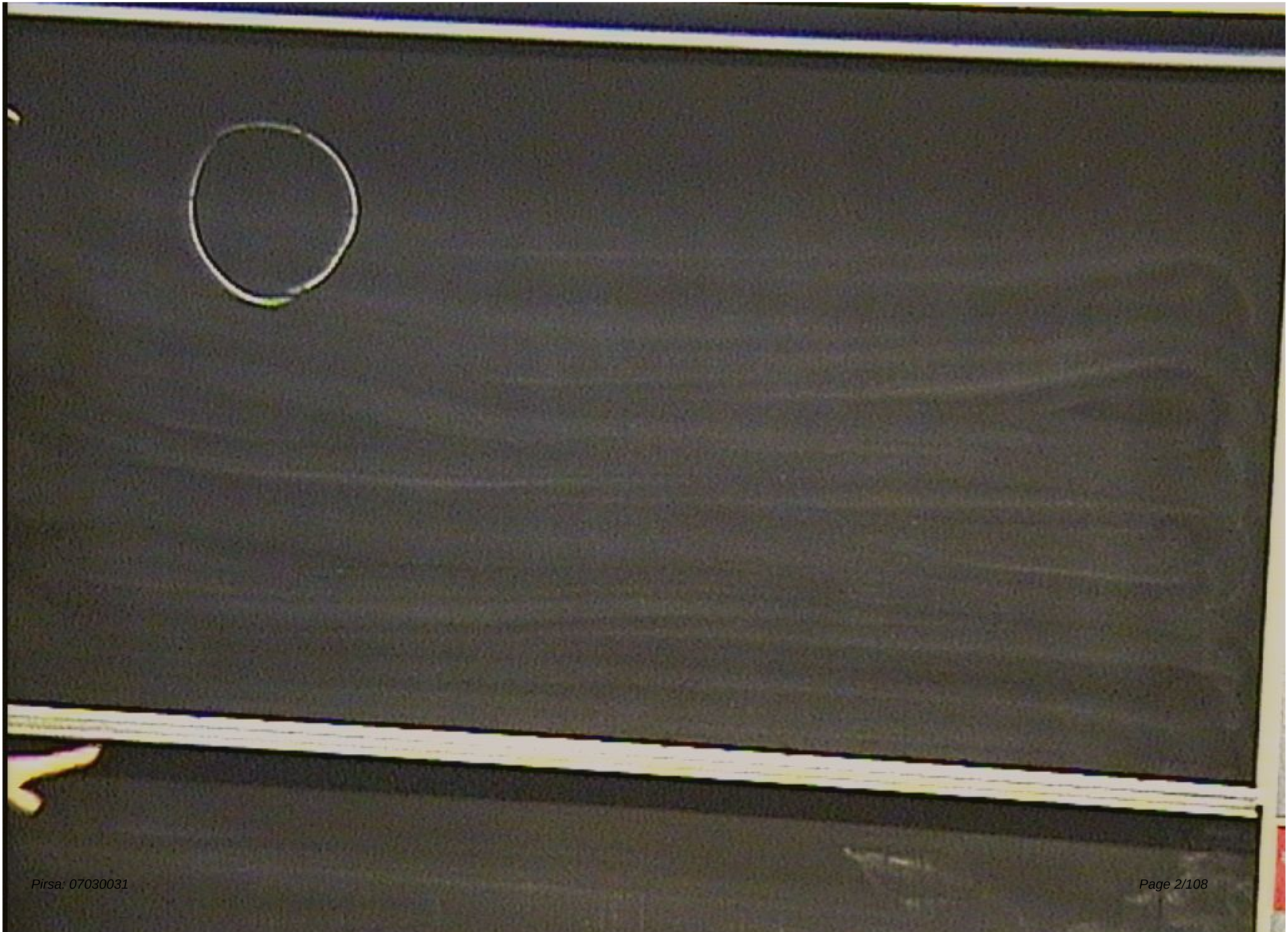
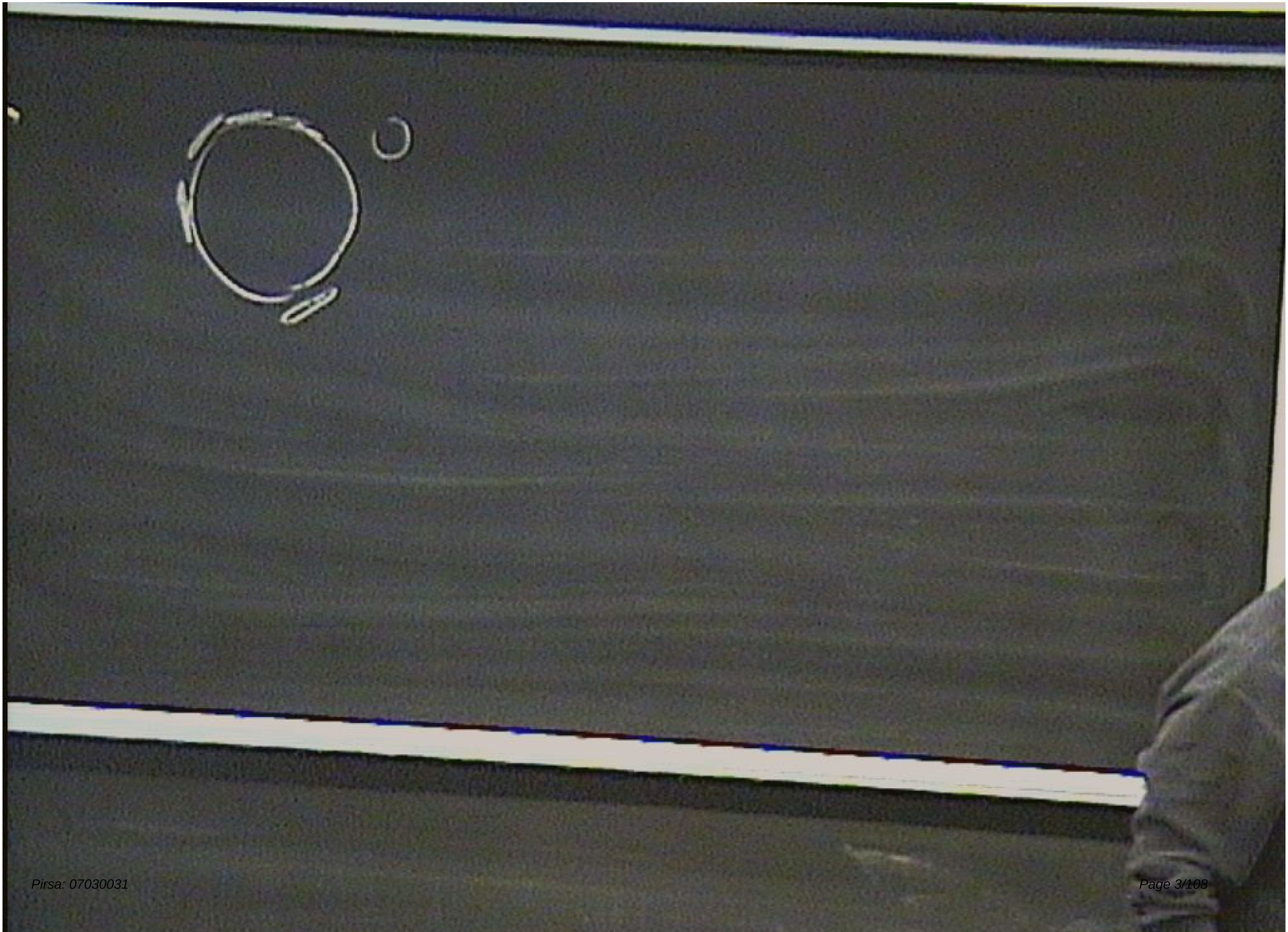
Title: Black Holes and Holography: Mini-Course - Lecture 4

Date: Mar 23, 2007 10:30 AM

URL: http://pirsa.org/07030031

Abstract: <div id="Cleaner">Distinguished theoretical physicist Leonard Susskind, Professor of Physics at Stanford, will give a series of lectures on Black Holes and Holography at Perimeter Institute in Waterloo. This mini-course is open to all university professors and students.





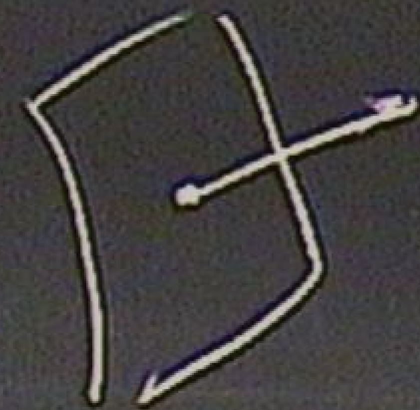
$$\sigma = \gamma T^3$$

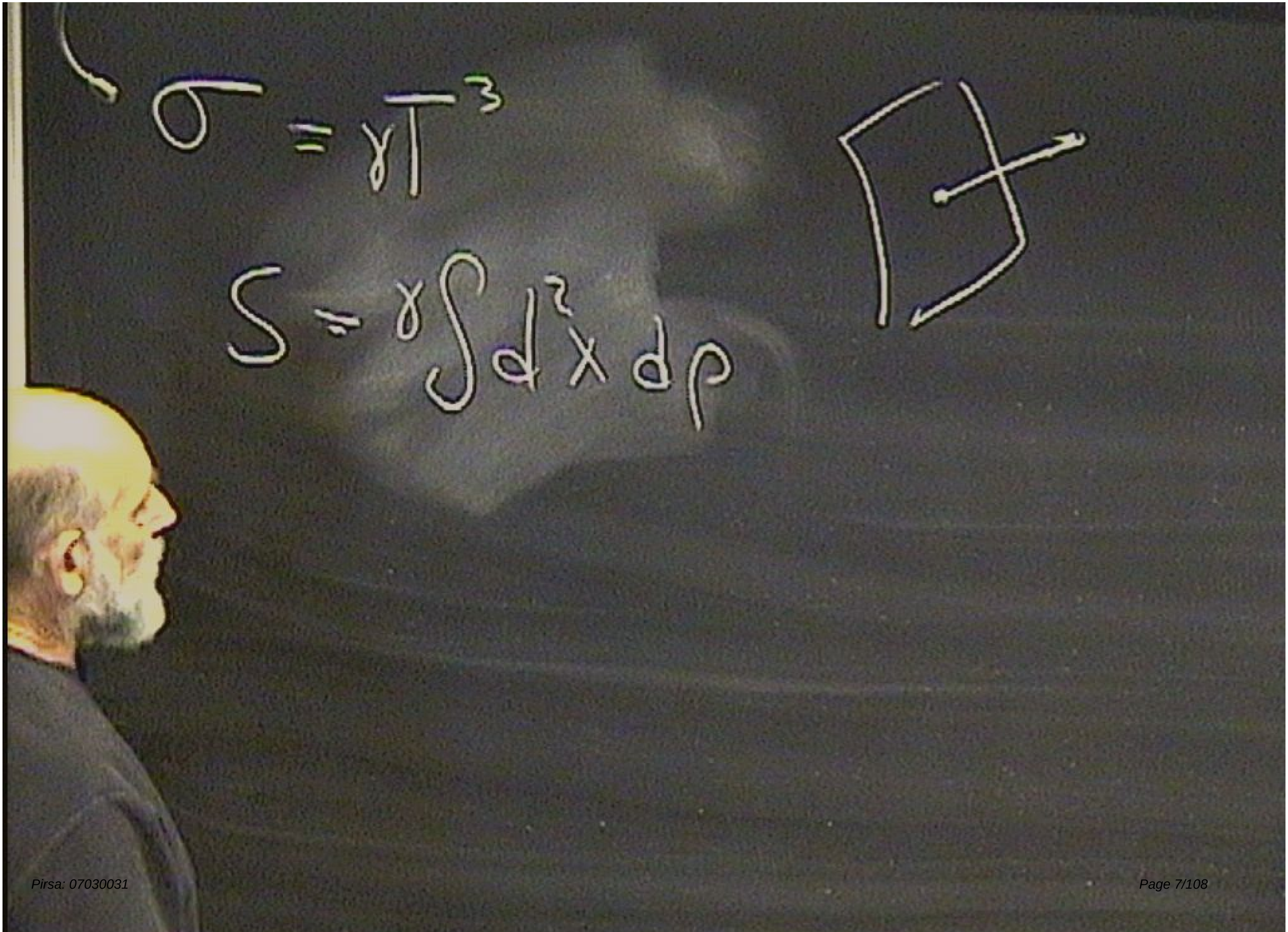
$\sigma = \gamma T^3$

S

$$\sigma = \gamma T^3$$

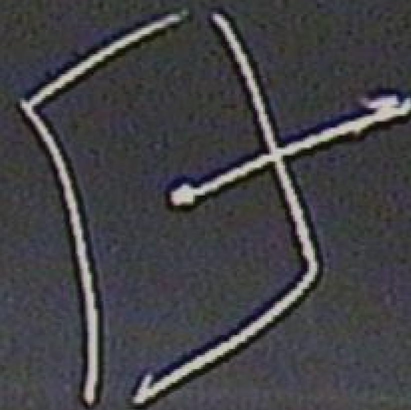
$$S = \int d^2x \, d\rho$$



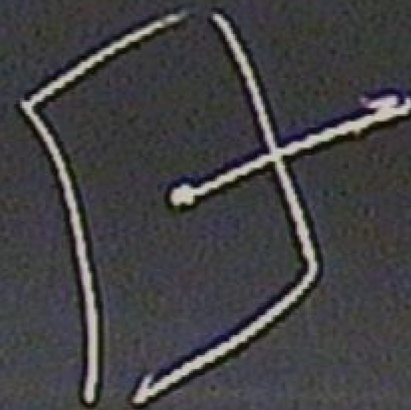

$\sigma = \gamma T^3$
$S = \gamma \int d^2x \, d\rho$

$$\sigma = \gamma T^3$$

$$S = \gamma \int d^2x \, dp \, \frac{1}{(2\pi p)^3}$$



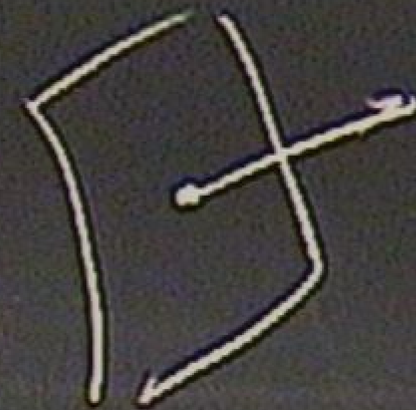
$$\sigma = \gamma T^3$$



$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

$$= \gamma$$

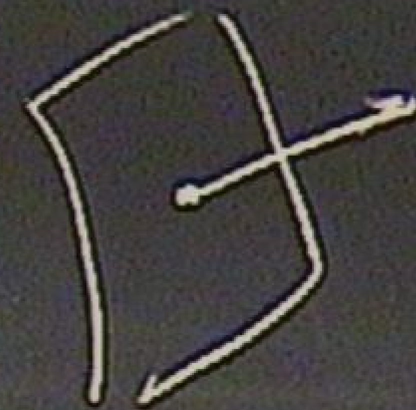
$$\sigma = \gamma T^3$$



$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

$$= \gamma A$$

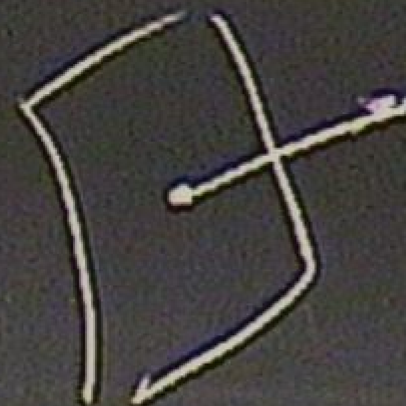
$$\sigma = \gamma T^3$$



$$S = \gamma \int d^2x \, dp \, \frac{1}{(2\pi p)^3}$$

$$= \gamma A$$

$$\sigma = \gamma T^3$$



$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

$$= \gamma A$$

$$\sigma = \gamma T^3$$

$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

$$= \frac{\gamma A}{\rho_0^2}$$

$$\sigma = \gamma T^3$$

$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

$$= \frac{\gamma A}{\rho_0^2}$$

$$\rho_0 \approx l_P = \sqrt{\frac{G\hbar}{c^3}}$$

$$\sigma = \gamma T^3$$

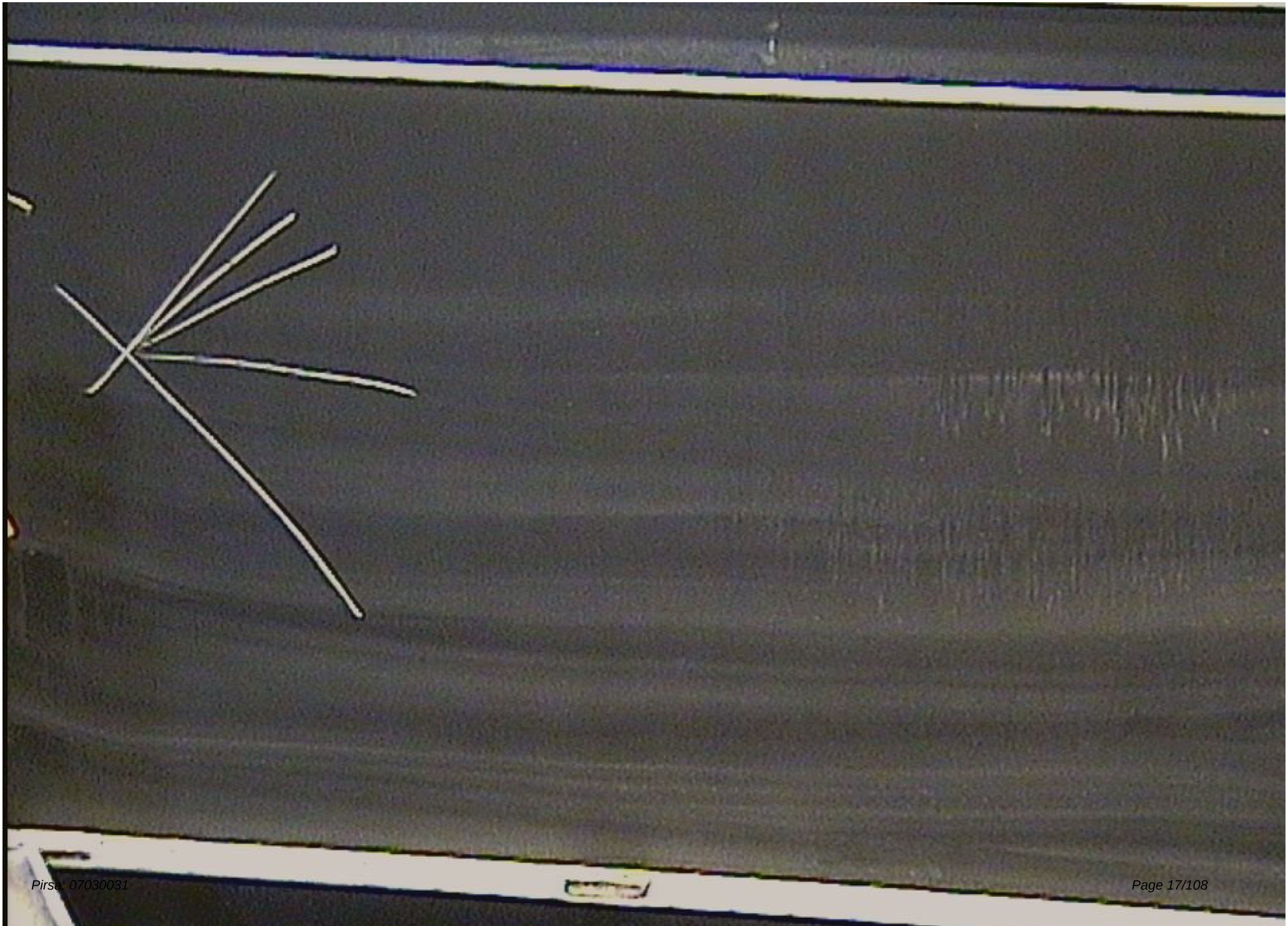
$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

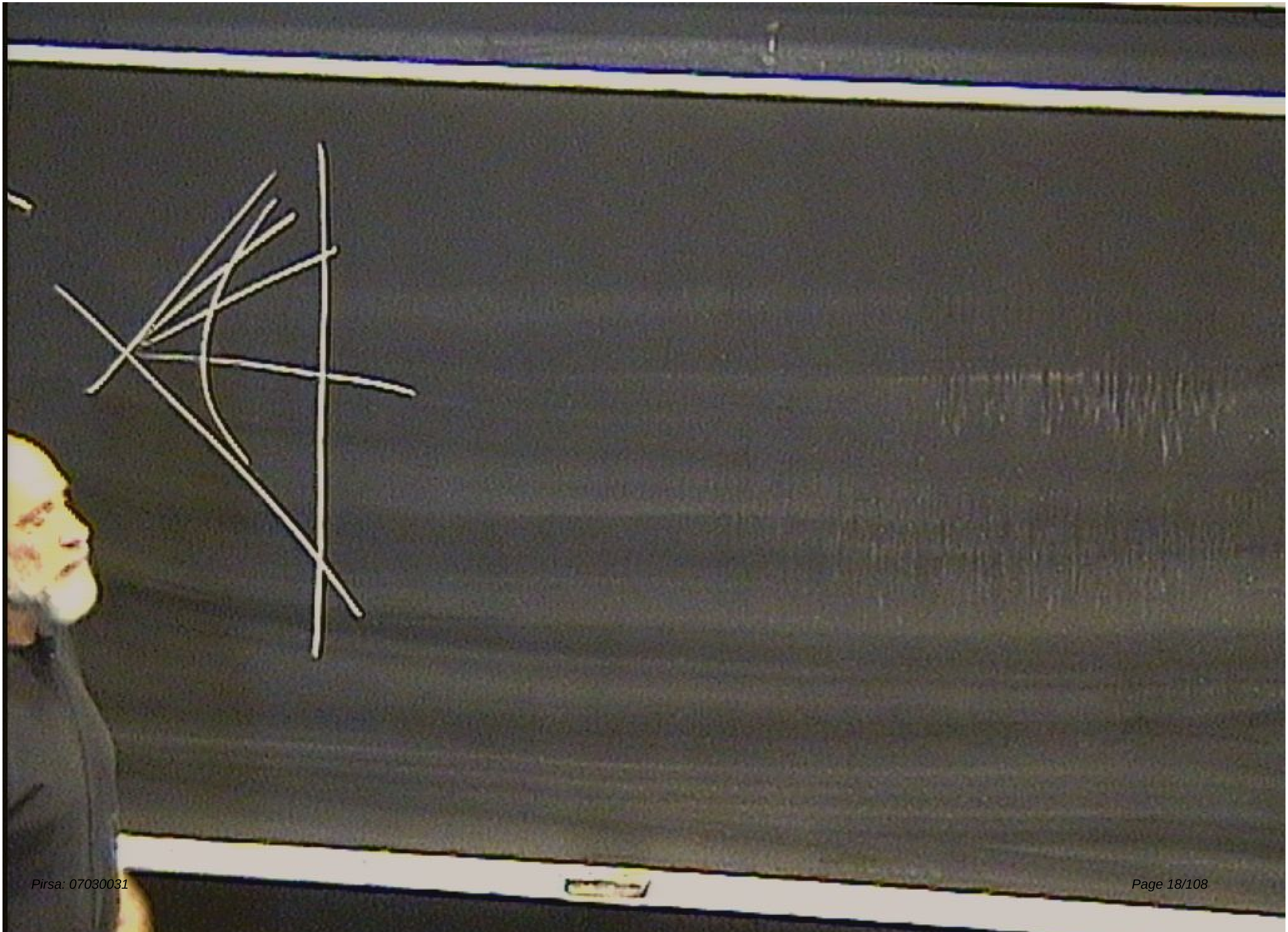
$$= \frac{\gamma A}{\rho_0^2} \qquad \rho_0 \approx l_P = \sqrt{\frac{G\hbar}{c^3}}$$

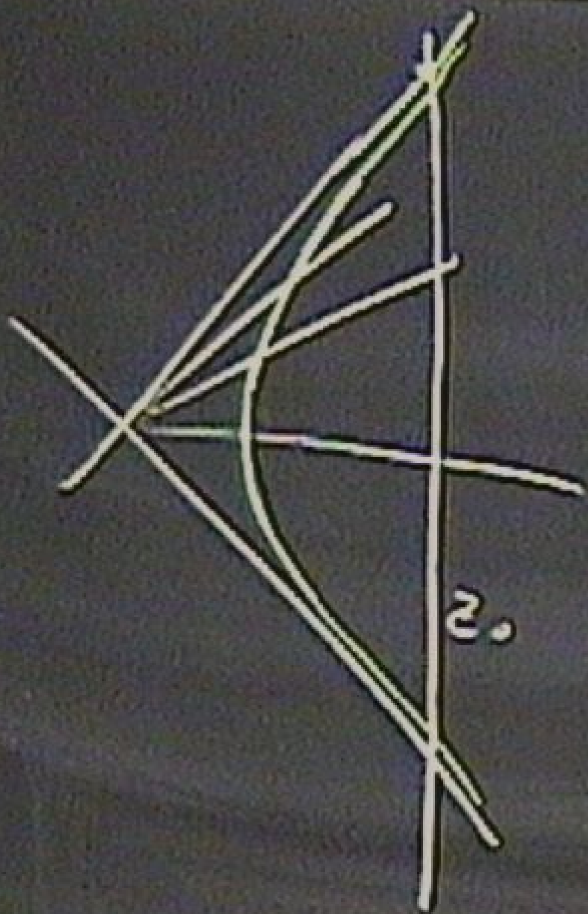
$$\sigma = \gamma T^3$$

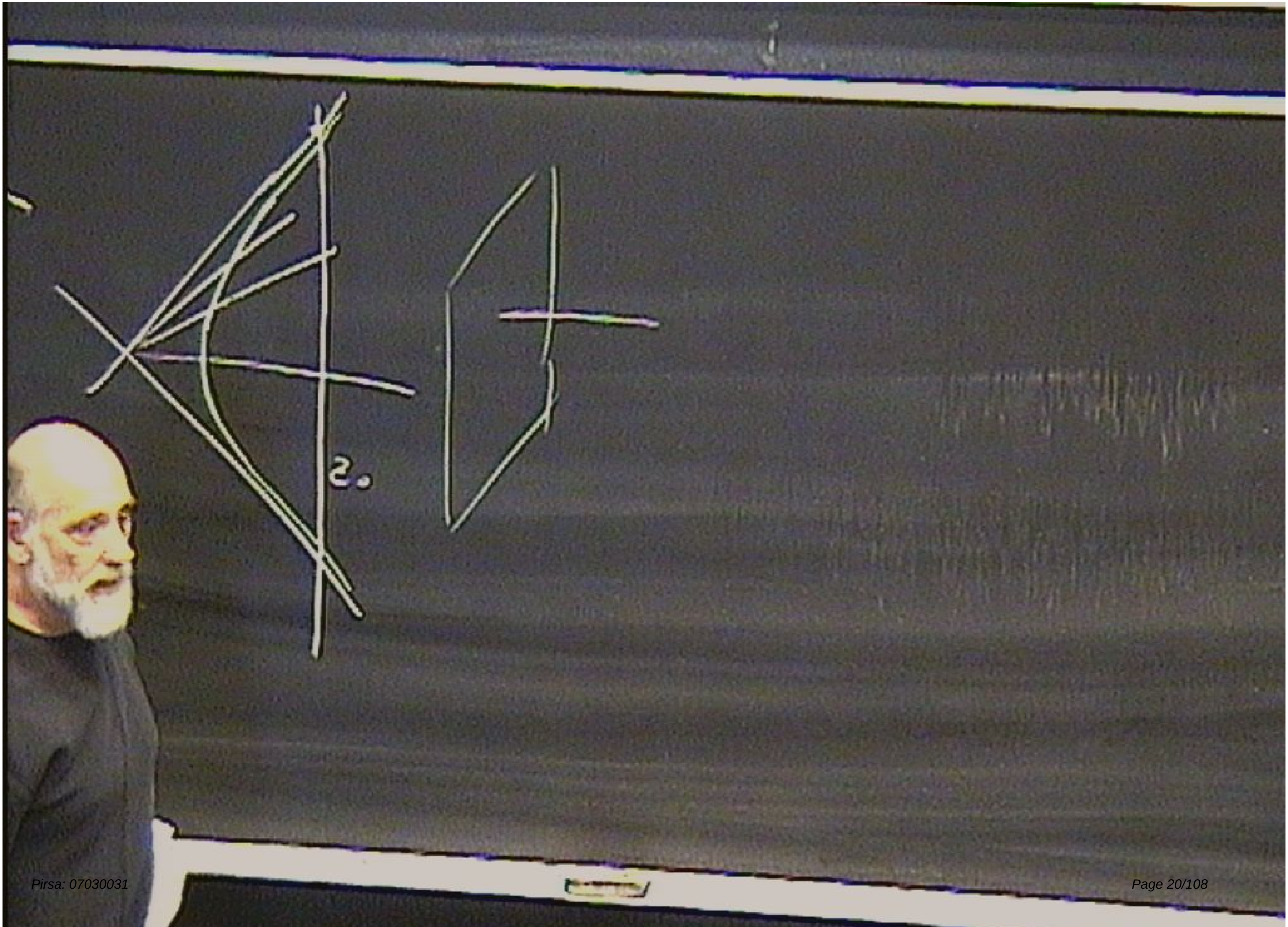
$$S = \gamma \int d^2x \, d\rho \, \frac{1}{(2\pi\rho)^3}$$

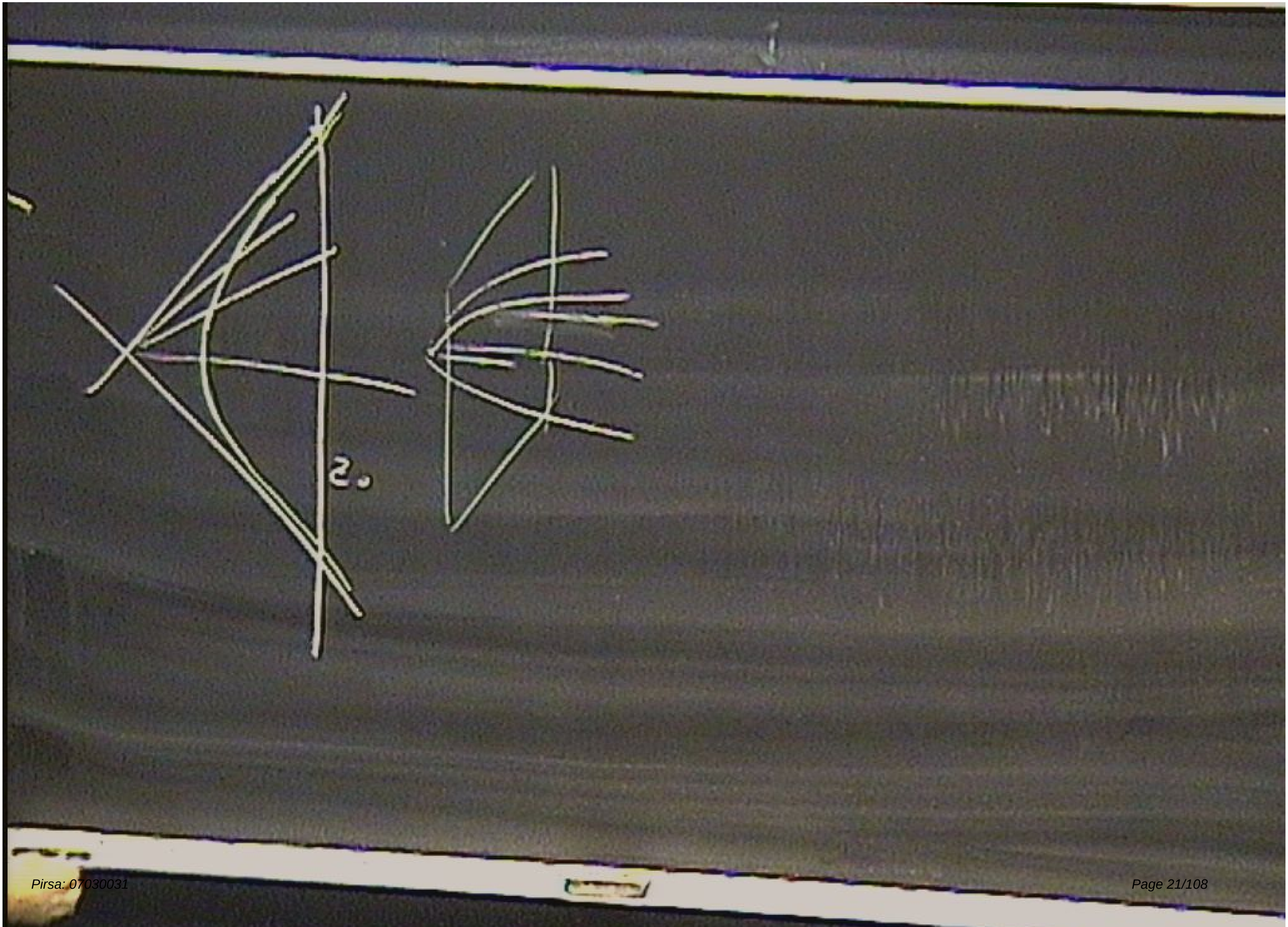
$$= \frac{\gamma A}{\rho_0^2} \qquad \rho_0 \approx \ell_P = \sqrt{\frac{G\hbar}{c^3}}$$

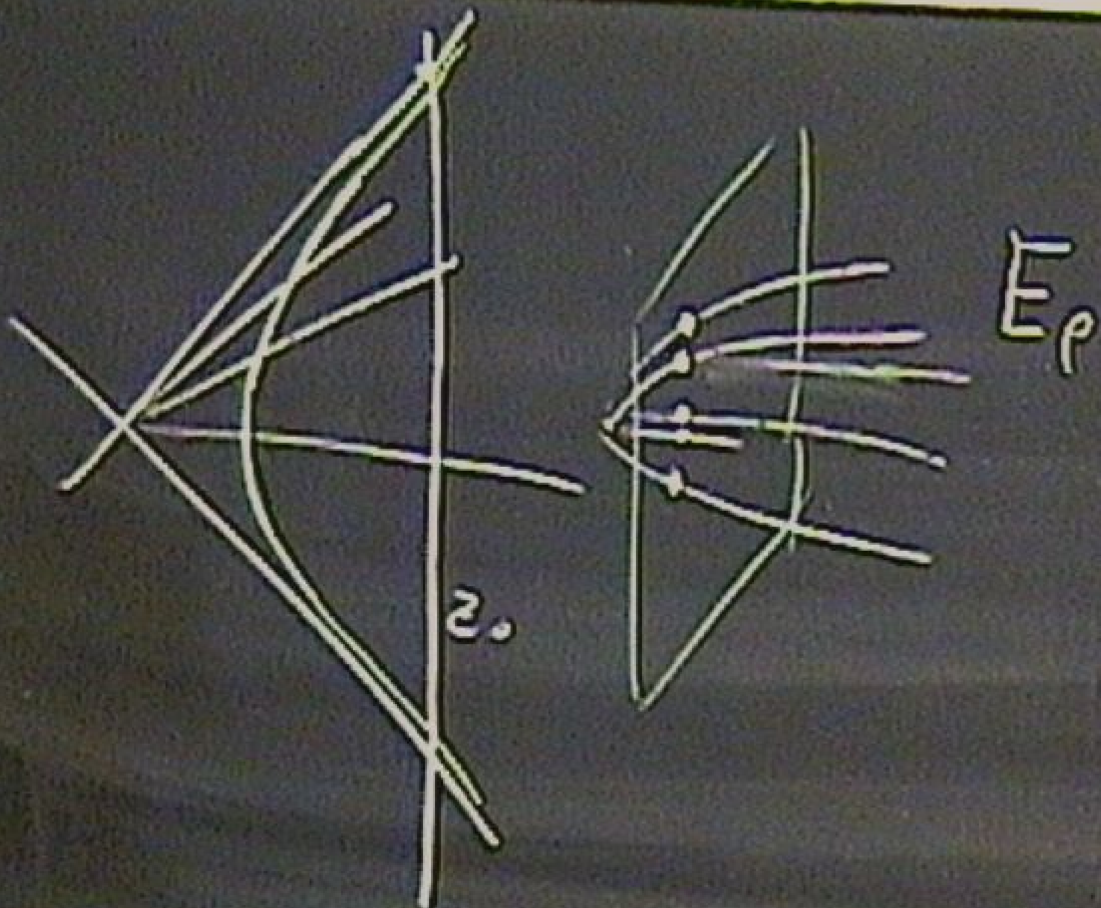


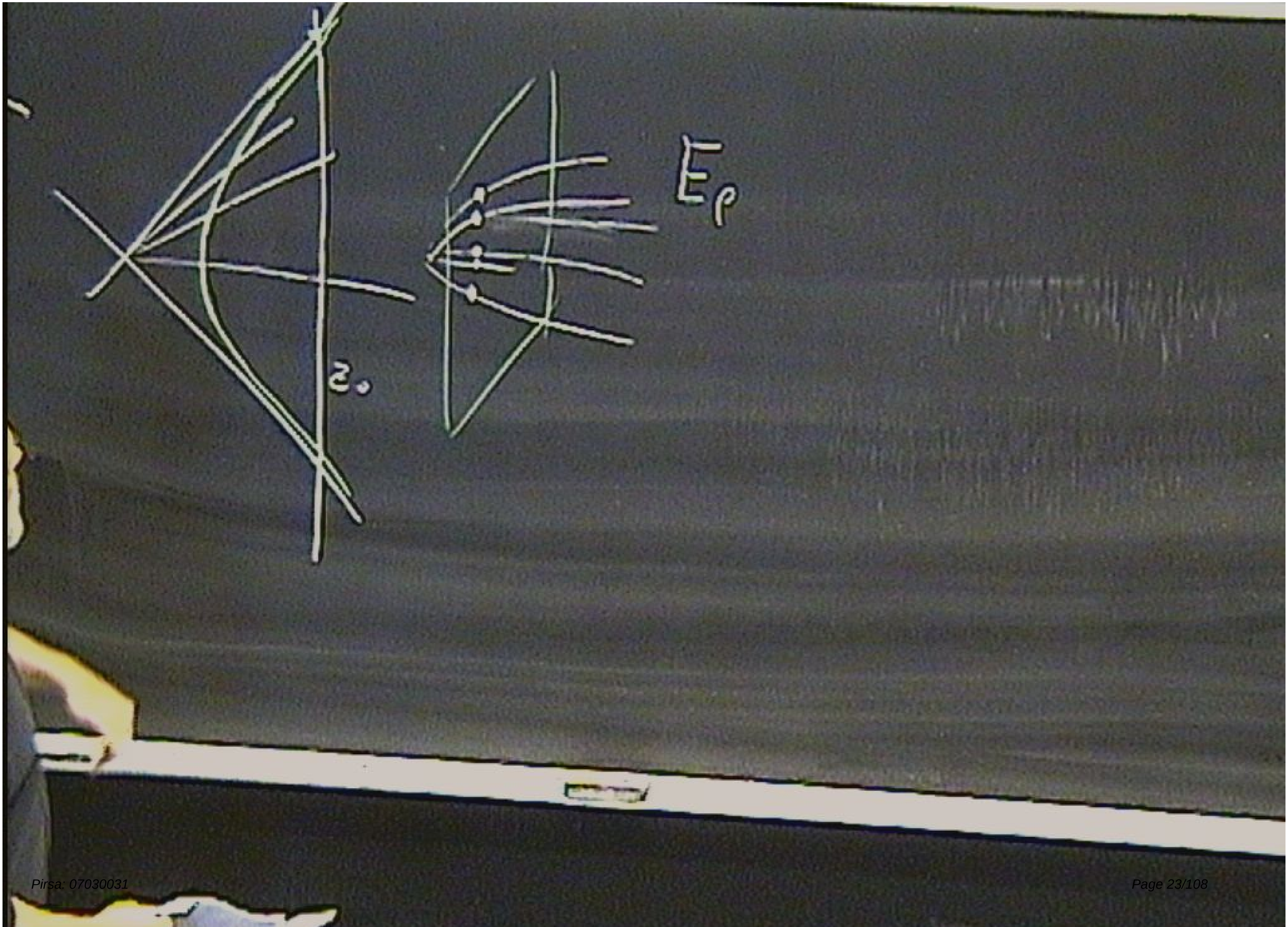



z_0

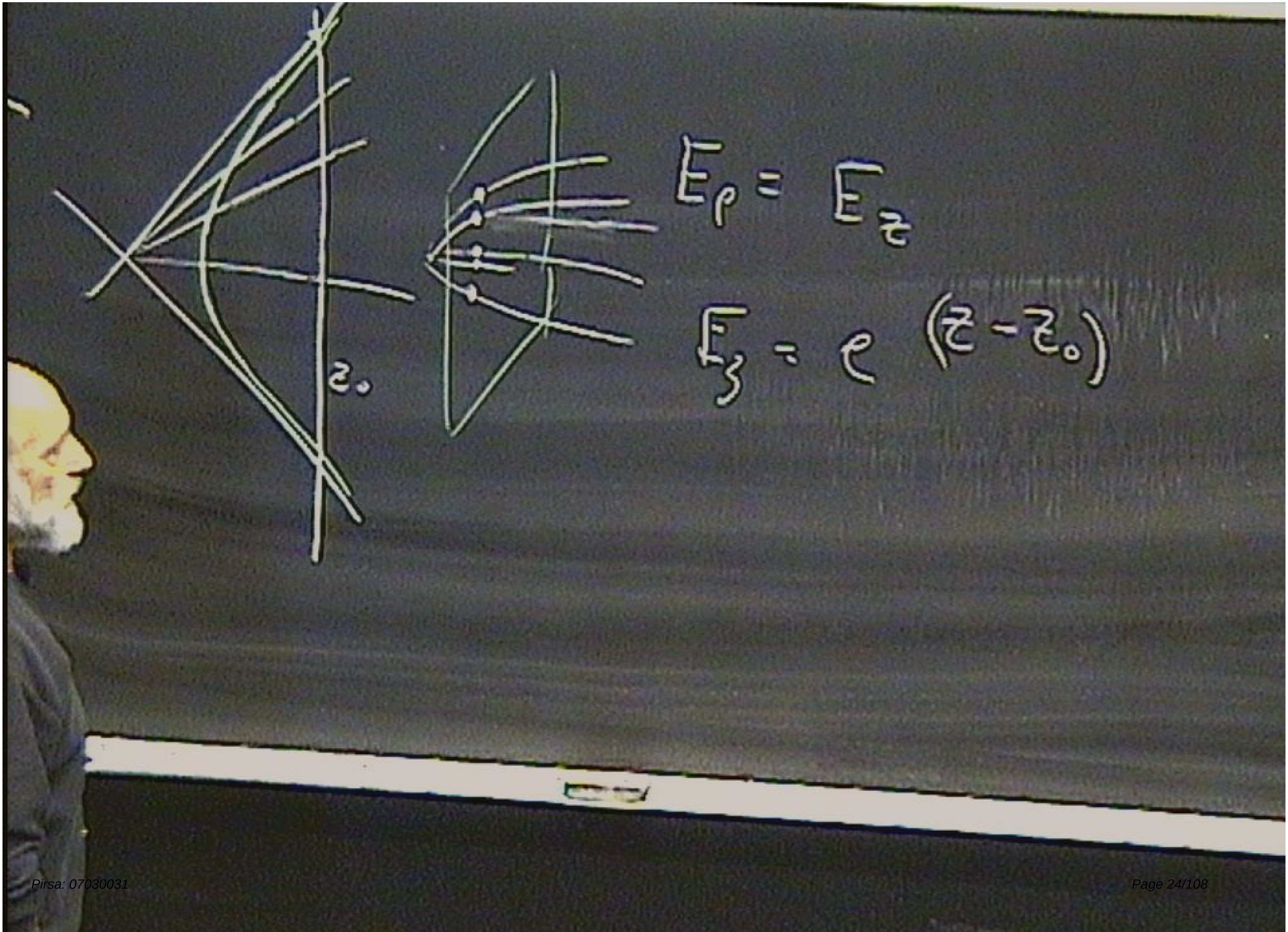



2.

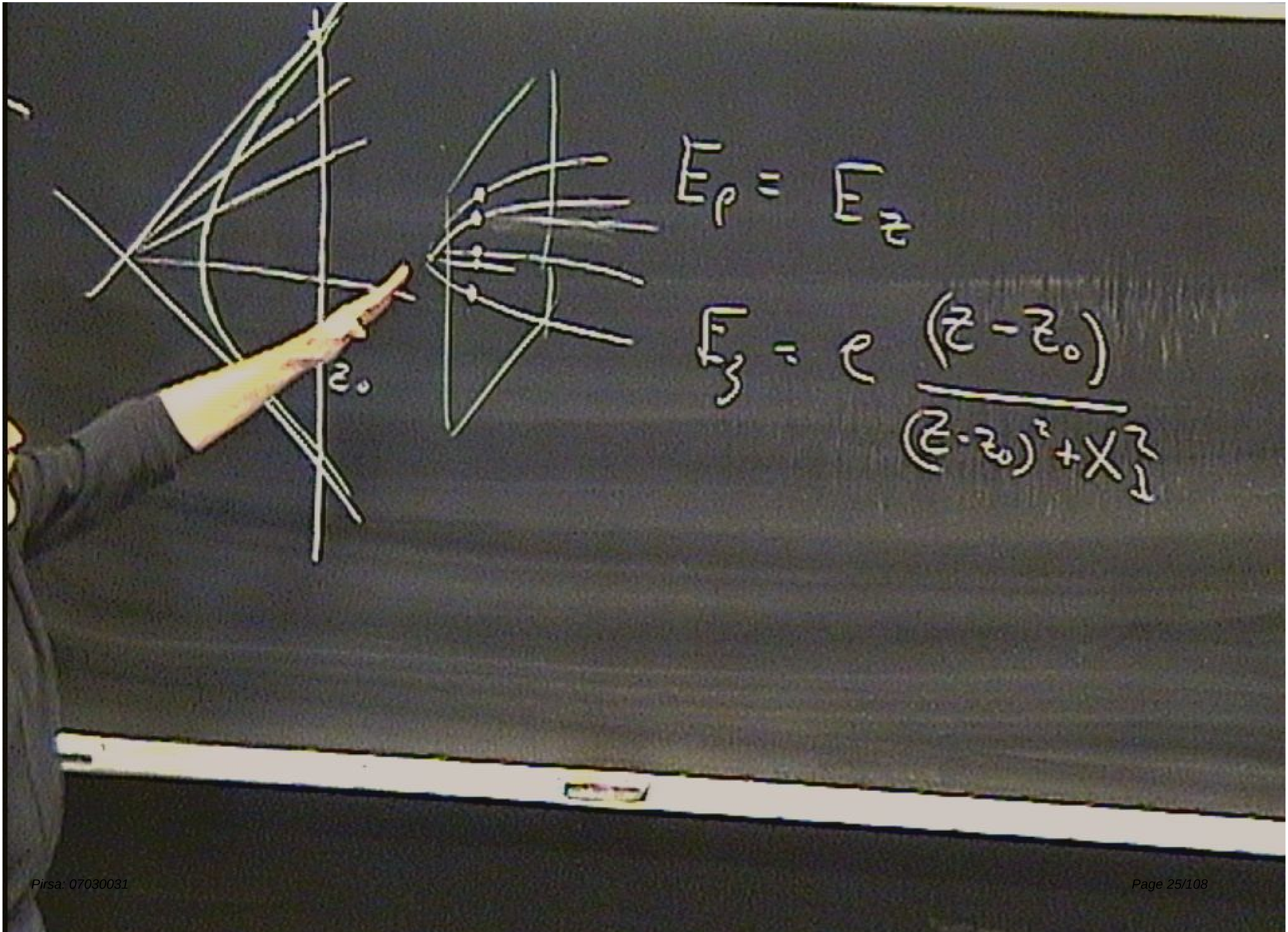

z_0
E_ρ

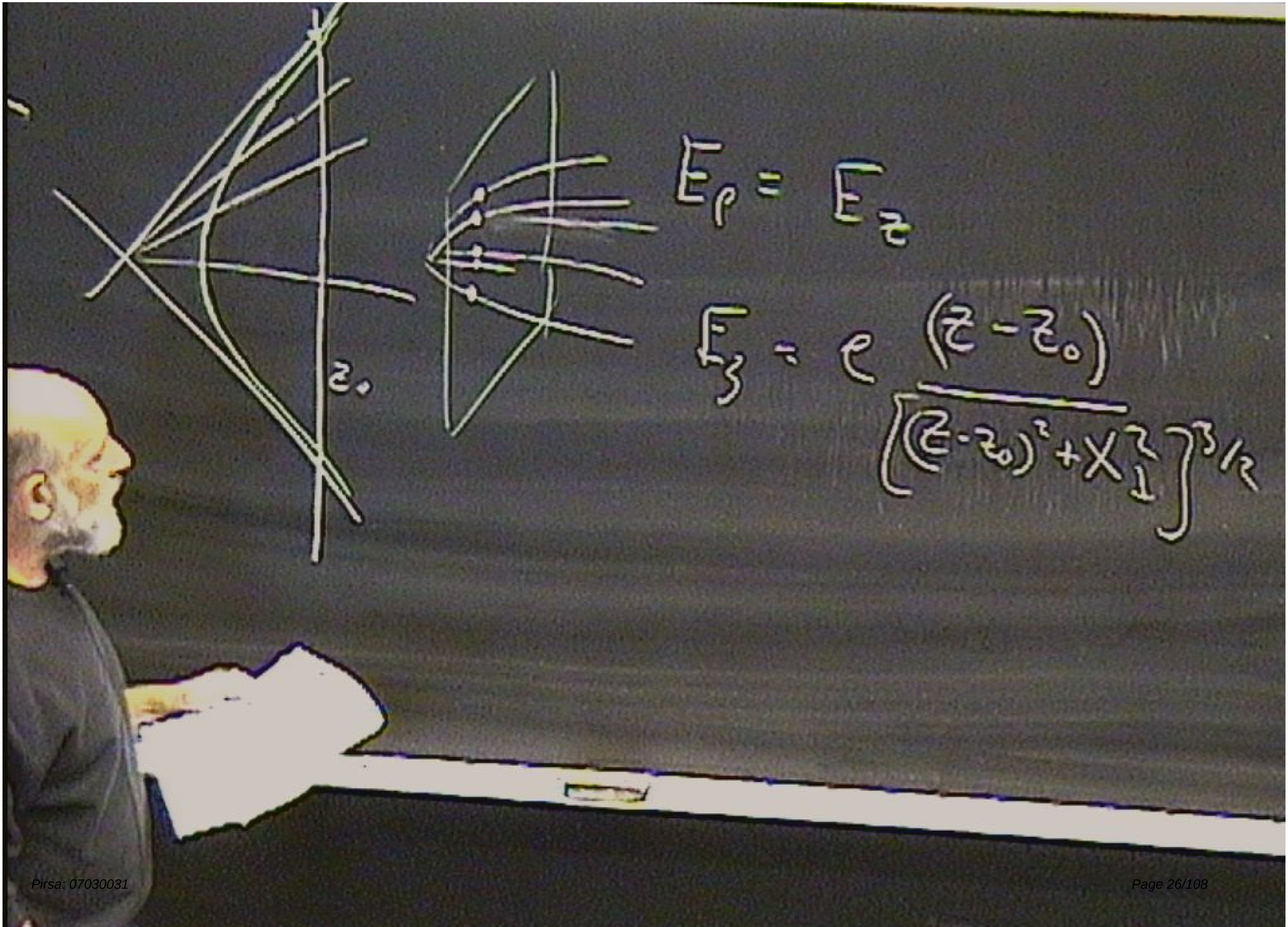


z₀
Eρ

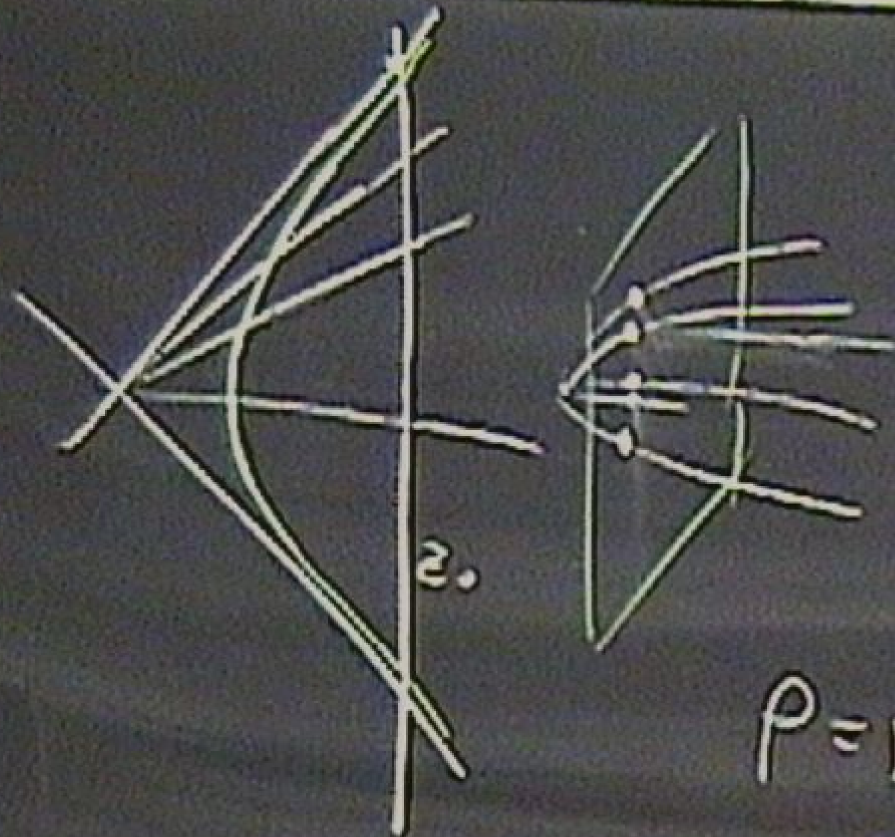


$E_\rho = E_z$
$E_\zeta = e\,(z - z_0)$
z_0


z₀
$E_\rho = E_z$
$E_\zeta = e \frac{(z-z_0)}{(z-z_0)^2+X_1^2}$



$E_\rho = E_z$
$E_z = e \frac{(z - z_0)}{[(z-z_0)^2 + X_1^2]^{3/2}}$
z_0

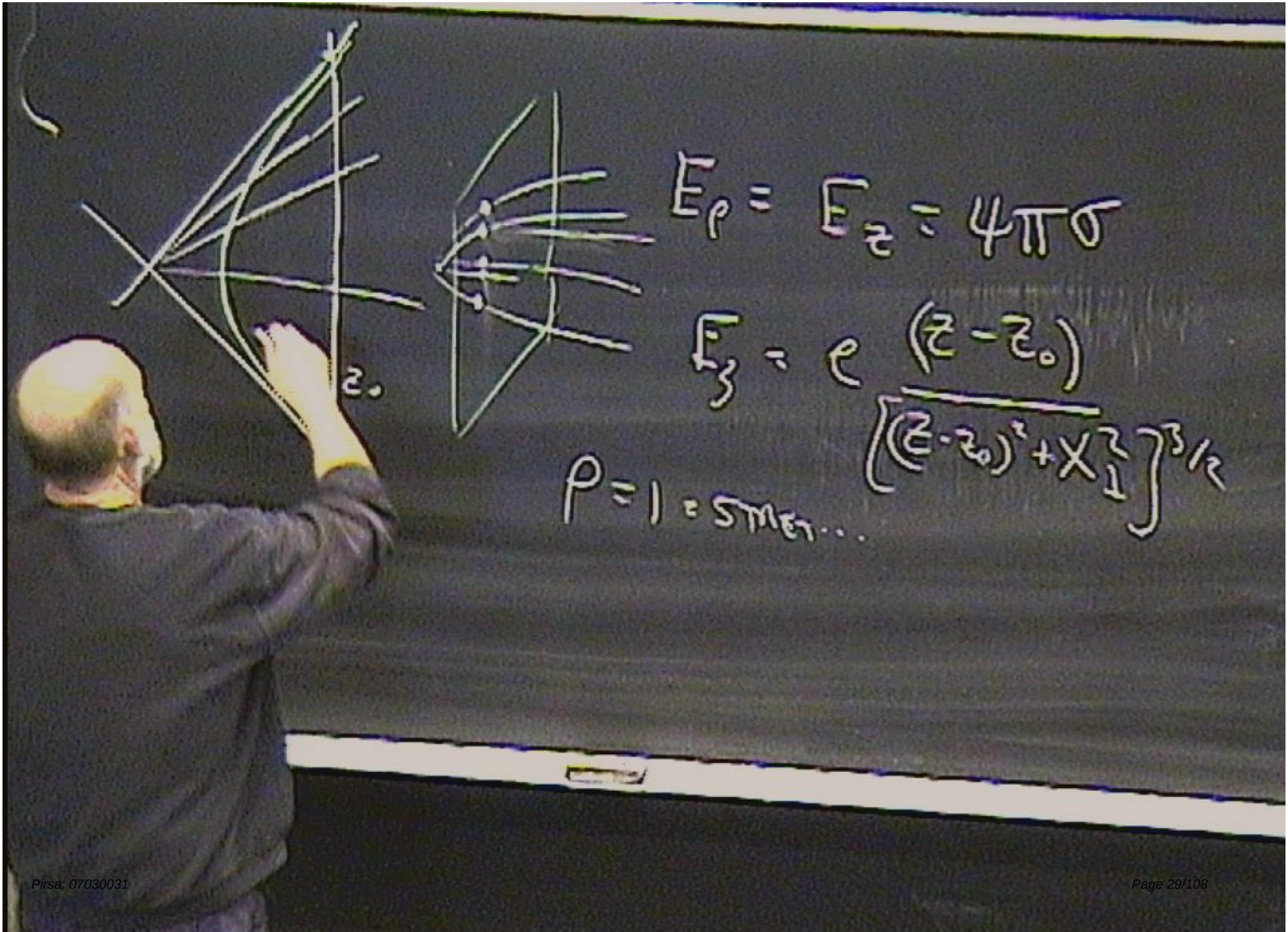


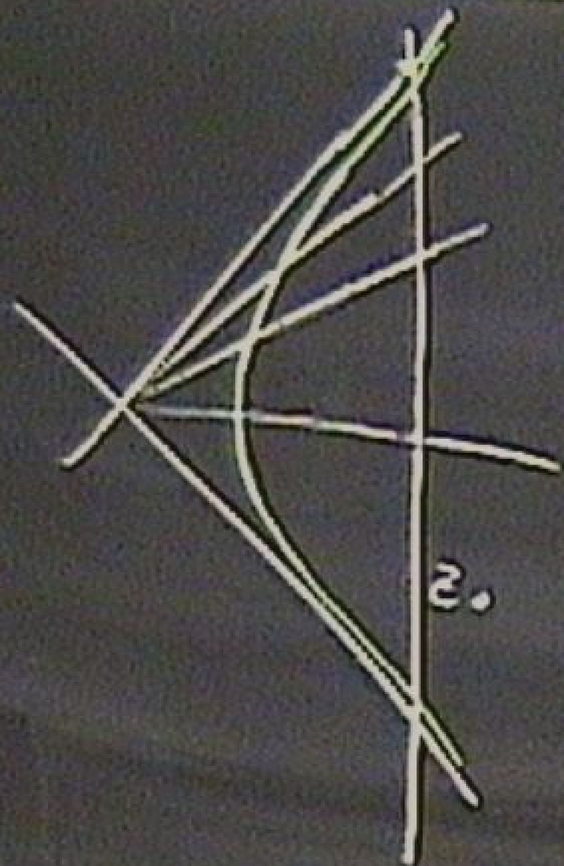
$$E_\rho = E_z = 4\pi\sigma$$

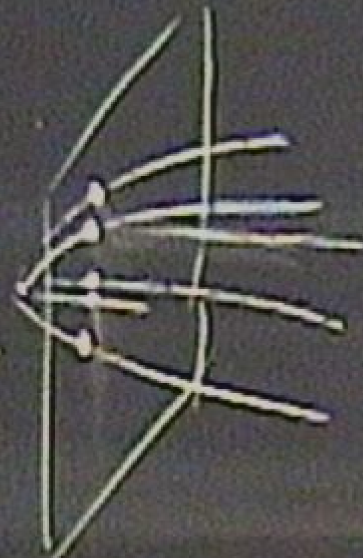
$$E_\zeta = e\,\frac{(z-z_0)}{\left[(z-z_0)^2 + X_1^2\right]^{3/2}}$$

$\rho = 1 =$ SMEN...

$$Z = \rho \cosh W$$


z0
Eρ = Ez = 4πσ
Ez = e (z − z0) / [(z − z0)² + X⊥²]^(3/2)
ρ = 1 = SMET...





$$E_\rho = E_z = 4\pi\sigma$$

$$E_z = e\,\frac{(z - z_0)}{\left[(z-z_0)^2 + X_\perp^2\right]^{3/2}}$$

$\rho = 1 =$ smear...

$$z = \rho_0 \cosh w$$

$$\rho e^{w}$$

$$Z = \rho_0 \cosh w$$

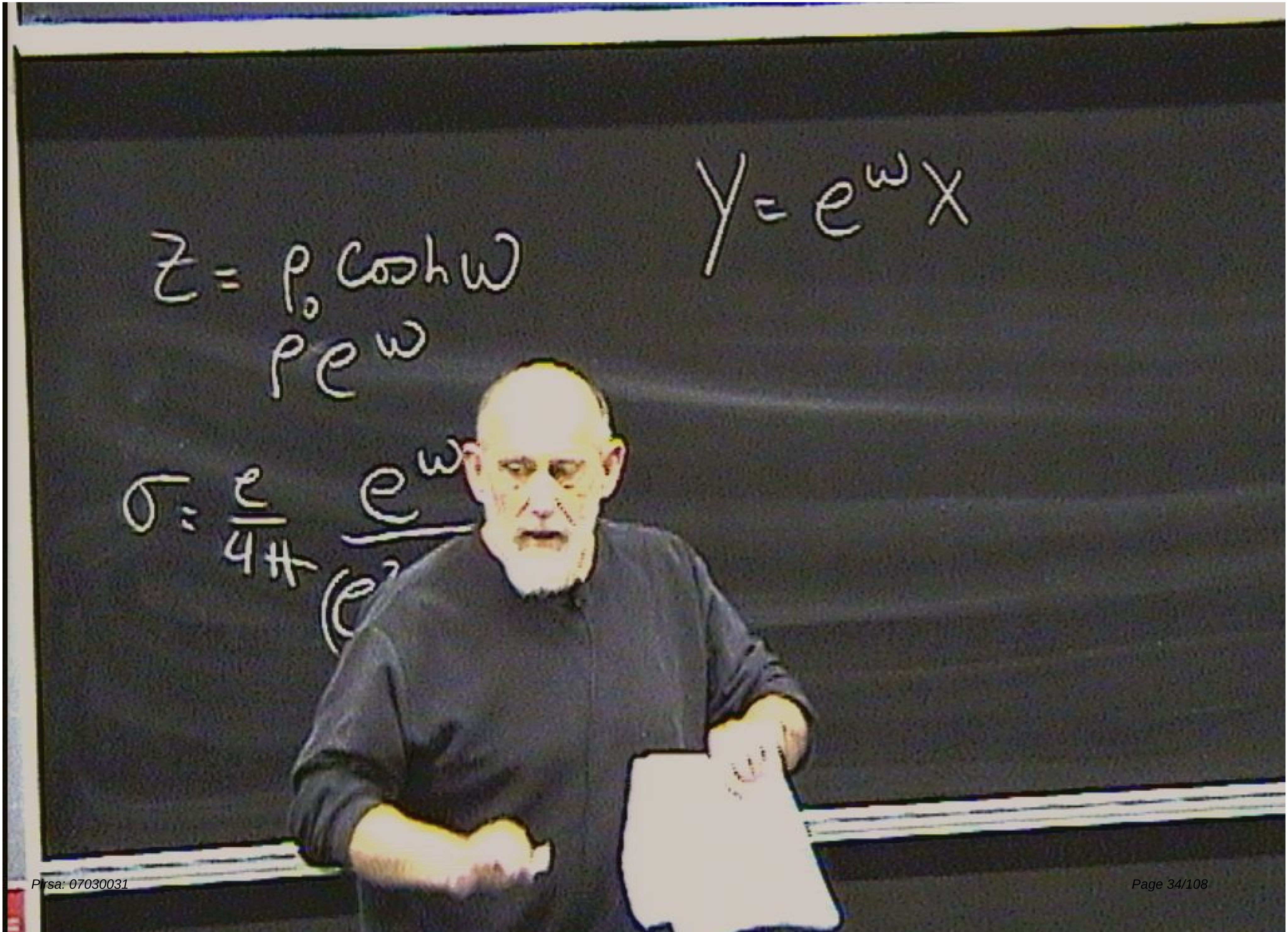
$$\rho e^{w}$$

$$\sigma = \frac{c}{4\pi}$$

$$z = \rho_0 \cosh \omega$$

$$\rho e^{\omega}$$

$$\sigma = \frac{e}{4\pi} \frac{e^{\omega}}{\left(e^{2\omega} + x_\perp^2\right)^{3/2}}$$


$Y = e^{w} X$
$Z = \rho_0 \cosh w$
ρe^{w}
$\sigma = \frac{e}{4\pi} \frac{e^{w}}{(e}$

$$Y = e^{\omega} X$$

$$Z = \rho_0 \cosh \omega$$

$$\rho e^{\omega}$$

$$\sigma = \frac{e}{4\pi} \frac{e^{\omega}}{\left(e^{2\omega} + X_{\perp}^2\right)^{3/2}} = \sigma = \frac{e}{4\pi} \frac{e^{-2\omega}}{\left(\rho_0^2 + Y_{\perp}^2\right)}$$

$$Z = \rho_0 \cosh \omega$$

$$\rho e^{\omega}$$

$$Y = e^{\omega} X$$

$$\frac{e}{4\pi} \frac{e^{\omega}}{\left(e^{2\omega} + X_\perp^2\right)^{3/2}} = \sigma = \frac{e}{4\pi} \frac{e^{-2\omega}}{\left(\rho_0^2 + Y_\perp^2\right)}$$

$$z = \rho_0 \cosh w$$

$$\rho e^{w}$$

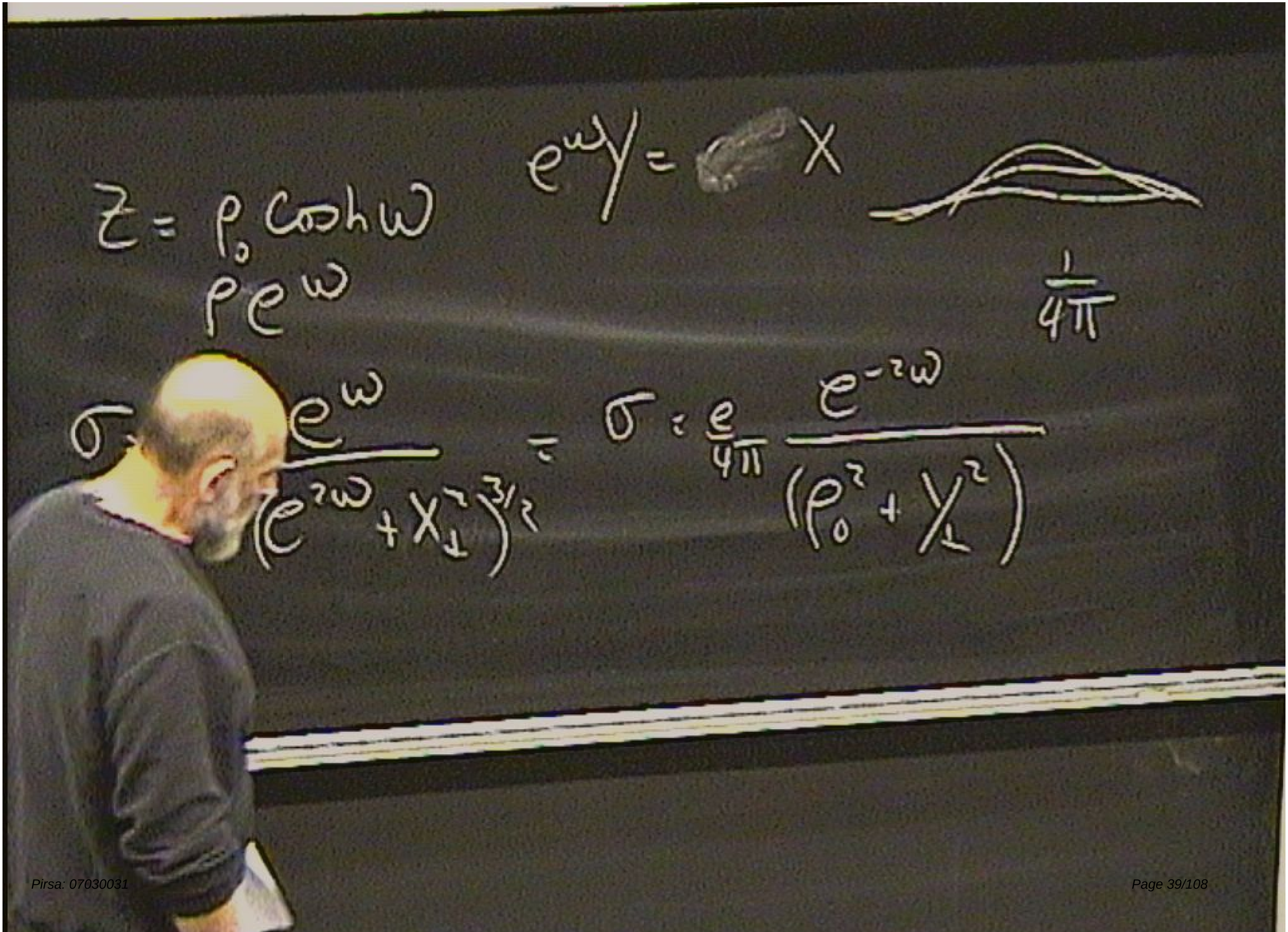
$$e^{w} y = \quad x$$

$$\sigma = \frac{e}{4\pi} \frac{e^{w}}{\left(e^{2w} + x_\perp^2\right)^{3/2}} = \sigma = \frac{e}{4\pi} \frac{e^{-2w}}{\left(\rho_0^2 + y_\perp^2\right)}$$

$$Z = \rho_0 \cosh \omega \qquad e^{\omega} Y = \quad X$$

$$\rho e^{\omega}$$

$$\sigma = \frac{e}{4\pi} \frac{e^{\omega}}{\left(e^{2\omega} + X_\perp^2\right)^{3/2}} = \sigma = \frac{e}{4\pi} \frac{e^{-2\omega}}{\left(\rho_0^2 + Y_\perp^2\right)}$$


$z = \rho_0 \cosh \omega$
ρe^{ω}
$e^{\omega} Y = X$
$\frac{1}{4\pi}$
$\sigma \; \frac{e^{\omega}}{(e^{2\omega} + X_1^2)^{3/2}} =$
$\sigma = \frac{e}{4\pi} \frac{e^{-2\omega}}{(\rho_0^2 + Y_1^2)}$

$$Z = \rho_0 \cosh w$$

$$\rho e^{w}$$

$$e^{w} = \frac{2MG}{r_p}$$

$$w = \log \frac{2MG}{r_p}$$

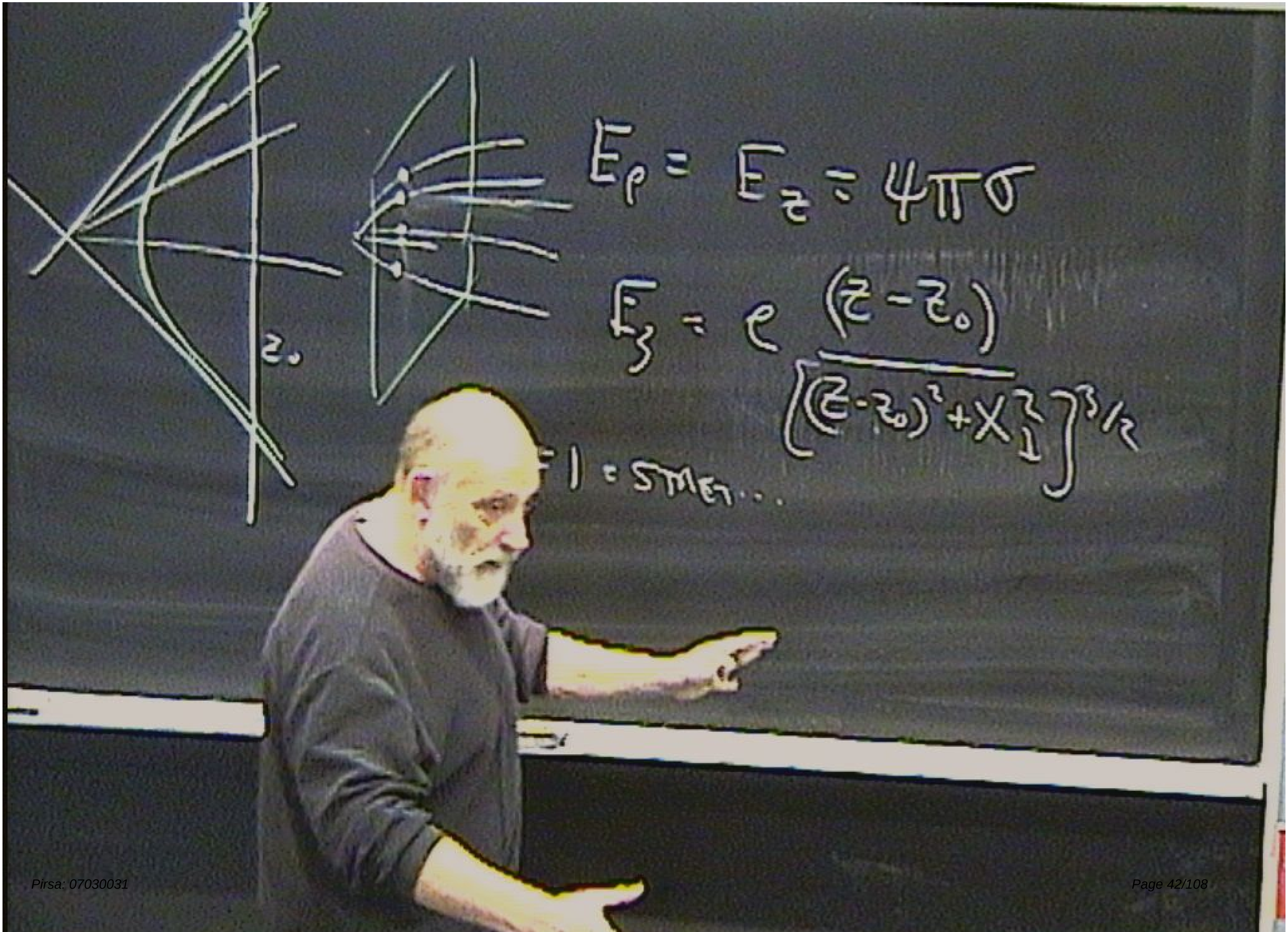
$$\frac{1}{4\pi}$$

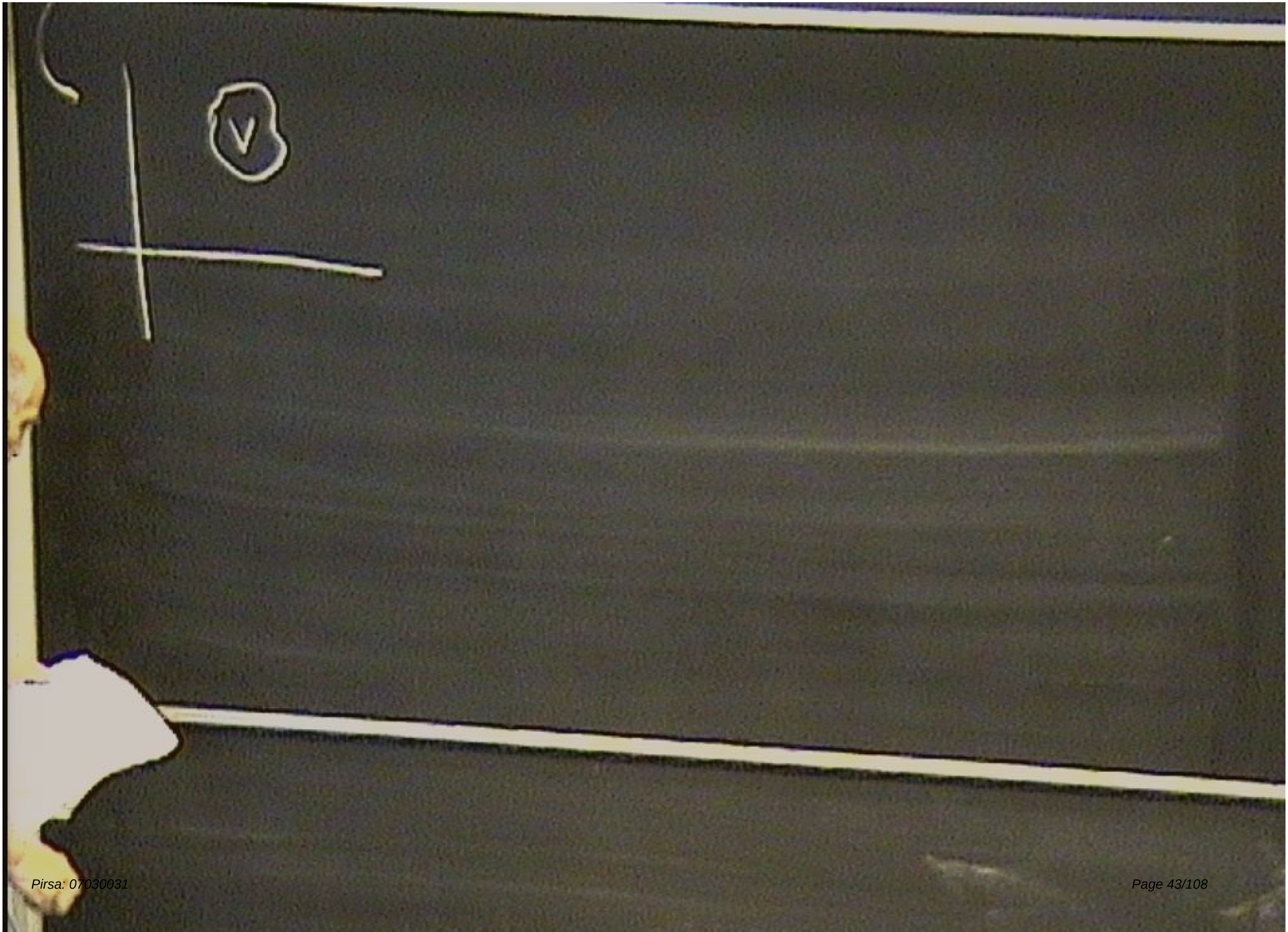
$$\sigma = \frac{e}{4\pi} \frac{e^{w}}{\left(e^{2w} + X_\perp^2\right)^{3/2}} = \sigma = \frac{e}{4\pi} \frac{e^{-2w}}{\left(\rho_0^2 + X_\perp^2\right)}$$

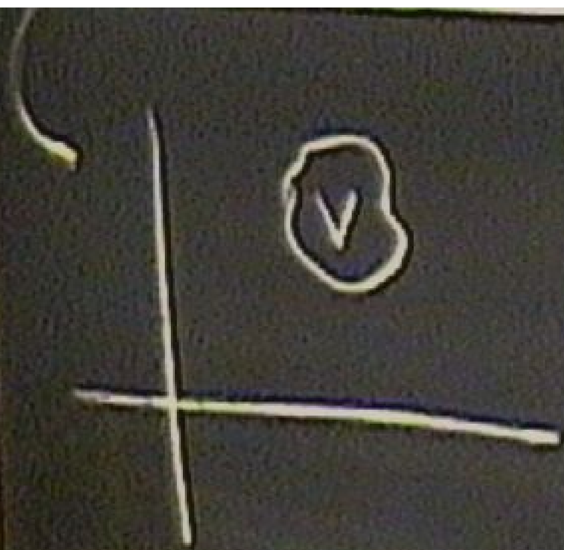
$$z = \rho_0 \cosh \omega \qquad e^{\omega} = \frac{2MG}{r_p}$$

$$\rho e^{\omega} \qquad t = 4MG \log \frac{2MG}{r_p} \qquad \frac{1}{4\pi}$$

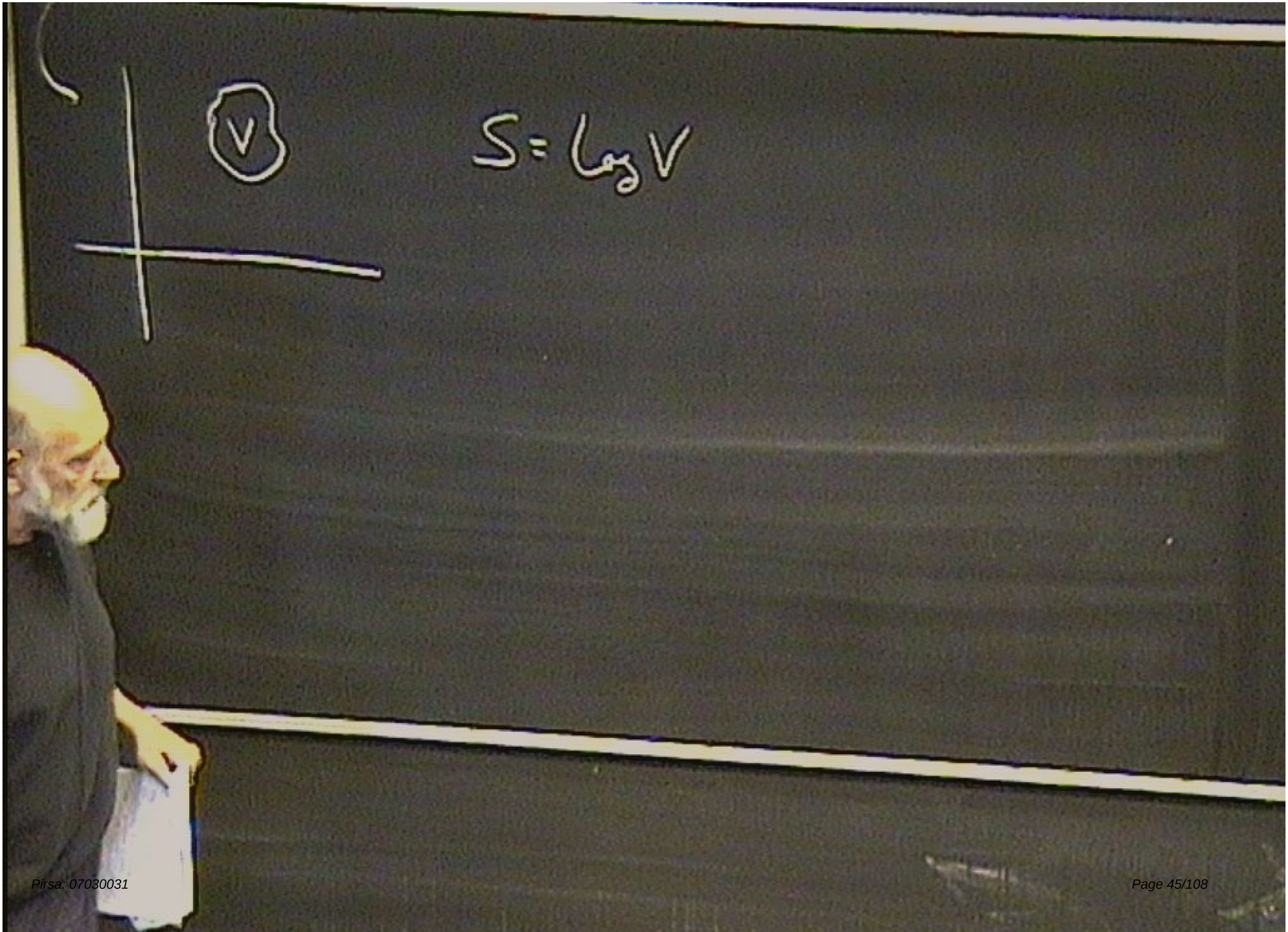
$$\sigma = \frac{e}{4\pi} \frac{e^{\omega}}{\left(e^{2\omega} + X_\perp^2\right)^{3/2}} = \sigma = \frac{e}{4\pi} \frac{e^{-2\omega}}{\left(\rho_0^2 + X_\perp^2\right)}$$

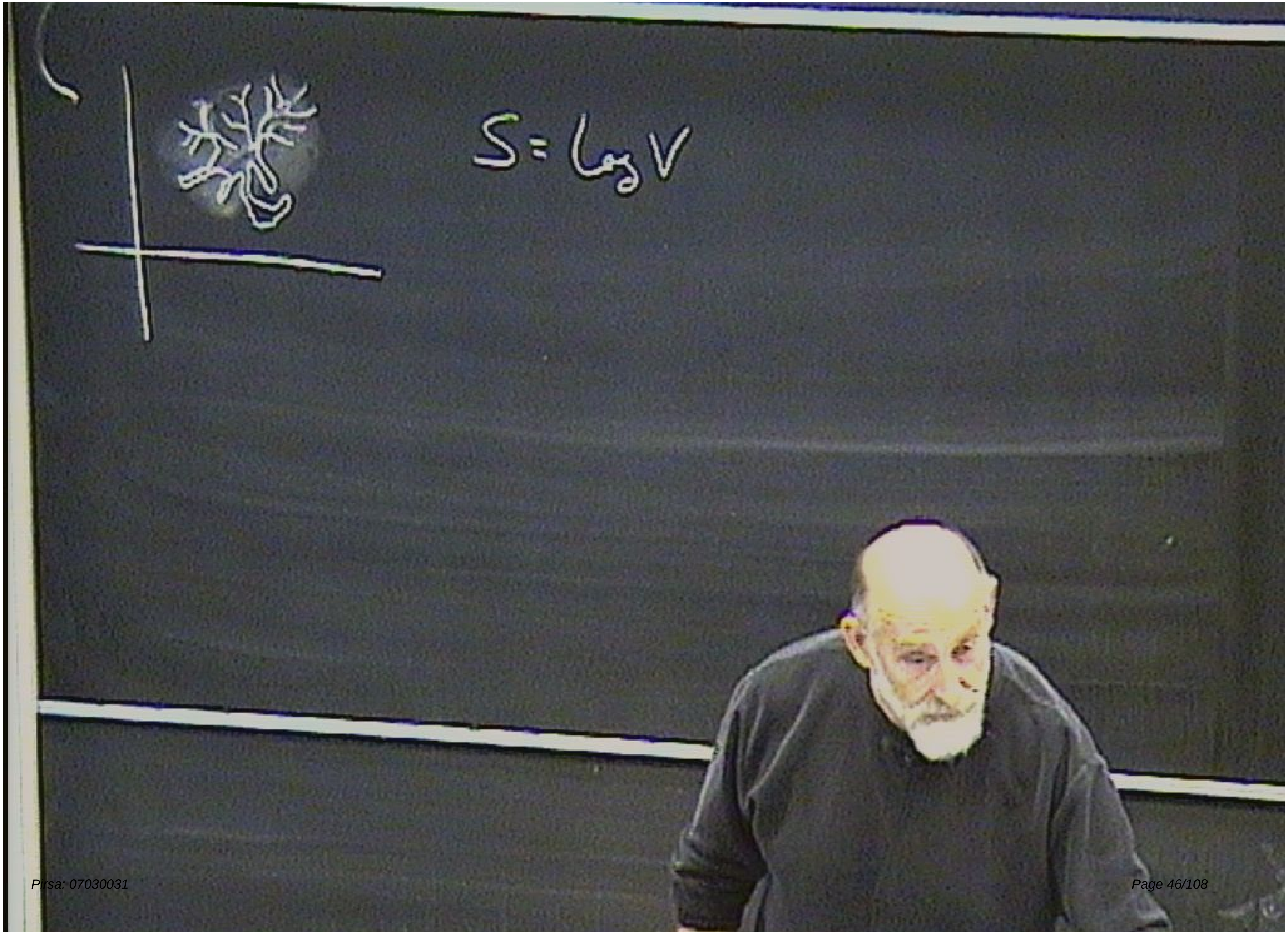

$E_\rho = E_z = 4\pi\sigma$
$E_z = e \frac{(z - z_0)}{[(z-z_0)^2 + X_1^2]^{3/2}}$
z_0

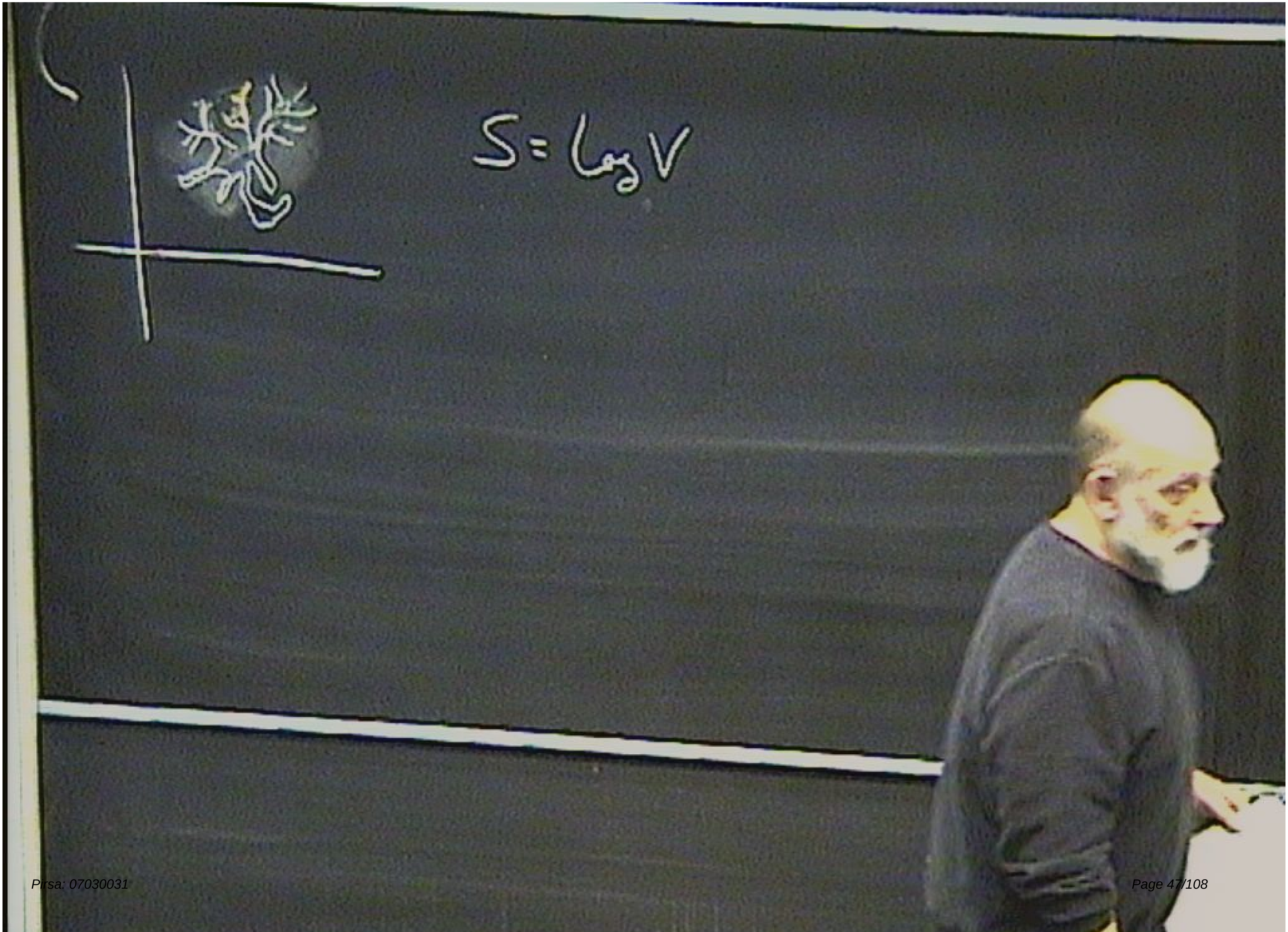

V

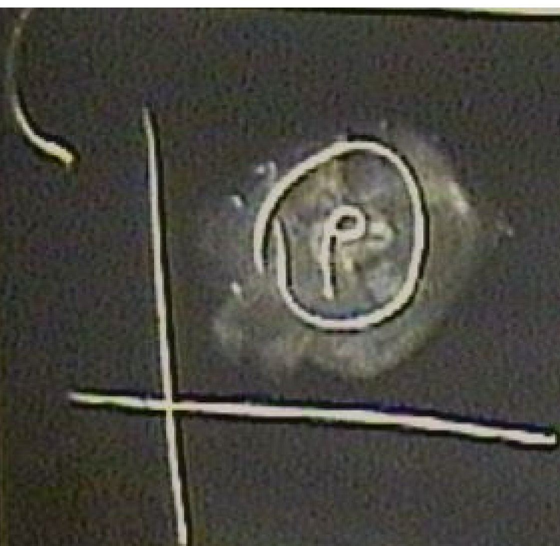


$S = \log V$

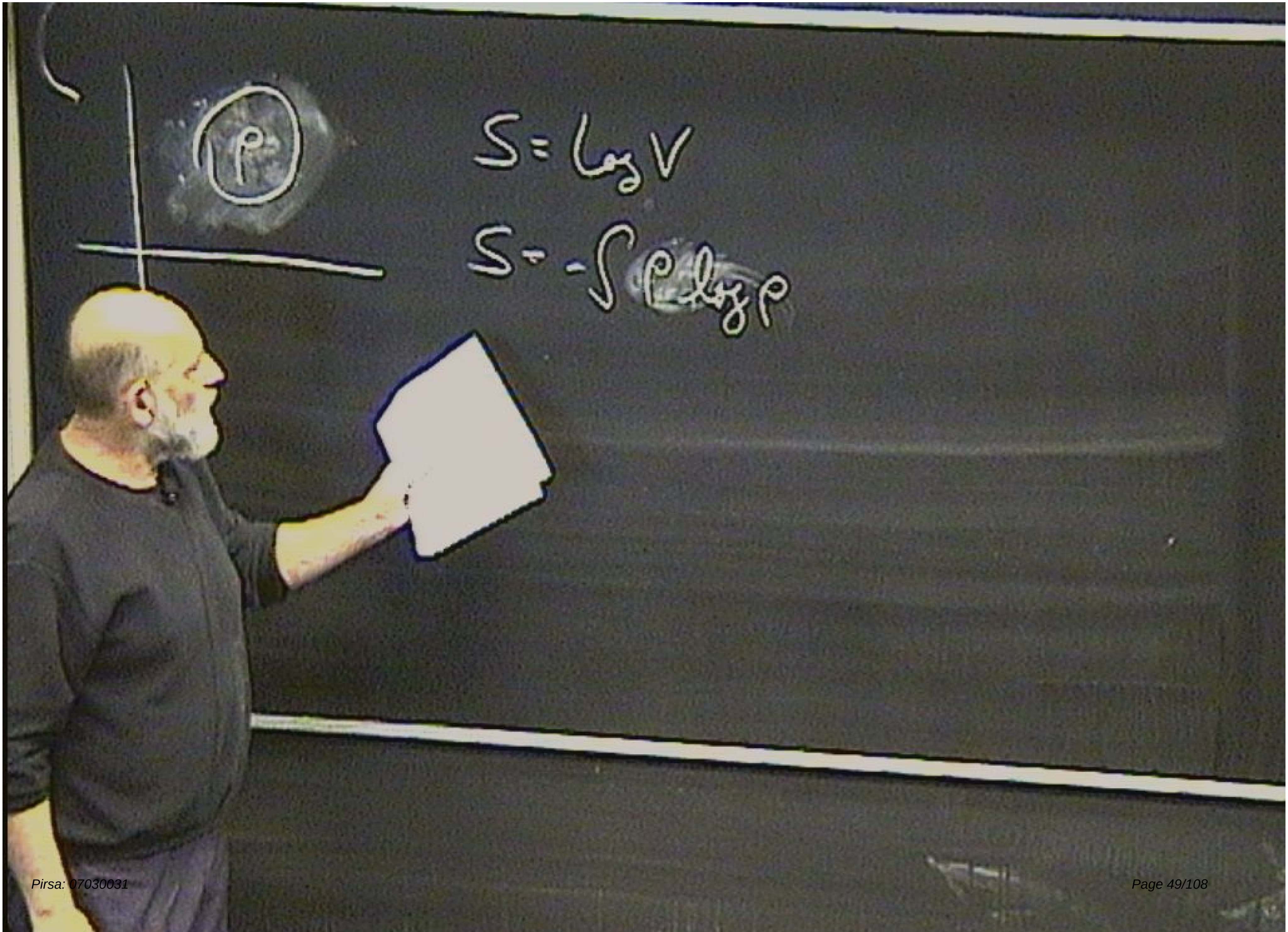

V
S = Log V


S = Log V


S = Log V



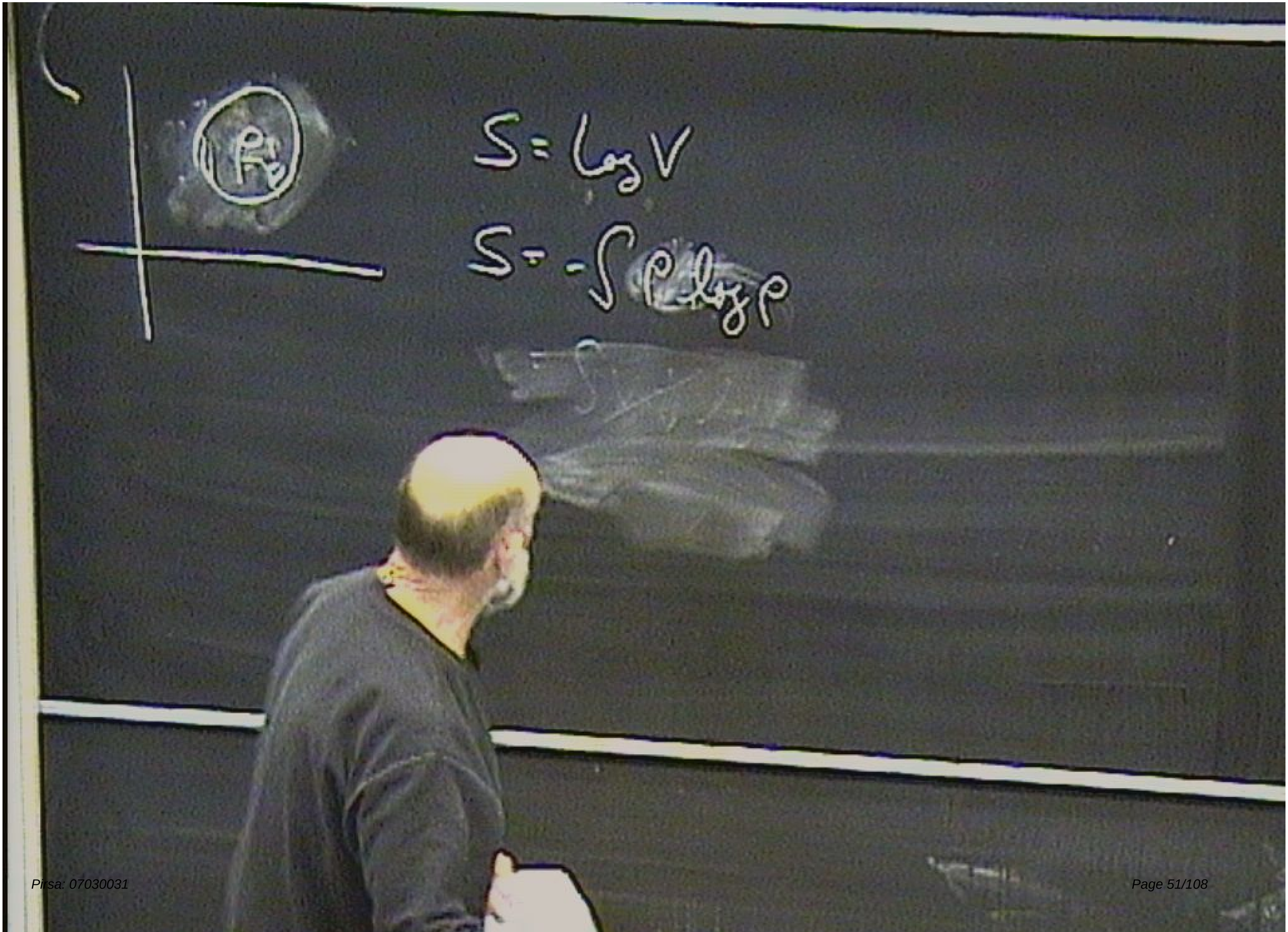
$$S = \log V$$

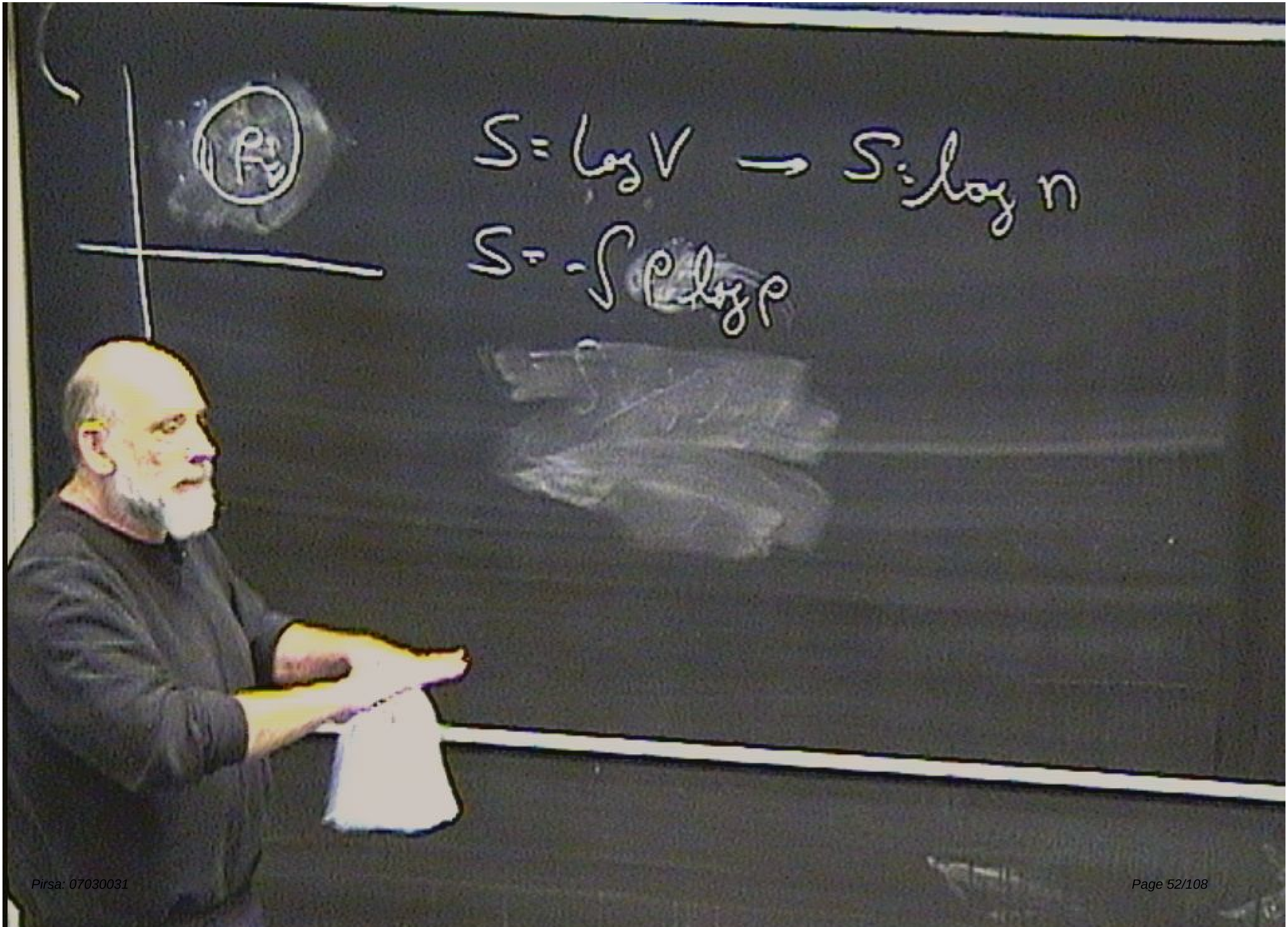

ρ
S = Log V
S = -∫ ρ log ρ

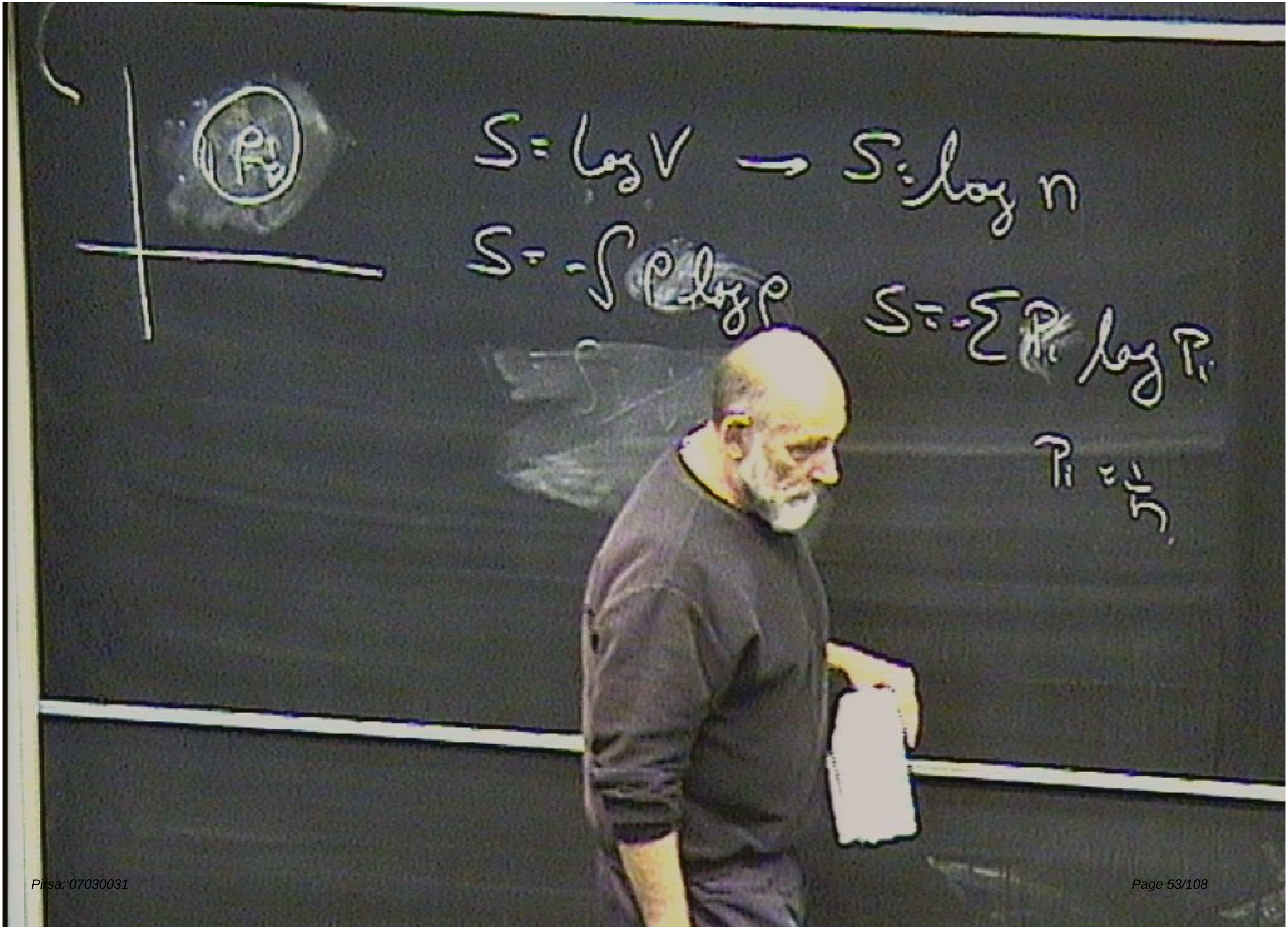
$$S = \log V$$

$$S = -\int \rho \log \rho$$

$$= \int \cancel{V}\frac{1}{\cancel{V}} \log V$$


S = log V
S = -∫ ρ log ρ


$S = \log V \rightarrow S = \log n$
$S = -\int \rho \log \rho$


S = log V → S = log n
S = -∫ ρ log ρ
S = -Σ P_i log P_i
P_i = 1/n

$$S = \log V \rightarrow S = \log n$$

$$S = -\int \rho \log \rho \qquad S = -\sum P_i \log P_i$$

$$\rho = \qquad\qquad P_i = \frac{1}{n}$$

$$S = \log V \longrightarrow S = \log n$$

$$S = -\int \rho \log \rho \qquad S = -\sum P_i \log P_i$$

$$\rho = \begin{pmatrix} p_1 & & 0 \\ & p_2 & \\ 0 & & p_3 \\ & & & \ddots \end{pmatrix} \qquad P_i = \frac{1}{n}$$

$S = \log V \rightarrow S = \log n$

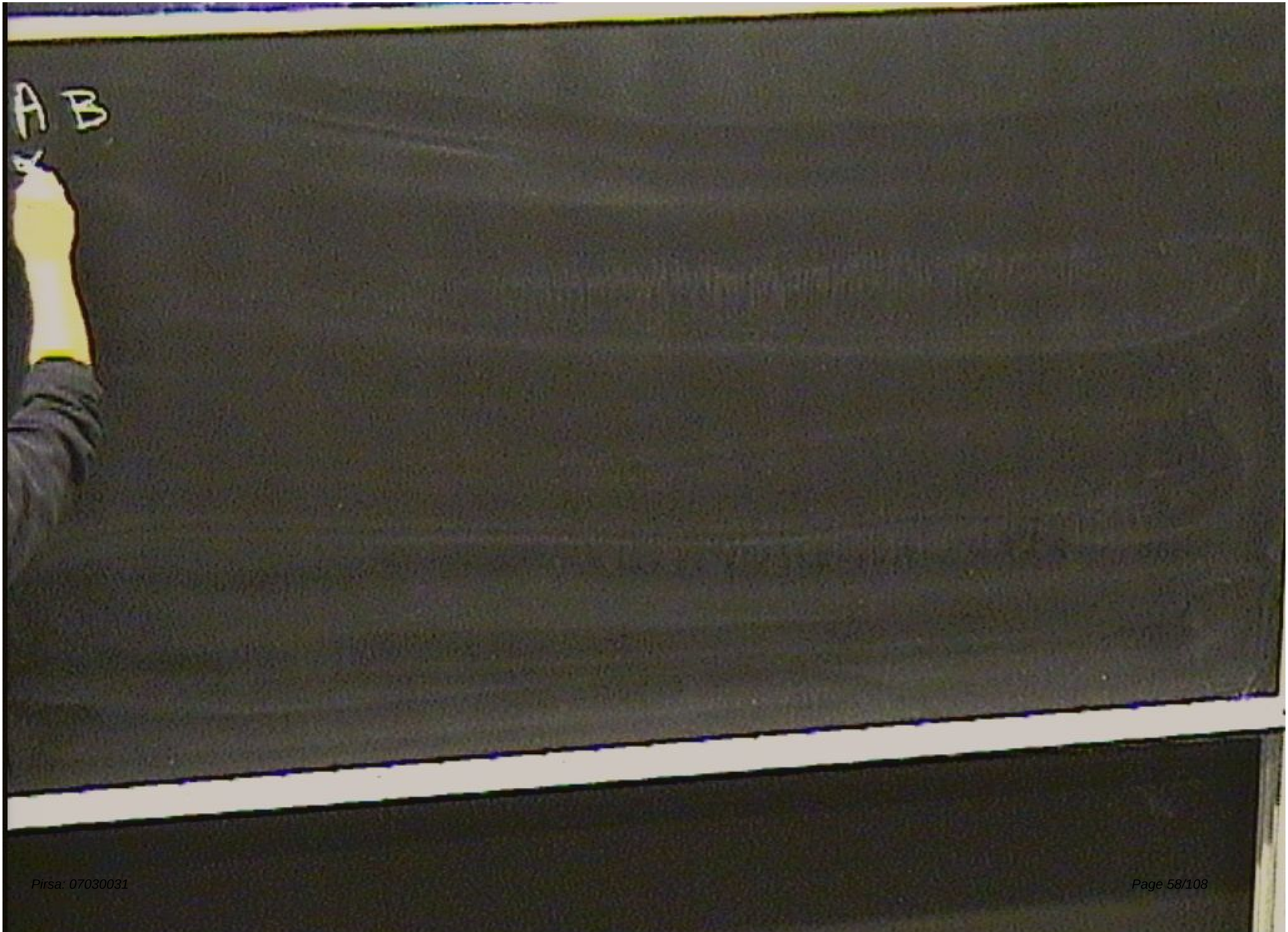
$S = -\int \rho \log \rho \qquad S = -\sum P_i \log P_i$

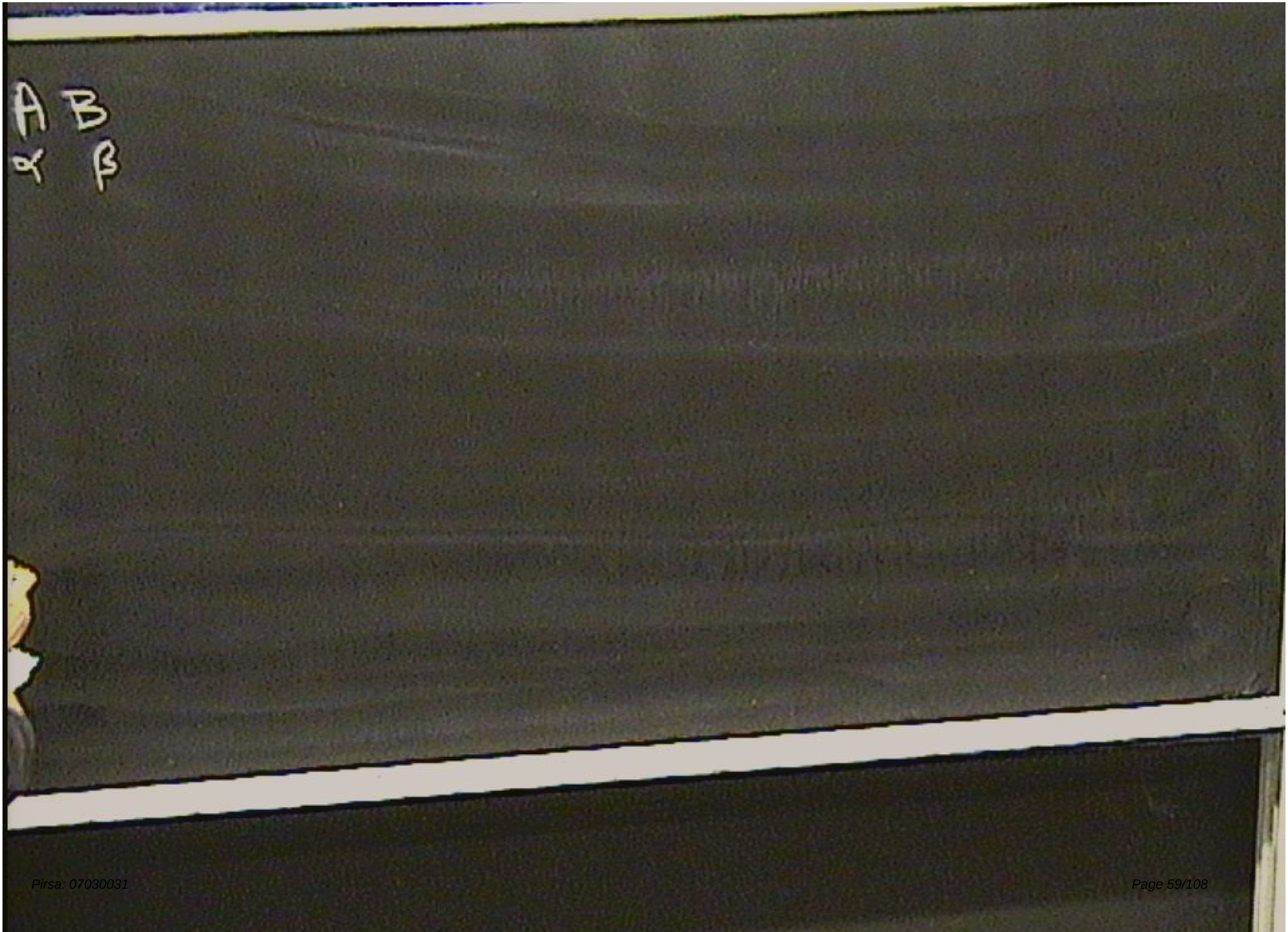
$$\rho = \begin{pmatrix} P_1 & & 0 \\ & P_1 & \\ 0 & & P_1 \\ & & & \ddots \end{pmatrix} \quad \boxed{S = -\mathrm{Tr}\, \rho \log \rho} \quad P_i = \frac{1}{n}$$

$S = \log V \rightarrow S = \log n$

$S = -\int \rho \log \rho \qquad S = -\sum P_i \log P_i$

$$\rho = \begin{pmatrix} \ddots & & 0 \\ 0 & \ddots & \\ & & \ddots \end{pmatrix} \quad \boxed{S = -\mathrm{Tr}\, \rho \log \rho} \quad P_i = \frac{1}{n}$$


A B


A B
α β

$A \quad B$

$\alpha \quad \beta$

$\psi(\alpha\beta)$

$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$

$A \quad B$

$\alpha \quad \beta$

$$\psi(\alpha\beta)$$

$$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$$

$$\rho_B = \psi^*(\alpha\beta)\psi(\alpha\beta')$$

$A \quad B$

$\alpha \quad \beta$

$$\psi(\alpha\beta)$$

$$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$$

$$\rho_B = \psi^*(\alpha\beta)\psi(\alpha\beta')$$

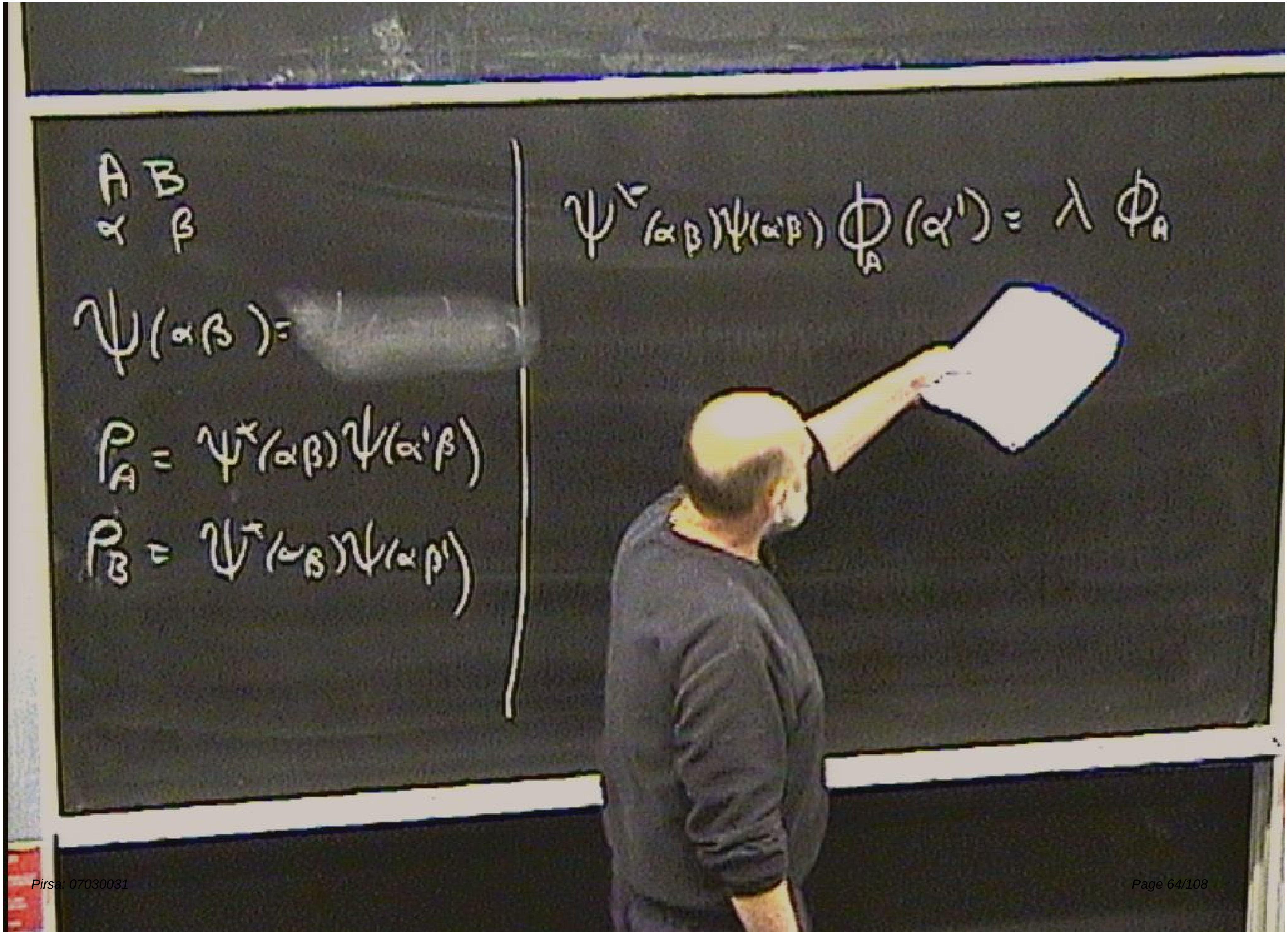
$A \quad B$

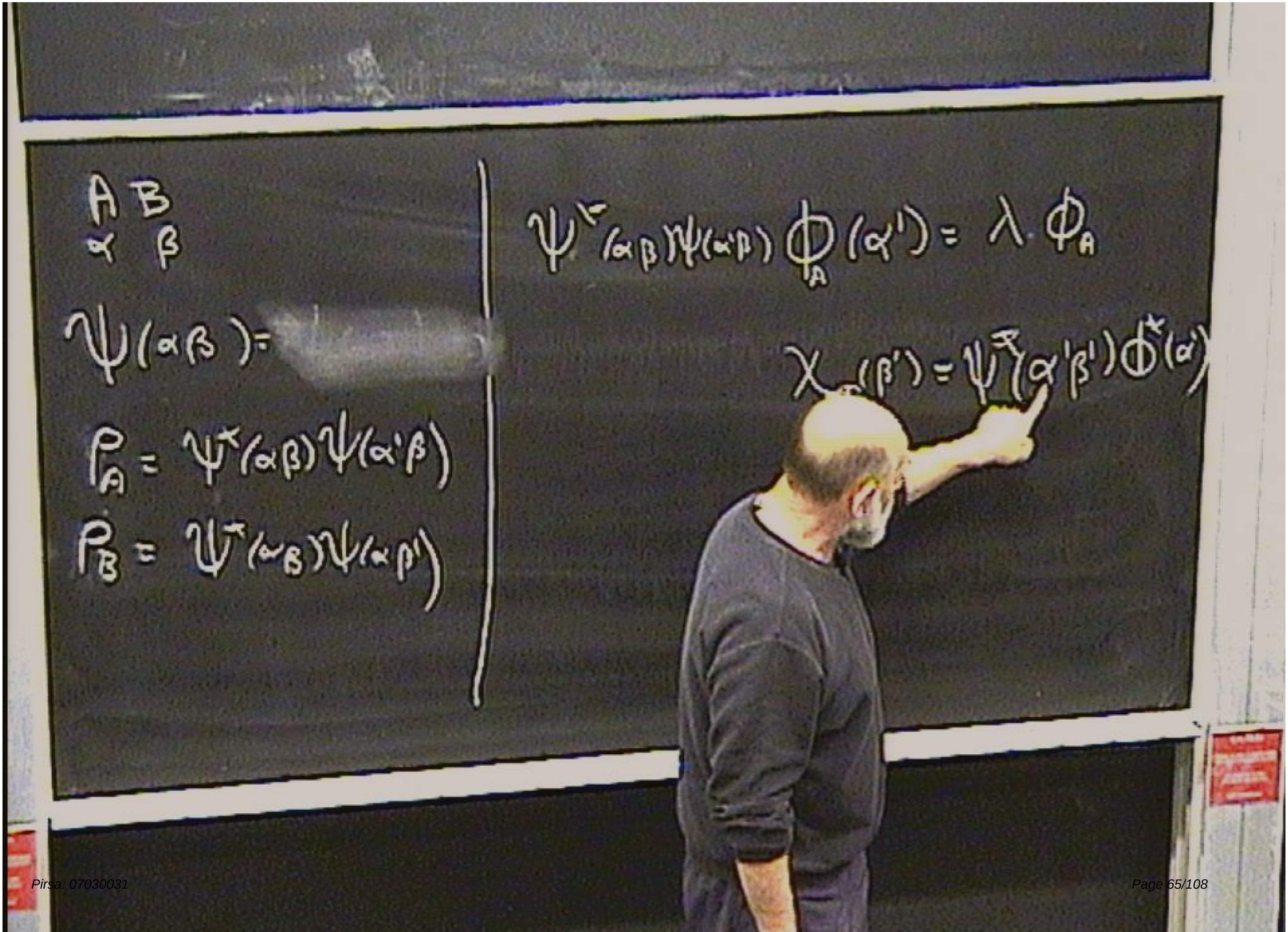
$\alpha \quad \beta$

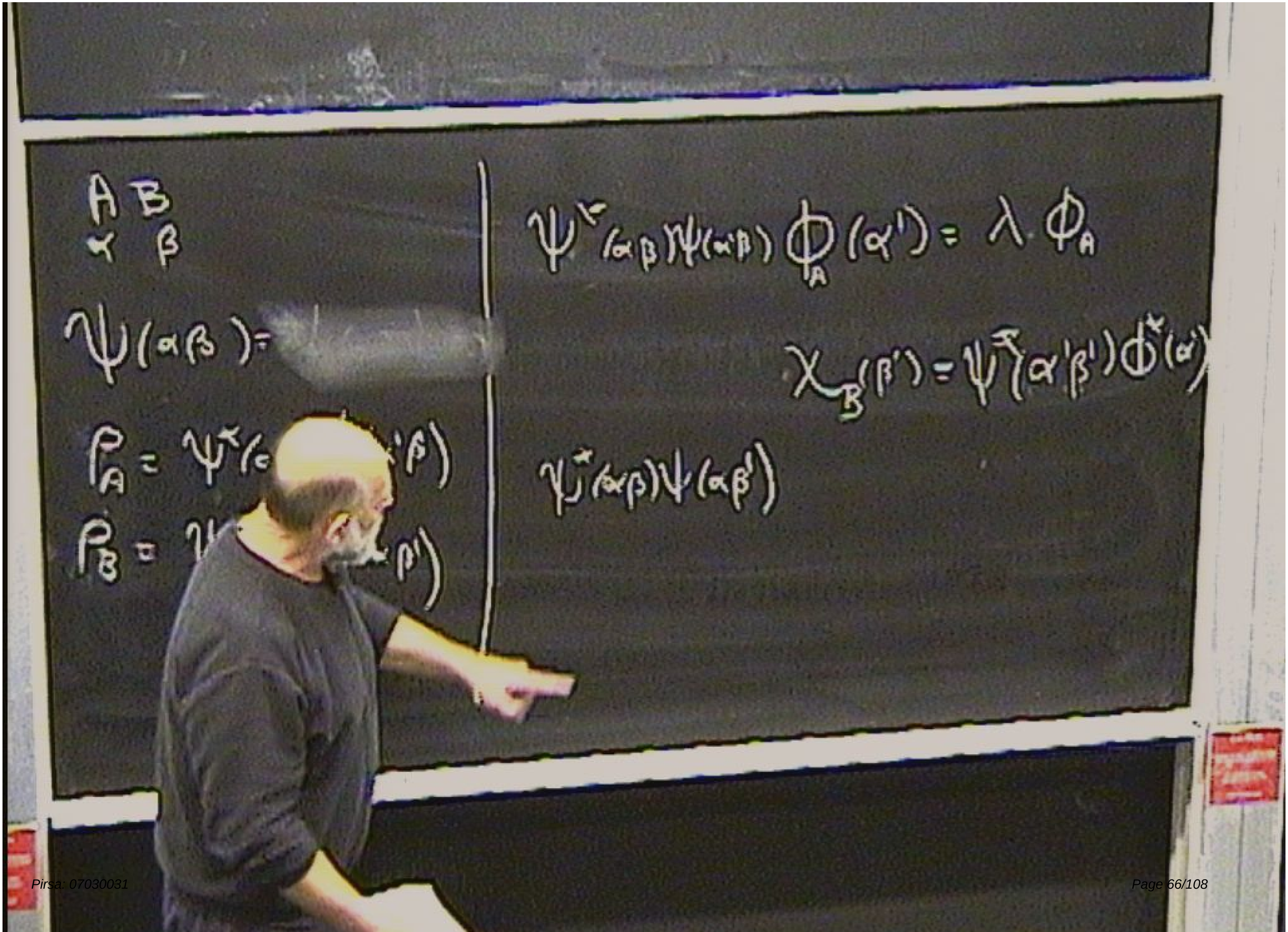
$\psi(\alpha\beta) =$

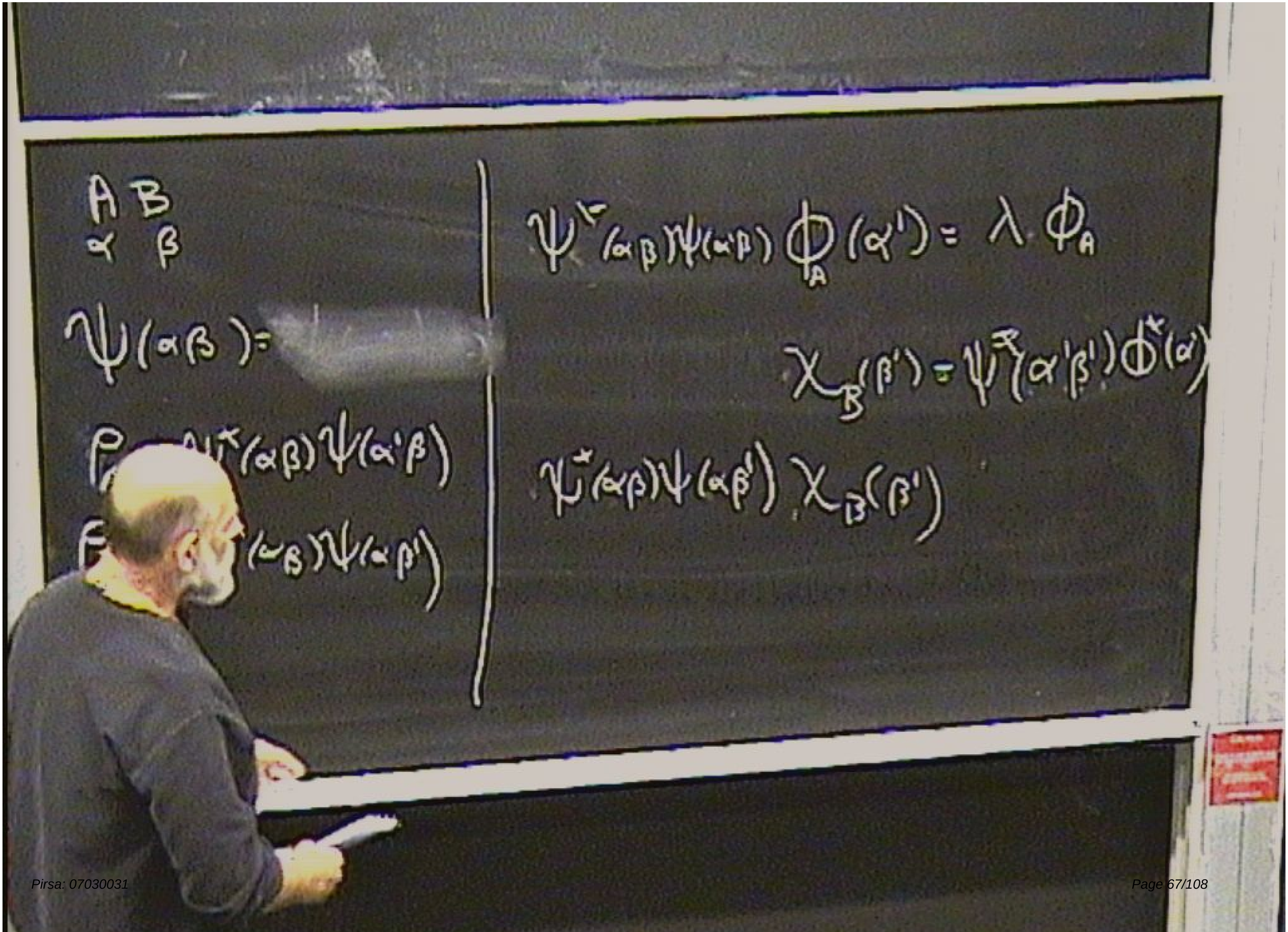
$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$

$\rho_B = \psi^*(\alpha\beta)\psi(\alpha\beta')$


A B
α β
$\psi(\alpha\beta) =$
$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$
$\rho_B = \psi^*(\alpha\beta)\psi(\alpha\beta')$
$\psi^*(\alpha\beta)\psi(\alpha'\beta)\phi_A(\alpha') = \lambda\phi_A$


A B
α β
$\psi(\alpha\beta) =$
$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$
$\rho_B = \psi^*(\alpha\beta)\psi(\alpha\beta')$
$\psi^*(\alpha\beta)\psi(\alpha'\beta)\,\phi_A(\alpha') = \lambda\,\phi_A$
$\chi(\beta') = \psi^*(\alpha'\beta')\,\phi^*(\alpha')$


A B
α β
$\psi(\alpha\beta) =$
$\psi^*(\alpha\beta)\psi(\alpha'\beta)\,\phi_A(\alpha') = \lambda\,\phi_A$
$\chi_B(\beta') = \psi^*(\alpha'\beta')\phi^*(\alpha')$
$\psi^*(\alpha\beta)\psi(\alpha\beta')$


A B
α β
ψ(αβ)=
ψ*(αβ)ψ(α'β) φ_A(α') = λ φ_A
χ_B(β') = ψ*(α'β') φ*(α')
ψ*(αβ)ψ(αβ') χ_B(β')

$A \quad B$

$\alpha \quad \beta$

$$\psi(\alpha\beta) =$$

$$\rho_A = \psi^*(\alpha\beta)\psi(\alpha'\beta)$$

$$\rho_B = \psi^*(\alpha\beta)\psi(\alpha\beta')$$

$$\psi^*(\alpha\beta)\psi(\alpha'\beta)\,\phi_A(\alpha') = \lambda\,\phi_A$$

$$\chi_B(\beta') = \underline{\psi^*(\alpha'\beta')\phi^*(\alpha')}$$

$$\psi^*(\alpha\beta)\psi(\alpha\beta')\,\chi_B(\beta')$$

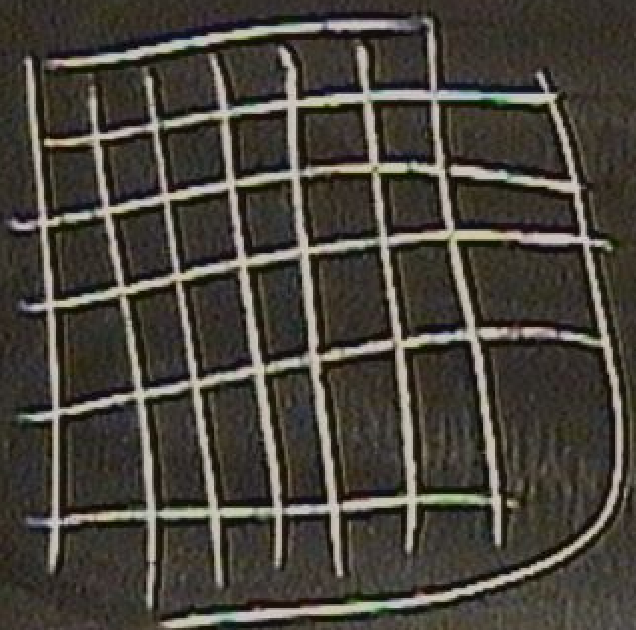
$S_A = S_B$

$$S_A = S_B$$

$$S_{A+B} = 0$$

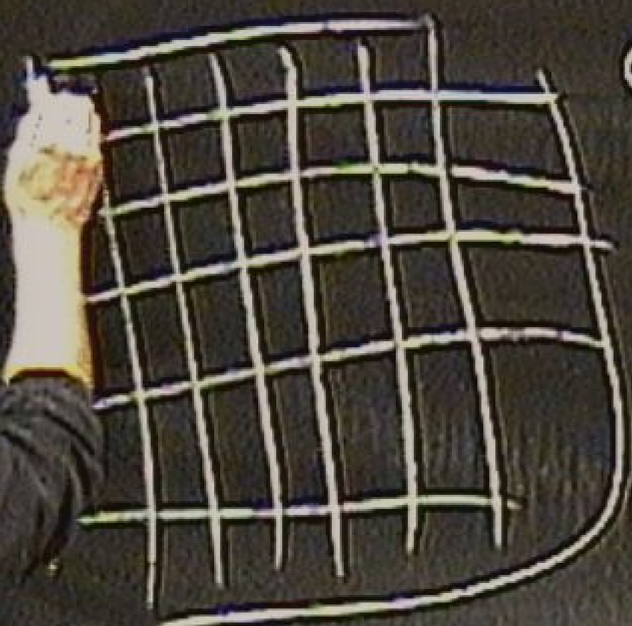
$$S_A = S_B$$

$$S_{A+B} = 0$$



$S_A = S_B$

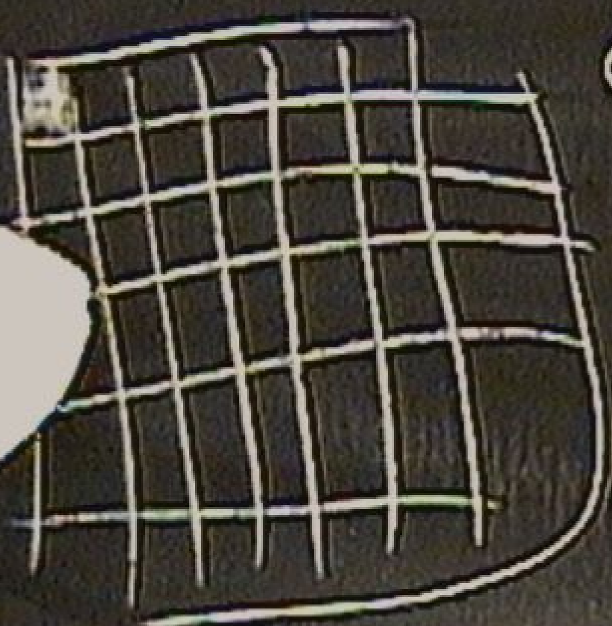
$S_{A+B} = 0$



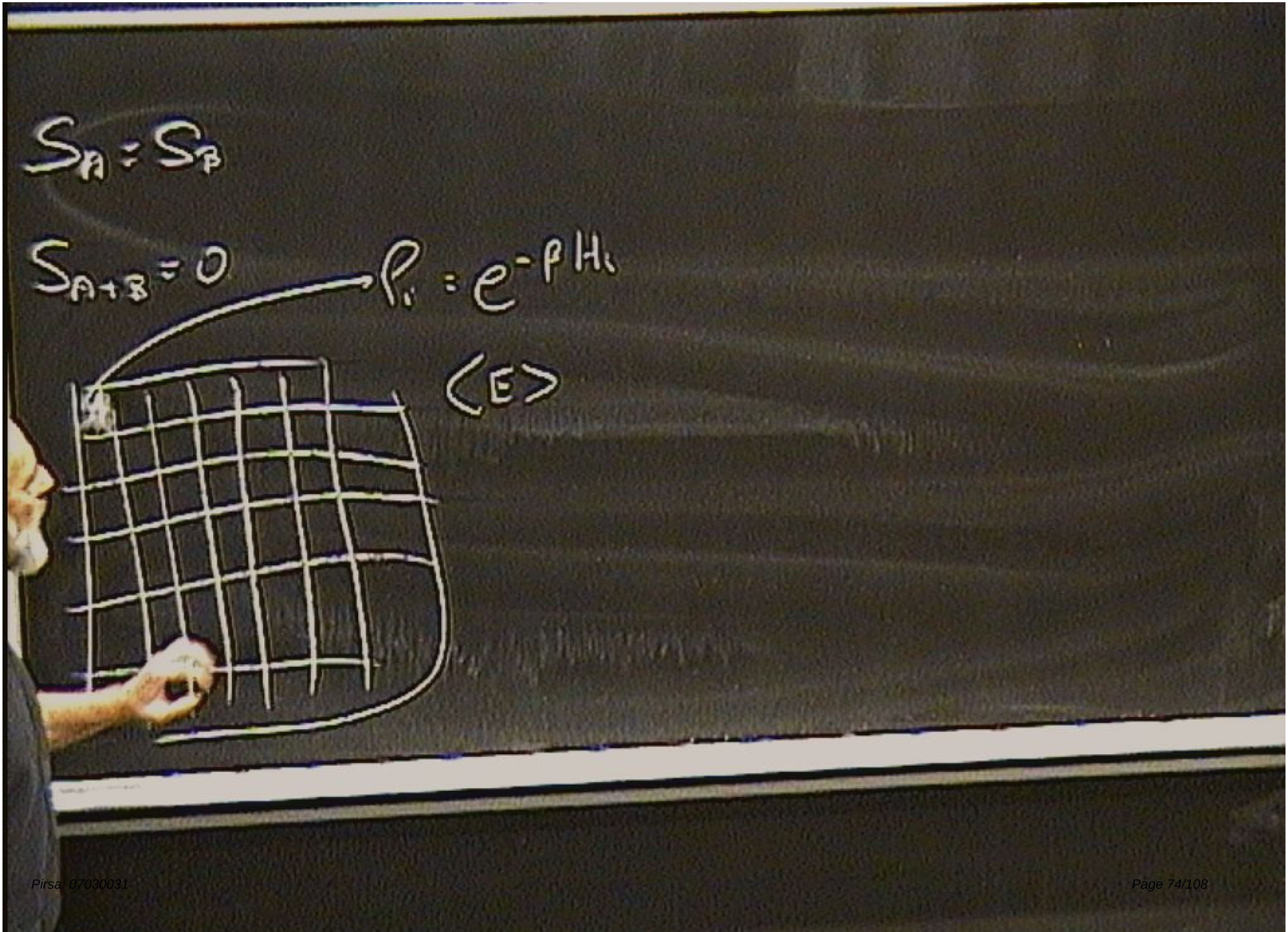
$\langle E \rangle$

$S_A = S_B$

$S_{A+B} = 0$



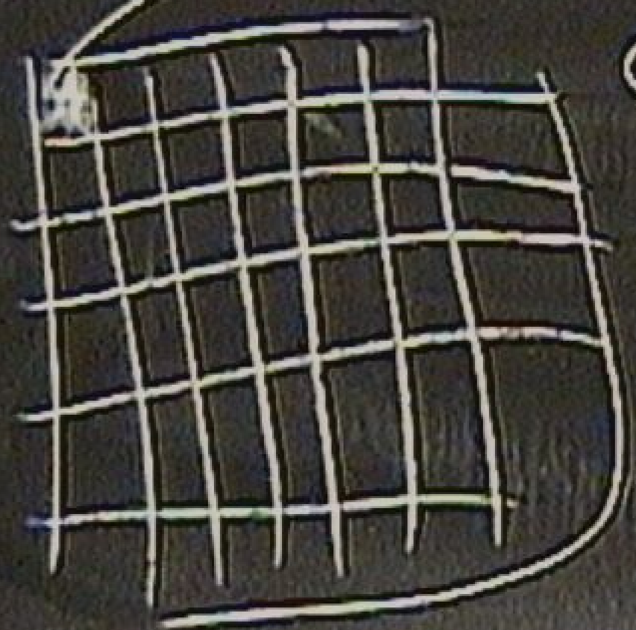
$\langle E \rangle$

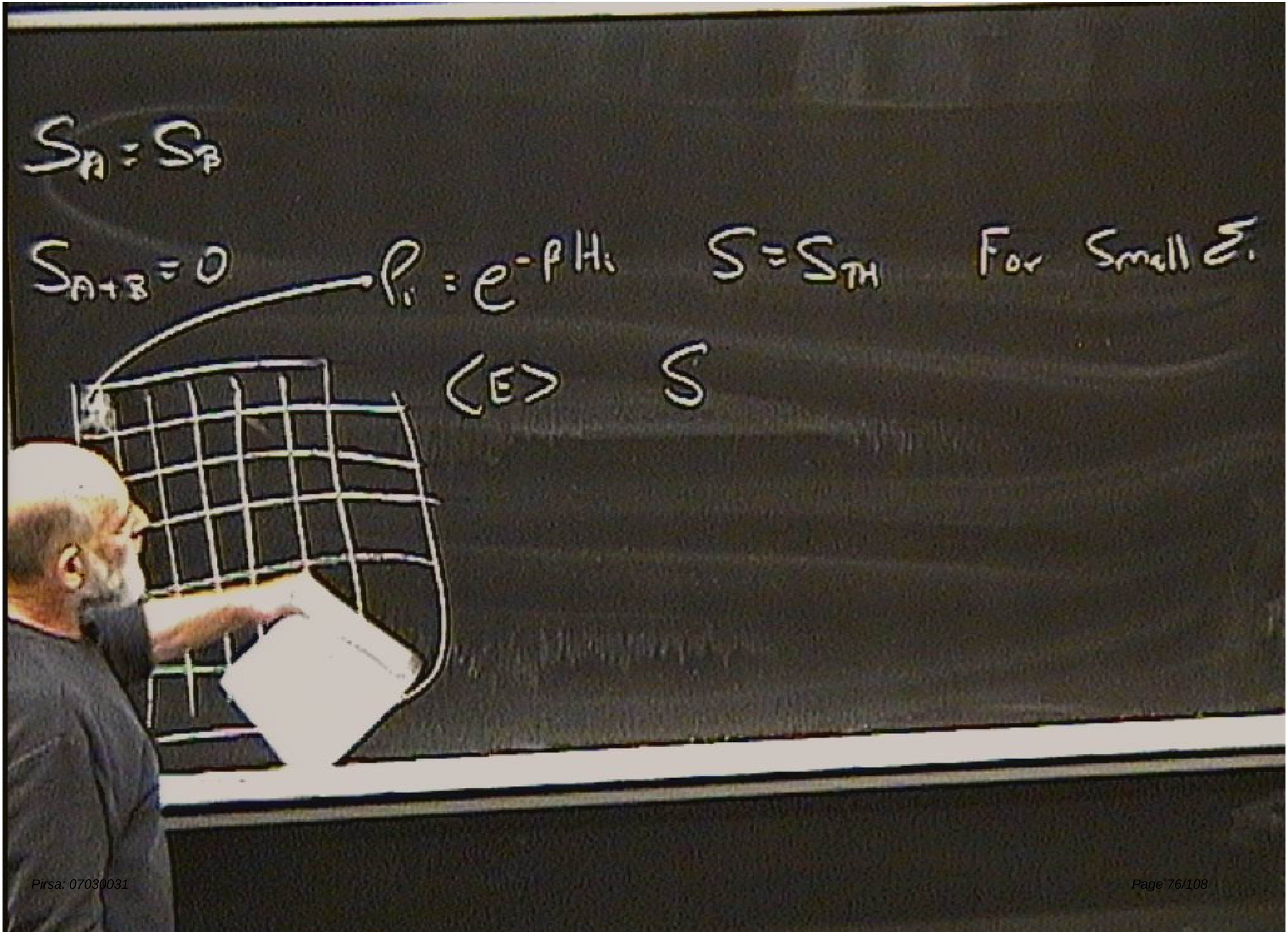

$S_A = S_B$
$S_{A+B} = 0$
$\rho_i = e^{-\beta H_i}$
$\langle E \rangle$

$S_A = S_B$

$S_{A+B} = 0$ $\rho_i = e^{-\beta H_i}$ $S = S_{TH}$ For Small

$\langle E \rangle$

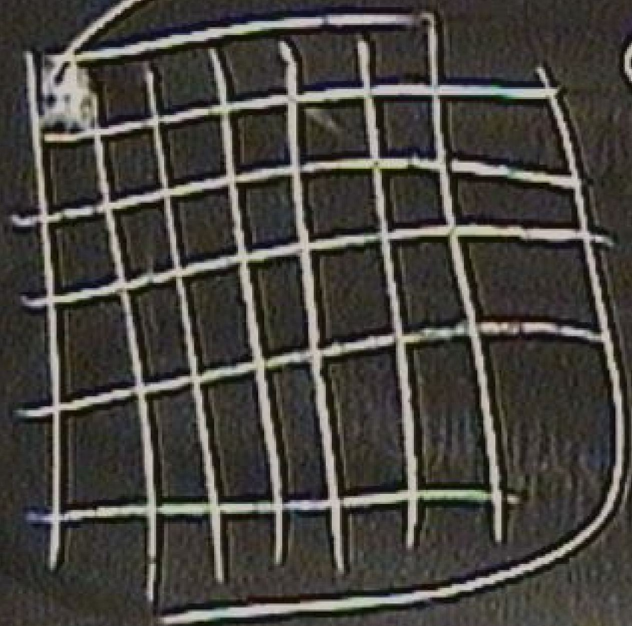



$S_A = S_B$
$S_{A+B} = 0$
$\rho_i = e^{-\beta H_i}$
$S = S_{TH}$
For Small ε.
$\langle E \rangle$
S

$S_A = S_B$

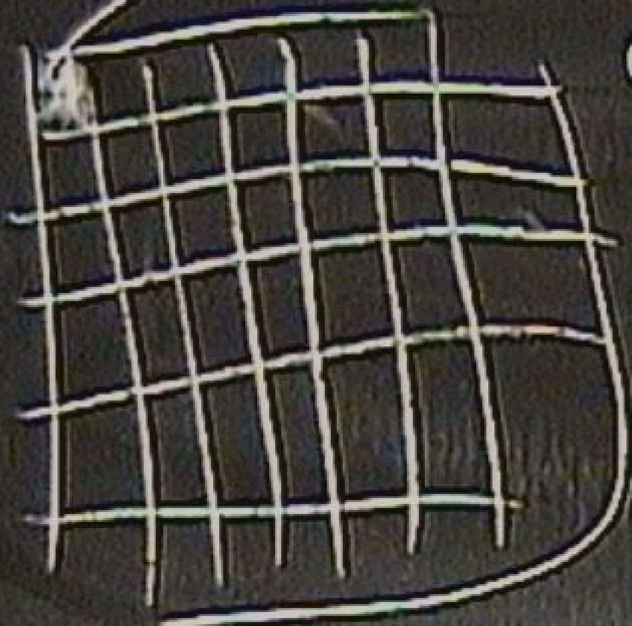
$S_{A+B} = 0$ $\quad \rho_i = e^{-\beta H_i} \quad S = S_{TH}$ For small ε_i

$\langle E \rangle \qquad S_{THER} \equiv \sum S_{TH}(i)$



$S_A = S_B$

$S_{A+B} = 0$ $\rho_i = e^{-\beta H_i}$ $S = S_{TH}$ For Small ε_i

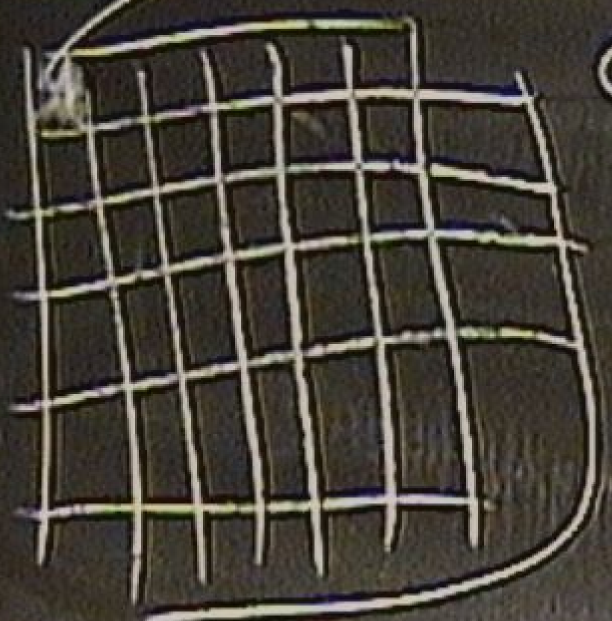


$\langle E \rangle$ $S_{THER} \equiv \sum S_{TH}(i)$

$S_\varepsilon \leq S_{THERMAL}$

$S_A = S_B$

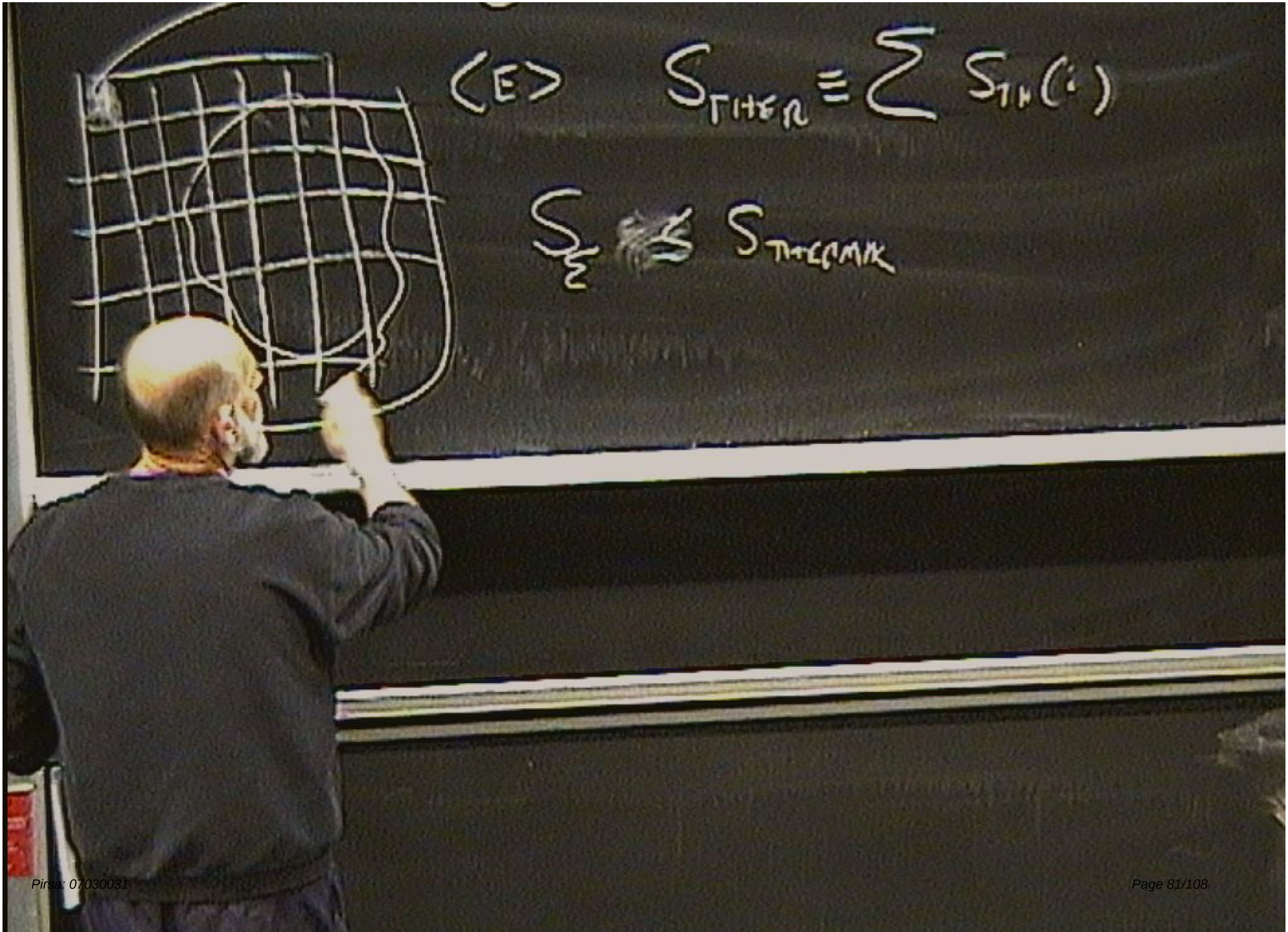
$S_{A+B} = 0$ $\rho_i = e^{-\beta H_i}$ $S = S_{TH}$ For Small $\mathcal{E}_i$

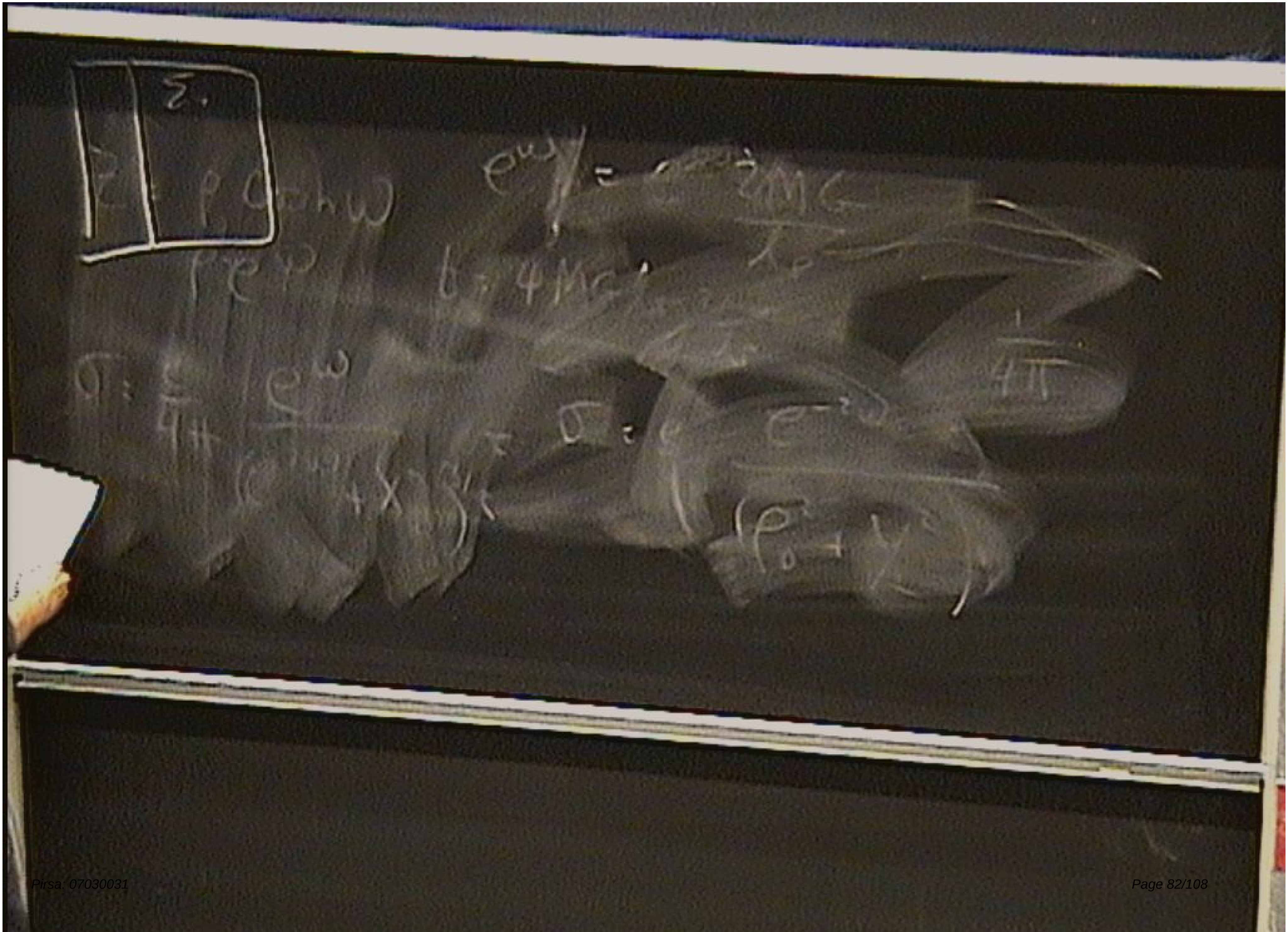


$\langle E \rangle$ $S_{THER} \equiv \sum S_{TH}(i)$

$S_\mathcal{E} \leq S_{THERMAL}$

$$I = S_{\text{THERMAL}} - S$$


<E>


Σ.
ρ cosh ω
b = 4MG
4π

$\Sigma = \Sigma$ $\quad \Sigma_0$

$= f \Sigma$

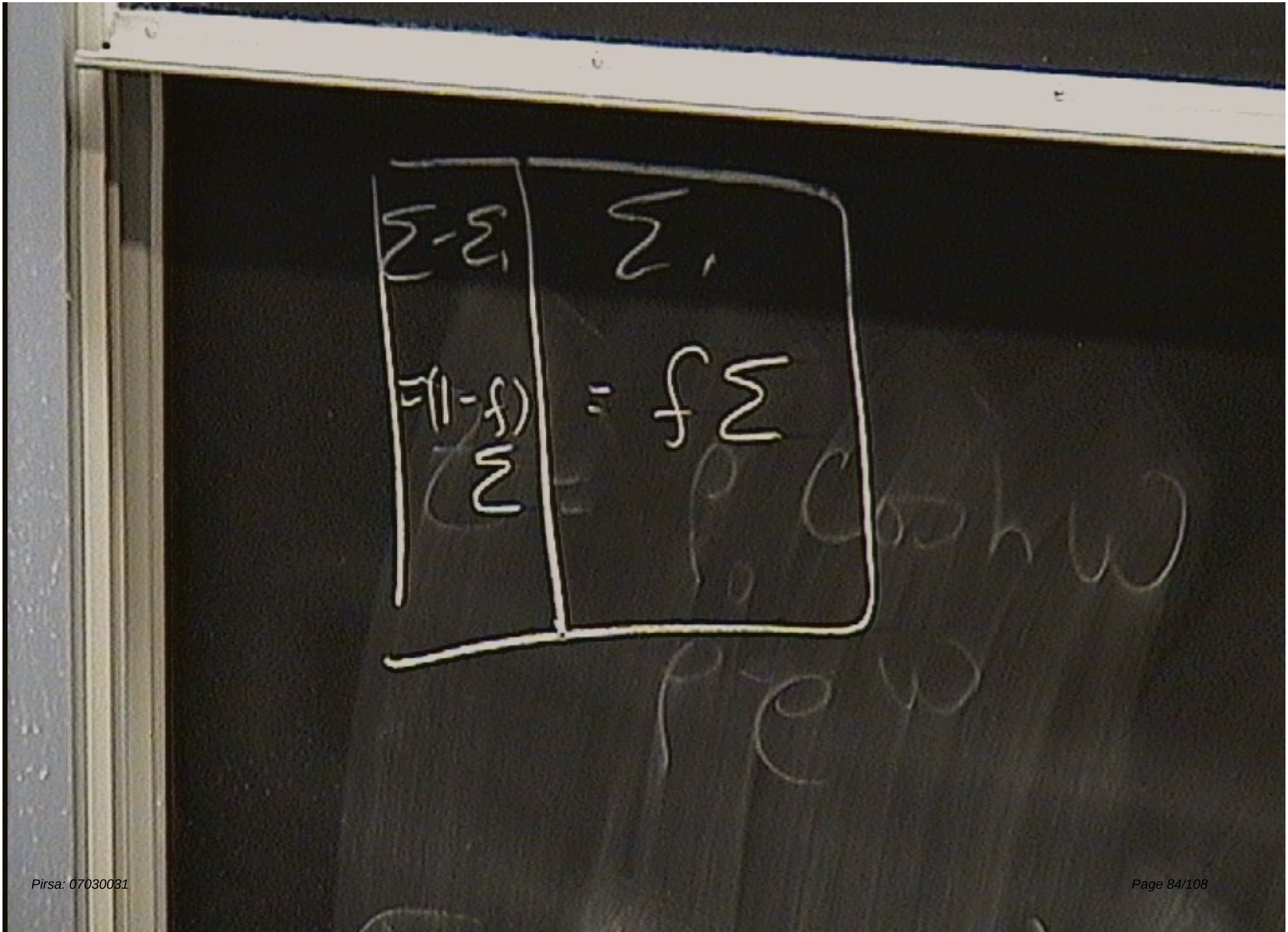
$e^{\omega} = e^{\ldots 2MG}$

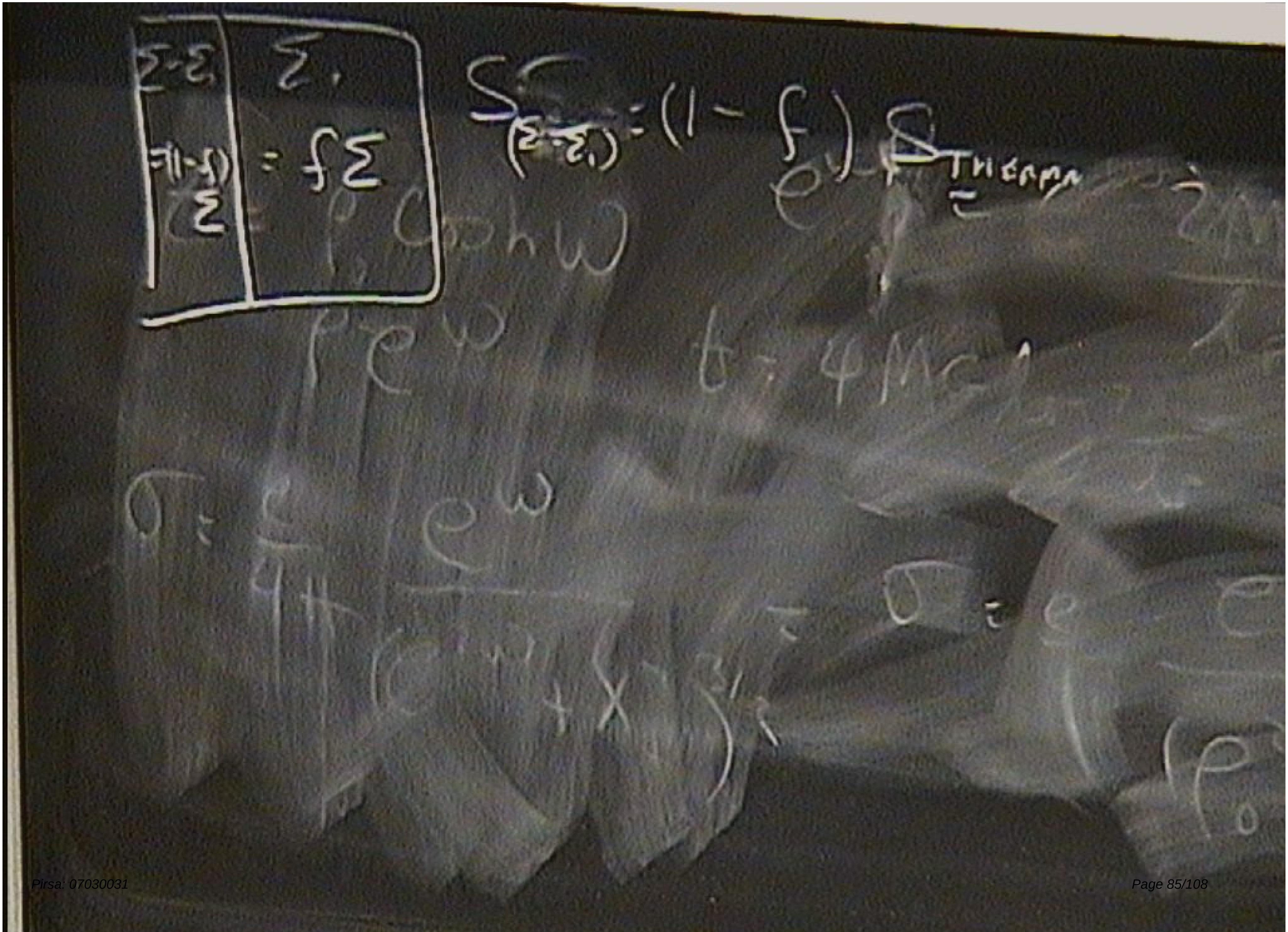
$b = 4M$

$\sigma = \frac{e^{\omega}}{4\pi}$

$\frac{1}{4\pi}$

$\sigma = e \; \frac{e^{-2\omega}}{(\rho_0^2 + x^2)}$


Σ - Σ1
Σ1
(1-f) Σ
= f Σ
ρ0 cosh ω



$\Sigma - \Sigma_1$	Σ_1
$(1-f)\,\Sigma$	$= f\Sigma$

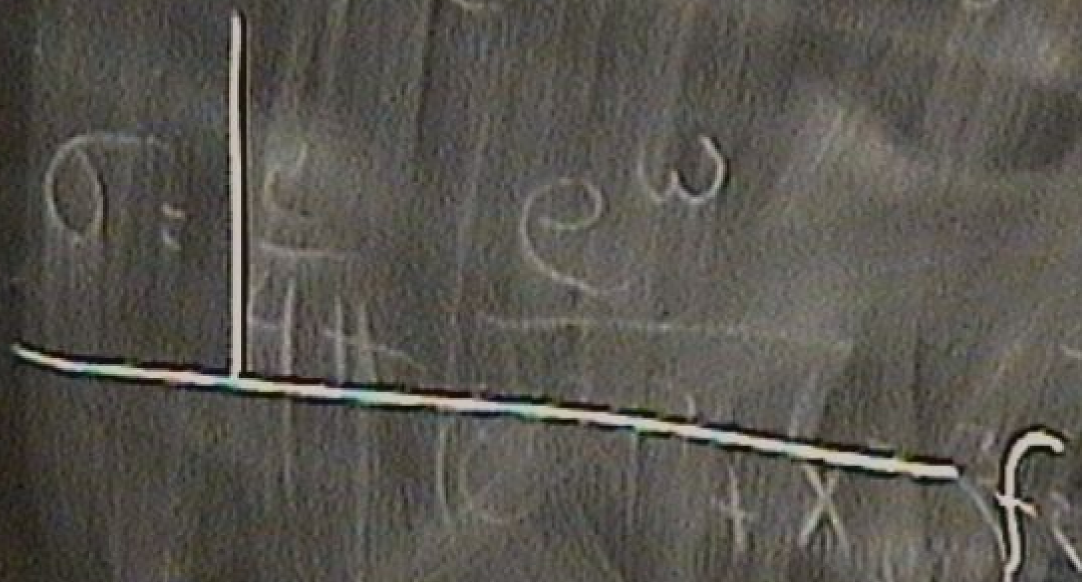
$$S_{(\Sigma-\Sigma_1)} = (1-f)\, S_{\text{THERMA}}$$

$$S_{\Sigma} = (1-f)\, S_{\text{THER}}$$

$\Sigma - \Sigma_1$	Σ_1
$f(1-f)\,\Sigma$	$= f\Sigma$

$$S_{(\Sigma-\Sigma_1)} = (1-f)\, S_{\text{THERMAL}}$$

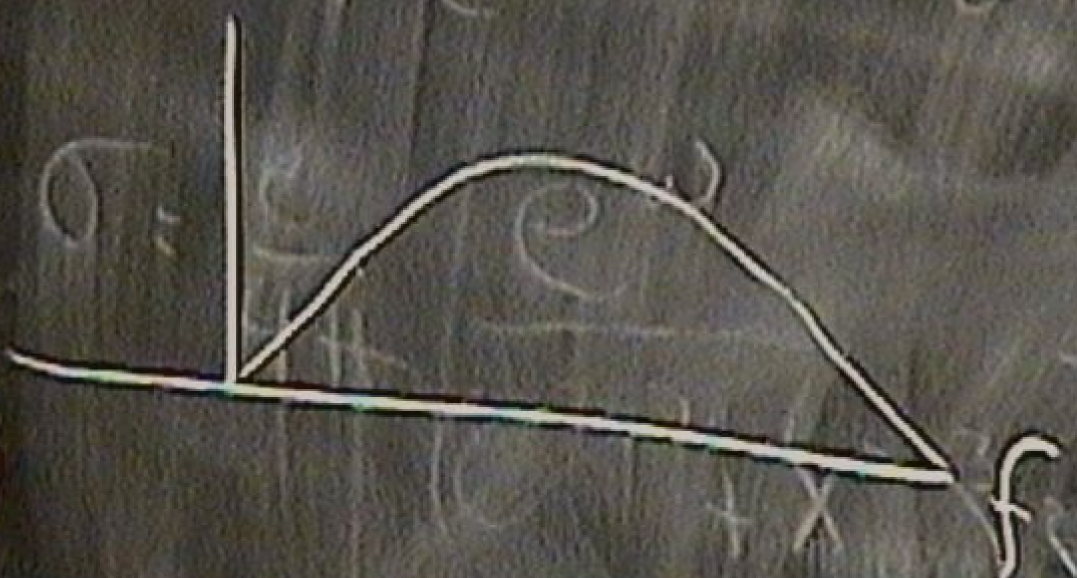
$$S_{\Sigma} = (1-f)\, S_{\text{THER}}$$

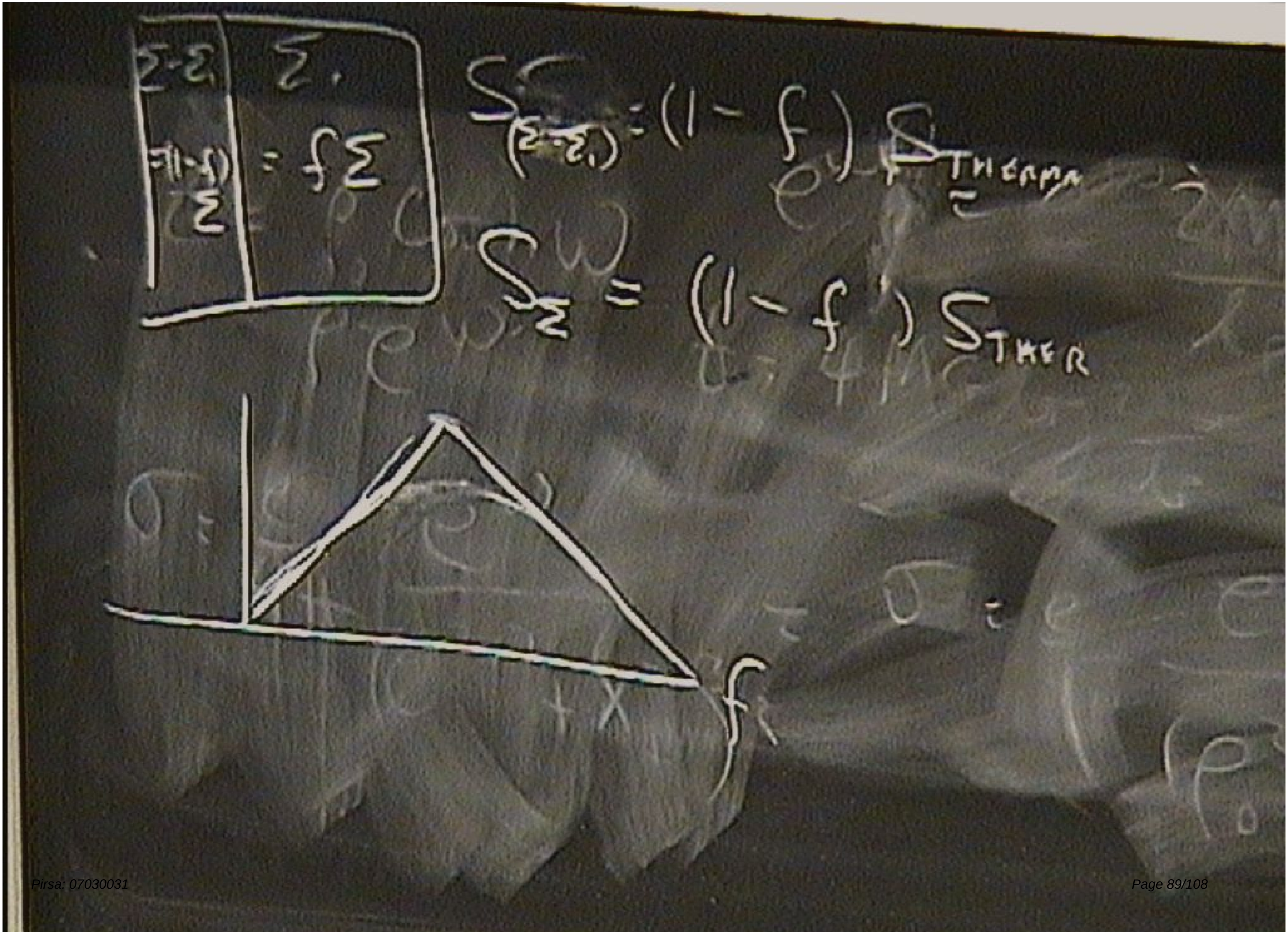


$\Sigma - \Sigma_1$	Σ_1
$f(1-f)\,\Sigma$	$= f\Sigma$

$$S_{(\Sigma-\Sigma_1)} = (1-f)\, S_{THERM}$$

$$S_{\Sigma} = (1-f)\, S_{THER}$$

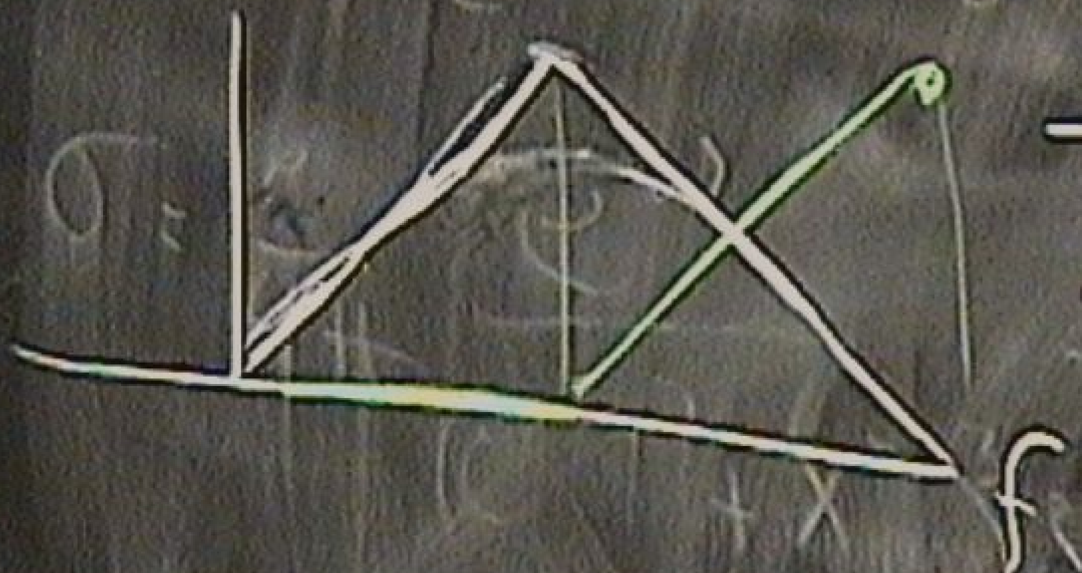



Σ-Σ₁
Σ₁
f(1-f)Σ
= fΣ
S(Σ-Σ₁) = (1 - f) STHERM
SΣ = (1 - f) STHER
f

$\Sigma-\Sigma_1$	Σ_1
$f(1-f)\,\Sigma$	$= f\Sigma$

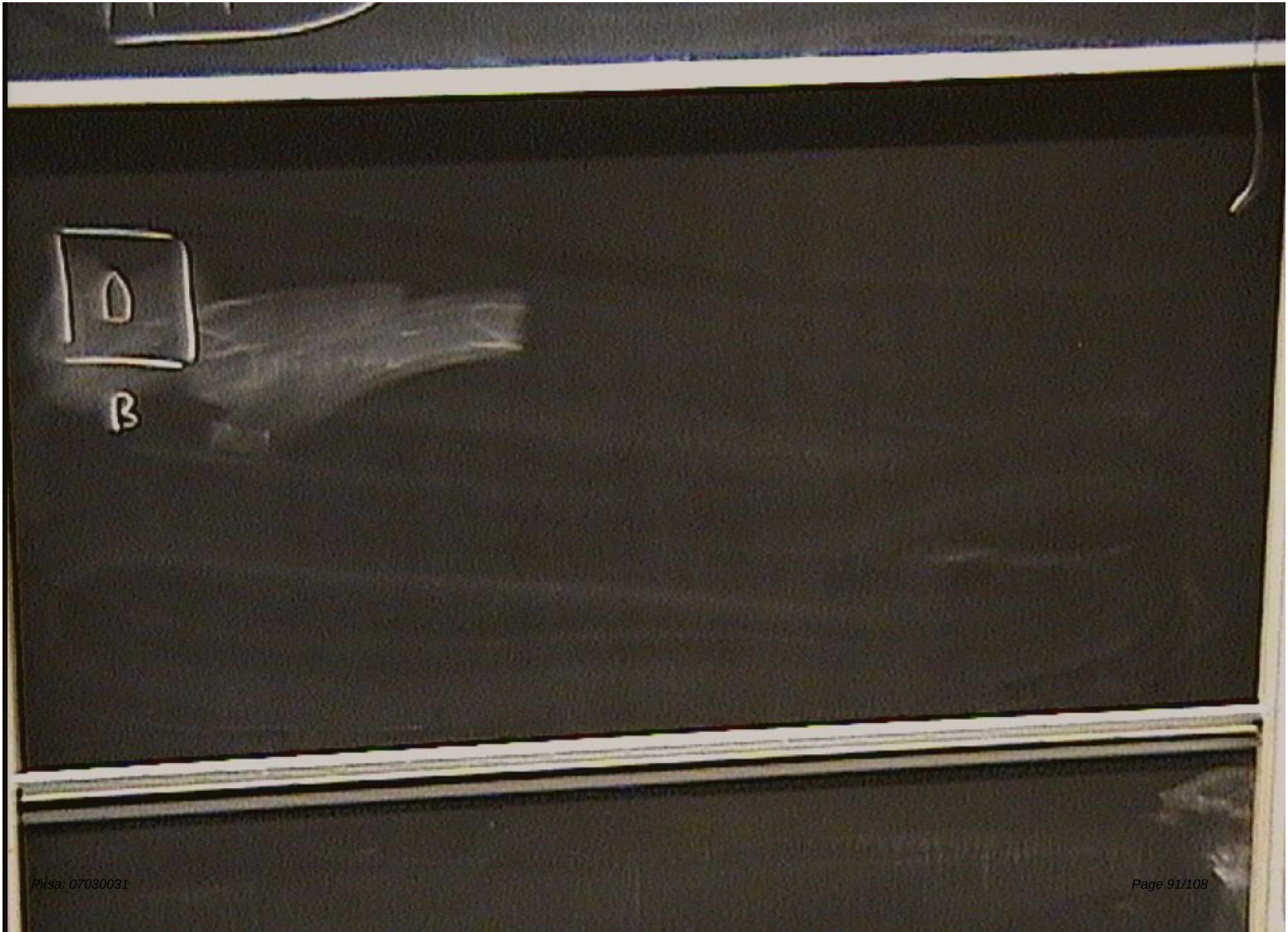
$$S_{(\Sigma-\Sigma_1)} = (1-f)\,S_{THERM}$$

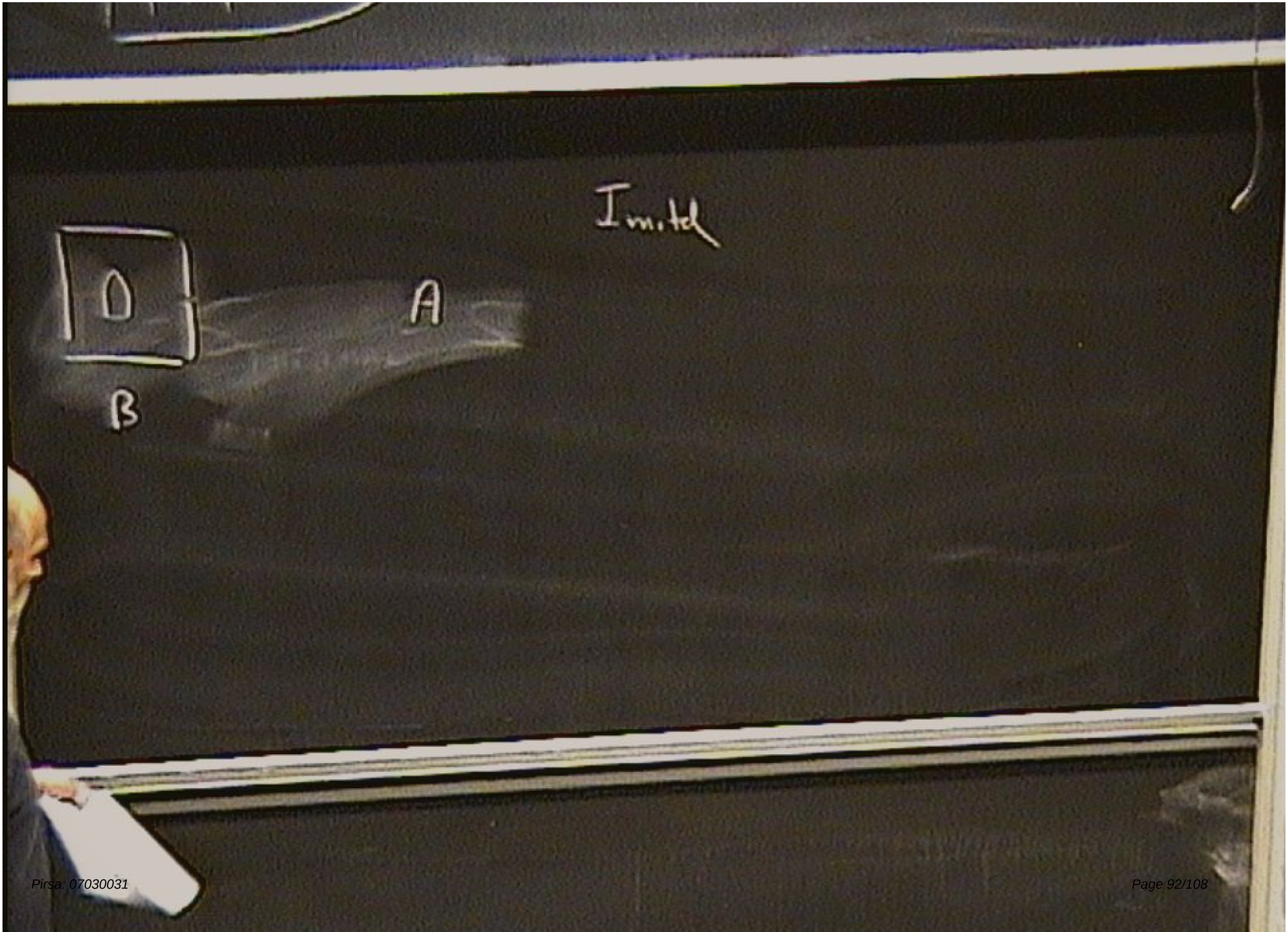
$$S_{\Sigma} = (1-f)\,S_{THER}$$



$$I = f\,S_{THER} -$$

$$= (2f-1$$


B


A
B

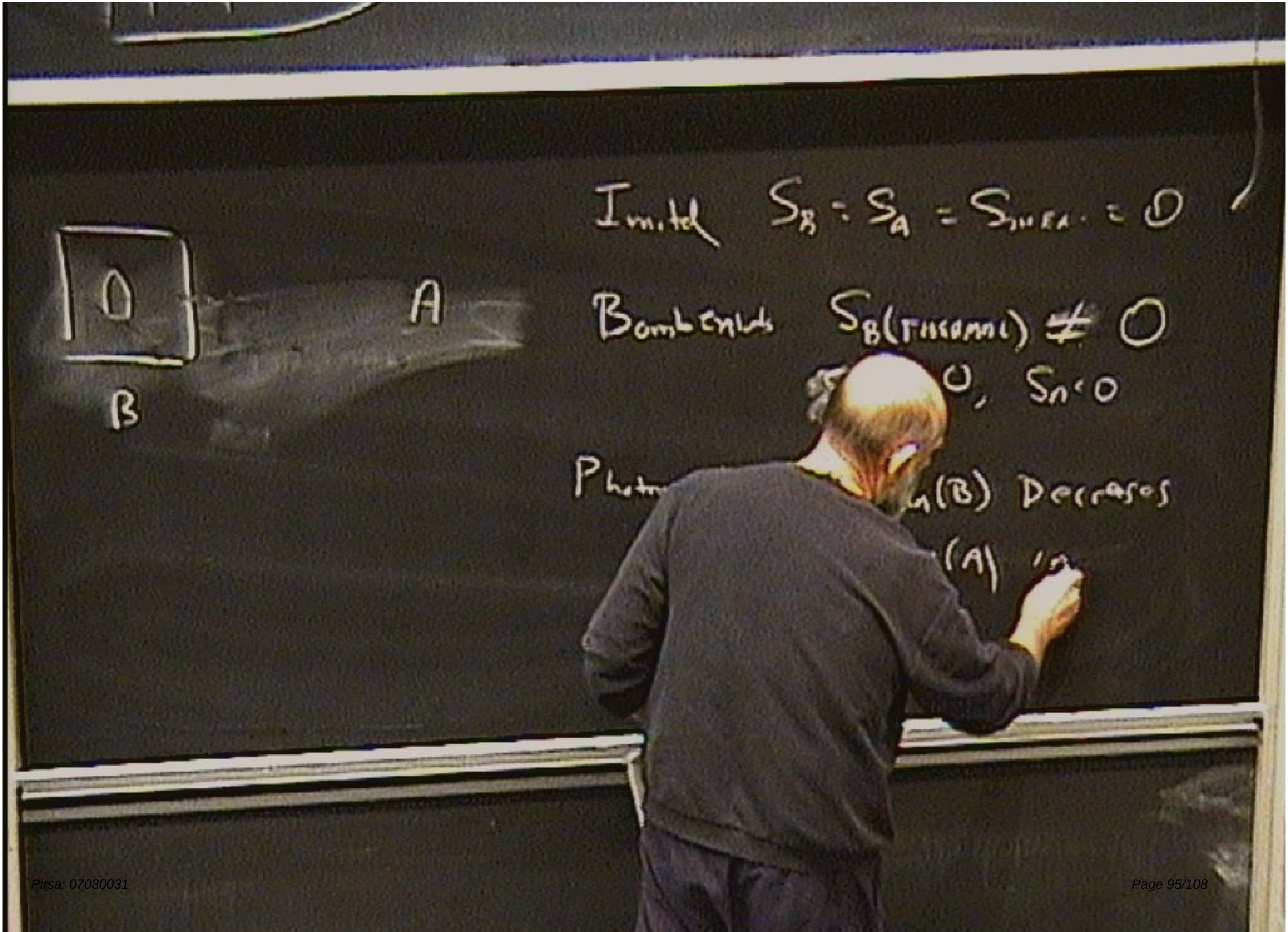
Initial $S_B = S_A = S_{\text{[illegible]}} = 0$

Bomb [illegible] $S_B(\text{[illegible]}) \neq 0$

Initial $S_B = S_A = S_{\text{linear}} = 0$

Bomb explodes $S_B(\text{reasonable}) \neq 0$

$S_B = 0, \ S_A = 0$


A
B

Initial $S_B = S_A = S_{\text{STER.}} = 0$

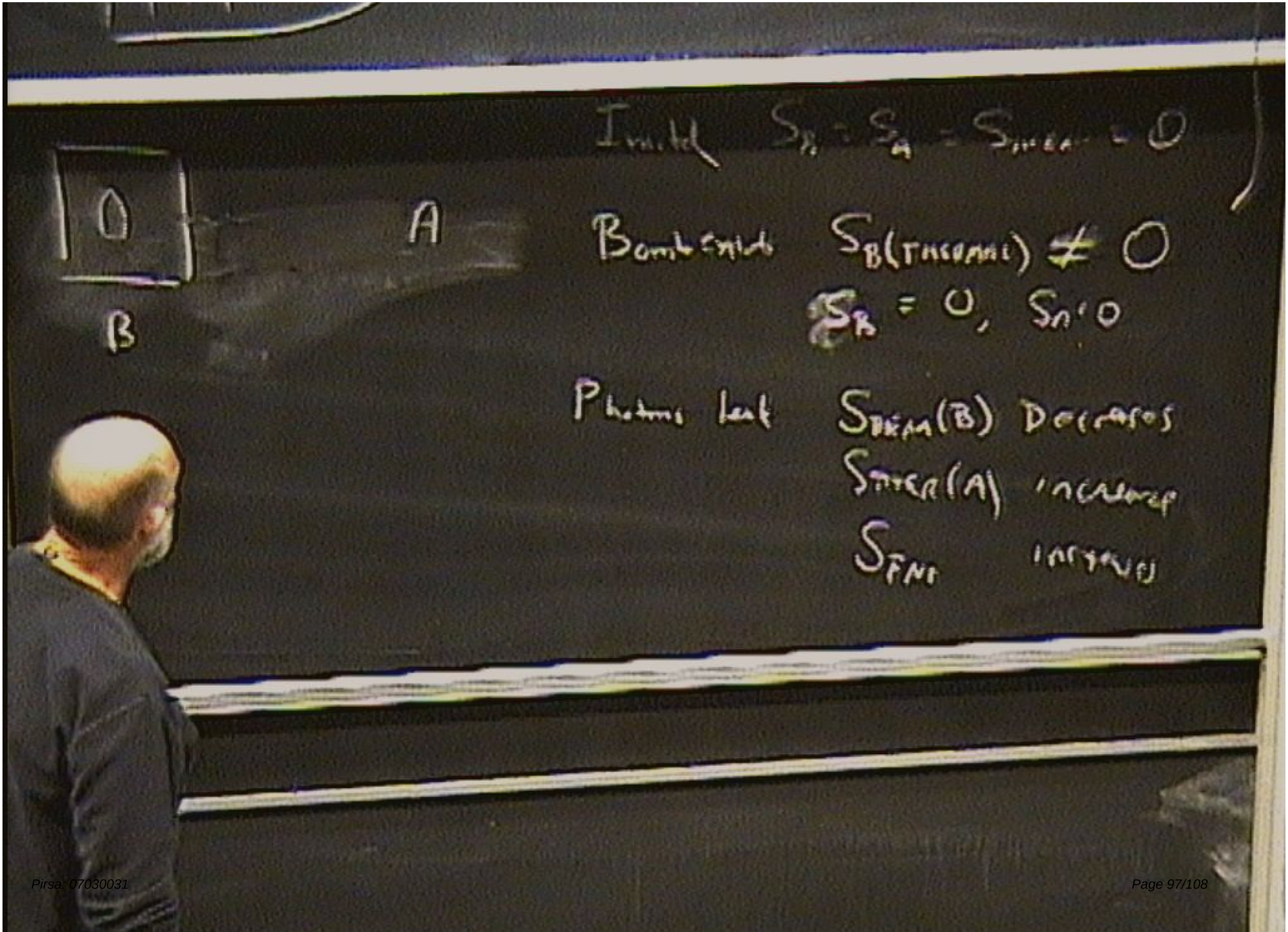
Bomb Explodes $S_B(\text{thermal}) \neq 0$

$S_B = 0, \quad S_A = 0$

Photons leak $S_{\text{BEAM}}(B)$ Decreases

$S_{\text{STER}}(A)$ increases

S


A
B
Initial $S_B = S_A = S_{FIELD} = 0$
Bomb explodes $S_B(\text{THERMAL}) \neq 0$
$S_B = 0, S_A = 0$
Photons leak $S_{BEAM}(B)$ Decreases
$S_{BEAM}(A)$ increases
S_{ENT} increases

Initial $S_B = S_A = S_{INTER} = 0$

Bomb explodes $S_B(\text{FINEGRAIN}) \neq 0$

$S_B = 0, \; S_A = 0$

Photons leak $S_{INTER}(B)$ Decreases

$S_{INTER}(A)$ increases

S_{ENT} increases

Final $S_B = S_{INTER}(B) = 0$

Initial $S_B = S_A = S_{INTER} = 0$

Bomb explodes $S_B(\text{THERMAL}) \neq 0$

$S_B = 0, \; S_A = 0$

Photons leak $S_{THERM}(B)$ Decreases

$S_{INTER}(A)$ increases

S_{ENT} increases

Final $S_B = S_{THERM}(B) = 0$

$S_{THERM}(A) \neq 0$

Initial $S_B = S_A = S_{inter} = 0$

Bomb explodes $S_B(\text{thermal}) \neq 0$

$S_B = 0, \; S_A = 0$

Photons leak $S_{inter}(B)$ Decreases

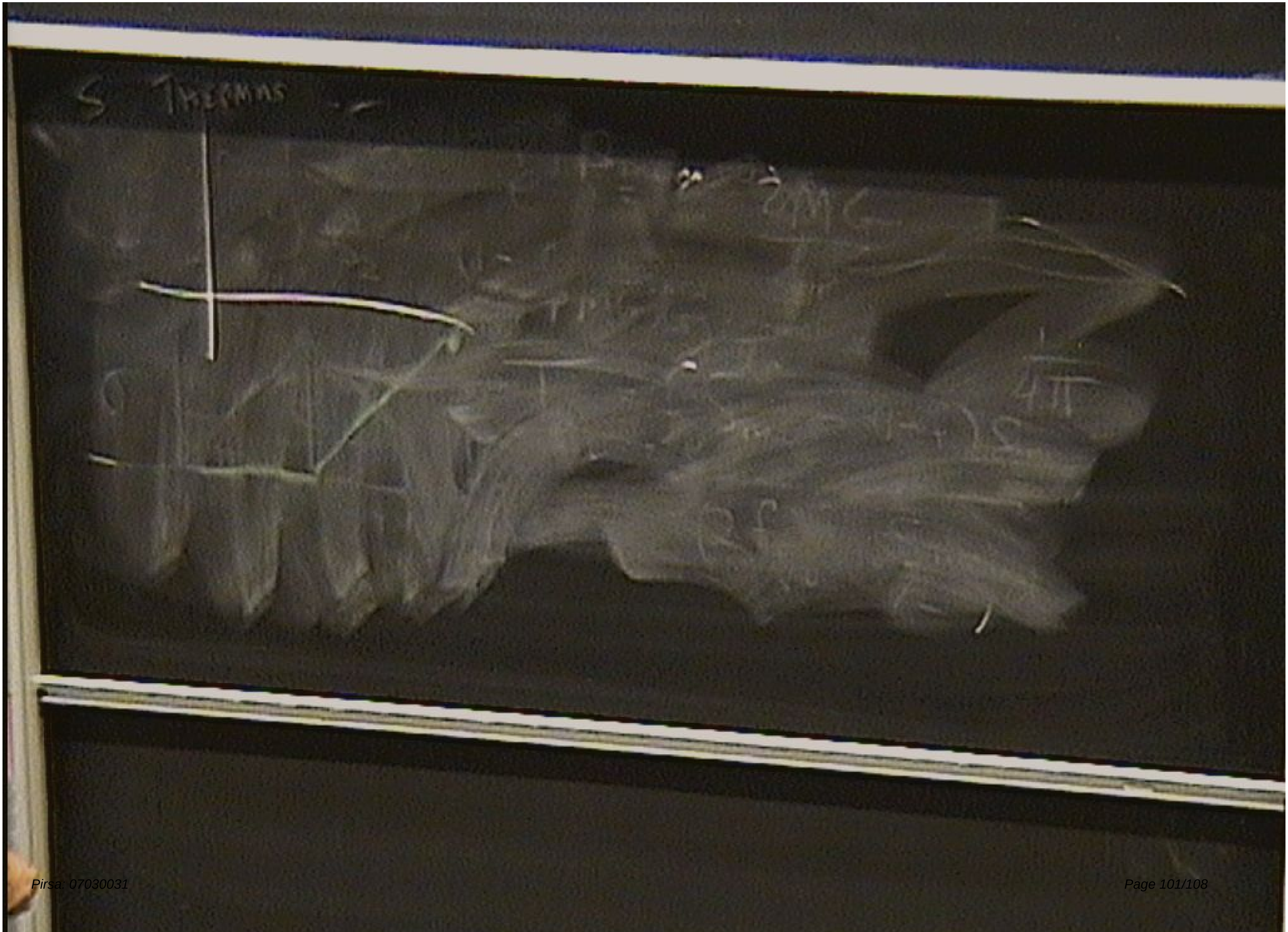
$S_{inter}(A)$ increases

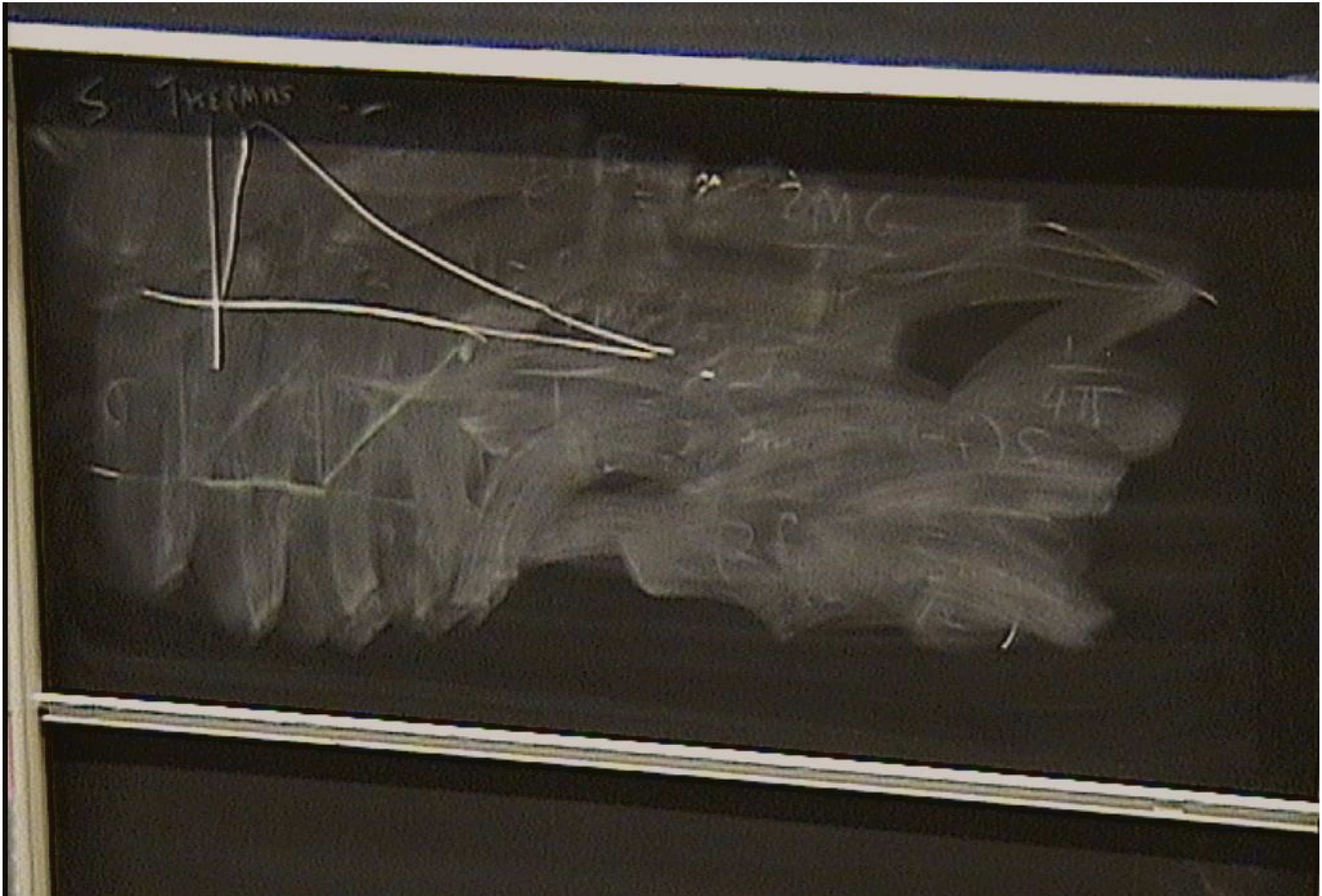
S_{ent} increases

Final $S_B = S_{inter}(B) = 0$

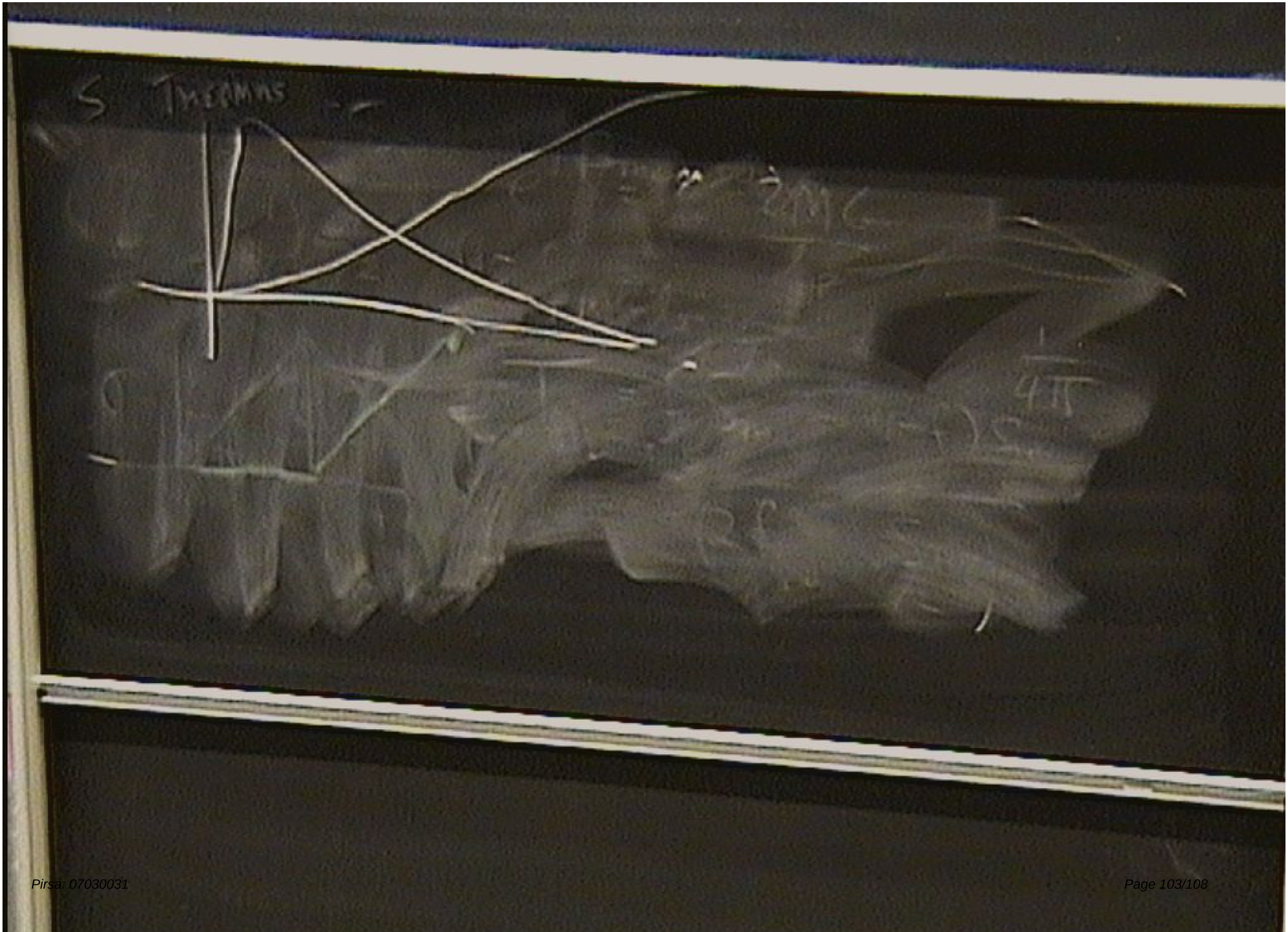
$S_{inter}(A) \neq 0$

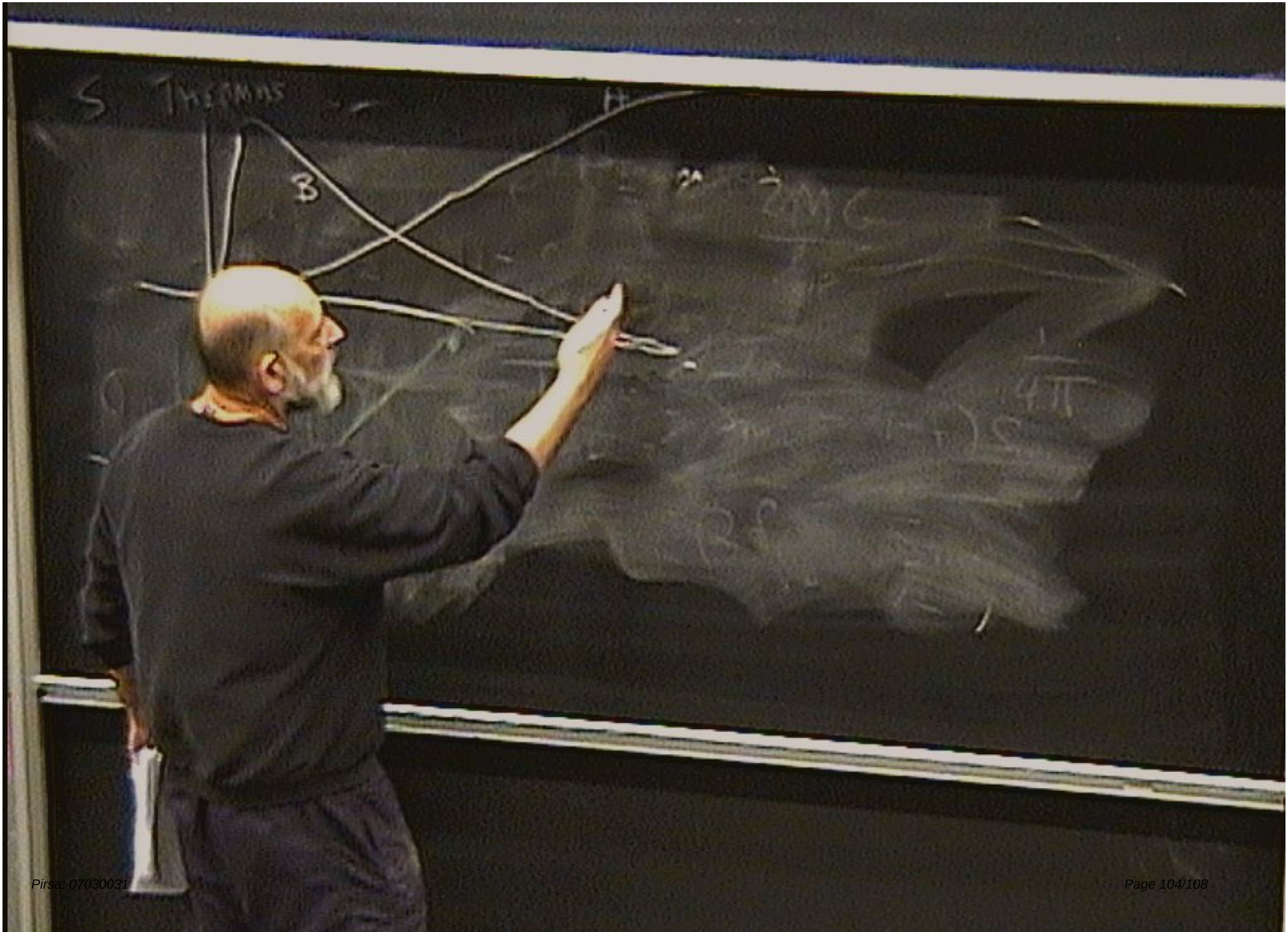
$S_B, S_A = 0$

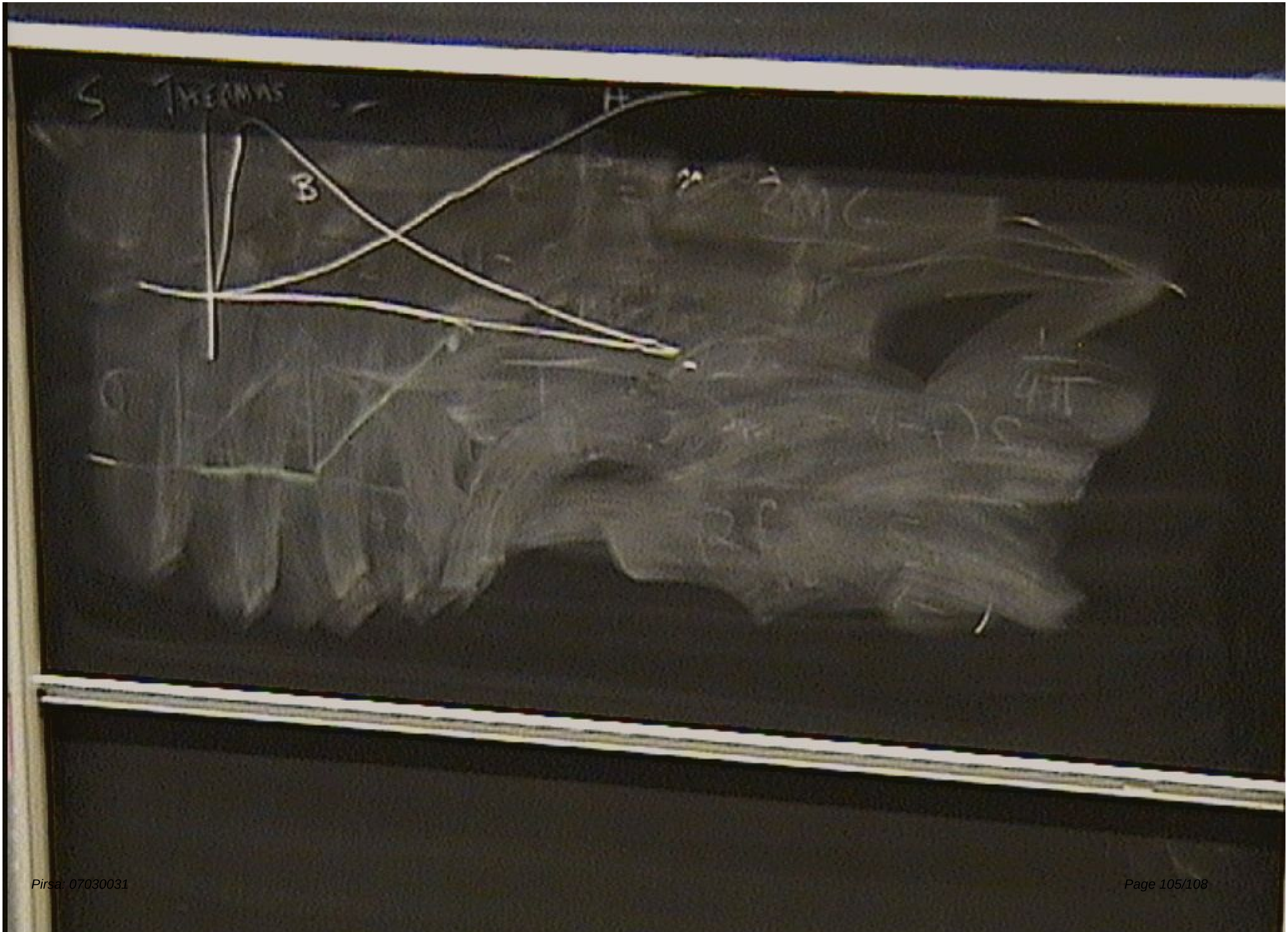


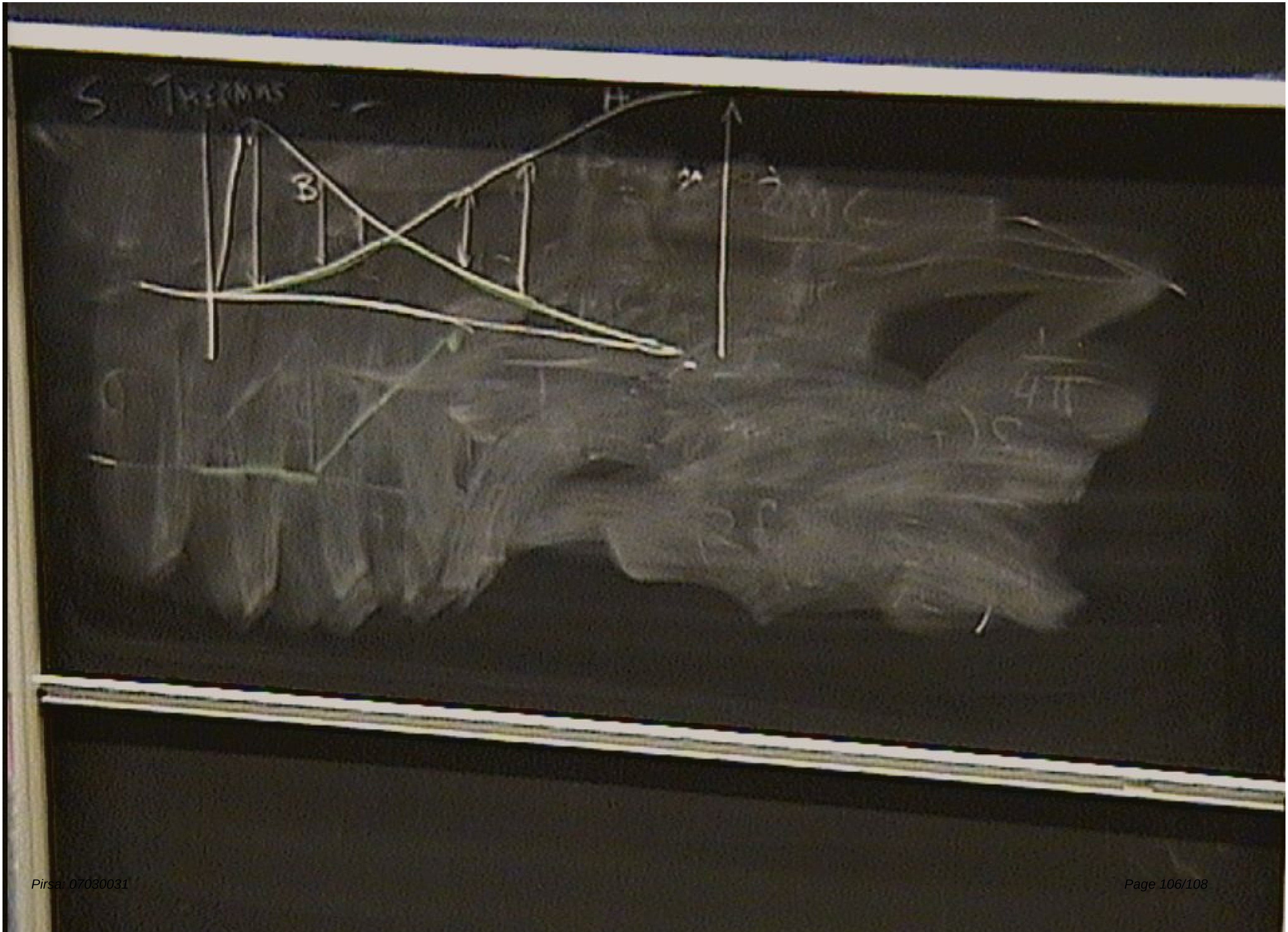


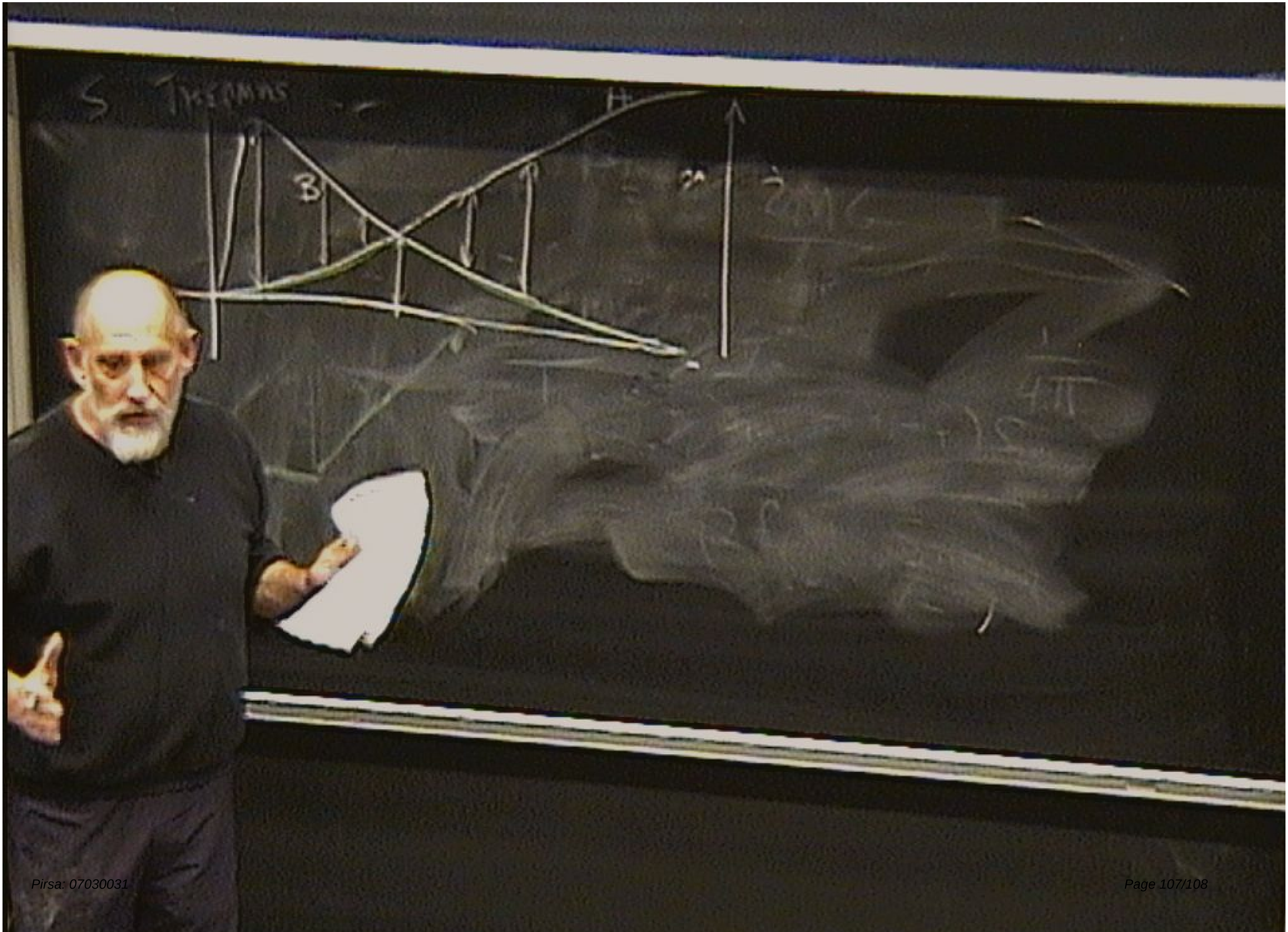
2MG

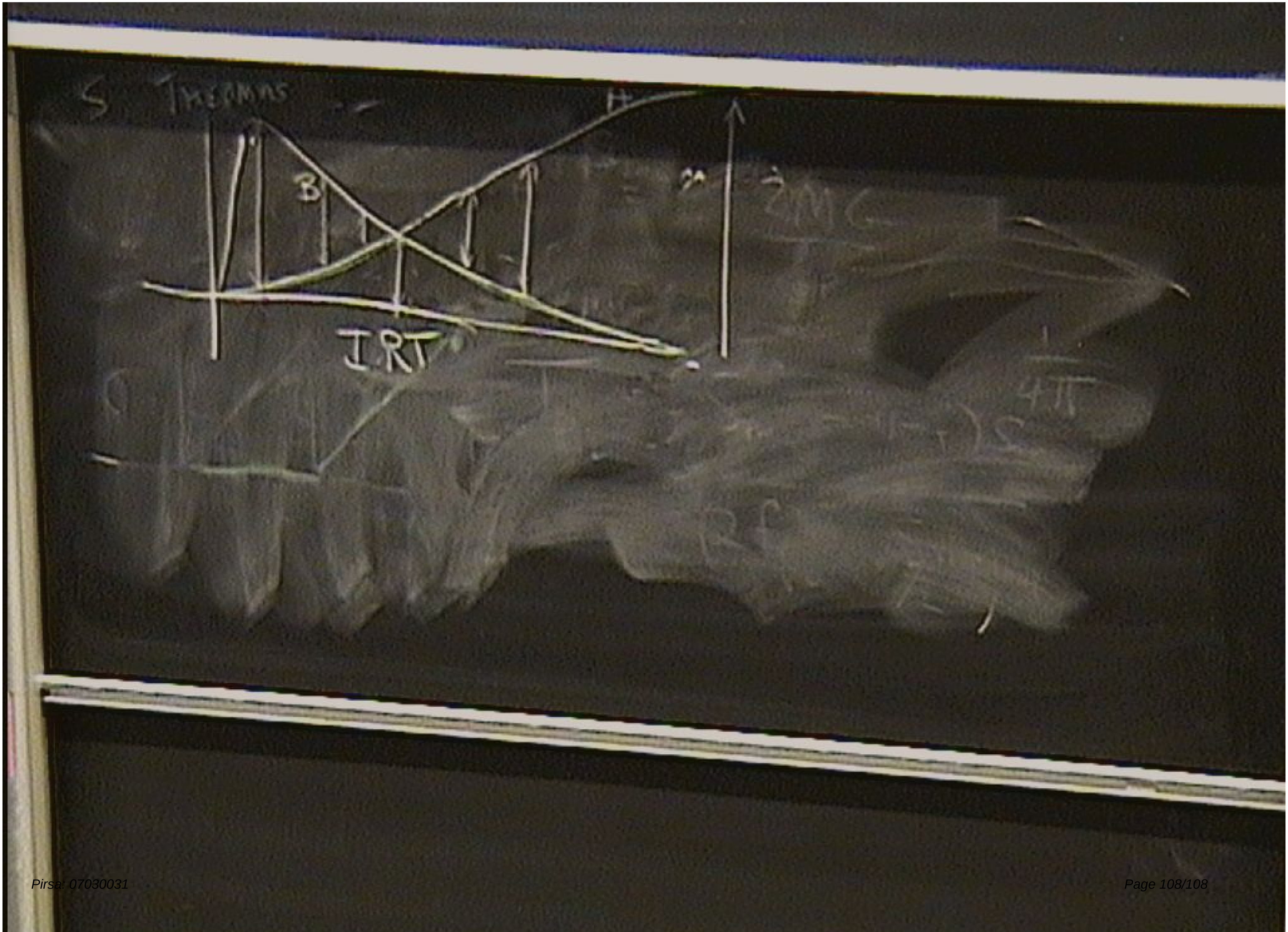





S
H
B






B
IRT