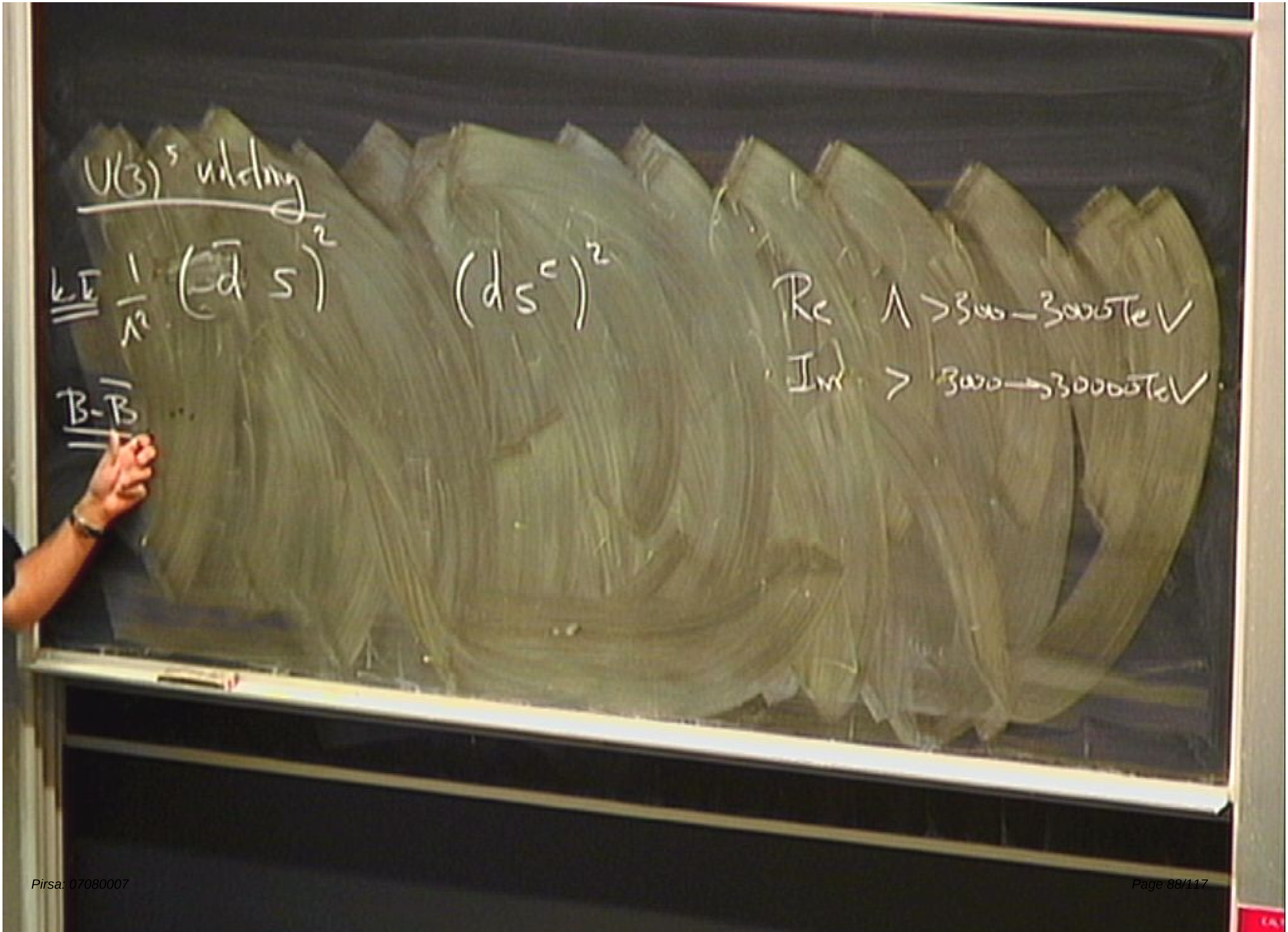
$\mathrm{tr}(G\, \partial_\mu G)$

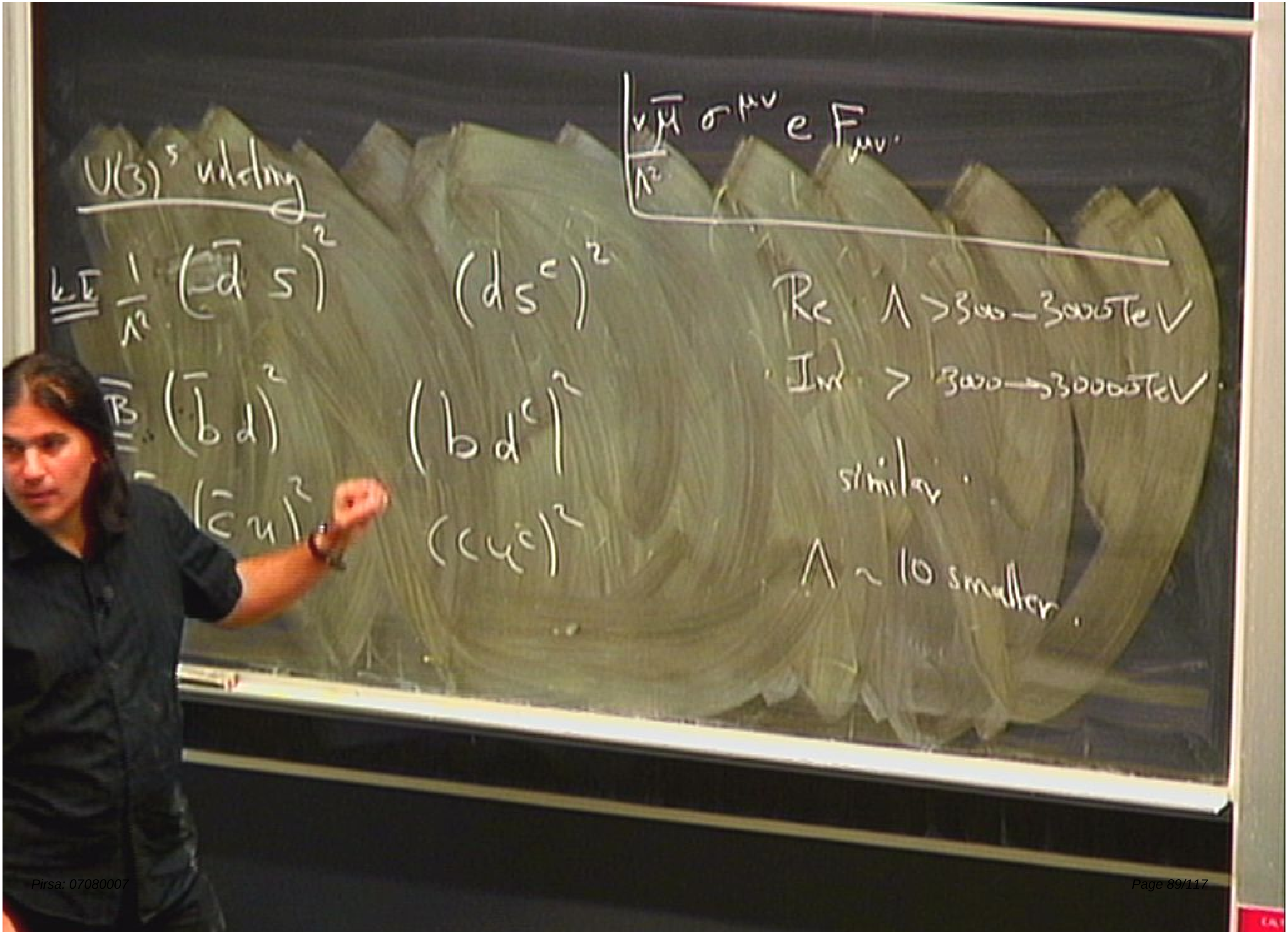
B, L $\Lambda \gtrsim 10^{14-16}$ GeV

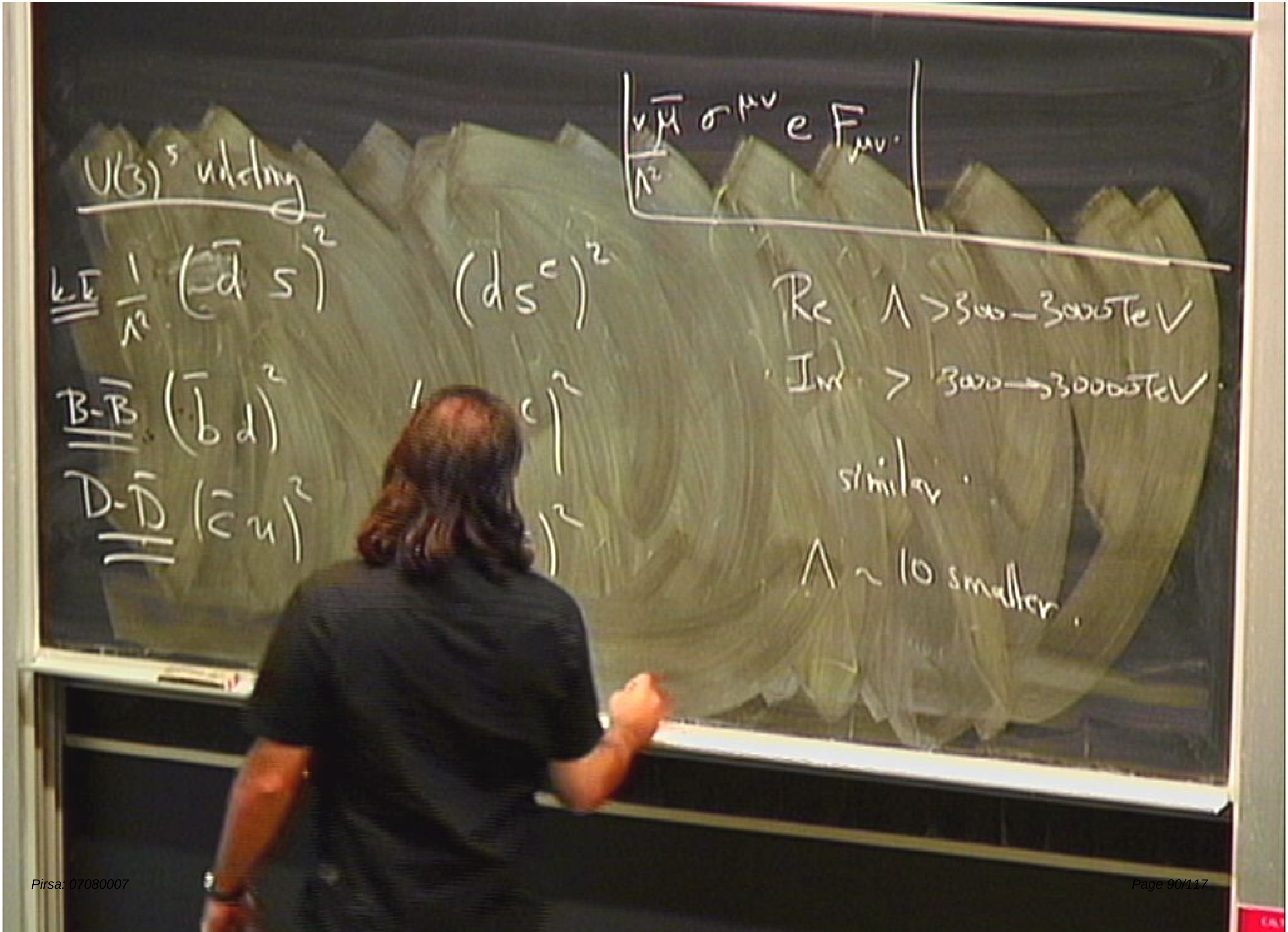
$\frac{qqq\ell}{\Lambda^2}$, $\frac{\ell h^* \ell h}{\Lambda}$

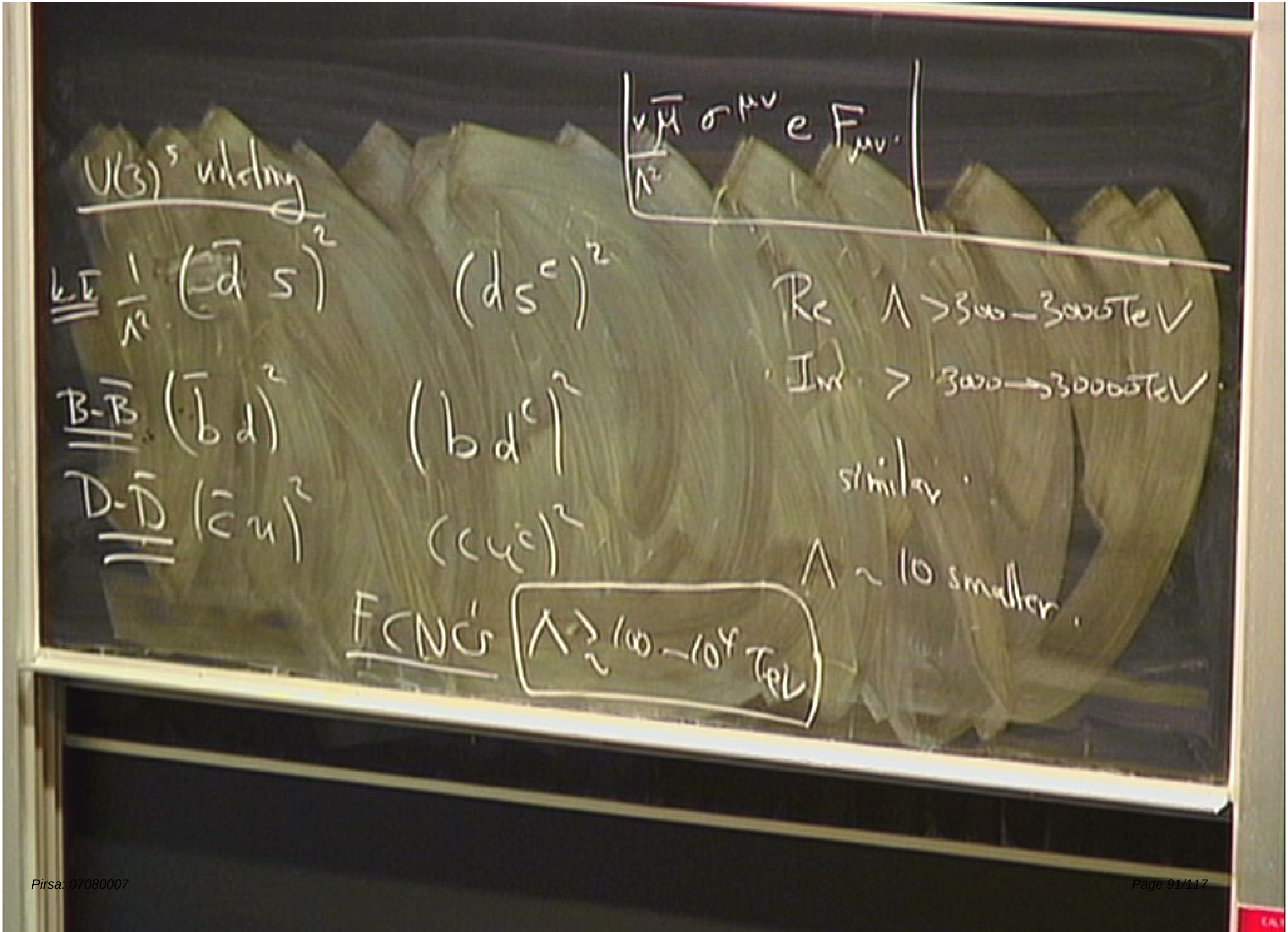

U(3)^5 violating
(d̄ s)^2
(d s^c)^2
Re Λ > 300 – 3000 TeV
Im >

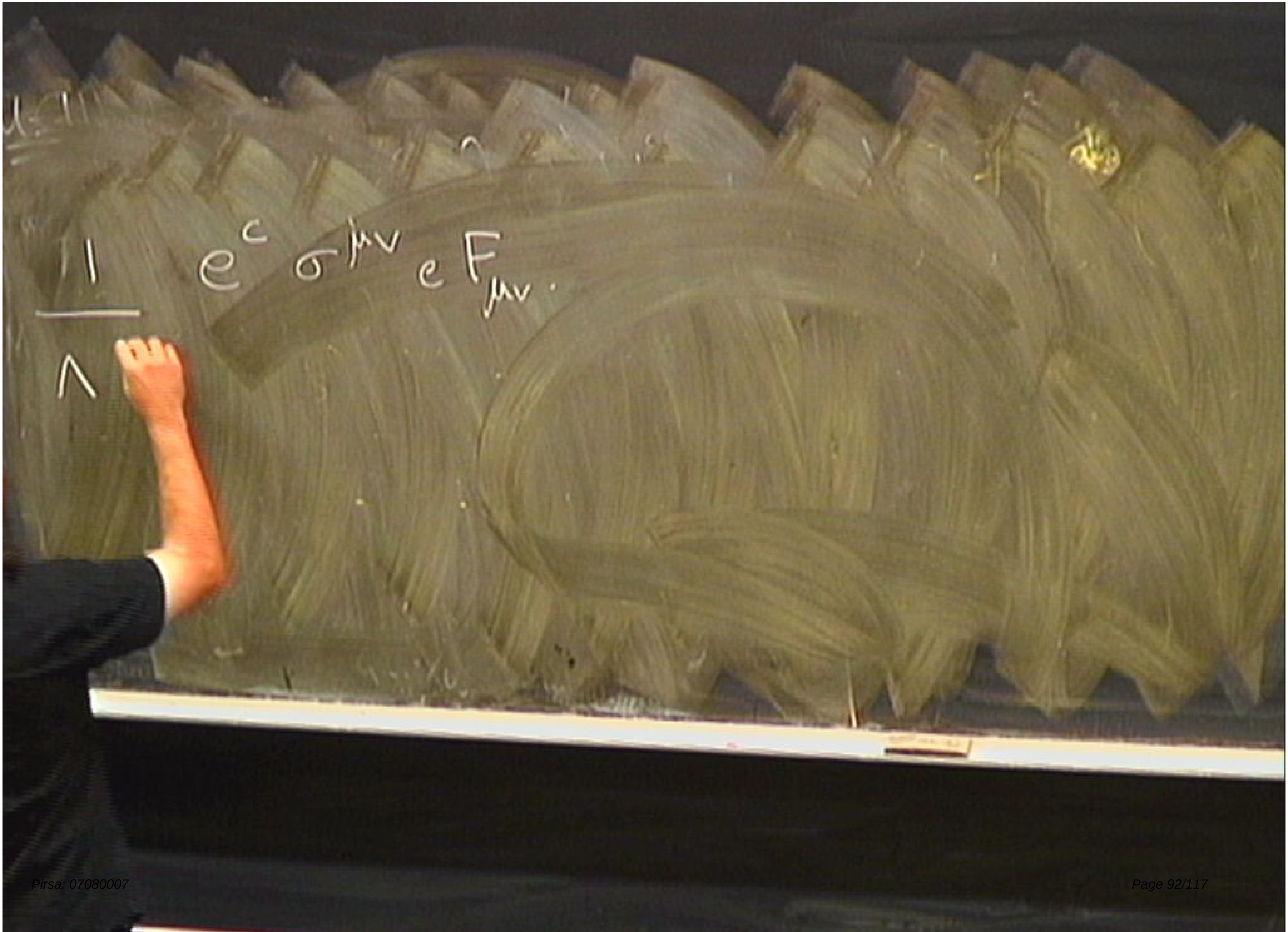

U(3)^5 violating
(d s^c)^2
Re Λ > 300 – 3000 TeV
Im > 3000 → 30000 TeV

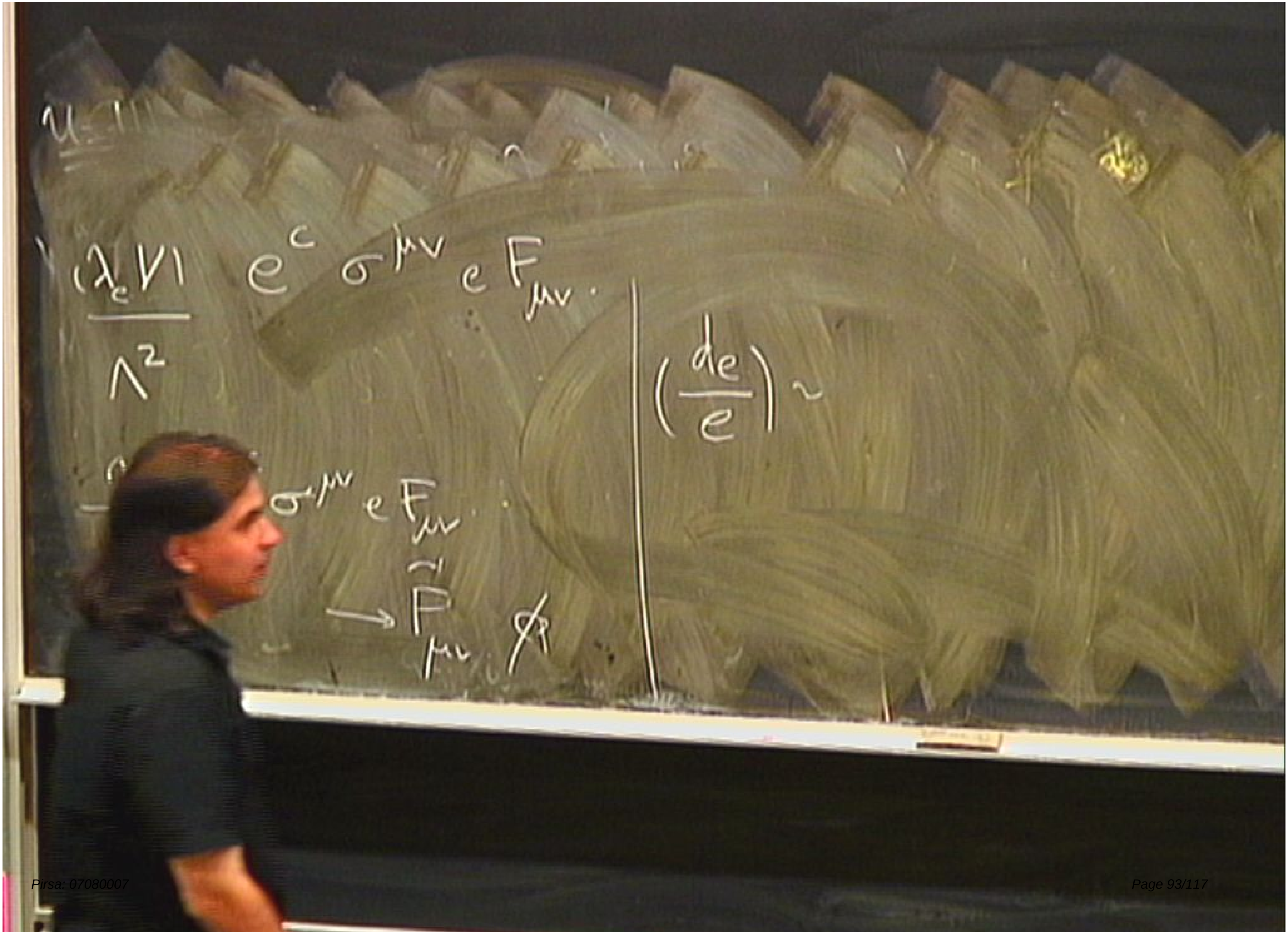

U(3)^5 violating
LL 1/Λ² (d̄ s)²
(d s^c)²
Re Λ > 300 – 3000 TeV
Im > 3000 → 30000 TeV
B-B̄ ...


U(3)^5 violating
$\frac{1}{\Lambda^2}\,\bar{\nu}\bar{\mu}\,\sigma^{\mu\nu} e F_{\mu\nu}$
$K\bar{K}$ $\frac{1}{\Lambda^2}(\bar{d}\,s)^2$ $(d\,s^c)^2$
$B\bar{B}$ $(\bar{b}\,d)^2$ $(b\,d^c)^2$
$(\bar{c}\,u)^2$ $(c\,u^c)^2$
Re $\Lambda > 300 - 3000$ TeV
Im $> 3000 \rightarrow 30000$ TeV
similar
$\Lambda \sim 10$ smaller


ν μ̄ σ^μν e F_μν
Λ²
K-K̄ 1/Λ² (d̄ s)²
(d s^c)²
B-B̄ (b̄ d)²
D-D̄ (c̄ u)²
Re Λ > 300 – 3000 TeV
Im > 3000 → 30000 TeV
similar.
Λ ~ 10 smaller.


U(3)^5 violating
K-K̄ 1/Λ² (s̄ d s)²
(d s^c)²
B-B̄ (b̄ d)²
(b d^c)²
D-D̄ (c̄ u)²
(c u^c)²
FCNC's Λ ≳ 100 – 10^4 TeV
μ̄ σ^{μν} e F_{μν} / Λ²
Re Λ > 300 – 3000 TeV
Im > 3000 → 30000 TeV
similar
Λ ~ 10 smaller


$\frac{1}{\Lambda} e^c \sigma^{\mu\nu} e F_{\mu\nu}$.

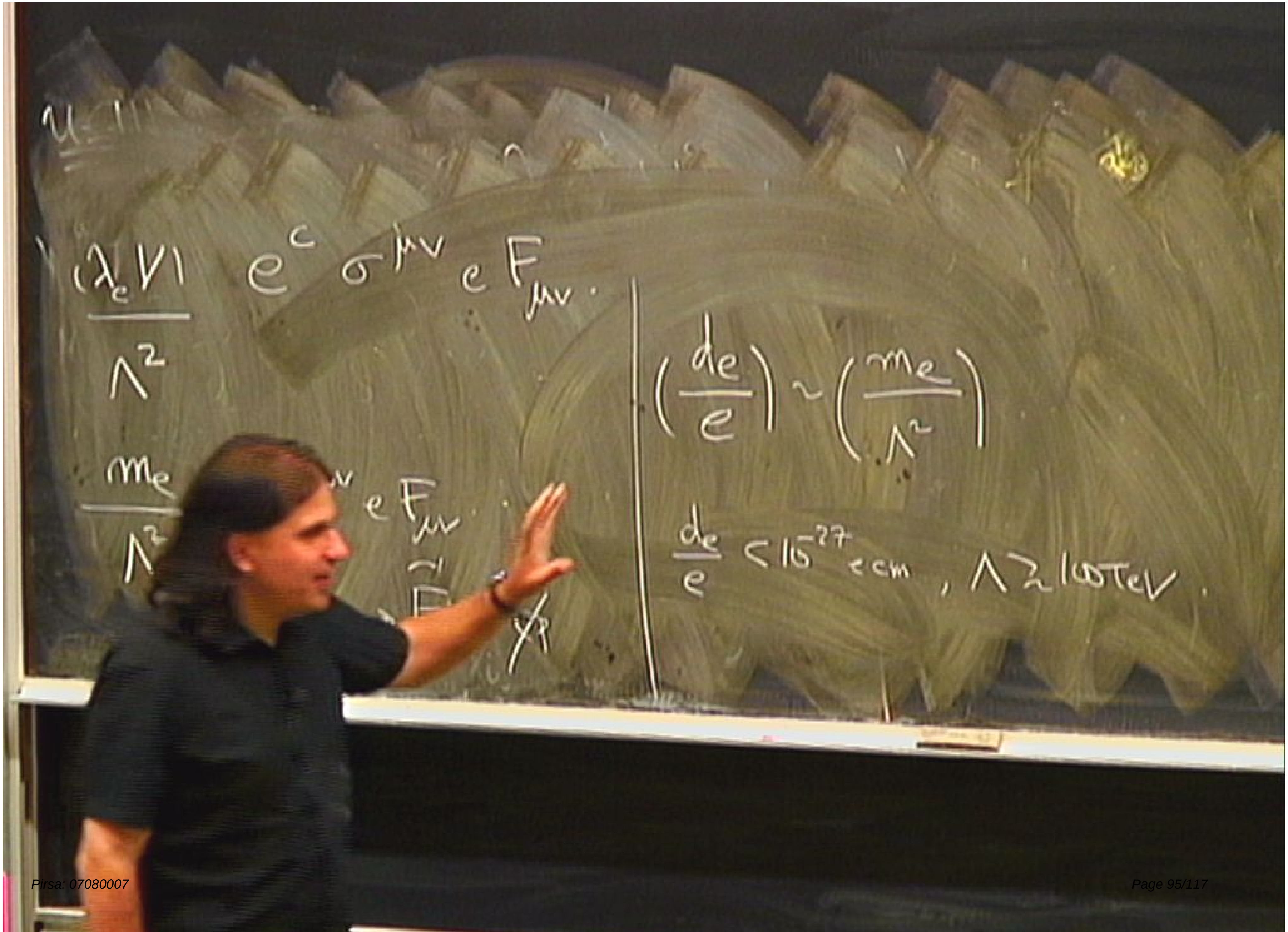

(λ_c V) / Λ^2   e^c σ^{μν} e F_{μν}
(d_e / e) ~
σ^{μν} e F_{μν}
→ F̃_{μν}

$$\frac{(\lambda_e v)}{\Lambda^2} \, e^c \sigma^{\mu\nu} e F_{\mu\nu}.$$

$$\frac{m_e}{\Lambda^2} \, e^c \sigma^{\mu\nu} e F_{\mu\nu}$$

$$\longrightarrow \tilde{F}_{\mu\nu} \quad \not{CP}$$

$$\left(\frac{d_e}{e}\right) \sim \left(\frac{m_e}{\Lambda^2}\right)$$


e^c σ^μν e F_μν
(d_e/e) ~ (m_e/Λ^2)
d_e/e < 10^-27 e cm , Λ ≳ 100 TeV

$$\frac{(\lambda_e V)}{\Lambda^2} \; e^c \sigma^{\mu\nu} e F_{\mu\nu}.$$

$$\frac{m_e}{\Lambda^2} \; e^c \sigma^{\mu\nu} e F_{\mu\nu}.$$

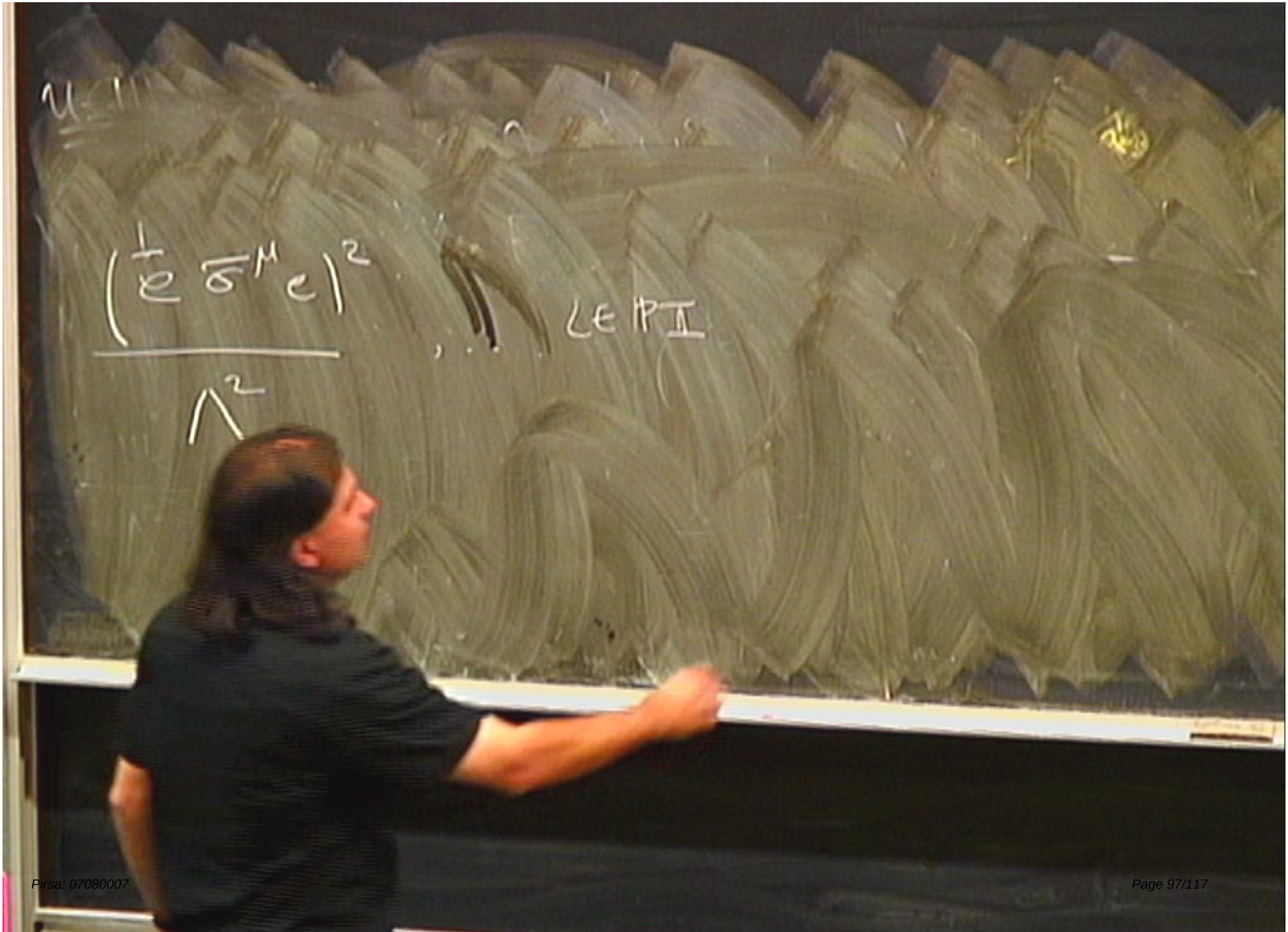
$$\rightarrow \tilde{F}_{\mu\nu} \; \not{CP}$$

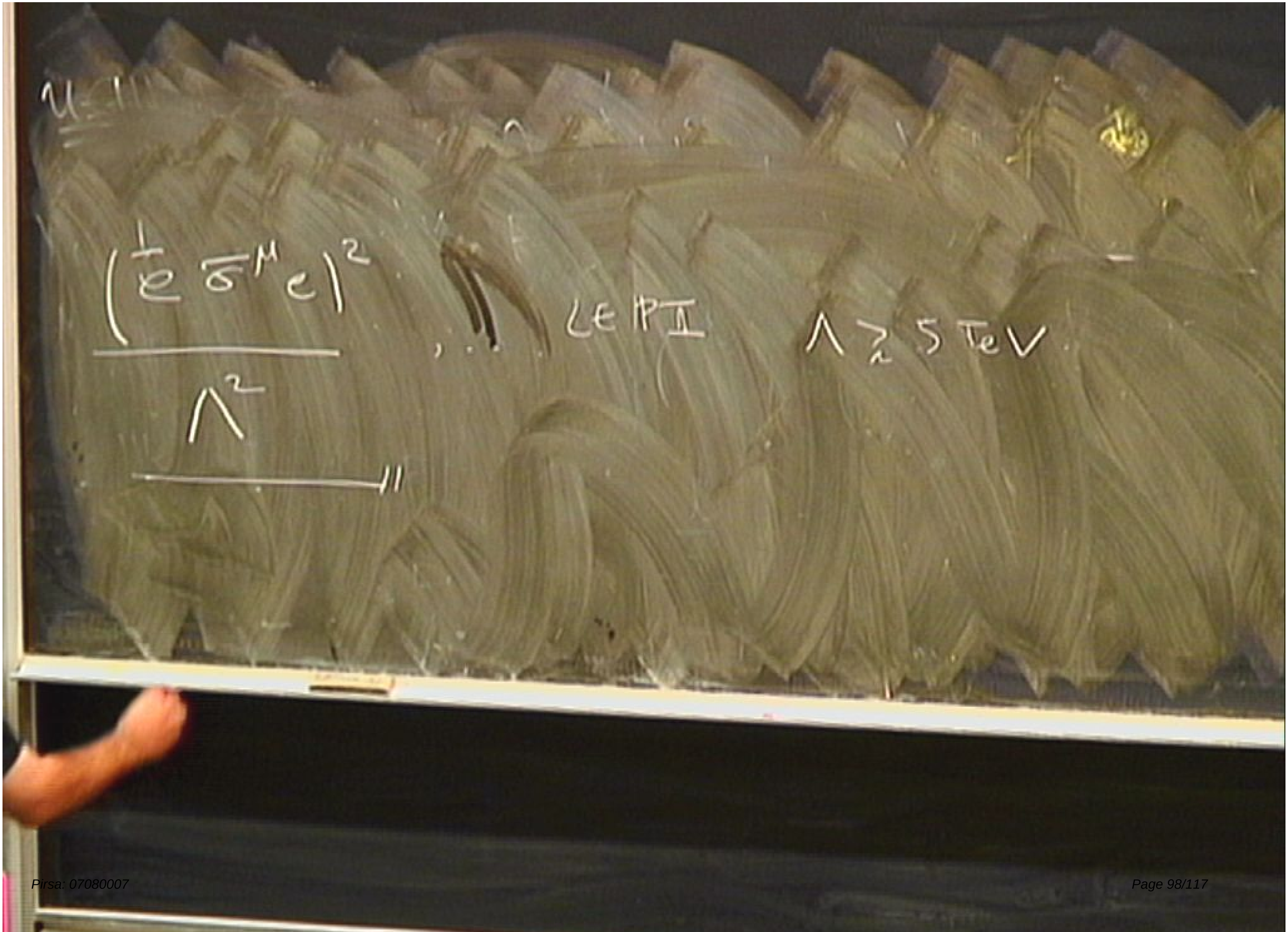
$$\left(\frac{d_e}{e}\right) \sim \left(\frac{m_e}{\Lambda^2}\right)$$

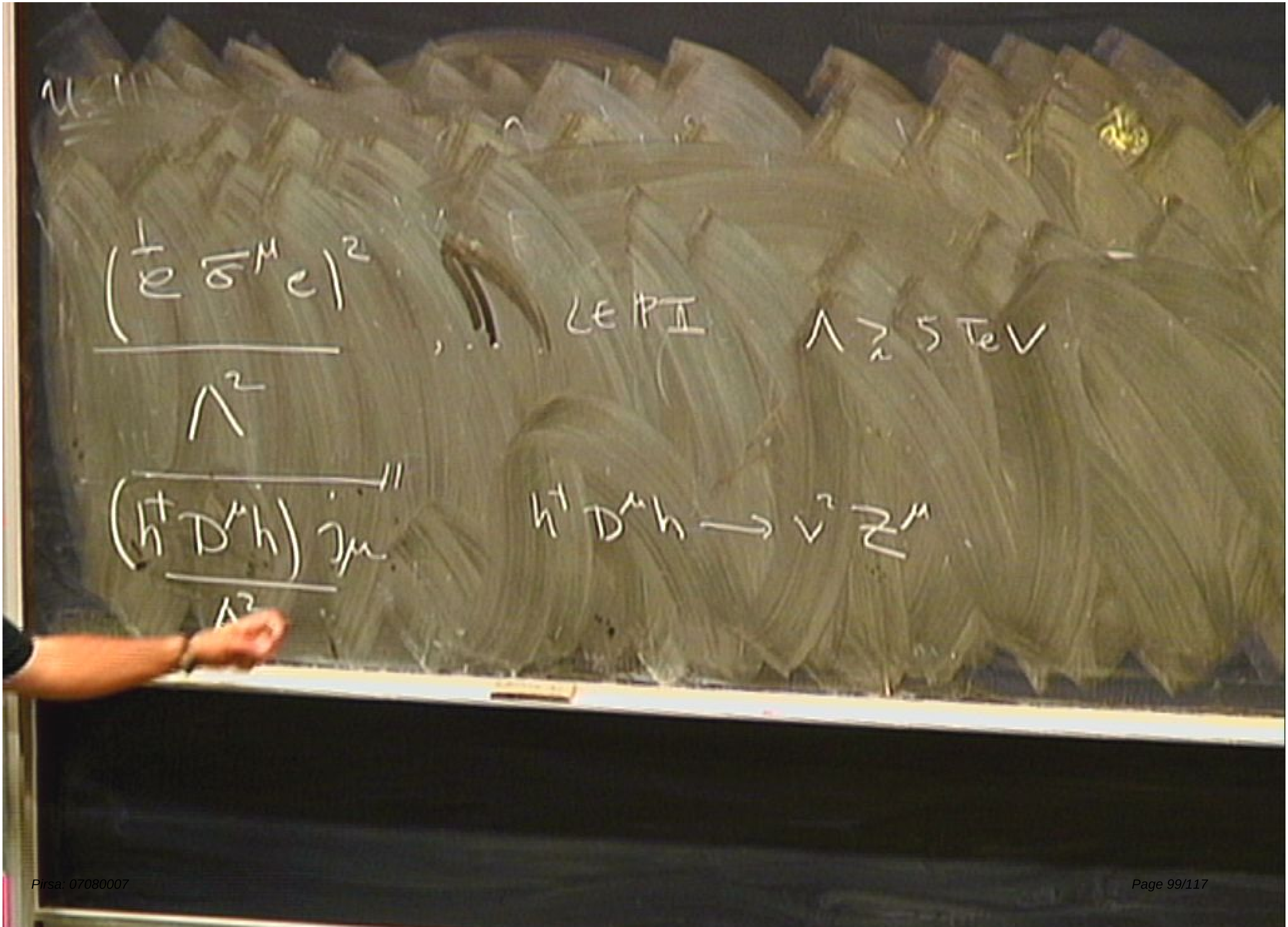
$$\left(\frac{d_e}{e}\right) \sim 10^{-34}\, c$$

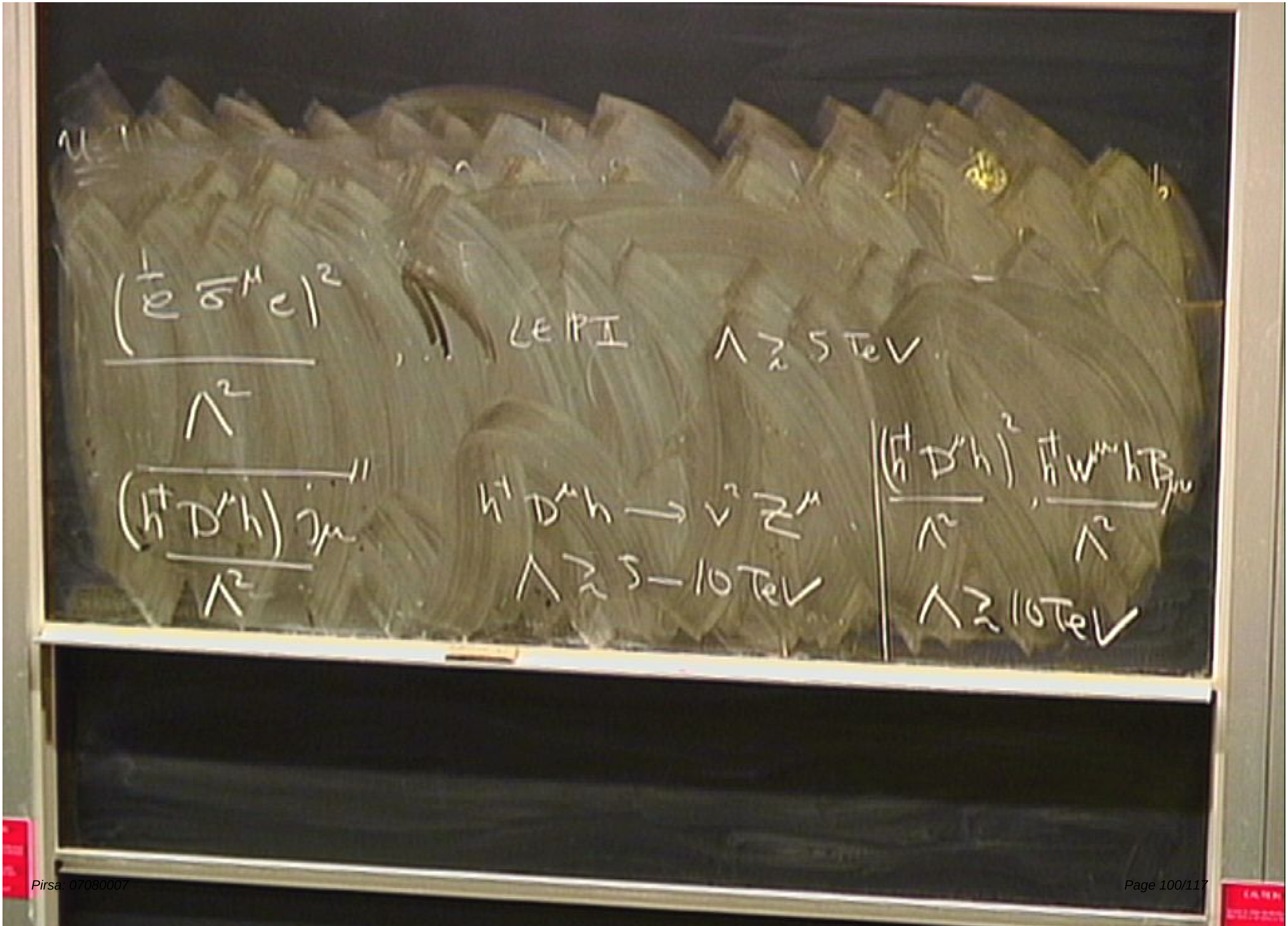
$$\frac{d_e}{e} < 10^{-27}\, e\,\mathrm{cm}, \quad \Lambda \gtrsim 100\,\mathrm{TeV}.$$

$$\left(\frac{d_n}{n}\right) < 10^{-25}\, e\,\mathrm{cm}.$$




$\frac{(\bar{e}\,\bar{\sigma}^{\mu} e)^2}{\Lambda^2}$
LEP II
$\Lambda \gtrsim 5$ TeV

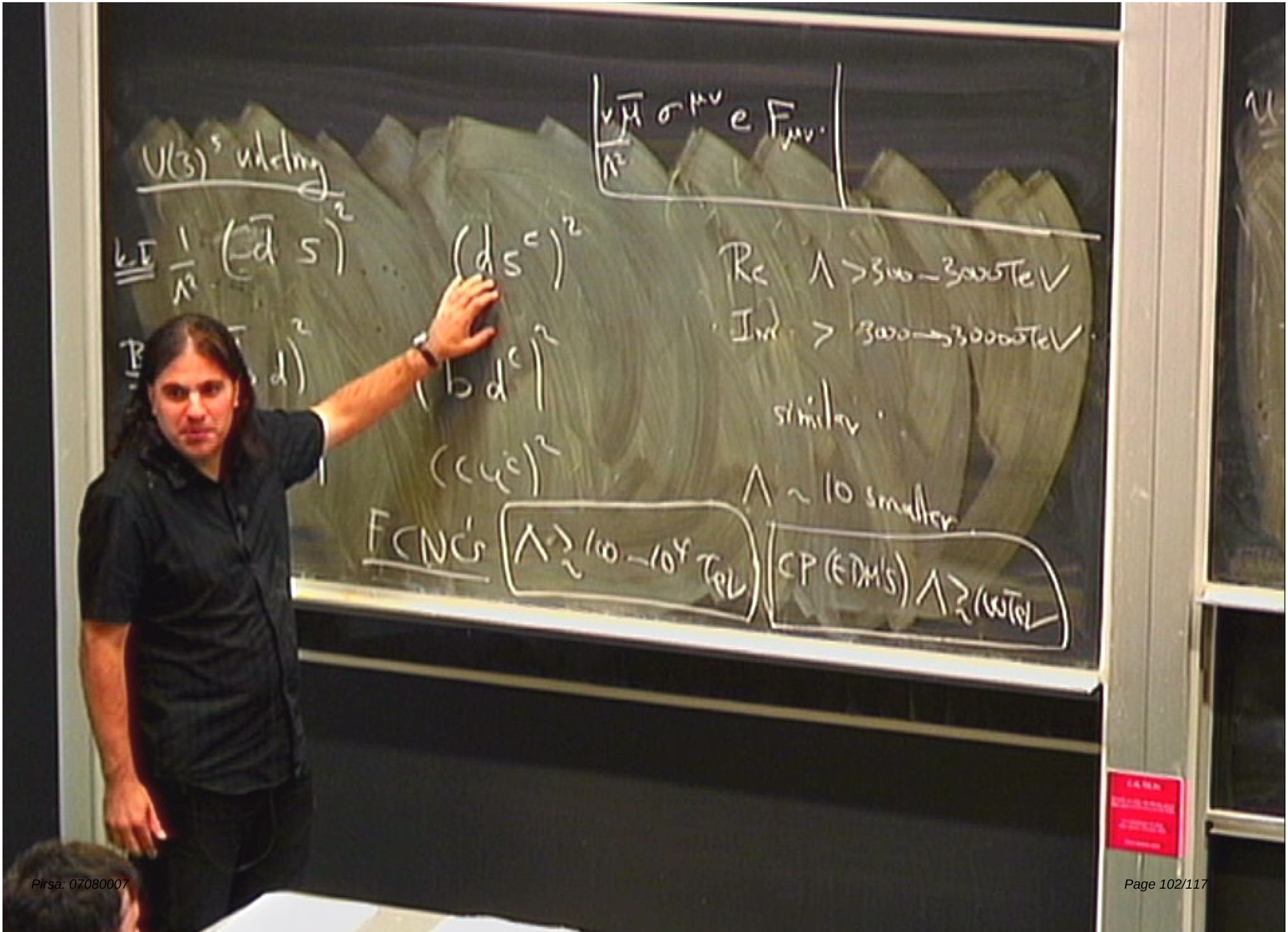

(ē σ̄^μ e)^2 / Λ^2
LEP II
Λ ≳ 5 TeV
(h† D^μ h) j_μ / Λ^2
h† D^μ h → v^2 Z^μ


$\frac{(\bar{e}\bar{\sigma}^\mu e)^2}{\Lambda^2}$
LEP I
$\Lambda \gtrsim 5$ TeV
$\frac{(h^\dagger D^\mu h) J_\mu}{\Lambda^2}$
$h^\dagger D^\mu h \longrightarrow v^2 Z^\mu$
$\Lambda \gtrsim 5-10$ TeV
$\frac{(h^\dagger D^\mu h)^2}{\Lambda^2}, \frac{h^\dagger W^{\mu\nu} h B_{\mu\nu}}{\Lambda^2}$
$\Lambda \gtrsim 10$ TeV

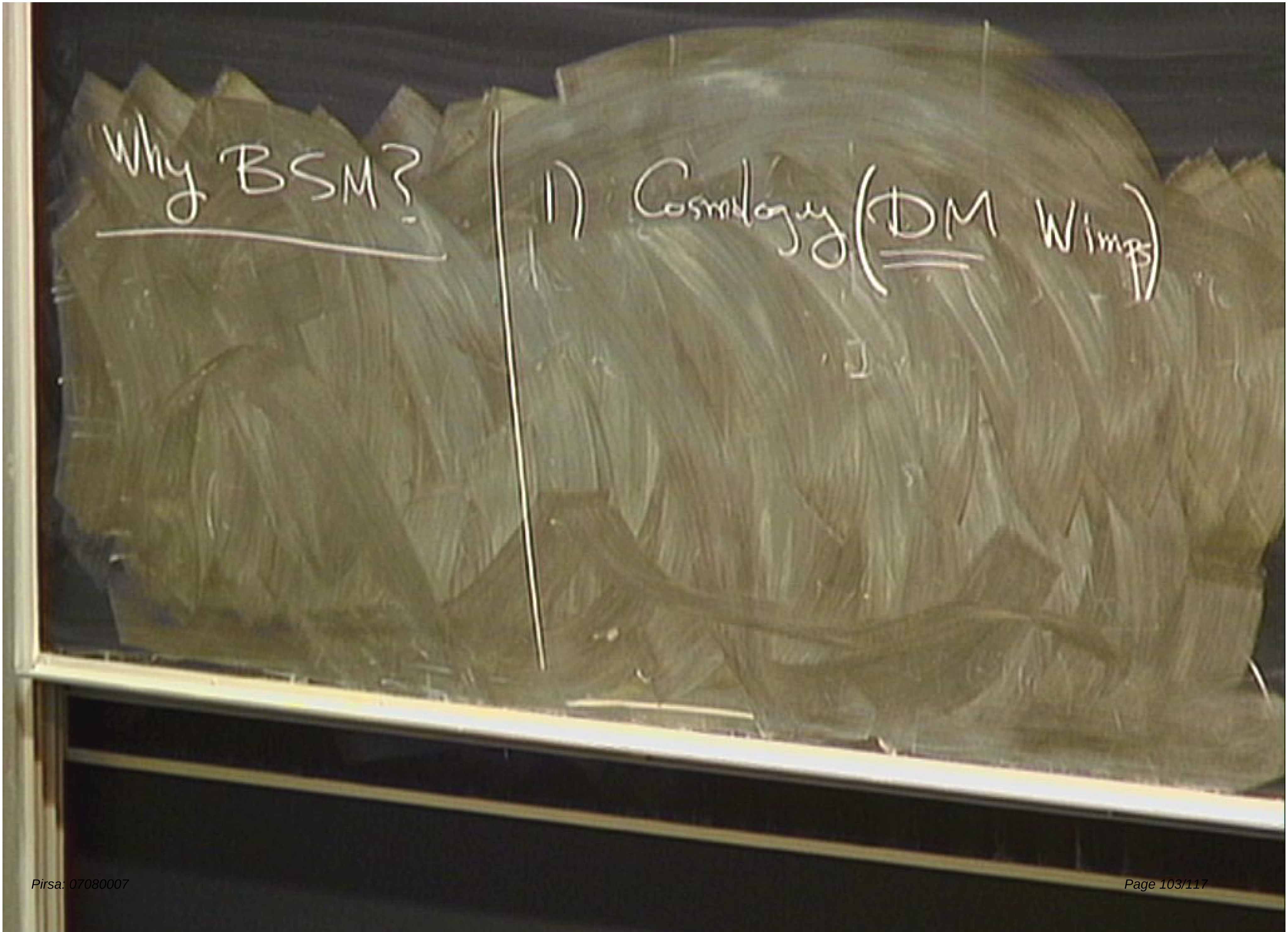
$$\frac{(\bar{e}\,\bar{\sigma}^\mu e)^2}{\Lambda^2}, \ldots \quad \text{LEP II} \quad \Lambda \gtrsim 5\ \text{TeV}$$

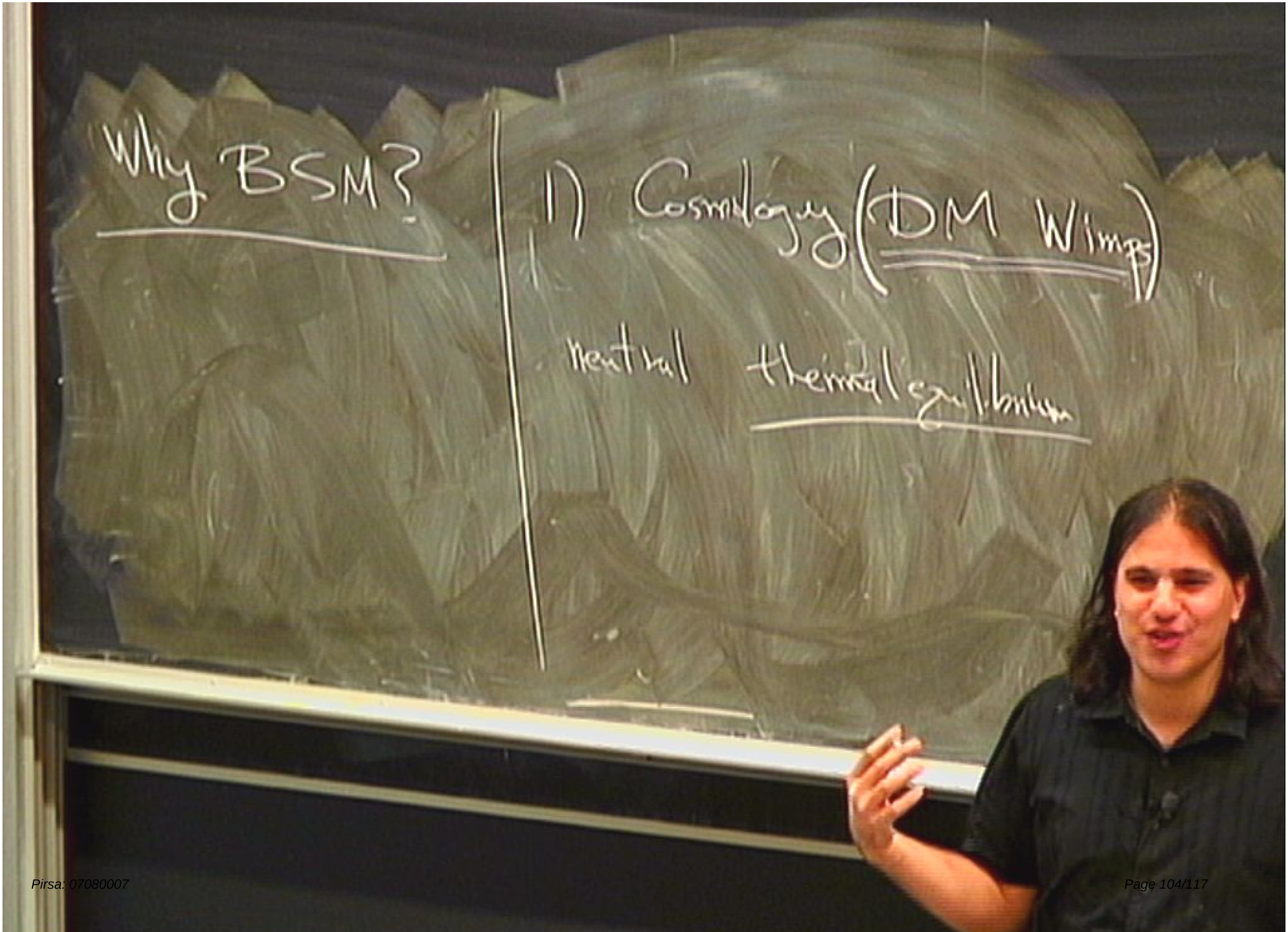
$$\frac{(h^\dagger D^\mu h)\, j_\mu}{\Lambda^2} \qquad h^\dagger D^\mu h \longrightarrow v^2 Z^\mu \qquad \Lambda \gtrsim 5-10\ \text{TeV}$$

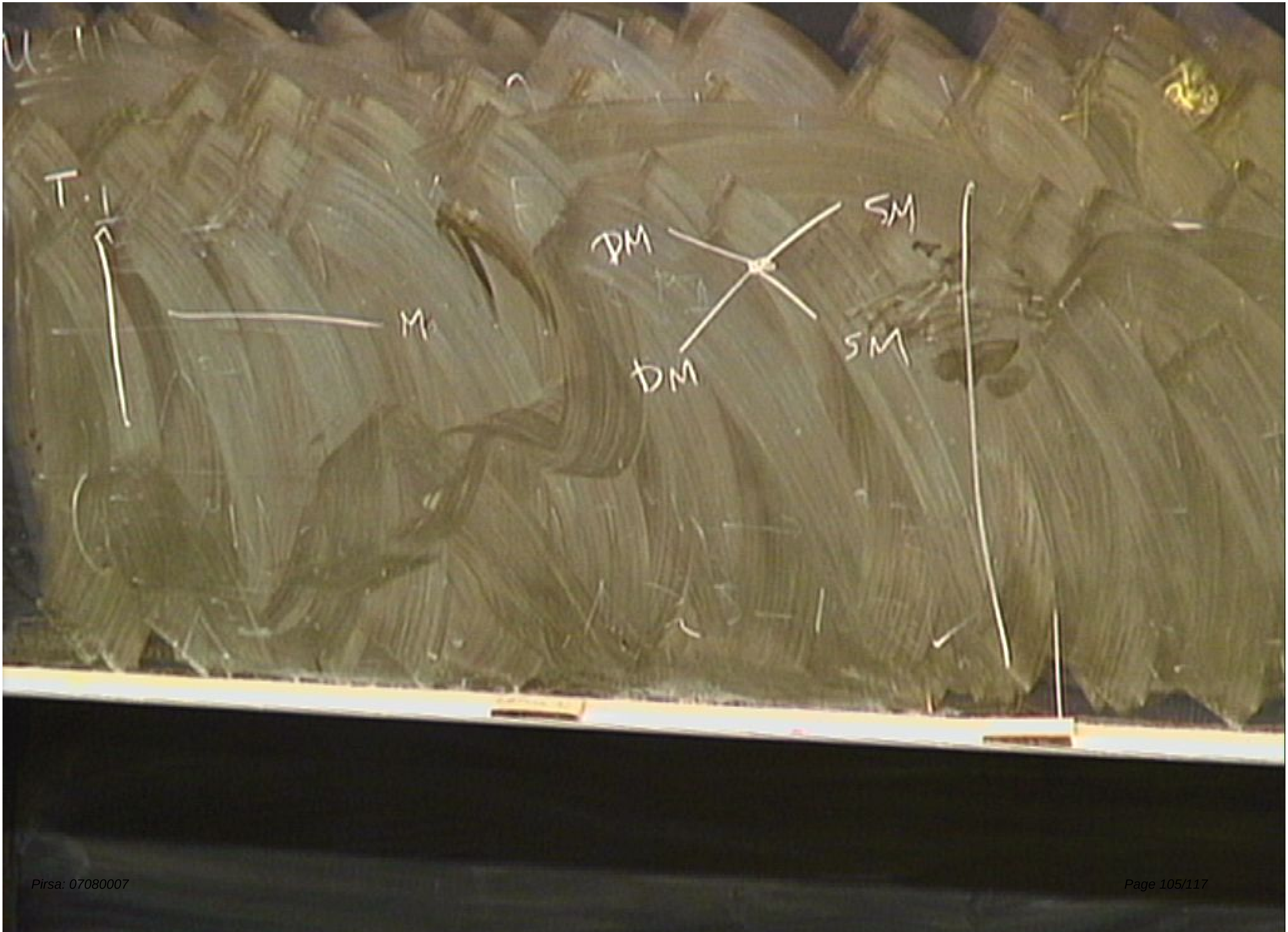
$$\frac{(h^\dagger D^\mu h)^2}{\Lambda^2}, \ \frac{h^\dagger W^{\mu\nu} h B_{\mu\nu}}{\Lambda^2} \qquad \Lambda \gtrsim 10\ \text{TeV}$$

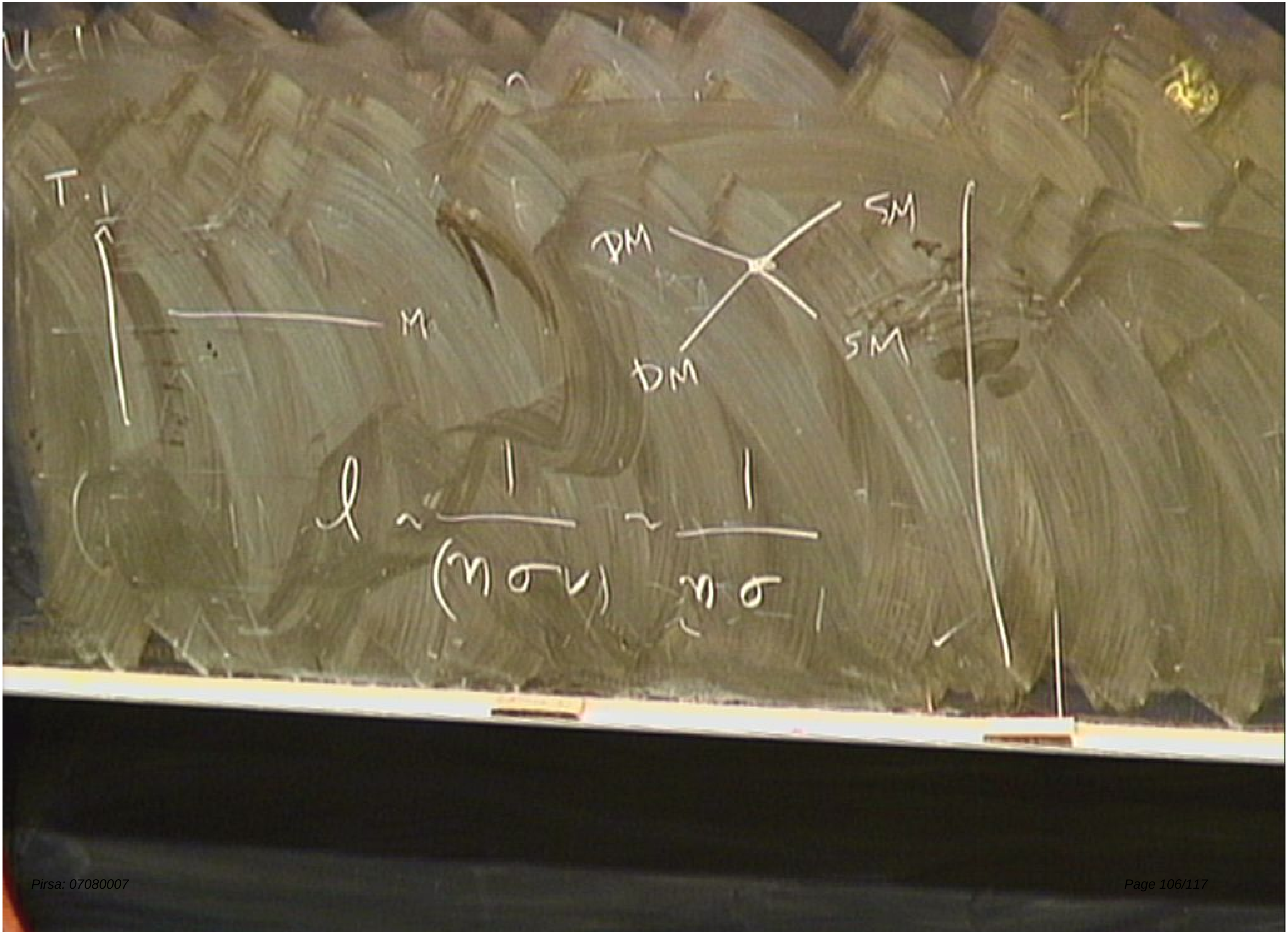


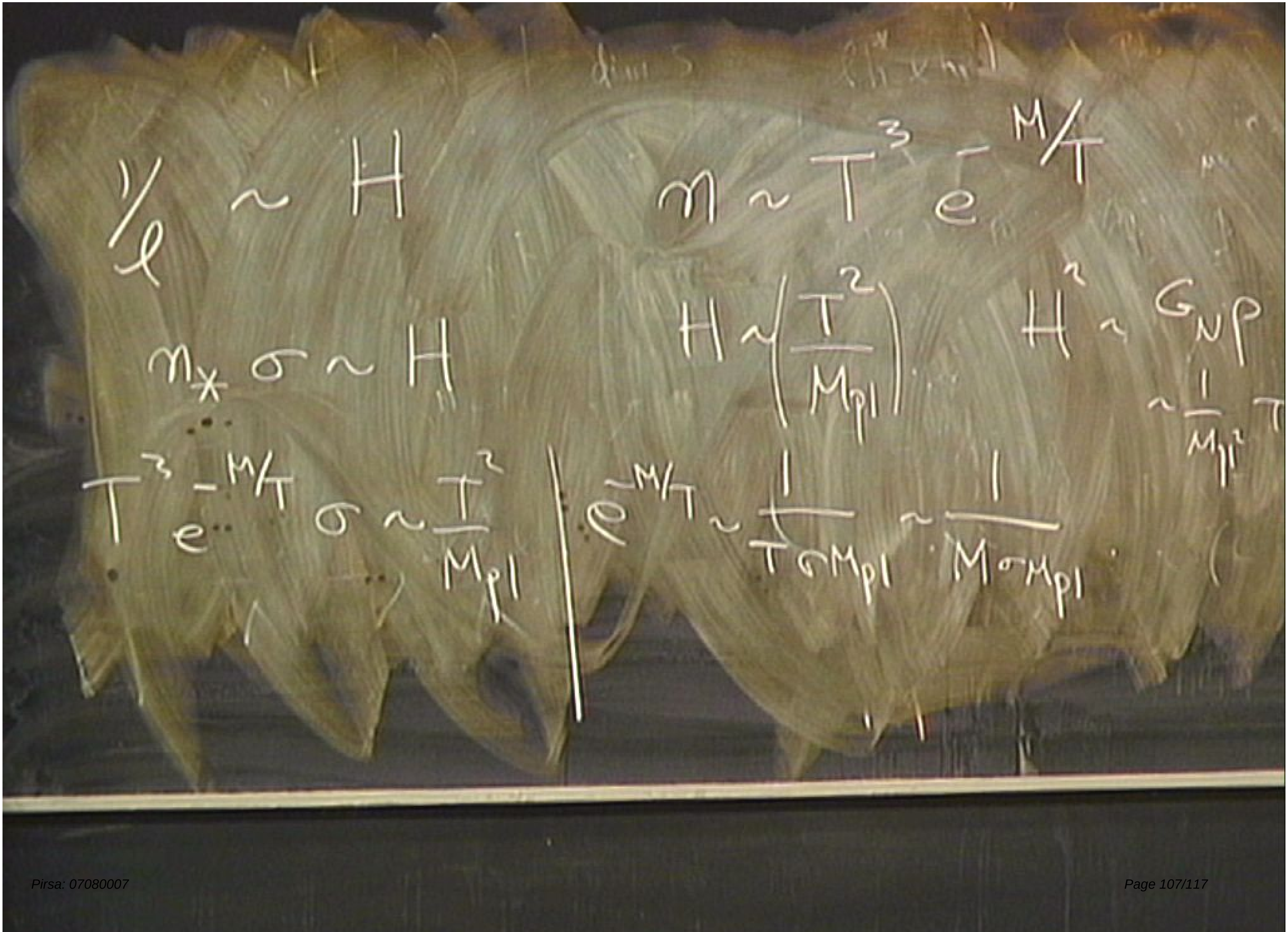
U(3)^3 violating
$\frac{1}{\Lambda^2}(\bar{d}s)^2$
$(ds^c)^2$
$(bd^c)^2$
$(cu^c)^2$
Re Λ > 300 – 3000 TeV
Im > 3000 → 30000 TeV
similar
Λ ~ 10 smaller
FCNC's Λ ≳ 10 – 10^4 TeV
CP (EDM's) Λ ≳ 100 TeV

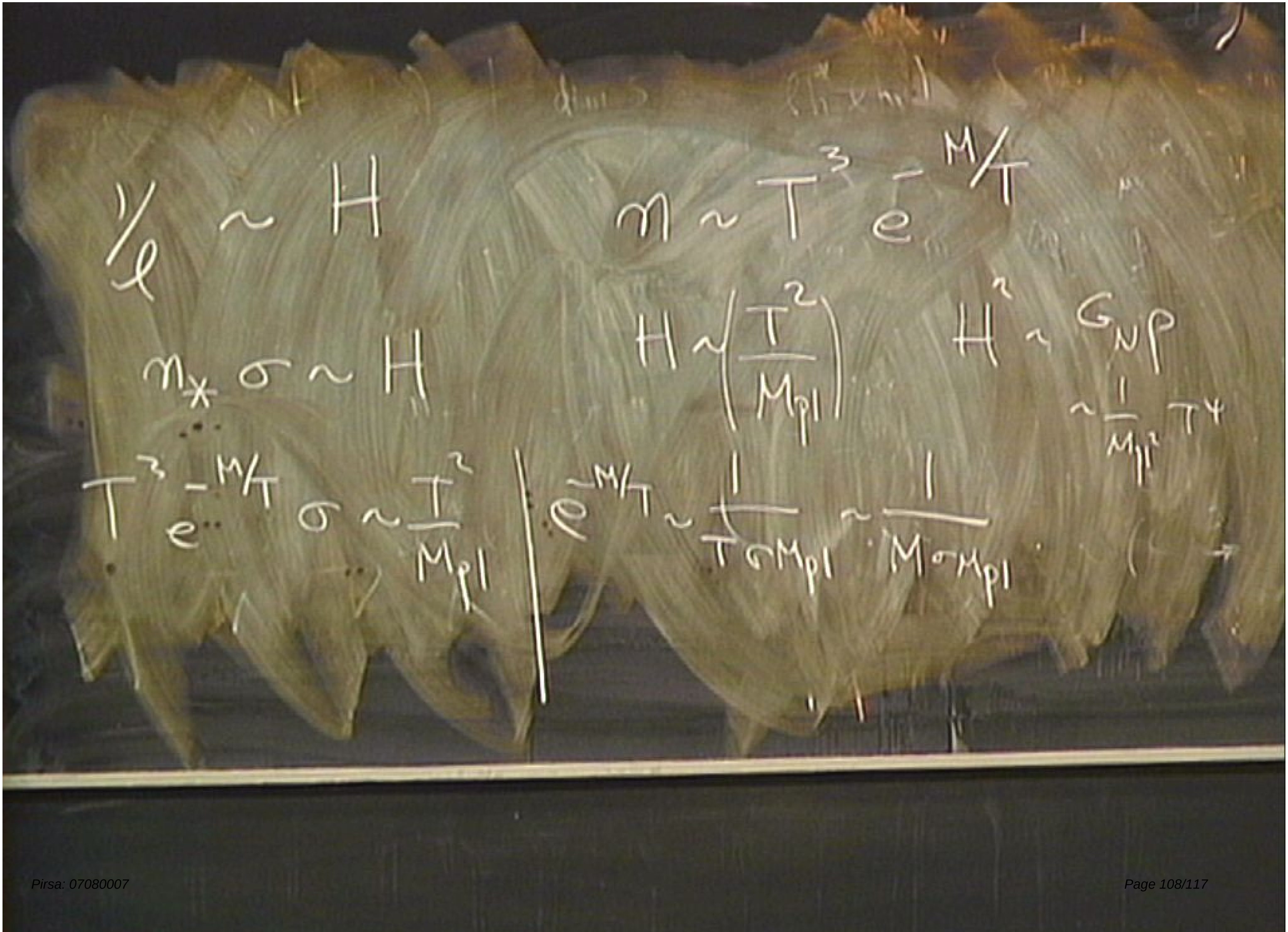

Why BSM?
1) Cosmology (DM Wimps)


Why BSM?
1) Cosmology (DM Wimps)
neutral
thermal equilibrium

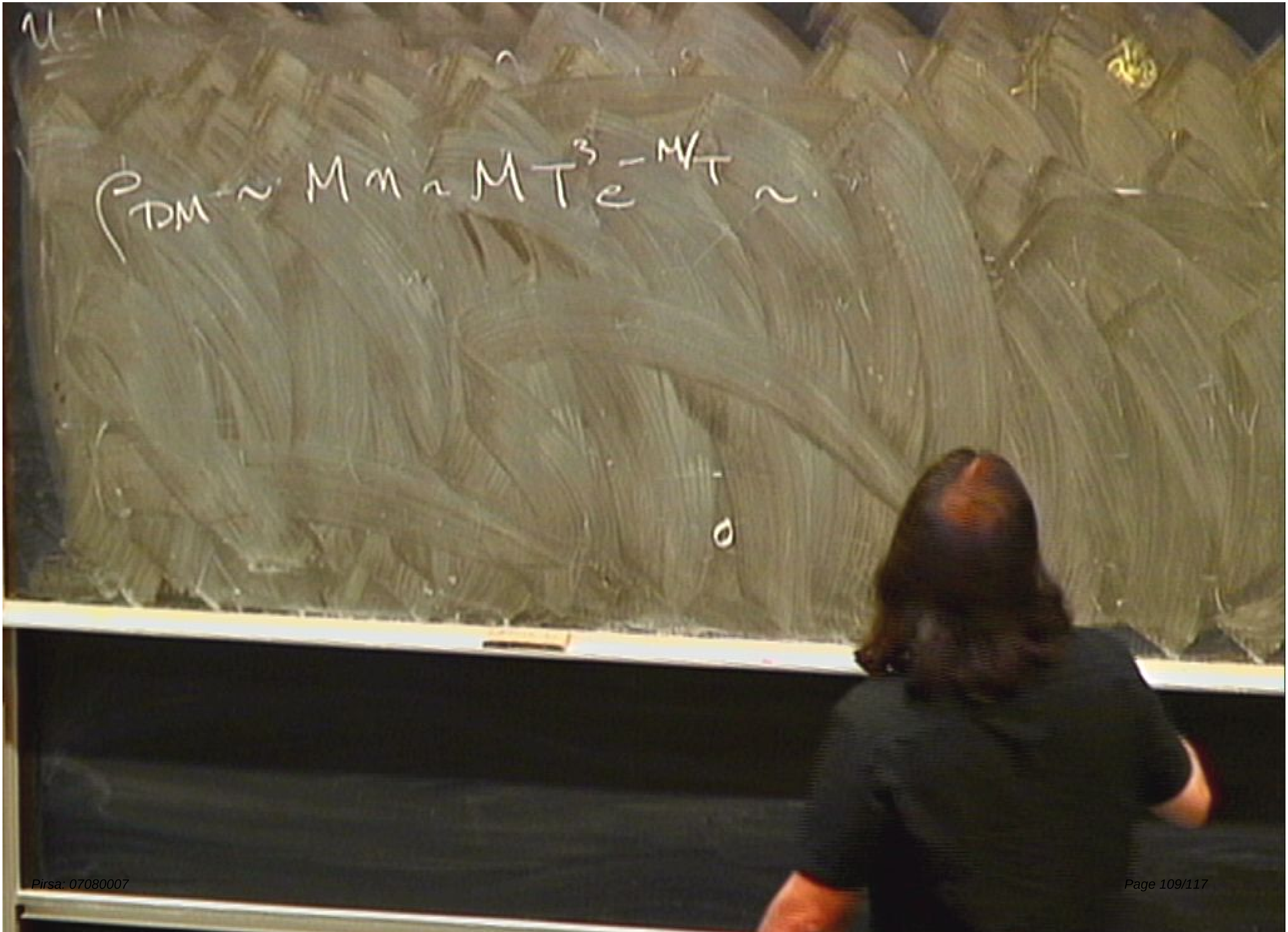

T.1
M
DM
SM
DM
SM


T
M
DM
SM
DM
SM
ℓ ~ 1/(nσv) ~ 1/(nσ)


1/ℓ ~ H
n ~ T^3 e^-M/T
H ~ (T^2/Mpl)
H^2 ~ G_N ρ
~ 1/Mpl^2 T
n* σ ~ H
T^3 e^-M/T σ ~ T^2/Mpl
e^-M/T ~ 1/(TσMpl) ~ 1/(MσMpl)



$1/\ell \sim H$
$n \sim T^3 e^{-M/T}$
$n_* \sigma \sim H$
$H \sim \left(\frac{T^2}{M_{pl}}\right)$
$H^2 \sim G_N \rho$
$\sim \frac{1}{M_{pl}^2} T^4$
$T^3 e^{-M/T} \sigma \sim \frac{T^2}{M_{pl}}$
$e^{-M/T} \sim \frac{1}{T \sigma M_{pl}} \sim \frac{1}{M \sigma M_{pl}}$

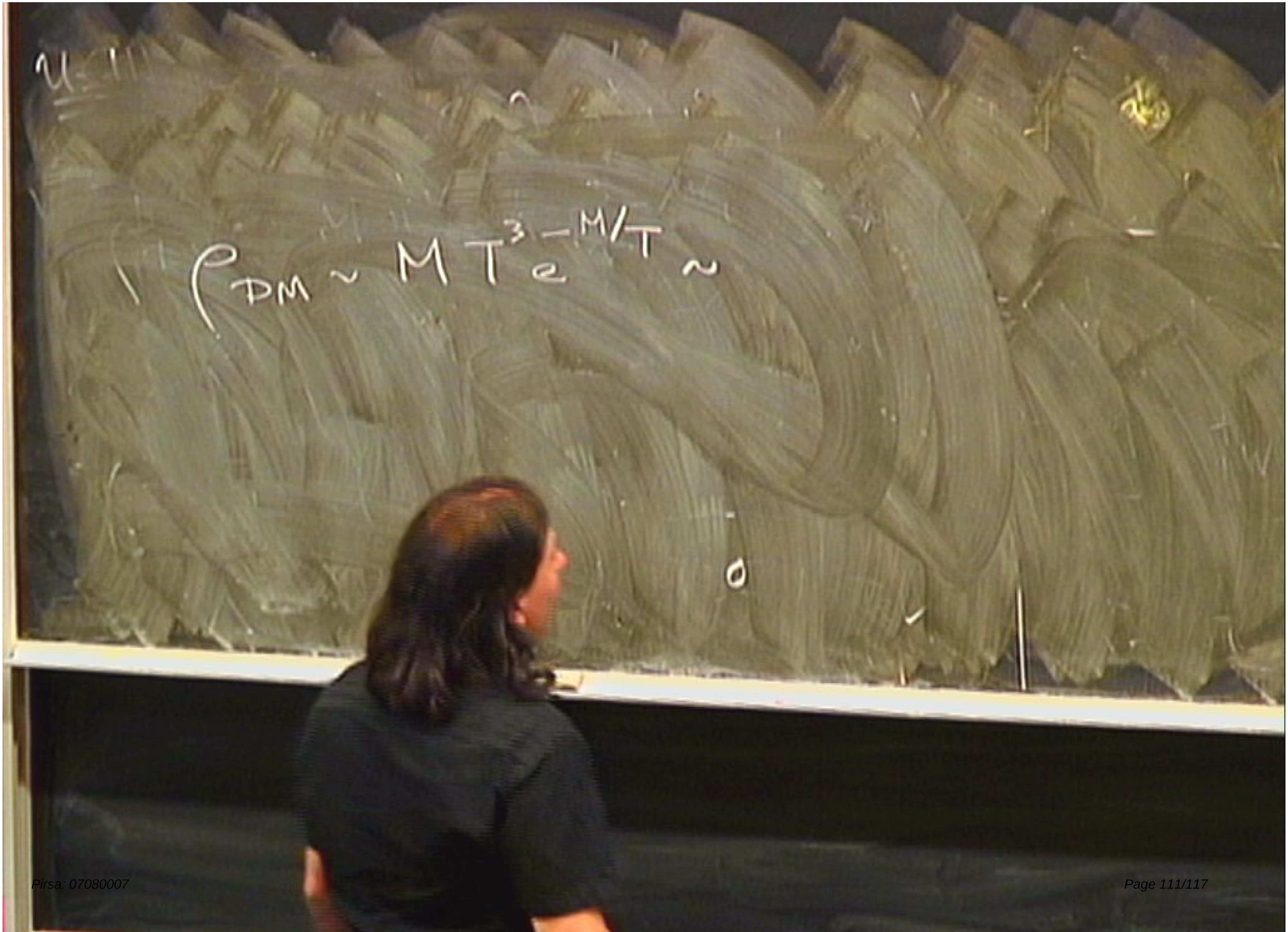

$\rho_{DM} \sim M n \sim M T^3 e^{-M/T} \sim$

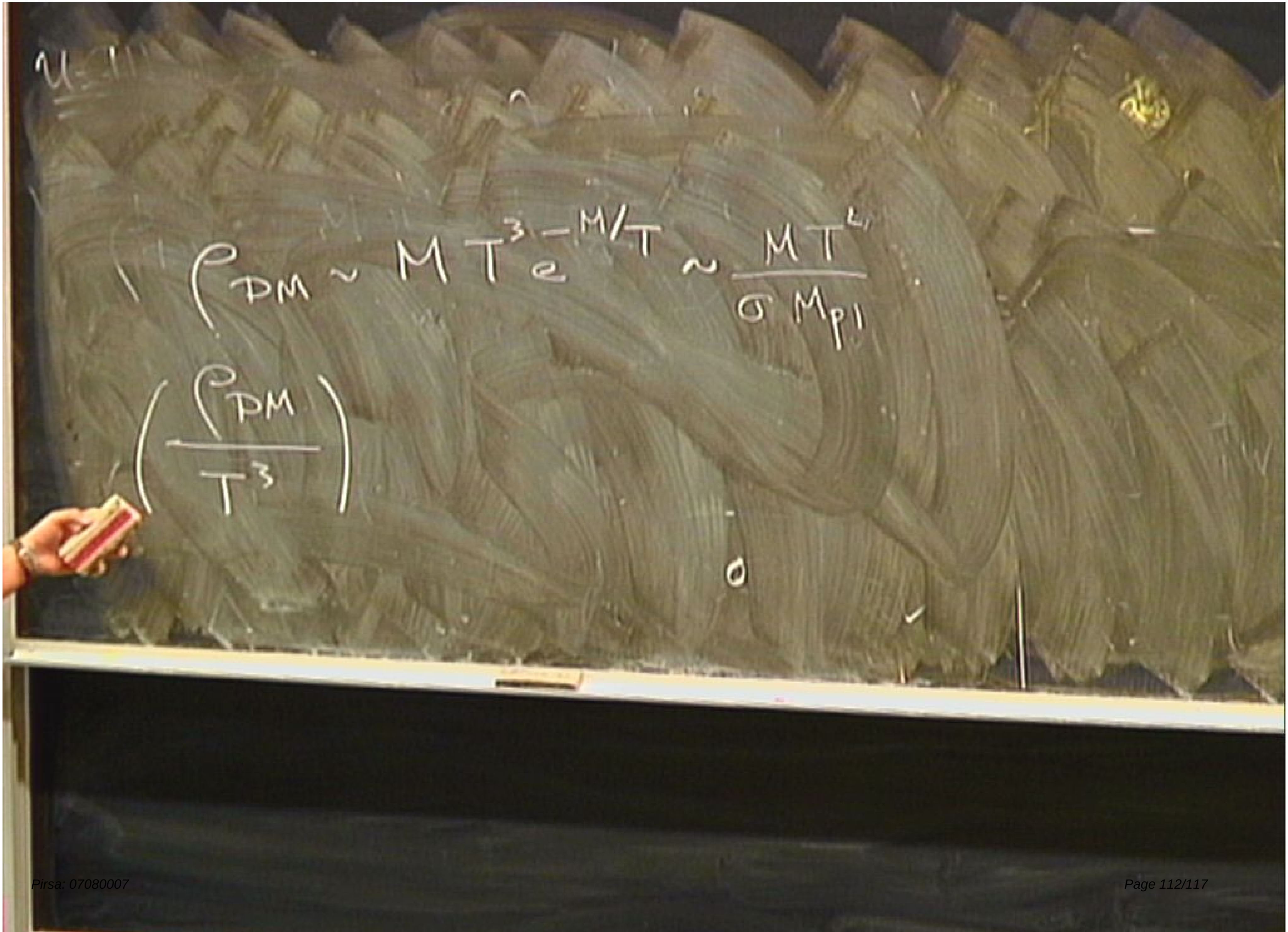
$$\frac{1}{\ell} \sim H \qquad n \sim T^3 e^{-M/T}$$

$$n_* \sigma \sim H \qquad H \sim \left(\frac{T^2}{M_{pl}}\right) \qquad H^2 \sim G_N \rho \sim \frac{1}{M_{pl}^2} T^4$$

$$T^3 e^{-M/T} \sigma \sim \frac{T^2}{M_{pl}} \qquad e^{-M/T} \sim \frac{1}{T \sigma M_{pl}} \sim \frac{1}{M \sigma M_{pl}}$$

$$\frac{T}{M} \sim \frac{1}{\log(M \sigma M_{pl})}$$


$\rho_{DM} \sim M T^3 e^{-M/T} \sim$

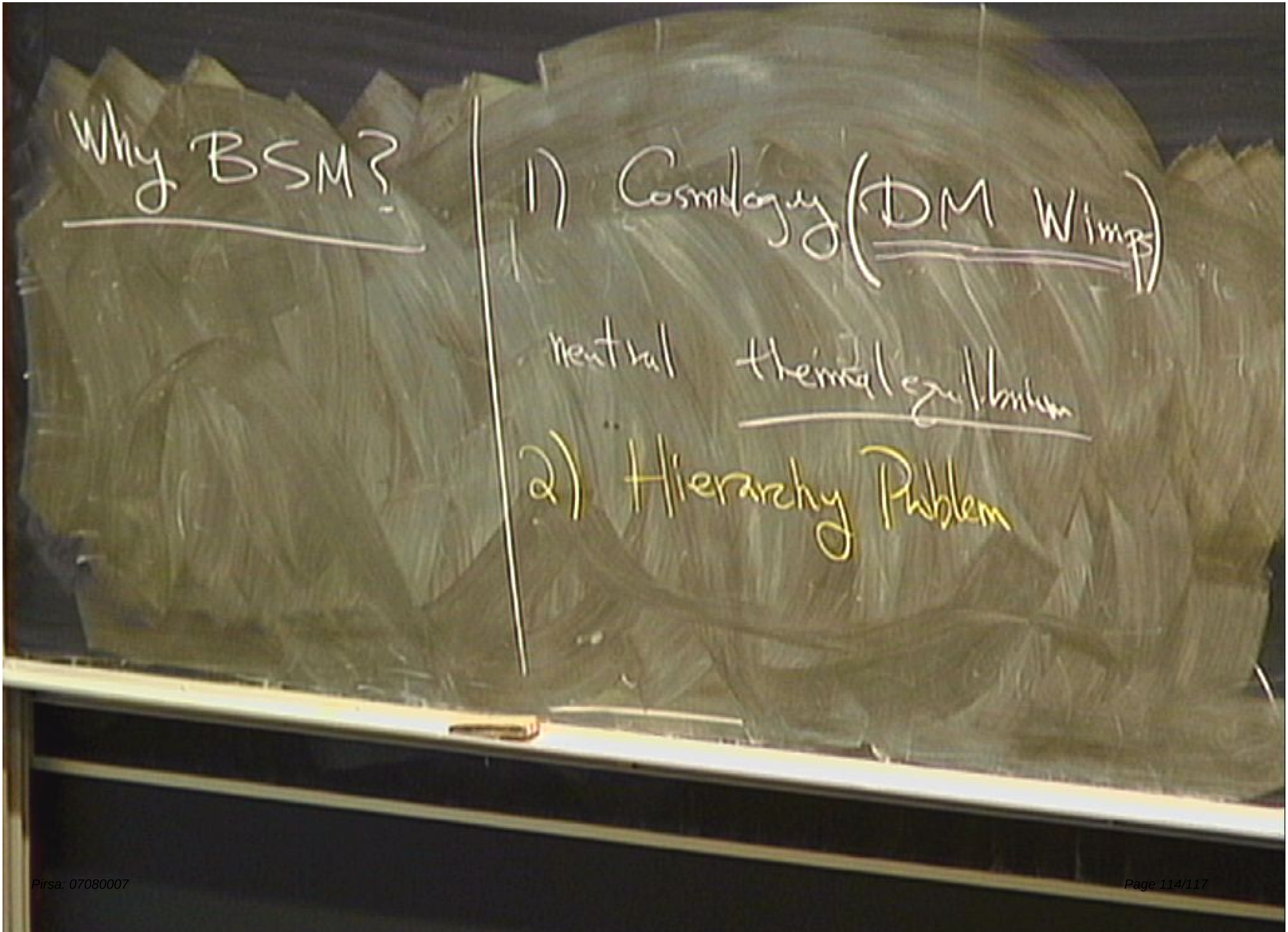

$\rho_{DM} \sim M T^3 e^{-M/T} \sim \frac{M T^4}{\sigma M_{pl}}$
$\left(\frac{\rho_{DM}}{T^3} \right)$

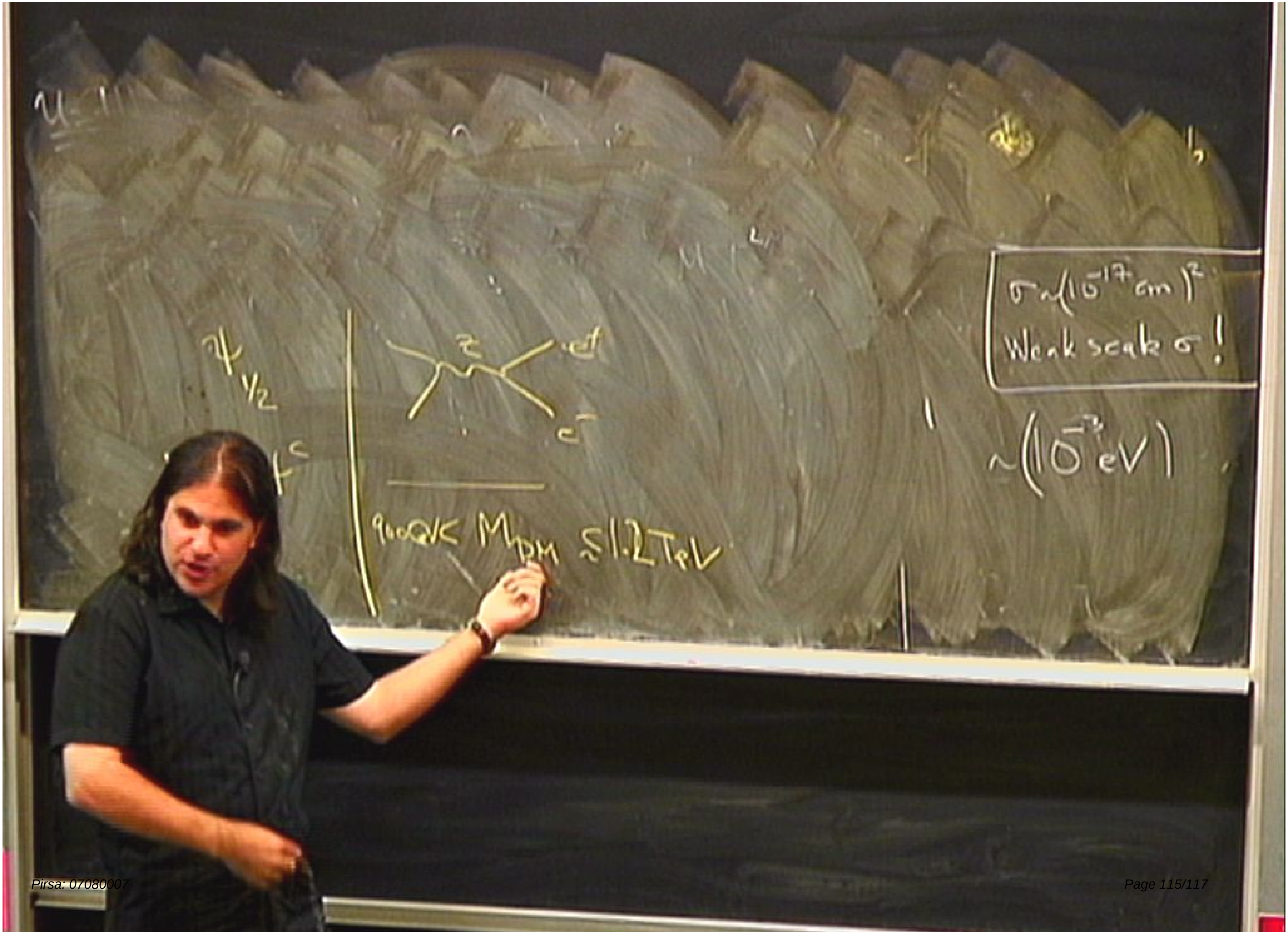
$$\rho_{DM} \sim M T^3 e^{-M/T} \sim \frac{M T^4}{\sigma M_{pl}}$$

$$\left(\frac{\rho_{DM}}{T^3}\right) \sim \frac{M}{T}\,\frac{1}{\sigma M_{pl}} \sim \frac{\log M \sigma M_{pl}}{\sigma M_{pl}} \sim (10^{-3}\,\mathrm{eV})$$

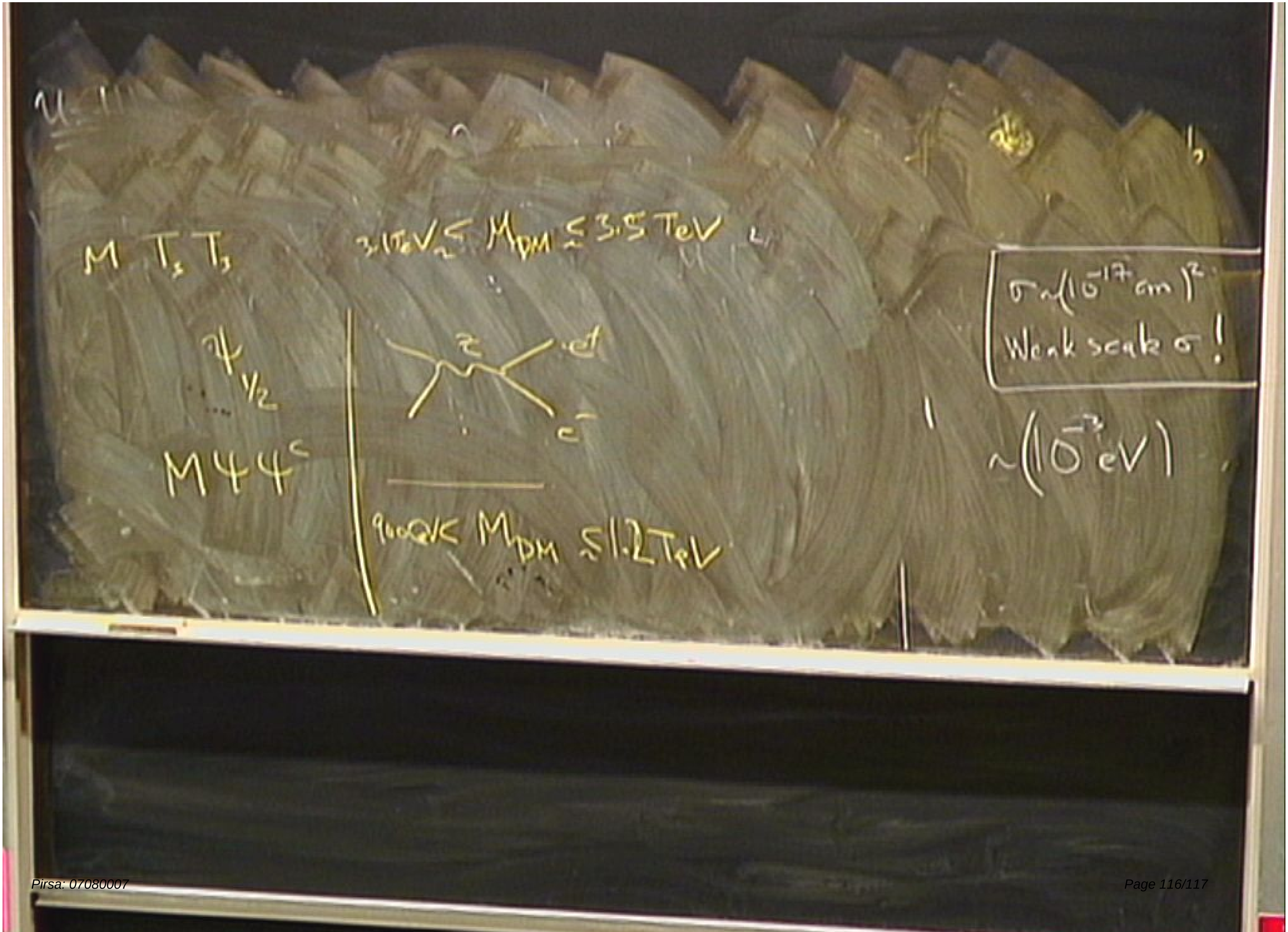
$\sigma \sim (10^{-17}\,\mathrm{cm})^2$

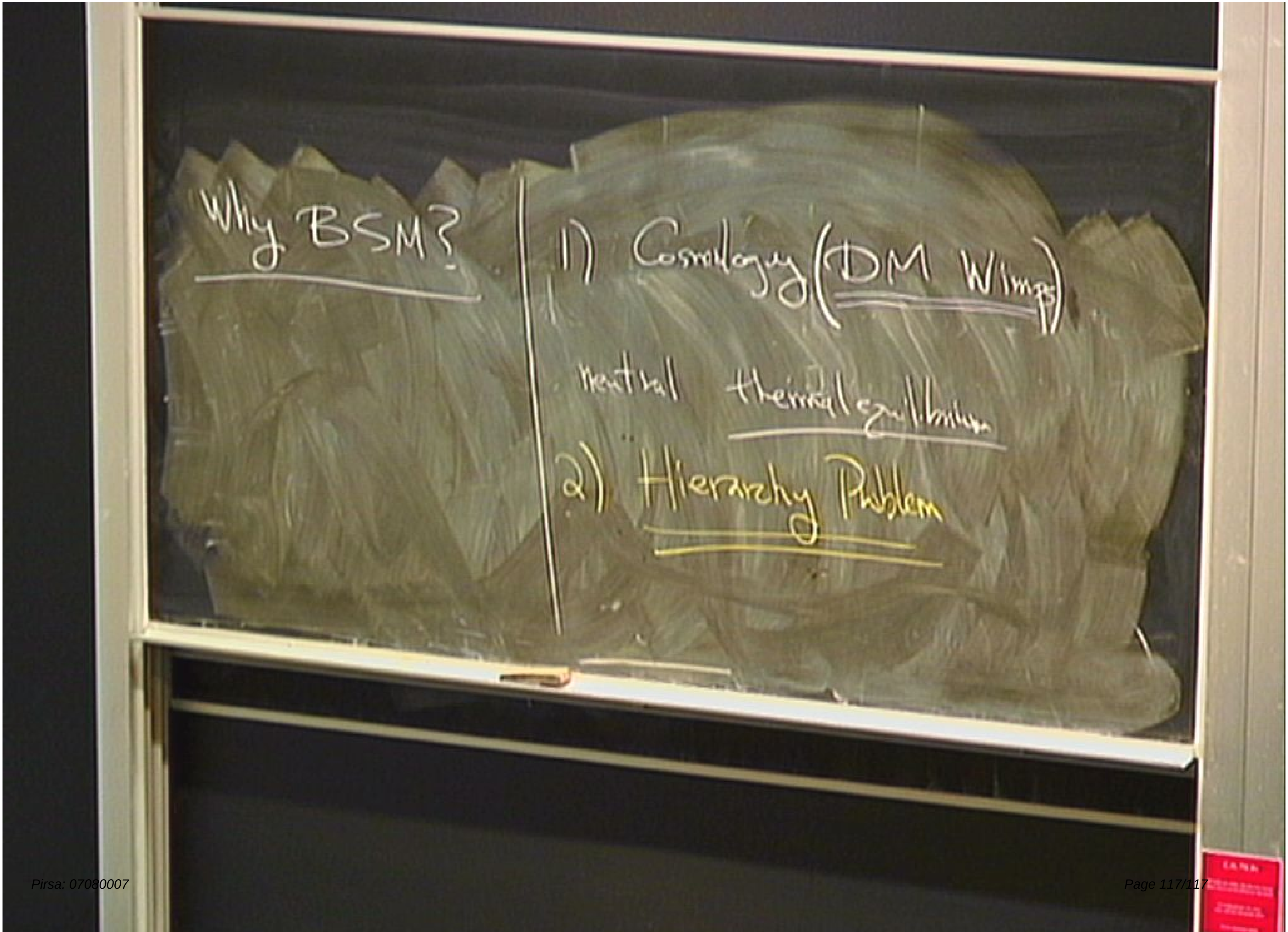
Weak scale σ!


Why BSM?
1) Cosmology (DM Wimps)
neutral thermal equilibrium
2) Hierarchy Problem



σ ~ (10^-17 cm)^2
Weak scale σ !
M_DM ≲ 1.2 TeV


M T2 T3
3.1TeV ≲ MDM ≲ 3.5 TeV
ψ1/2
Mψψc
Z
e+
e−
900GeV ≲ MDM ≲ 1.2TeV
σ ~ (10−17 cm)2
Weak scale σ !
~(10−3 eV)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