Title: Explorations in String Theory (PHYS 647) - Lecture 14

Date: Mar 03, 2010 03:30 PM

URL: http://pirsa.org/10030065

Abstract:

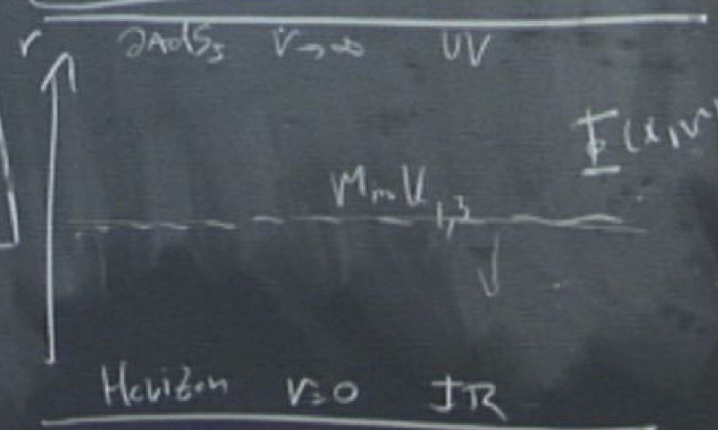
AdS/CFT from D3-branes (cont'd)

$$\boxed{\begin{array}{c} D=4 \ \ \mathcal{N}=4 \\ SU(N_c) \ \ SYM \end{array}} = \boxed{\begin{array}{c} \text{Type IIB s.t. on} \\ AdS_5 \times S^5 \end{array}}$$

$$\boxed{\frac{R^4}{l_s^4} \sim g_{YM}^2 N_c \qquad g_s \sim g_{YM}^2}$$

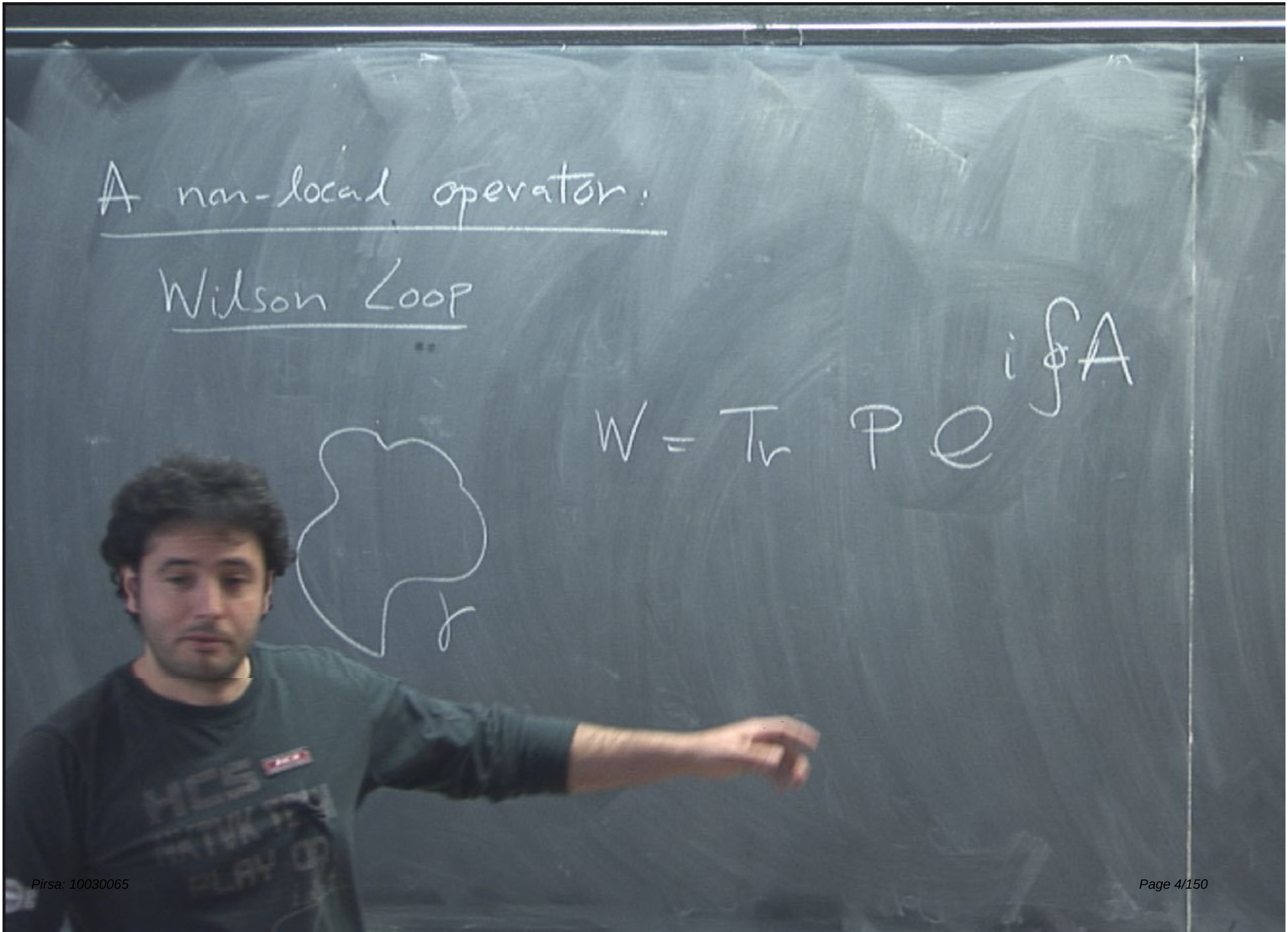
$$\boxed{ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2}\, dr^2}$$

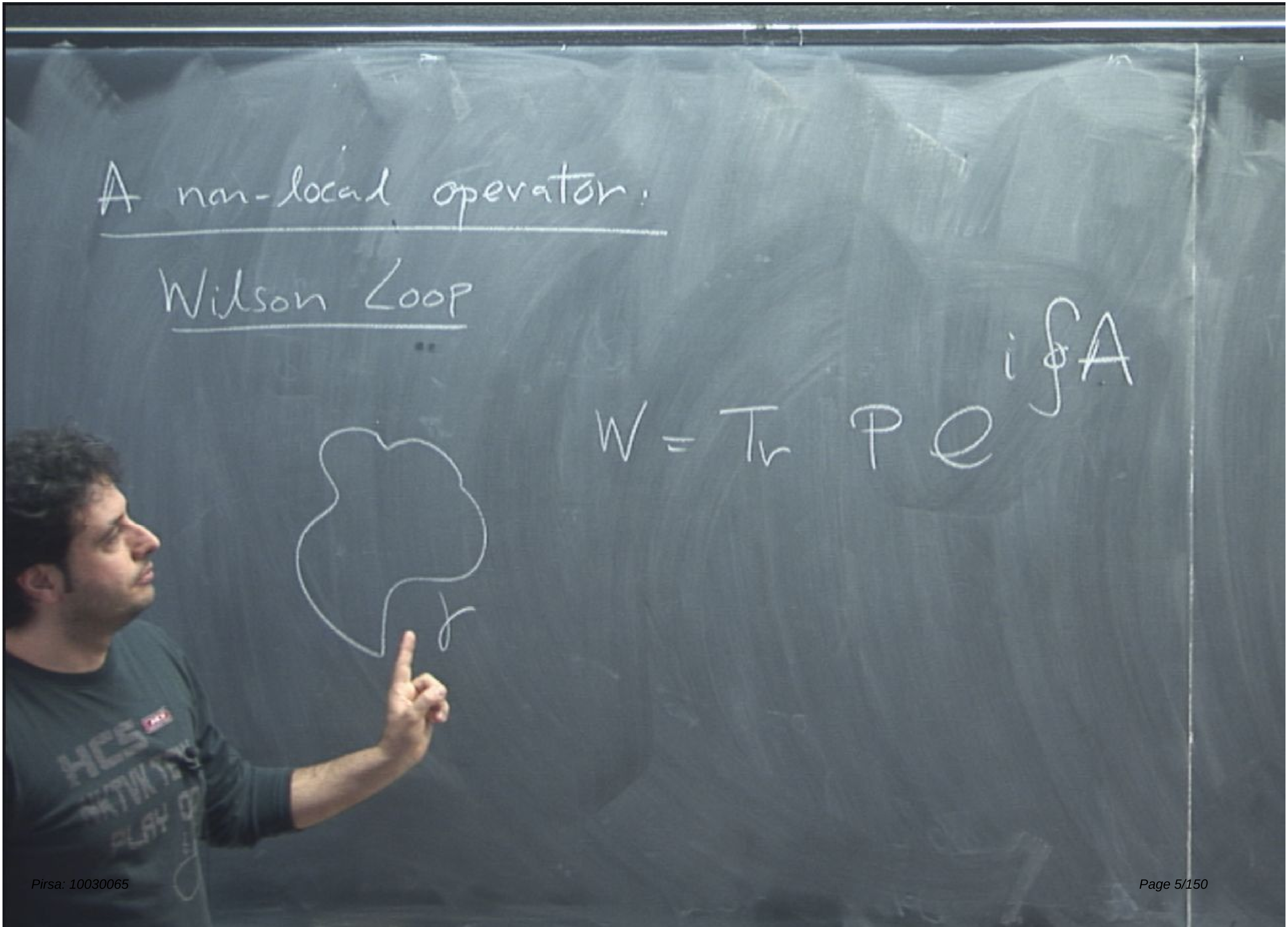
D. $x^\mu \to \Lambda x^\mu$ $\quad r \to r/\Lambda$



A non-local operator:

Wilson Loop


A non-local operator:
Wilson Loop
$W = \mathrm{Tr}\, P\, e^{i\oint A}$
γ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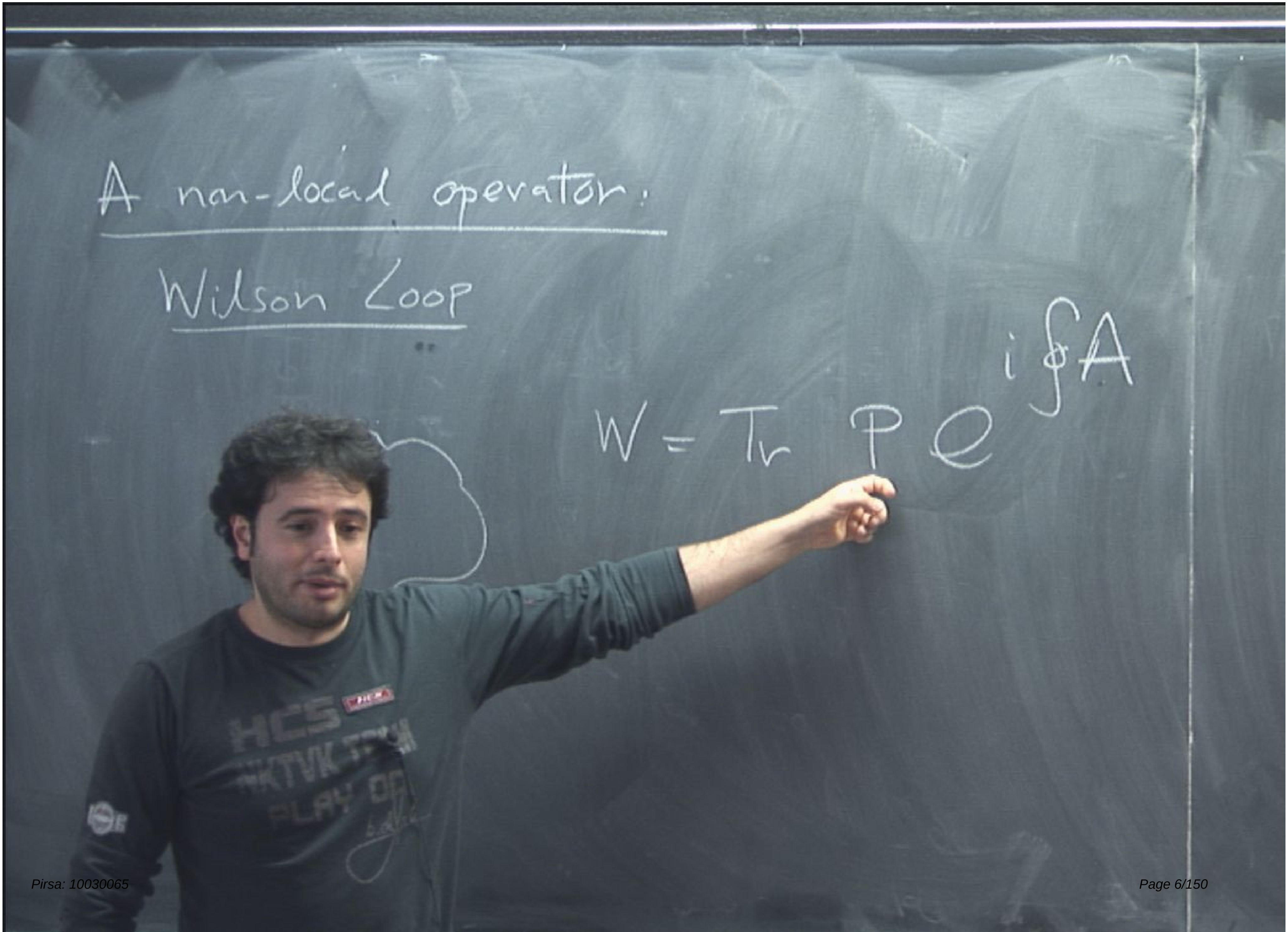
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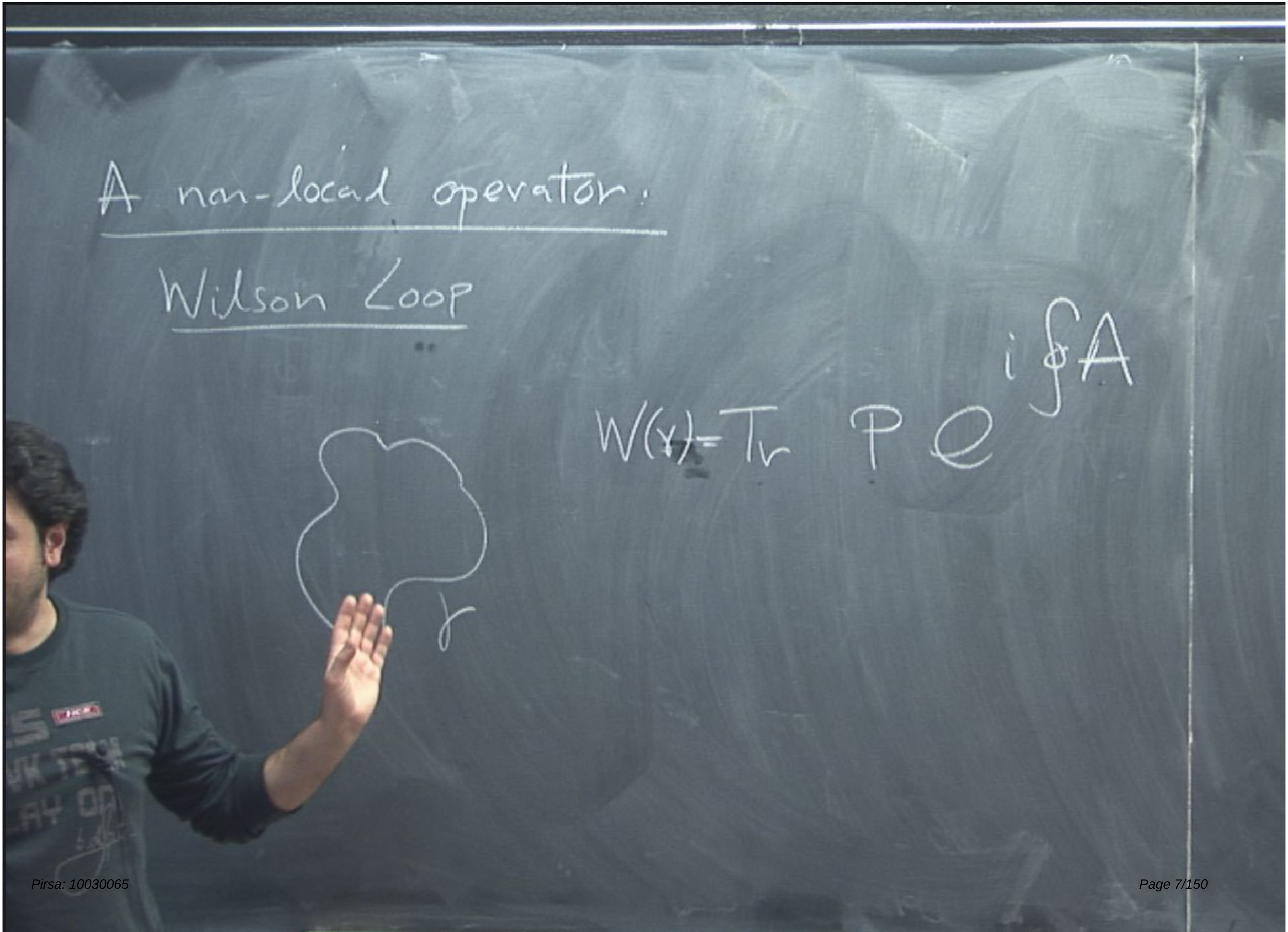

A non-local operator:
Wilson Loop
$W(\gamma) = \mathrm{Tr}\, P\, e^{i\oint A}$
γ

A non-local operator:

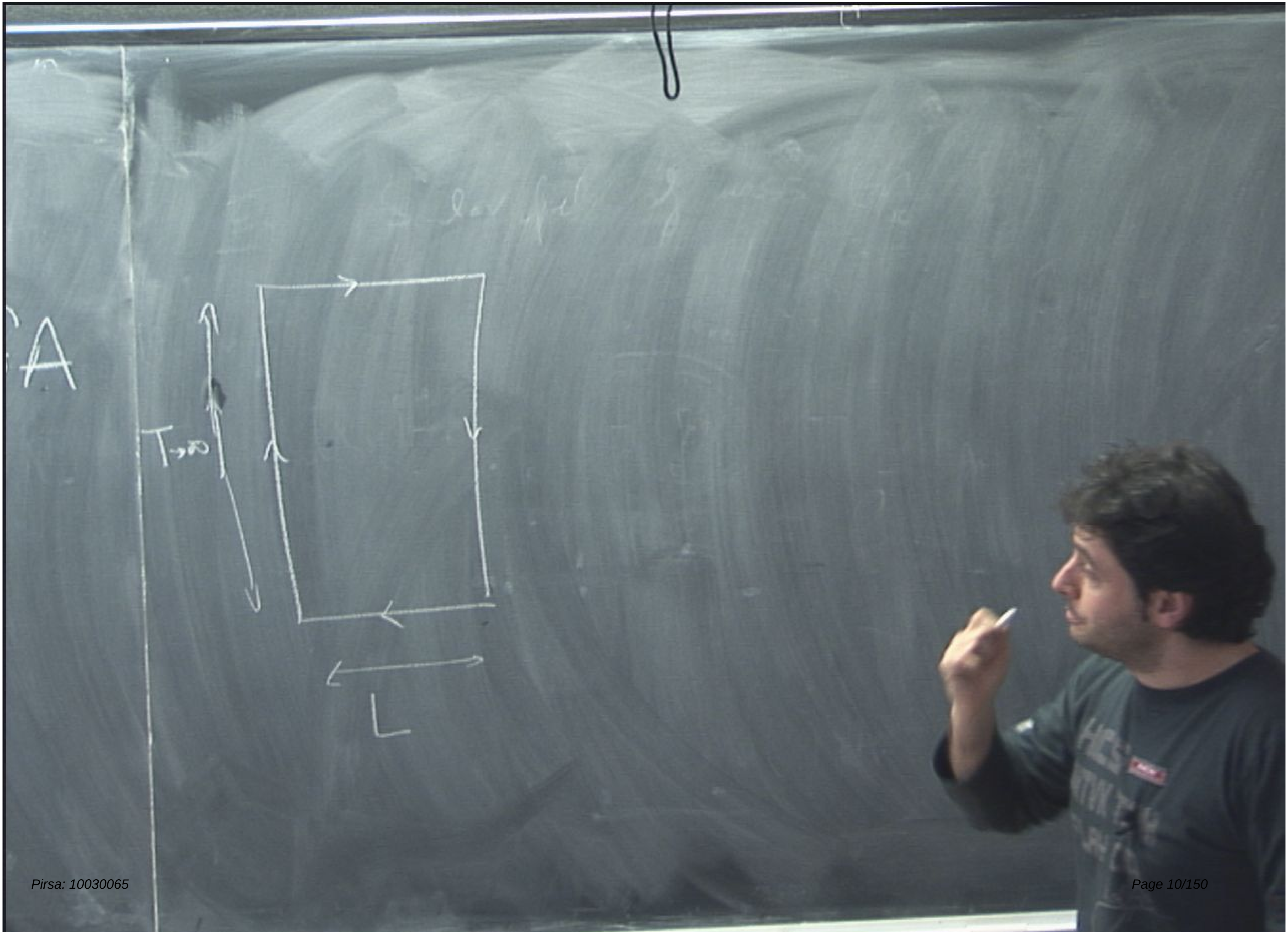
Wilson Loop

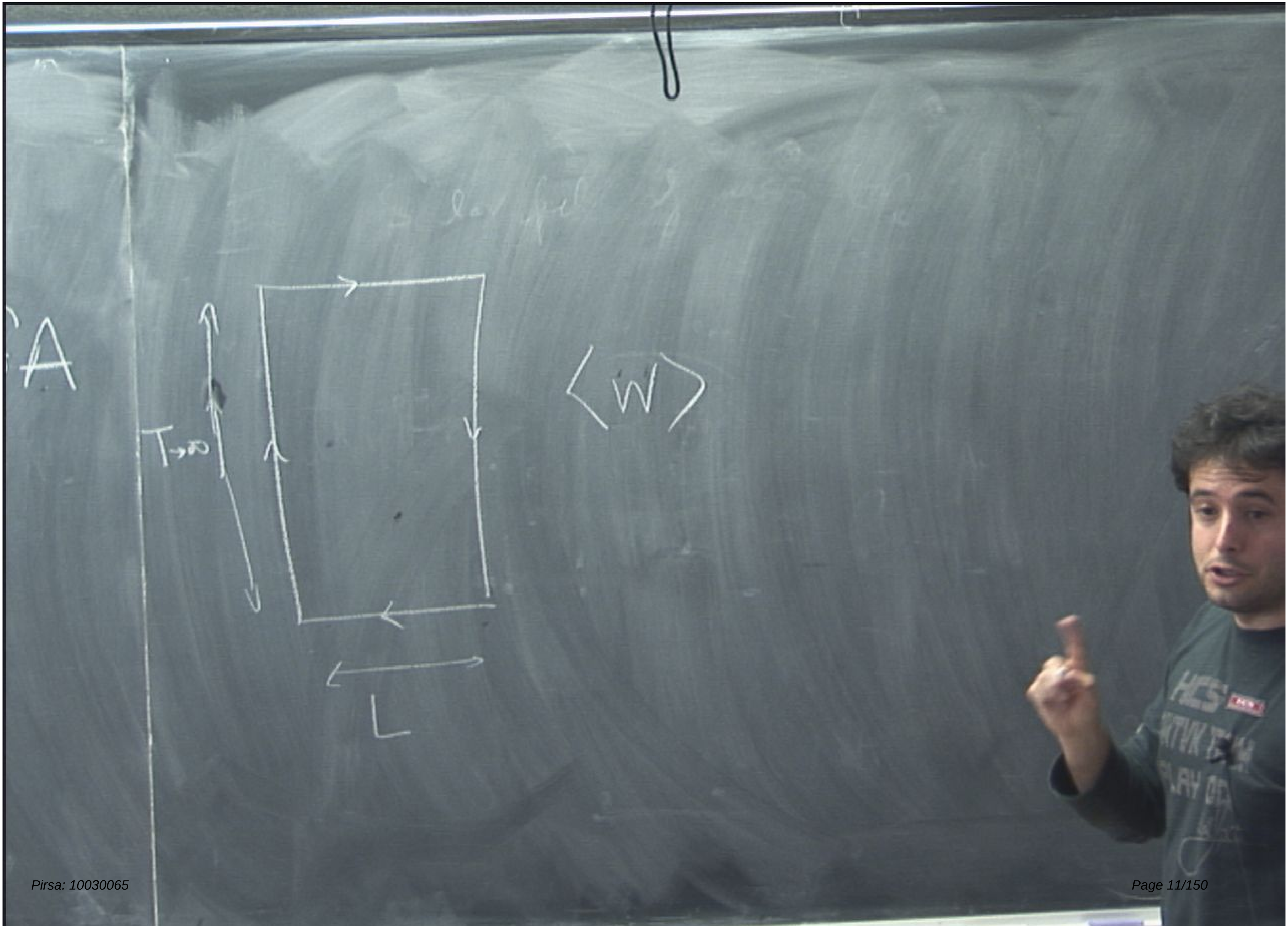
$$W(\gamma) = \mathrm{Tr}\, P\, e^{i\oint A}$$

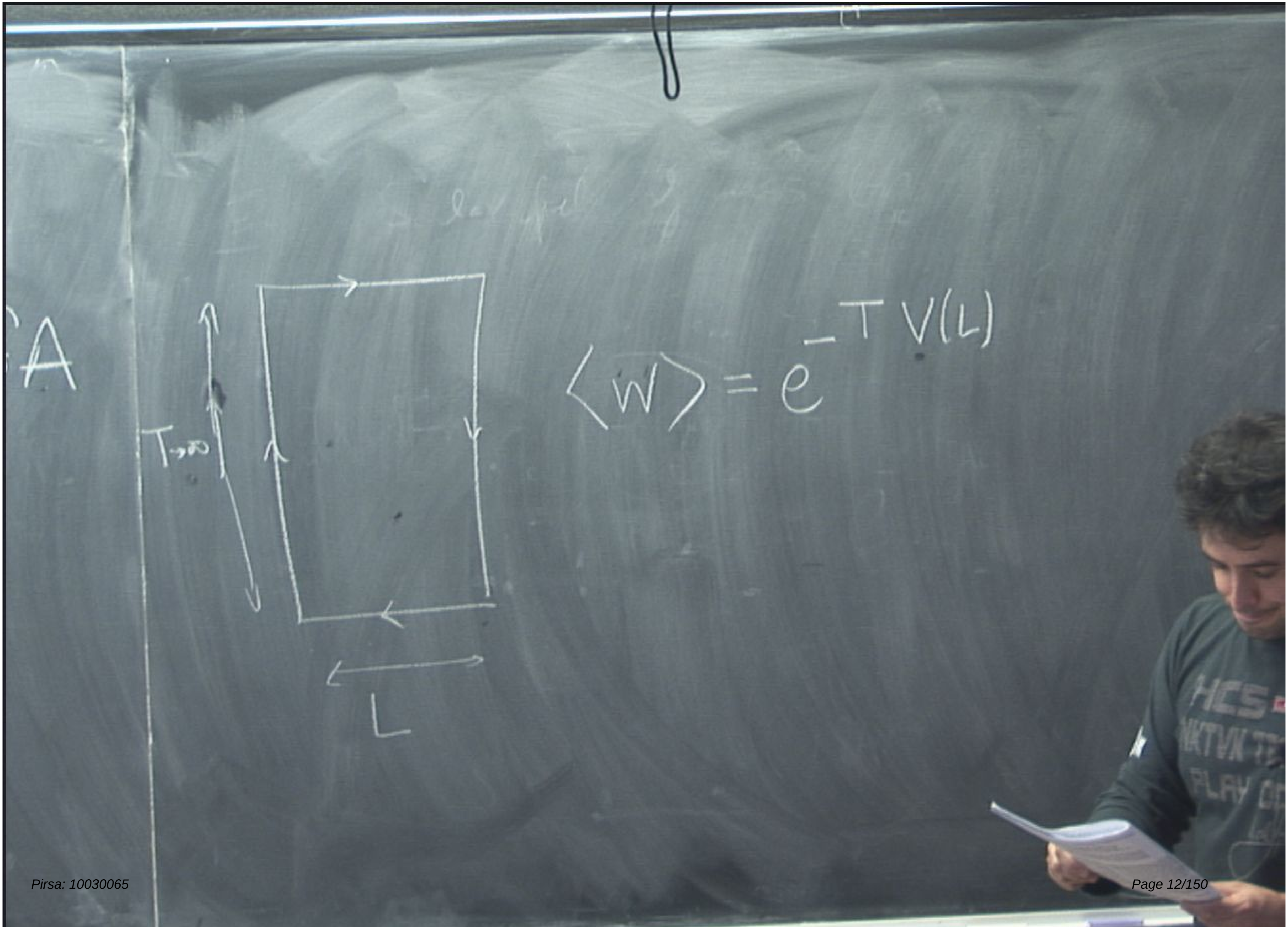
operator:

oop

$$W(\gamma) = \mathrm{Tr}\, P\, e^{i\oint A}$$

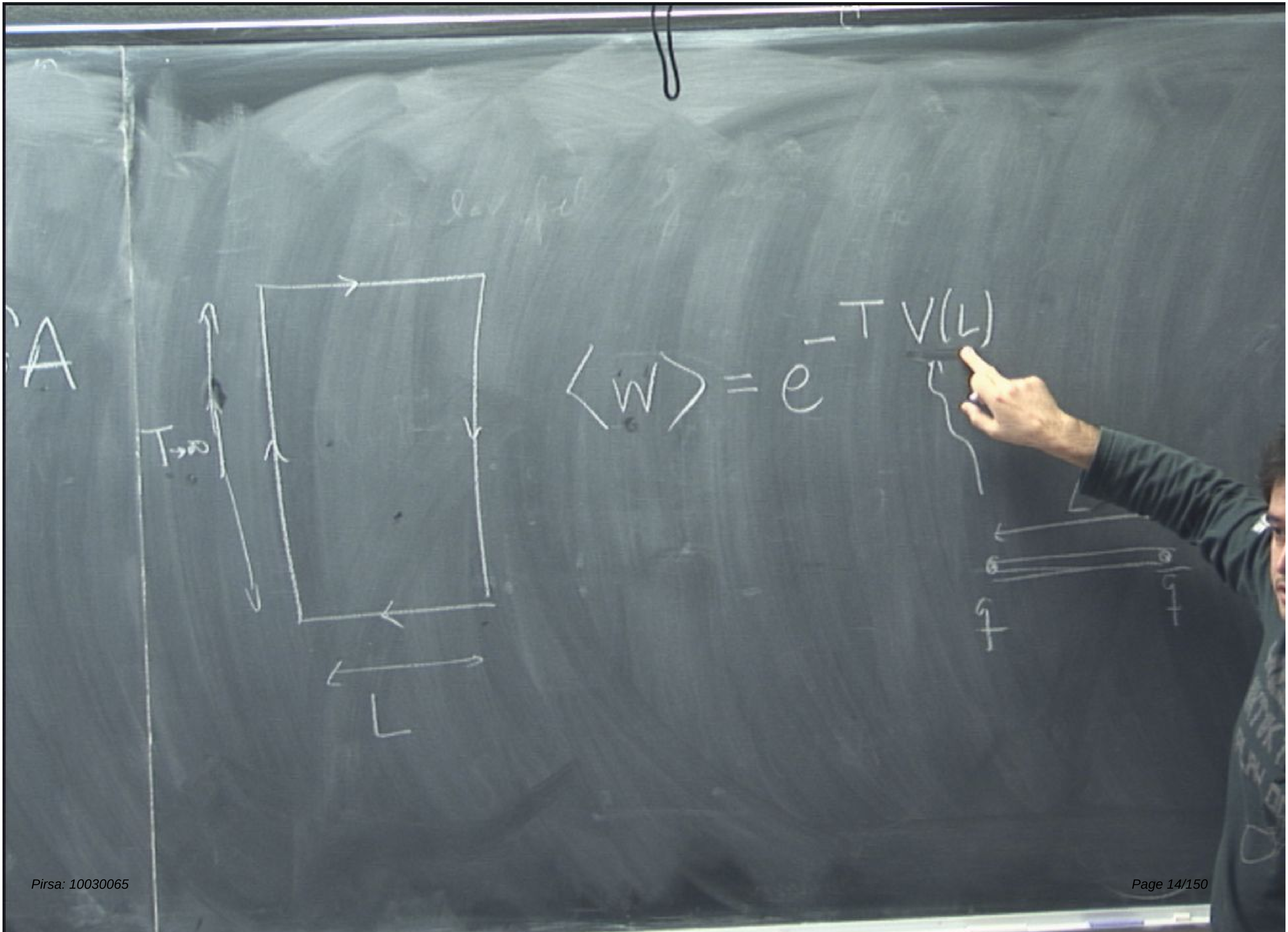

A
T→∞
L


$T \to \infty$
$\langle W \rangle$
L


A
$T \to \infty$
L
$\langle W \rangle = e^{-T\,V(L)}$

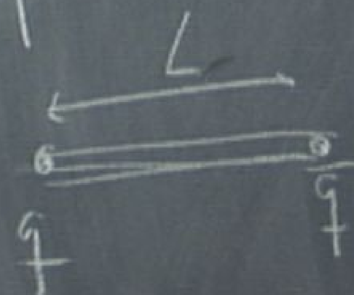
A

$$\langle W \rangle = e^{-T\,V(L)}$$


$\langle W \rangle = e^{-T\,V(L)}$
$T \to \infty$
L
q
$\bar{q}$
A

$$\langle W \rangle = e^{-T\,V(L)}$$

$$\langle W \rangle = e^{-T\,V(L)}$$



A non-local operator:

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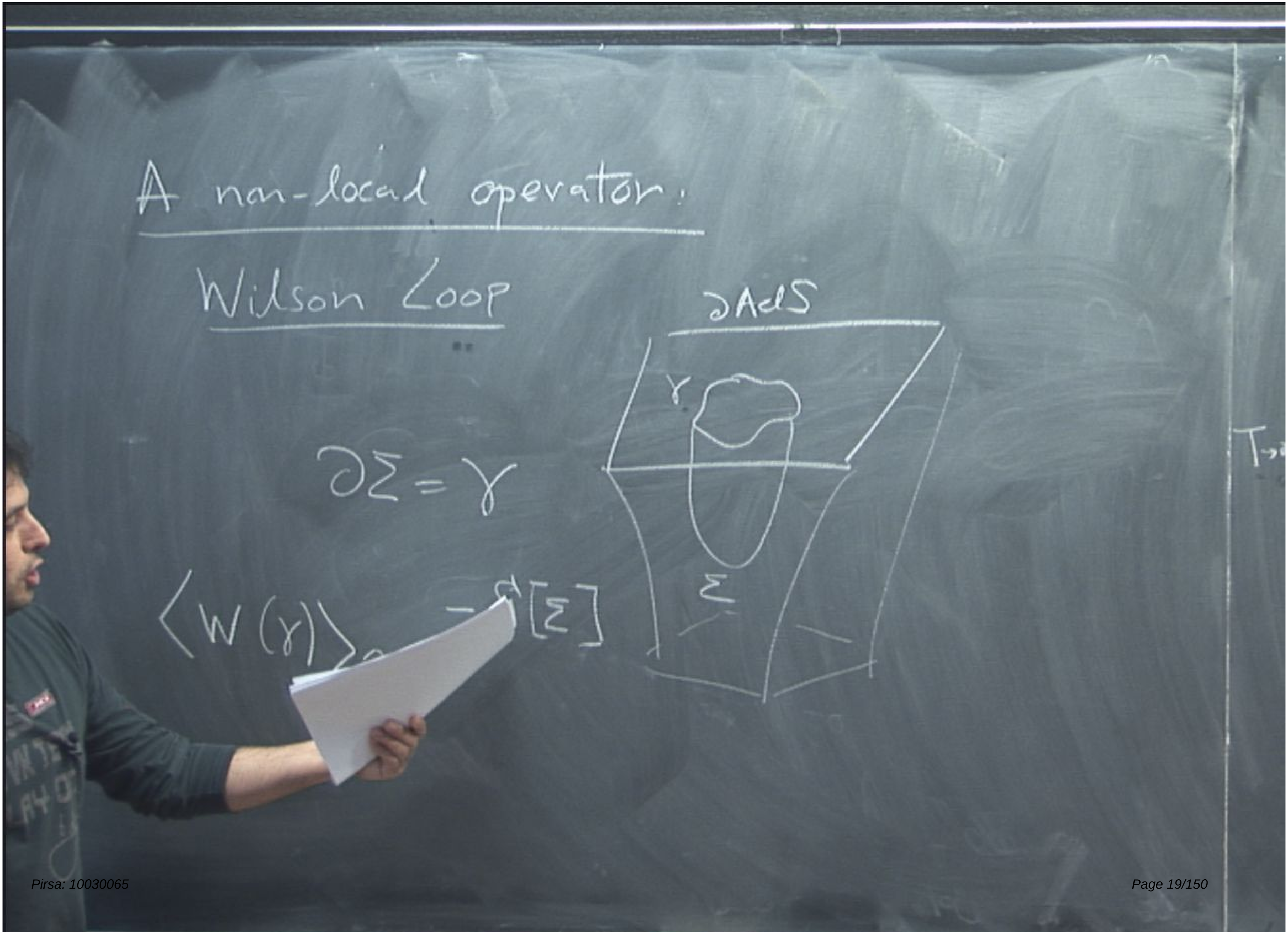
A non-local operator:
Wilson Loop
$\partial \Sigma = \gamma$
$\langle W(\gamma) \rangle$
$[\Sigma]$
∂AdS
γ
Σ

A non-local operator:

Wilson Loop

$$\partial\Sigma = \gamma$$

$$\langle W(\gamma)\rangle \simeq e^{-S[\Sigma]}$$

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Wilson Loop

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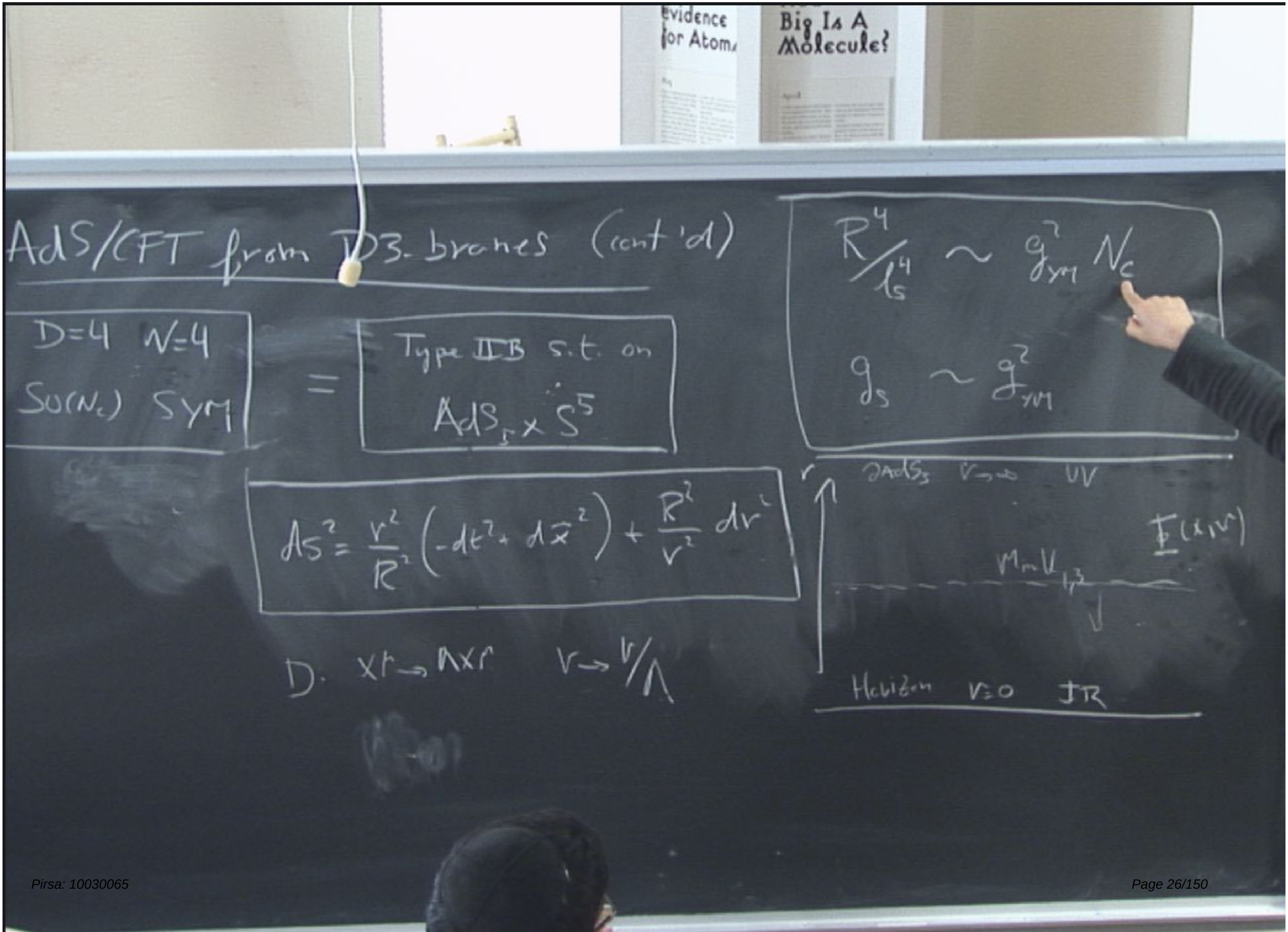

Big Is A Molecule?
AdS/CFT from D3-branes (cont'd)
D=4 N=4
SU(N_c) SYM
=
Type IIB s.t. on
$AdS_5 \times S^5$
$R^4/l_s^4 \sim g_{YM}^2 N_c$
$g_s \sim g_{YM}^2$
$ds^2 = \frac{r^2}{R^2}(-dt^2 + d\vec{x}^2) + \frac{R^2}{r^2} dr^2$
D. $x^\mu \to \Lambda x^\mu$ $r \to r/\Lambda$
r
∂AdS_5 $r \to \infty$ UV
$\Phi(x,r)$
$M \sim V_{1,3}$
Horizon $r=0$ IR

A non-local operator:

Wilson Loop

$$\partial\Sigma = \gamma$$

$$\langle W(\gamma)\rangle \simeq e^{-S[\Sigma]}$$

$$V_{q\bar{q}} = V(L) +$$

$T \to \infty$

A non-local operator:

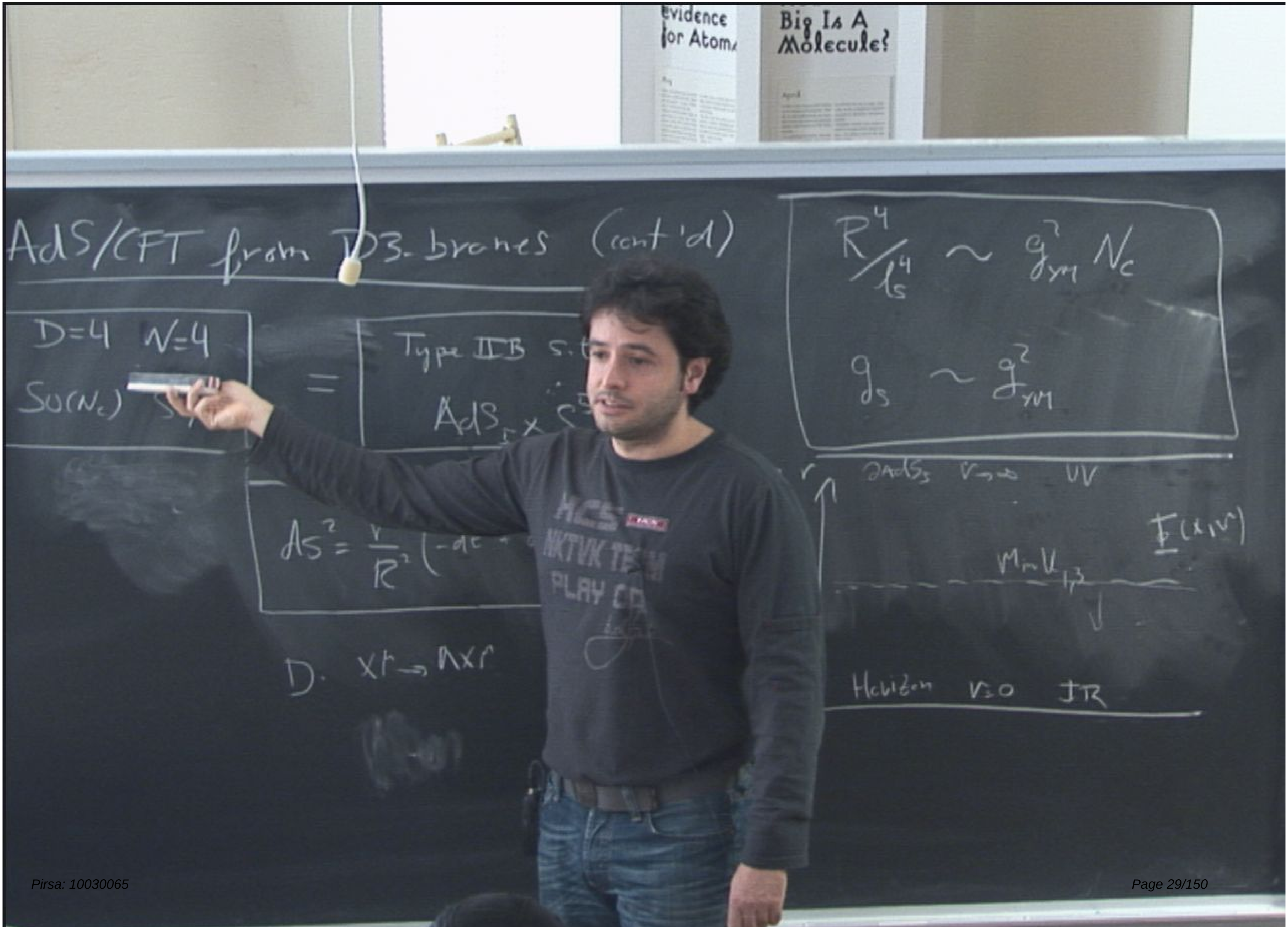
Wilson Loop

$$\partial \Sigma = \gamma$$

$$\langle W(\gamma) \rangle \simeq e^{-S[\Sigma]}$$

$$V_{1\times 41} = V(L) + \frac{1}{\sqrt{\lambda}} + \frac{1}{N_c}$$

$T \to \infty$



Big Is A Molecule?
AdS/CFT from D3-branes (cont'd)
D=4 N=4
SU(N_c)
Type IIB
R^4/l_s^4 ~ g_YM^2 N_c
g_s ~ g_YM^2
∂AdS5 r→∞ UV
Horizon r=0 IR

AdS/CFT from D3-branes (cont'd)

$\boxed{\begin{array}{c} D=4 \quad \mathcal{N}=4 \\ SU(N_c) \ \text{SYM} \end{array}} = \boxed{\begin{array}{c} \text{Type IIB s.t. on} \\ AdS_5 \times S^5 \end{array}}$

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$$\boxed{ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^{\,2}\right) + \frac{R^2}{r^2}\, dr^2}$$

D. $x^\mu \to \Lambda x^\mu \qquad r \to r/\Lambda$

r

$\partial AdS_5 \quad r \to \infty \quad UV$

$\Phi(x, r)$

$m \sim V_{1,3}$

Horizon $\quad r = 0 \quad IR$

3) Finite T and RHIC Physics (1)

$$\boxed{\begin{matrix} D=4 \quad \mathcal{N}=4 \\ SU(N_c) \ \text{SYM} \end{matrix}} = \boxed{\begin{matrix} \text{Type IIB s.t. on} \\ AdS_5 \times S^5 \end{matrix}}$$

$$\boxed{\begin{matrix} R^4/l_s^4 \sim g_{YM}^2 N_c \\ g_s \sim g_{YM}^2 \end{matrix}}$$

$$\boxed{ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^{\,2}\right) + \frac{R^2}{r^2}\, dr^2}$$

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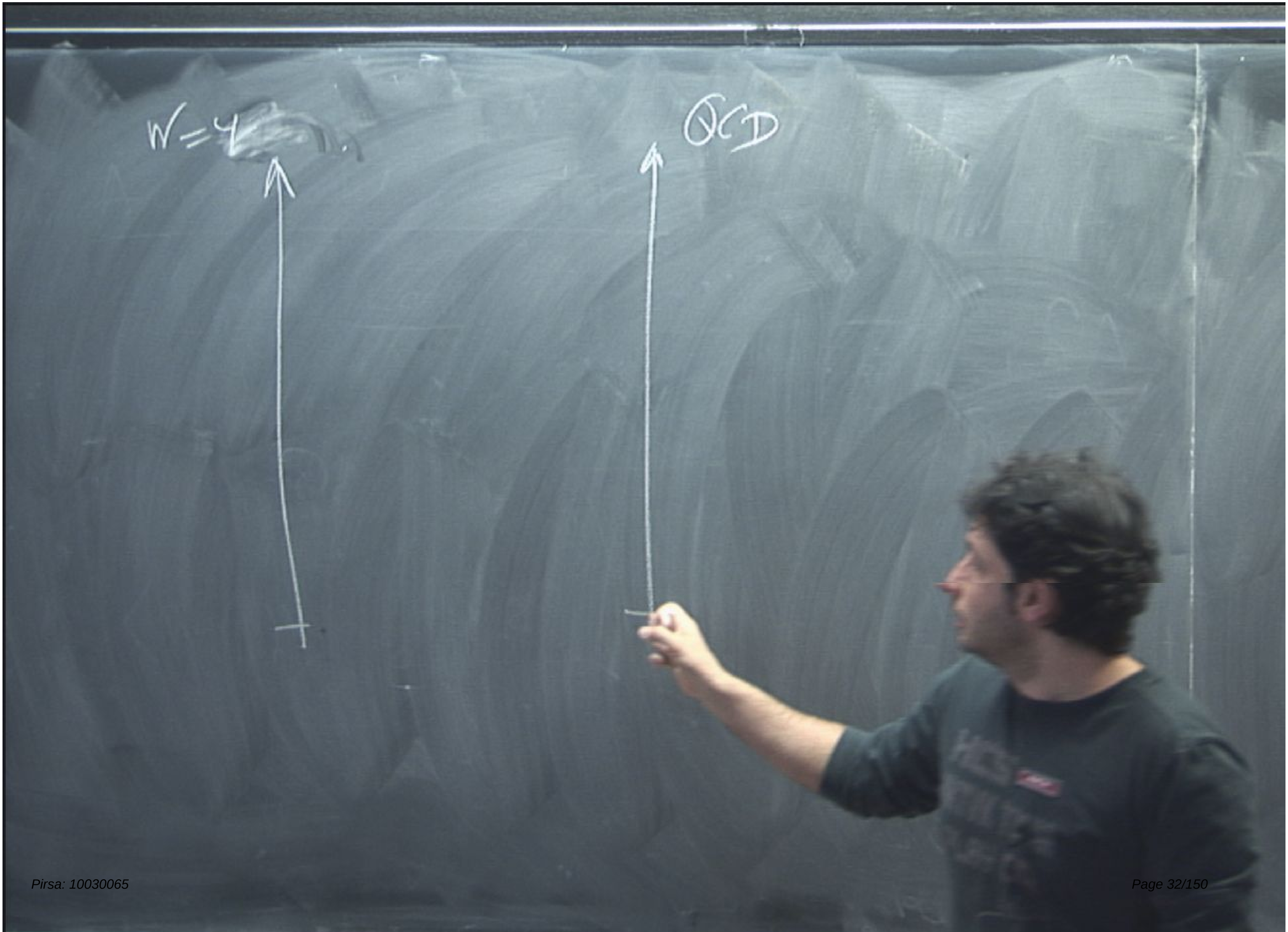
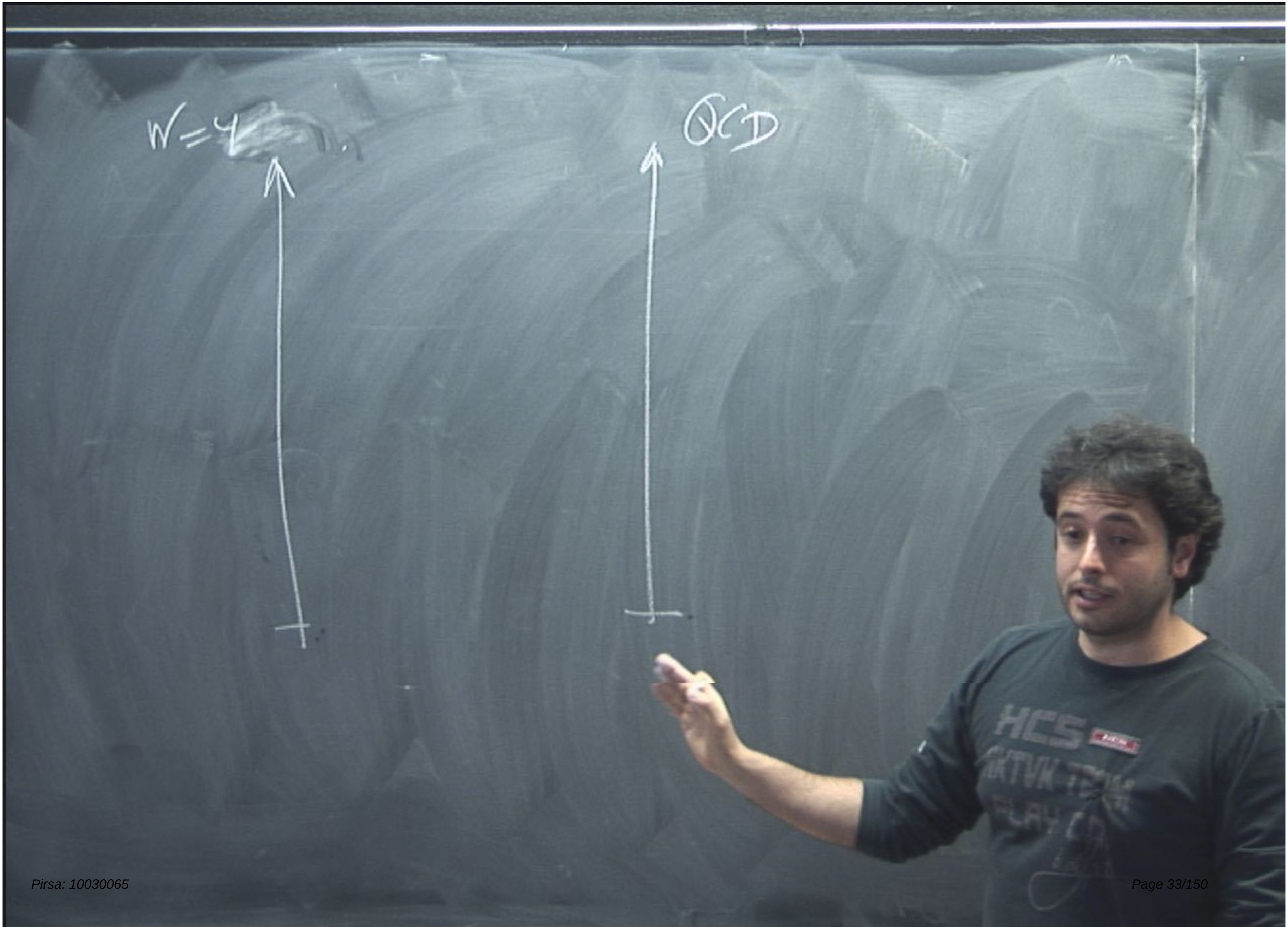
$\partial AdS_5 \quad r \to \infty \quad$ UV

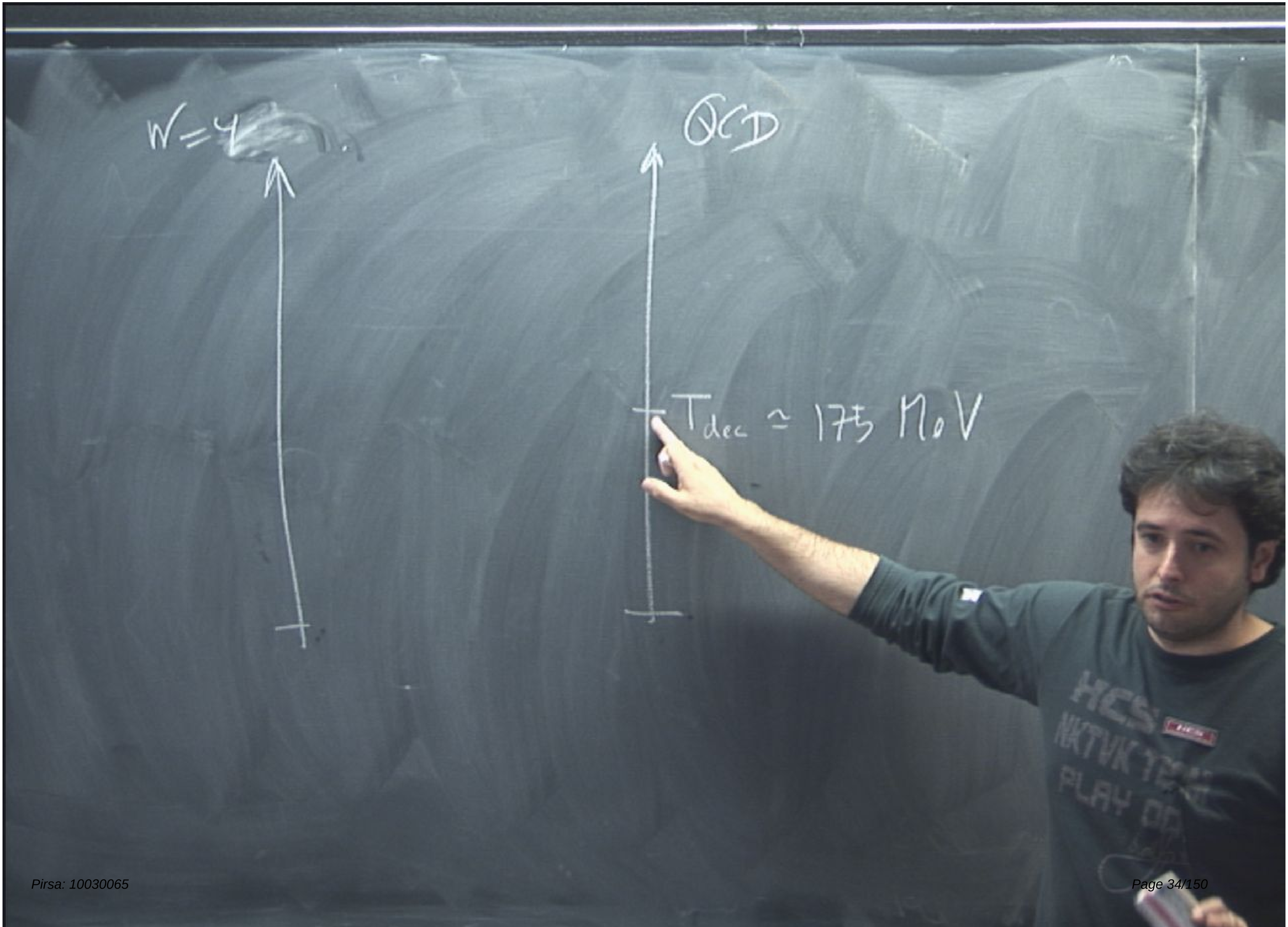
$\Phi(x, r)$

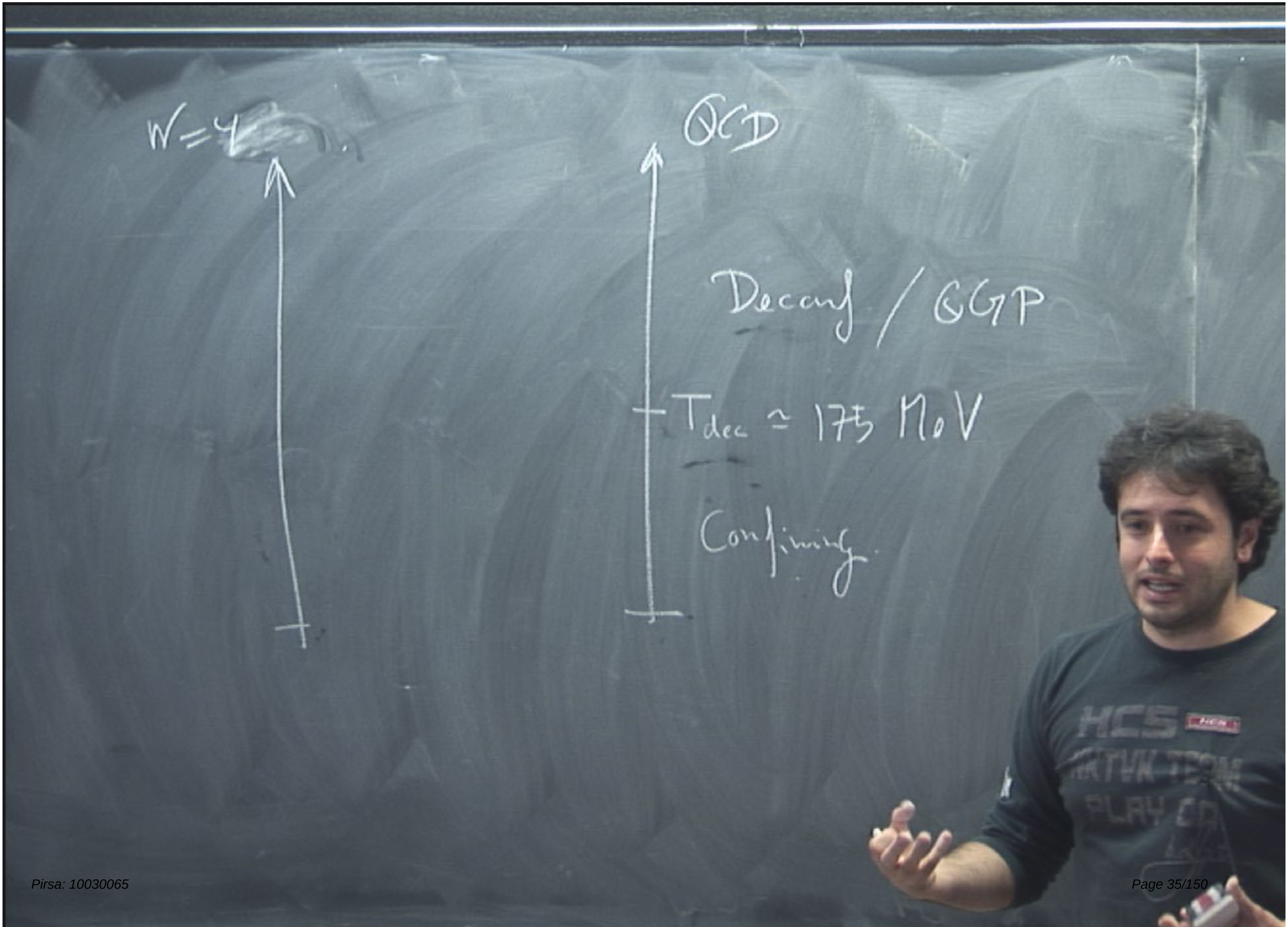
$M \sim V_{1,3}$

Horizon $r = 0$ IR

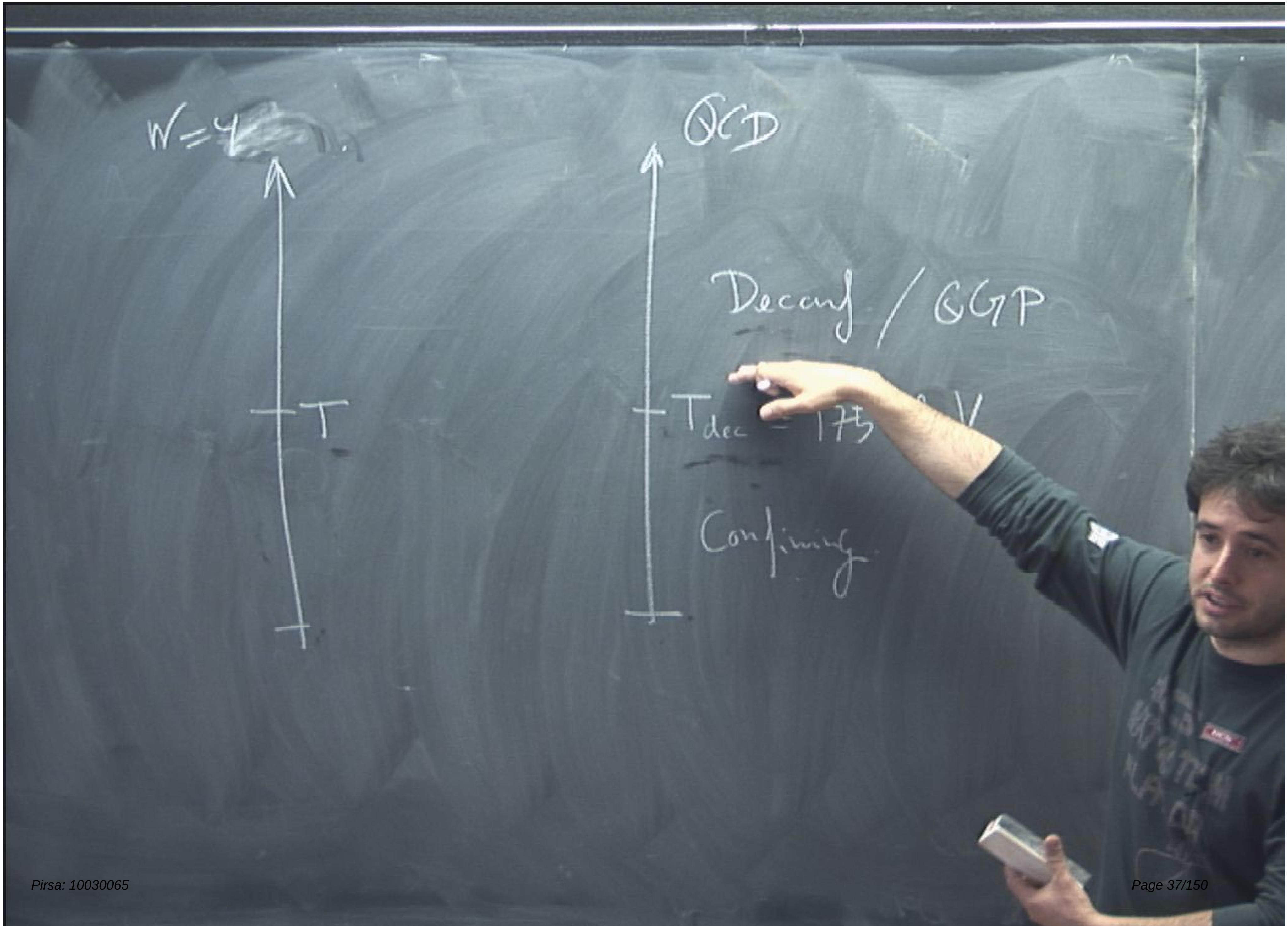

N=4
QCD

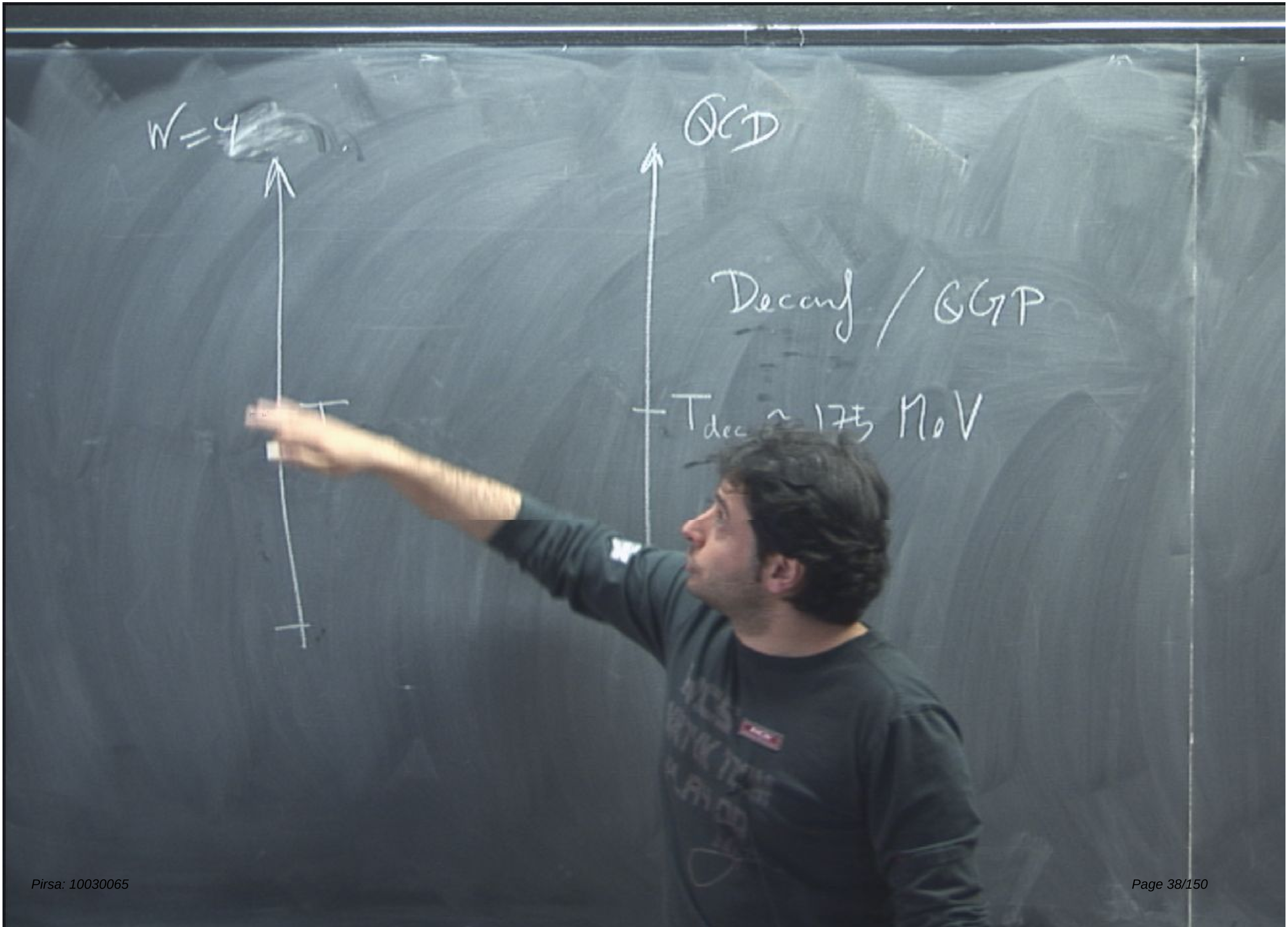

N=4
QCD

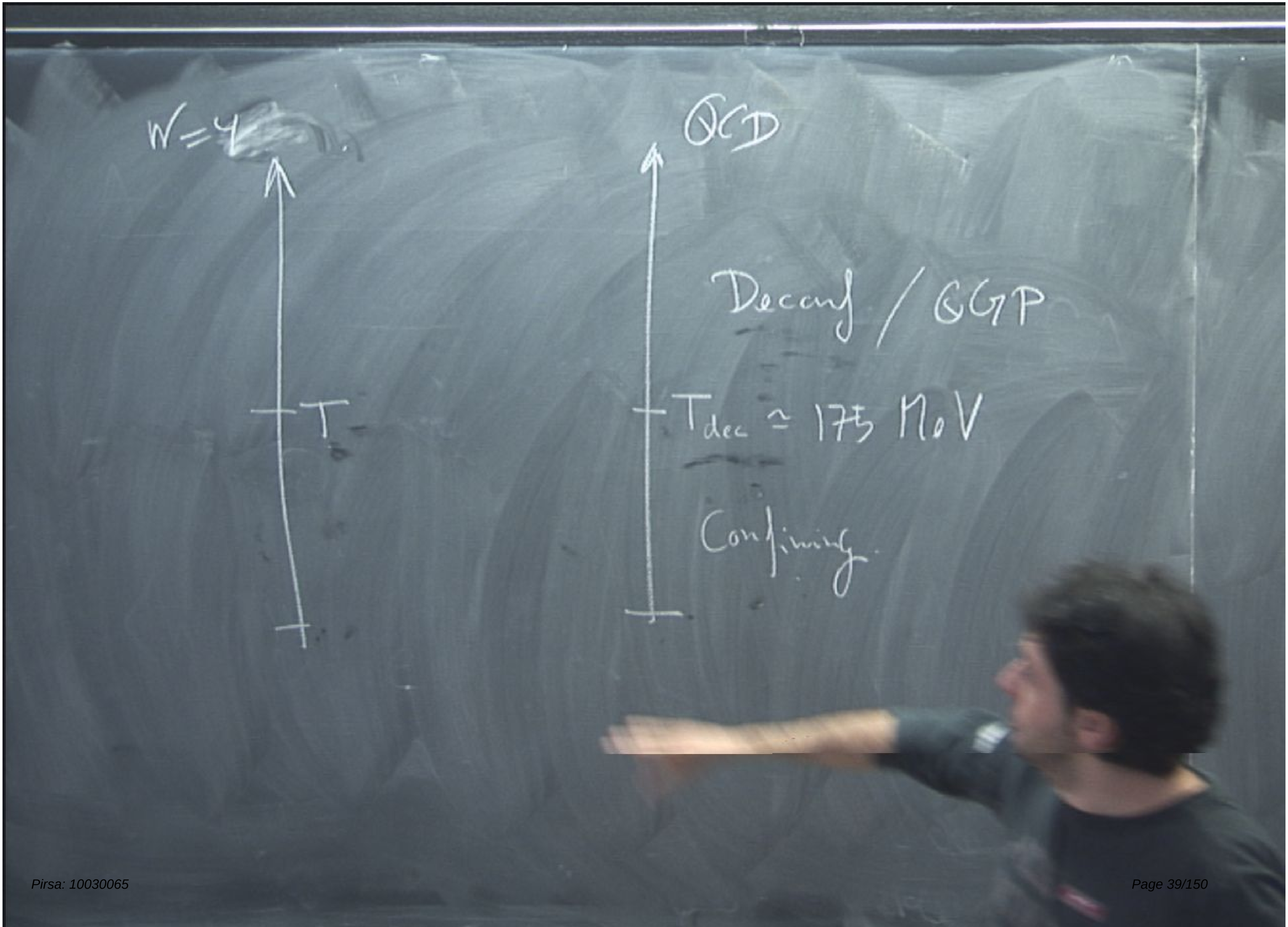

N=4
QCD
$T_{dec} \simeq 175$ MeV

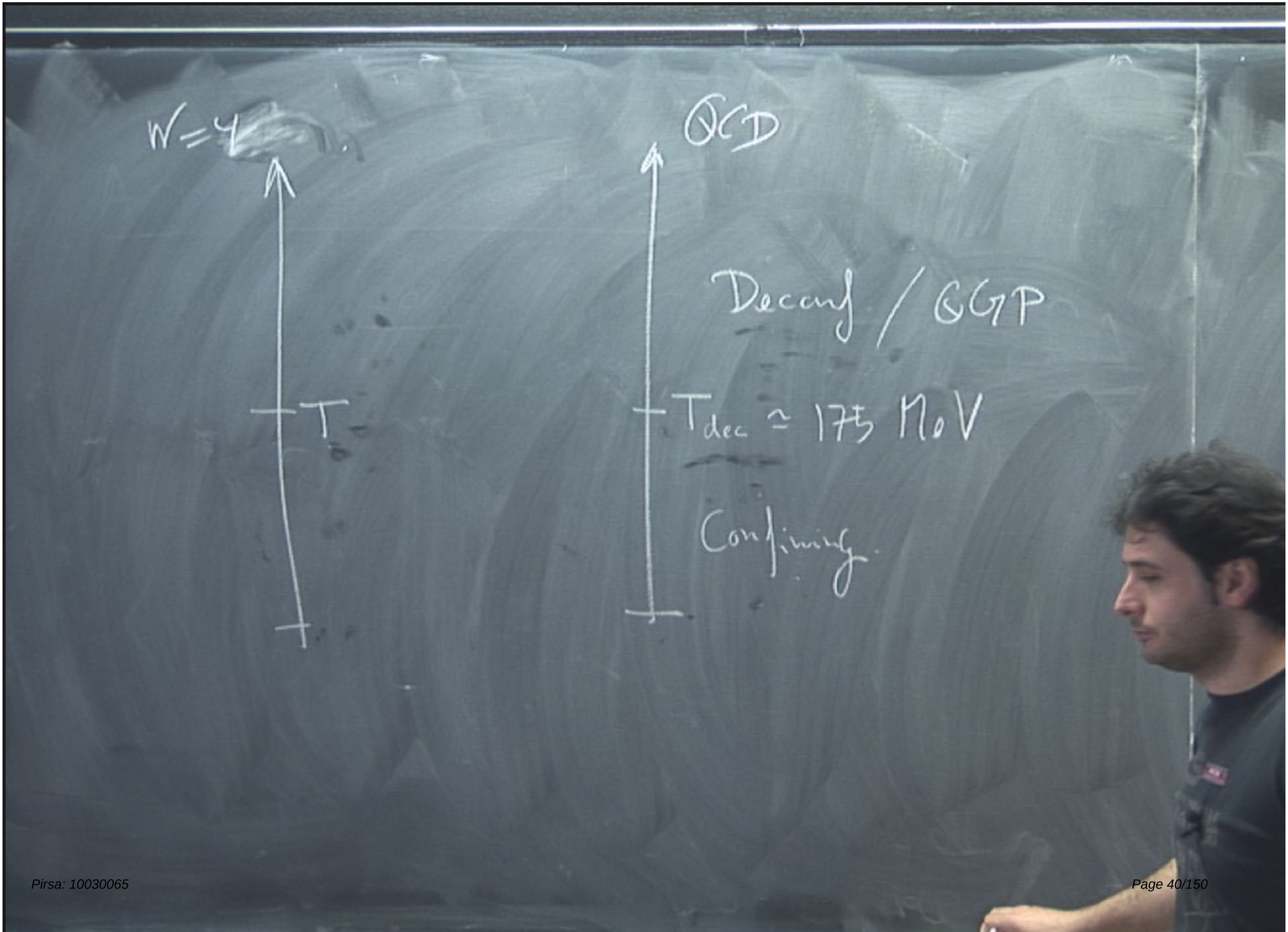

N=4
QCD
Deconf / QGP
$T_{dec} \simeq 175$ MeV
Confining

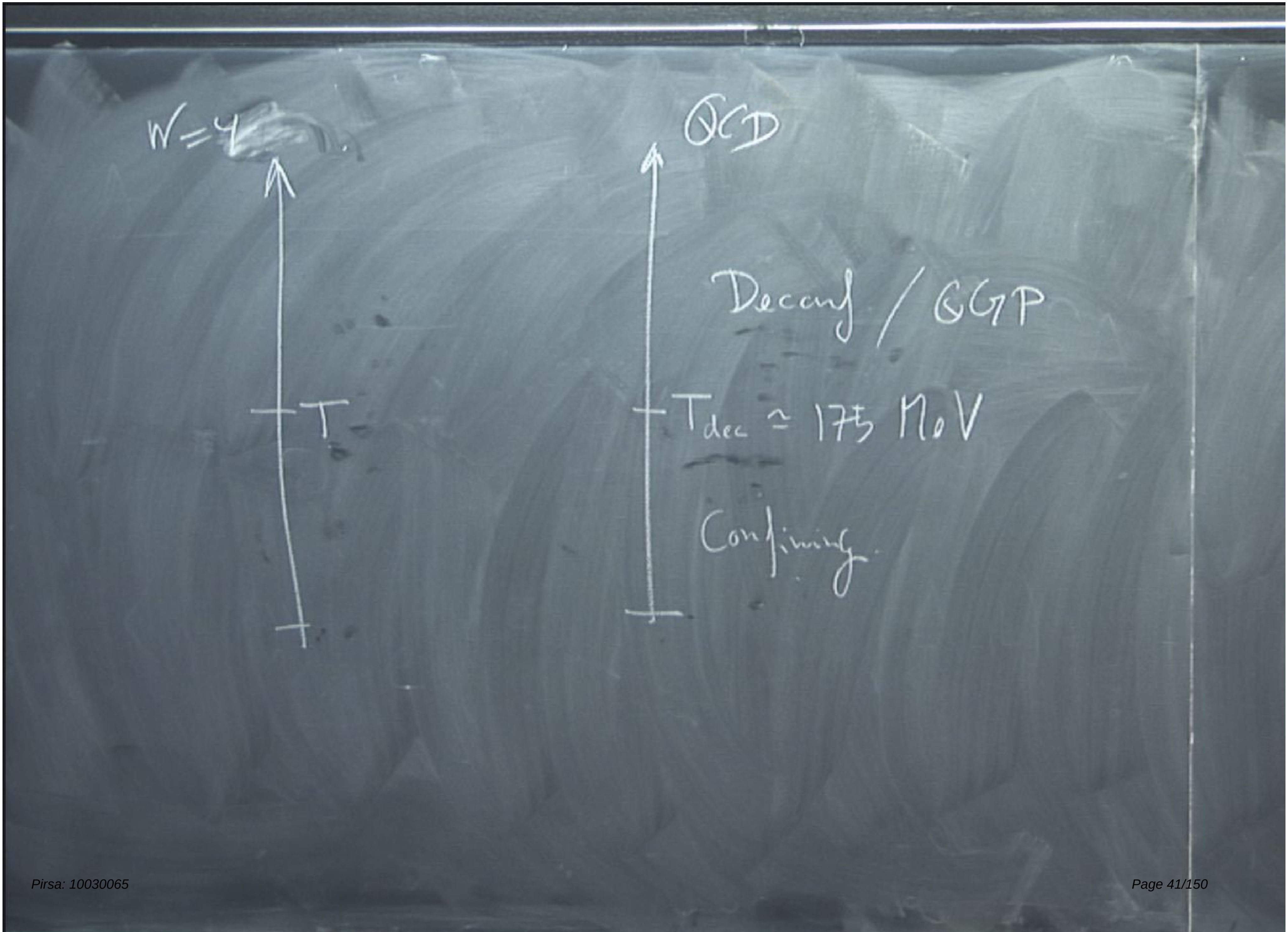

N=4
T
QCD
Deconf / QGP
T_dec ≃ 175 MeV
Confining

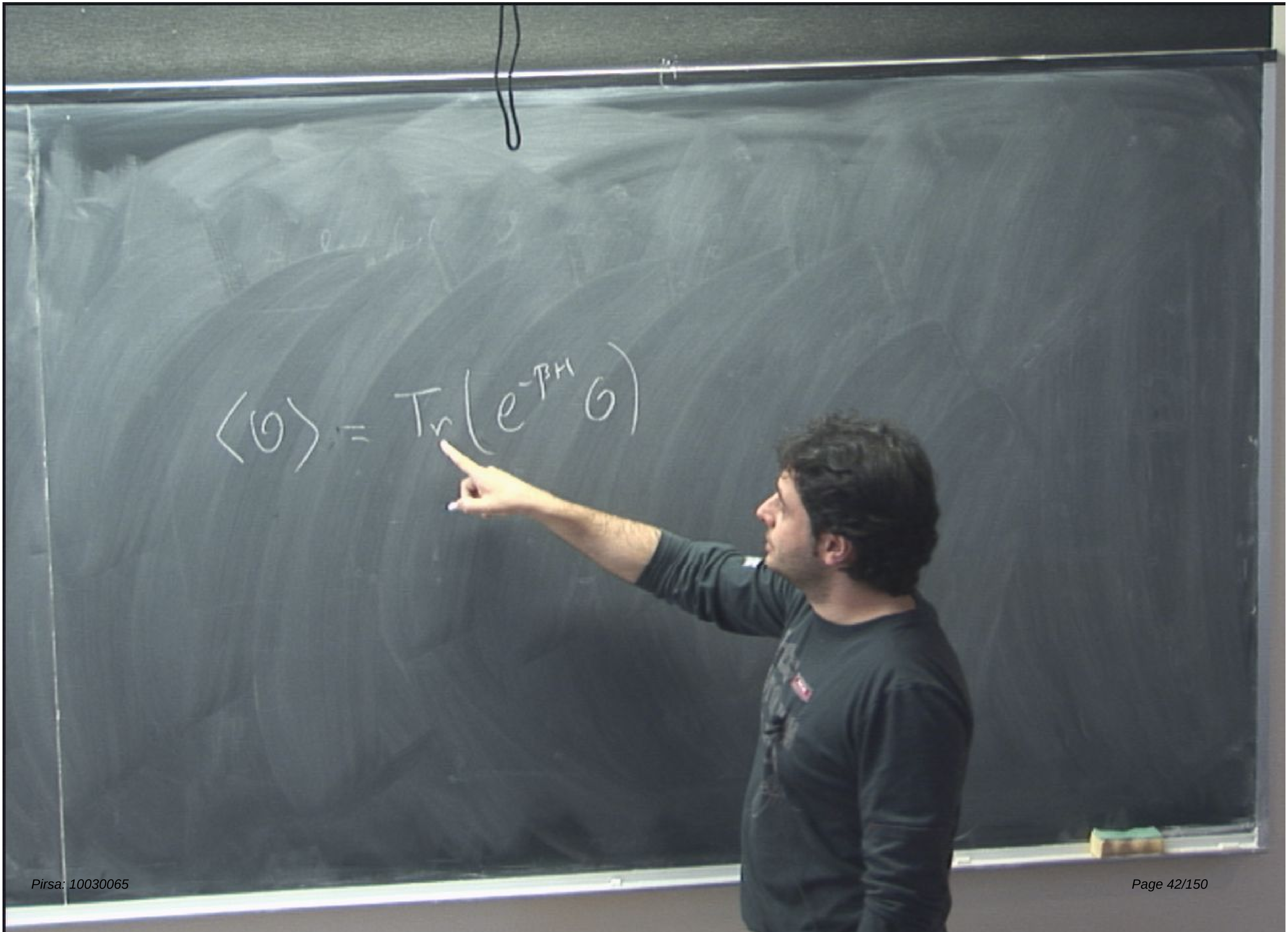

N=4
QCD
Deconf / QGP
T
Confining

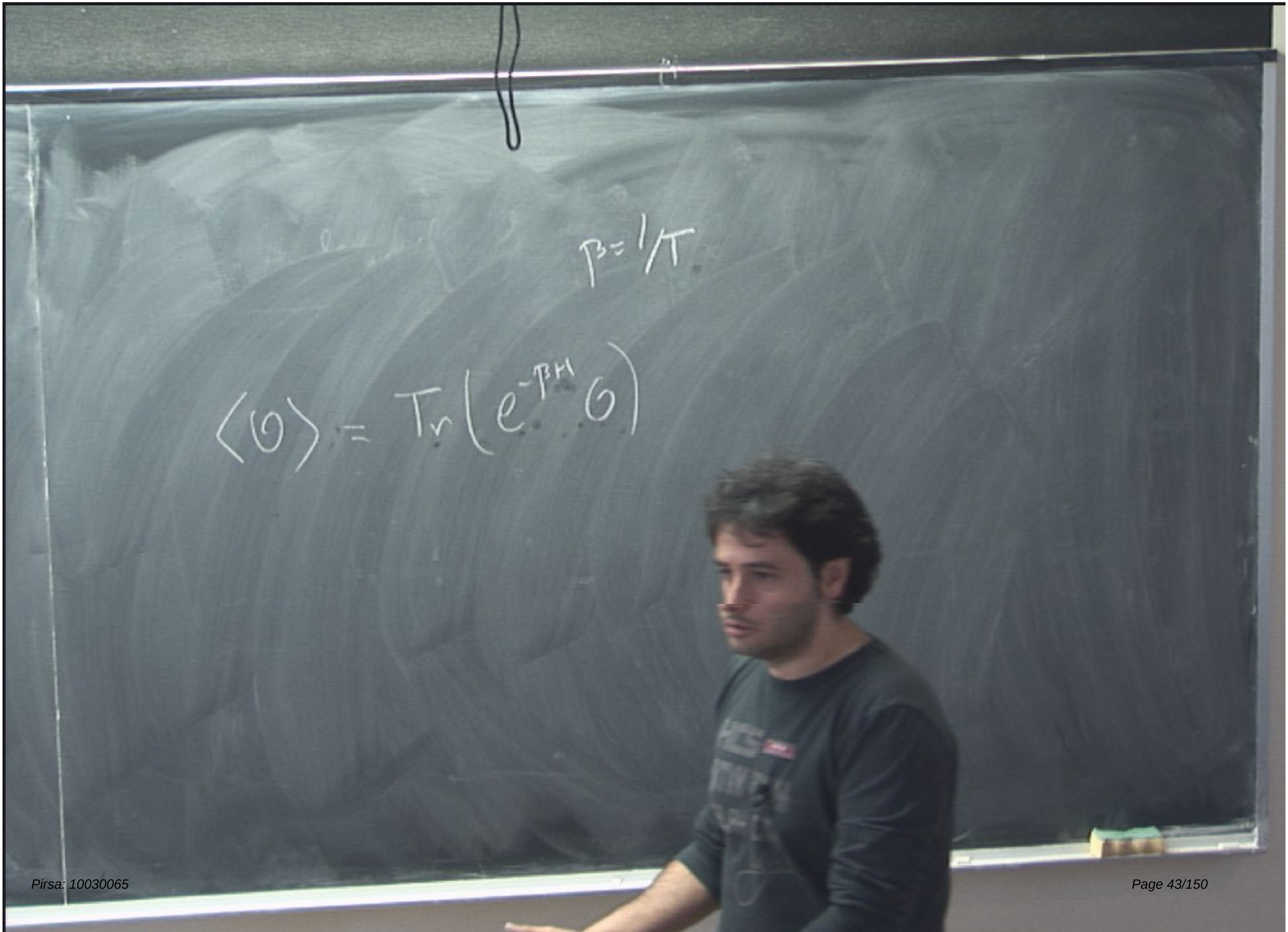

N=4
QCD
Deconf / QGP
T_dec ~ 175 MeV


N=4
QCD
Deconf / QGP
T
Tdec ≃ 175 MeV
Confining


N=4
QCD
Deconf / QGP
T
$T_{dec} \simeq 175$ MeV
Confining

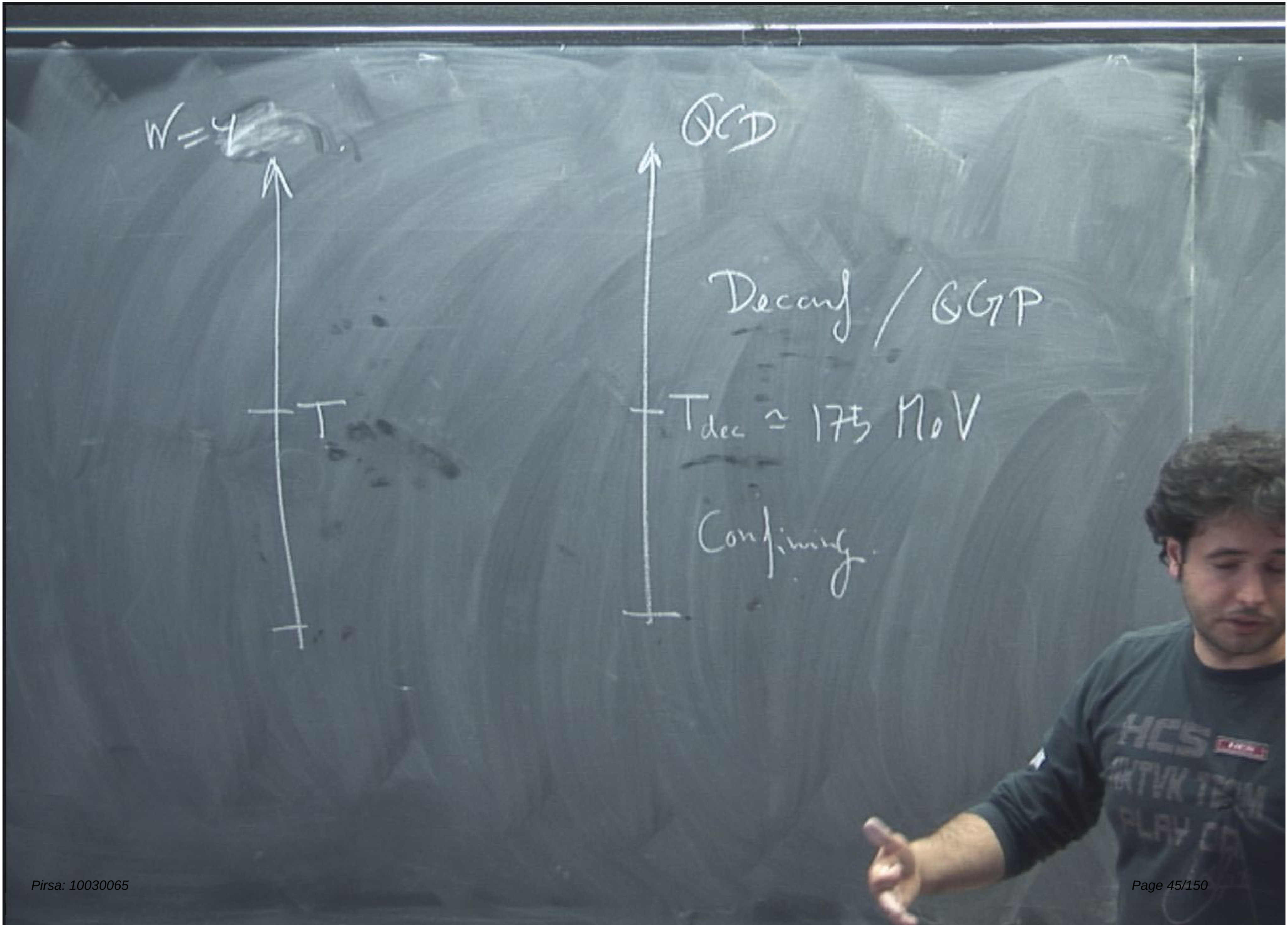

N=4
T
QCD
Deconf / QGP
$T_{dec} \simeq 175$ MeV
Confining

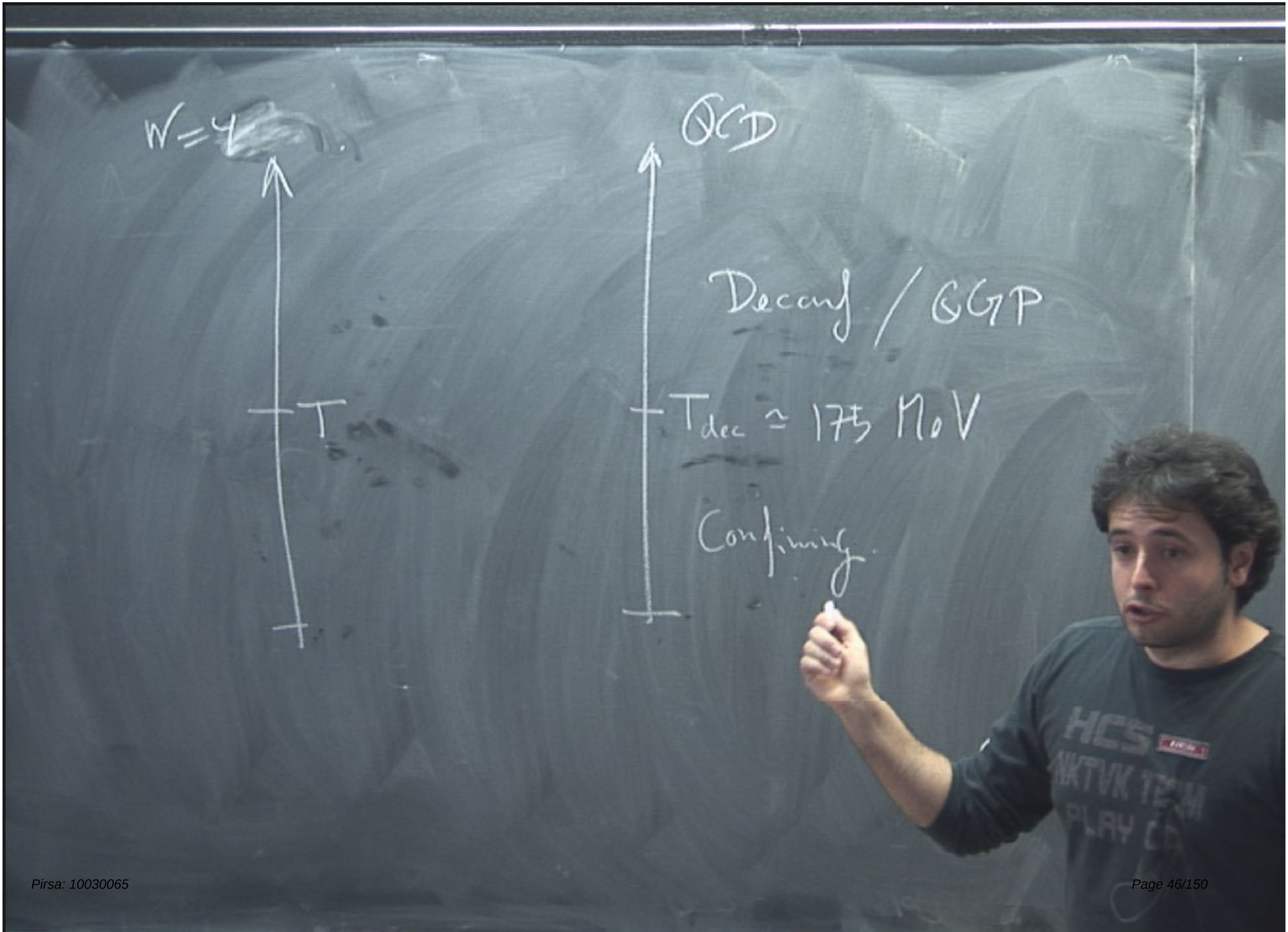

$\langle O \rangle = \mathrm{Tr}\left(e^{-\beta H} O\right)$

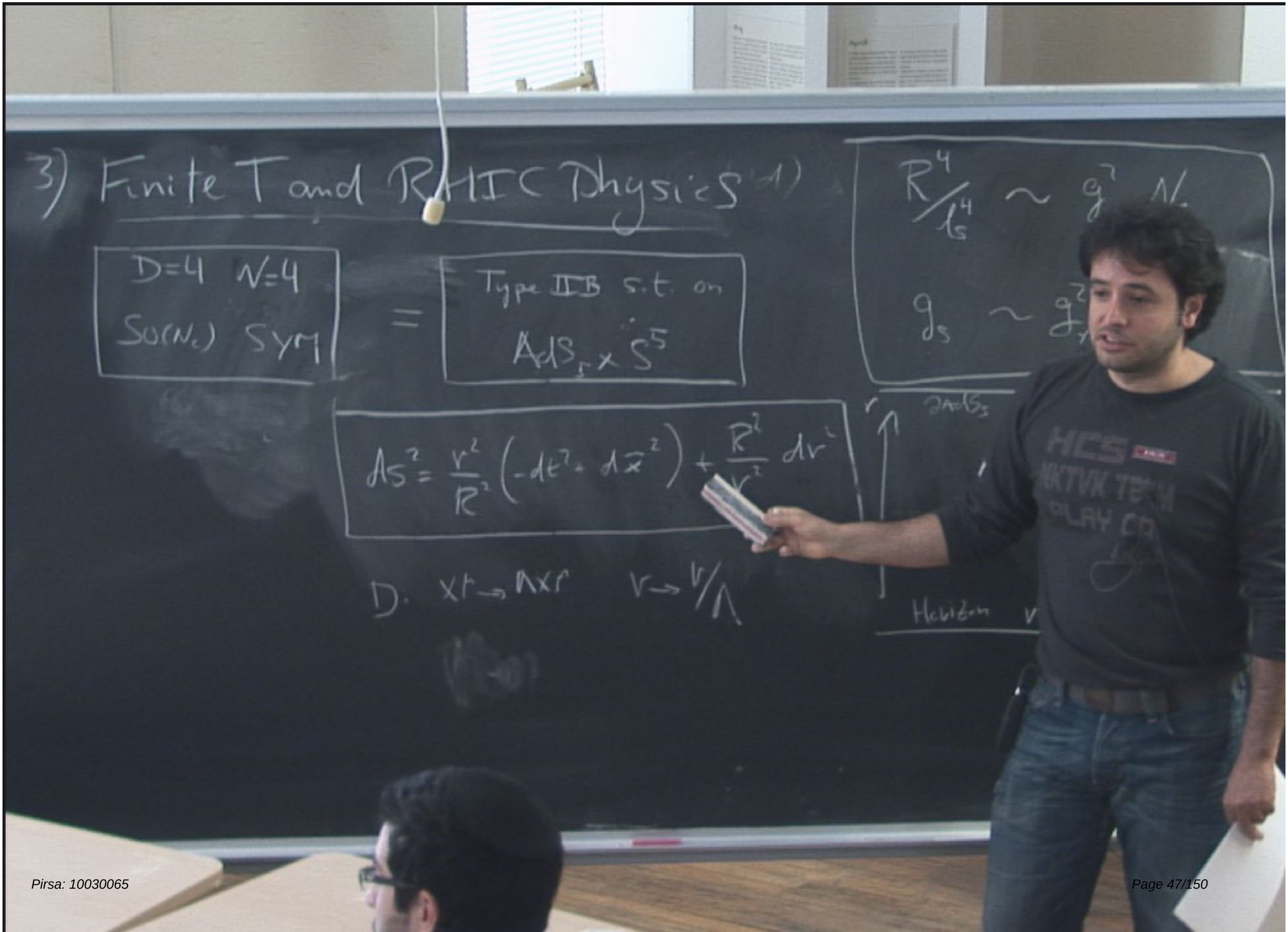

$\beta = 1/T$
$\langle O \rangle = \mathrm{Tr}(e^{-\beta H} O)$

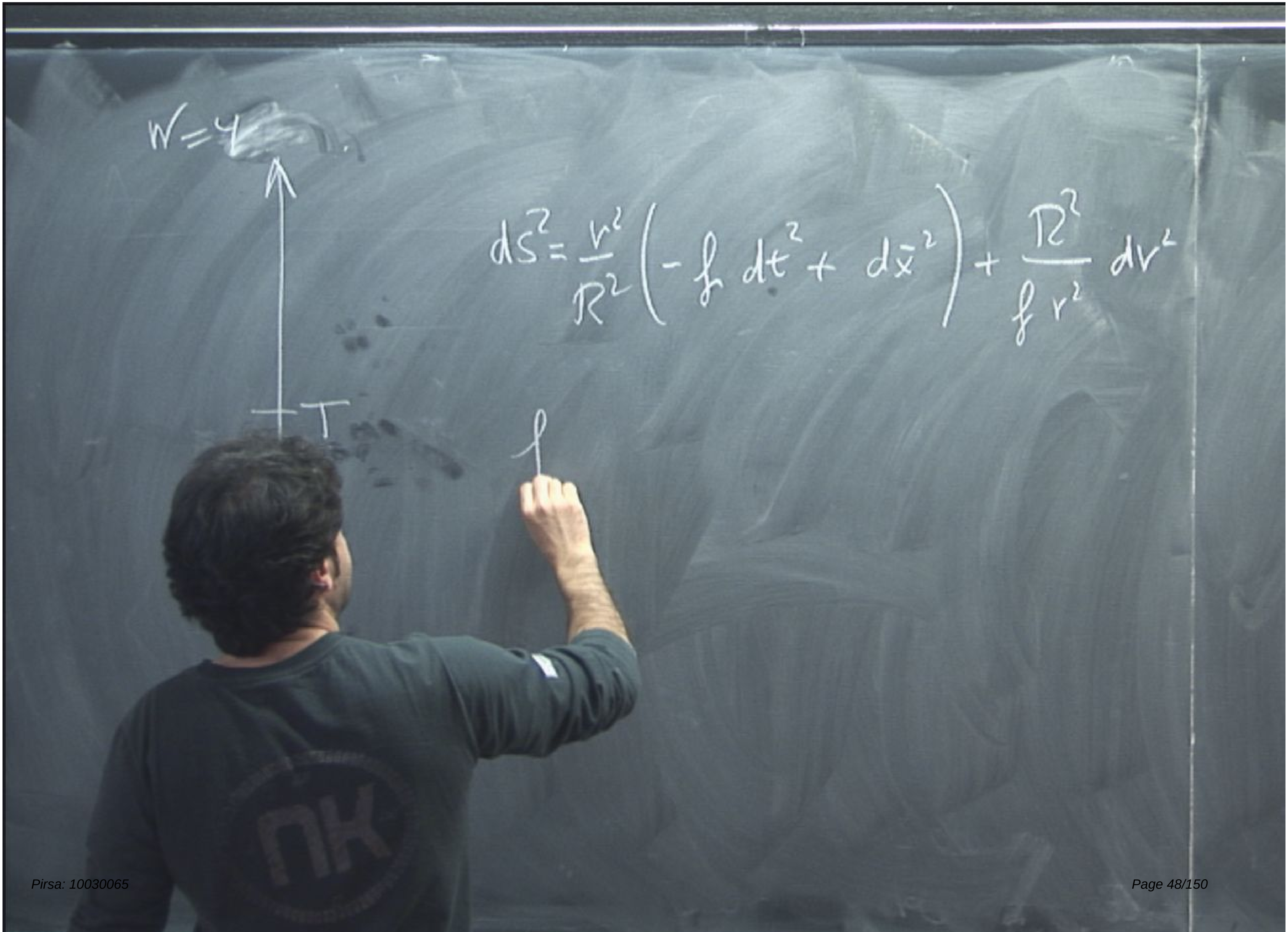
$\beta = 1/T$

$$\langle \mathcal{O} \rangle = \mathrm{Tr}\left(e^{-\beta H}\,\mathcal{O}\right)$$

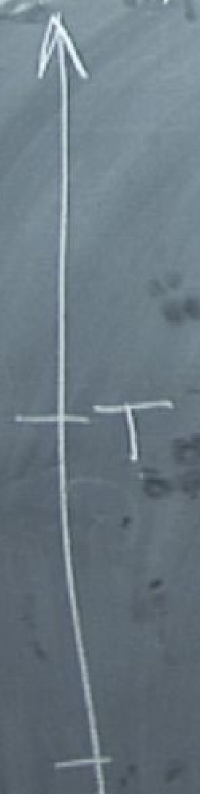

QCD
Deconf / QGP
T
$T_{dec} \simeq 175$ MeV
Confining


W=4
T
QCD
Deconf / QGP
T_dec ≃ 175 MeV
Confining


3) Finite T and RHIC Physics
D=4 N=4
SU(Nc) SYM
=
Type IIB s.t. on
AdS5 x S5
ds² = r²/R² (-dt² + dx²) + R²/r² dr²
D. xμ → Λxμ   r → r/Λ
R4/ls4 ~ g² N
gs ~ g²
∂AdS5
Horizon

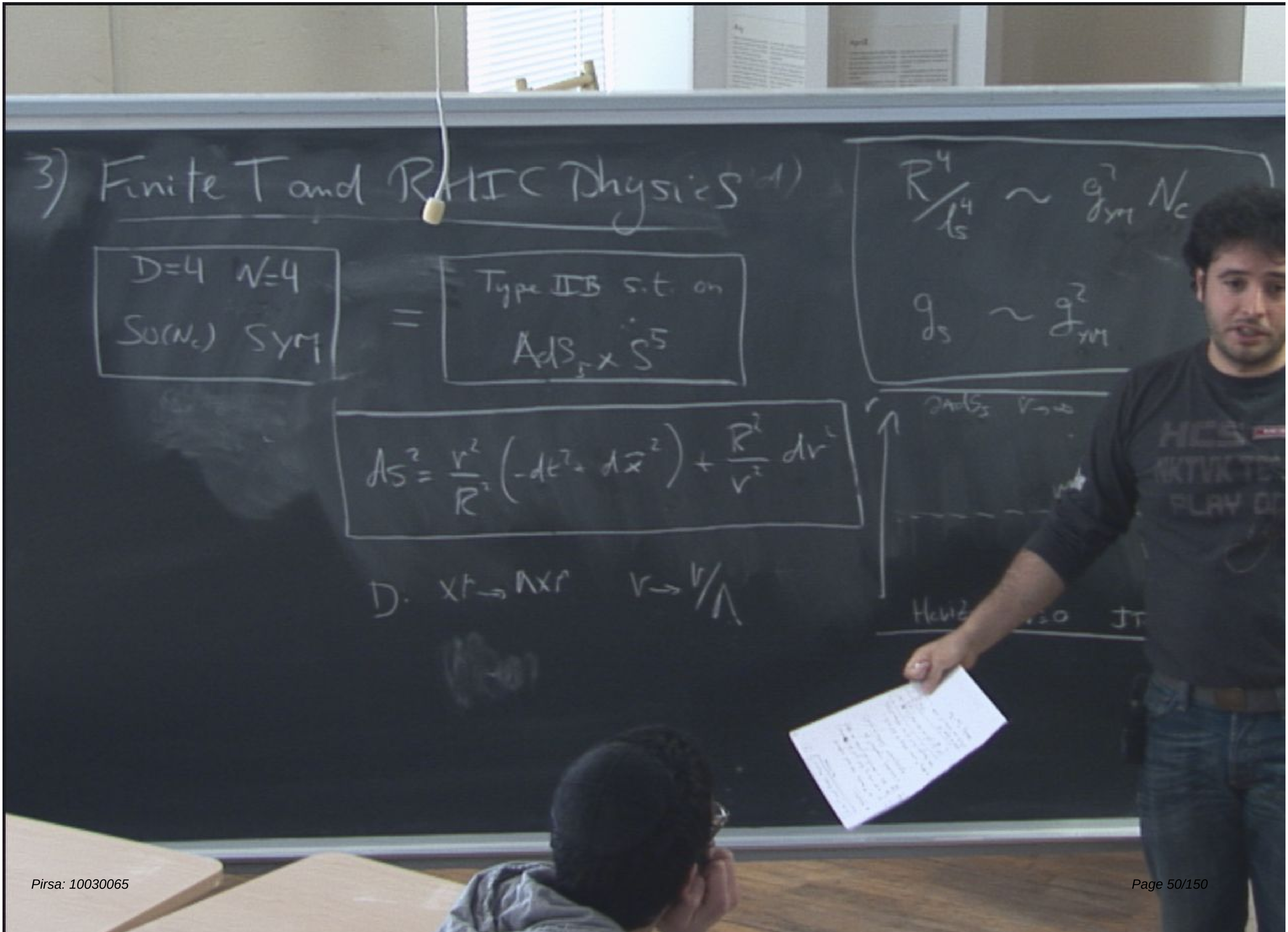

W = 4
$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2}\,dr^2$
T
f

$N=4$



$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\bar{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2$$

$$f = 1 - \frac{r_0^4}{r^4} \qquad r_0 = \text{const.}$$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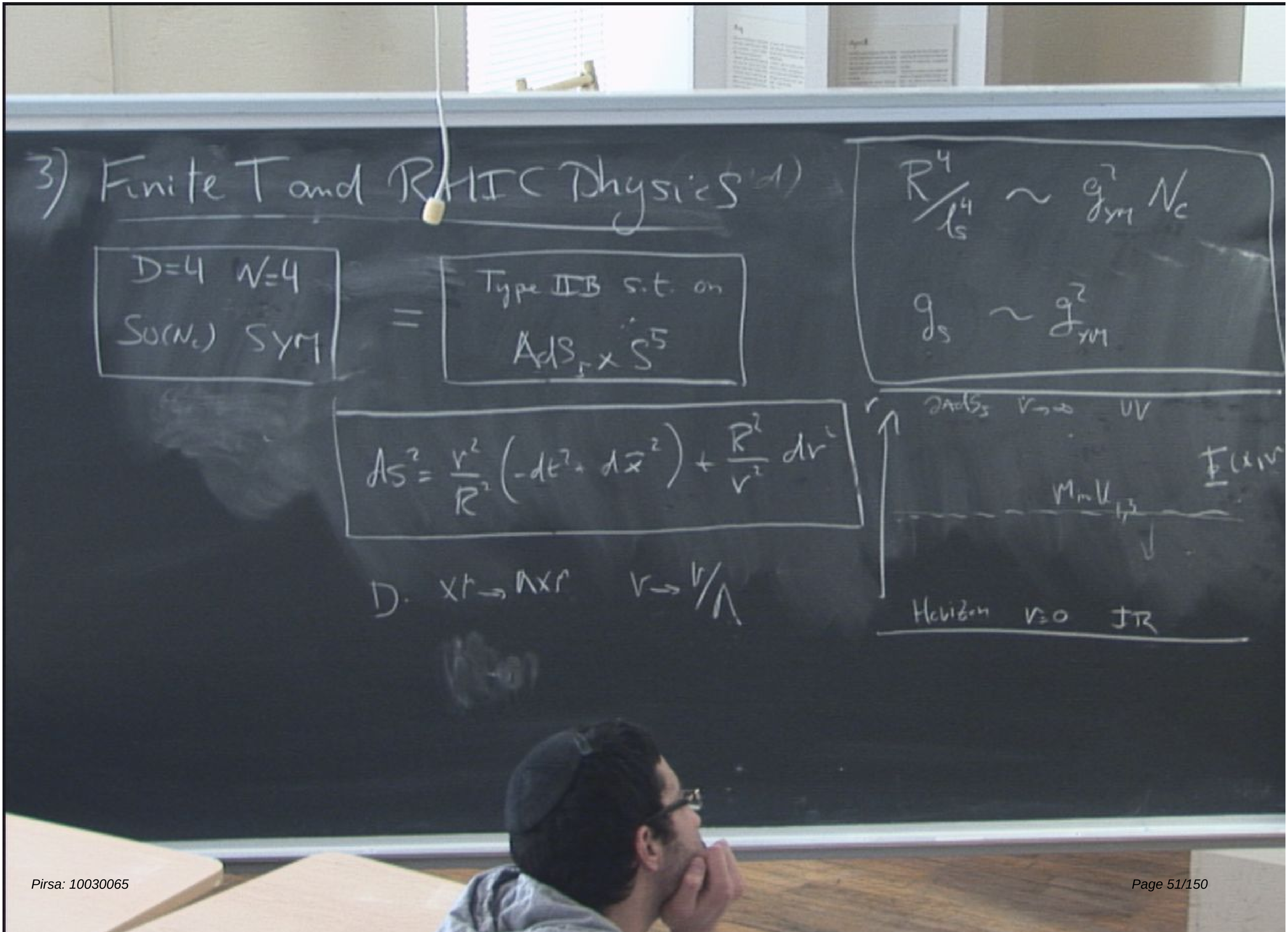
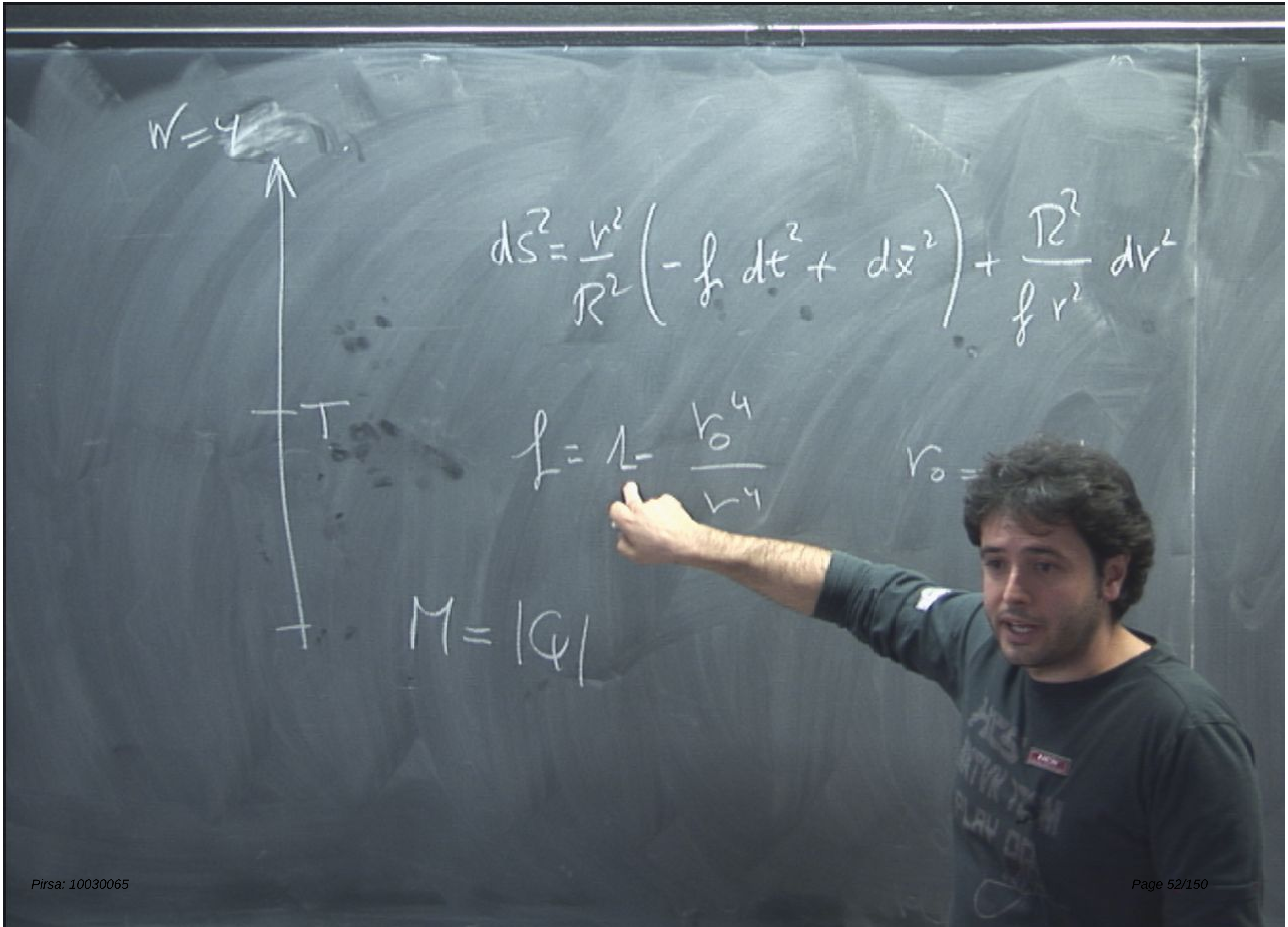
Type IIB s.t. on
AdS5 x S5
R4/ls4 ~ g2YM Nc
gs ~ g2YM
ds2 = r2/R2 (-dt2 + dx2) + R2/r2 dr2
D. xμ → Λxμ   r → r/Λ


3) Finite T and RHIC Physics (cont'd)
D=4 N=4 SU(N_c) SYM
=
Type IIB s.t. on AdS_5 x S^5
R^4/l_s^4 ~ g_YM^2 N_c
g_s ~ g_YM^2
ds^2 = r^2/R^2 (-dt^2 + dx^2) + R^2/r^2 dr^2
D. x^μ → Λx^μ   r → r/Λ
r
∂AdS_5   r→∞   UV
Φ(x,r)
Horizon   r=0   IR



$N=4$
T
$M = |Q|$
$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2} dr^2$
$f = 1 - \frac{r_0^4}{r^4}$
$r_0 =$

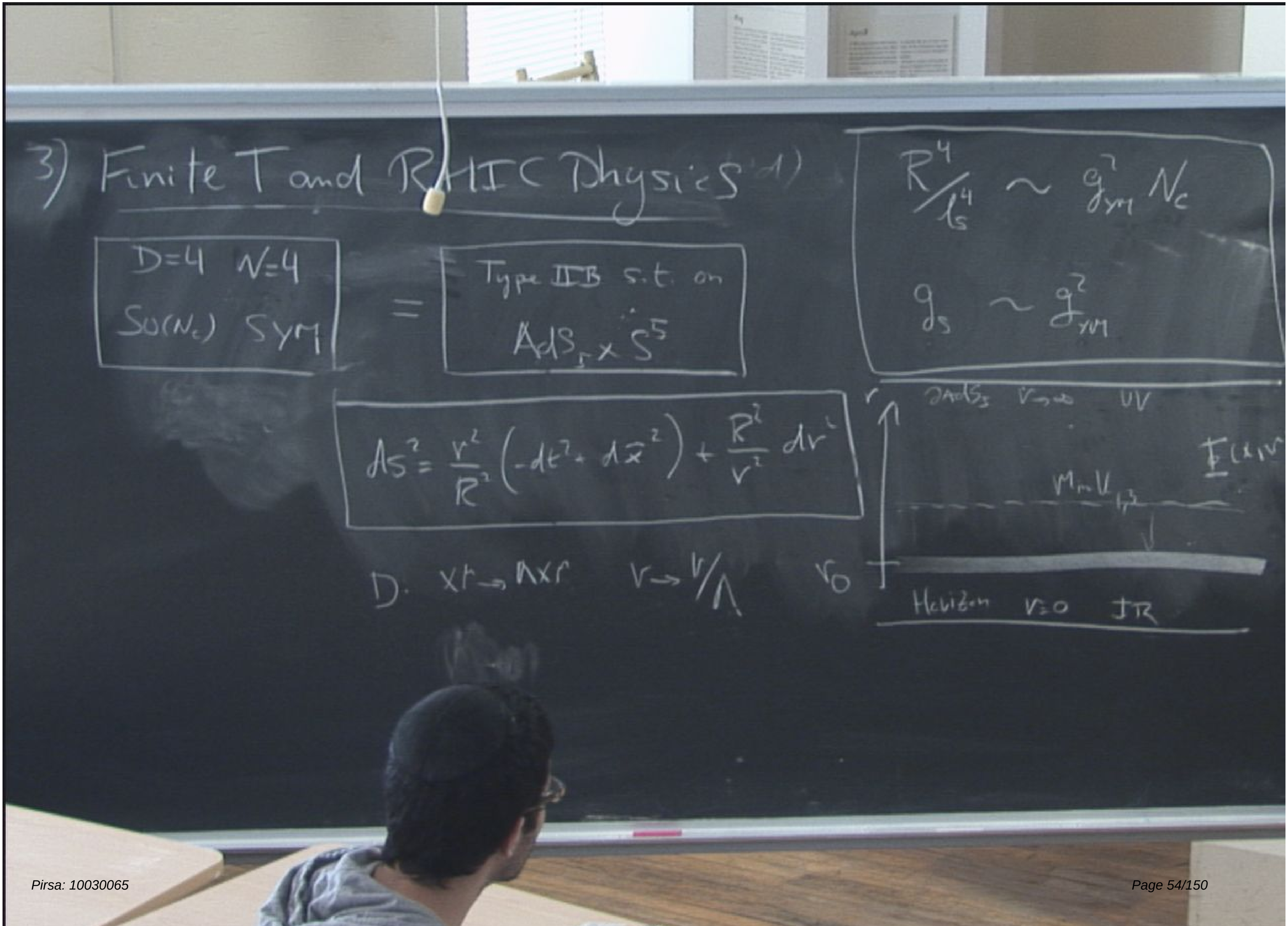
$\mathcal{N}=4$

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^{\,2}\right) + \frac{R^2}{f\,r^2}\,dr^2$$

T

$$f = 1 - \frac{r_0^4}{r^4} \qquad r_0 = \text{const.}$$

$$M = |Q|$$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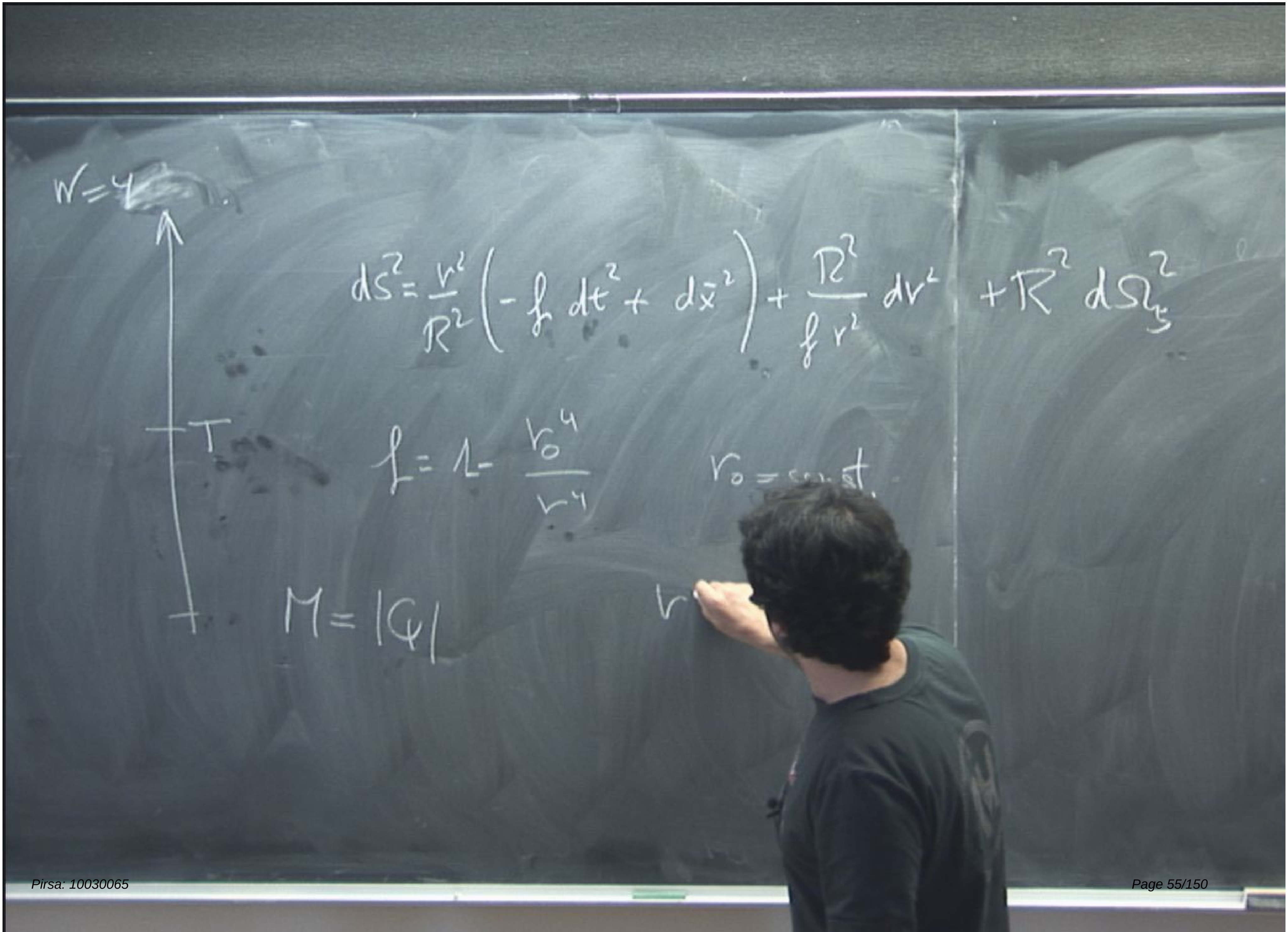
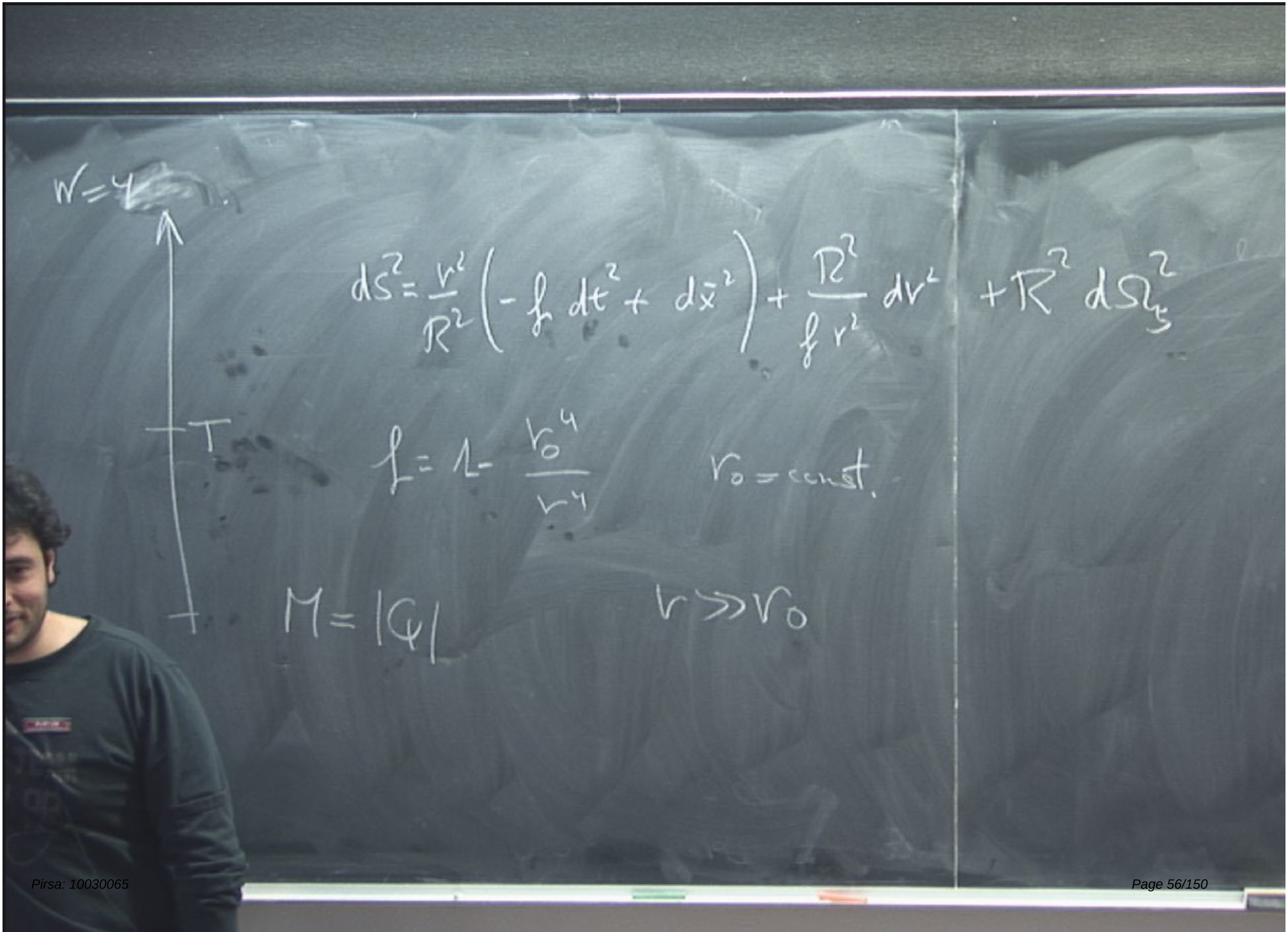
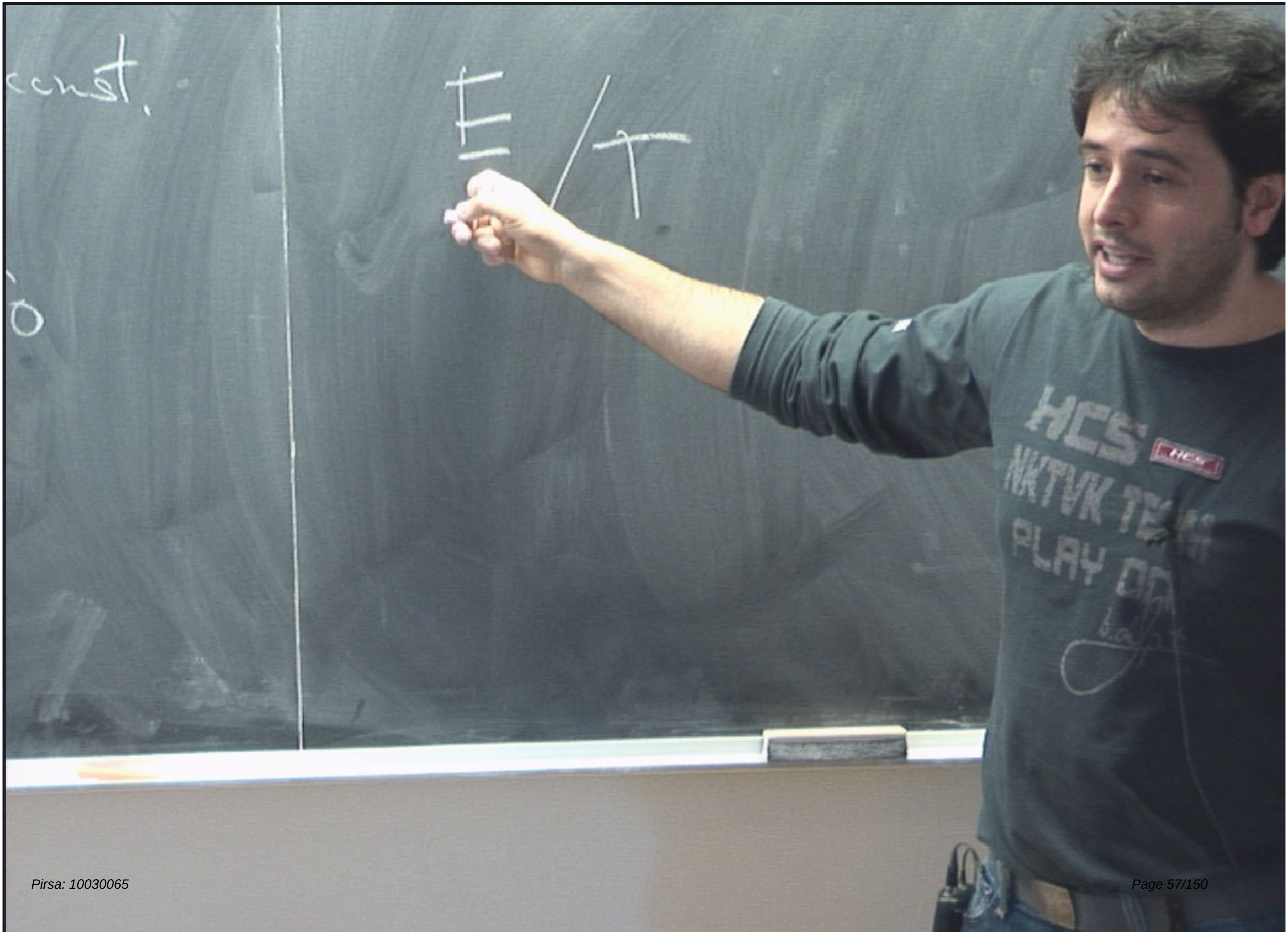
D. x^μ → Λx^μ   r → r/Λ
r_0
r
∂AdS_5   r→∞   UV
Horizon   r=0   IR

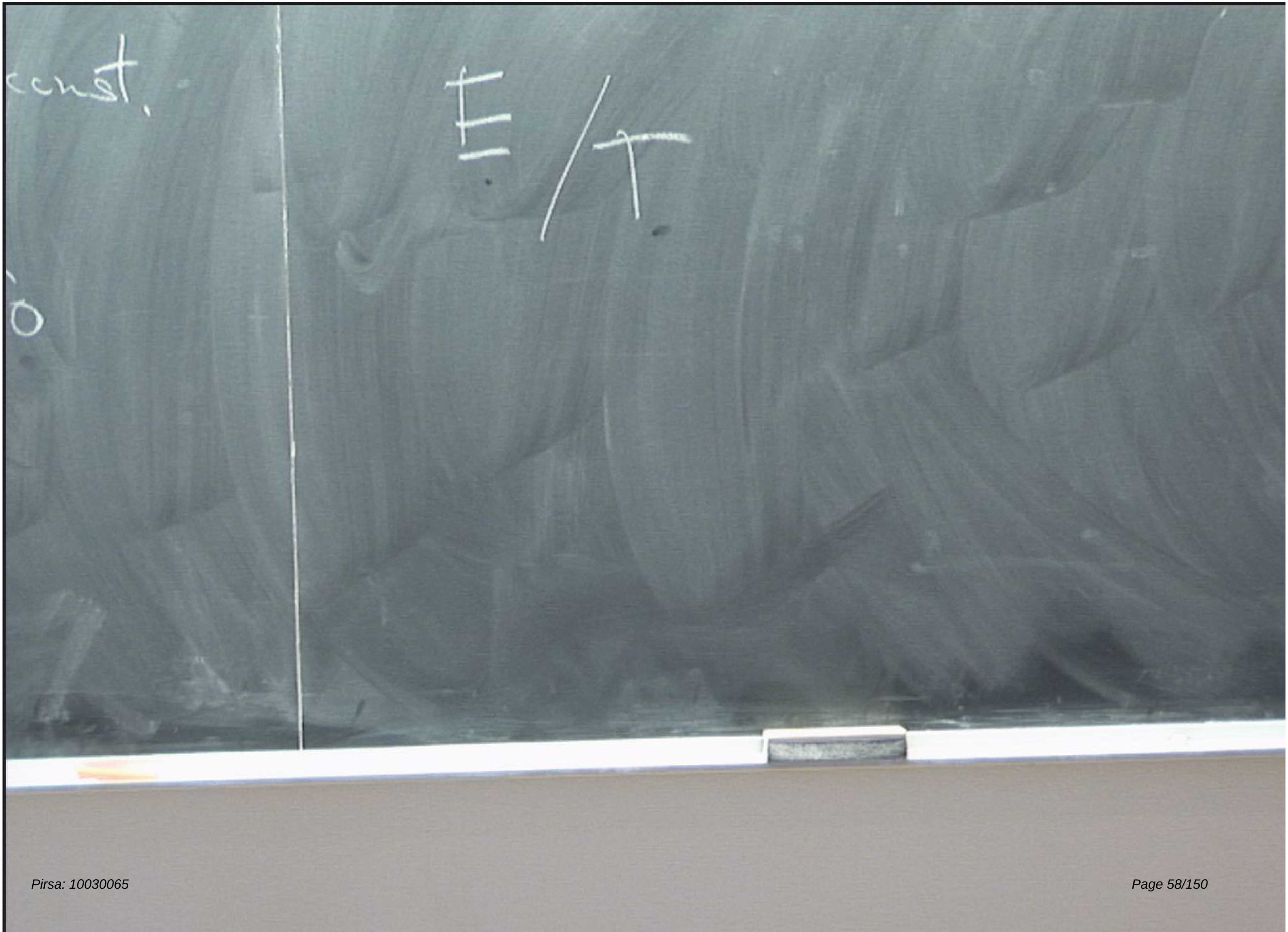


$N=4$
T
$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2} dr^2 + R^2 d\Omega_5^2$
$f = 1 - \frac{r_0^4}{r^4}$
$r_0 = \text{const.}$
$M = |\Phi|$
r



N=4
T
$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2}\,dr^2 + R^2\,d\Omega_5^2$
$f = 1 - \frac{r_0^4}{r^4}$
$r_0 = \text{const.}$
$M = |Q|$
$r \gg r_0$


E/τ
HCS
PLAY


const.
E/T

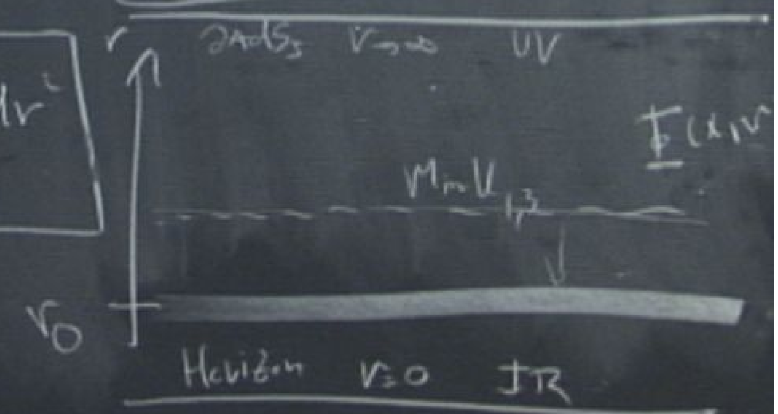
3) Finite T and RHIC Physics (1)

$$\boxed{\begin{array}{c} D=4 \ \ \mathcal{N}=4 \\ SU(N_c) \ \text{SYM} \end{array}} = \boxed{\begin{array}{c} \text{Type IIB s.t. on} \\ AdS_5 \times S^5 \end{array}}$$

$$\boxed{\begin{array}{c} R^4/l_s^4 \sim g_{YM}^2 N_c \\ g_s \sim g_{YM}^2 \end{array}}$$

$$\boxed{ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2}\, dr^2}$$

D. $x^\mu \to \Lambda x^\mu \quad r \to r/\Lambda$



3) Finite T and RHIC Physics (cont'd)

$$\boxed{\begin{array}{c} D=4 \quad \mathcal{N}=4 \\ SU(N_c)\ \text{SYM} \end{array}} = \boxed{\begin{array}{c} \text{Type IIB s.t. on} \\ AdS_5 \times S^5 \end{array}}$$

$$\frac{R^4}{l_s^4} \sim g_{YM}^2 N_c$$

$$g_s \sim$$

$$\boxed{ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2}\, dr^2}$$

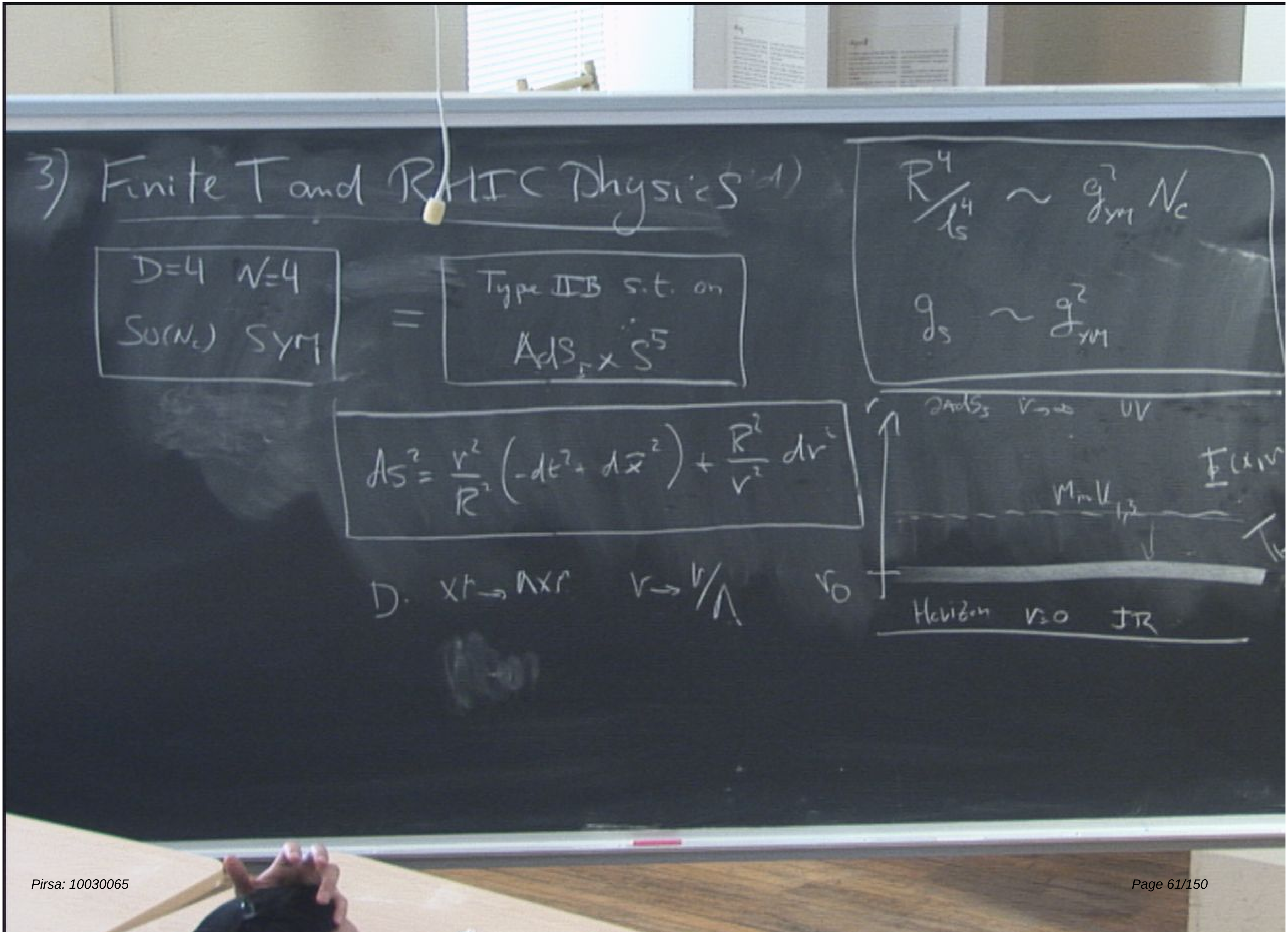
r — ∂AdS_5 $\quad r \to \infty \quad$ UV

$\Phi(x, r$

r_0

Horizon $\quad r = 0 \quad$ IR

D. $\quad x^\mu \to \Lambda x^\mu \qquad r \to r/\Lambda$



3) Finite T and RHIC Physics
D=4 N=4
SU(N_c) SYM
=
Type IIB s.t. on
$AdS_5 \times S^5$
$R^4/l_s^4 \sim g_{YM}^2 N_c$
$g_s \sim g_{YM}^2$
$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2} dr^2$
D. $x^\mu \to \Lambda x^\mu$ $r \to r/\Lambda$
r
∂AdS_5 $r \to \infty$ UV
r_0
Horizon $r=0$ IR

$\mathcal{N}=4$

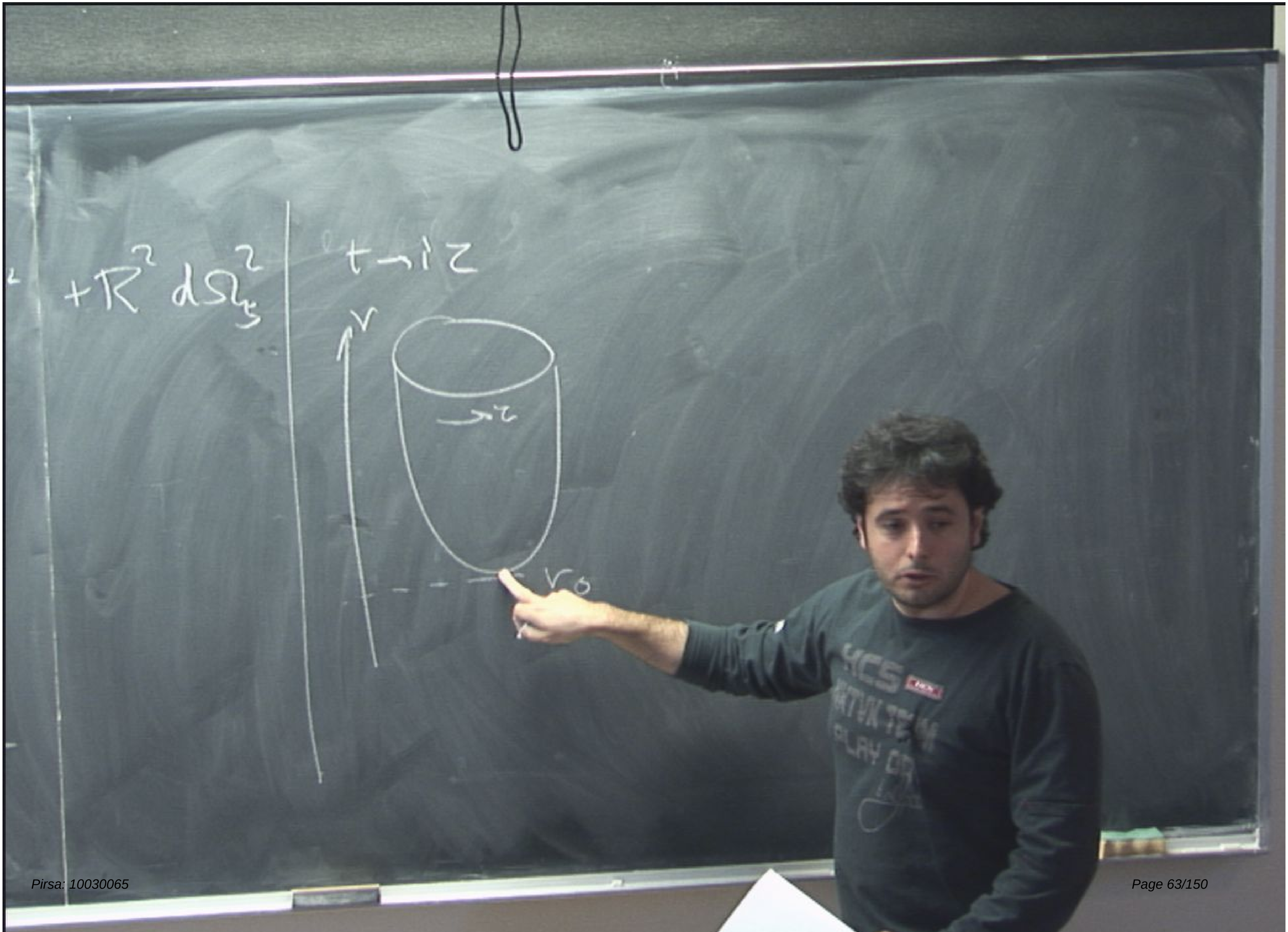
T

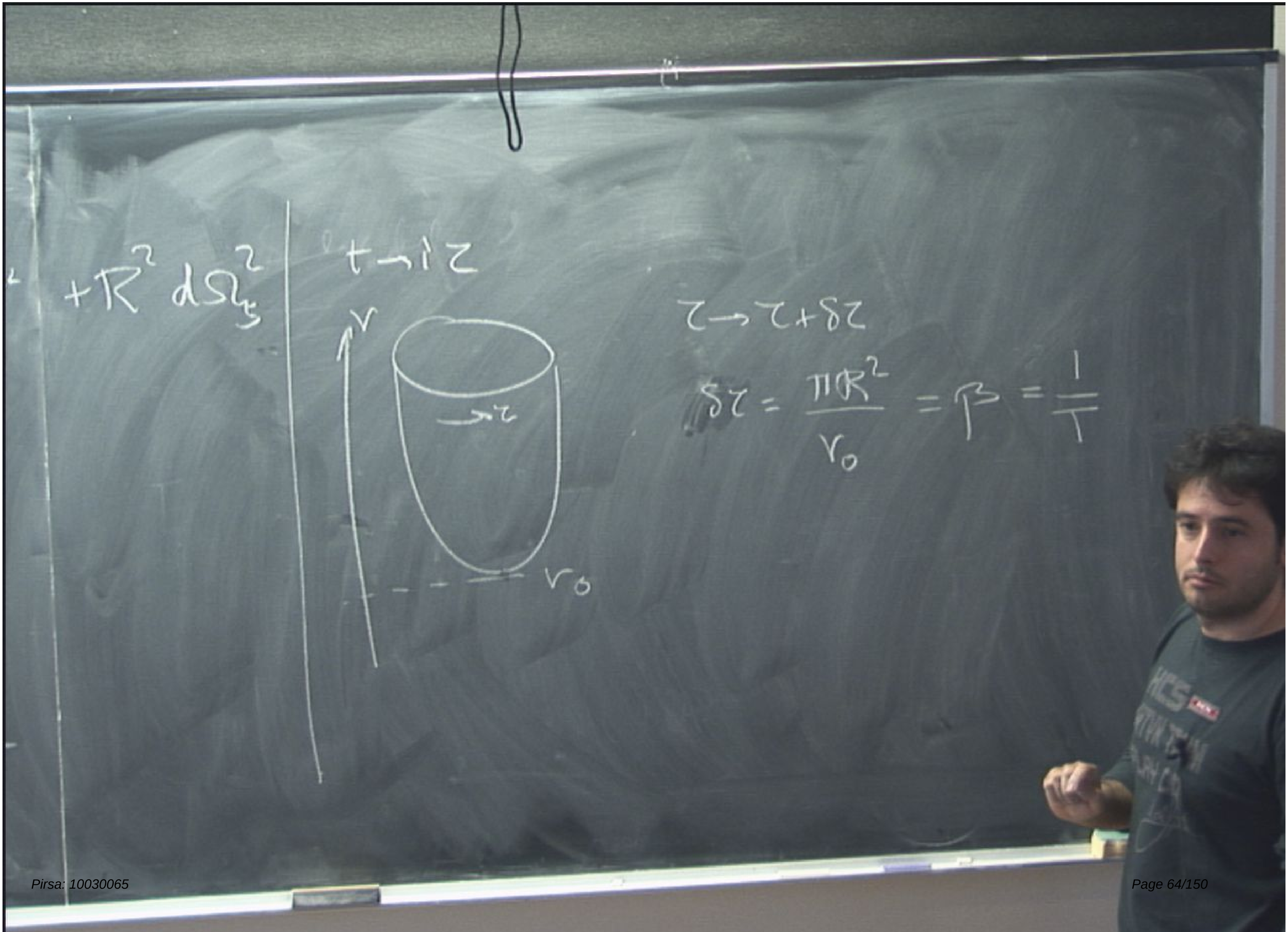
$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^{\,2}\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + \ldots$$

$$f = 1 - \frac{r_0^4}{r^4} \qquad r_0 = \text{const.}$$

$$M = |Q| \qquad r \gg r_0$$

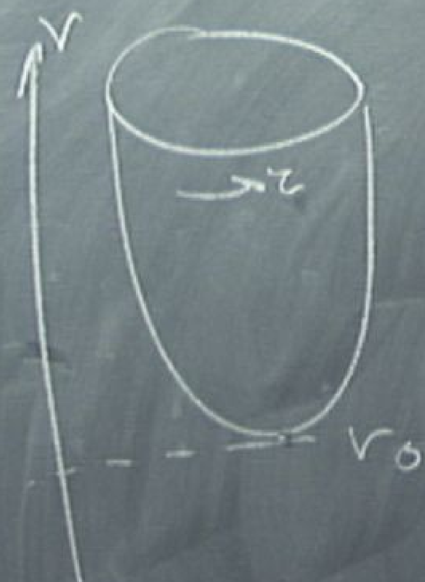
$$T_{Haw} = T_{CFT}$$


+R^2 dΩ_5^2
t → iτ
r
τ
r_0


$+R^2 \, d\Omega_5^2$
$t \to i\tau$
r
τ
r_0
$\tau \to \tau + \delta\tau$
$\delta\tau = \frac{\pi R^2}{r_0} = \beta = \frac{1}{T}$

$$+R^2\, d\Omega_5^2$$

$$t \to i\tau$$

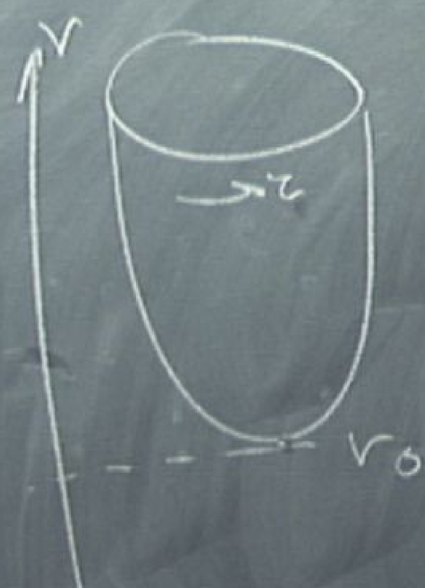


$$\tau \to \tau + \delta\tau$$

$$\delta\tau = \frac{\pi R^2}{r_0} = \beta = \frac{1}{T}$$

$$+R^2\, d\Omega_5^2$$

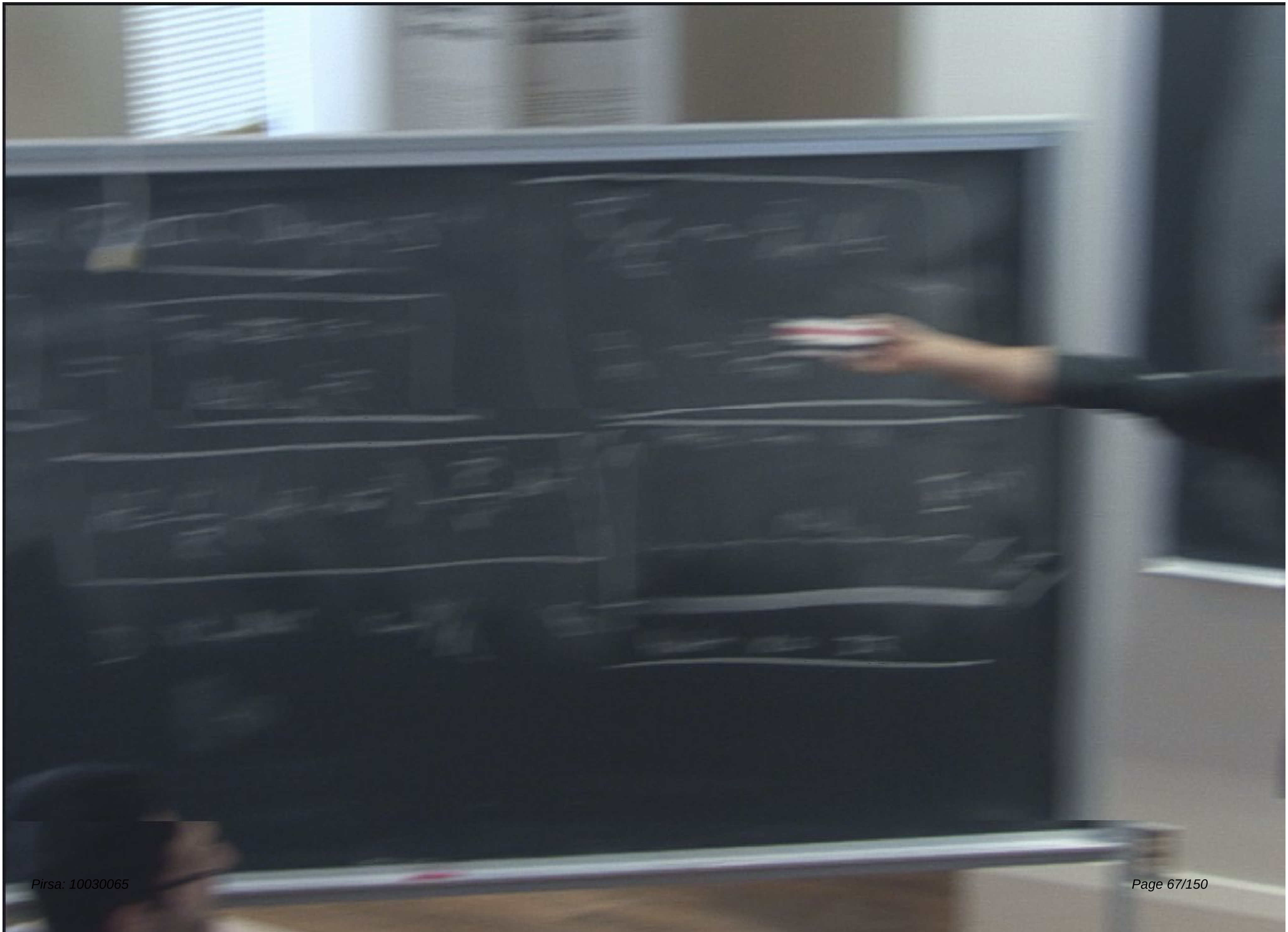
$$t \to i\tau$$

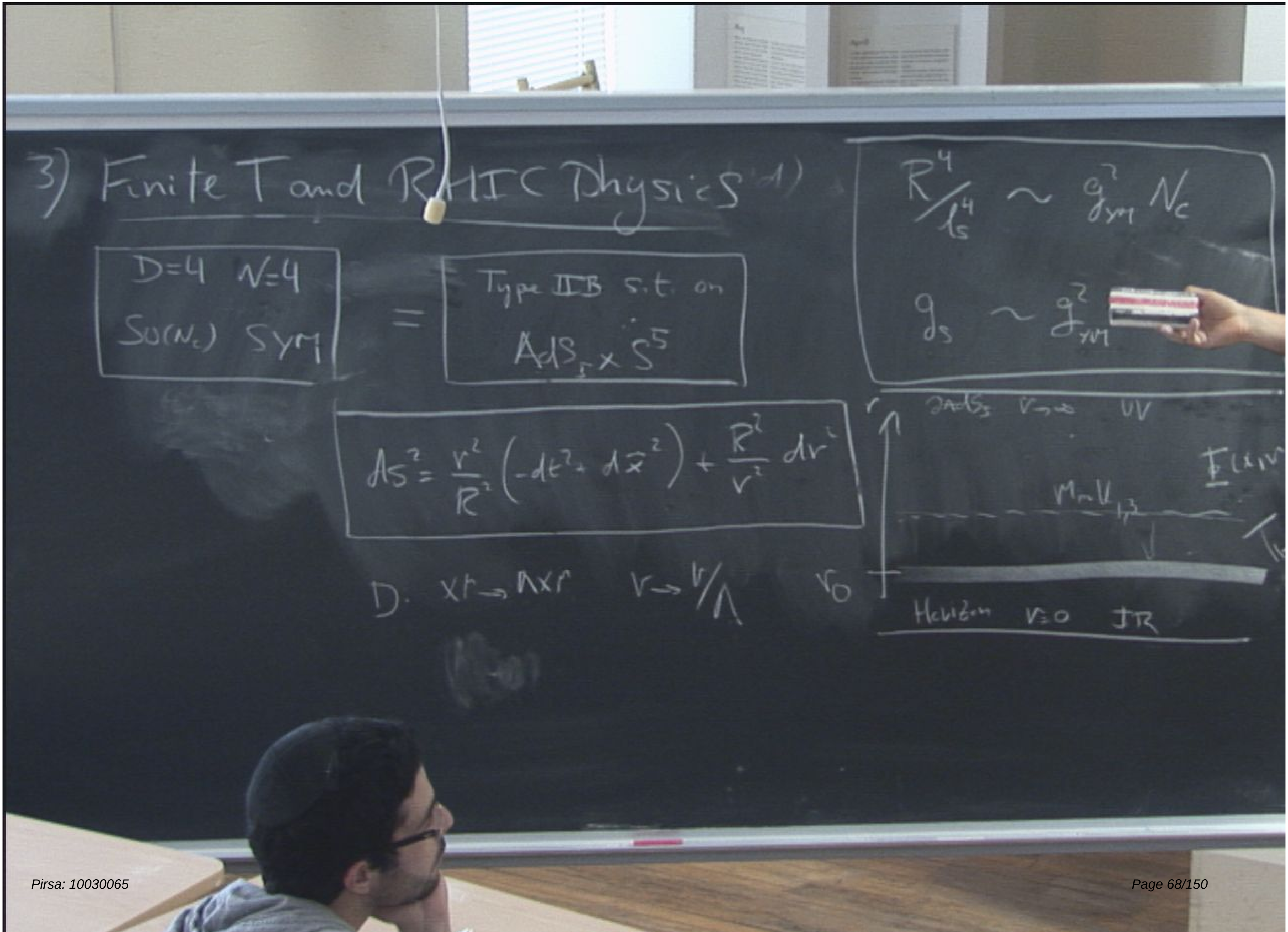


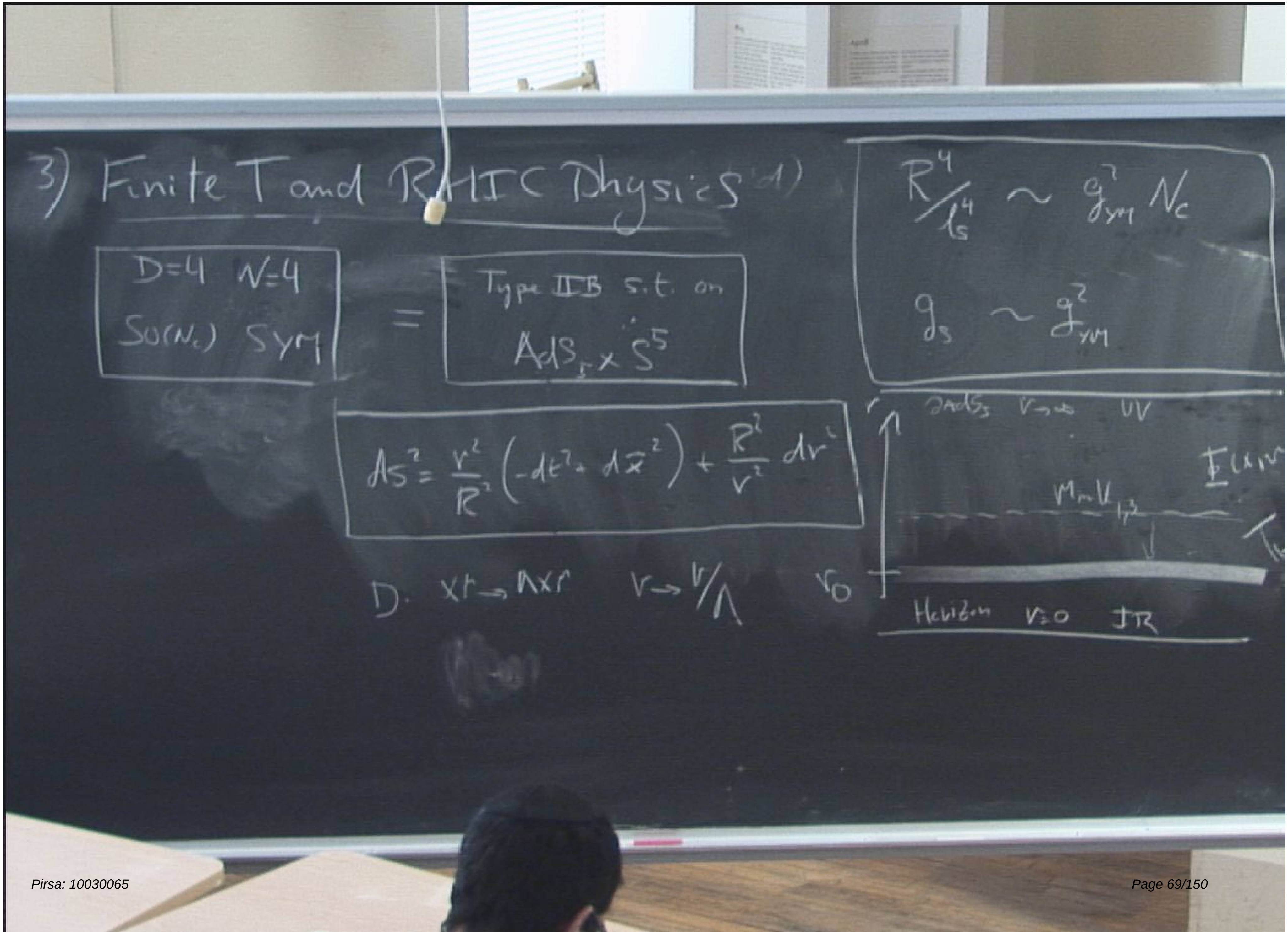
$$\tau \to \tau + \delta\tau$$

$$\delta\tau = \frac{\pi R^2}{r_0} = \beta = \frac{1}{T}$$

$$\boxed{T = \frac{r_0}{\pi R^2}}$$

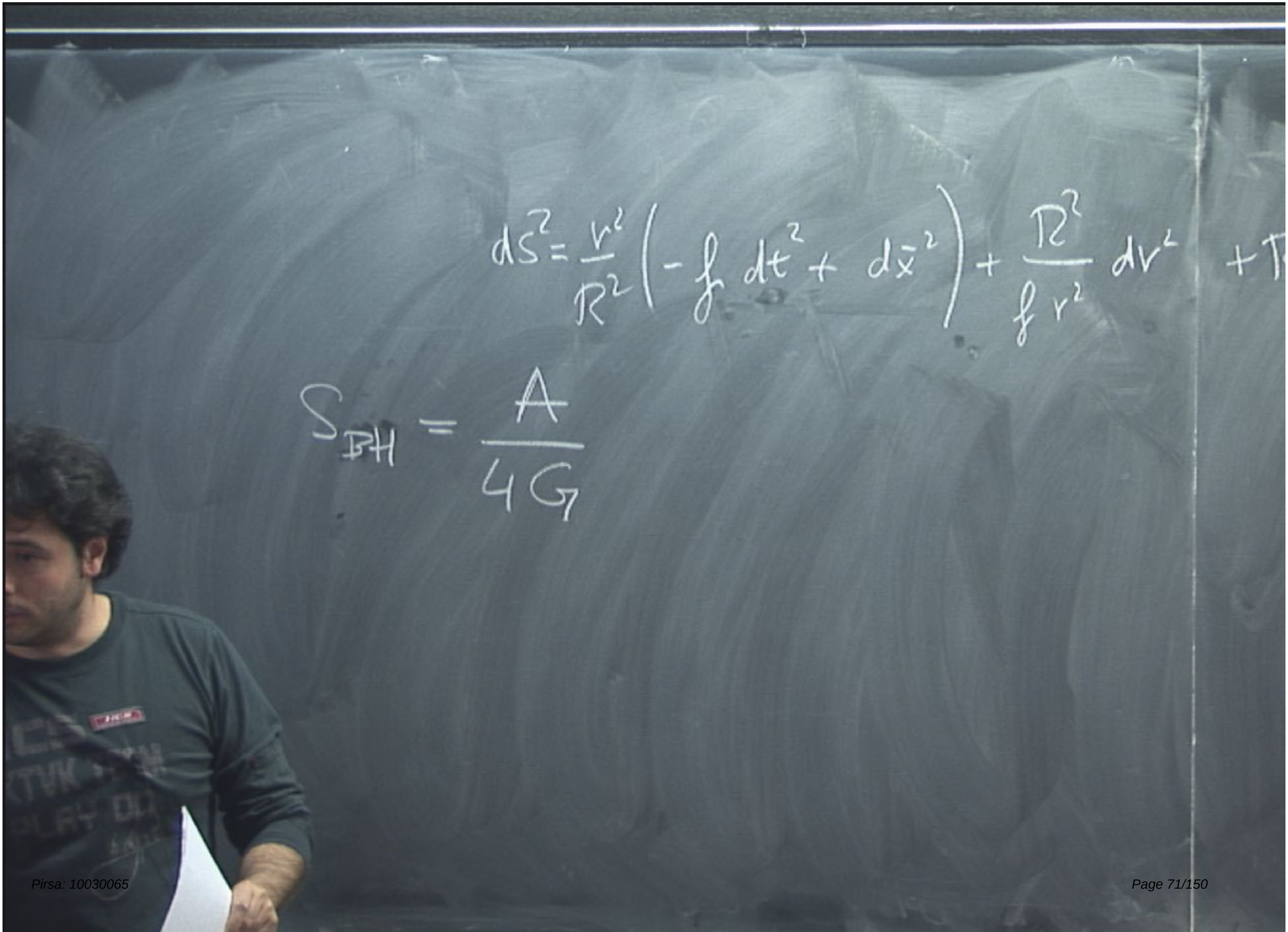


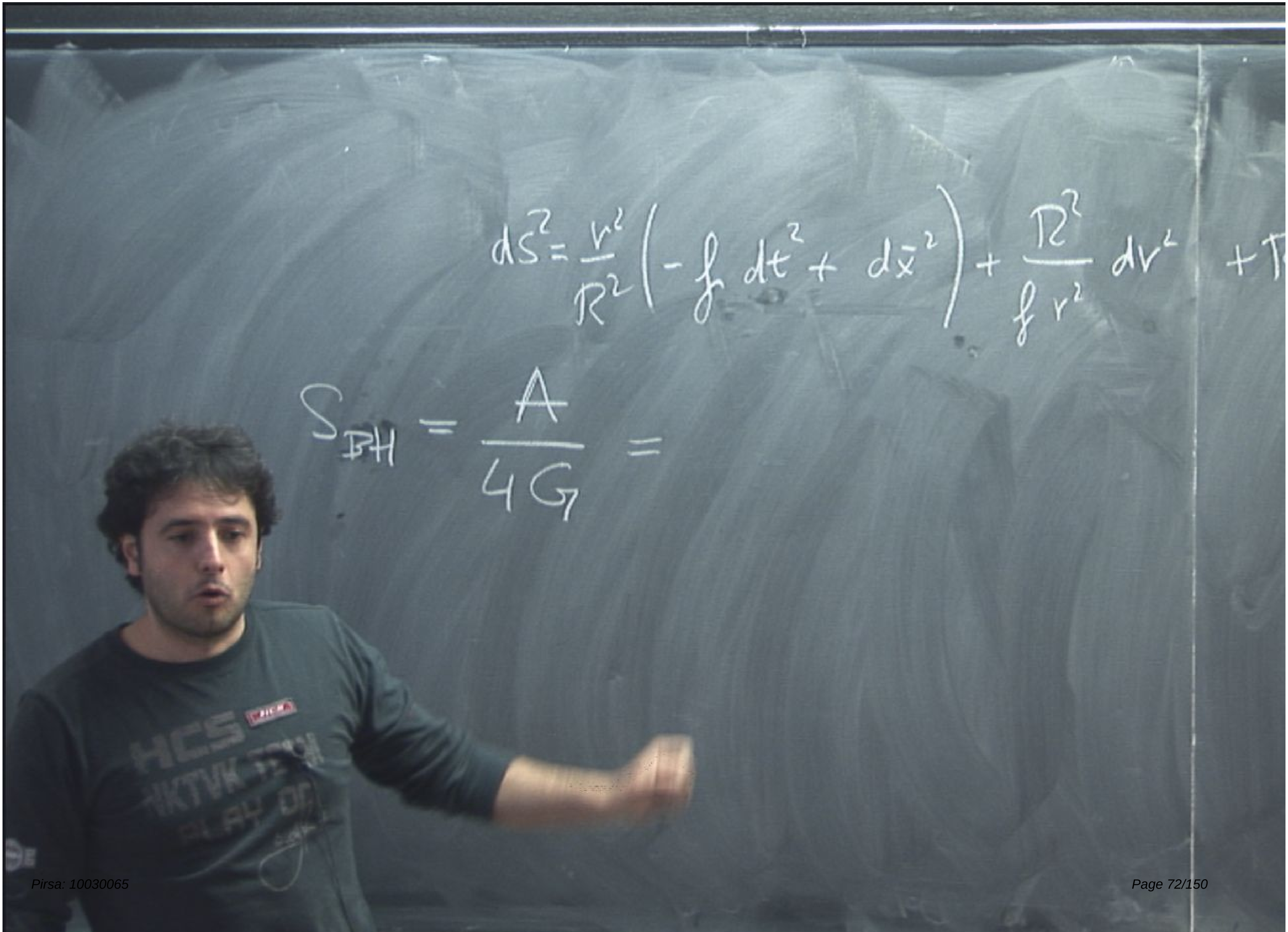

3) Finite T and RHIC Physics
D=4 N=4
SU(N_c) SYM
=
Type IIB s.t. on
AdS_5 × S^5
R^4/l_s^4 ~ g_YM^2 N_c
g_s ~ g_YM^2
ds^2 = r^2/R^2 (-dt^2 + dx^2) + R^2/r^2 dr^2
D. x^μ → Λx^μ   r → r/Λ
r_0
∂AdS_5   r → ∞   UV
Horizon   r=0   IR


3) Finite T and RHIC Physics
D=4 $\mathcal{N}=4$
$SU(N_c)$ SYM
=
Type IIB s.t. on
$AdS_5 \times S^5$
$R^4/l_s^4 \sim g_{YM}^2 N_c$
$g_s \sim g_{YM}^2$
$ds^2 = \frac{r^2}{R^2}\left(-dt^2 + d\vec{x}^2\right) + \frac{R^2}{r^2} dr^2$
D. $x^\mu \to \Lambda x^\mu$ $r \to r/\Lambda$
r_0
r
∂AdS_5 $r \to \infty$ UV
Horizon $r=0$ IR

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + R$$

$$S_{BH} = \frac{A}{4G}$$


$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + T$
$S_{BH} = \frac{A}{4G_7}$


$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\bar{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + T$
$S_{BH} = \frac{A}{4G_7} =$

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + R$$

$$S_{BH} = \frac{A}{4G} =$$

$$H_{\dots} =$$

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 + R^2\,d\Omega_5^2$$

$$S_{BH} = \frac{A}{4G} =$$

$$H_{hor} = \mathbb{R}^3 \times S^5$$

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + R^2\,d\Omega_5^2$$

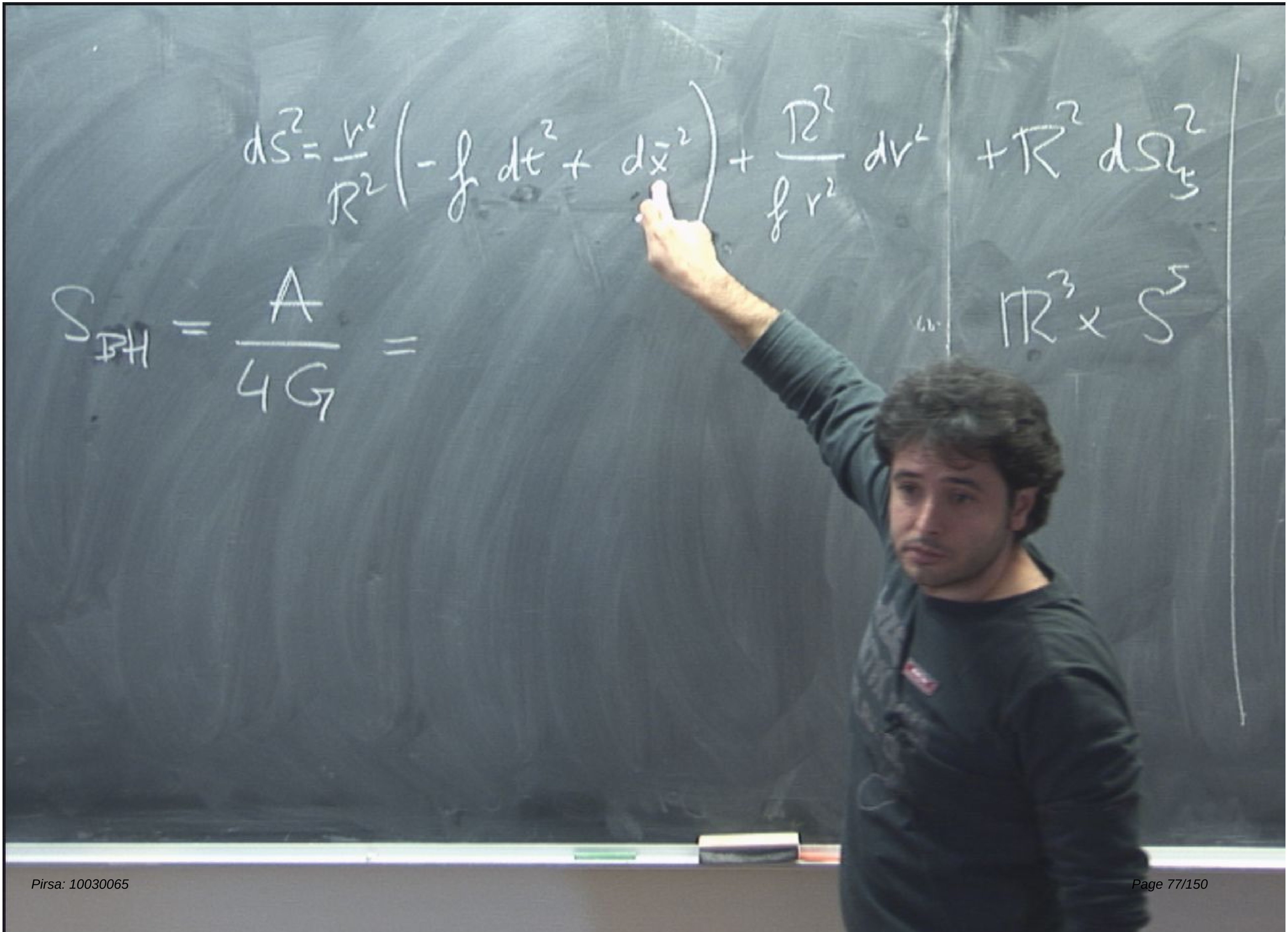
$$S_{BH} = \frac{A}{4G_7} =$$

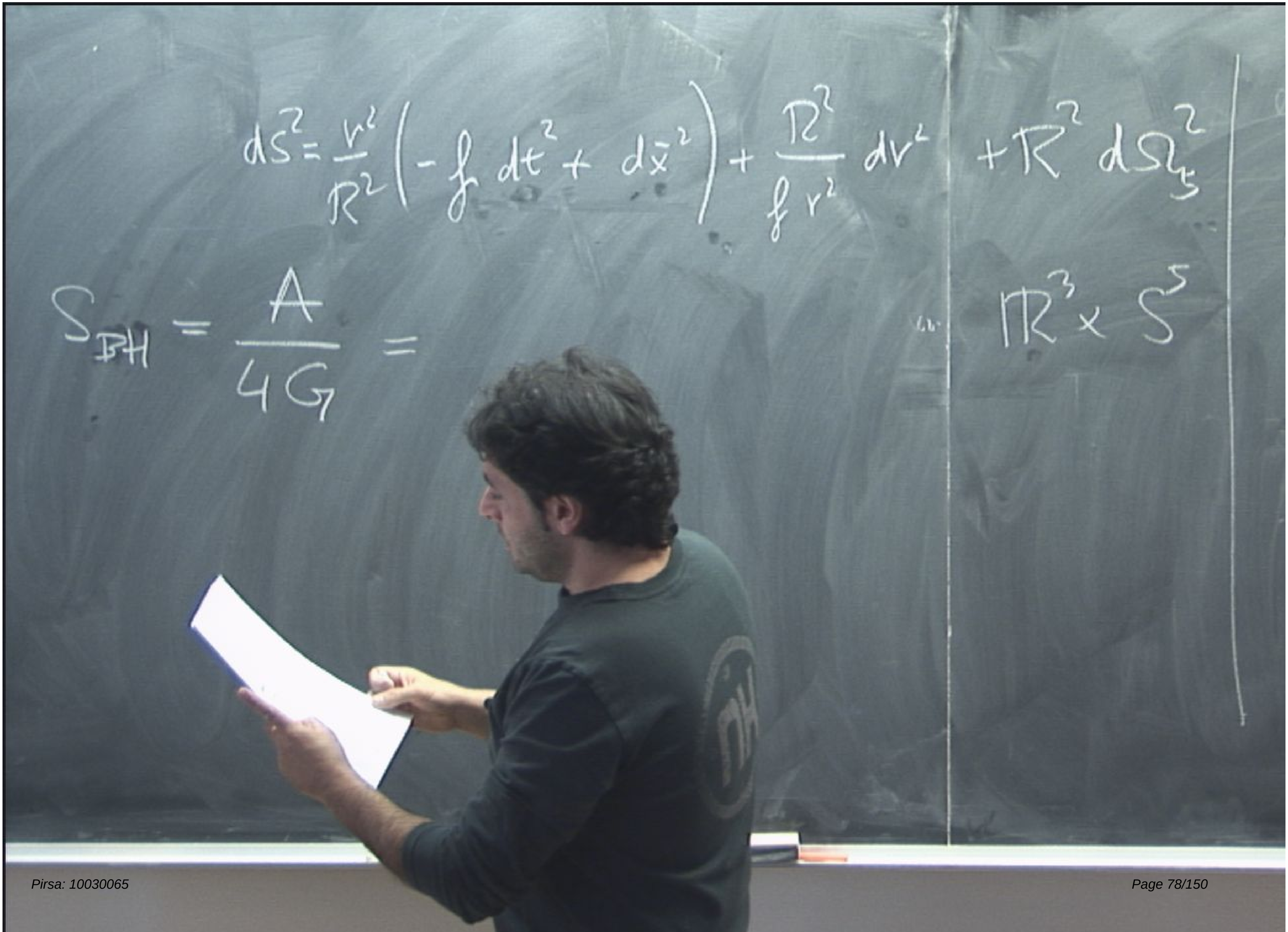
$$\mathcal{H}_{\ldots} = \mathbb{R}^3 \times S^5$$

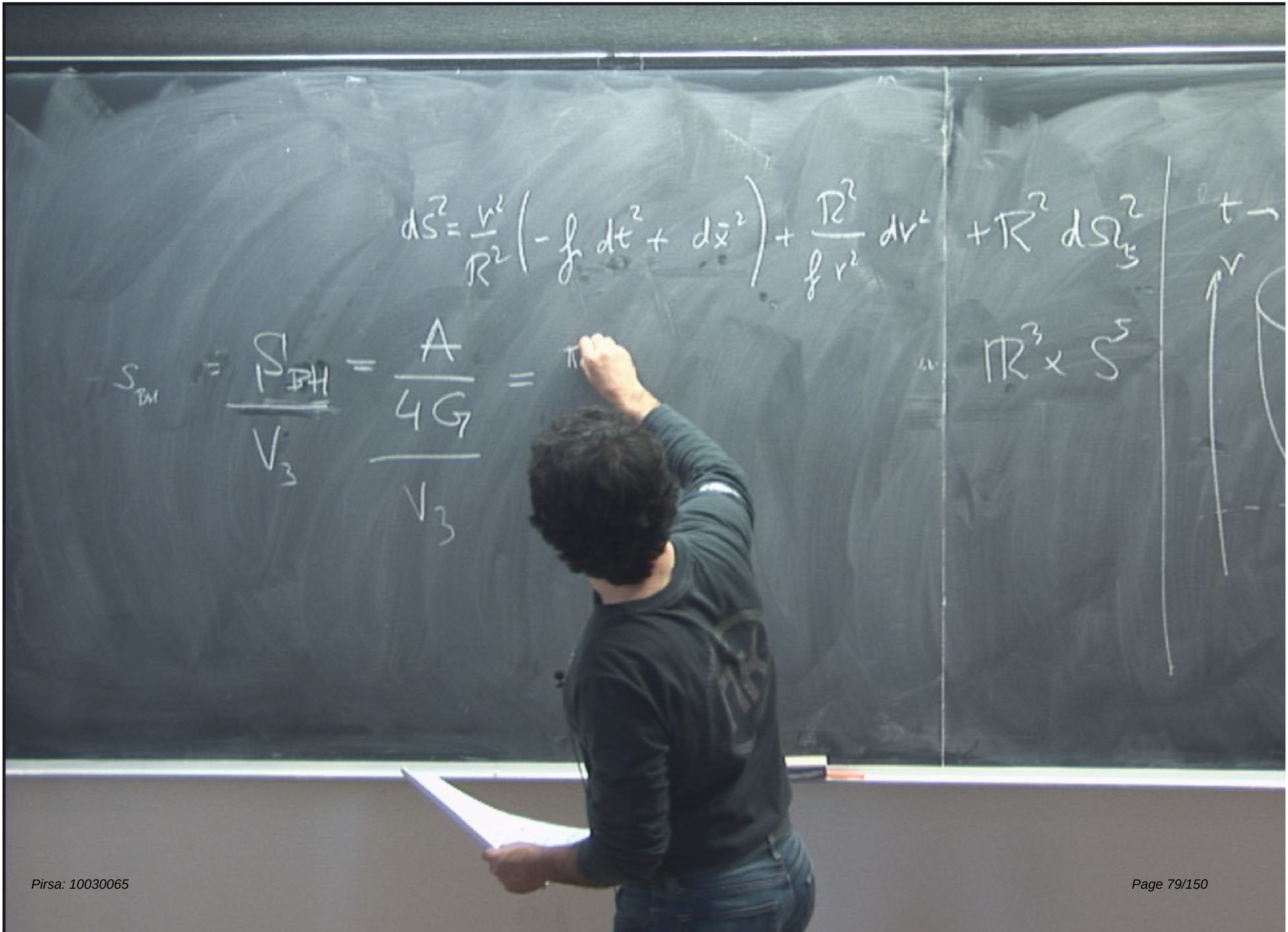
$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2}\,dr^2 + R^2\,d\Omega_5^2$$

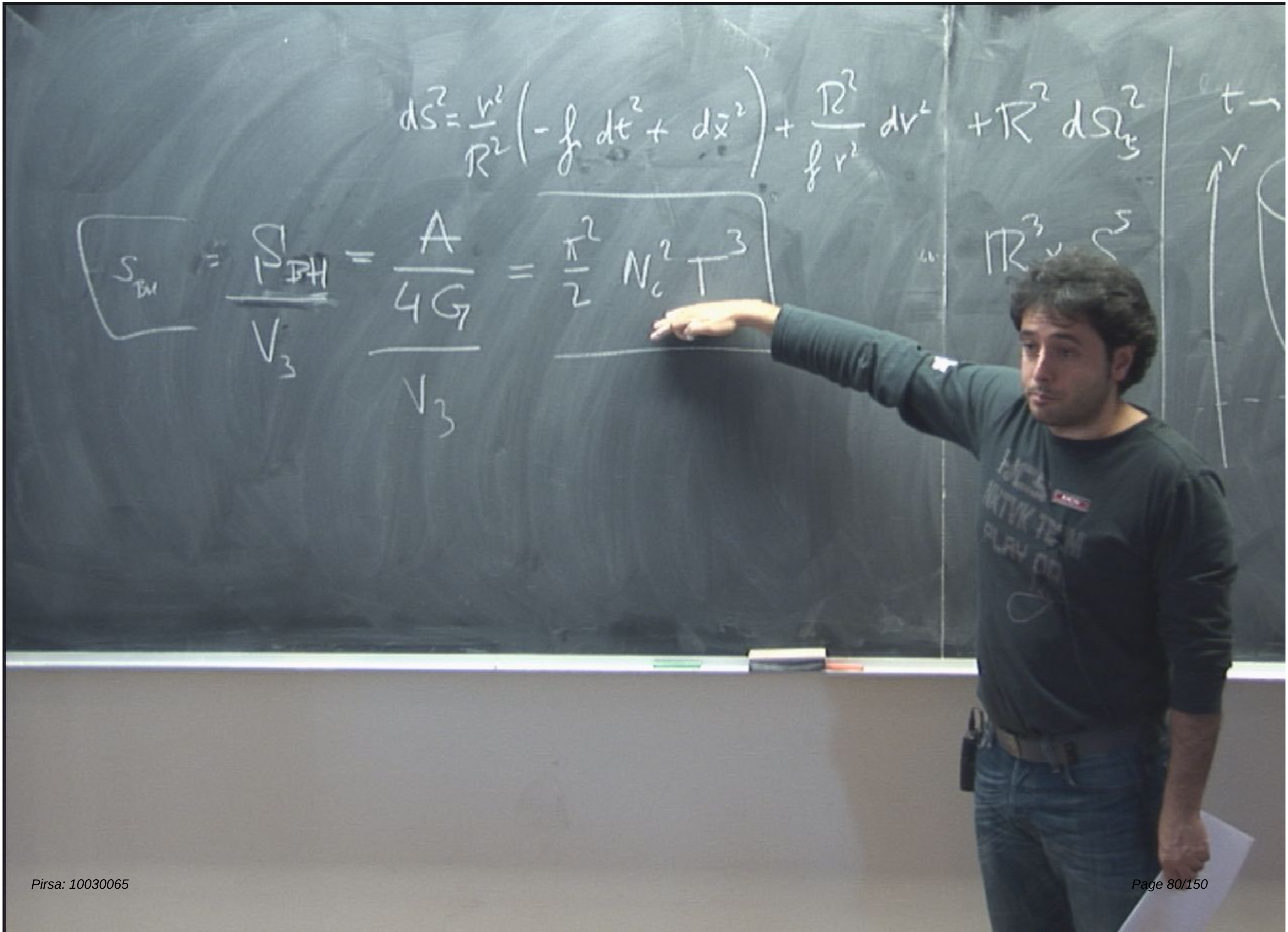
$$S_{BH} = \frac{A}{4G_7} =$$

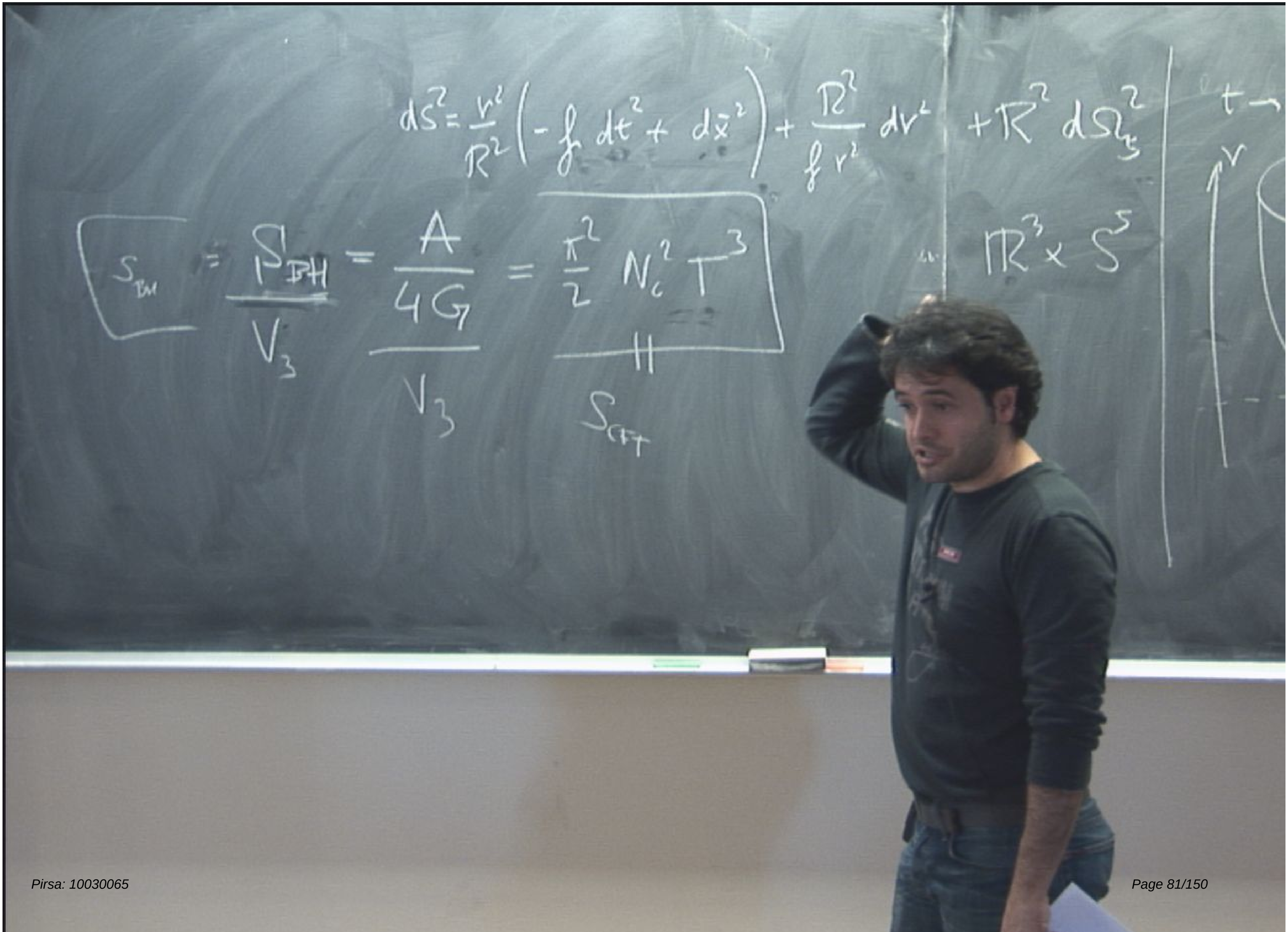
$$\mathbb{R}^3 \times S^5$$


$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2} dr^2 + R^2 d\Omega_5^2$
$S_{BH} = \frac{A}{4G_7} =$
$\mathbb{R}^3 \times S^5$

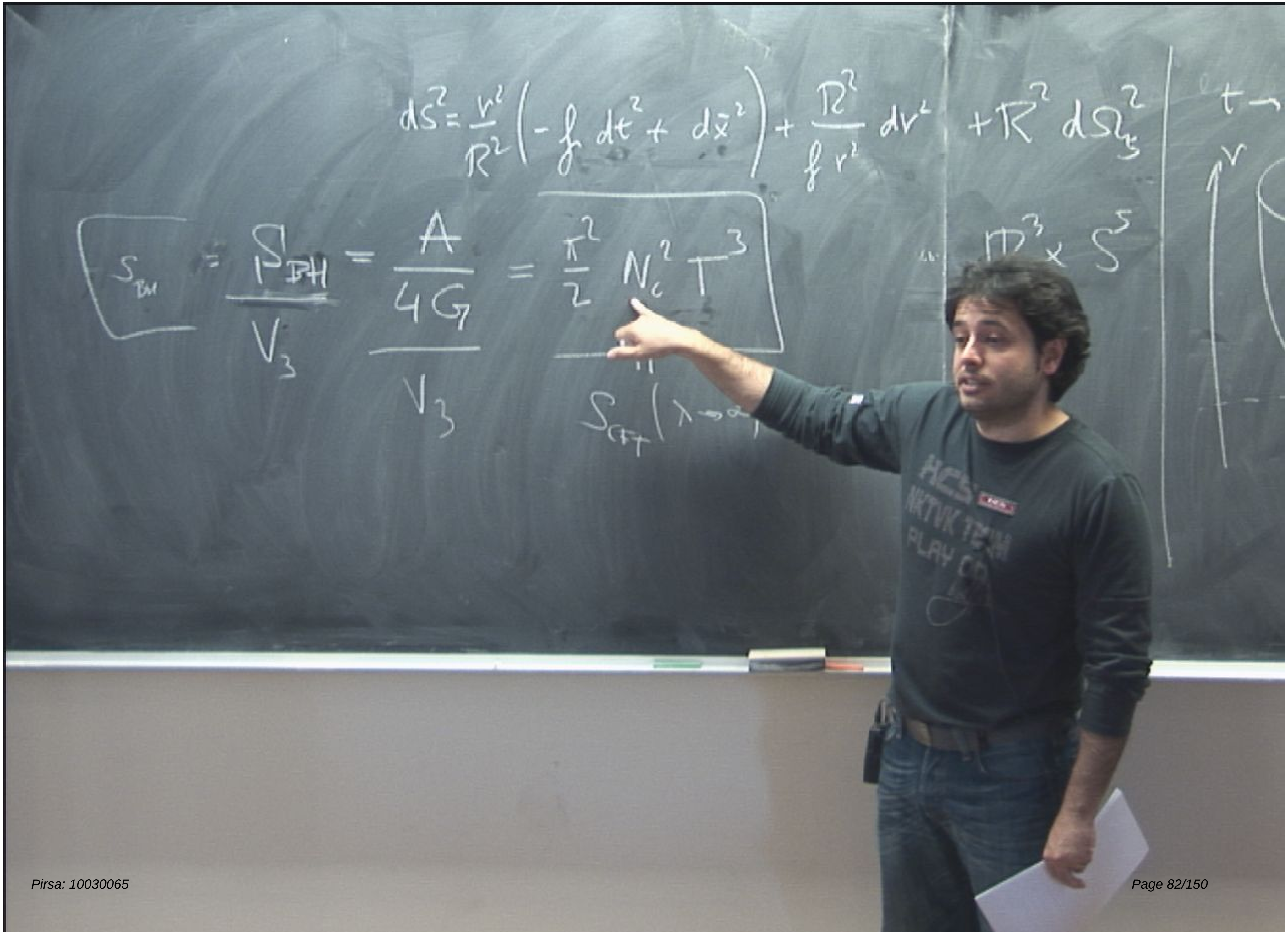

$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2} dr^2 + R^2 d\Omega_5^2$
$S_{BH} = \frac{A}{4G_7} =$
$\mathbb{R}^3 \times S^5$


$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2}dr^2 + R^2 d\Omega_5^2$
$s_{BH} = \frac{S_{BH}}{V_3} = \frac{\frac{A}{4G}}{V_3} = \pi$
$\mathbb{R}^3 \times S^5$
$t \to$
r


ds² = r²/R² (−f dt² + dx²) + R²/(f r²) dr² + R² dΩ₅²
S_BH / V₃ = A/4G₇ / V₃ = π²/2 N_c² T³
ℝ³ × S⁵
t
r



ds² = r²/R² (−f dt² + dx²) + R²/(f r²) dr² + R² dΩ₅²
t →
r
S_BH = S_BH/V₃ = (A/4G₇)/V₃ = π²/2 N_c² T³ = S_CFT
ℝ³ × S⁵

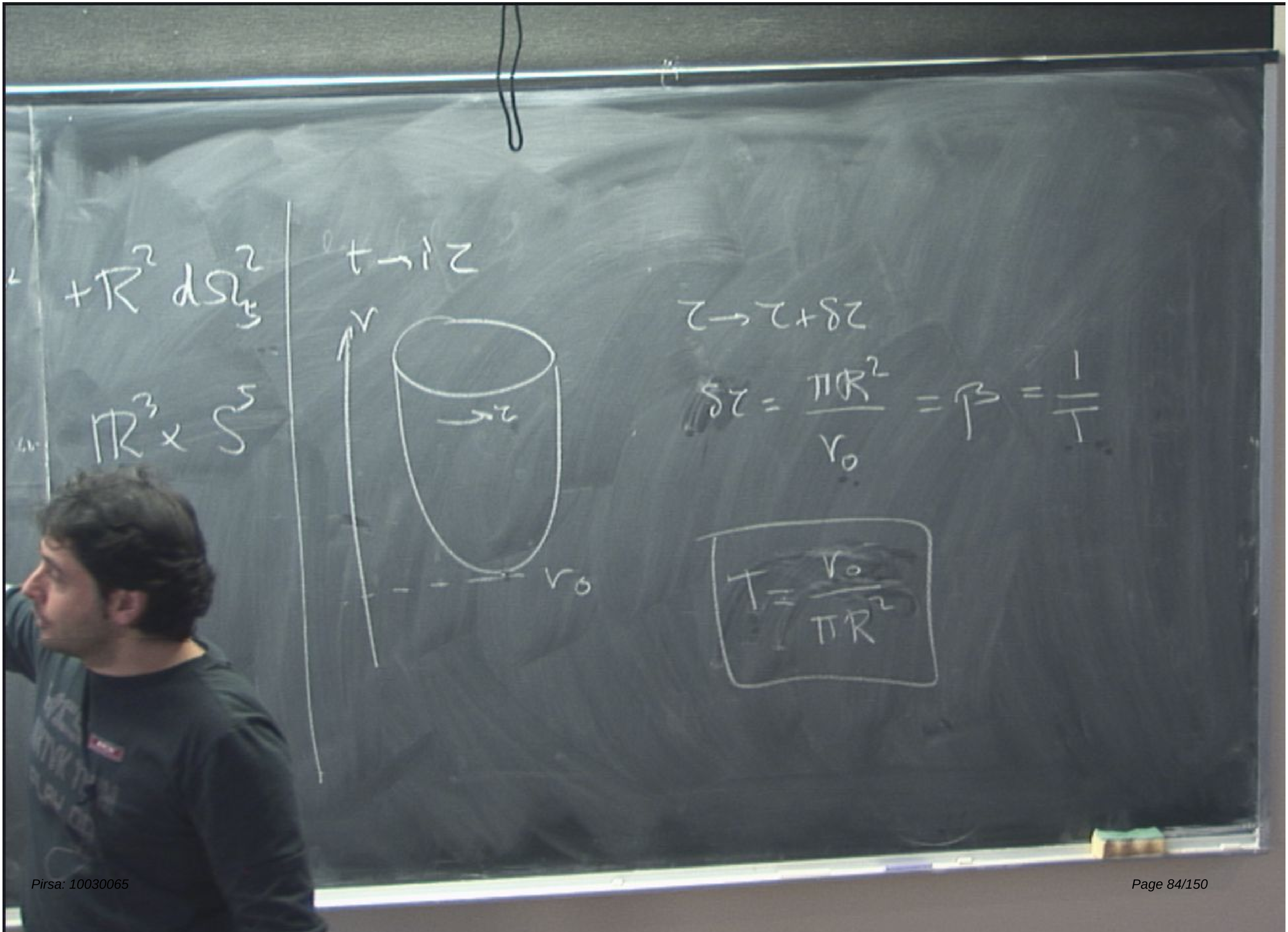


$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f r^2} dr^2 + R^2 d\Omega_5^2$
$\boxed{\frac{S_{BH}}{V_3}} = \frac{S_{BH}}{V_3} = \frac{A/4G_7}{V_3} = \boxed{\frac{\pi^2}{2} N_c^2 T^3}$
$= S_{CFT}(\lambda \to \infty)$
$R^3 \times S^5$
$t \to$
r

$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 + R^2\,d\Omega_5^2$$

$$\boxed{s_{BH}} = \frac{S_{BH}}{V_3} = \frac{\frac{A}{4G_7}}{V_3} = \boxed{\frac{\pi^2}{2} N_c^2 T^3} = S_{CFT}(\lambda \to \infty)$$

$$\mathbb{R}^3 \times S^5$$


$+R^2\, d\Omega_5^2$
$\mathbb{R}^3 \times S^5$
$t \to i\tau$
r
τ
r_0
$\tau \to \tau + \delta\tau$
$\delta\tau = \frac{\pi R^2}{r_0} = \beta = \frac{1}{T}$
$\boxed{T = \frac{r_0}{\pi R^2}}$

$$\boxed{s_{BH}} = \frac{S_{BH}}{V_3} = \frac{\frac{A}{4G_7}}{V_3} = \boxed{\frac{\pi^2}{2} N_c^2 T^3}$$

$$\frac{\pi^2}{2} N_c^2 T^3 = S_{CFT}(\lambda \to \infty)$$

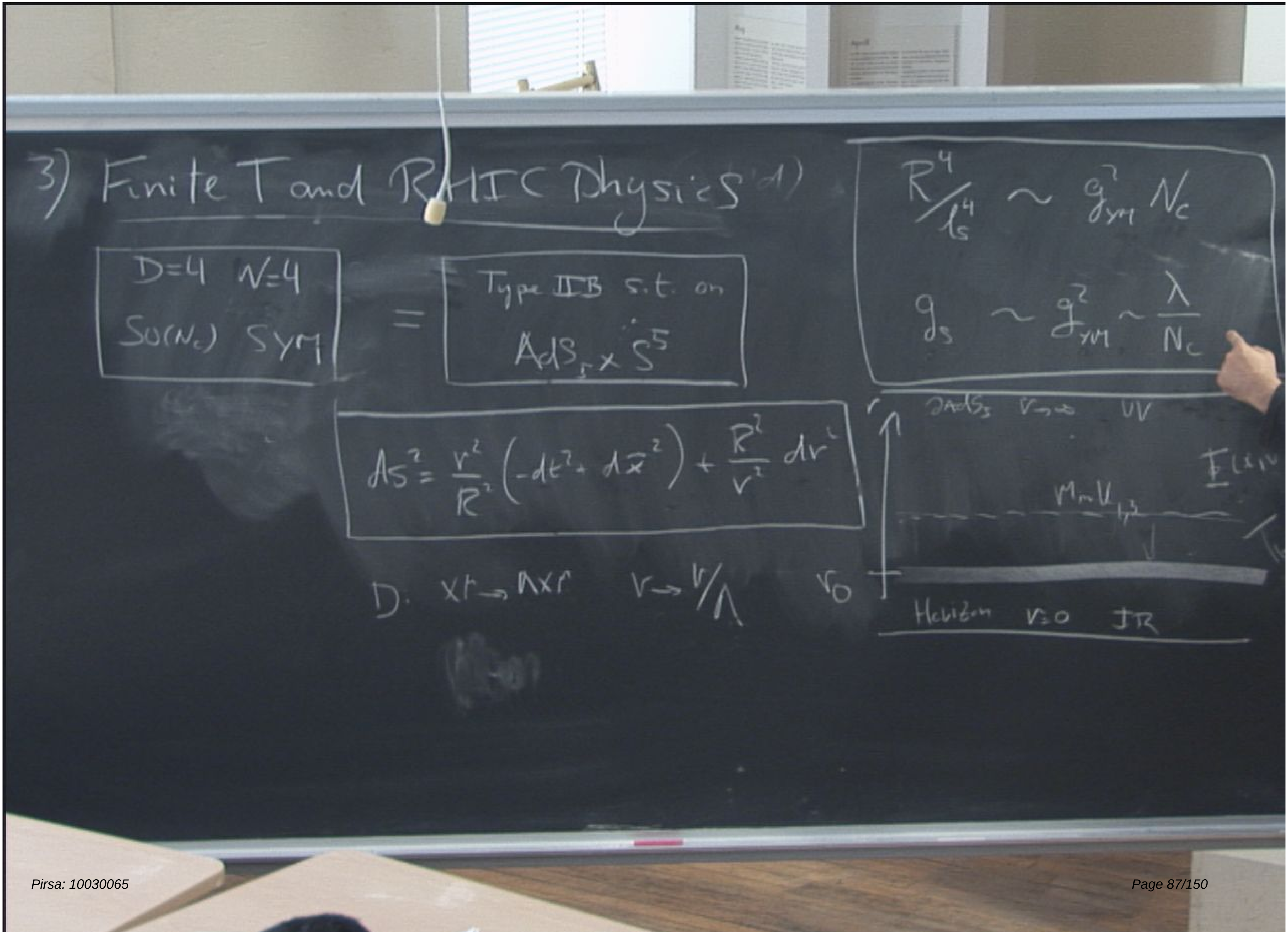
G_7

$$= \frac{S_{BH}}{V_3} = \frac{\frac{A}{4G_7}}{V_3} = \boxed{\frac{\pi^2}{2} N_c^2 T^3}$$

$$= S_{CFT}(\lambda \to \infty)$$

$$\mathbb{R}^3 \times S^5$$

$$G_7 \sim g_s^2$$


3) Finite T and RHIC Physics
D=4 N=4
SO(N_c) SYM
=
Type IIB s.t. on
AdS_5 x S^5
R^4/l_s^4 ~ g_YM^2 N_c
g_s ~ g_YM^2 ~ λ/N_c
ds^2 = r^2/R^2 (-dt^2 + dx^2) + R^2/r^2 dr^2
D. x^μ → Λx^μ   r → r/Λ
∂AdS_5   r→∞   UV
r_0
Horizon   r=0   IR

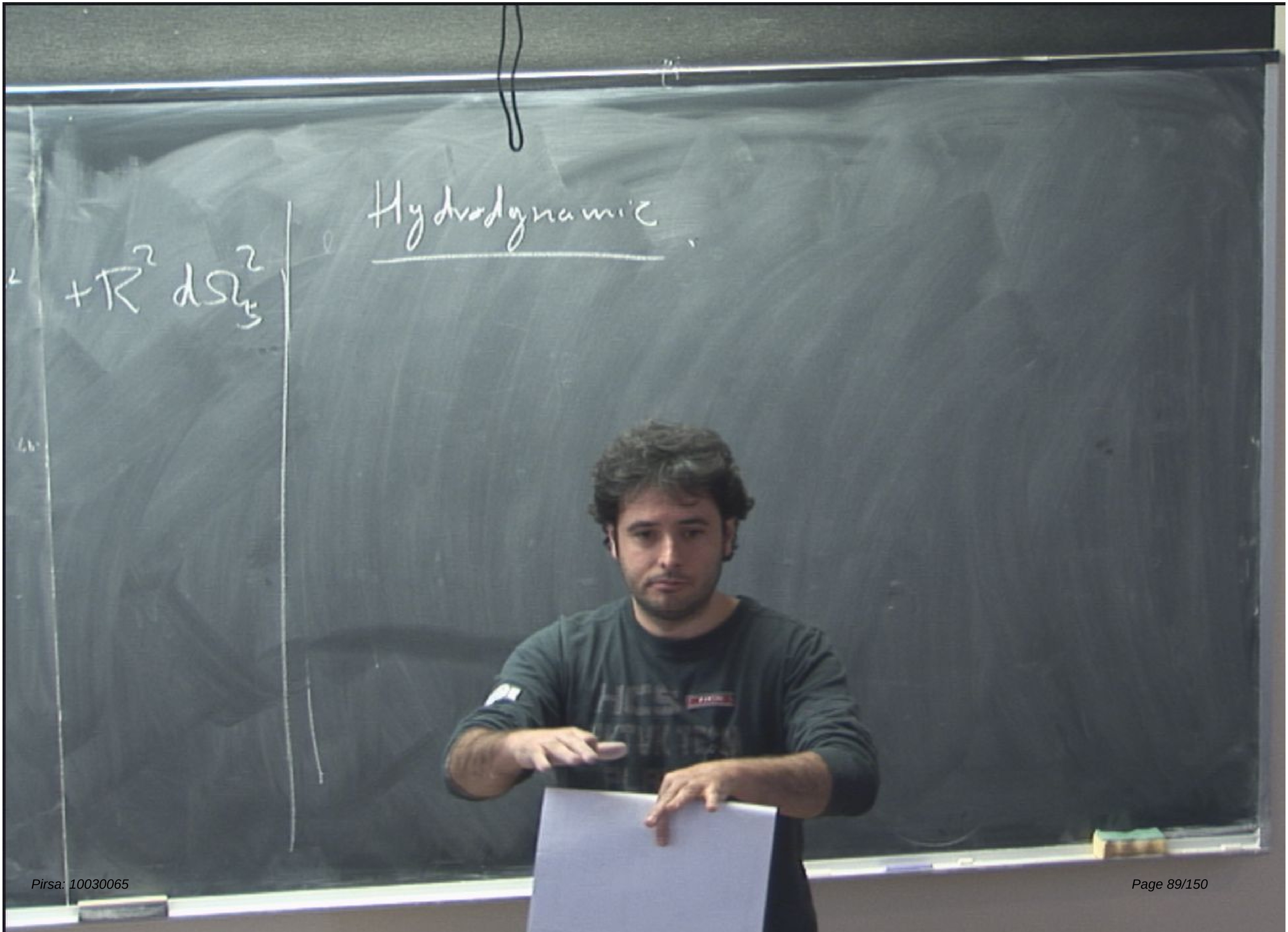
Thermodynamic

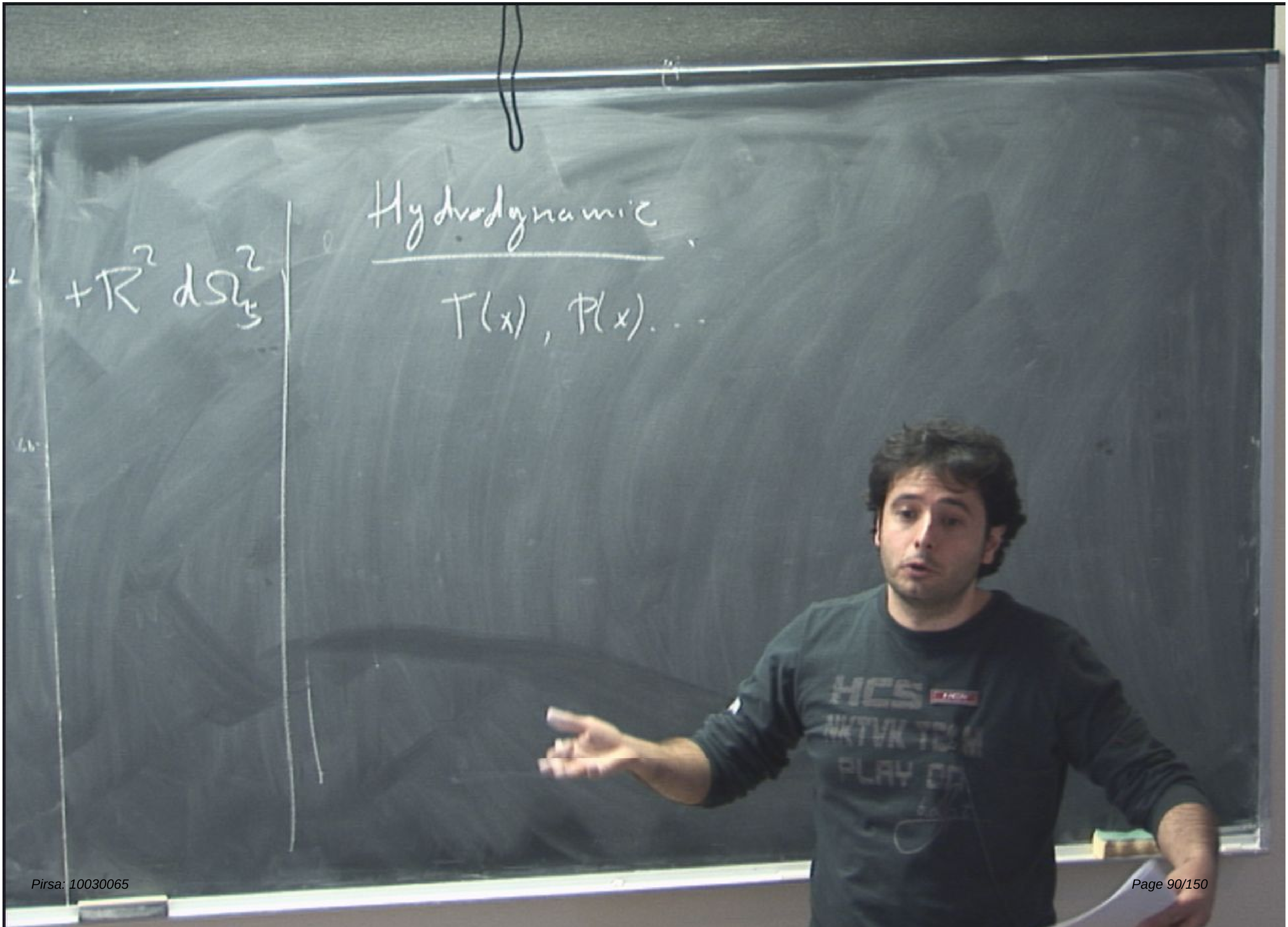
$$ds^2 = \frac{r^2}{R^2}\left(-f\,dt^2 + d\vec{x}^2\right) + \frac{R^2}{f\,r^2}\,dr^2 \quad + R$$

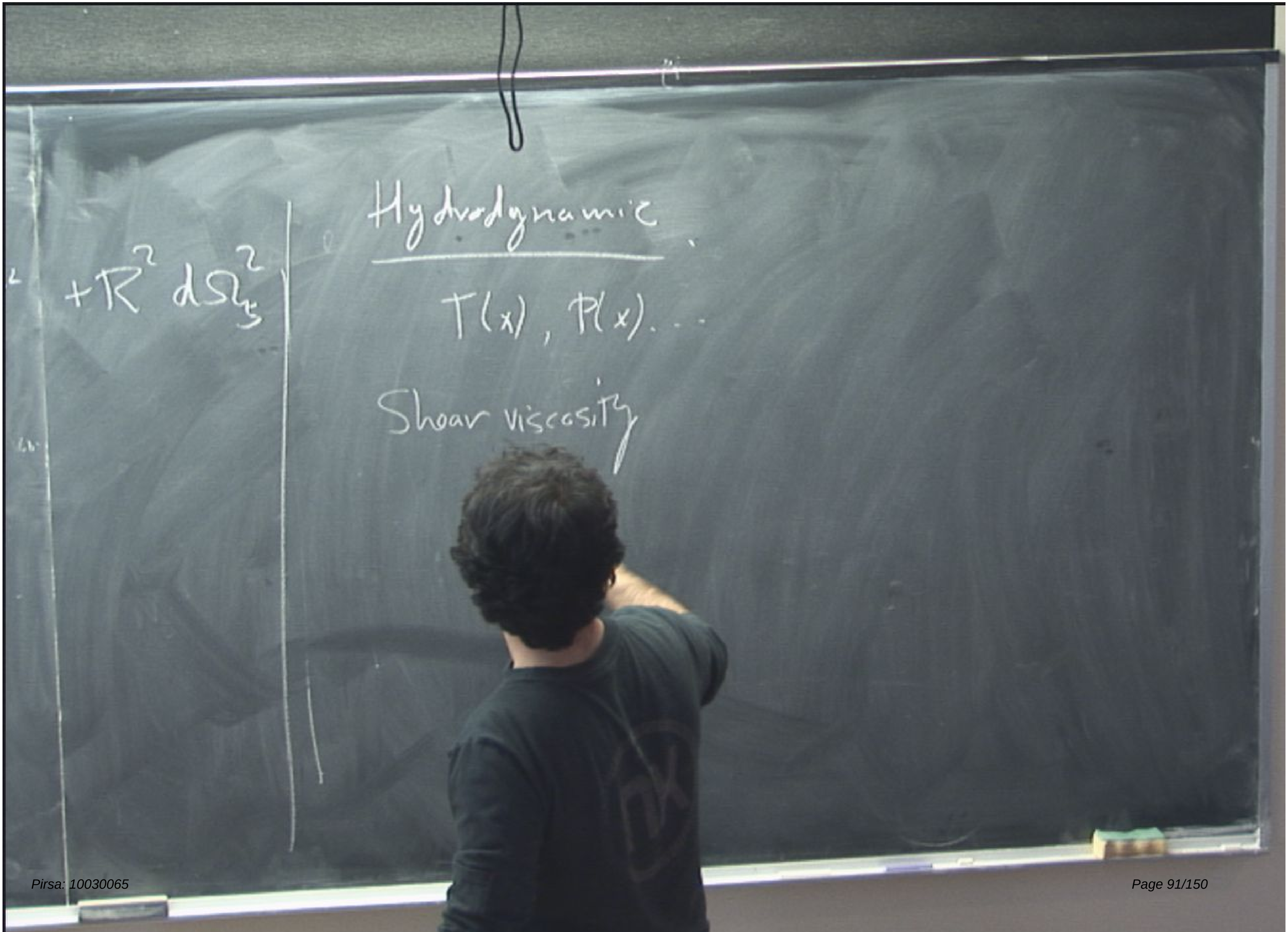
$$\boxed{s_{BH}} = \frac{S_{BH}}{V_3} = \frac{\frac{A}{4G}}{V_3} = \boxed{\frac{\pi^2}{2} N_c^2 T^3}$$

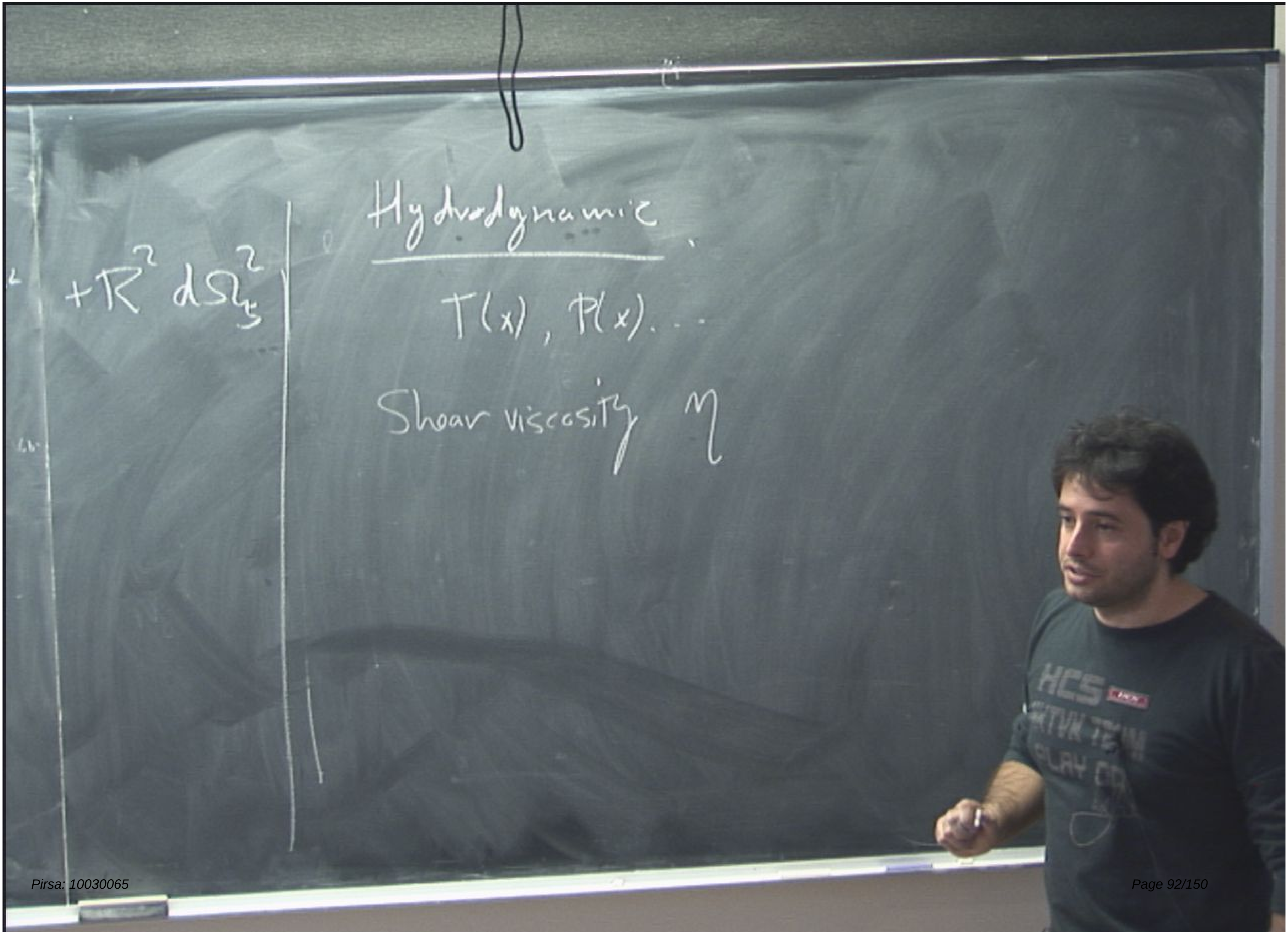
$$= S_{CFT}(\lambda \to \infty)$$

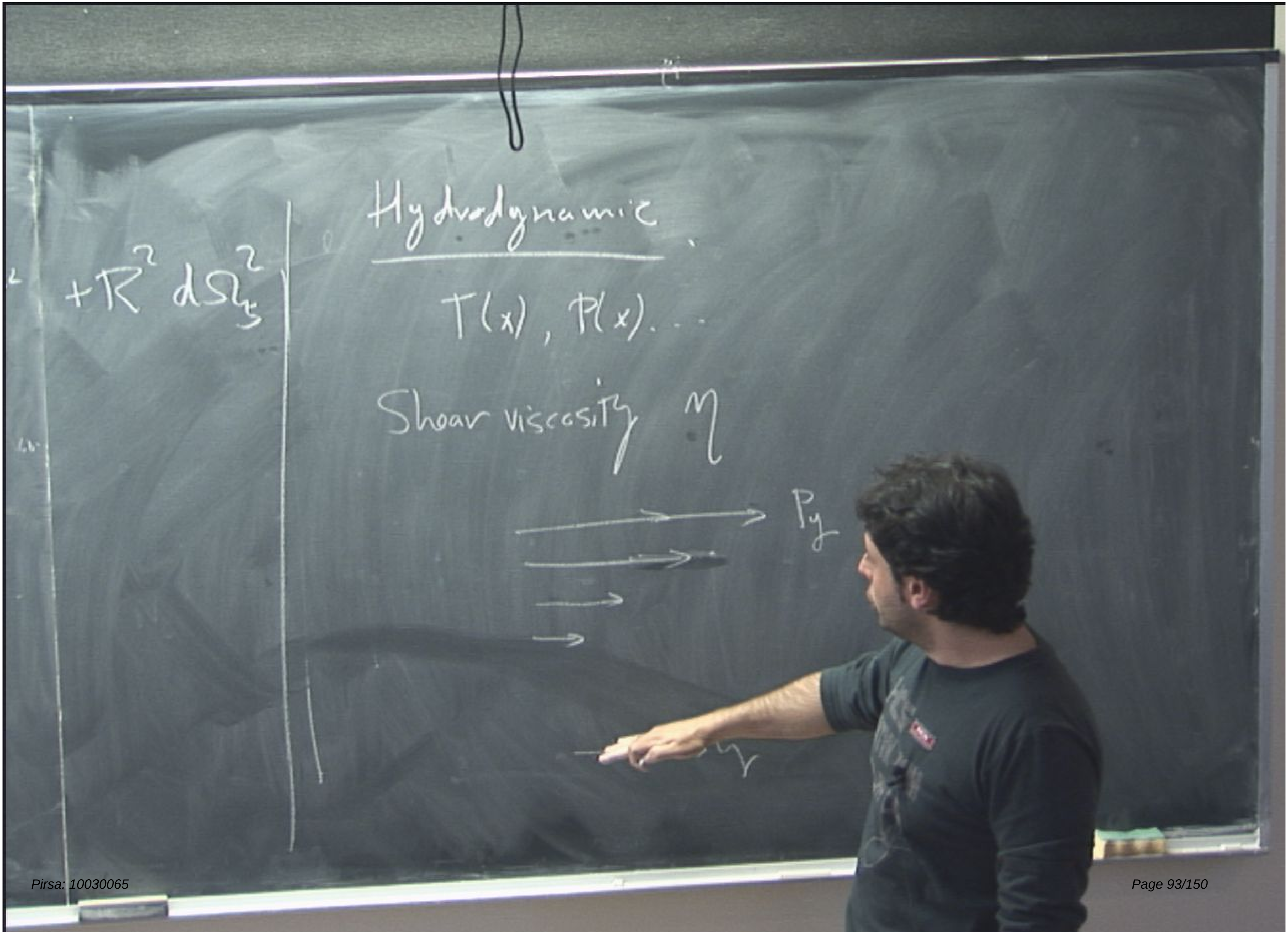
$$G \sim g_s^2 \sim$$


Hydrodynamic
$+R^2 d\Omega_5^2$


$+R^2\, d\Omega_5^2$
Hydrodynamic
$T(x)\,,\ P(x)\ldots$


+R^2 dΩ_5^2
Hydrodynamic
T(x), P(x)...
Shear viscosity


+R^2 dΩ_5^2
Hydrodynamic
T(x), P(x)...
Shear viscosity η

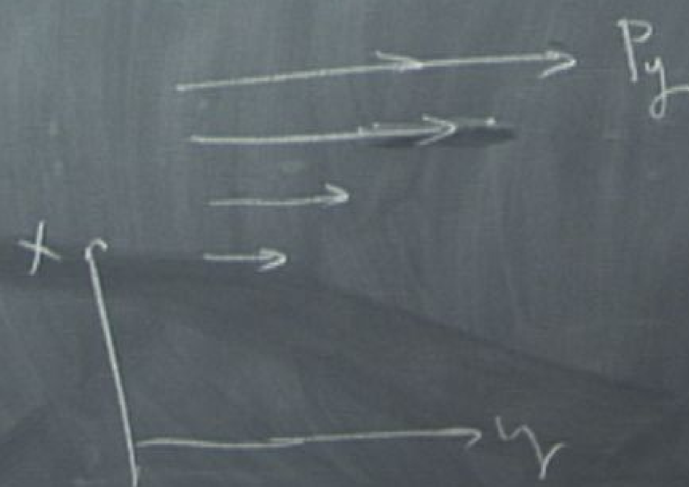

+R^2 dΩ_5^2
Hydrodynamic
T(x), P(x)...
Shear viscosity η
P_y

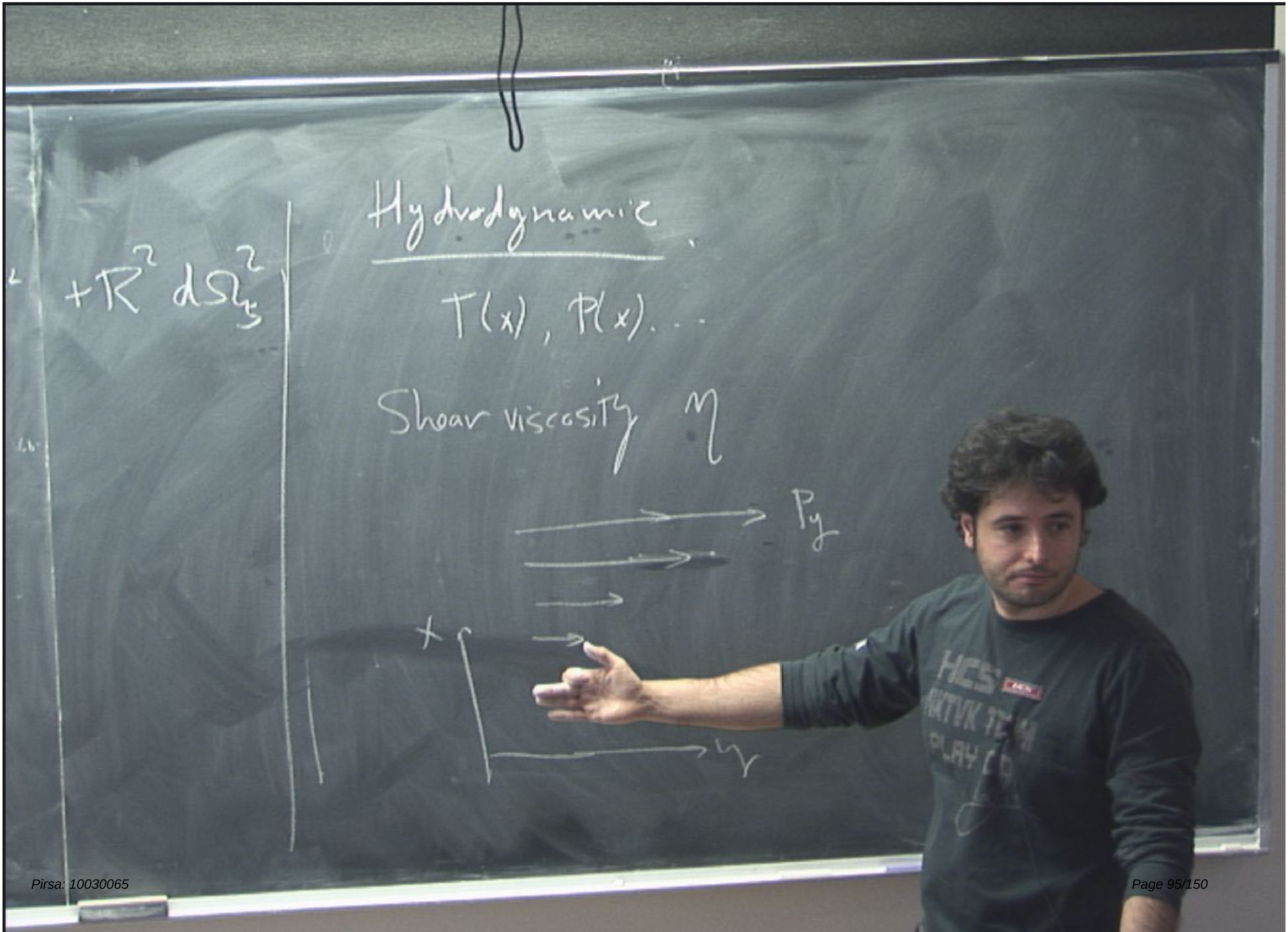
$+R^2\, d\Omega_5^2$

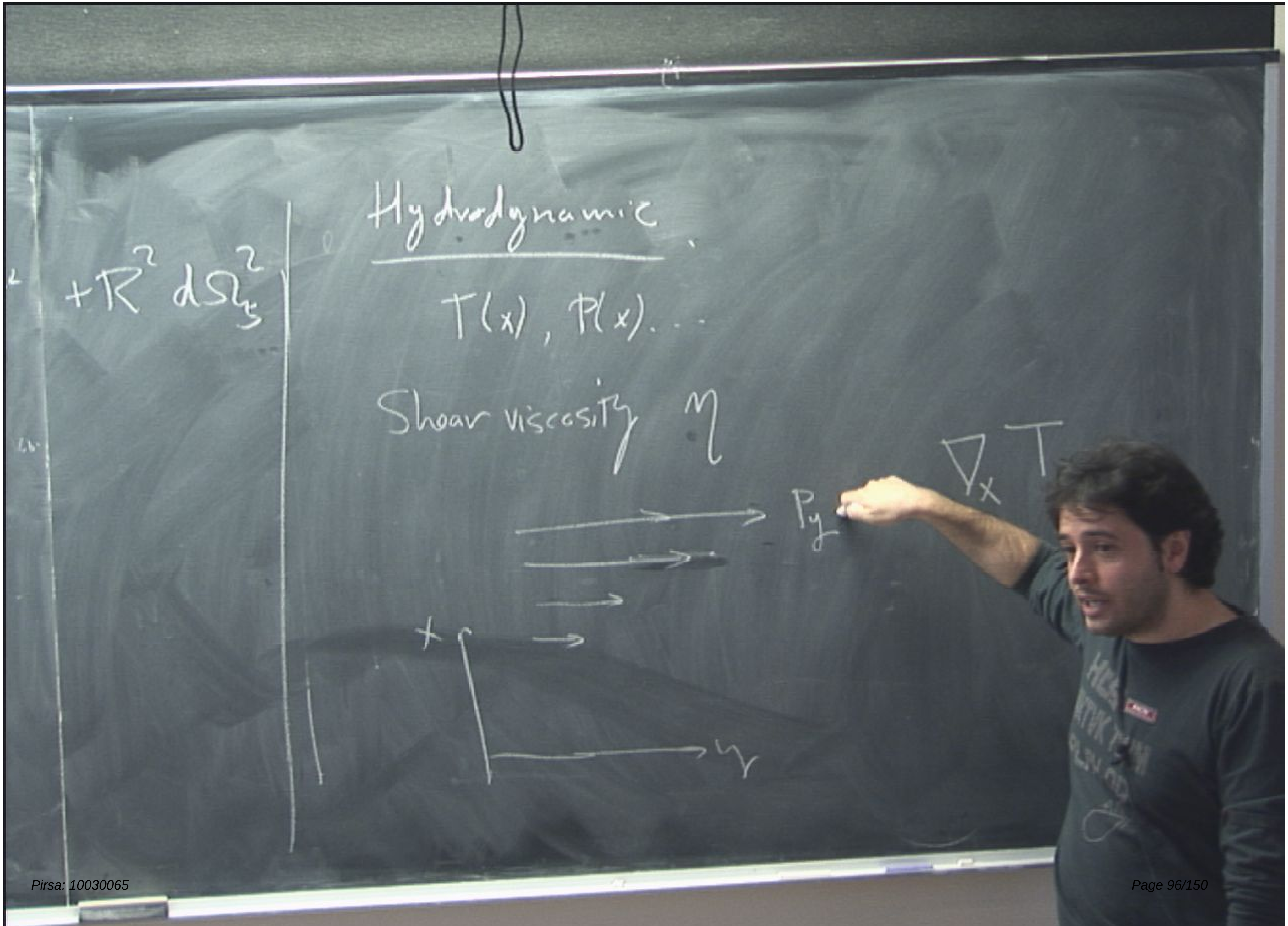
Hydrodynamic

$T(x)\,,\ P(x)\ldots$

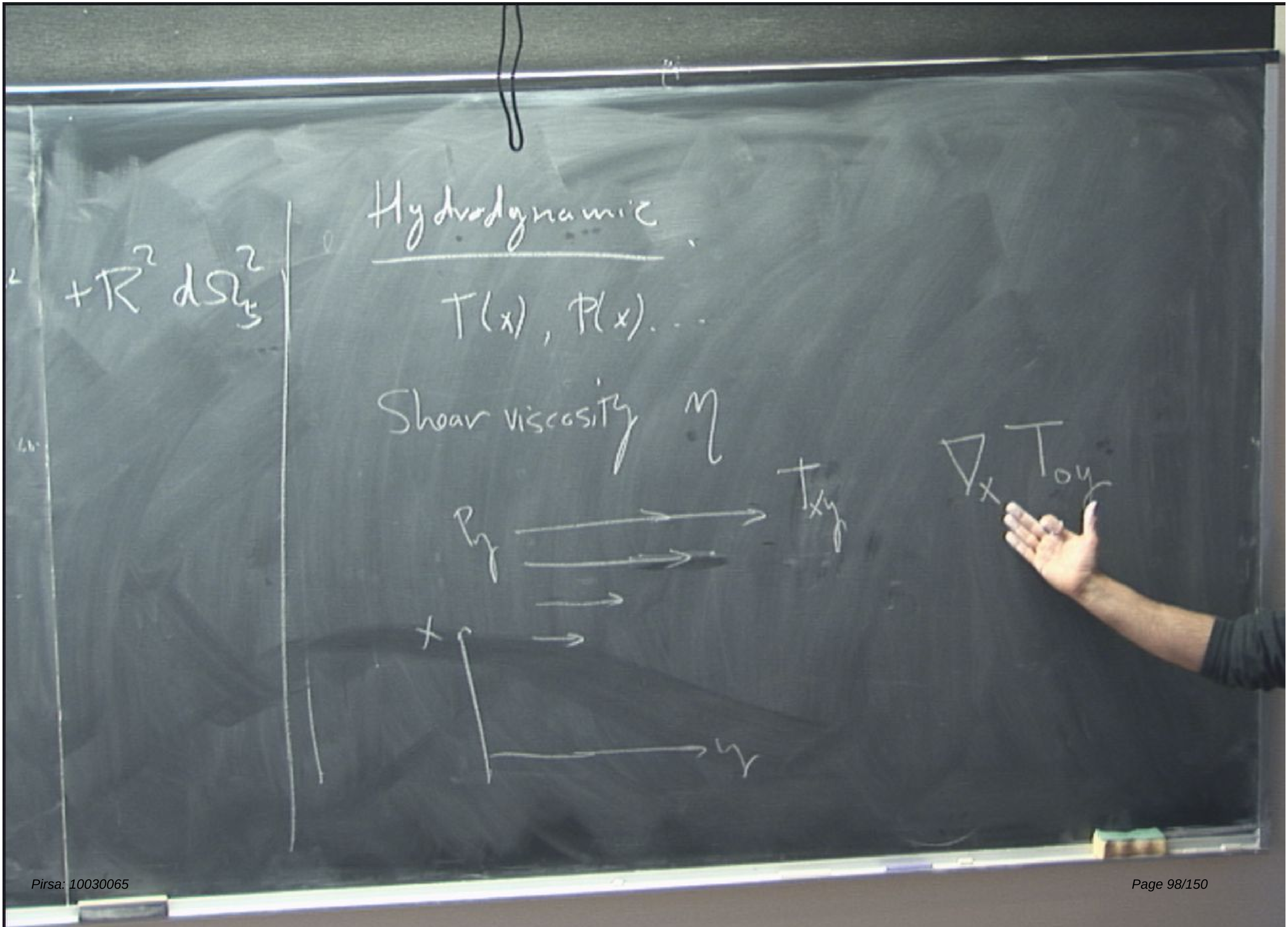
Shear viscosity η

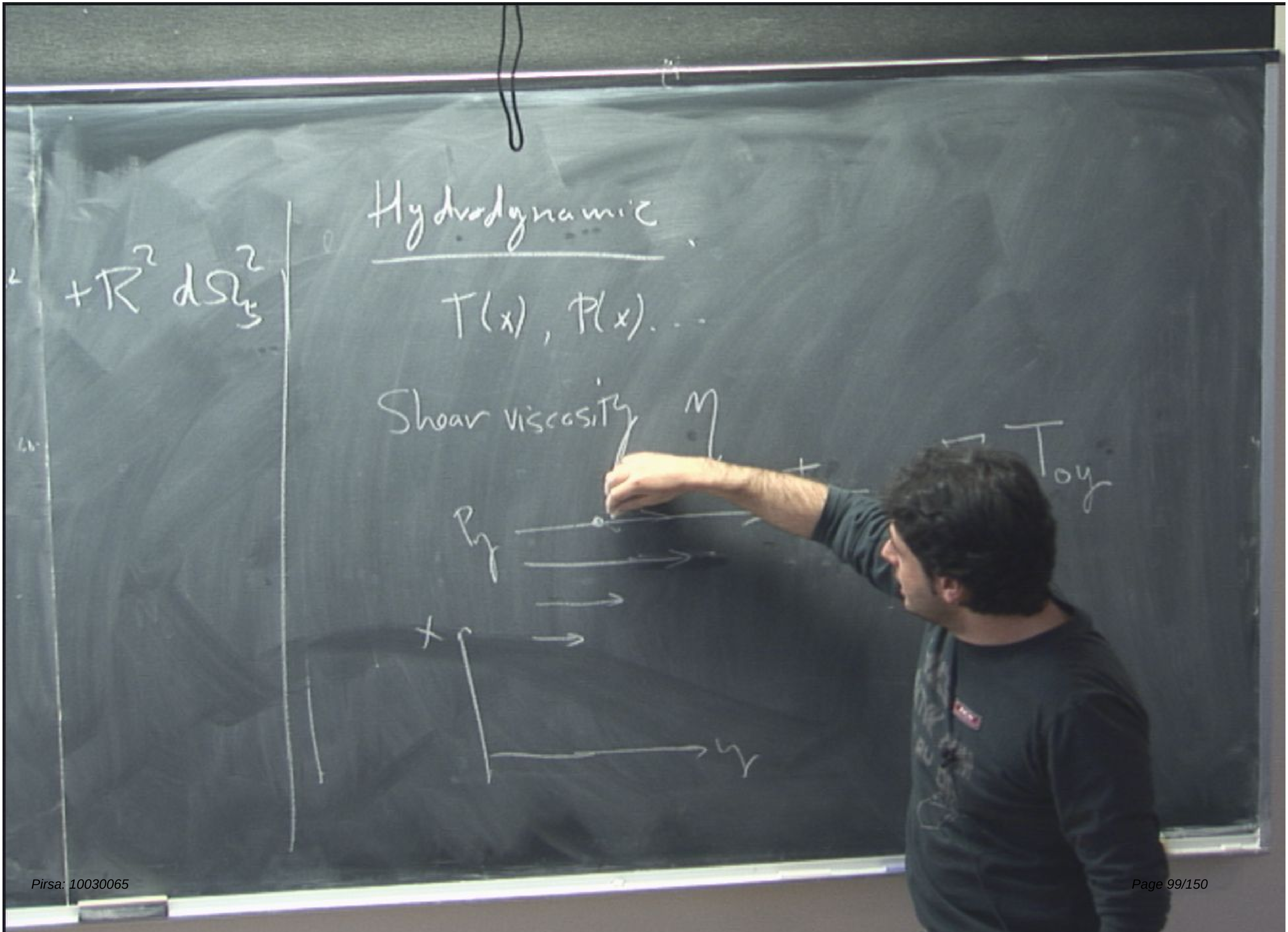


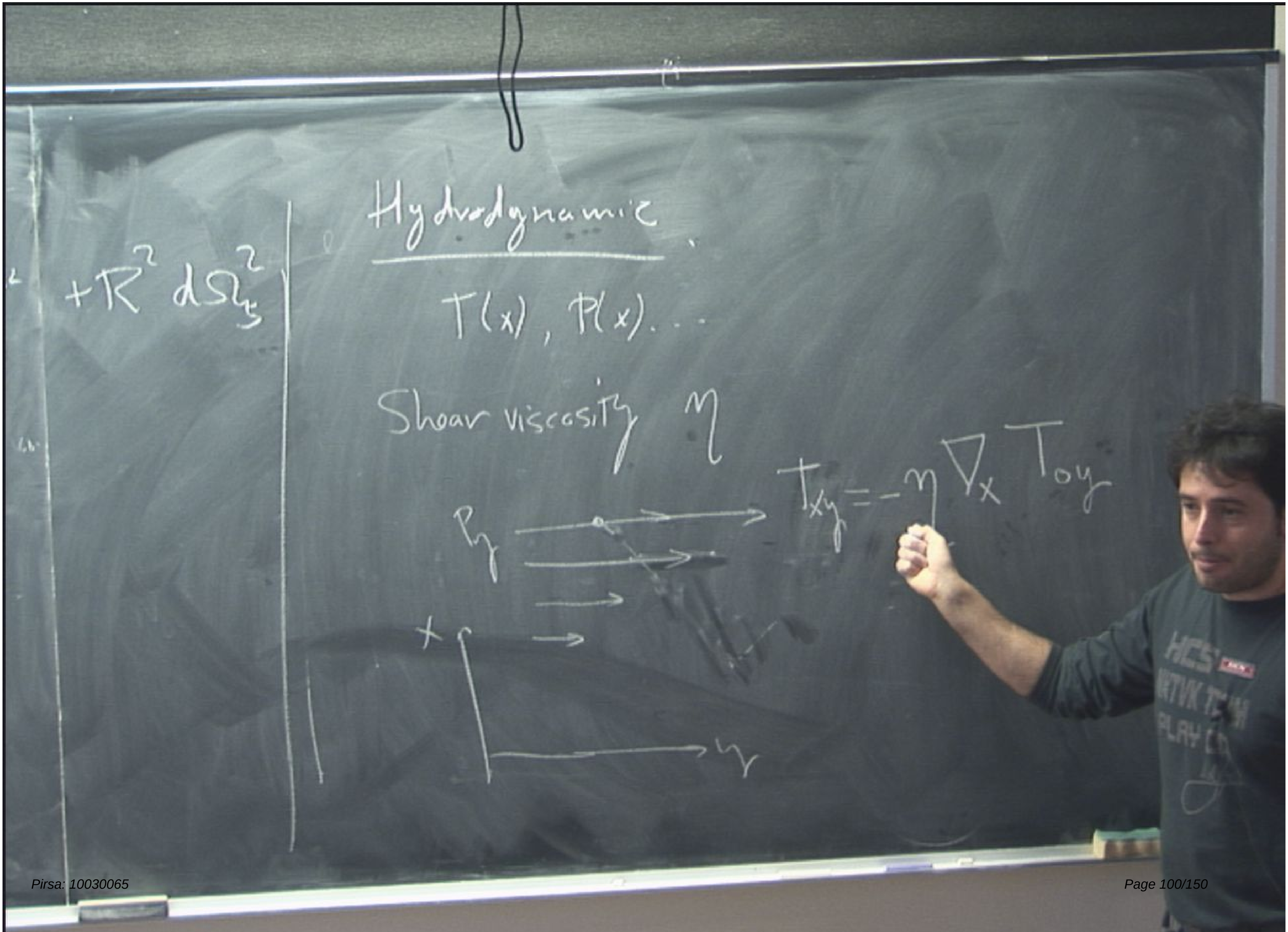

$+R^2 d\Omega_5^2$
Hydrodynamic
$T(x)$, $P(x)$...
Shear viscosity η
P_y
v_y


$+R^2 d\Omega_5^2$
Hydrodynamic
T(x), P(x)...
Shear viscosity η
$\nabla_x T$
P_y
x
y


Hydrodynamic
+R² dΩ₅²
T(x), P(x)...
Shear viscosity η
P_y
x
v_y


$+R^2 d\Omega_5^2$
Hydrodynamic
$T(x)$, $P(x)$ ...
Shear viscosity η
P_y
T_{xy}
$\nabla_x T_{0y}$
x
y


$+R^2 d\Omega_5^2$
Hydrodynamic
$T(x), P(x) \dots$
Shear viscosity η
T_{oy}
P_y
x
y


+R^2 dΩ_5^2
Hydrodynamic
T(x), P(x)...
Shear viscosity η
T_xy = -η ∇_x T_0y
P_y
x
y

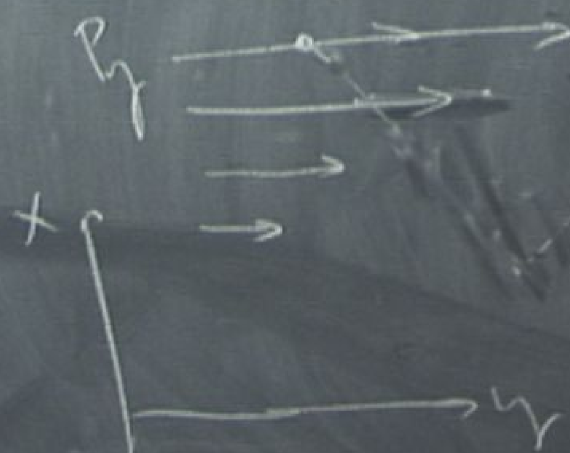
$+R^2\, d\Omega_5^2$

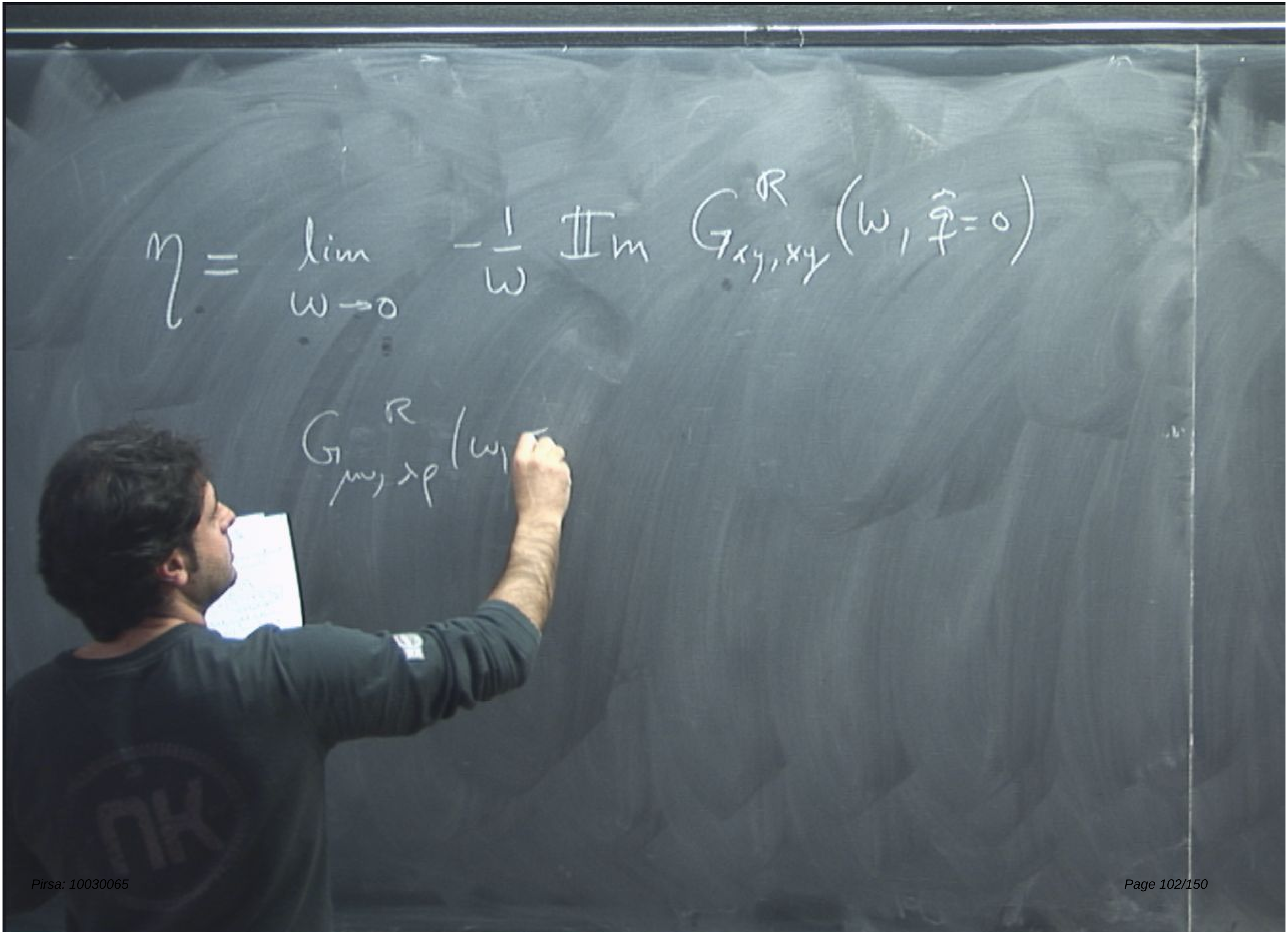
Hydrodynamic

$T(x),\ P(x) \ldots$

Shear viscosity η

$T_{xy} = -\eta \nabla_x T_{0y}$

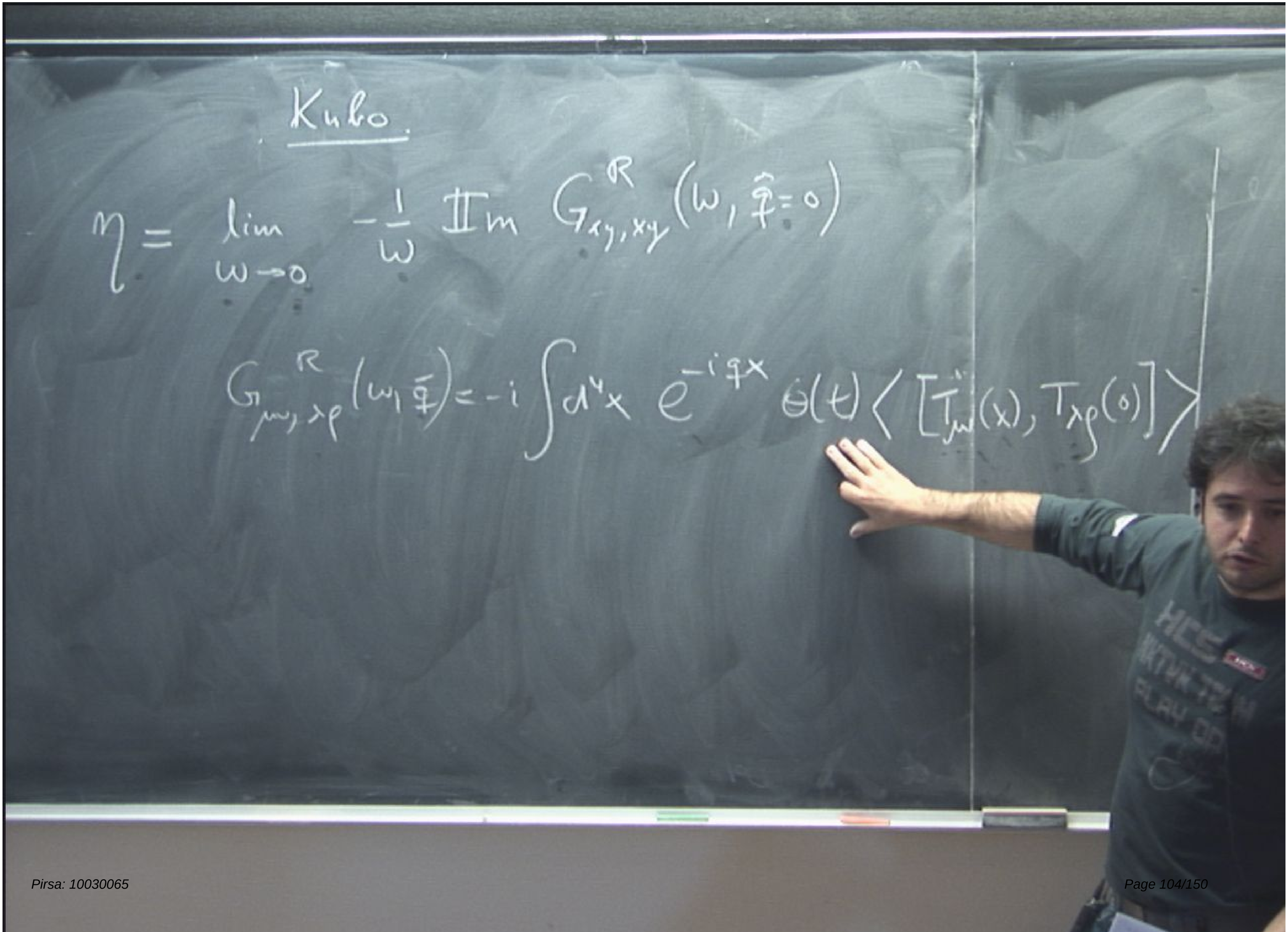




$\eta = \lim_{\omega \to 0} -\frac{1}{\omega} \mathrm{Im}\, G^{R}_{xy,xy}(\omega, \vec{q}=0)$
$G^{R}_{\mu\nu,\lambda\rho}(\omega,$

$$\eta = \lim_{\omega \to 0} -\frac{1}{\omega} \, \mathrm{Im} \, G^{R}_{xy,xy}(\omega, \vec{q}=0)$$

$$G^{R}_{\mu\nu,\lambda\rho}(\omega, \vec{q}) = -i \int d^4x \, e^{-iqx} \, \theta(t) \left\langle \left[T_{\mu\nu}(x), T_{\lambda\rho}(0) \right] \right\rangle$$


Kubo
$\eta = \lim_{\omega \to 0} -\frac{1}{\omega} \mathrm{Im}\, G^{R}_{xy,xy}(\omega, \vec{q}=0)$
$G^{R}_{\mu\nu,\lambda\rho}(\omega, \vec{q}) = -i \int d^4x\, e^{-iqx}\, \theta(t) \langle [T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$

Kubo

$$\eta = \lim_{\omega \to 0} -\frac{1}{\omega}\, \mathrm{Im}\, G^{R}_{xy,xy}(\omega, \vec{q}=0)$$

$$G^{R}_{\mu\nu,\lambda\rho}(\omega, \vec{q}) = -i \int d^4x\, e^{-iqx}\, \theta(t) \langle [T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$$

Kubo

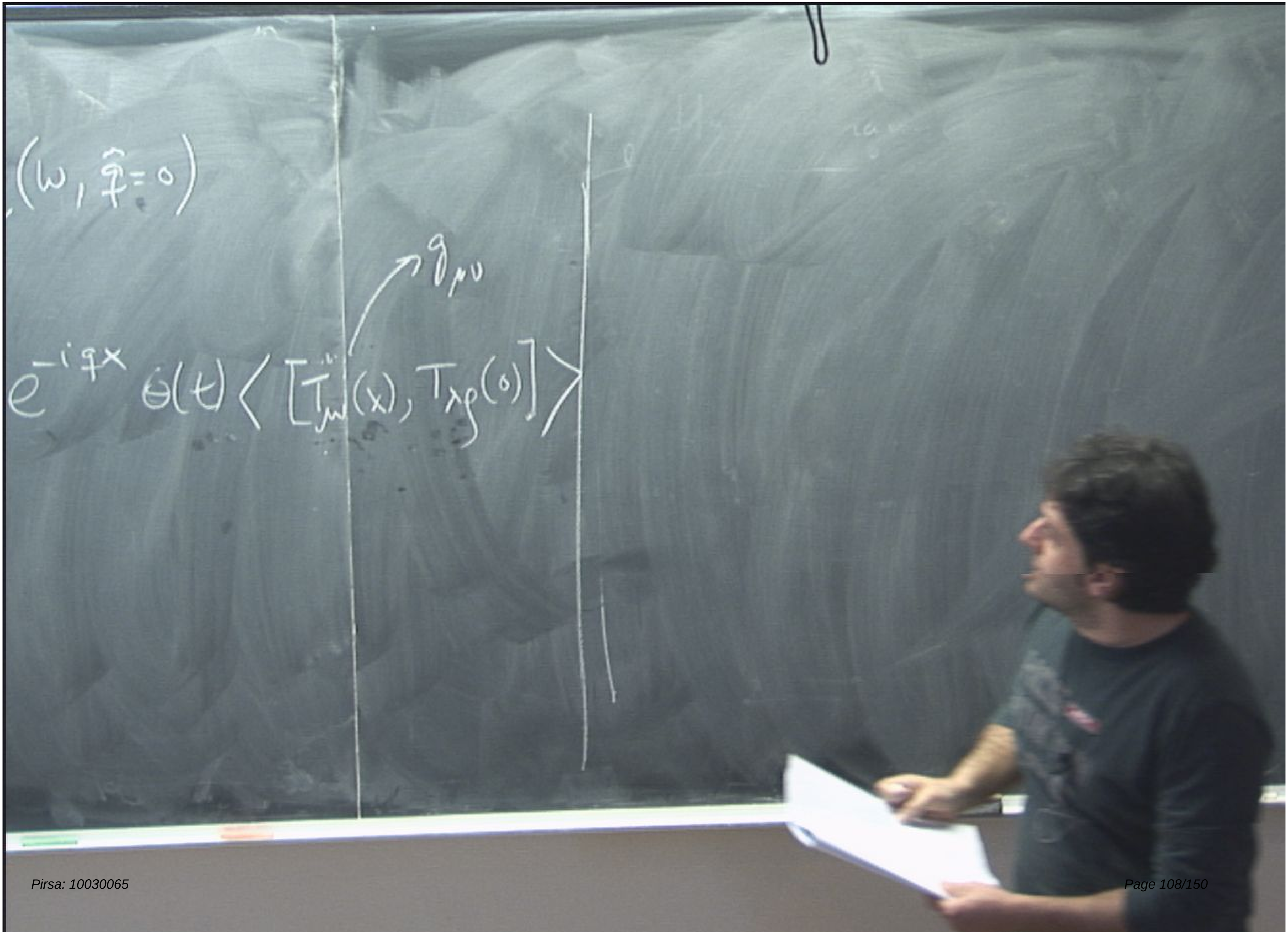
$$\eta = \lim_{\omega \to 0} -\frac{1}{\omega} \, \mathrm{Im} \, G^{R}_{xy,xy}(\omega, \vec{q}=0)$$

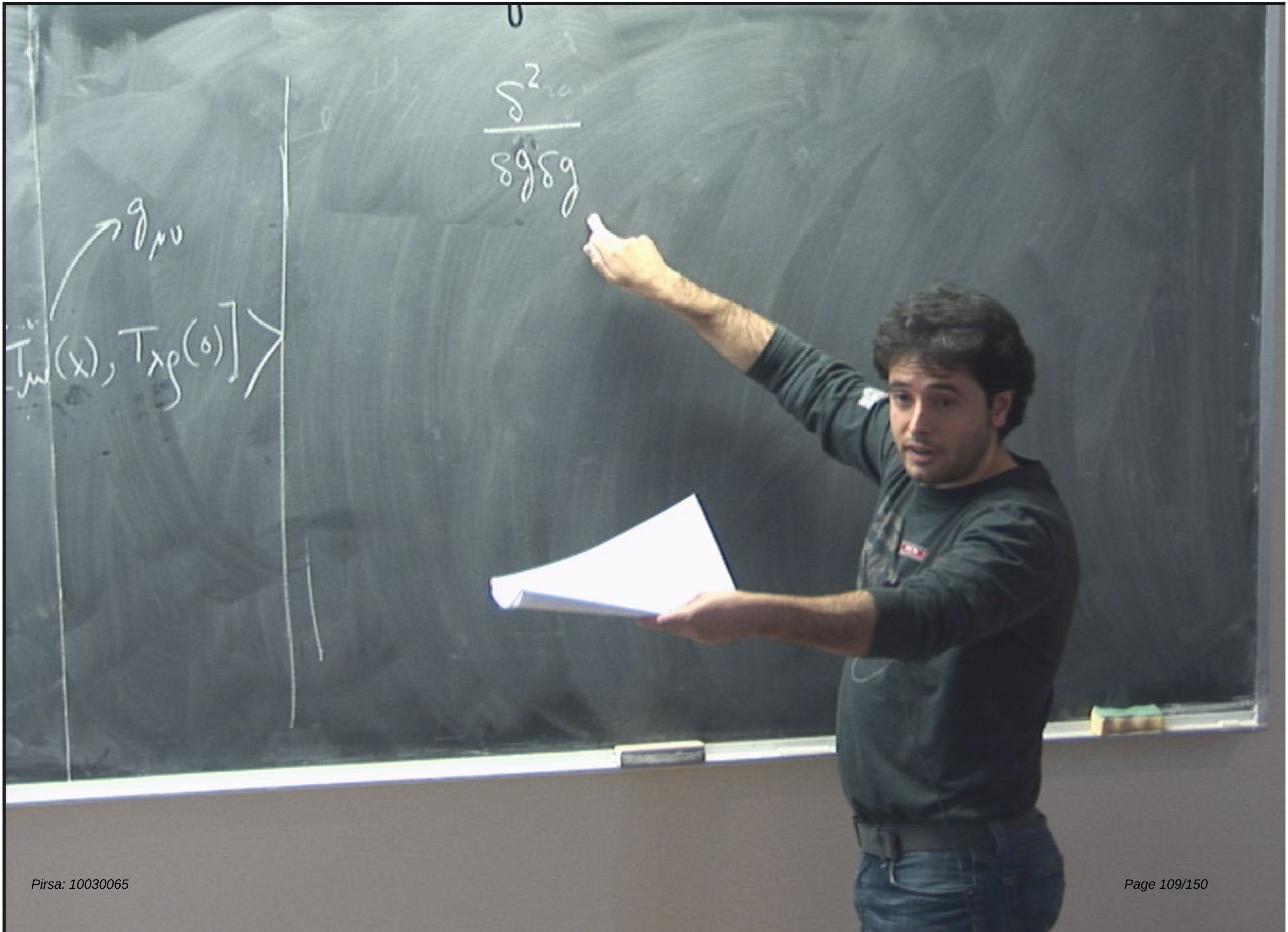
$$G^{R}_{\mu\nu,\lambda\rho}(\omega, \vec{q}) = -i \int d^4x \, e^{-iqx} \, \theta(t) \langle [T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$$

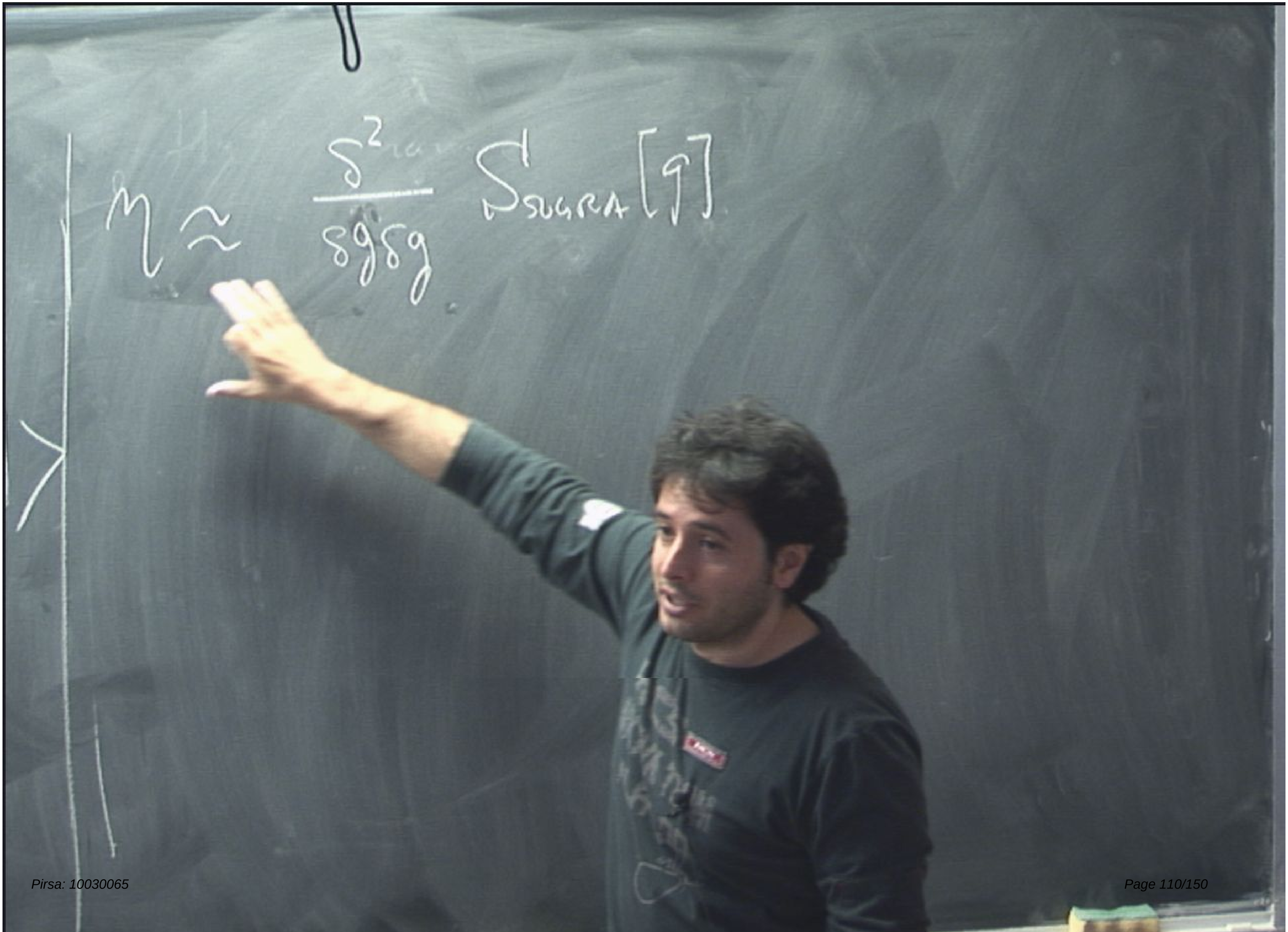
Kubo

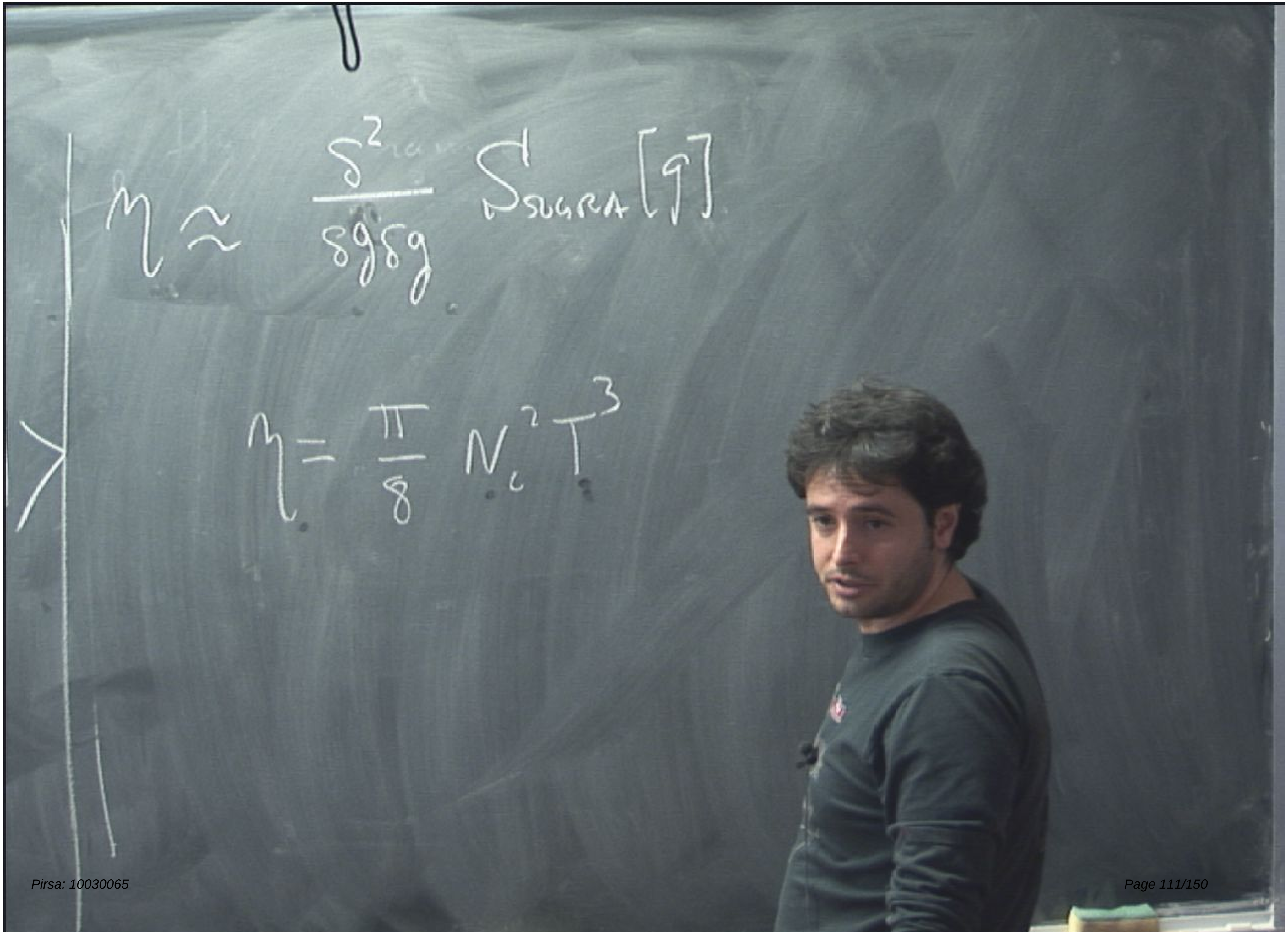
$$\eta = \lim_{\omega \to 0} -\frac{1}{\omega} \operatorname{Im} G^{R}_{xy,xy}(\omega, \vec{q}=0)$$

$$G^{R}_{\mu\nu,\lambda\rho}(\omega, \vec{q}) = -i \int d^4x \, e^{-iqx} \, \theta(t) \langle [T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$$


$(\omega, \hat{q} = 0)$
$g_{\mu\nu}$
$e^{-iqx}\,\theta(t)\,\langle [T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$

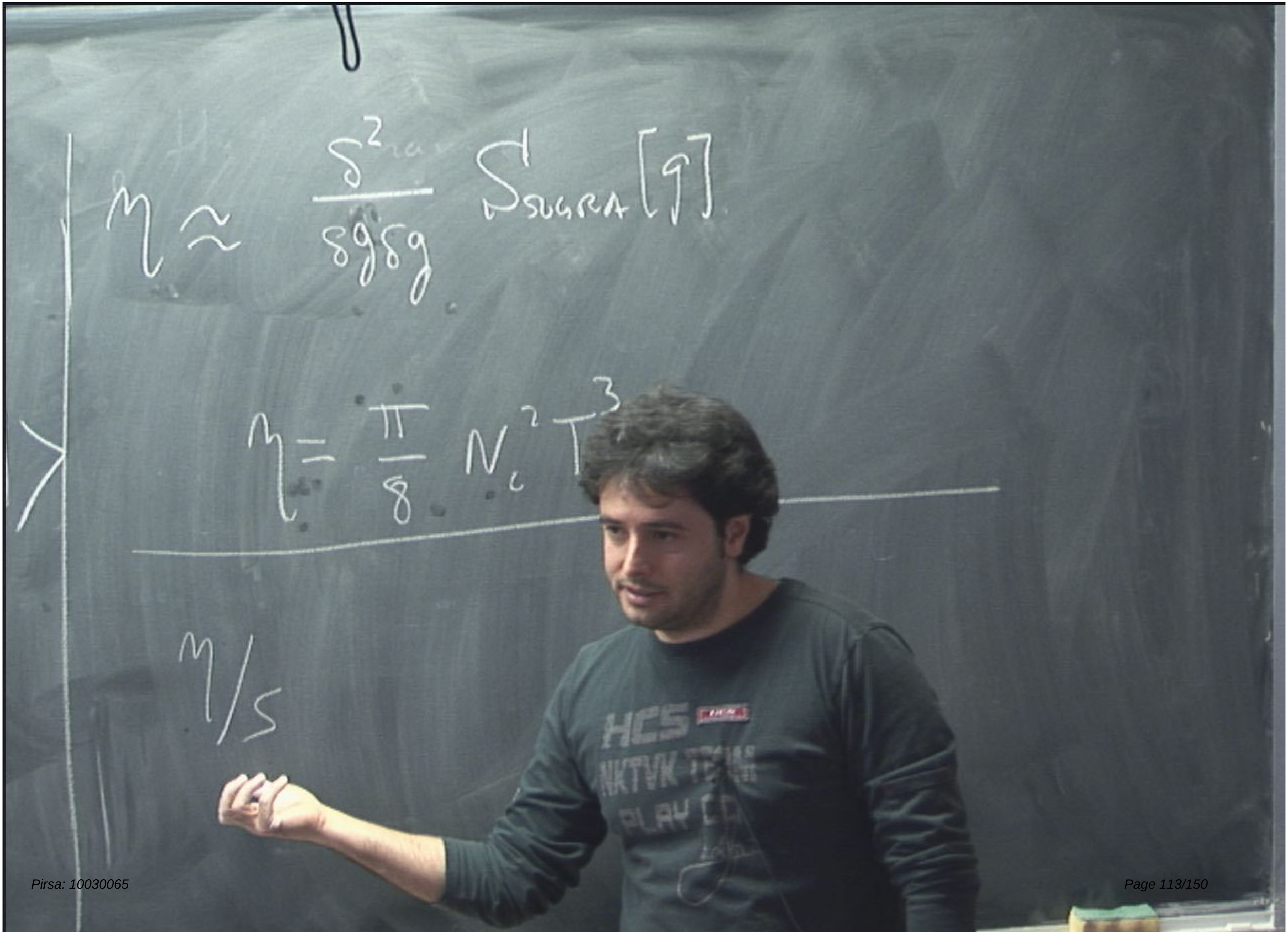

δ²/δgδg
g_μν
T_μν(x), T_λρ(0)] >

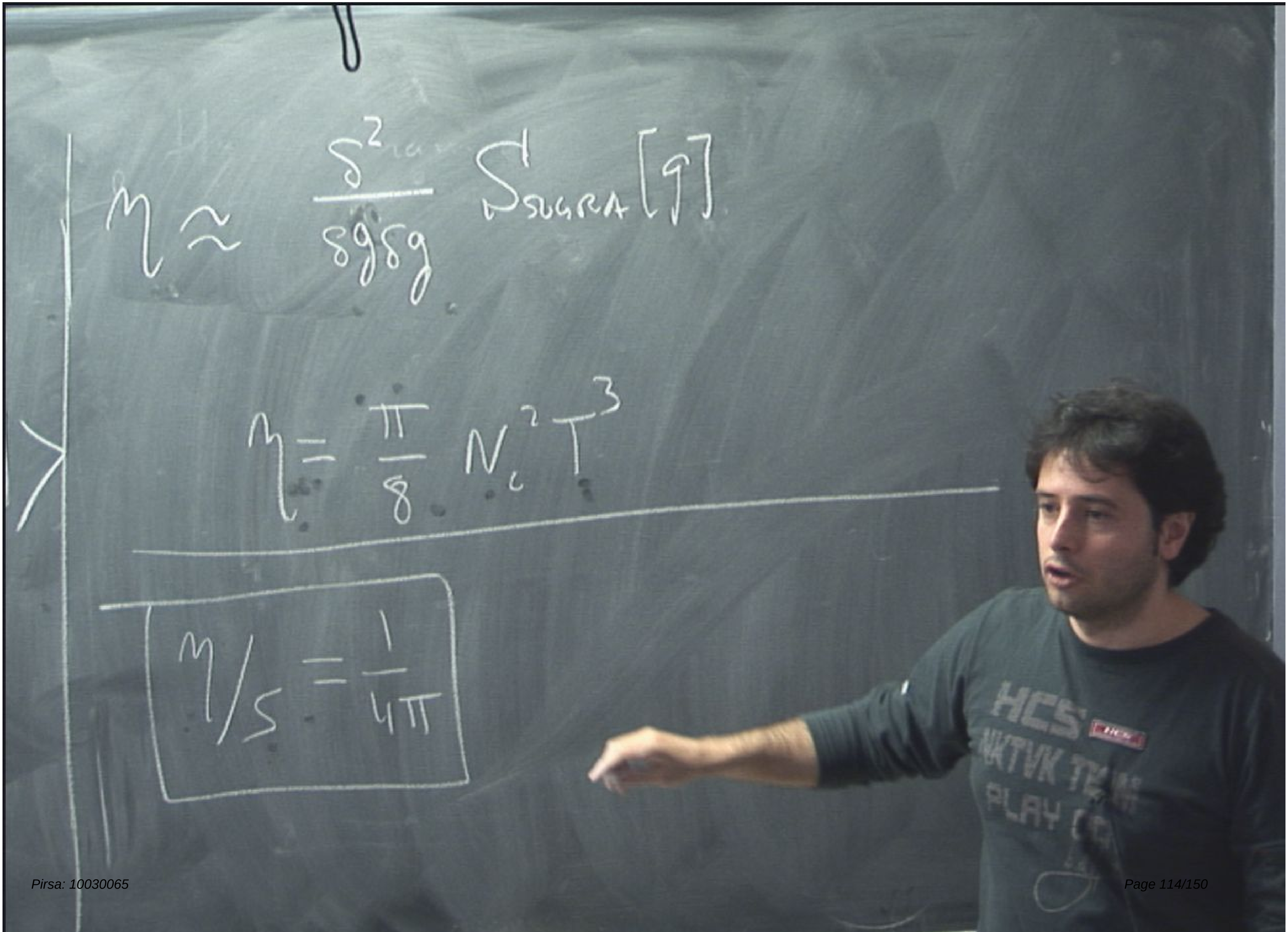

$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$

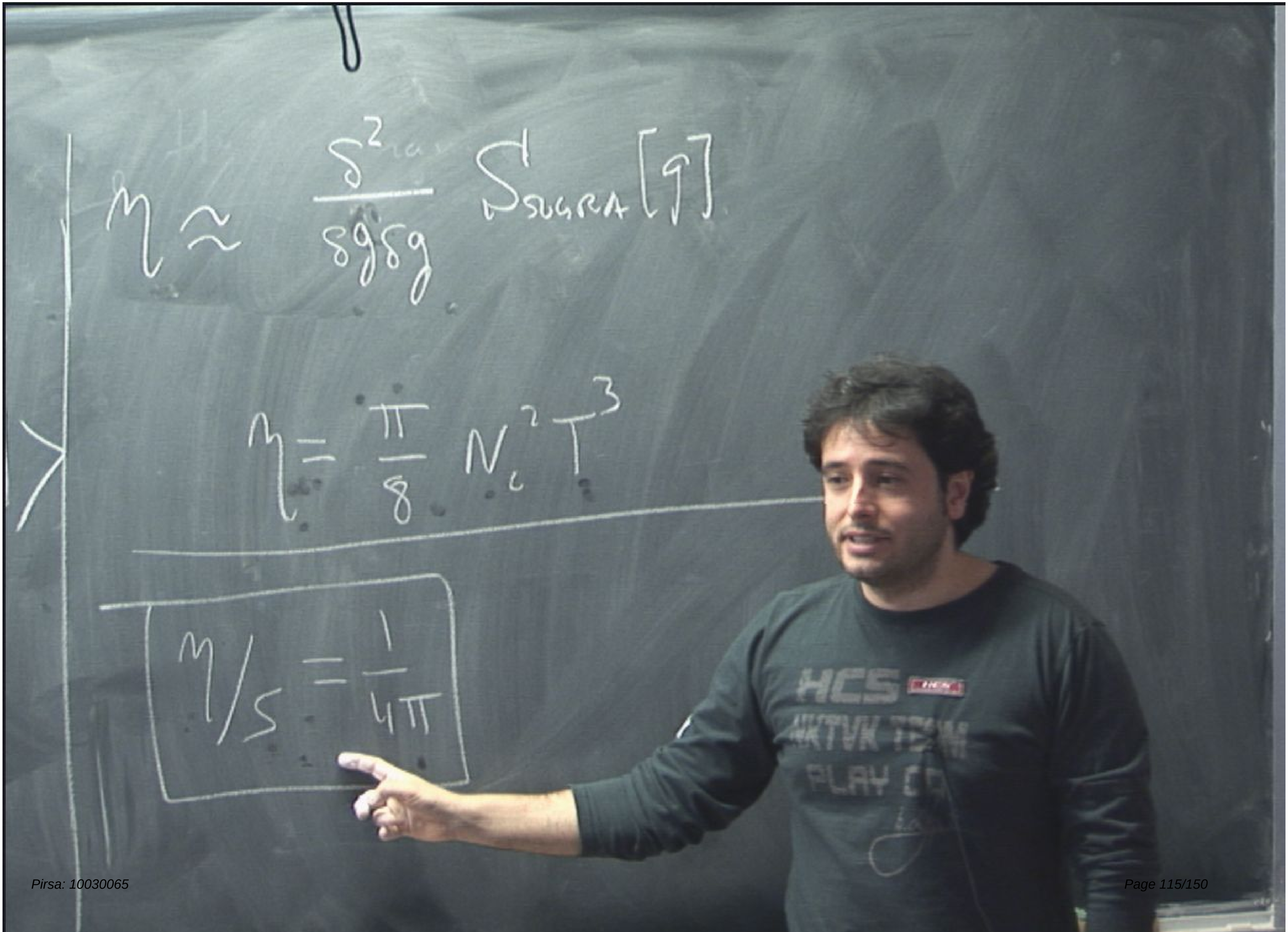

$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$
$\eta = \frac{\pi}{8} N_c^2 T^3$

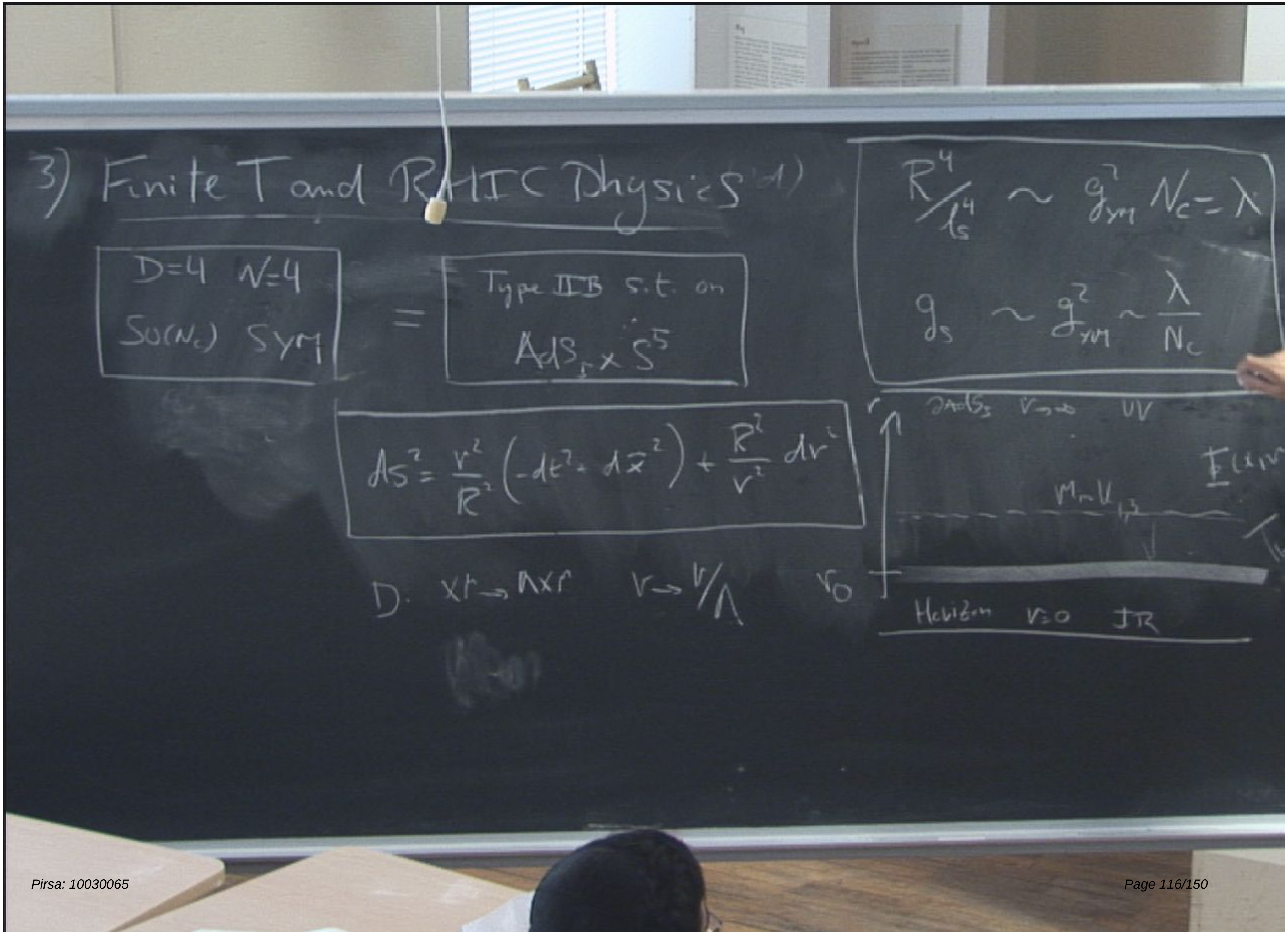
$$\eta \approx \frac{\delta^2}{\delta g\,\delta g} S_{SUGRA}[g]$$

$$\eta = \frac{\pi}{8} N_c^2 T^3$$


$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$
$\eta = \frac{\pi}{8} N_c^2 T^3$
η / s


$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$
$\eta = \frac{\pi}{8} N_c^2 T^3$
$\boxed{\eta/s = \frac{1}{4\pi}}$
HCS


$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$
$\eta = \frac{\pi}{8} N_c^2 T^3$
$\boxed{\eta/s = \frac{1}{4\pi}}$
HCS


3) Finite T and RHIC Physics
D=4 N=4
SU(N_c) SYM
=
Type IIB s.t. on
AdS_5 x S^5
R^4/l_s^4 ~ g_YM^2 N_c = λ
g_s ~ g_YM^2 ~ λ/N_c
ds^2 = r^2/R^2 (-dt^2 + dx^2) + R^2/r^2 dr^2
D. x^μ → Λx^μ   r → r/Λ
r_0
∂AdS_5   r → ∞   UV
Horizon   r=0   IR

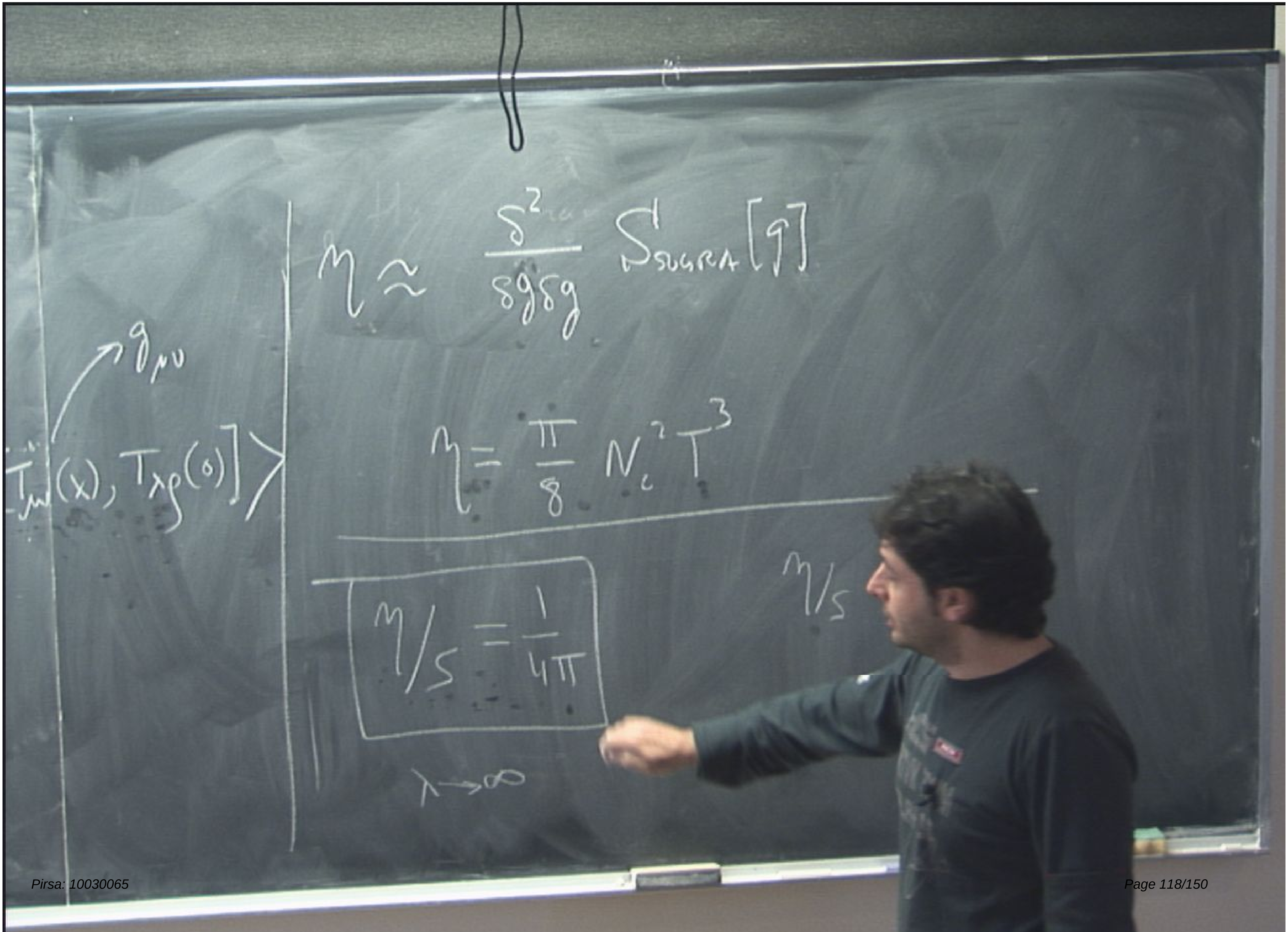
$$\eta \simeq \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$$

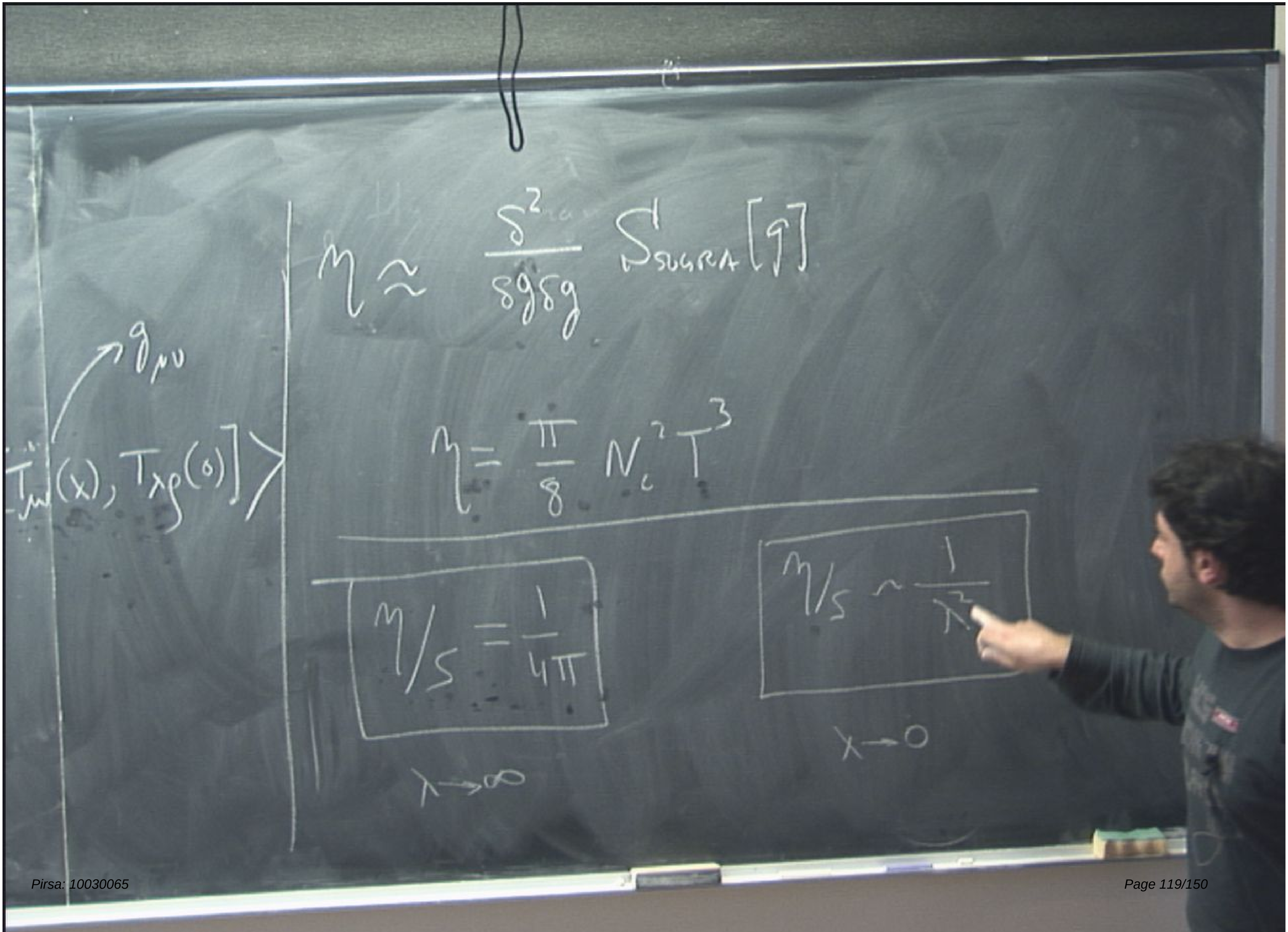
$\nearrow g_{\mu\nu}$

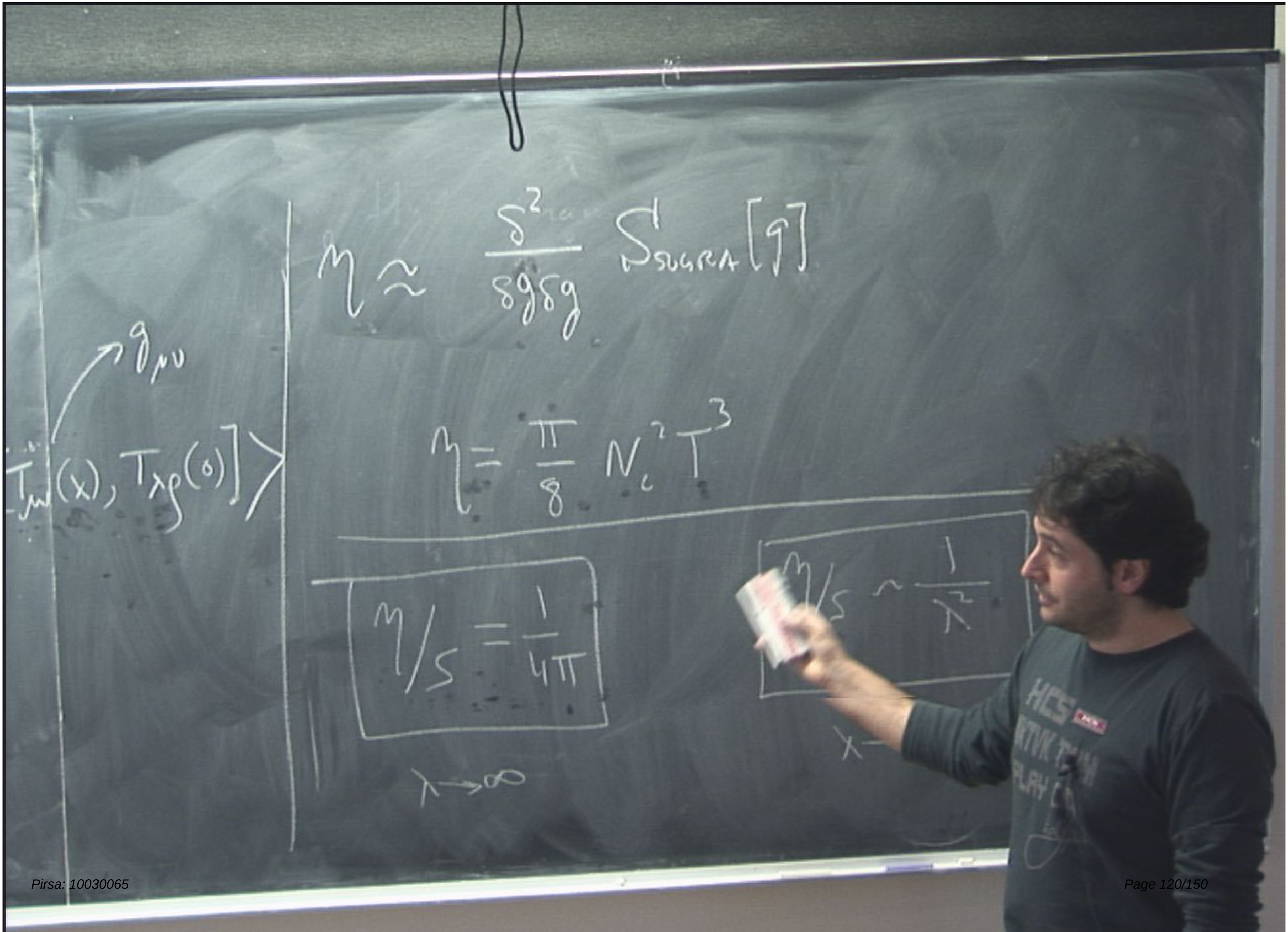
$T_{\mu\nu}(x), T_{\lambda\rho}(0)]\rangle$

$$\eta = \frac{\pi}{8} N_c^2 T^3$$

$$\boxed{\eta/s = \frac{1}{4\pi}}$$


η ≈ δ²/δgδg S_SUGRA[g]
g_μν
T_μν(x), T_λρ(0)] ⟩
η = π/8 N_c² T³
η/s = 1/4π
η/s
λ → ∞


$\eta \simeq \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$
$g_{\mu\nu}$
$T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$
$\eta = \frac{\pi}{8} N_c^2 T^3$
$\boxed{\eta/s = \frac{1}{4\pi}}$
$\lambda \to \infty$
$\boxed{\eta/s \sim \frac{1}{\lambda^2}}$
$\lambda \to 0$


$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$
$g_{\mu\nu}$
$T_{\mu\nu}(x), T_{\lambda\rho}(0)] \rangle$
$\eta = \frac{\pi}{8} N_c^2 T^3$
$\eta/s = \frac{1}{4\pi}$
$\lambda \to \infty$
$\eta/s \sim \frac{1}{\lambda^2}$
$\lambda \to$

$$\eta \approx \frac{\delta^2}{\delta g \delta g} S_{SUGRA}[g]$$

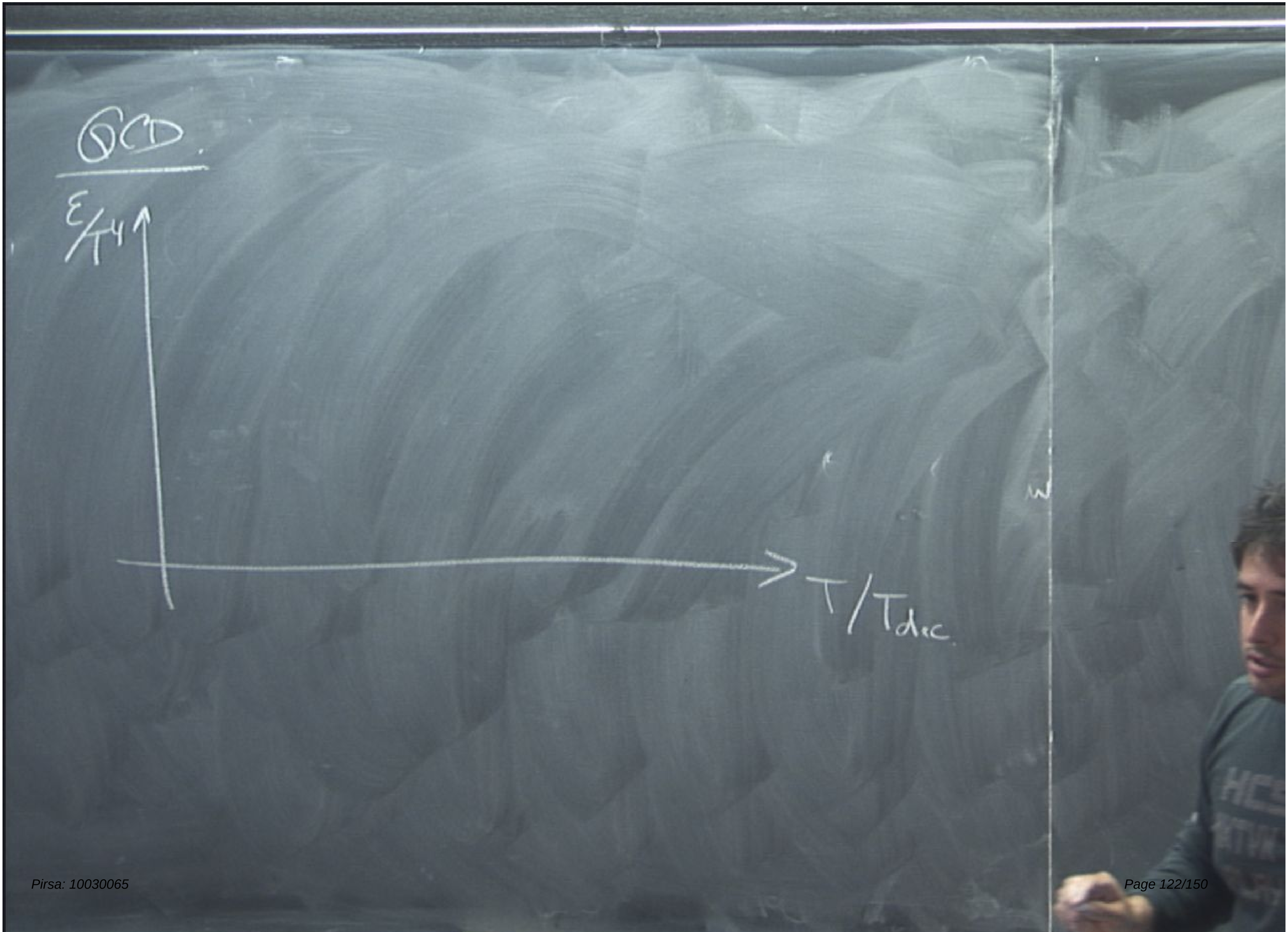
$$\eta = \frac{\pi}{8} N_c^2 T^3$$

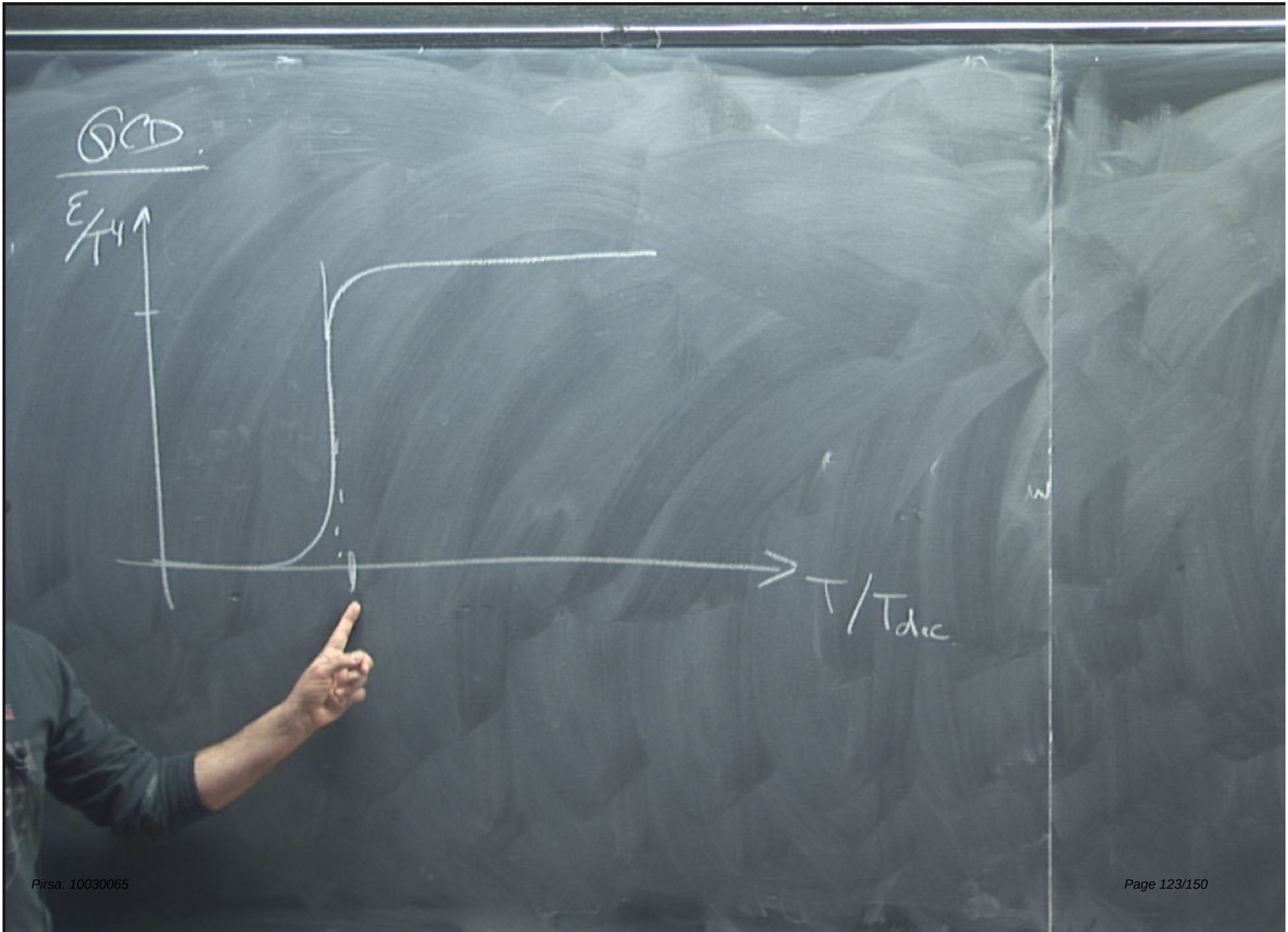
$$\boxed{\eta/s = \frac{1}{4\pi}}$$

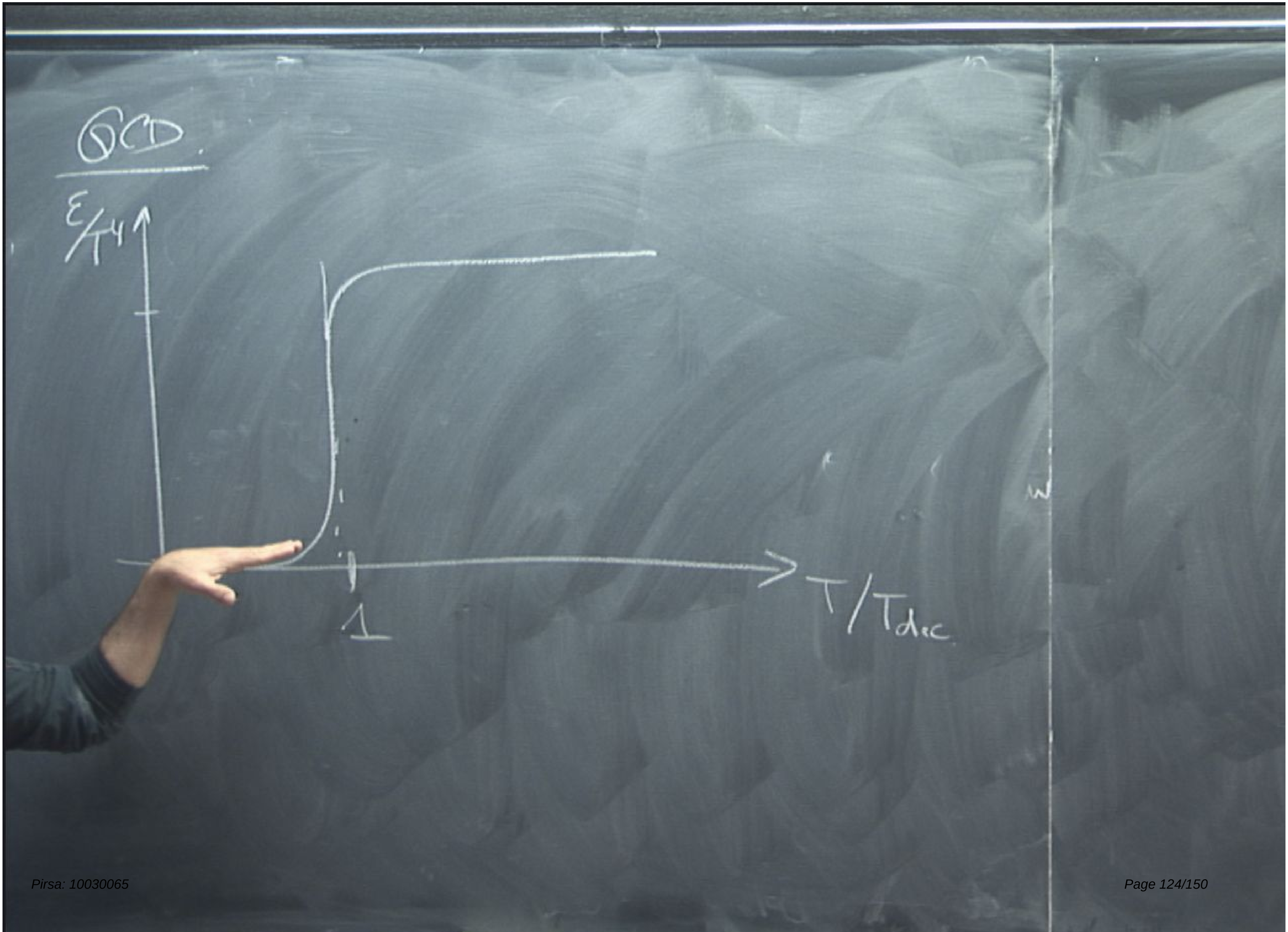
$\lambda \to \infty$

$$\boxed{\eta/s \sim \frac{1}{\lambda^2}}$$

$\lambda \to 0$


QCD.
ε/T⁴
T/Tdec

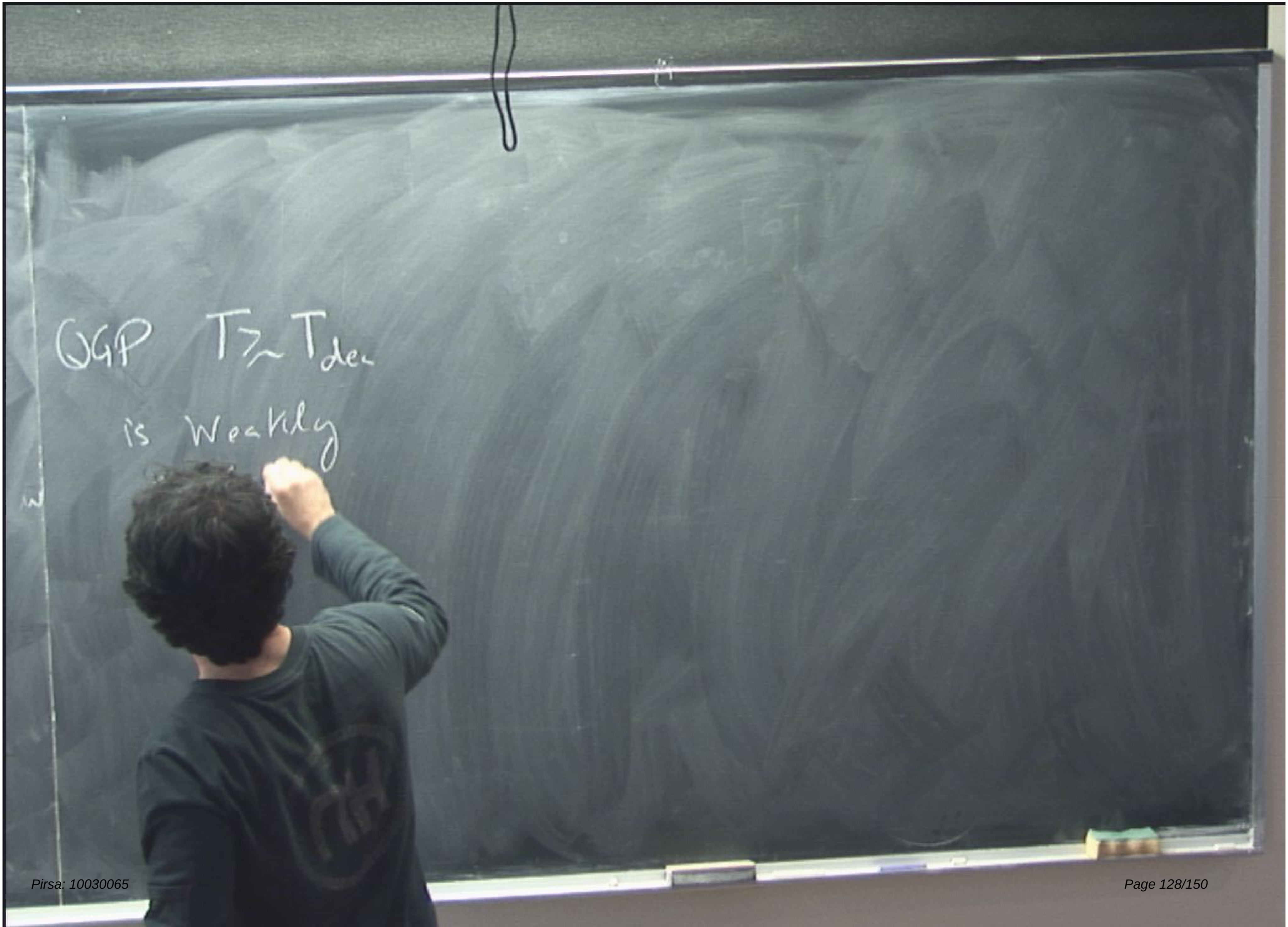

QCD
ε/T^4
T/T_dec

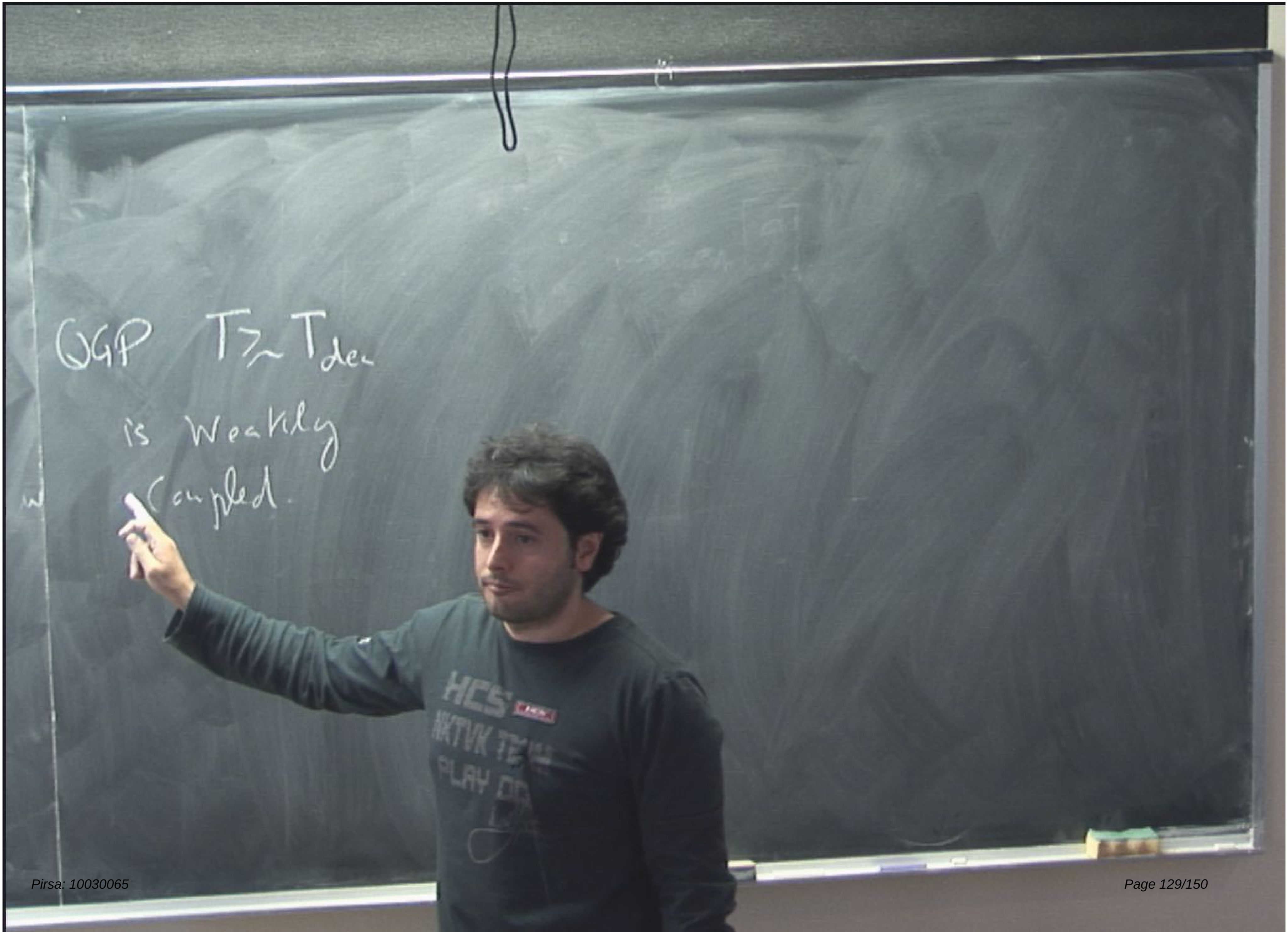

QCD
ε/T⁴
1
T/T_dec

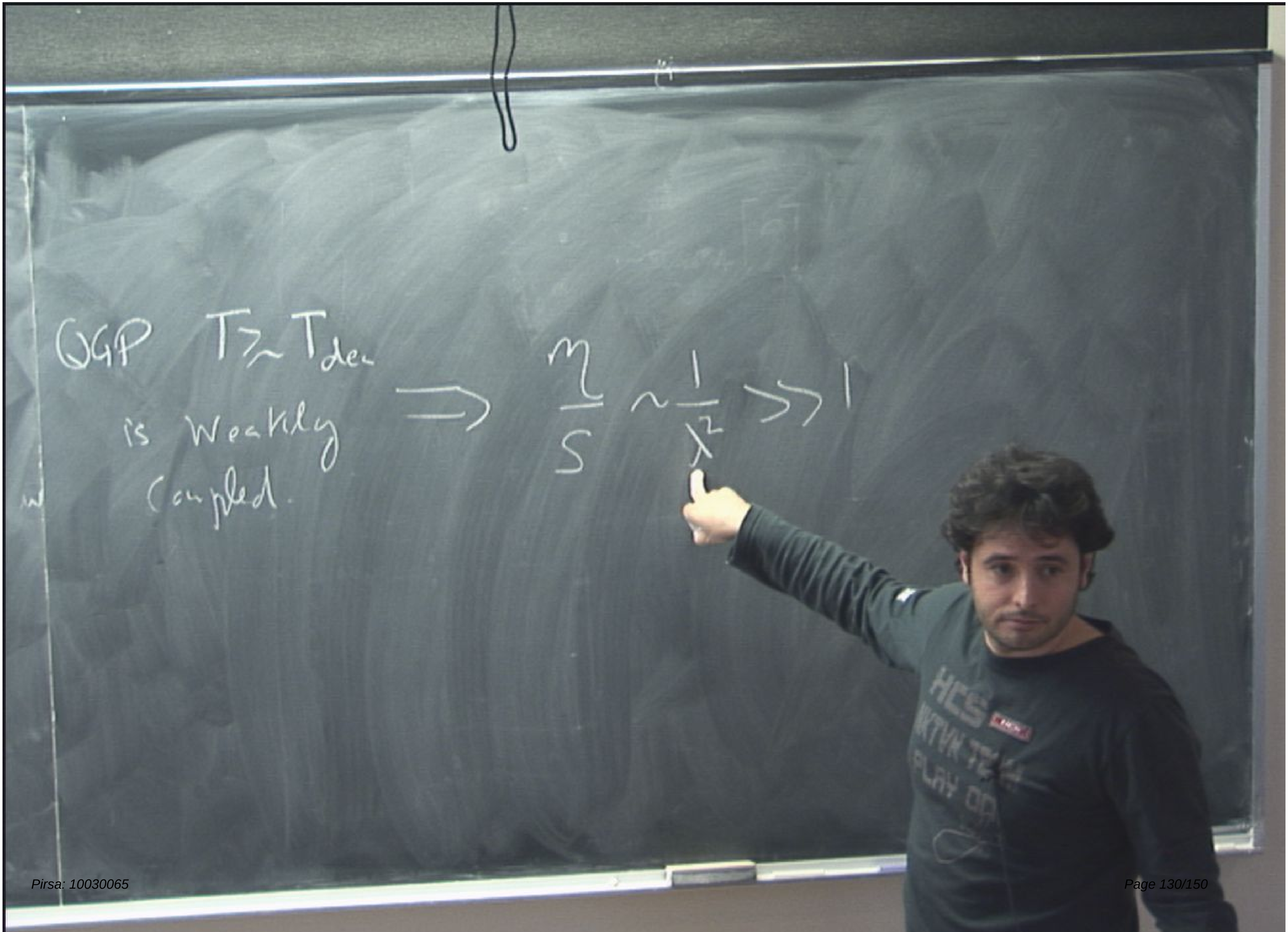
QCD.

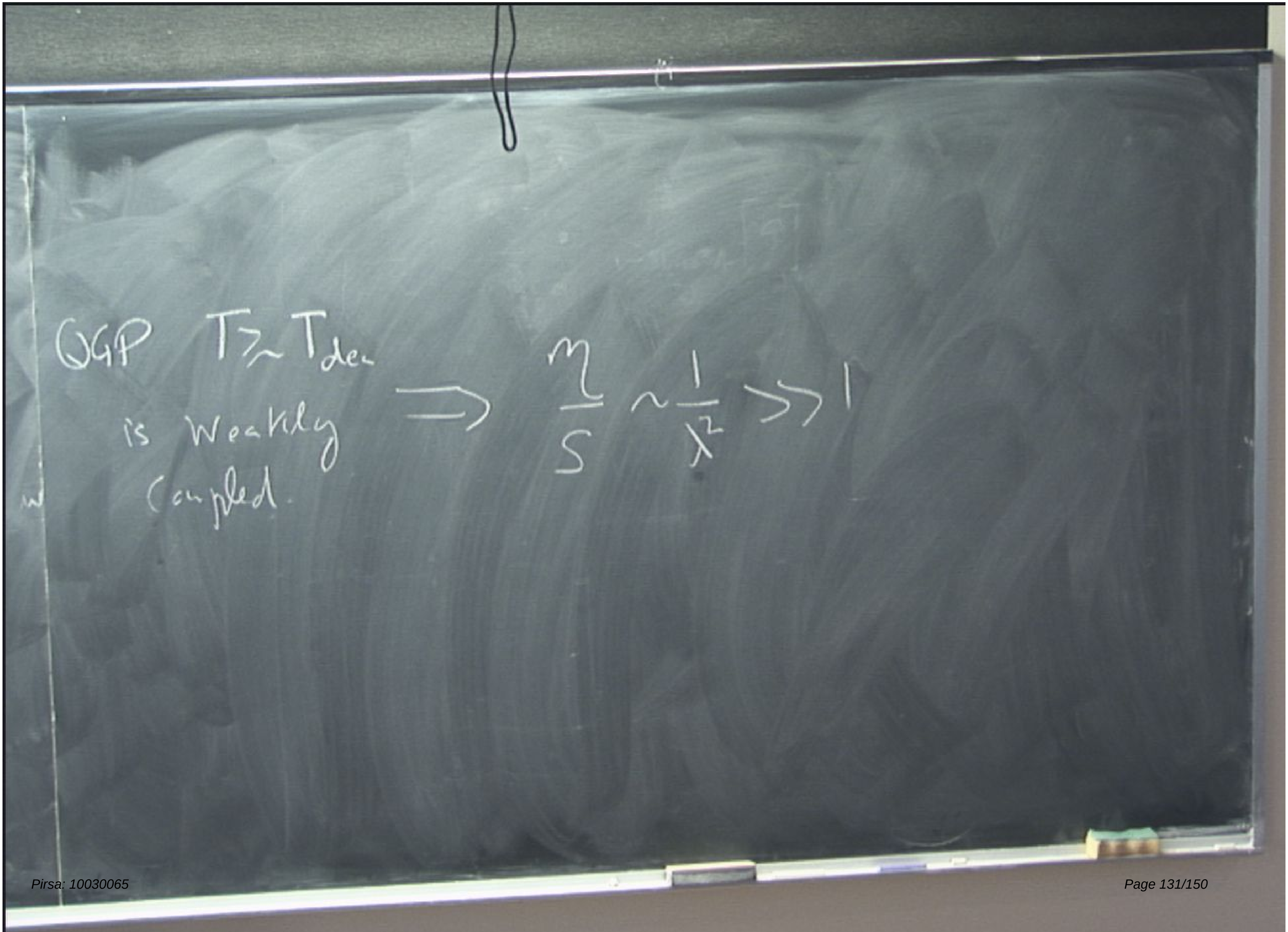
QCD.

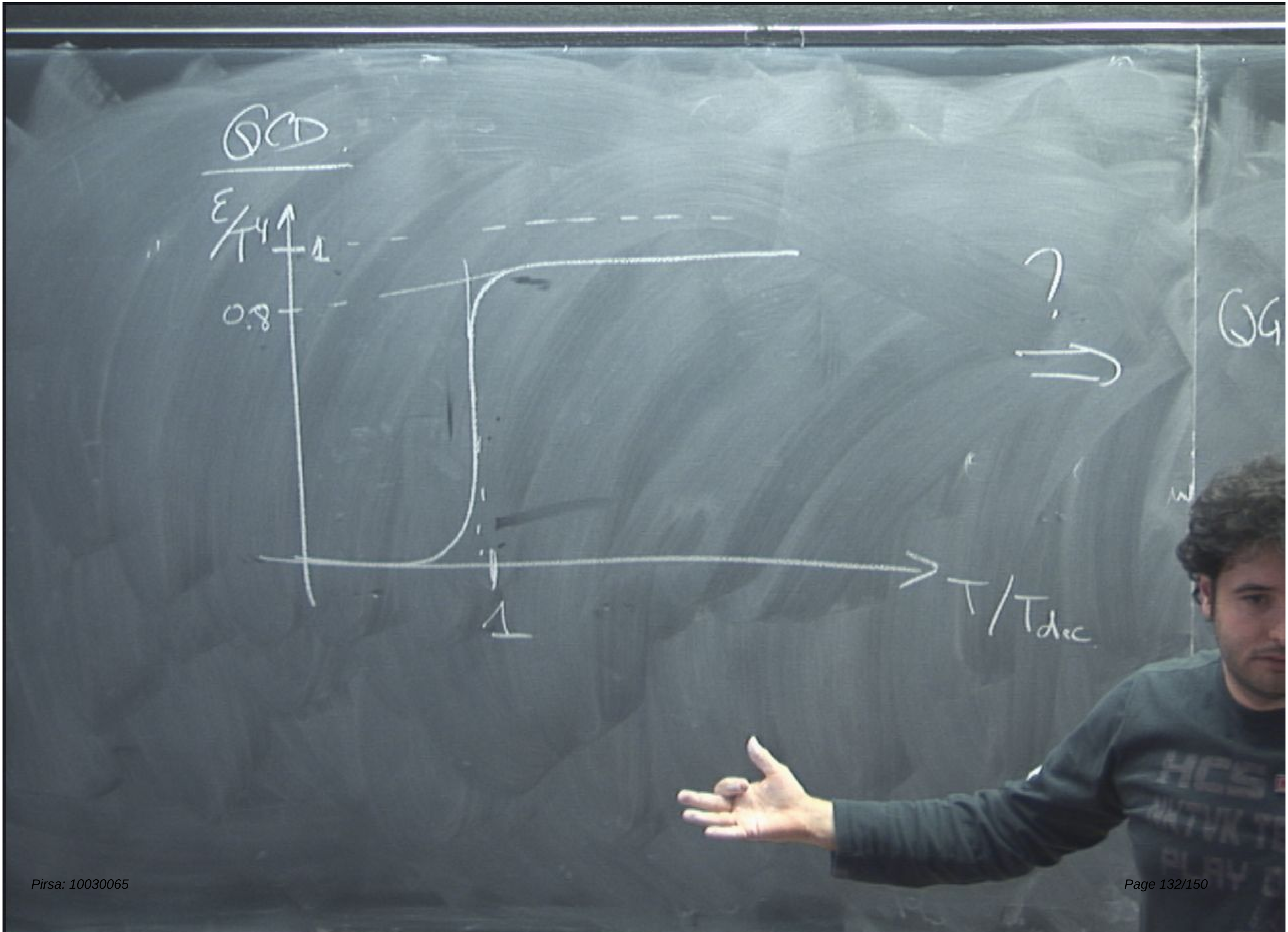
QCD.

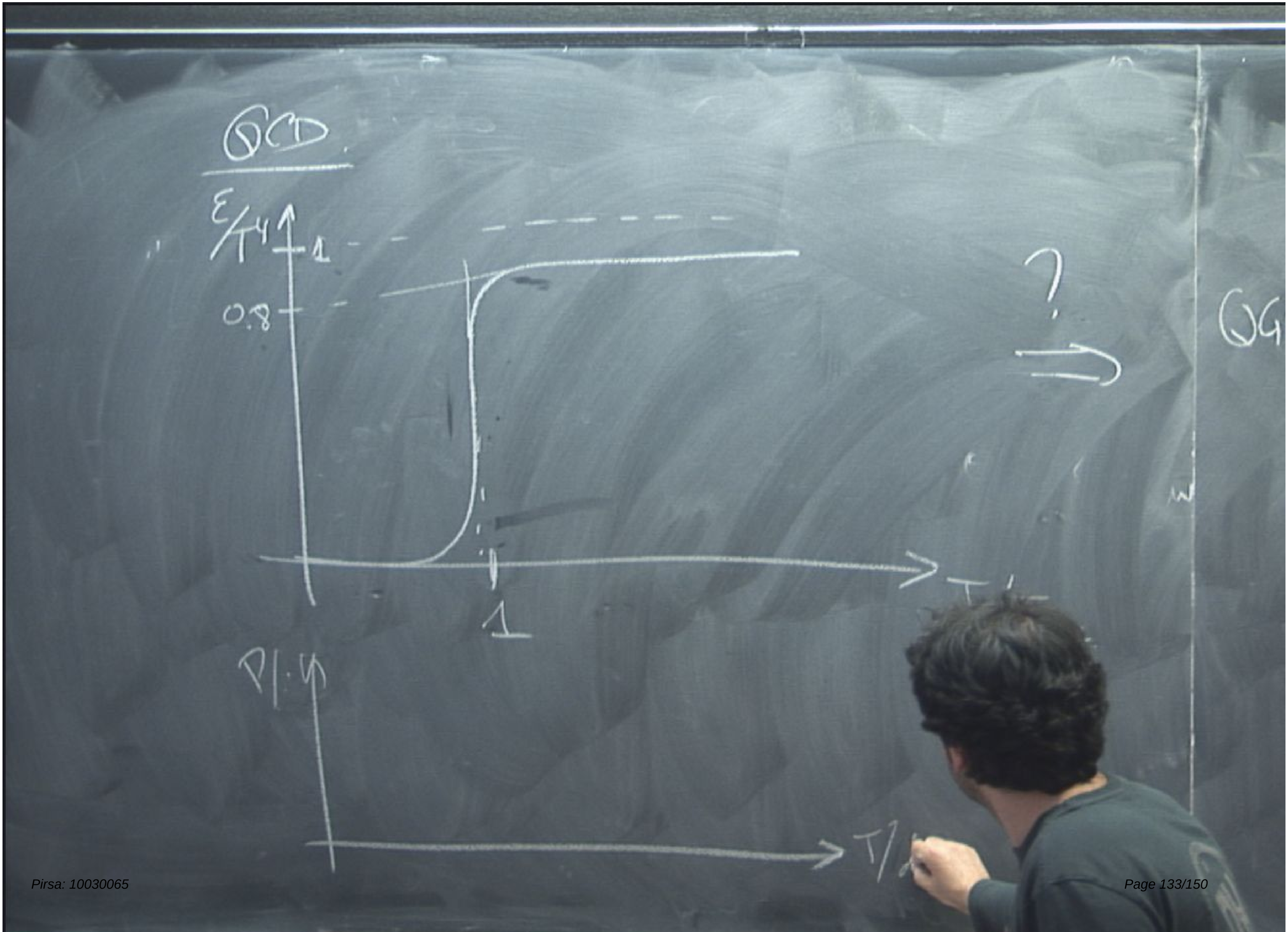

QGP T ≳ T_dec
is Weakly

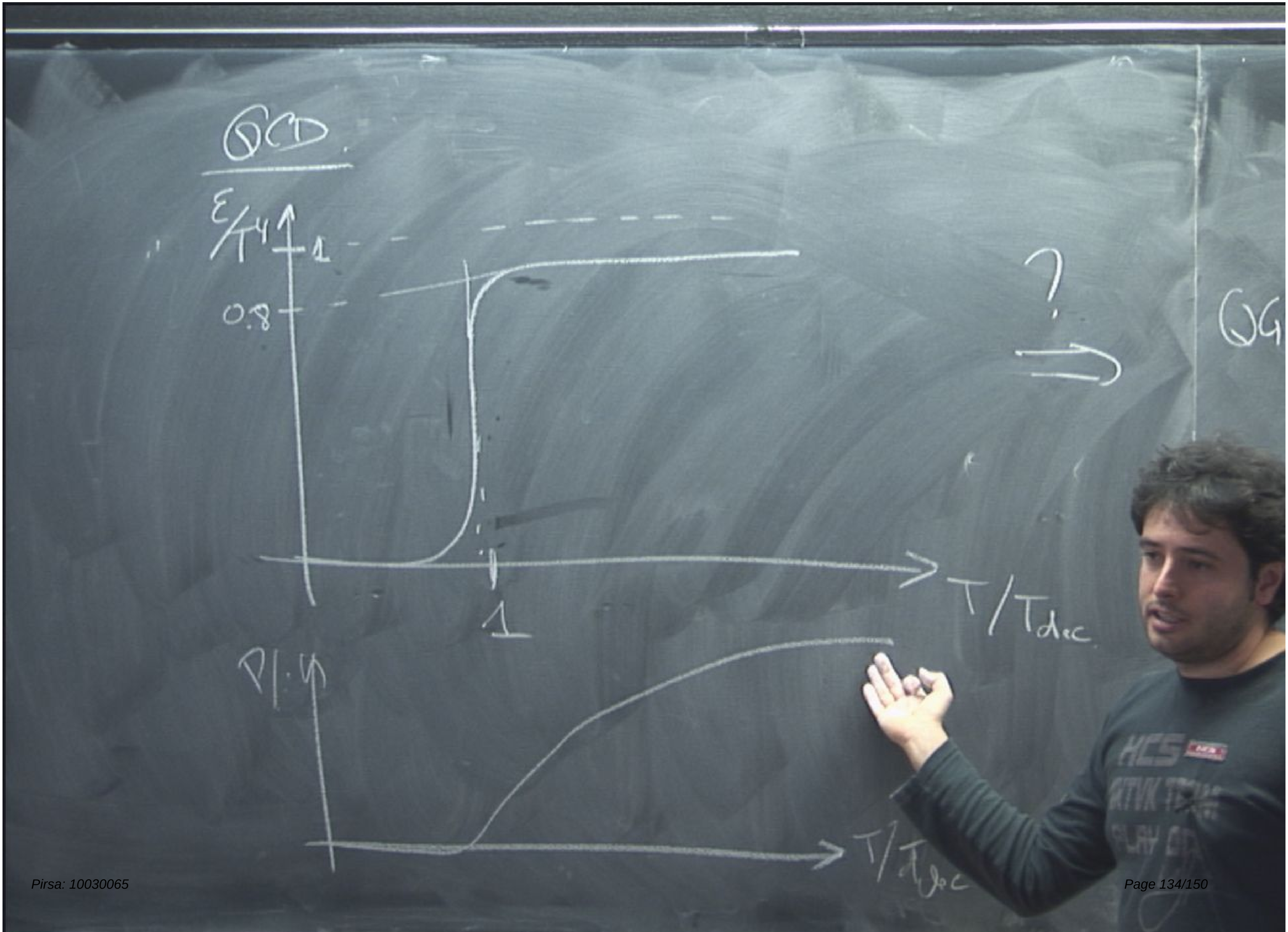

QGP $T \gtrsim T_{dec}$
is weakly
coupled.

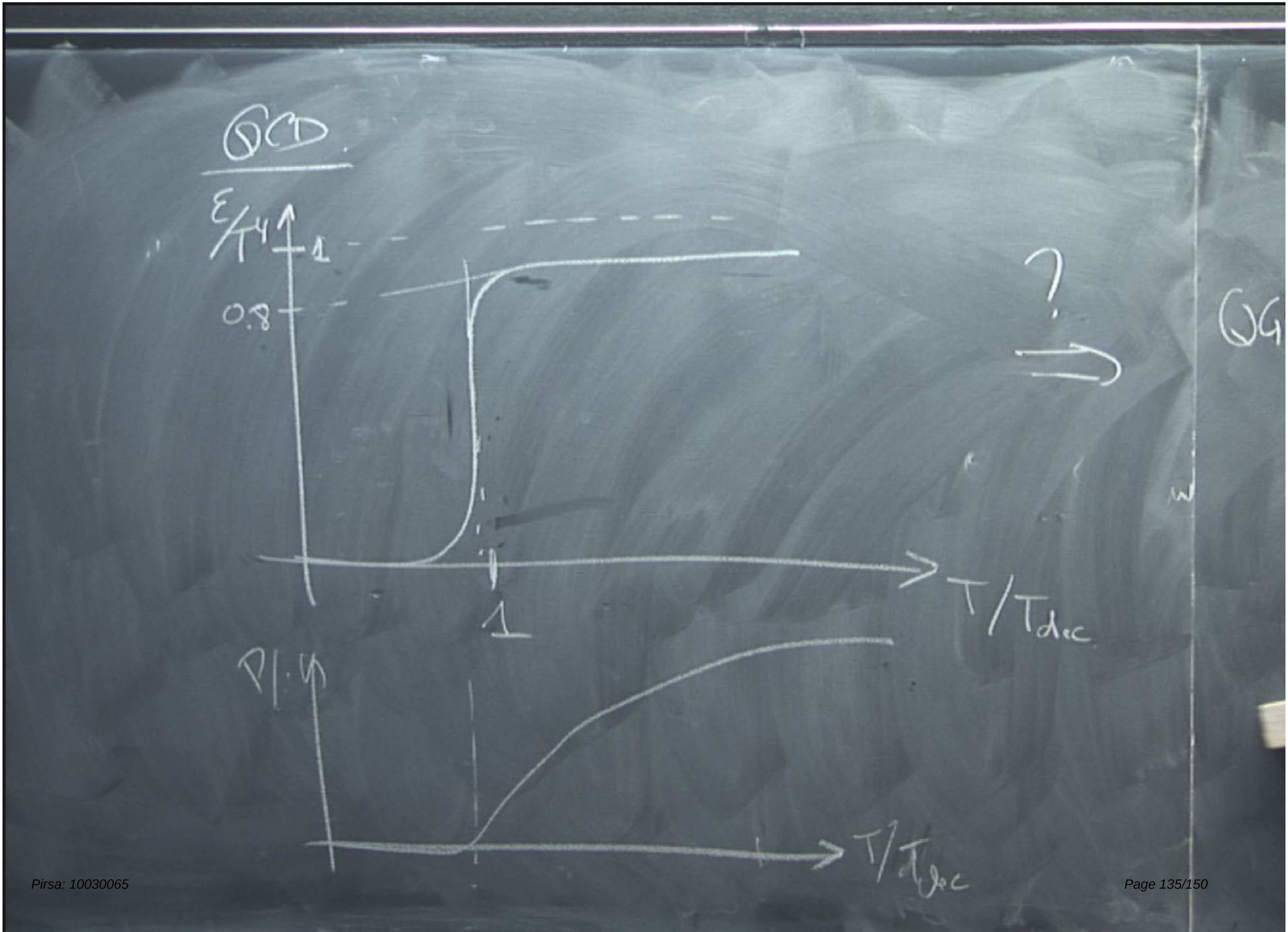

QGP $T \gtrsim T_{dec}$
is weakly
coupled.
$\Longrightarrow \frac{\eta}{s} \sim \frac{1}{\lambda^2} >> 1$


QGP $T \gtrsim T_{dec}$
is Weakly
Coupled.
$\Rightarrow \frac{\eta}{s} \sim \frac{1}{\lambda^2} \gg 1$

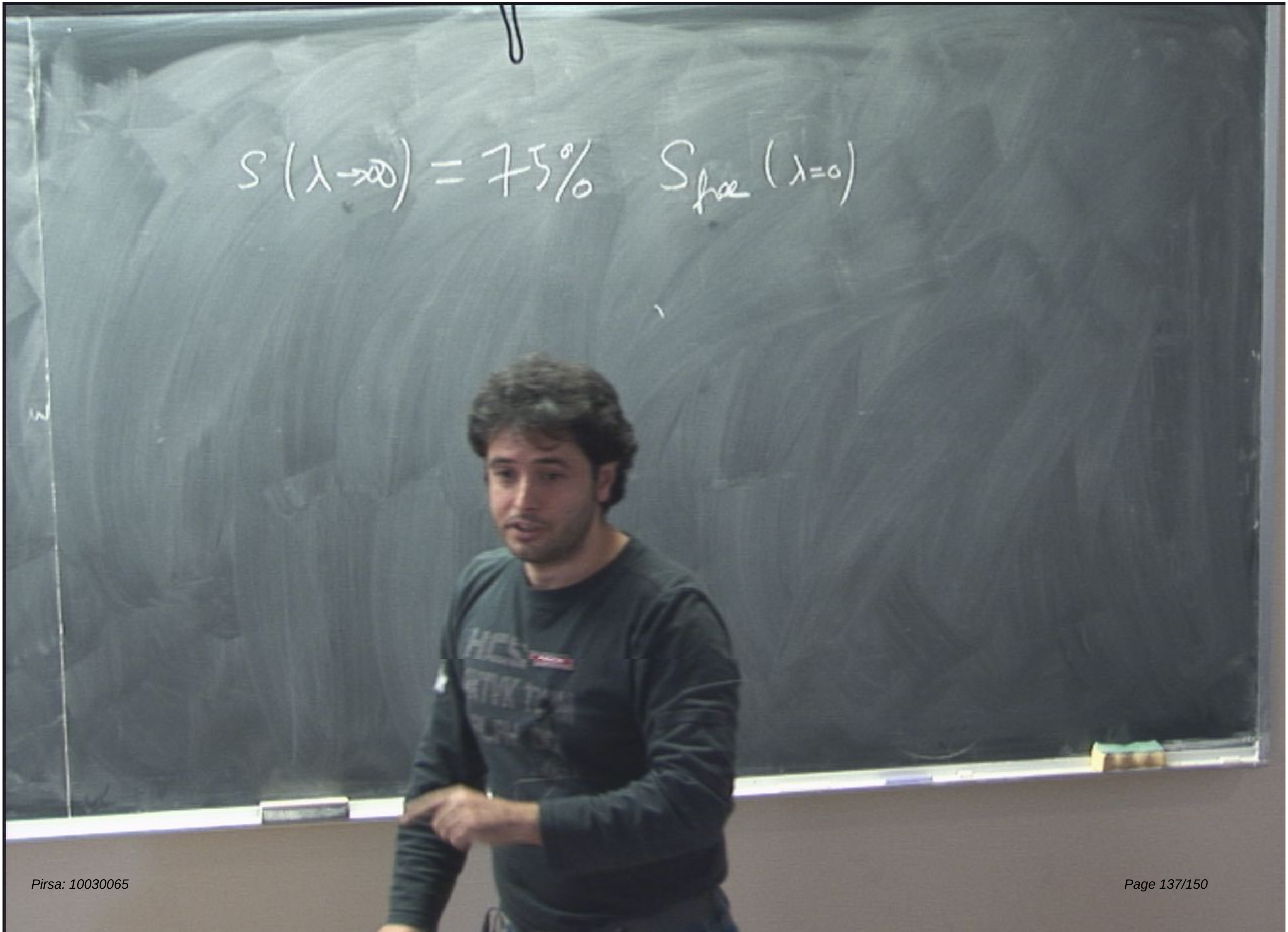

QCD
ε/T^4
1
0.8
?
1
T/T_dec

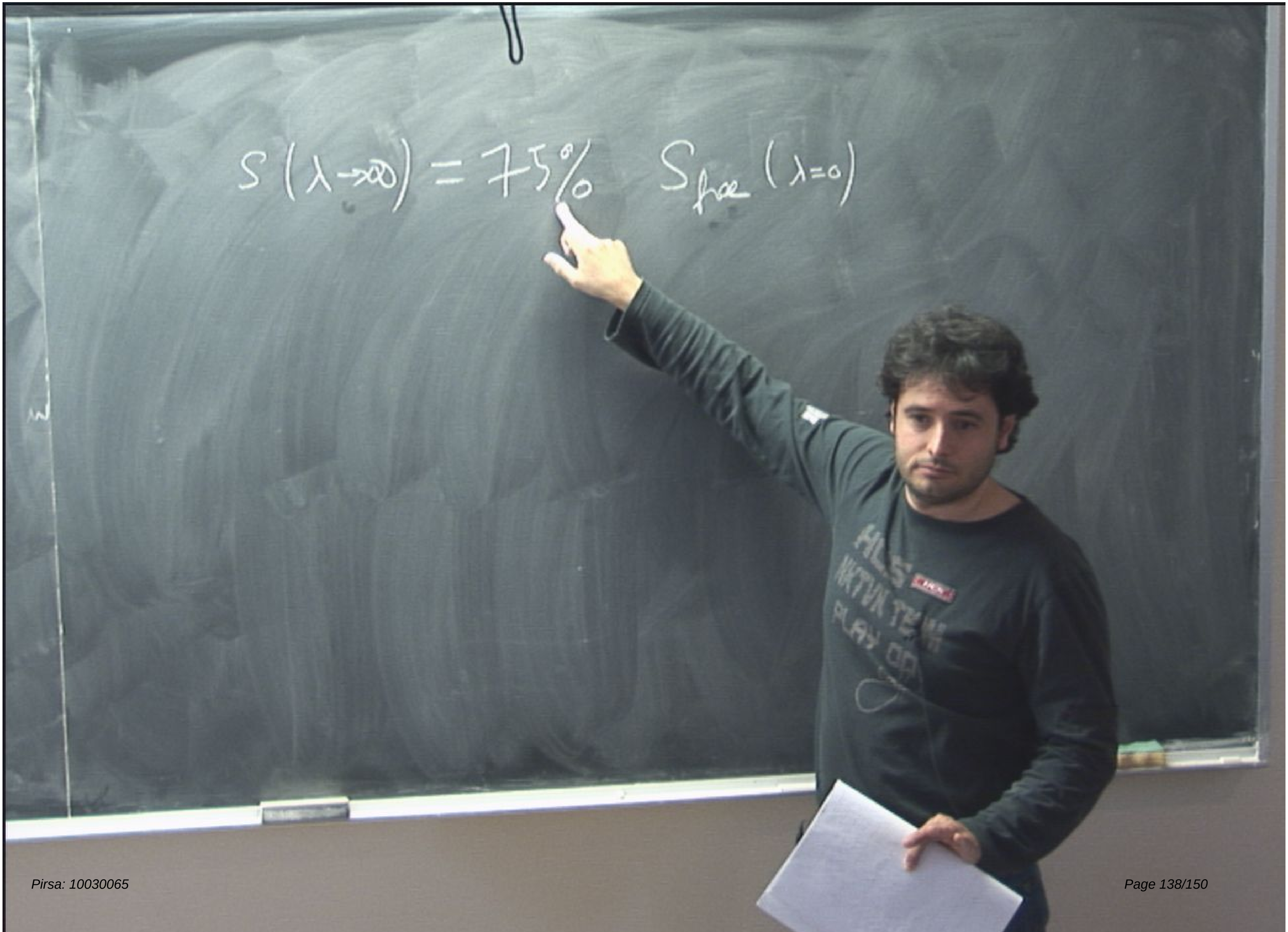

QCD
ε/T⁴
1
0.8
1
?


QCD
ε/T⁴
1
0.8
1
T/Tdec
?
T/Tdec
QG

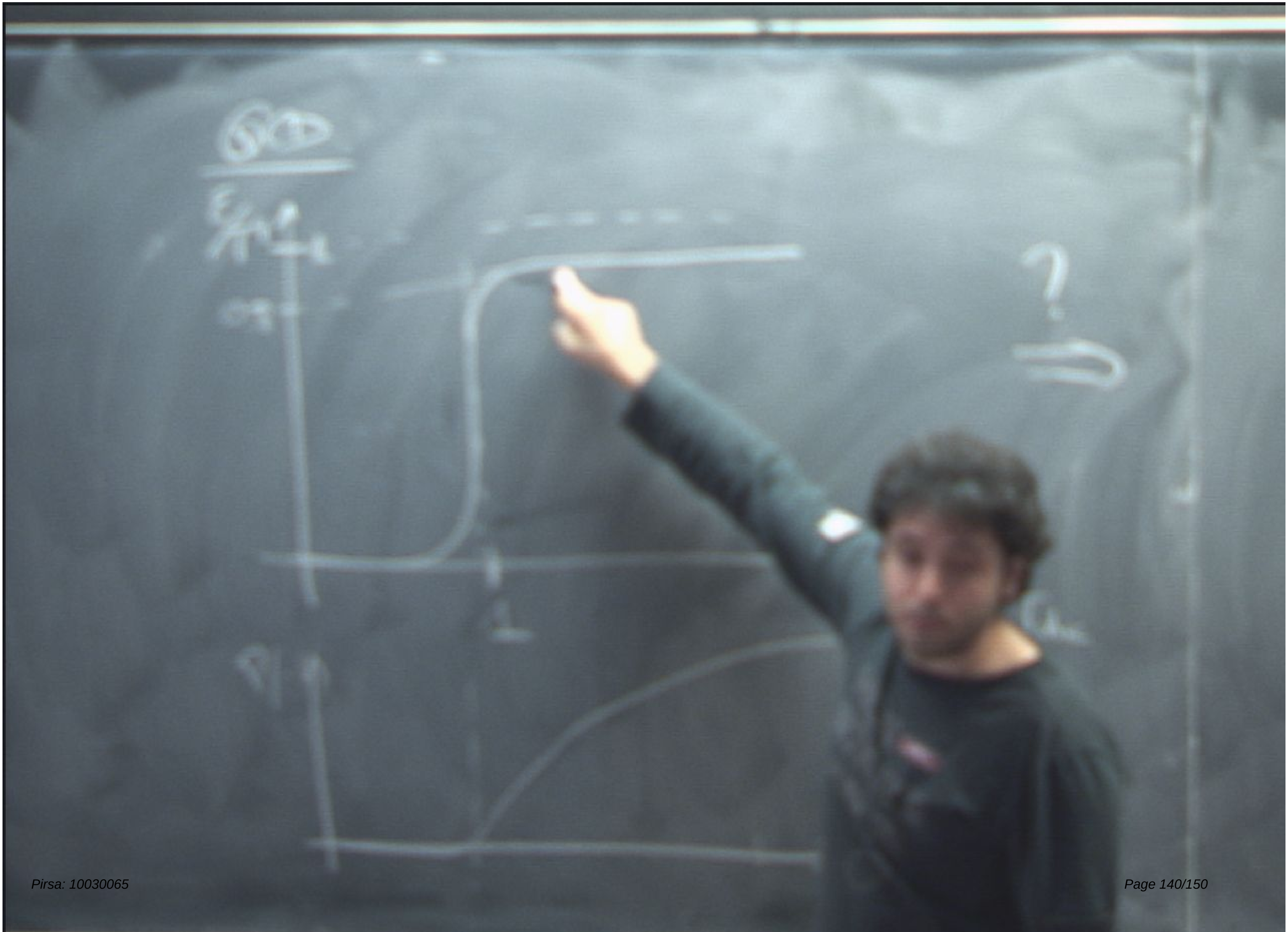

QCD
ε/T⁴
1
0.8
1
T/T_dec
?
T/T_dec

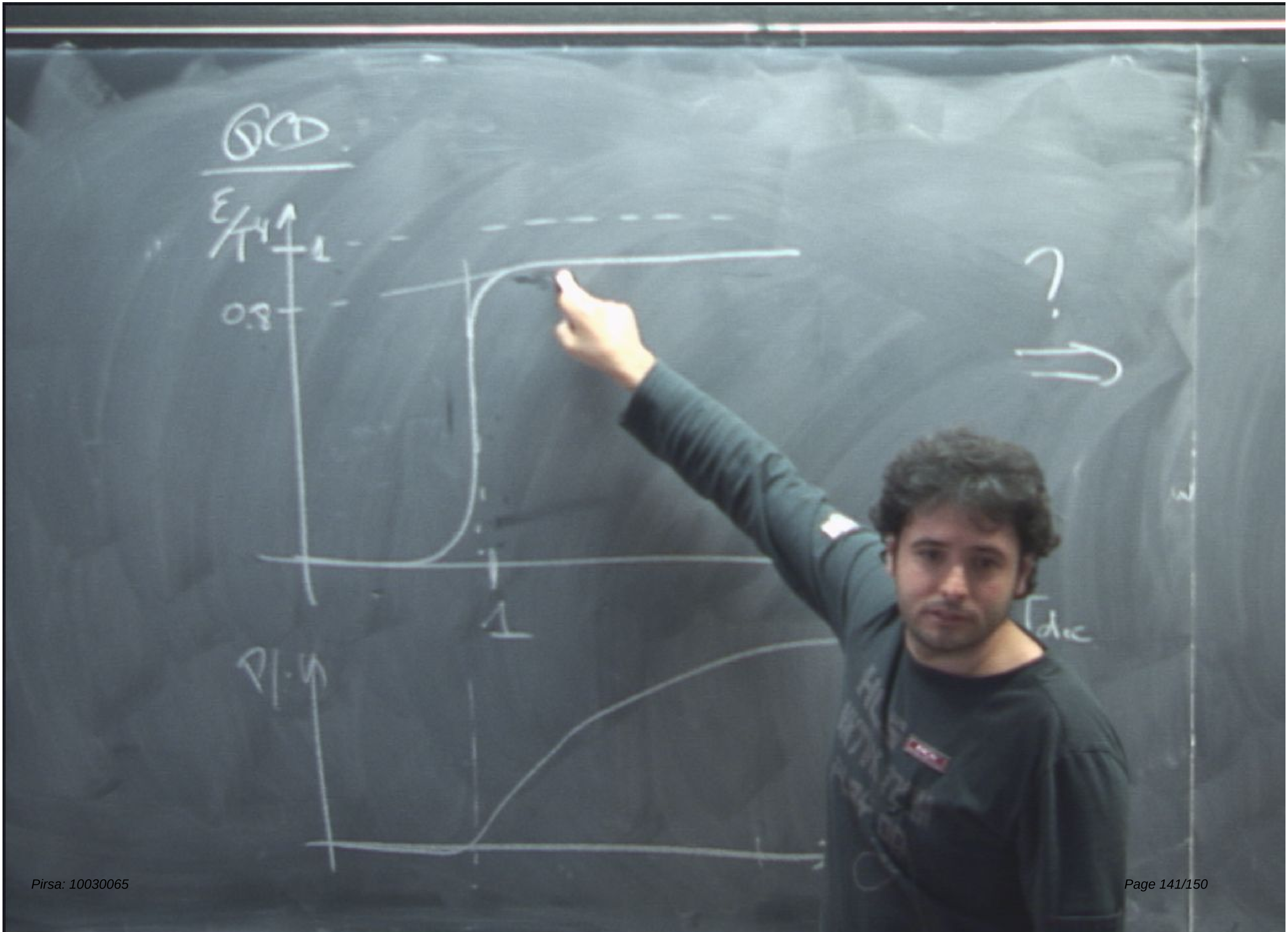

$S(\lambda \to \infty)$


$S(\lambda \to \infty) = 75\% \; S_{free}(\lambda = 0)$


S (λ→∞) = 75%   S_free (λ=0)

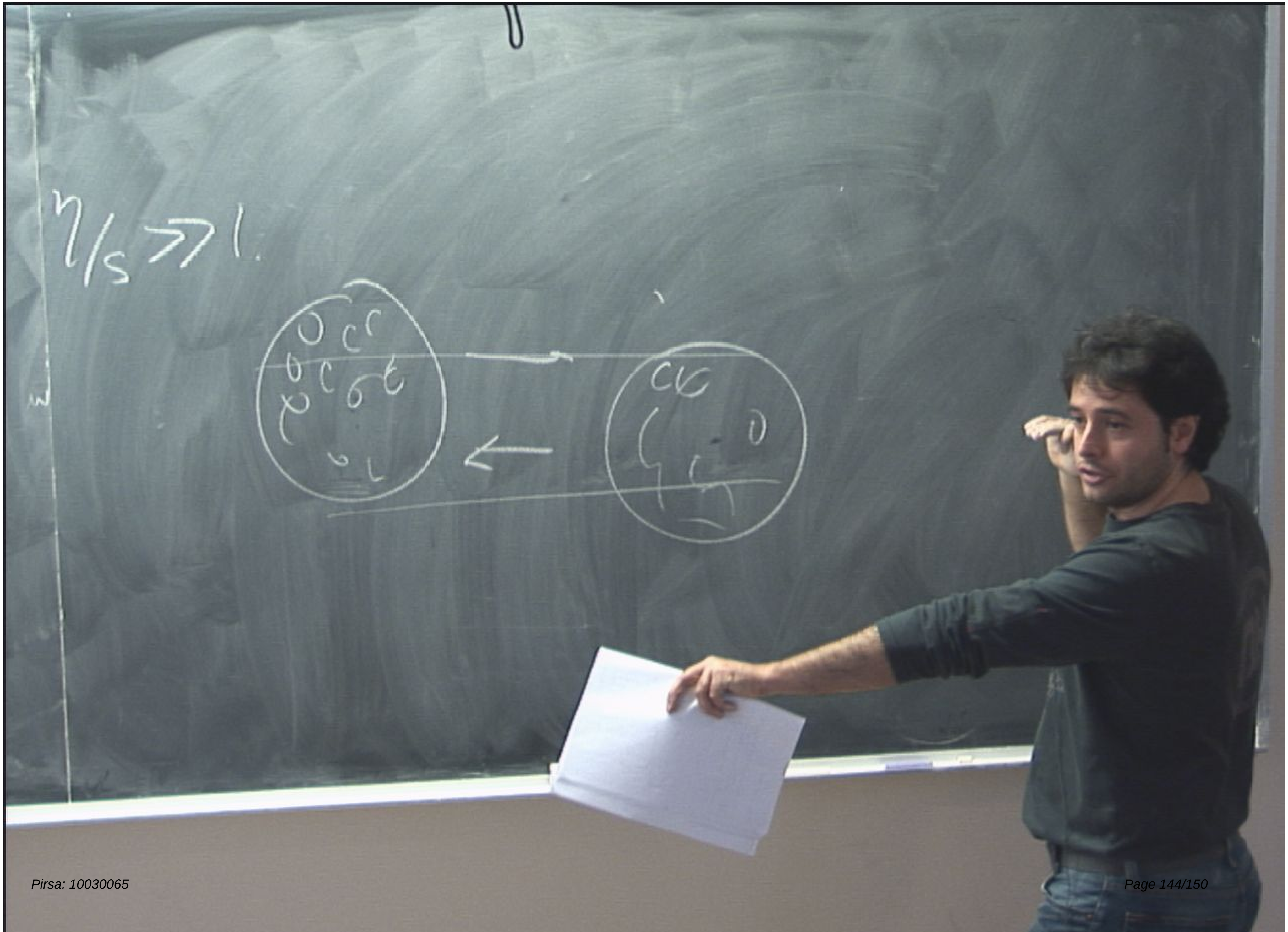
$S(\lambda \to \infty) = 75\% \quad S_{free}(\lambda = 0)$

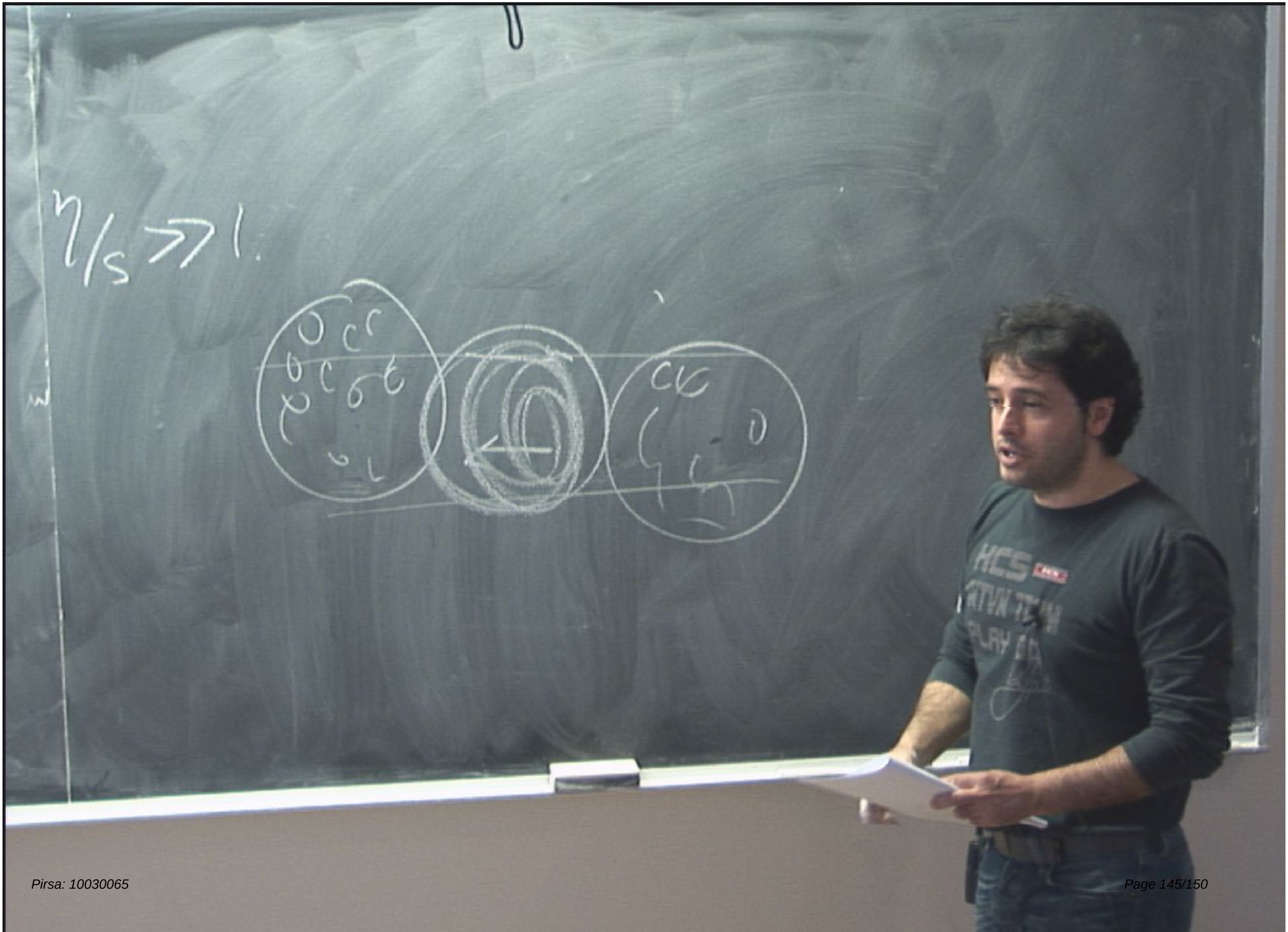


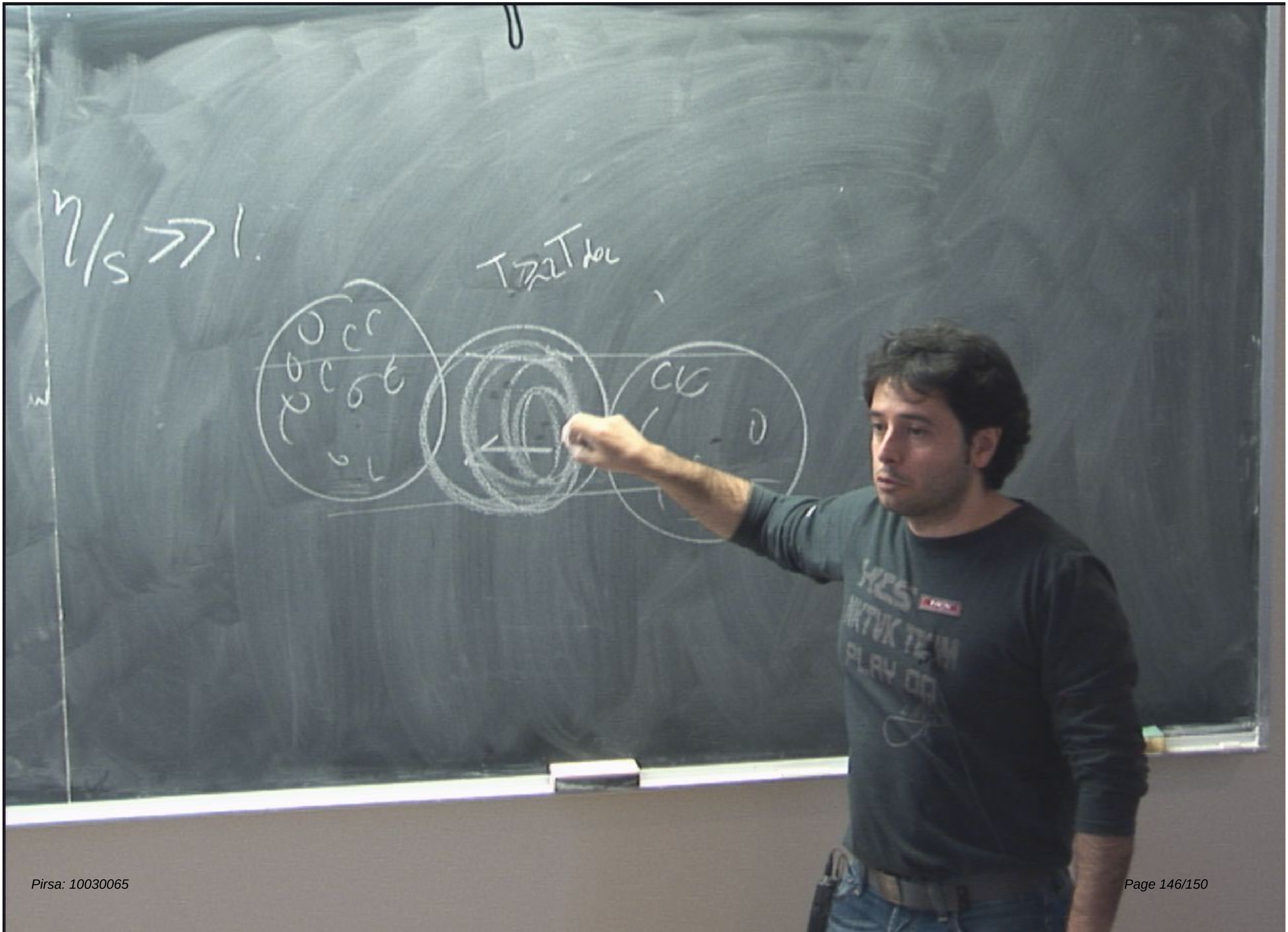

QCD
0.8
1
?

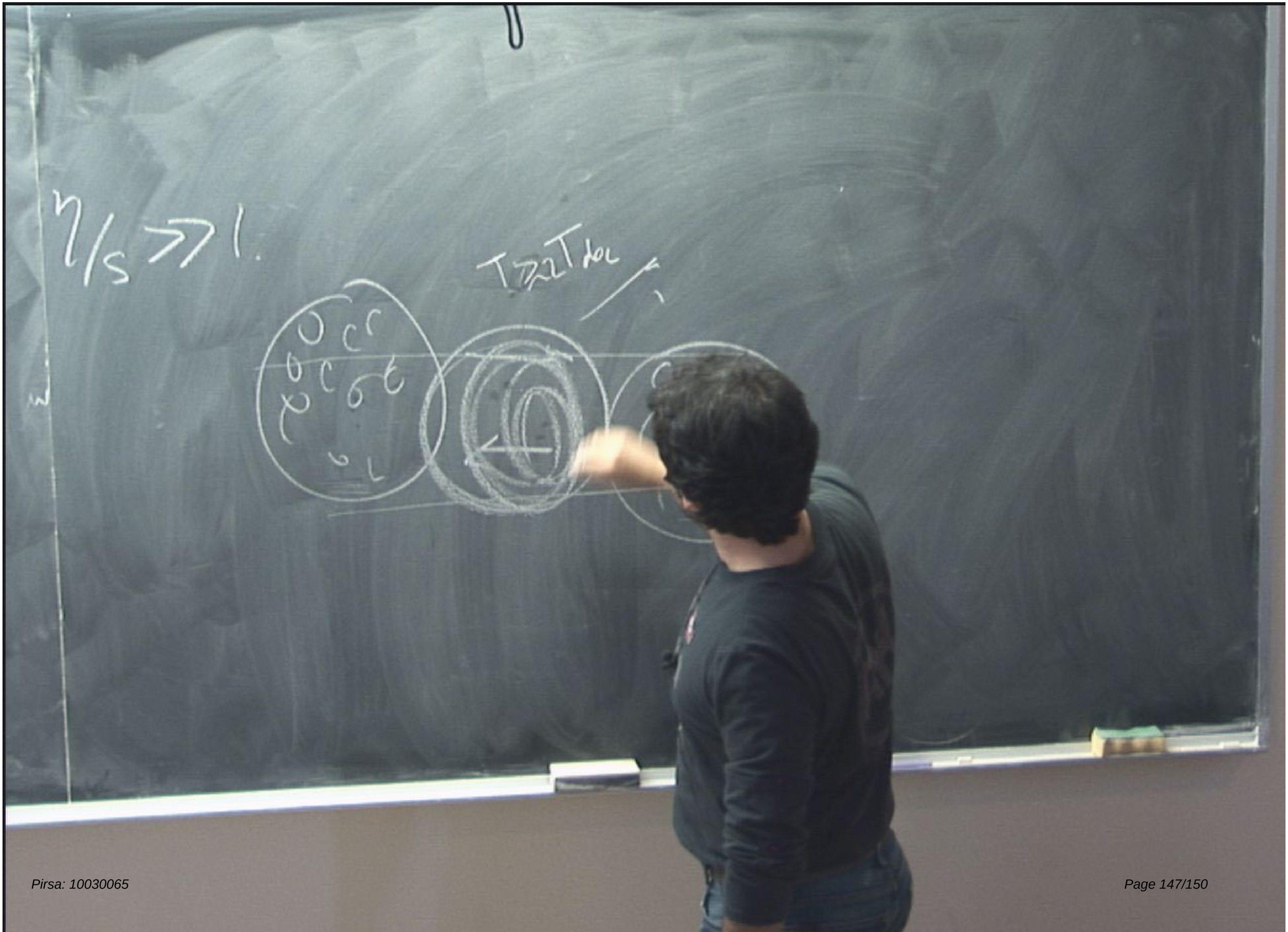

$\eta/s \gg 1$.

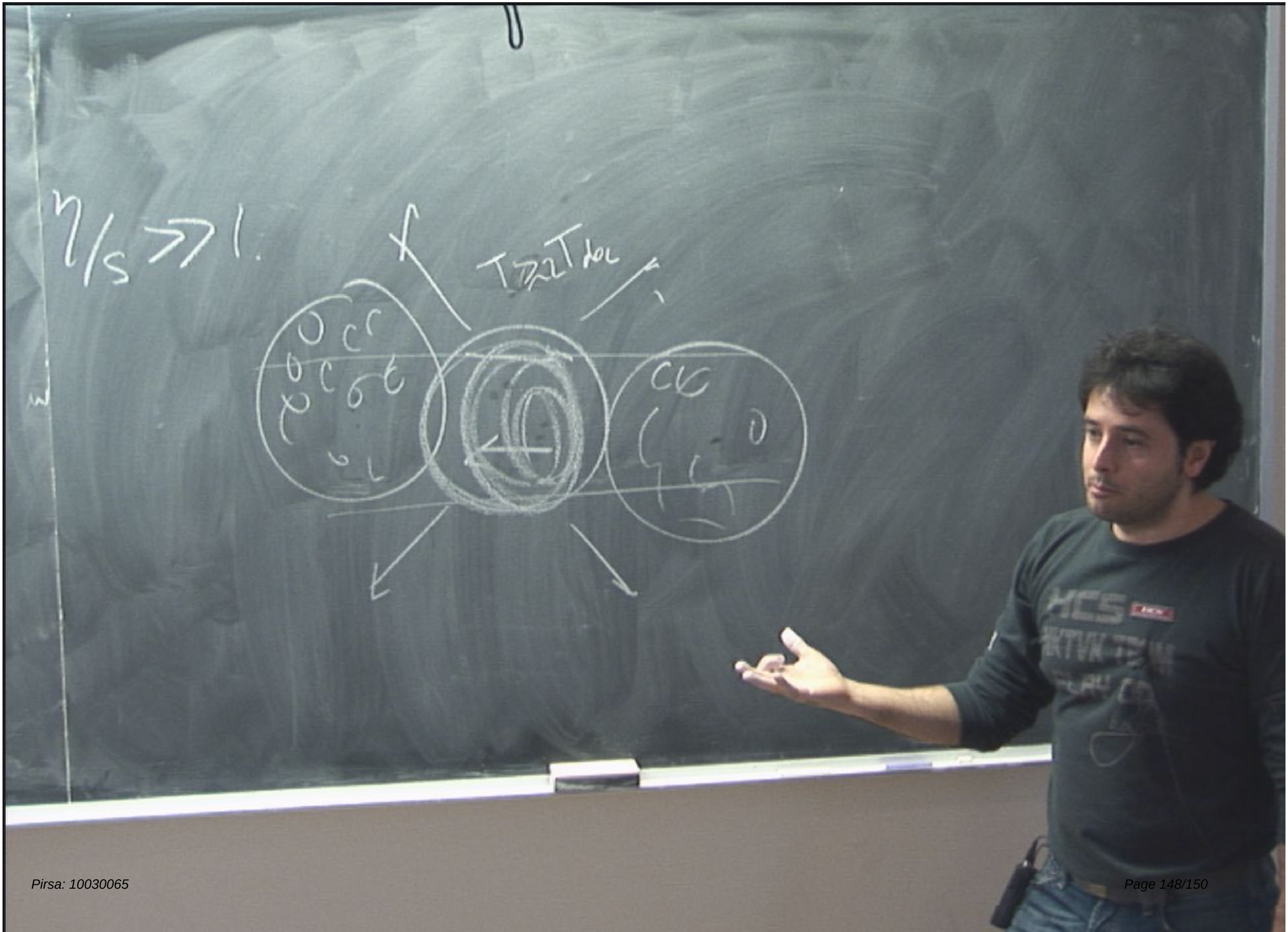

η/s >> 1.


$\eta/s \gg 1$.

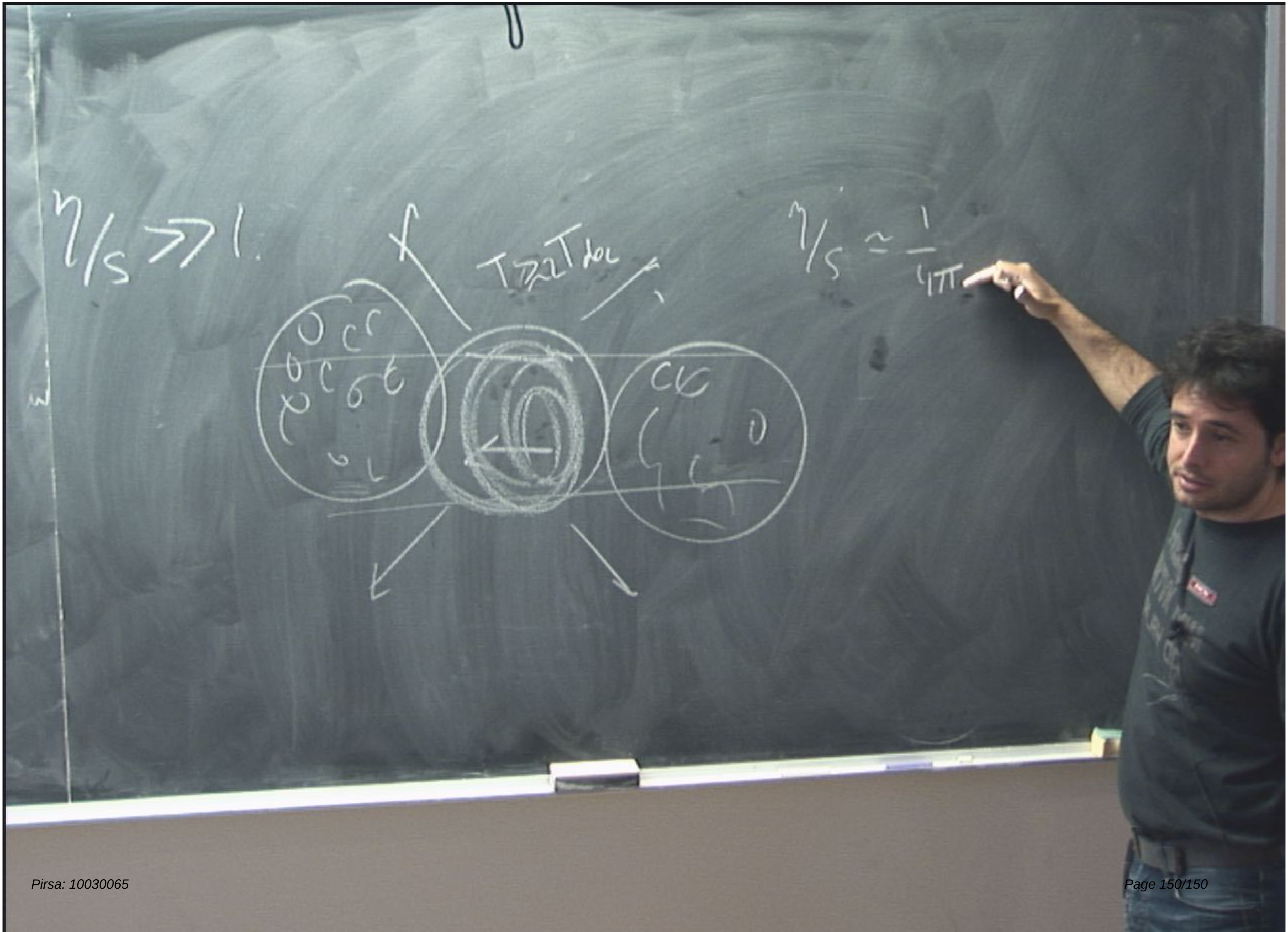

η/s >> 1
HCS


η/s >> 1.


η/s >> 1.


$\eta/s \gg 1.$

η/s >> 1.
η/s ≃ 1/4π


$\eta/s \gg 1$
$\eta/s \simeq \frac{1}{4\pi}$