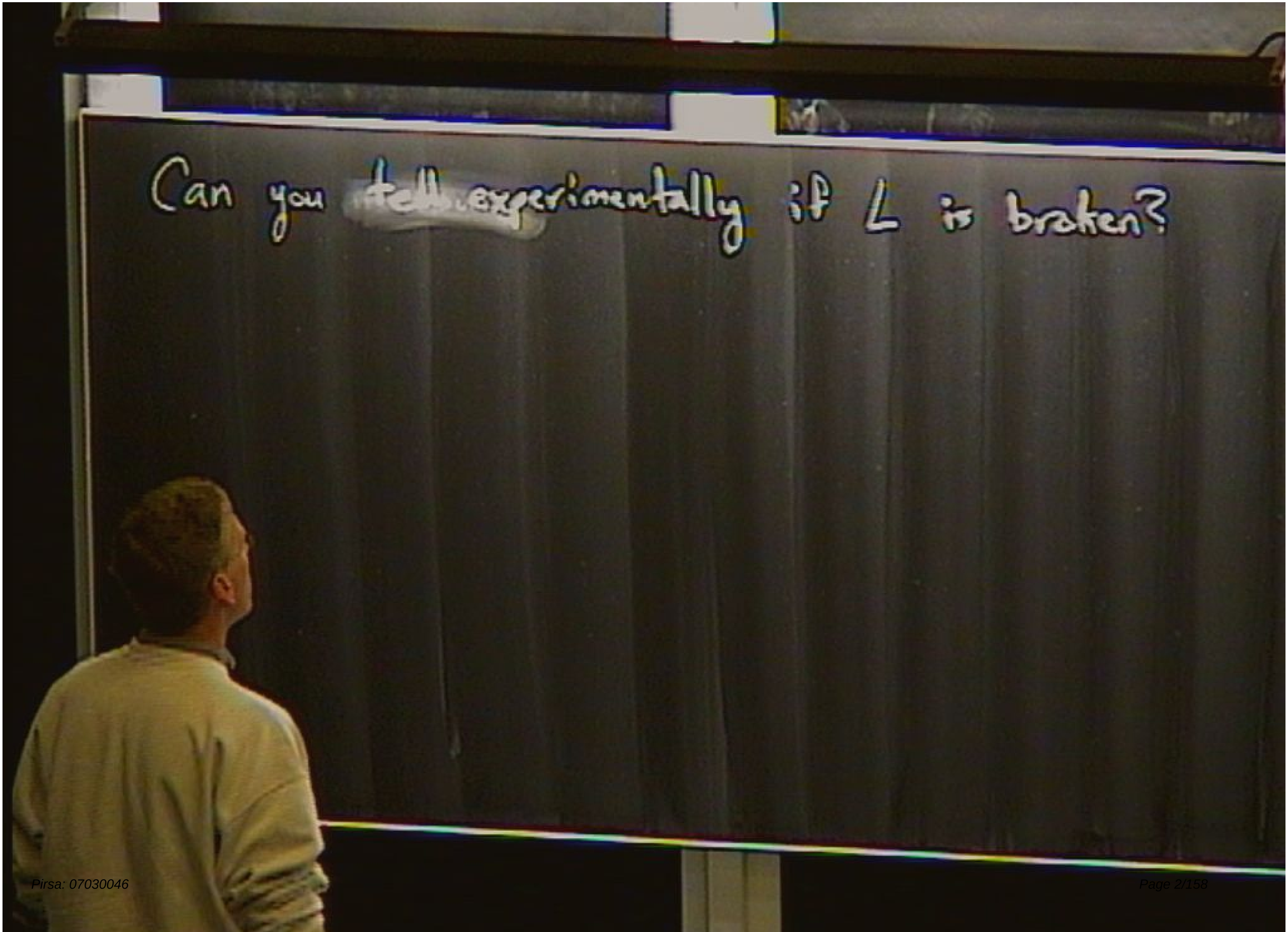
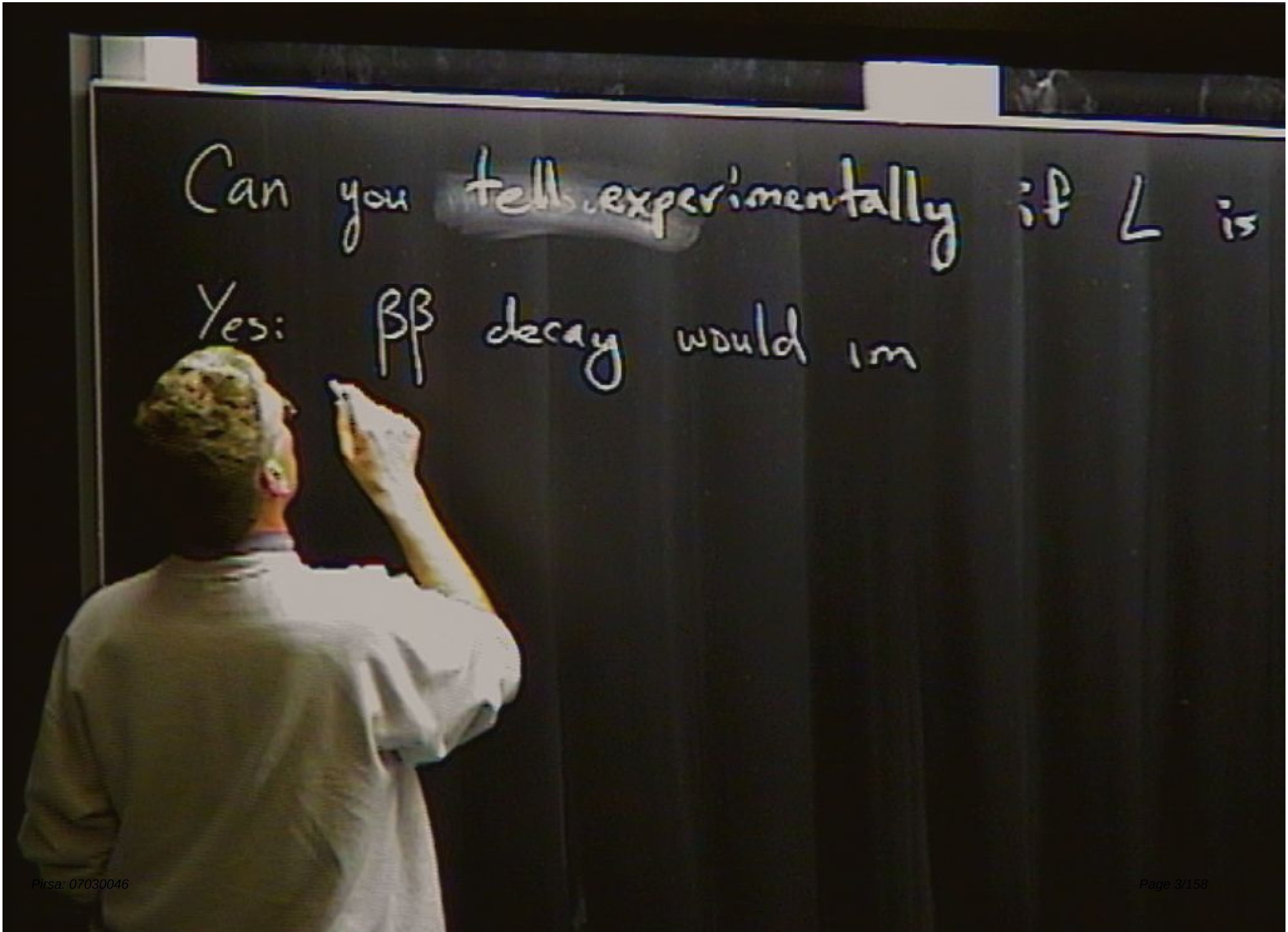
Title: Graduate Course on Standard Model & Quantum Field Theory - 16B

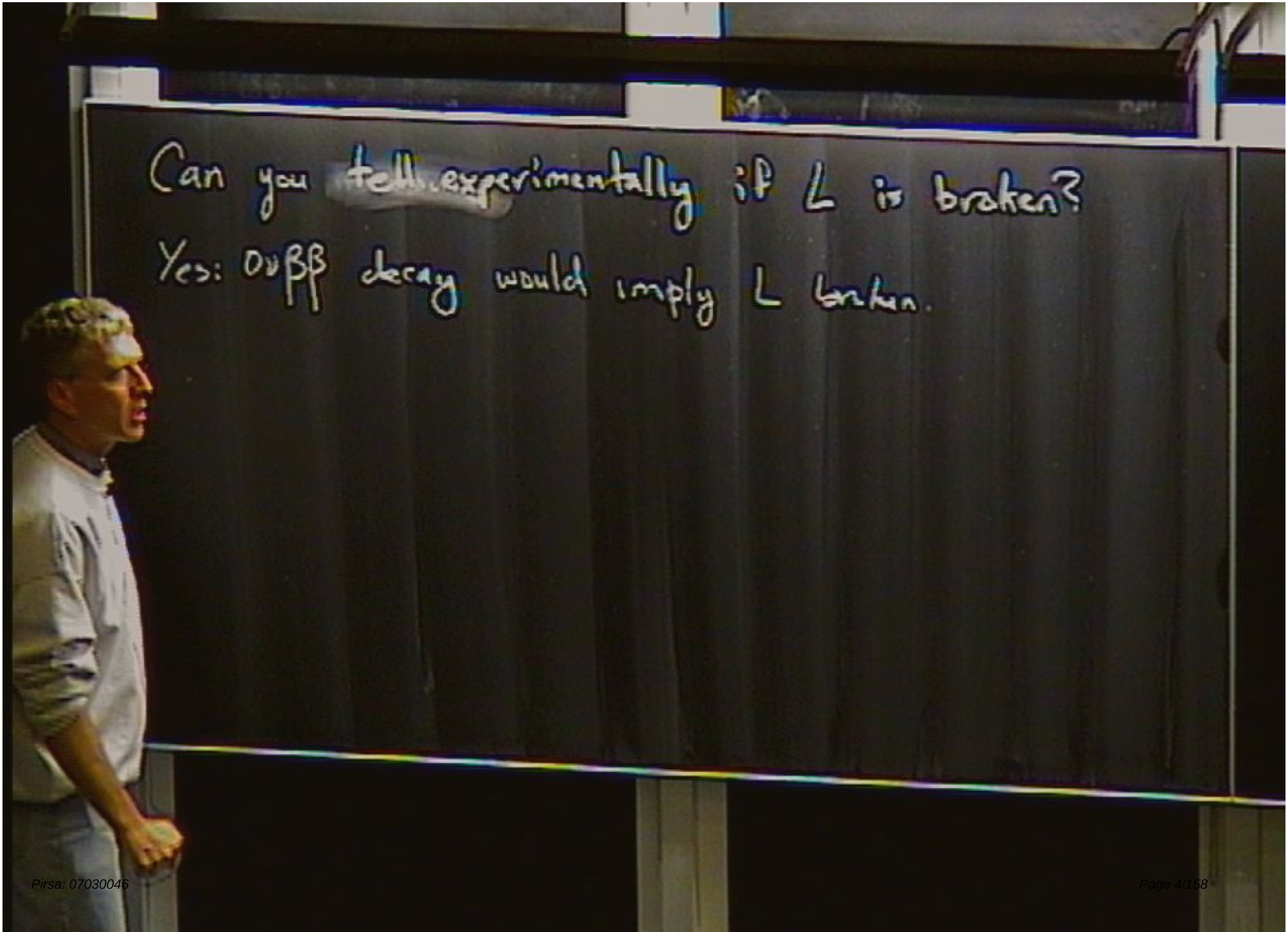
Date: Mar 28, 2007 03:30 PM

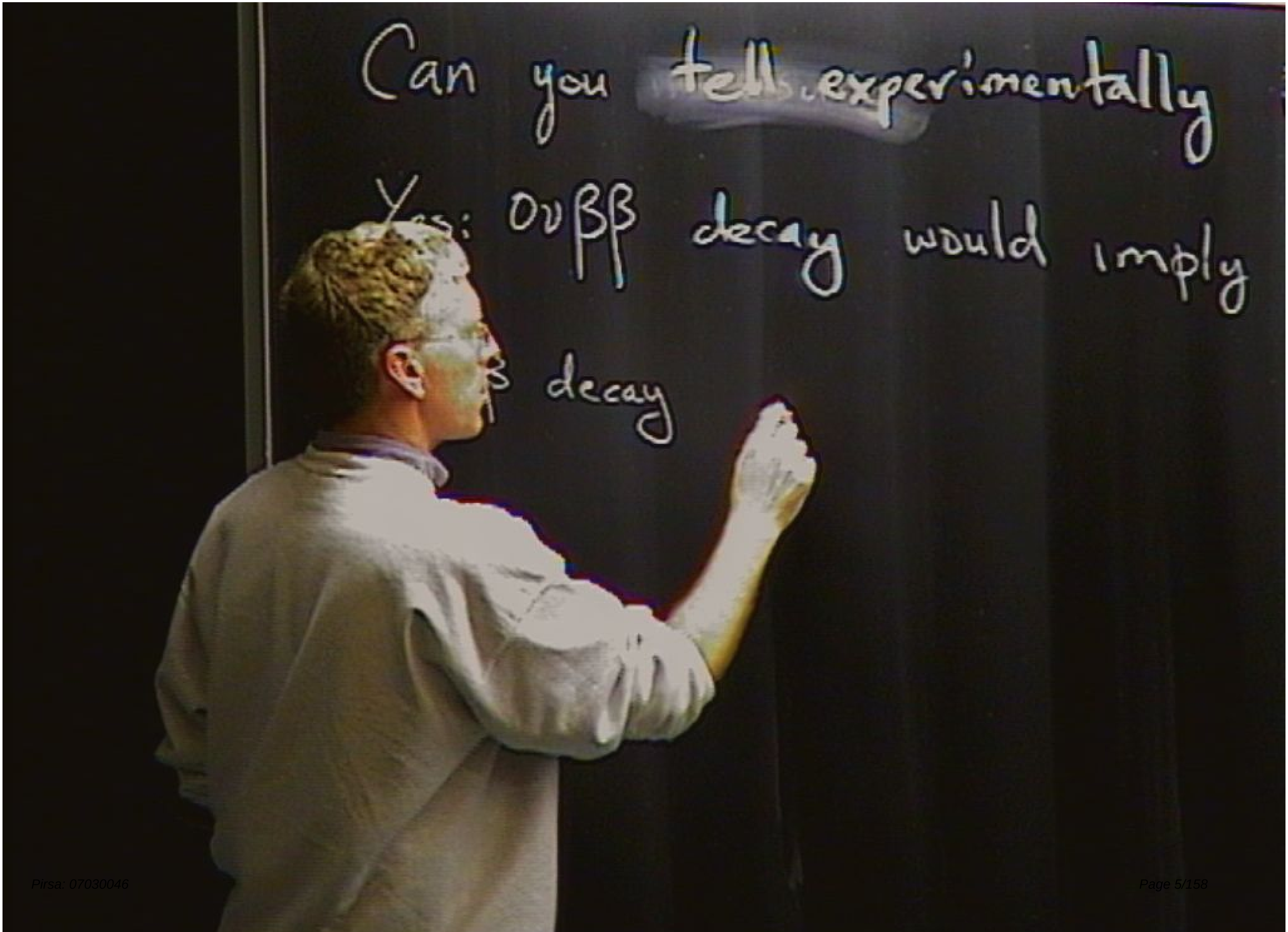
URL: http://pirsa.org/07030046

Abstract: Graduate Course on Standard Model & Quantum Field Theory


Can you tell experimentally if L is broken?


Can you tell experimentally if L is
Yes: ββ decay would im

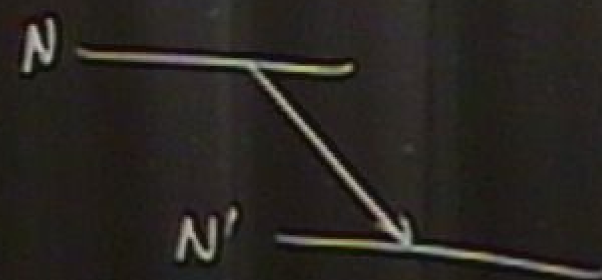

Can you tell experimentally if L is broken?
Yes: 0νββ decay would imply L broken.

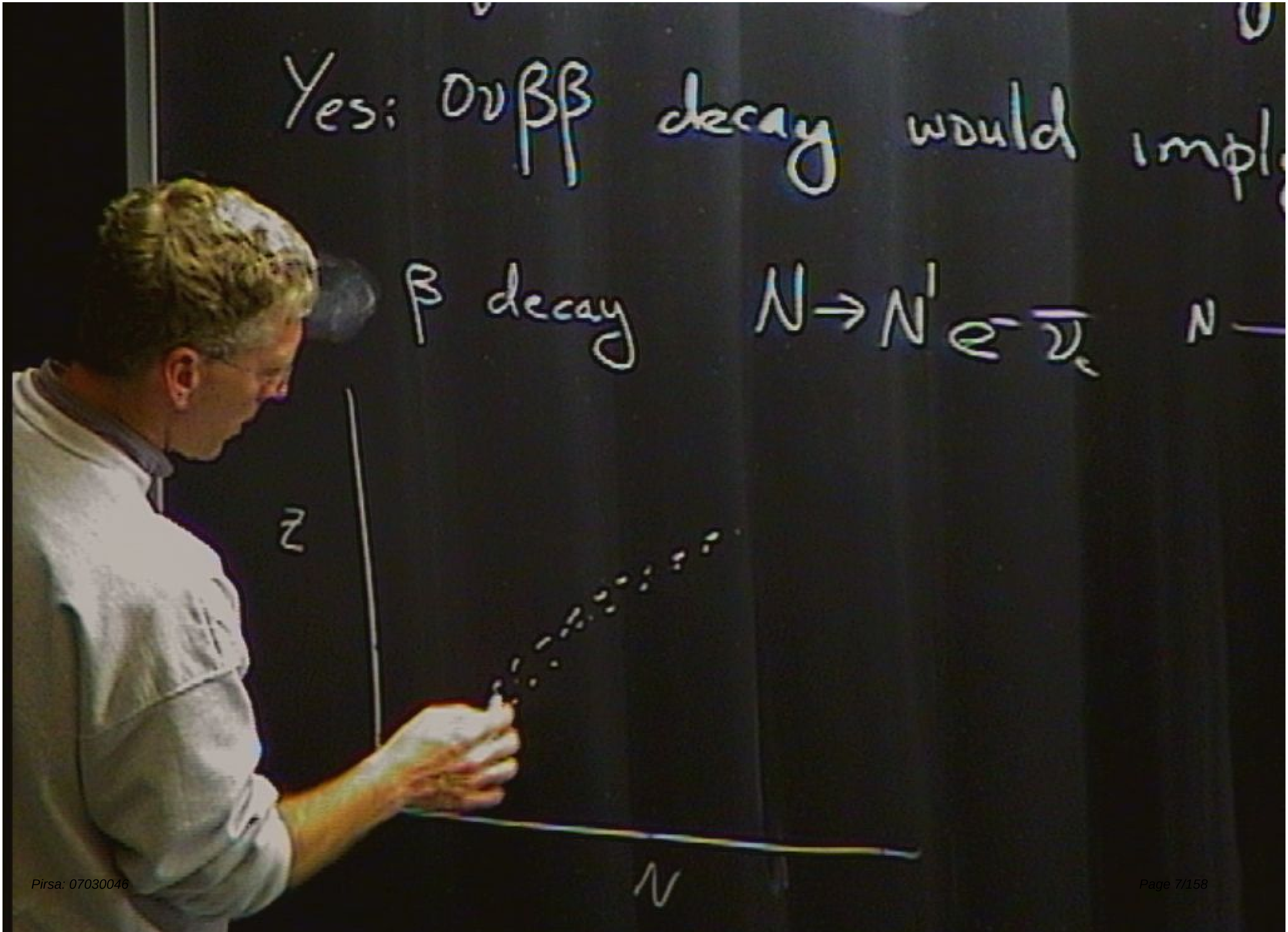

Can you tell experimentally
Yes: 0νββ decay would imply
decay

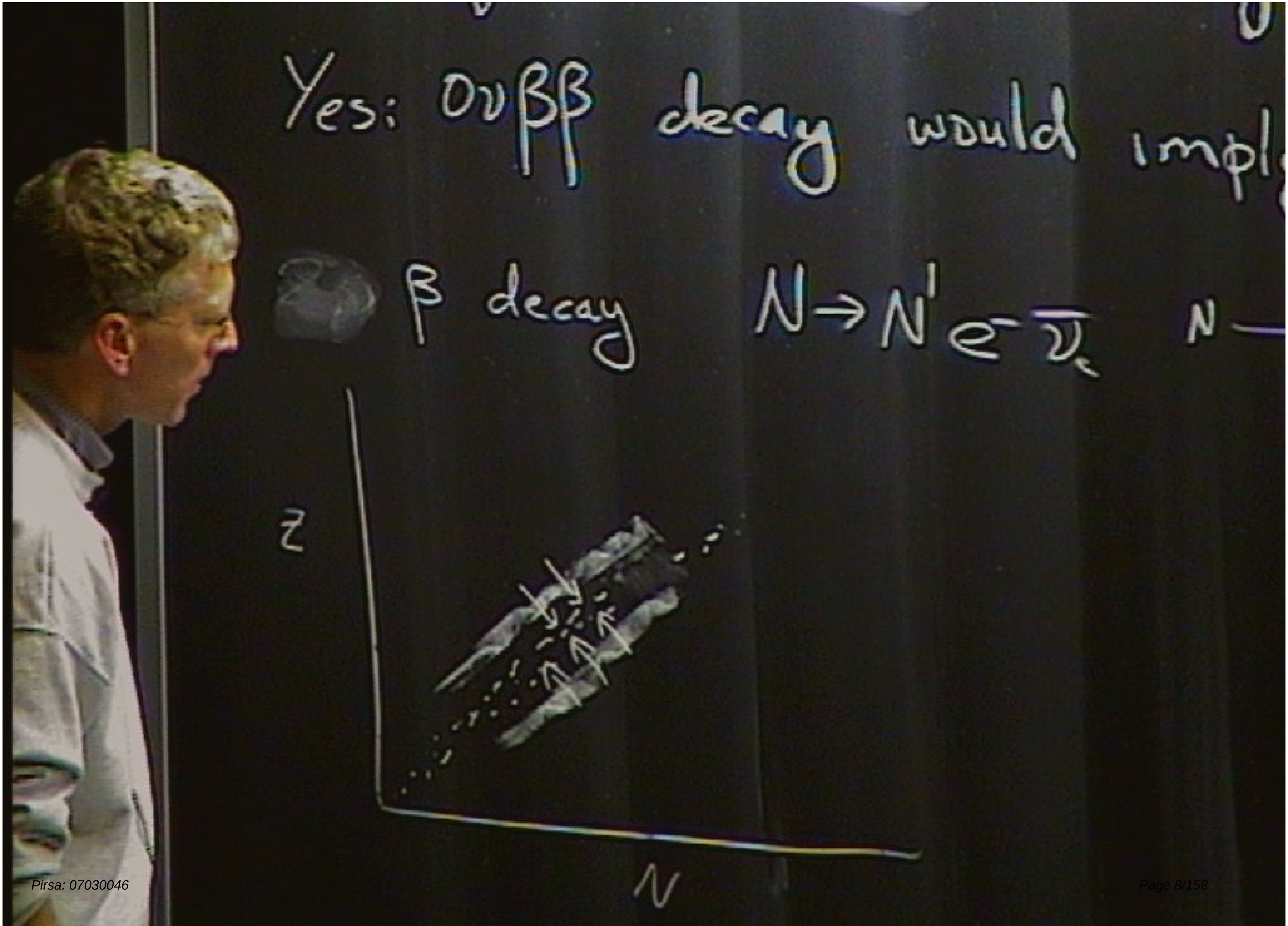
Can you tell experimentally if L is br

Yes: $0\nu\beta\beta$ decay would imply L broken.

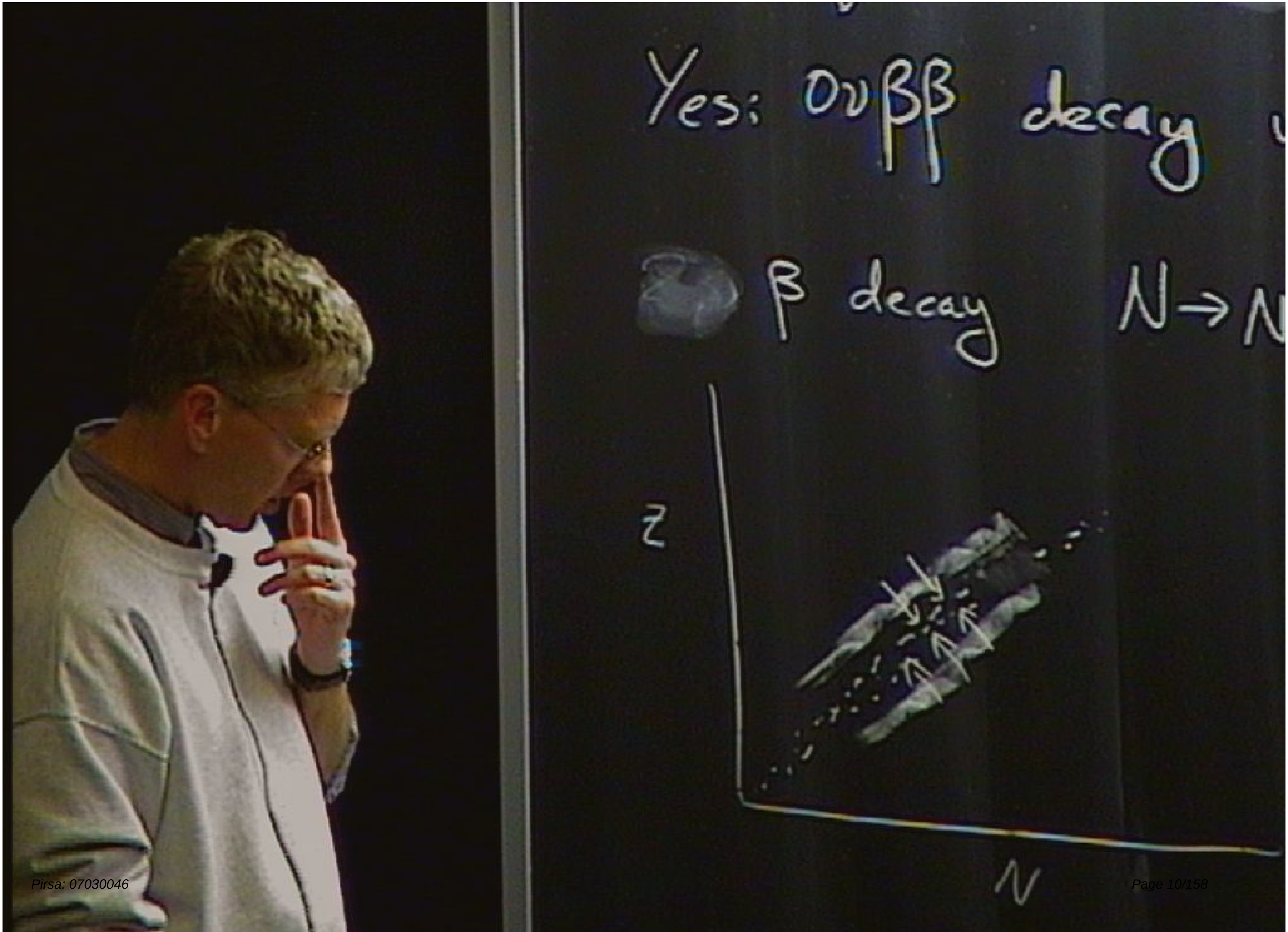
β decay $\quad N \to N' e^- \bar{\nu}_e$

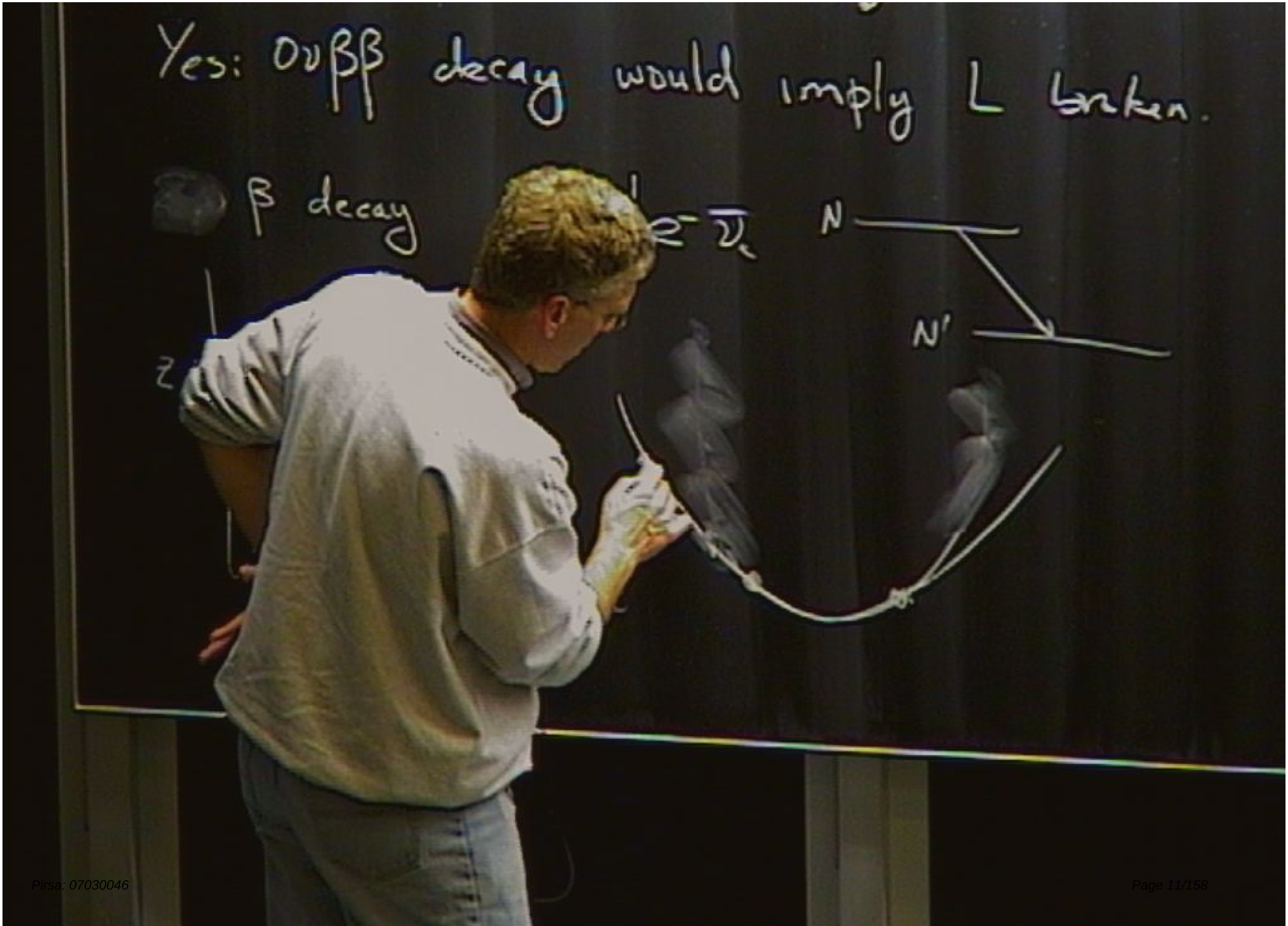


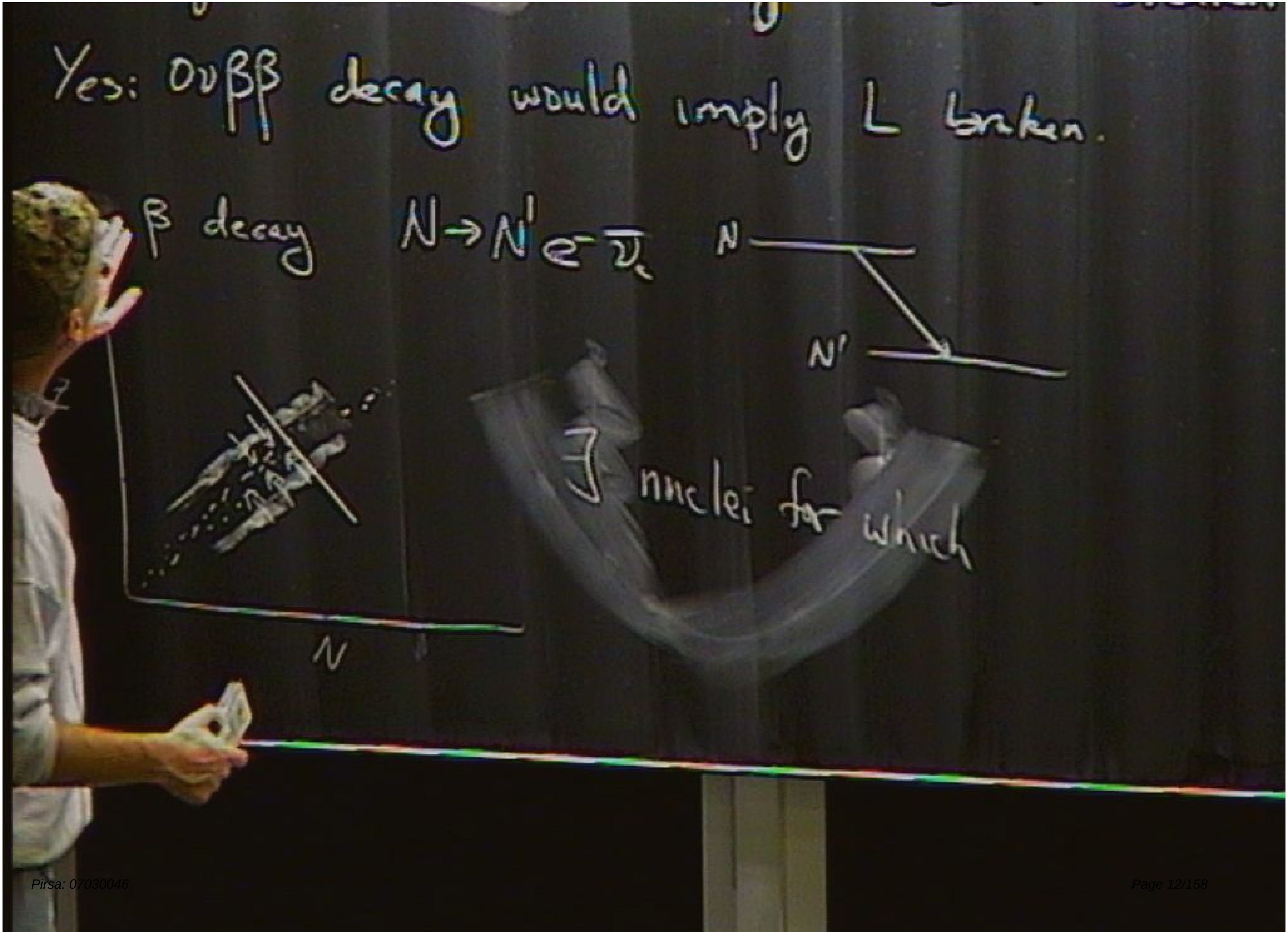

Yes: 0νββ decay would imply
β decay N → N' e⁻ ν̄e N
Z
N

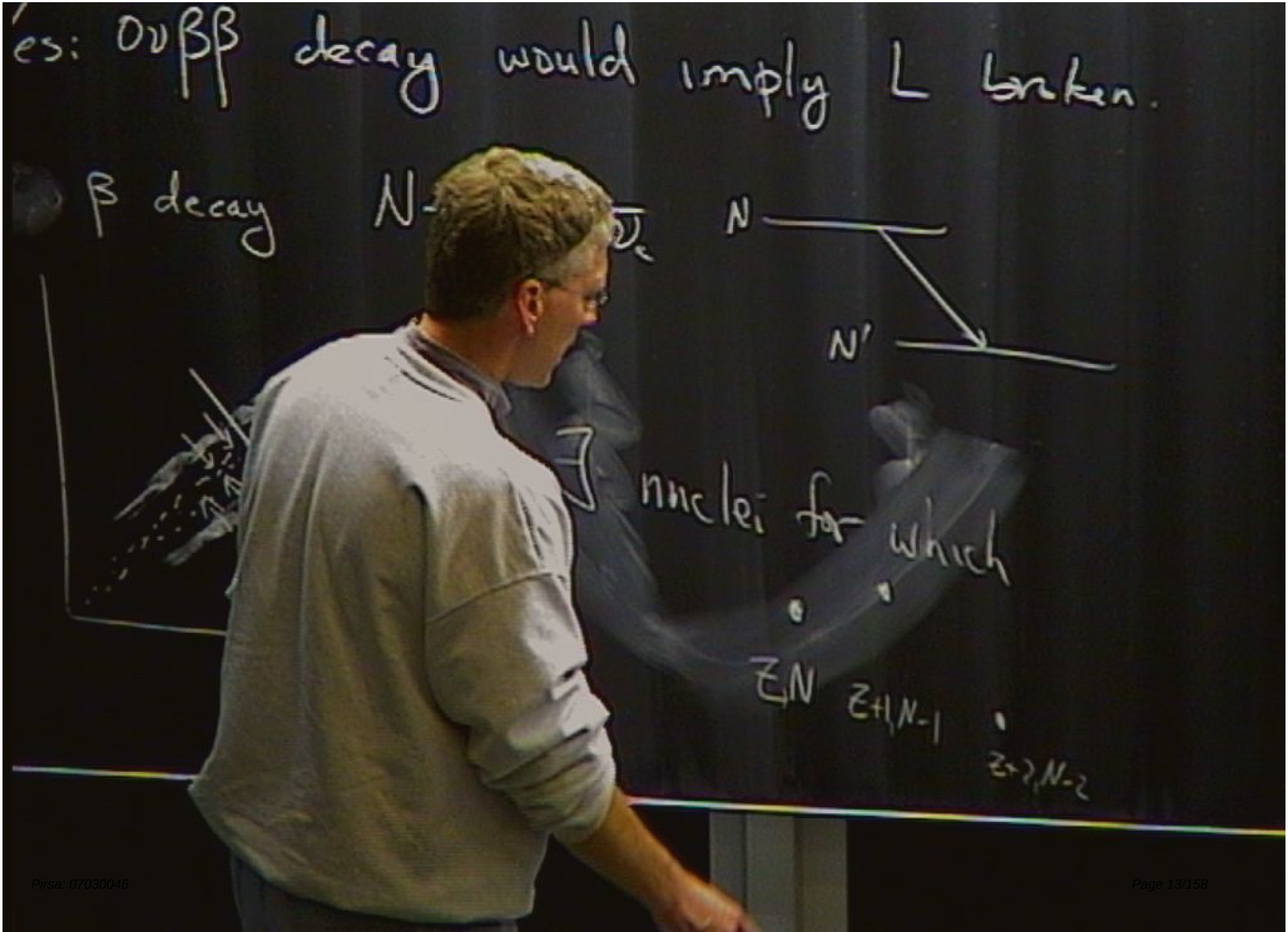

Yes: 0νββ decay would imply
β decay N → N' e⁻ ν̄ₑ N —
Z
N

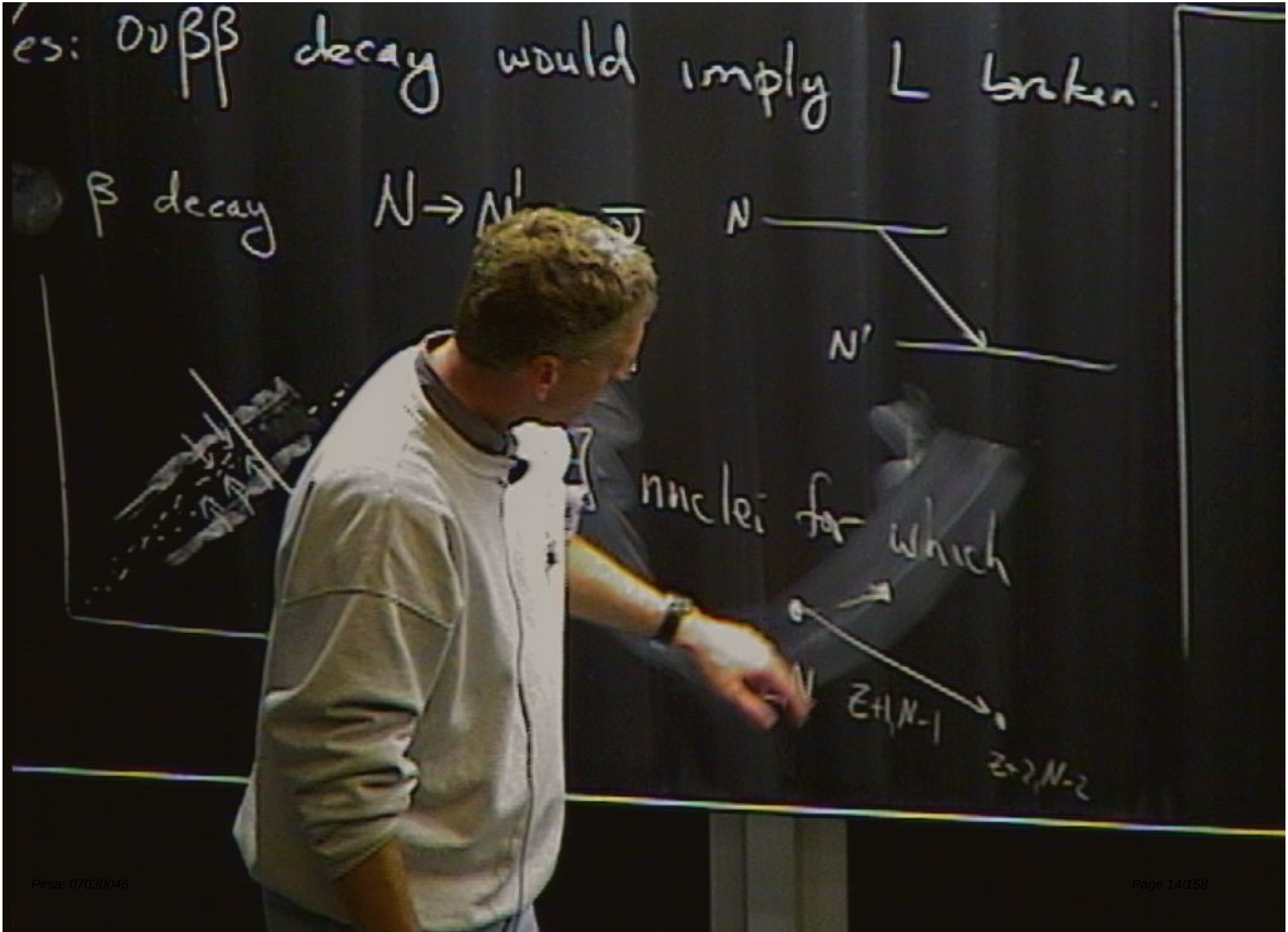

Yes: 0νββ decay
β decay
N→N
Z
N

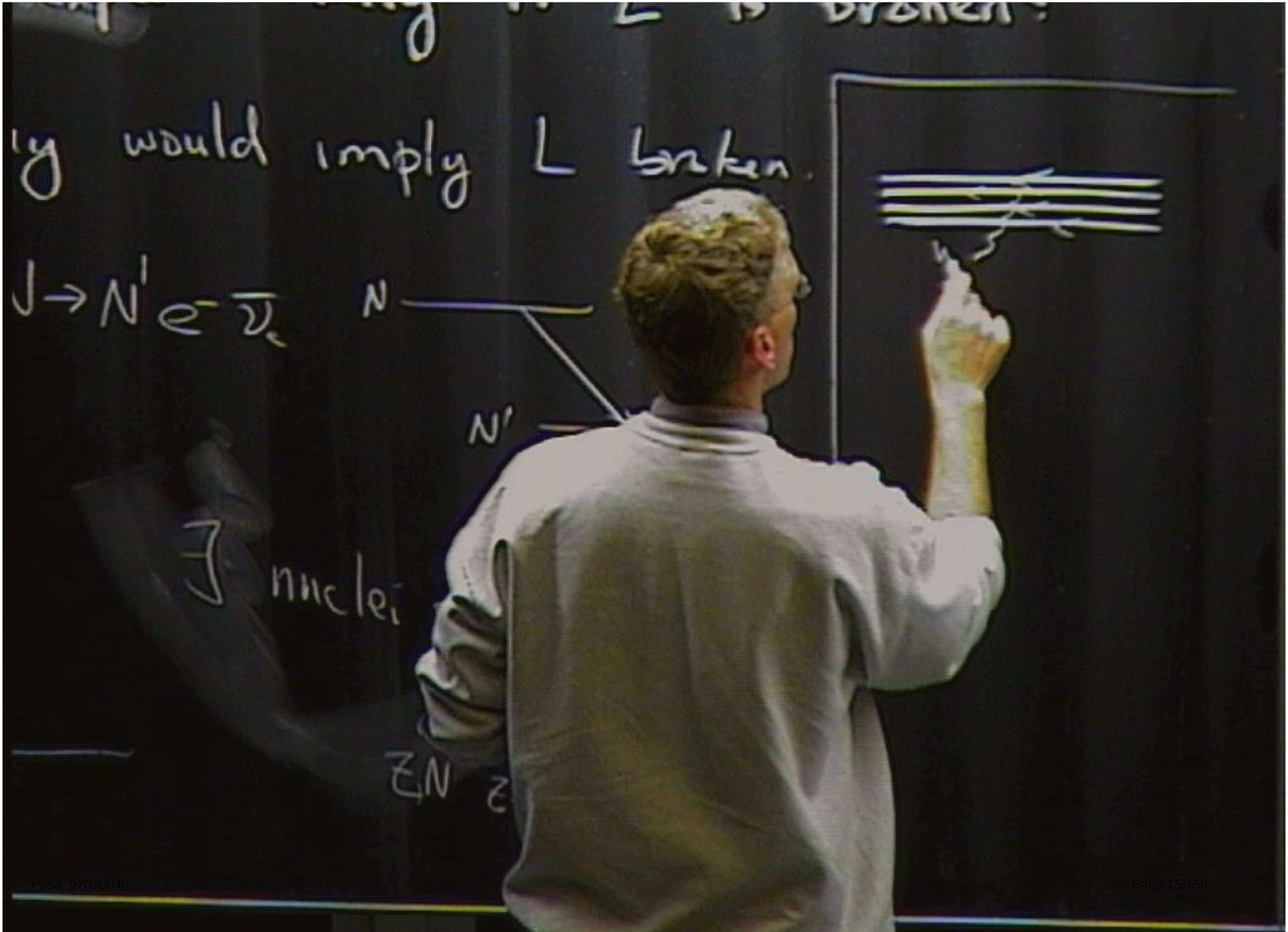

Yes: 0νββ decay
β decay N→N
Z
N

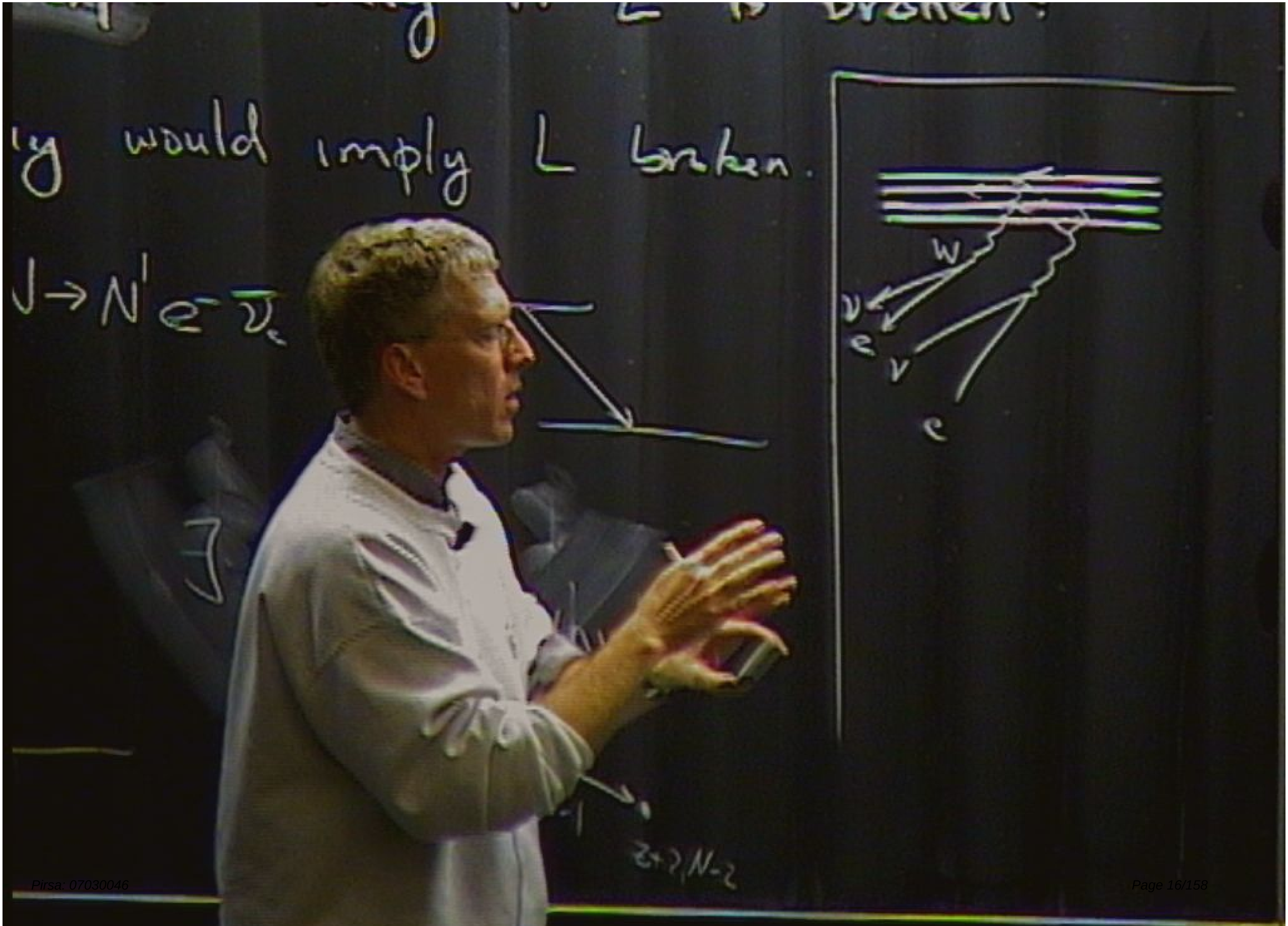

Yes: 0νββ decay would imply L broken.
β decay
e⁻ ν̄ₑ
N
N'

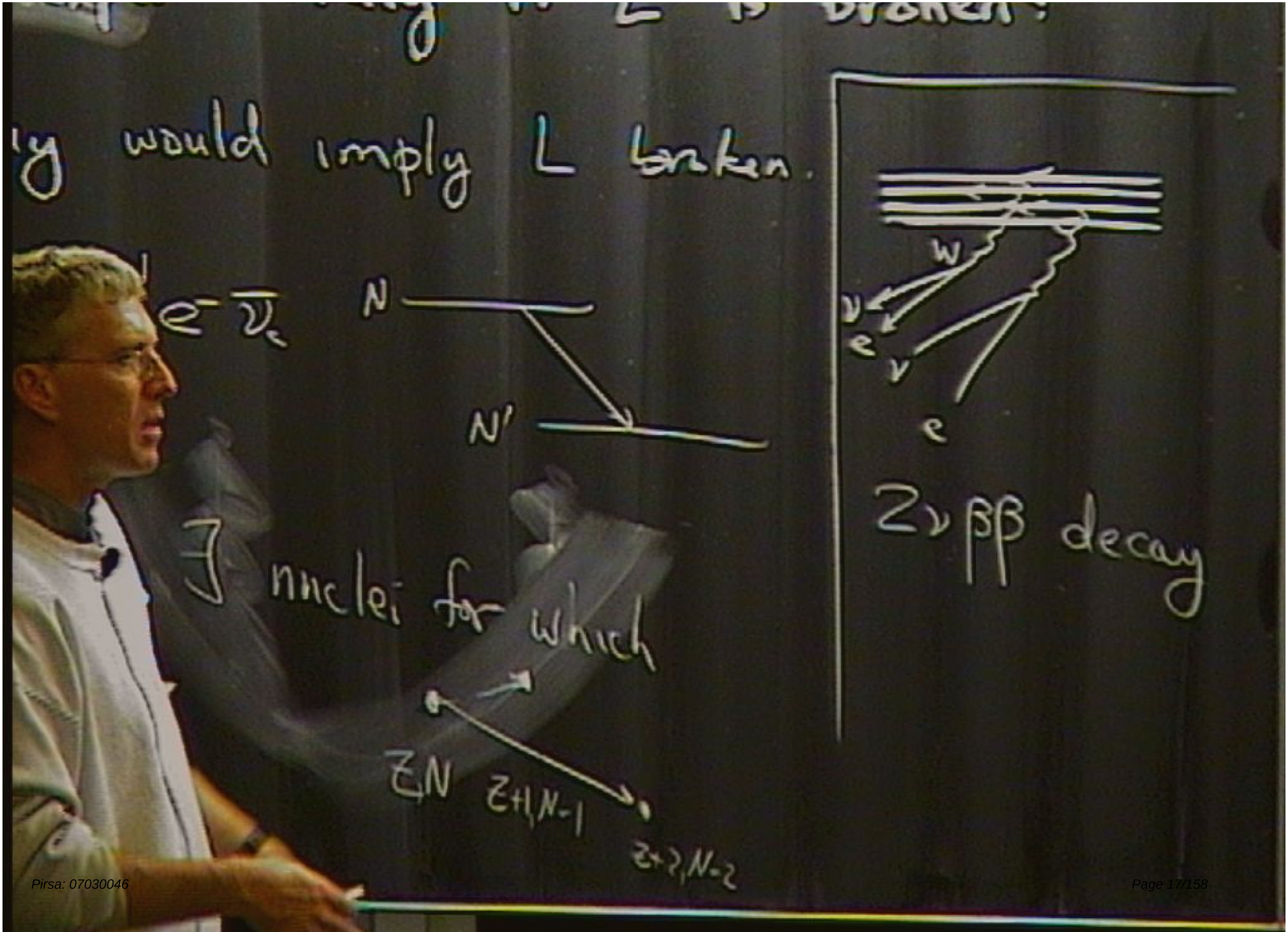

Yes: 0νββ decay would imply L broken.
β decay N → N' e⁻ ν̄ₑ
N
N'
N
∃ nuclei for which

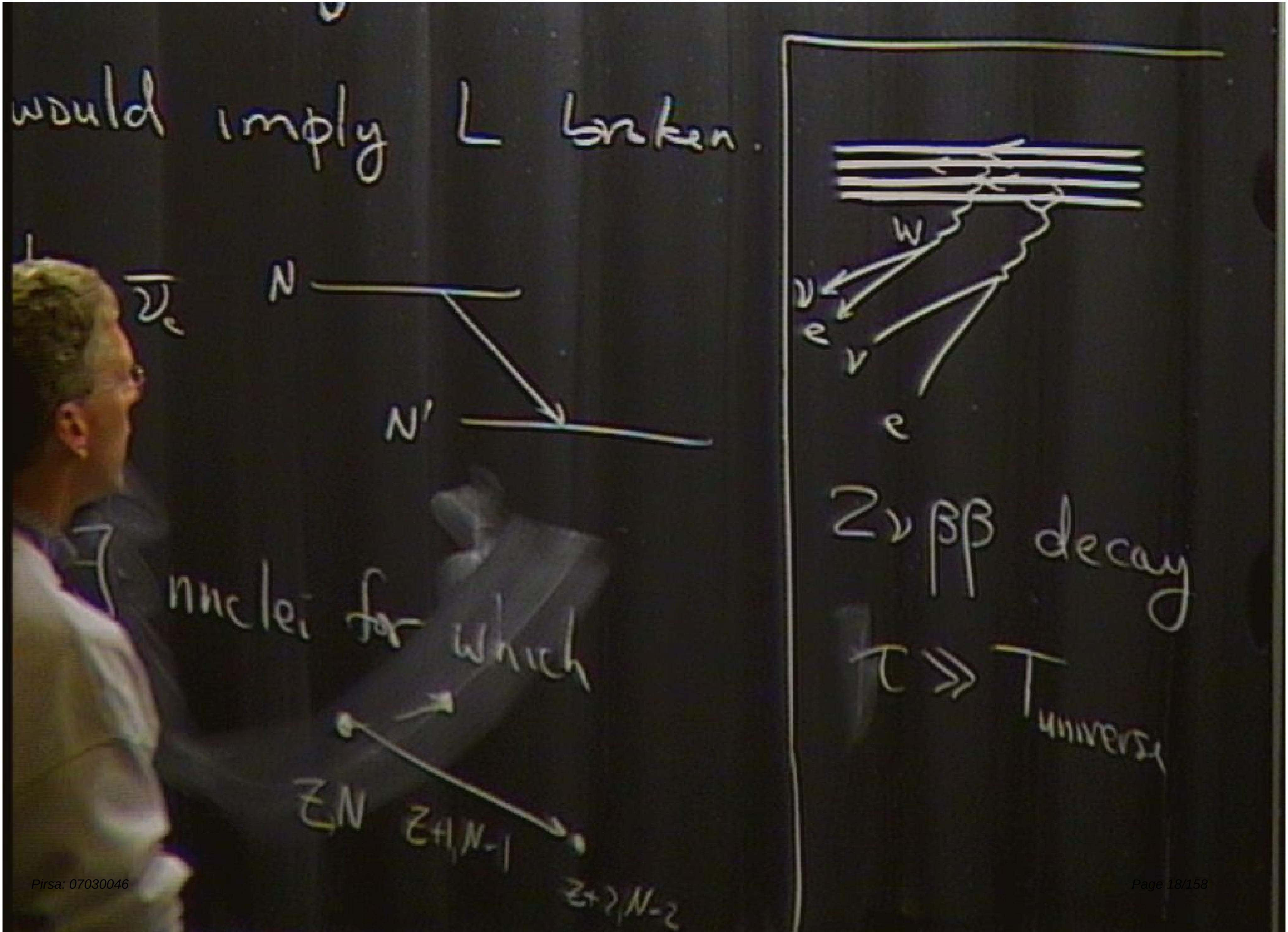

es: 0νββ decay would imply L broken.
β decay
N
N'
∃ nuclei for which
Z,N
Z+1,N-1
Z+2,N-2

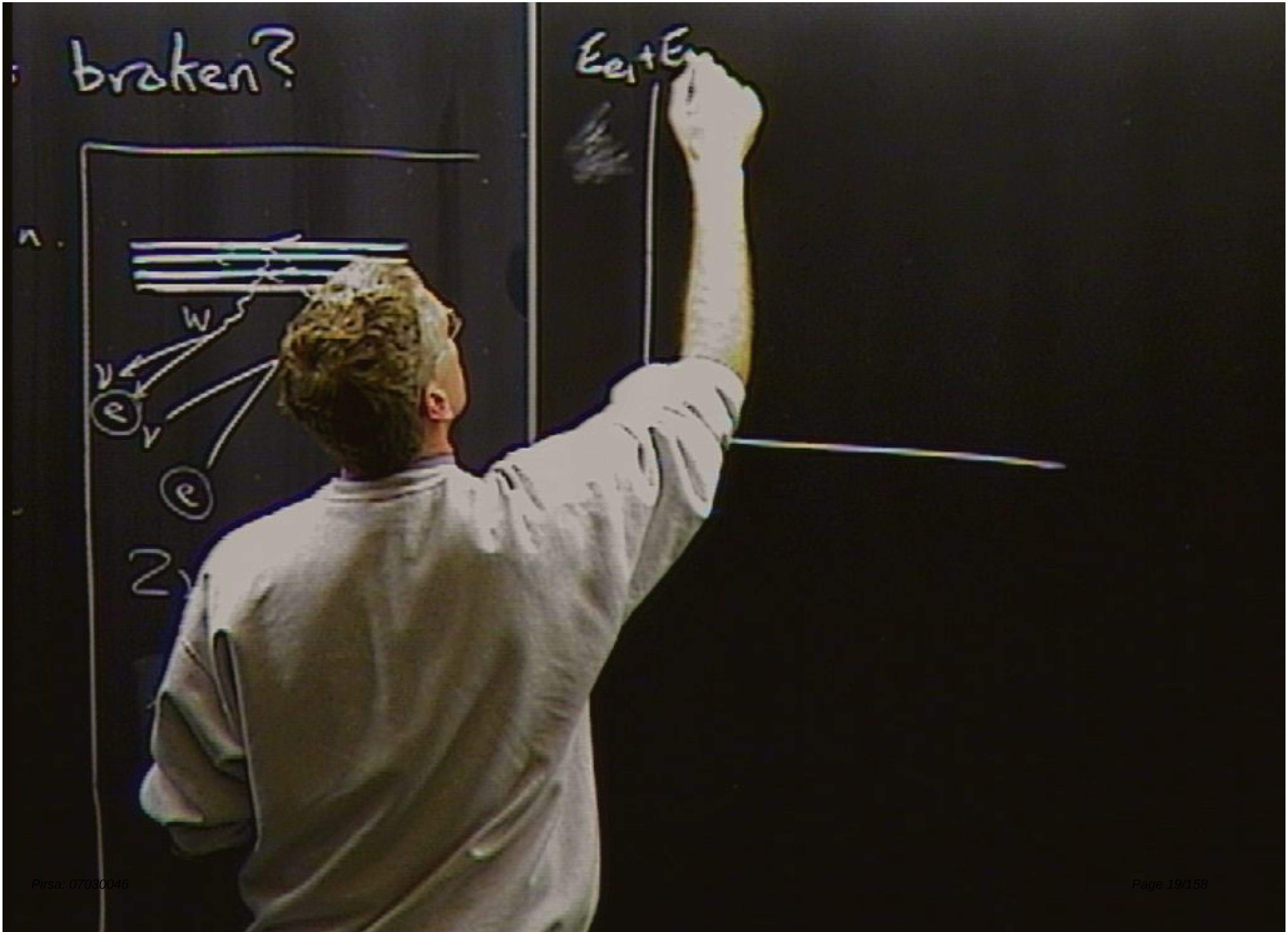

es: 0νββ decay would imply L broken.
β decay N→N'
N
N'
nuclei for which
Z+1, N-1
Z+2, N-2

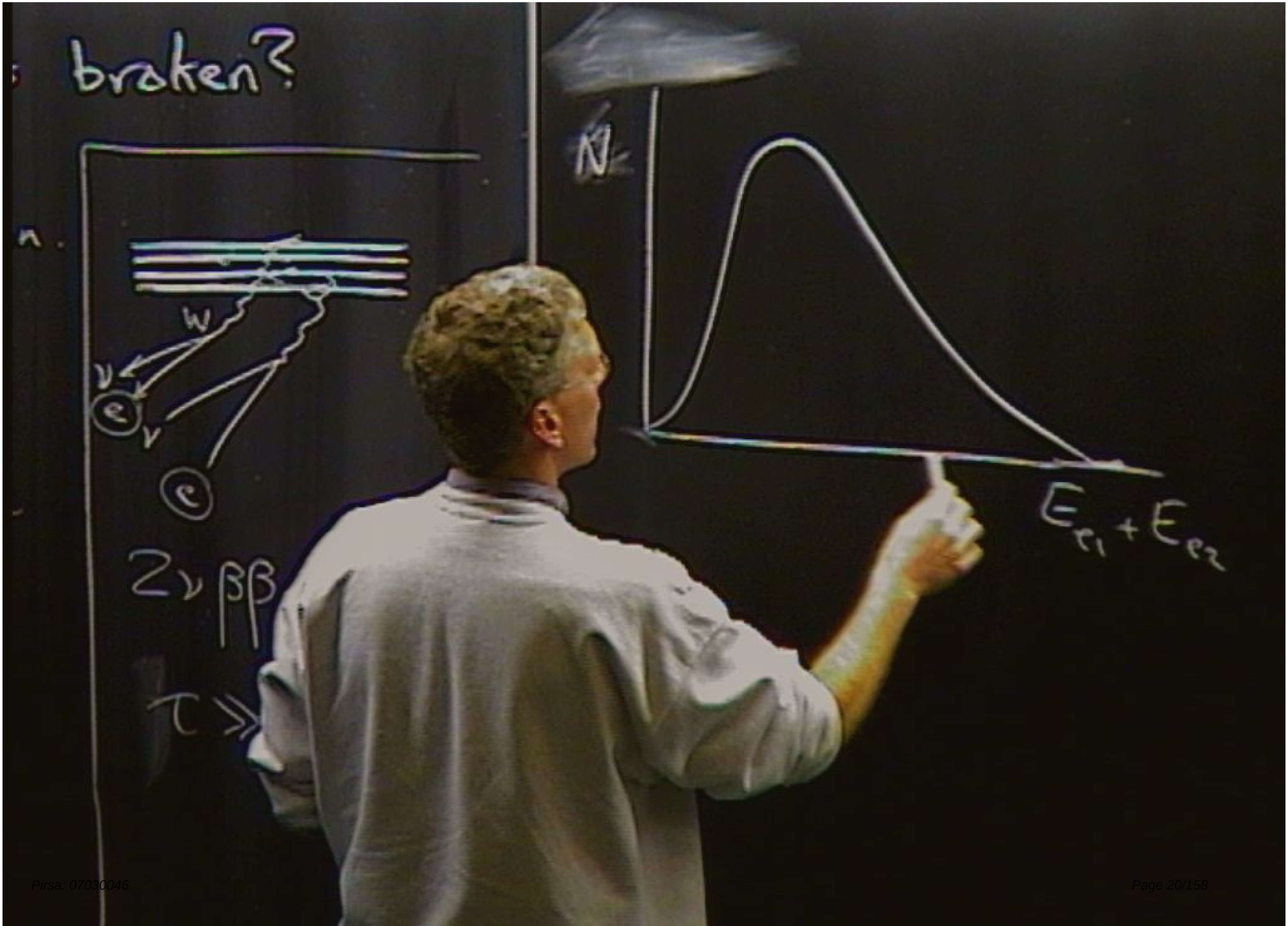

would imply L broken.
N
N'
∃ nuclei

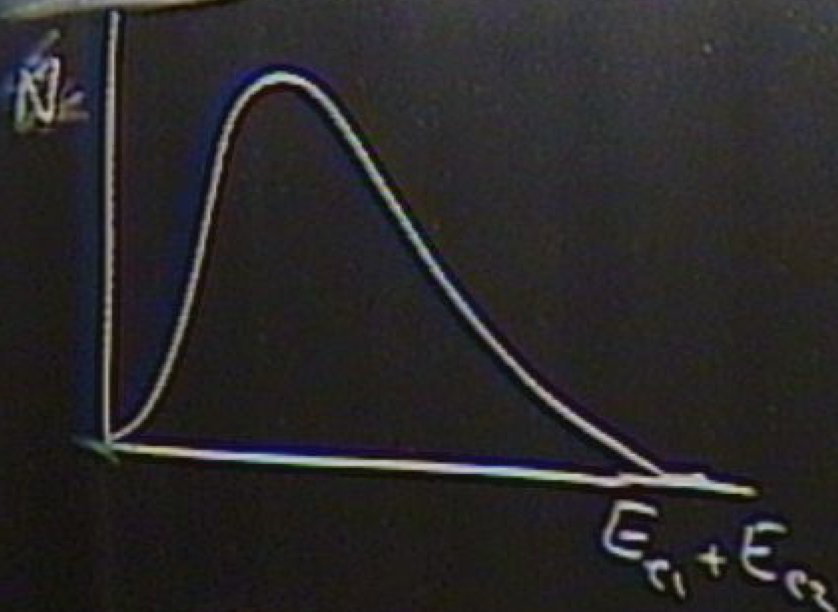

would imply L broken.
N' e⁻ ν̄e
W
ν
e
ν
e
Z+2, N-2


would imply L broken.
e⁻ ν̄ₑ
N
N'
∃ nuclei for which
Z,N
Z+1,N-1
Z+2,N-2
W
ν
e
ν
e
2ν ββ decay


would imply L broken.
N
N'
ν̄e
W
ν
e
ν
e
2νββ decay
τ ≫ T universe
∃ nuclei for which
Z,N
Z+1,N-1
Z+2,N-2


broken?
W
e
e


broken?
W
ν
e
2ν ββ
τ ≫
N
E e1 + E e2

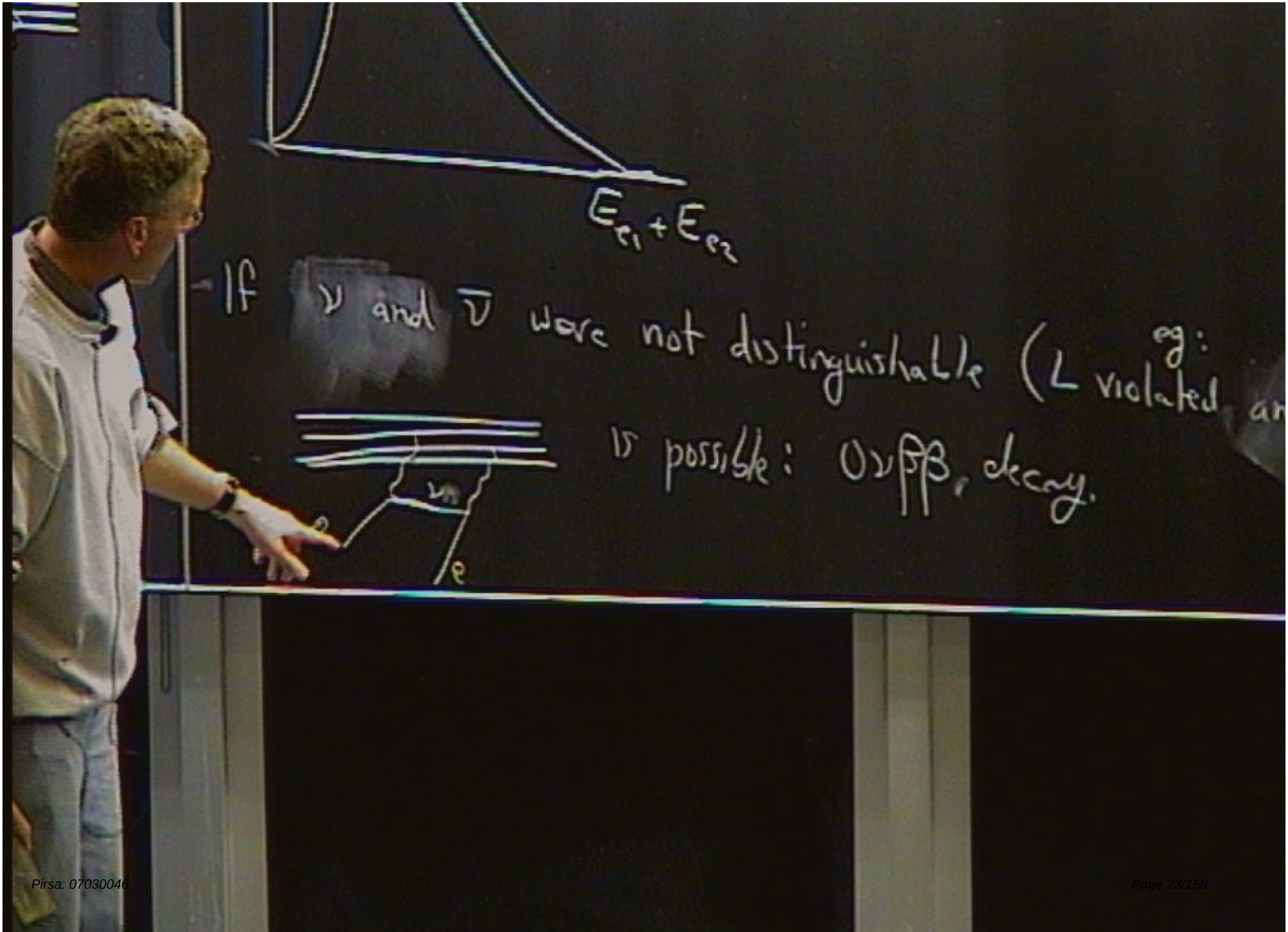


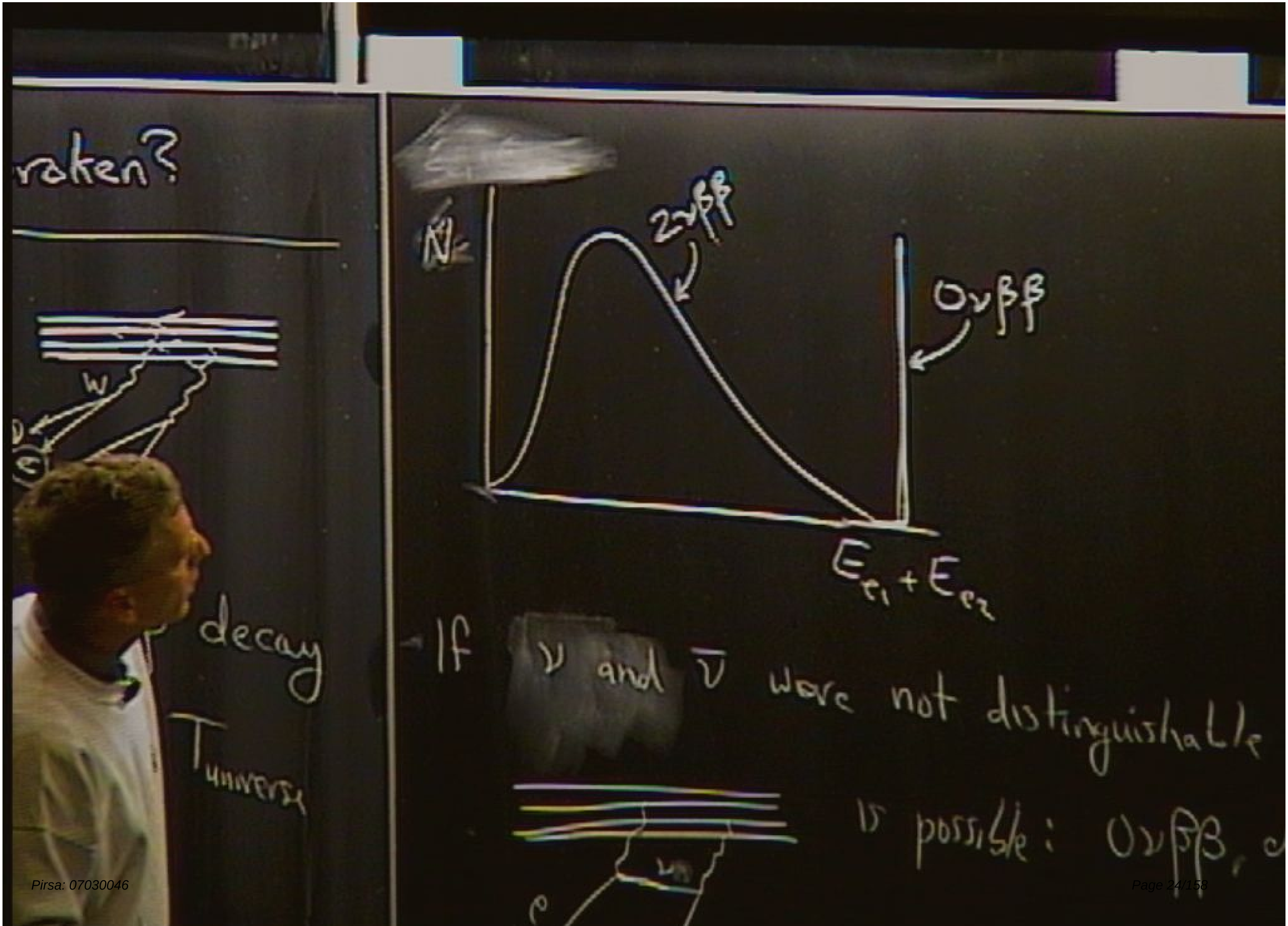
If ν and $\bar{\nu}$ were not distinguishable (L violated, mass) cay

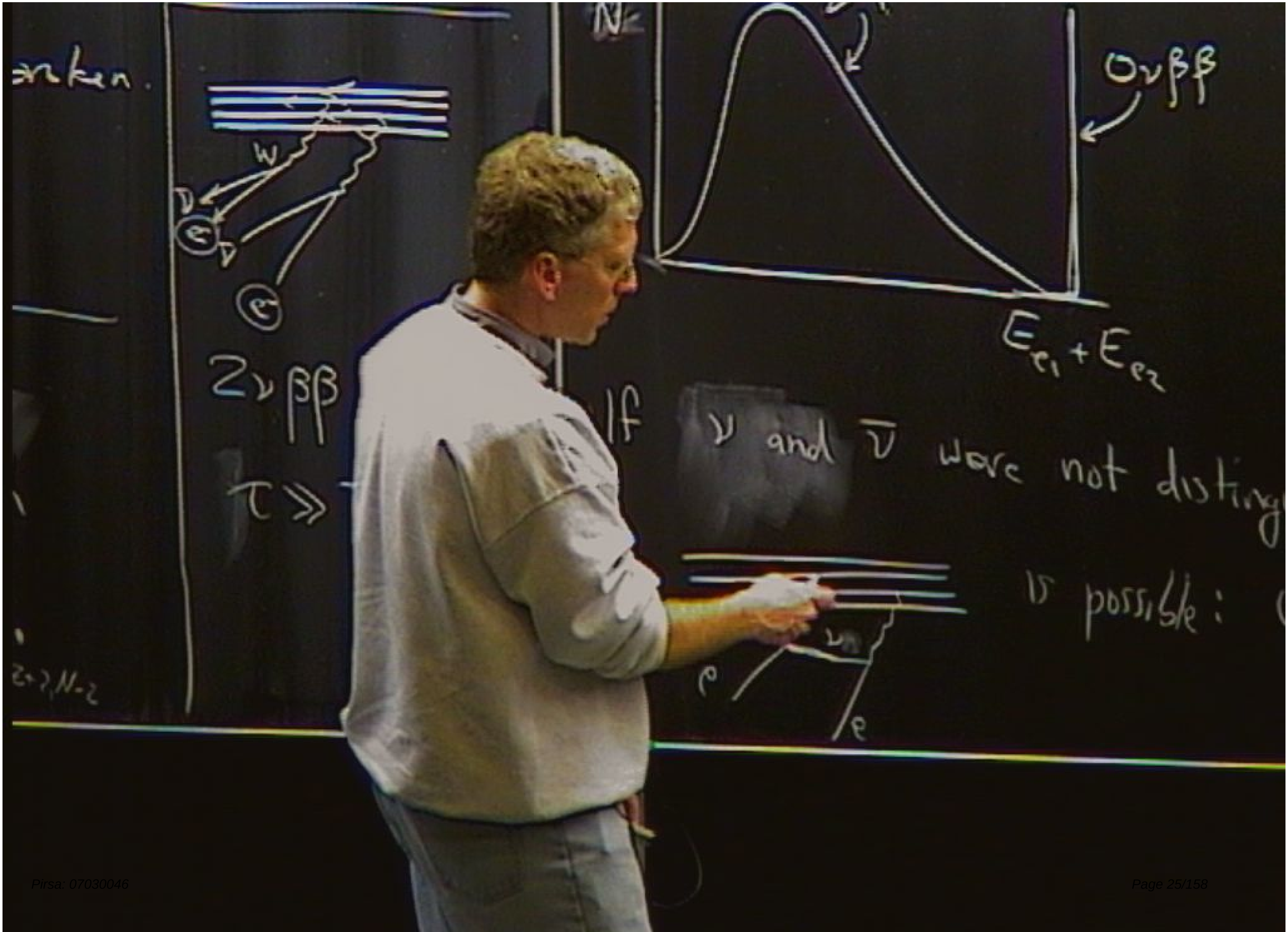
erse

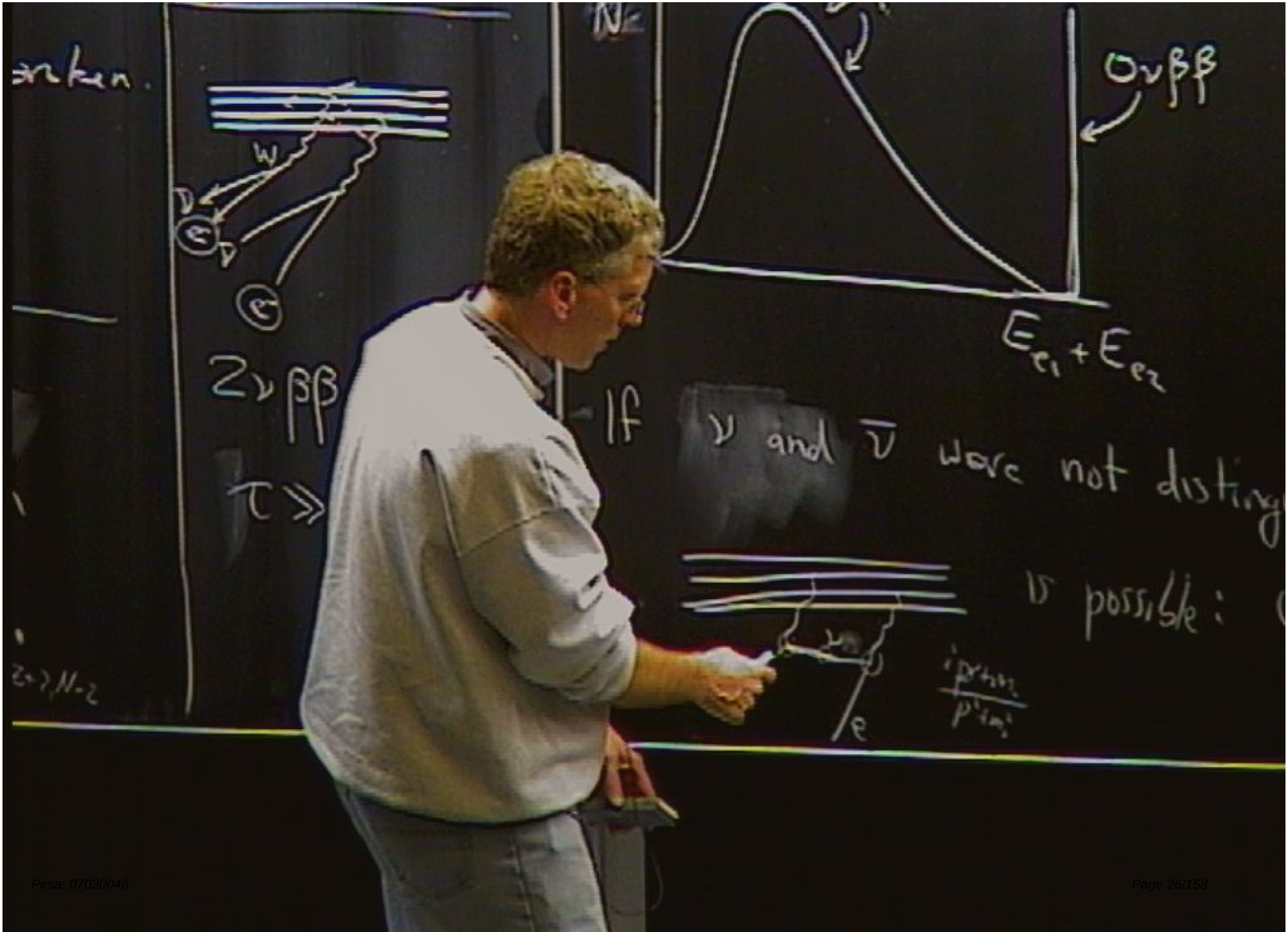
$E_{e_1} + E_{e_2}$

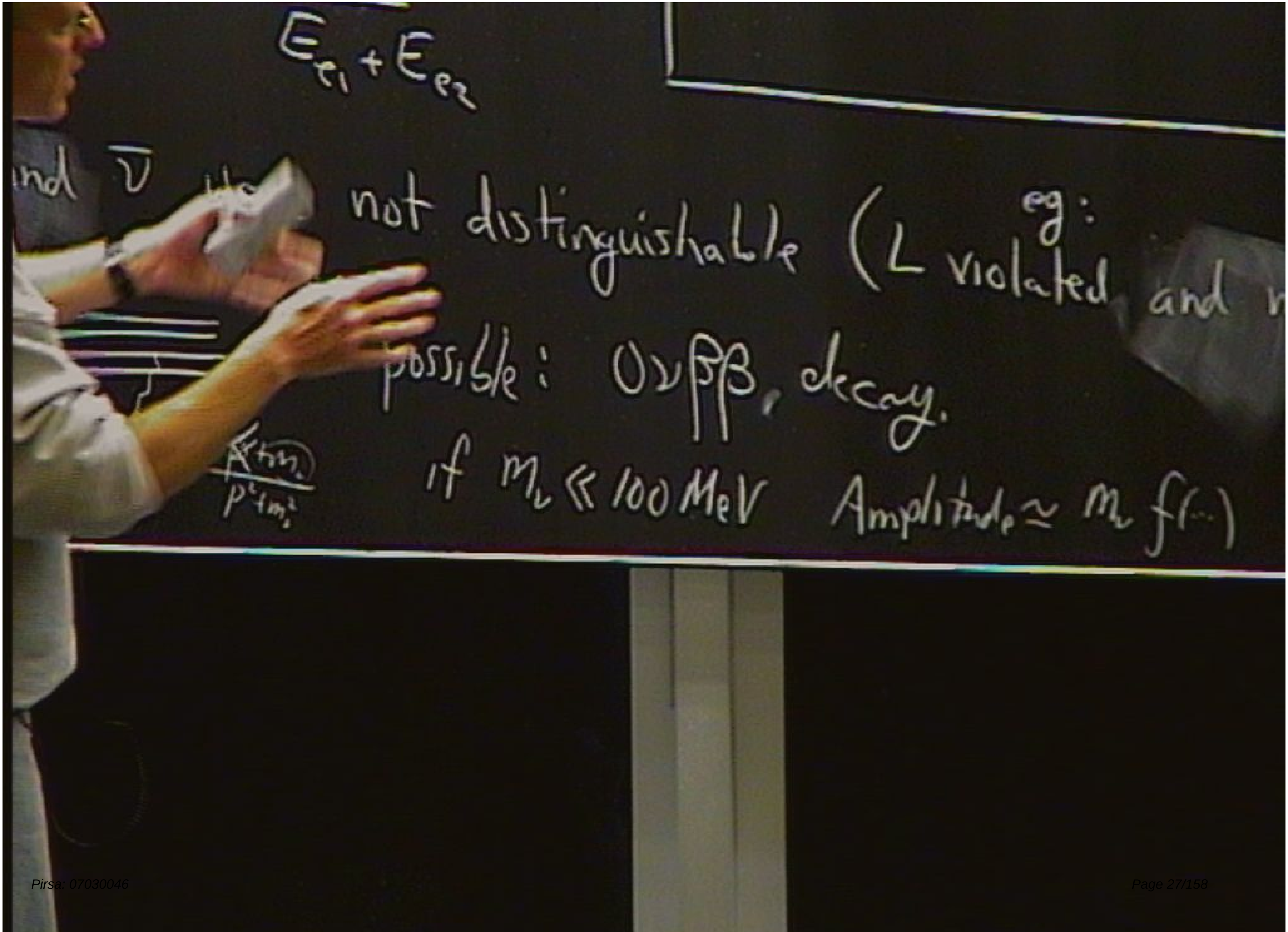
If ν and $\bar{\nu}$ were not dis


$E_{e_1}+E_{e_2}$
If ν and $\bar{\nu}$ were not distinguishable (L violated eg: an
is possible: $0\nu\beta\beta$ decay.
e
e

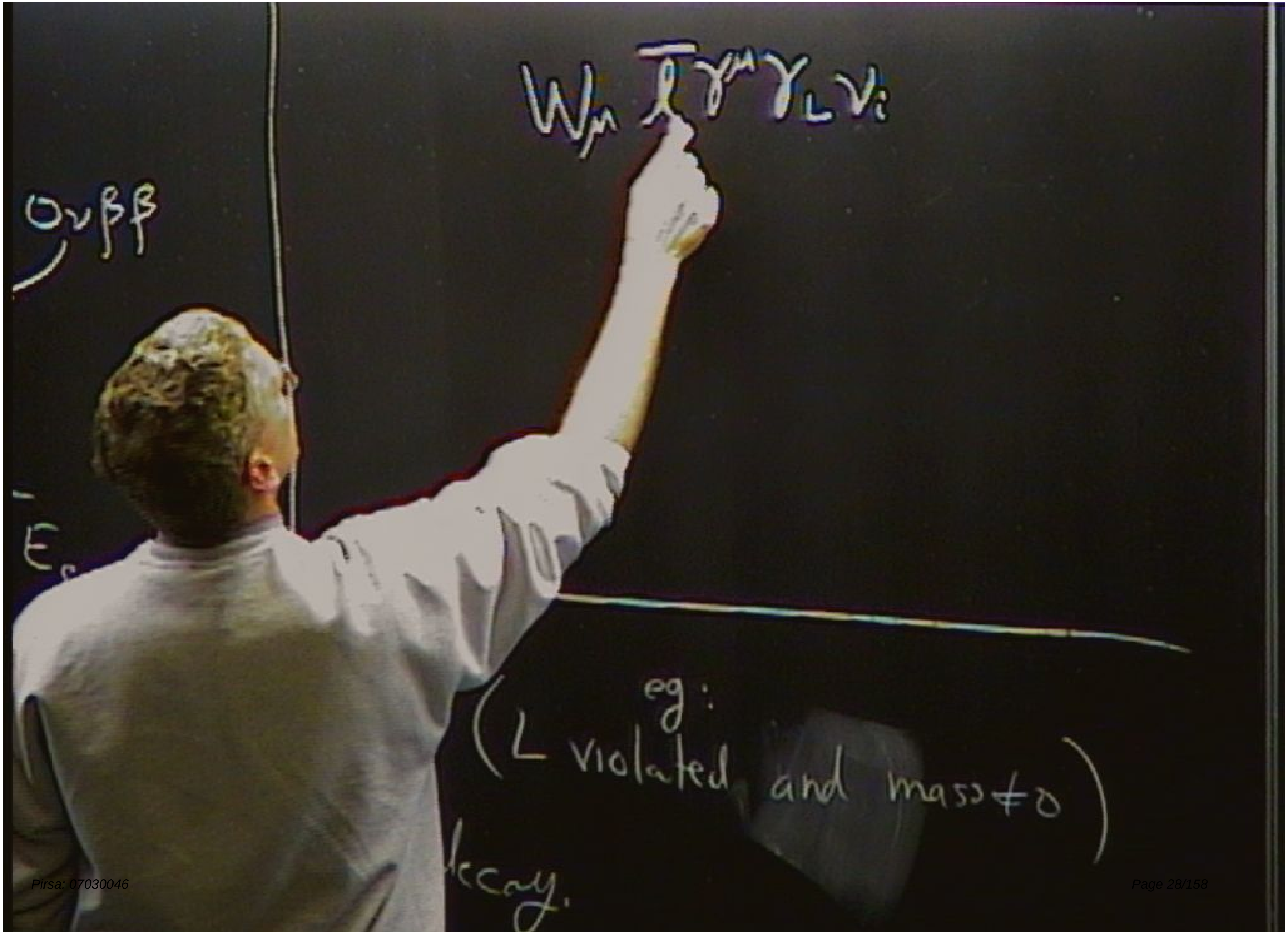

raken?
W
decay
N
2νββ
0νββ
$E_{e_1} + E_{e_2}$
If ν and ν̄ were not distinguishable
is possible: 0νββ,

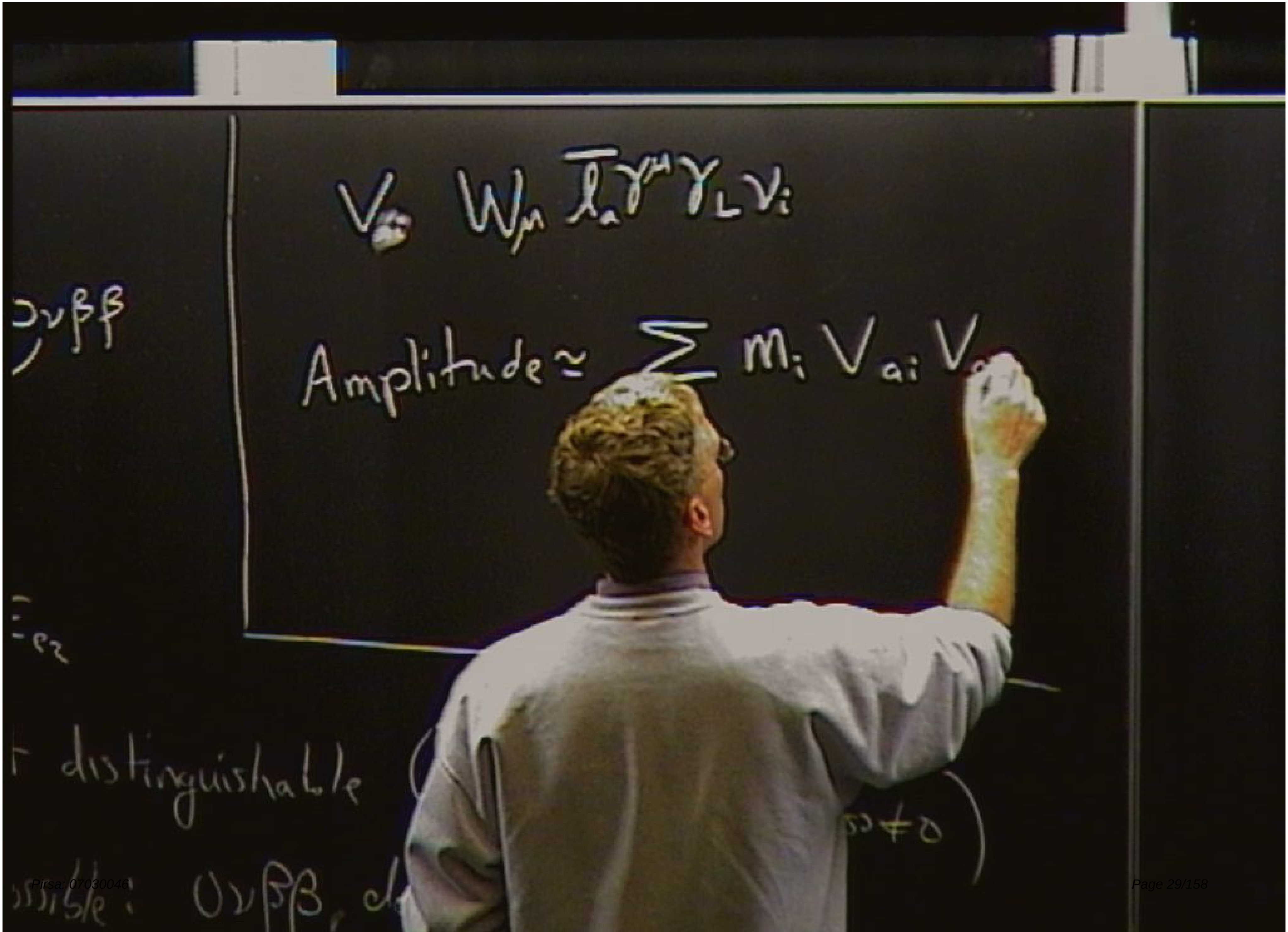

0νββ
2νββ
W
τ ≫
Ee1 + Ee2
If ν and ν̄ were not disting
is possible:

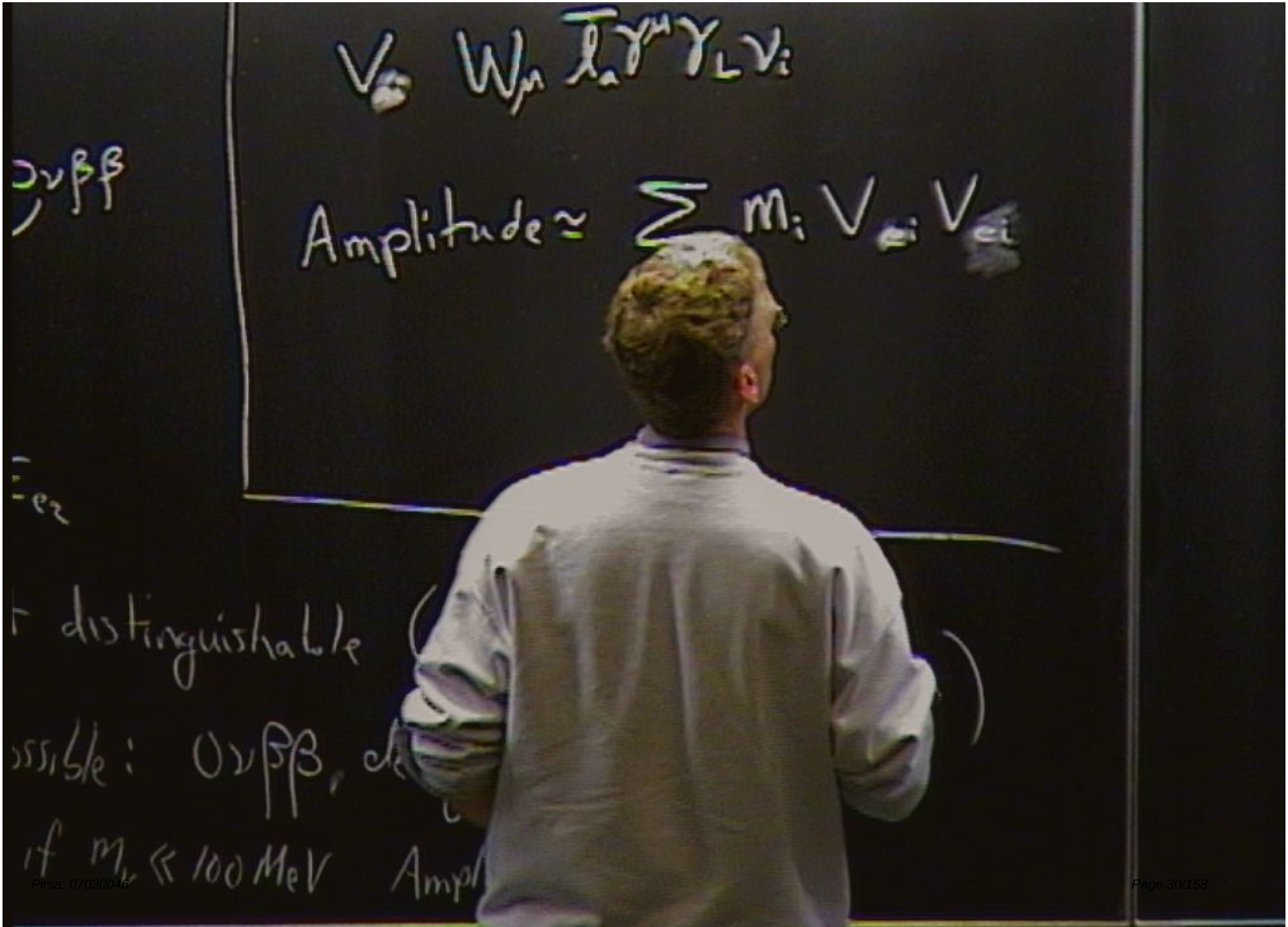

0νββ
E e1 + E e2
2νββ
W
τ ≫
If ν and ν̄ were not disting
is possible:



$E_{e_1} + E_{e_2}$
nd $\bar{\nu}$
not distinguishable (L violated and
eg:
possible: $0\nu\beta\beta$ decay.
if $m_\nu \ll 100$ MeV Amplitude $\simeq m_\nu f(\dots)$


$W_\mu \bar{\ell} \gamma^\mu \gamma_L \nu_i$
0νββ
eg:
(L violated and mass ≠ 0)


$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i$
Amplitude $\simeq \sum m_i V_{ai} V$
0νββ
distinguishable
0νββ


$V_{ei} W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i$
0νββ
Amplitude $\simeq \sum m_i V_{ei} V_{ei}$
distinguishable
0νββ,
if $m_\nu \ll 100$ MeV

$\bar{\nu}_e \, W_\mu \, \bar{l}_a \gamma^\mu \gamma_L \nu_i$

$0\nu\beta\beta$

$$\text{Amplitude} \simeq \sum_i m_i V_{ei} V_{ei}$$

$$= m_{eff}$$

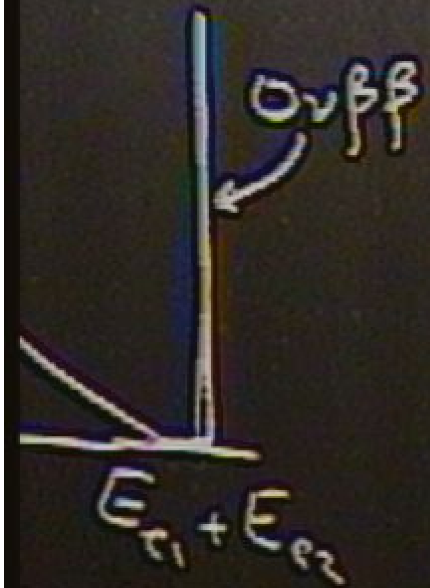
$$= m_{ee}$$

e_2

t distinguishable (L violated, and mass $\neq 0$) eg:

ossible: $0\nu\beta\beta$, decay.

if $m_\nu \ll 100$ MeV Amplitude $\simeq m_\nu f(\dots)$



$V_{ei}\, W_\mu\, \bar{\ell}_\alpha \gamma^\mu \gamma_L \nu_i$

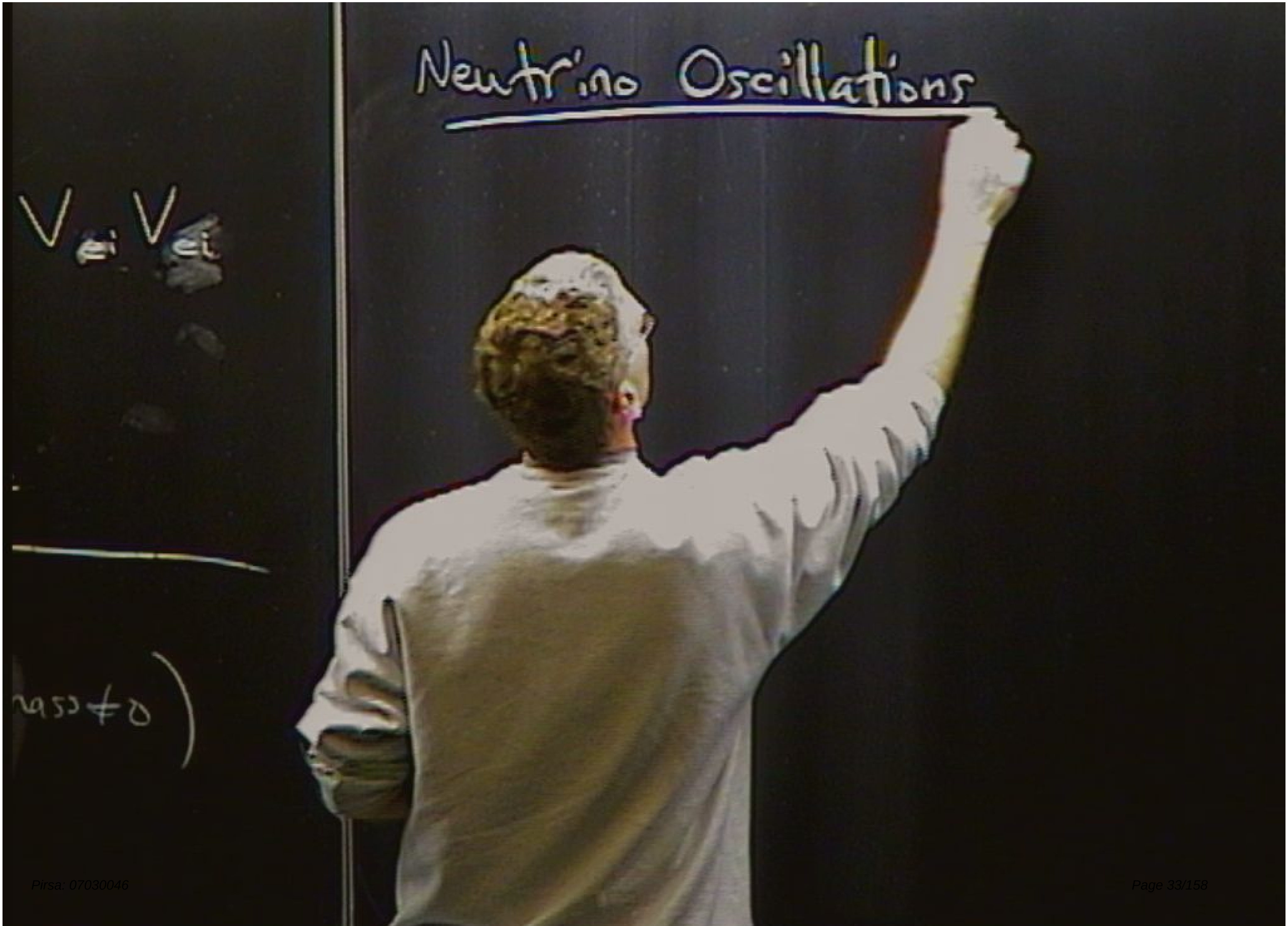
$$\text{Amplitude} \simeq \sum_i m_i V_{ei} V_{ei}$$
$$= m_{eff}$$
$$= m_{ee}$$

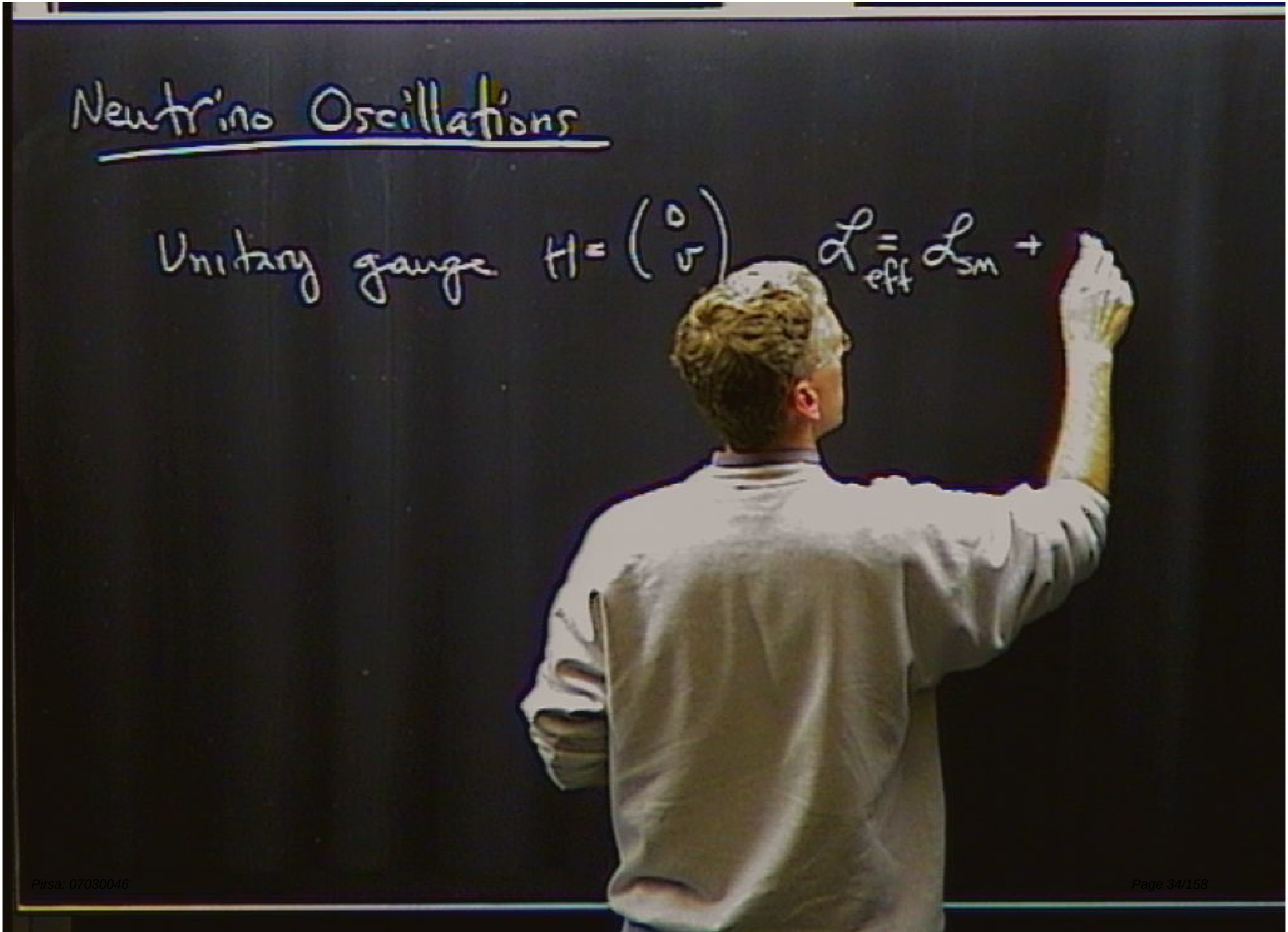
$|m_{ee}| \lesssim 1\,\text{eV}$

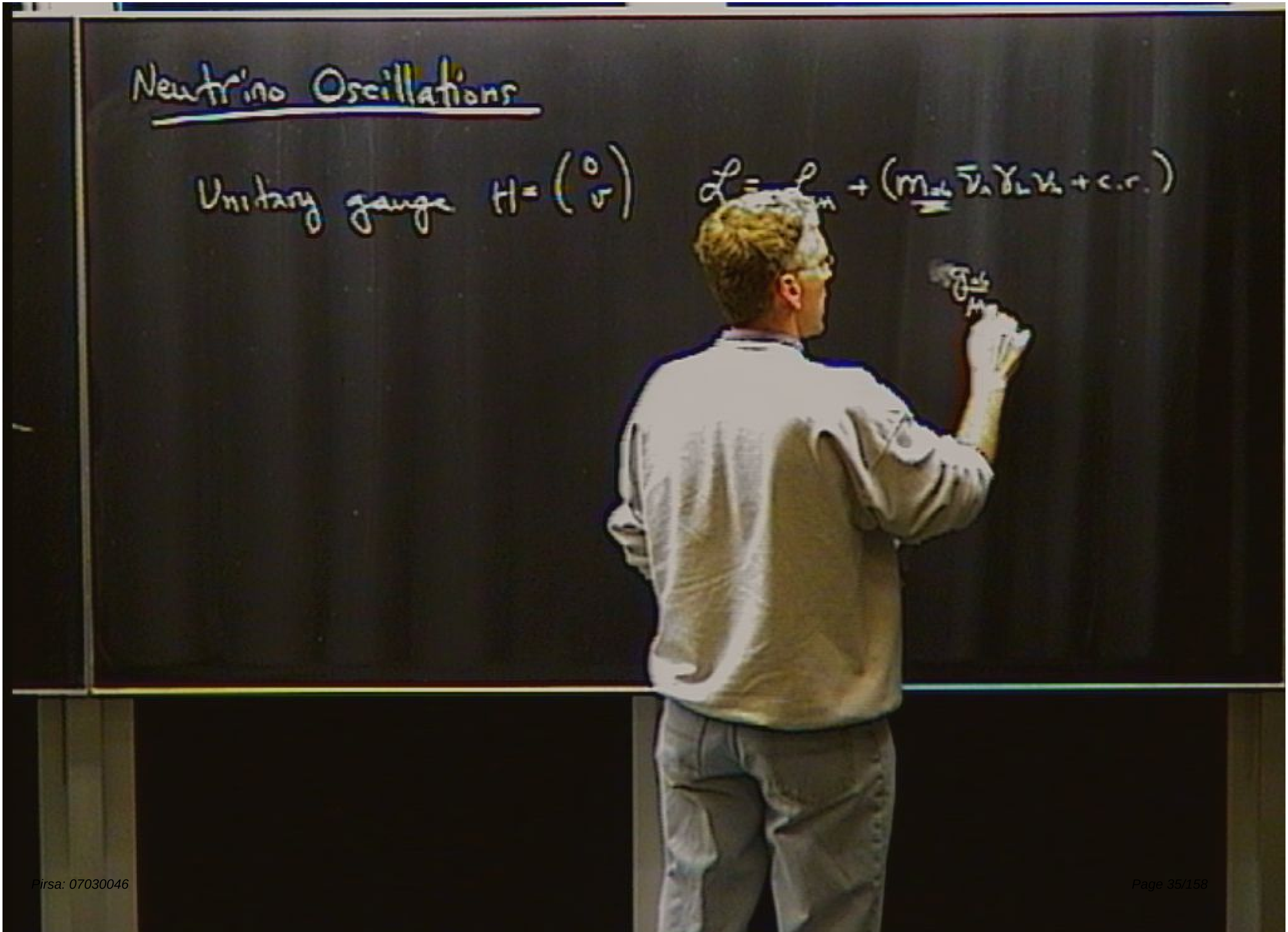
...are not distinguishable (L violated, eg: and mass ≠ 0)

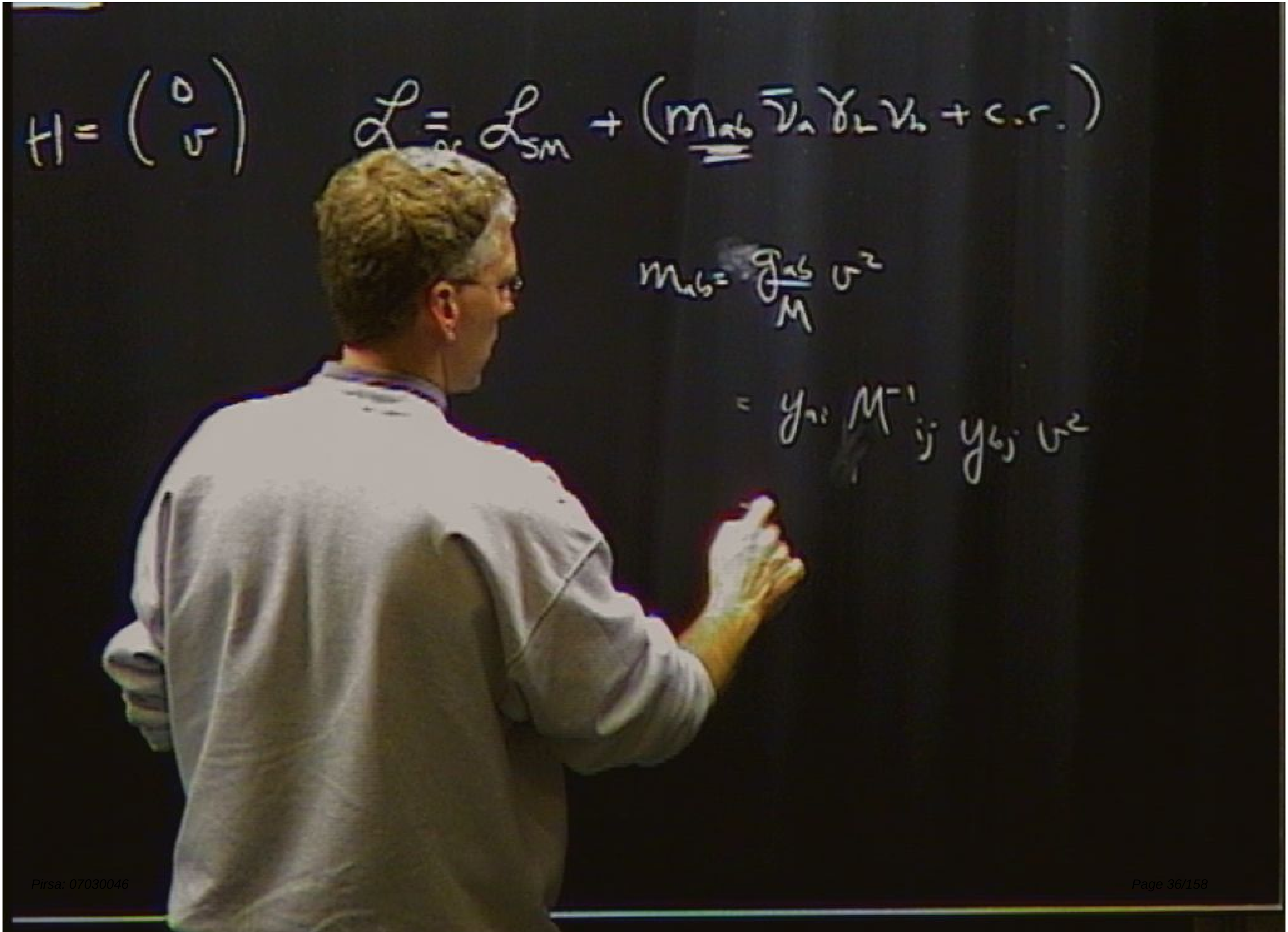
... is possible: $0\nu\beta\beta$, decay.

$\frac{\not{p}+m_i}{p^2+m_i^2}$ if $m_\nu \ll 100\,\text{MeV}$ Amplitude $\simeq m_\nu f(\ldots)$


Neutrino Oscillations


Neutrino Oscillations
Unitary gauge $H = \begin{pmatrix} 0 \\ v \end{pmatrix}$
$\mathcal{L}_{eff} = \mathcal{L}_{SM} +$

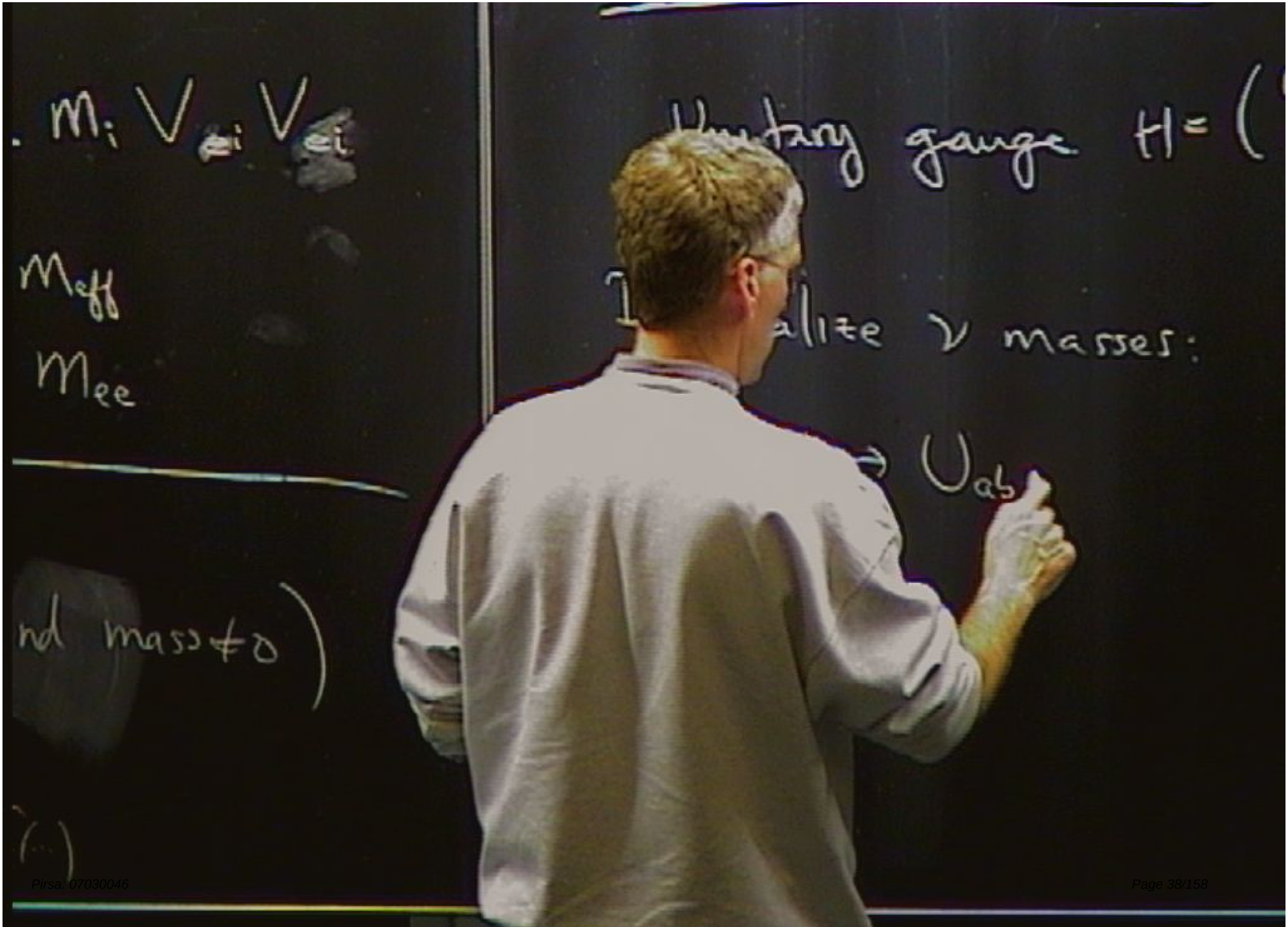

Neutrino Oscillations
Unitary gauge H = (0 v)
+ c.c.



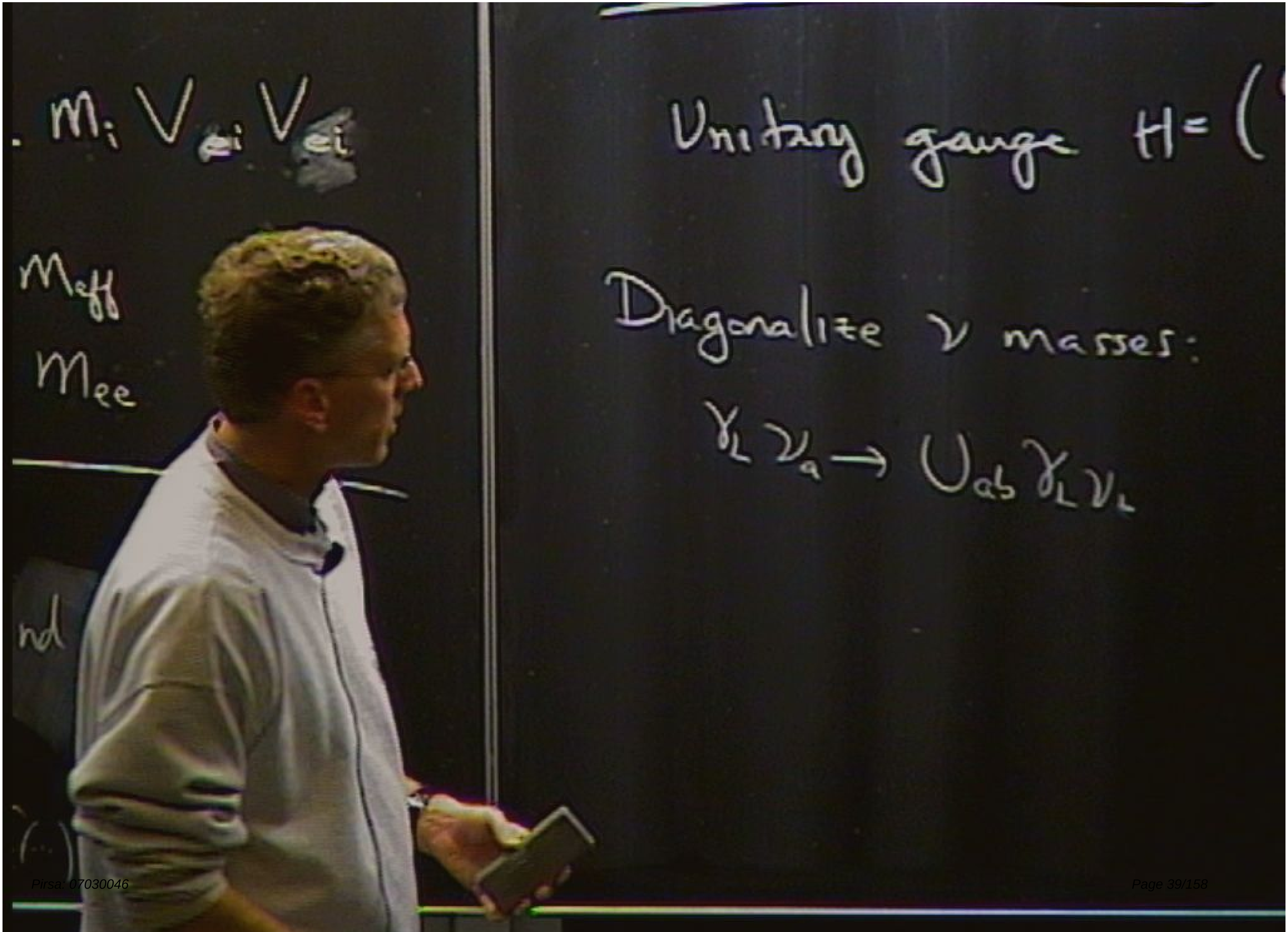
$H = \begin{pmatrix} 0 \\ v \end{pmatrix}$
$\mathcal{L} \underset{\text{ef}}{=} \mathcal{L}_{SM} + \left(m_{ab} \bar{\nu}_a \gamma_L \nu_b + c.c. \right)$
$m_{ab} = \frac{g_{ab}}{M} v^2$
$= y_{ai} M^{-1}_{ij} y_{bj} v^2$

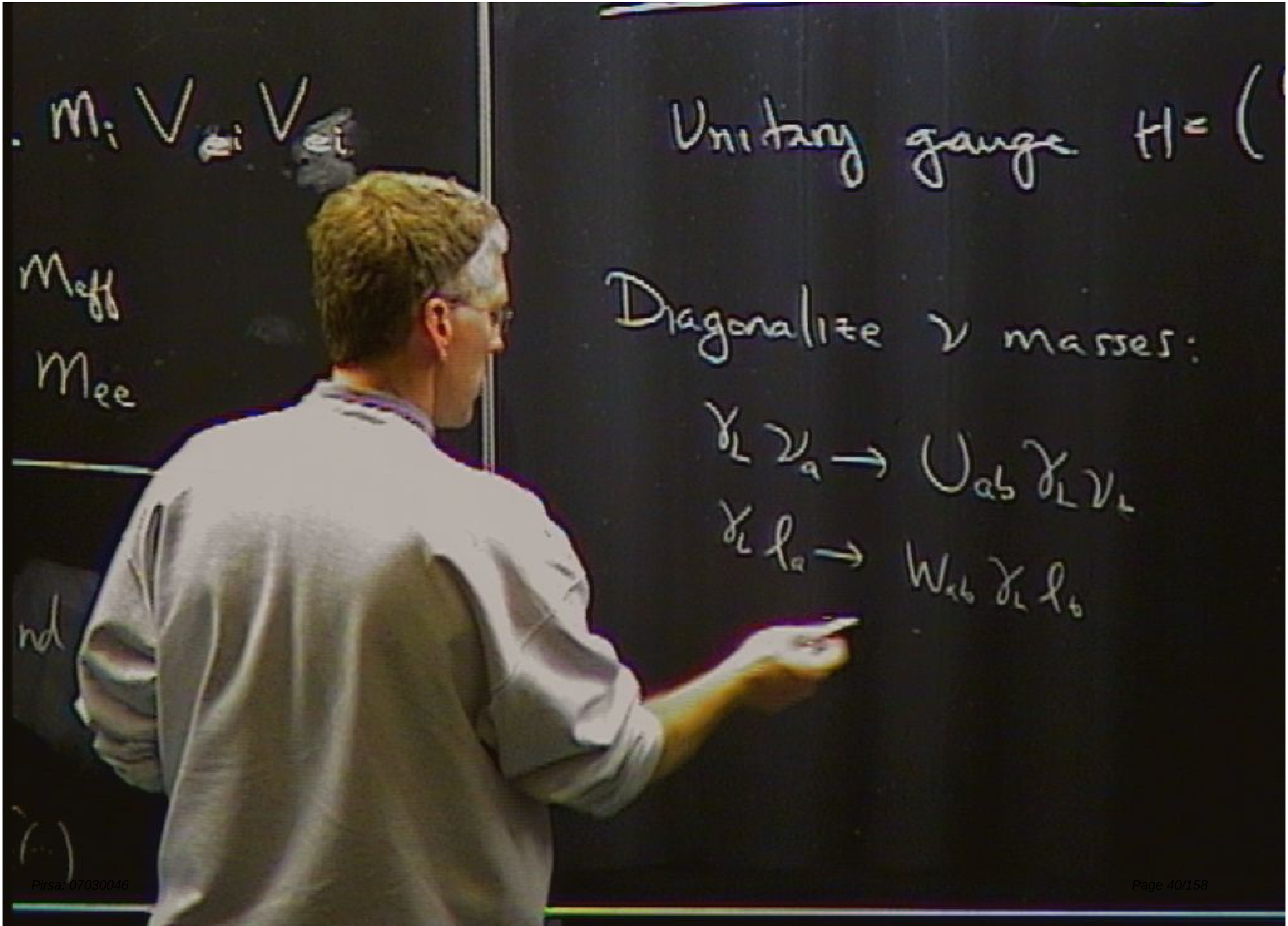
$$H = \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \mathcal{L}_{eff} = \mathcal{L}_{SM} + \left(\underline{\underline{m_{ab}}}\, \bar{\nu}_a \gamma_L \nu_b + c.c. \right)$$

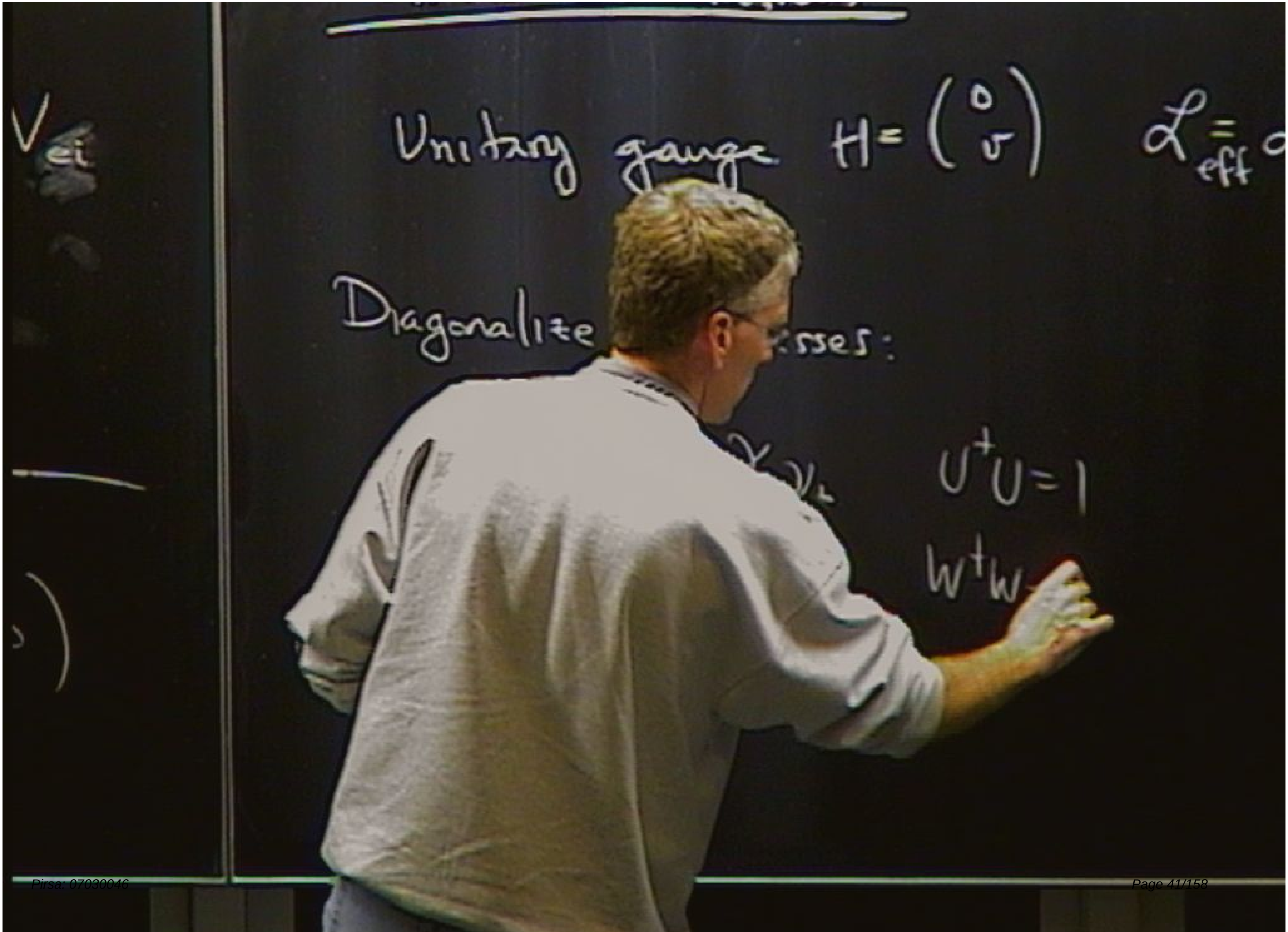
$$m_{ab} = \begin{cases} \dfrac{g_{ab}}{M} v^2 \\[2ex] y_{ai} M^{-1}_{ij} y_{bj} v^2 \end{cases}$$



m_i V_ei V_ei
M_eff
M_ee
nd mass≠0
gauge H= (
alize ν masses:
U_ab


m_i V_ei V_ei
m_eff
m_ee
nd
Unitary gauge H= (
Diagonalize ν masses:
γ_L ν_a → U_ab γ_L ν_L


$m_i V_{ei} V_{ei}$
M_{eff}
M_{ee}
nd
Unitary gauge $H = ($
Diagonalize ν masses:
$\gamma_L \nu_a \rightarrow U_{ab} \gamma_L \nu_b$
$\gamma_L l_a \rightarrow W_{ab} \gamma_L l_b$


Unitary gauge $H = \begin{pmatrix} 0 \\ v \end{pmatrix}$
$\mathcal{L}_{eff} =$
Diagonalize
sses:
$U^{\dagger}U = 1$
$W^{\dagger}W$

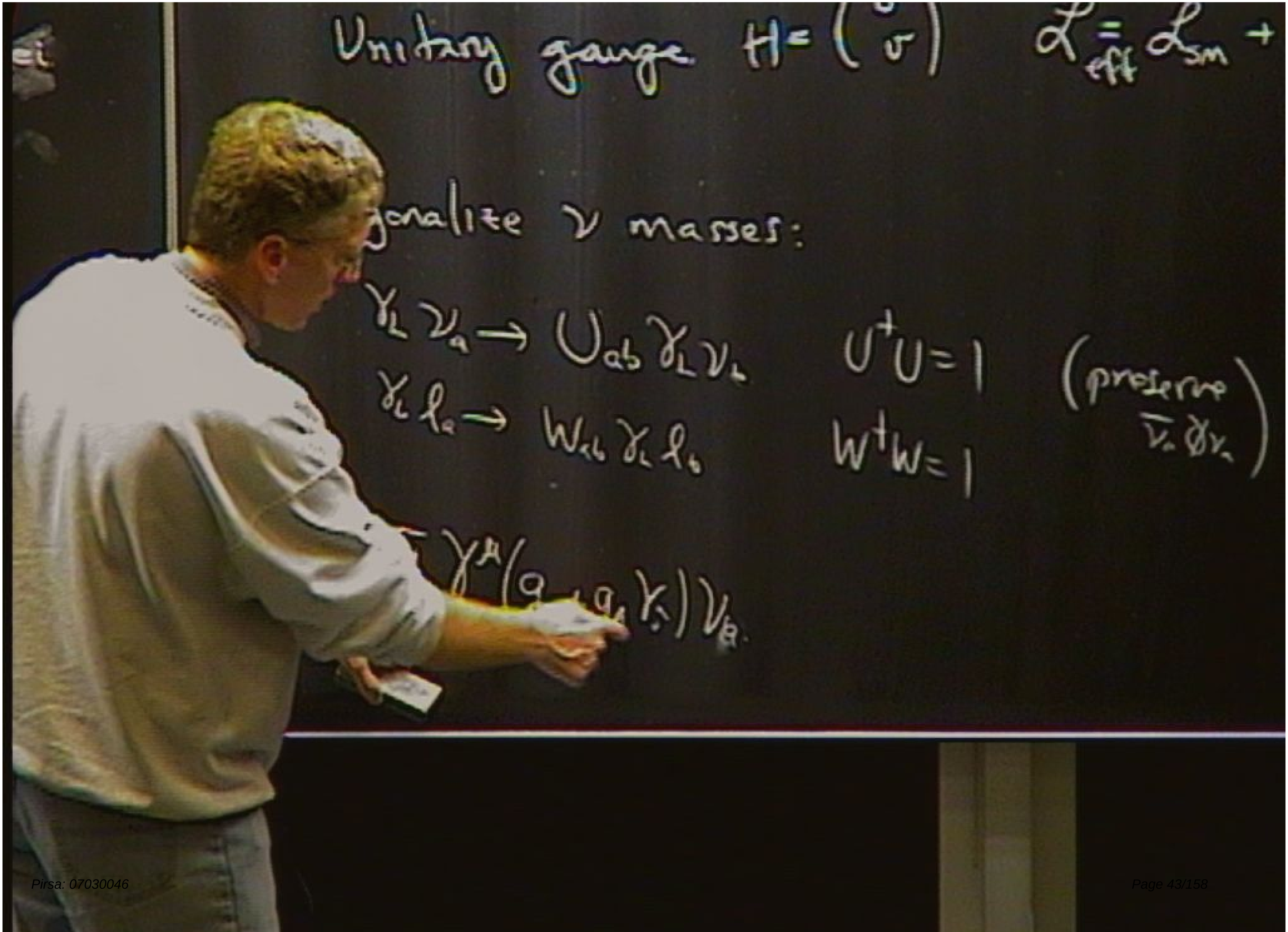
Unitary gauge $H = \begin{pmatrix} 0 \\ v \end{pmatrix}$ $\mathcal{L}_{eff} = \mathcal{L}_{SM} + ($

m

Diagonalize ν masses:

$\gamma_L \nu_a \to U_{ab} \gamma_L \nu_b$ $U^\dagger U = 1$ (preserve $\bar{\nu}_a \not{\partial} \nu_a$)

$\gamma_L l_a \to W_{ab} \gamma_L l_b$ $W^\dagger W = 1$


Unitary gauge H = (0 v)
L_eff = L_SM +
gonalize ν masses:
γ_L ν_a → U_ab γ_L ν_b
U†U = 1
(preserve ν̄ γ ν)
γ_L l_a → W_ab γ_L l_b
W†W = 1

Unitary gauge $H = \begin{pmatrix} 0 \\ v \end{pmatrix}$ $\qquad \mathcal{L}_{eff} = \mathcal{L}_{SM} +$

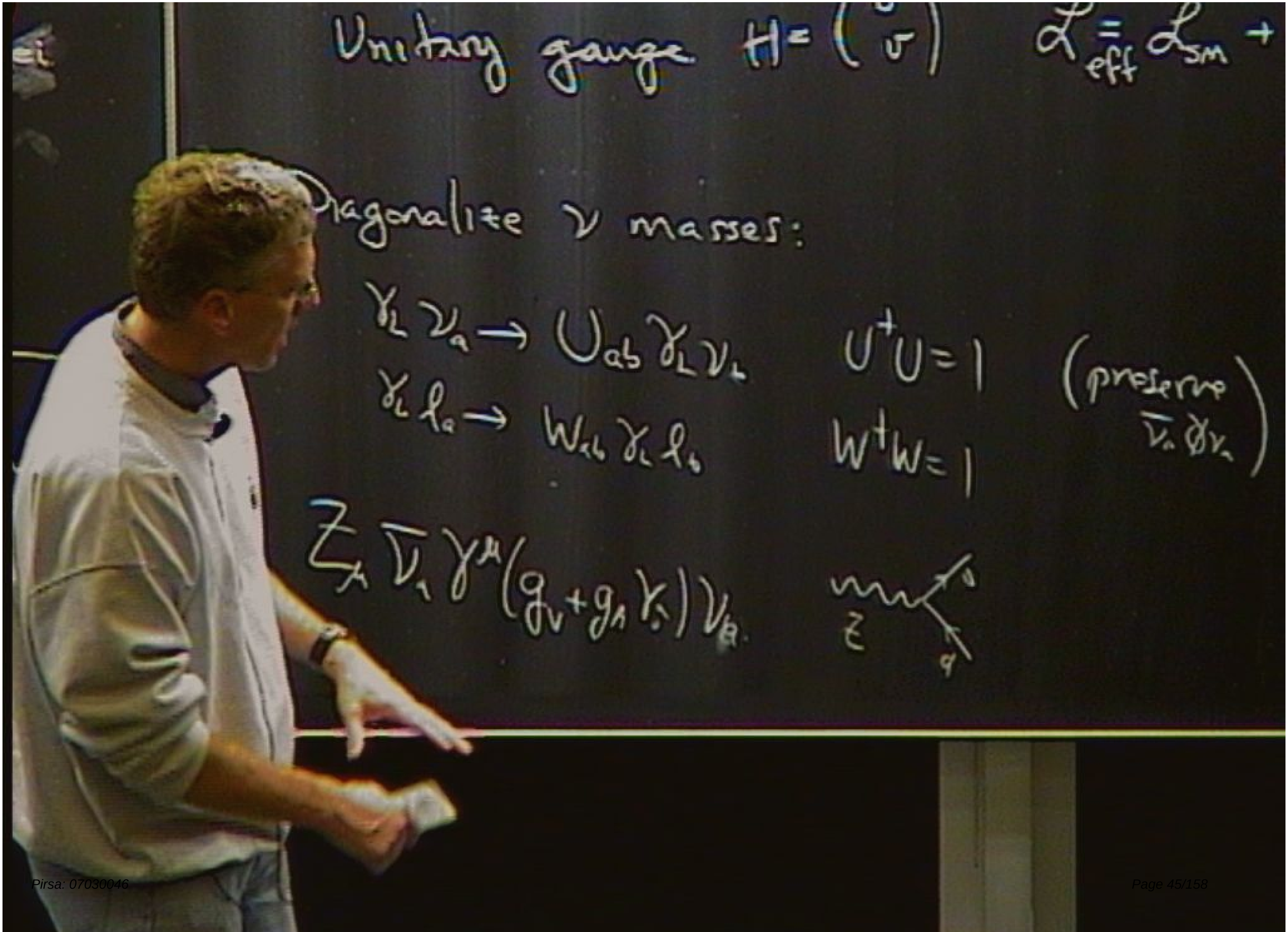
Diagonalize ν masses:

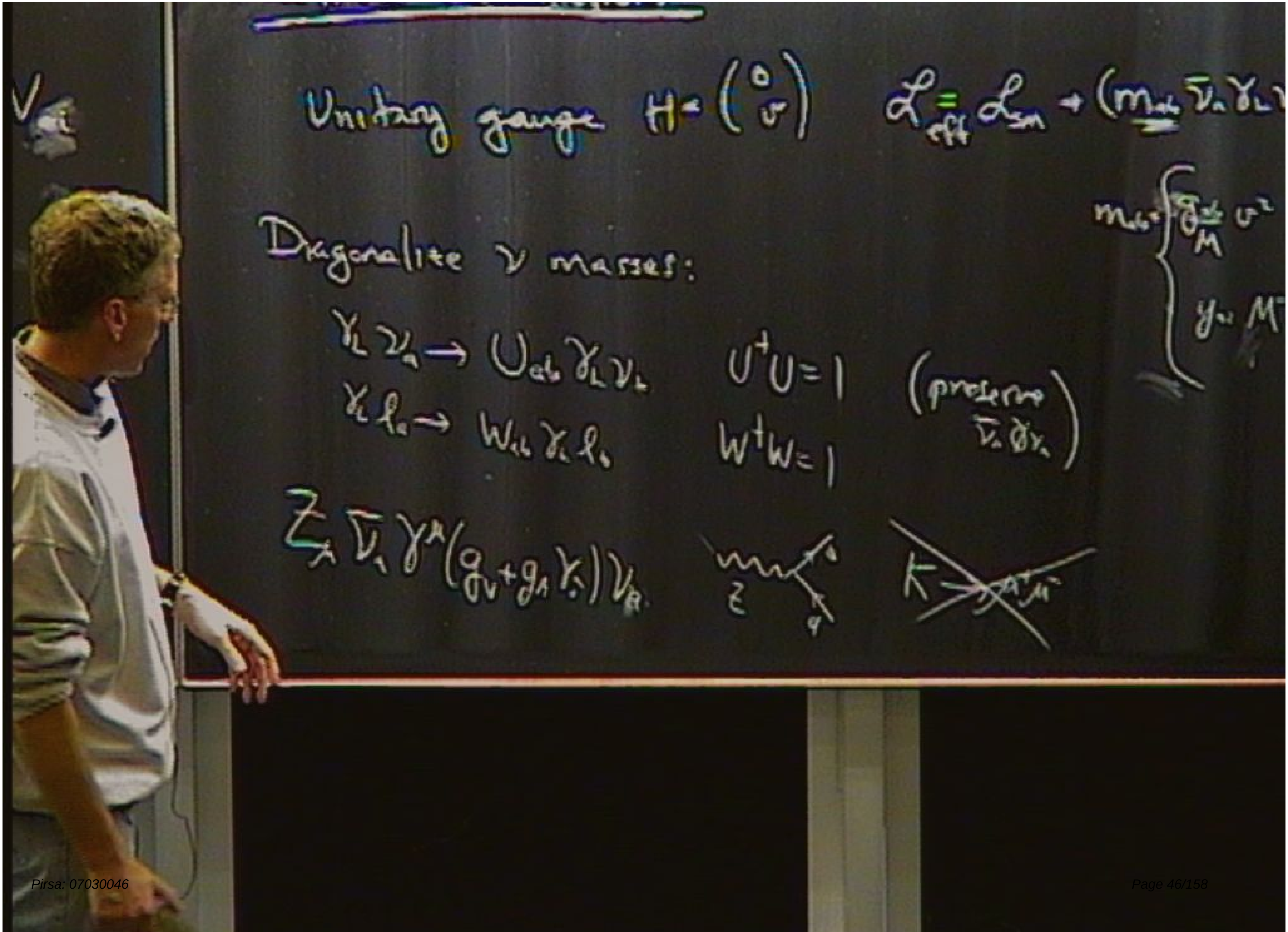
$$\gamma_L \nu_a \to U_{ab}\,\gamma_L \nu_b \qquad U^\dagger U = 1$$

$$\gamma_L \ell_a \to W_{ab}\,\gamma_L \ell_b \qquad W^\dagger W = 1$$

(preserve $\bar{\nu}_a \not{\partial} \nu_a$)

$$Z_\lambda\, \bar{\nu}_a \gamma^\mu (g_V + g_A \gamma_5)\, \nu_a$$


Unitary gauge $H = \begin{pmatrix} 0 \\ v \end{pmatrix}$ $\mathcal{L}_{eff} = \mathcal{L}_{SM} +$
Diagonalize ν masses:
$\gamma_L \nu_a \to U_{ab} \gamma_L \nu_b$ $U^\dagger U = 1$ (preserve $\bar{\nu}_a \not{\partial} \nu_a$)
$\gamma_L l_a \to W_{ab} \gamma_L l_b$ $W^\dagger W = 1$
$Z_\mu \bar{\nu}_a \gamma^\mu (g_V + g_A \gamma_5) \nu_a$
Z

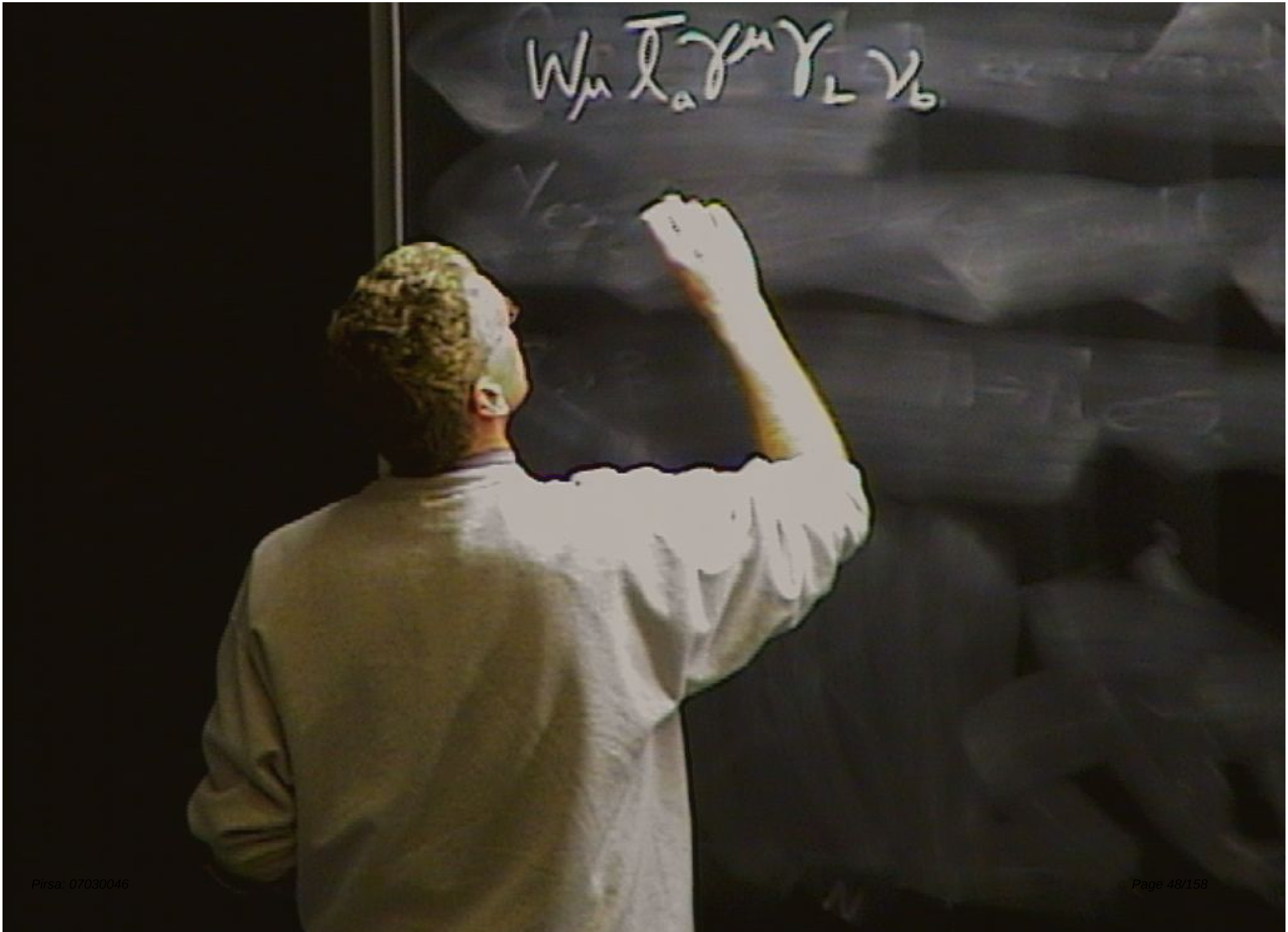

Unitary gauge
Diagonalize ν masses:
U†U = 1
W†W = 1
(preserve

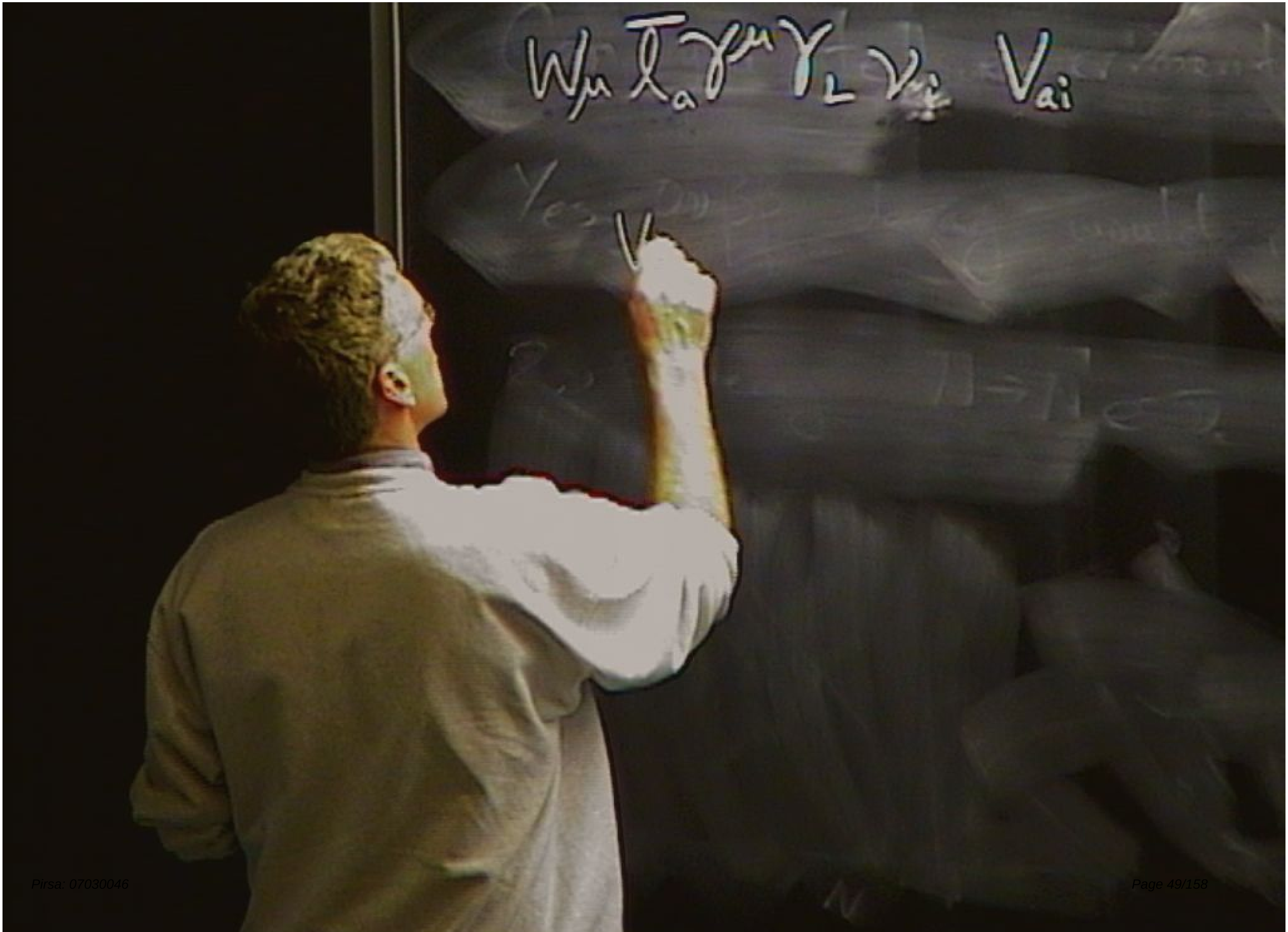
$$m_{ab} = \begin{cases} \dfrac{g_{ab}}{M} v^2 \\ y_{ai} M^{-1}_{ij} y_{bj} v^2 \end{cases}$$

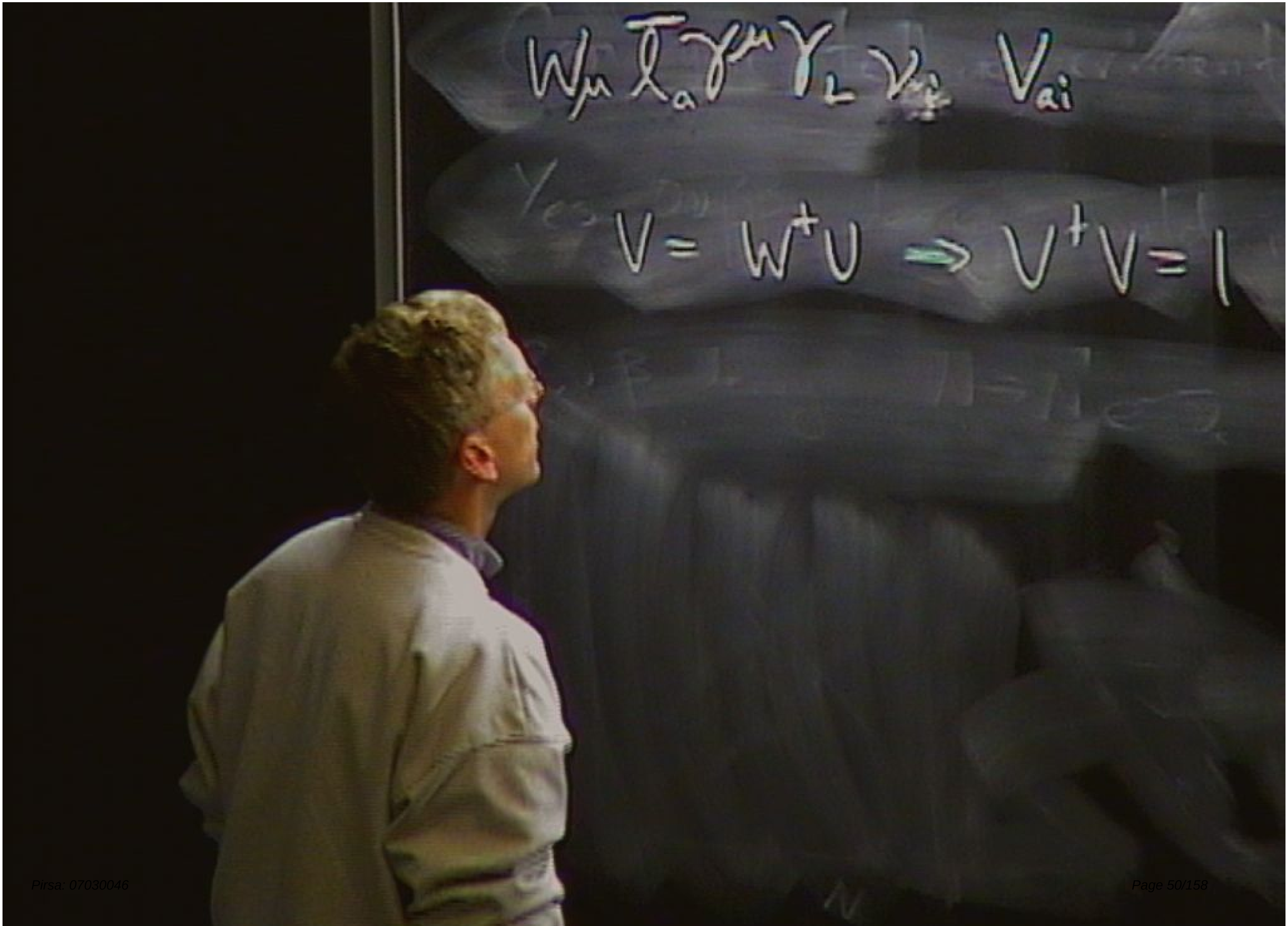
(preserve $\bar{\nu}_a \gamma \nu_a$)

$\cancel{K \to \mu^+ \mu^-}$

$Z \to e^+ \mu^-$

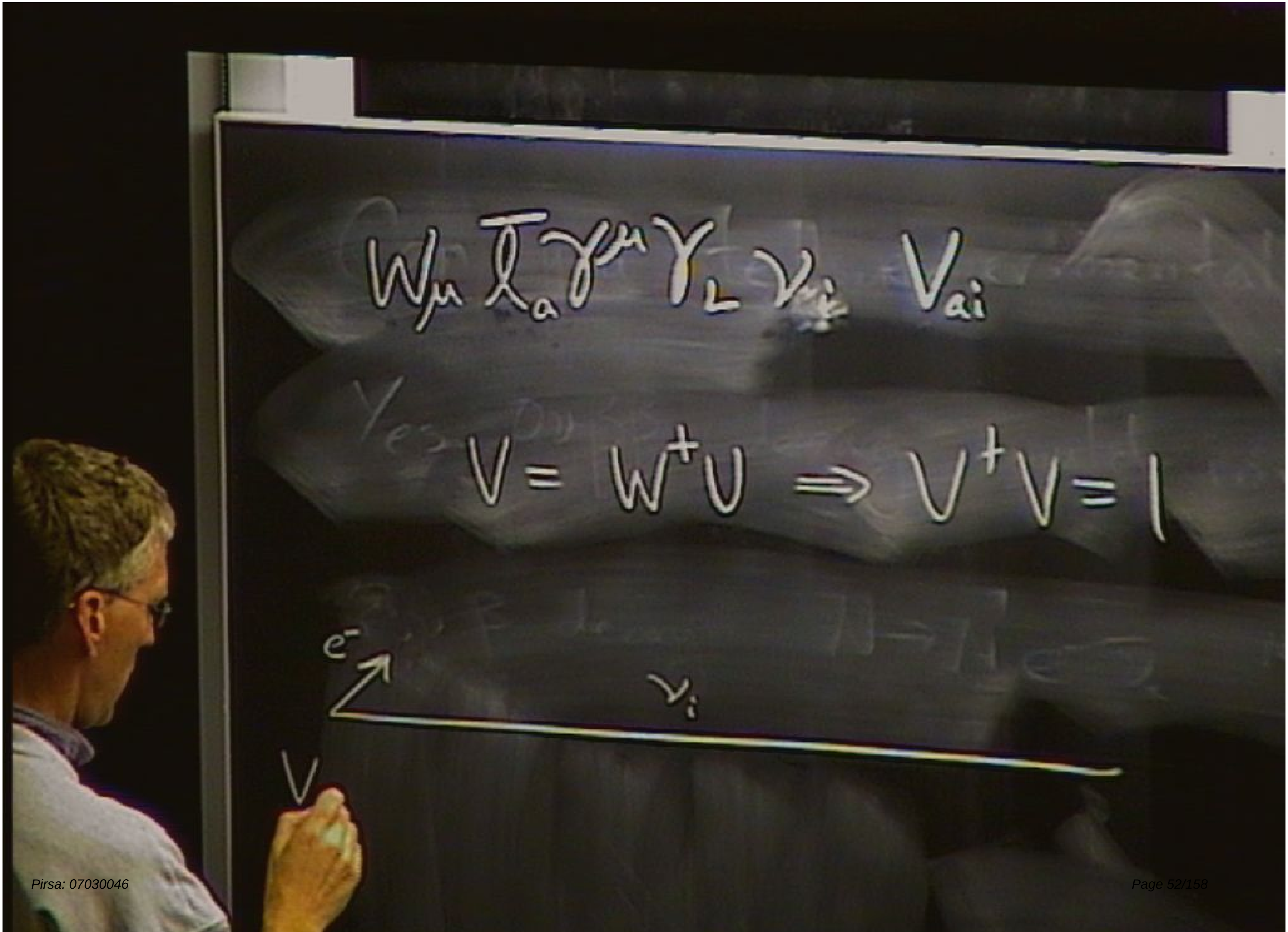

$W_\mu \bar{\ell}_a \gamma^\mu \gamma_L \nu_b$

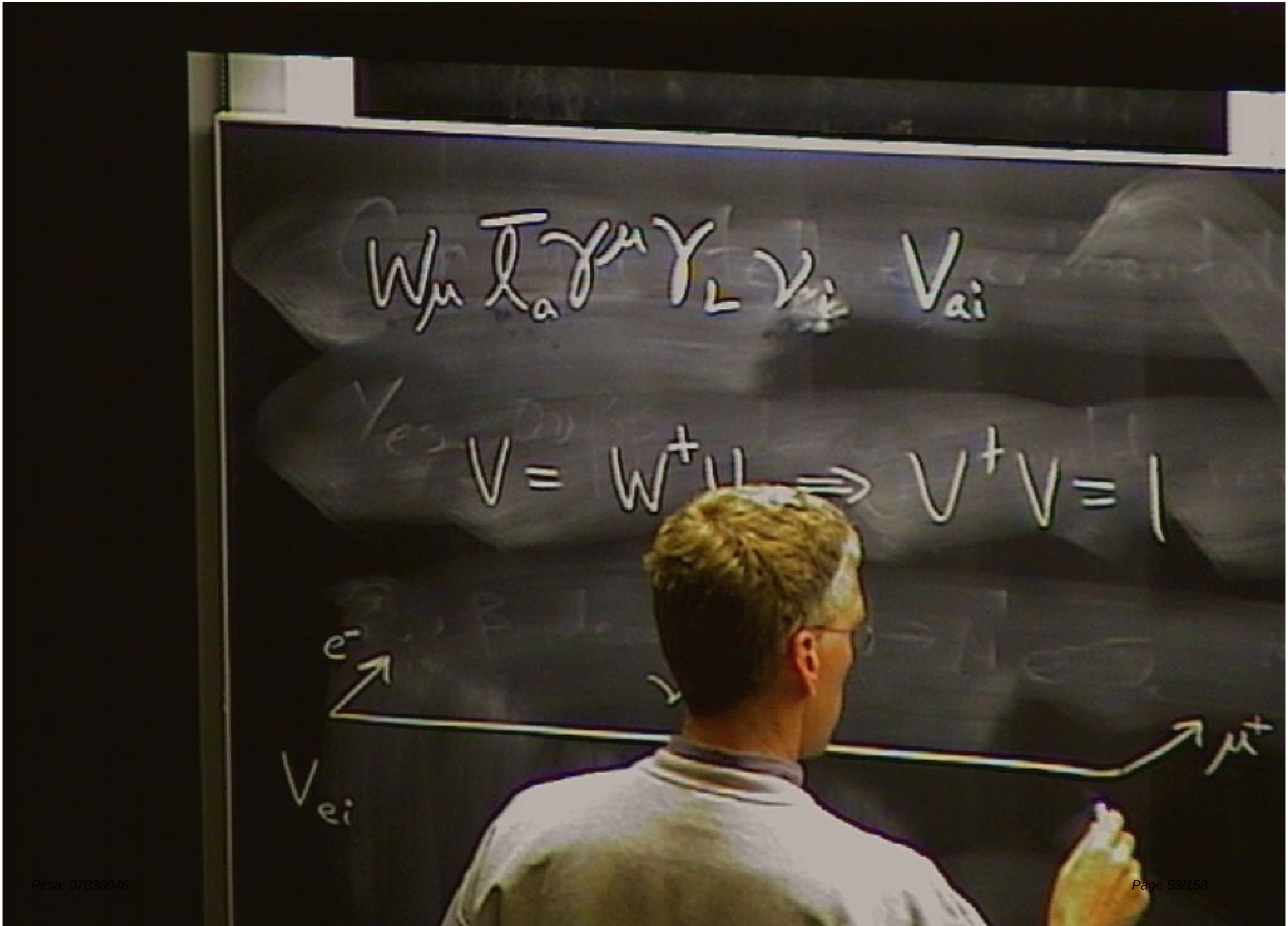

$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i$ V_{ai}

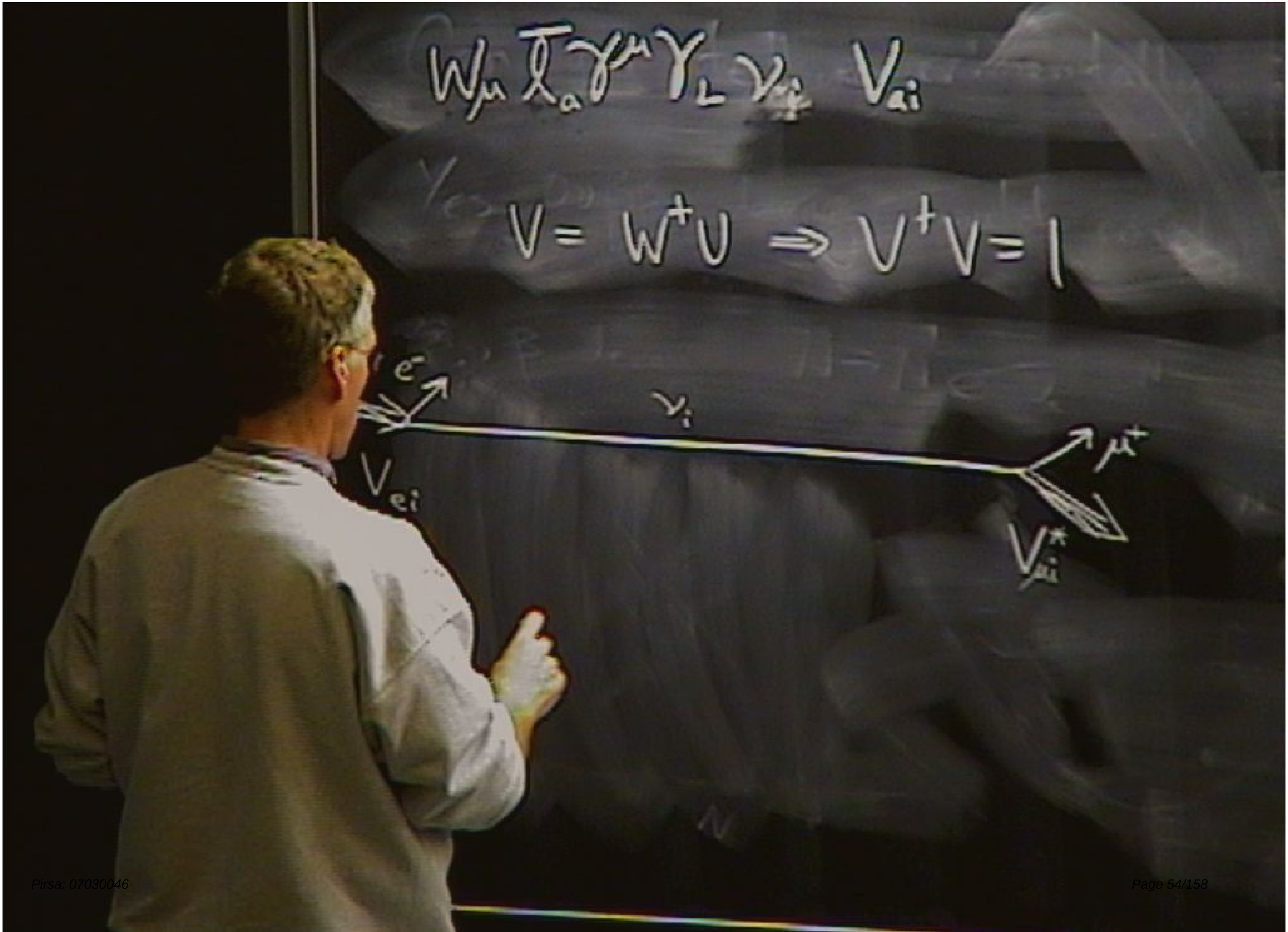

$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i \quad V_{ai}$
$V = W^\dagger U \Rightarrow V^\dagger V = 1$

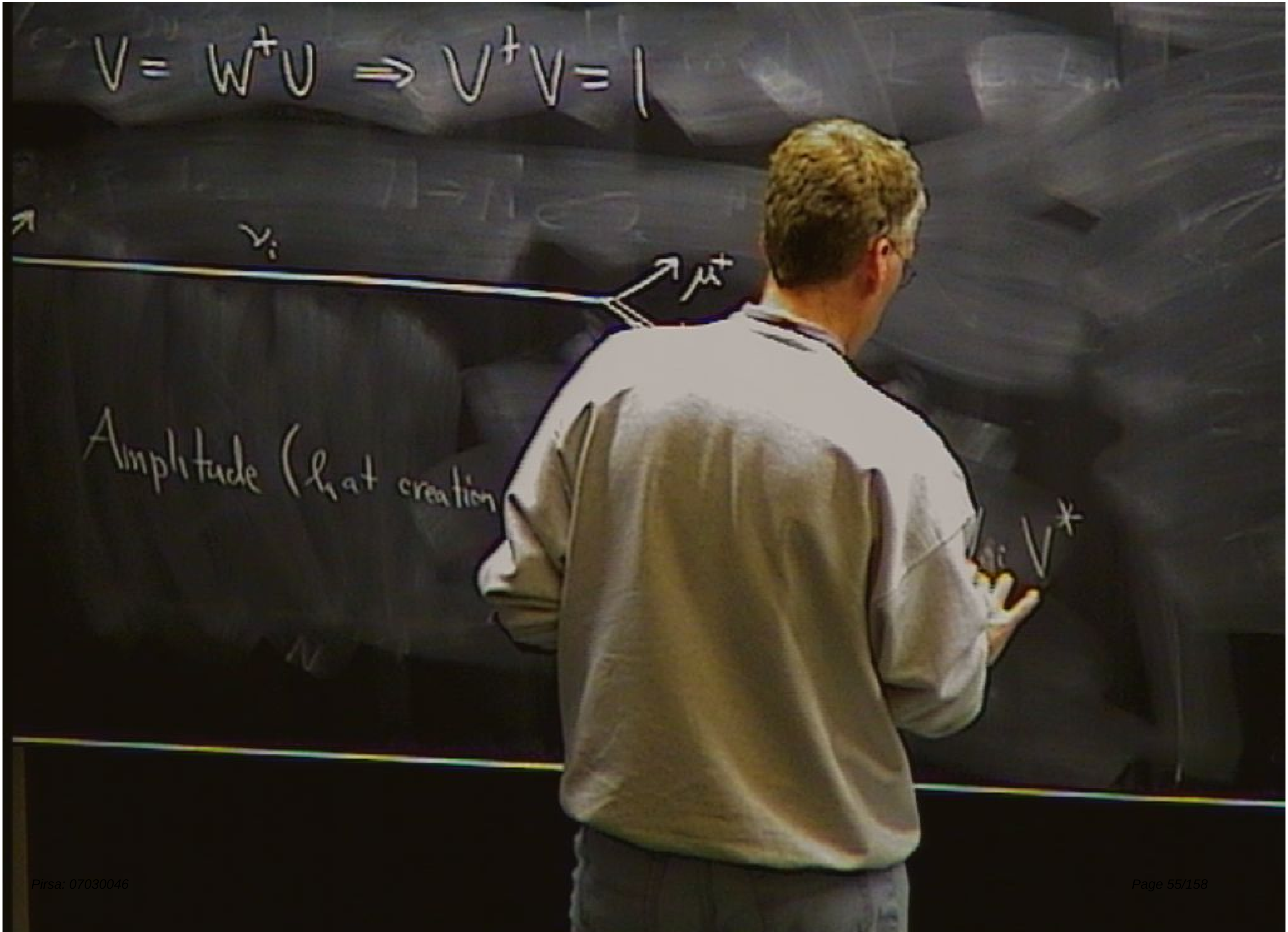
$$W_\mu \bar{\ell}_a \gamma^\mu \gamma_L \nu_i \quad V_{ai}$$

$$V = W^\dagger U \Rightarrow V^\dagger V = 1$$


$W_\mu \bar{\ell}_a \gamma^\mu \gamma_L \nu_i \quad V_{ai}$
$V = W^\dagger U \Rightarrow V^\dagger V = 1$
e^-
ν_i
V

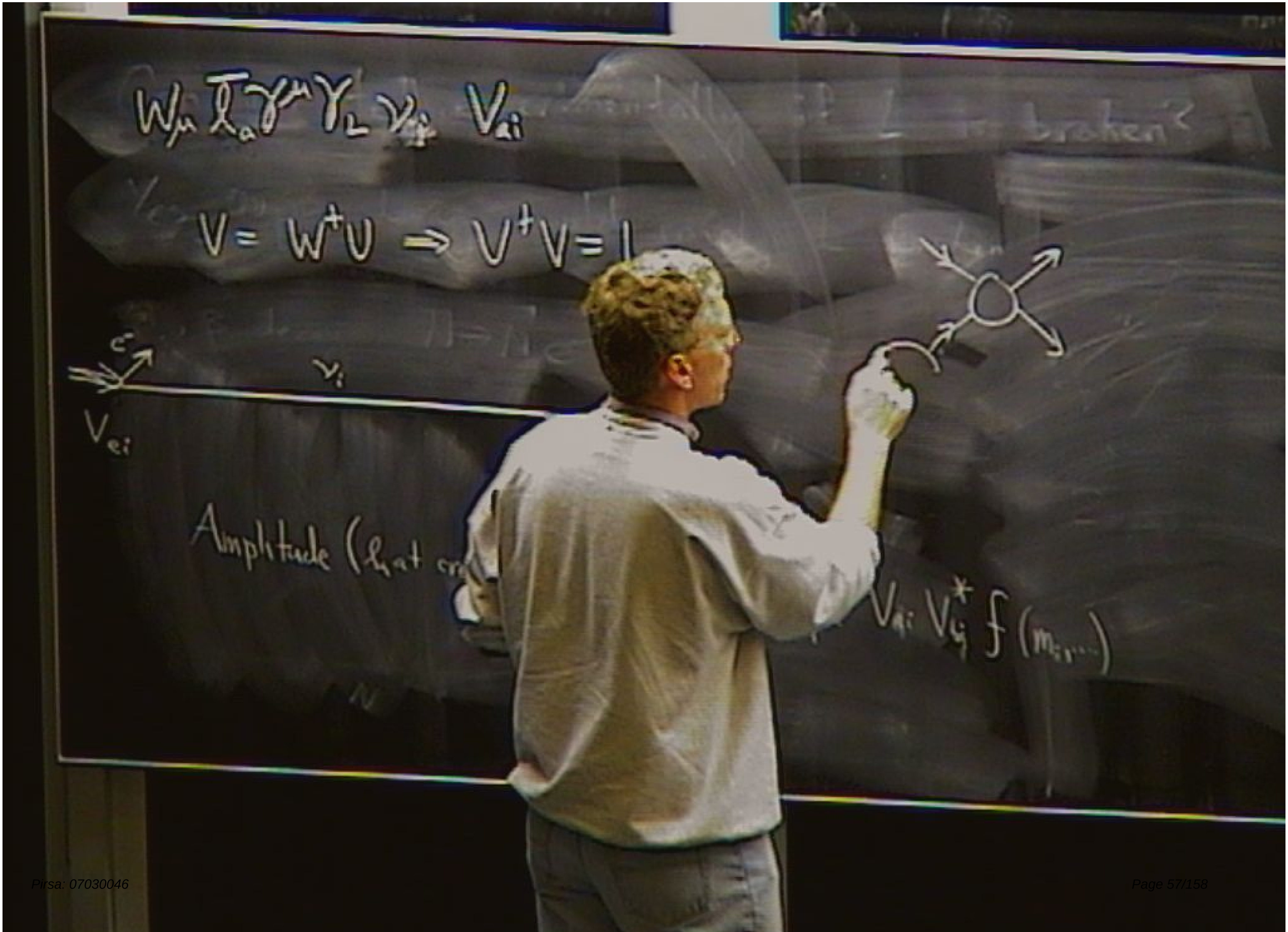

$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i \quad V_{ai}$
$V = W^\dagger U \Rightarrow V^\dagger V = 1$
e^-
μ^+
V_{ei}

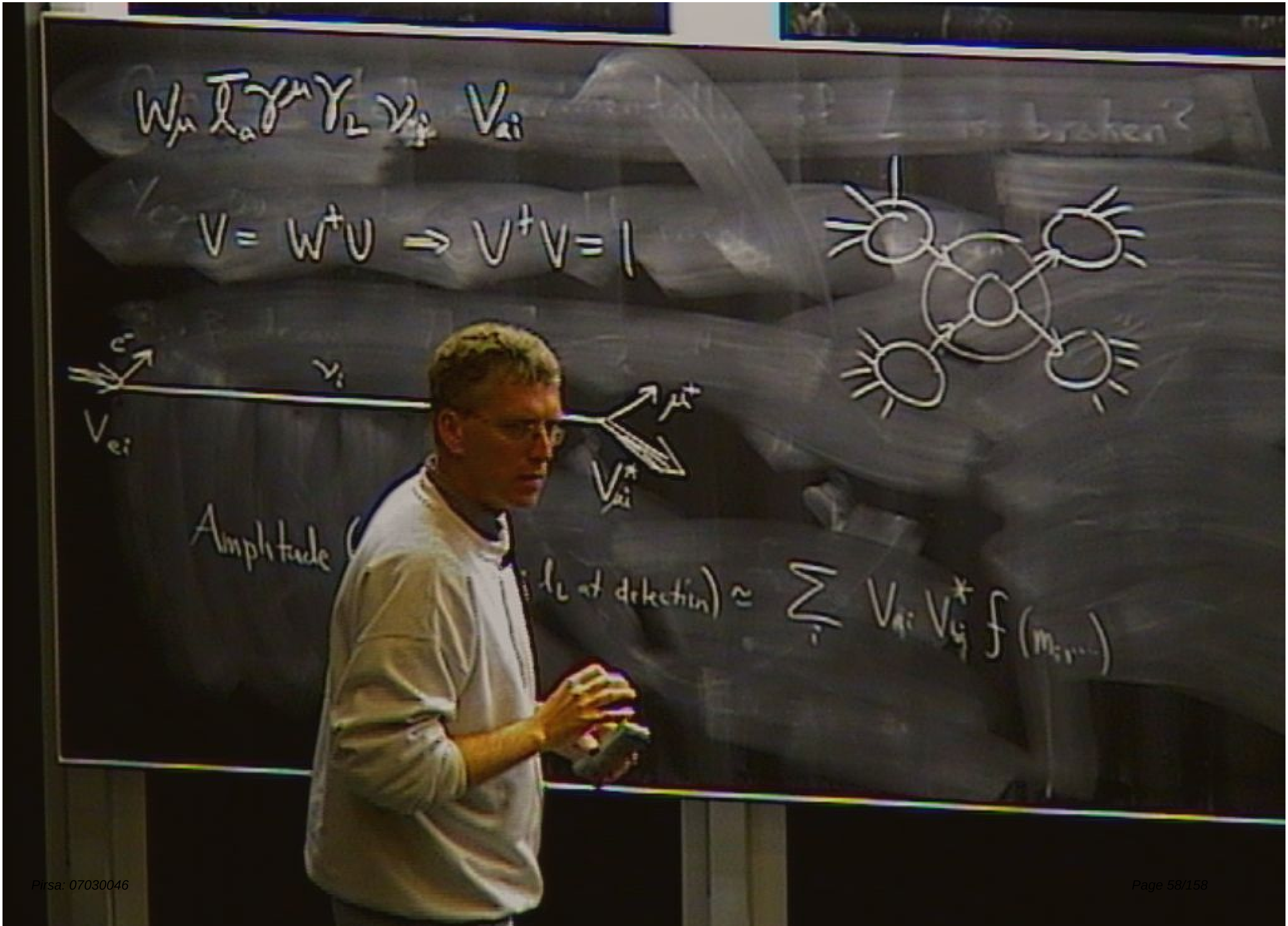

$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i \; V_{ai}$
$V = W^\dagger U \Rightarrow V^\dagger V = 1$
e^-
ν_i
μ^+
V_{ei}
$V^*_{\mu i}$

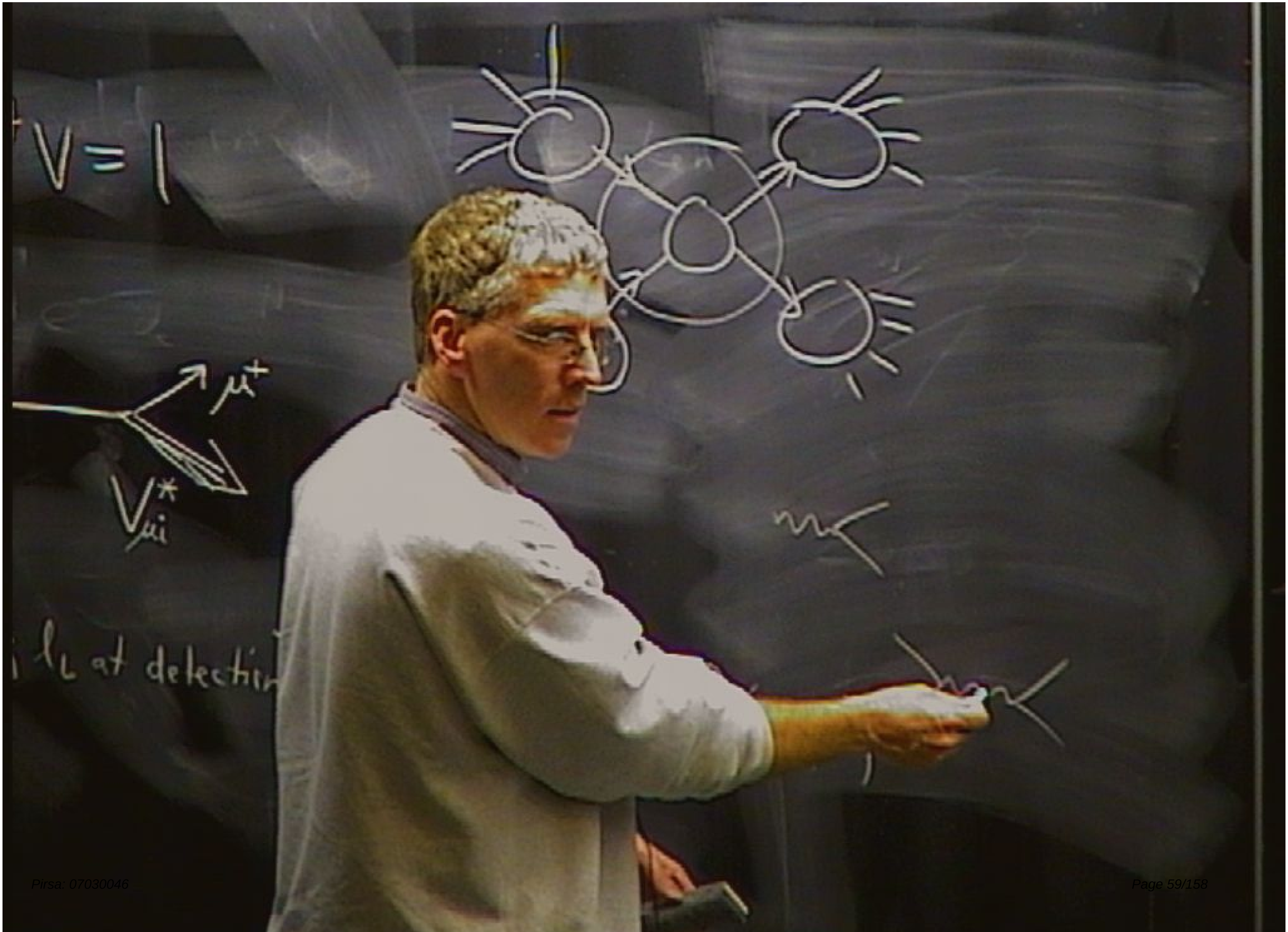

V = W+U ⇒ V+V = 1
ν_i
μ+
Amplitude (hat creation
V*

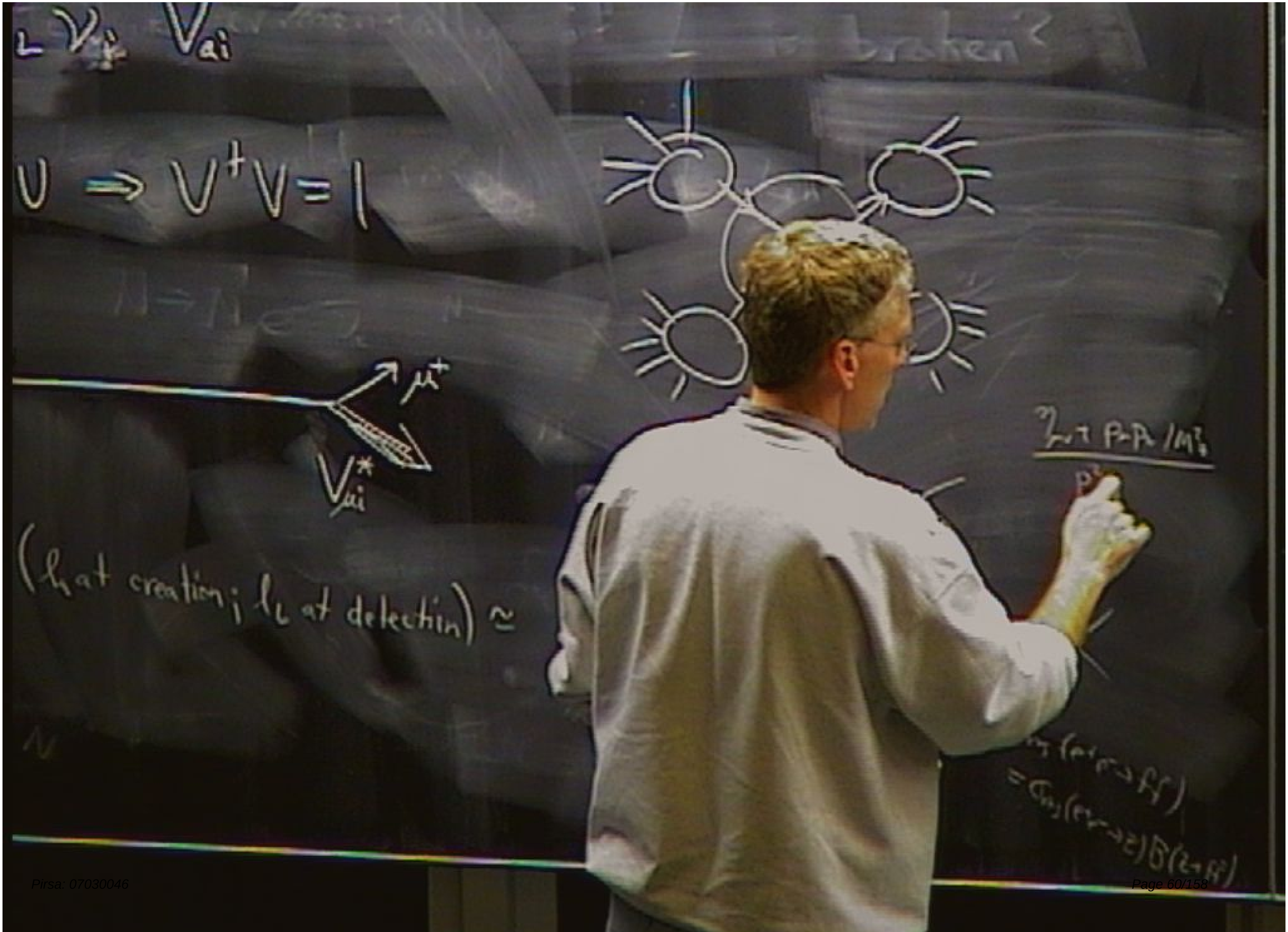
$$V = W^{\dagger} U \Rightarrow V^{\dagger} V = 1$$

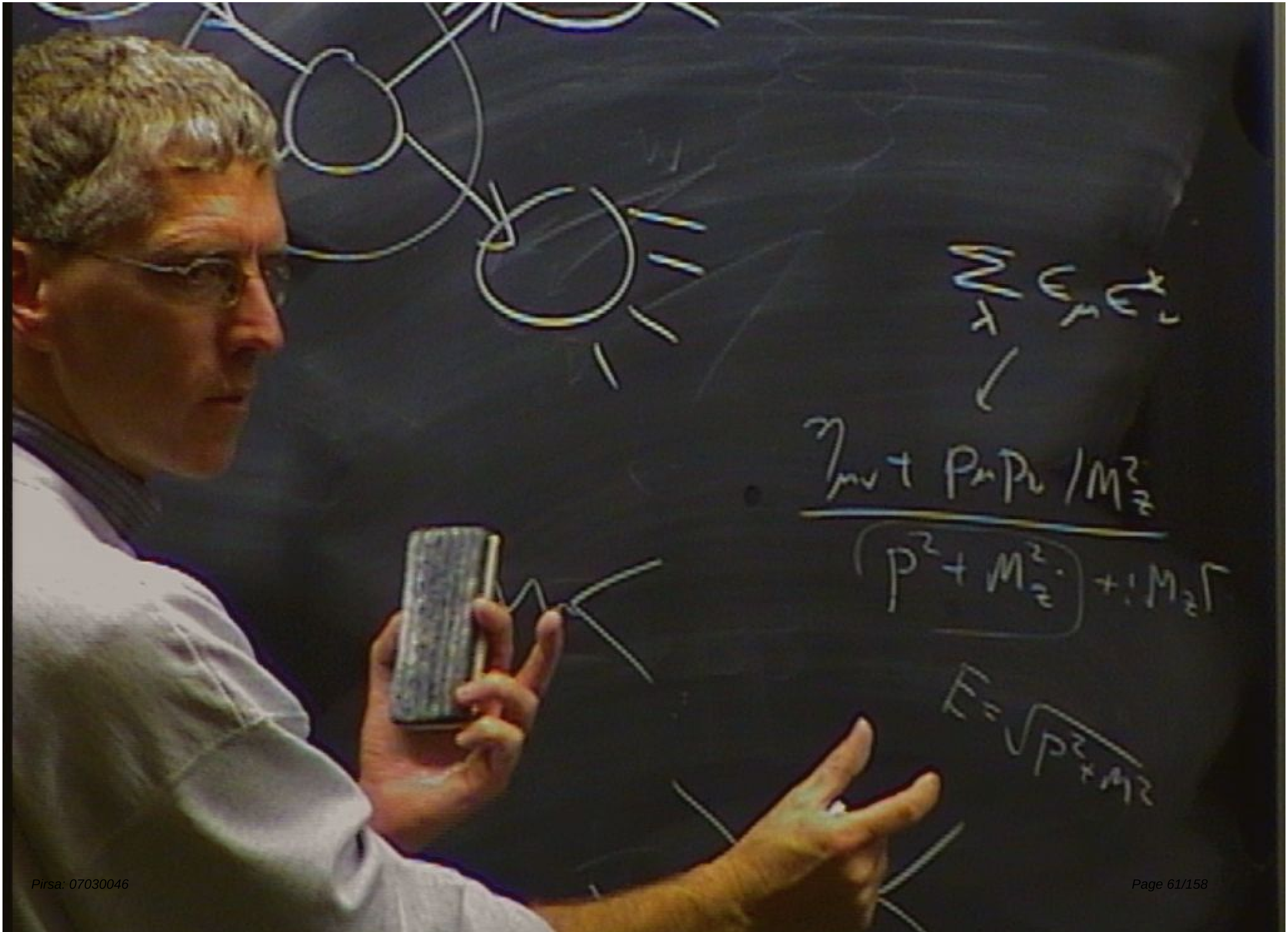
$$\text{Amplitude}\,(l_\alpha \text{ at creation; } l_\beta \text{ at detection}) \simeq \sum_i V_{\alpha i} V^*_{\beta i}\, f(m_i, \ldots)$$

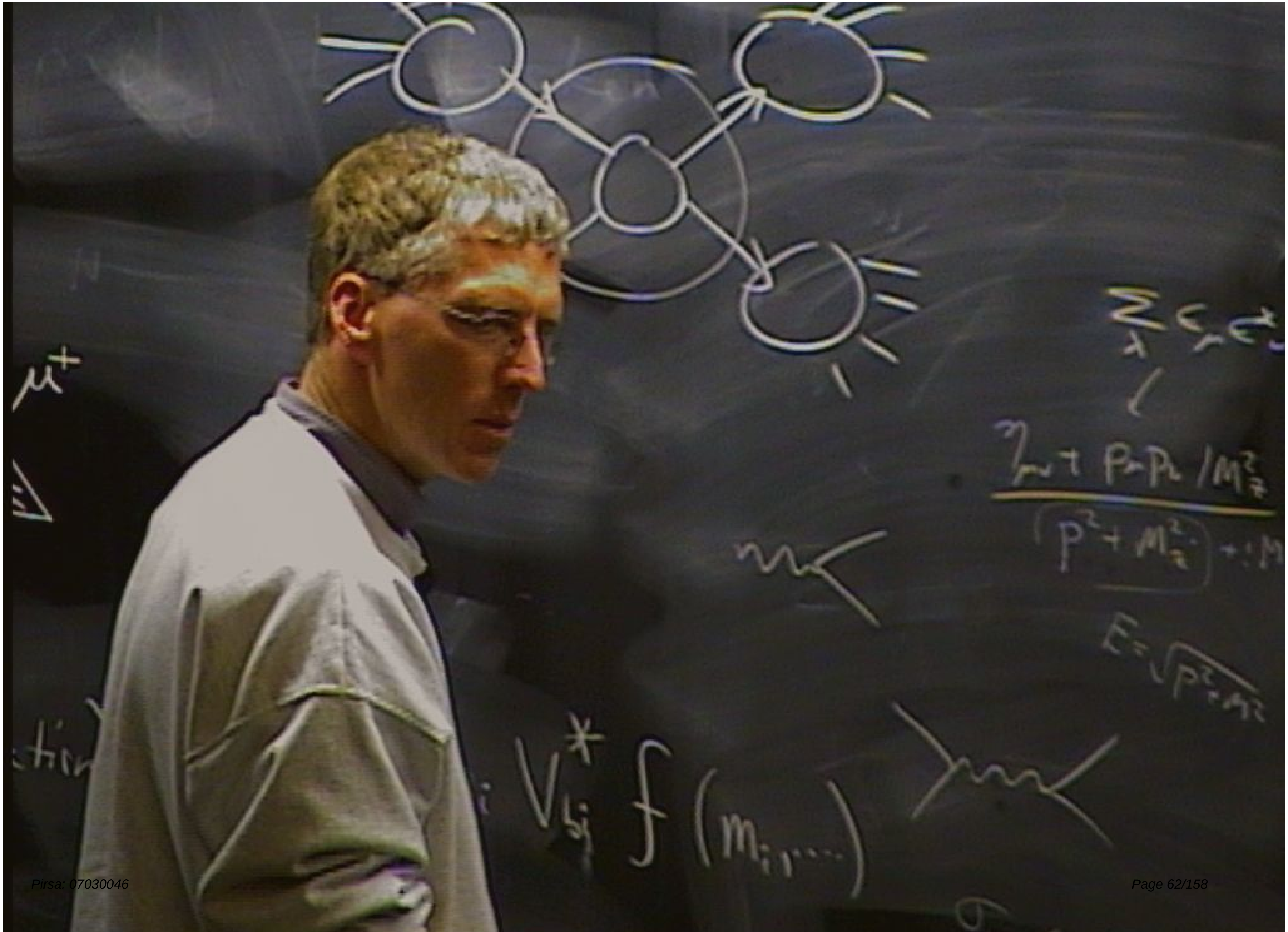

$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i \quad V_{ai}$
broken
$V = W^\dagger U \Rightarrow V^\dagger V = 1$
e
ν_i
V_{ei}
Amplitude
$V_{ai} V^*_{ij} f(m_i, \ldots)$

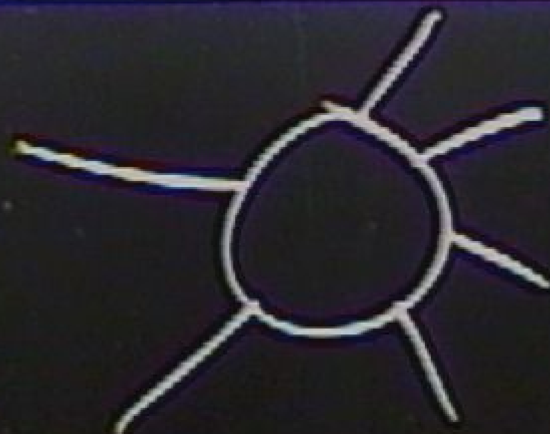

$W_\mu \bar{l}_a \gamma^\mu \gamma_L \nu_i \quad V_{ai}$
broken?
$V = W^\dagger U \Rightarrow V^\dagger V = 1$
e^-
ν_i
V_{ei}
μ^+
$V^*_{\mu i}$
Amplitude (
l_L at detection) $\simeq \sum_i V_{ai} V^*_{bi} f(m_i, \ldots)$


V = 1
μ^+
$V^*_{\mu i}$
l_L at detection


V_ai
U ⇒ V†V = 1
μ+
V*μi
(l_a at creation; l_L at detection) ≈

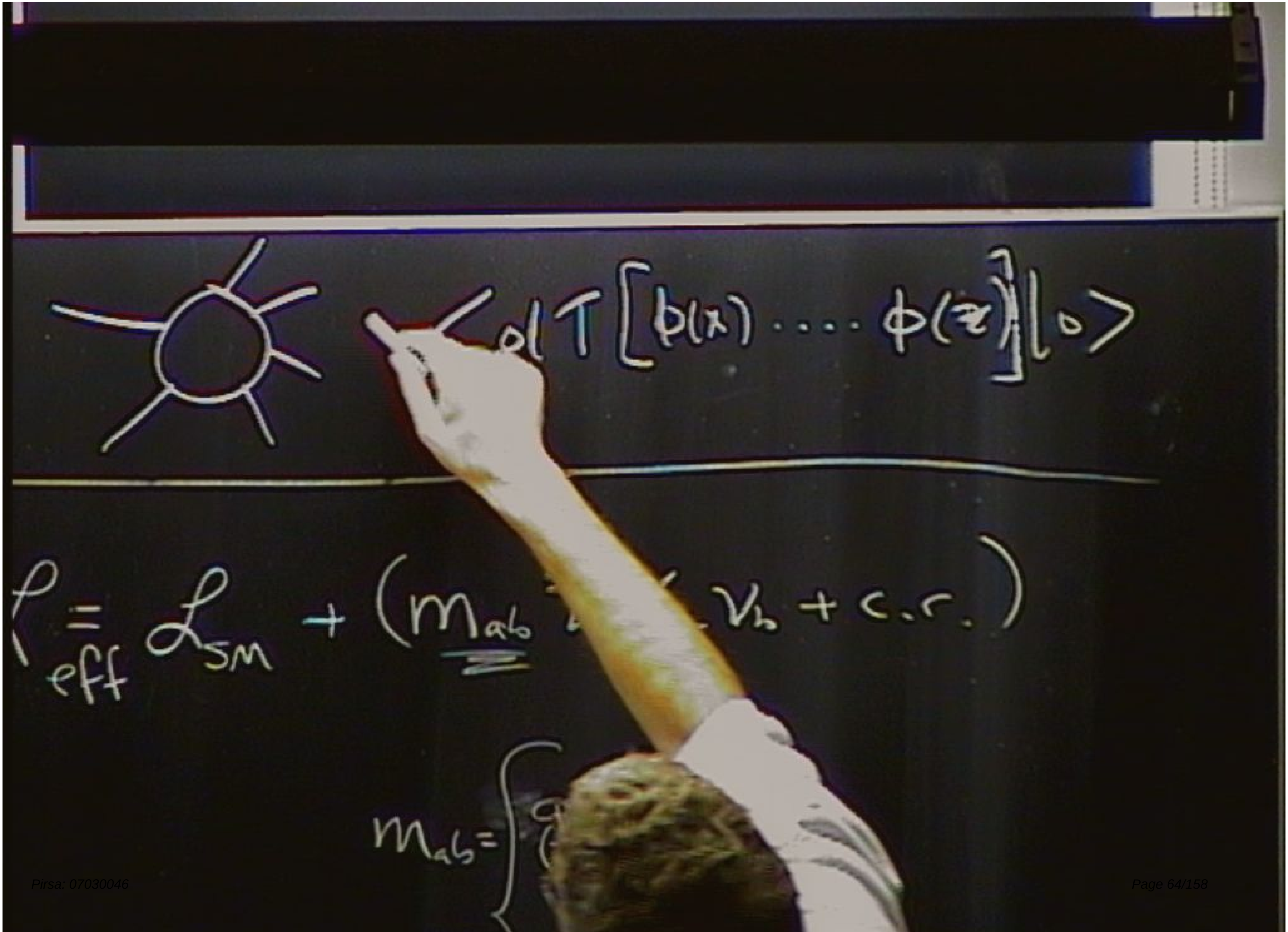

$\sum_\lambda \epsilon_\mu \epsilon^*_\nu$
$\eta_{\mu\nu} + p_\mu p_\nu / M_Z^2$
$p^2 + M_Z^2 + i M_Z \Gamma$
$E = \sqrt{p^2 + M_Z^2}$

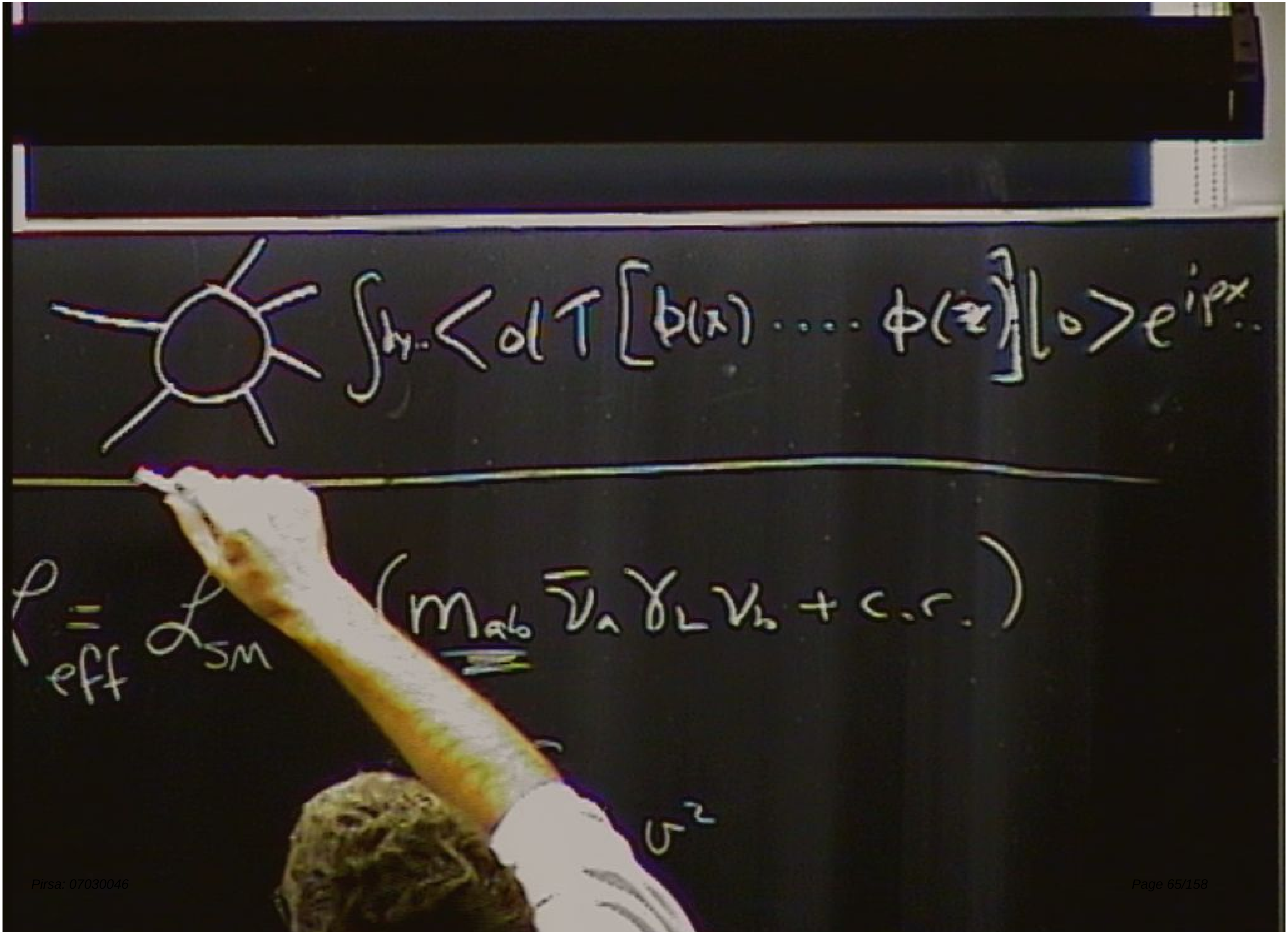




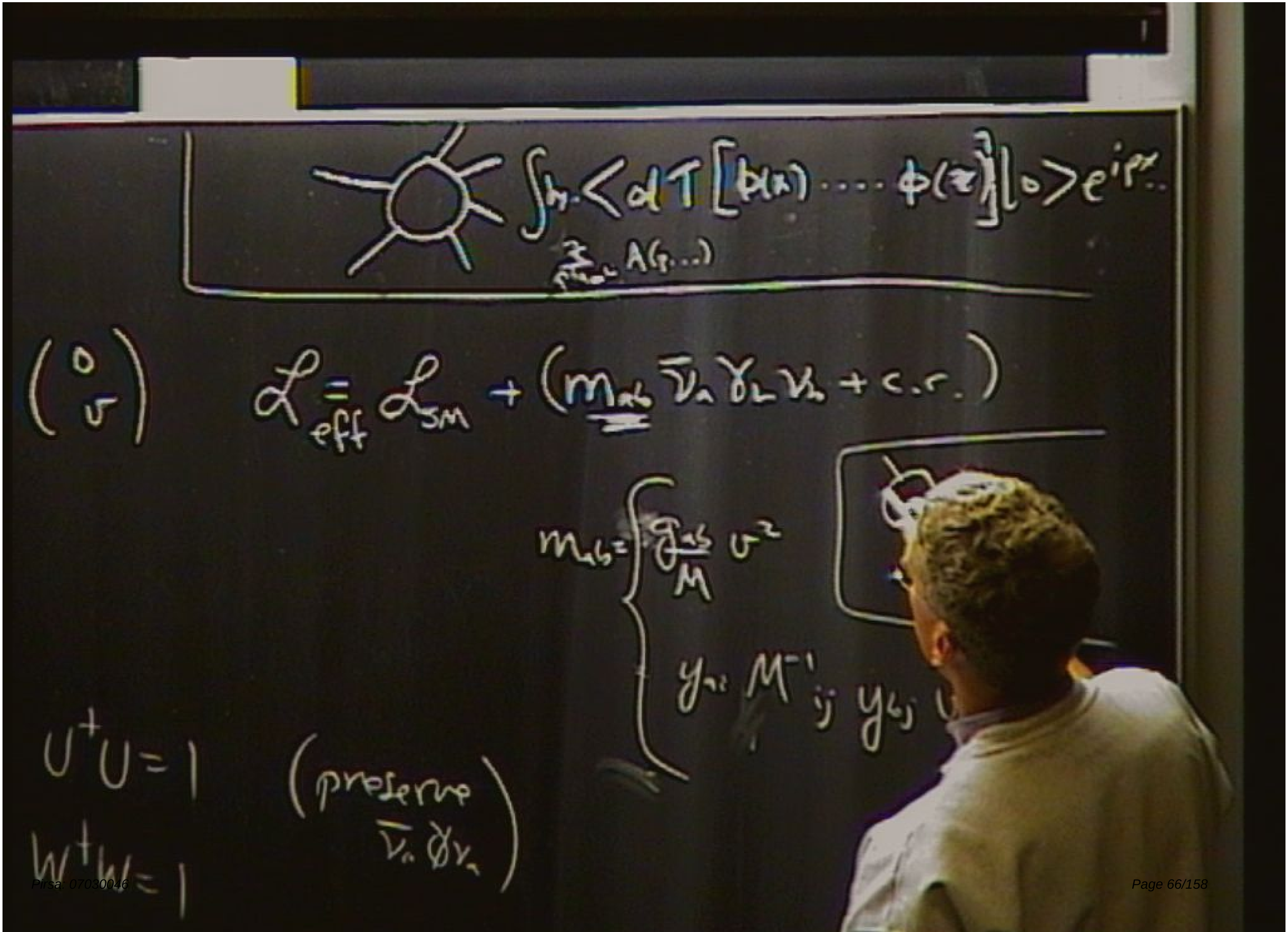
$\langle 0 | T [\phi(x) \cdots$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \left(\underline{m_{ab}} \, \bar{\nu}_a \gamma_L \nu_b + \right.$$


$\langle 0| T[\phi(x) \cdots \phi(z)]|0\rangle$
$\mathcal{L}_{eff} = \mathcal{L}_{SM} + (m_{ab}$
$\nu_b + c.c.)$
$m_{ab} =$



$\int dy \ldots \langle 0 | T [\phi(x) \ldots\ldots \phi(z)] | 0 \rangle e^{ipx} \ldots$
$\mathcal{L}_{eff} = \mathcal{L}_{SM}$ $(m_{ab} \bar{\nu}_a \gamma_L \nu_b + c.c.)$
v^2



$\int d^4x \langle \alpha | T[\phi(x) \cdots \phi(z)] |0\rangle e^{ipx}$
$\begin{pmatrix}0\\ v\end{pmatrix}$
$\mathcal{L}_{eff} = \mathcal{L}_{SM} + (m_{ab} \bar{\nu}_a \gamma_L \nu_b + c.c.)$
$m_{ab} = \frac{g_{ab}}{M} v^2$
$y_{ai} M^{-1}_{ij} y_{bj}$
$U^\dagger U = 1$
$W^\dagger W = 1$
(preserve $\bar{\nu}_a \not\partial \nu_a$)

 $\int d^4x \langle \alpha | T[\phi(x) \cdots \phi(z)] |0\rangle e^{ipx}\ldots$

$A(g,\ldots)$

$\begin{pmatrix} 0 \\ v \end{pmatrix}$

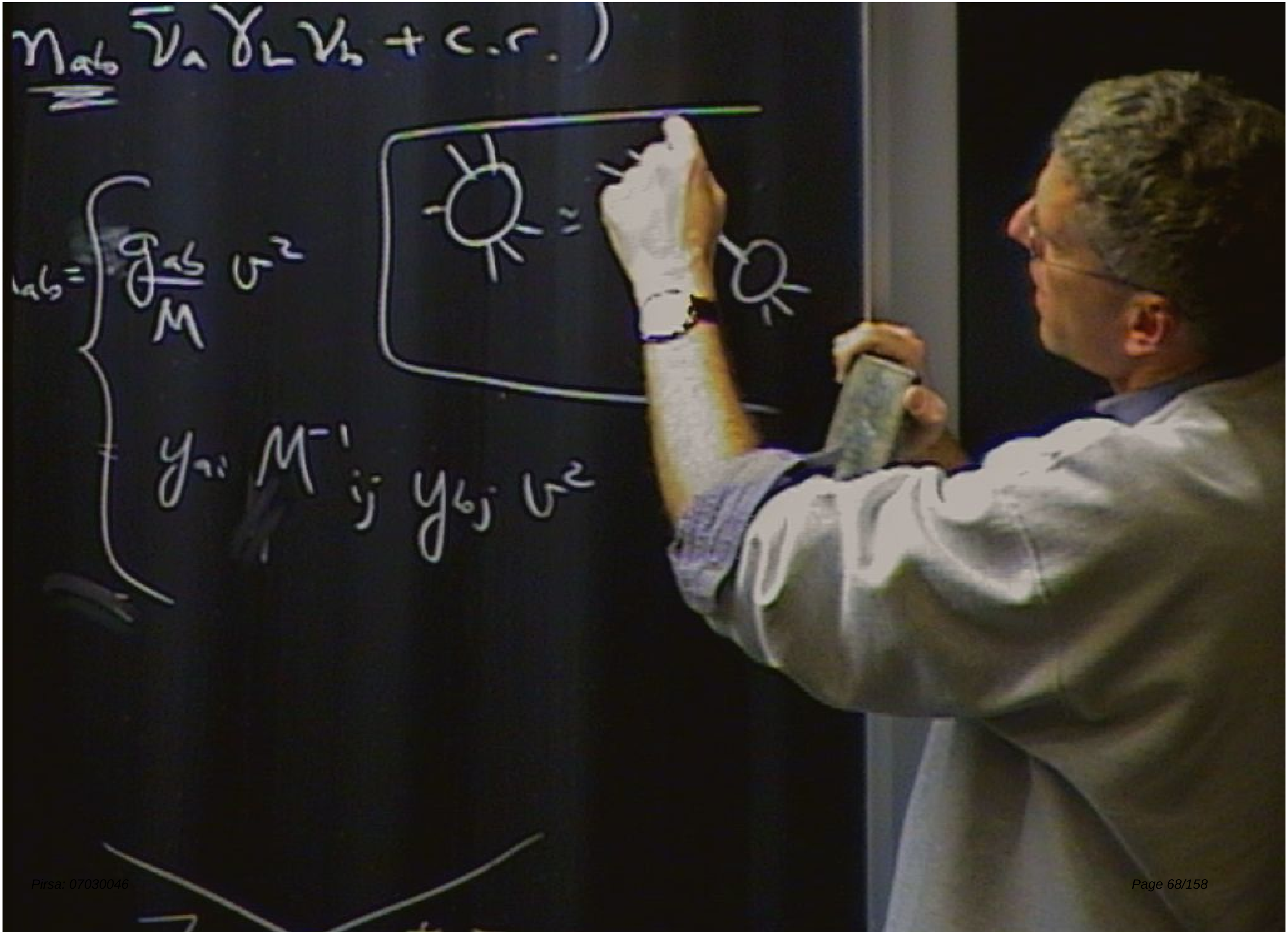
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + (m_{ab}\,\bar{\nu}_a \gamma_L \nu_b + c.c.)$$

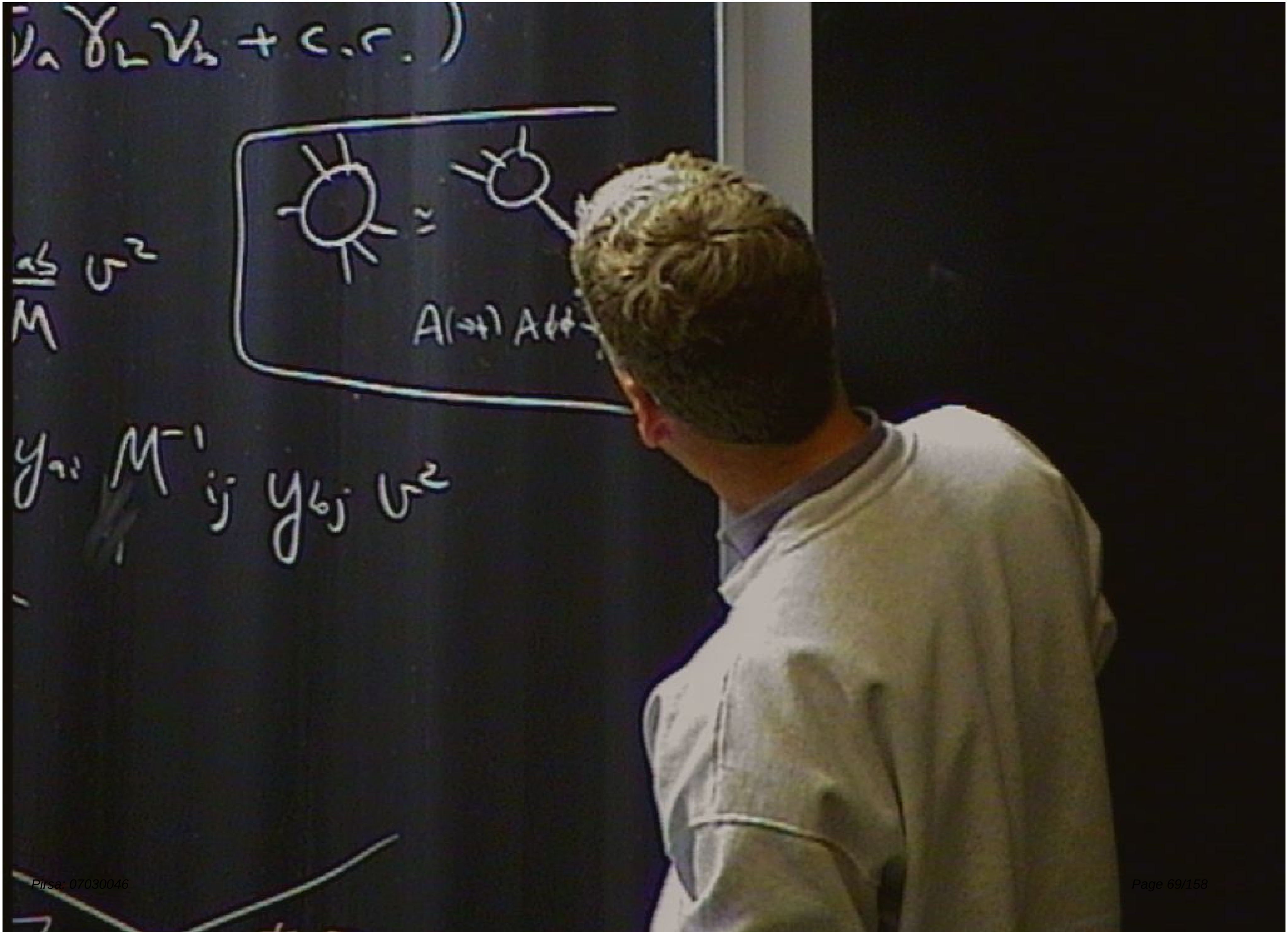
$$m_{ab} = \begin{cases} \frac{g_{ab}}{M} v^2 \\ y_{ai} M^{-1}_{ij} y_{bj} v^2 \end{cases}$$

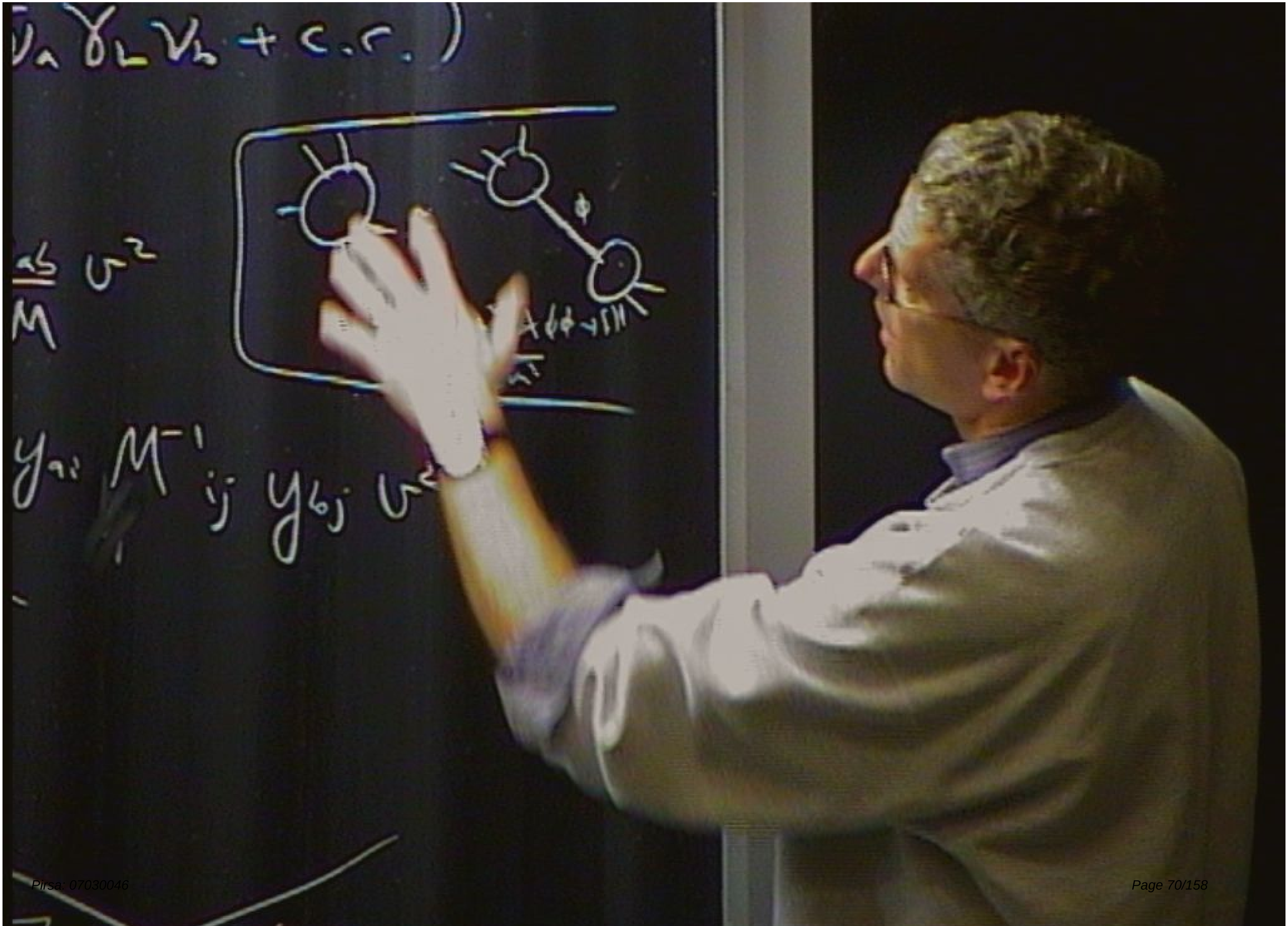
$U^\dagger U = 1$

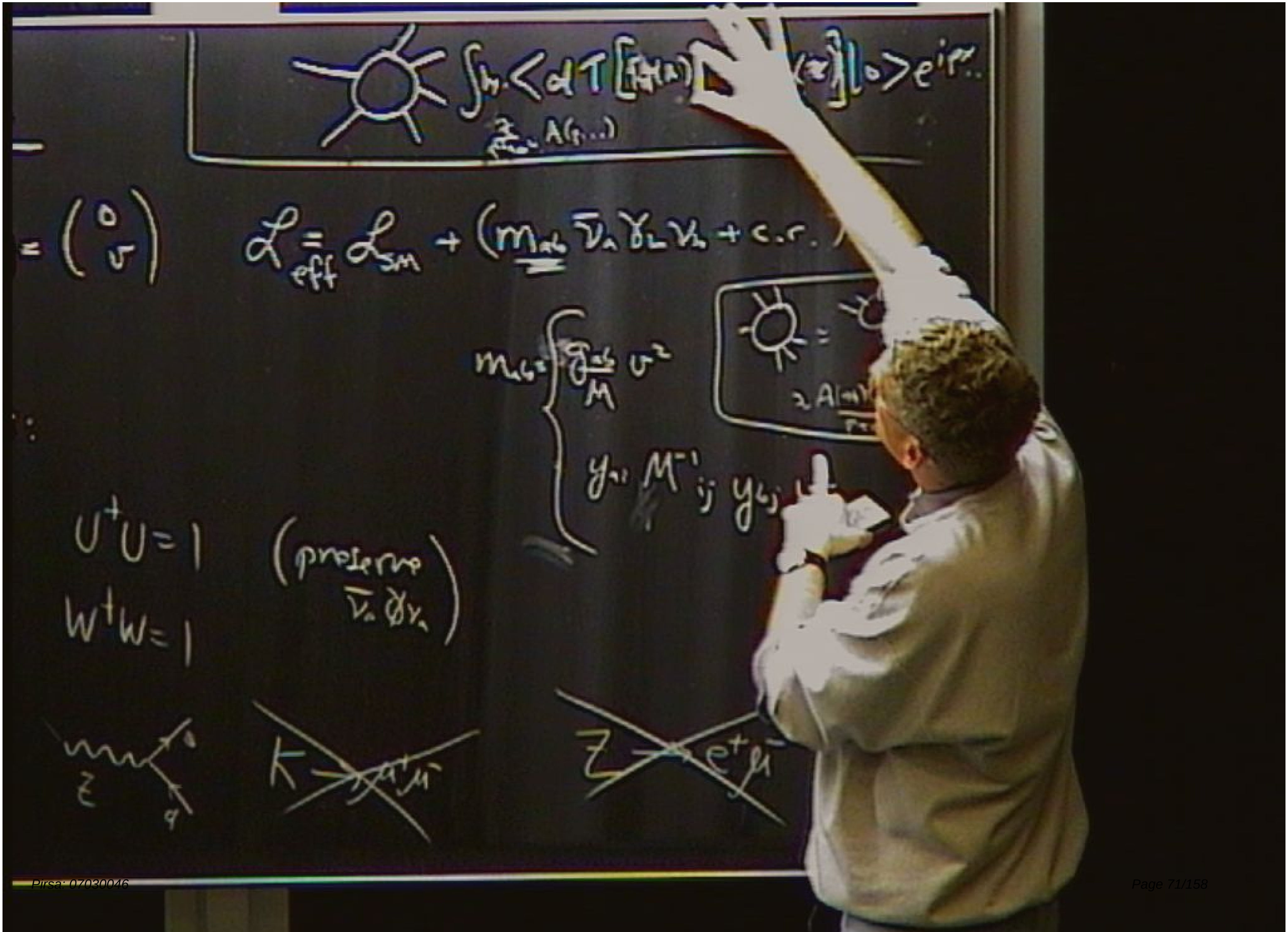
$W^\dagger W = 1$

(preserve $\bar{\nu}_a \not{\partial} \nu_a$)


$m_{ab}\bar{\nu}_a\gamma_L\nu_b + c.c.)$
$m_{ab} = \frac{g_{ab}}{M}v^2$
$= y_{ai}M^{-1}_{ij}y_{bj}v^2$






$U^\dagger U = 1$
$W^\dagger W = 1$
(preserve

$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \left(\underline{m_{ab}}\, \bar{\nu}_a \gamma_L \nu_b + c.c. \right)$

$$m_{ab} = \begin{cases} \dfrac{g_{ab}}{M} v^2 \\ = y_{ai}\, M^{-1}_{ij}\, y_{bj}\, v^2 \end{cases}$$

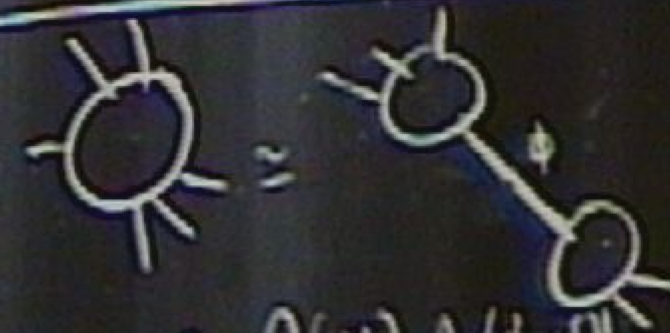
$\approx \dfrac{A(\to\phi)\, A(\phi \ldots)}{p^2 - m^2}$

reserve

$\bar{\nu}_a \not\partial \nu_a$

$$\ldots f \quad \mathcal{L}_{SM} + \left(\underline{m_{ab}}\,\bar{\nu}_a \gamma_L \nu_b + c.c.\right)$$

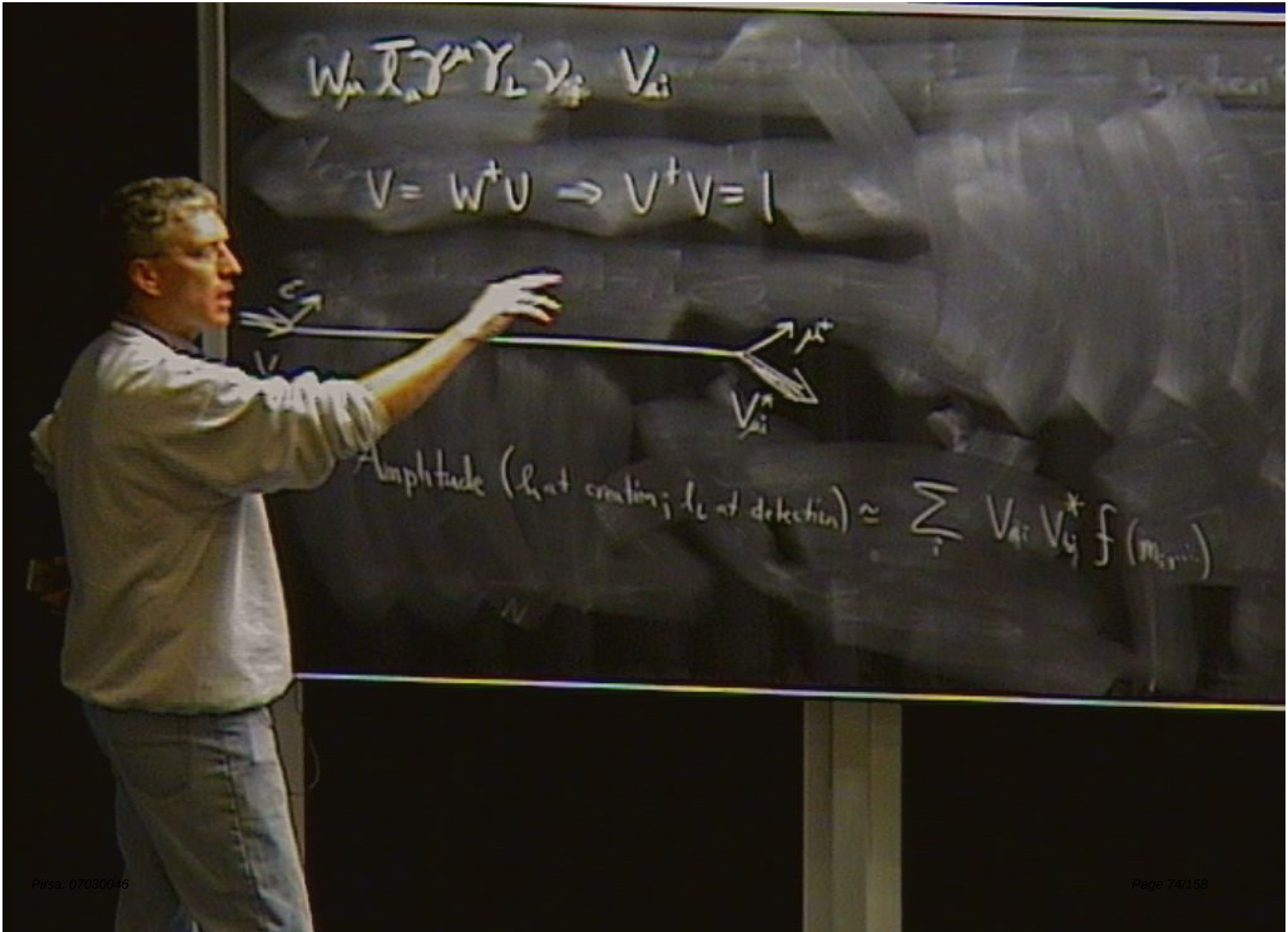
$$m_{ab} = \begin{cases} \dfrac{g_{ab}}{M}\, v^2 \\[2ex] y_{ai}\, M^{-1}_{ij}\, y_{bj}\, v^2 \end{cases}$$

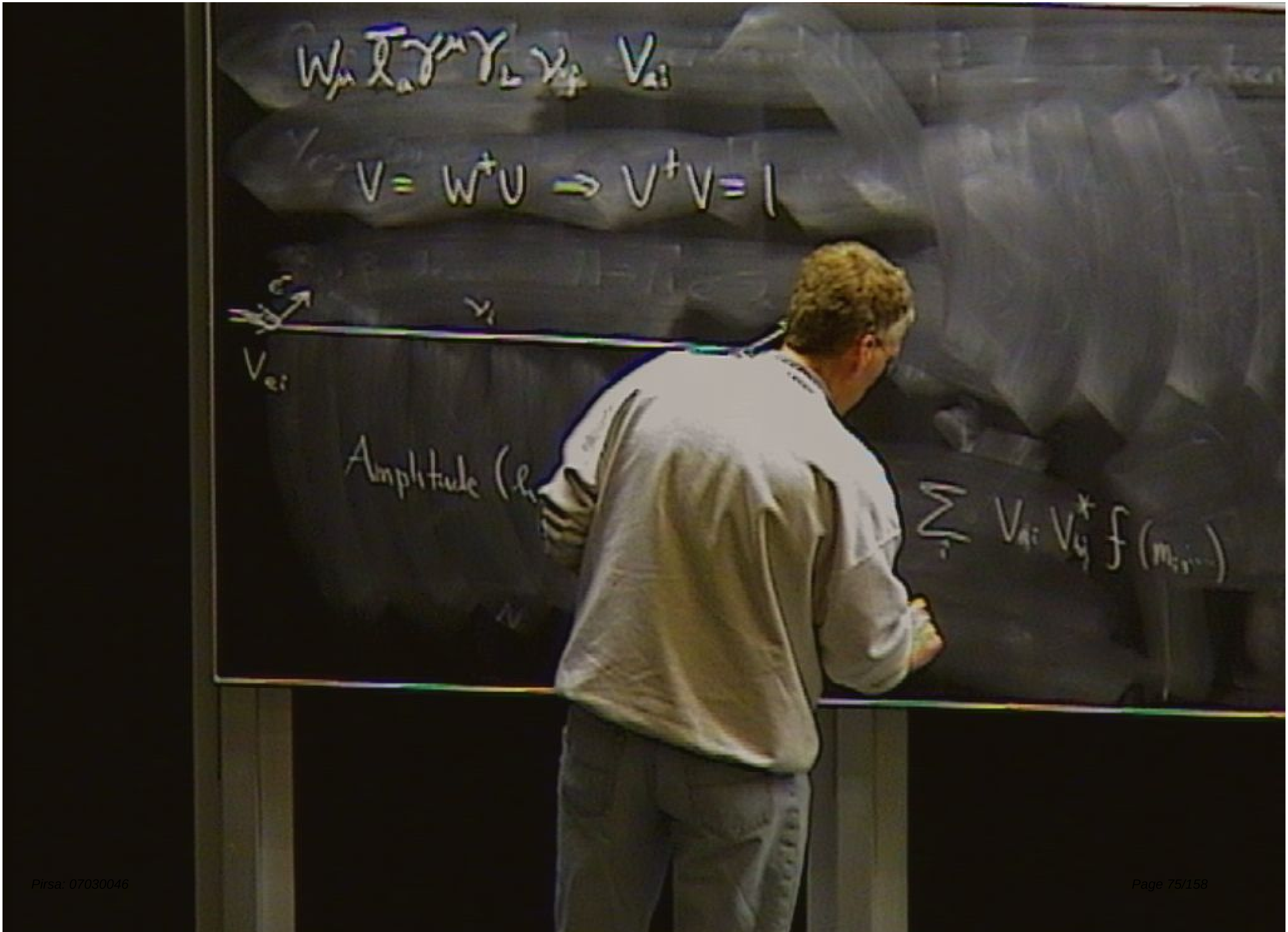


$$\approx \frac{A(\to\phi)\,A(\phi\to SM)}{p^2+m^2}$$

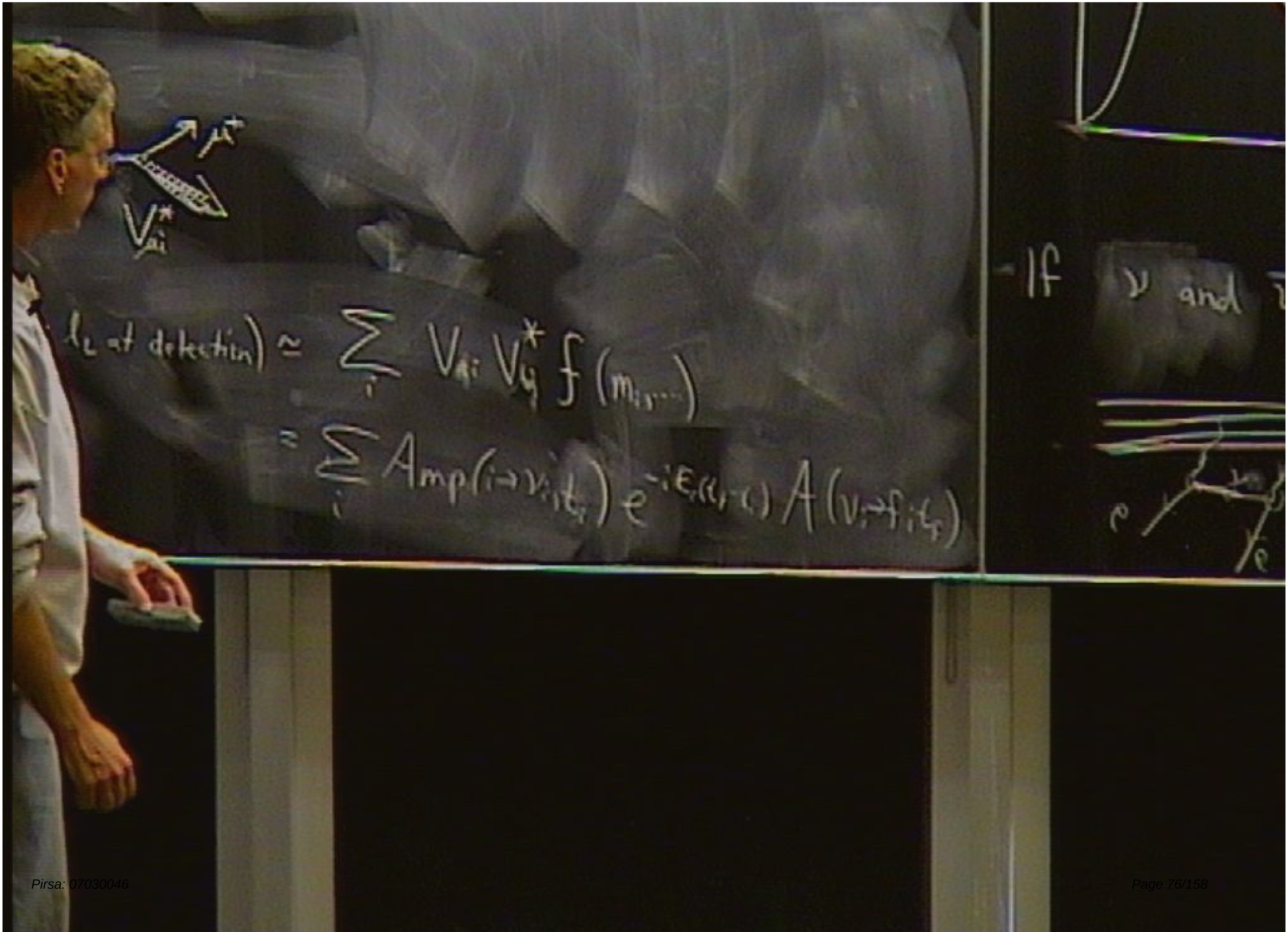
reference

$\bar{\nu}_a \not{\partial} \nu_a$

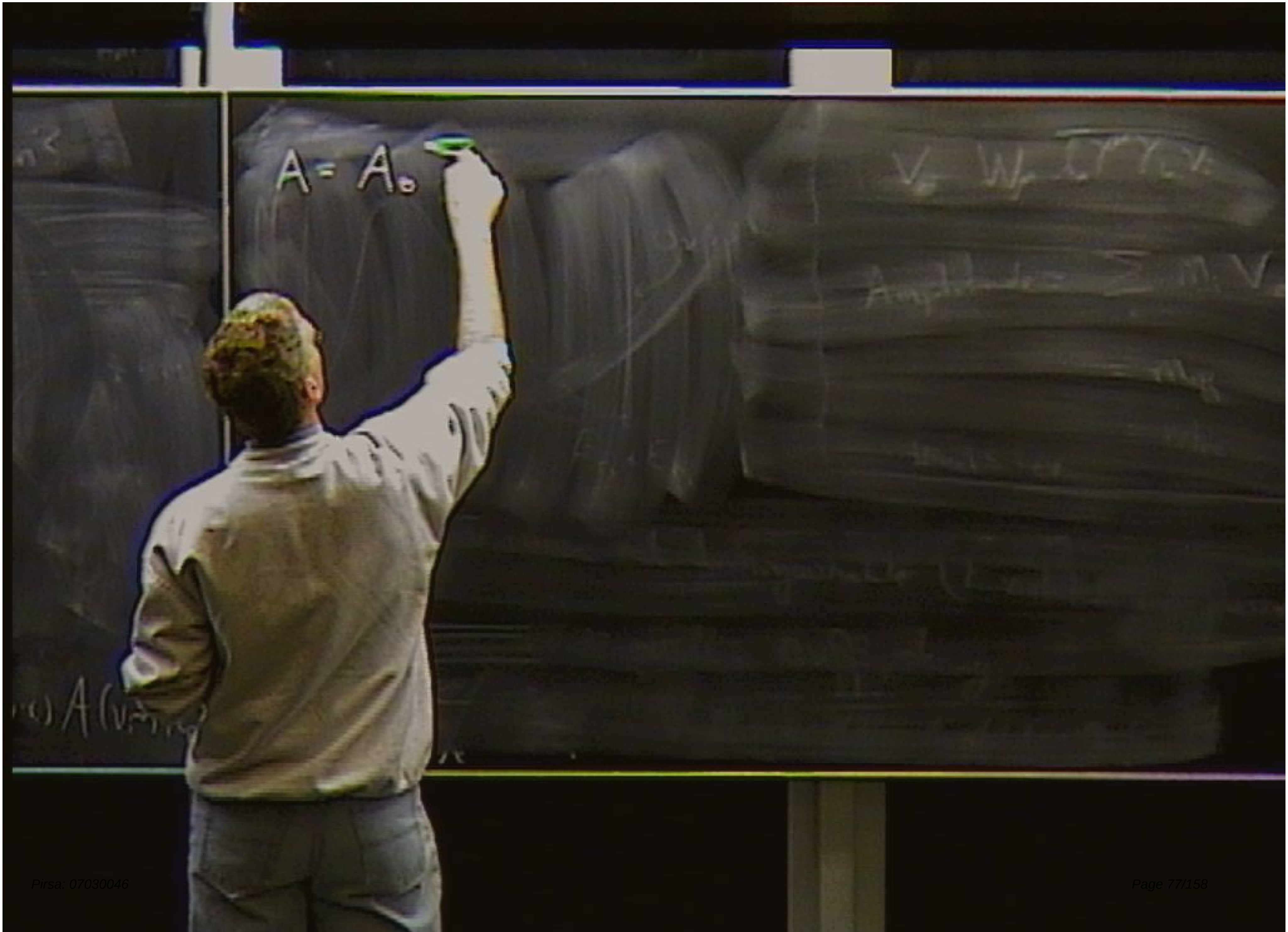

V = W†U ⇒ V†V = 1
Amplitude (ℓα at creation; ℓβ at detection) ≈ ∑i Vαi V*βi f(mi, ...)

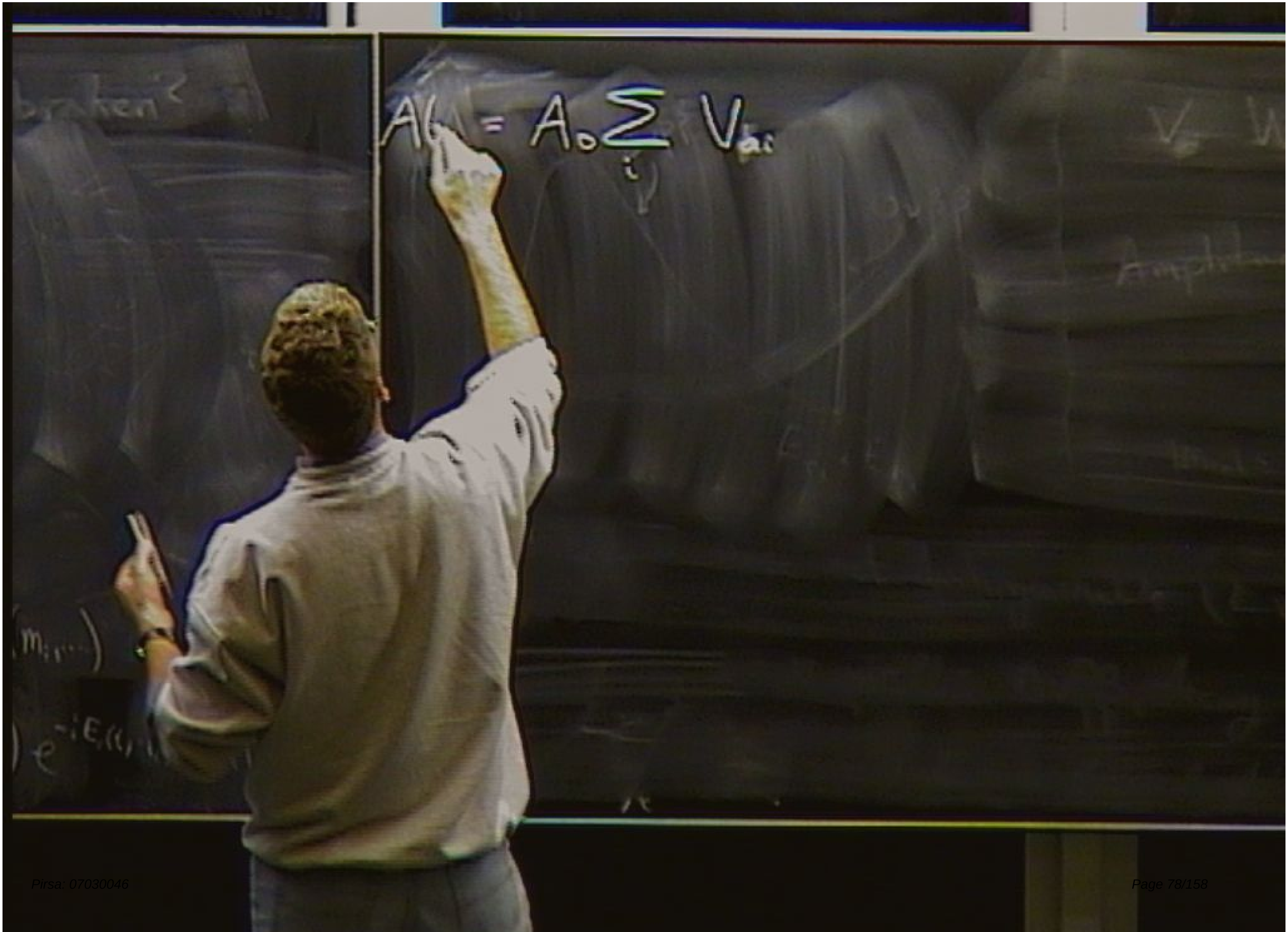


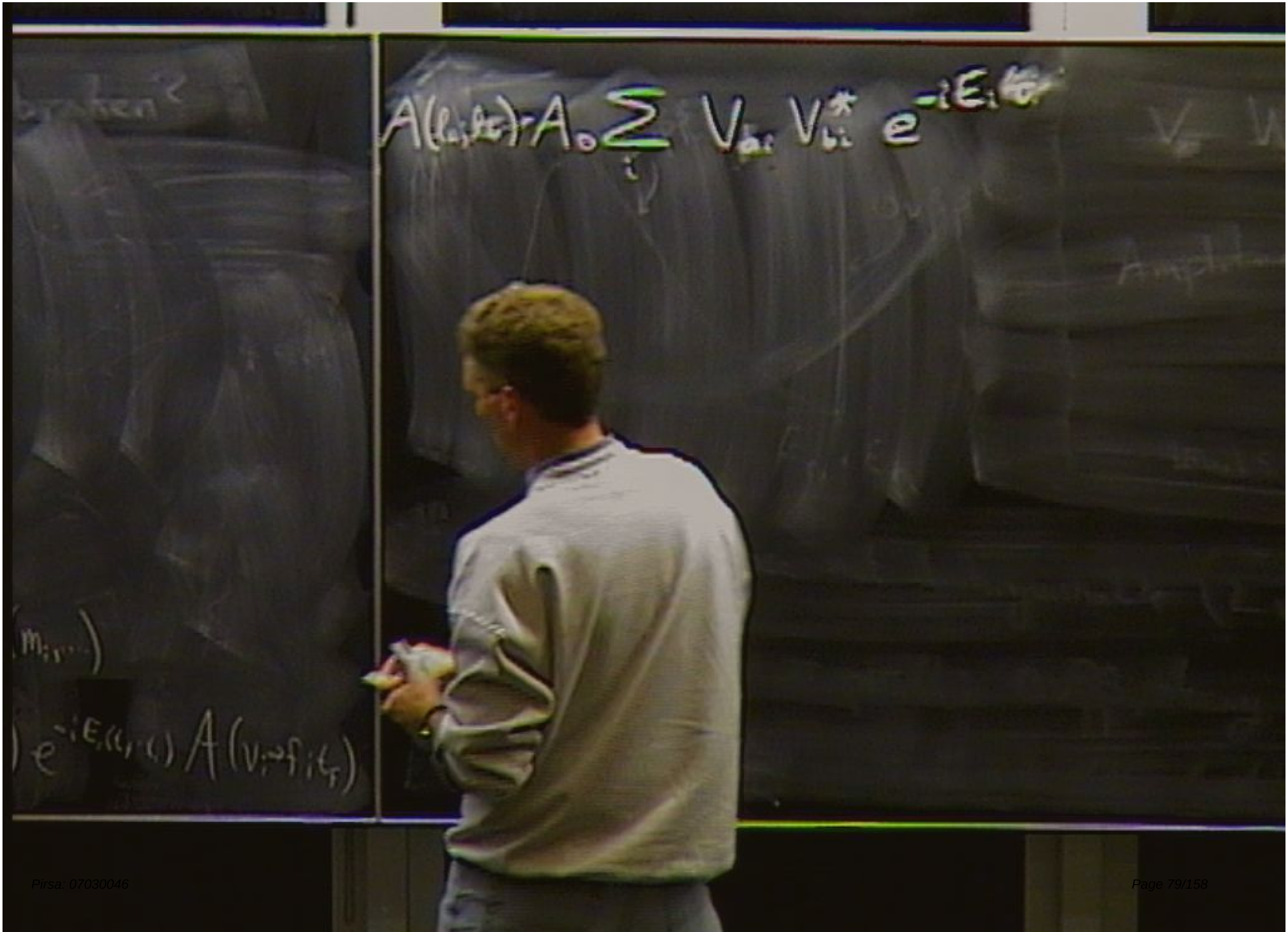
$W_\mu \bar{\ell}_a \gamma^\mu \gamma_L \nu_{i} \; V_{ai}$
$V = W^\dagger U \Rightarrow V^\dagger V = 1$
V_{ei}
Amplitude (
$\sum_i V_{ai} V^*_{bi} f(m_i, \ldots)$



μ^+
$V^*_{\mu i}$
ℓ_L at detection) $\simeq \sum_i V_{\ell i} V^*_{\ell i} f(m_i, \ldots)$
$= \sum_i Amp(i \to \nu_i; t_i)\, e^{-iE_i(t_f - t_i)} A(\nu_i \to f; t_f)$
If ν and

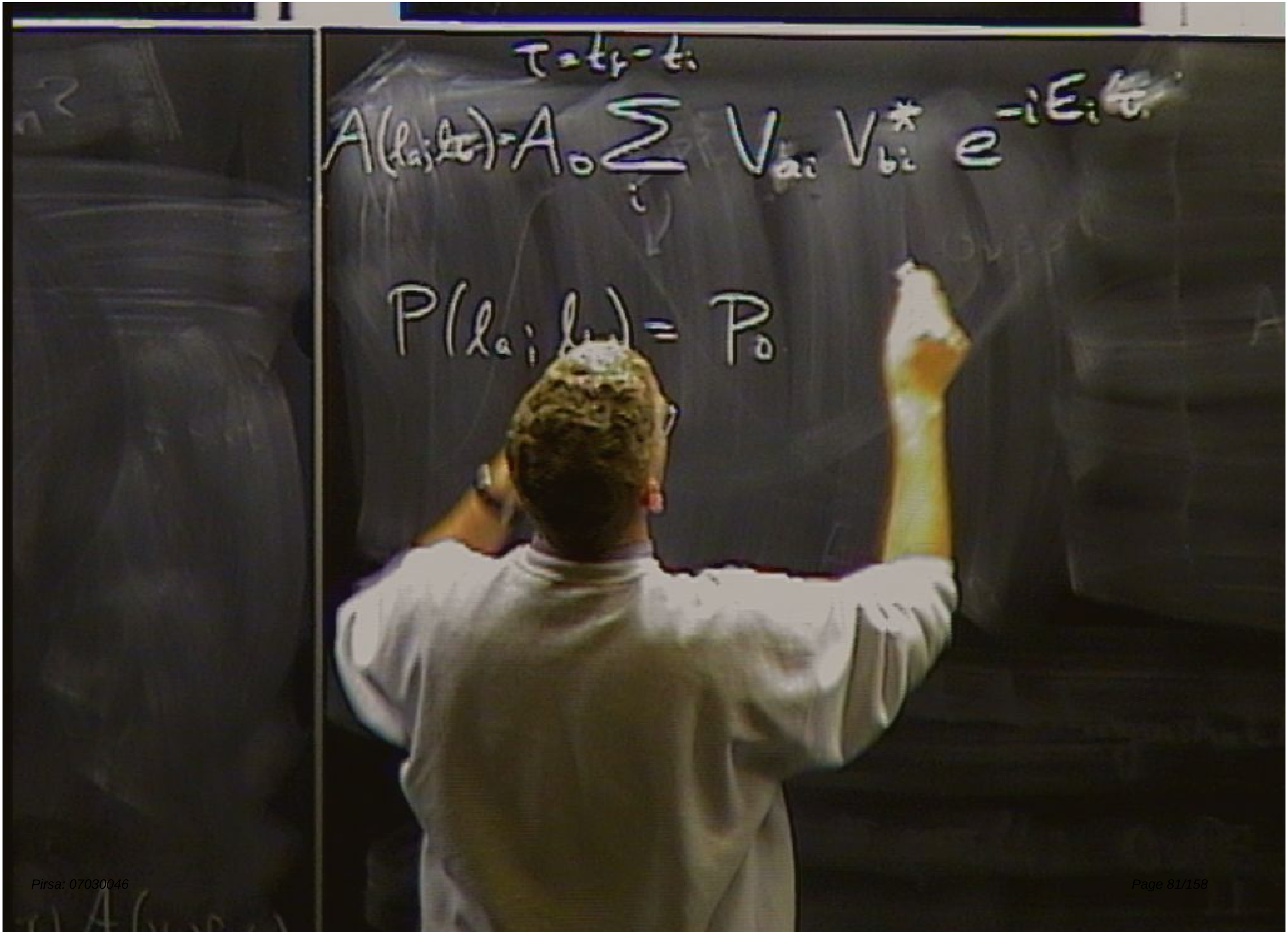

A = A₀

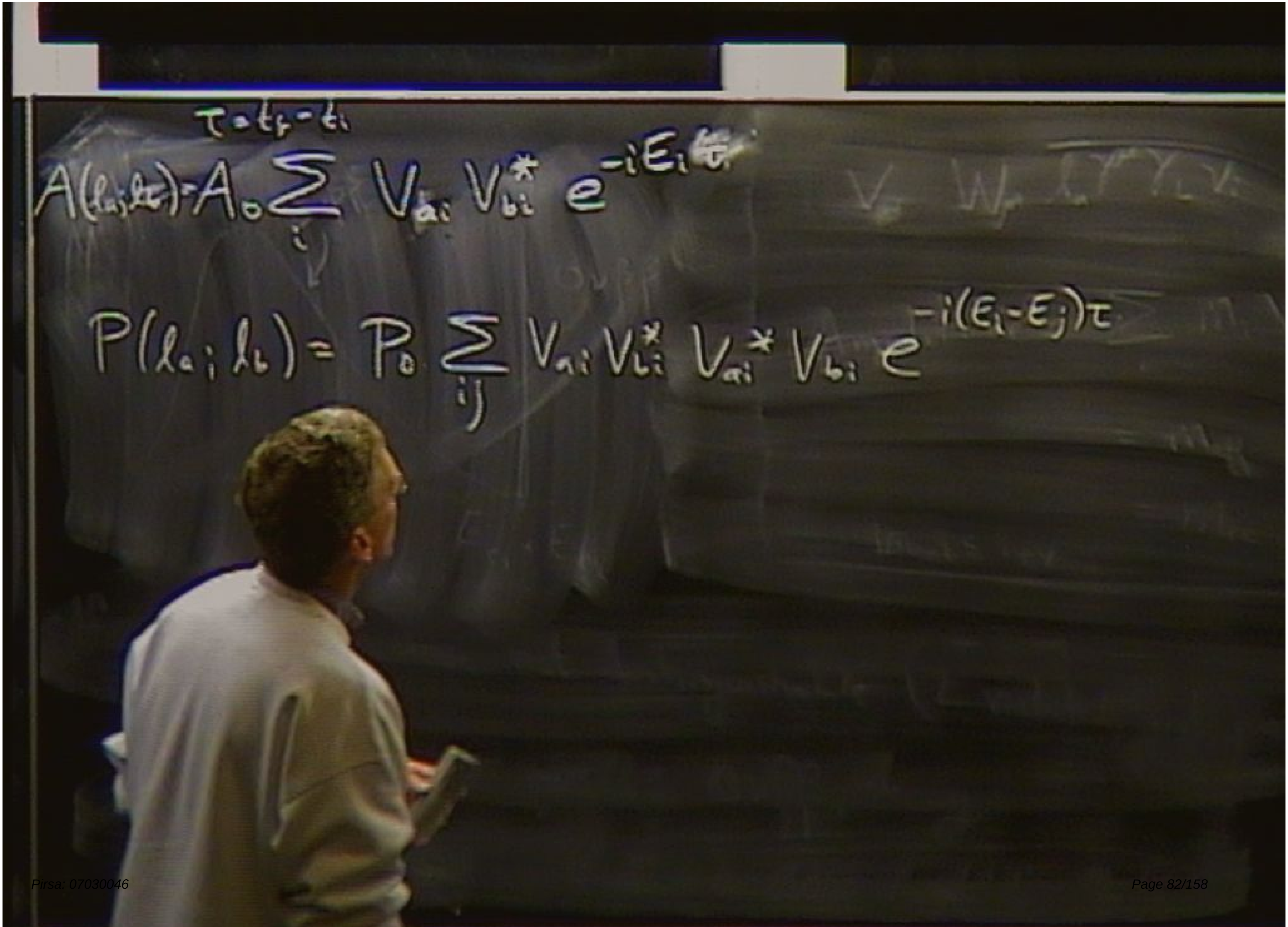


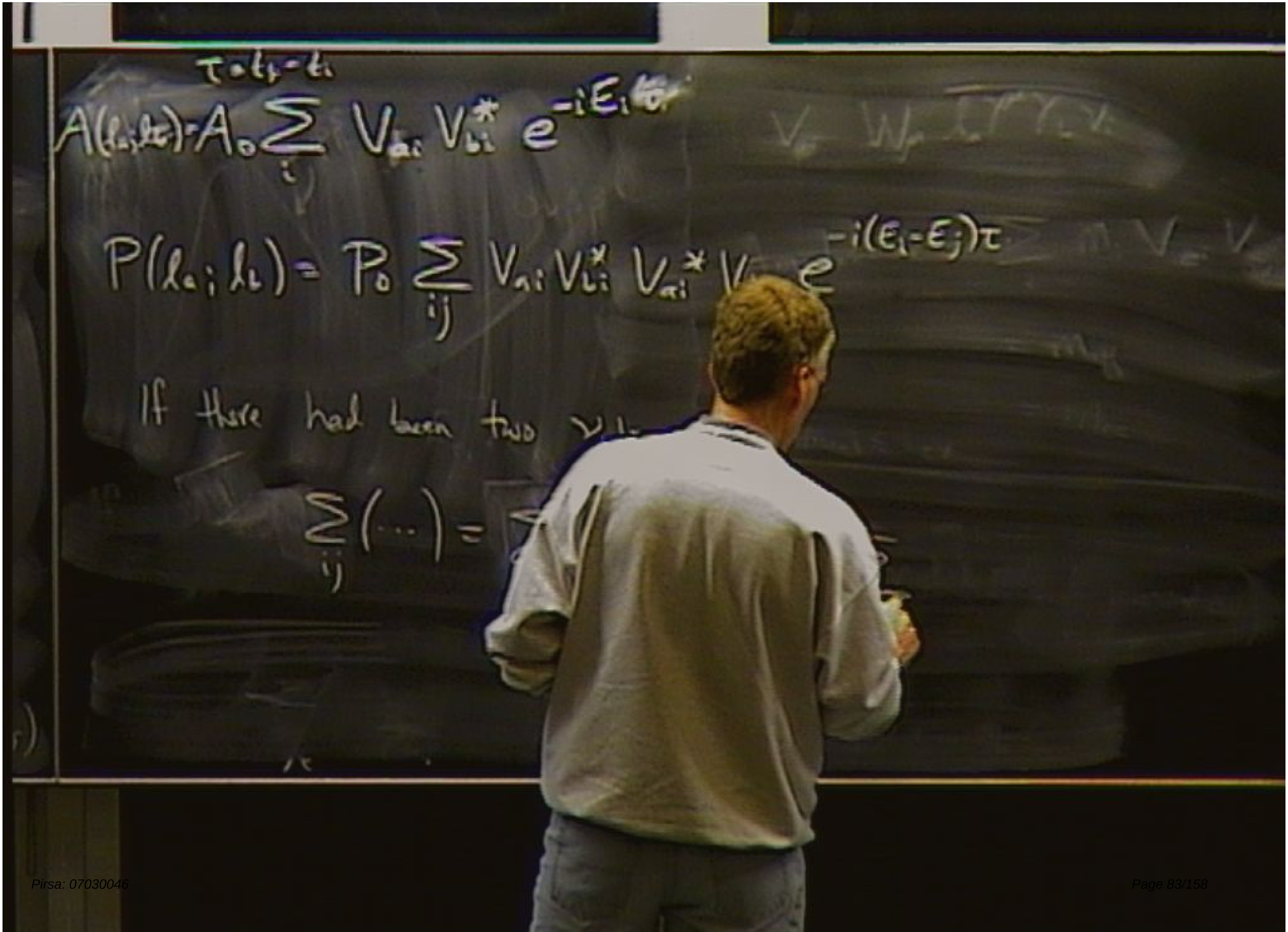


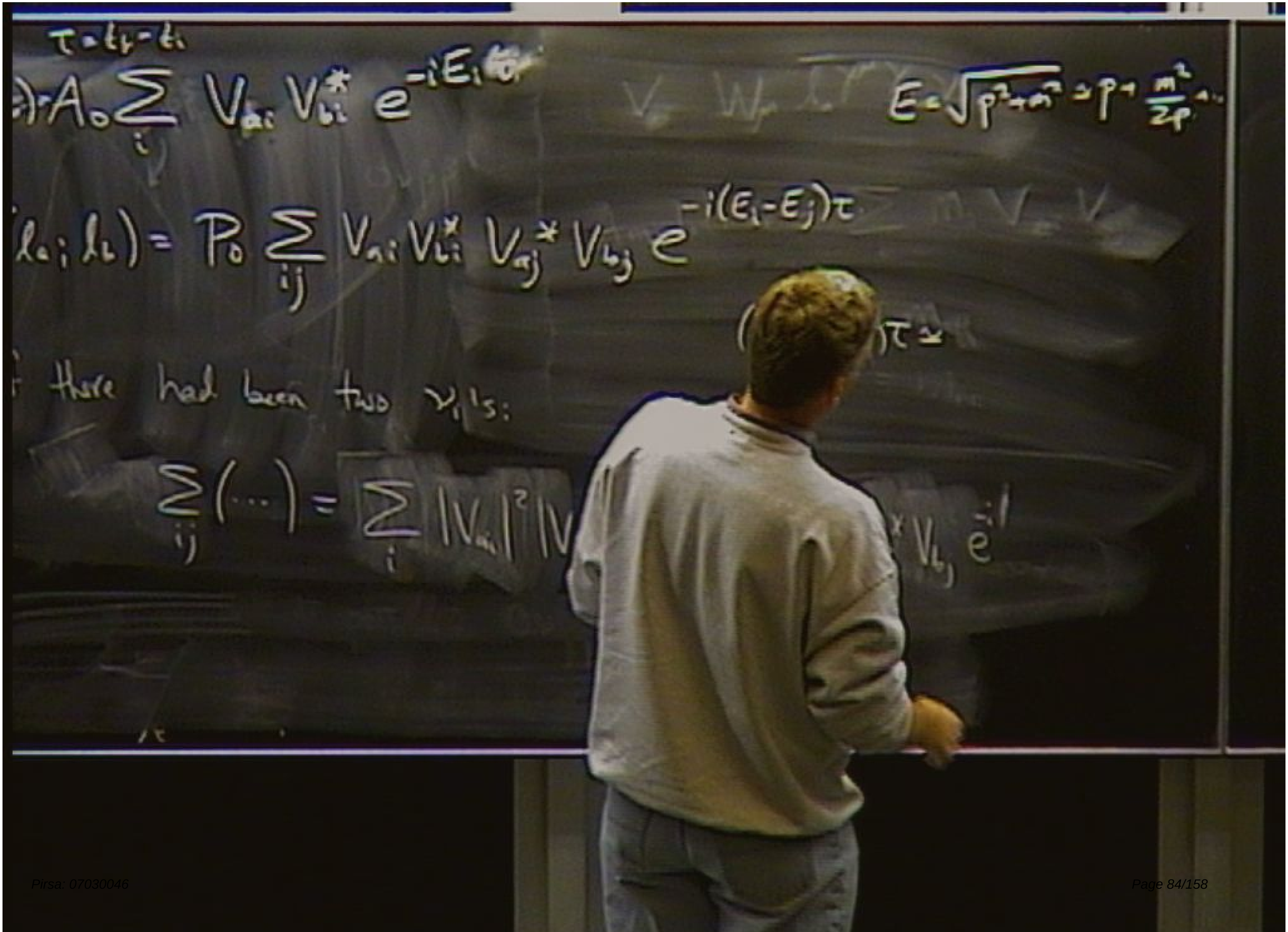
$$\tau = t_f - t_i$$

$$A(l_a, l_b) = A_0 \sum_i V_{ai} V_{bi}^* e^{-iE_i \tau}$$


τ = t_f − t_i
A(l_a; l_b t) = A_0 Σ_i V_ai V*_bi e^{−iE_i t}
P(l_a; l_b) = P_0


$\tau = t_f - t_i$
$A(l_a; l_b) = A_0 \sum_i V_{ai} V^*_{bi} e^{-iE_i \tau}$
$P(l_a; l_b) = P_0 \sum_{ij} V_{ai} V^*_{bi} V^*_{ai} V_{bi} e^{-i(E_i - E_j)\tau}$

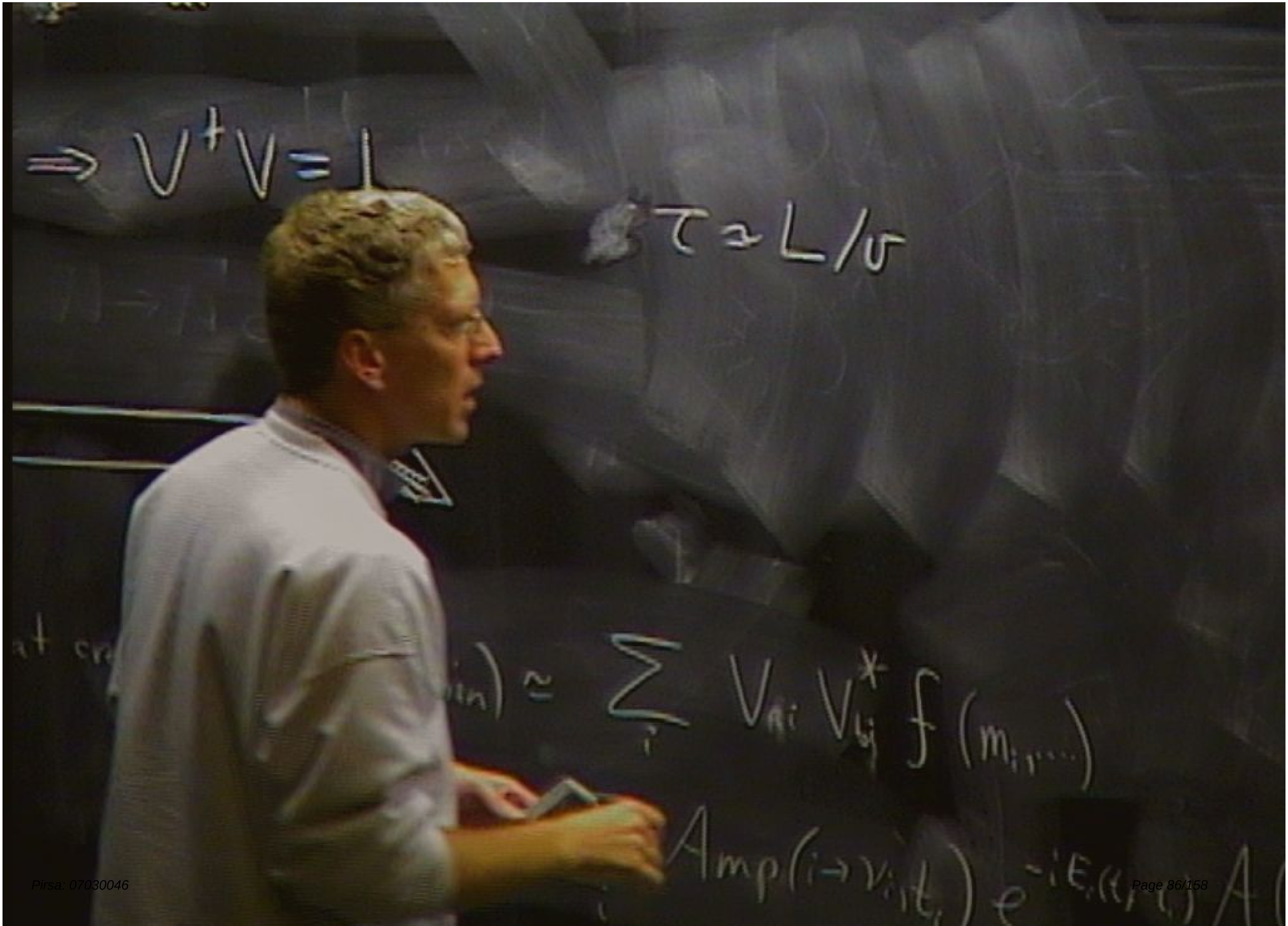

$\tau = t_f - t_i$
$A(l_a; l_b) = A_0 \sum_i V_{ai} V_{bi}^* e^{-iE_i \tau}$
$P(l_a; l_b) = P_0 \sum_{ij} V_{ai} V_{bi}^* V_{aj}^* V \; e^{-i(E_i - E_j)\tau}$
If there had been two
$\sum_{ij} (\ldots) =$

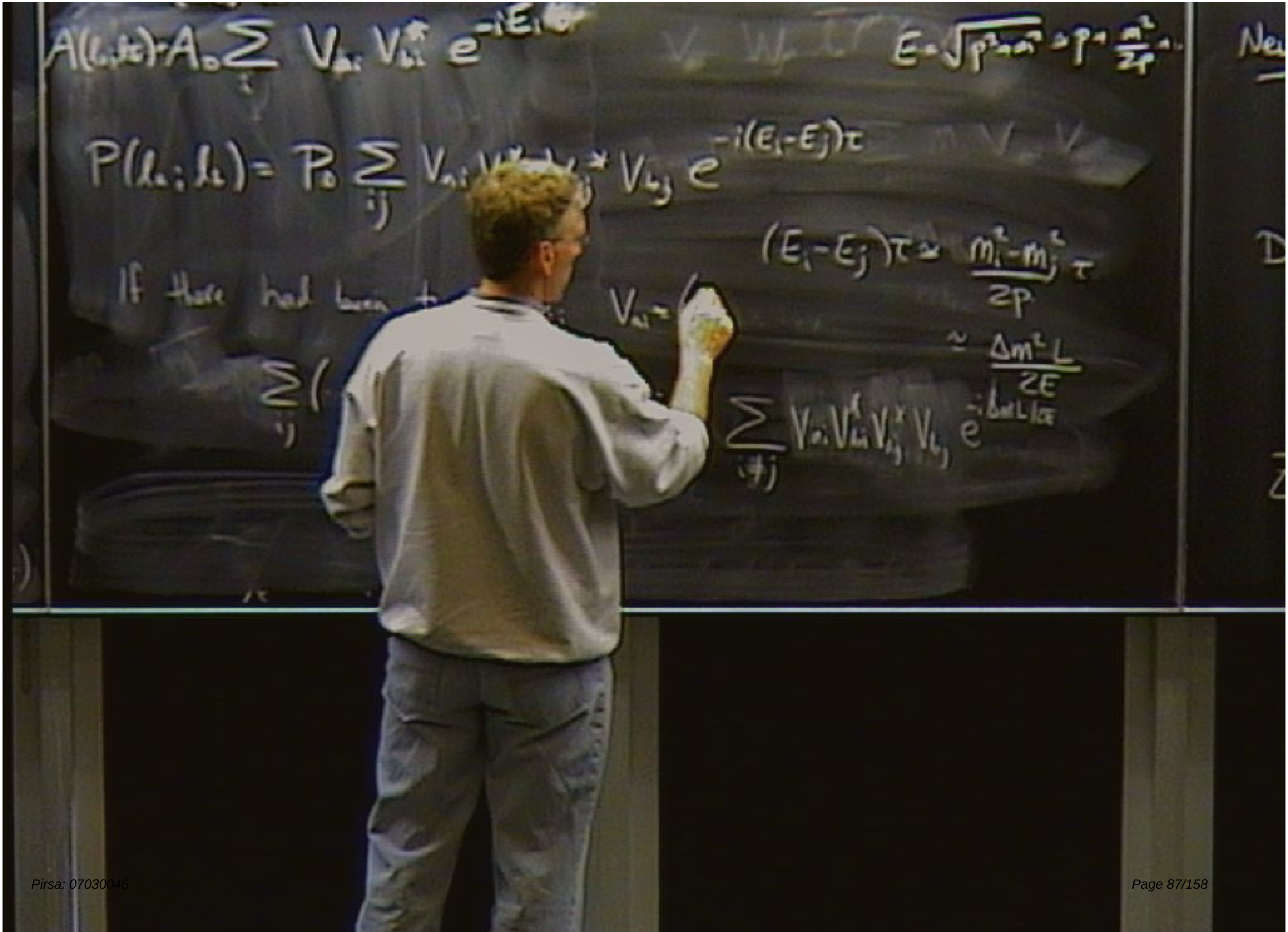

τ = t_f − t_i
) = A_0 Σ_i V_ai V_bi^* e^{−iE_i
E = √(p² + m²) ≃ p + m²/2p + ...
(l_a; l_b) = P_0 Σ_ij V_ai V_bi^* V_aj^* V_bj e^{−i(E_i − E_j)τ}
f there had been two ν_i's:
Σ_ij (...) = Σ_i |V_ai|² |V
V_bj e

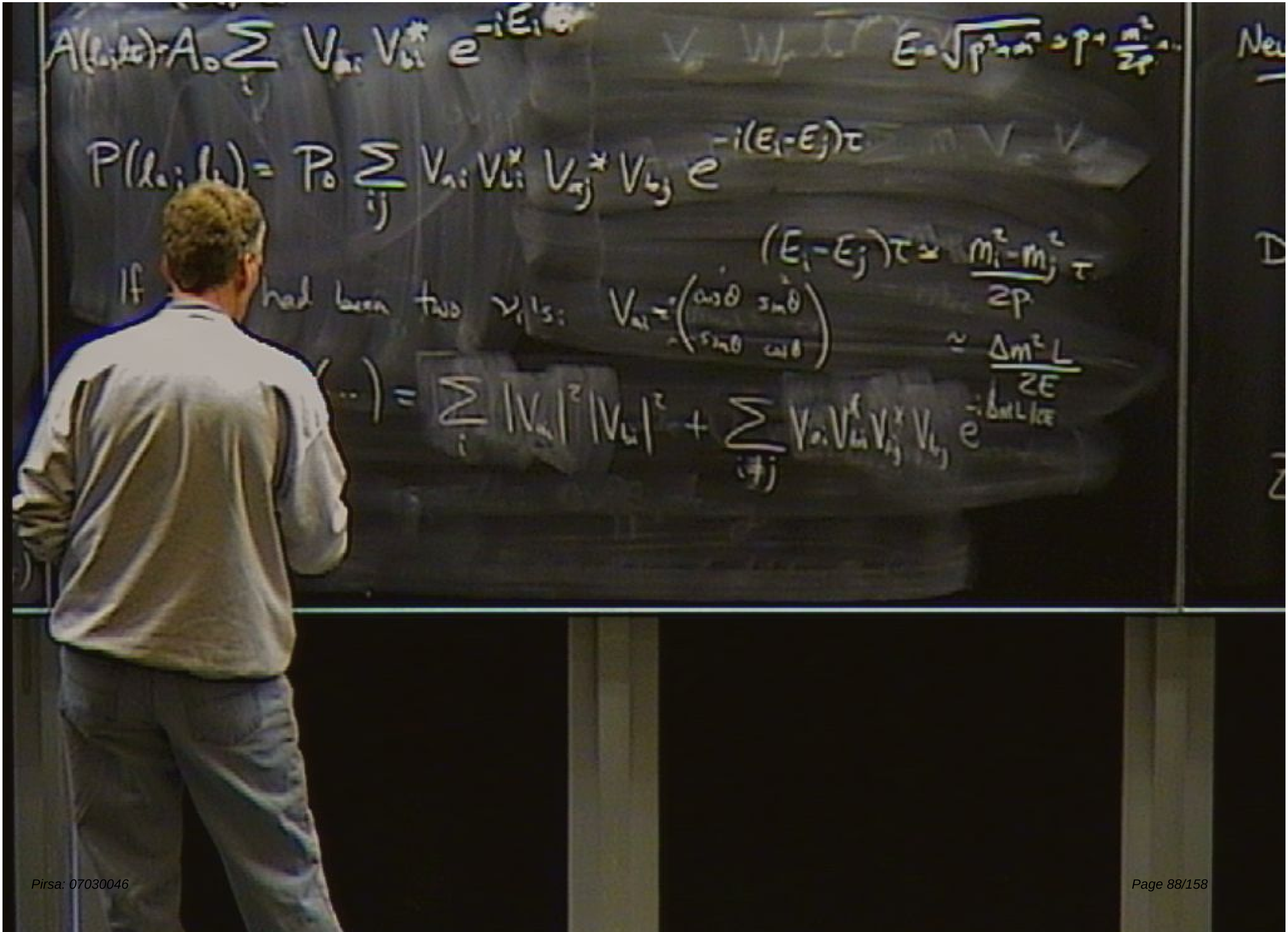
$$E = \sqrt{p^2 + m^2} \simeq p + \frac{m^2}{2p} + \dots$$

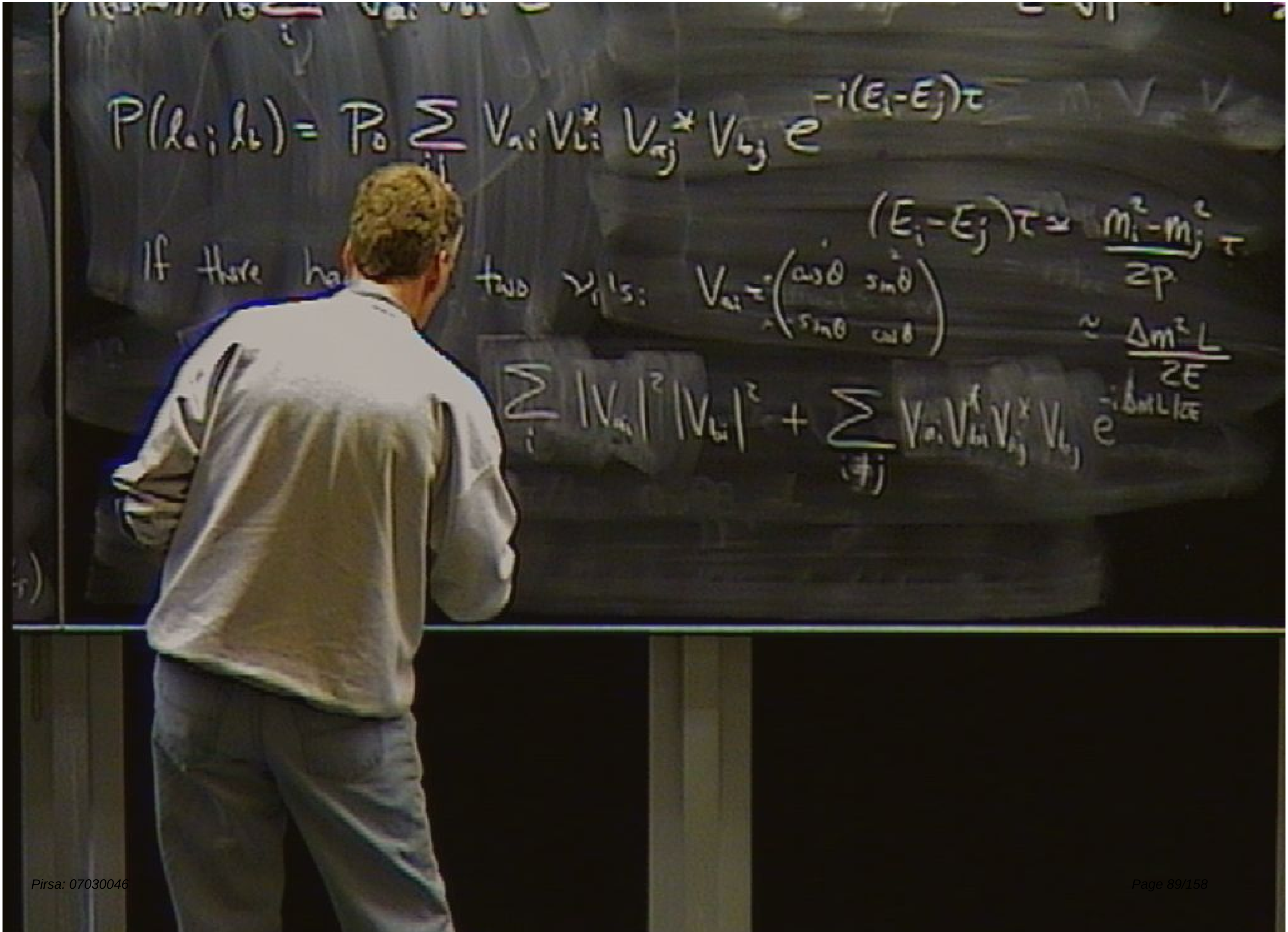
$$\ldots_j\, e^{-i(E_i - E_j)\tau}$$

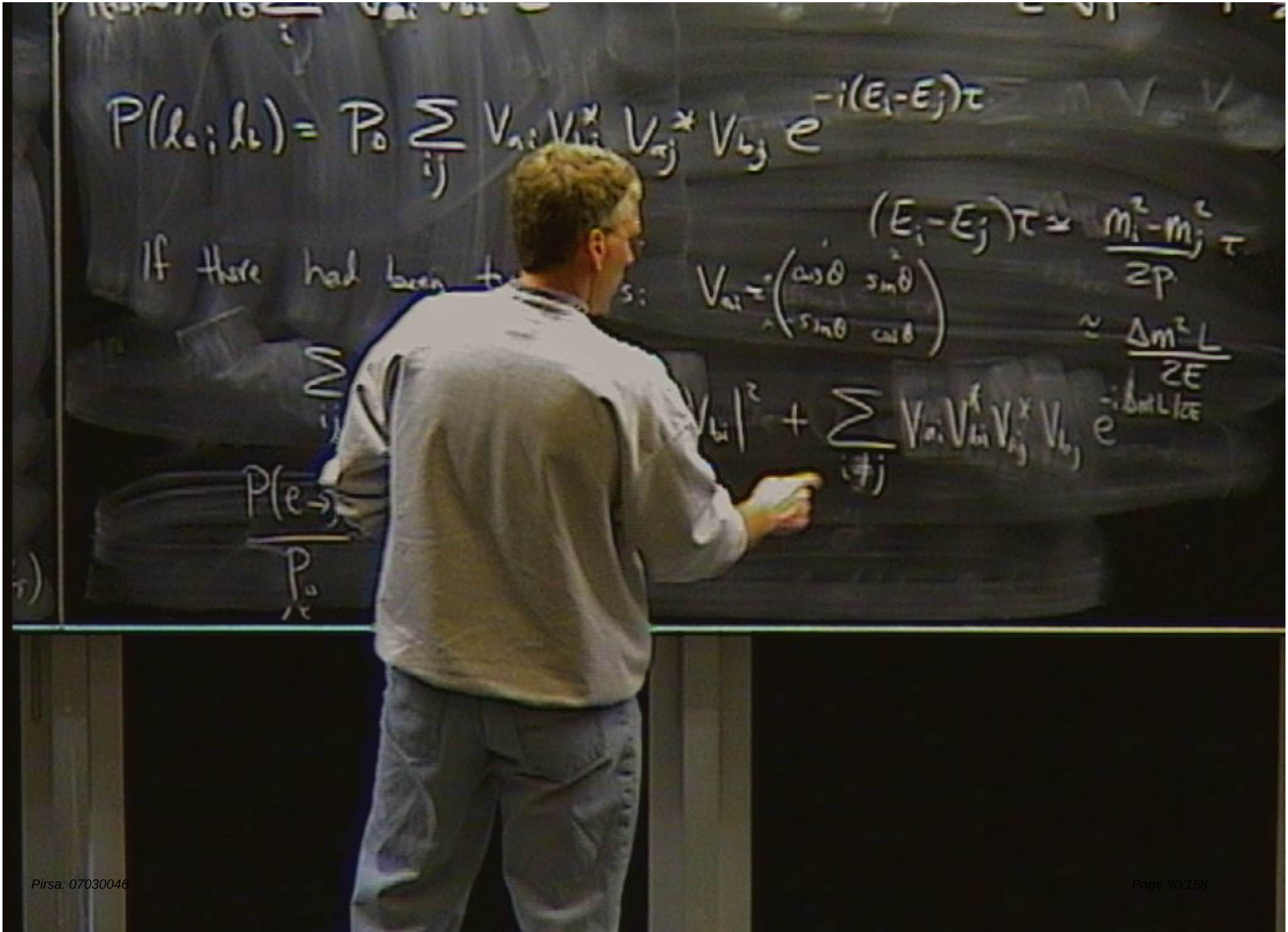
$$(E_i - E_j)\tau \simeq \frac{m_i^2 - m_j^2}{2p}\,\tau$$

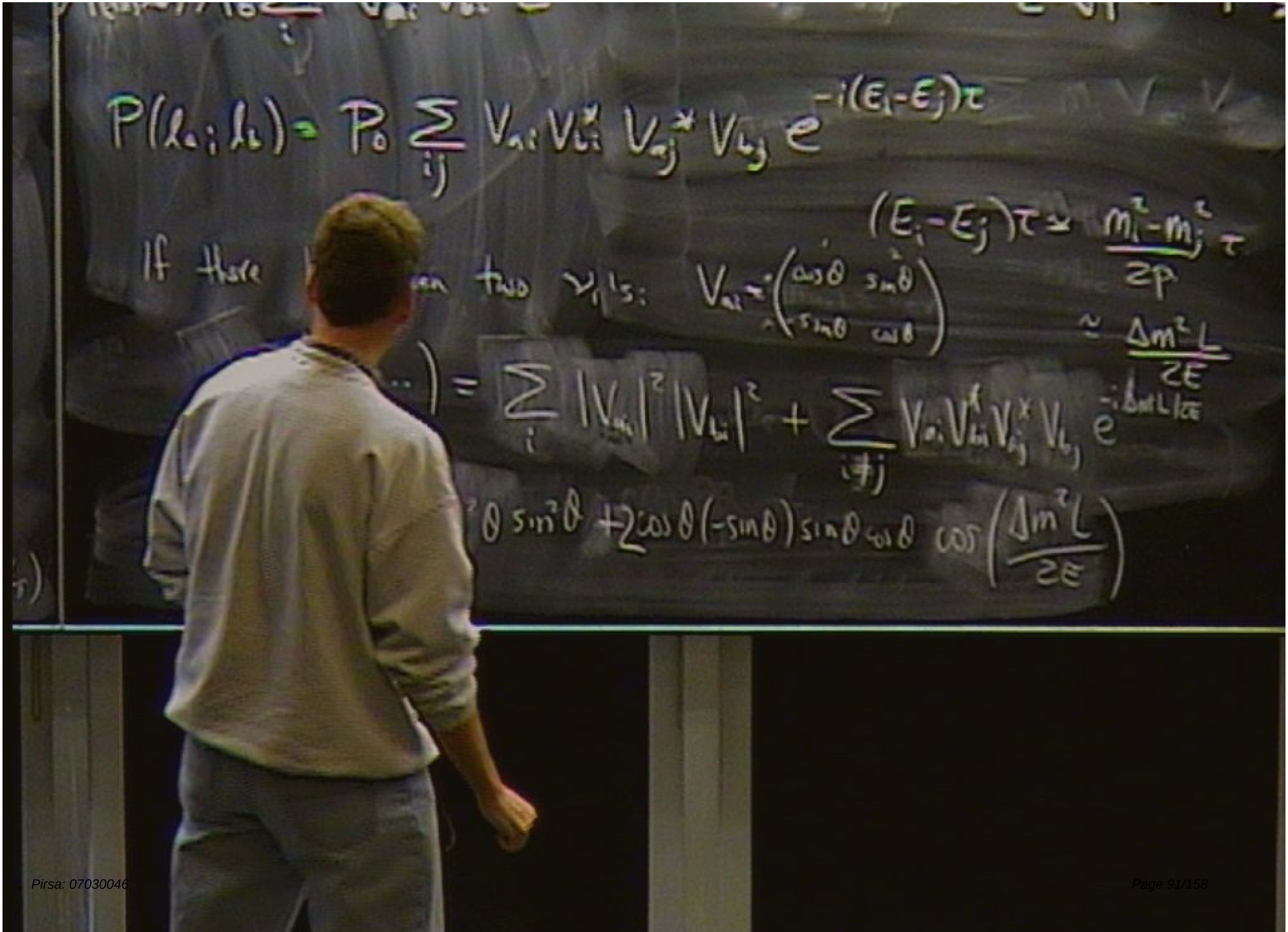

⇒ V†V = 1
τ ≈ L/v
≈ Σ V V* f (m, ...)
Amp(i→ν, t) e

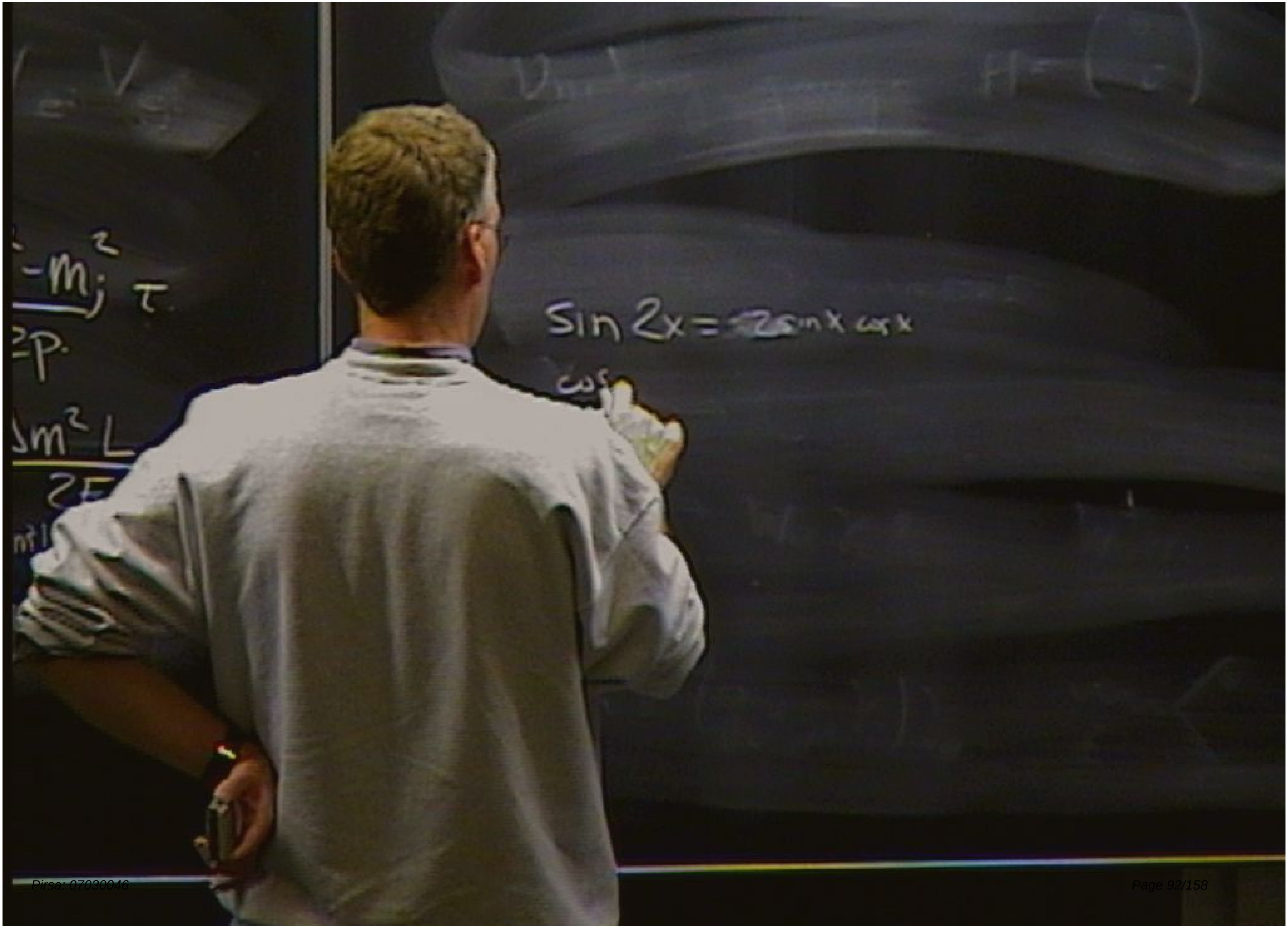

If there had been

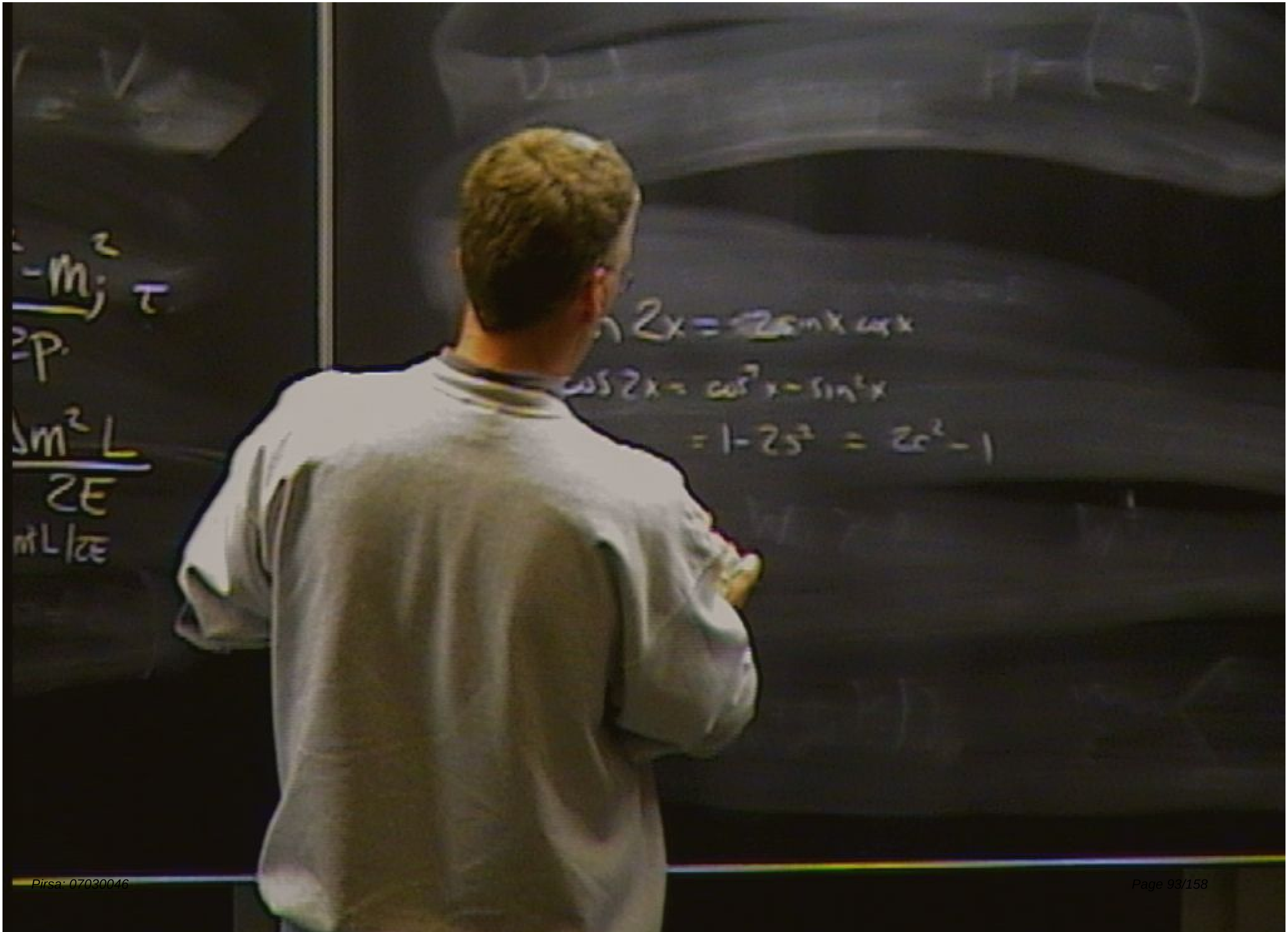

A(la;lb) = A0 Σi Vai Vbi* e^-iEiτ
E = √(p²+m²) ≈ p + m²/2p ...
P(la;lb) = P0 Σij Vai Vbi* Vaj* Vbj e^-i(Ei-Ej)τ
(Ei-Ej)τ ≈ (mi²-mj²)/2p τ
≈ Δm²L/2E
If had been two νi's: Vai = (cosθ sinθ / -sinθ cosθ)
(...) = Σi |Vai|² |Vbi|² + Σi≠j Vai Vbi* Vaj* Vbj e^-iΔm²L/2E


P(l_a ; l_b) = P_0 Σ_{ij} V_{ai} V_{bi}^* V_{aj}^* V_{bj} e^{-i(E_i - E_j)τ}
(E_i - E_j)τ ≈ (m_i^2 - m_j^2)/(2p) τ
If there ha… two ν_i's: V_{ai} = (cos θ sin θ / -sin θ cos θ)
≈ Δm^2 L / 2E
Σ_i |V_{ai}|^2 |V_{bi}|^2 + Σ_{i≠j} V_{ai} V_{bi}^* V_{aj}^* V_{bj} e^{-iΔm L/2E}

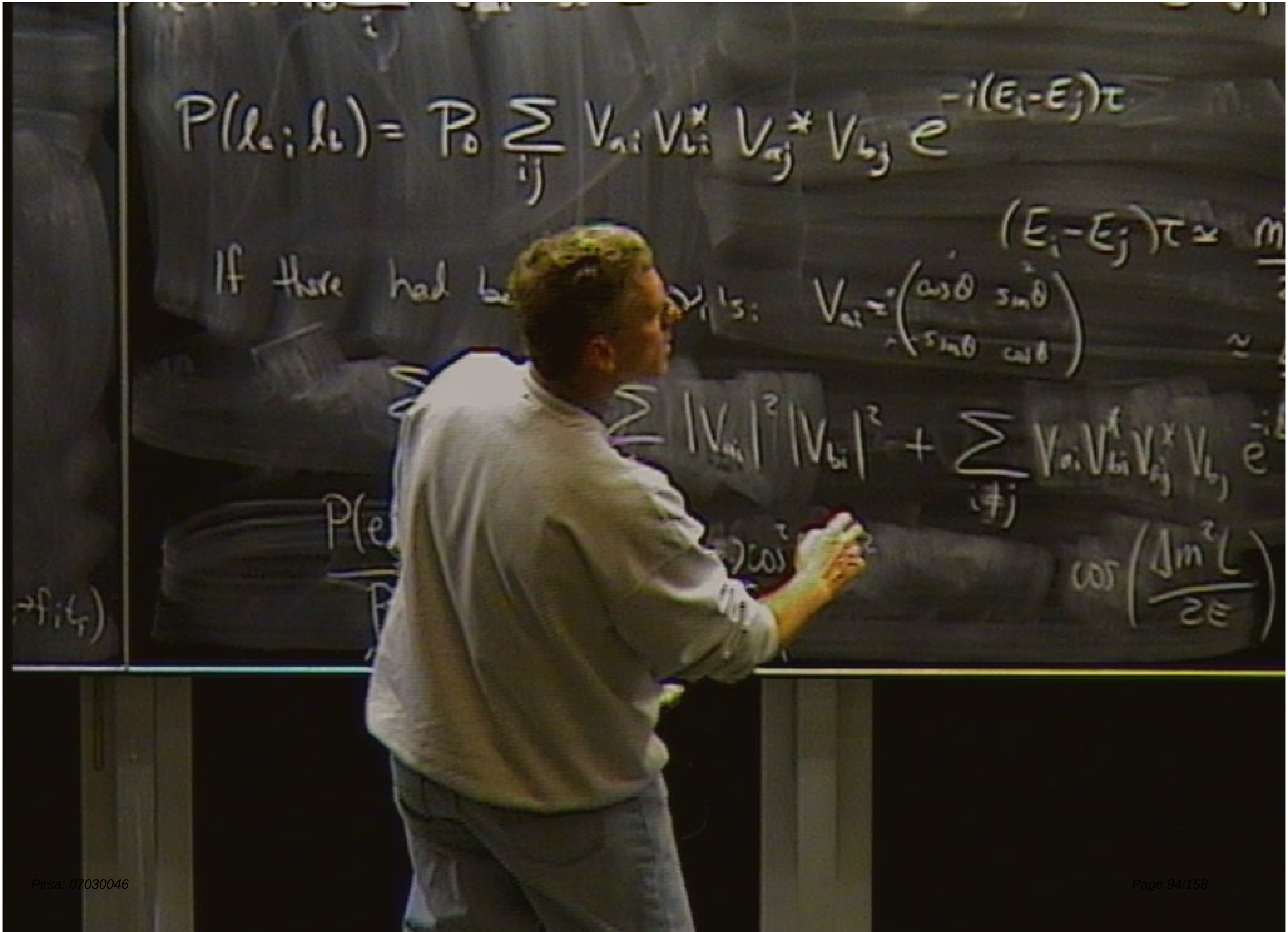

$P(l_a; l_b) = P_0 \sum_{ij} V_{ai} V_{bi}^* V_{aj}^* V_{bj}\, e^{-i(E_i - E_j)\tau}$
$(E_i - E_j)\tau \simeq \frac{m_i^2 - m_j^2}{2p}\tau$
$\simeq \frac{\Delta m^2 L}{2E}$
If there had been
$V_{ai} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$
$+ \sum_{i \neq j} V_{ai} V_{bi}^* V_{aj}^* V_{bj}\, e^{-i\Delta m L/2E}$


P(la; lb) = P0 Σij Vai Vbi* Vaj* Vbj e^-i(Ei-Ej)τ
(Ei-Ej)τ ≃ (mi² - mj²)/2p τ
≃ Δm² L/2E
If there ... than two νi's: Vai = (cosθ sinθ / -sinθ cosθ)
= Σi |Vai|² |Vbi|² + Σi≠j Vai Vbi* Vaj* Vbj e^-iΔm L/2E
θ sin²θ + 2cosθ(-sinθ) sinθ cosθ cos(Δm² L/2E)

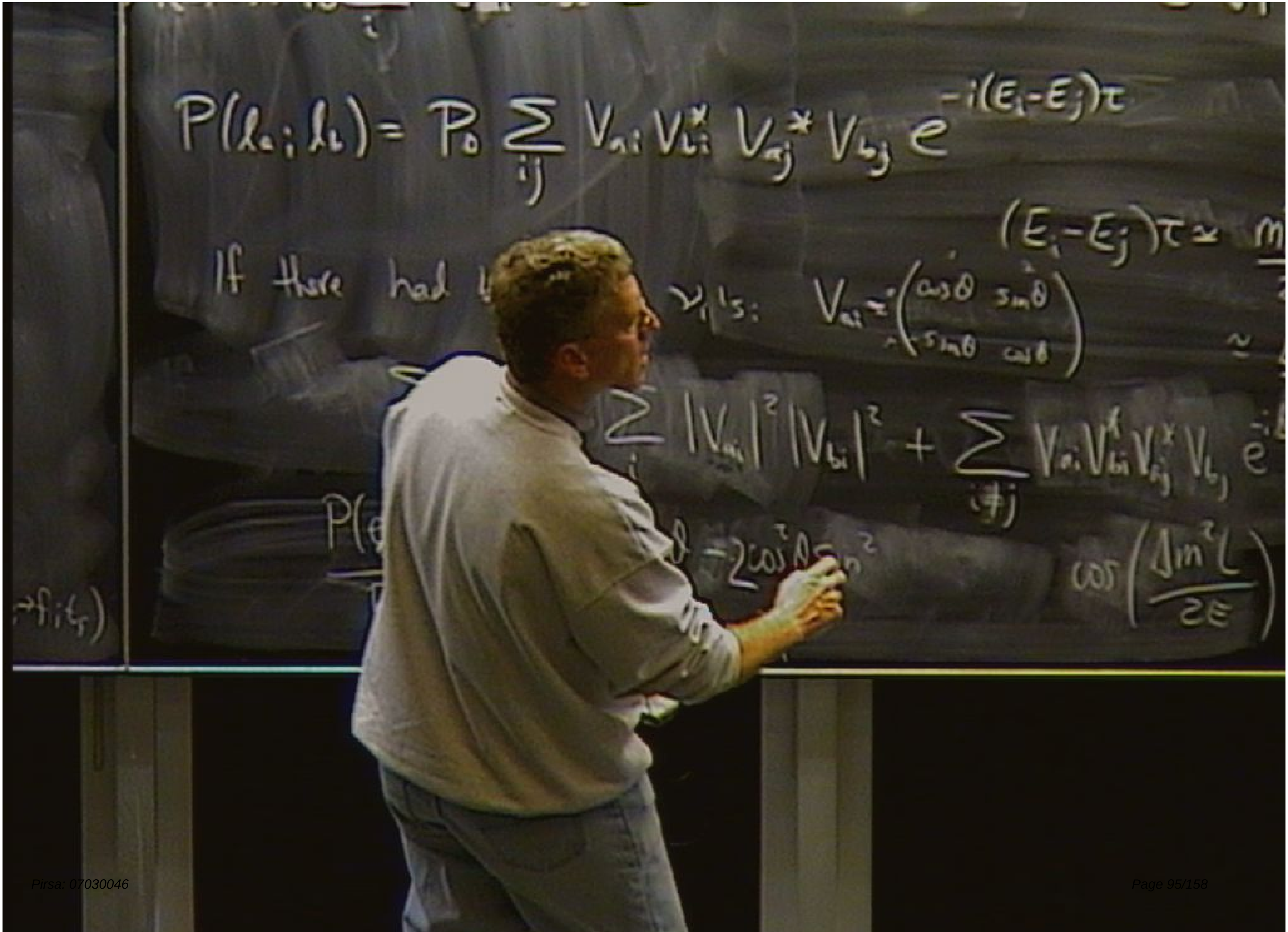

sin 2x = sin x cos x
cos

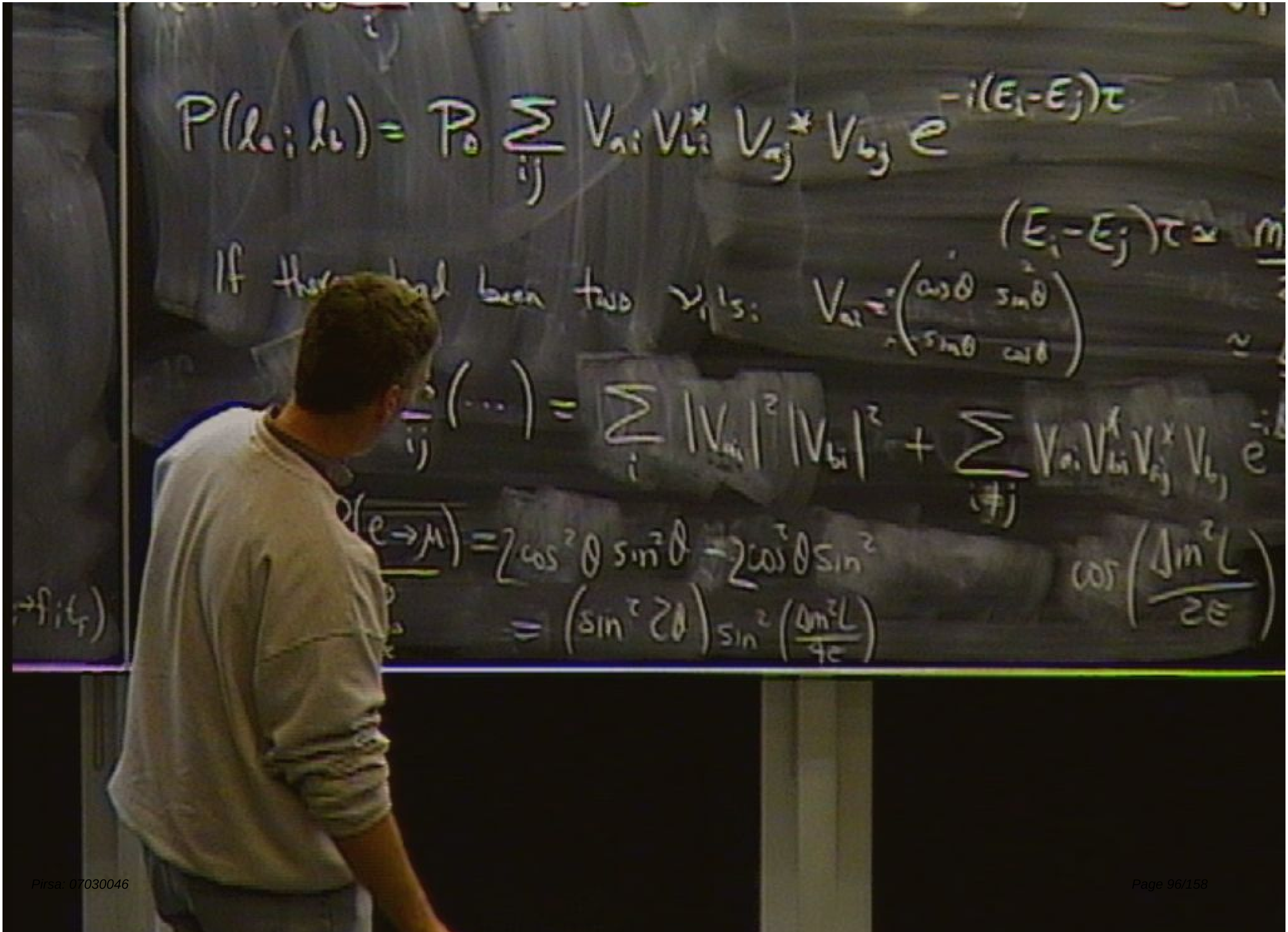


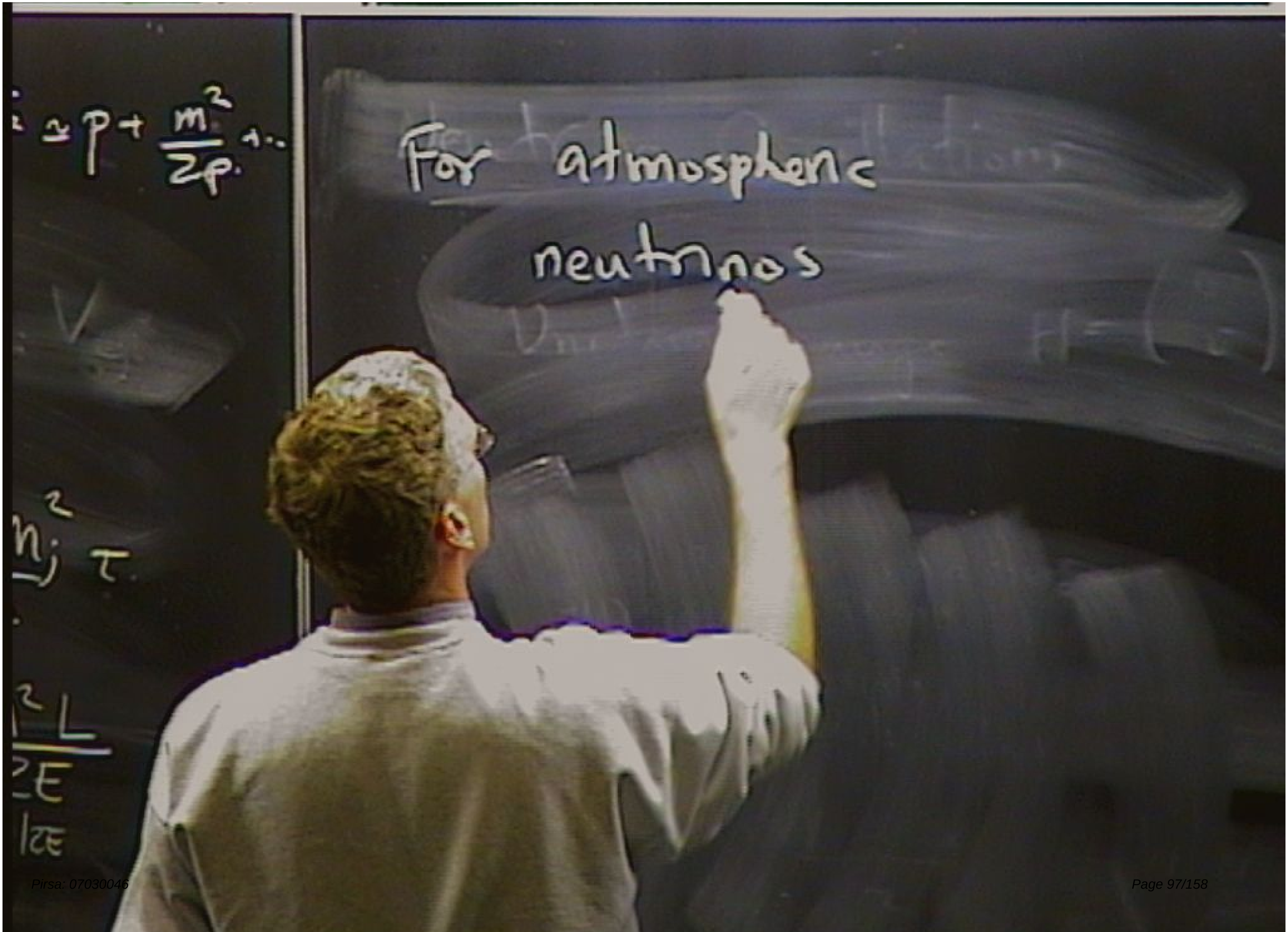
2x = 2 sin x cos x
cos 2x = cos² x − sin² x
= 1 − 2s² = 2c² − 1
Δm² L
2E

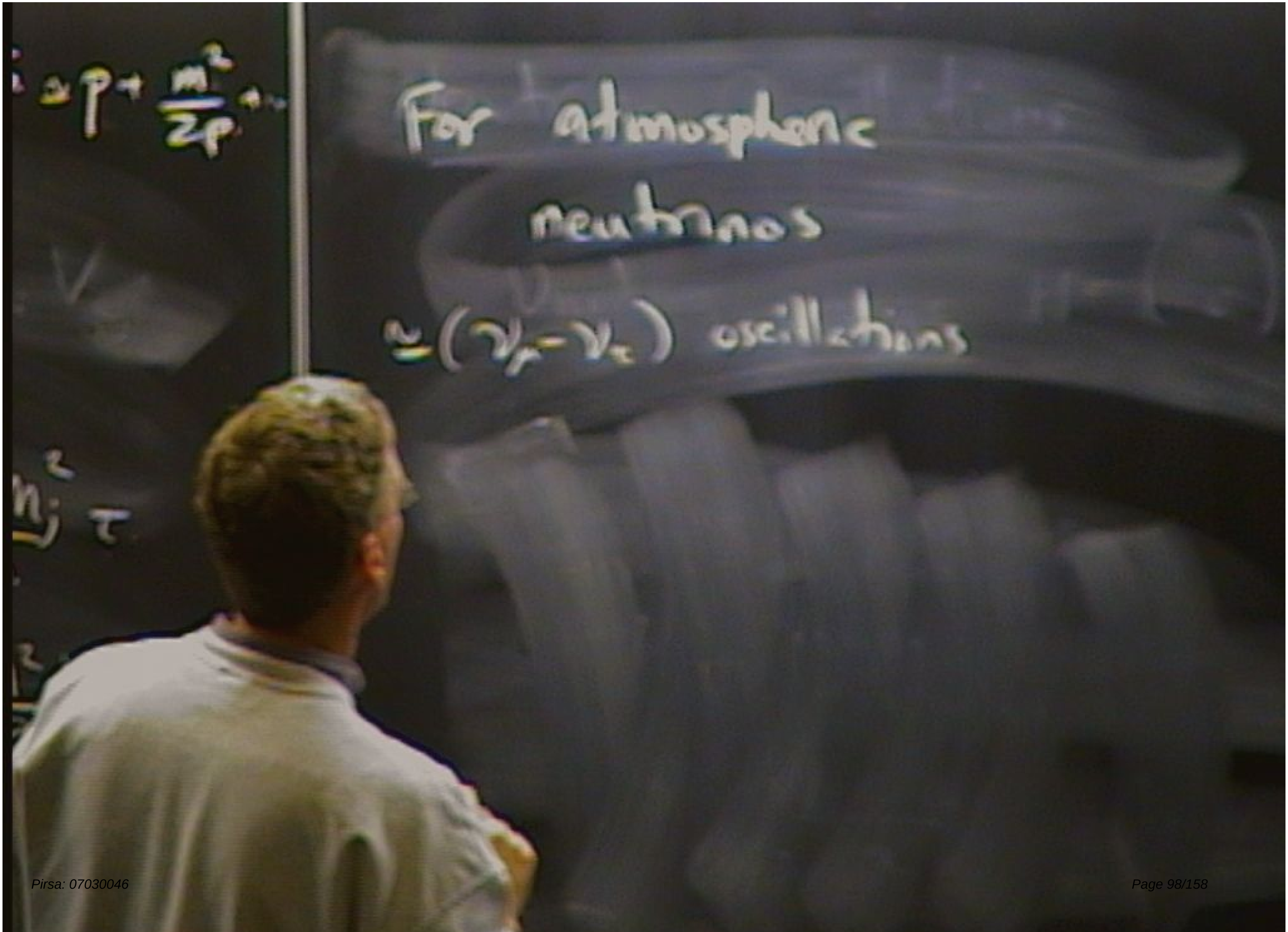


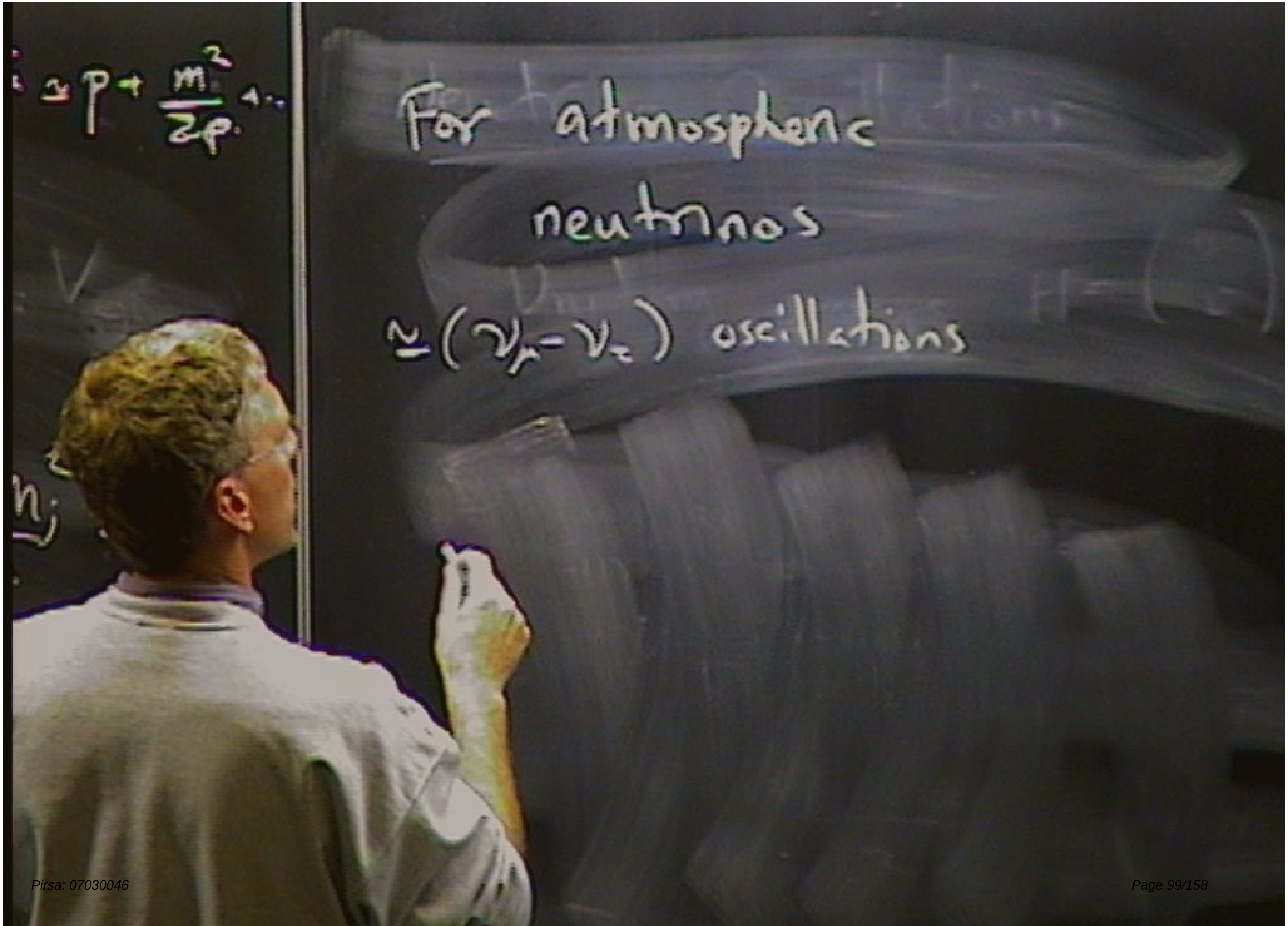
$P(l_a; l_b) = P_0 \sum_{ij} V_{ai} V_{bi}^* V_{aj}^* V_{bj}\, e^{-i(E_i-E_j)\tau}$
$(E_i - E_j)\tau \simeq$
If there had been
$V_{ai} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$
$\sum |V_{ai}|^2 |V_{bi}|^2 + \sum_{i \neq j} V_{ai} V_{bi}^* V_{aj}^* V_{bj}\, e^{-i}$
$\cos\left(\frac{\Delta m^2 L}{2E}\right)$


P(la; lb) = P0 Σij Vai V*bi Vaj* Vbj e^-i(Ei-Ej)τ
(Ei-Ej)τ ≈
If there had
νi's: Vai ≈ (cosθ sinθ / -sinθ cosθ)
Σi |Vai|² |Vbi|² + Σi≠j Vai V*bi V*aj Vbj e
cos(Δm²L / 2E)


P(la ; lb) = P0 Σij Vai Vbi* Vaj* Vbj e^(-i(Ei-Ej)τ)
(Ei-Ej)τ ≈
If there had been two ν's:
cos θ sin θ
-sin θ cos θ
Σi |Vai|² |Vbi|² + Σi≠j Vai Vbi* Vaj* Vbj
P(e→μ) = 2cos²θ sin²θ - 2cos²θ sin²
cos (Δm²L / 2E)
= (sin² 2θ) sin² (Δm²L / 4E)


For atmospheric
neutrinos


$\simeq p + \frac{m^2}{2p} + \dots$
For atmospheric
neutrinos
$\simeq (\nu_\mu - \nu_\tau)$ oscillations


For atmospheric
neutrinos
≃ ($\nu_\mu - \nu_\tau$) oscillations
$\simeq p + \frac{m^2}{2p} + \ldots$

$\simeq p + \frac{m^2}{2p} + \dots$

$m_j^2 \, \tau$

$\frac{m^2 L}{2E}$

For atmospheric neutrinos

$\simeq (\nu_\mu - \nu_\tau)$ oscillations

$\Delta m^2 \simeq$

$\simeq p + \frac{m^2}{2p} + \ldots$

For atmospheric neutrinos

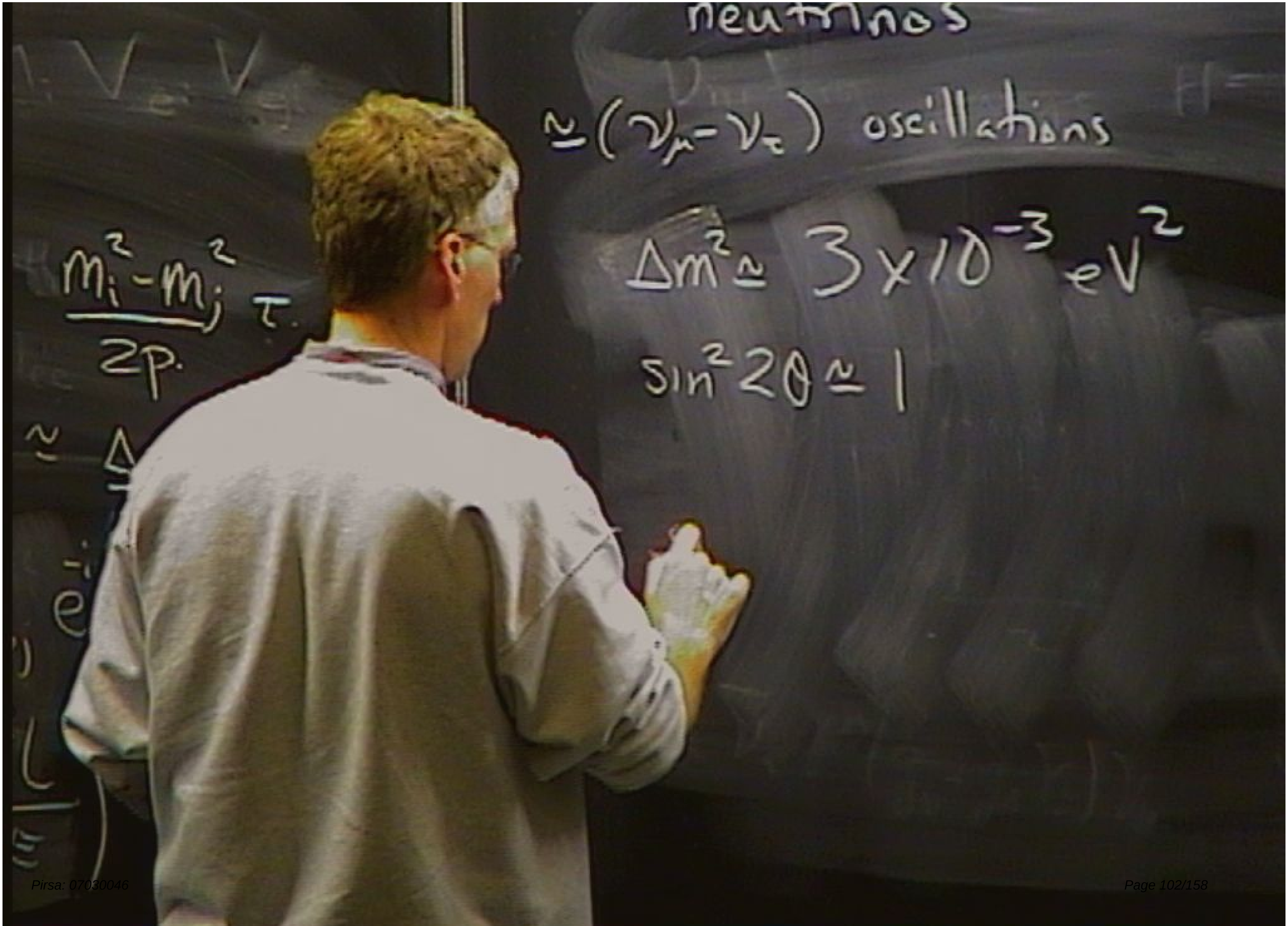
$\simeq (\nu_\mu - \nu_\tau)$ oscillations

$\Delta m^2 \simeq 3 \times 10^{-3}\ eV^2$

sin

τ.

$\frac{{}^2 L}{2E}$


neutrinos
$\simeq (\nu_\mu - \nu_\tau)$ oscillations
$\Delta m^2 \simeq 3 \times 10^{-3}\ eV^2$
$\sin^2 2\theta \simeq 1$
$\frac{m_i^2 - m_j^2}{2p} \tau$

$$\frac{m_i^2 - m_j^2}{2p}\,\tau$$

$$\simeq \frac{\Delta m^2 L}{2E}$$

$$e^{-i\Delta m^2 L/2E}$$

neutrinos

$\simeq (\nu_\mu - \nu_\tau)$ oscillations

$$\Delta m^2 \simeq 3 \times 10^{-3}\ eV^2$$

$$\sin^2 2\theta \simeq 1$$

For solar neutrino oscillations

$$\nu_e - (\nu_\mu, \nu_\tau)$$

$$\Delta m^2 \simeq$$

neutrinos

$\simeq (\nu_\mu - \nu_\tau)$ oscillations

$\Delta m^2 \simeq 3 \times 10^{-3}\, eV^2$

$\sin^2 2\theta \simeq 1$

For solar neutrino oscillations

$\nu_e - (\nu_\mu, \nu_\tau)$

$\Delta m^2 \simeq 8 \times 10^{-5}\, eV^2$

$\sin^2 2\theta \simeq$

neutrinos

$\simeq (\nu_\mu - \nu_\tau)$ oscillations

$$\Delta m^2 \simeq 3 \times 10^{-3}\ eV^2$$

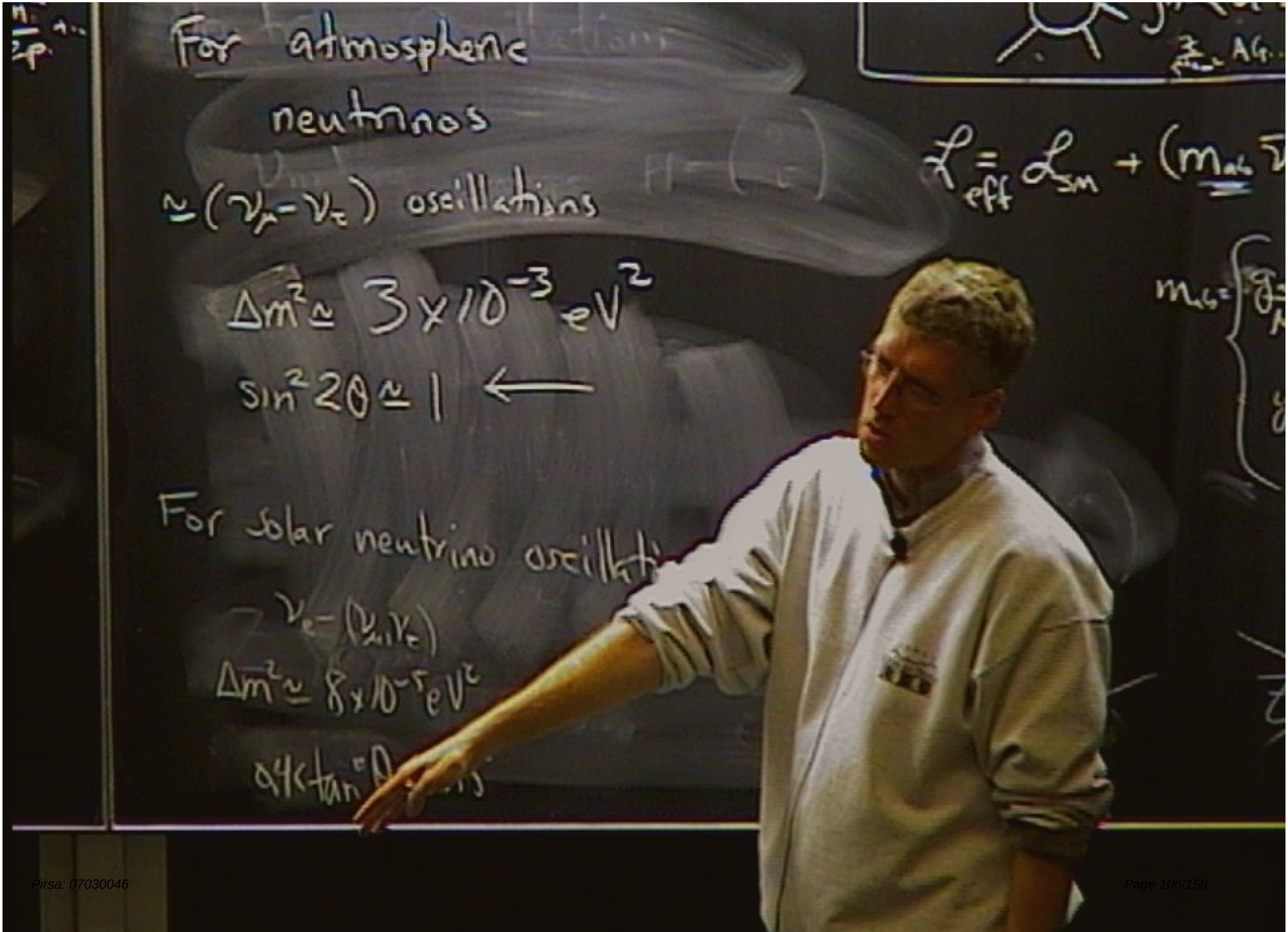
$$\sin^2 2\theta \simeq 1$$

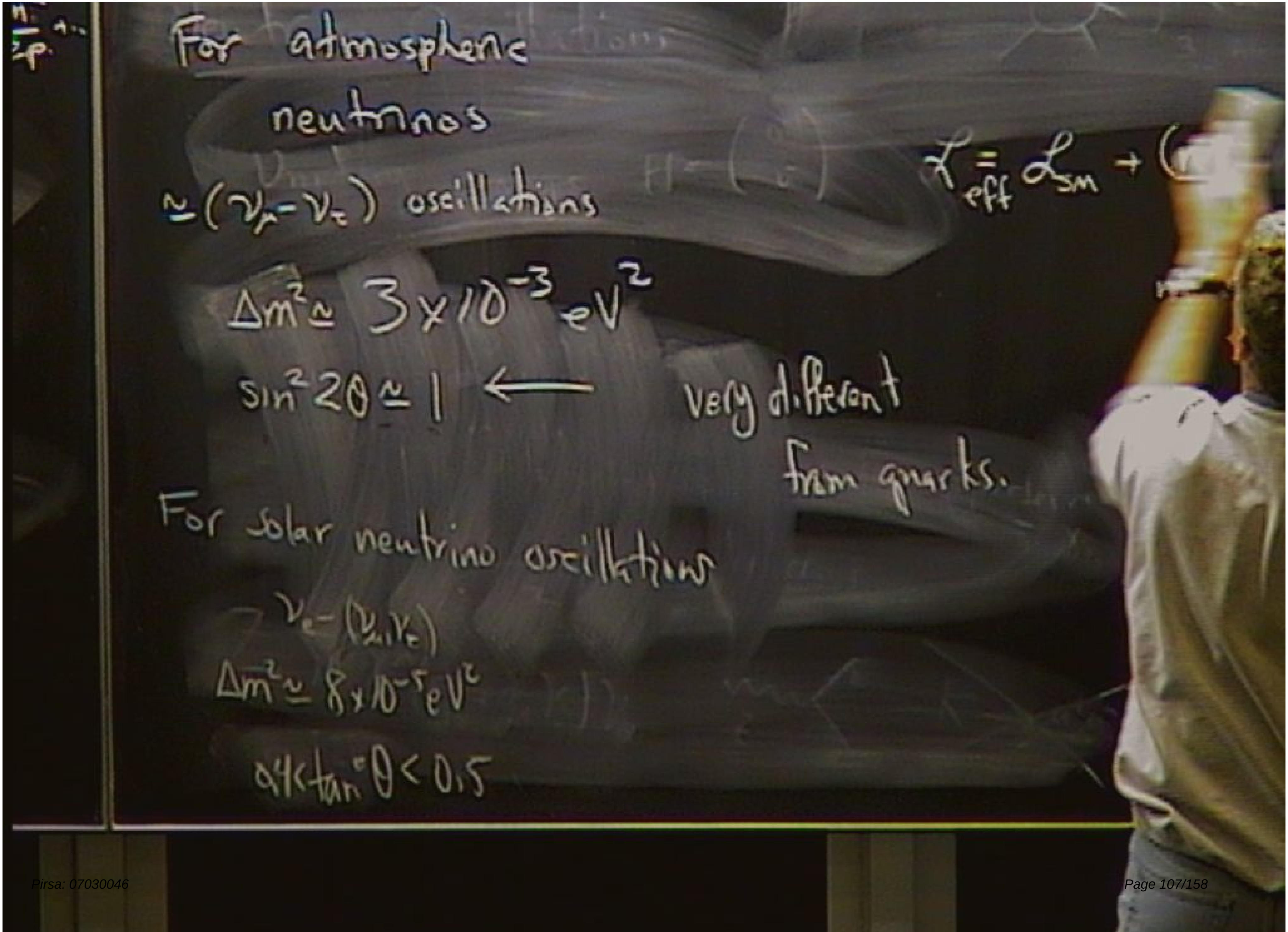
For solar neutrino oscillations

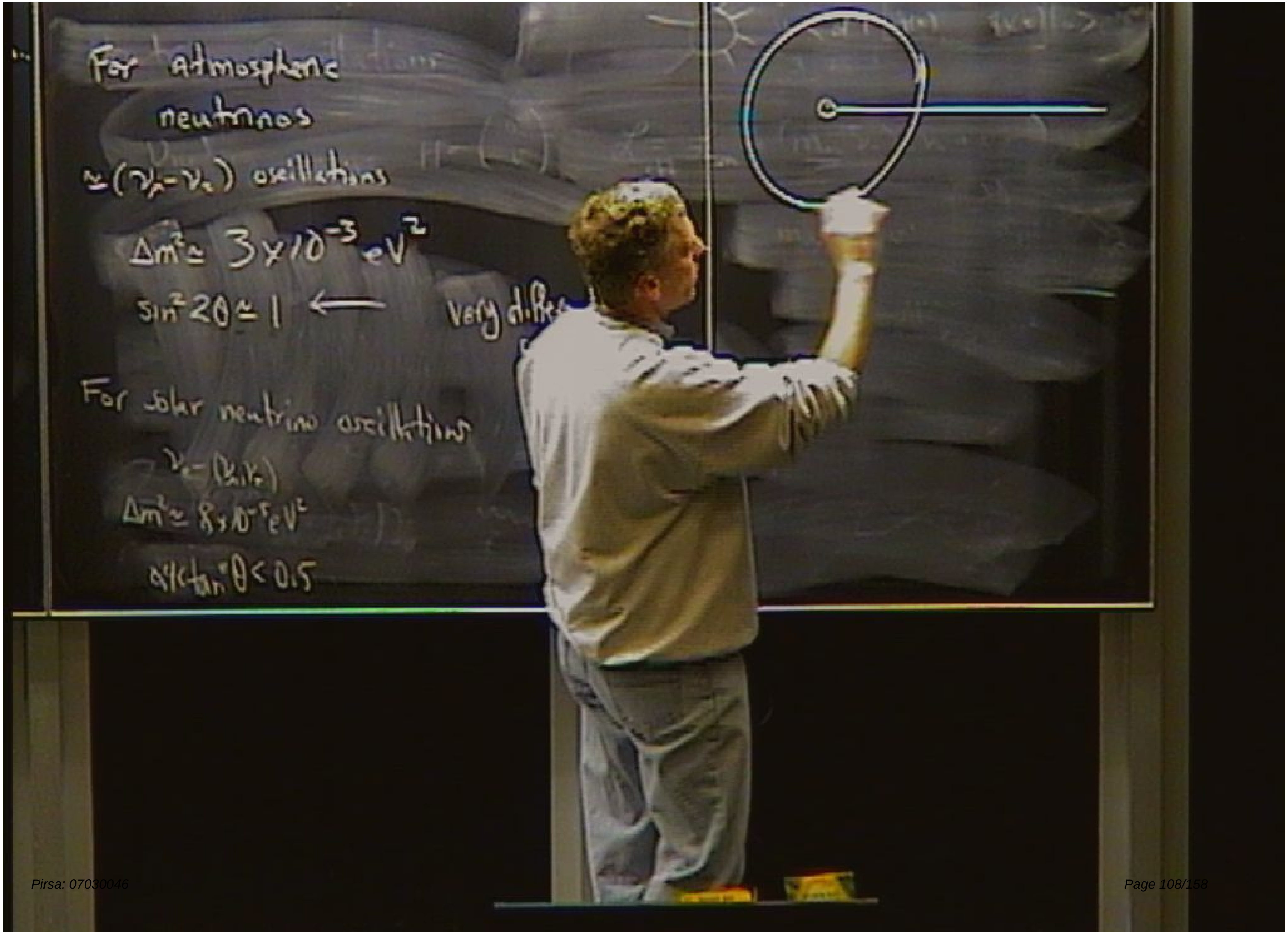
$$\nu_e - (\nu_\mu, \nu_\tau)$$

$$\Delta m^2 \simeq 8 \times 10^{-5}\ eV^2$$

$$0.4 < \tan^2\theta < 0.5$$


For atmospheric neutrinos
≃ (νμ - ντ) oscillations
Δm² ≃ 3 × 10⁻³ eV²
sin² 2θ ≃ 1
For solar neutrino oscill
νe - (νμ, ντ)
Δm² ≃ 8 × 10⁻⁵ eV²


For atmospheric
neutrinos
$\simeq (\nu_\mu - \nu_\tau)$ oscillations
$\Delta m^2 \simeq 3 \times 10^{-3}\, eV^2$
$\sin^2 2\theta \simeq 1$
very different
from quarks.
For solar neutrino oscillations
$\nu_e - (\nu_\mu, \nu_\tau)$
$\Delta m^2 \simeq 8 \times 10^{-5}\, eV^2$
$0.4 < \tan^2\theta < 0.5$
$\mathcal{L}_{eff} = \mathcal{L}_{SM} +$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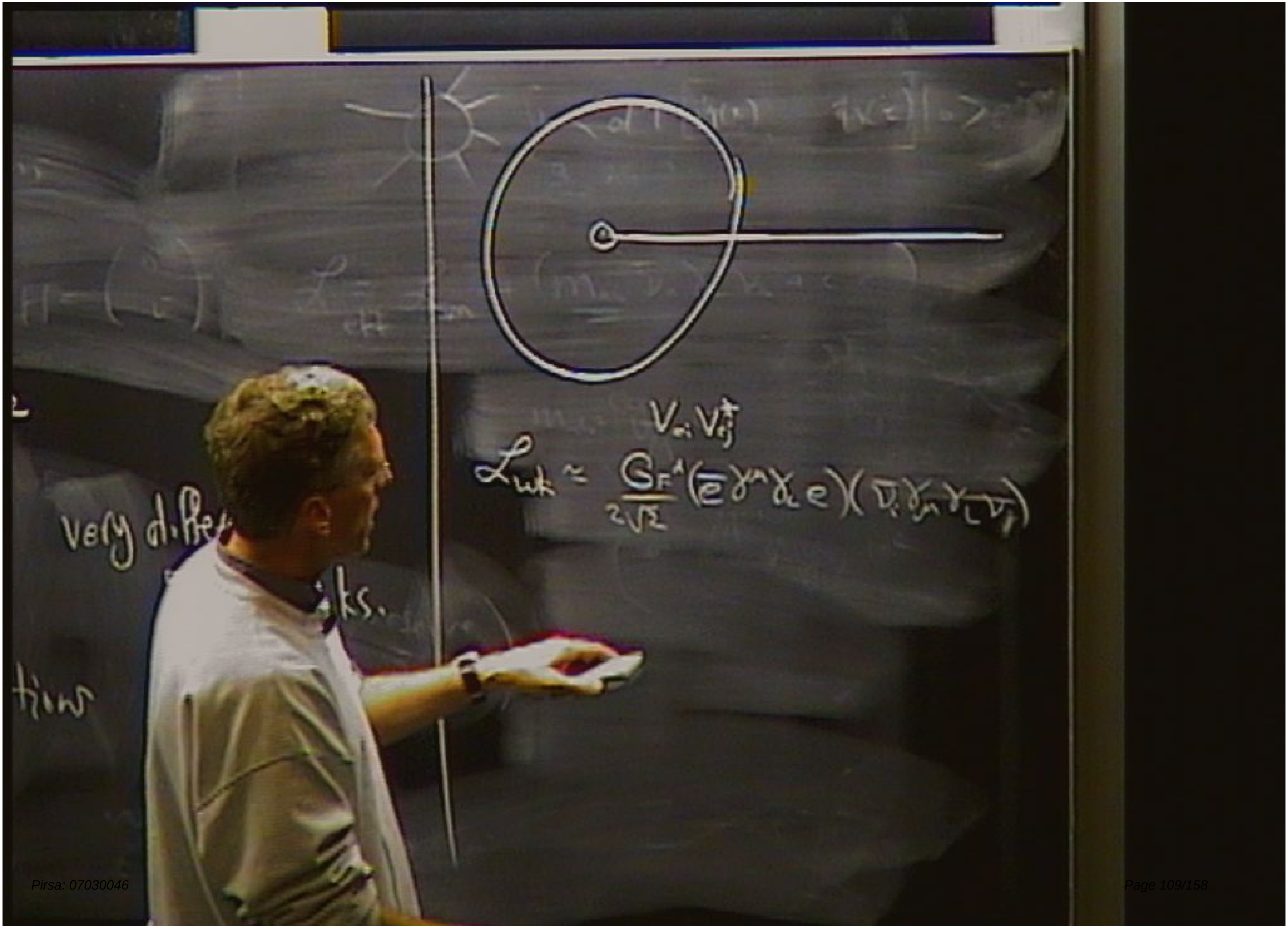
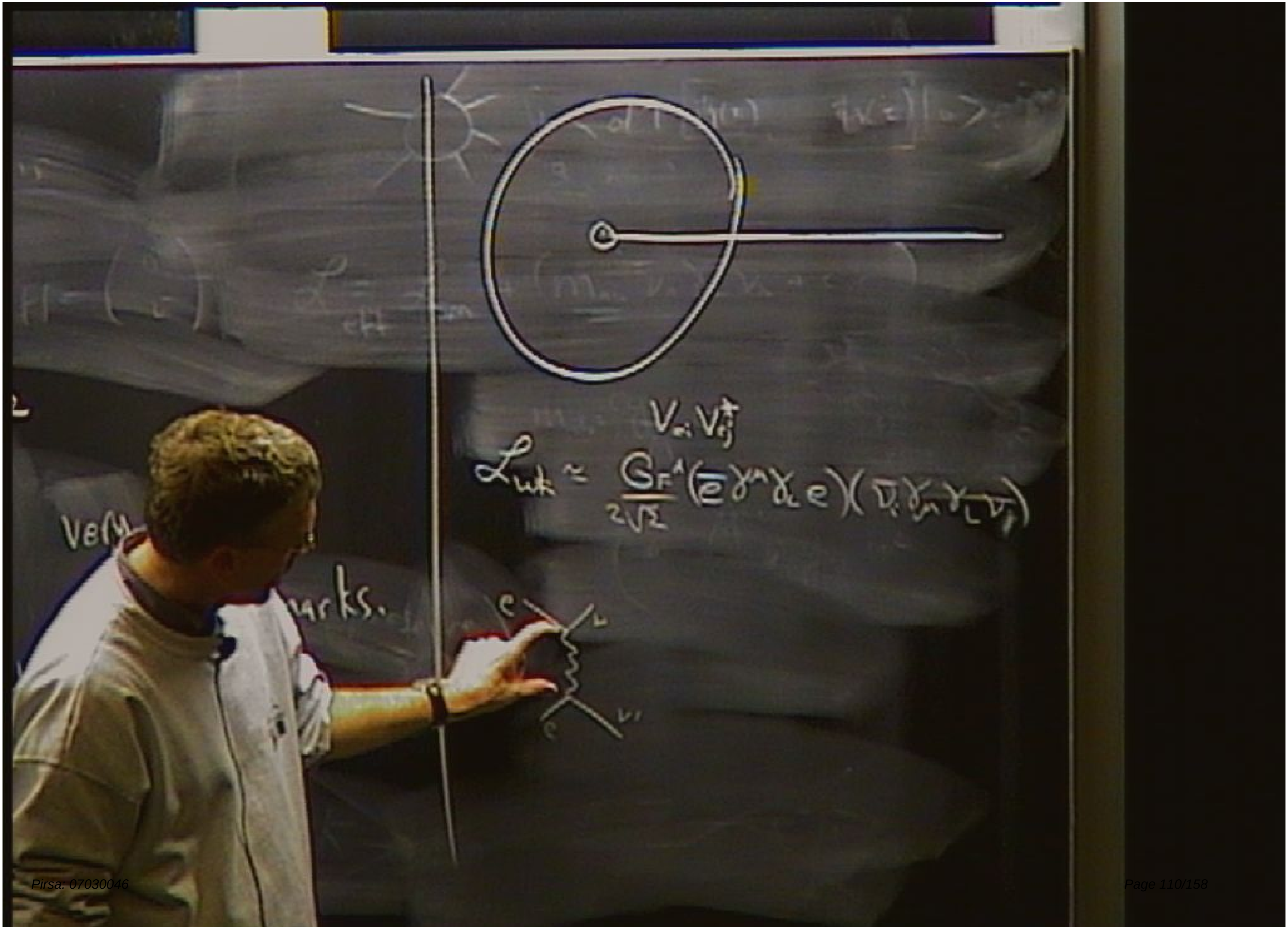
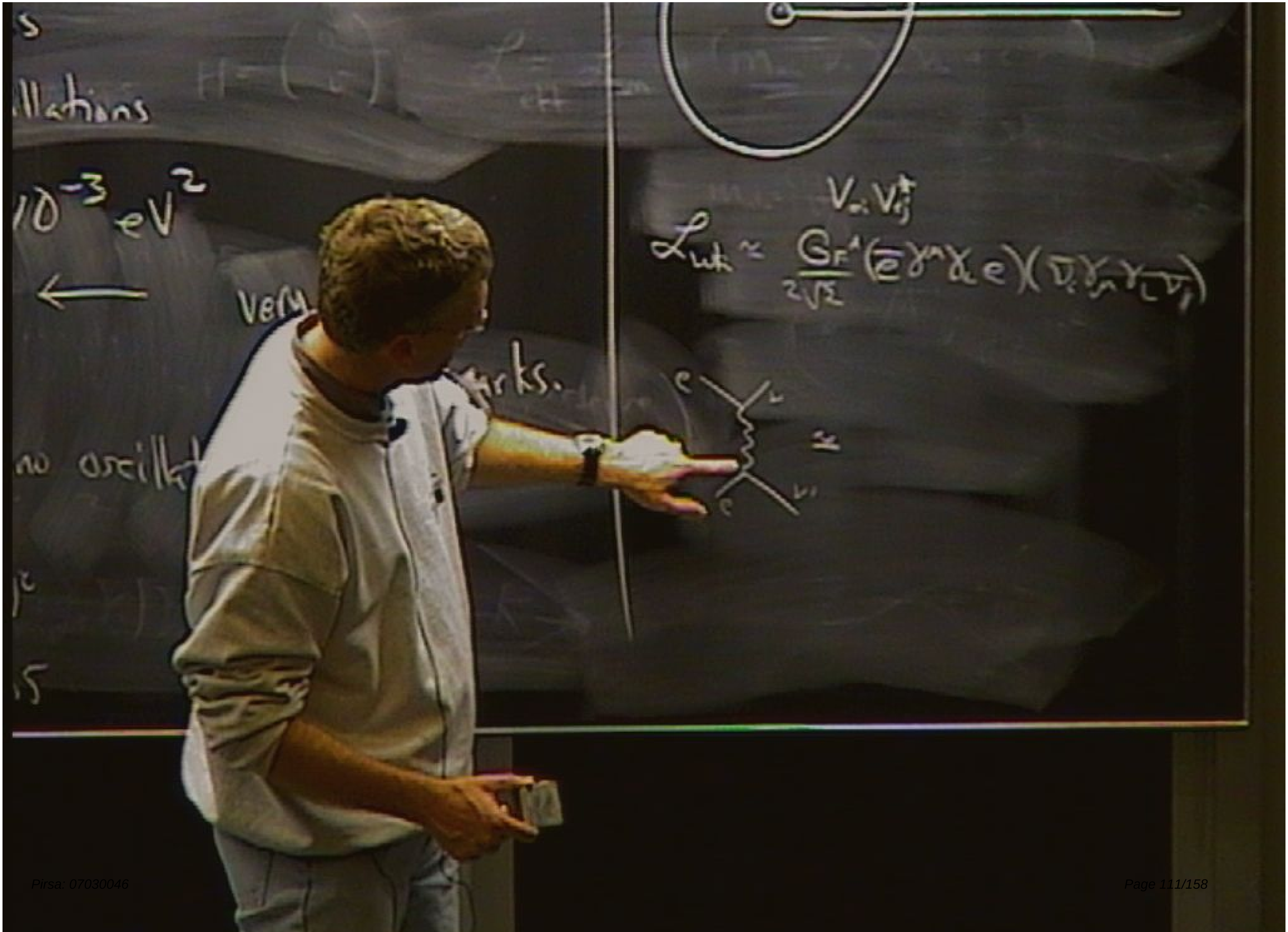
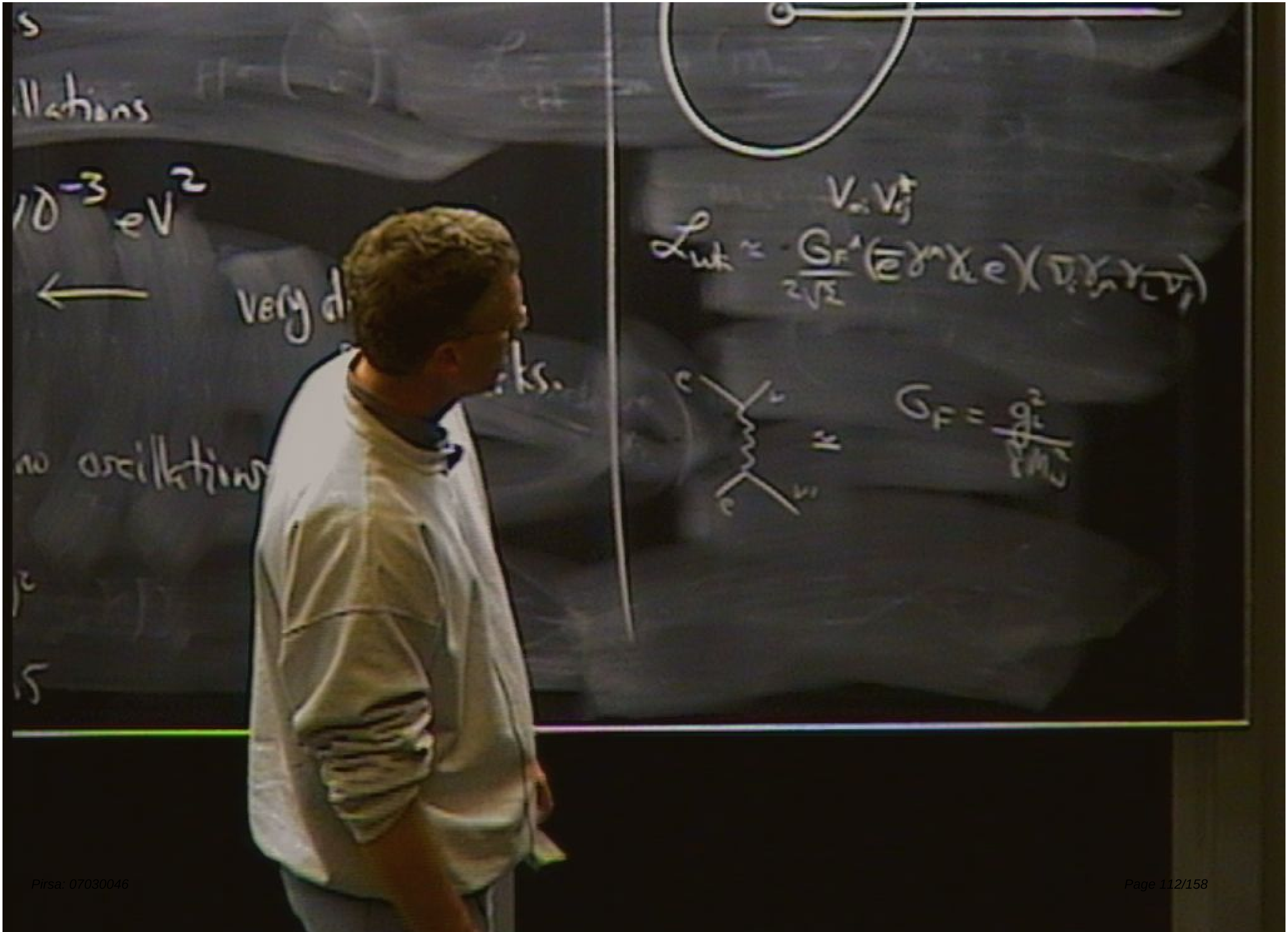


$V_{ei} V_{ej}^*$
$\mathcal{L}_{wk} \simeq \frac{G_F}{2\sqrt{2}} (\bar{e} \gamma^\mu \gamma_L e)(\bar{\nu}_i \gamma_\mu \gamma_L \nu_j)$
very


$V_{ei} V_{ej}^*$
$\mathcal{L}_{wk} \simeq \frac{G_F}{2\sqrt{2}} (\bar{e}\gamma^\mu \gamma_L e)(\bar{\nu}_i \gamma_\mu \gamma_L \nu_j)$
e
e


llations
10^{-3} eV^2
very
rks.
no oscill
$V_{ei} V_{ej}^*$
$\mathcal{L}_{wk} \approx \frac{G_F}{2\sqrt{2}} (\bar{e} \gamma^\mu \gamma_L e)(\bar{\nu}_i \gamma_\mu \gamma_L \nu_j)$
e
e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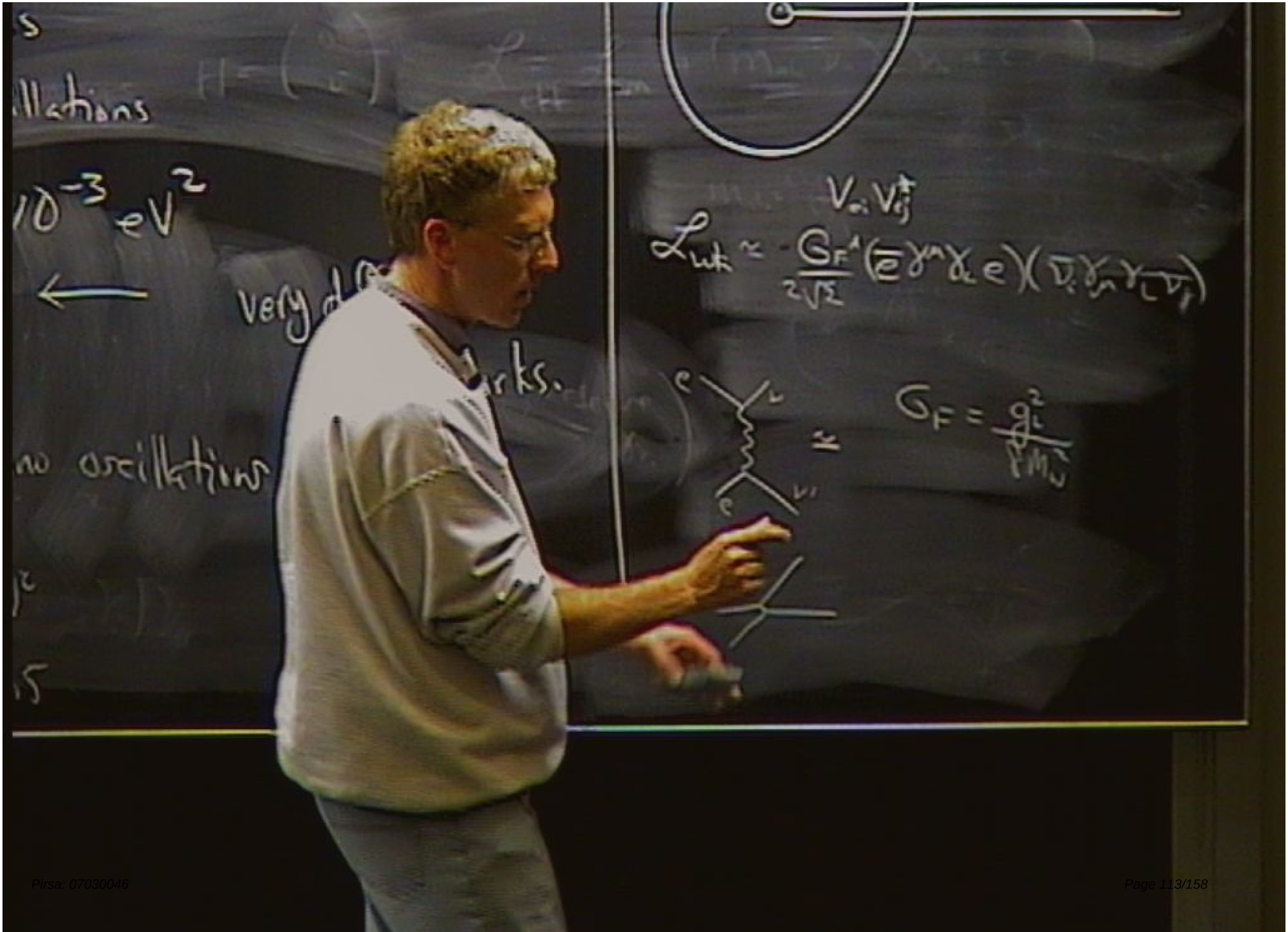
no oscillations
V_ei V_ej*
G_F = g^2 / 8M_W^2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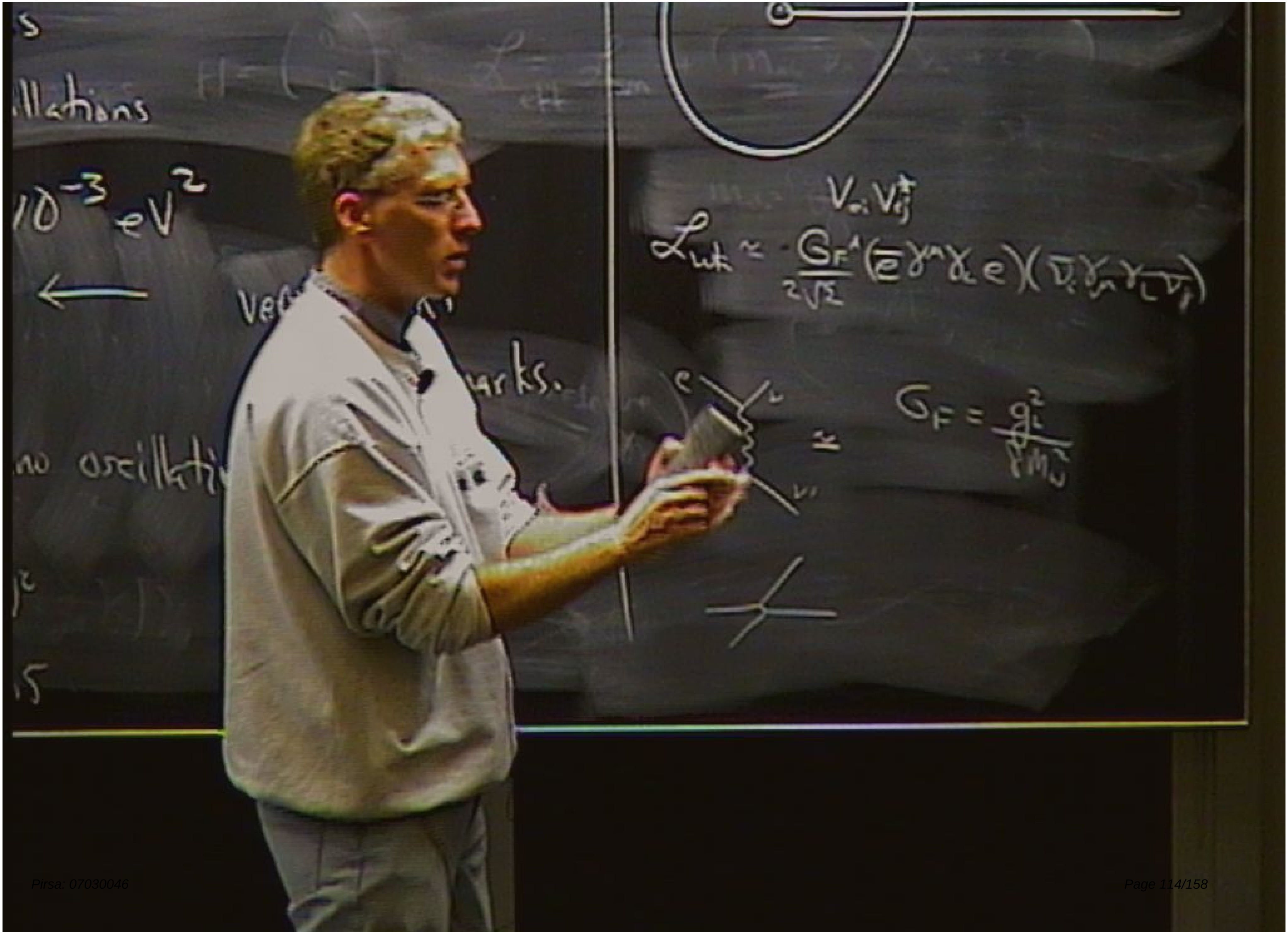
G_F = g^2 / 8 M_W^2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$V_{ei} V_{ej}^*$
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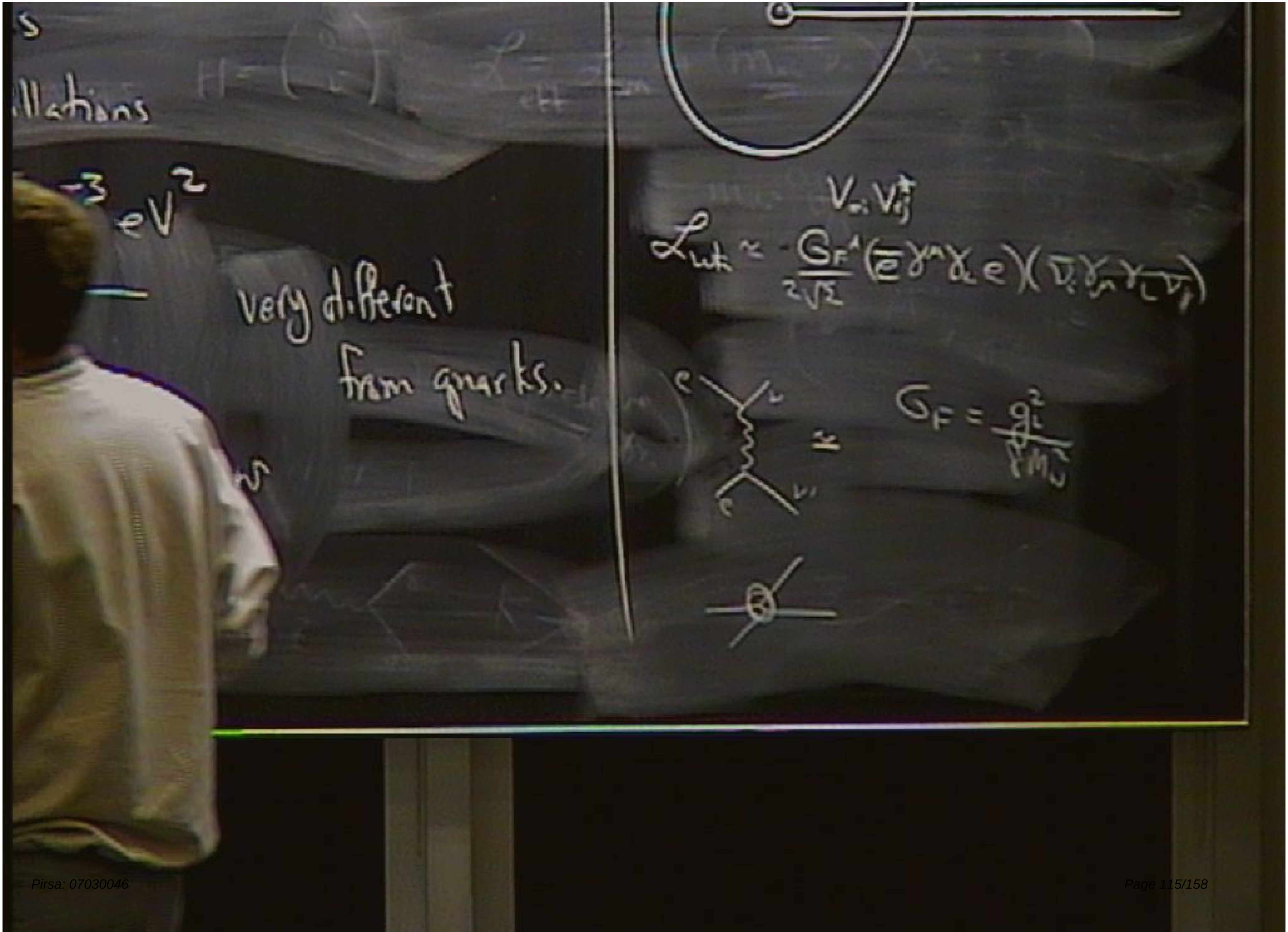
llations
eV²
very different
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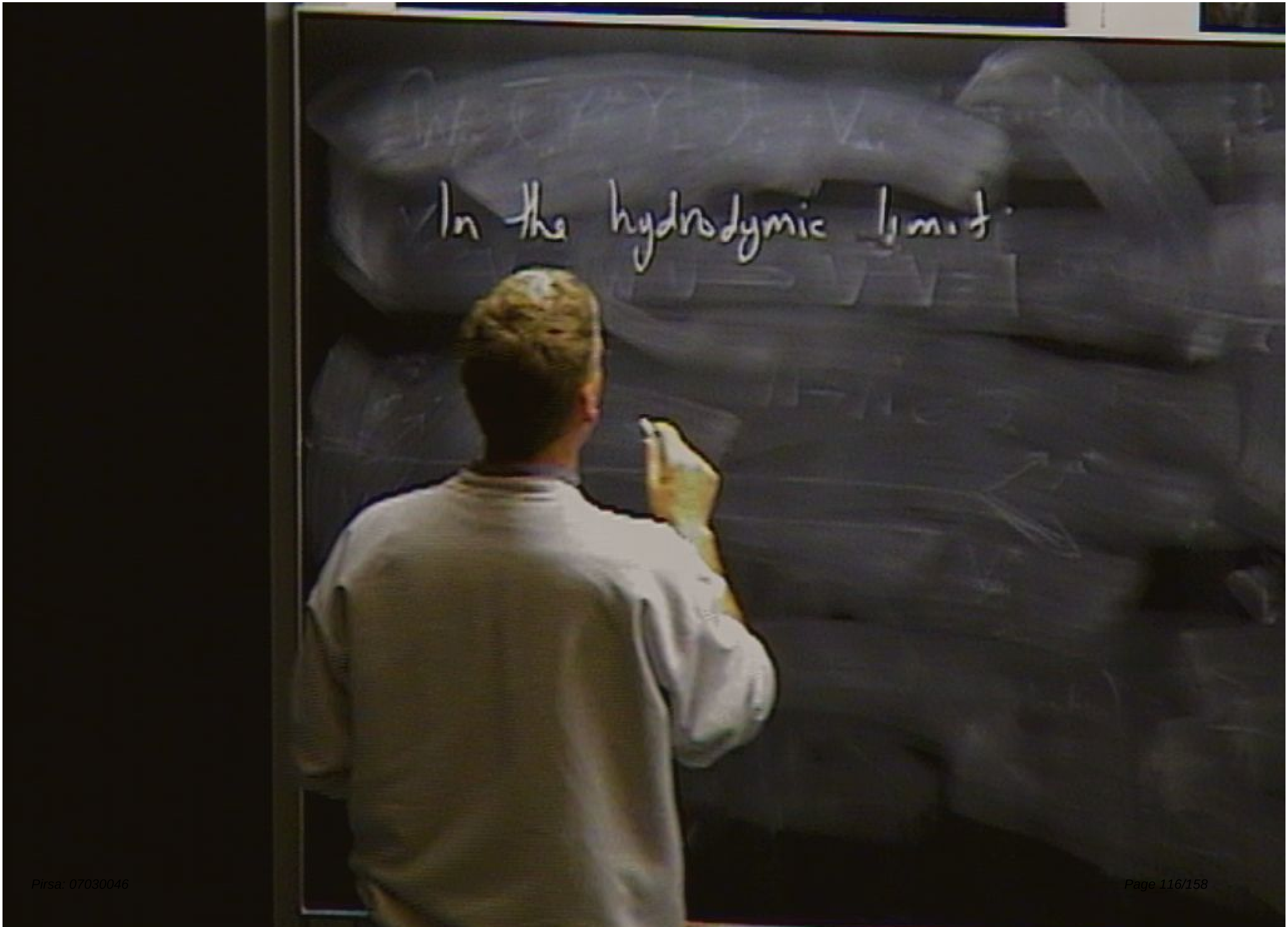
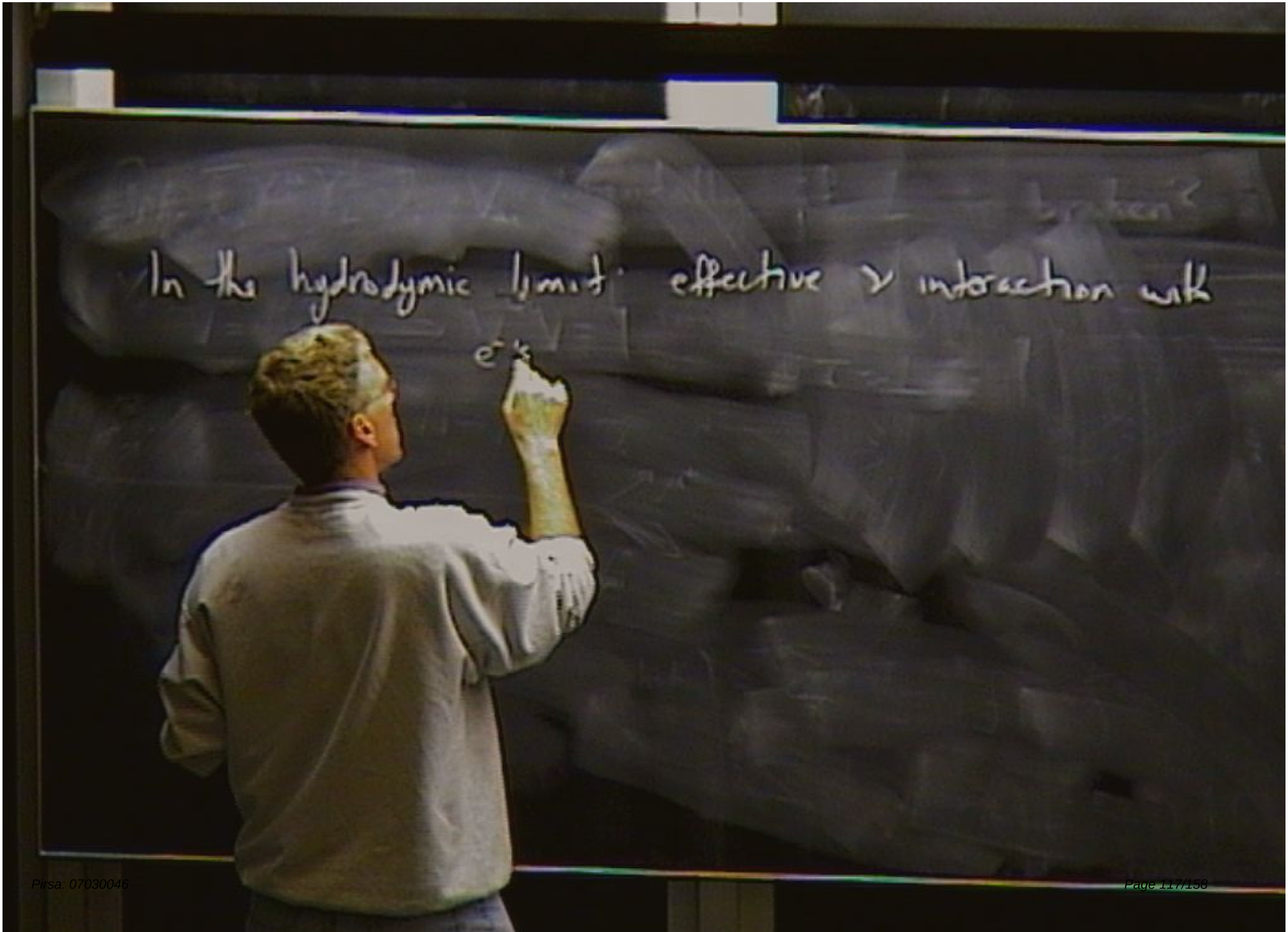
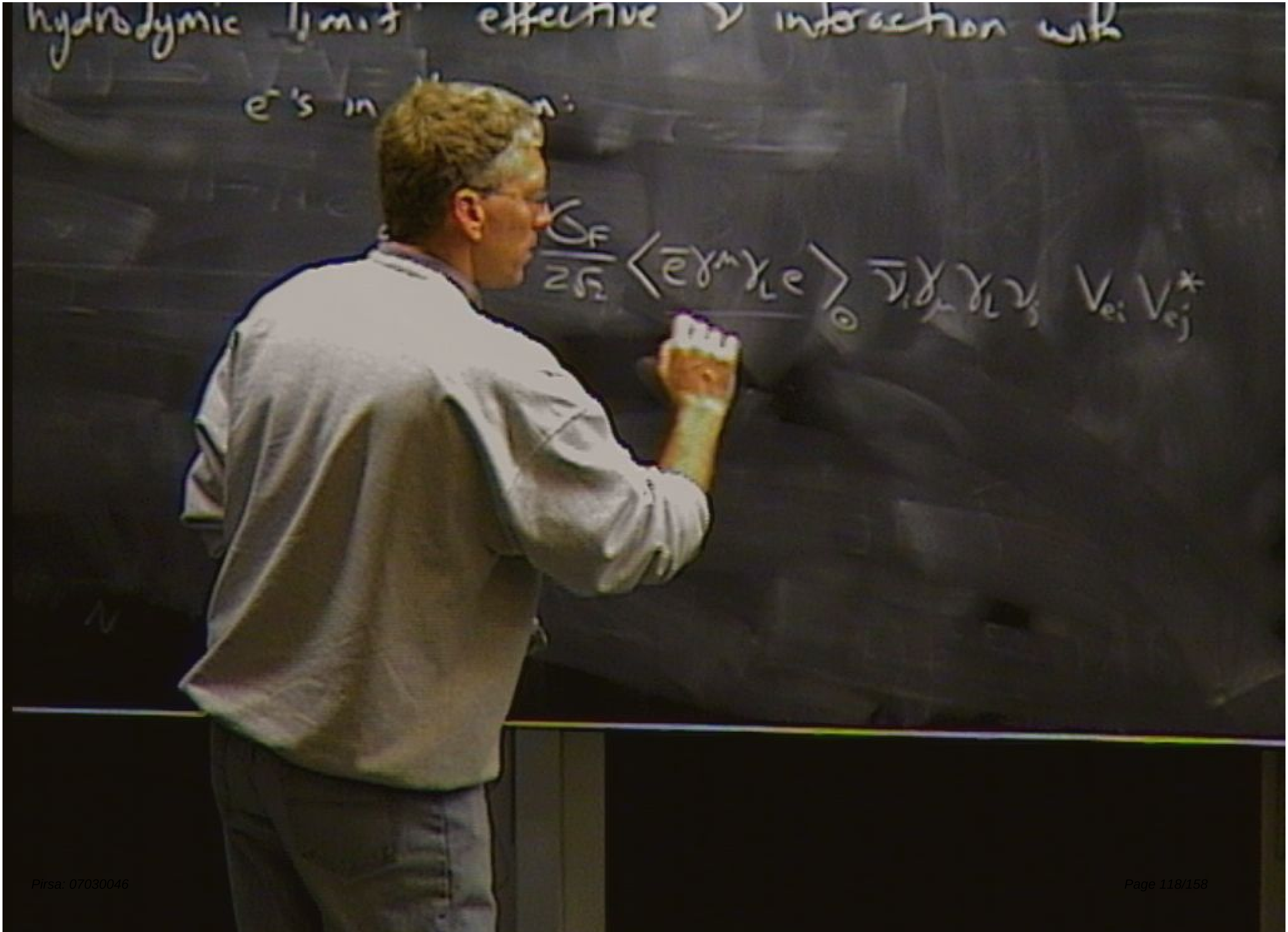
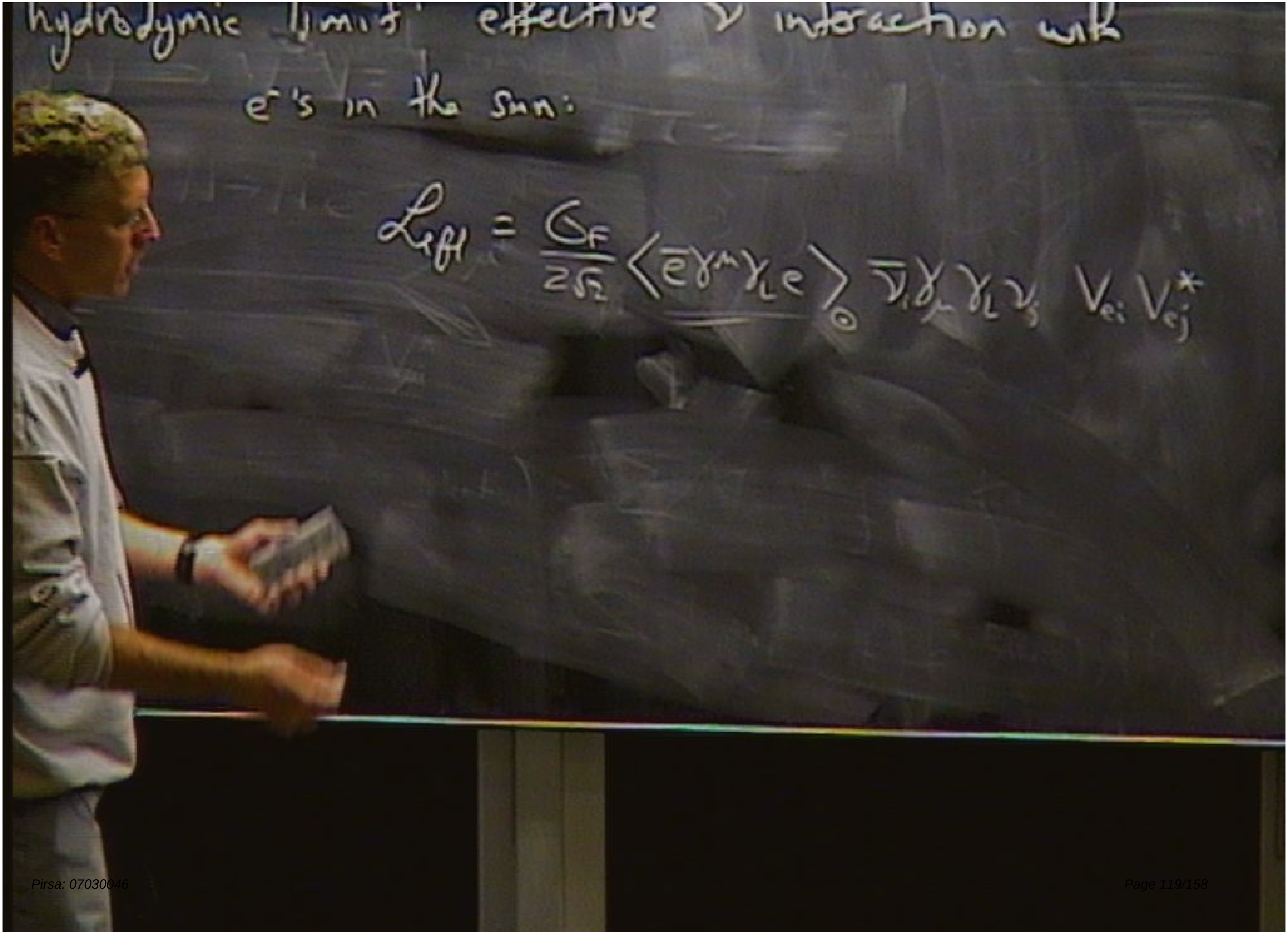
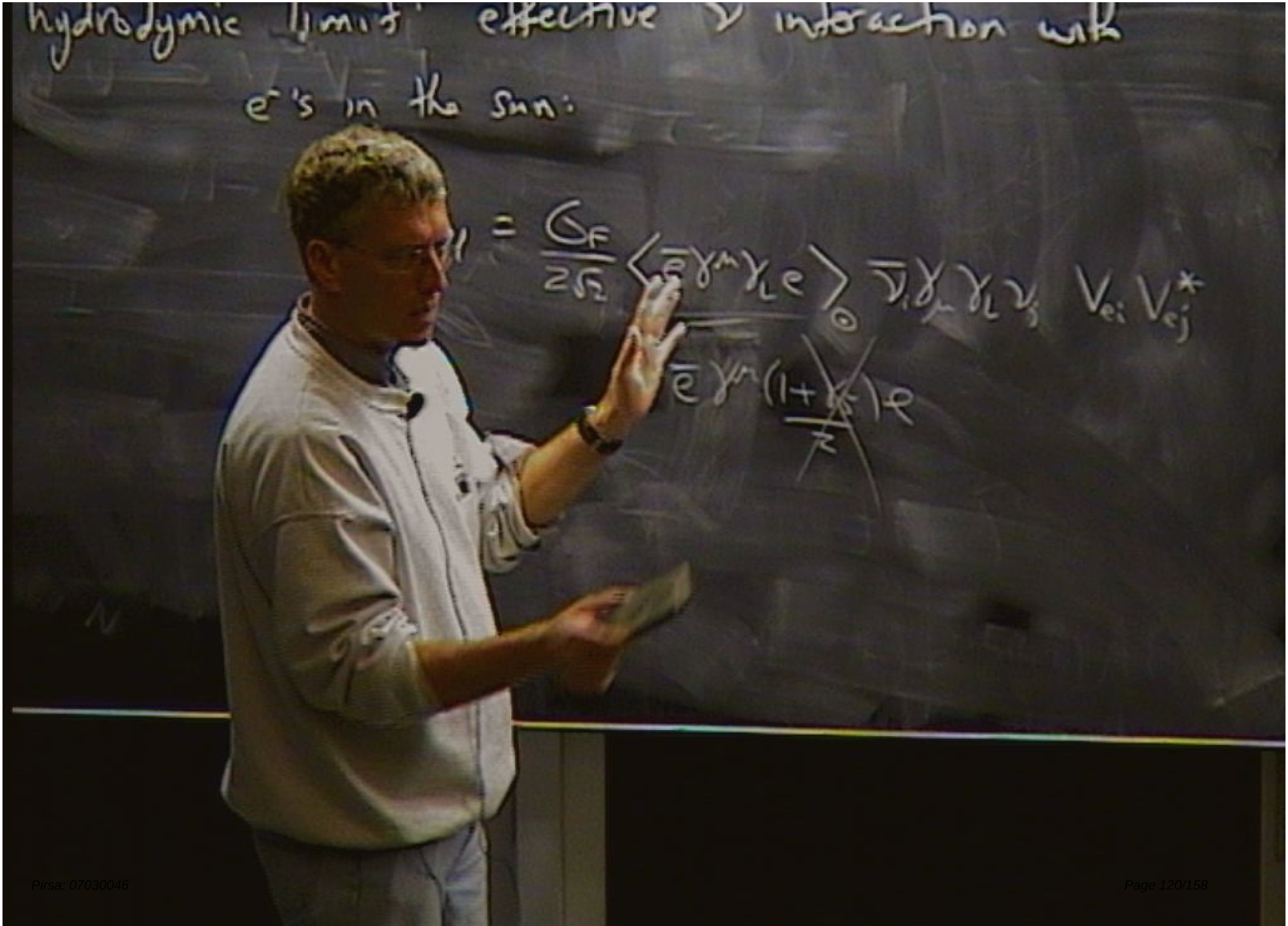
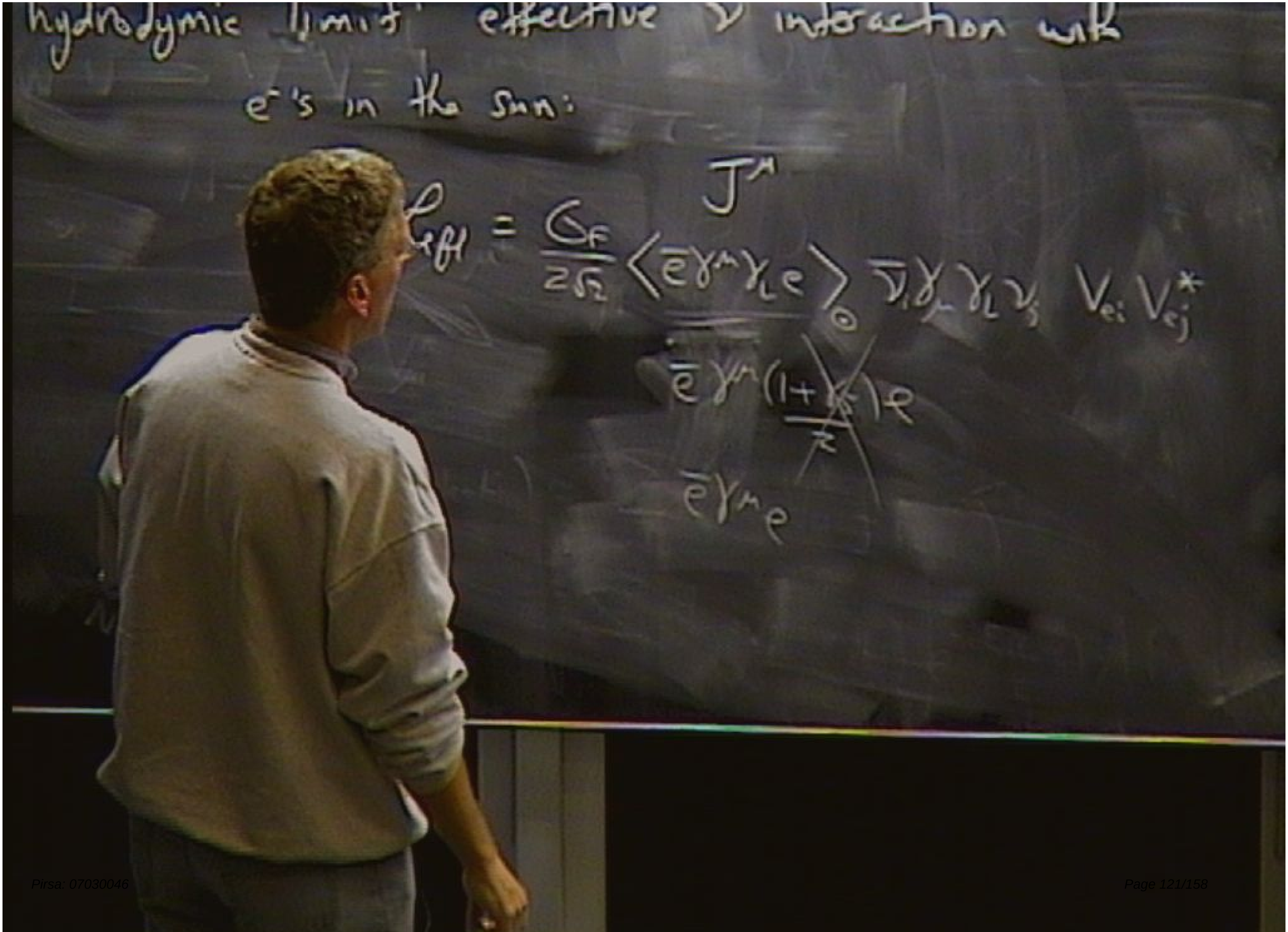

In the hydrodymic limit

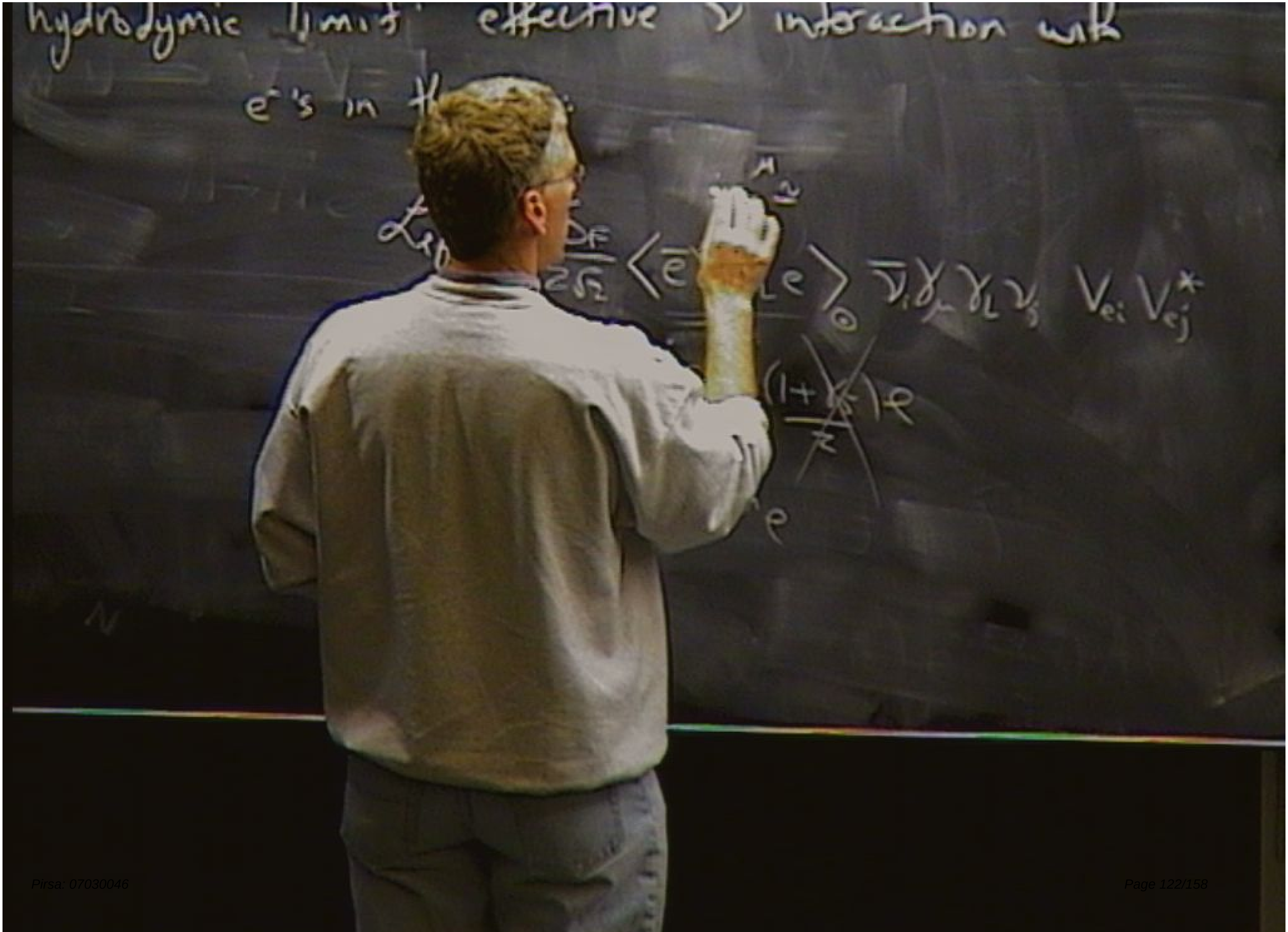

In the hydrodymic limit: effective ν interaction with

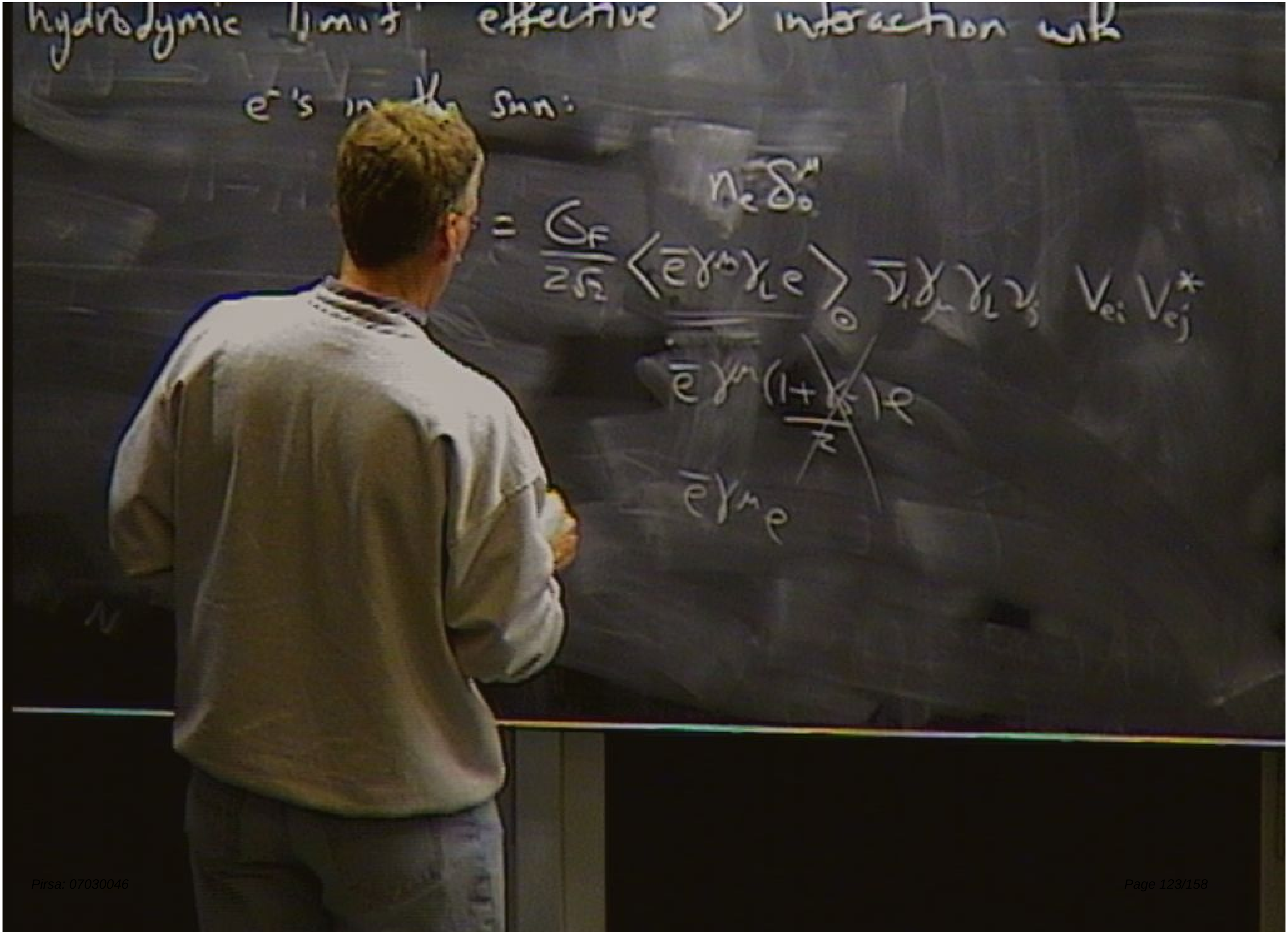

hydrodymic limit: effective ν interaction with
e⁻'s in
$\frac{G_F}{2\sqrt{2}} \langle \bar{e}\gamma^\mu \gamma_L e \rangle_0 \bar{\nu}_i \gamma_\mu \gamma_L \nu_j \; V_{ei} V_{ej}^*$

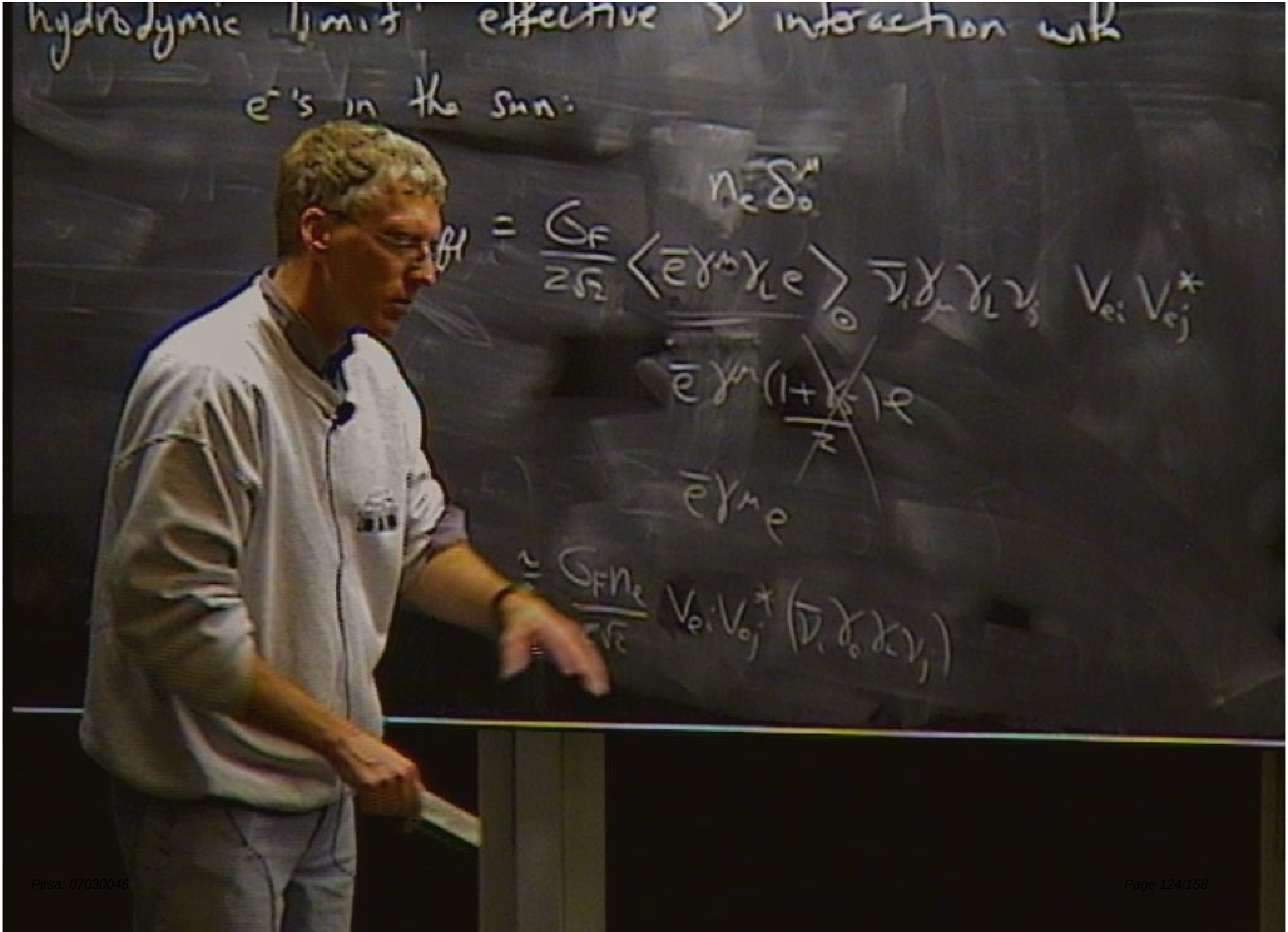

hydrodymic limit: effective ν interaction with
e^-'s in the sun:
$\mathcal{L}_{eff} = \frac{G_F}{2\sqrt{2}} \langle \bar{e}\gamma^{\mu}\gamma_L e \rangle_0 \, \bar{\nu}_i \gamma_{\mu} \gamma_L \nu_j \, V_{ei} V_{ej}^*$

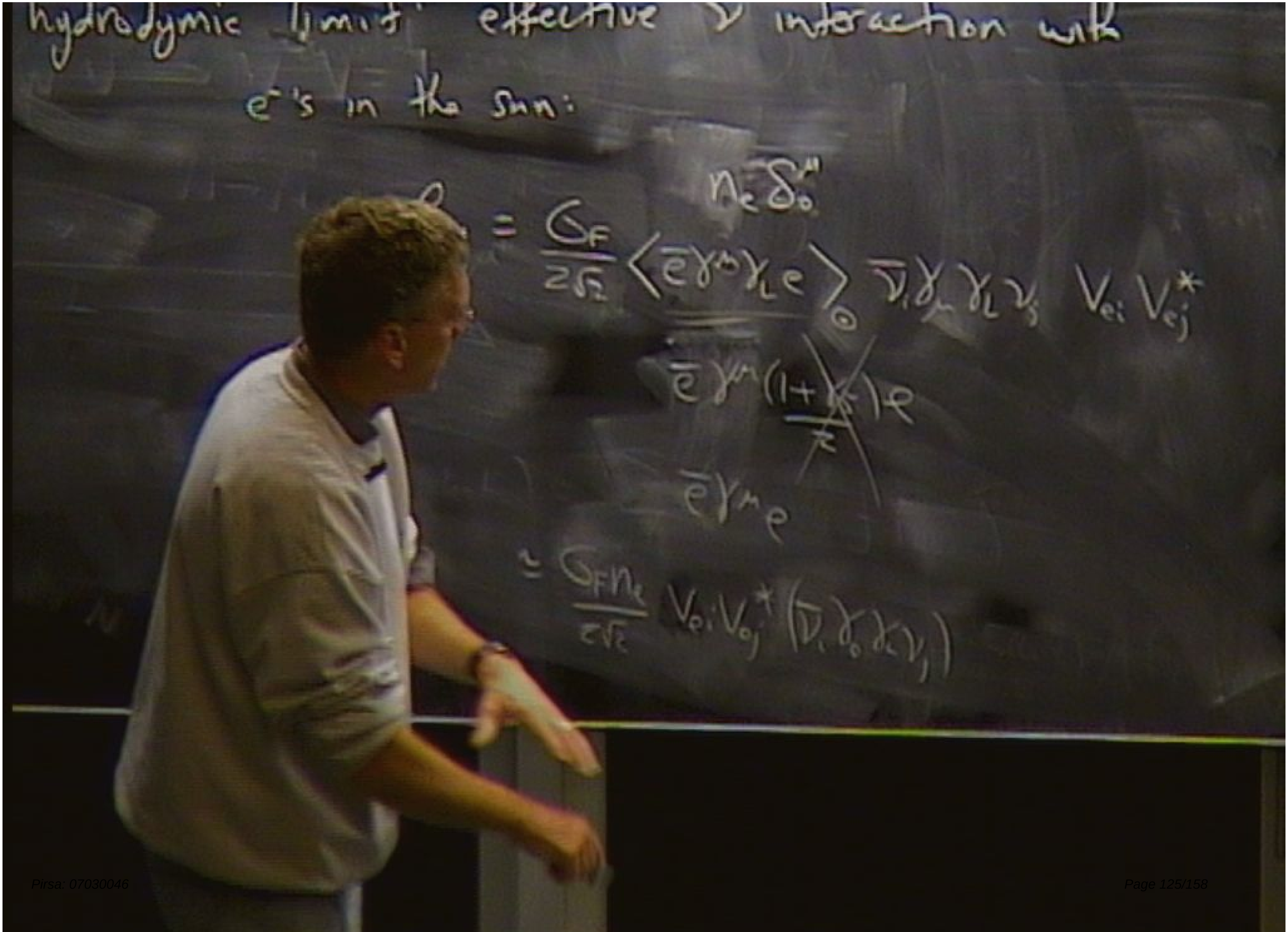

hydrodymic limit: effective ν interaction with
e⁻'s in the sun:
= G_F/2√2 ⟨ē γ^μ γ_L e⟩₀ ν̄_i γ_μ γ_L ν_j V_ei V*_ej
ē γ^μ (1+γ5)/2 e


hydrodymic limit: effective ν interaction with
e^-'s in the sun:
J^μ
$\mathcal{L}_{eff} = \frac{G_F}{2\sqrt{2}} \langle \bar{e}\gamma^\mu \gamma_L e \rangle_0 \bar{\nu}_i \gamma_\mu \gamma_L \nu_j \; V_{ei} V_{ej}^*$
$\bar{e}\gamma^\mu \left(\frac{1+\cancel{\gamma_5}}{2}\right) e$
$\bar{e}\gamma^\mu e$


hydrodymic limit: effective ν interaction with
e⁻'s in th


hydrodymic limit: effective ν interaction with
e⁻'s in the sun:
$n_e \delta_0^\mu$
$= \frac{G_F}{2\sqrt{2}} \langle \bar{e} \gamma^\mu \gamma_L e \rangle_0 \, \bar{\nu}_i \gamma_\mu \gamma_L \nu_j \; V_{ei} V_{ej}^*$
$\bar{e} \gamma^\mu \frac{(1+\gamma_5)}{2} e$
$\bar{e} \gamma^\mu e$


hydrodymic limit: effective ν interaction with
e^-'s in the sun:
$n_e \delta^\mu_0$
$= \frac{G_F}{2\sqrt{2}} \langle \bar{e}\gamma^\mu \gamma_L e \rangle_0 \, \bar{\nu}_i \gamma_\mu \gamma_L \nu_j \; V_{ei} V^*_{ej}$
$\bar{e}\gamma^\mu \left(\frac{1+\gamma_5}{2}\right) e$
$\bar{e}\gamma^\mu e$
$\simeq \frac{G_F n_e}{\sqrt{2}} V_{ei} V^*_{ej} \left(\bar{\nu}_i \gamma_0 \gamma_L \nu_j\right)$


hydrodymic limit: effective ν interaction with
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$n_e \delta^\mu_0$
$\mathcal{L} = \frac{G_F}{2\sqrt{2}} \langle \bar{e}\gamma^\mu \gamma_L e \rangle_0 \, \bar{\nu}_i \gamma_\mu \gamma_L \nu_j \; V_{ei} V_{ej}^*$
$\bar{e}\gamma^\mu \left(\frac{1+\cancel{\gamma_5}}{2}\right) e$
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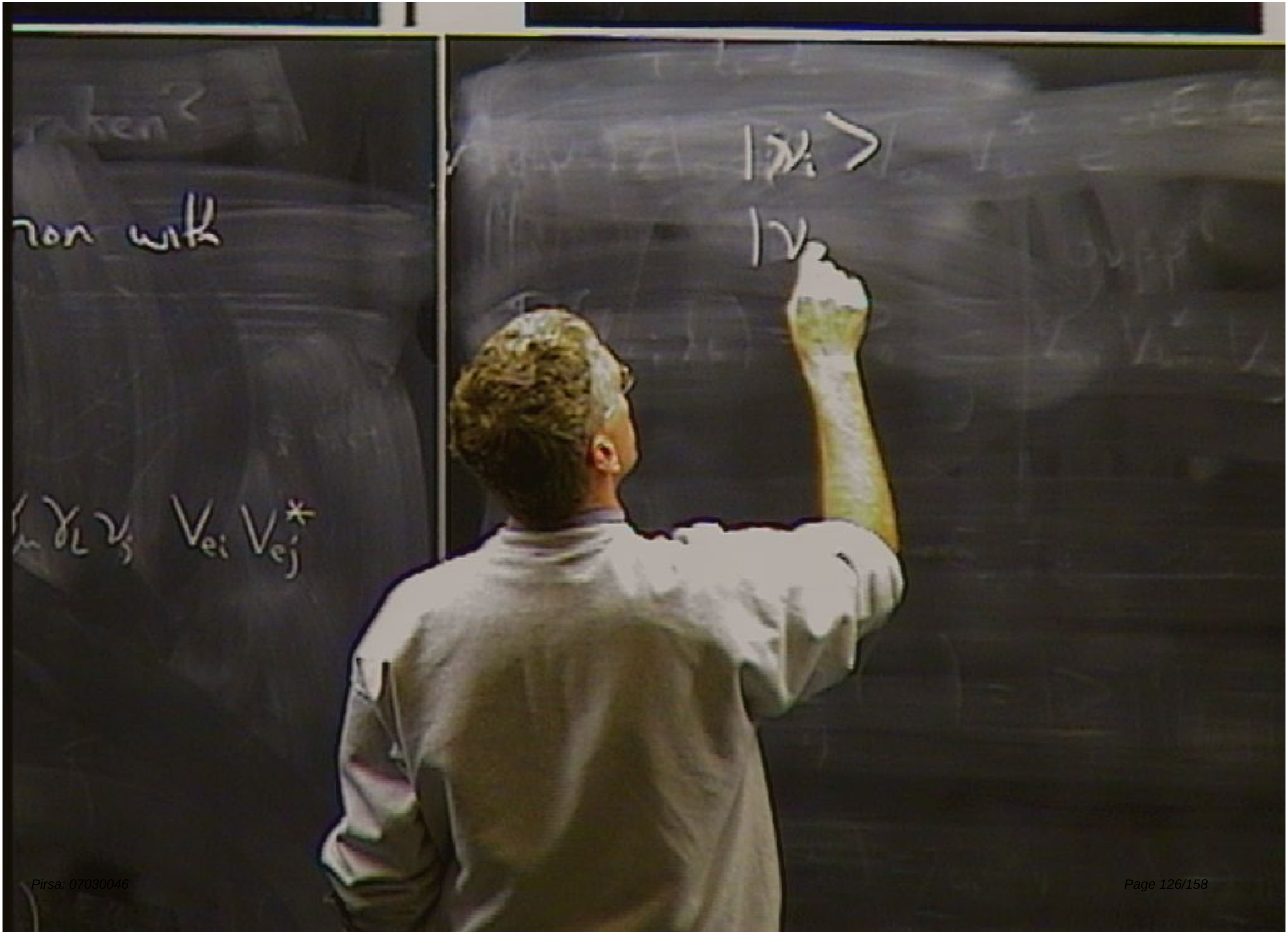
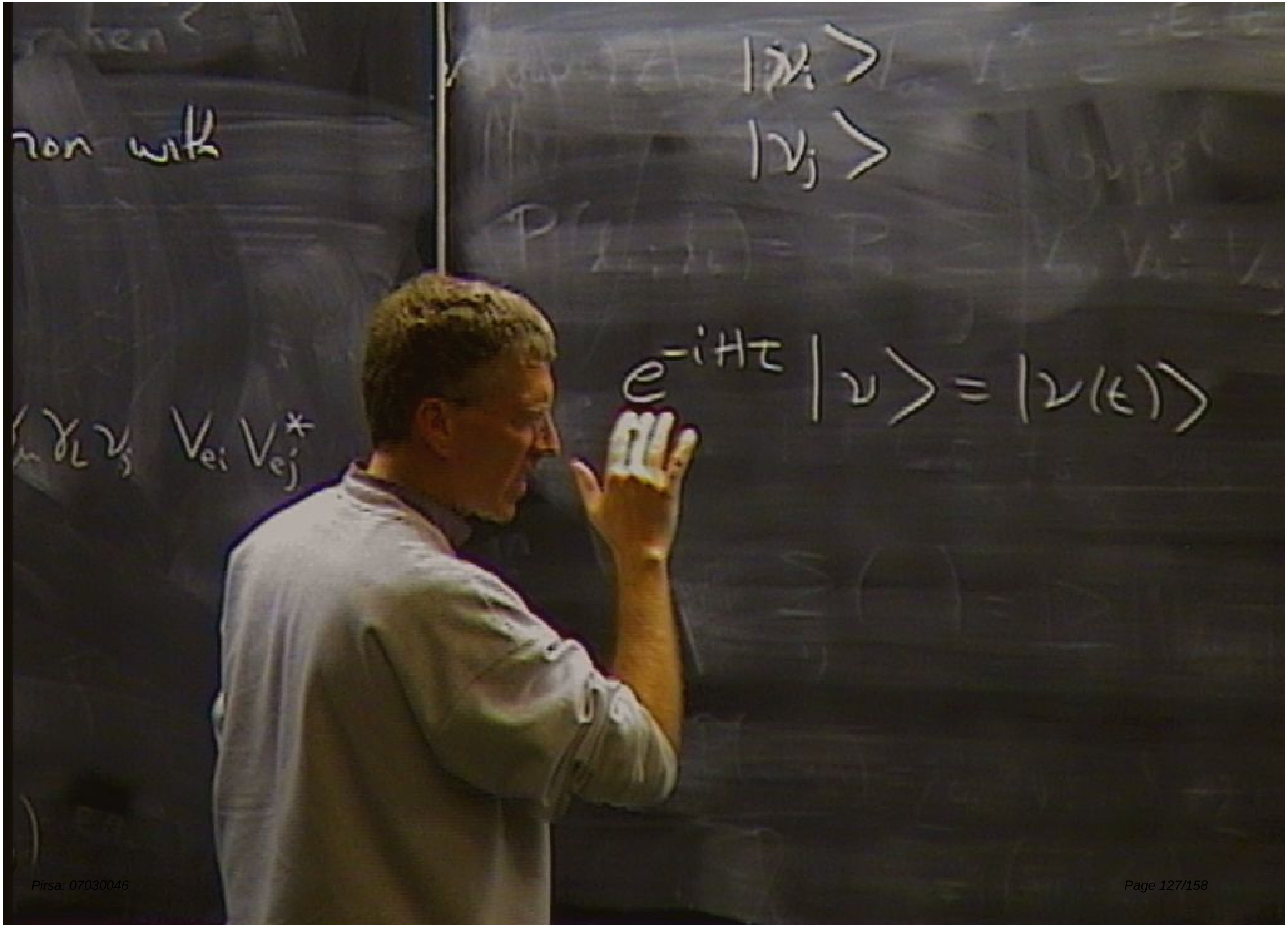
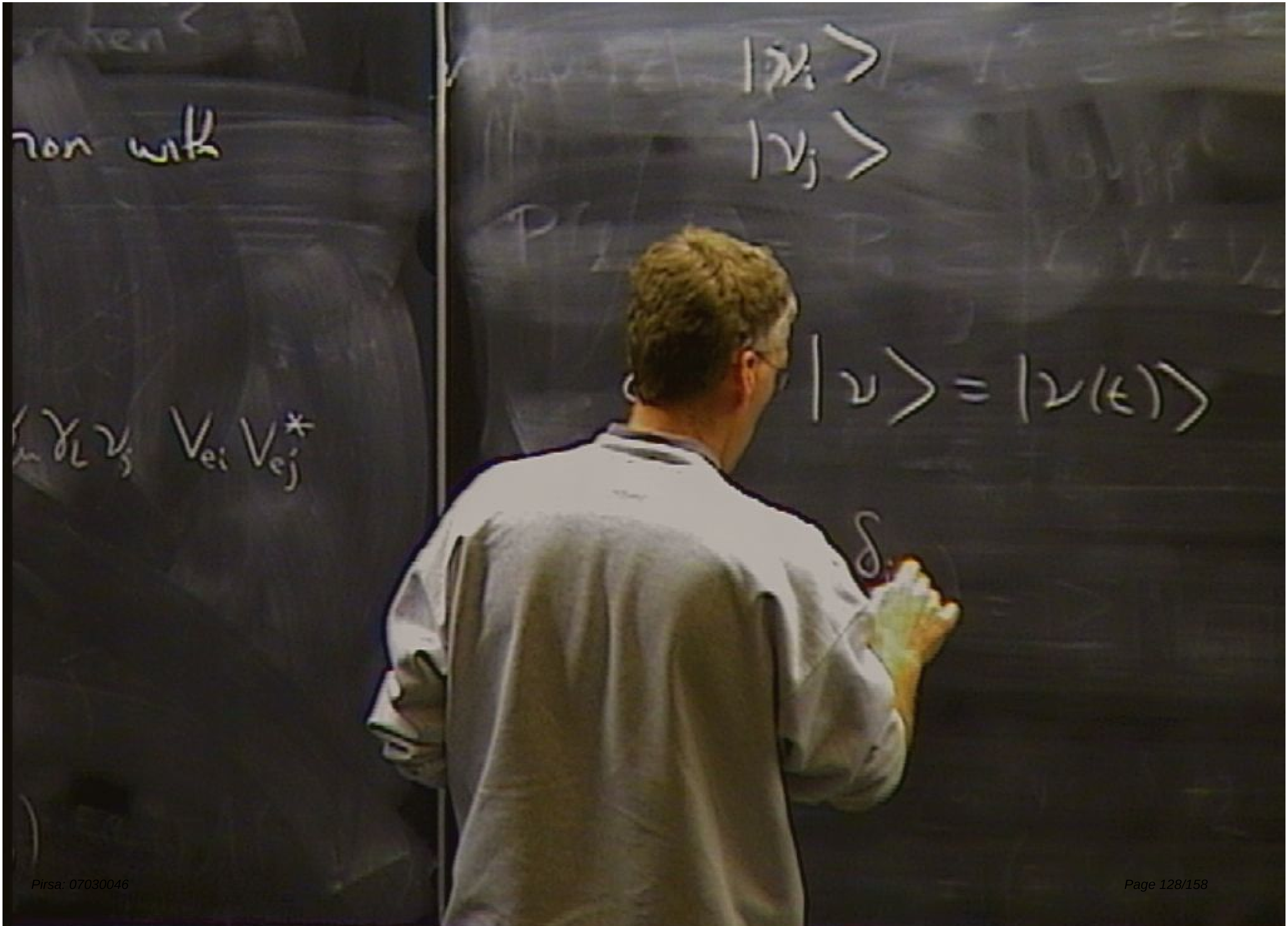
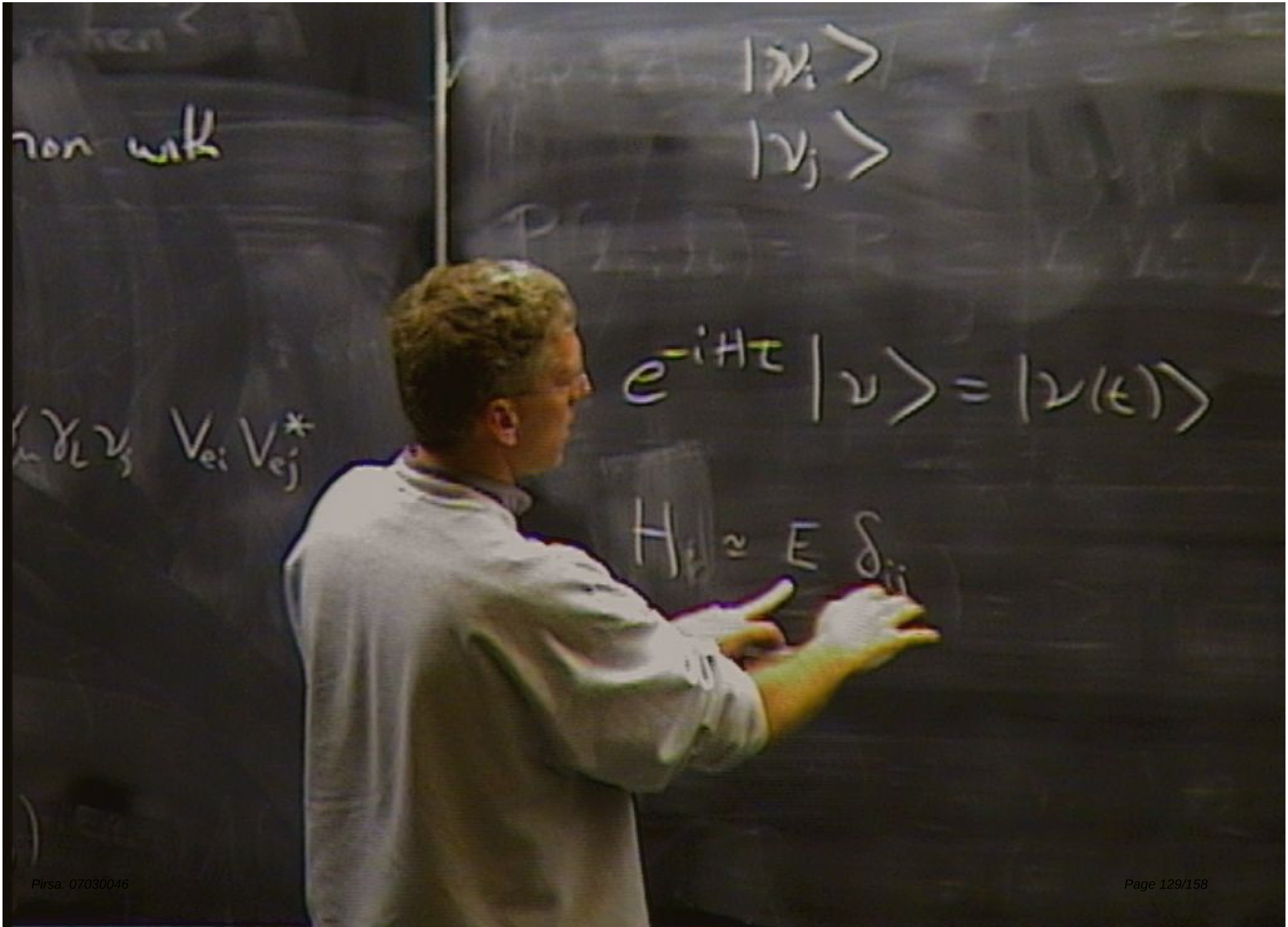
$\simeq \frac{G_F n_e}{2\sqrt{2}} V_{ei} V_{ej}^* \left(\bar{\nu}_i \gamma_0 \gamma_L \nu_j\right)$

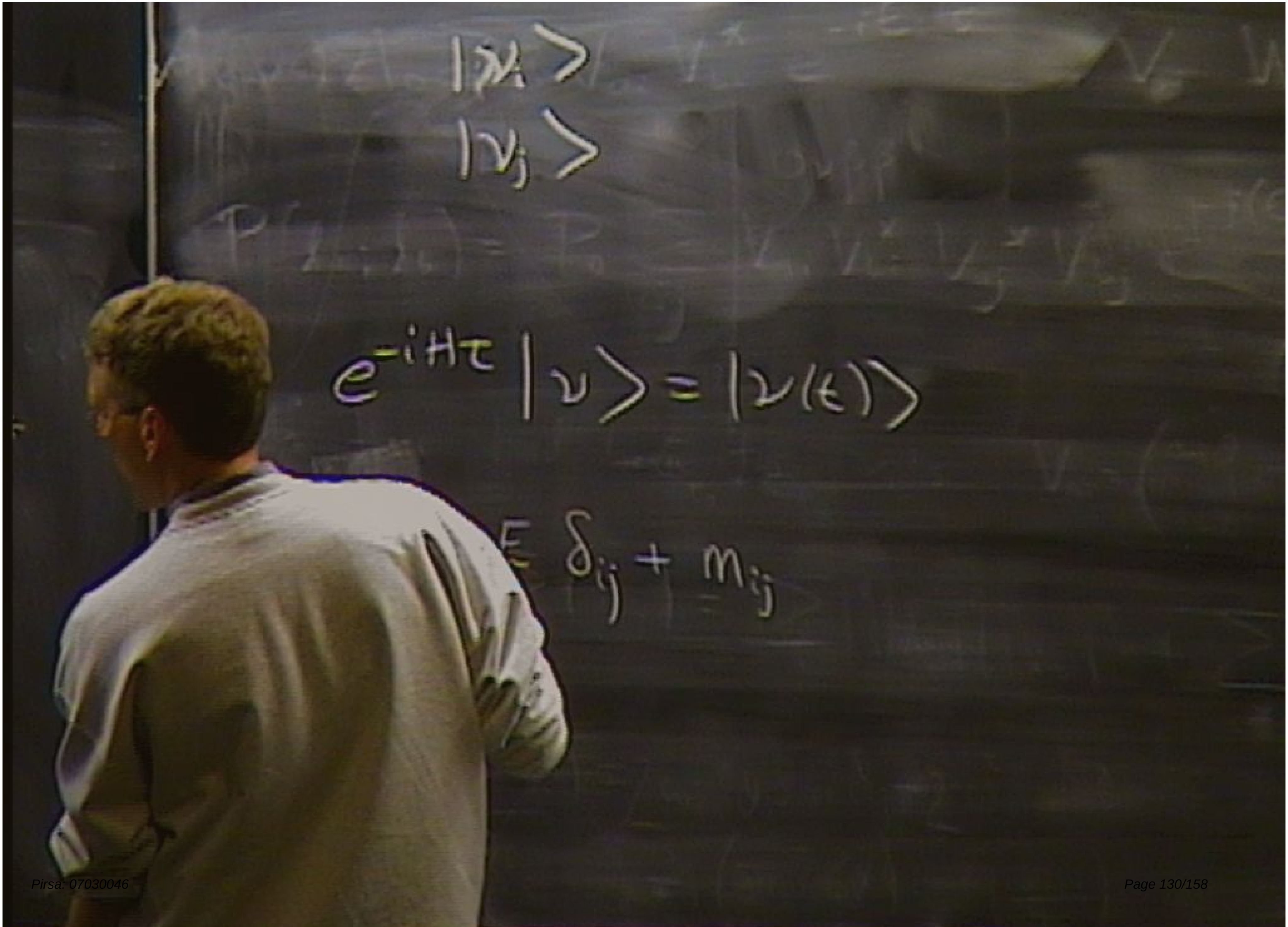

non with
$V_{ei} V_{ej}^*$
$|\nu_i\rangle$
$|\nu$


non with
$|\nu_i\rangle$
$|\nu_j\rangle$
$V_{ei} V_{ej}^*$
$e^{-iHt}|\nu\rangle = |\nu(t)\rangle$

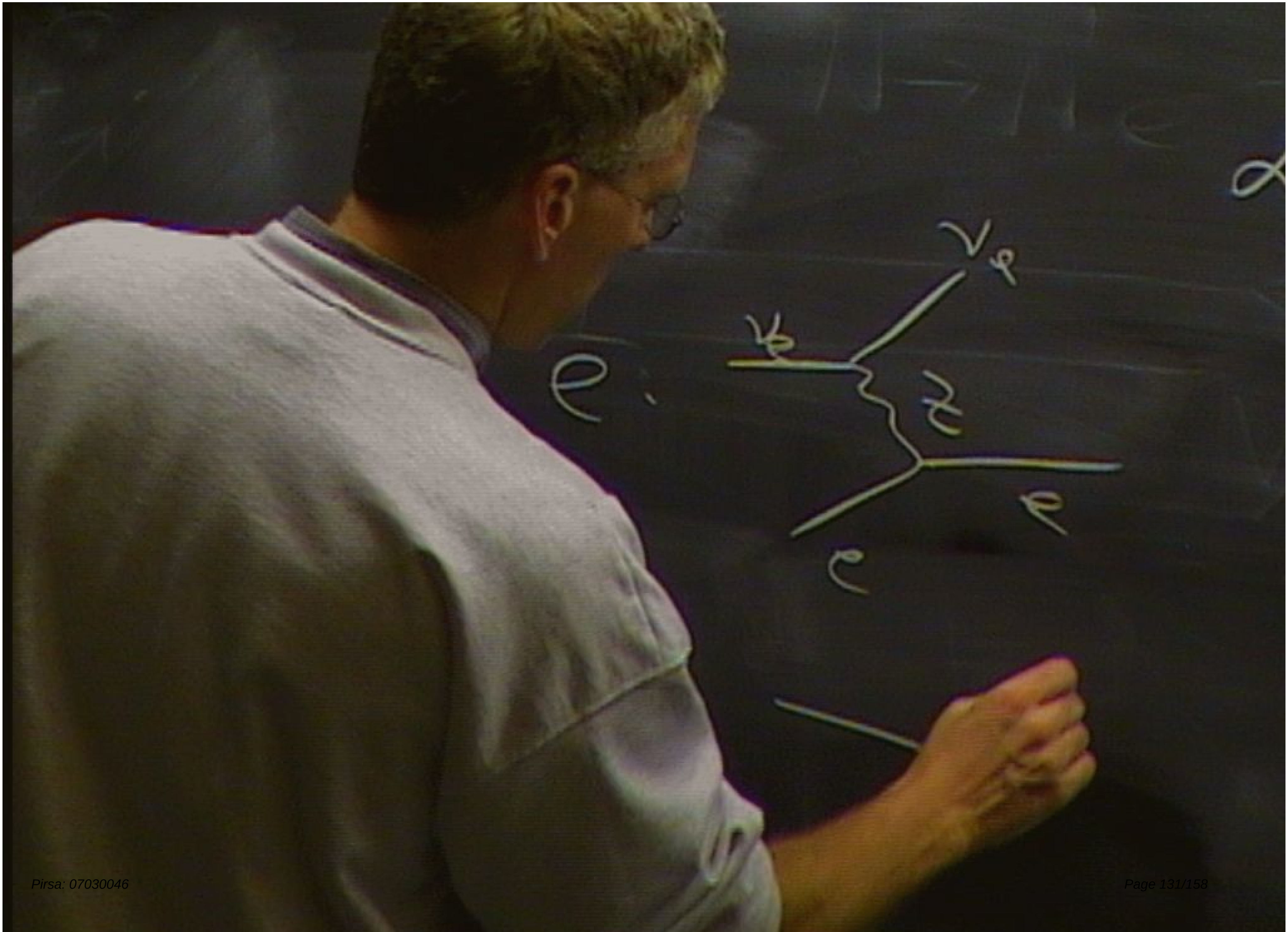

non with
|ν_i >
|ν_j >
|ν > = |ν(t)>
V_ei V*_ej

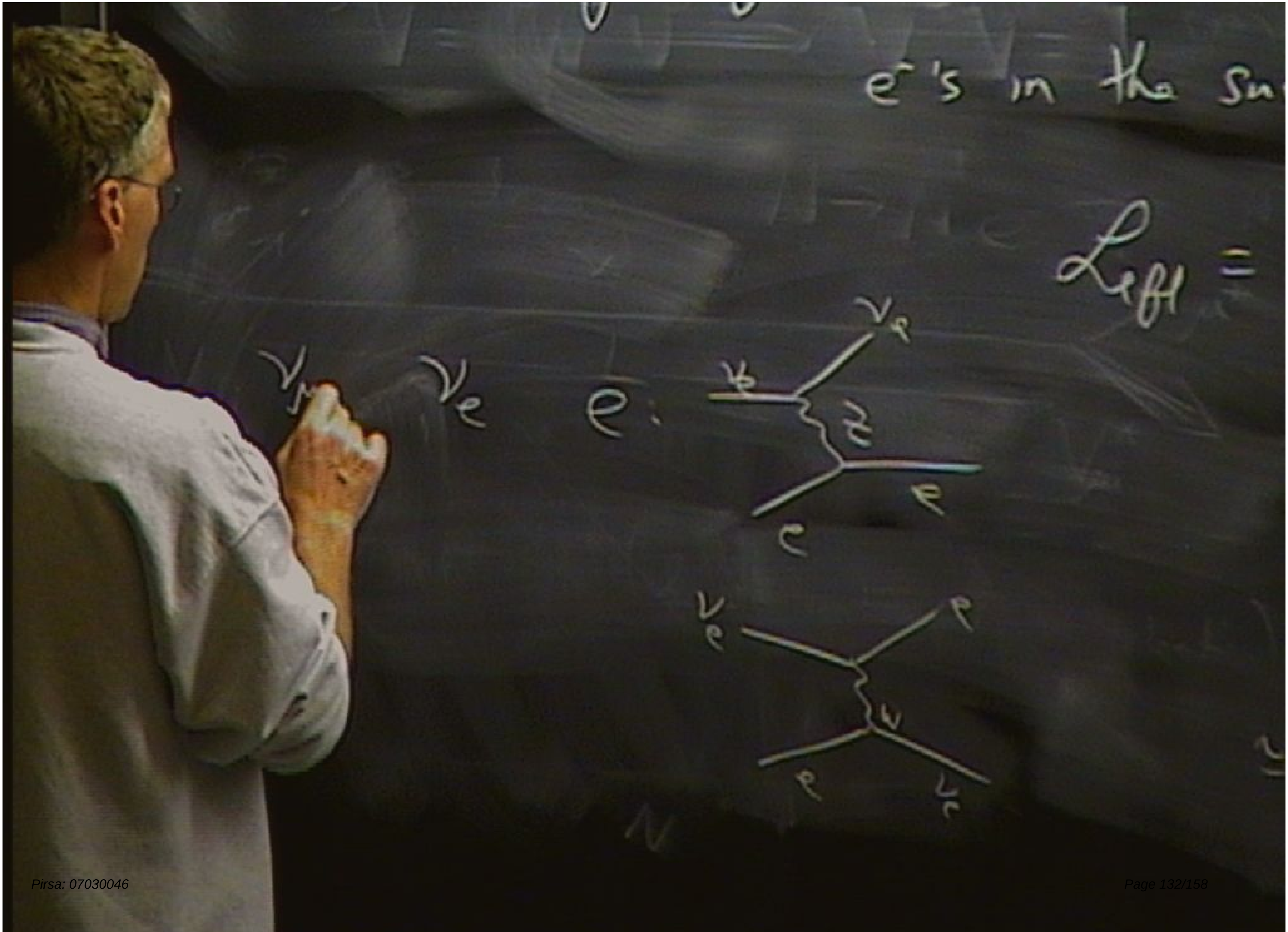


non wk
$\gamma_L \nu_j \quad V_{ei} V_{ej}^*$
$|\nu_i\rangle$
$|\nu_j\rangle$
$e^{-iHt}|\nu\rangle = |\nu(t)\rangle$
$H_{ij} \approx E\,\delta_{ij}$



$|\nu_i\rangle$
$|\nu_j\rangle$
$e^{-iHt}|\nu\rangle = |\nu(t)\rangle$
$E\,\delta_{ij} + m_{ij}$


e:
ν_e
ν_e
Z
e
e

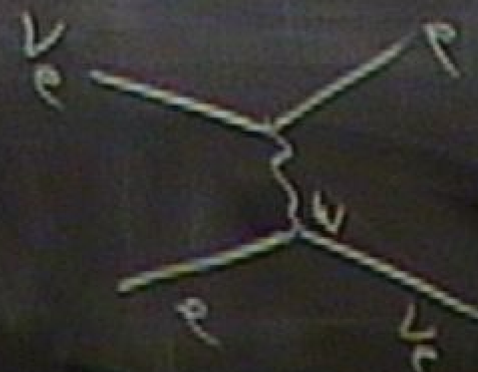


e⁻'s in the Su
Left =
ν_μ ν_e e:
ν_e
Z
e
e
ν_e
e
W
e

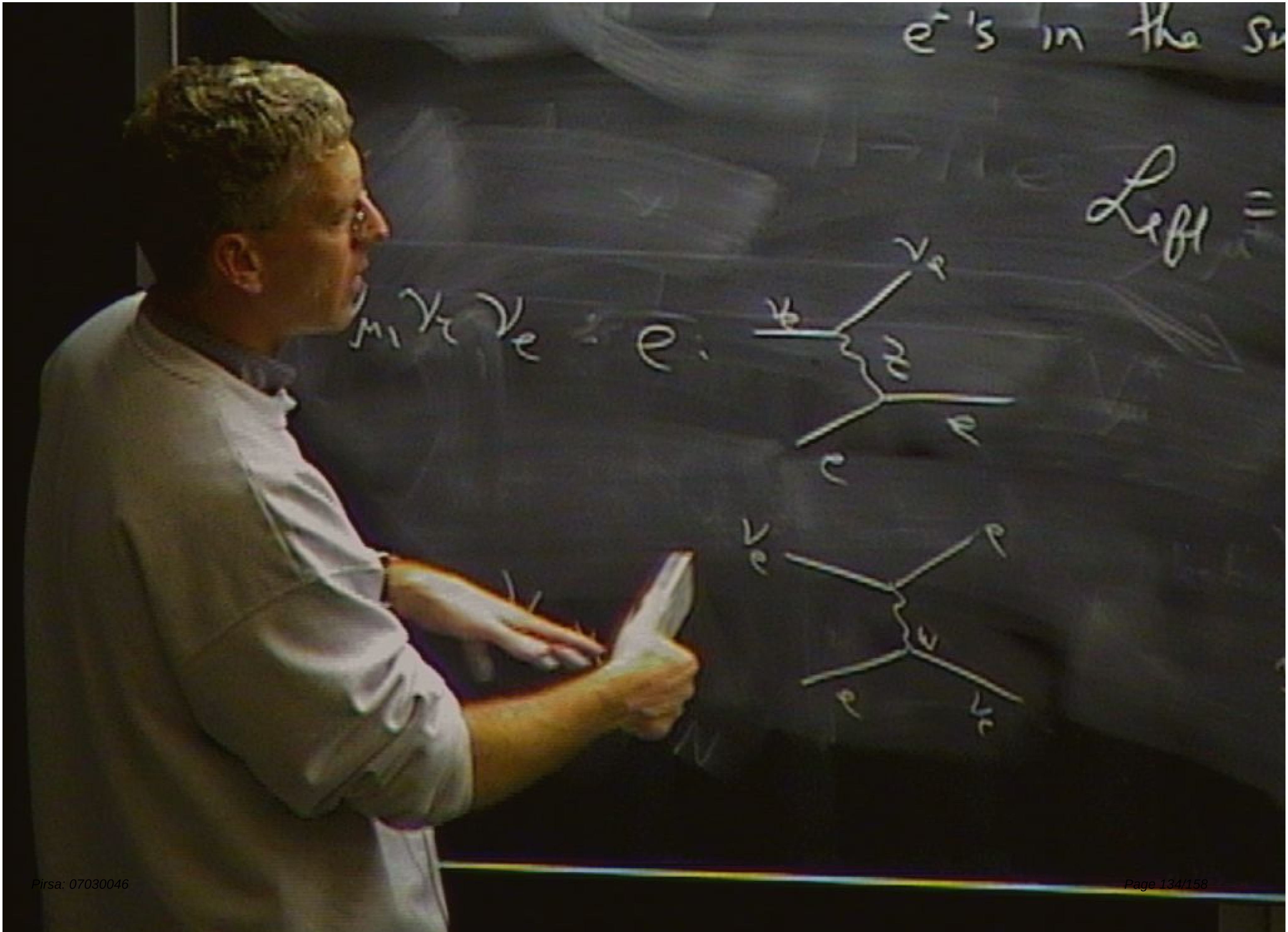
e's in the

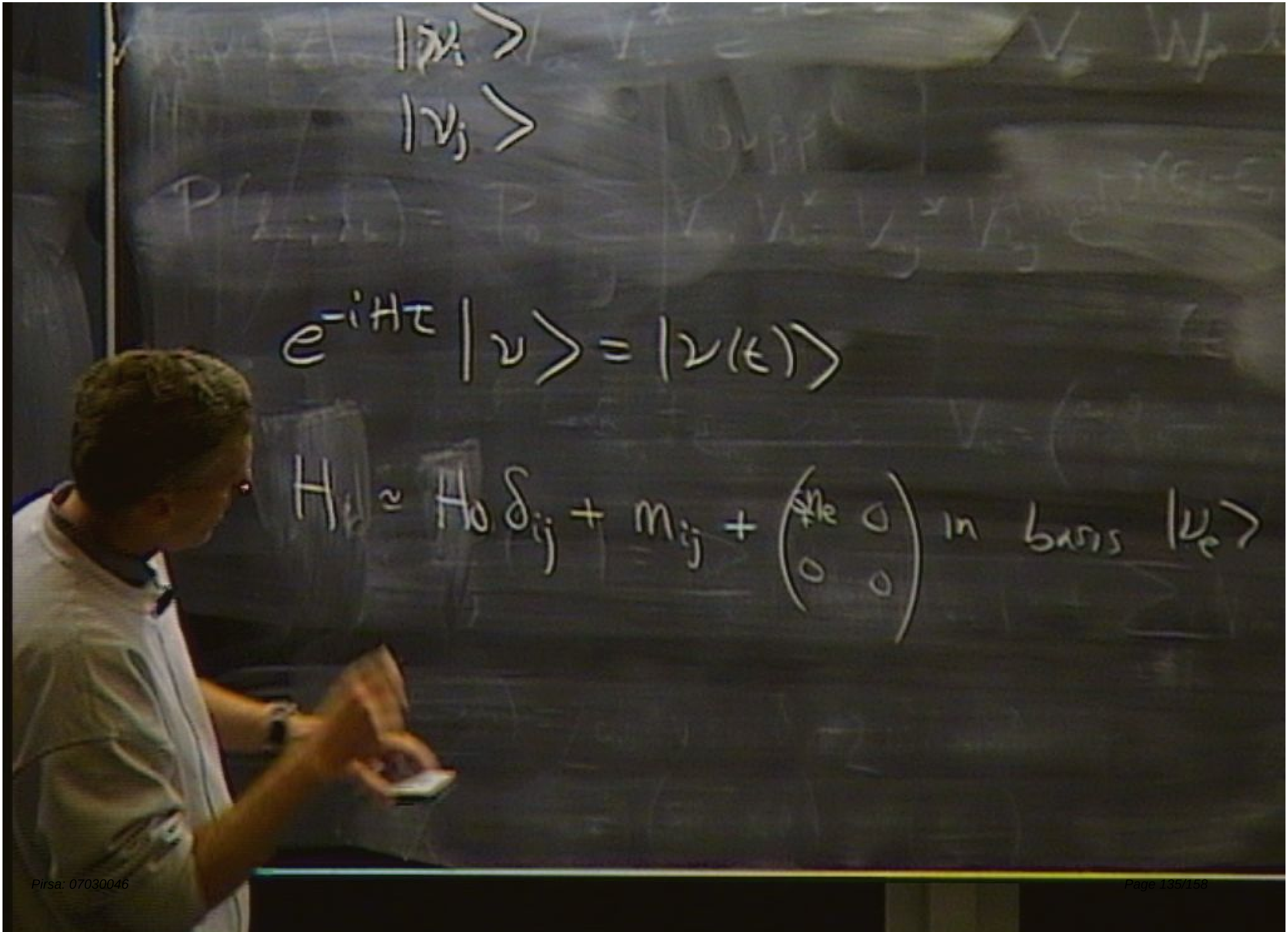
Left

ν_μ, ν_τ, ν_e + e:

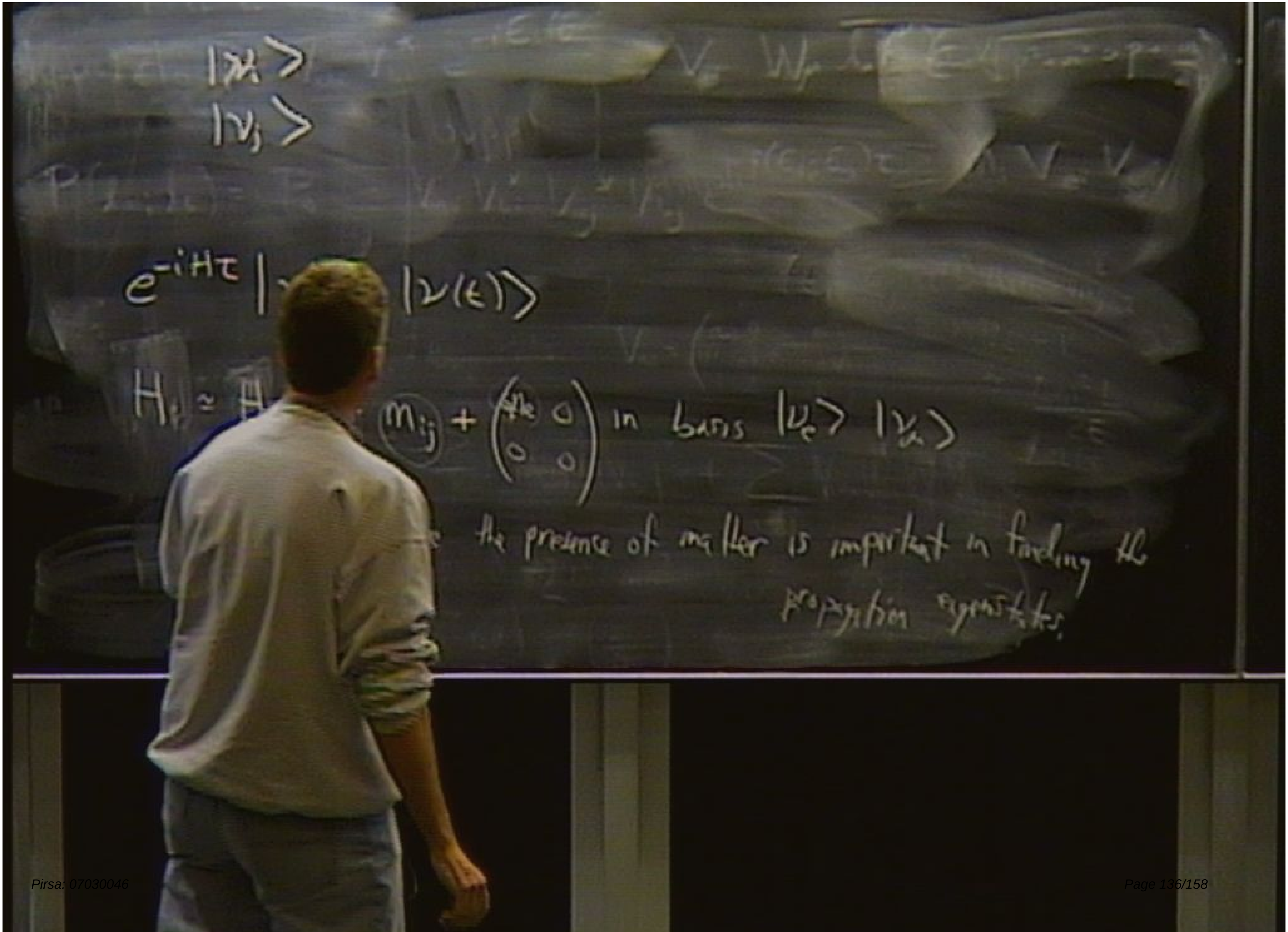


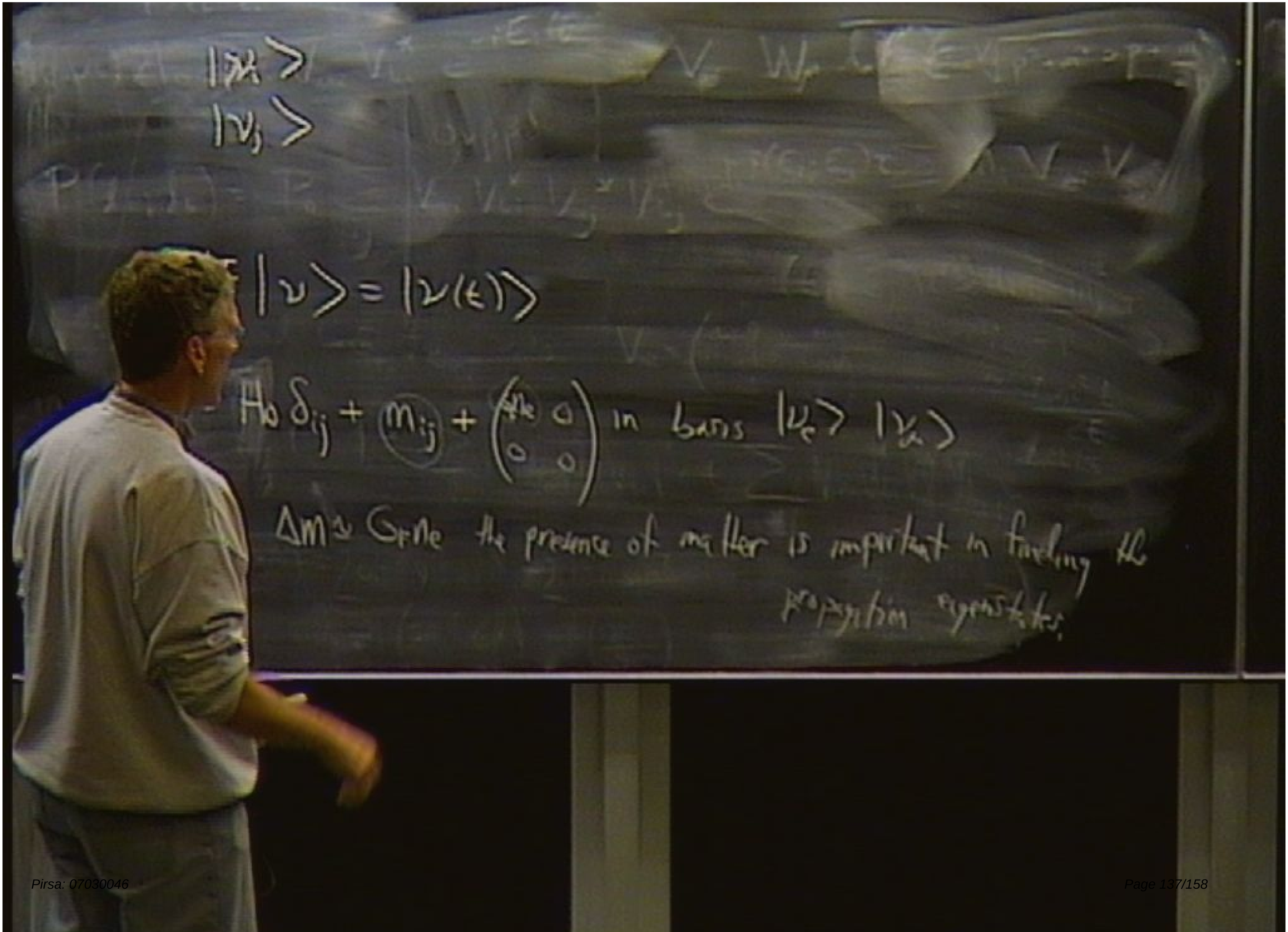
ν_e only.

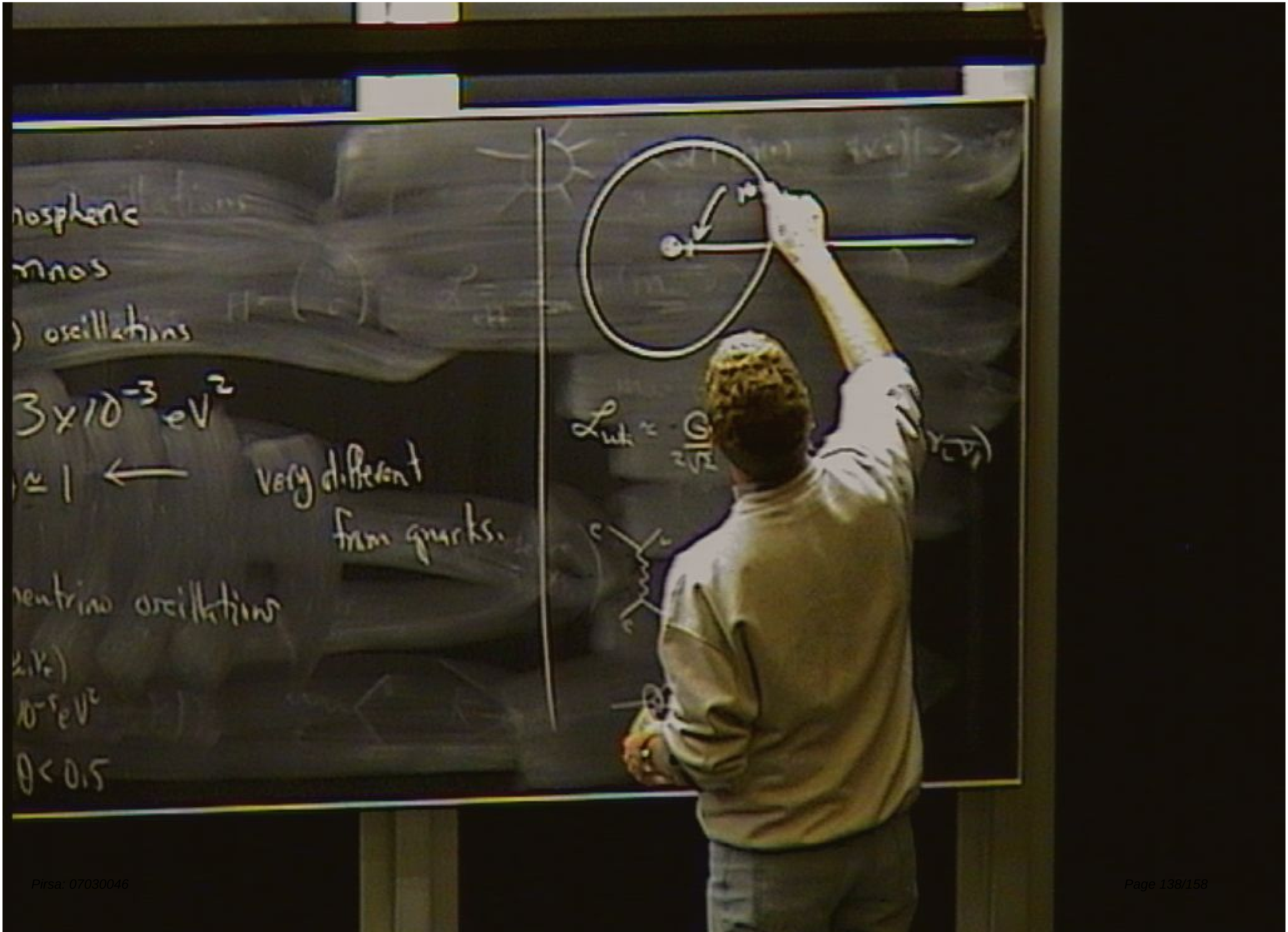

e⁻'s in the
Leff =



$|\nu_i\rangle$
$|\nu_j\rangle$
$e^{-iHt}|\nu\rangle = |\nu(t)\rangle$
$H_{ij} \simeq H_0\,\delta_{ij} + m_{ij} + \begin{pmatrix} V_e & 0 \\ 0 & 0 \end{pmatrix}$ in basis $|\nu_e\rangle$


|ν_α>
|ν_i>
e^{-iHτ} |ν(t)>
in basis |ν_e> |ν_μ>
the presence of matter is important in finding the propagation eigenstates.


|νμ >
|νj >
|ν > = |ν(t)>
H0 δij + mij + in basis |νe > |νμ >
Δm ≈ GF Ne the presence of matter is important in finding the propagation eigenstates.


nosphenc
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) oscillations
3x10^-3 eV^2
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from quarks.
neutrino oscillations
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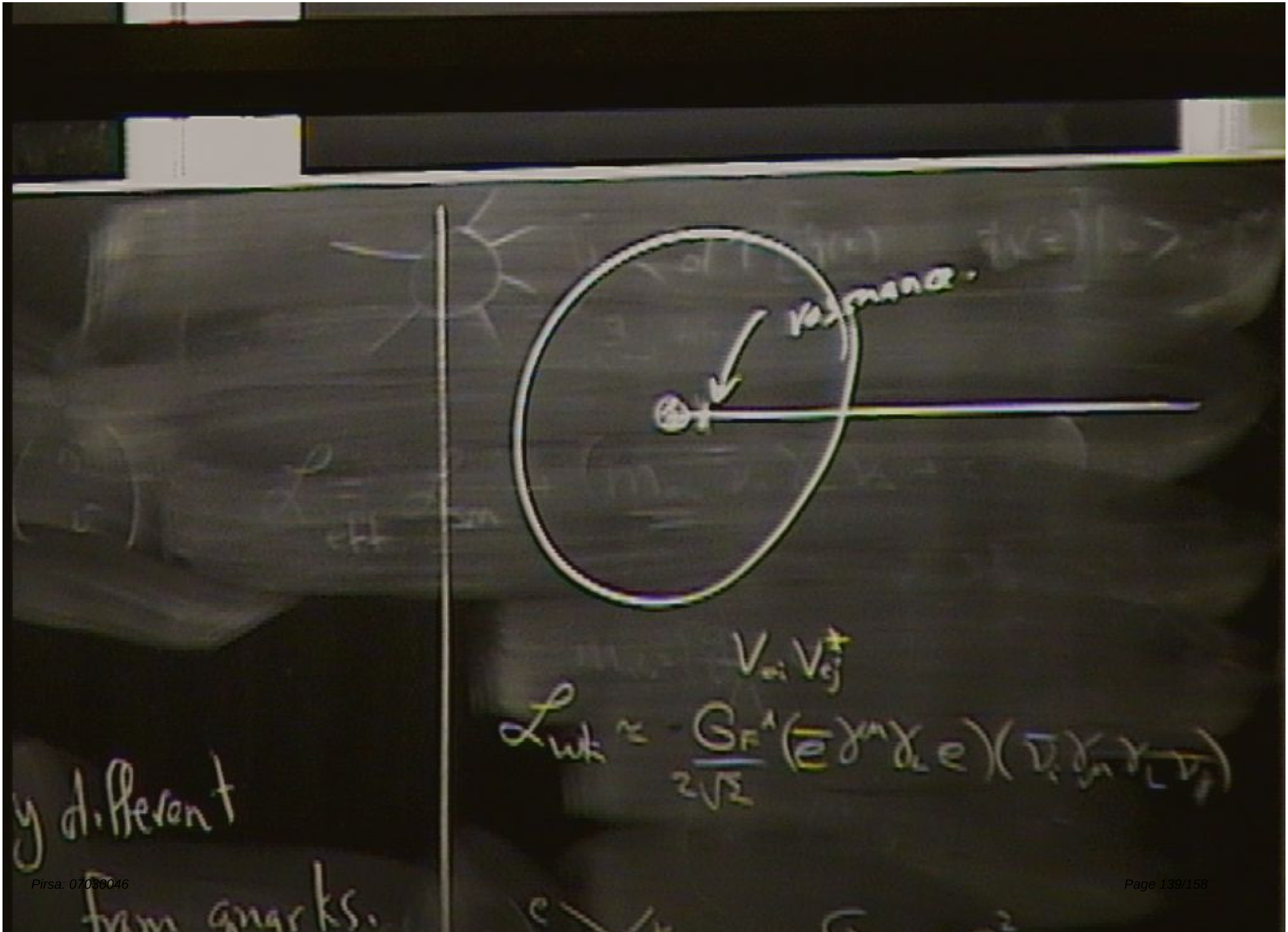
resonance.
$V_{ui} V_{cj}^{*}$
$\mathcal{L}_{wk} \simeq -\frac{G_F}{2\sqrt{2}}(\bar{e}\gamma^{\mu}\gamma_L e)(\bar{\nu}_i\gamma_{\mu}\gamma_L \nu_i)$
y different
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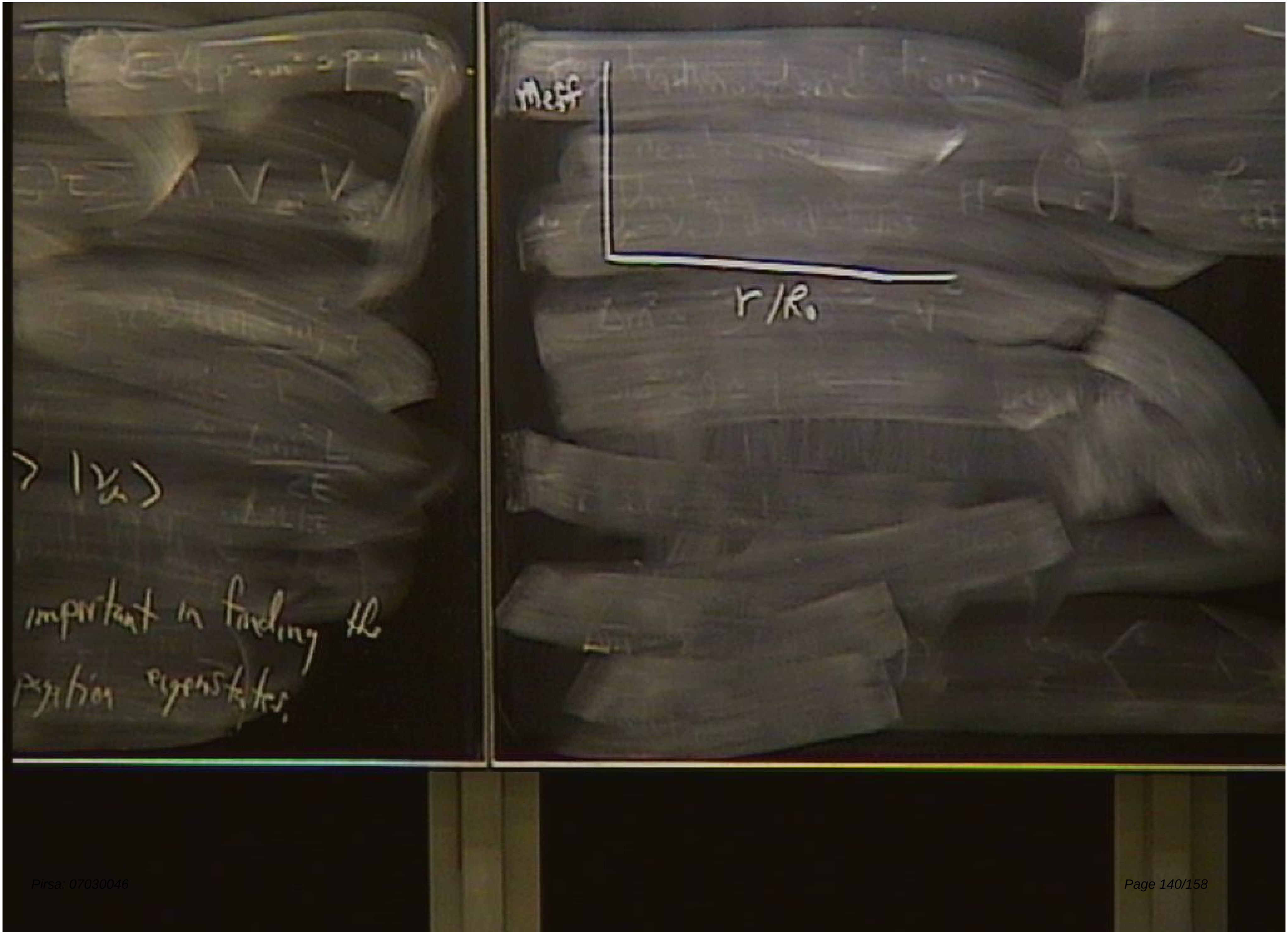
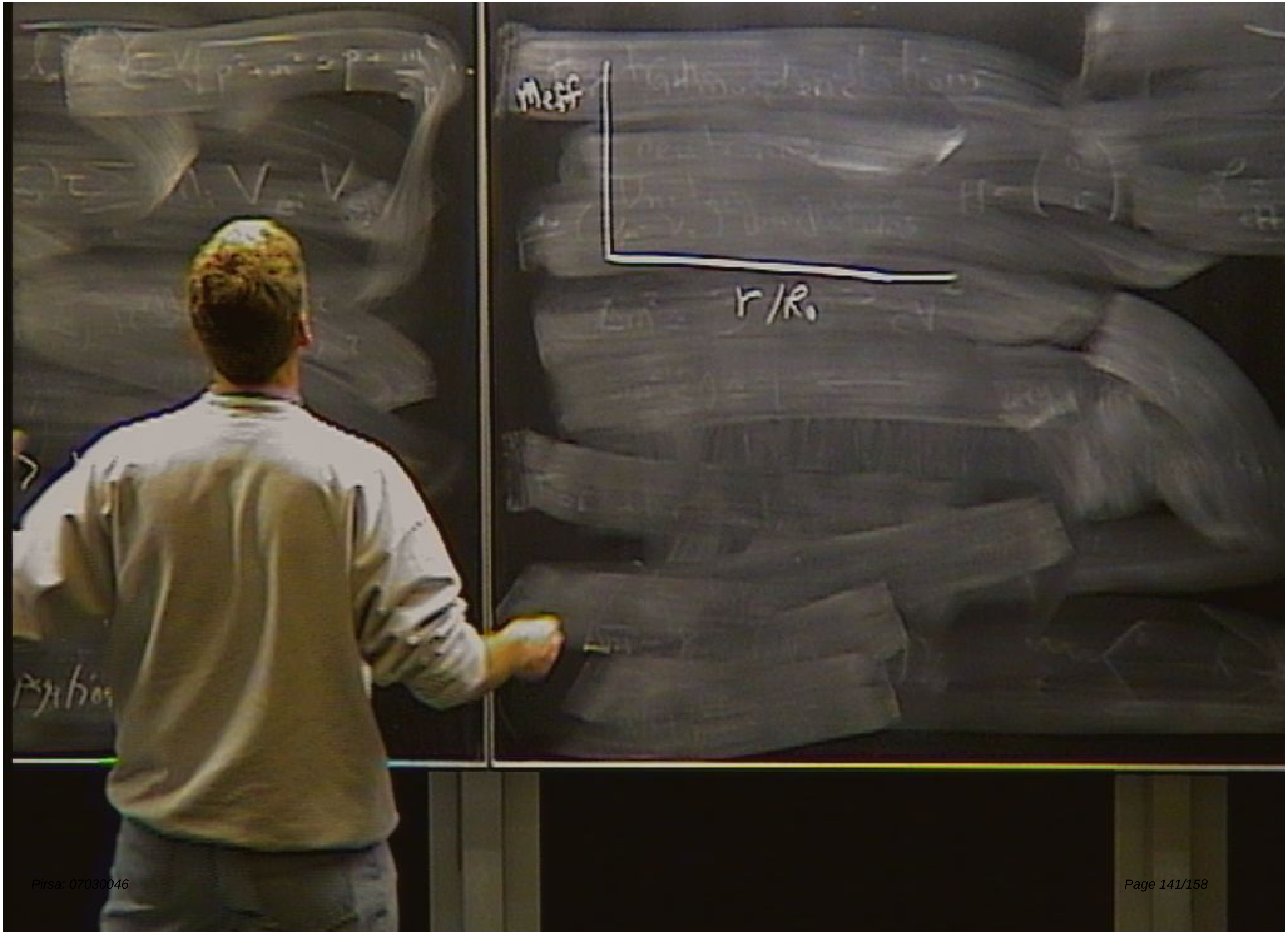
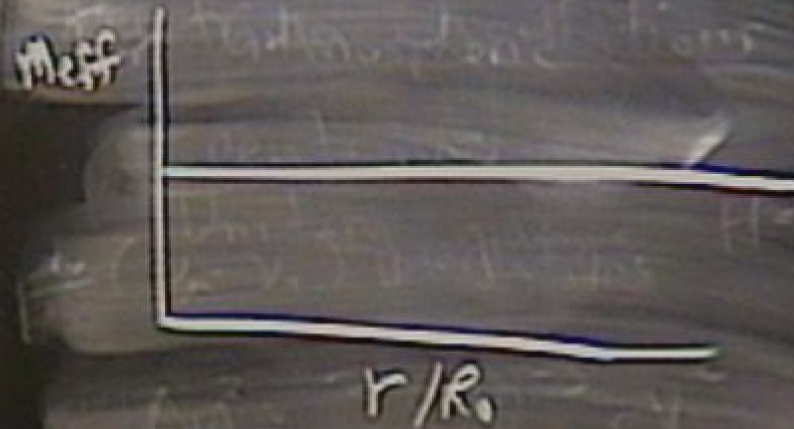
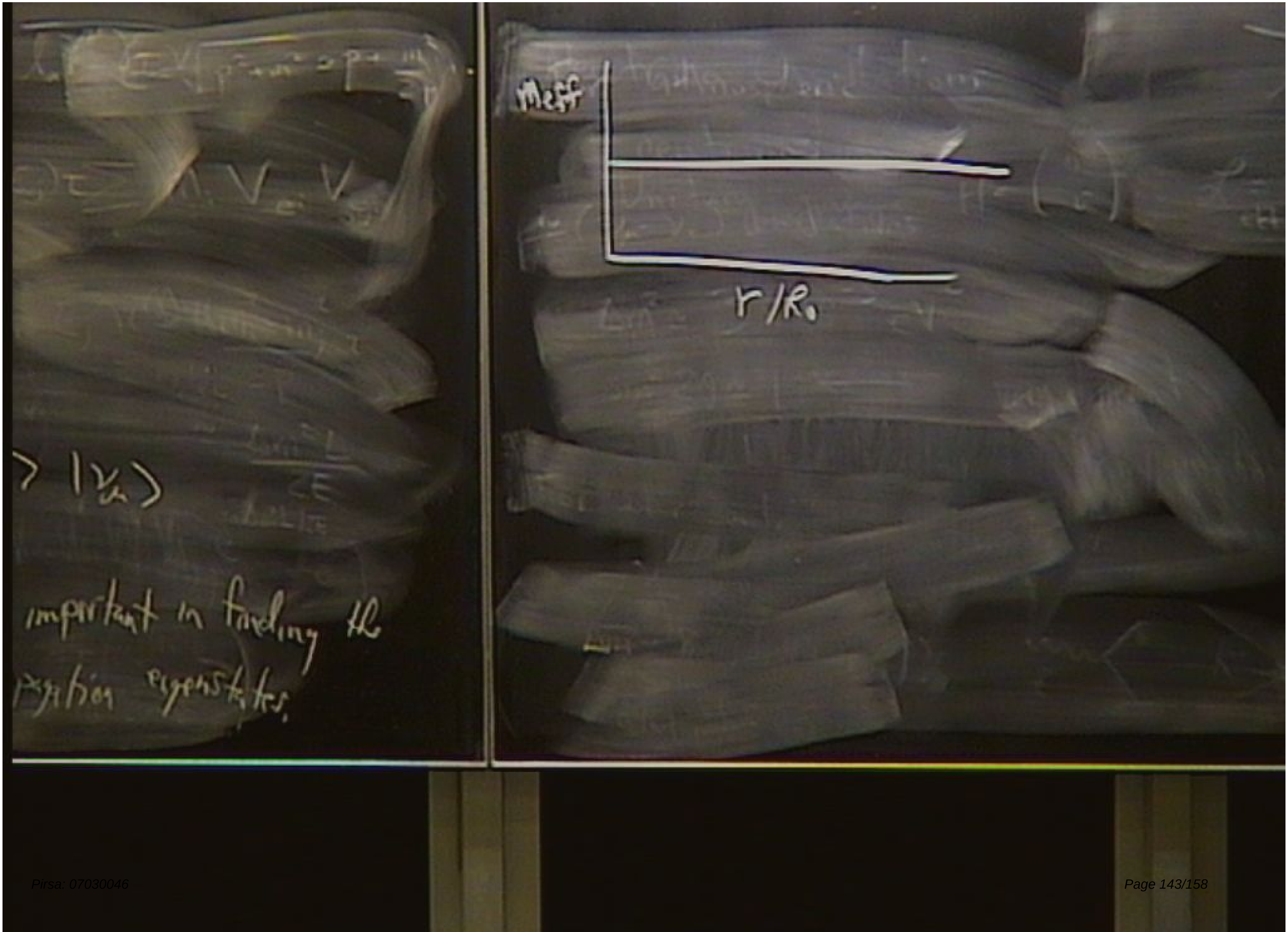

M_{eff}
r/R_0
$\rangle \; |\psi_n\rangle$
important in finding the
position eigenstates.


Meff
r/R₀

$\rangle \; |\psi_n\rangle$

important in finding the position eigenstates;




Meff
r/R0
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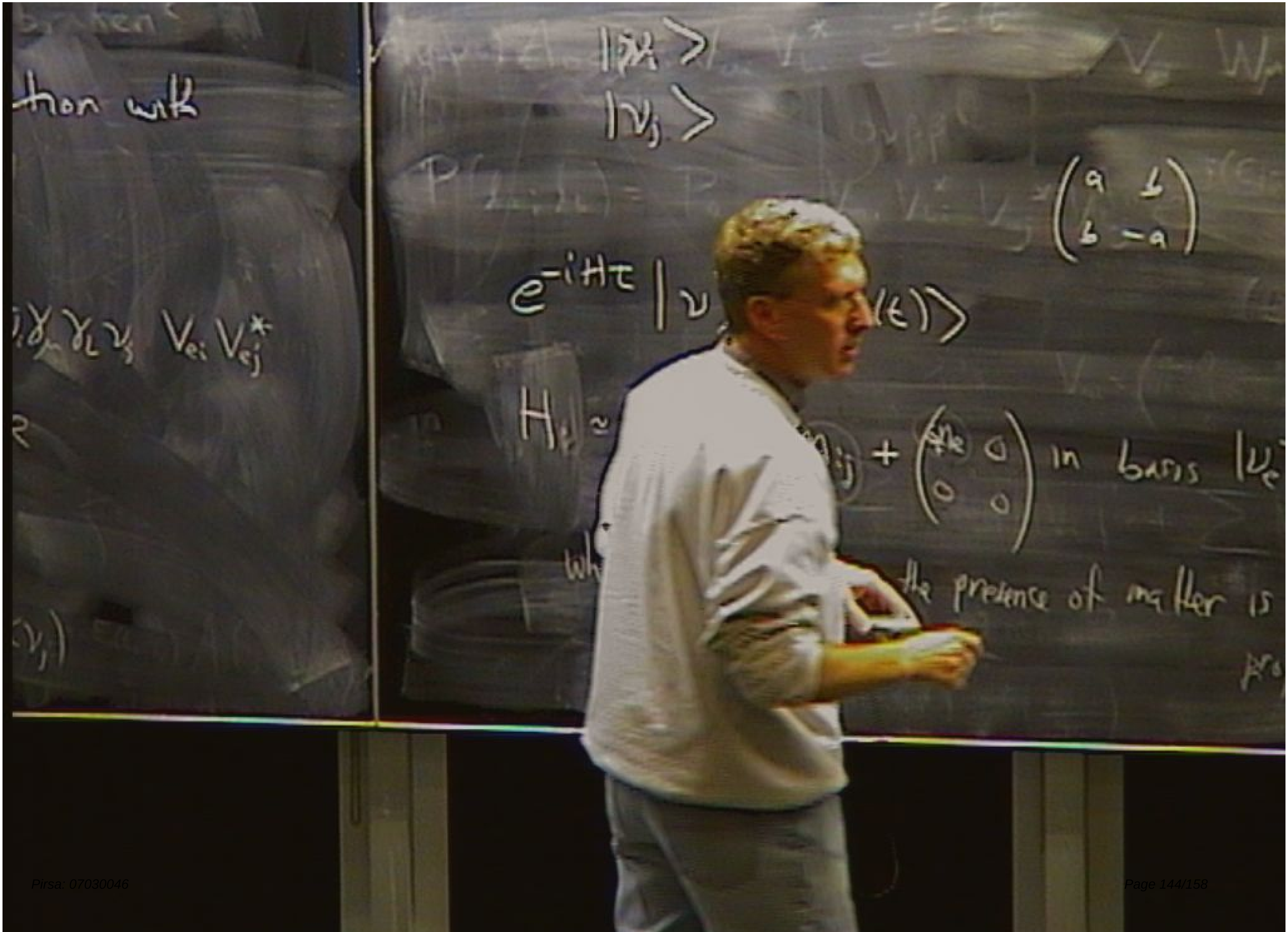
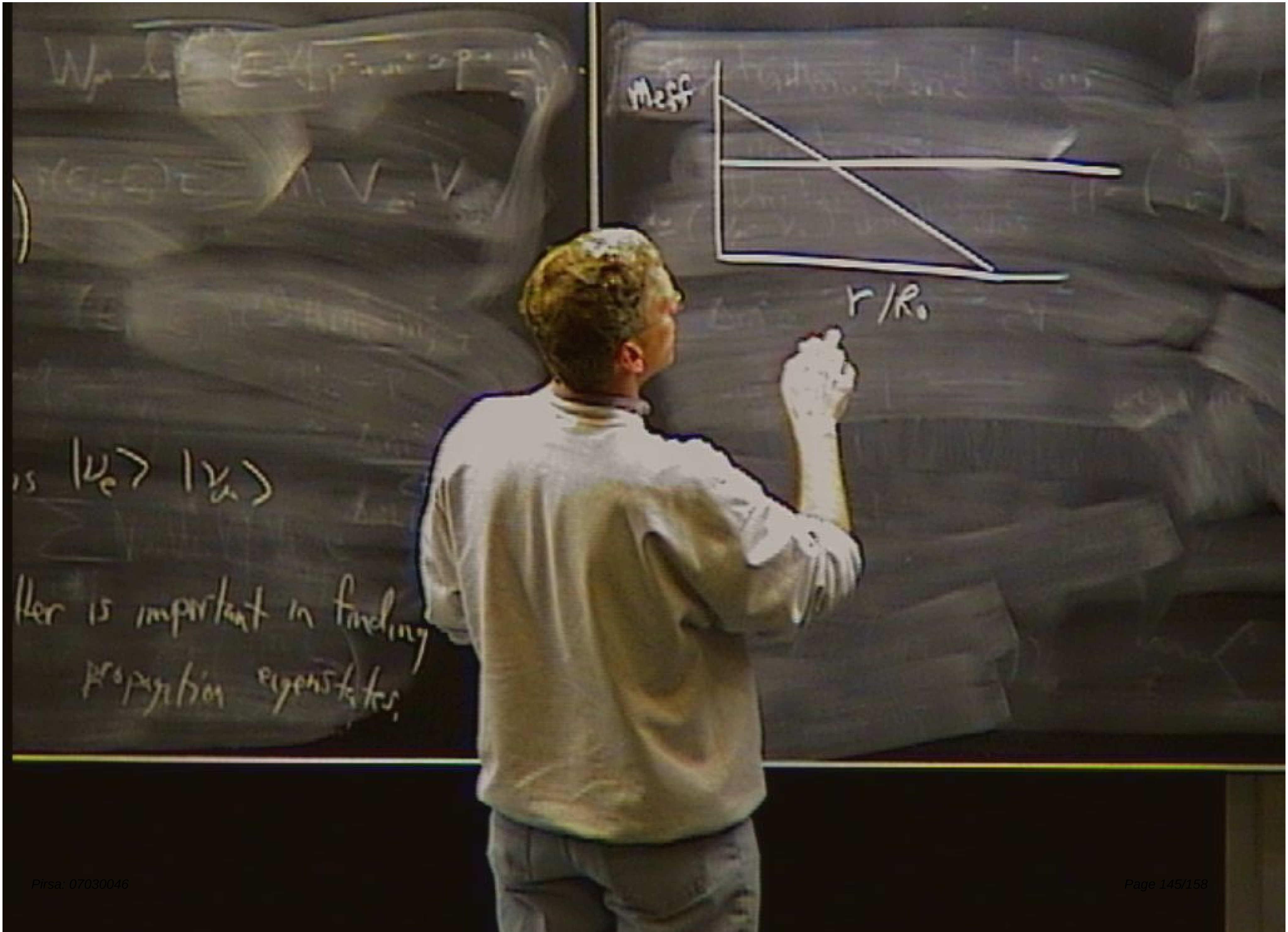
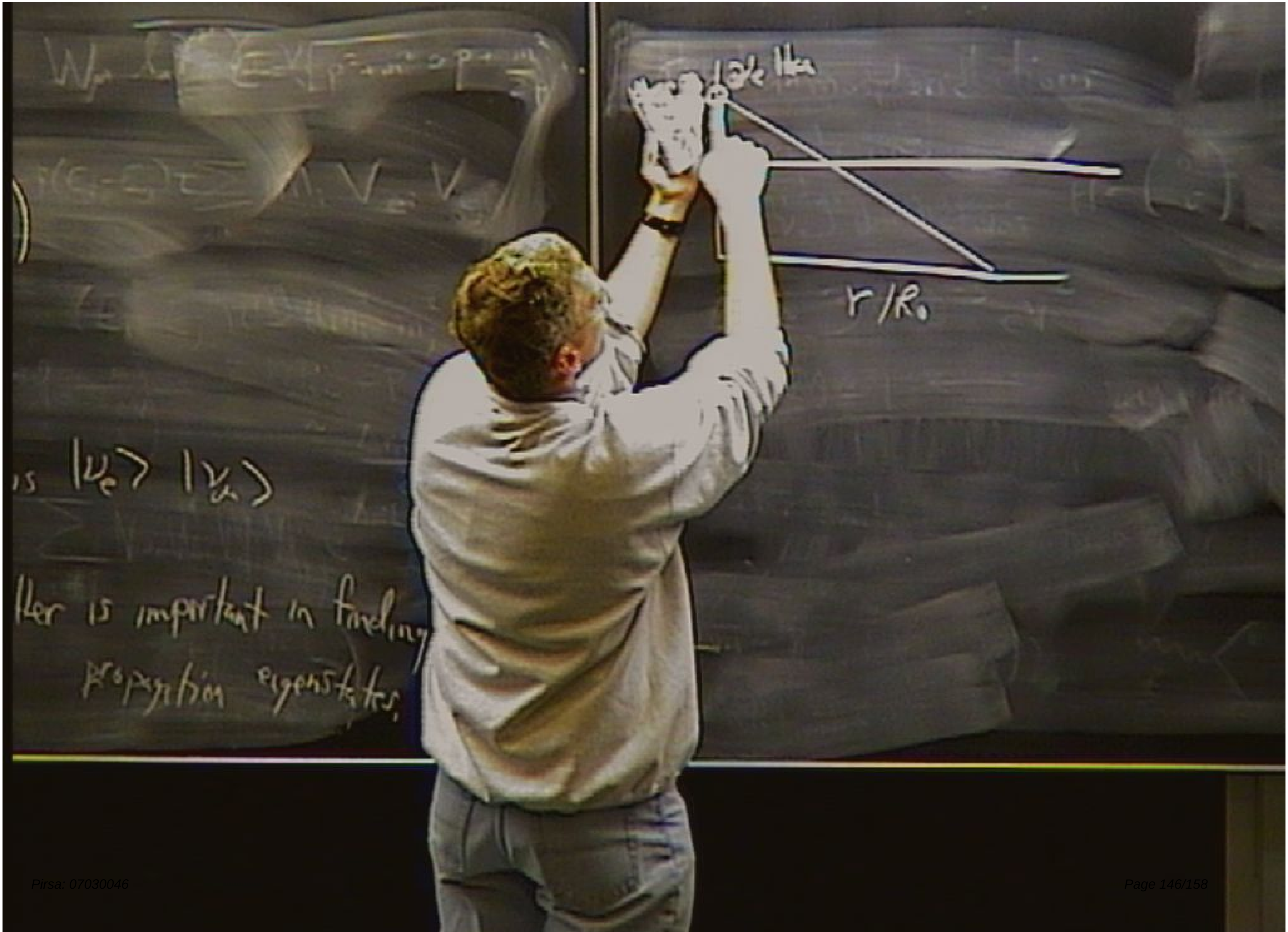

tion with
|ν_j >
e^{-iHt} |ν
H ≈
in basis
the presence of matter is


M_{eff}
r/R_0
is $|\nu_e\rangle$ $|\nu_\mu\rangle$
tter is important in finding
propagation eigenstates,


r/R_0
is $|\nu_e\rangle$ $|\nu_\mu\rangle$
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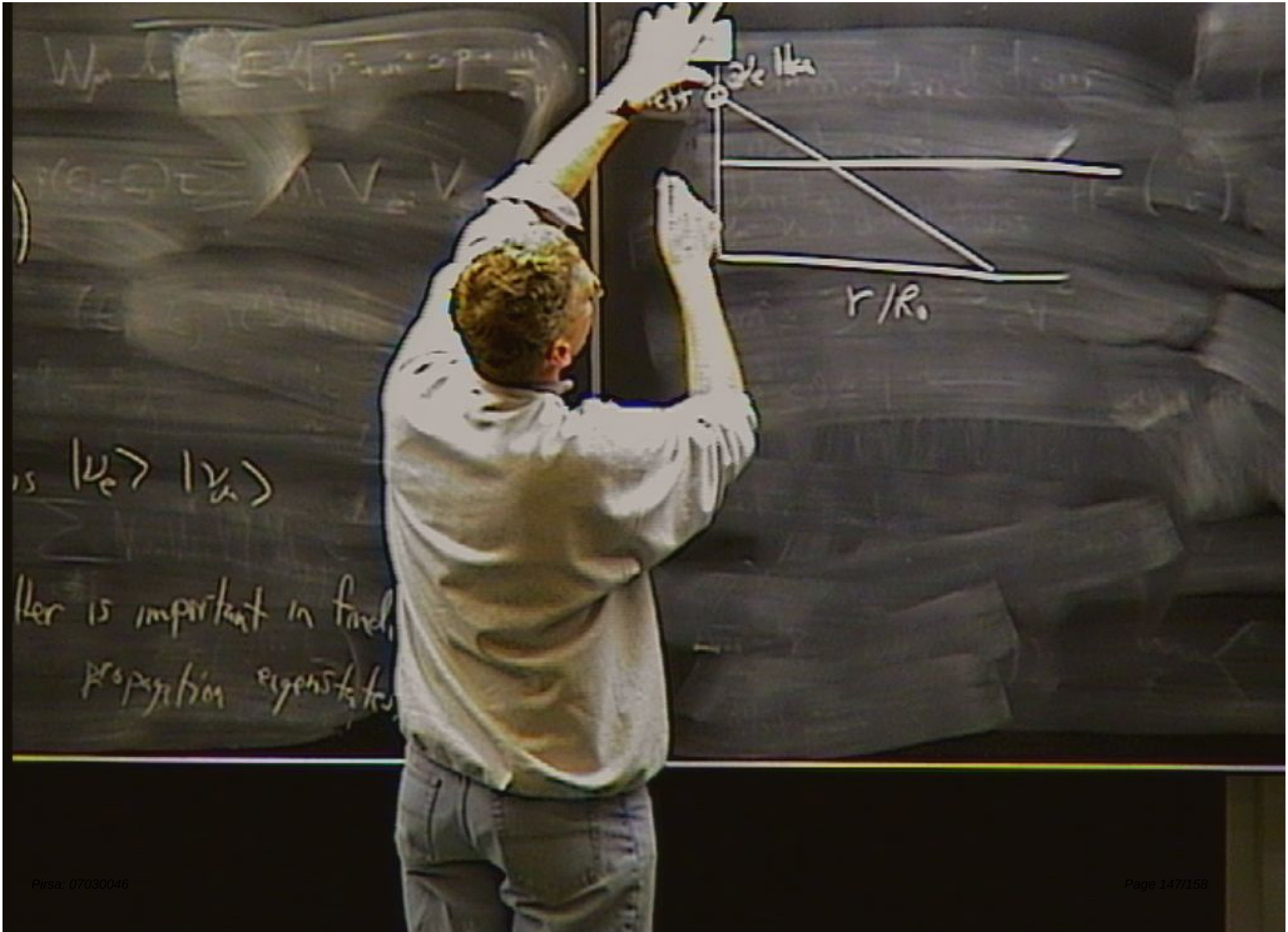
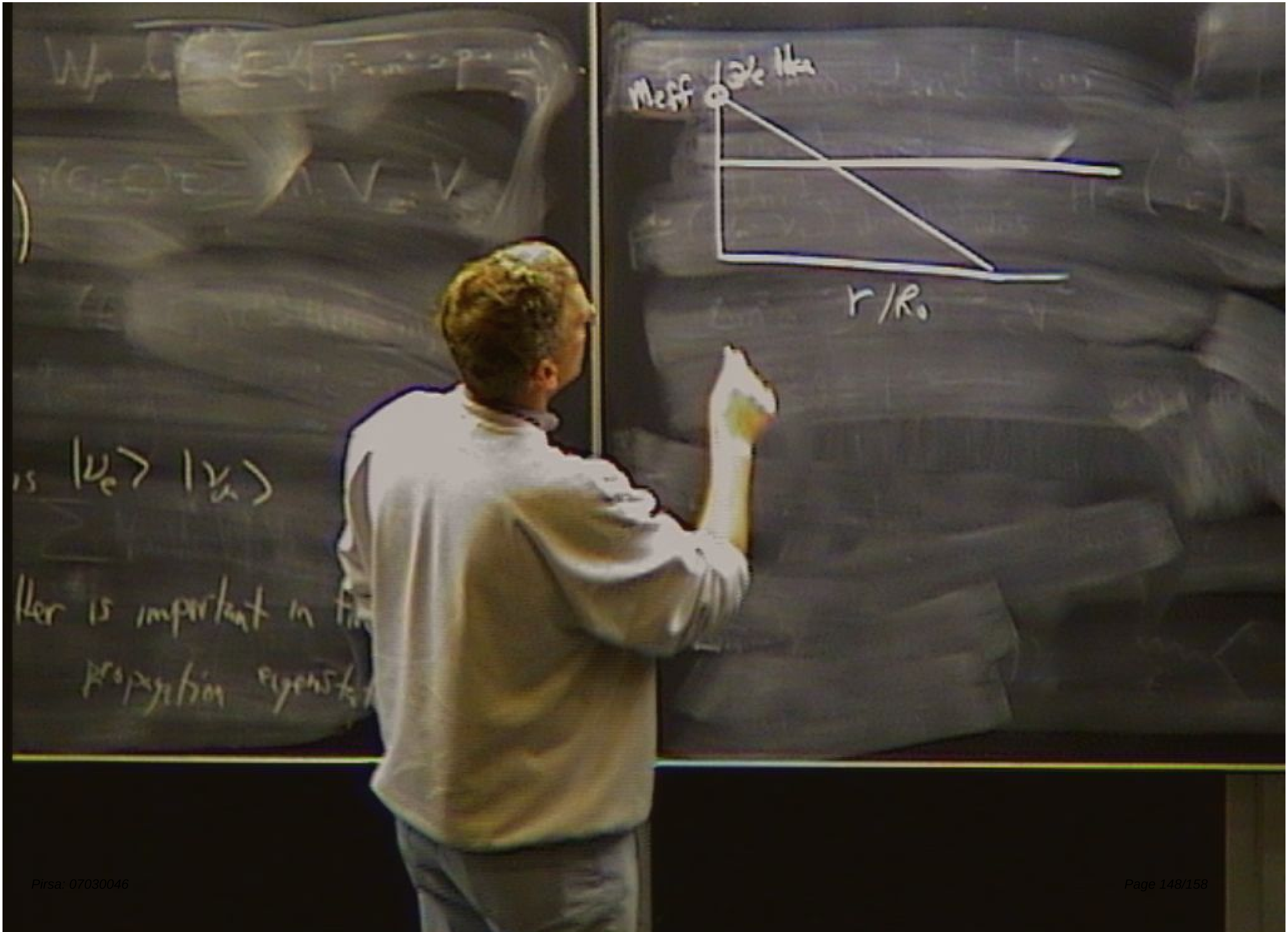

r / R
$|\nu_e\rangle$ $|\nu_\mu\rangle$
is important in


Meff
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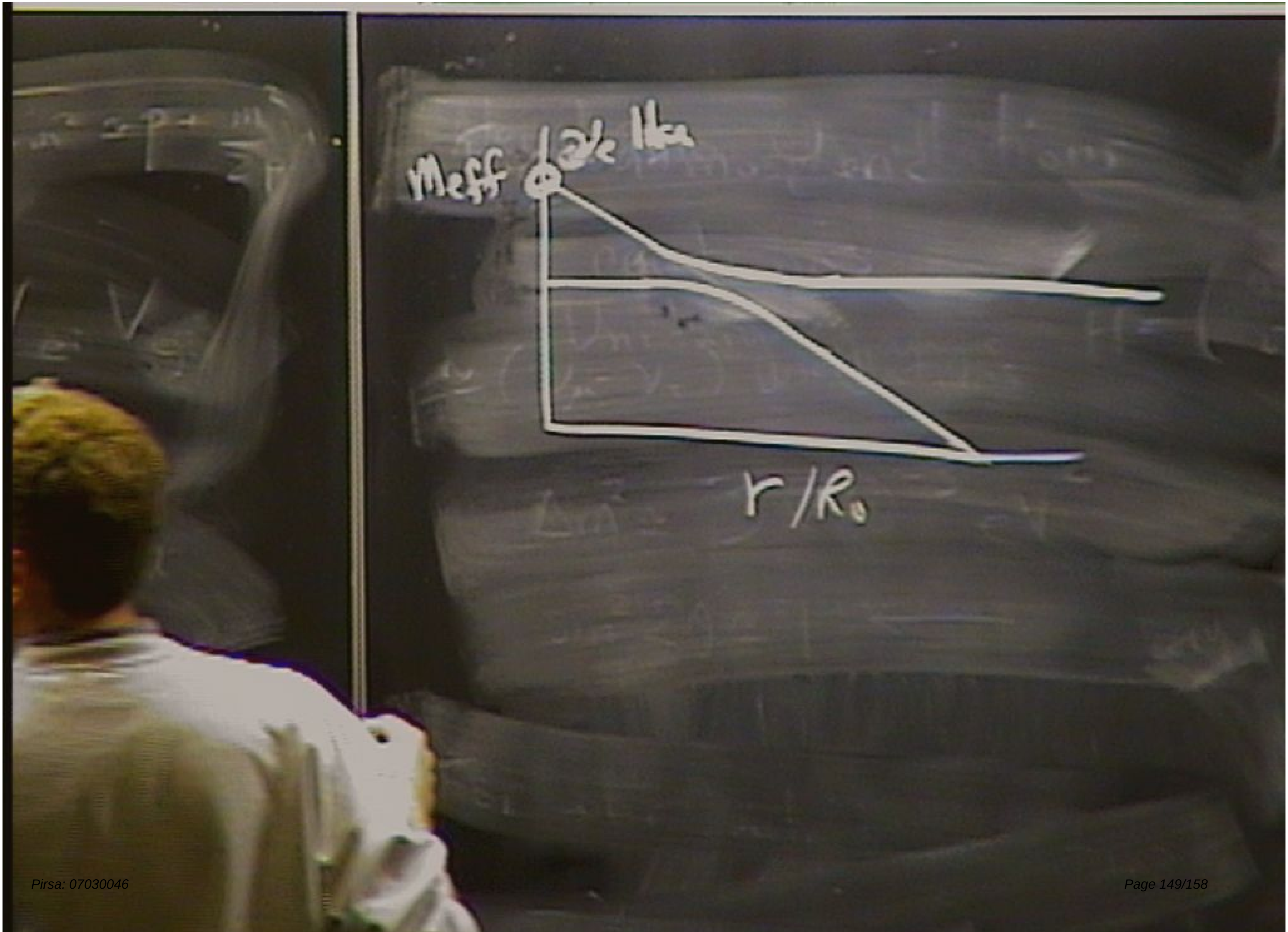
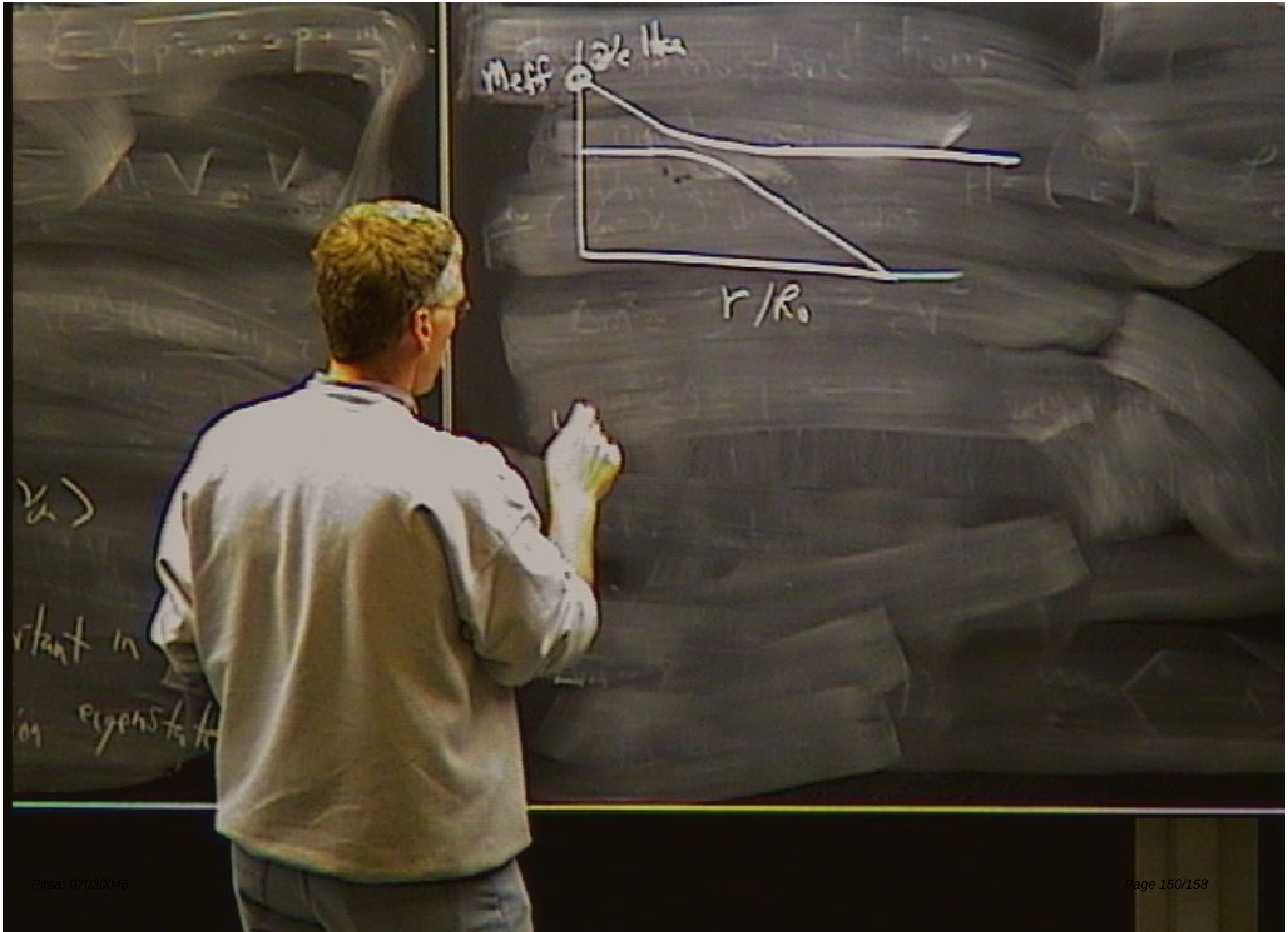
is |νe> |νμ>
ller is important in th
propagation eigenst


Meff
r /R0


Meff
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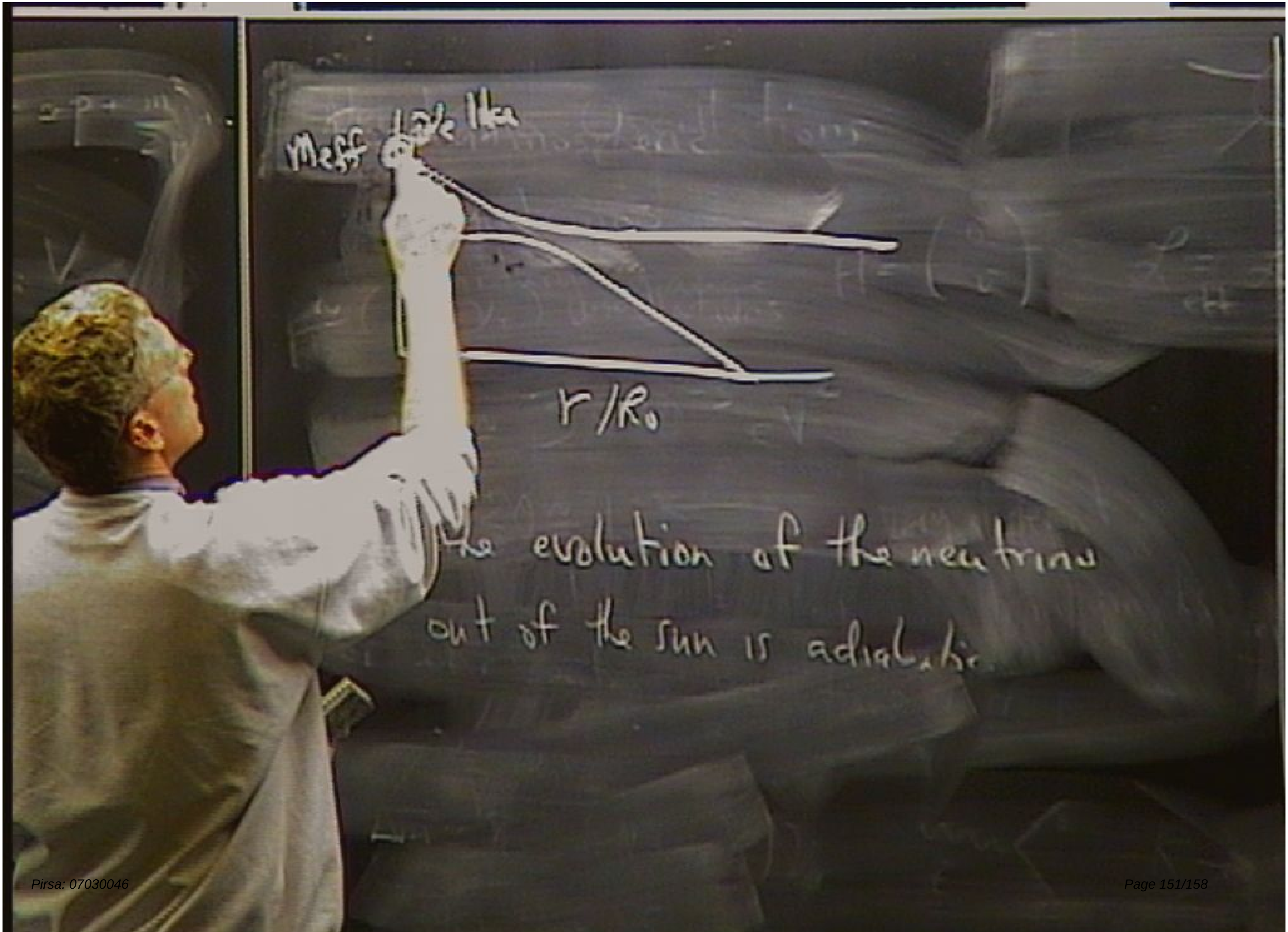
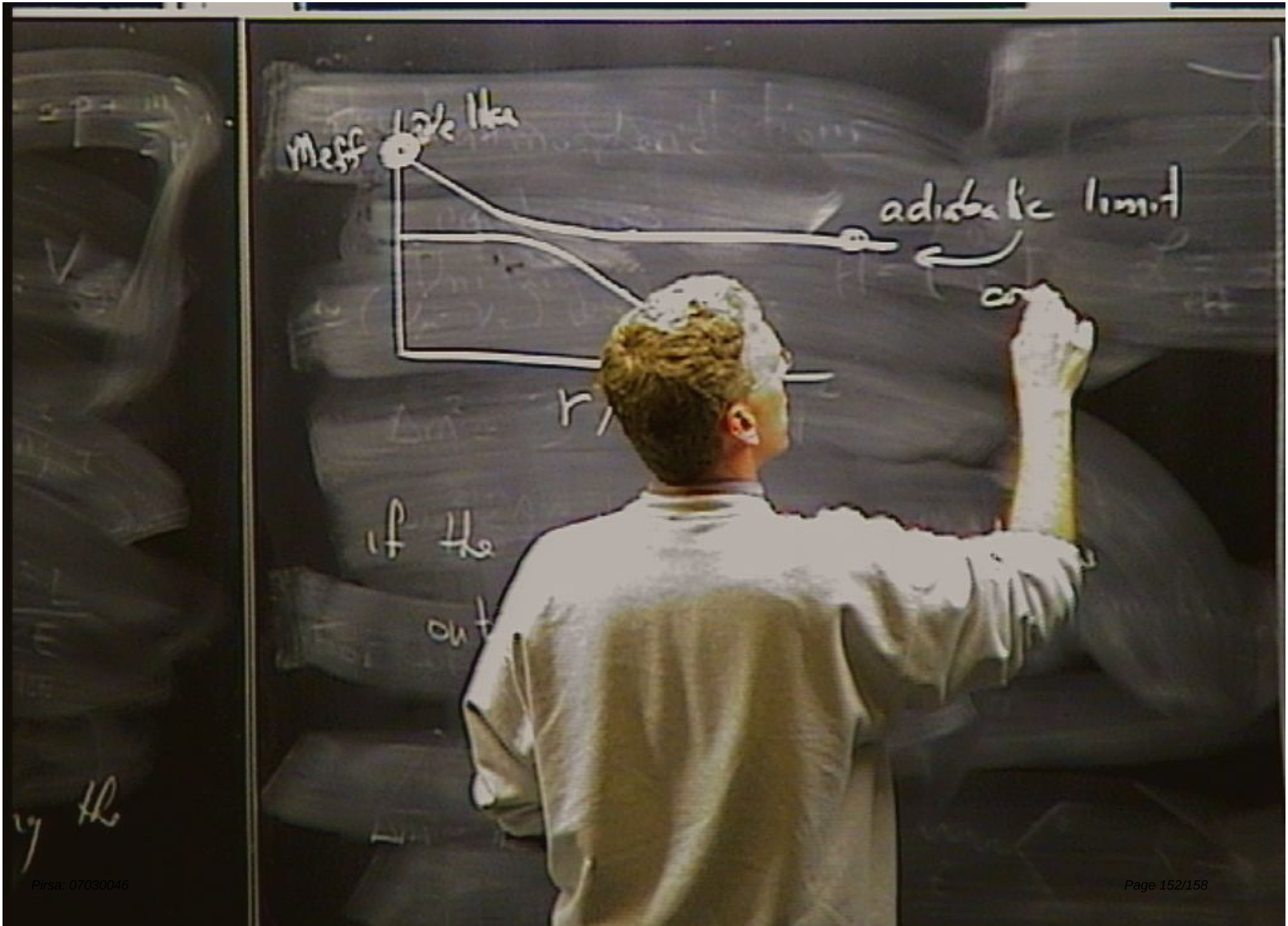


Meff
r / R
evolution of the neutrino
out of the sun is adiab


Meff
adiabatic limit
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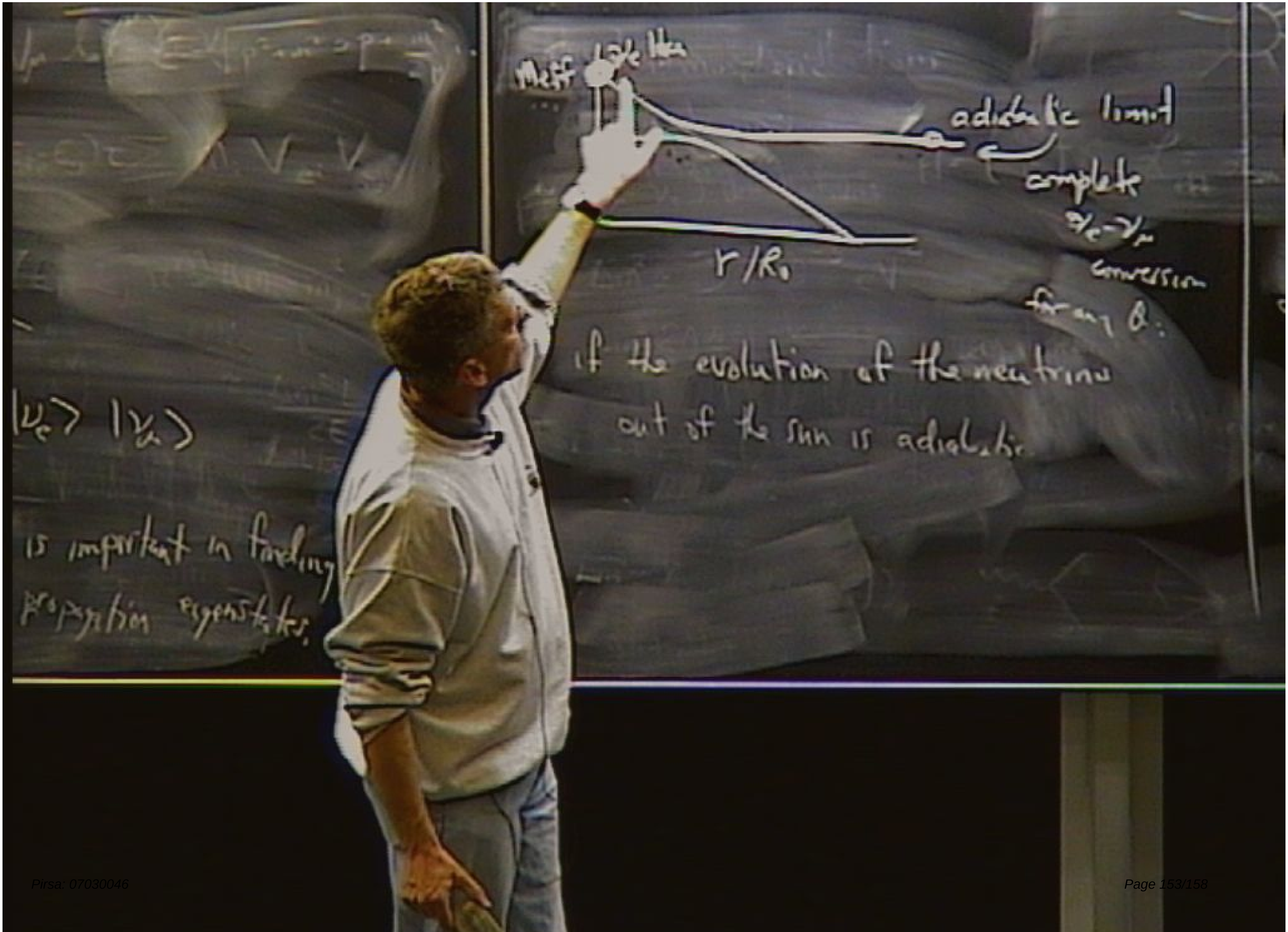
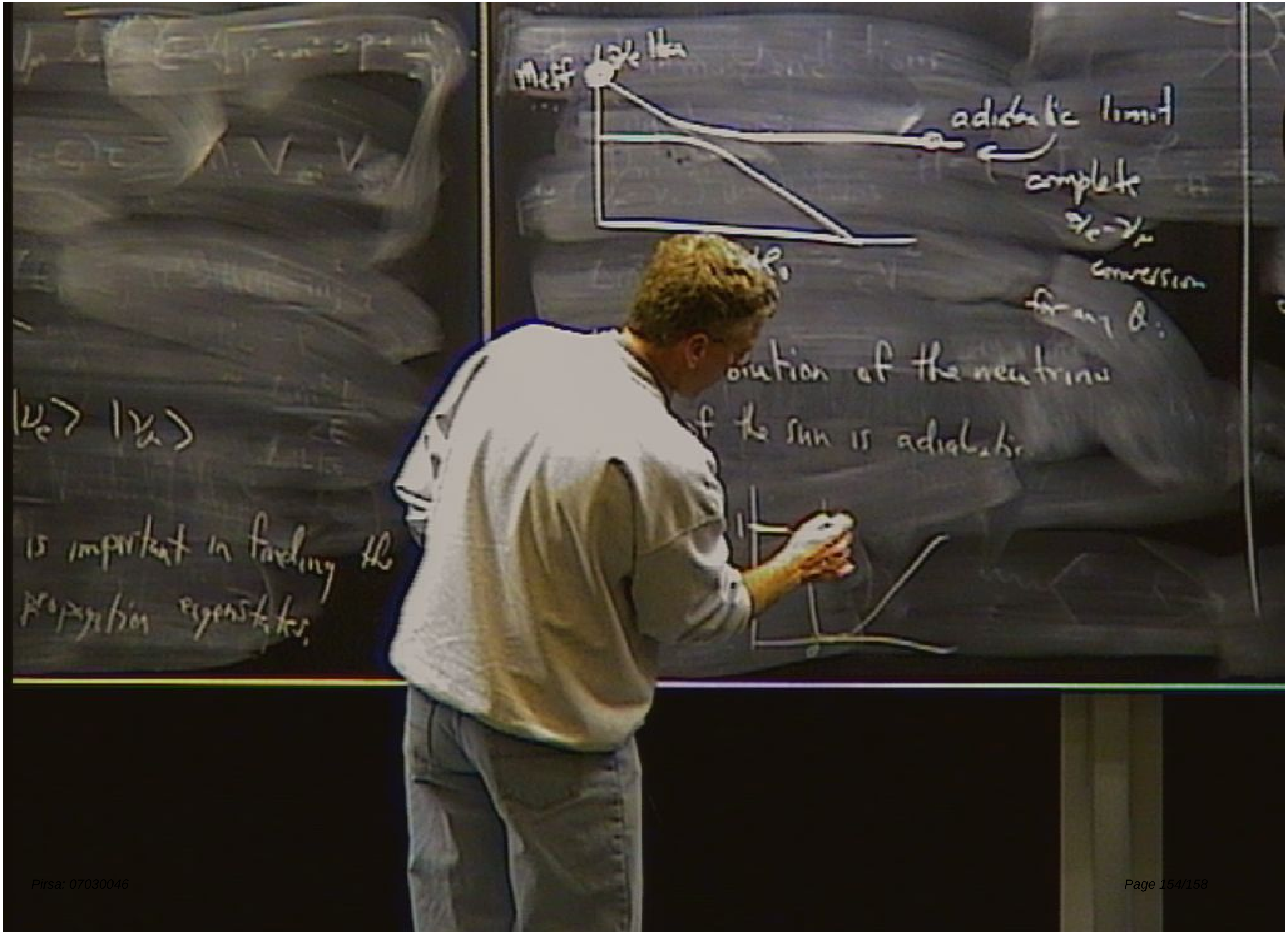

Meff
adiabatic limit
complete
$\nu_e - \nu_\mu$
conversion
for any θ:
r/R_0
if the evolution of the neutrino
out of the sun is adiabatic
$|\nu_e\rangle$ $|\nu_\mu\rangle$
is important in finding
propagation eigenstates.


Meff
adiabatic limit
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conversion
for any θ:
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f the sun is adiabatic
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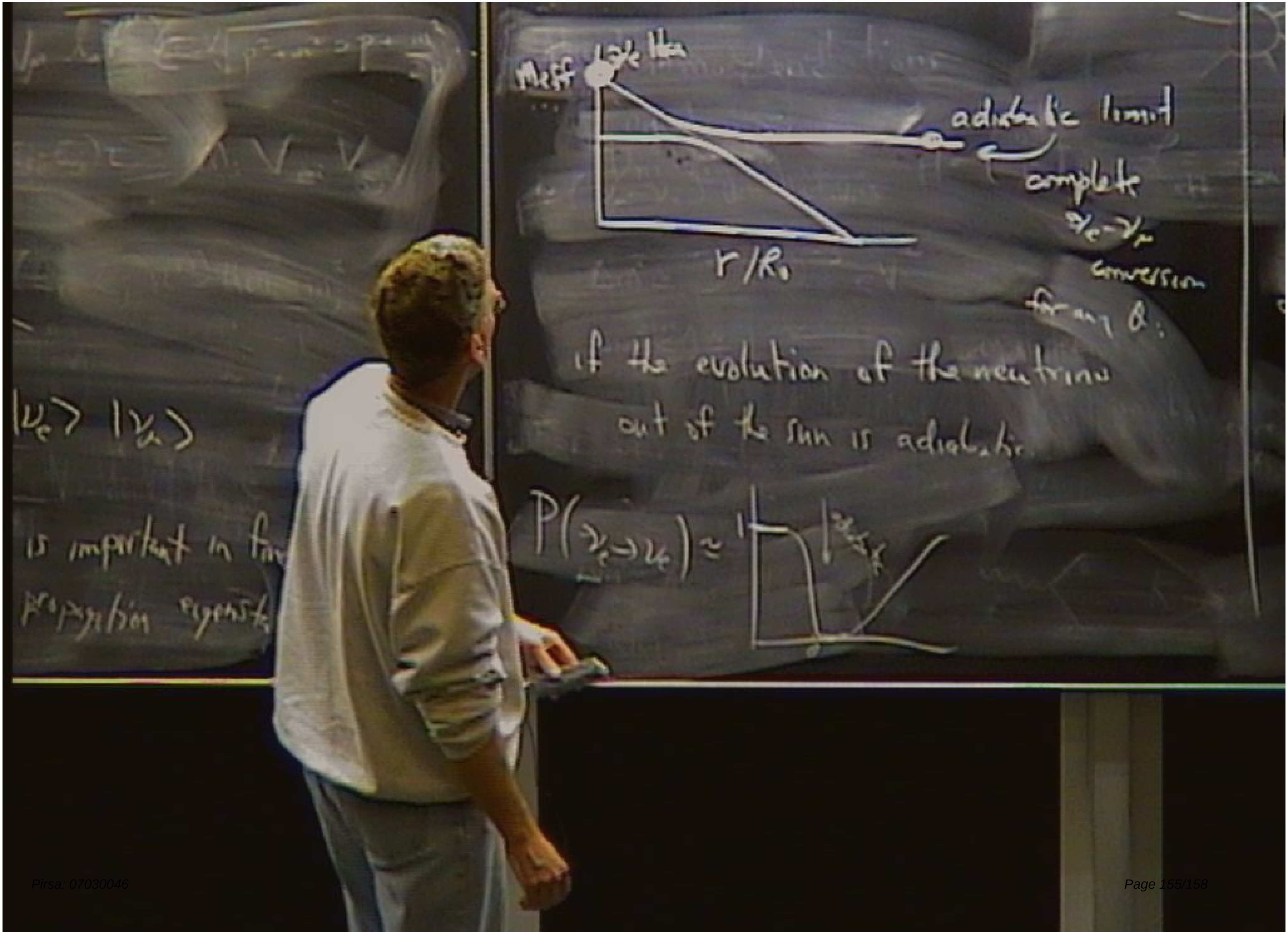
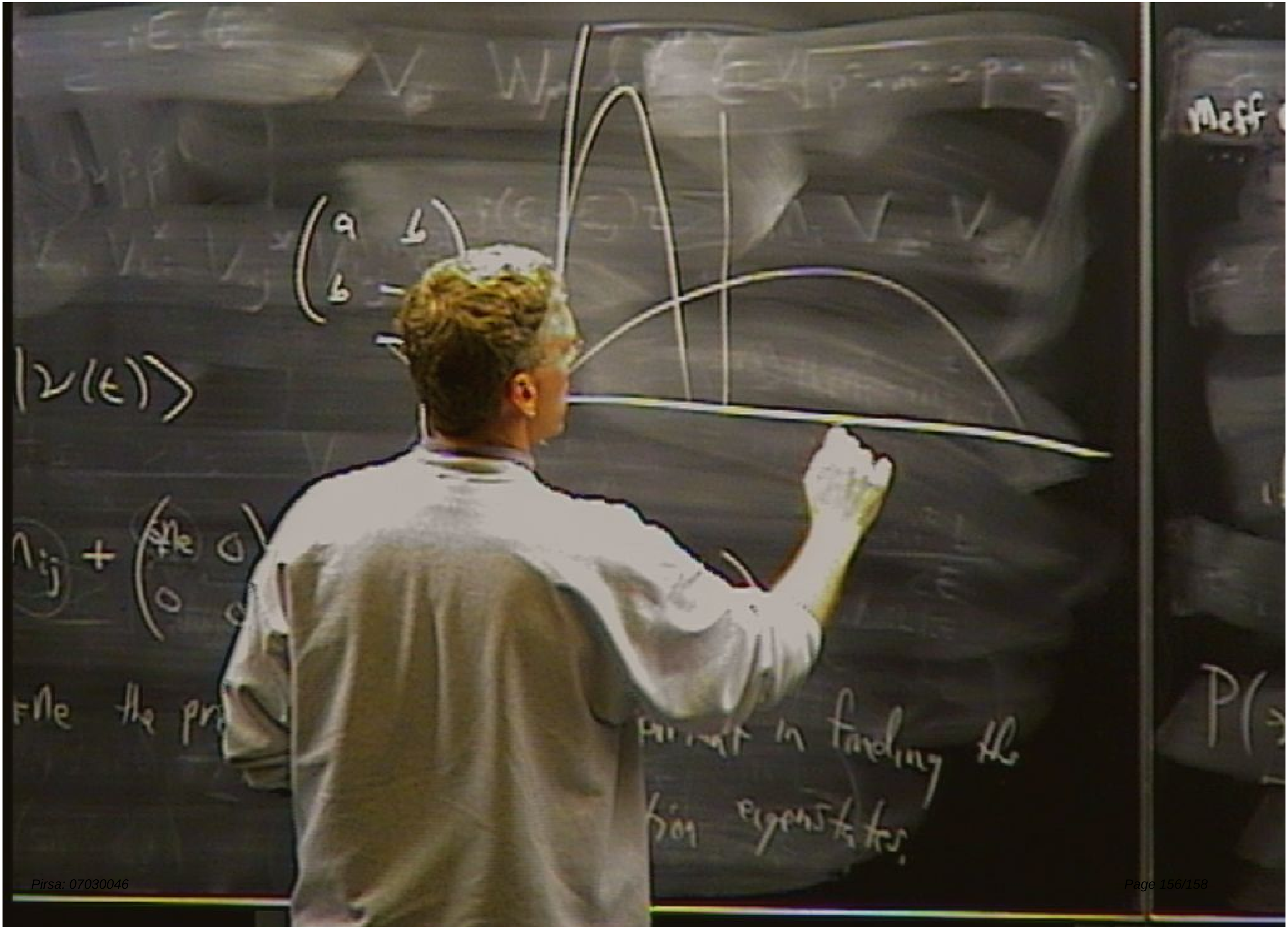
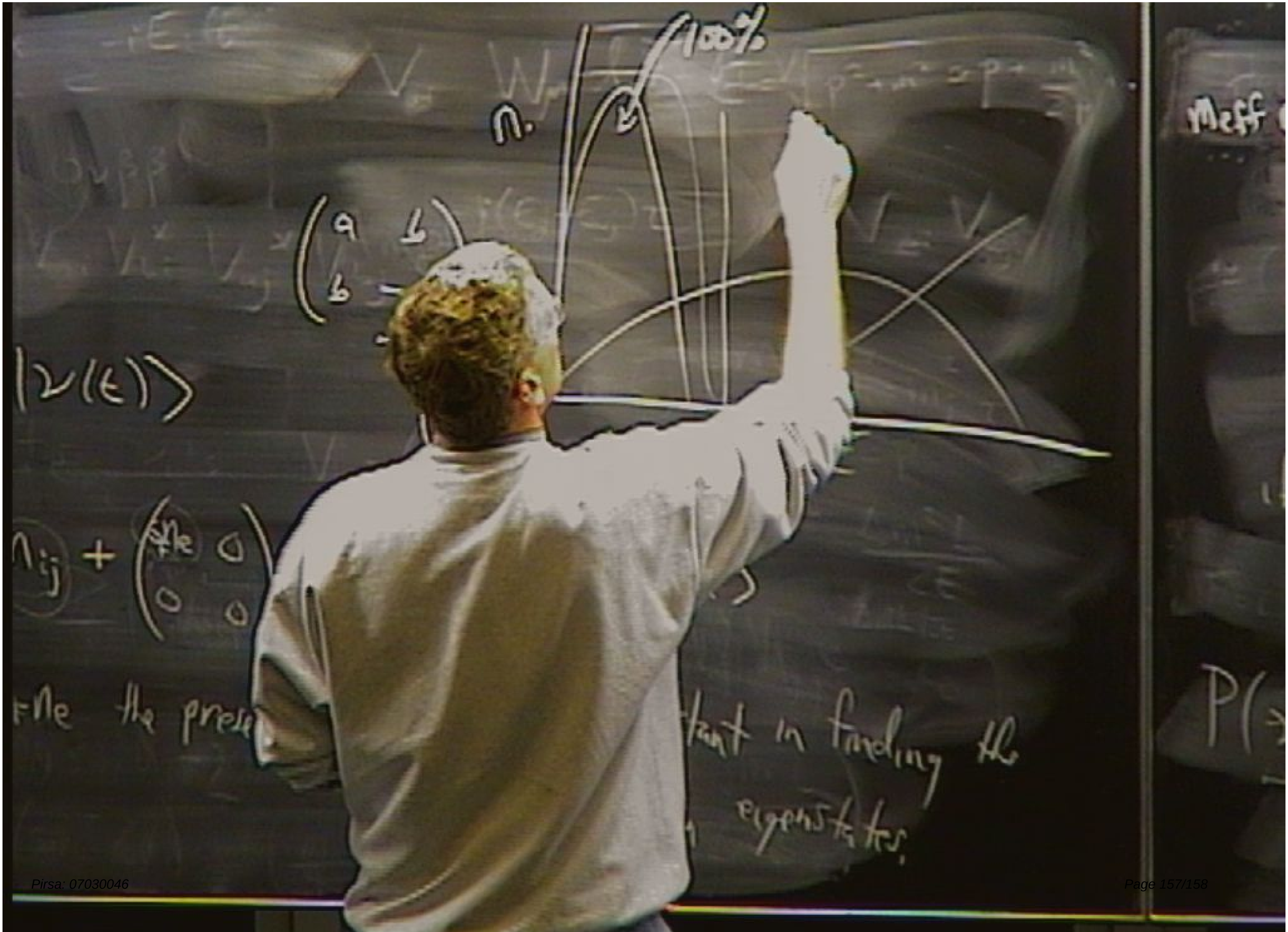
is important in finding the
propagation eigenstates.


Meff
adiabatic limit
complete
ν_e-ν_μ
conversion
r/R⊙
for any θ:
if the evolution of the neutrino
out of the sun is adiabatic
$P(\nu_e \to \nu_e) \simeq 1$
$|\nu_e\rangle$ $|\nu_\mu\rangle$
is important in


in finding the
eigenstates.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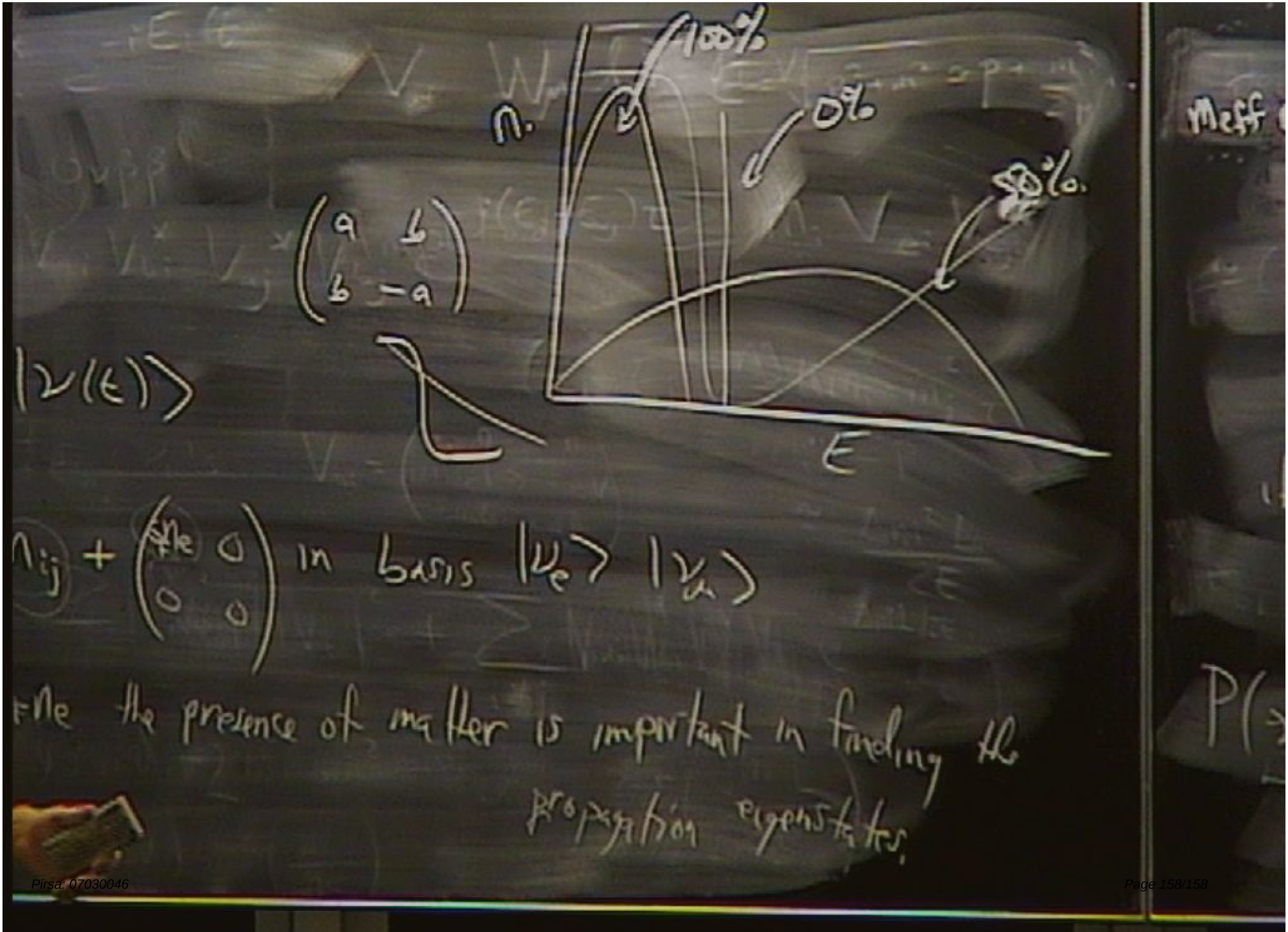
Meff
$|\nu(t)\rangle$
fine the prese
tant in finding the
eigenstates.


100%
0%
80%.
$\begin{pmatrix} a & b \\ b & -a \end{pmatrix}$
$|\nu(t)\rangle$
E
$m_{ij} + \begin{pmatrix} \cdot & 0 \\ 0 & 0 \end{pmatrix}$ in basis $|\nu_e\rangle\ |\nu_\mu\rangle$
the presence of matter is important in finding the propagation eigenstates.
Meff