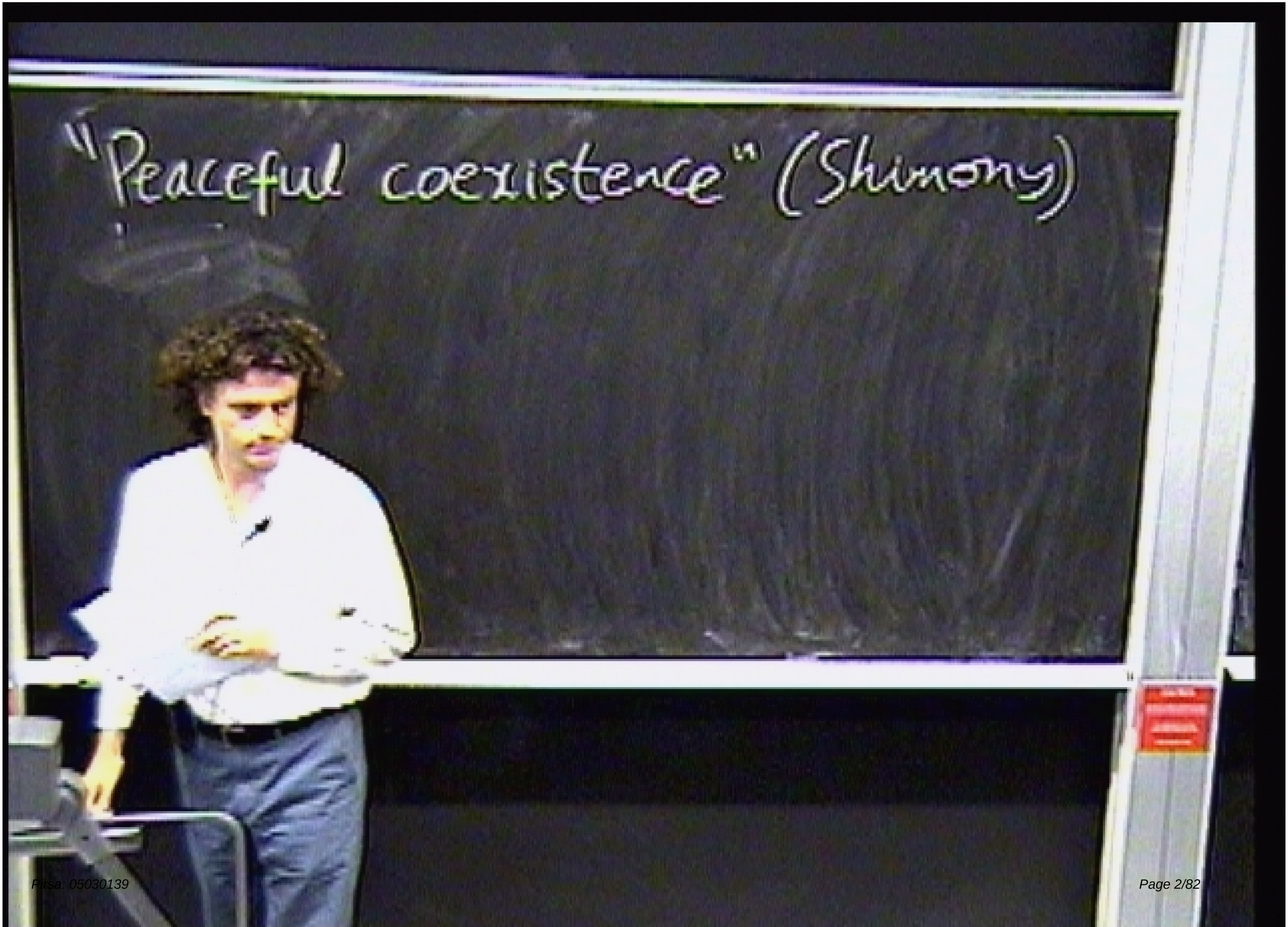
Title: Interpretation of Quantum Theory: Lecture 23

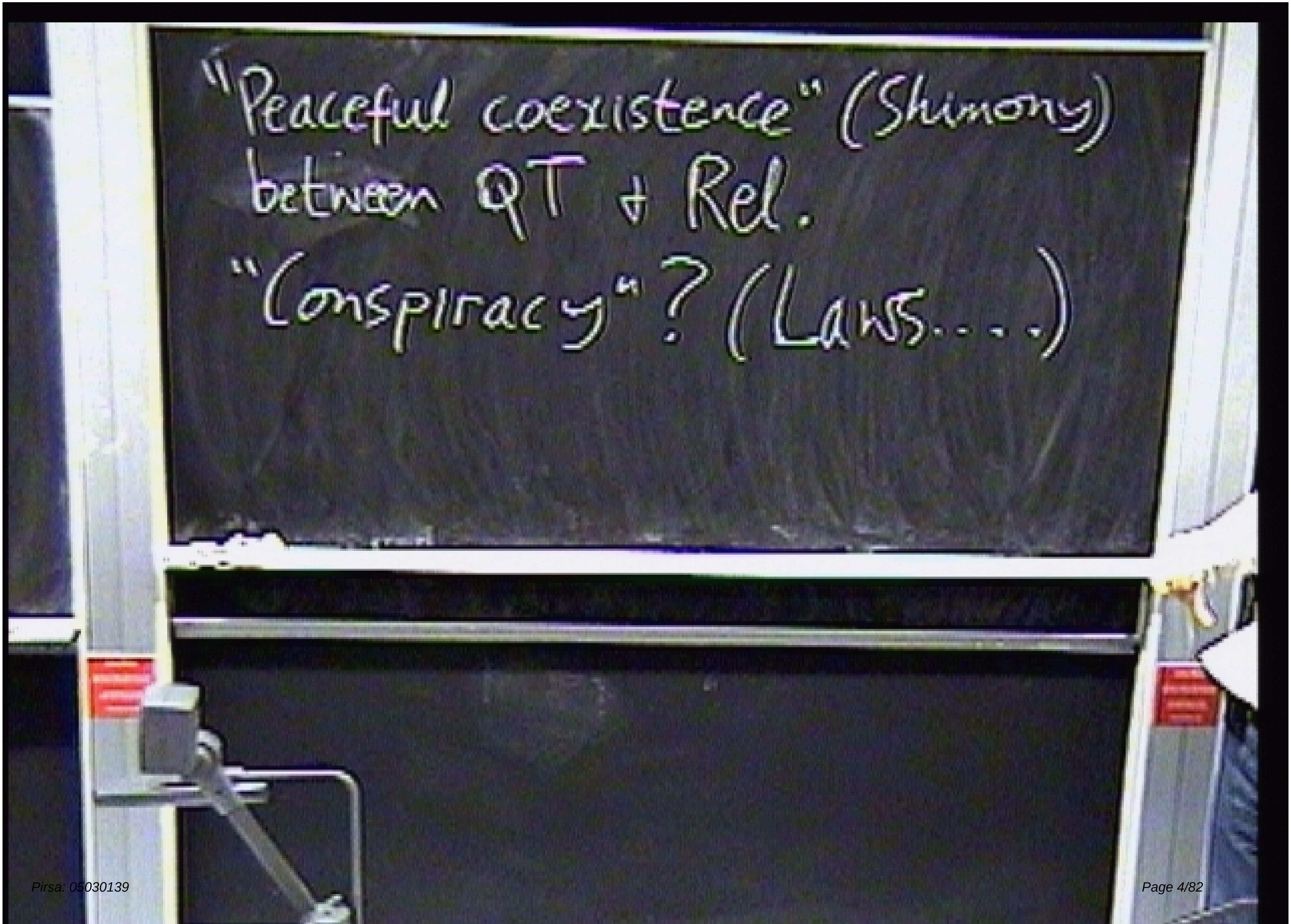
Date: Mar 29, 2005 02:15 PM

URL: http://pirsa.org/05030139

Abstract:


"Peaceful coexistence" (Shimony)

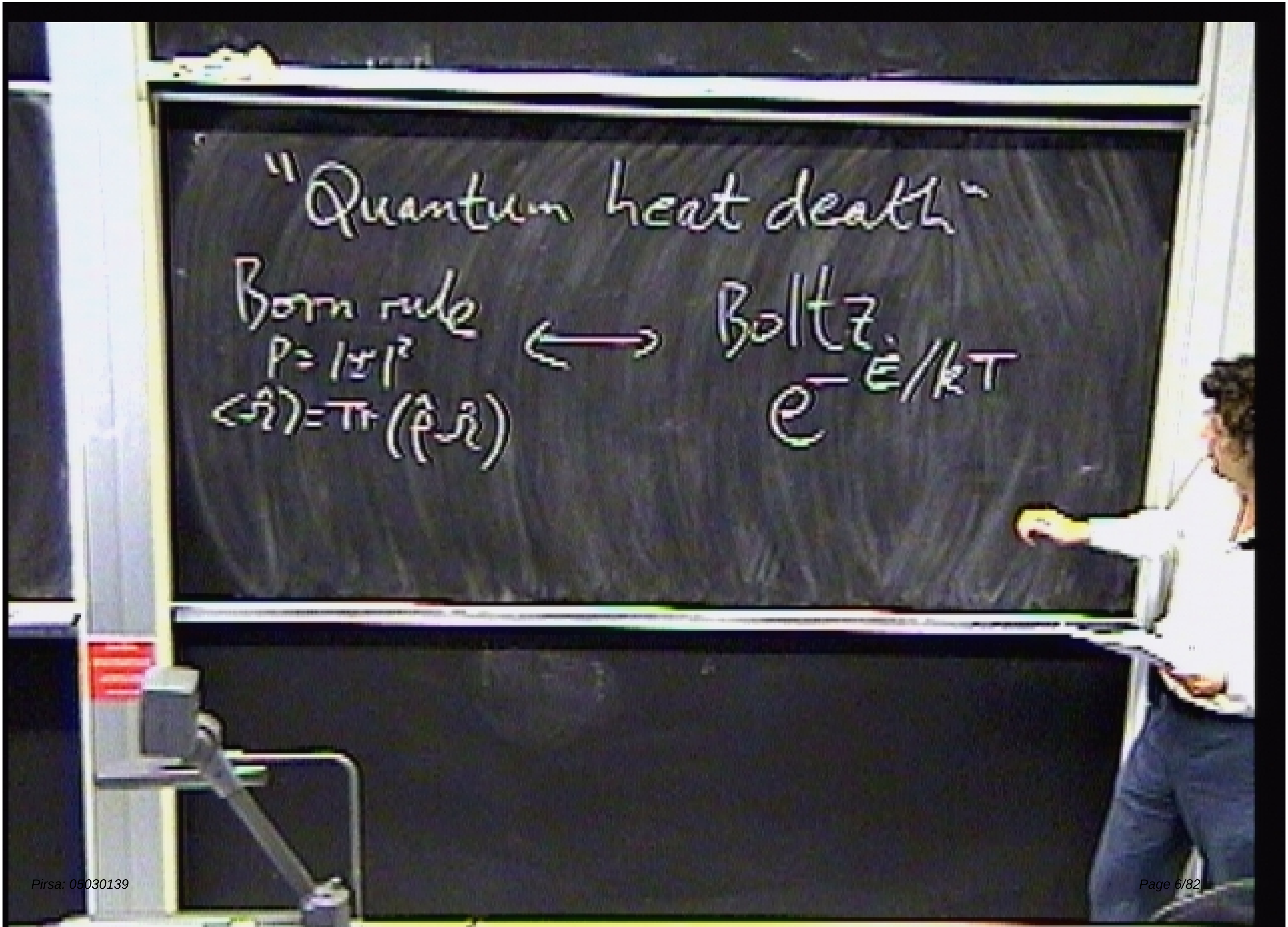

"Peaceful coexistence" (Shimony)
between QT & Rel.


"Peaceful coexistence" (Shimony)
between QT + Rel.
"Conspiracy"? (Laws....)

"Peaceful coexistence" (Shimony)
between QT + Rel.

"Conspiracy"? (Laws....)

"Accident".....


"Quantum heat death"
Born rule
$P=|\psi|^2$
$\langle\hat{A}\rangle=\mathrm{Tr}(\hat{\rho}\hat{A})$
⟷
Boltz.
$e^{-E/kT}$

"Quantum heat death"

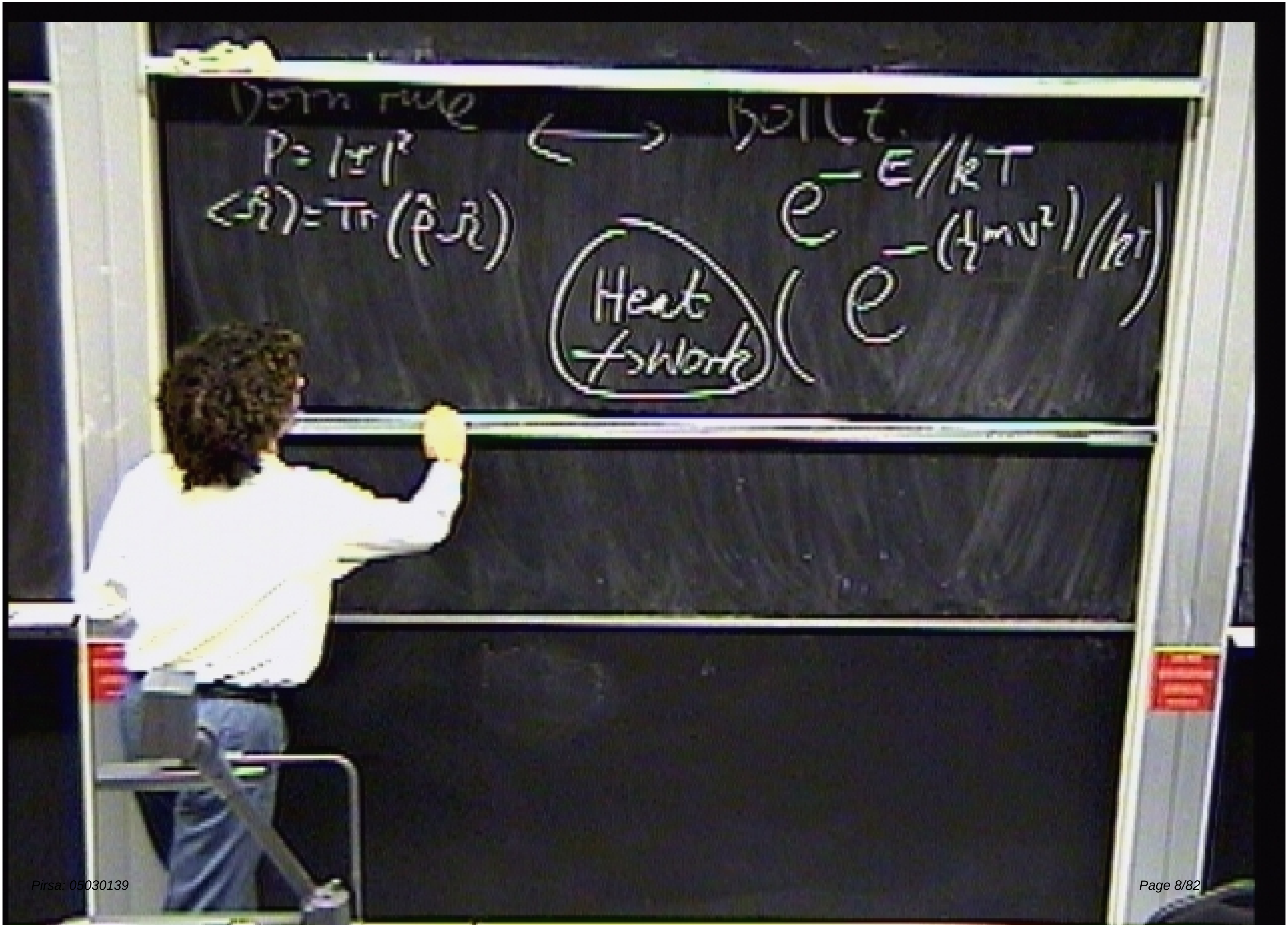
Born rule $\longleftrightarrow$ Boltz.

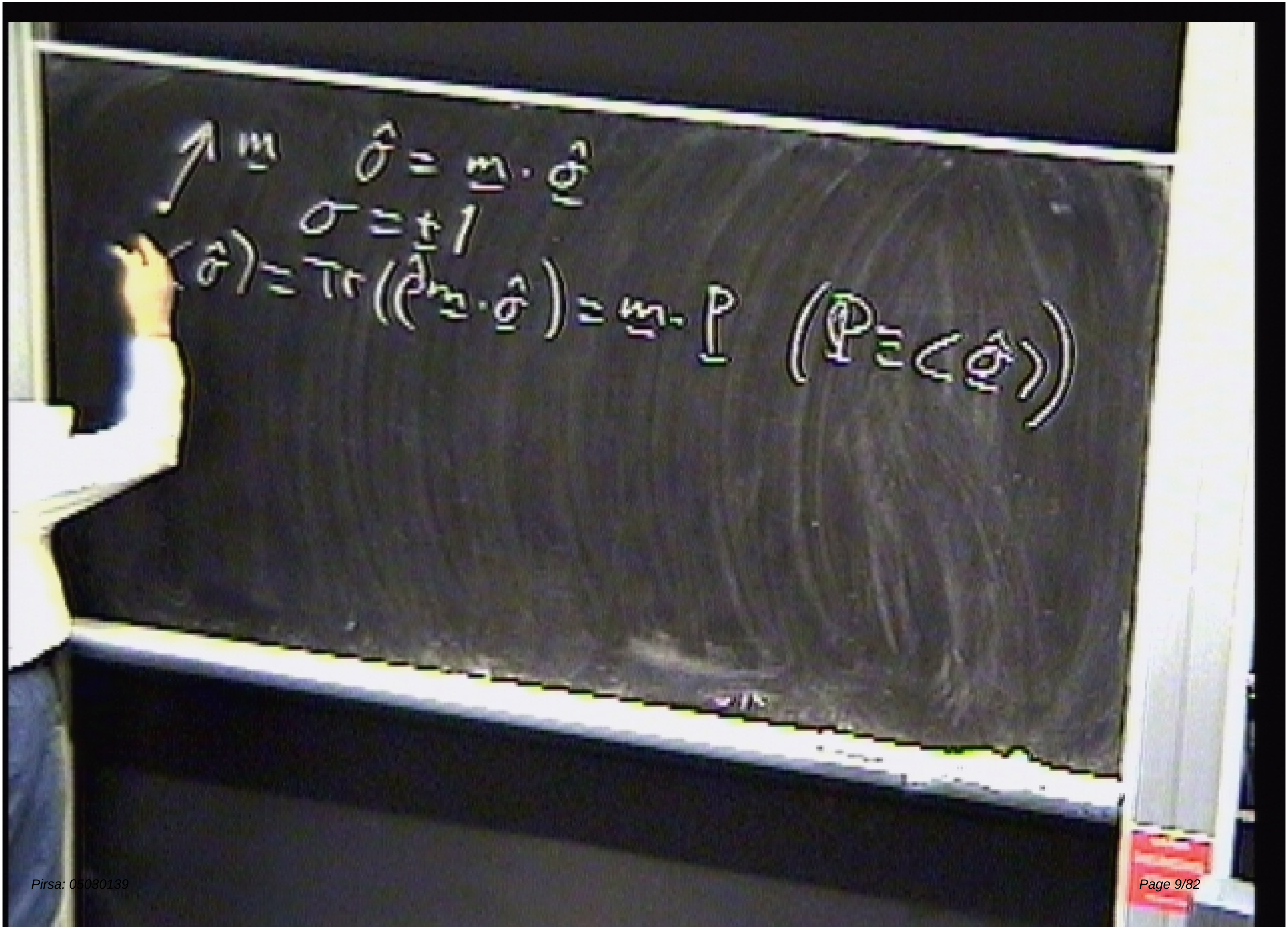
$P = |\psi|^2$

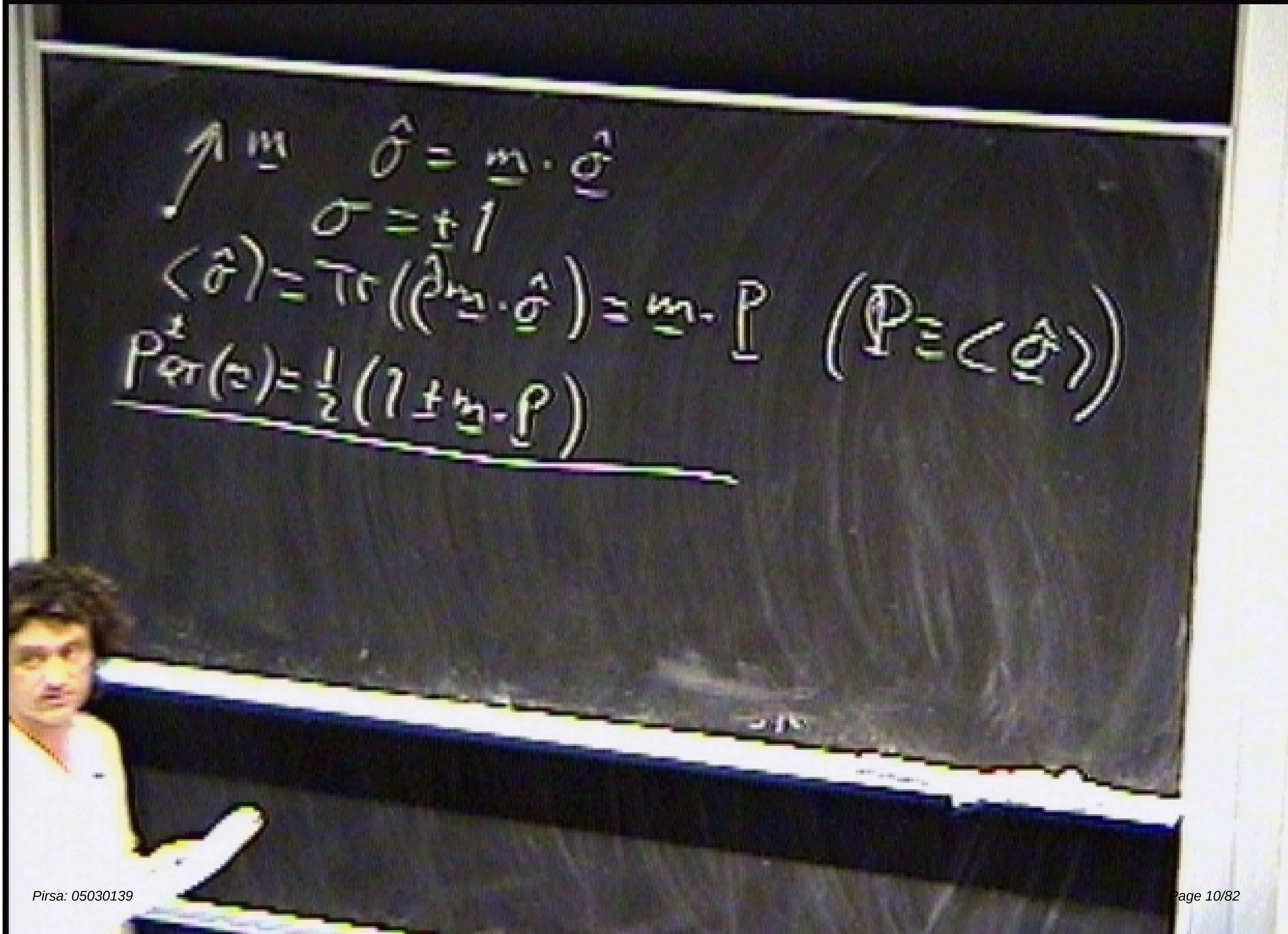
$\langle \hat{A} \rangle = \mathrm{Tr}(\hat{\rho}\hat{A})$

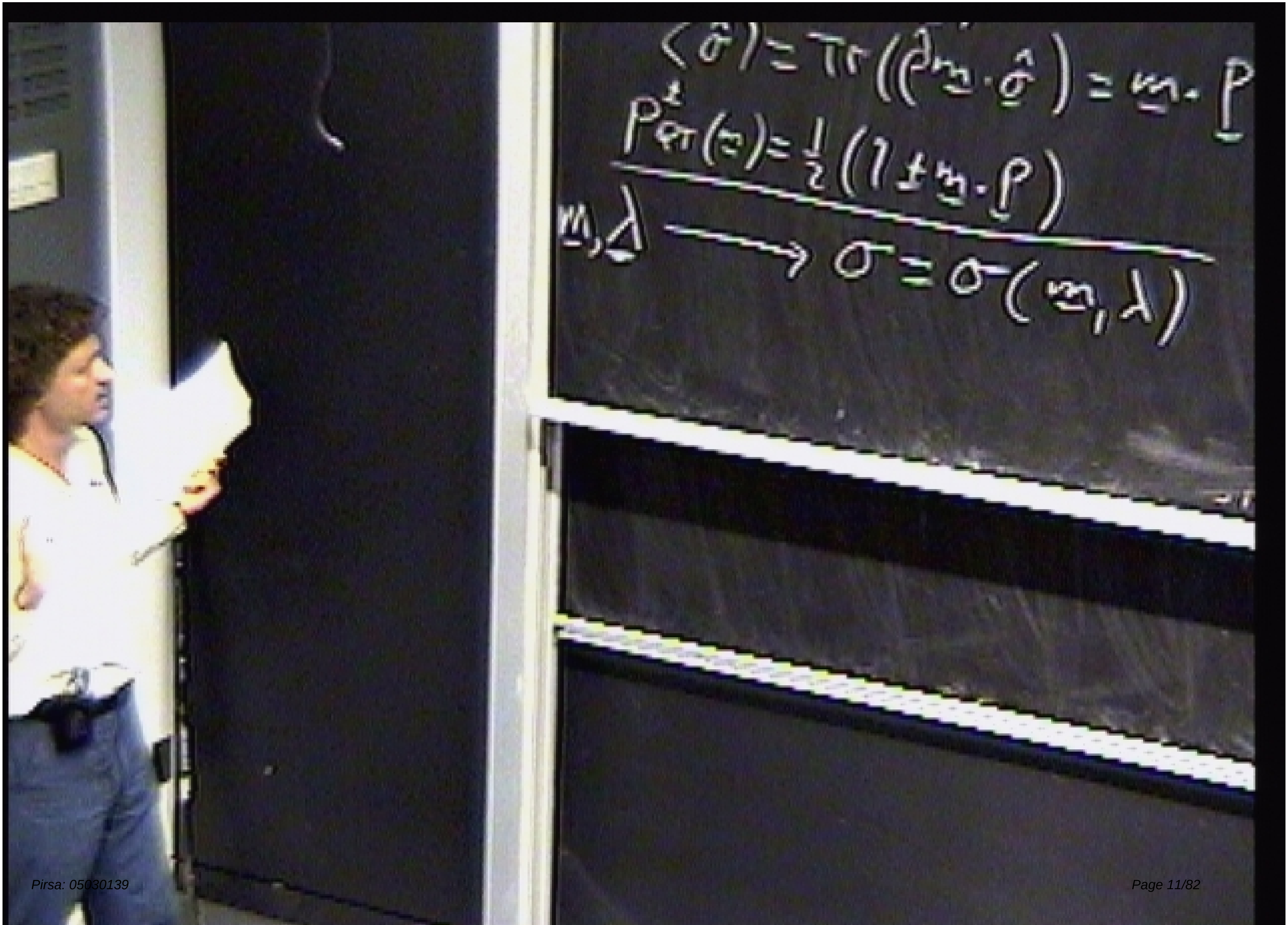
$e^{-E/kT}$

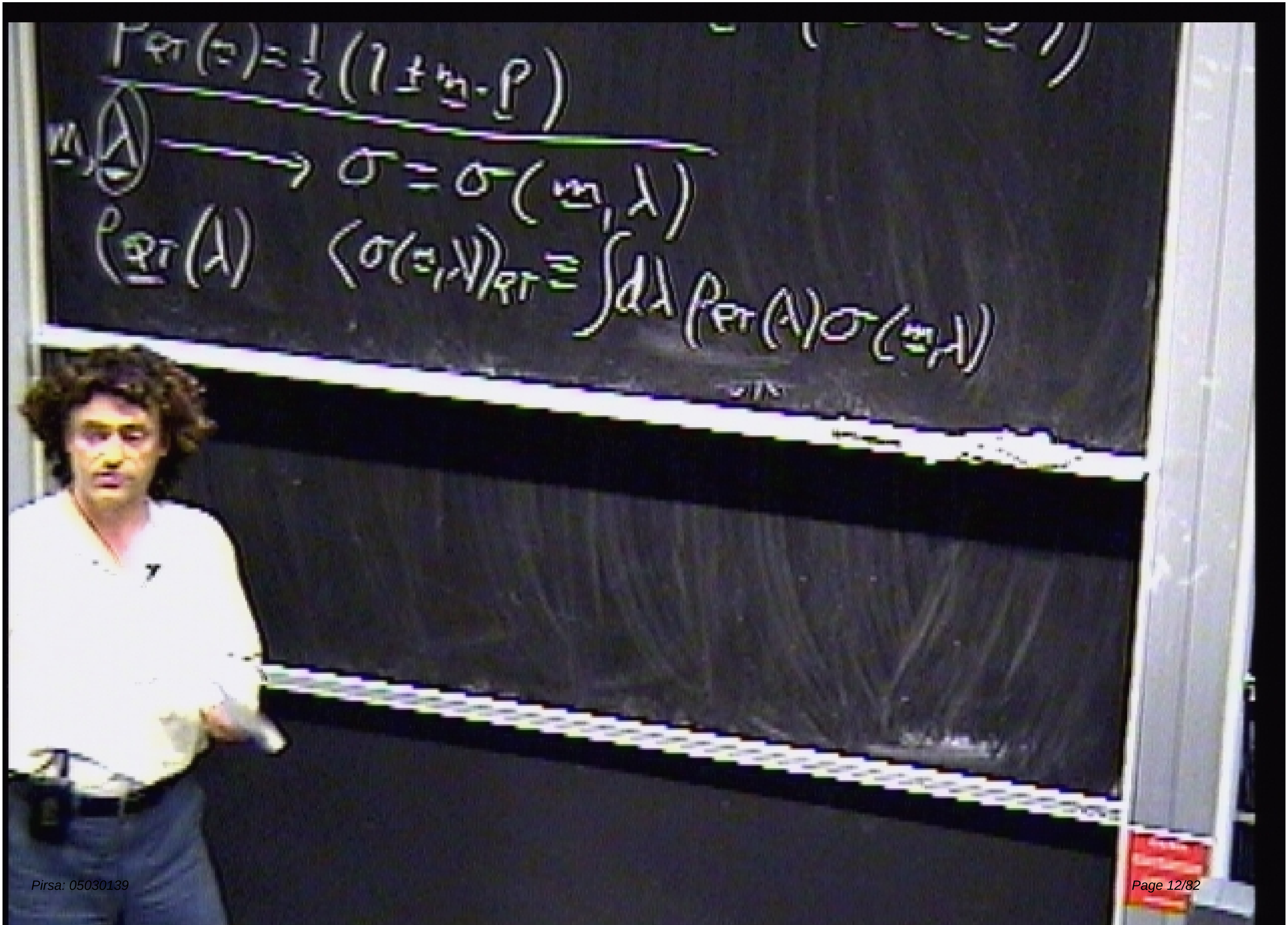
$\left(e^{-(\frac{1}{2}mv^2)/(kT)} \right)$

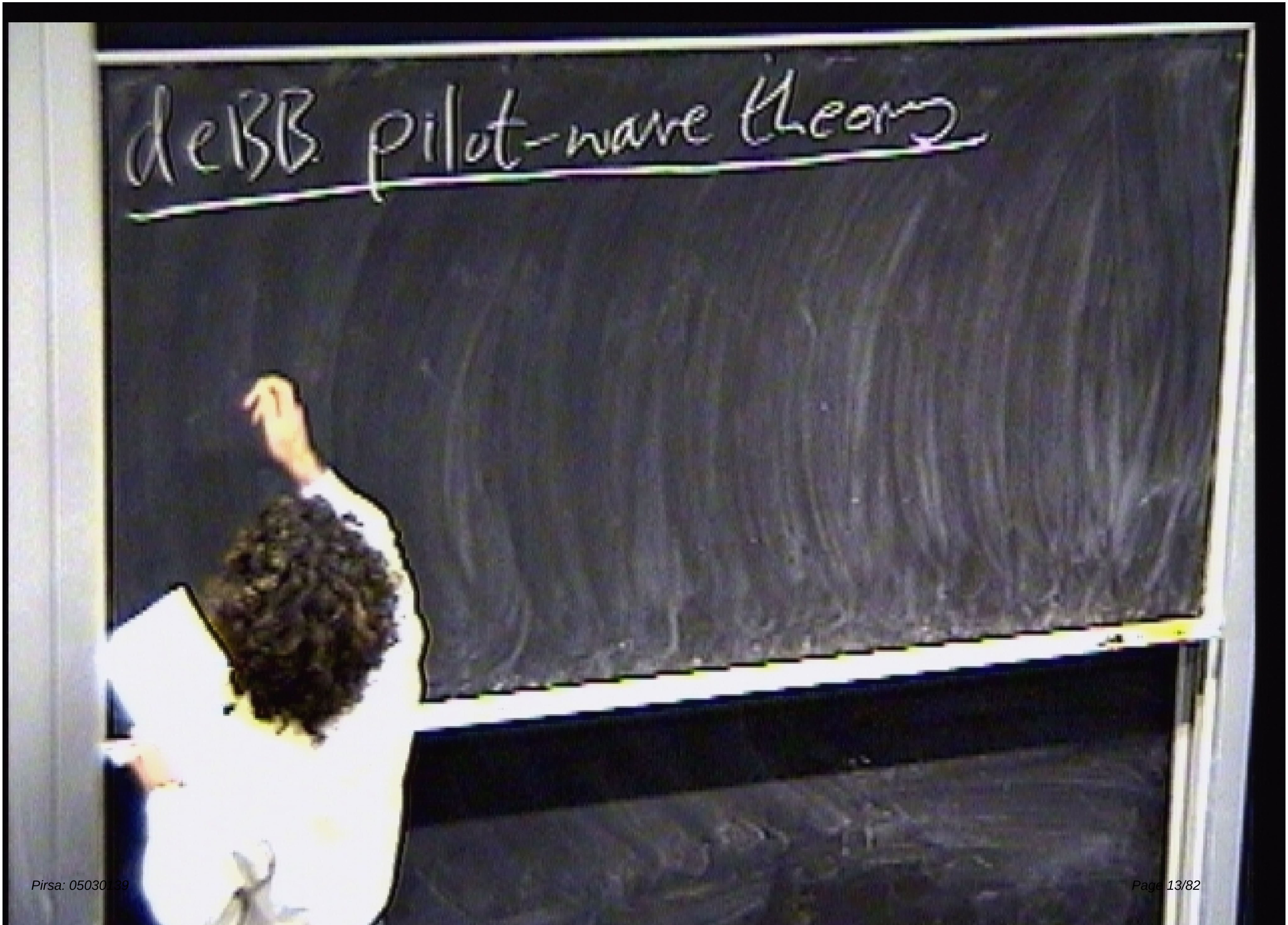

Born rule ⟷ Boltz.
P = |ψ|²
<Ω> = Tr(ρ̂ Ω̂)
e^{-E/kT}
e^{-(½mv²)/(kT)}
Heat
Work


$\underline{m}$ $\hat{\sigma} = \underline{m} \cdot \hat{\underline{\sigma}}$
$\sigma = \pm 1$
$\langle \hat{\sigma} \rangle = \mathrm{Tr}(\hat{\rho}\, \underline{m} \cdot \hat{\underline{\sigma}}) = \underline{m} \cdot \underline{P}$ $(\underline{P} \equiv \langle \hat{\underline{\sigma}} \rangle)$


$\underline{m}$ $\quad \hat\sigma = \underline{m}\cdot\hat{\underline{\sigma}}$
$\sigma = \pm 1$
$\langle\hat\sigma\rangle = \mathrm{Tr}(\hat\rho\,\underline{m}\cdot\hat{\underline{\sigma}}) = \underline{m}\cdot\underline{P} \quad (\underline{P} \equiv \langle\hat{\underline{\sigma}}\rangle)$
$p^{\pm}_{\hat\sigma}(\underline{m}) = \frac{1}{2}(1 \pm \underline{m}\cdot\underline{P})$

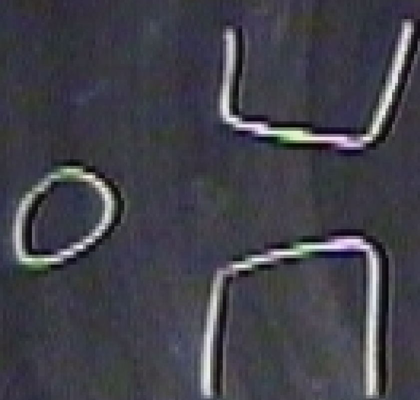

⟨σ̂⟩ = Tr((ρ̂ m · σ̂)) = m · ρ
ρ±m(σ) = ½(1 ± m · ρ)
m, λ → σ = σ(m, λ)

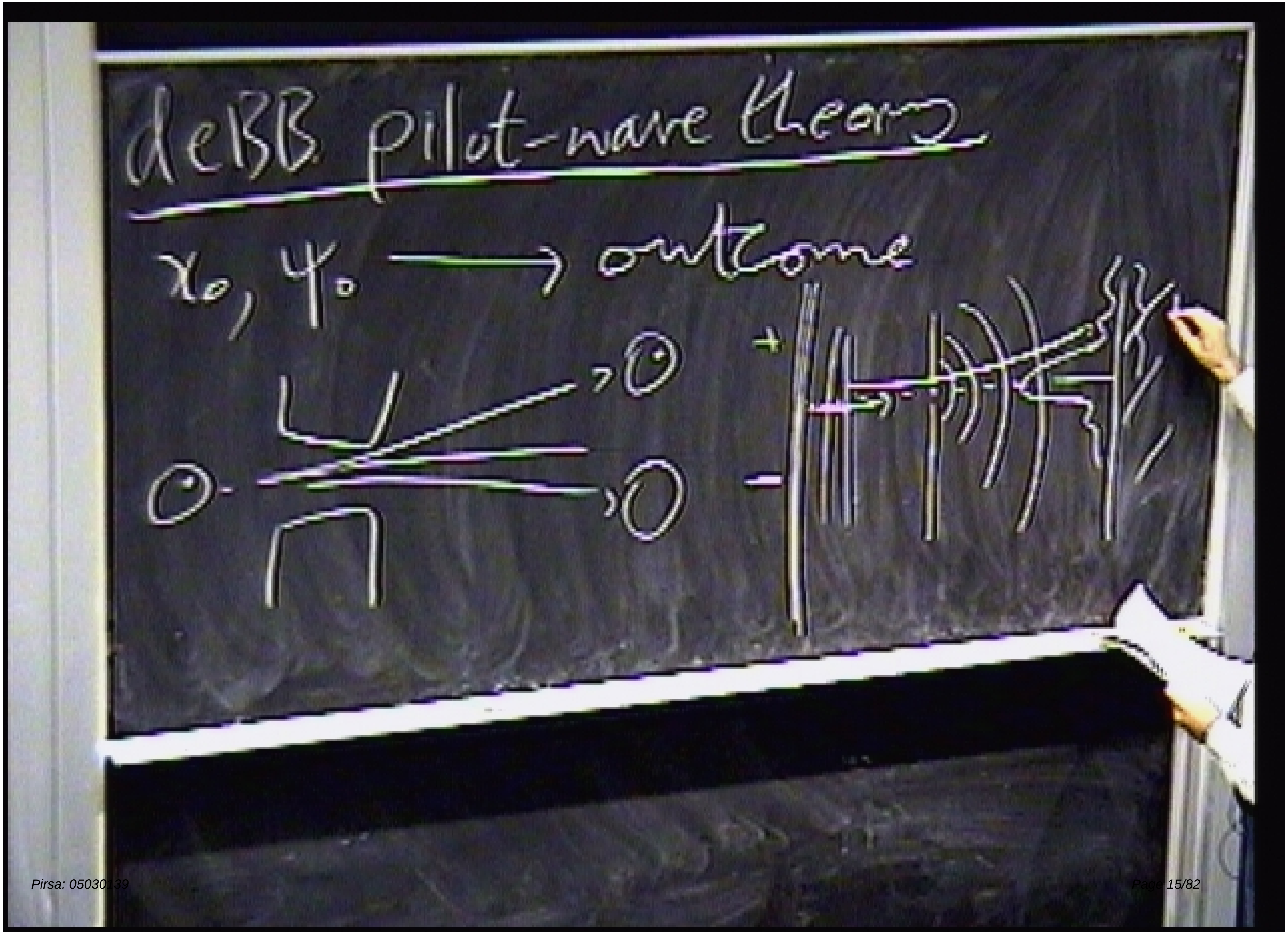

ρRT(m) = ½(1 ± m·ρ)
m, λ → σ = σ(m, λ)
ρRT(λ)
⟨σ(m,λ)⟩RT ≡ ∫dλ ρRT(λ) σ(m,λ)

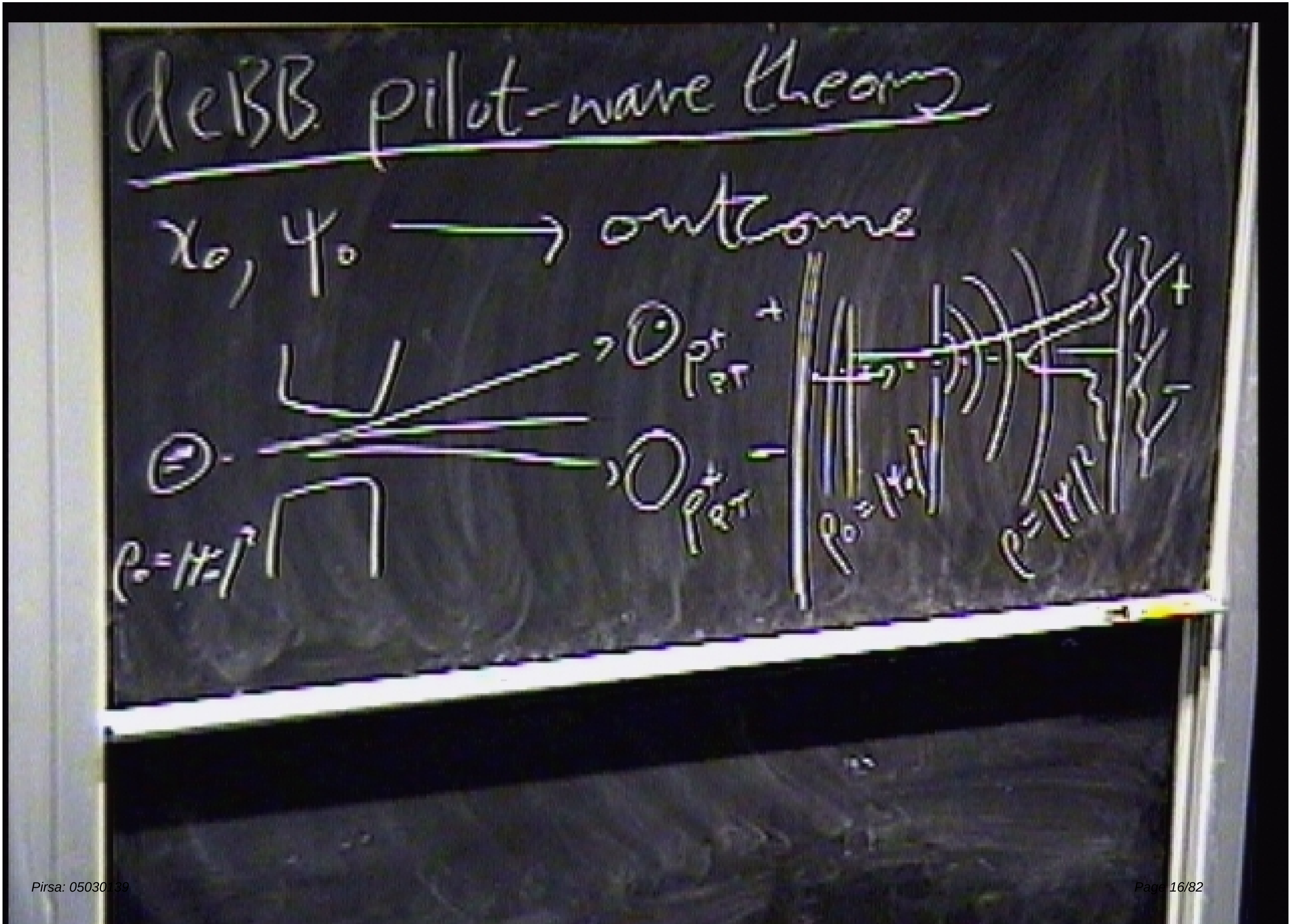

deBB pilot-wave theory

deBB pilot-wave theory

$x_0, \psi_0 \longrightarrow$ outcome



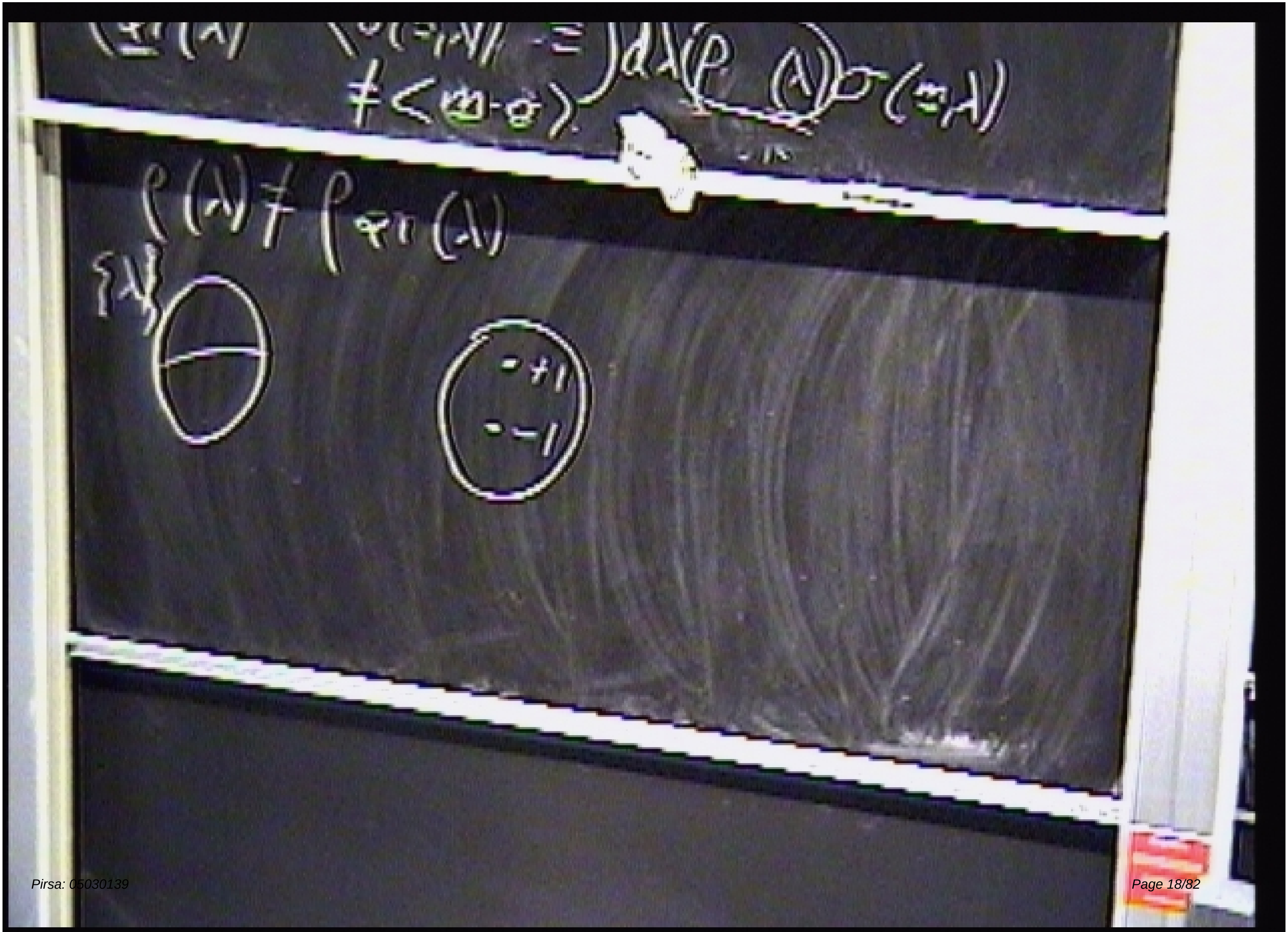

deBB pilot-wave theory
$x_0, \psi_0 \longrightarrow$ outcome

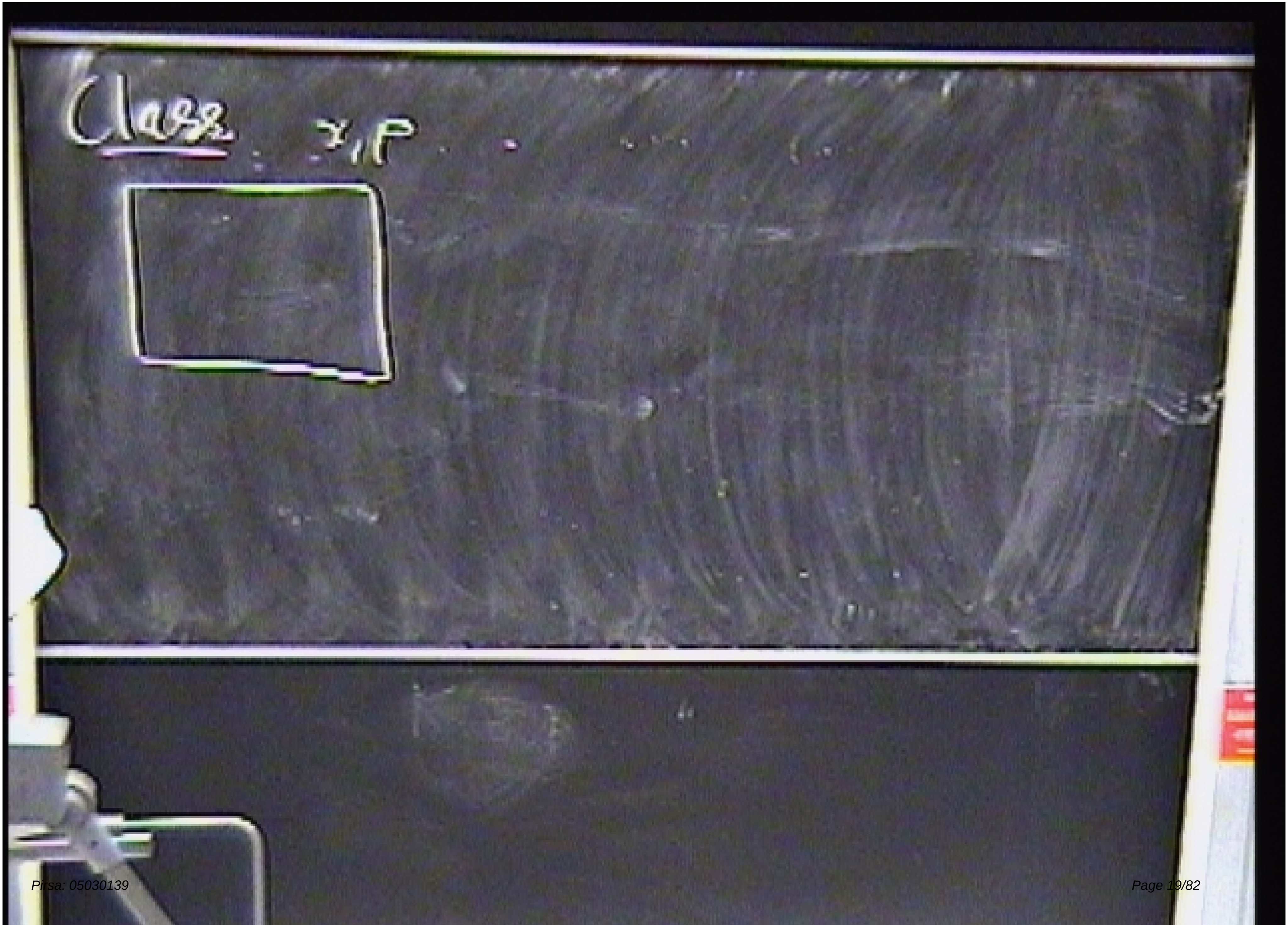

deBB pilot-wave theory
$x_0, \psi_0 \longrightarrow$ outcome
$\rho_0 = |\psi_0|^2$
$\rho_0 = |\psi_0|^2$
$\rho = |\psi|^2$
+
−

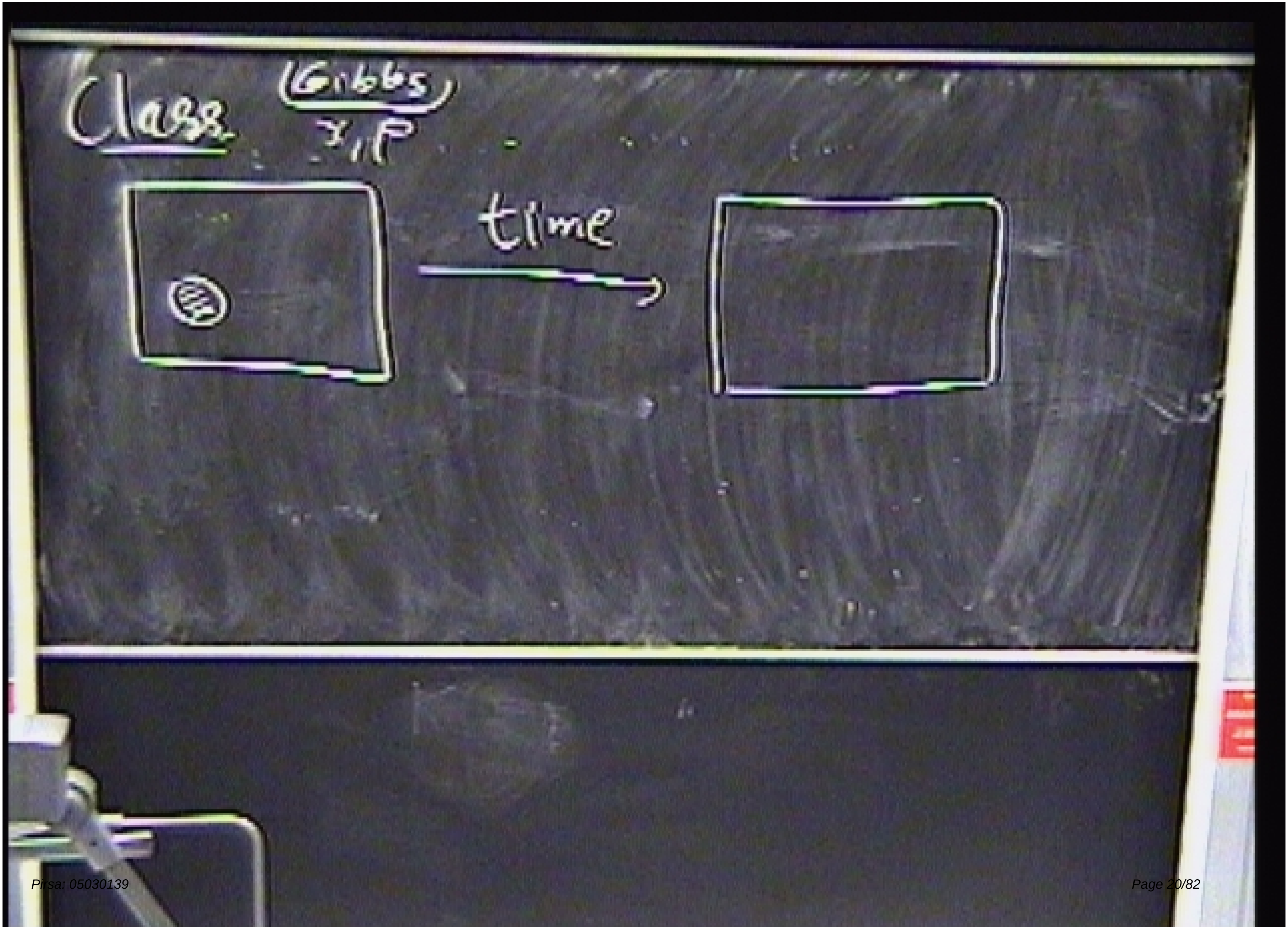
$$= \int d\lambda\, \rho_{QT}(\lambda)\,\sigma(m,\lambda)$$

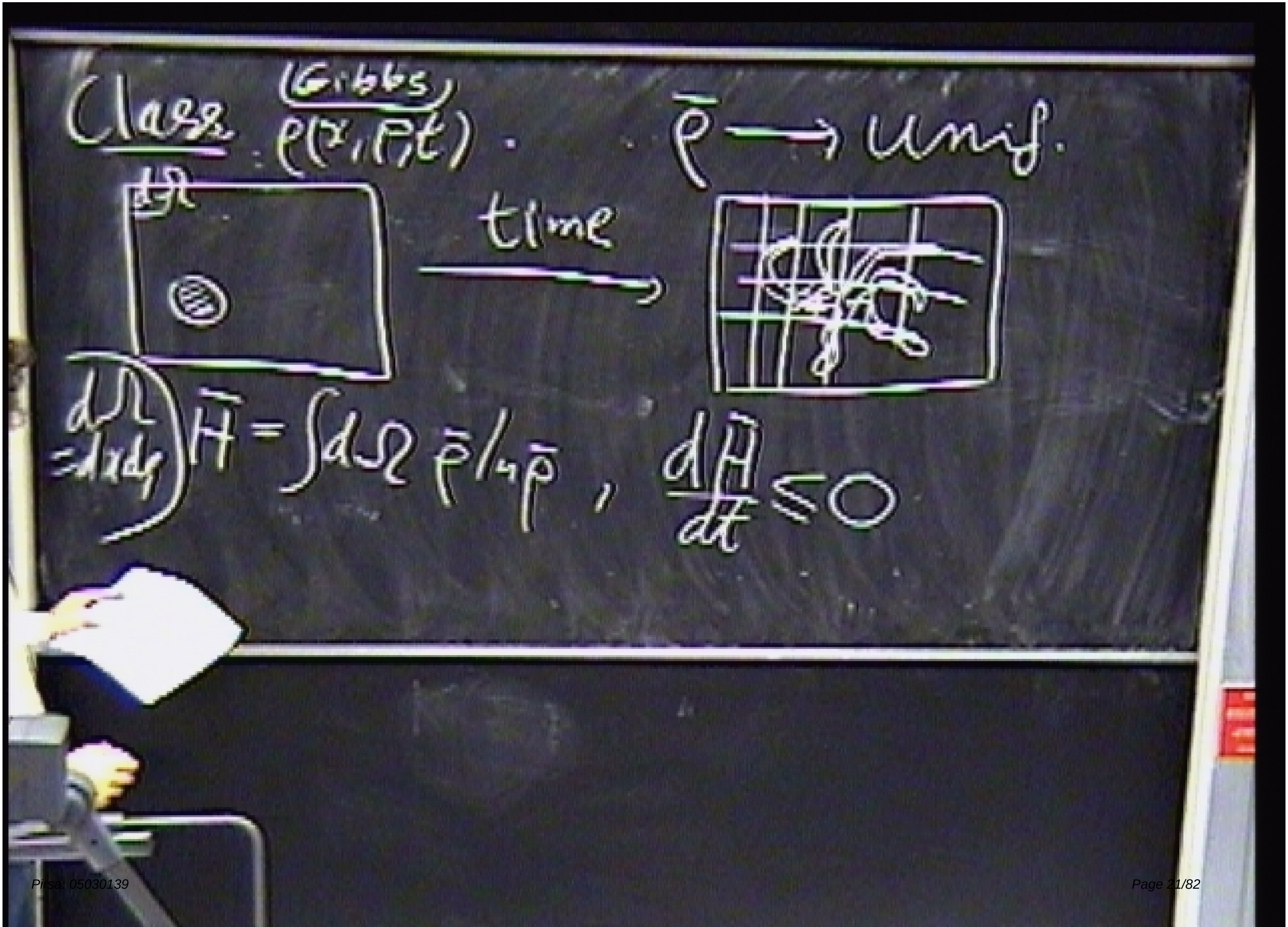
$$= \langle m\cdot\sigma\rangle$$

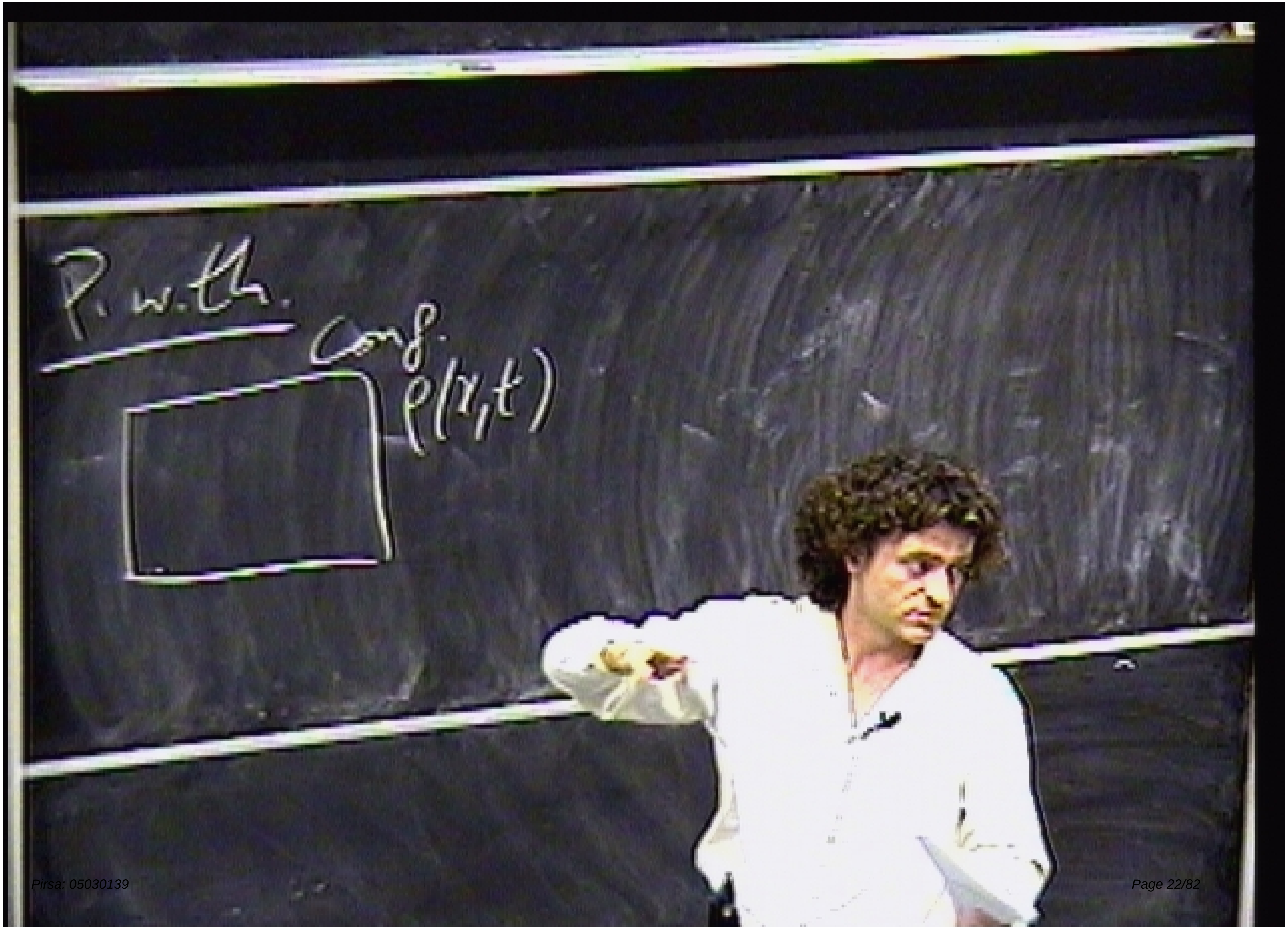
$$\rho(\lambda) \neq \rho_{QT}(\lambda)$$


{λ}
+1
−1


Class
x, p


Class
(Gibbs)
x, p
time


Class. (Gibbs) ρ(x,p,t)
ρ̄ → unif.
dΩ
time
dΩ = dx dp
H̄ = ∫dΩ ρ̄ ln ρ̄ , dH̄/dt ≤ 0


P. w. th.
Conf.
ρ(x,t)

P. w. th.

Config.

$\rho(x,t)$

$|\psi(x,t)|^2$

$\xrightarrow{\text{time}}$

$\bar{\rho} \longrightarrow \overline{|\psi|^2}$

P. w. th.

Conf.

$\rho(x,t)$

$|\psi(x,t)|^2$

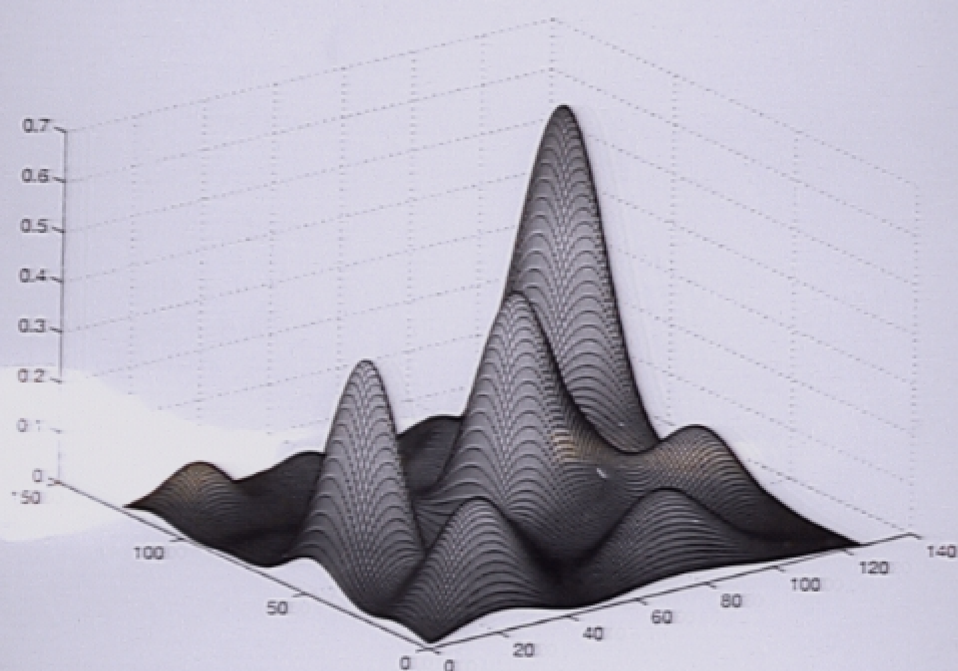
$\xrightarrow{\text{time}}$

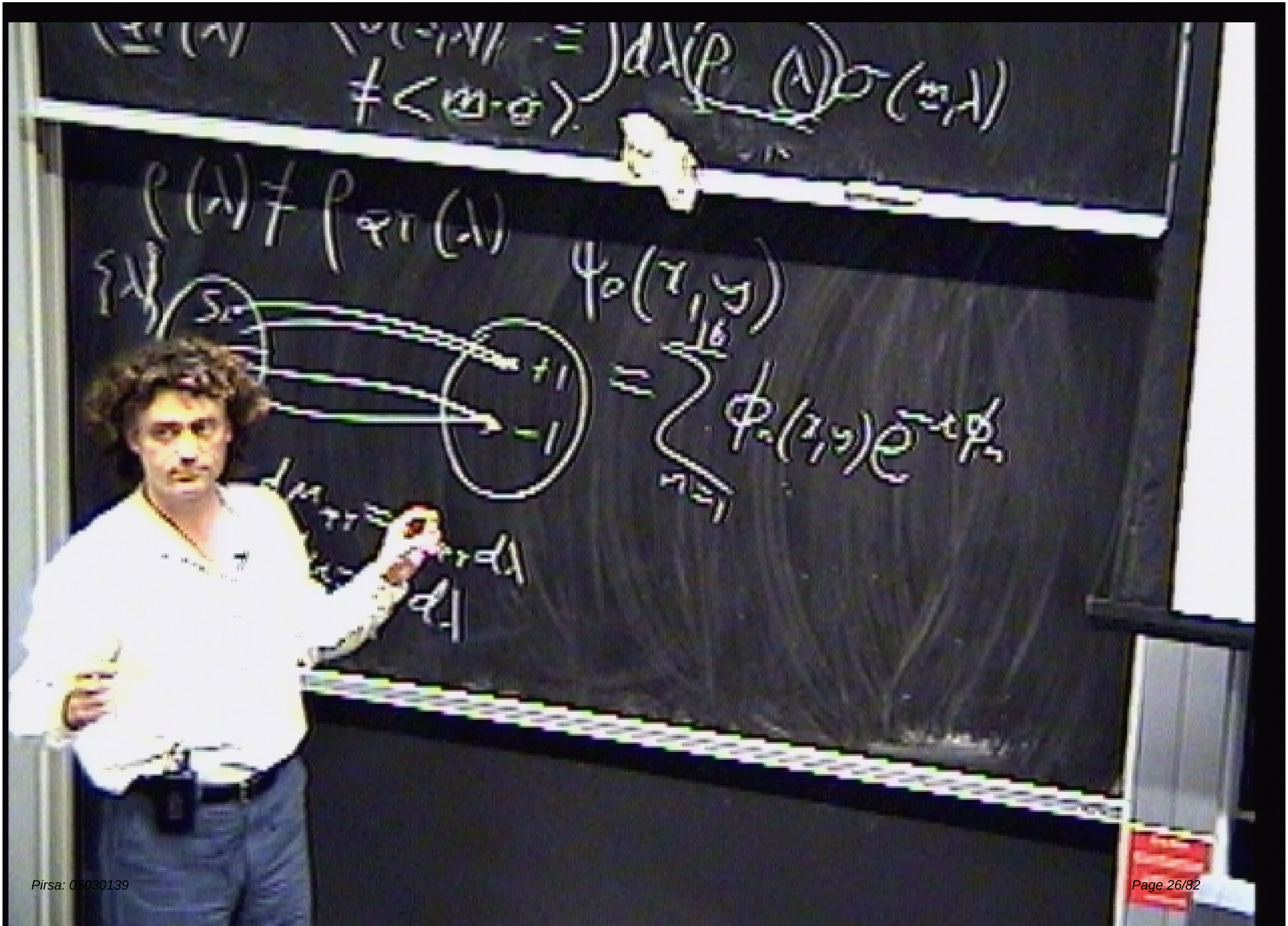
$\bar{\rho} \longrightarrow \overline{|\psi|^2}$

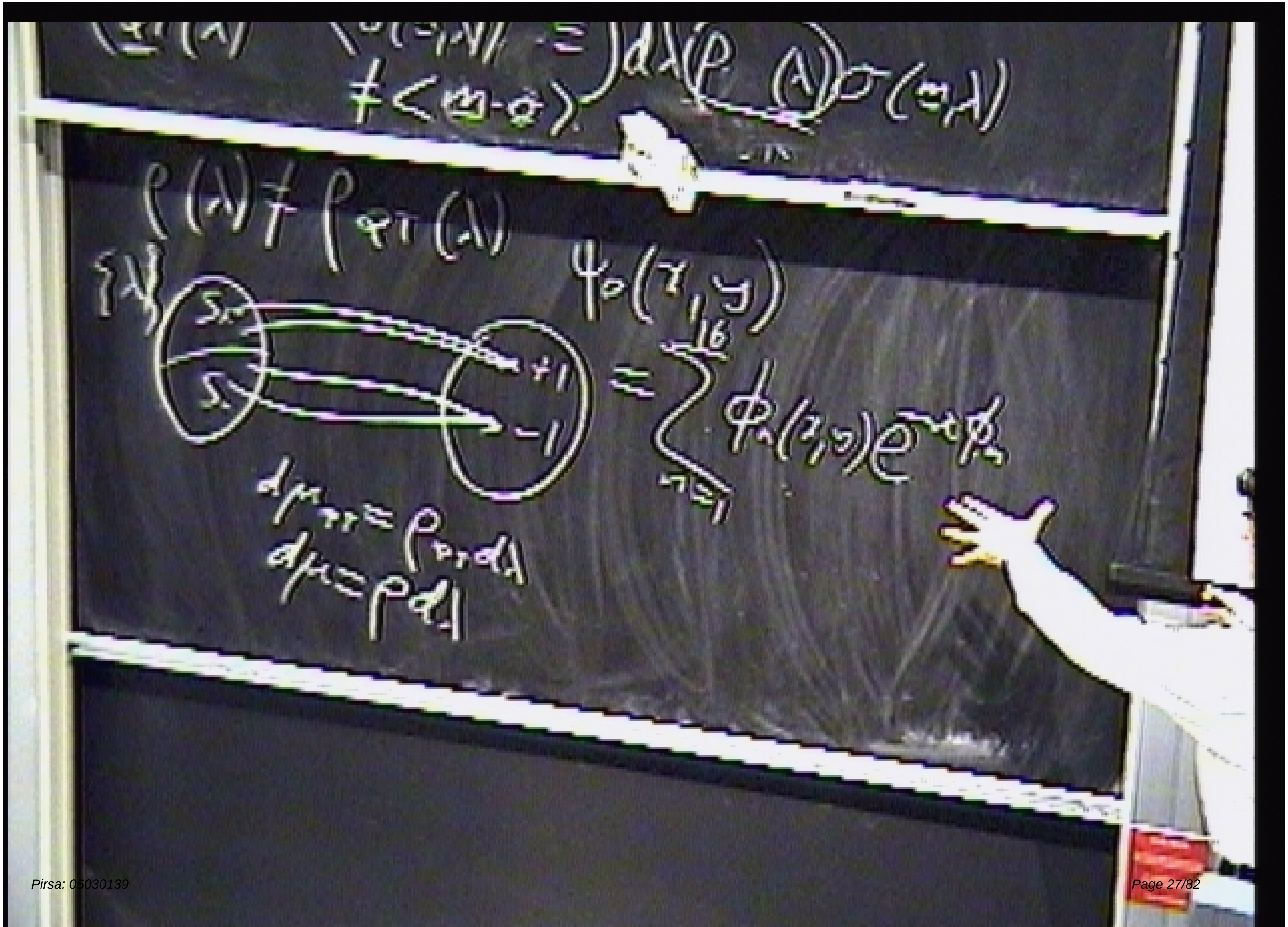
$$\bar{H} = \int dx\, \bar{\rho} \ln\left(\bar{\rho}/\overline{|\psi|^2}\right), \quad d\bar{H}/dt \leq 0$$

(with Hans Westman) (Proc. Roy. Soc. A 2005)

|Wavefunction$|^2$ at $t=0$

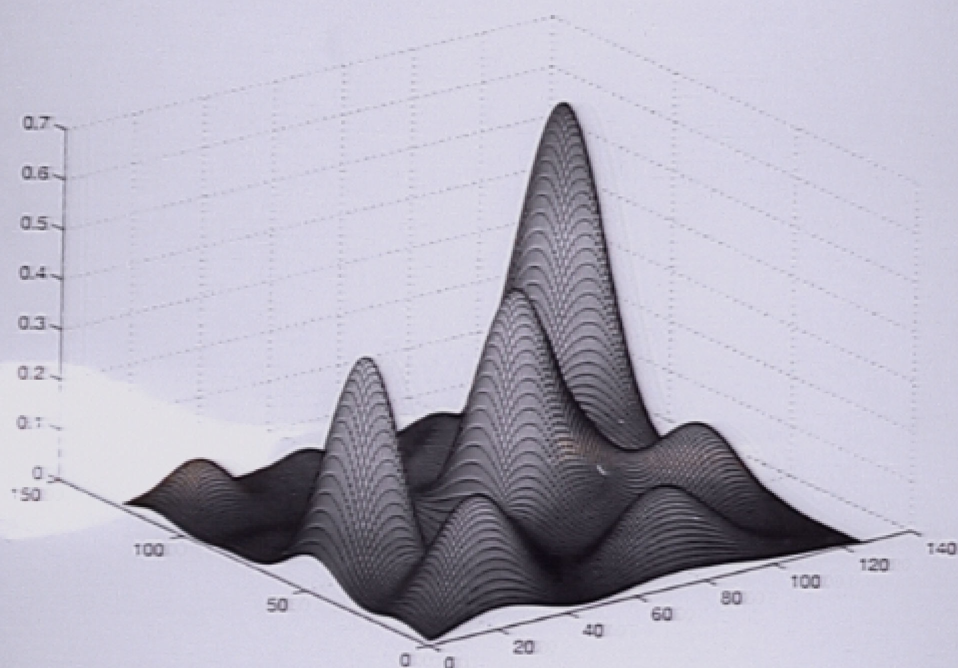




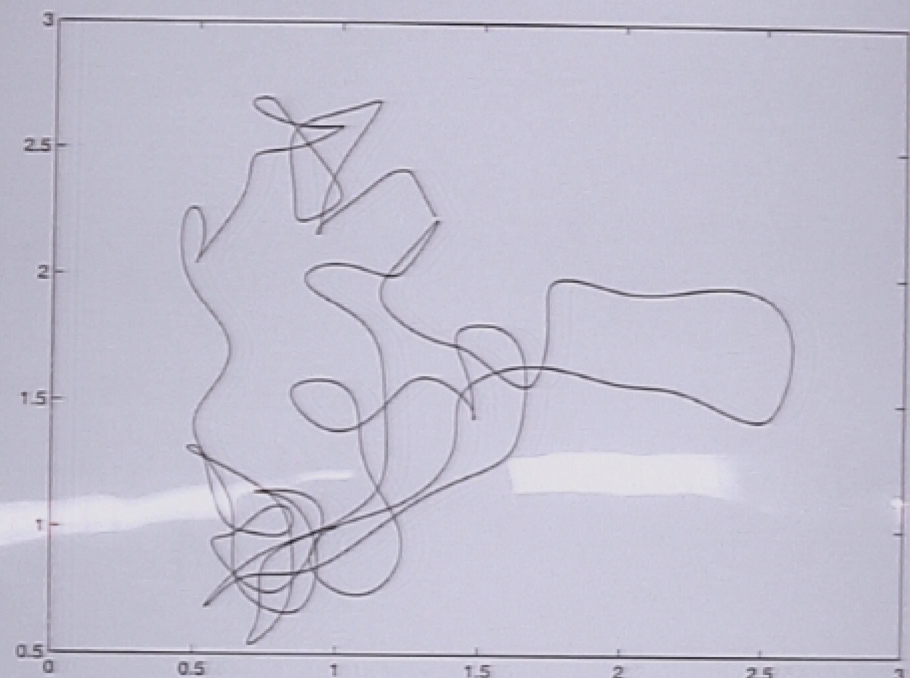

ρ(λ) ≠ ρ_QT(λ)
{λ}
+1
−1
ψ₀(x, y) = Σ φₙ(x,y) e^{−iφₙ}
16
n=1
dμ_QT = ρ_QT dλ
dμ = ρ dλ

(with Hans Westman) (Proc. Roy. Soc. A 2005)

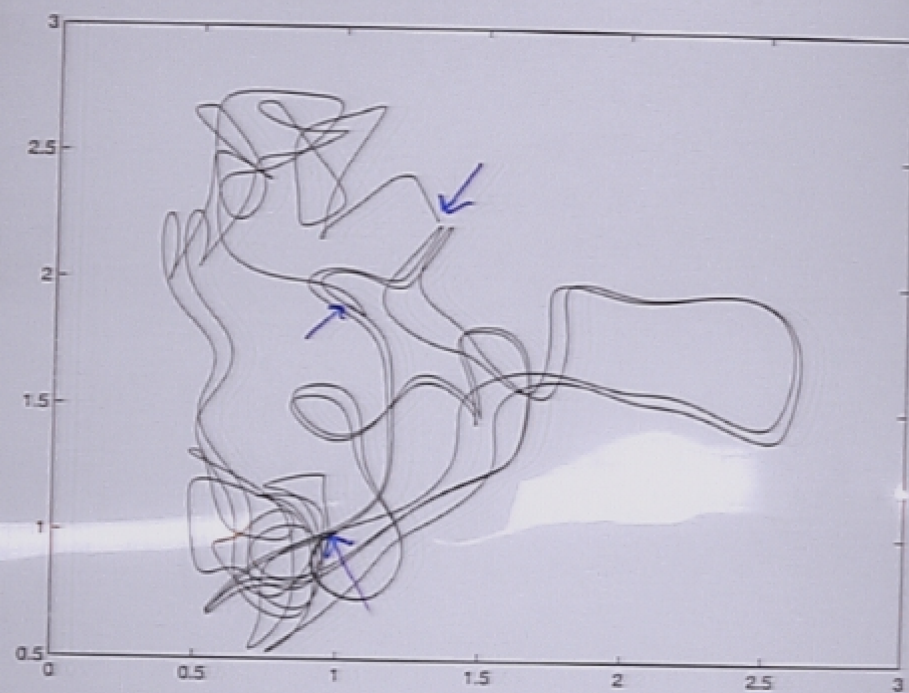
|Wavefunction|^2 at $t=0$



Example of a trajectory.

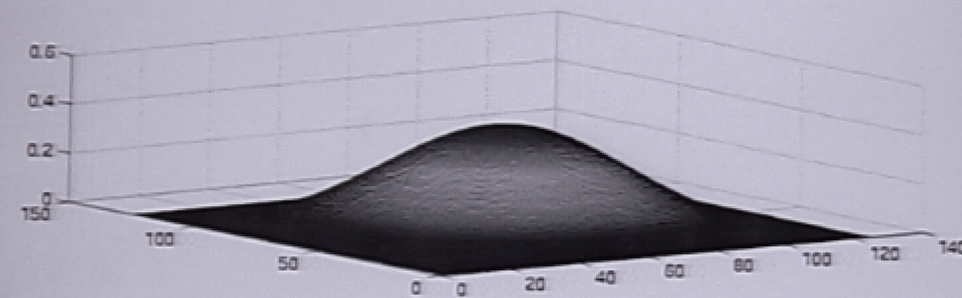


Diverging trajectories

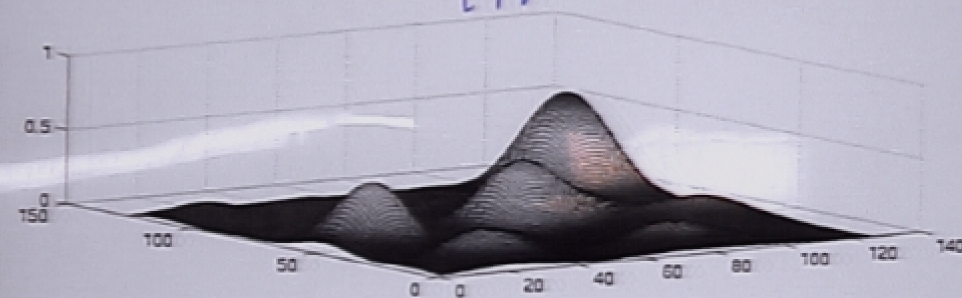


$t=0$

P

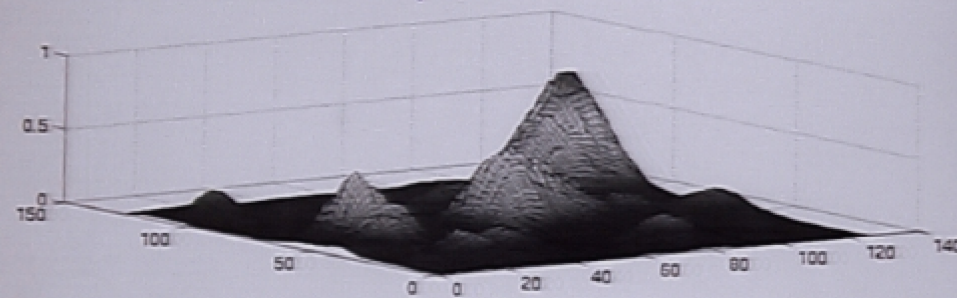

0.6
0.4
0.2
0
150
100
50
0
0
20
40
60
80
100
120
140

$|\psi|^2$

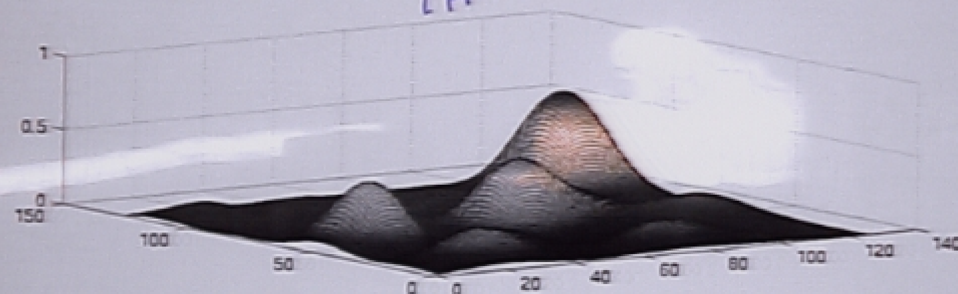

1
0.5
0
150
100
50
0
0
20
40
60
80
100
120
140

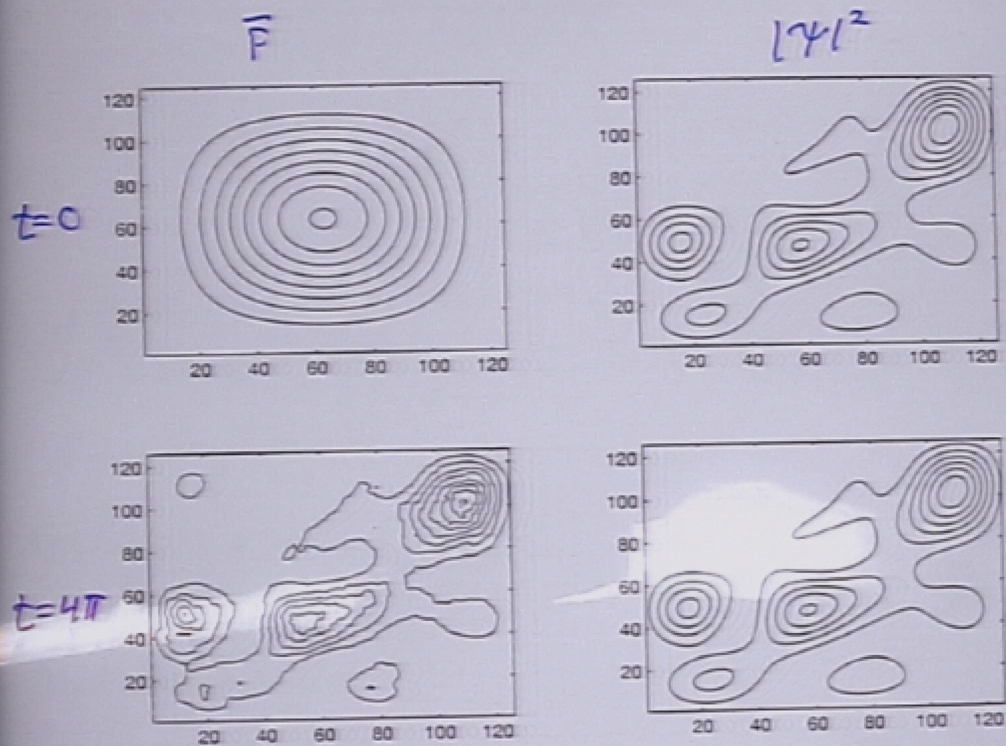
$t = 4\pi$

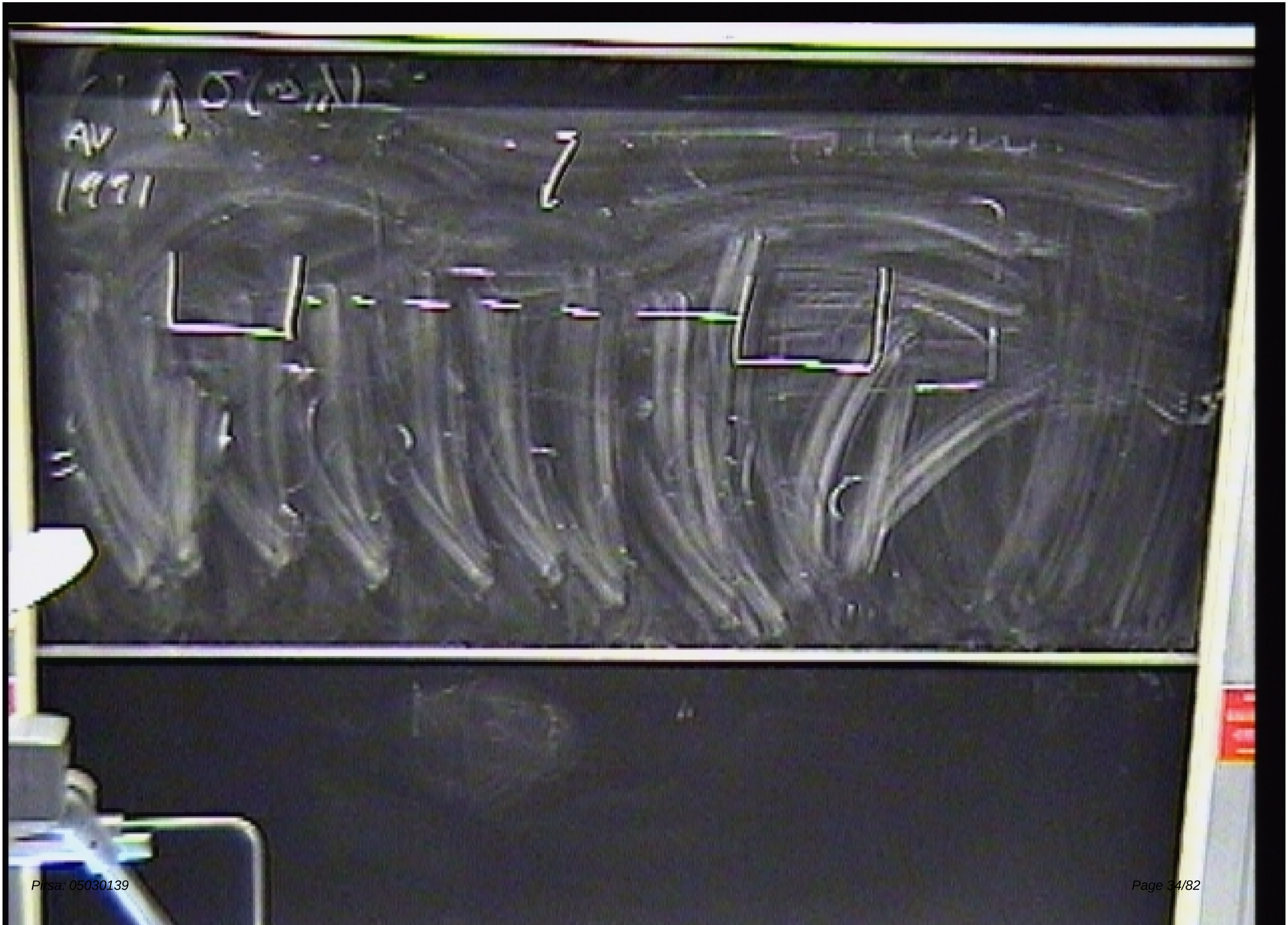
$\overline{P}$

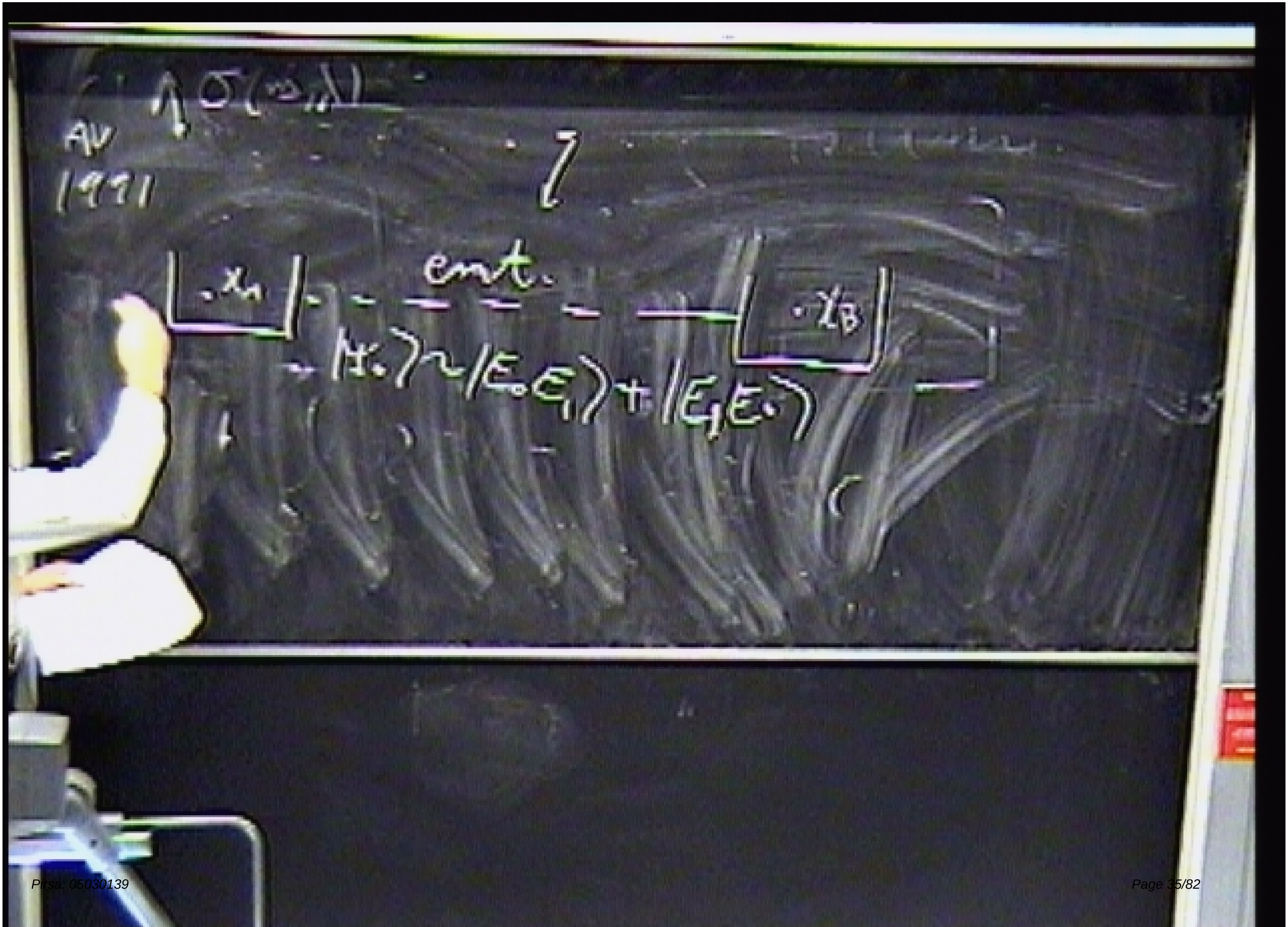


$|\psi|^2$




$\bar{F}$
$|\psi|^2$
$t=0$
$t=4\pi$
20 40 60 80 100 120


AV
1991


AV
1991
emt.
x_A
x_B
$|\psi_0\rangle \sim |E_0 E_1\rangle + |E_1 E_0\rangle$

AV 1991

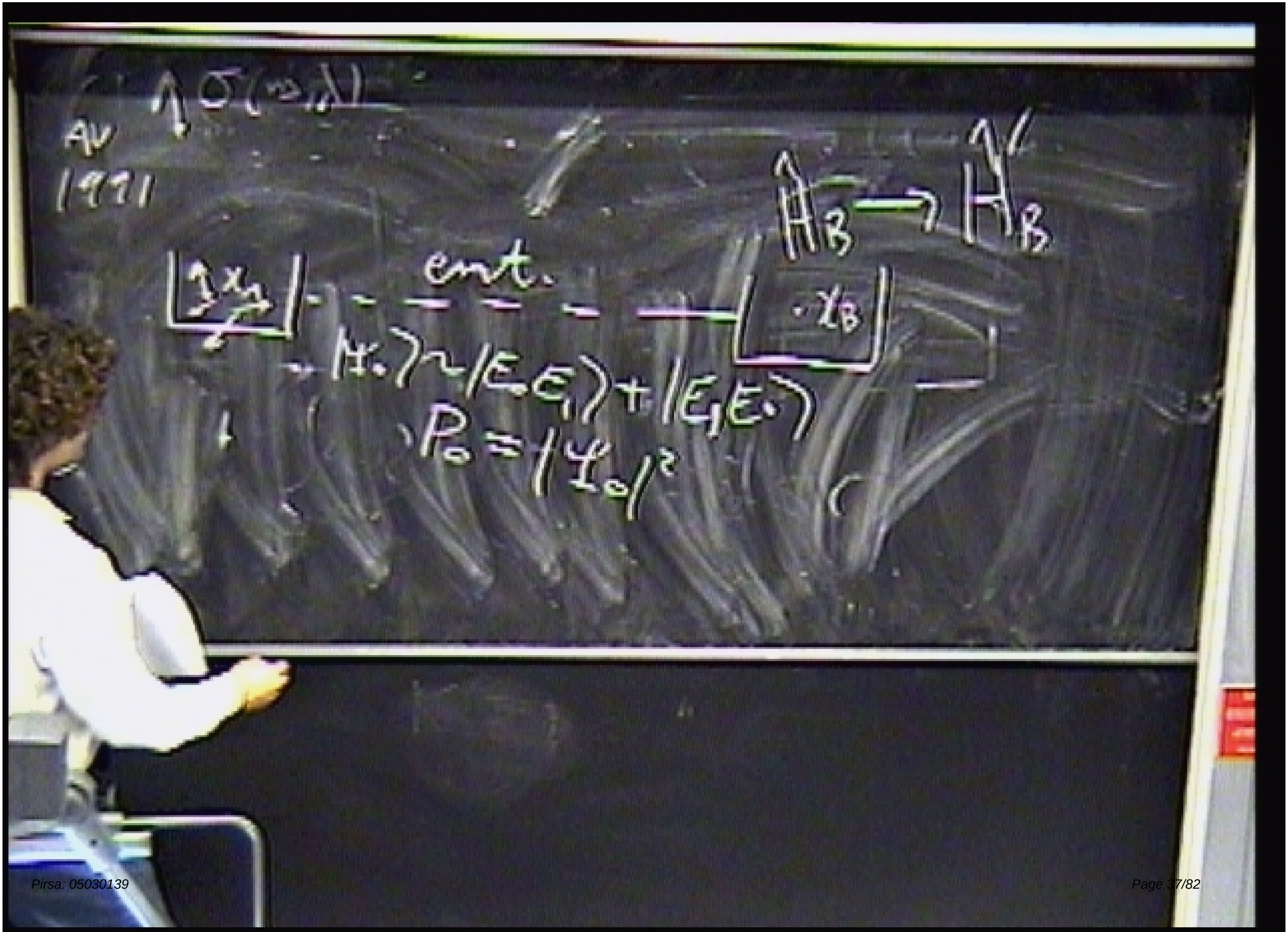
$\sigma(m,\lambda)$

$\hat{H}_B \to \hat{H}'_B$

$\boxed{x_A}$ - - - ent. - - - $\boxed{x_B}$

$|\Psi_0\rangle \sim |E_0 E_1\rangle + |E_1 E_0\rangle$

$P_0 = |\Psi_0|^2$


AV
1991
ent.
$P_0 = |\Psi_0|^2$

AV 1991

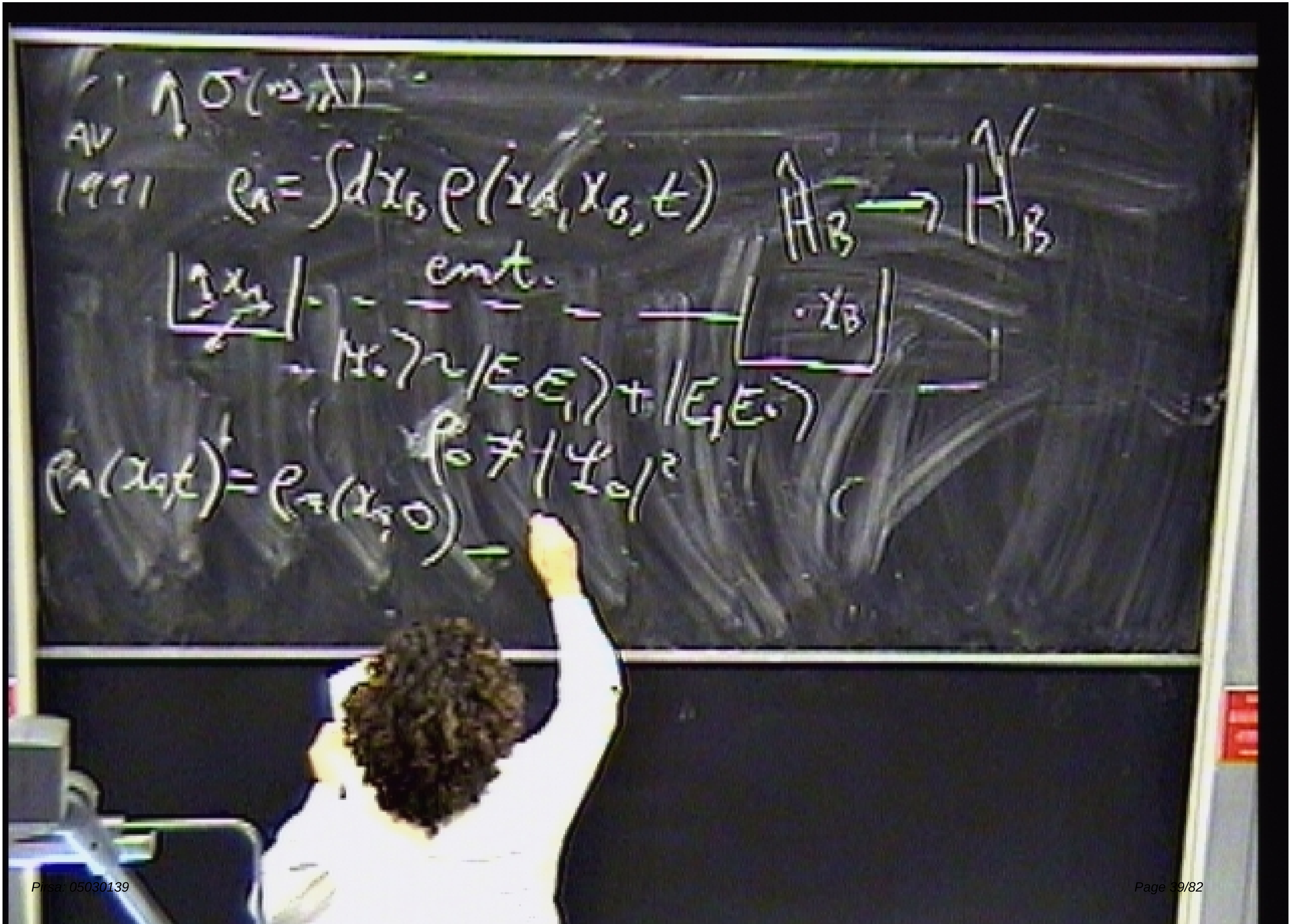
$\uparrow \sigma(m,\lambda)$

$$\rho_A = \int dx_B\, \rho(x_A, x_B, t) \qquad \hat{H}_B \to \hat{H}'_B$$

$\boxed{x_A}$ emt. $\boxed{x_B}$

$$|\Psi_0\rangle \sim |E_0 E_1\rangle + |E_1 E_0\rangle$$

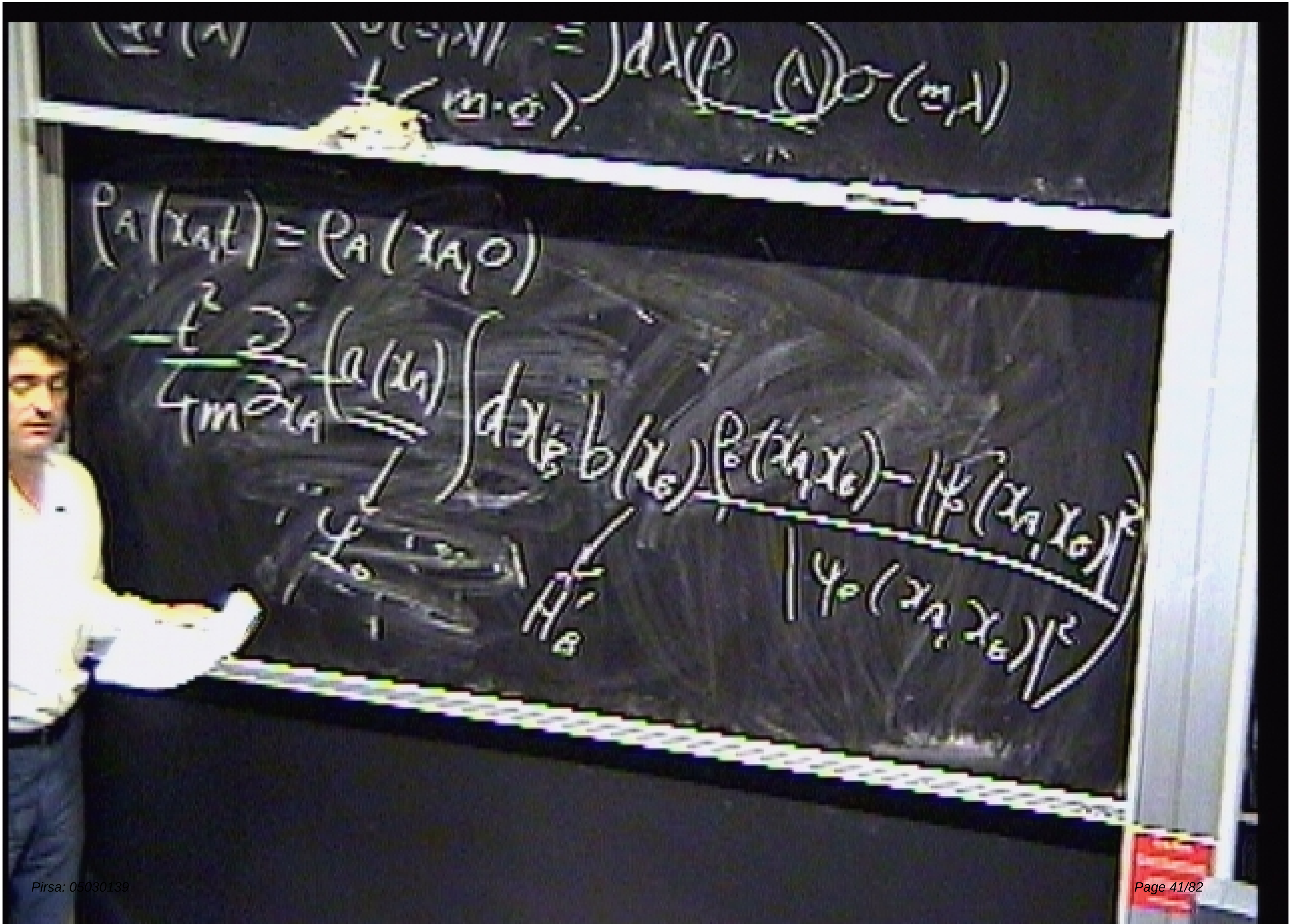
$$\rho_0 \neq |\Psi_0|^2$$

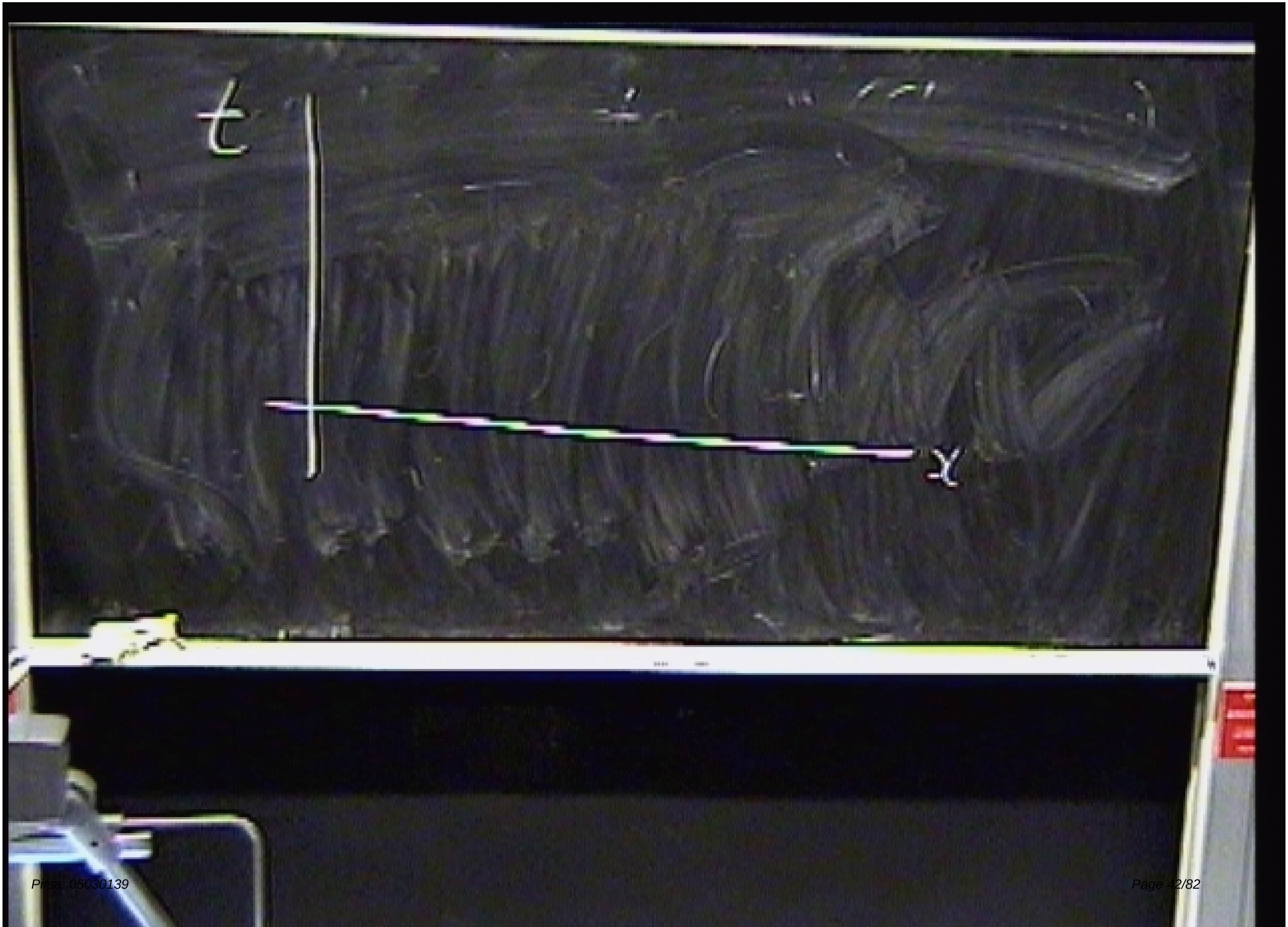

AV
1991
emt.

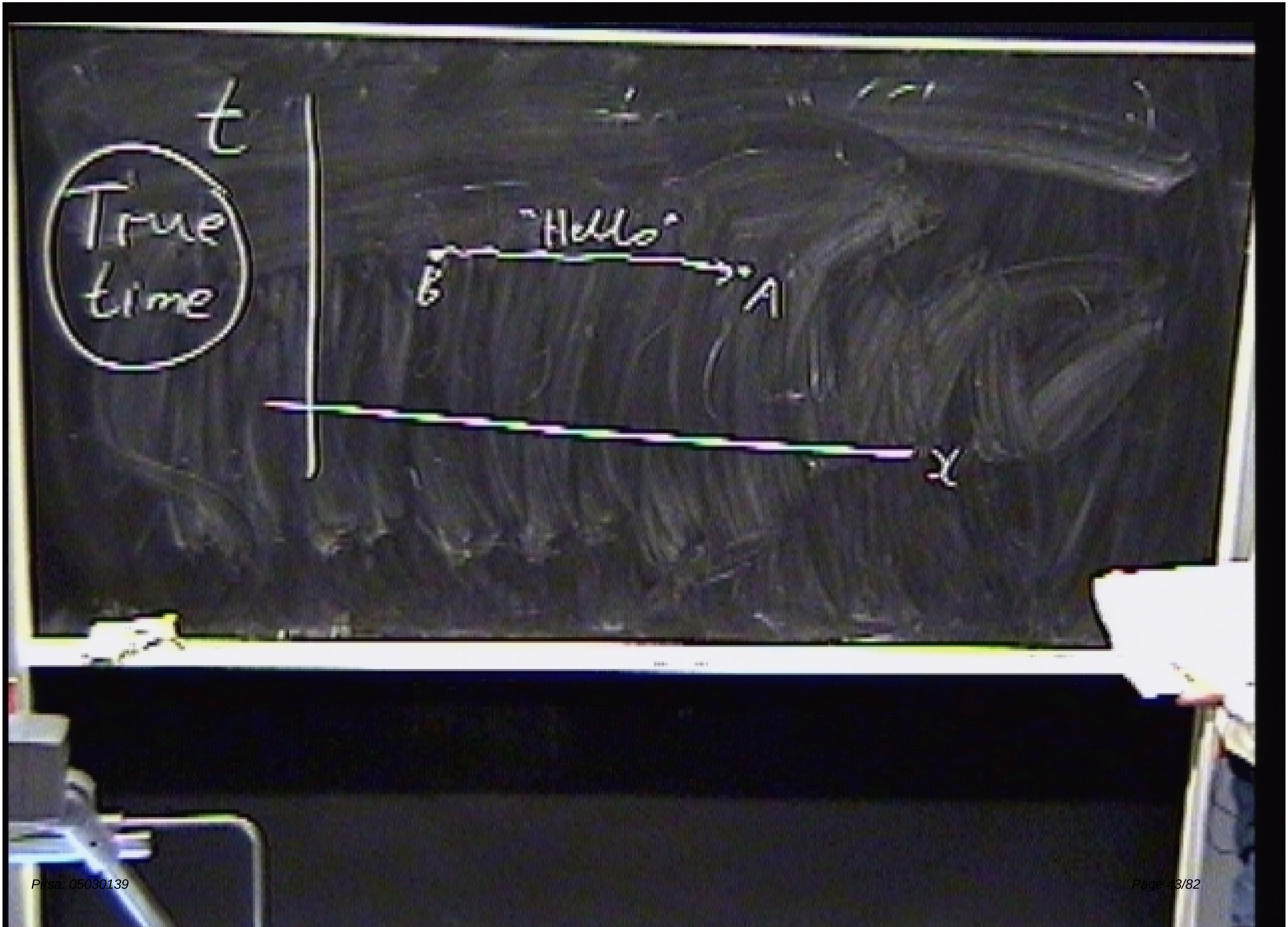
$$\langle \sigma(m,\lambda)\rangle = \int d\lambda\, \rho(\lambda)\, \sigma(m,\lambda)$$

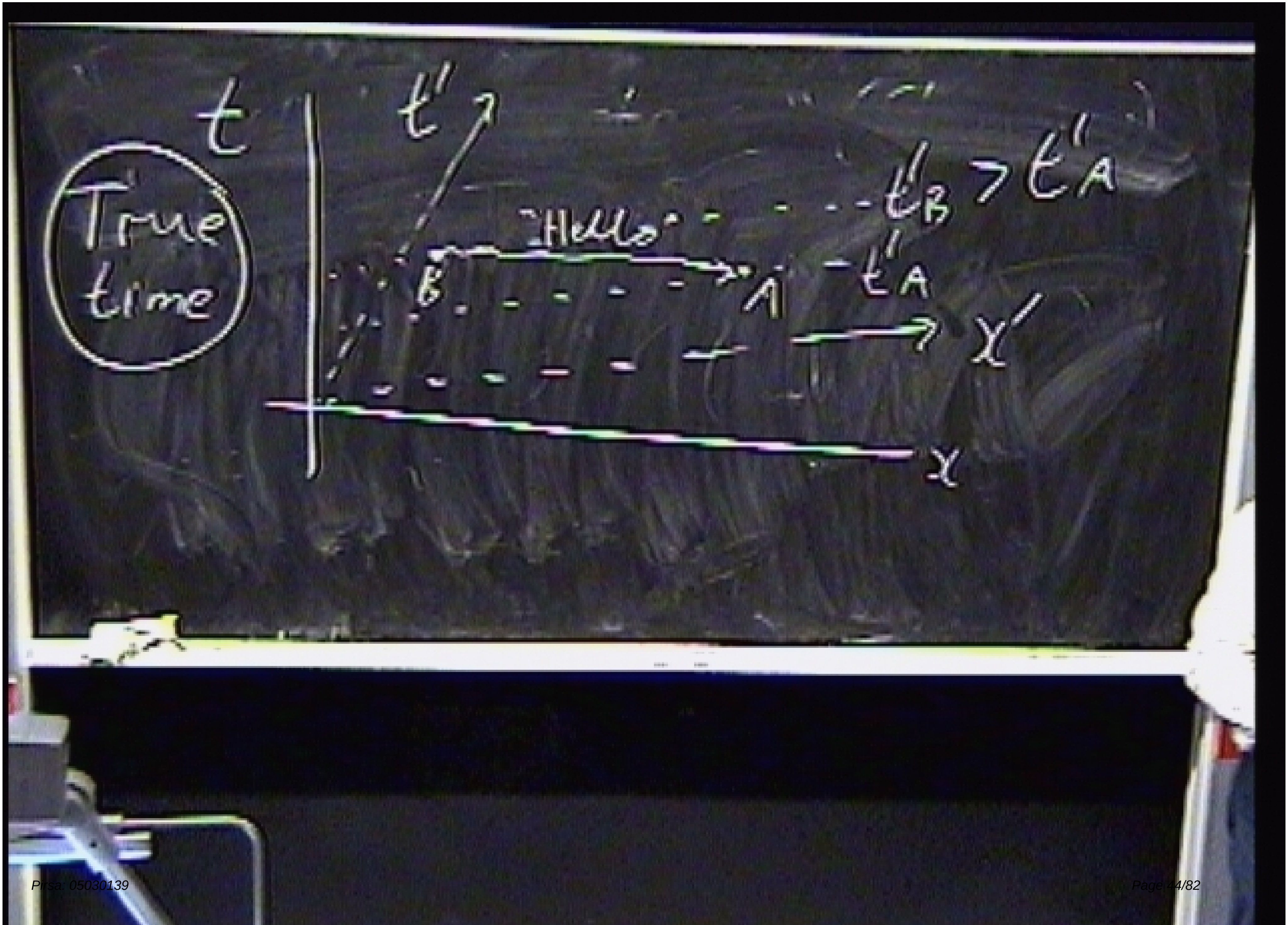
$$\langle m\cdot\sigma\rangle$$

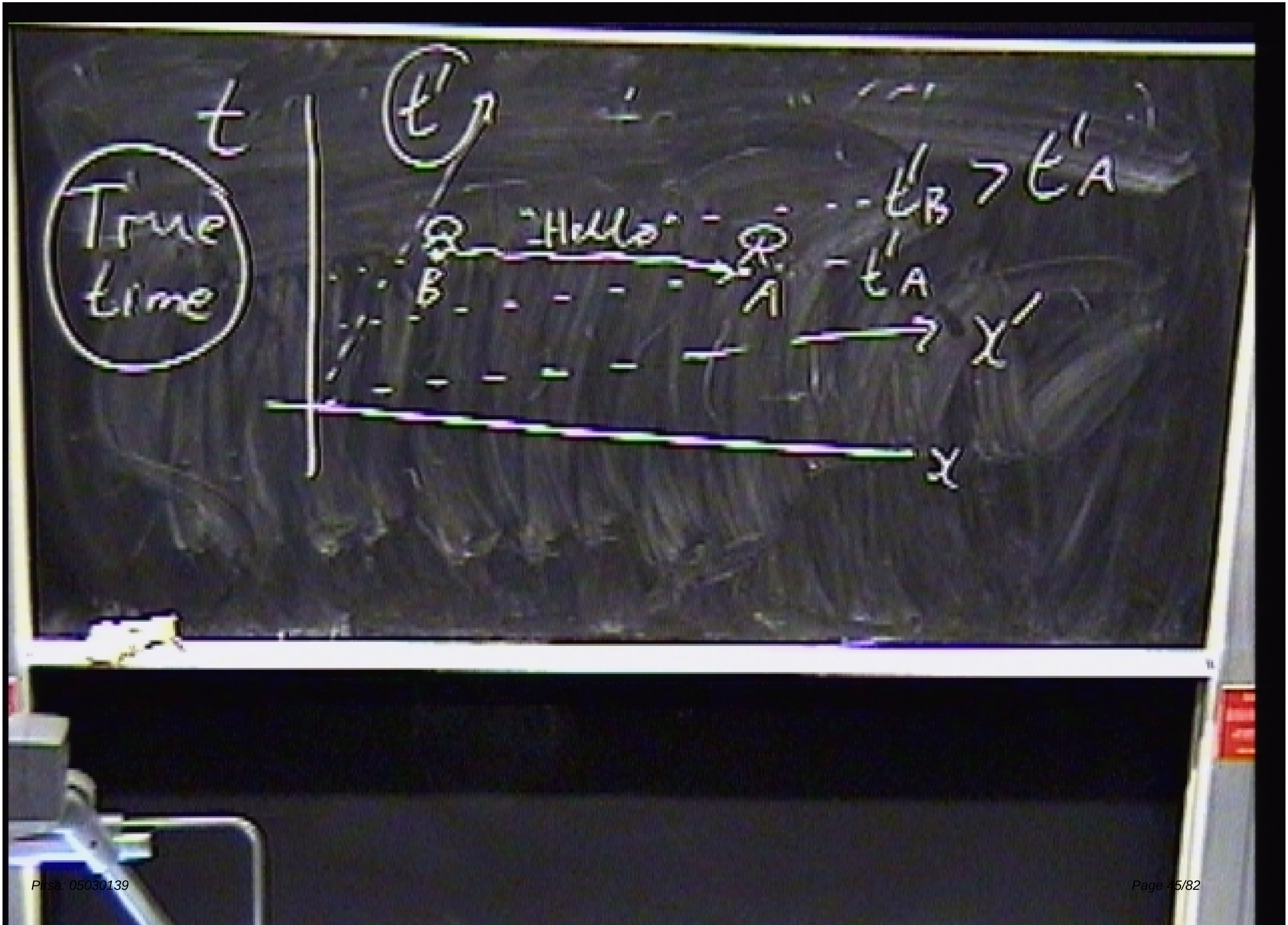
$$\rho_A(x_A,t) = \rho_A(x_A,0) - \frac{t^2}{4m}\frac{\partial}{\partial x_A}\left(a(x_A)\right.$$

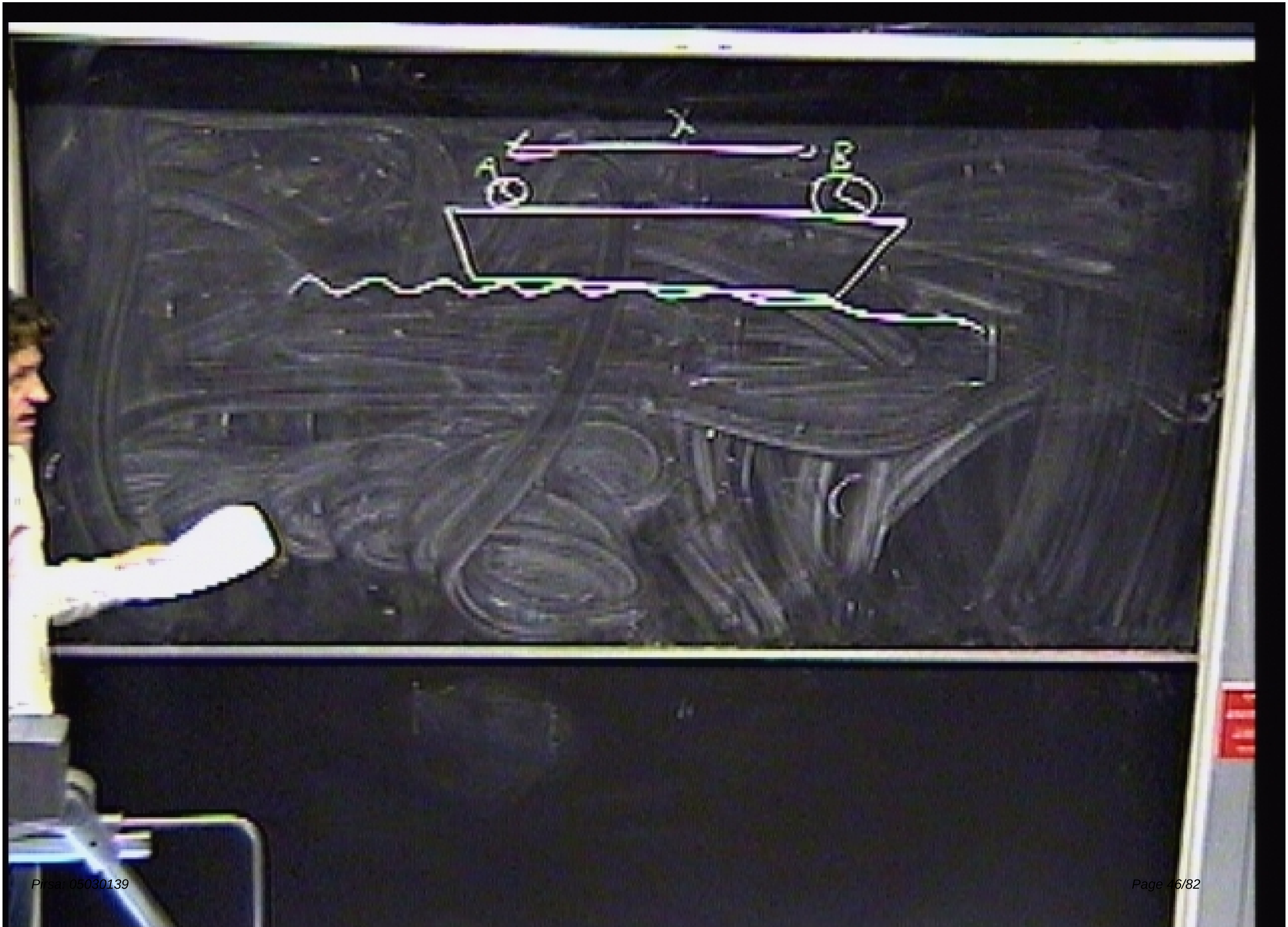

$\langle \sigma(m,\lambda)\rangle = \int d\lambda\, \rho(\lambda)\,\sigma(m,\lambda)$
$\neq \langle m\cdot\sigma\rangle$
$\rho_A(x_A,t) = \rho_A(x_A,0)$
$-\frac{t^2}{4m}\frac{\partial}{\partial x_A}\left(a(x_A)\int dx_B\, b(x_B)\left(\rho_0(x_A,x_B) - \frac{|\psi_0(x_A,x_B)|^2}{|\psi_0(x_A,x_B)|^2}\right)\right)$


t
x

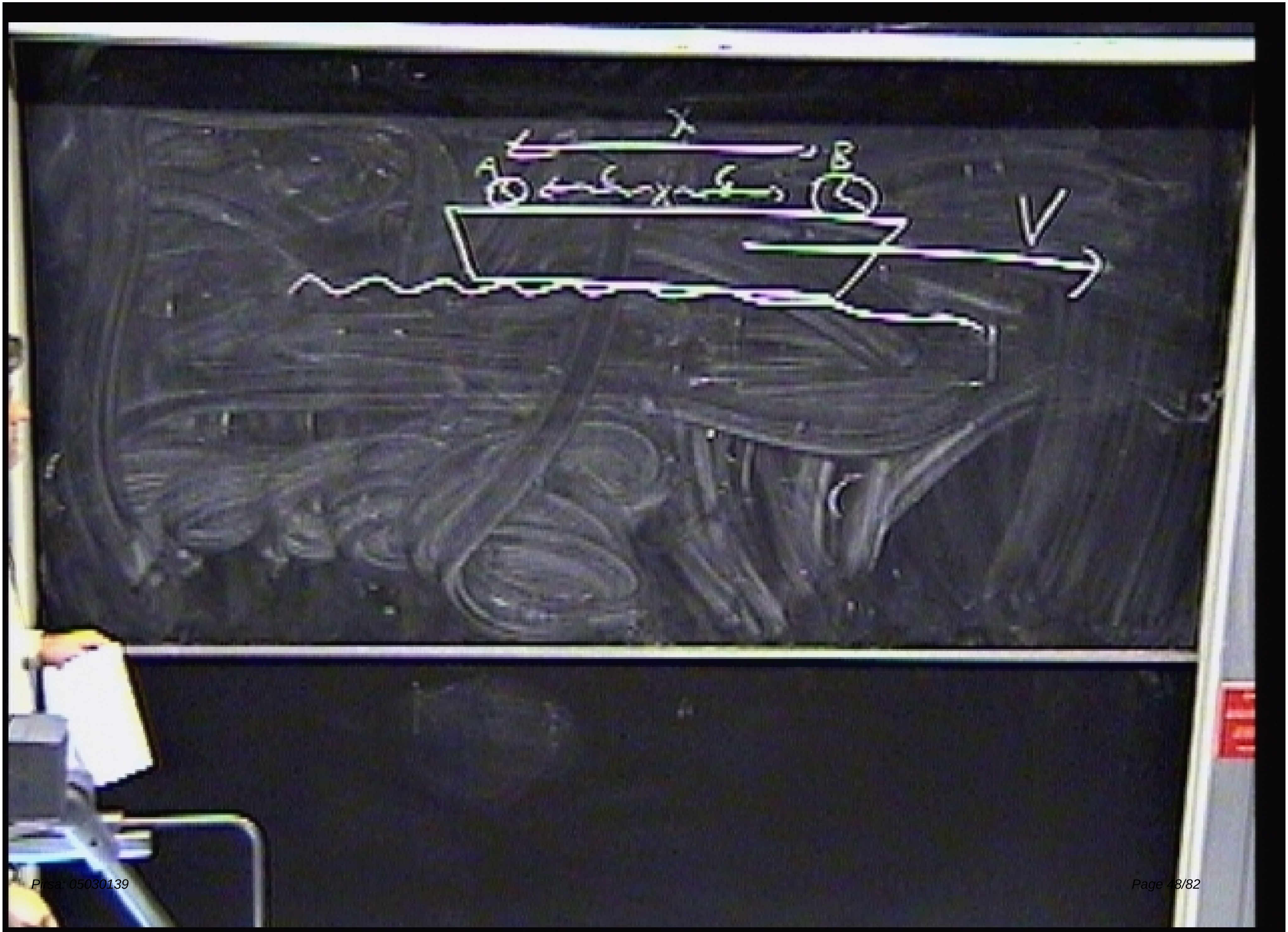

t
True time
"Hello"
B
A
x

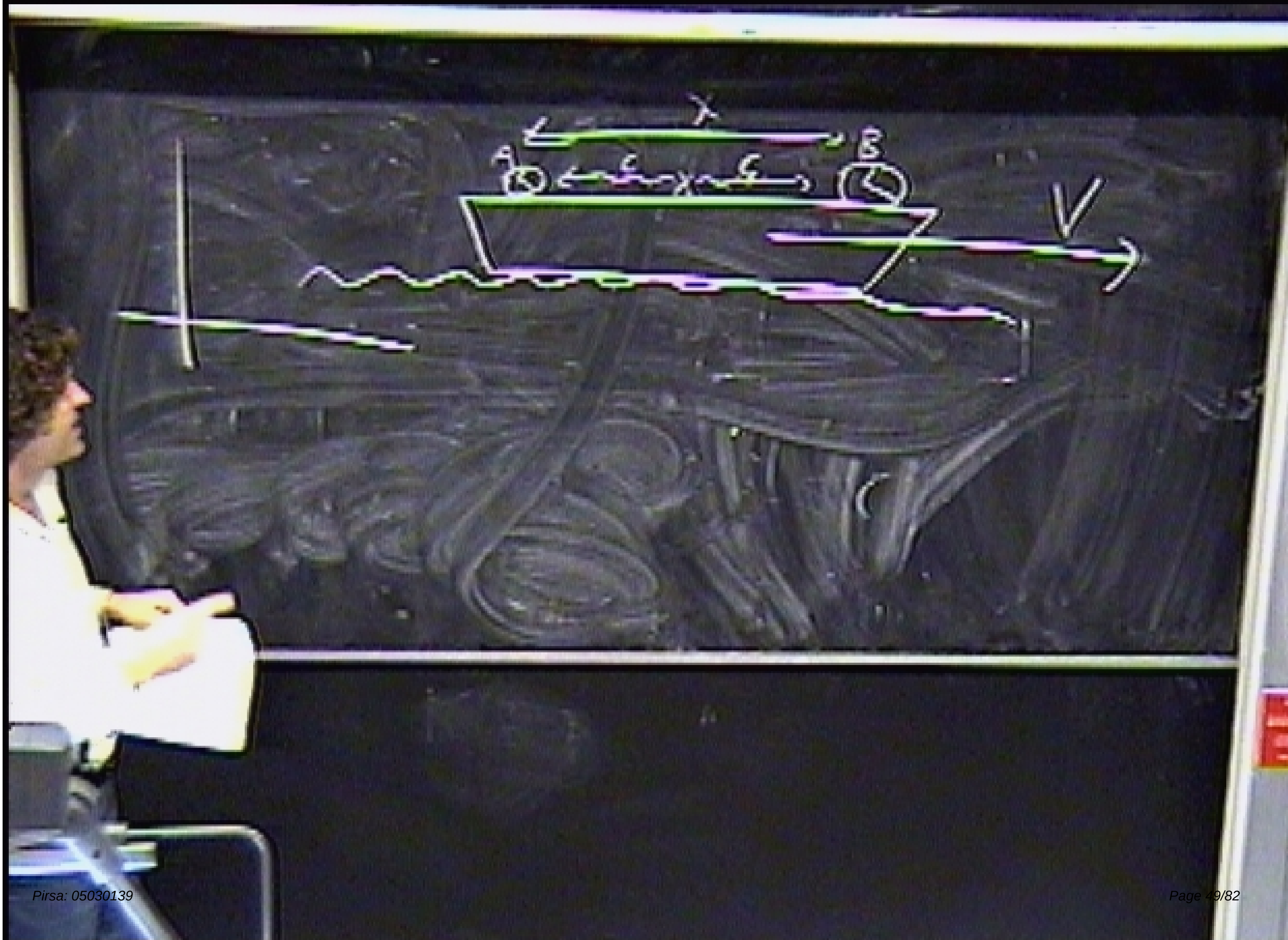

True time
t
t'
"Hello"
B
A
t'B > t'A
t'A
x'
x

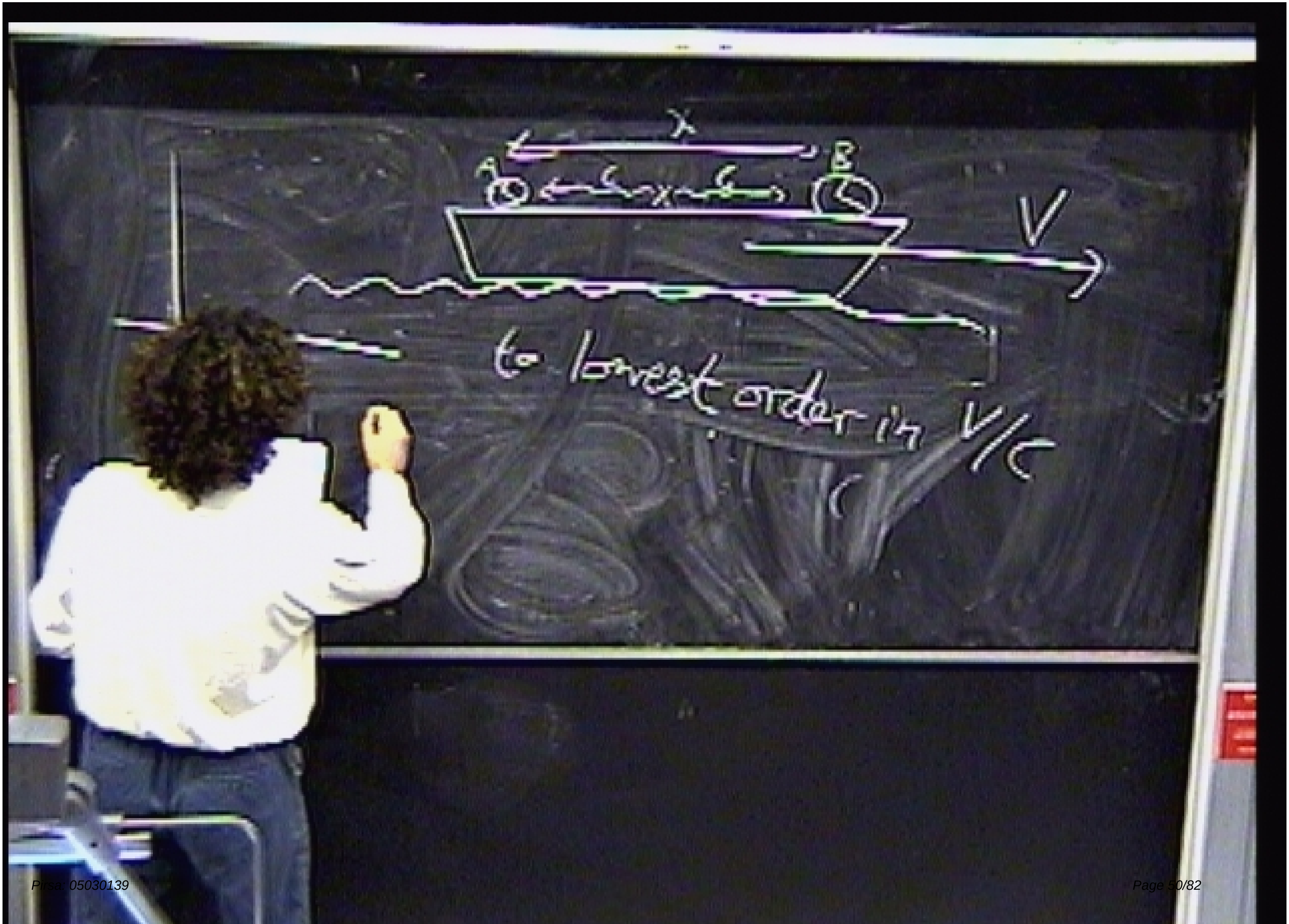

True time
t
t'
"Hello"
B
A
t'B > t'A
t'A
X'
X

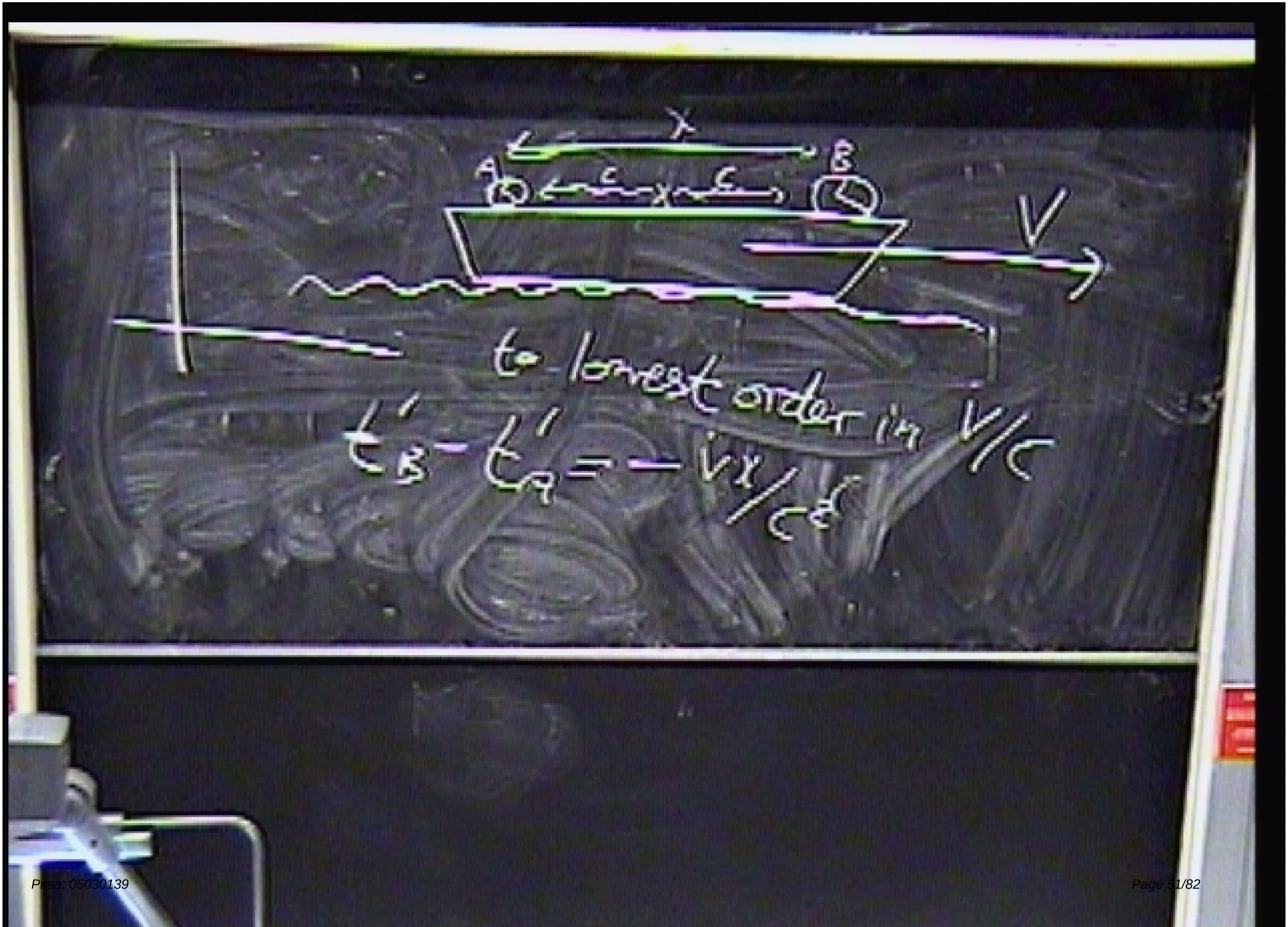

X
A
B

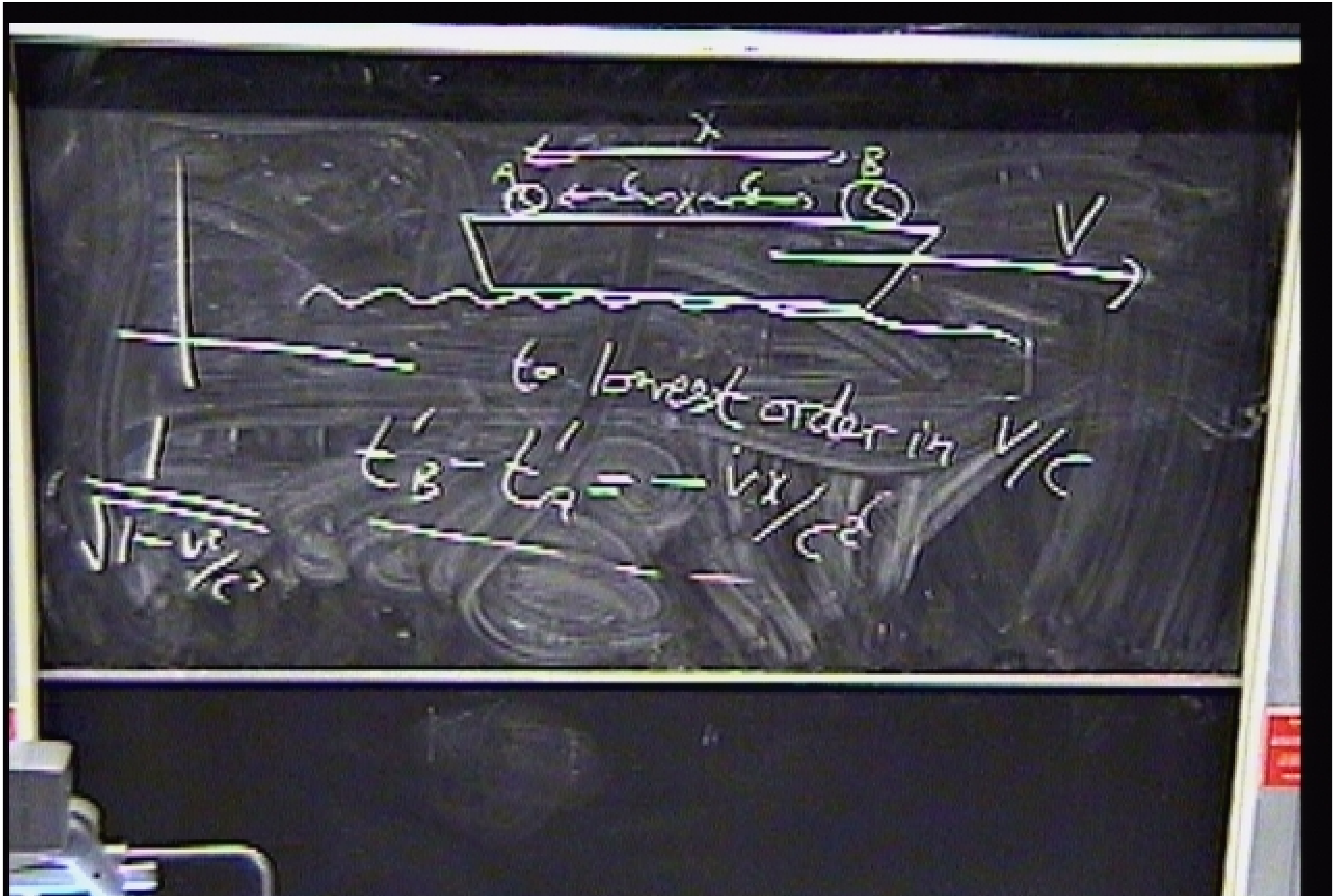

x
A
B
x

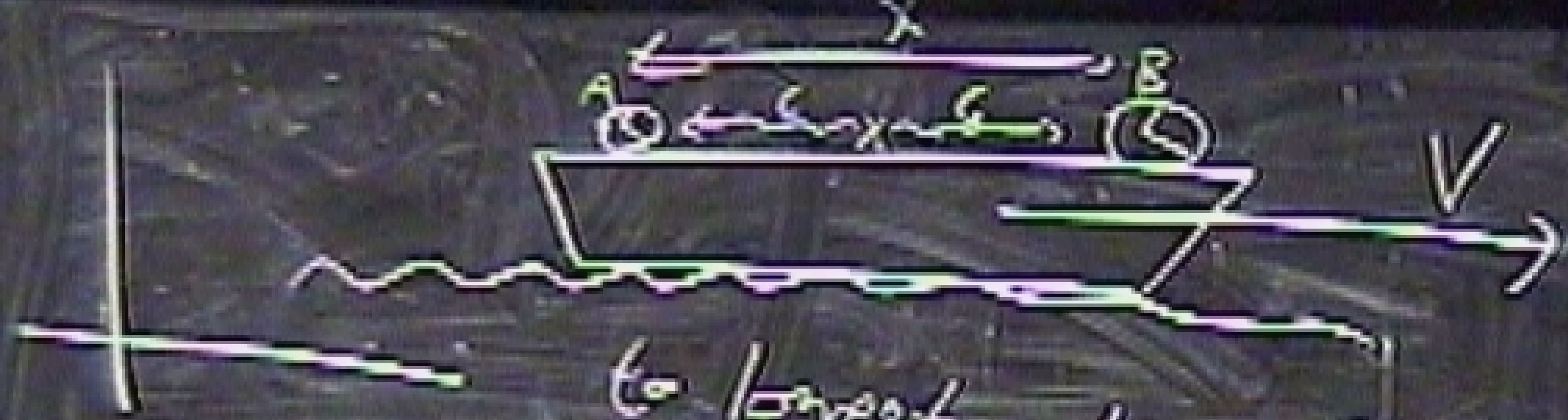

x
A
B
x
V


x
B
V


x
A
B
V
to lowest order in V/c


x
A
B
V
to lowest order in V/c
t'B - t'A = - Vx/c²

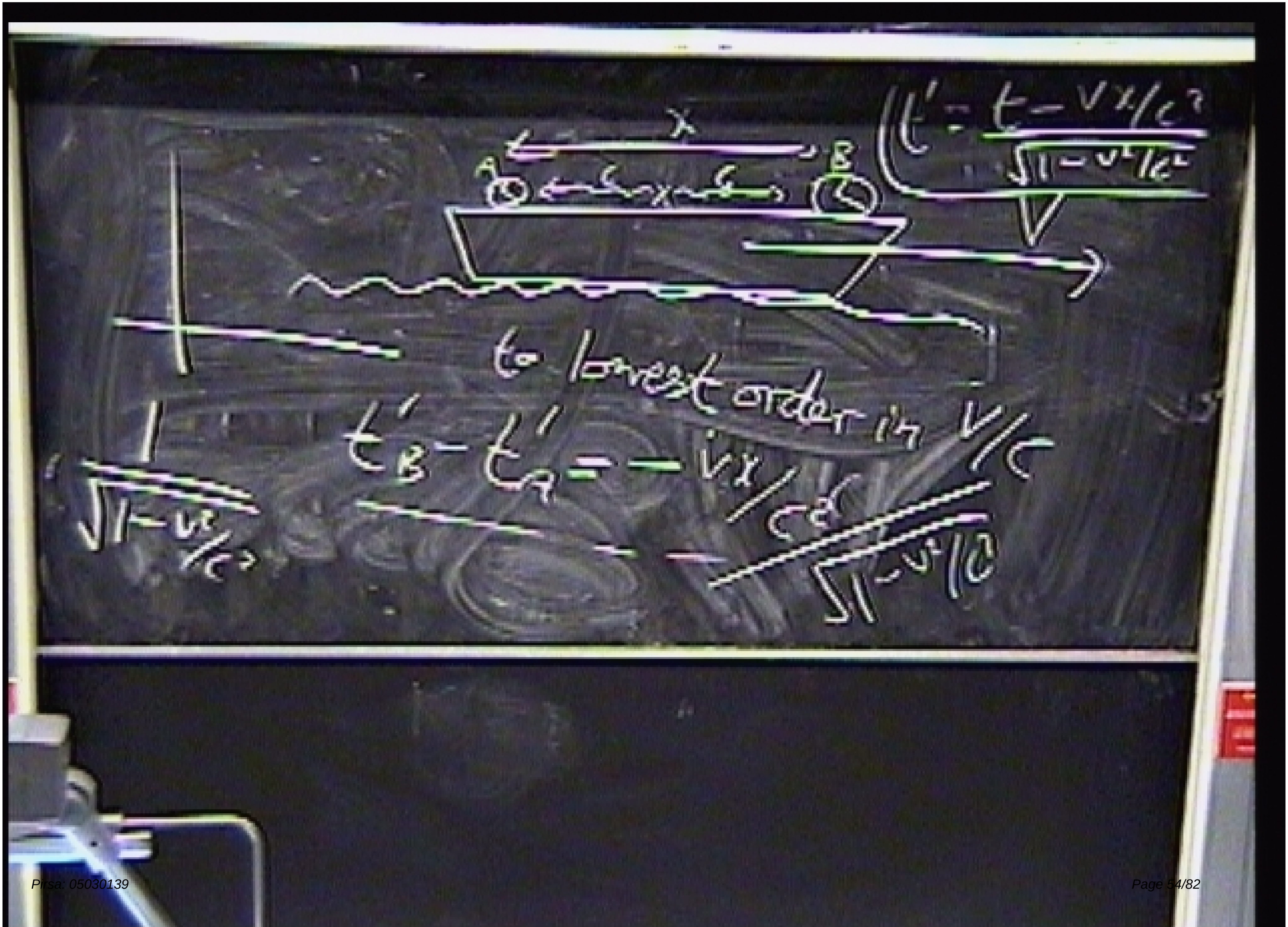

x
A
B
V
to lowest order in V/c
t'B - t'A = - vx/c²
1/√(1 - v²/c²)



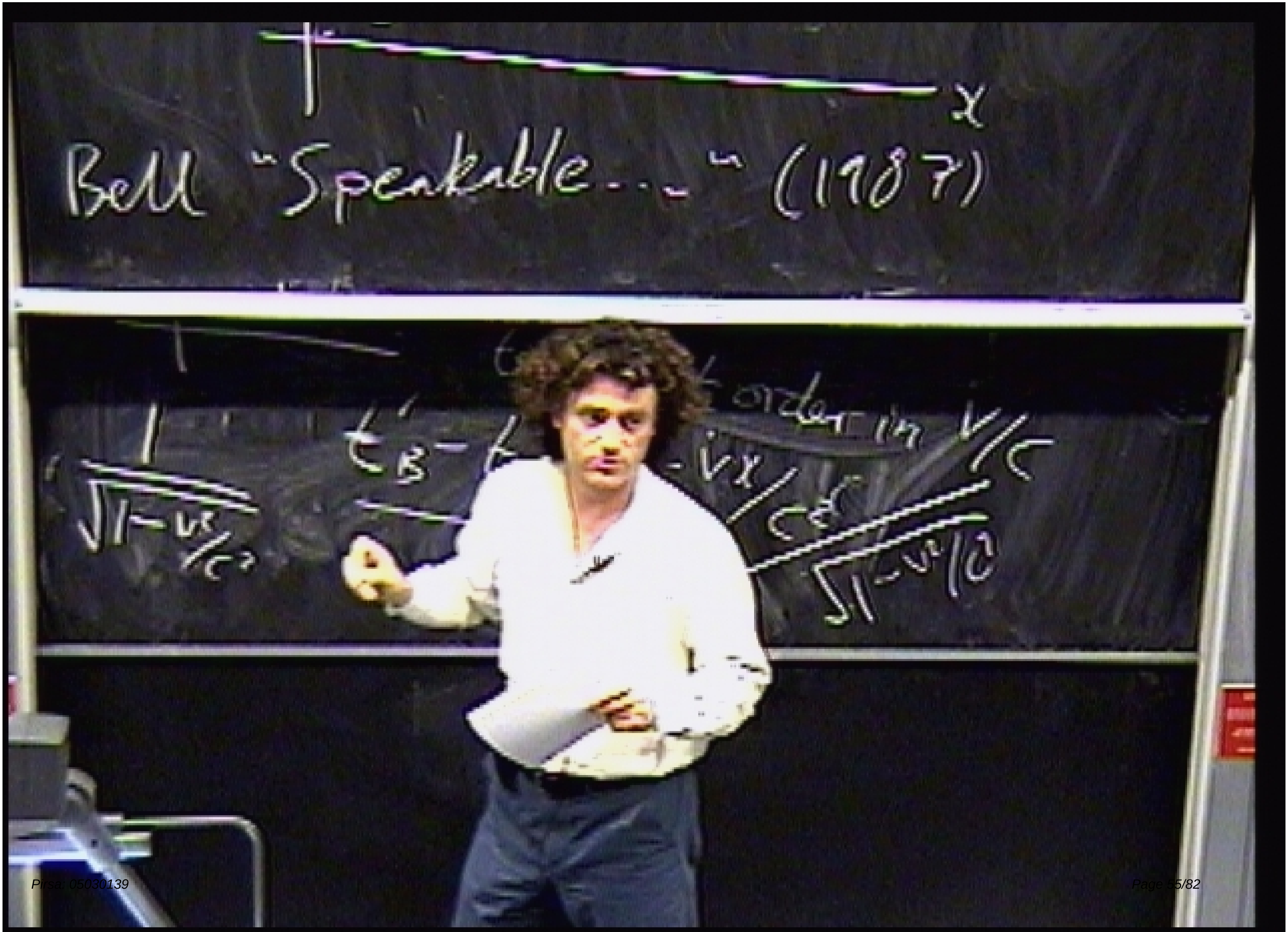
to lowest order in v/c

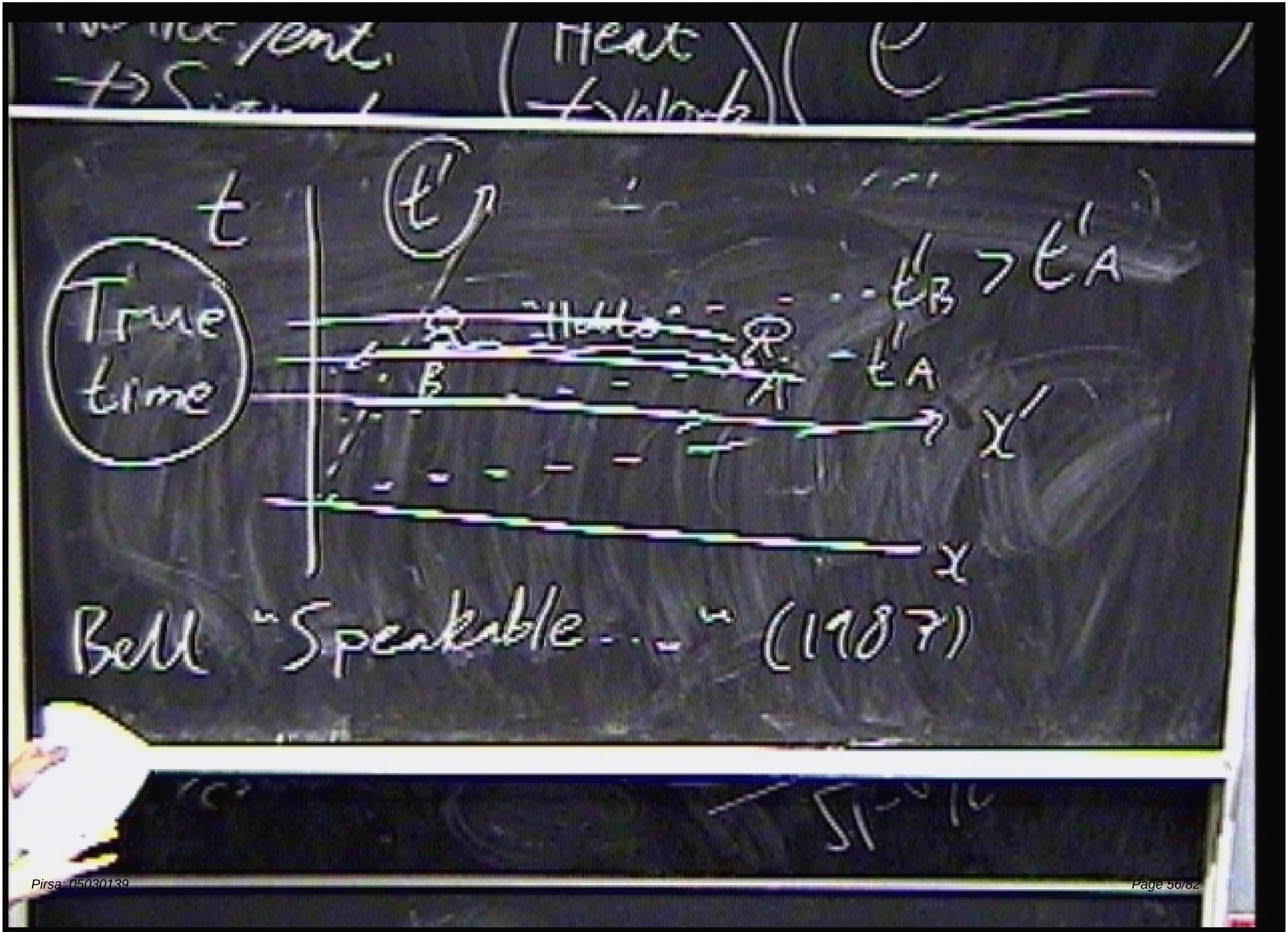
$$\frac{1}{\sqrt{1-v^2/c^2}}$$

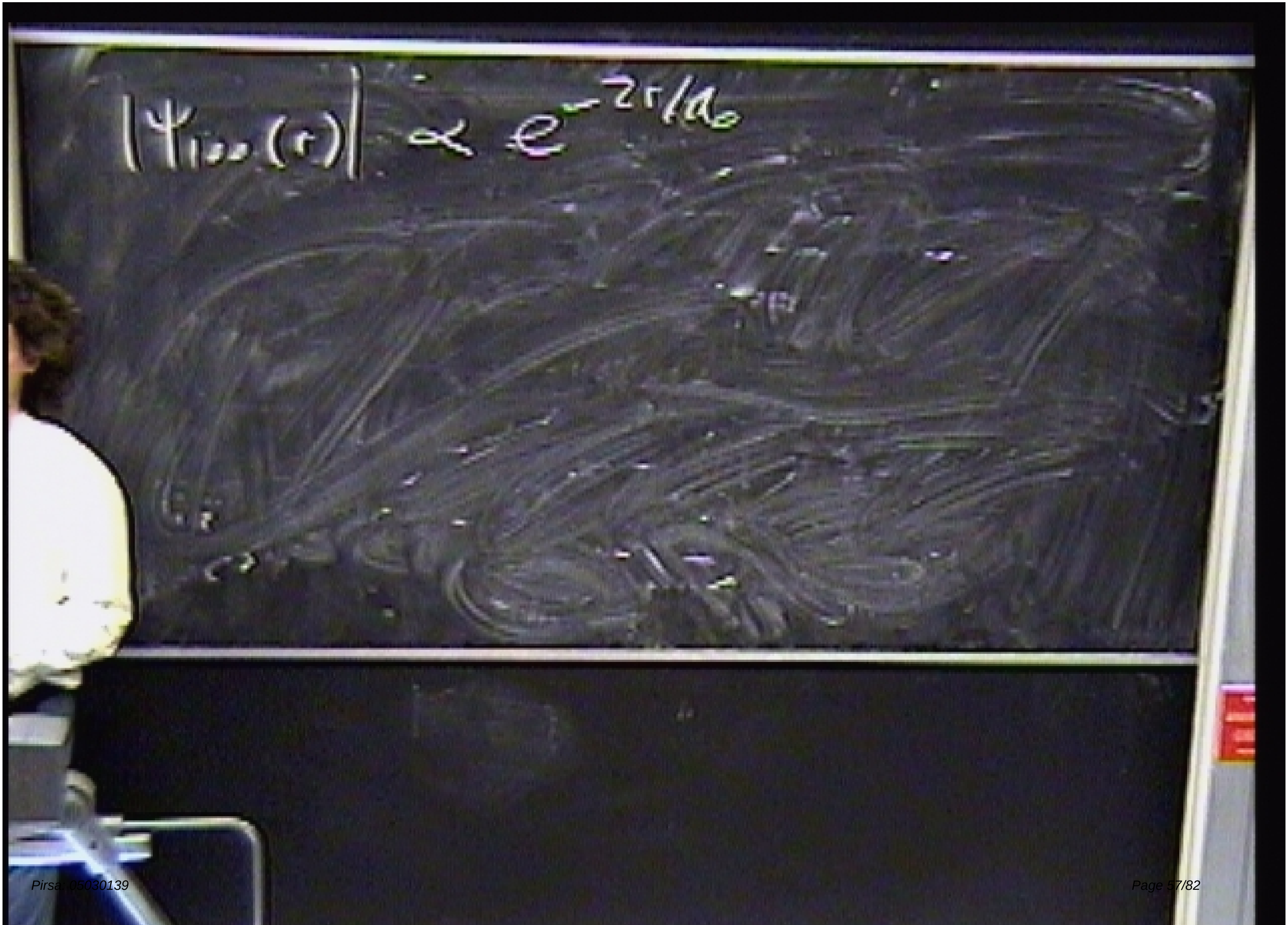
$$t'_B - t'_A = -\frac{vx/c^2}{\sqrt{1-v^2/c^2}}$$

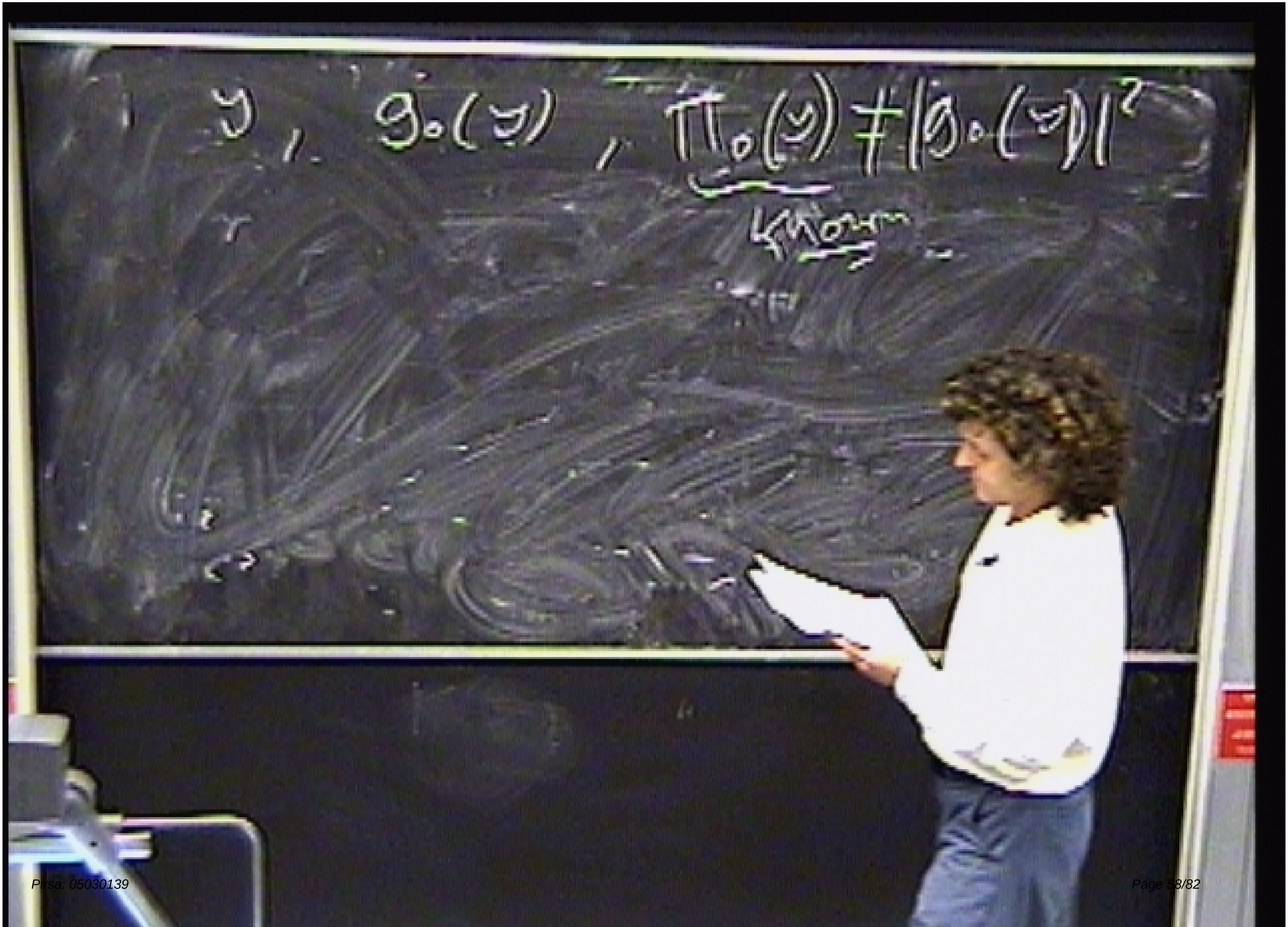


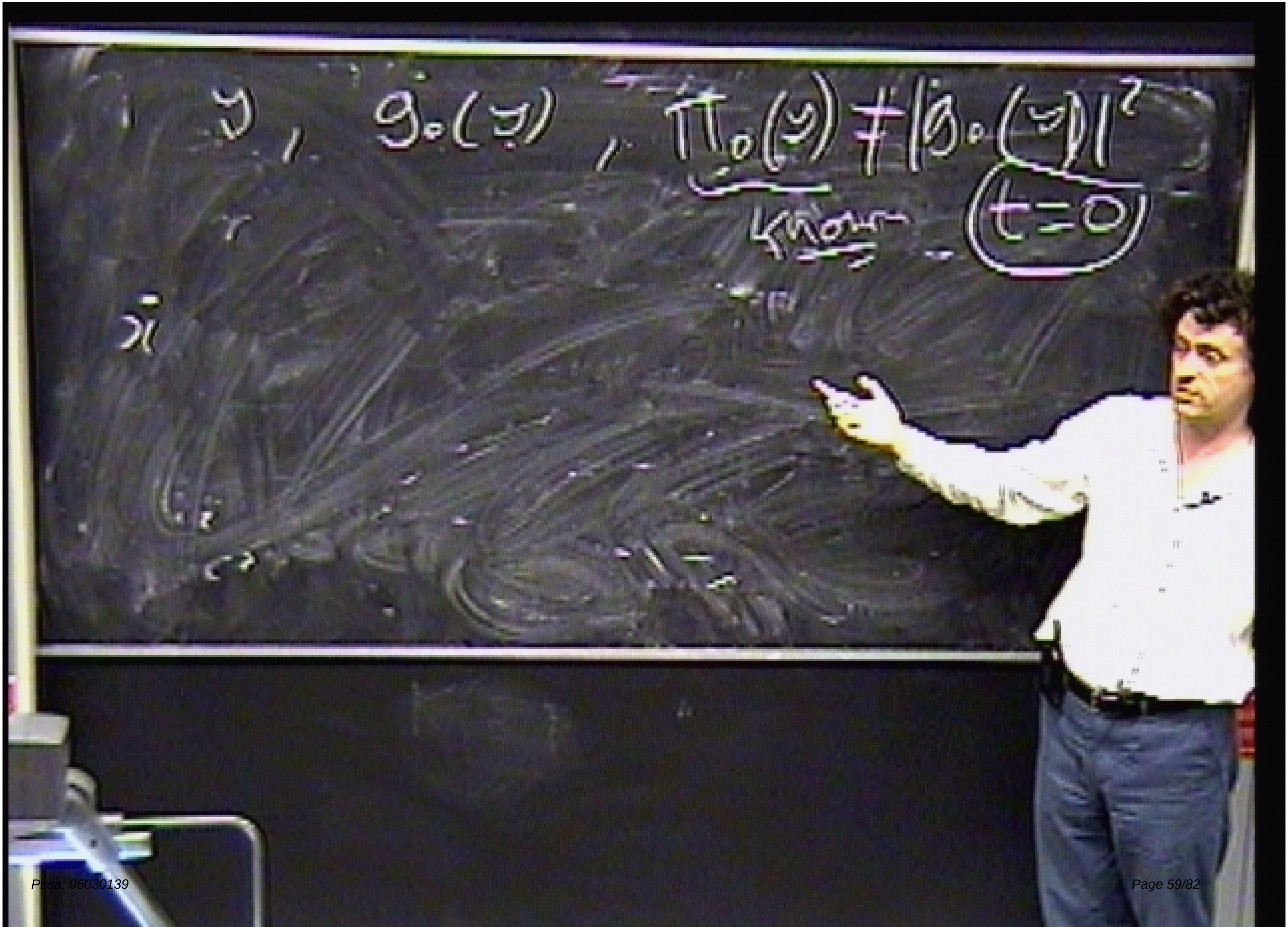
$t' = \frac{t - vx/c^2}{\sqrt{1 - v^2/c^2}}$
x
A
B
V
to lowest order in V/c
$t'_B - t'_A = -\frac{vx/c^2}{\sqrt{1 - v^2/c^2}}$
$\frac{1}{\sqrt{1 - v^2/c^2}}$

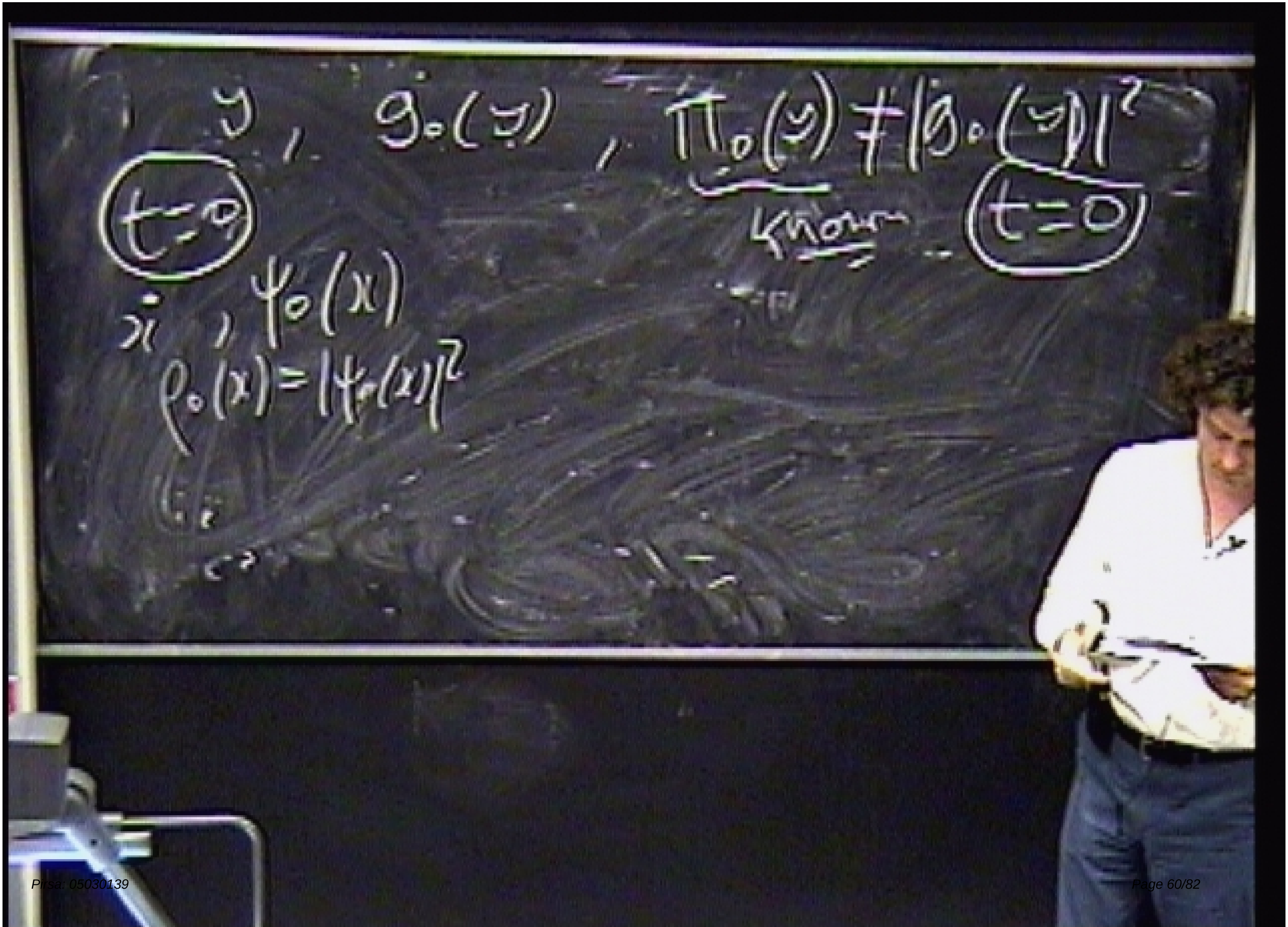

Bell "Speakable..." (1987)
order in v/c


Heat
t
t'
True time
t'_B > t'_A
t'_A
B
A
x'
x
Bell "Speakable ... " (1987)


$|\psi_{100}(r)| \propto e^{-2r/a_0}$


y , $g_0(y)$, $\pi_0(y) \neq |g_0(y)|^2$
known


y , g₀(y) , π₀(y) ≠ |φ₀(y)|²
known
t=0
x


y , $g_0(y)$, $\pi_0(y) \neq |g_0(y)|^2$
$t=0$
known
$t=0$
x , $\psi_0(x)$
$\rho_0(x) = |\psi_0(x)|^2$

y , $g_0(y)$, $\underline{\pi_0(y)} \neq |g_0(y)|^2$

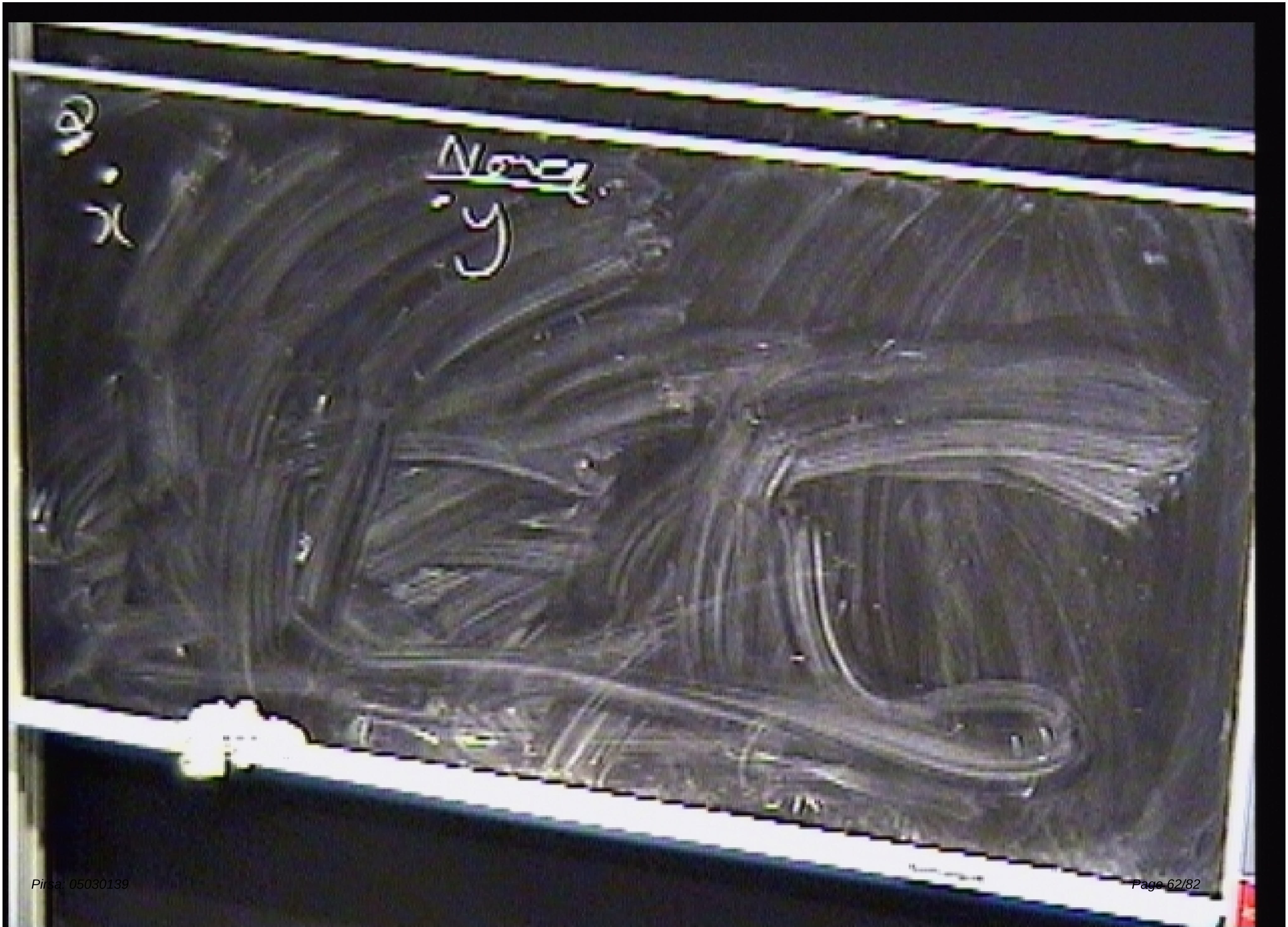
known

$t=0$ $\quad$ $t=0$

$|g|^2$

x , $\psi_0(x)$

$\rho_0(x) = |\psi_0(x)|^2$


x
y

$\hat{x}$ Nonce $\hat{y}$

$\hat{A} = a\,\hat{x}\,\hat{P}_y$

$\dot{x}$

Note.

$\dot{y}$

$\hat{H} = a\hat{x}\hat{p}_y$

$$\Psi = \Psi(x, y, t)$$

$$\frac{\partial \Psi}{\partial t} = -ax\frac{\partial \Psi}{\partial y}$$

$\dot{x}$

$\hat{A} - - \quad \overset{\text{None}}{\dot{y}}$

$\underline{\hat{A} = a\hat{x}\hat{p}_y}$

$\Psi = \Psi(x, y, t)$

$\frac{\partial \Psi}{\partial t} = -ax\frac{\partial \Psi}{\partial y}$

$\Rightarrow \frac{\partial |\Psi|^2}{\partial t} + ax\frac{\partial |\Psi|^2}{\partial y} = 0$

Now a.

$\dot{x}$ — — $\dot{y}$

$\hat{H} = a\hat{x}\hat{p}_y$

$(x(t), y(t))$

$$\Psi = \Psi(x, y, t)$$

$$\frac{\partial \Psi}{\partial t} = -ax\frac{\partial \Psi}{\partial y}$$

$$\Rightarrow \frac{\partial |\Psi|^2}{\partial t} + ax\frac{\partial |\Psi|^2}{\partial y} = 0$$

Nonce.

$\dot{x} \quad \dot{y}$

$\hat{A} = a\hat{x}\hat{p}_y$

$x(t), y(t)$

$$\Psi = \Psi(x,y,t)$$

$$\frac{\partial\Psi}{\partial t} = -ax\frac{\partial\Psi}{\partial y}$$

$$\Rightarrow \frac{\partial|\Psi|^2}{\partial t} + ax\frac{\partial|\Psi|^2}{\partial y} = 0$$

$$\frac{\partial|\Psi|^2}{\partial t} + \frac{\partial}{\partial x}\left(|\Psi|^2\dot{x}\right) + \frac{\partial}{\partial y}\left(|\Psi|^2\dot{y}\right) = 0$$

$@$ $\dot{x}$

Nonex

$\dot{y}$

$\hat{A} = a\hat{x}\hat{p}_y$

$\dot{x} = 0$

$$\Psi = \Psi(x, y, t)$$

$$\frac{\partial \psi}{\partial t} = -ax\frac{\partial \psi}{\partial y}$$

$$\Rightarrow \frac{\partial |\psi|^2}{\partial t} + ax\frac{\partial |\psi|^2}{\partial y} = 0$$

$$\frac{\partial |\psi|^2}{\partial t} + \frac{\partial}{\partial x}\left(|\psi|^2 \dot{x}\right) + \frac{\partial}{\partial y}\left(|\psi|^2 \dot{y}\right) = 0$$

@

Nonce.

$\dot{x}$ — — $\dot{y}$

$\hat{H} = a\hat{x}\hat{p}_y$

$\dot{x} = 0, \; \dot{y} = ax$

$$\Psi = \Psi(x, y, t)$$

$$\frac{\partial \Psi}{\partial t} = -ax\frac{\partial \Psi}{\partial y}$$

$$\Rightarrow \frac{\partial |\Psi|^2}{\partial t} + ax\frac{\partial |\Psi|^2}{\partial y} = 0$$

$$\frac{\partial |\Psi|^2}{\partial t} + \frac{\partial}{\partial x}\left(|\Psi|^2 \dot{x}\right) + \frac{\partial}{\partial y}\left(|\Psi|^2 \dot{y}\right) = 0$$

2.

$\dot{x}$ $\hat{A}$ Nonq. $\dot{y}$

$\hat{A} = a x \partial_y$

$\dot{x} = 0, \quad \dot{y} = a x$

$x(t) = x_0$

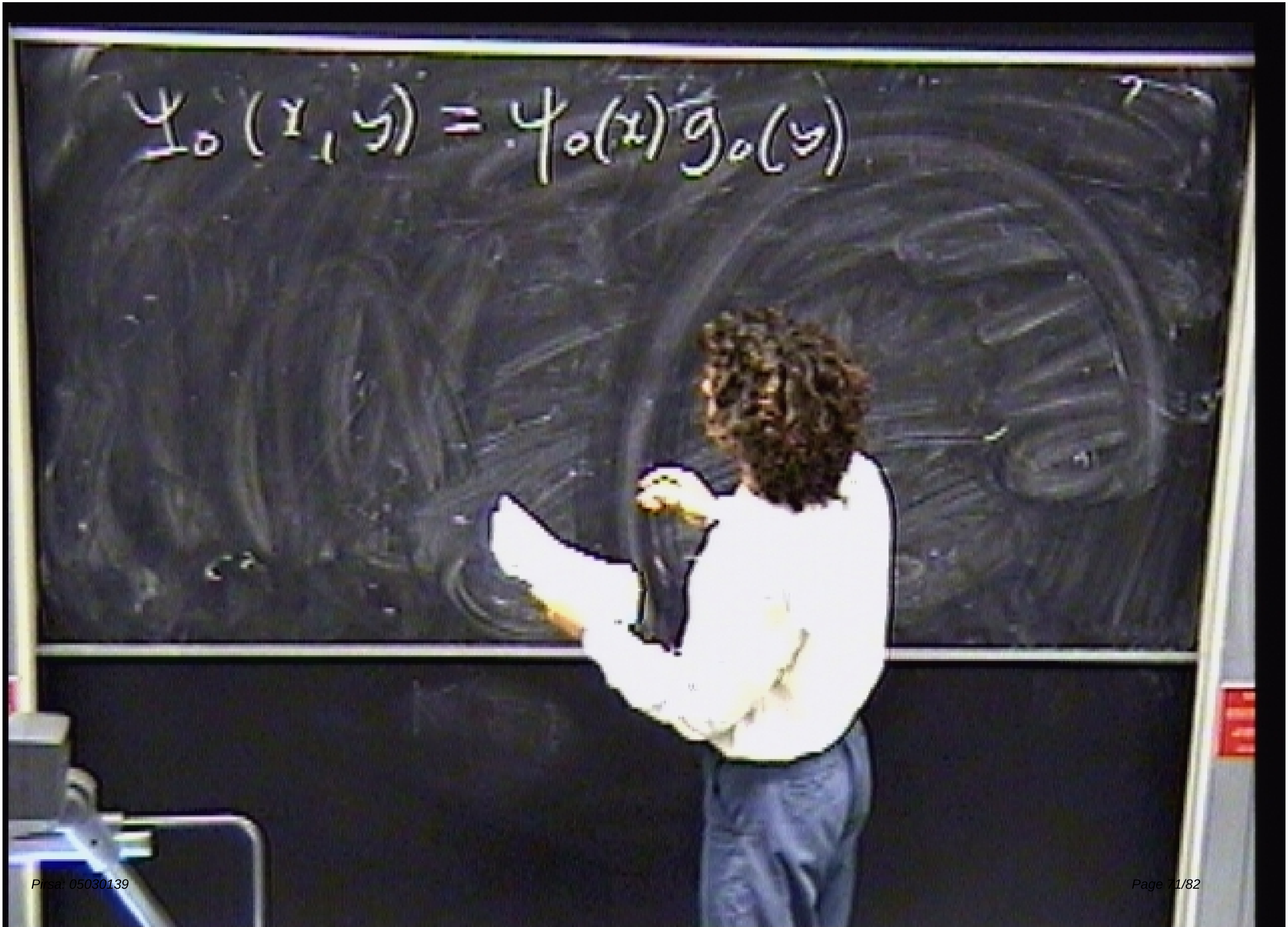
$y(t) = y_0 + a x_0 t$

$$\Psi = \Psi(x, y, t)$$

$$\frac{\partial \Psi}{\partial t} = -a x \frac{\partial \Psi}{\partial y}$$

$$\Rightarrow \frac{\partial |\Psi|^2}{\partial t} + a x \frac{\partial |\Psi|^2}{\partial y} = 0$$

$$\frac{\partial |\Psi|^2}{\partial t} + \frac{\partial}{\partial x}\left(|\Psi|^2 \dot{x}\right) + \frac{\partial}{\partial y}\left(|\Psi|^2 \dot{y}\right) = 0$$


$\Psi_0(x,y) = \psi_0(x)\, g_0(y)$

$$\Psi_0(x,y) = \psi_0(x)\, g_0(y)$$

$$\longrightarrow \Psi(x,y,t) = \psi_0(x)\, g_0(y - axt)$$

$$\Psi_0(x,y) = \psi_0(x)\, g_0(y)$$

$$\longrightarrow \Psi(x,y,t) = \psi_0(x)\, g_0(y - a x t)$$

Small at: $\simeq \psi_0(x)\, g_0(y)$

$$\Psi_0(x,y) = \psi_0(x)\, g_0(y)$$

$$\longrightarrow \Psi(x,y,t) = \psi_0(x)\, g_0(y - axt)$$

Small at: $\simeq \psi_0(x)\, g_0(y)$

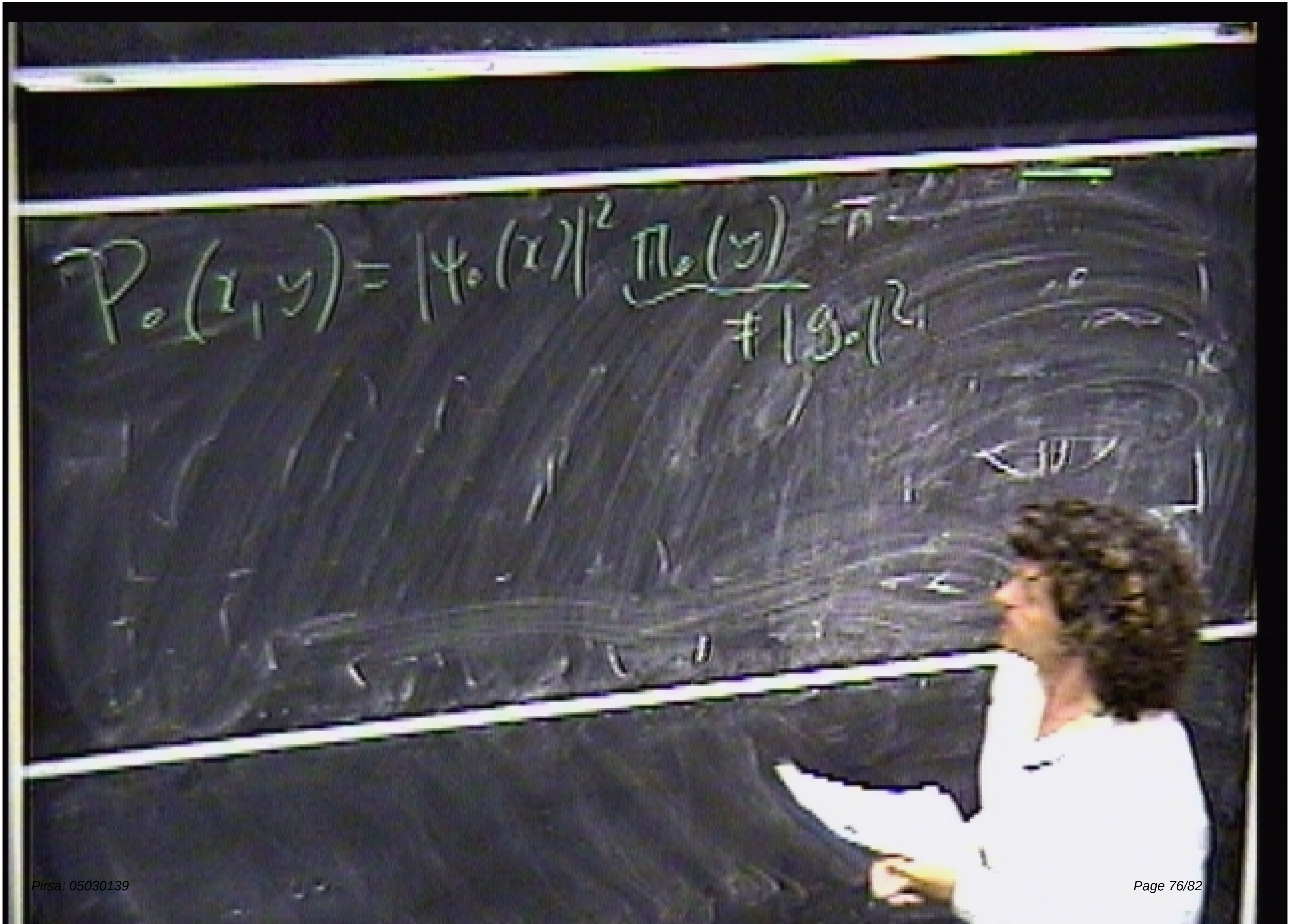
$$y(t) = y_0 + a x_0 t$$

$$\Psi_0(x,y) = \psi_0(x)\, g_0(y) \quad |\psi_0|\ |g_0|$$

$$\longrightarrow \Psi(x,y,t) = \psi_0(x)\, g_0(y - axt)$$

Small at: $\simeq \psi_0(x)\, g_0(y)$

$y(t) = y_0 + a x_0 t$

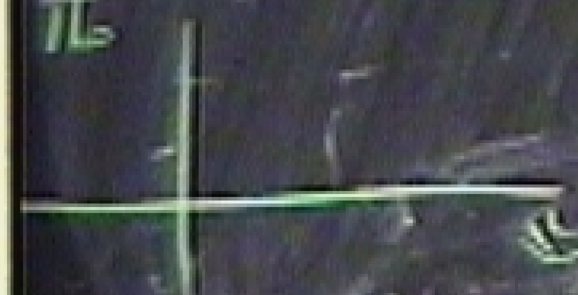

$P_0(x,y) = |\psi_0(x)|^2 \, \Pi_0(y)$

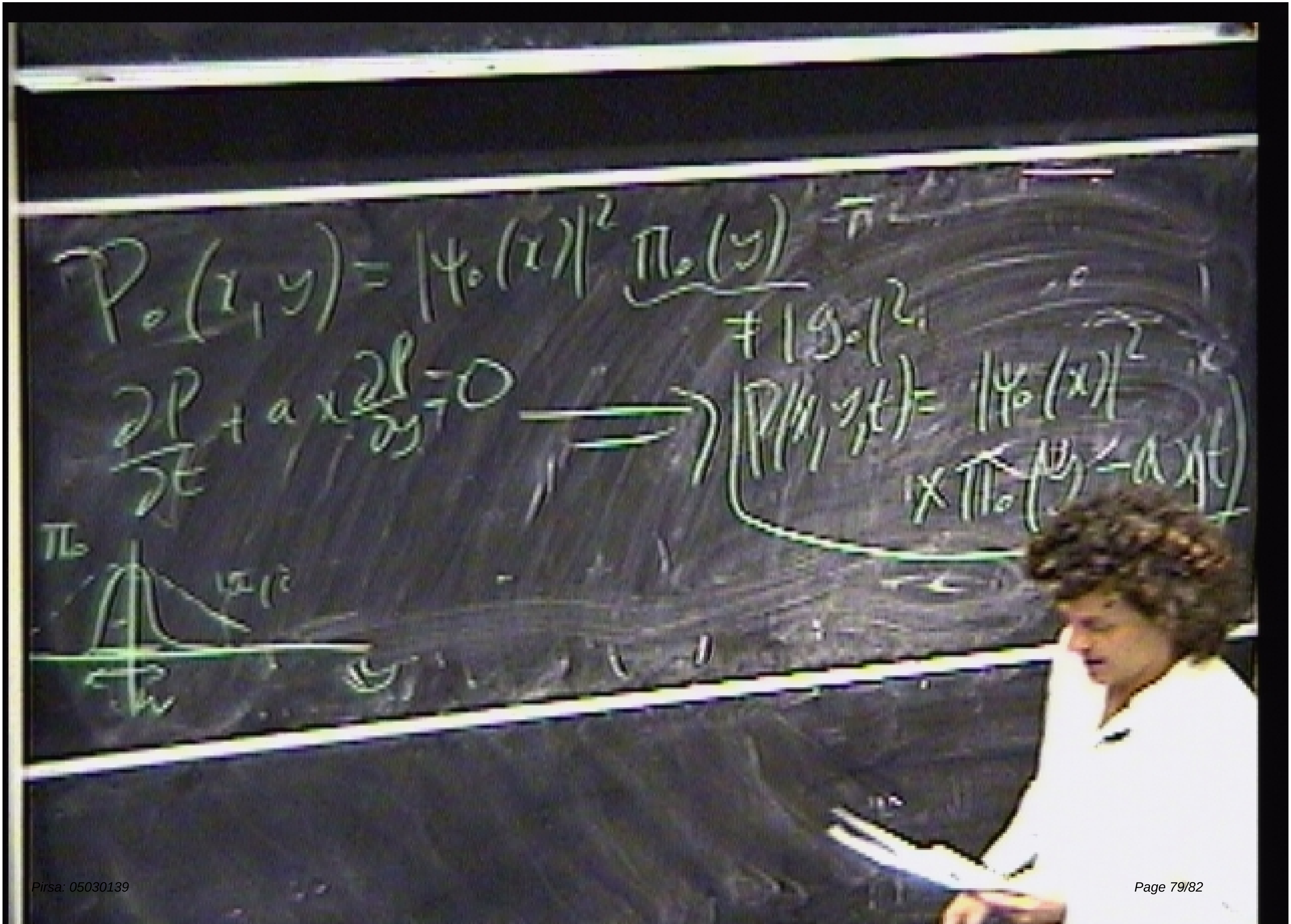
$$P_0(x,y) = |\psi_0(x)|^2 \, \underbrace{\pi_0(y)}_{\neq |g_0|^2}$$

$$\frac{\partial P}{\partial t} + a x \frac{\partial P}{\partial y} = 0 \longrightarrow P(x,y,t) = |\psi_0(x)|^2 \times \pi_0(y - a x t)$$

$$P_0(x,y) = |\psi_0(x)|^2 \underbrace{\pi_0(y)}_{\neq |g_0|^2}$$

$$\frac{\partial \rho}{\partial t} + a x \frac{\partial \rho}{\partial y} = 0 \Longrightarrow P(x,y,t) = |\psi_0(x)|^2 \times \pi_0(y - a x t)$$





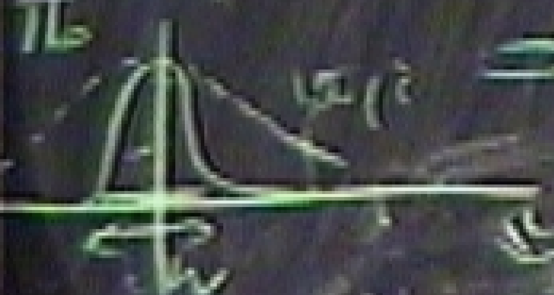
$P_0(x,y) = |\psi_0(x)|^2 \pi_0(y)$
$\neq |g_0|^2$
$\frac{\partial \rho}{\partial t} + a x \frac{\partial \rho}{\partial y} = 0 \Longrightarrow \rho(x,y,t) = |\psi_0(x)|^2$
$\times \pi_0(y - a x t)$
π_0

$$P_0(x,y) = |\psi_0(x)|^2 \, \pi_0(y)$$

$$\neq |\psi_0|^2$$

$$\frac{\partial P}{\partial t} + a x \frac{\partial P}{\partial y} = 0 \Longrightarrow P(x,y,t) = |\psi_0(x)|^2 \times \pi_0(y - a x t)$$

y_{meas}



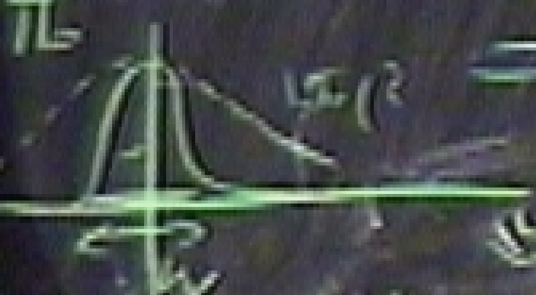
$$\Longrightarrow x \in \left(\frac{y_{meas}}{at} - \frac{w}{2at}, \frac{y_{meas}}{at} + \frac{w}{2at} \right)$$

$P_0(x,y) = |\psi_0(x)|^2 \, \pi_0(y)$ ≠ $|g_0|^2$

Error $\frac{\hbar}{2at\epsilon}$

$\frac{\partial \rho}{\partial t} + a x \frac{\partial \rho}{\partial y} = 0 \Longrightarrow P(y,x,t) = |\psi_0(x)|^2 \times \pi_0(y - axt)$

y_{mean}



$\Longrightarrow x \in \left(\frac{y_{mean}}{at} - \frac{\hbar}{2a\epsilon}, \frac{y_{mean}}{at} + \frac{\hbar}{2a\epsilon} \right)$

$$P_0(x,y) = |\psi_0(x)|^2\,\Pi_0(y) \neq |g_0|^2$$

Error

$\frac{\hbar t}{2at} \to 0$

$$\frac{\partial \rho}{\partial t} + a x \frac{\partial \rho}{\partial y} = 0 \Longrightarrow P(x,y,t) = |\psi_0(x)|^2 \times \Pi_0(y - a x t)$$

y_{meas}

Π_0

$\Rightarrow x \in \left(\frac{y_{\mathrm{meas}}}{at} - \frac{\hbar}{2at},\ \frac{y_{\mathrm{meas}}}{at} + \frac{\hbar}{2at}\right)$