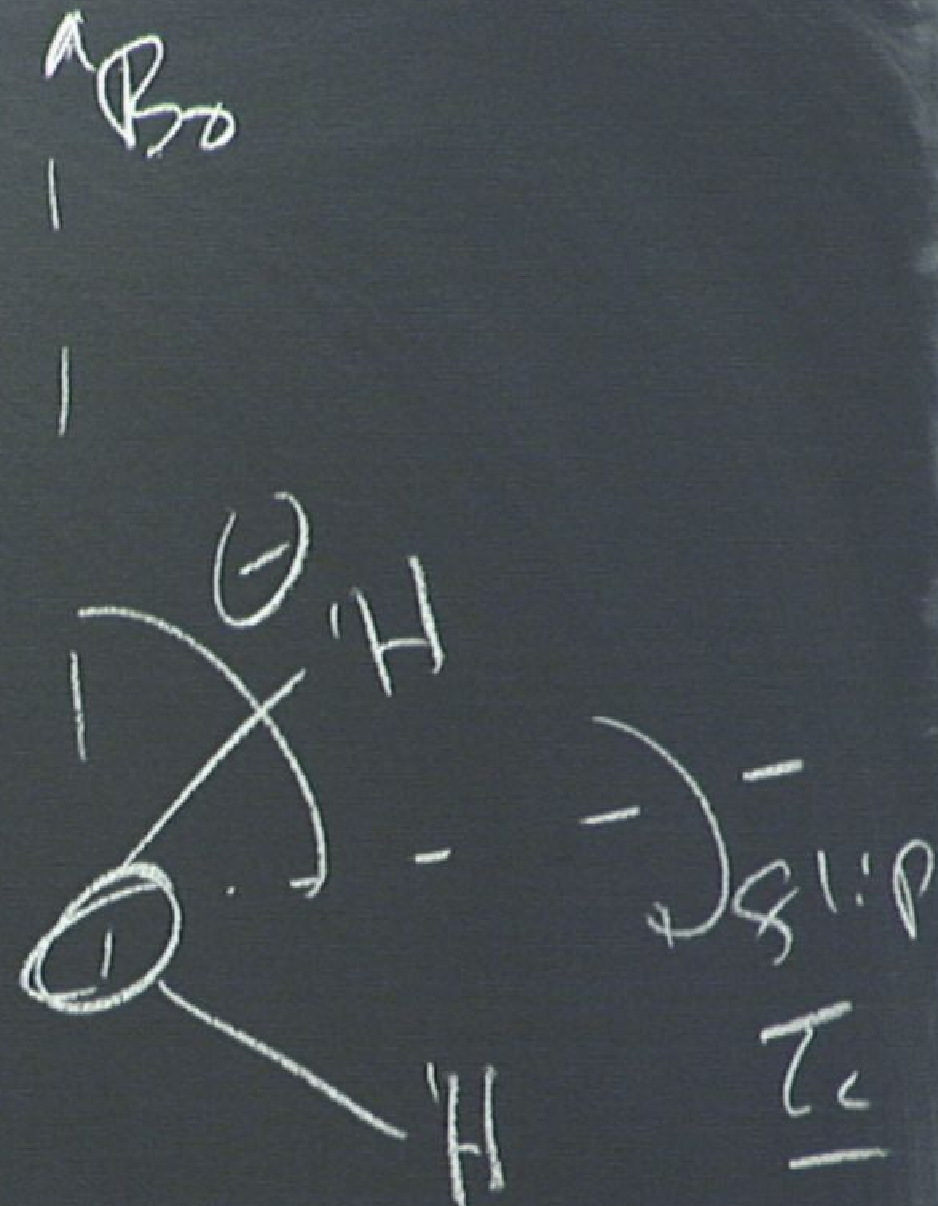
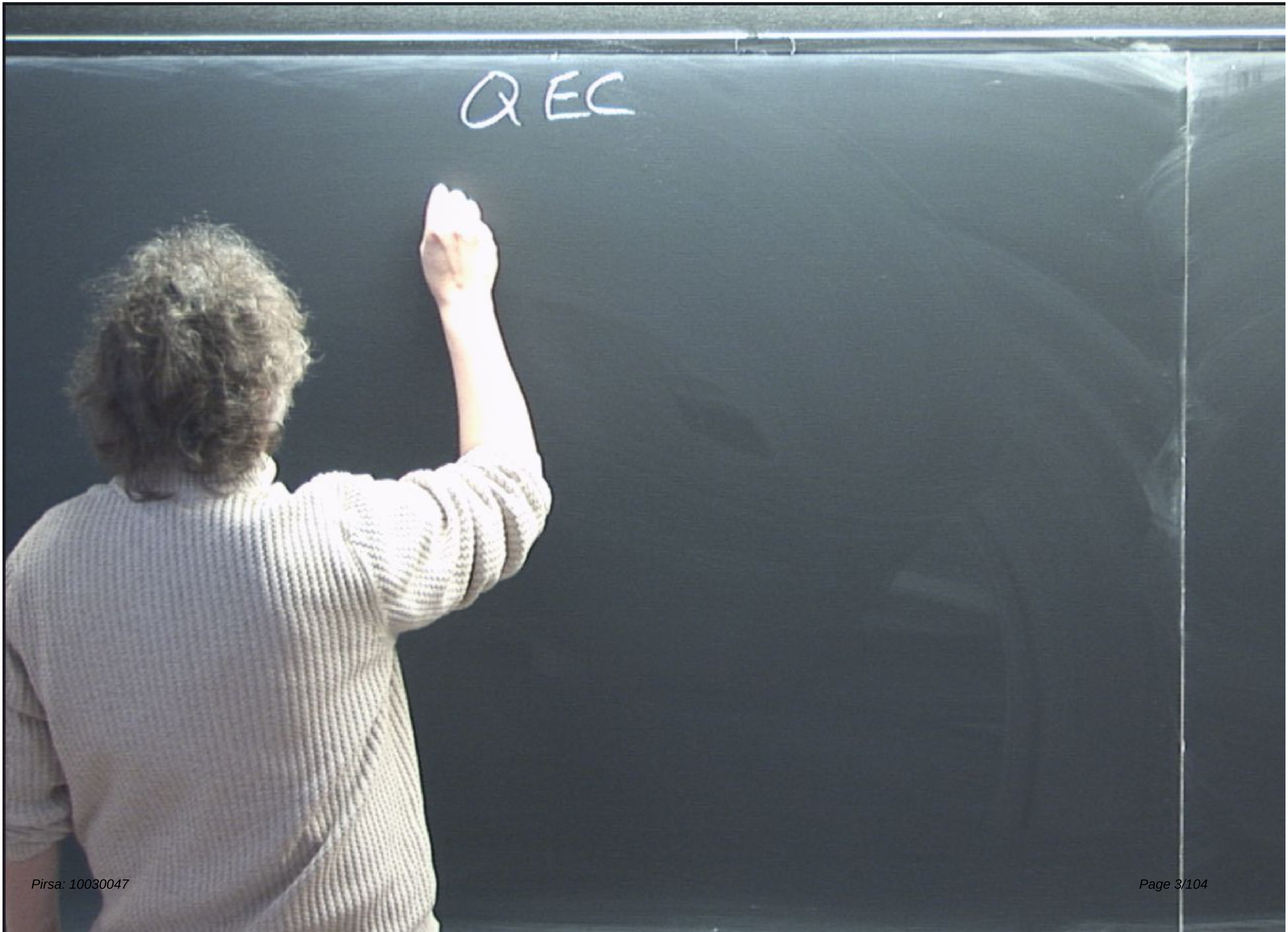
Title: Explorations in Quantum Info. (PHYS 641) - Lecture 14

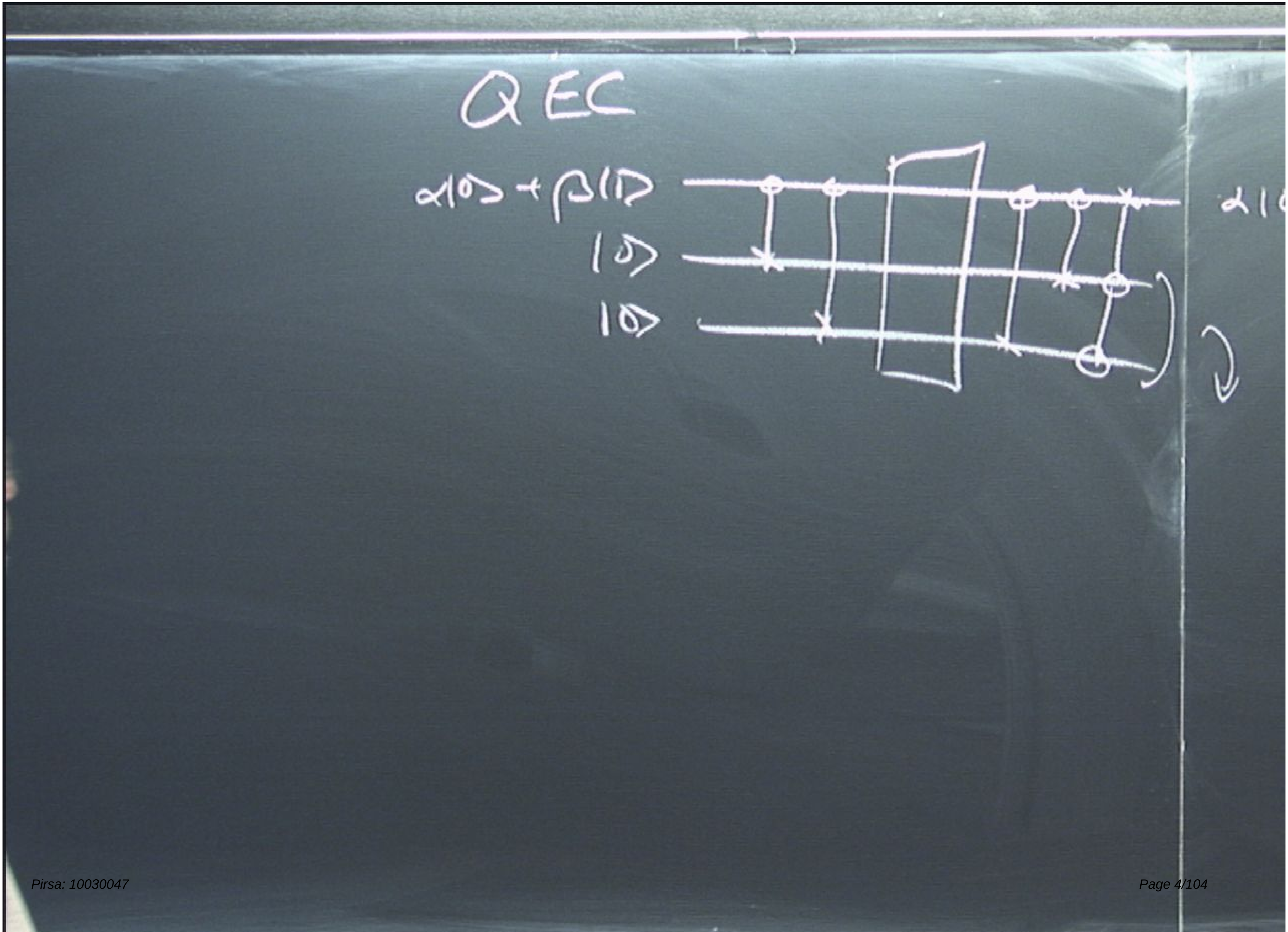
Date: Mar 05, 2010 09:00 AM

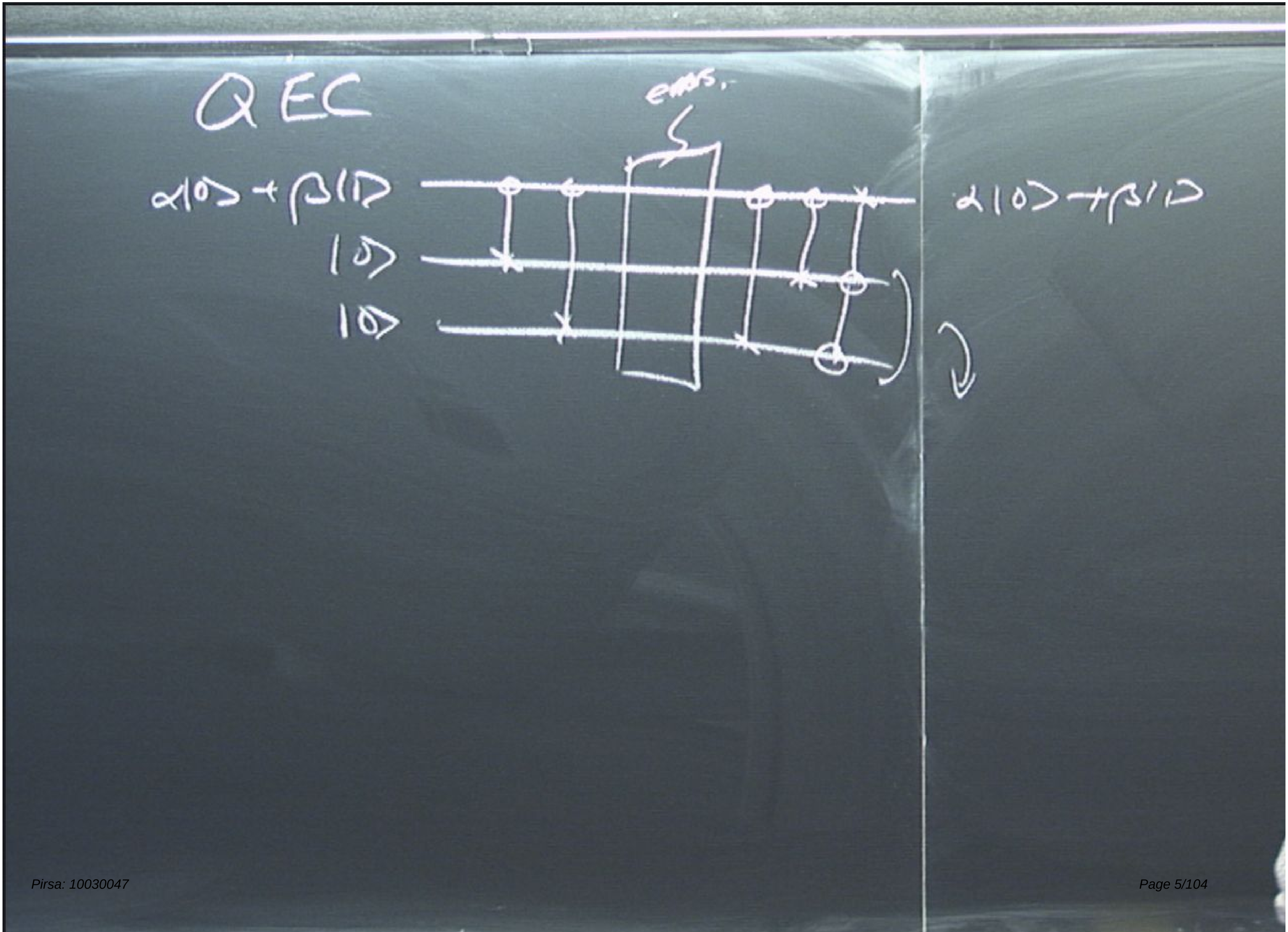
URL: http://pirsa.org/10030047

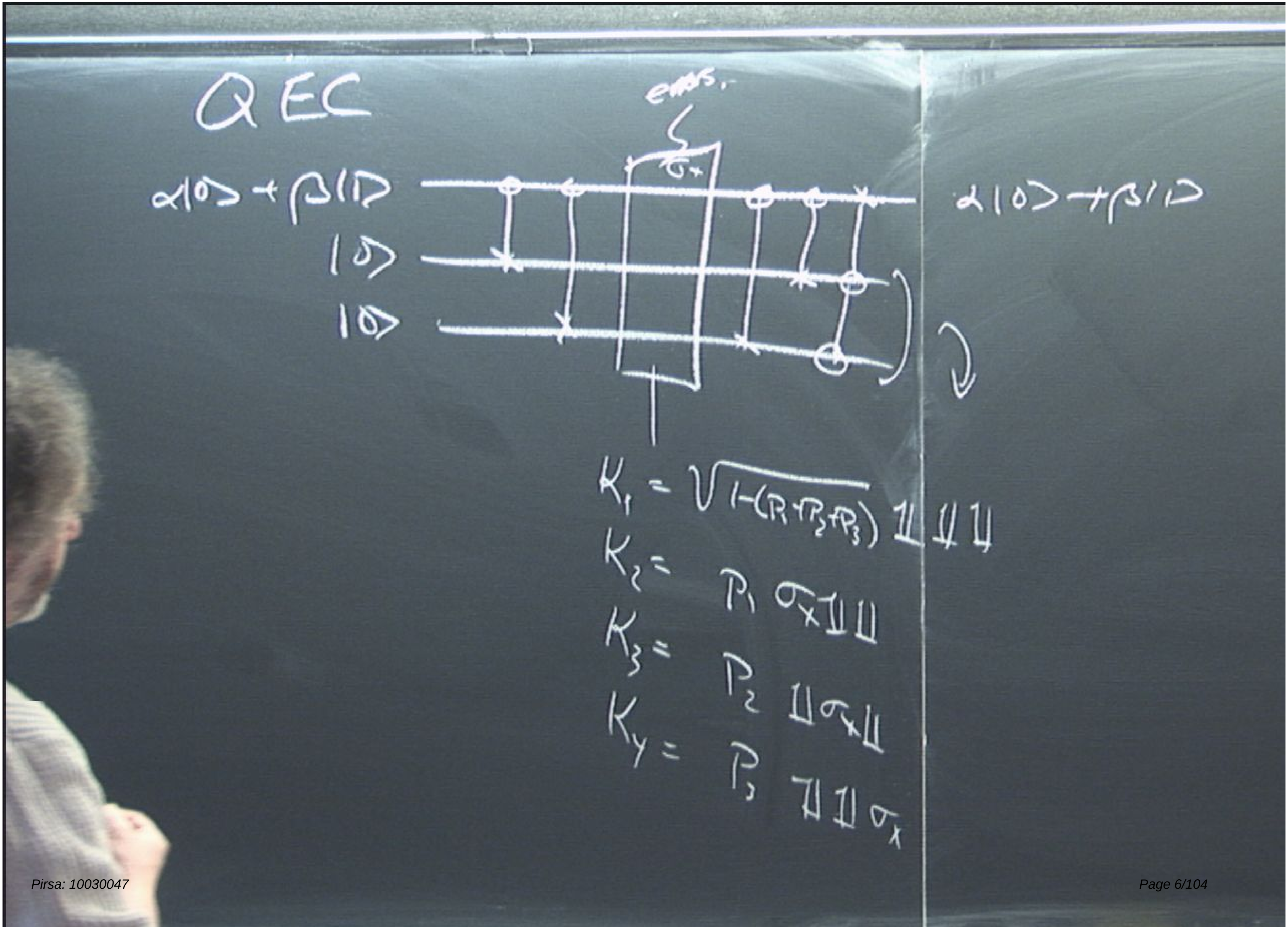
Abstract:

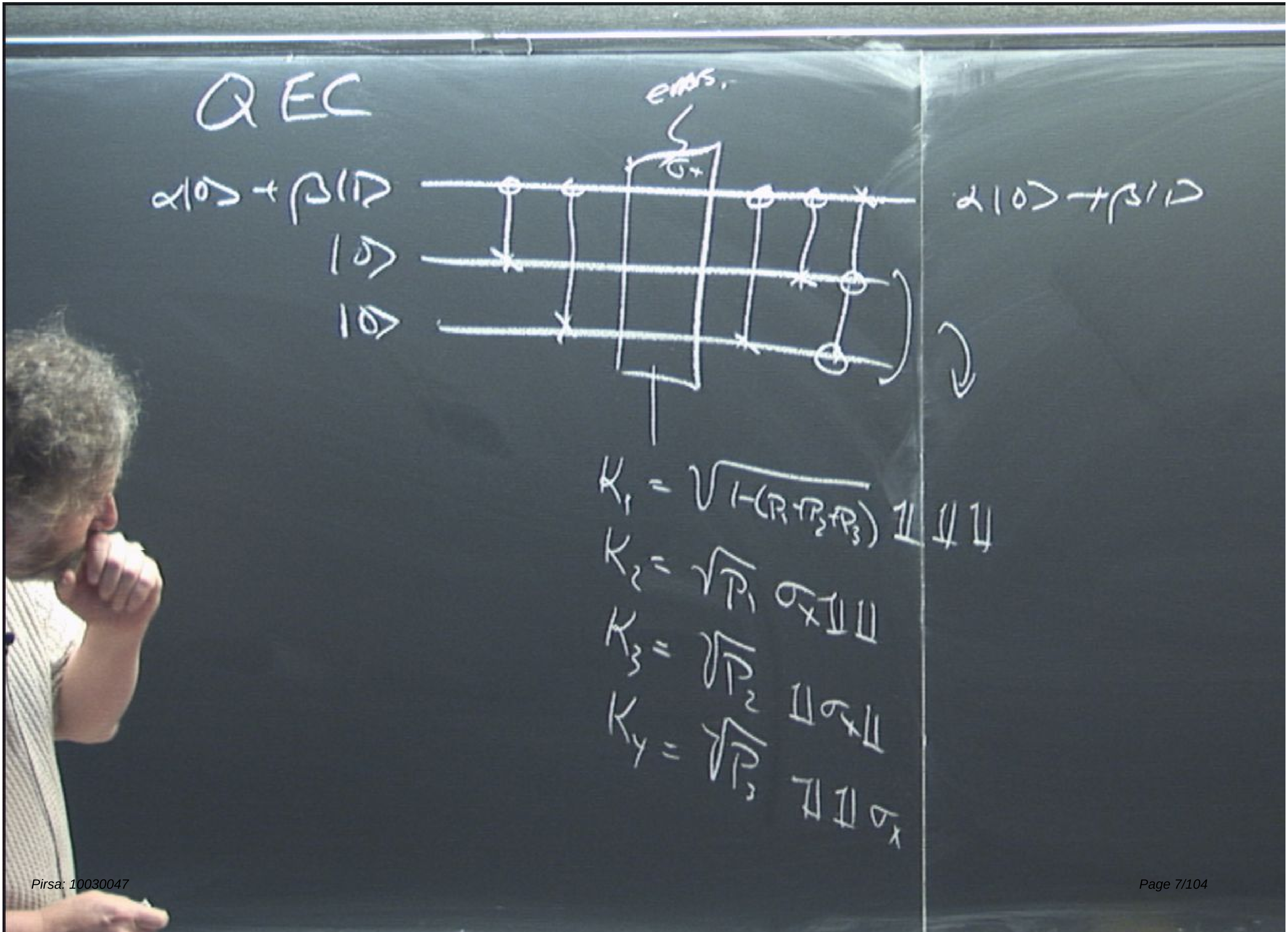

B_0
θ
^1H
^1H
slip
τ_c


QEC

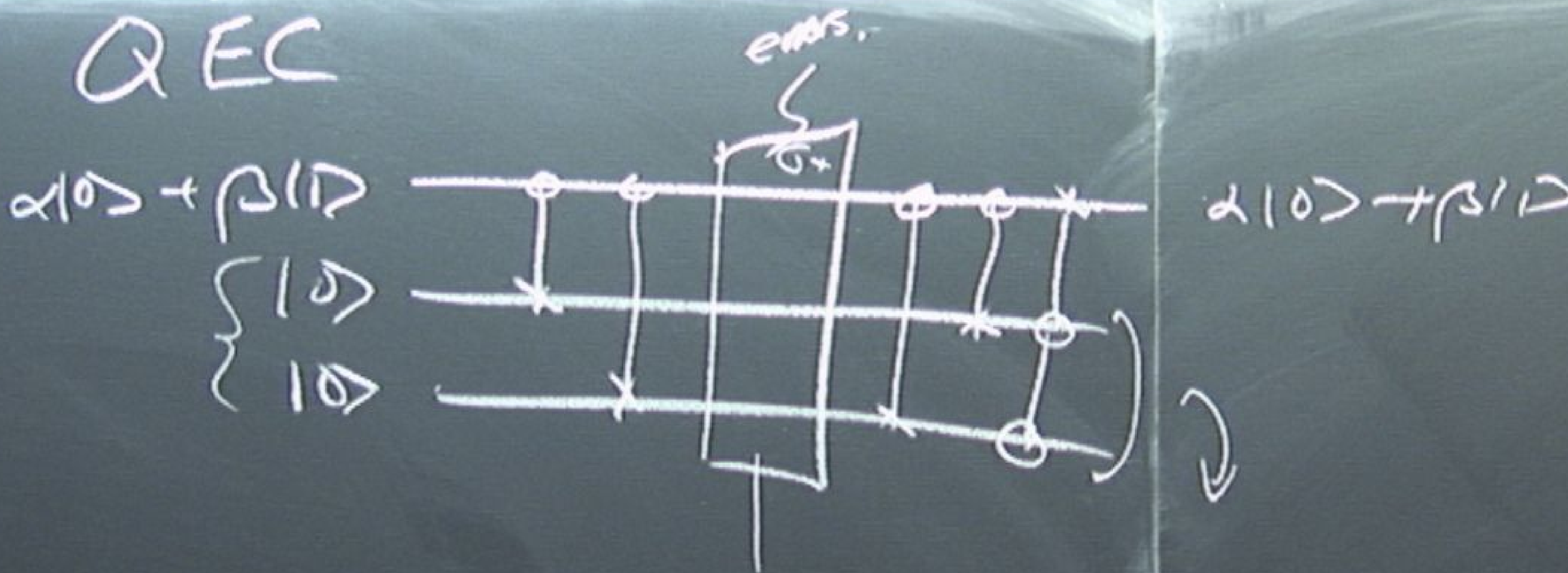

QEC
α|0> + β|1>
|0>
|0>
α|


QEC
errors.
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
$\alpha|0\rangle + \beta|1\rangle$


QEC
errors
σ_x
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
$\alpha|0\rangle + \beta|1\rangle$
$K_1 = \sqrt{1-(p_1+p_2+p_3)}\ \mathbb{1}\,\mathbb{1}\,\mathbb{1}$
$K_2 = p_1\ \sigma_x \mathbb{1}\,\mathbb{1}$
$K_3 = p_2\ \mathbb{1}\,\sigma_x \mathbb{1}$
$K_4 = p_3\ \mathbb{1}\,\mathbb{1}\,\sigma_x$


QEC
errors
σx
α|0> + β|1>
|0>
|0>
α|0> + β|1>
K1 = √(1-(P1+P2+P3)) 𝟙 𝟙 𝟙
K2 = √P1 σx 𝟙 𝟙
K3 = √P2 𝟙 σx 𝟙
K4 = √P3 𝟙 𝟙 σx

QEC

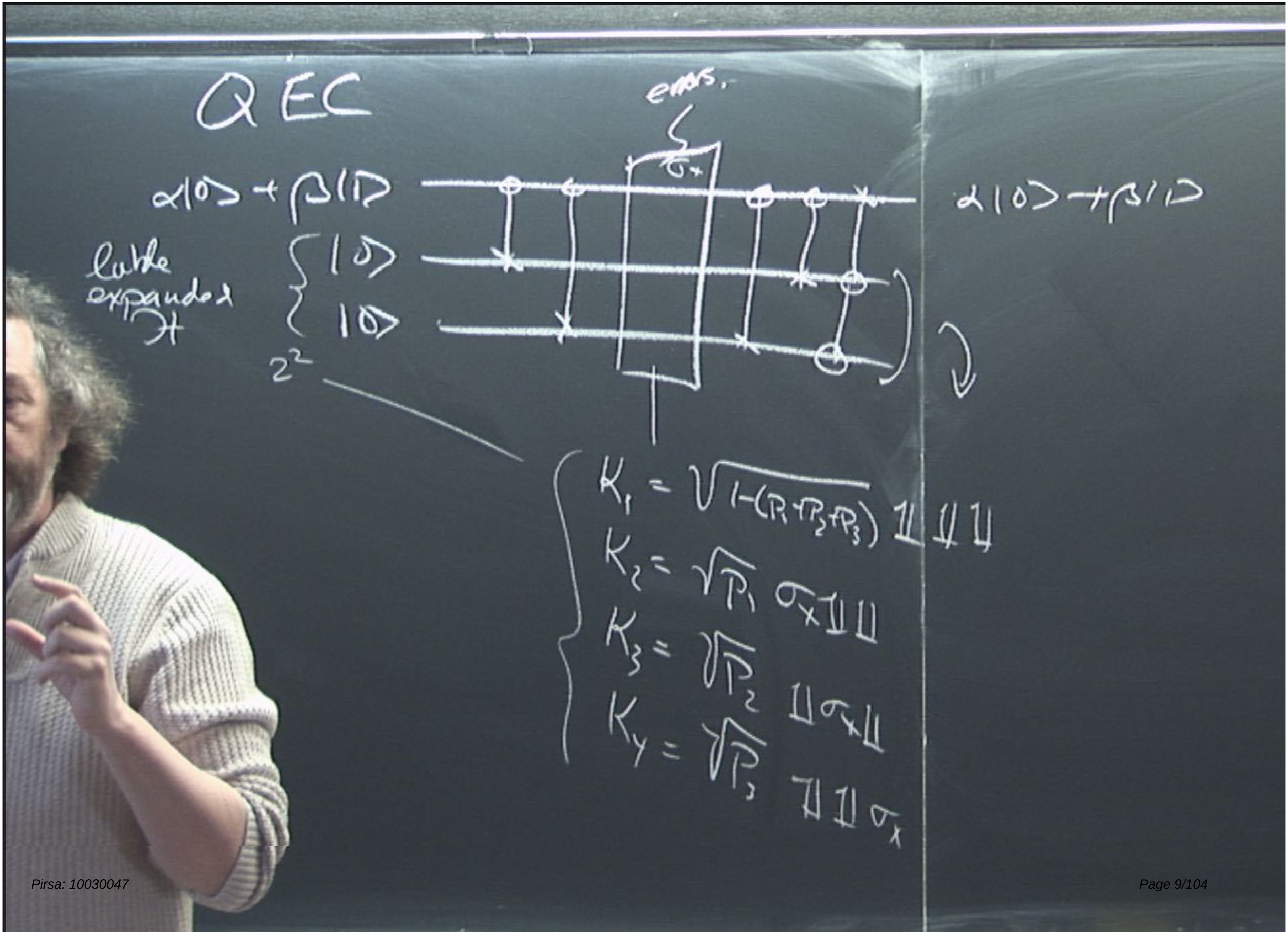


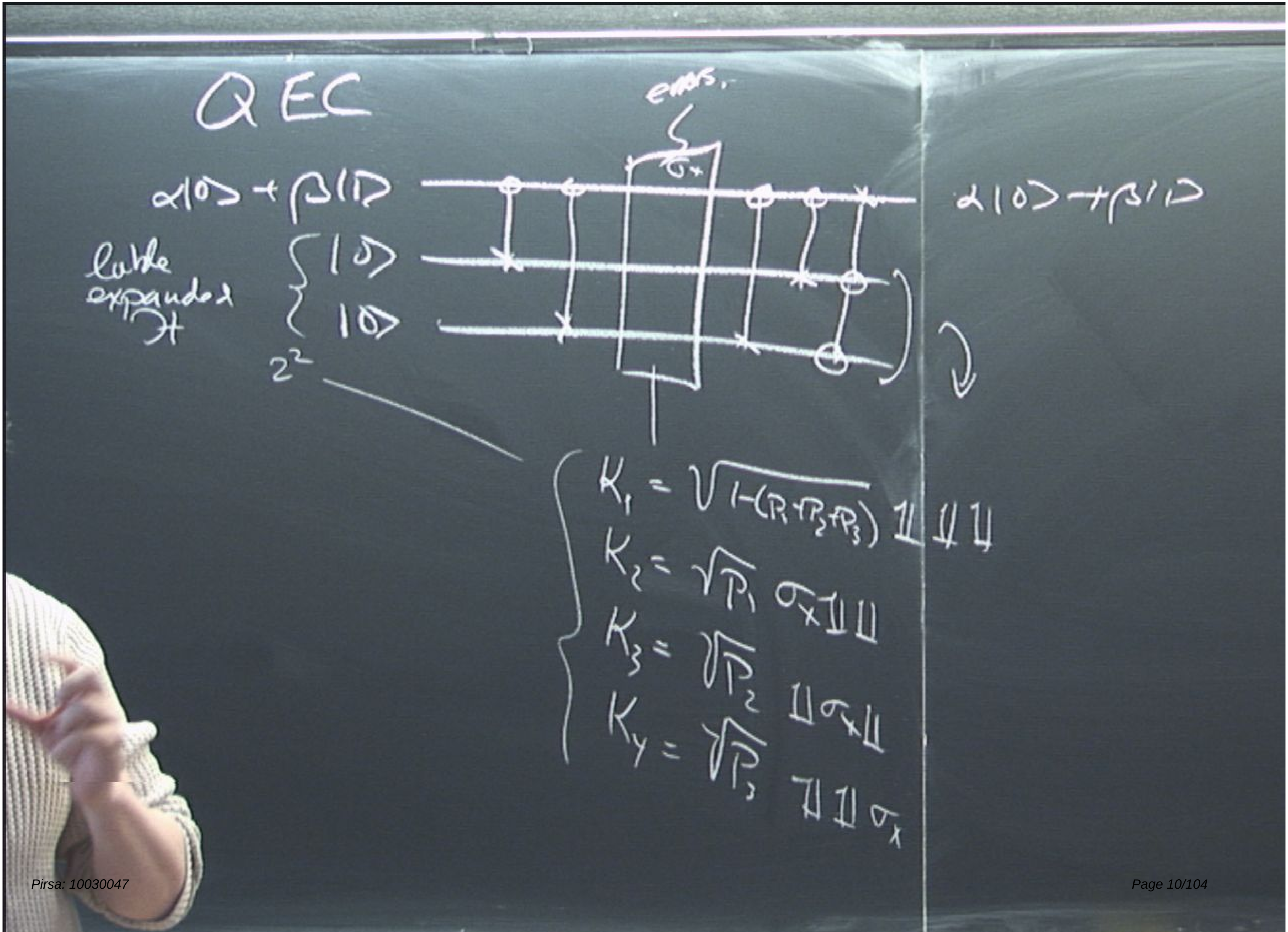
$$K_1 = \sqrt{1-(P_1+P_2+P_3)}\ \mathbb{1}\,\mathbb{1}\,\mathbb{1}$$

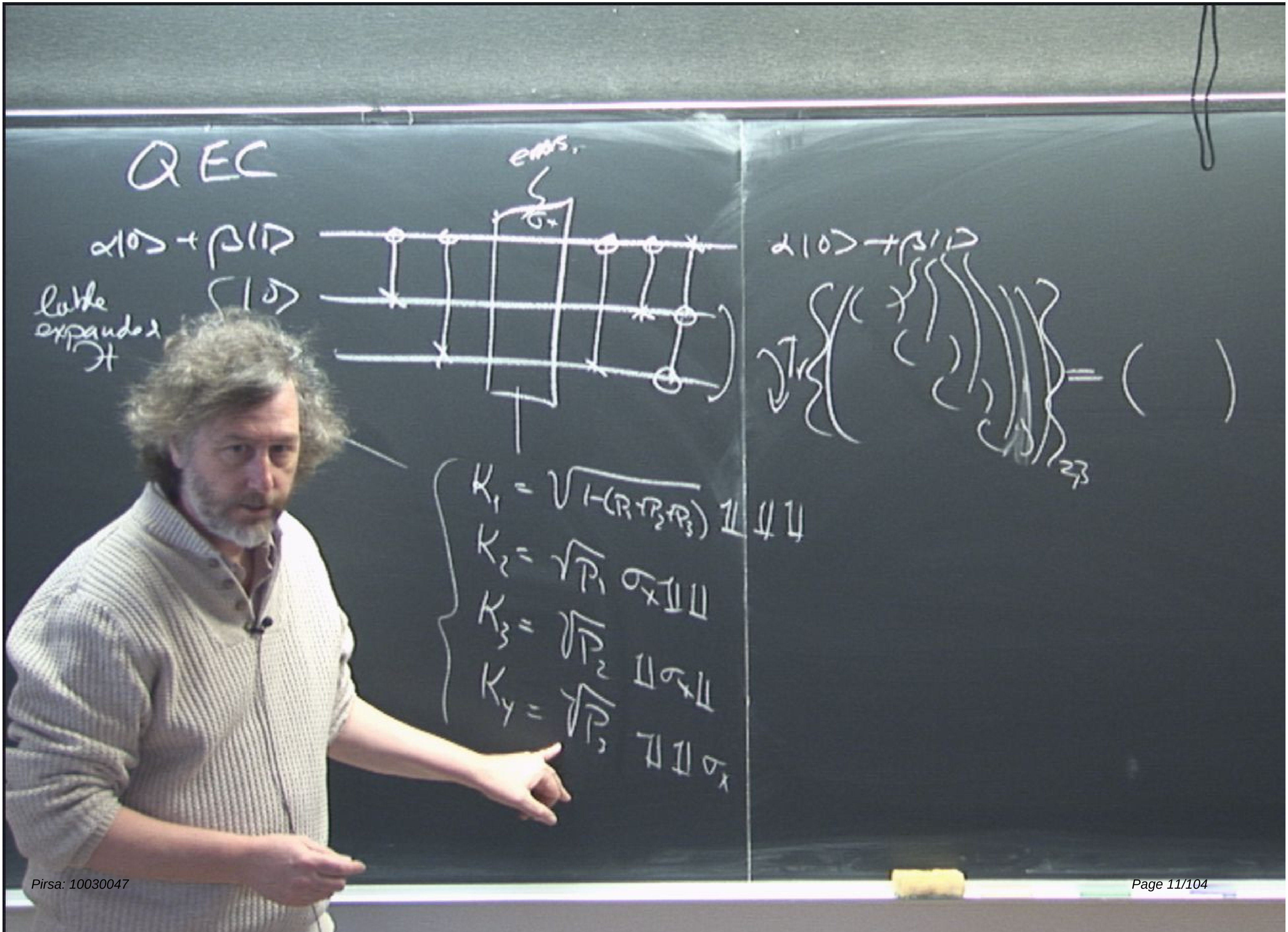
$$K_2 = \sqrt{P_1}\ \sigma_x \mathbb{1}\,\mathbb{1}$$

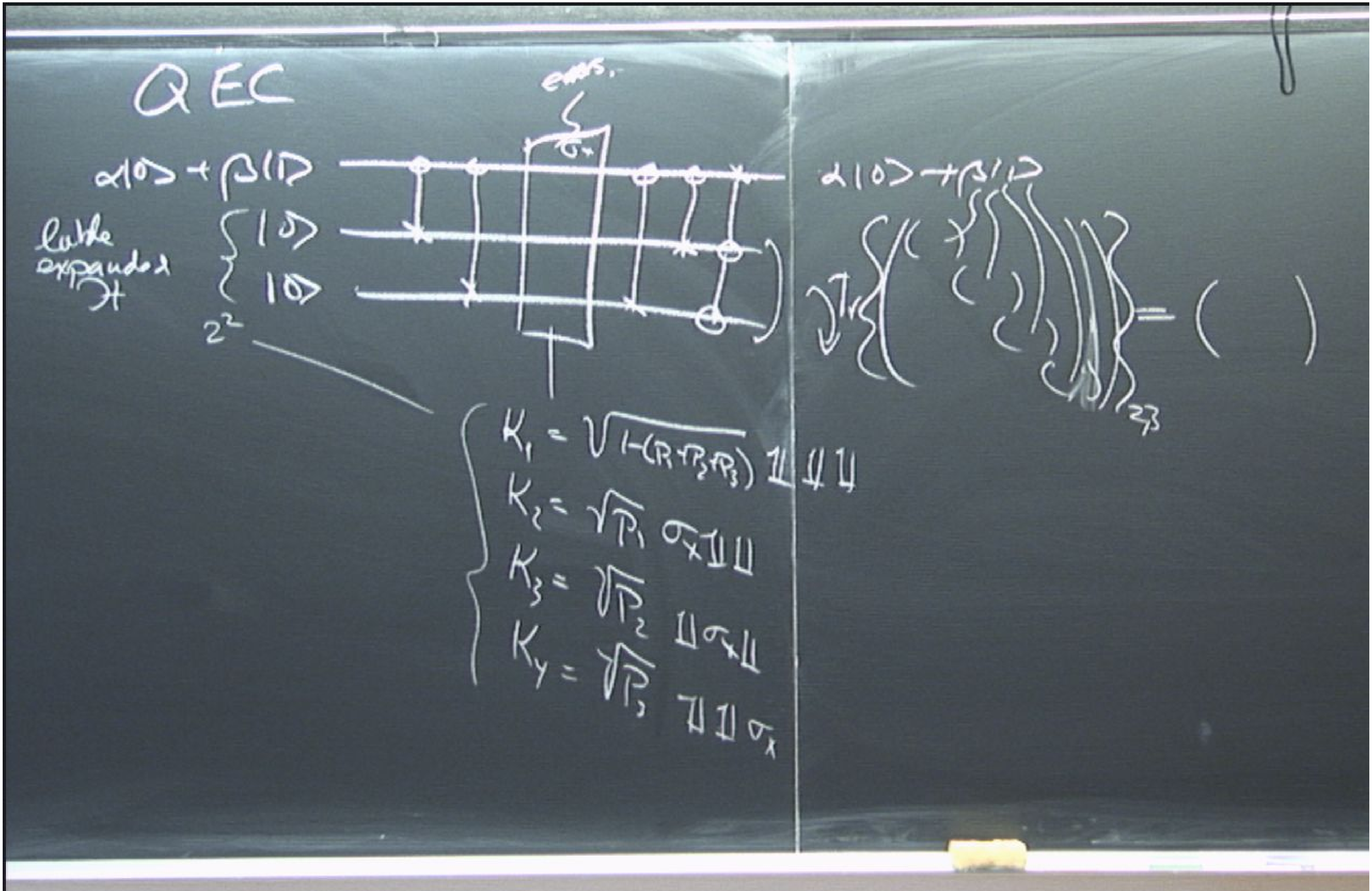
$$K_3 = \sqrt{P_2}\ \mathbb{1}\,\sigma_x \mathbb{1}$$

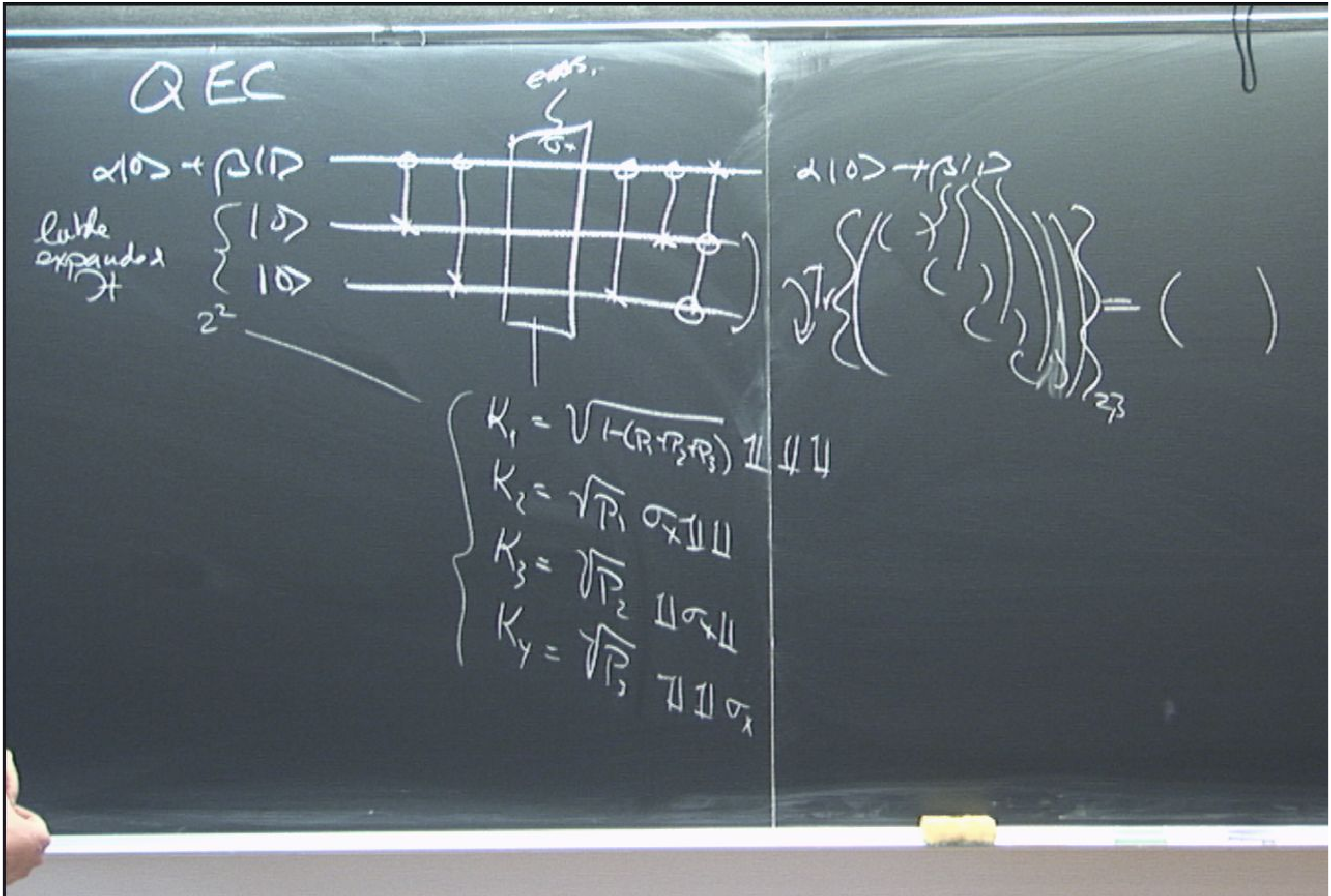
$$K_4 = \sqrt{P_3}\ \mathbb{1}\,\mathbb{1}\,\sigma_x$$

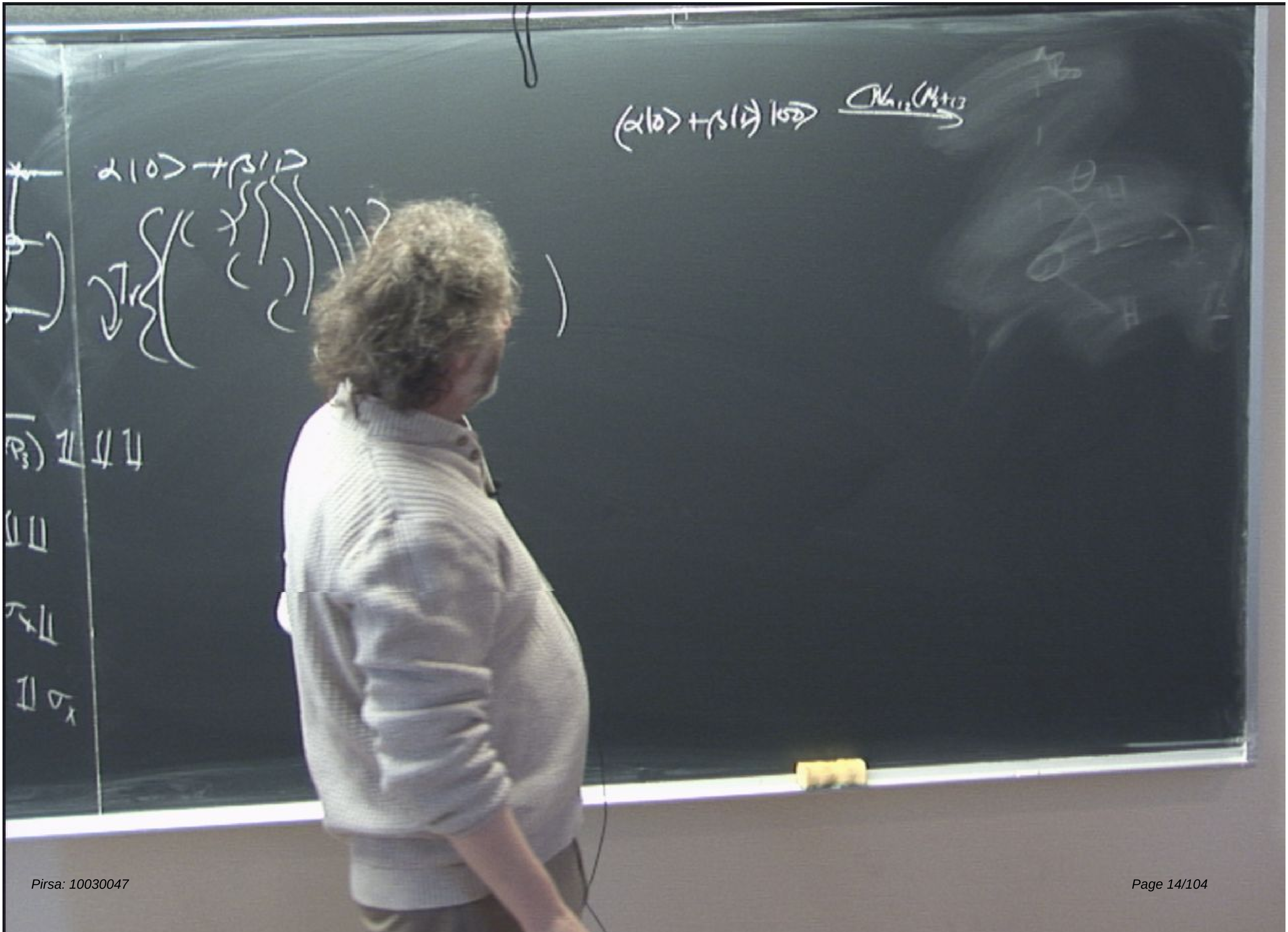

QEC
errors.
σx
α|0> + β|1>
|0>
|0>
2²
α|0> + β|1>
K1 = √(1-(P1+P2+P3)) 𝟙 𝟙 𝟙
K2 = √P1 σx 𝟙 𝟙
K3 = √P2 𝟙 σx 𝟙
K4 = √P3 𝟙 𝟙 σx

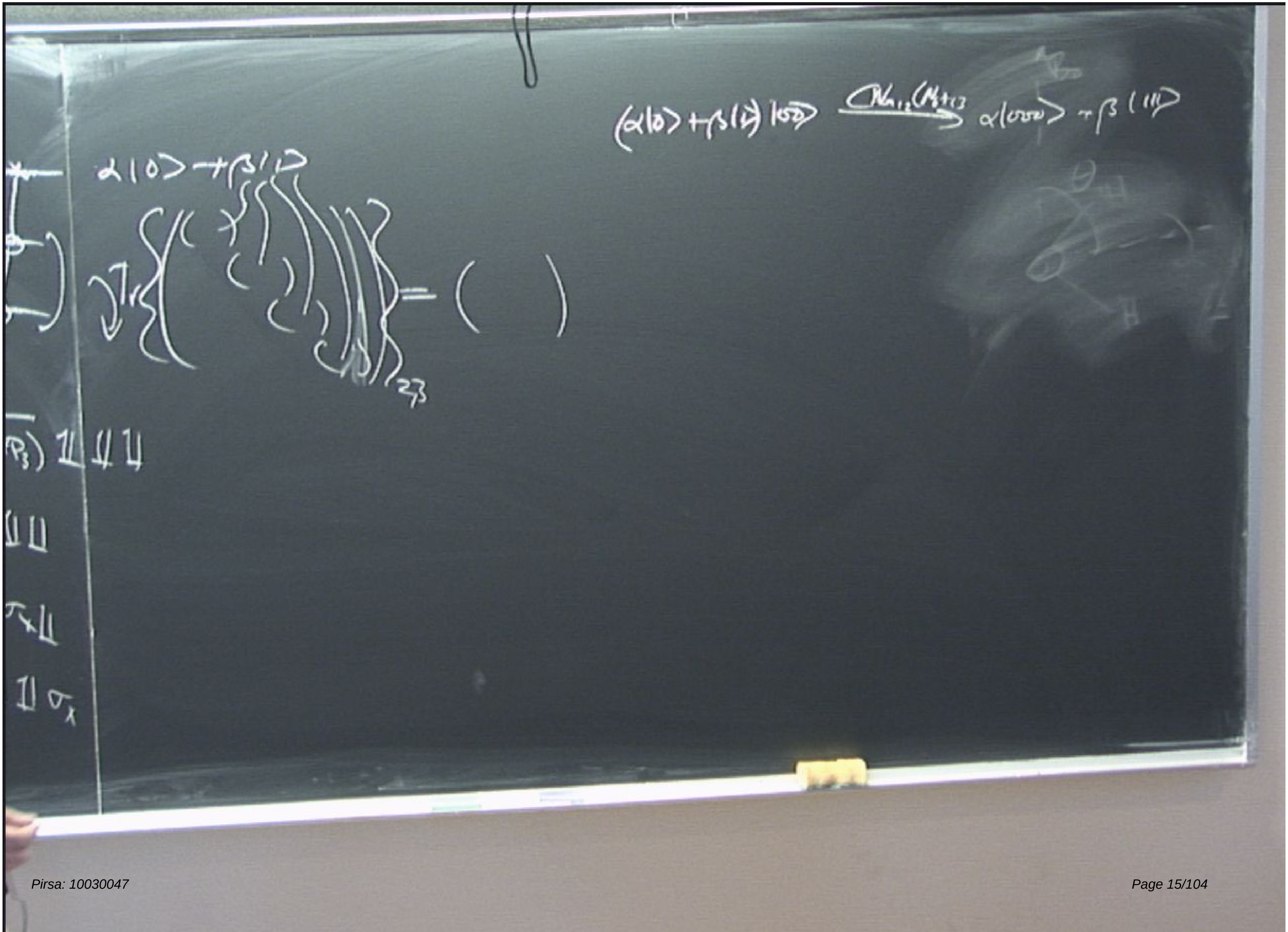

QEC
errors
σ_x
$\alpha|0\rangle + \beta|1\rangle$
little expanded $\mathcal{H}$
$|0\rangle$
$|0\rangle$
2^2
$\alpha|0\rangle + \beta|1\rangle$
$K_1 = \sqrt{1-(P_1+P_2+P_3)}\, \mathbb{1}\,\mathbb{1}\,\mathbb{1}$
$K_2 = \sqrt{P_1}\, \sigma_x \mathbb{1}\,\mathbb{1}$
$K_3 = \sqrt{P_2}\, \mathbb{1}\, \sigma_x \mathbb{1}$
$K_4 = \sqrt{P_3}\, \mathbb{1}\,\mathbb{1}\, \sigma_x$

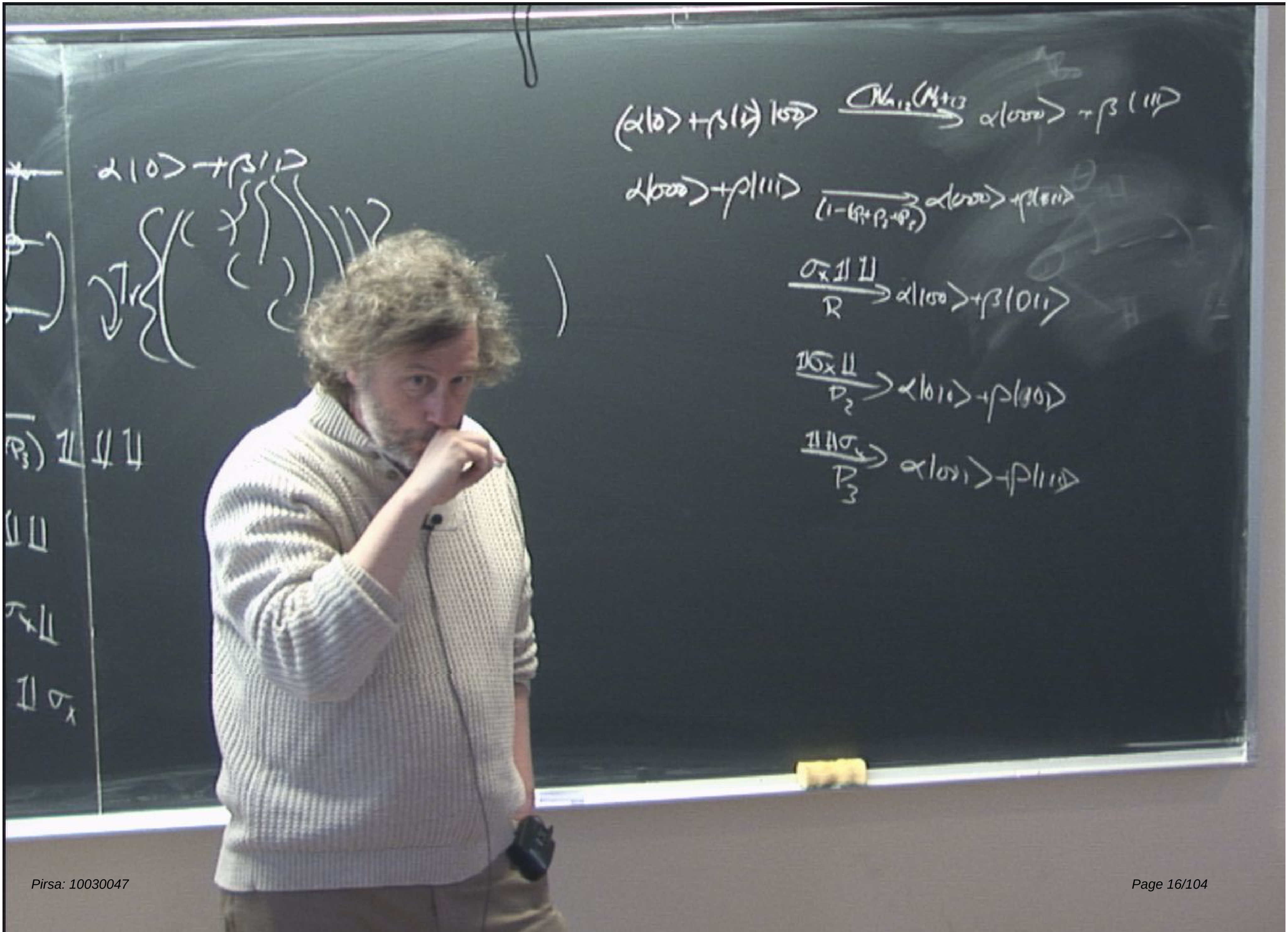

QEC
errors
α|0⟩ + β|1⟩
|0⟩
K1 = √(1−(p1+p2+p3)) 𝟙 𝟙 𝟙
K2 = √p1 σx 𝟙 𝟙
K3 = √p2 𝟙 σx 𝟙
K4 = √p3 𝟙 𝟙 σx

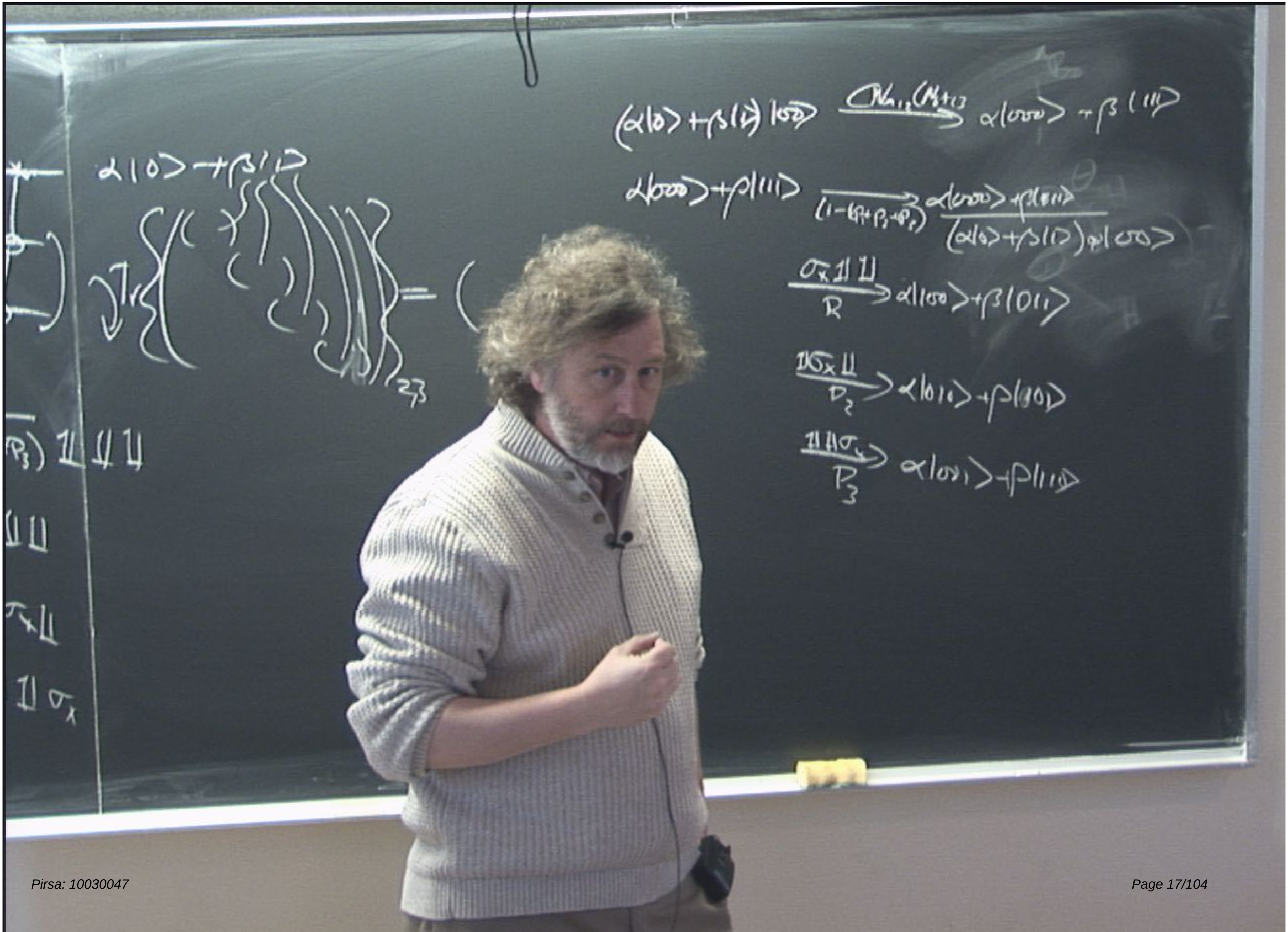

QEC
errors
σ_x
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
2^2
$K_1 = \sqrt{1-(P_1+P_2+P_3)}\ \mathbb{1}\,\mathbb{1}\,\mathbb{1}$
$K_2 = \sqrt{P_1}\ \sigma_x \mathbb{1}\,\mathbb{1}$
$K_3 = \sqrt{P_2}\ \mathbb{1}\,\sigma_x \mathbb{1}$
$K_4 = \sqrt{P_3}\ \mathbb{1}\,\mathbb{1}\,\sigma_x$
$\alpha|0\rangle + \beta|1\rangle$
2^3


QEC
errors
σ_x
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
expanded
2^2
$K_1 = \sqrt{1-(P_1+P_2+P_3)}\ 𝟙\,𝟙\,𝟙$
$K_2 = \sqrt{P_1}\ \sigma_x 𝟙\,𝟙$
$K_3 = \sqrt{P_2}\ 𝟙\,\sigma_x 𝟙$
$K_4 = \sqrt{P_3}\ 𝟙\,𝟙\,\sigma_x$
$\alpha|0\rangle + \beta|1\rangle$
$2,3$

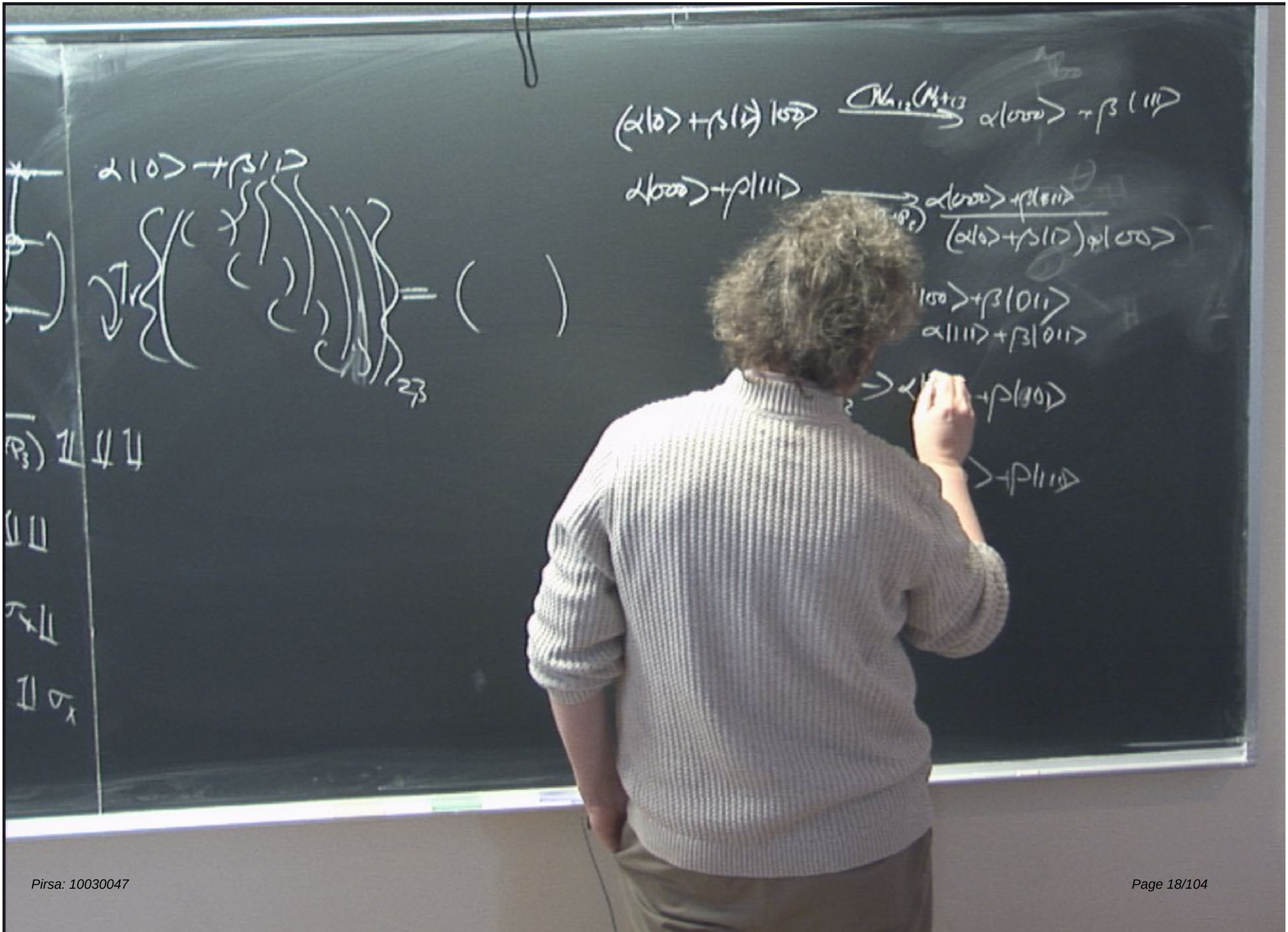


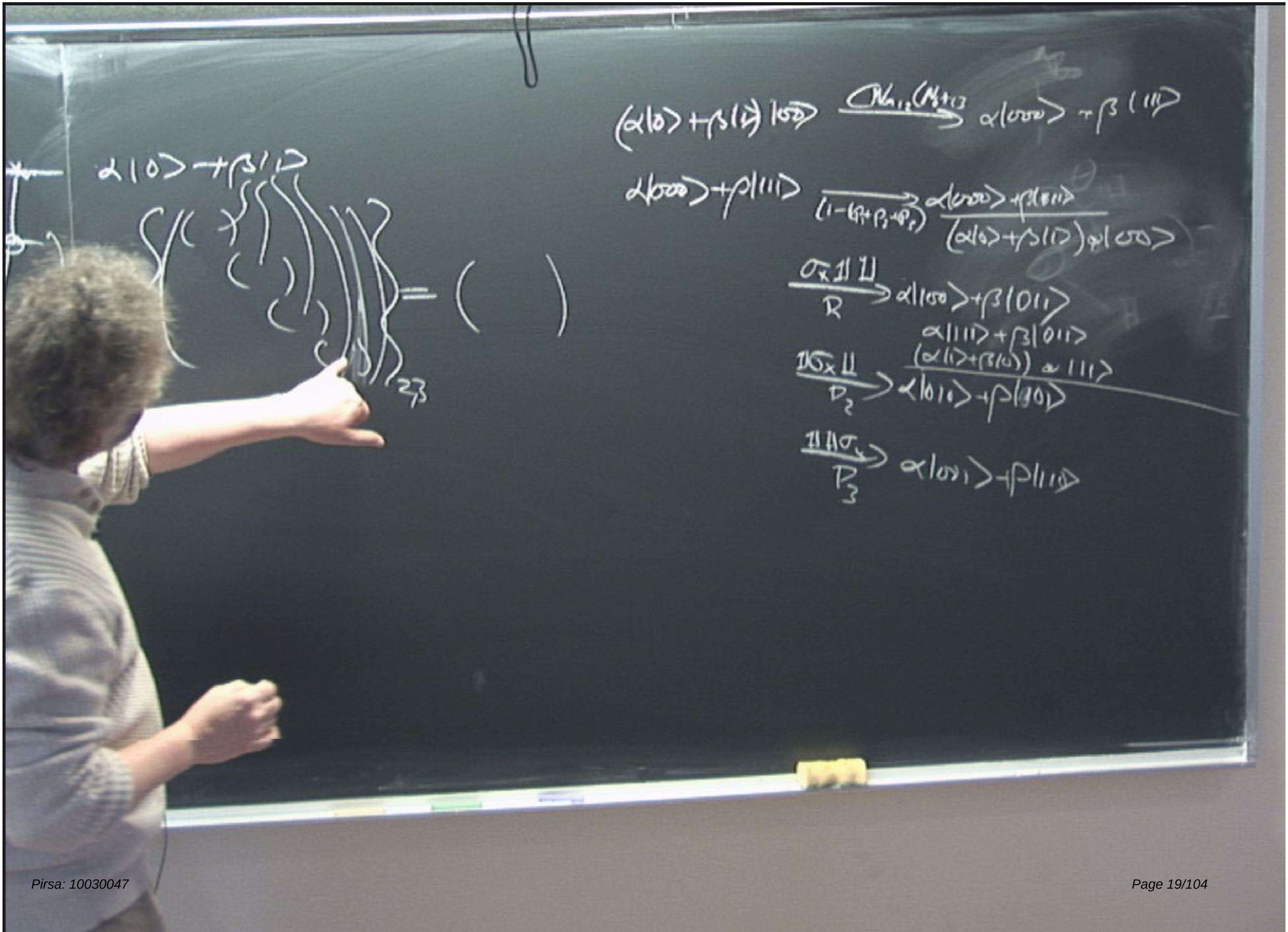


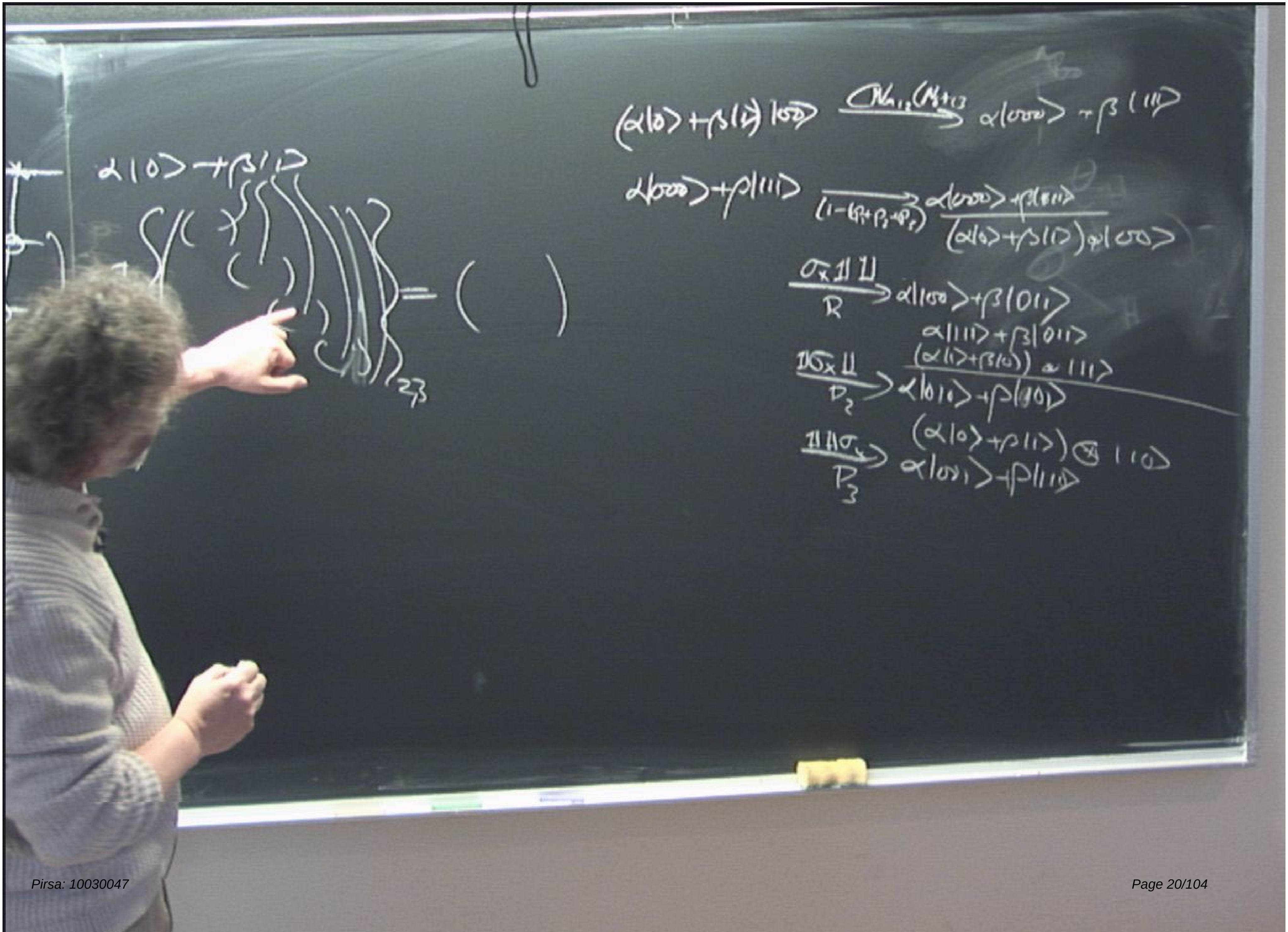

α|0> + β|1>
α|000> + β|111>
α|100> + β|011>
α|011> + β|111>

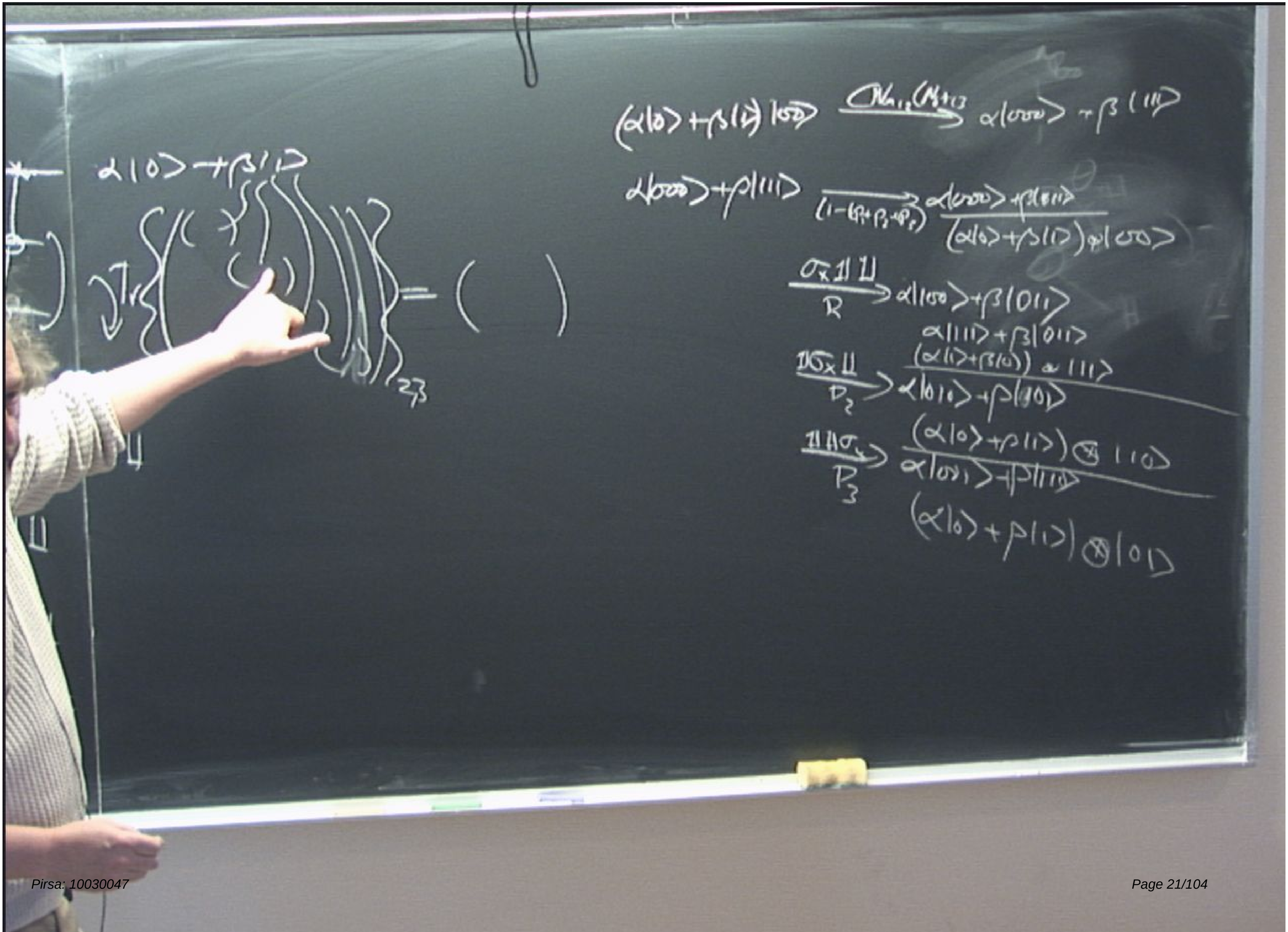


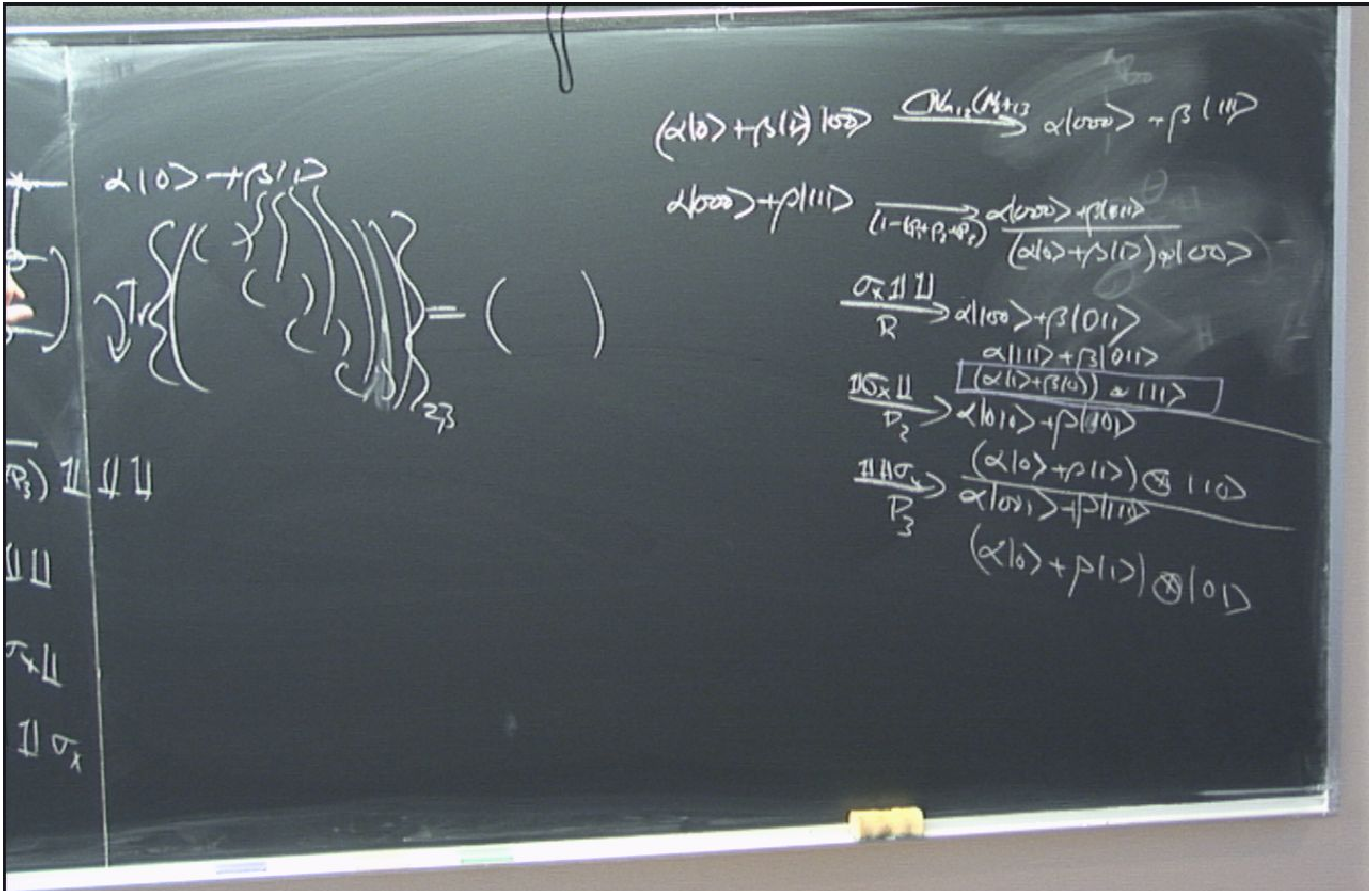
α|0> + β|1>
α|000> + β|111>
α|100> + β|011>
α|010> + β|101>

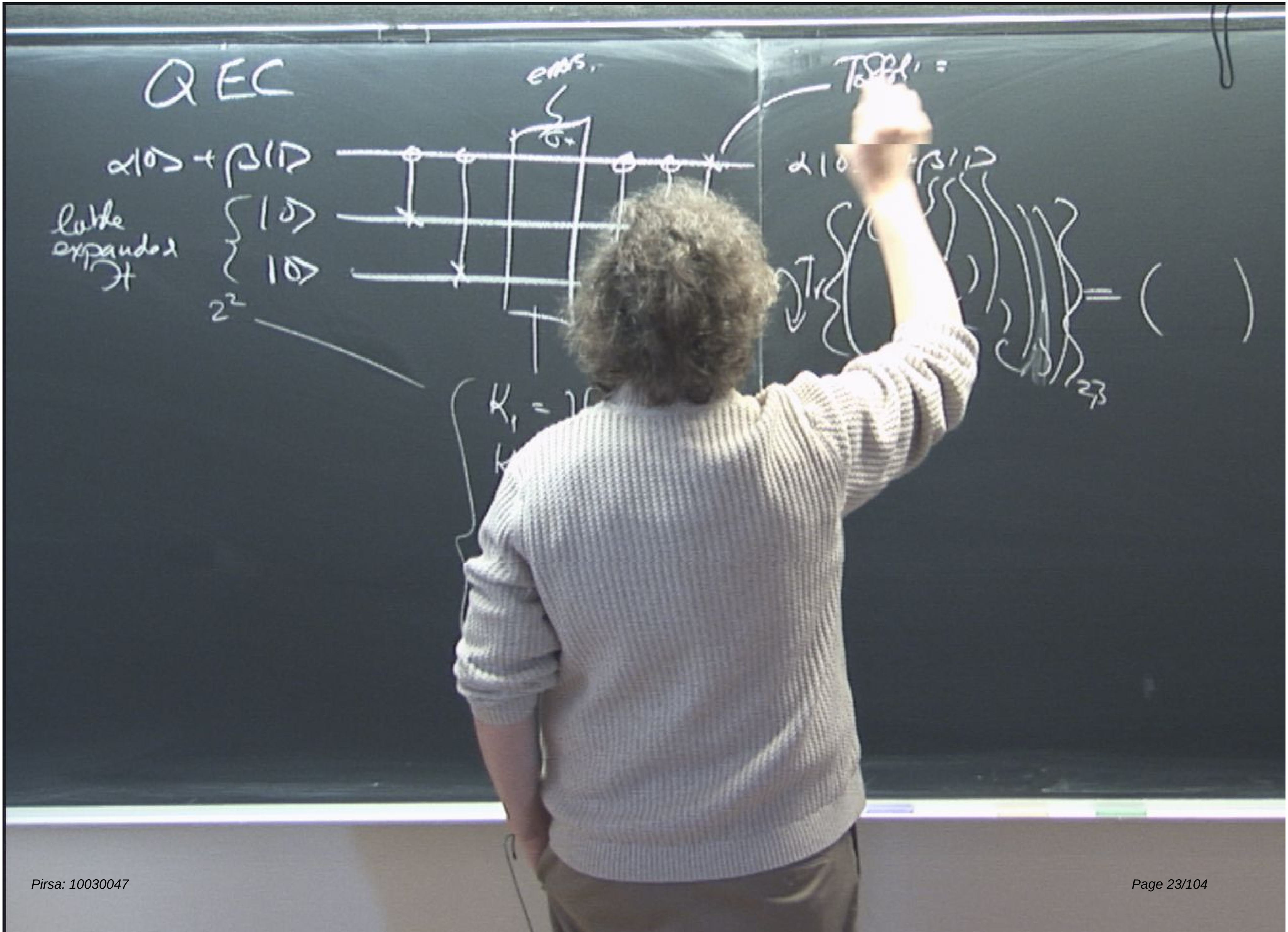


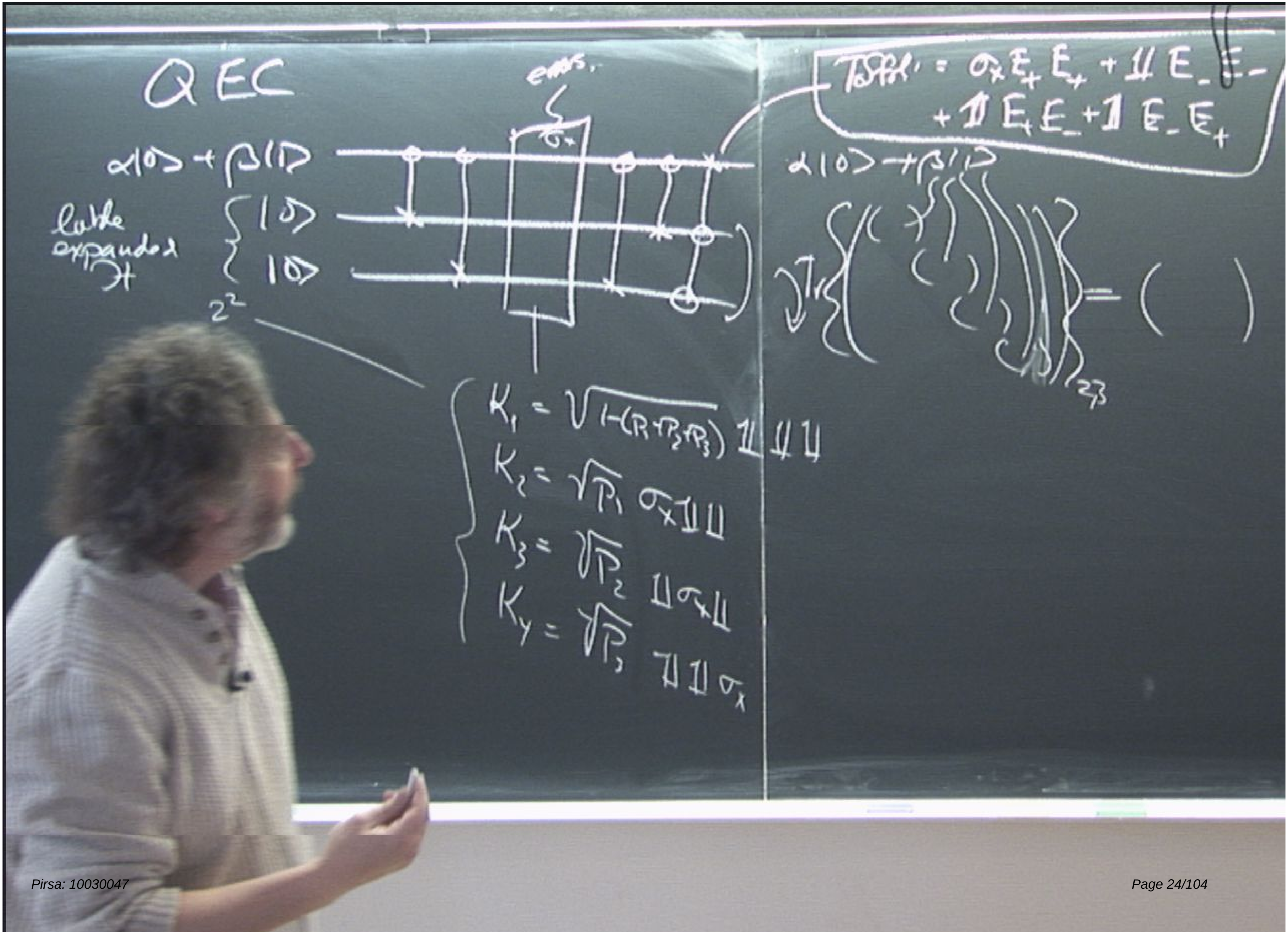


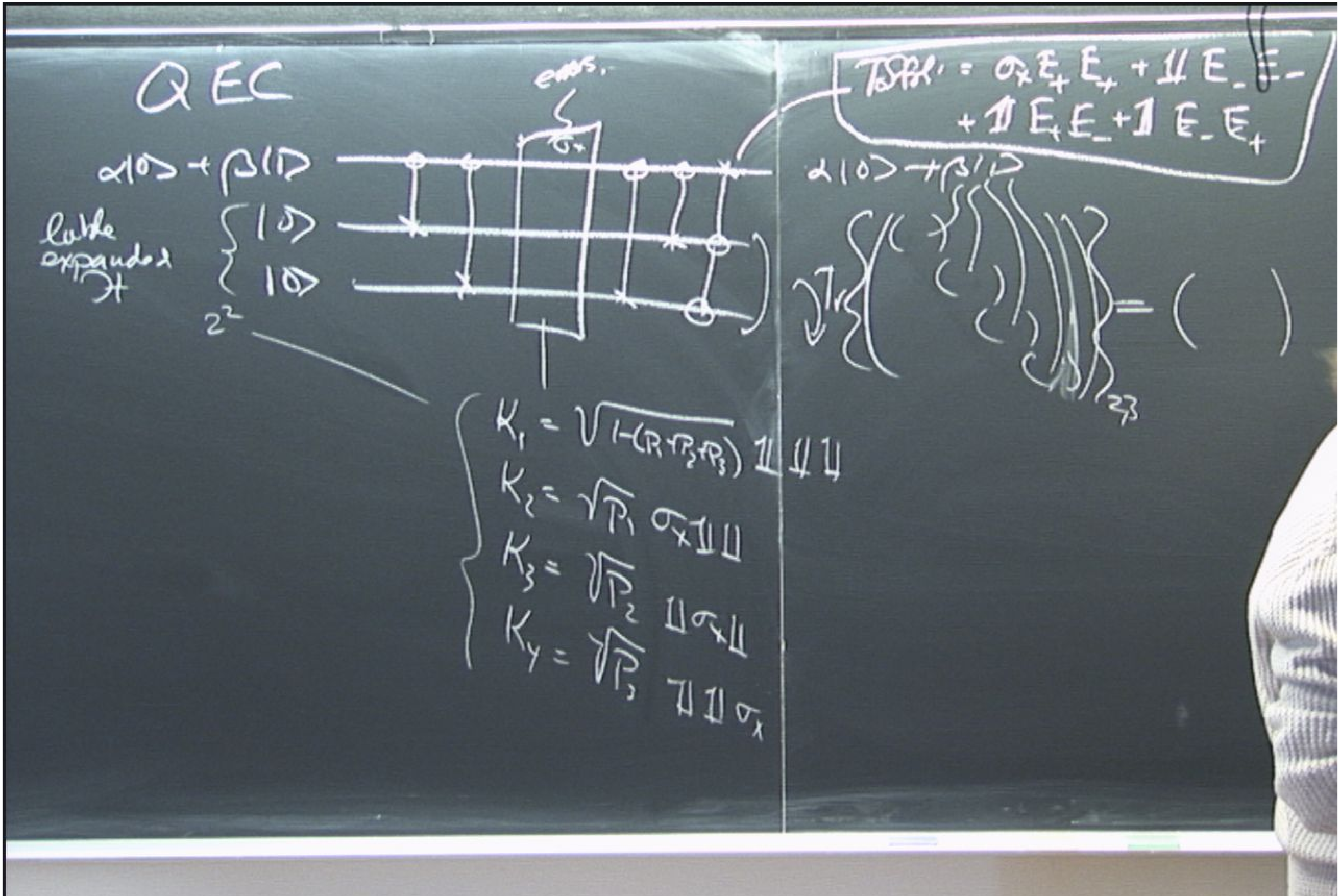


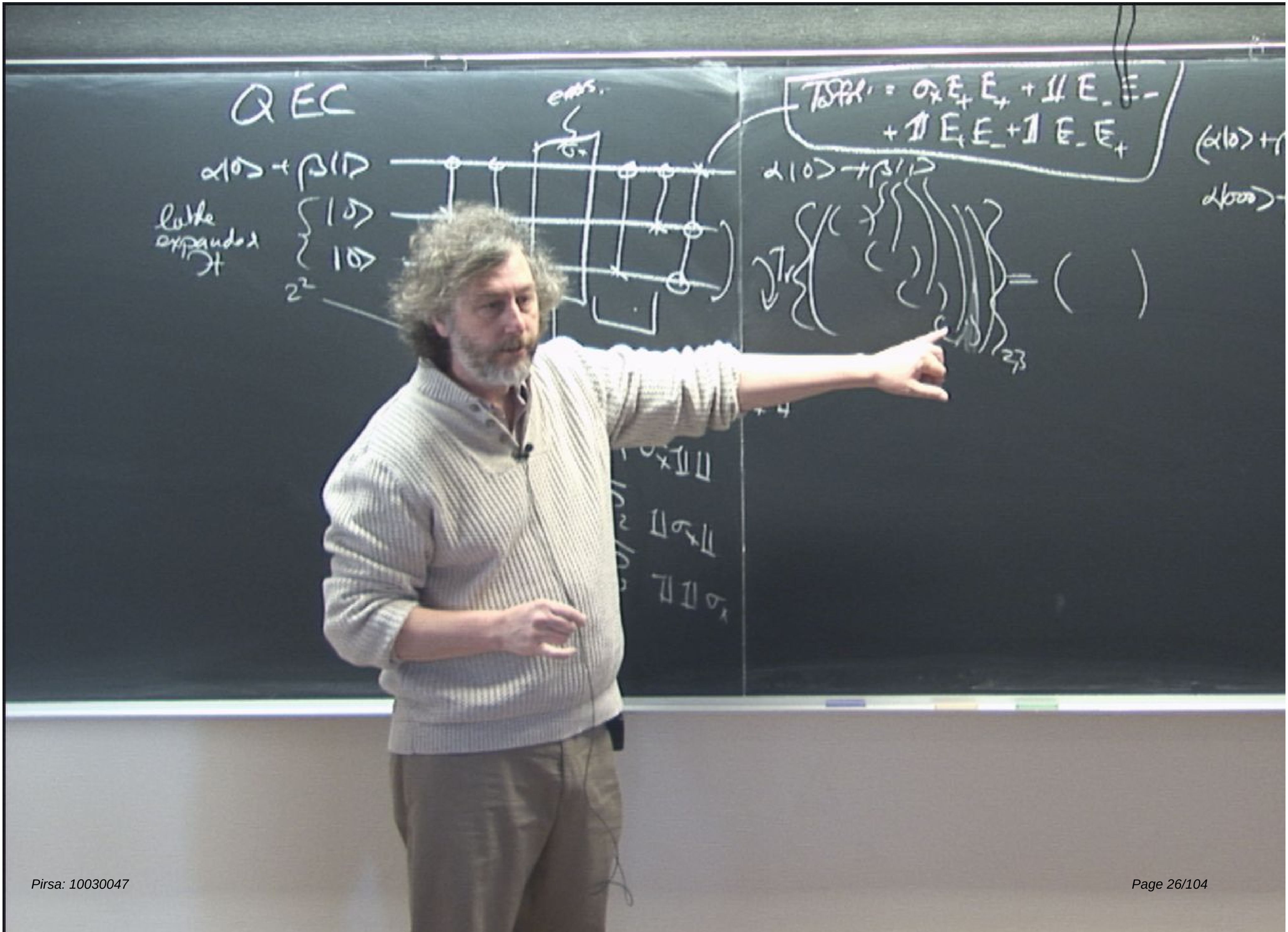

α|0> + β|1>
(α|0> + β|1>)|00> → α|000> + β|111>
α|000> + β|111>
σx 11
R
α|100> + β|011>
α|111> + β|011>
α|010> + β|101>
(α|0> + β|1>) ⊗ |10>
α|001> + β|110>
(α|0> + β|1>) ⊗ |01>

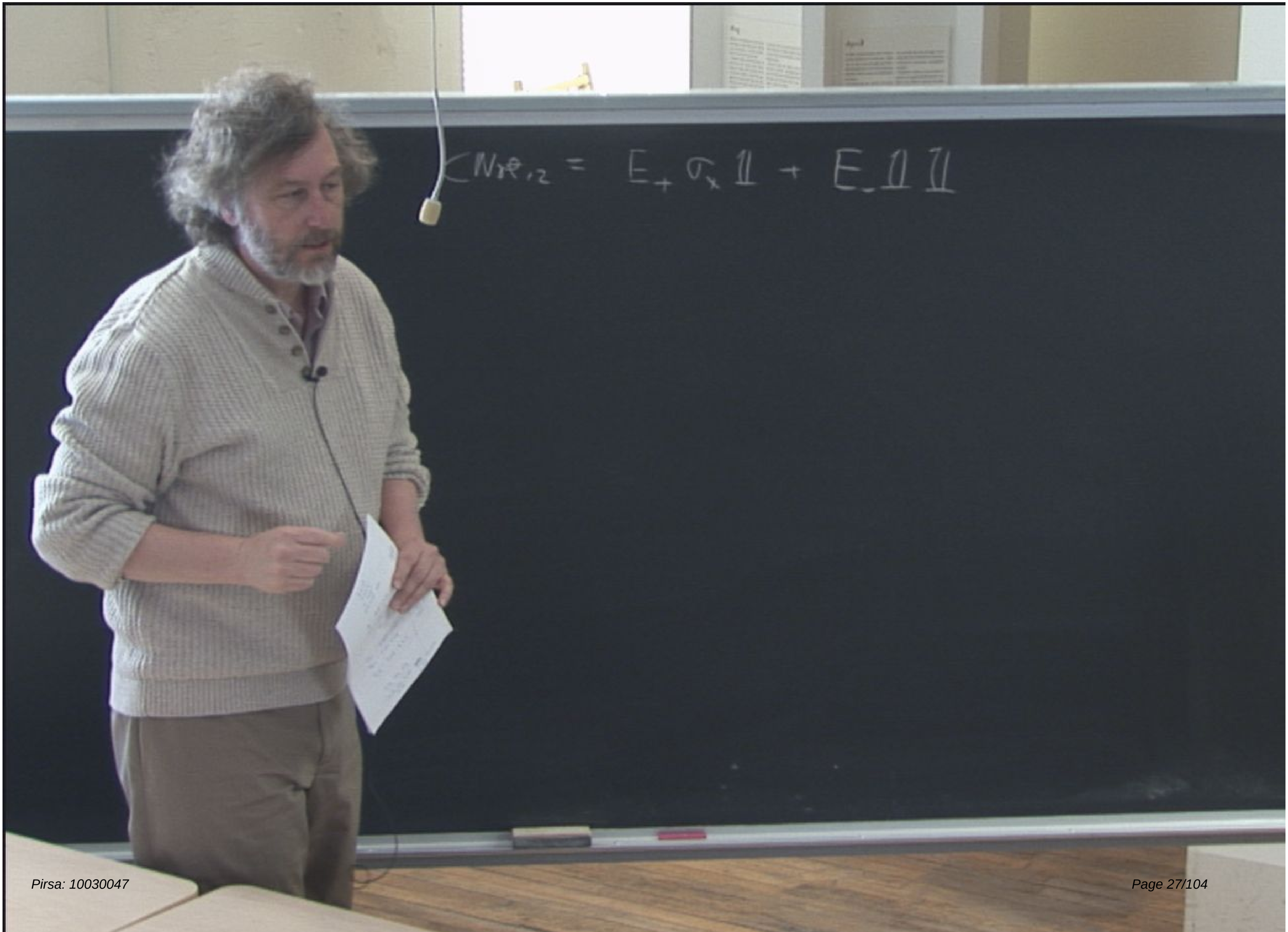

(α|0> + β|1>)|00> → α|000> + β|111>
α|0> + β|1>
α|000> + β|111>
α|000> + β|011>
(α|0> + β|1>) ⊗ |00>
α|100> + β|011>
α|111> + β|011>
α|010> + β|101>
(α|0> + β|1>) ⊗ |10>
α|001> + β|110>
(α|0> + β|1>) ⊗ |01>

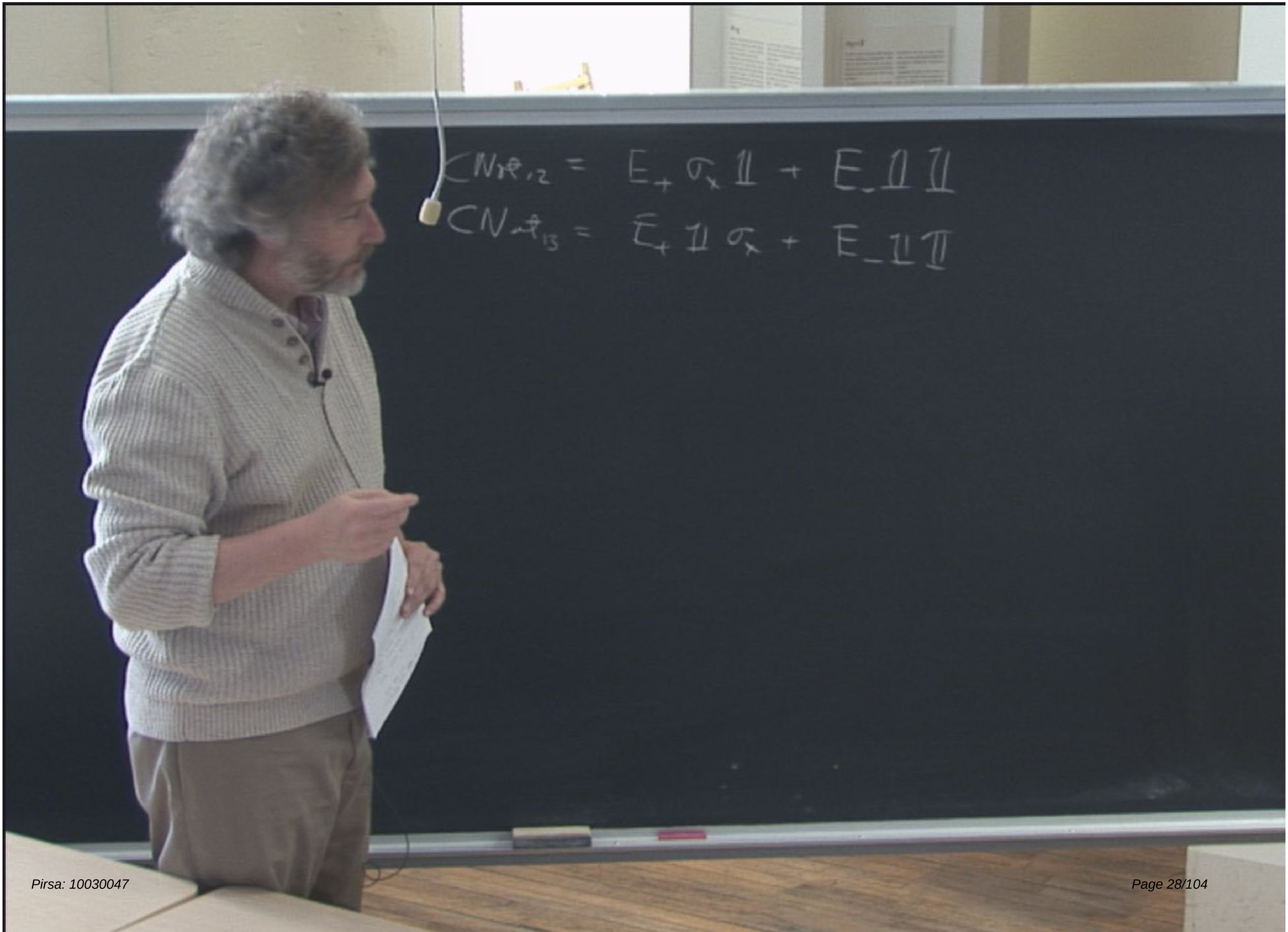

QEC
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
2^2

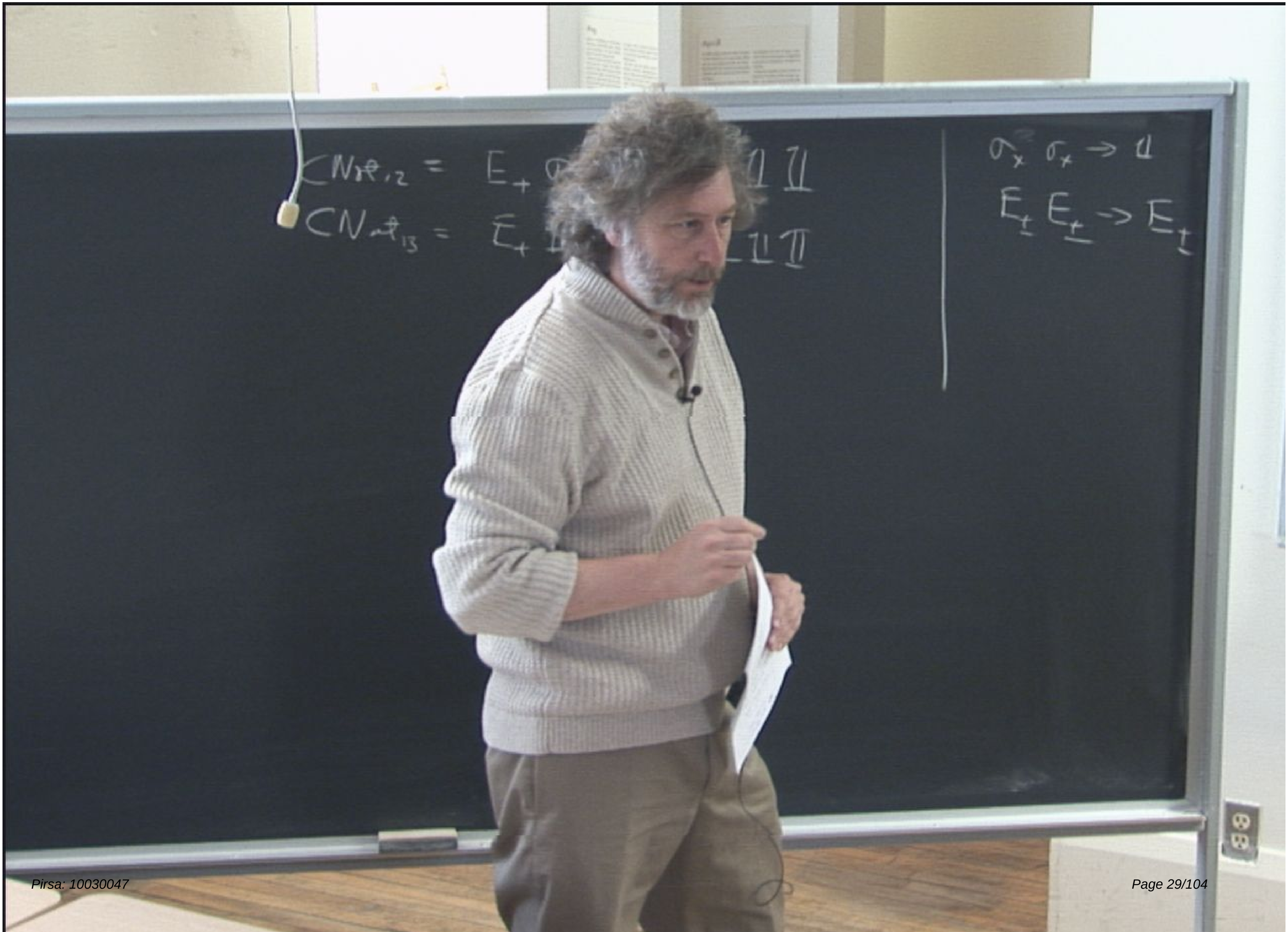

QEC
errors
α|0⟩ + β|1⟩
|0⟩
|0⟩
little expanded H
2²
K₁ = √(1−(P₁+P₂+P₃)) 𝟙 𝟙 𝟙
K₂ = √P₁ σₓ 𝟙 𝟙
K₃ = √P₂ 𝟙 σₓ 𝟙
K₄ = √P₃ 𝟙 𝟙 σₓ
= σₓ E₊ E₊ + 𝟙 E₋ E₋ + 𝟙 E₊ E₋ + 𝟙 E₋ E₊
α|0⟩ + β|1⟩
2,3

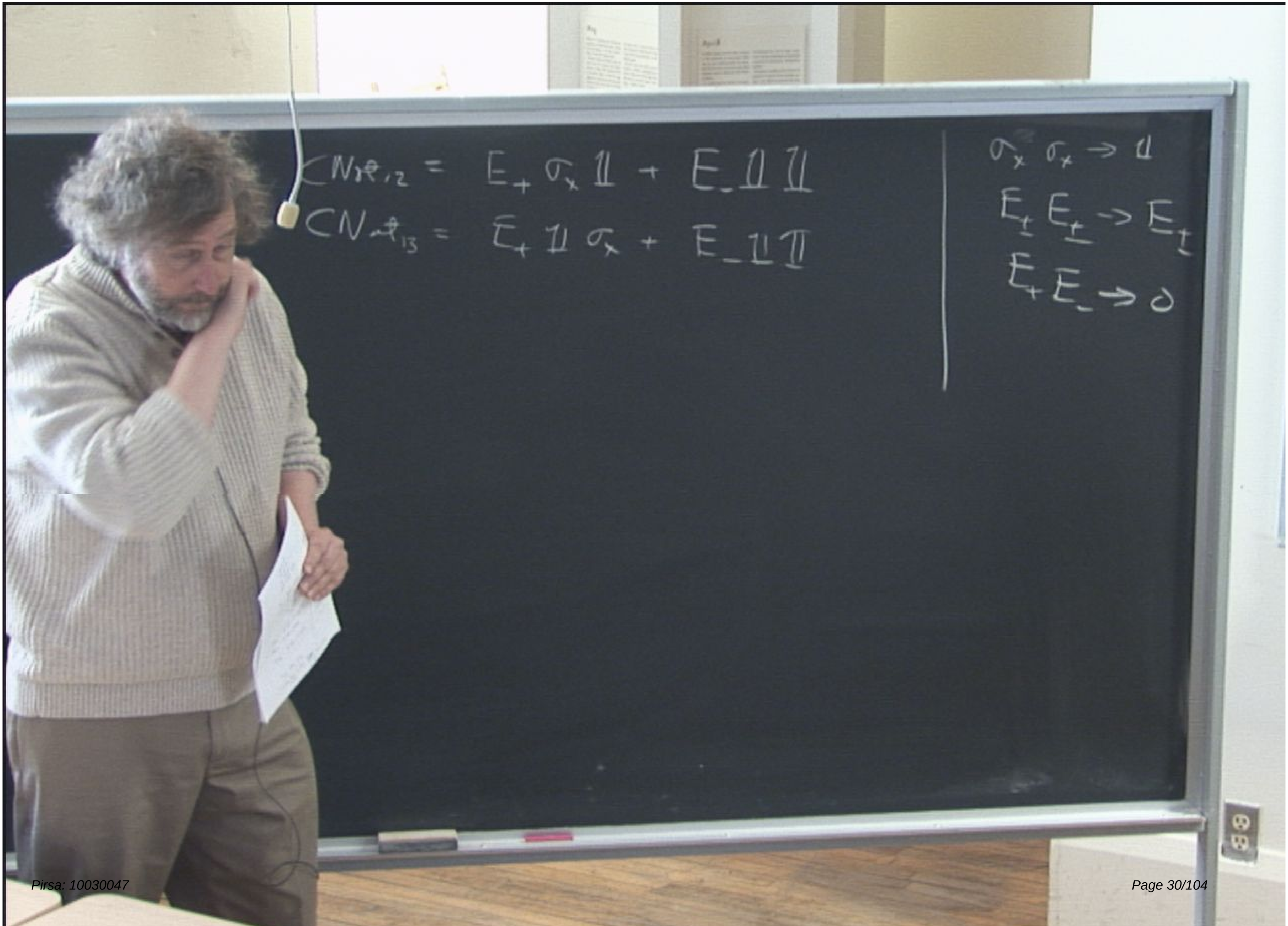

QEC
errors.
α|0⟩ + β|1⟩
|0⟩
|0⟩
expanded
2²
K₁ = √(1-(P₁+P₂+P₃)) 𝟙 𝟙 𝟙
K₂ = √P₁ σₓ 𝟙 𝟙
K₃ = √P₂ 𝟙 σₓ 𝟙
K₄ = √P₃ 𝟙 𝟙 σₓ
+ 𝟙 E₊ E₋ + 𝟙 E₋ E₊
α|0⟩ + β|1⟩

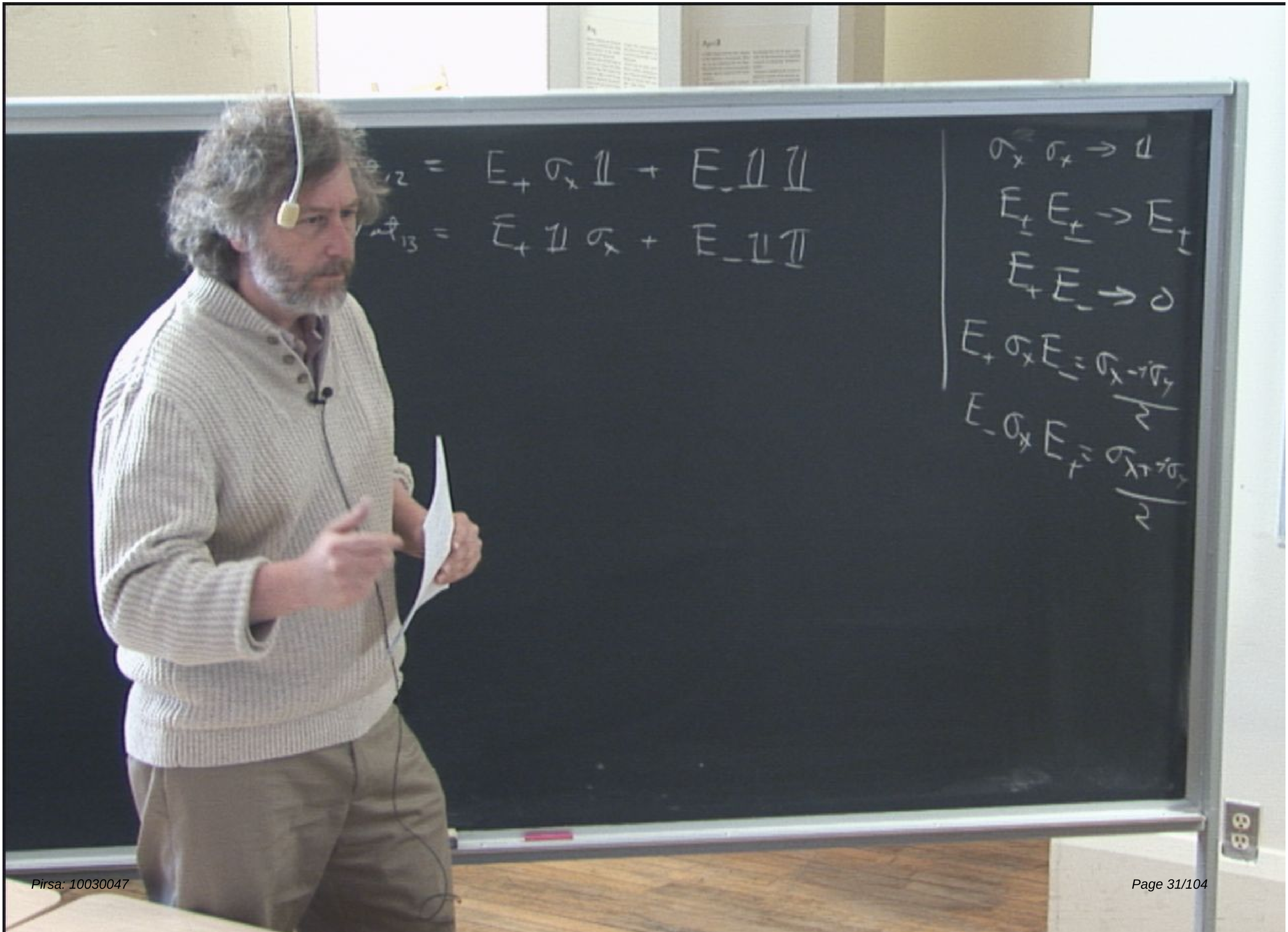

QEC


CNOT$_{1,2}$ = $E_+ \sigma_x \mathbb{1} + E_- \mathbb{1}\mathbb{1}$

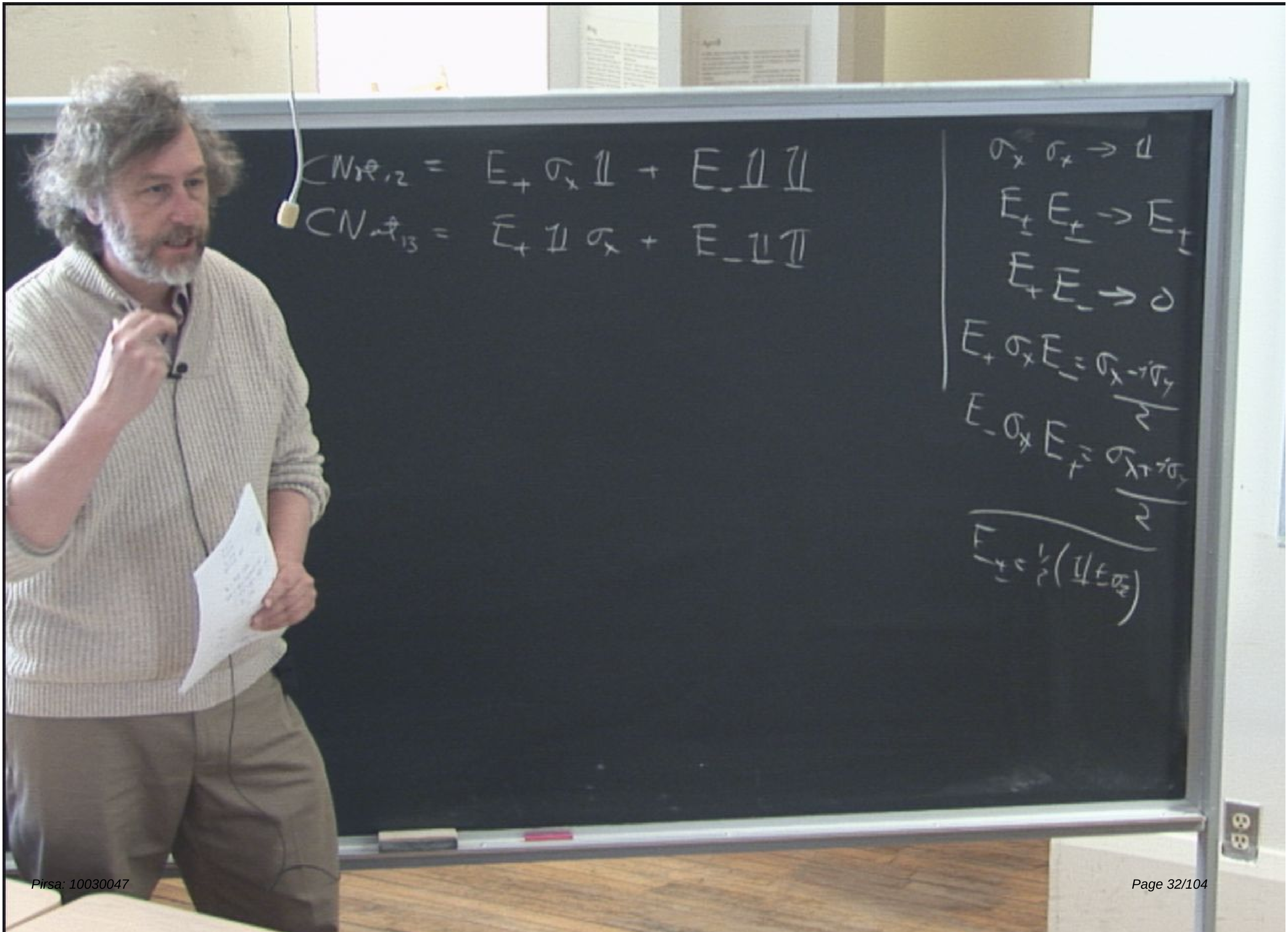

$CNot_{12} = E_+ \sigma_x 𝟙 + E_- 𝟙 𝟙$
$CNot_{13} = E_+ 𝟙 \sigma_x + E_- 𝟙 𝟙$

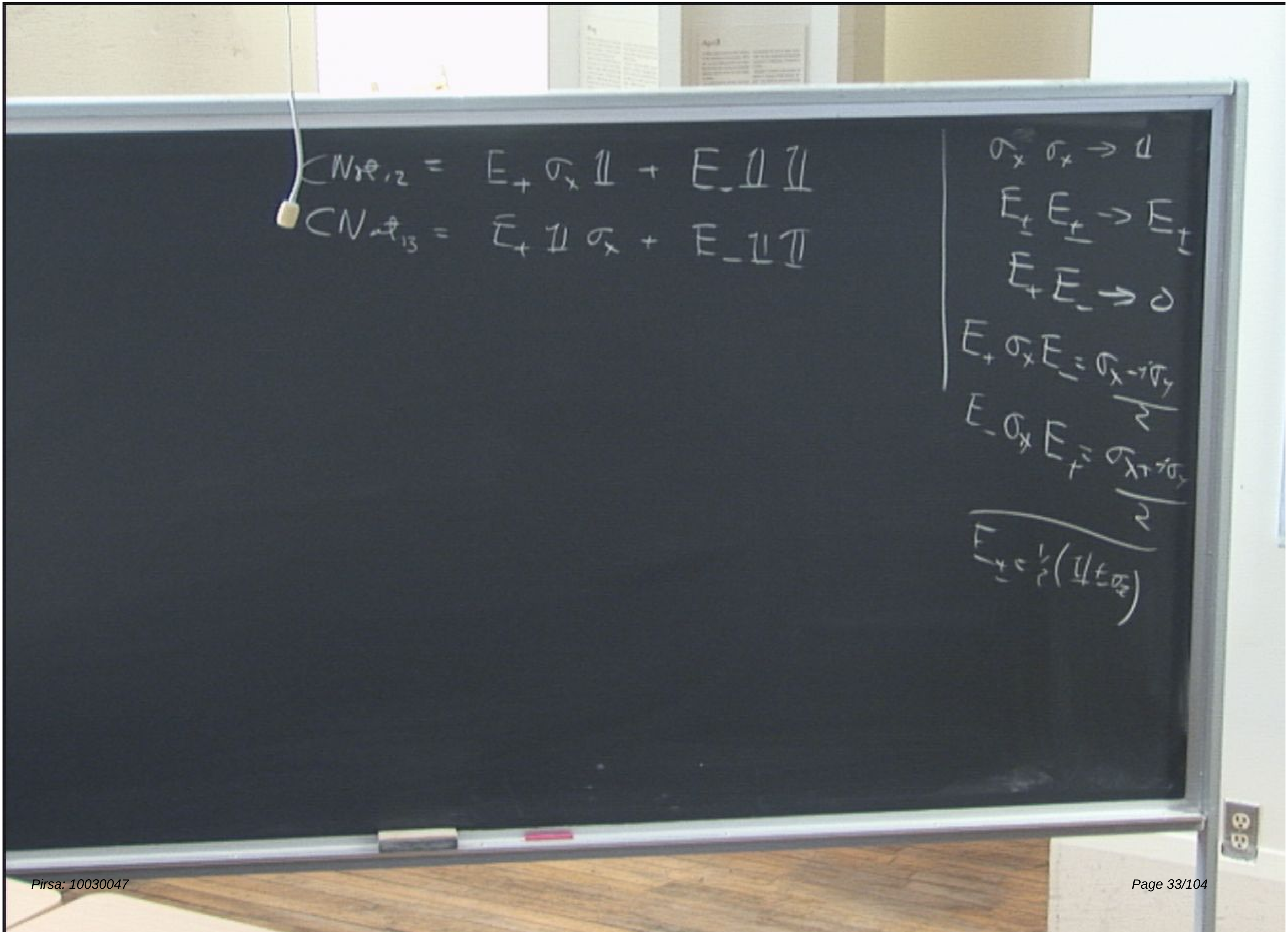

$\sigma_x \sigma_x \to 1\!\!1$
$E_\pm E_\pm \to E_\pm$

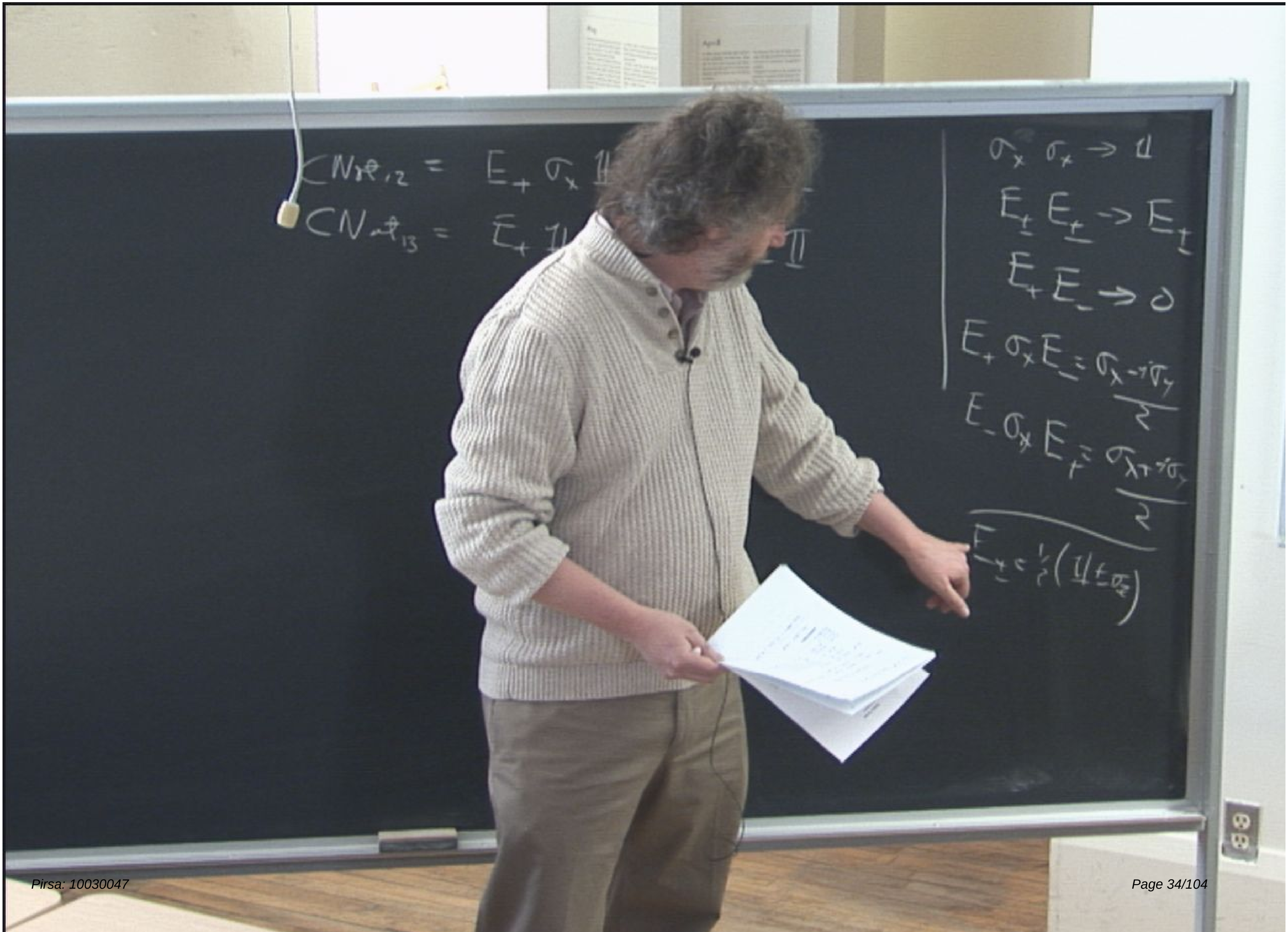

CNOT12 = E+ σx 𝟙 + E- 𝟙 𝟙
CNOT13 = E+ 𝟙 σx + E- 𝟙 𝟙
σx σx → 𝟙
E± E± → E±
E+ E- → 0



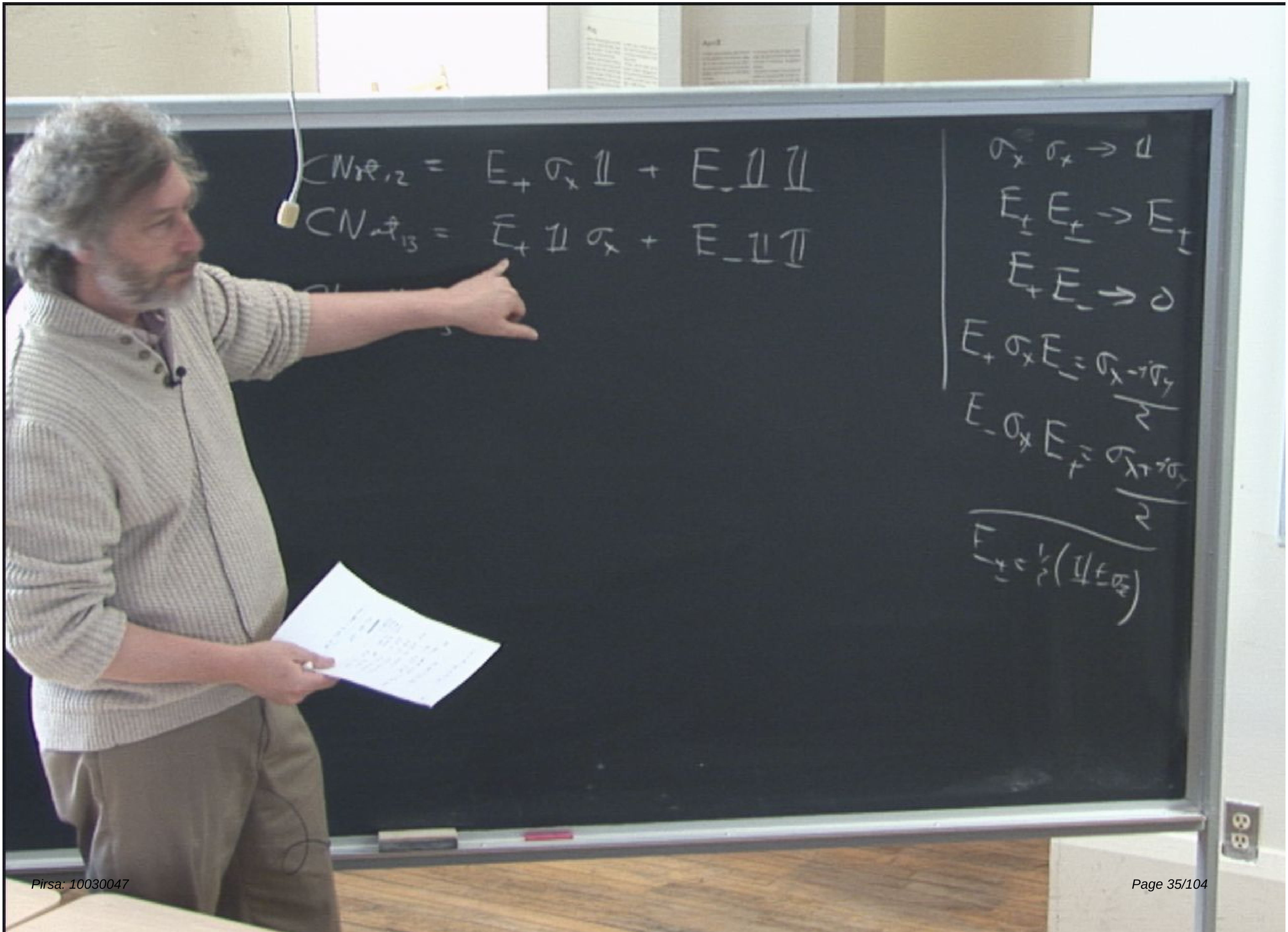
12 = E+ σx 1 + E- 1 1
13 = E+ 1 σx + E- 1 1
σx σx → 1
E± E± → E±
E+ E- → 0
E+ σx E- = (σx - iσy)/2
E- σx E+ = (σx + iσy)/2

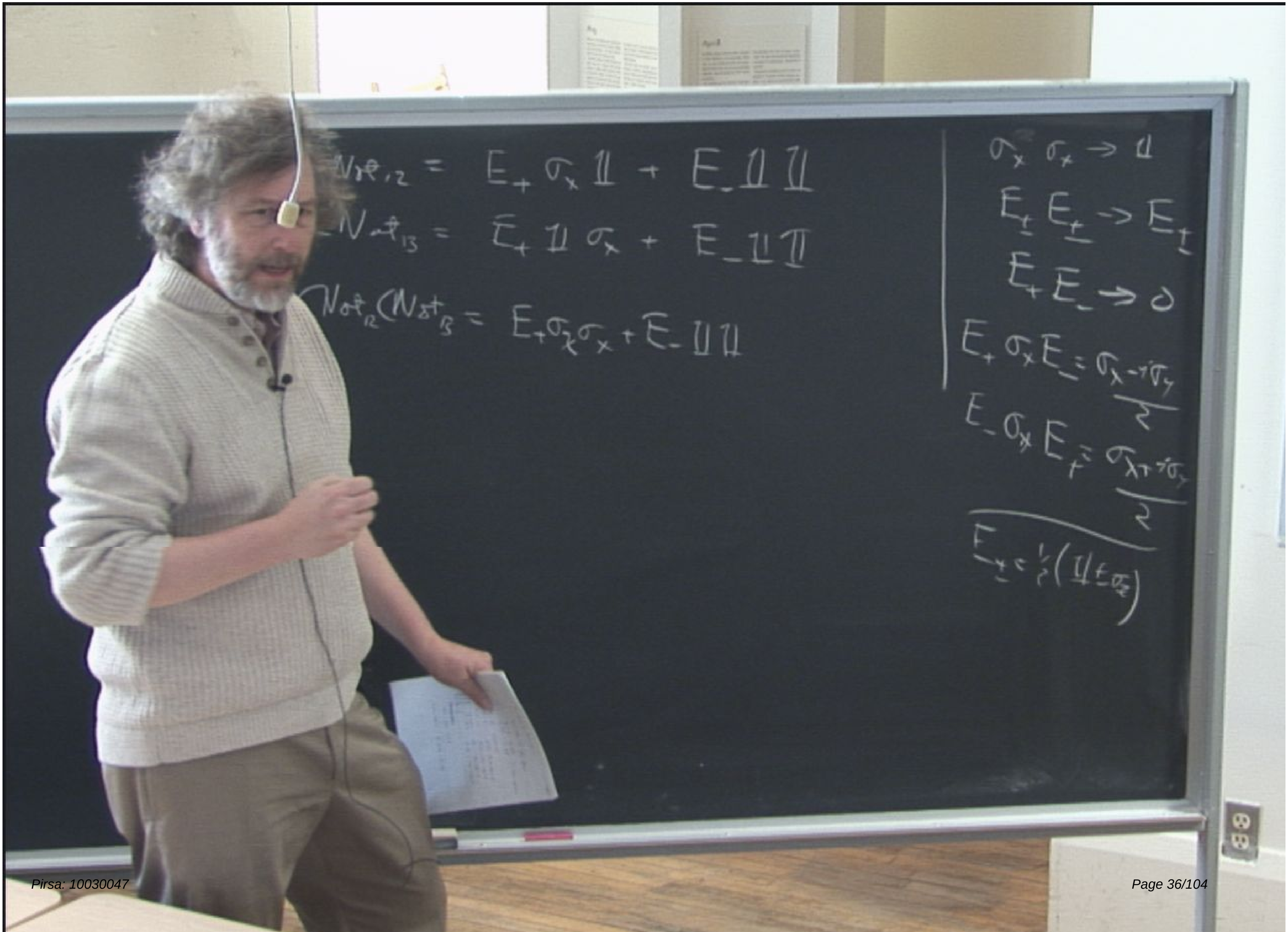

$CNOT_{12} = E_+ \sigma_x 1\!\!1 + E_- 1\!\!1\, 1\!\!1$
$CNOT_{13} = E_+ 1\!\!1\, \sigma_x + E_- 1\!\!1\, 1\!\!1$
$\sigma_x \sigma_x \to 1\!\!1$
$E_\pm E_\pm \to E_\pm$
$E_+ E_- \to 0$
$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$
$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$
$E_\pm = \frac{1}{2}(1\!\!1 \pm \sigma_z)$


CNot12 = E+ σx 1 + E- 1 1
CNot13 = E+ 1 σx + E- 1 1
σx σx → 1
E± E± → E±
E+ E- → 0
E+ σx E- = (σx - iσy)/2
E- σx E+ = (σx + iσy)/2
E± = ½(1 ± σz)

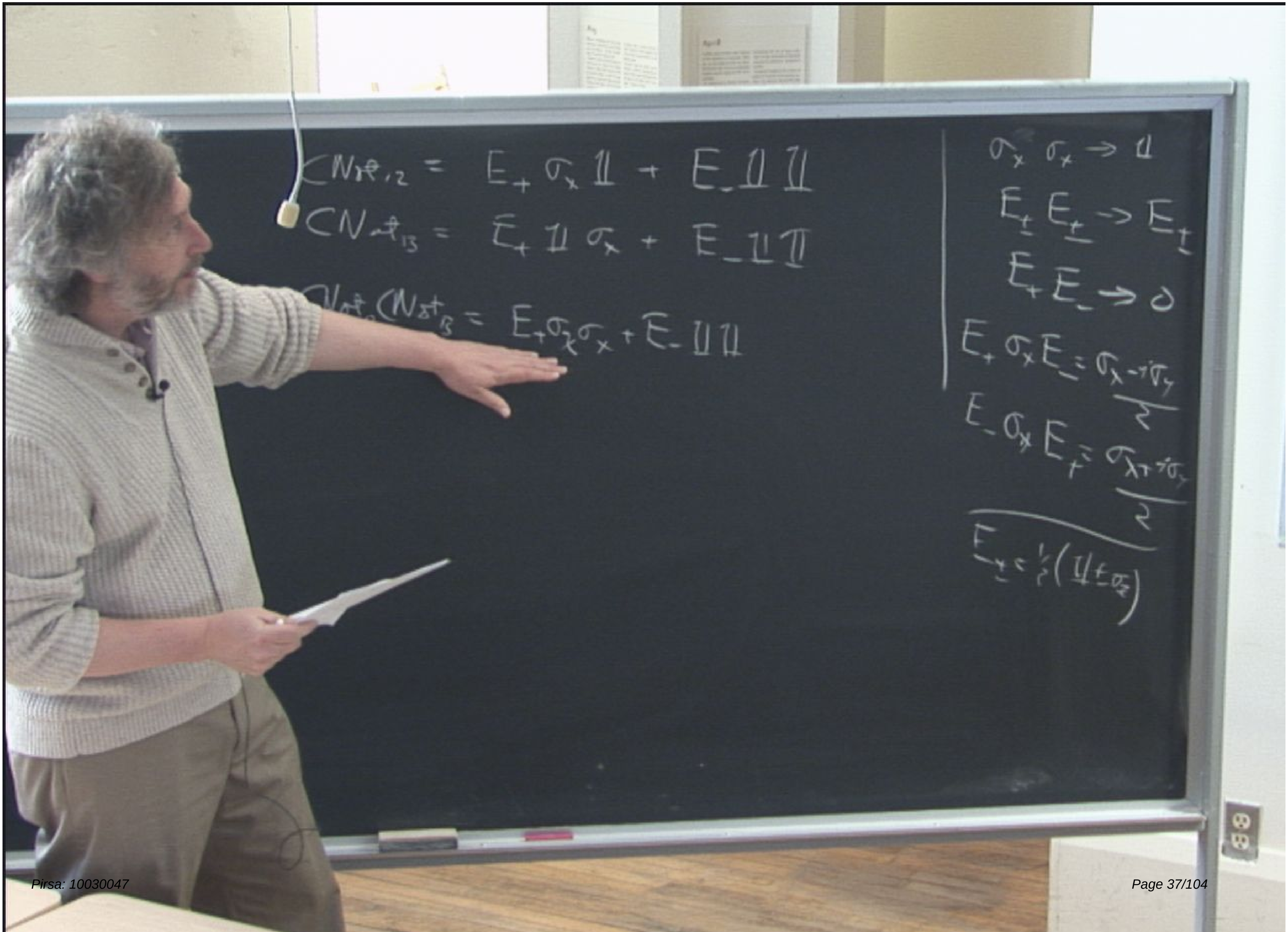


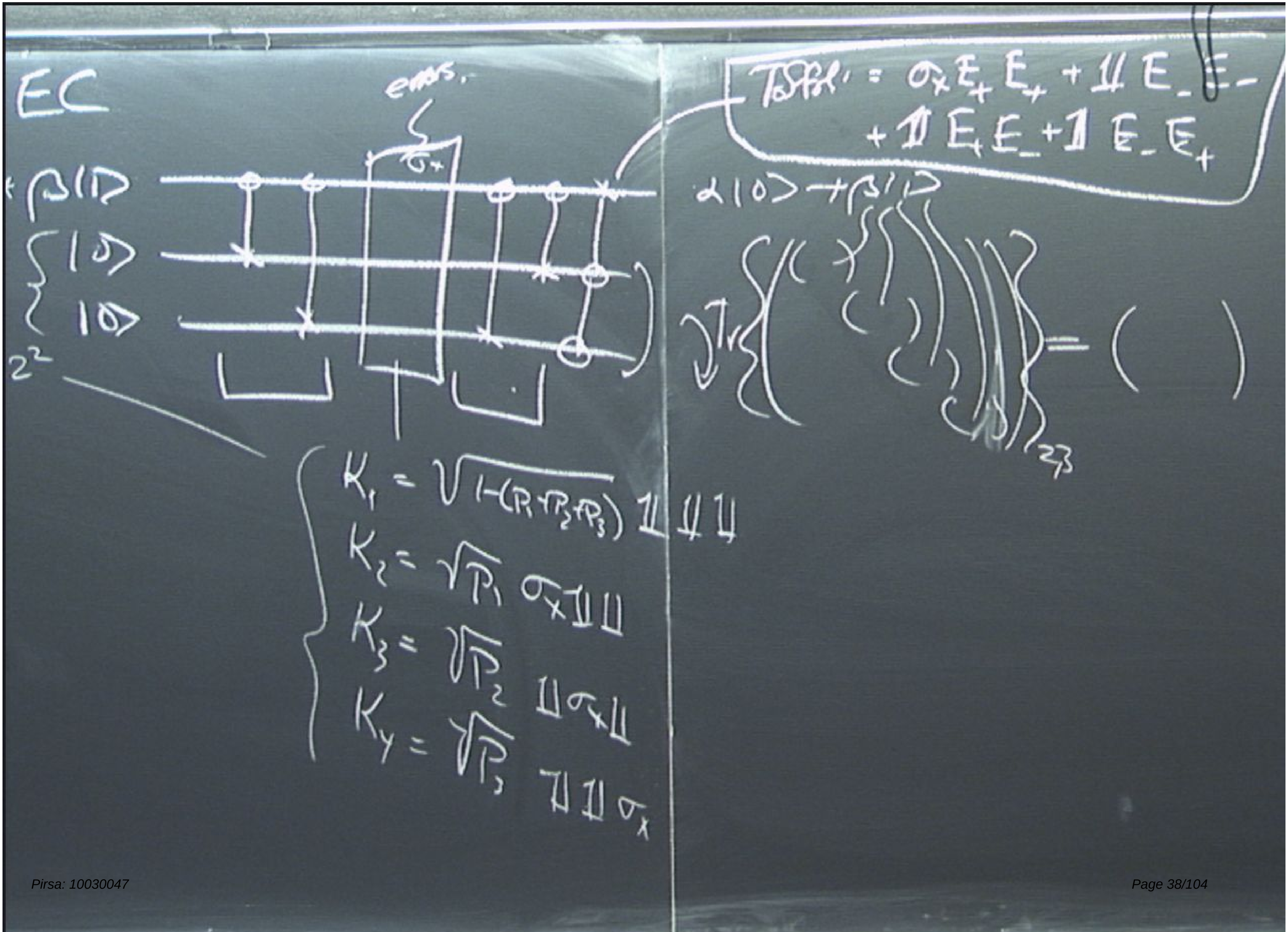
$\sigma_x \sigma_x \to 1\!\!1$
$E_\pm E_\pm \to E_\pm$
$E_+ E_- \to 0$
$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$
$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$
$E_\pm = \frac{1}{2}(1\!\!1 \pm \sigma_z)$

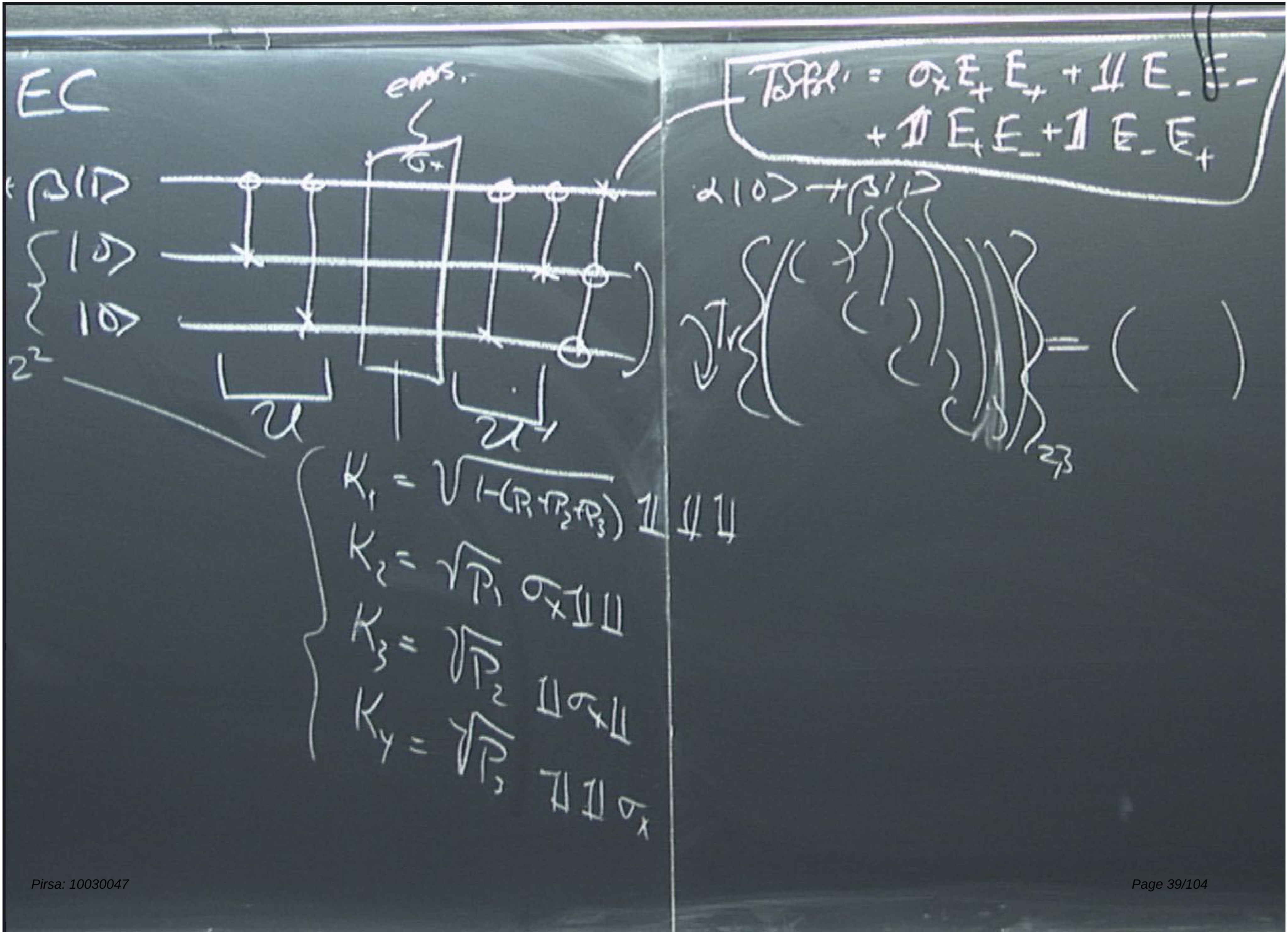

CNot12 = E+ σx 11 + E- 11 11
CNot13 = E+ 11 σx + E- 11 11
σx σx -> 11
E± E± -> E±
E+ E- -> 0
E+ σx E- = (σx - iσy)/2
E- σx E+ = (σx + iσy)/2
E± = 1/2 (11 ± σz)

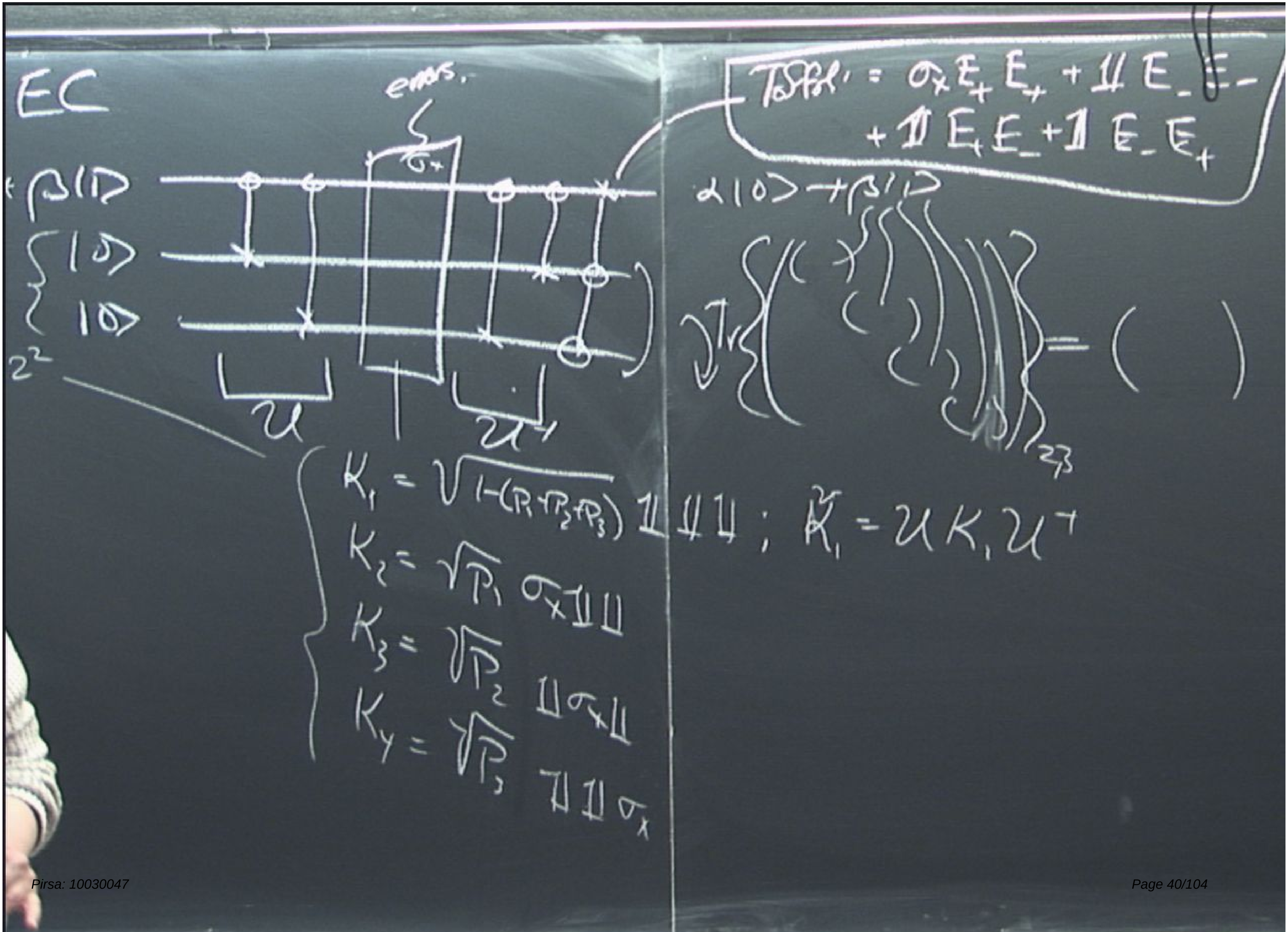


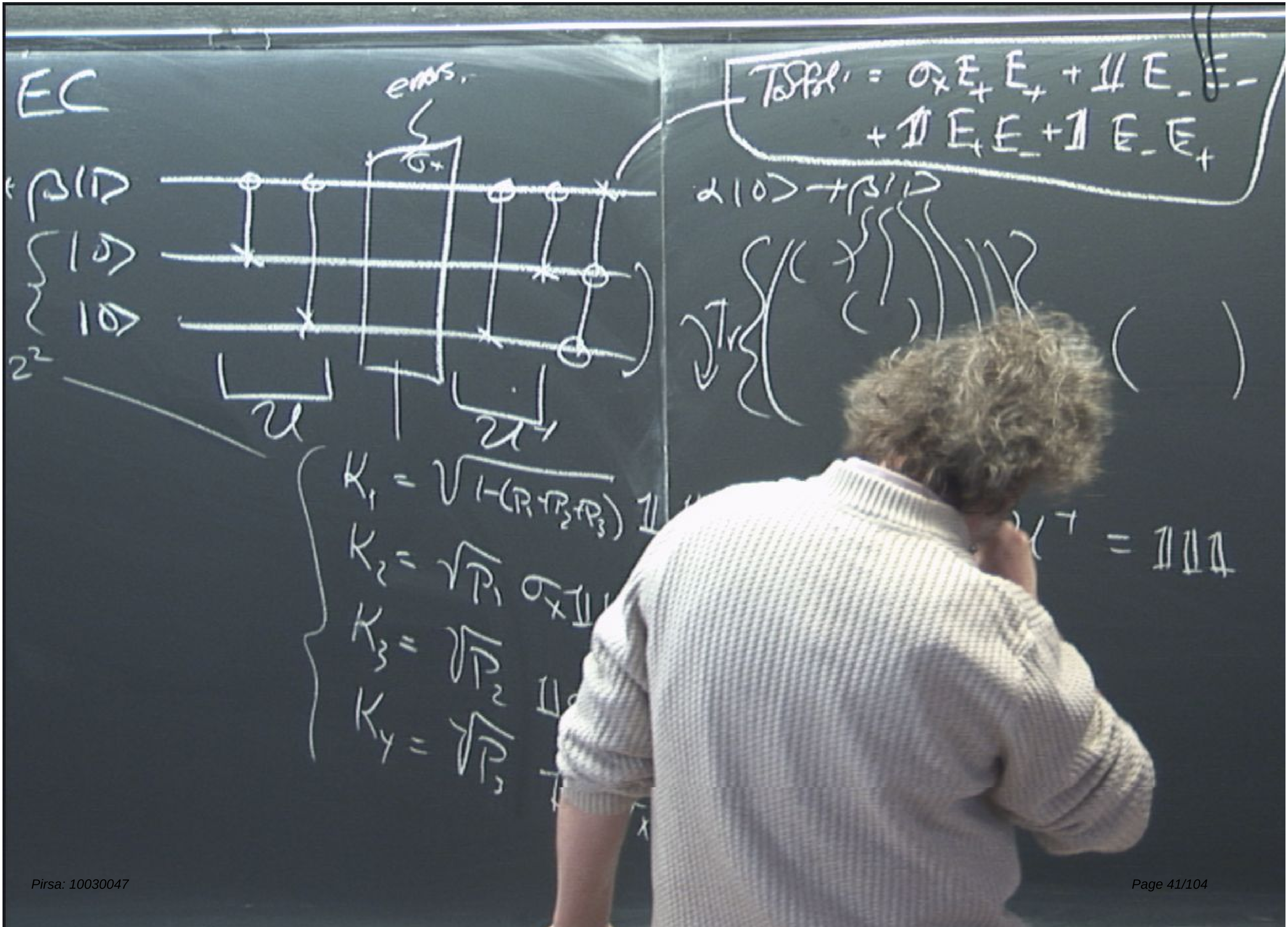
$N\sigma t_{12} = E_+ \sigma_x 1\!\!1 + E_- 1\!\!1 1\!\!1$
$N\sigma t_{13} = E_+ 1\!\!1 \sigma_x + E_- 1\!\!1 1\!\!1$
$N\sigma t_{12} N\sigma t_{13} = E_+ \sigma_x \sigma_x + E_- 1\!\!1 1\!\!1$
$\sigma_x \sigma_x \to 1\!\!1$
$E_\pm E_\pm \to E_\pm$
$E_+ E_- \to 0$
$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$
$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$
$E_\pm = \frac{1}{2}(1\!\!1 \pm \sigma_z)$

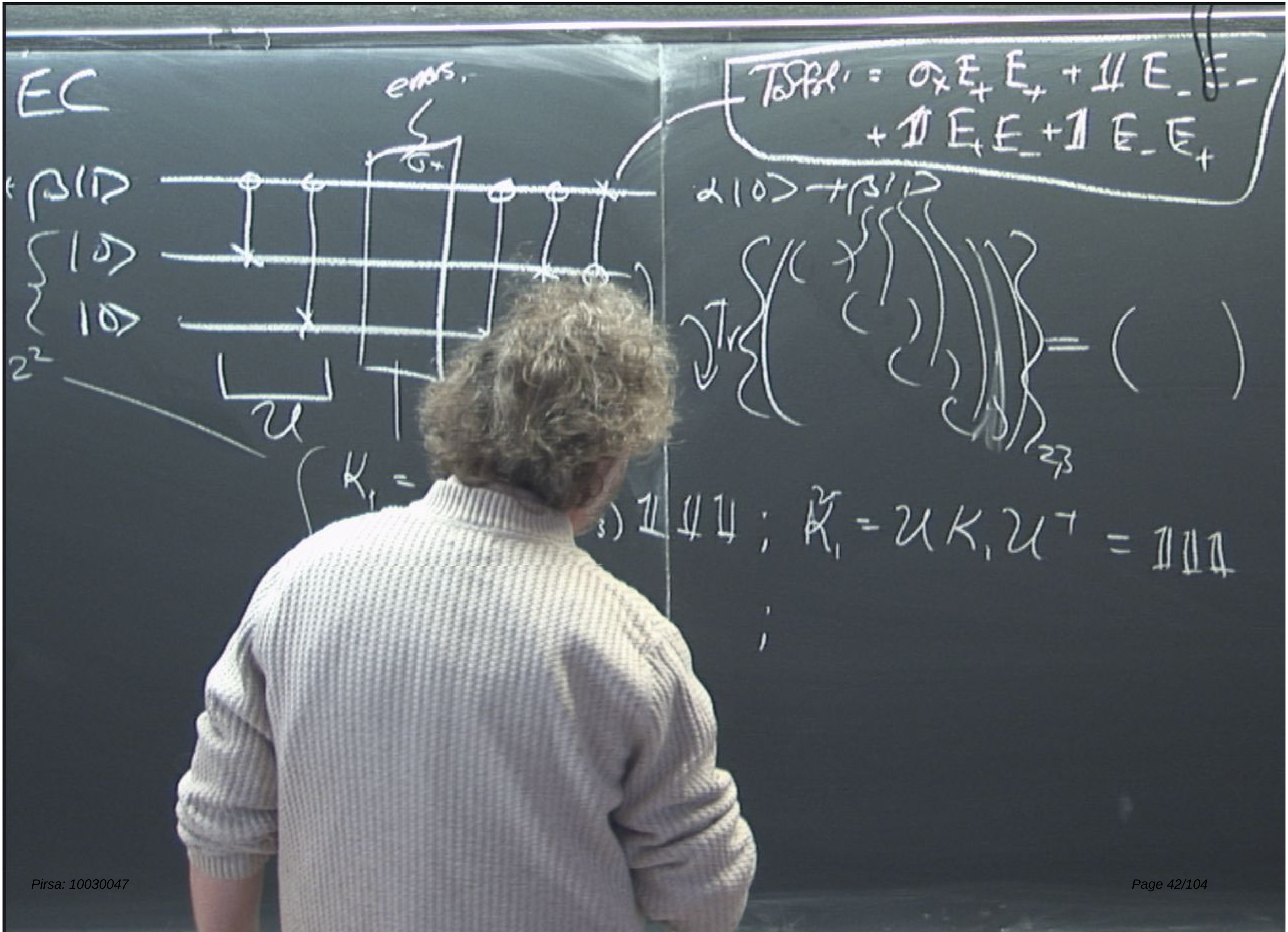

$\sigma_x \sigma_x \to 𝟙$
$E_\pm E_\pm \to E_\pm$
$E_+ E_- \to 0$
$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$
$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$
$E_\pm = \frac{1}{2}(𝟙 \pm \sigma_z)$

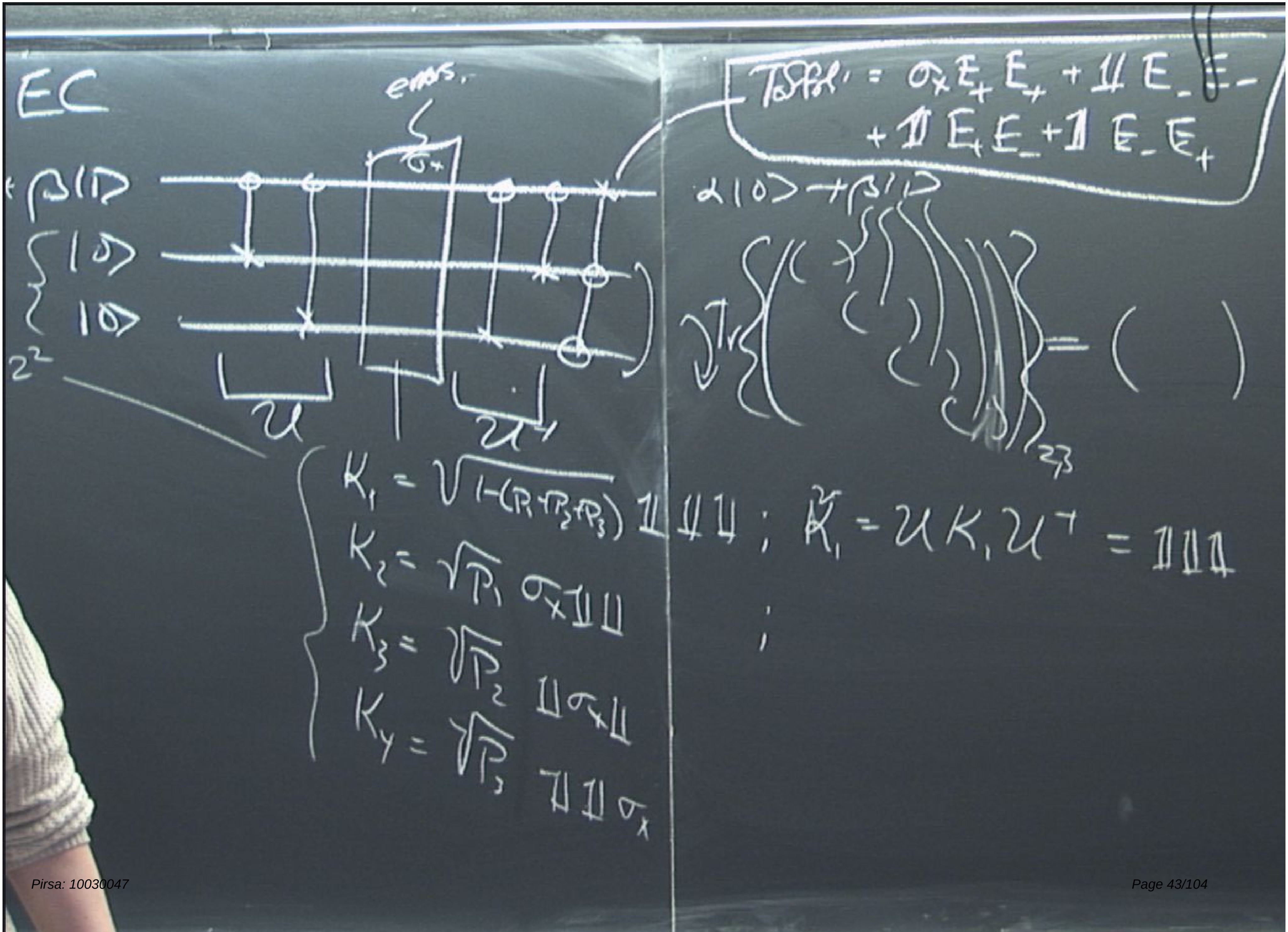

EC
errs.
α|0⟩ + β|1⟩
K1 = √(1-(P1+P2+P3)) 1 1 1
K2 = √P1 σx 1 1
K3 = √P2 1 σx 1
K4 = √P3 1 1 σx


EC
errors
σ_x
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
2^2
U
$U^\dagger$
$\sigma_x E_+ E_+ + 𝟙 E_- E_-$
$+ 𝟙 E_+ E_- + 𝟙 E_- E_+$
$K_1 = \sqrt{1-(p_1+p_2+p_3)}\, 𝟙 𝟙 𝟙$
$K_2 = \sqrt{p_1}\, \sigma_x 𝟙 𝟙$
$K_3 = \sqrt{p_2}\, 𝟙 \sigma_x 𝟙$
$K_4 = \sqrt{p_3}\, 𝟙 𝟙 \sigma_x$
2,3


EC
errors.
σx
α|0⟩ + β|1⟩
|0⟩
|0⟩
2²
U
U†
K1 = √(1-(P1+P2+P3)) 𝟙𝟙𝟙 ; K̃1 = U K1 U†
K2 = √P1 σx 𝟙𝟙
K3 = √P2 𝟙 σx 𝟙
K4 = √P3 𝟙𝟙 σx
α|0⟩ + β|1⟩
Tr
2,3


EC
errors


EC
errors.


EC
errors.
K1 = √(1-(P1+P2+P3)) 1 1 1 ; K̃1 = U K1 U† = 1 1 1
K2 = √P1 σx 1 1
K3 = √P2 1 σx 1
K4 = √P3 1 1 σx

$$CNot_{12} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1}\,\mathbb{1}$$

$$CNot_{13} = E_+ \mathbb{1}\, \sigma_x + E_- \mathbb{1}\,\mathbb{1}$$

$$CNot_{12}\, CNot_{13} = E_+ \sigma_x \sigma_x + E_- \mathbb{1}\,\mathbb{1} = \mathcal{U} = \mathcal{U}^{-1}$$

$\sigma_x \sigma_x \rightarrow$

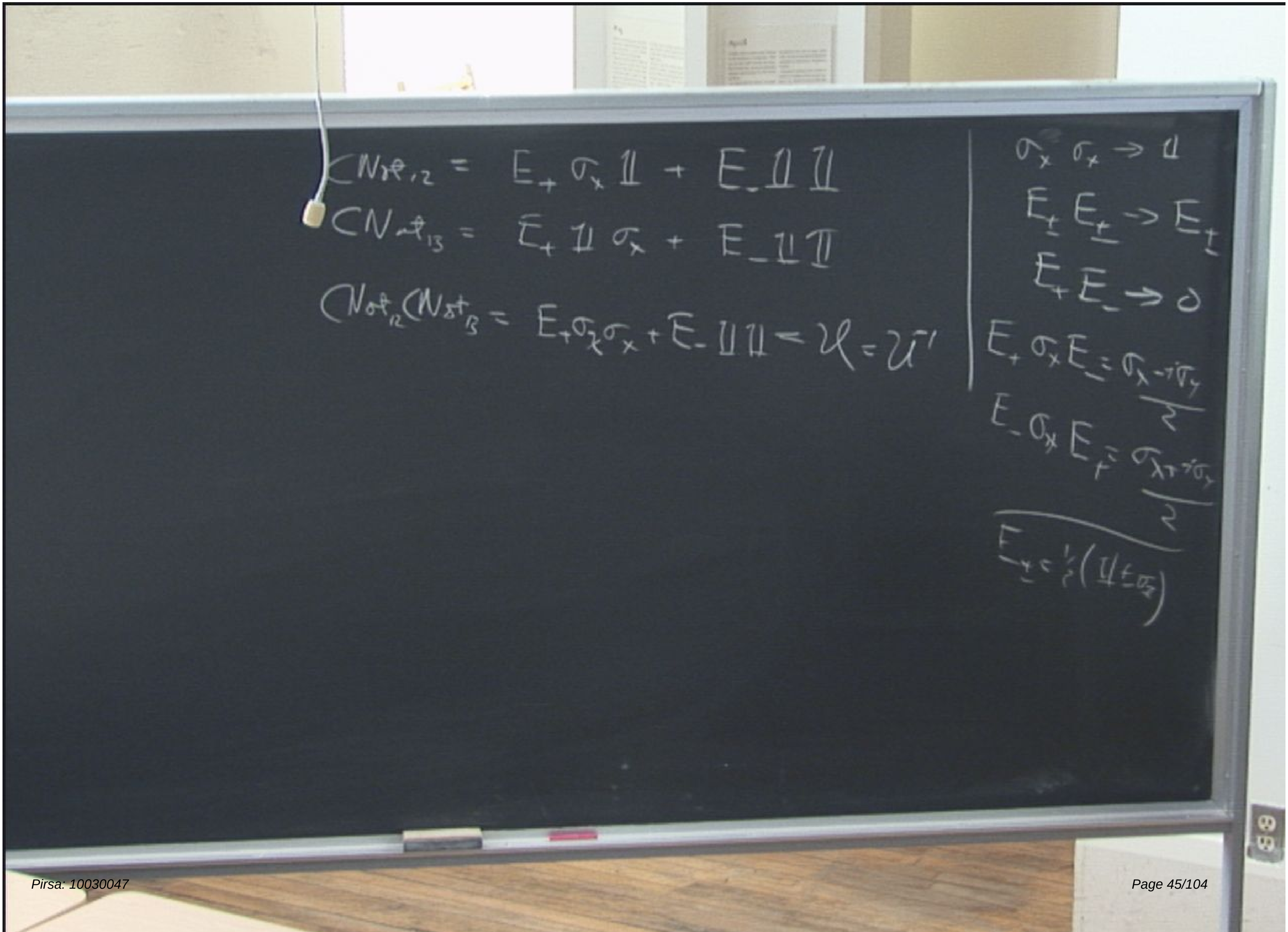
$E_\pm E_\pm \rightarrow$

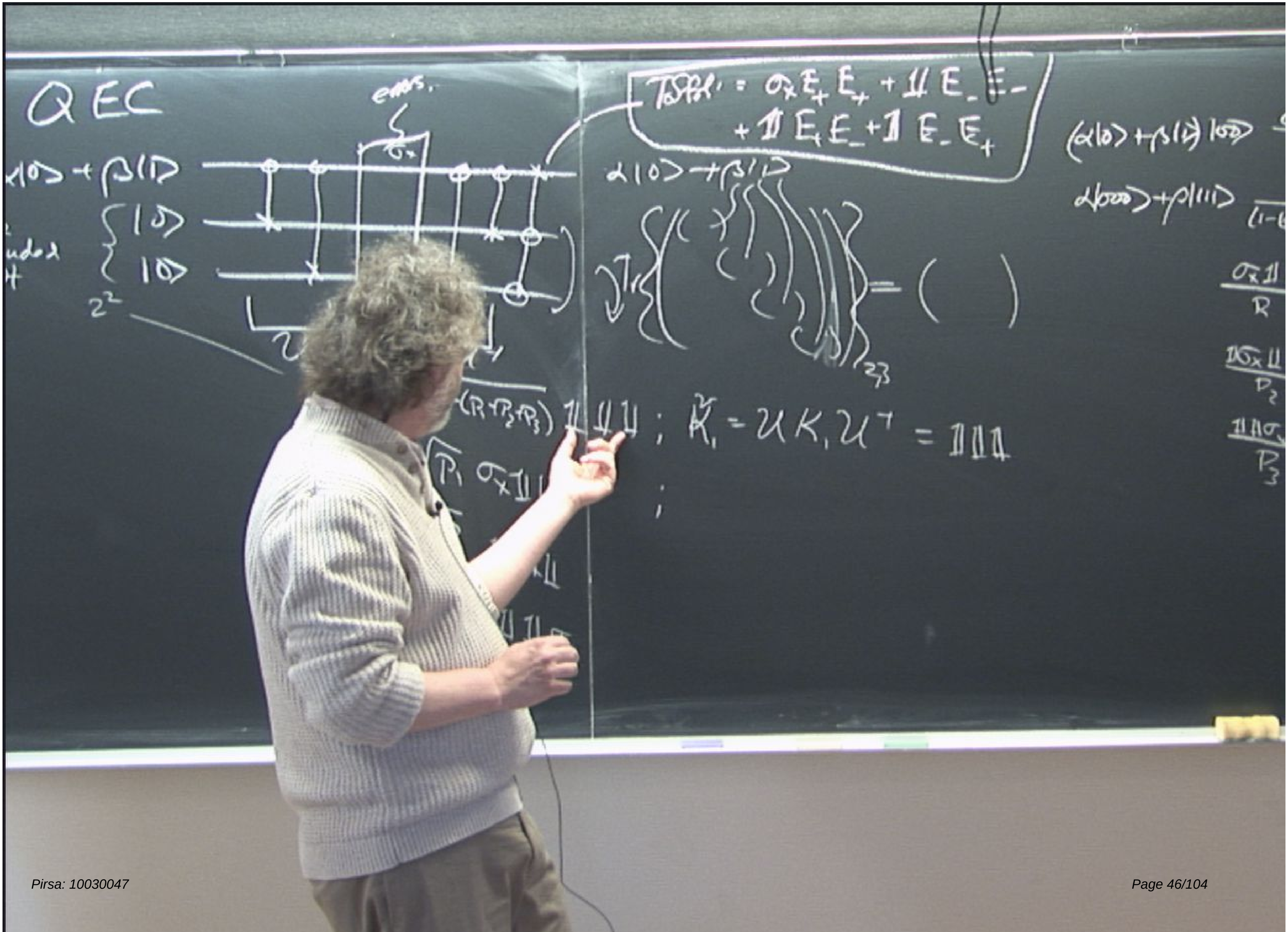
$E_+ E_- \rightarrow$

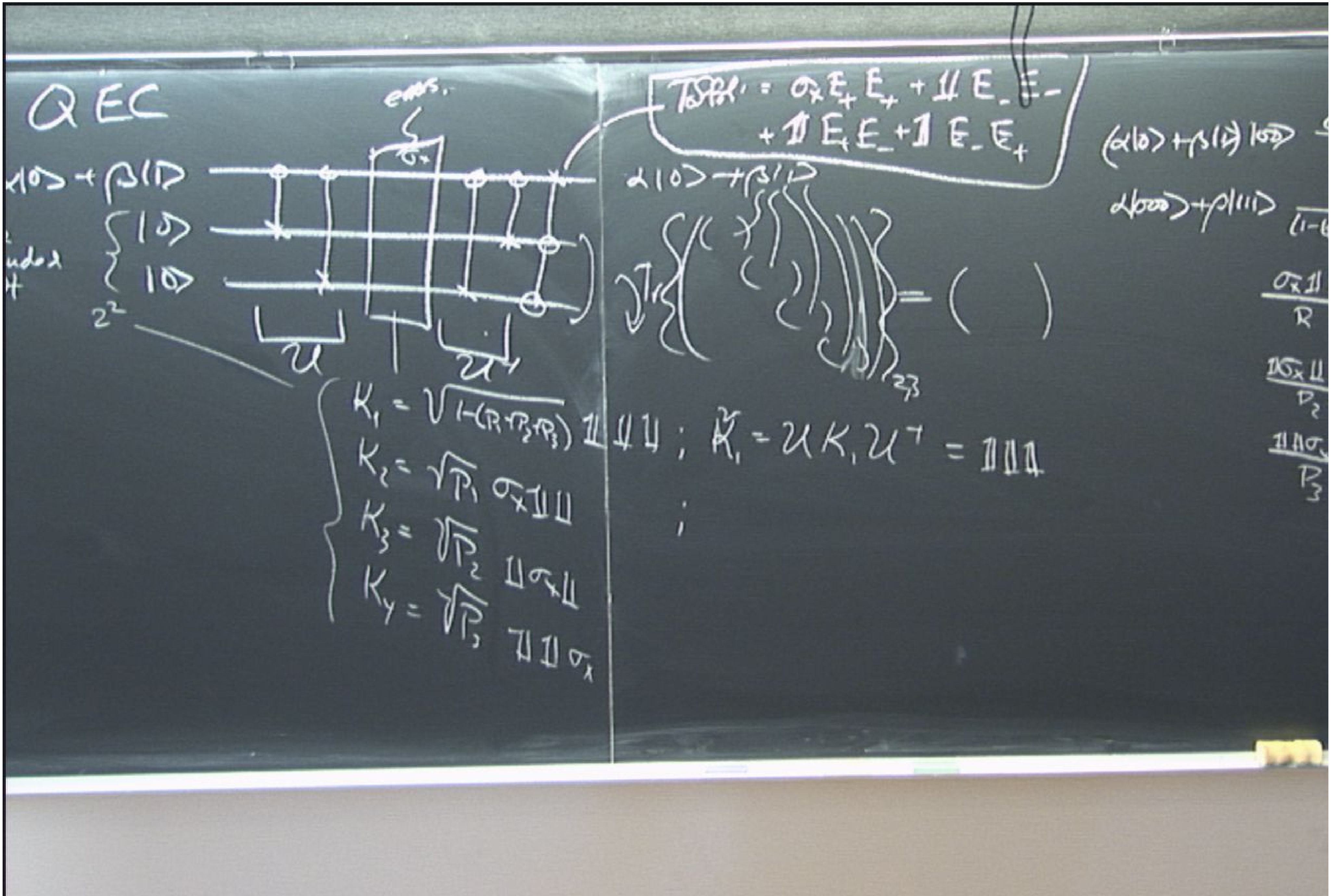
$E_+ \sigma_x E_- = \sigma_x$

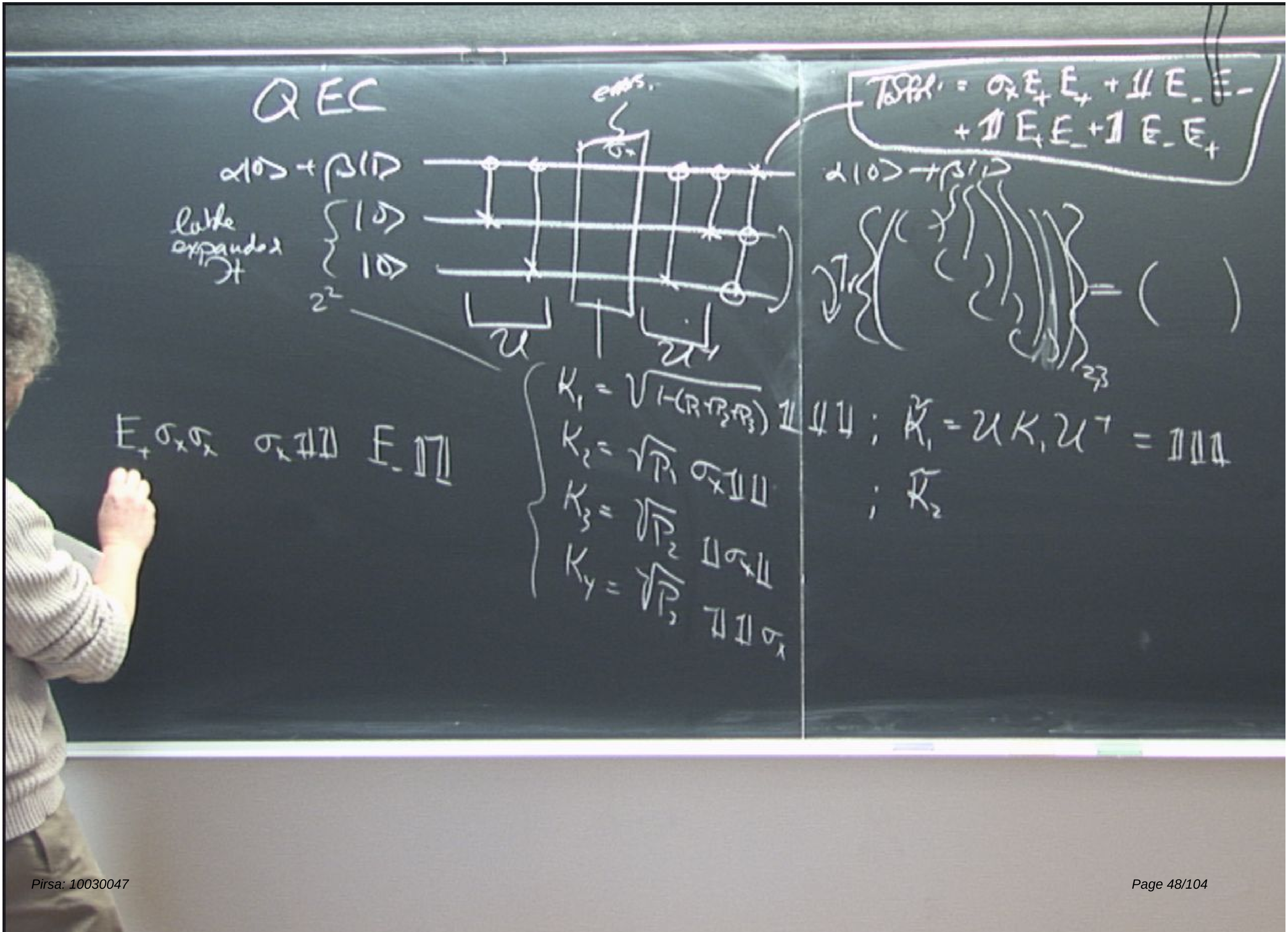
$E_- \sigma_x E_+ = \sigma_x$

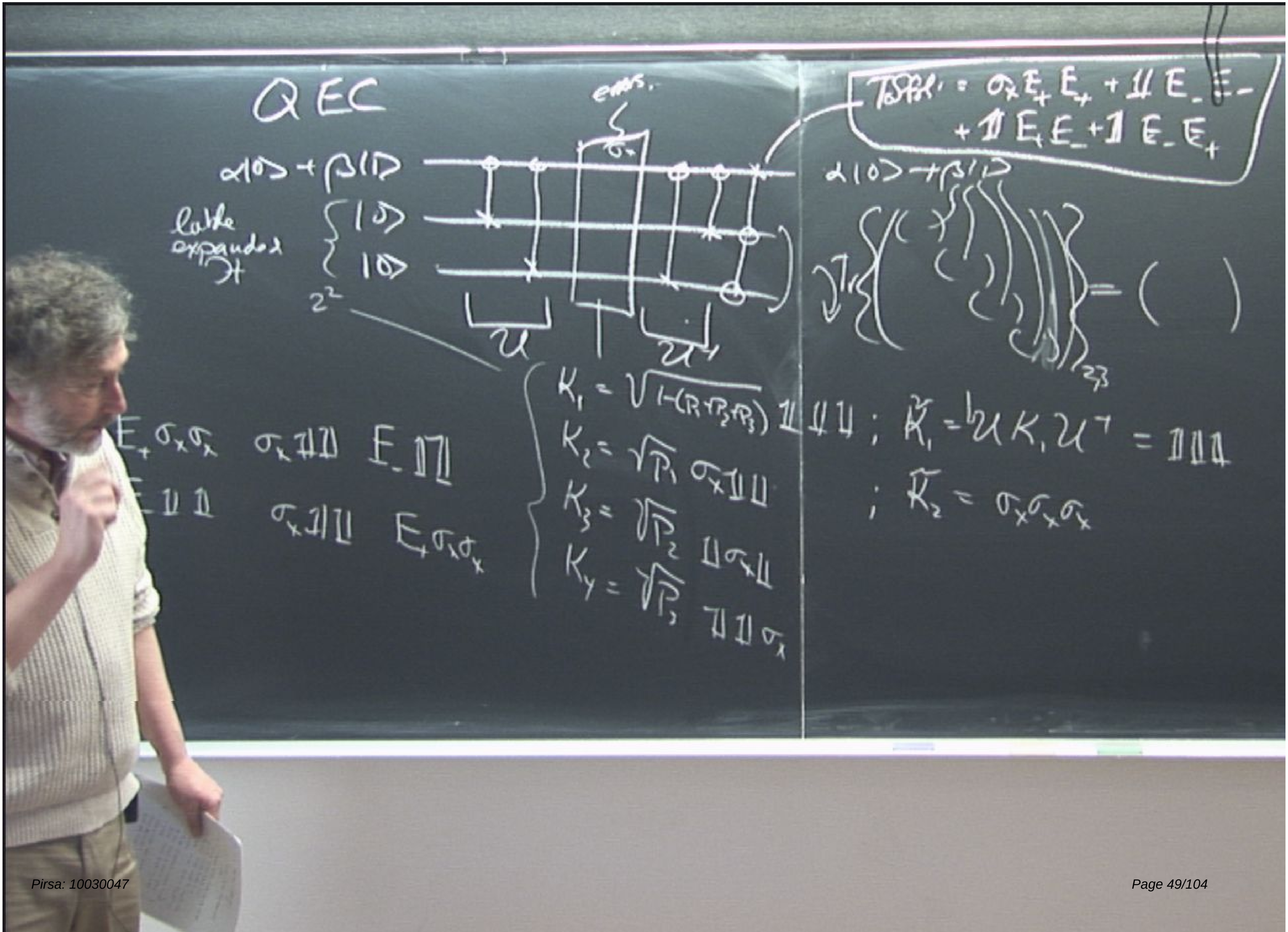
$E_\pm = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$

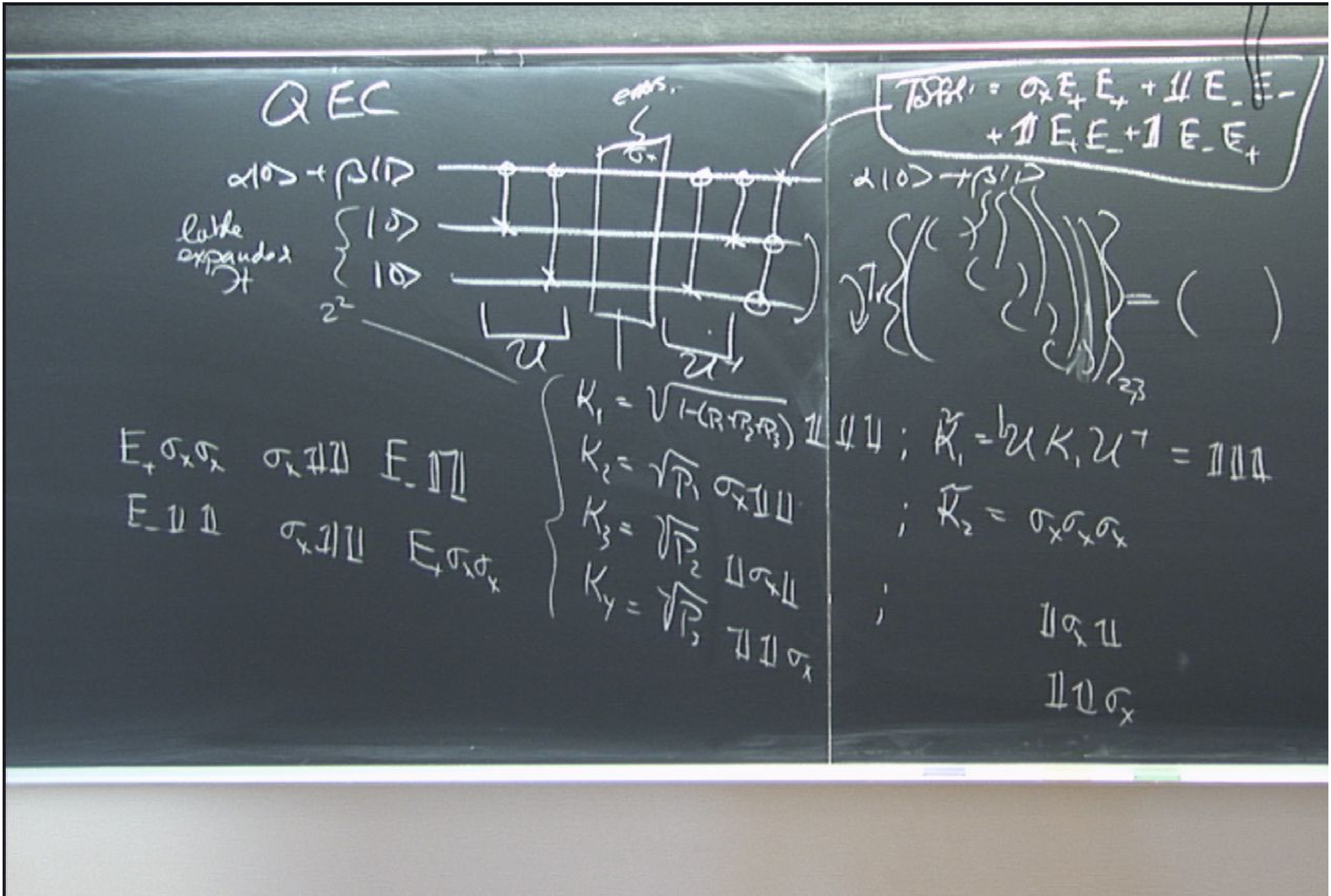

$CNot_{12} = E_+ \sigma_x \mathbb{1} + E_- \mathbb{1} \mathbb{1}$
$CNot_{13} = E_+ \mathbb{1} \sigma_x + E_- \mathbb{1} \mathbb{1}$
$CNot_{12} CNot_{13} = E_+ \sigma_x \sigma_x + E_- \mathbb{1} \mathbb{1} \leftarrow \mathcal{U} = \mathcal{U}^{-1}$
$\sigma_x \sigma_x \rightarrow \mathbb{1}$
$E_\pm E_\pm \rightarrow E_\pm$
$E_+ E_- \rightarrow 0$
$E_+ \sigma_x E_- = \frac{\sigma_x - i\sigma_y}{2}$
$E_- \sigma_x E_+ = \frac{\sigma_x + i\sigma_y}{2}$
$E_\pm = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$

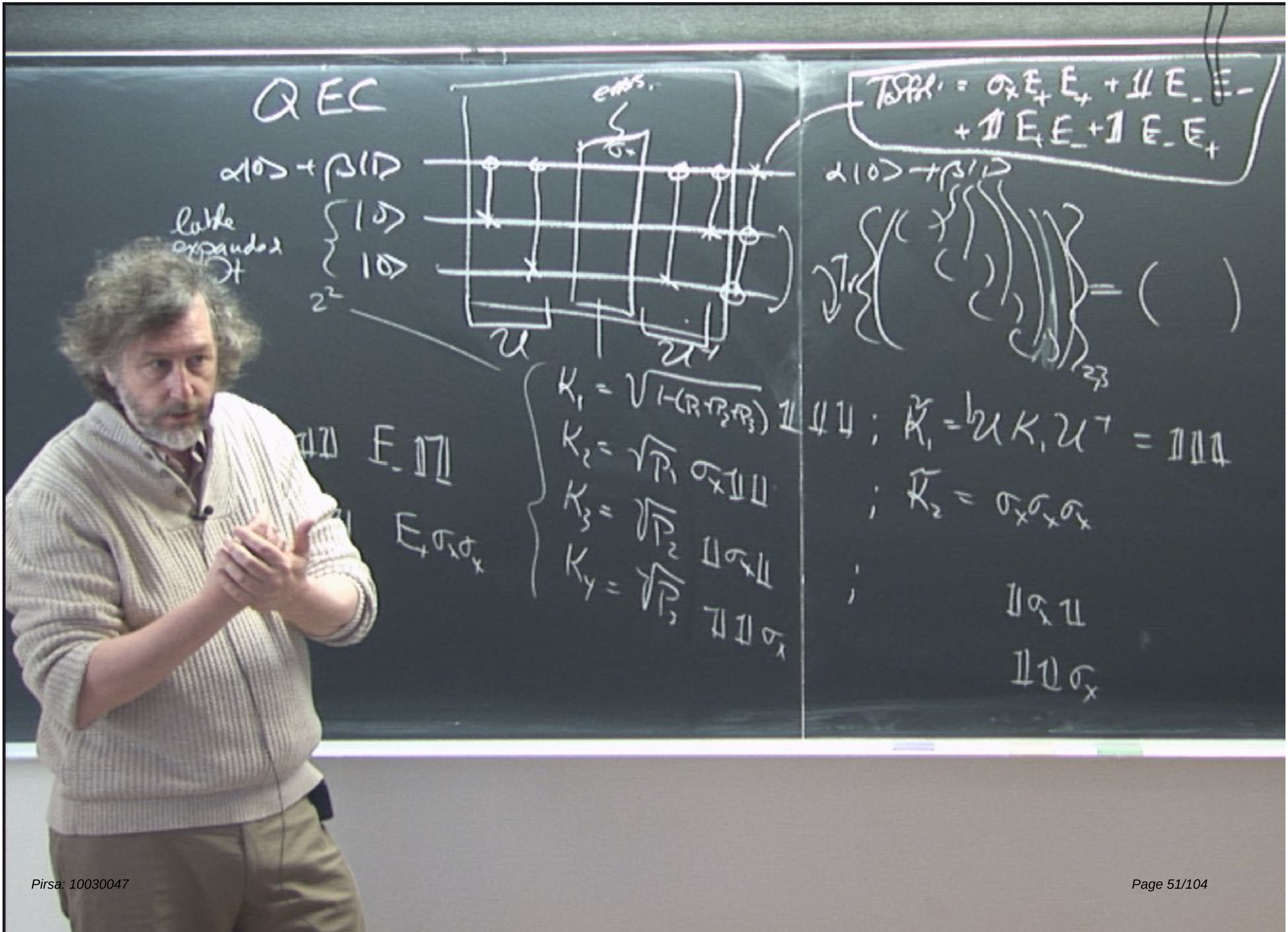

QEC
errors.

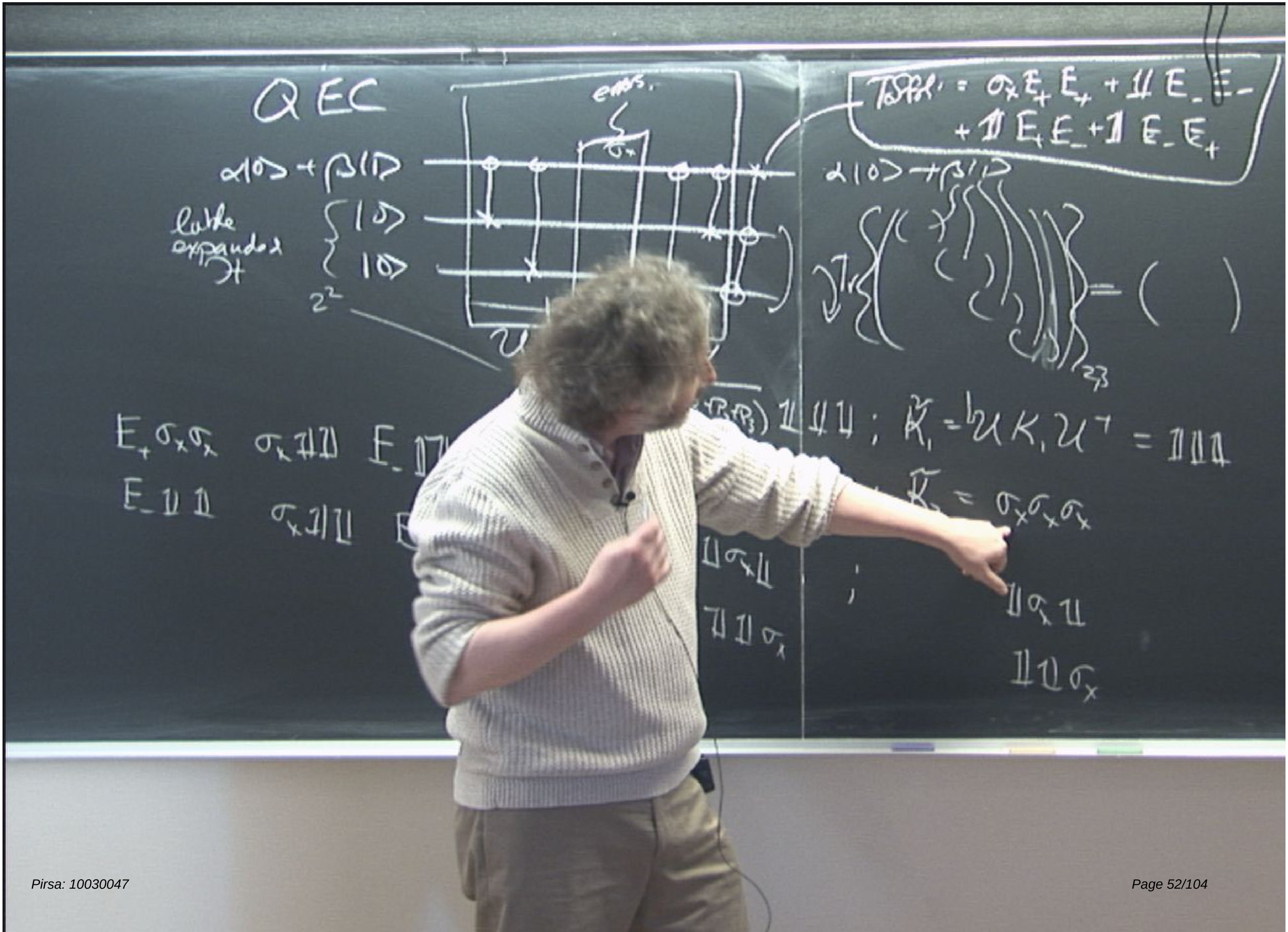

QEC
errors.
σ_x
$\alpha|0\rangle + \beta|1\rangle$
$|0\rangle$
$|0\rangle$
2^2
$\mathcal{U}$
$\mathcal{U}^\dagger$
$K_1 = \sqrt{1-(P_1+P_2+P_3)}\ \mathbb{1}\mathbb{1}\mathbb{1}$; $\tilde{K}_1 = \mathcal{U} K_1 \mathcal{U}^\dagger = \mathbb{1}\mathbb{1}\mathbb{1}$
$K_2 = \sqrt{P_1}\ \sigma_x \mathbb{1}\mathbb{1}$
$K_3 = \sqrt{P_2}\ \mathbb{1}\sigma_x\mathbb{1}$
$K_4 = \sqrt{P_3}\ \mathbb{1}\mathbb{1}\sigma_x$
$= \sigma_x E_+ E_+ + \mathbb{1} E_- E_-$
$+ \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$
$\alpha|0\rangle + \beta|1\rangle$
2,3
$(\alpha|0\rangle + \beta|1\rangle)|00\rangle$
$\alpha|000\rangle + \beta|111\rangle$

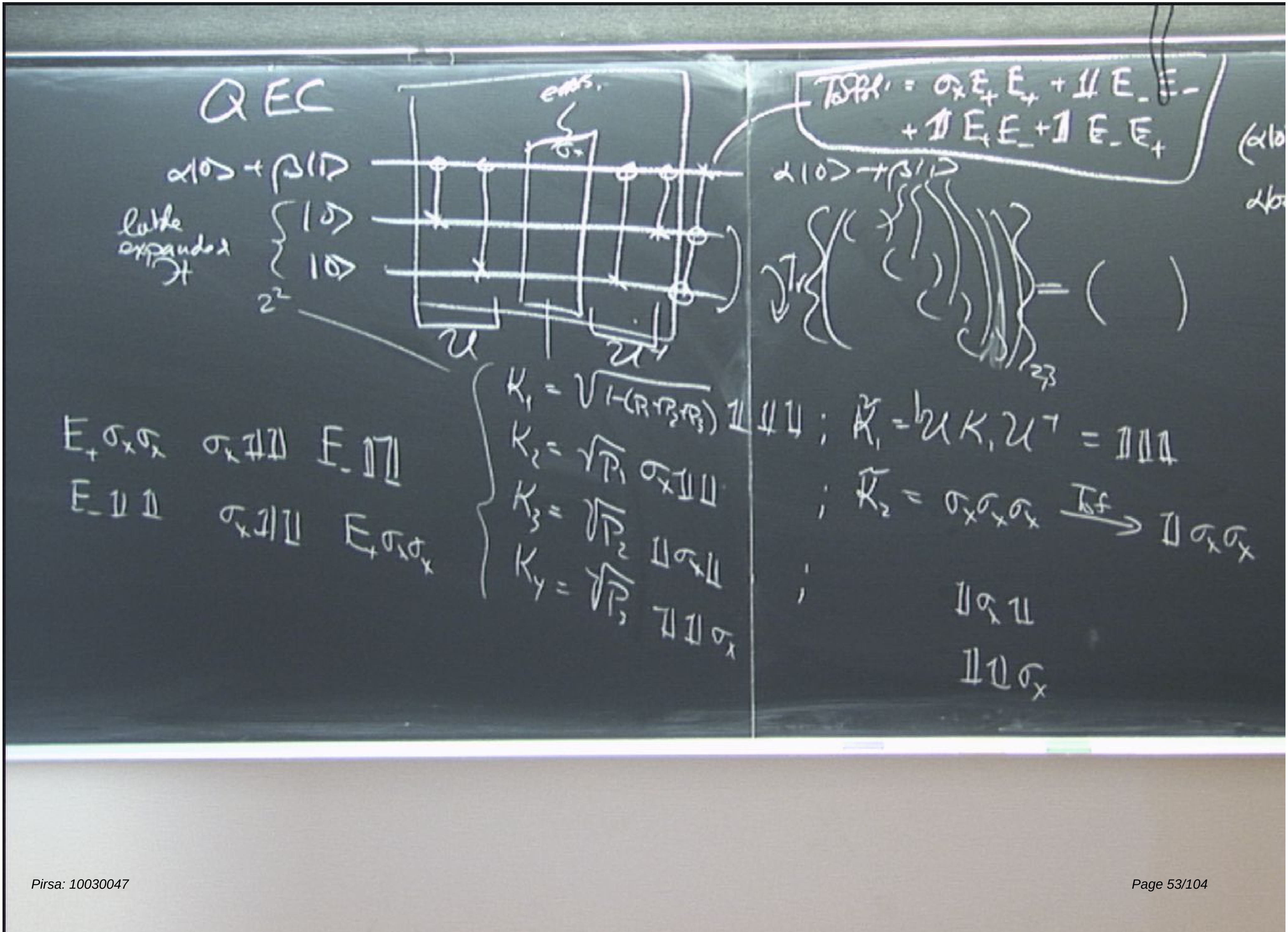

QEC
α|0⟩ + β|1⟩
|0⟩
|0⟩
2²
U
U†
σx
K₁ = √(1−(P₁+P₂+P₃)) 𝟙𝟙𝟙
K₂ = √P₁ σx 𝟙𝟙
K₃ = √P₂ 𝟙 σx 𝟙
K₄ = √P₃ 𝟙𝟙 σx
K̃₁ = U K₁ U† = 𝟙𝟙𝟙
K̃₂
E₊ σx σx   σx 𝟙𝟙   E₋ 𝟙𝟙

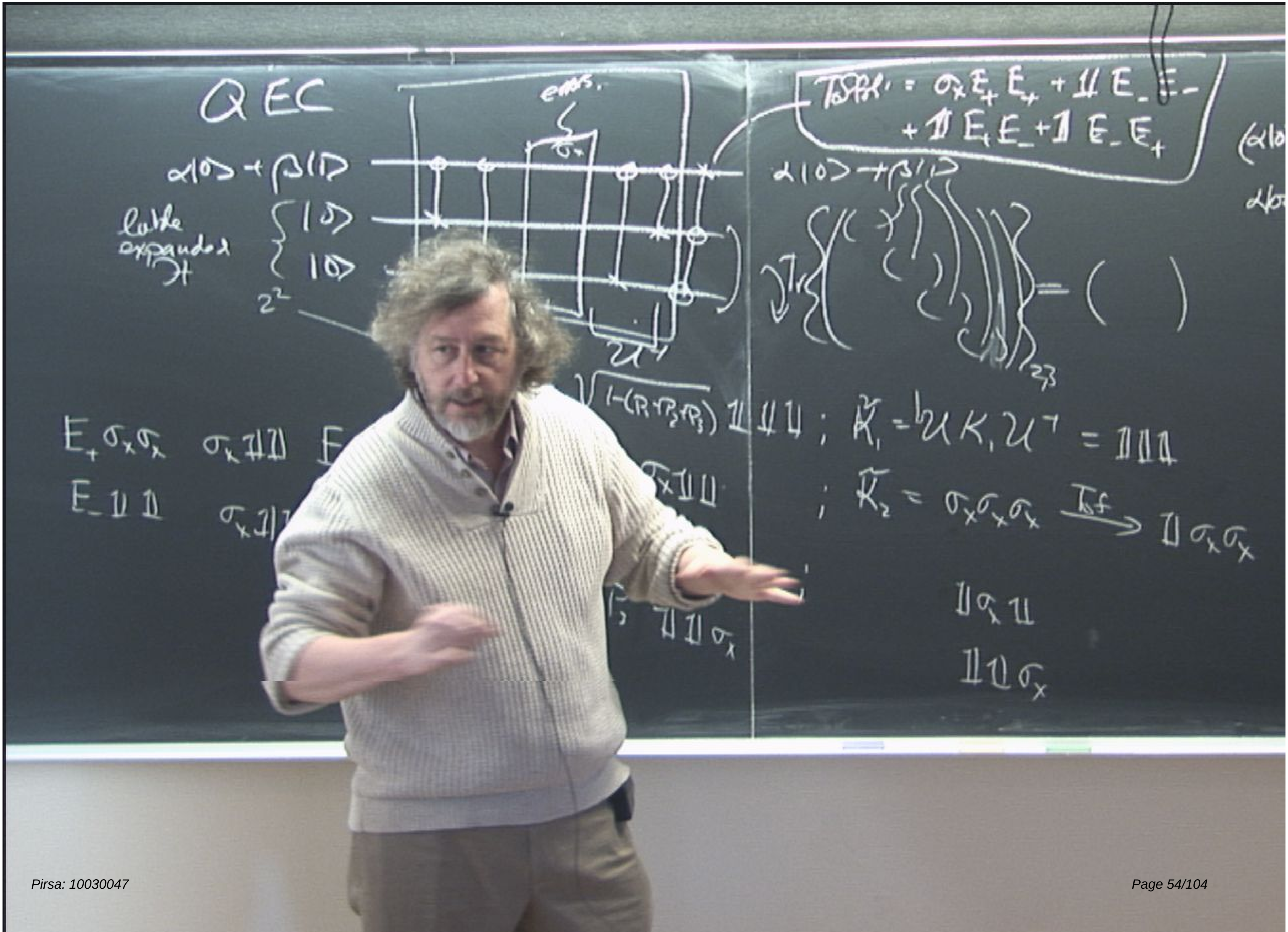

QEC
errors
α|0> + β|1>
|0>
|0>
expanded
2²
K₁ = √(1-(P₁+P₂+P₃)) 𝟙𝟙𝟙
K₂ = √P₁ σₓ𝟙𝟙
K₃ = √P₂ 𝟙σₓ𝟙
K₄ = √P₃ 𝟙𝟙σₓ
E₊σₓσₓ σₓ𝟙𝟙 E₋𝟙𝟙
σₓ𝟙𝟙 E₊σₓσₓ
= σₓE₊E₊ + 𝟙E₋E₋
+ 𝟙E₊E₋ + 𝟙E₋E₊
α|0> + β|1>
2,3
; K̃₂ = σₓσₓσₓ

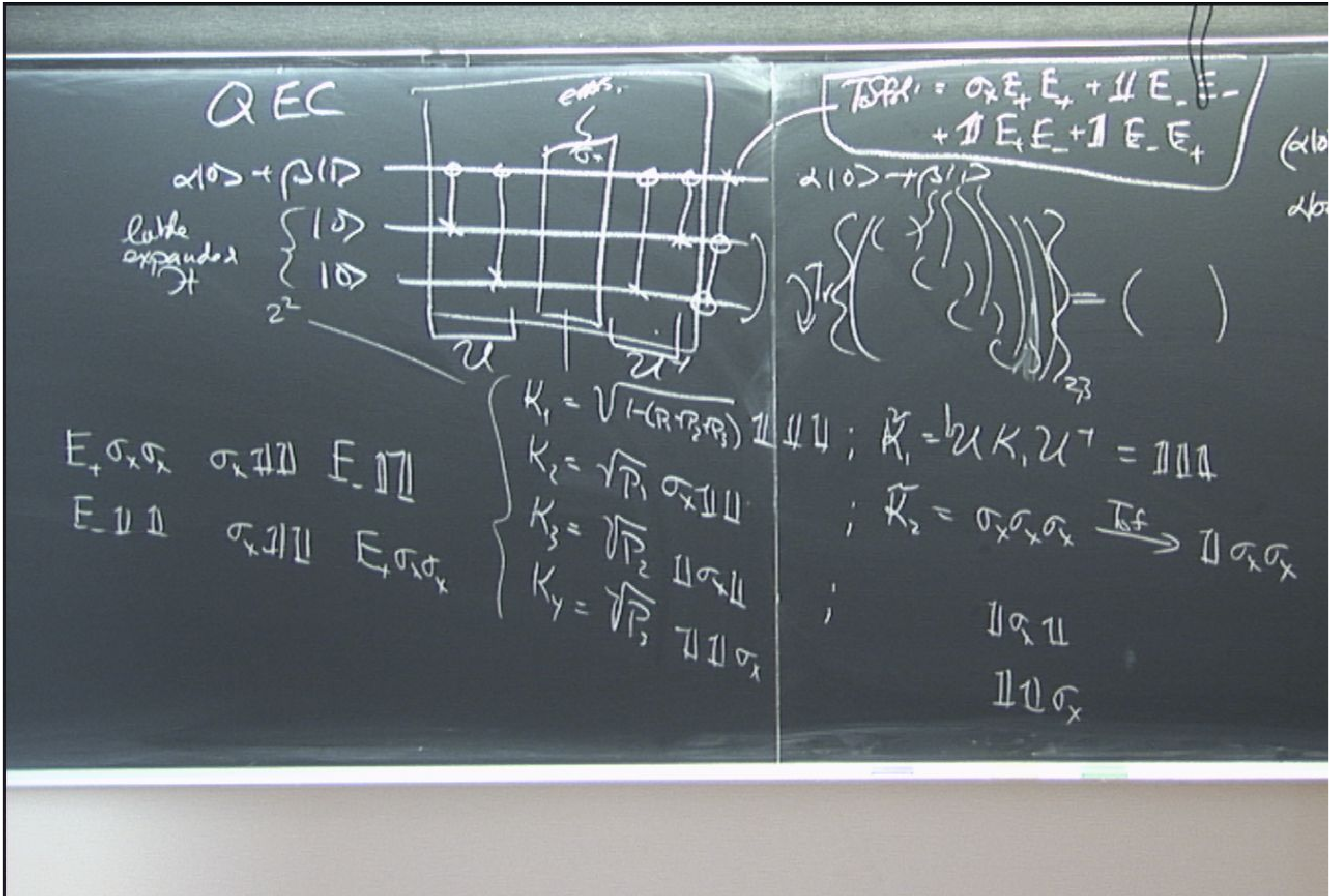

QEC
errors
α|0⟩ + β|1⟩
ancilla expanded H
|0⟩
|0⟩
2²
U
U†
K₁ = √(1−(P₁+P₂+P₃)) 𝟙𝟙𝟙 ; K̃₁ = U K₁ U† = 𝟙𝟙𝟙
K₂ = √P₁ σx𝟙𝟙 ; K̃₂ = σxσxσx
K₃ = √P₂ 𝟙σx𝟙 ; 𝟙σx𝟙
K₄ = √P₃ 𝟙𝟙σx ; 𝟙𝟙σx
E₊σxσx σx𝟙𝟙 E₋𝟙𝟙
E₋𝟙𝟙 σx𝟙𝟙 E₊σxσx
+ 𝟙 E₊E₋ + 𝟙 E₋E₊
α|0⟩ + β|1⟩

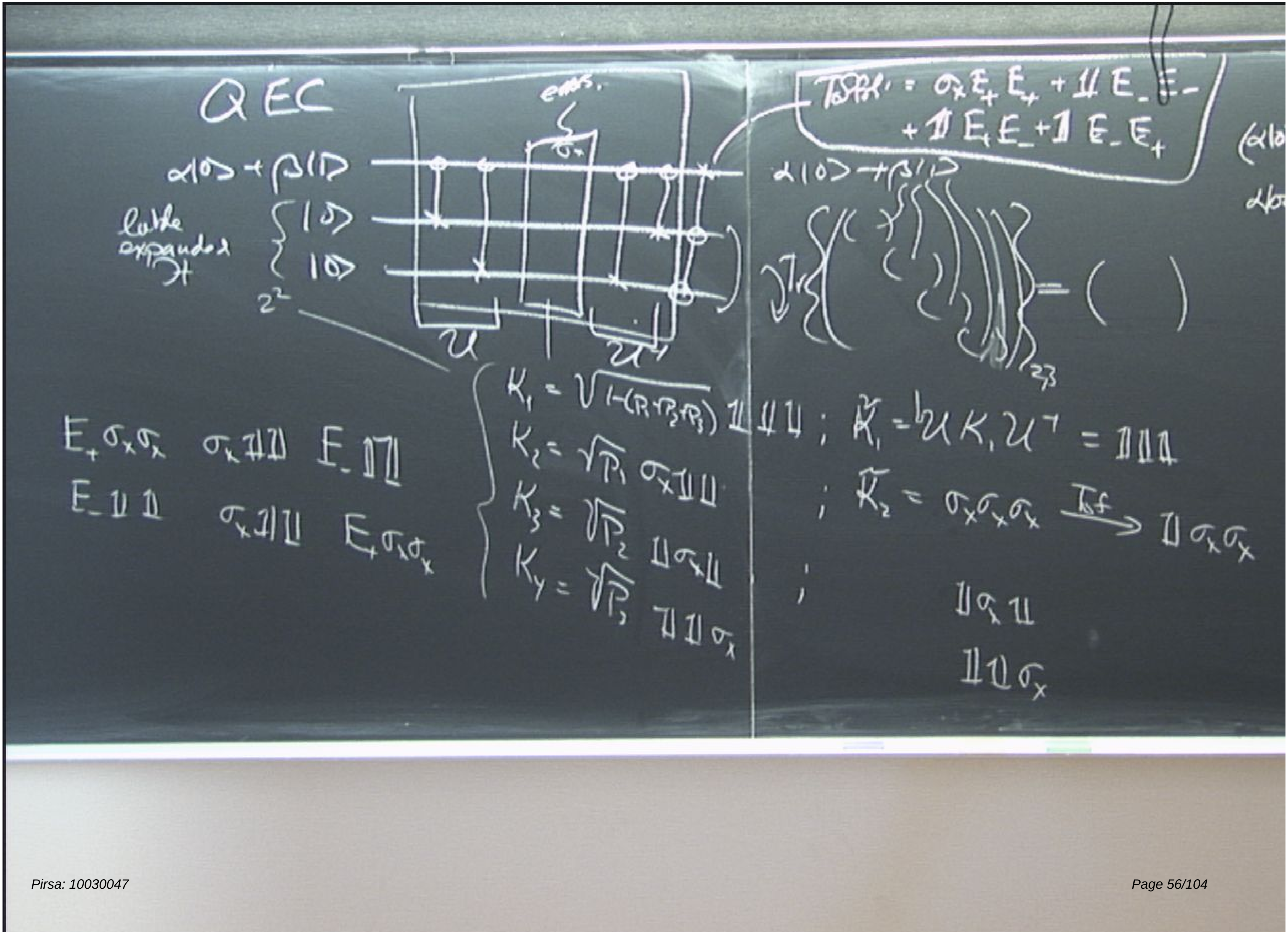

QEC

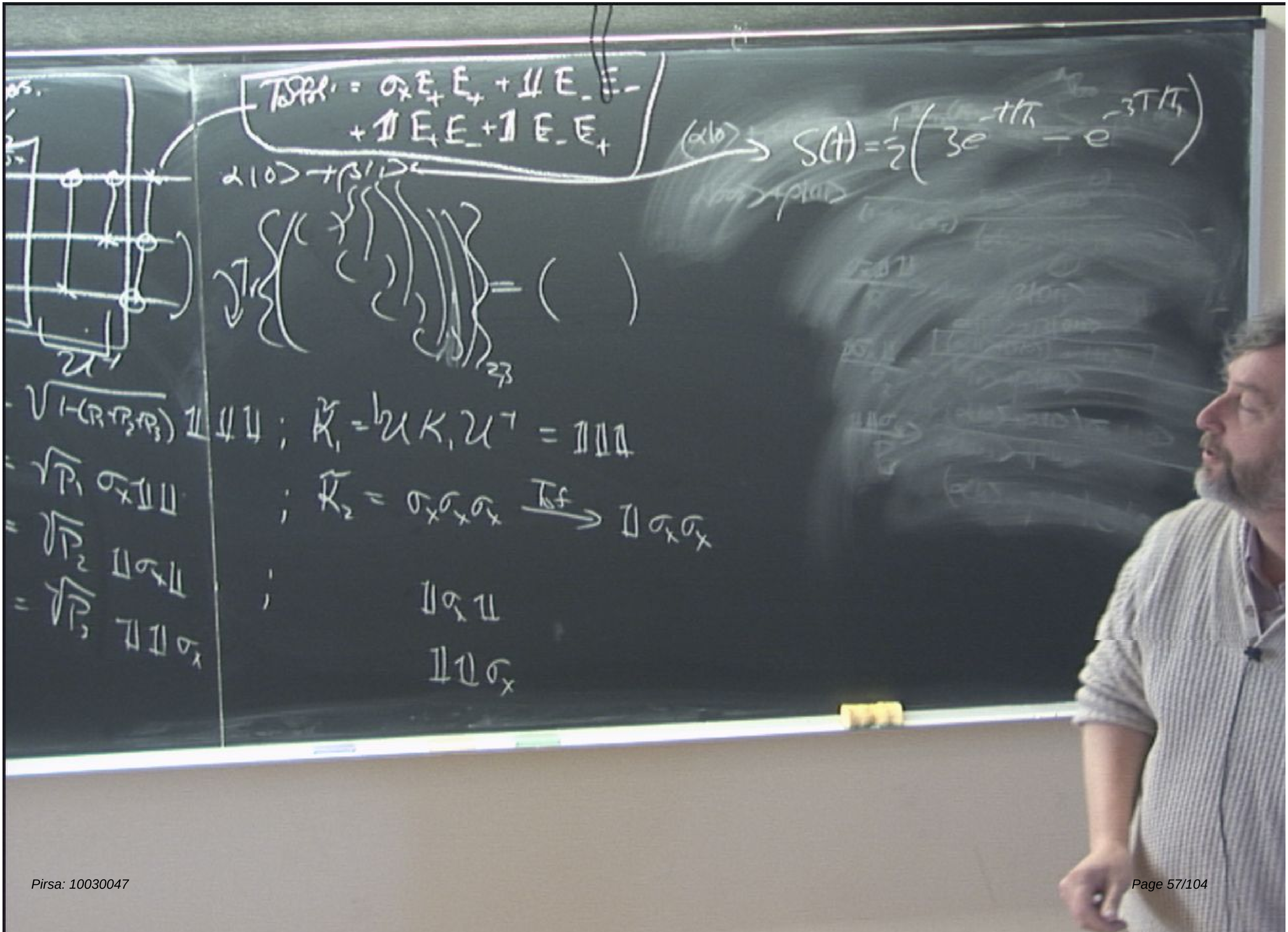

QEC


QEC
errs.
α|0⟩ + β|1⟩
|0⟩
|0⟩
expanded
2²
U
U†
K₁ = √(1−(P₁+P₂+P₃)) 𝟙𝟙𝟙 ; K̃₁ = U K₁ U† = 𝟙𝟙𝟙
K₂ = √P₁ σₓ𝟙𝟙 ; K̃₂ = σₓσₓσₓ → 𝟙σₓσₓ
K₃ = √P₂ 𝟙σₓ𝟙 ; 𝟙σₓ𝟙
K₄ = √P₃ 𝟙𝟙σₓ 𝟙𝟙σₓ
E₊σₓσₓ σₓ𝟙𝟙 E₋𝟙𝟙
E₋𝟙𝟙 σₓ𝟙𝟙 E₊σₓσₓ
= σₓE₊E₊ + 𝟙E₋E₋
+ 𝟙E₊E₋ + 𝟙E₋E₊
α|0⟩ + β|1⟩
2,3

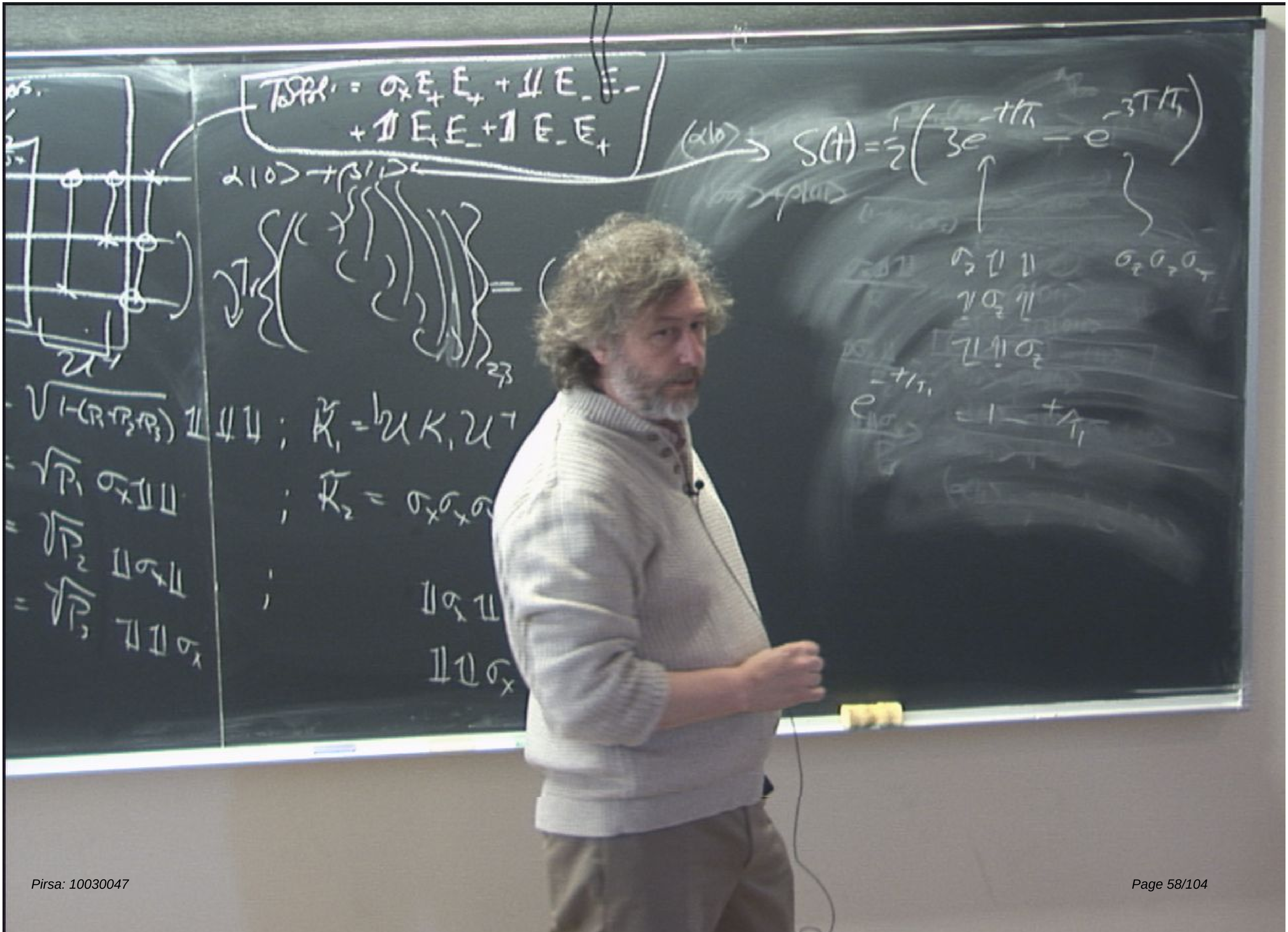

QEC

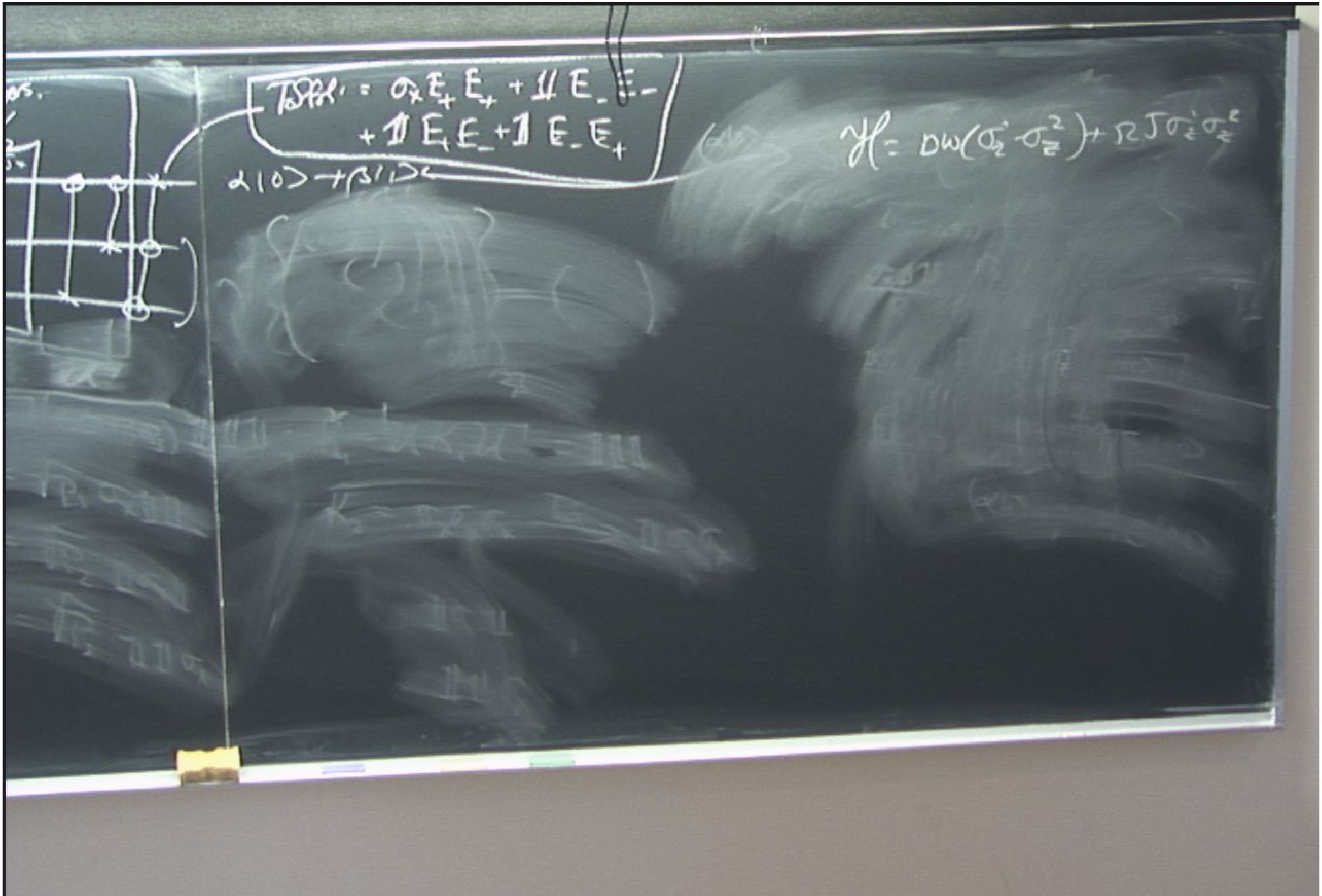

QEC
α|0⟩ + β|1⟩
|0⟩
|0⟩
2^2
$K_1 = \sqrt{1-(P_1+P_2+P_3)}\ 1\!\!1\,1\!\!1\,1\!\!1$
$K_2 = \sqrt{P_1}\ \sigma_x 1\!\!1\,1\!\!1$
$K_3 = \sqrt{P_2}\ 1\!\!1\,\sigma_x 1\!\!1$
$K_4 = \sqrt{P_3}\ 1\!\!1\,1\!\!1\,\sigma_x$
$\tilde{K}_2 = \sigma_x\sigma_x\sigma_x \xrightarrow{Tr_f} 1\!\!1\,\sigma_x\sigma_x$

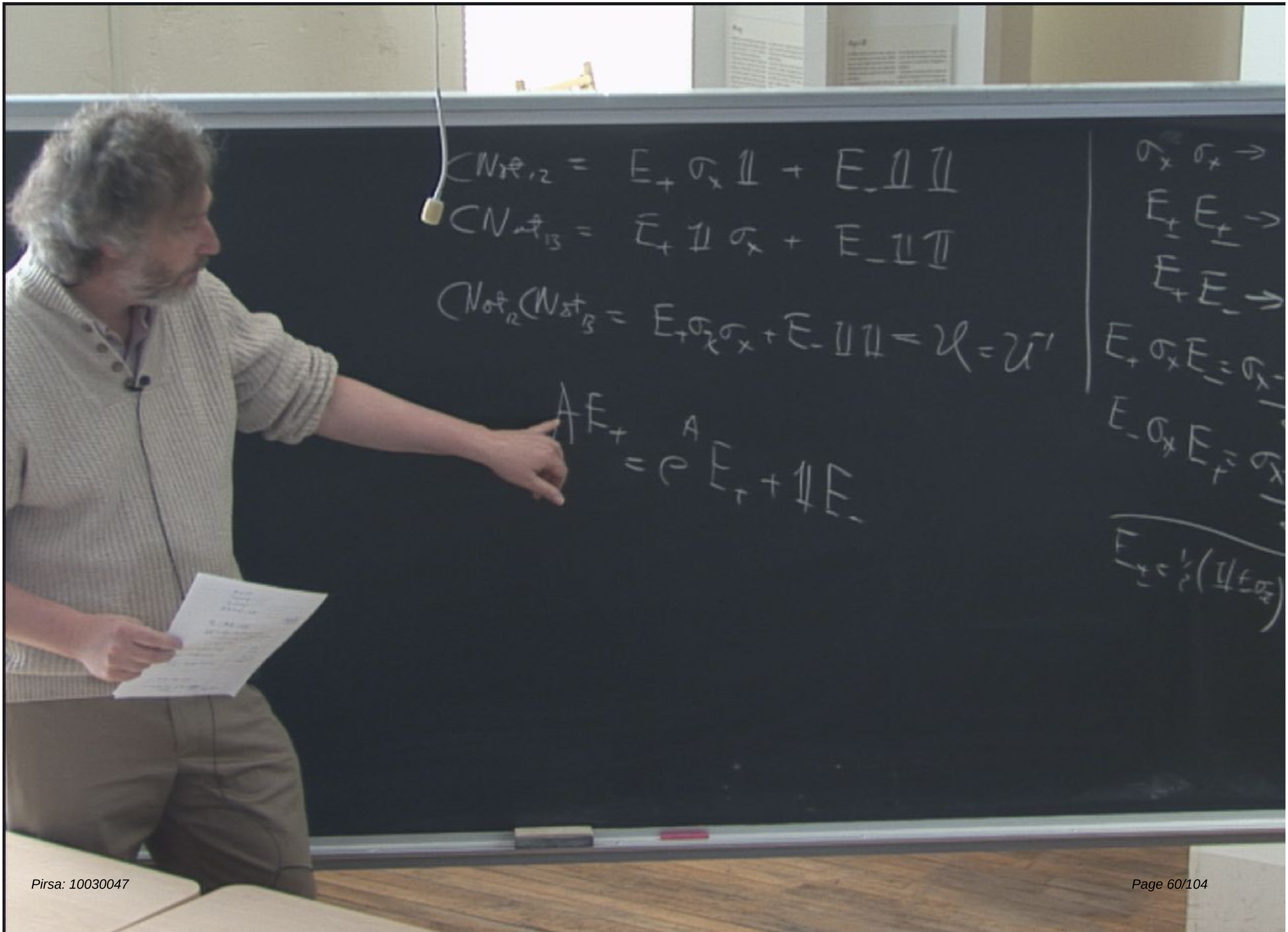

QEC
errs.
α|0⟩ + β|1⟩
|0⟩
|0⟩
2²
U
U†
Tr_BA = σ_x E_+ E_+ + 𝟙 E_- E_-
+ 𝟙 E_+ E_- + 𝟙 E_- E_+
α|0⟩ + β|1⟩
2,3
K_1 = √(1-(P_1+P_2+P_3)) 𝟙𝟙𝟙 ; K̃_1 = U K_1 U† = 𝟙𝟙𝟙
K_2 = √P_1 σ_x 𝟙𝟙 ; K̃_2 = σ_x σ_x σ_x → 𝟙 σ_x σ_x
K_3 = √P_2 𝟙 σ_x 𝟙 ; 𝟙 σ_x 𝟙
K_4 = √P_3 𝟙𝟙 σ_x ; 𝟙𝟙 σ_x
E_+ σ_x σ_x   σ_x 𝟙𝟙   E_- 𝟙𝟙
E_- 𝟙 𝟙   σ_x 𝟙𝟙   E_+ σ_x σ_x

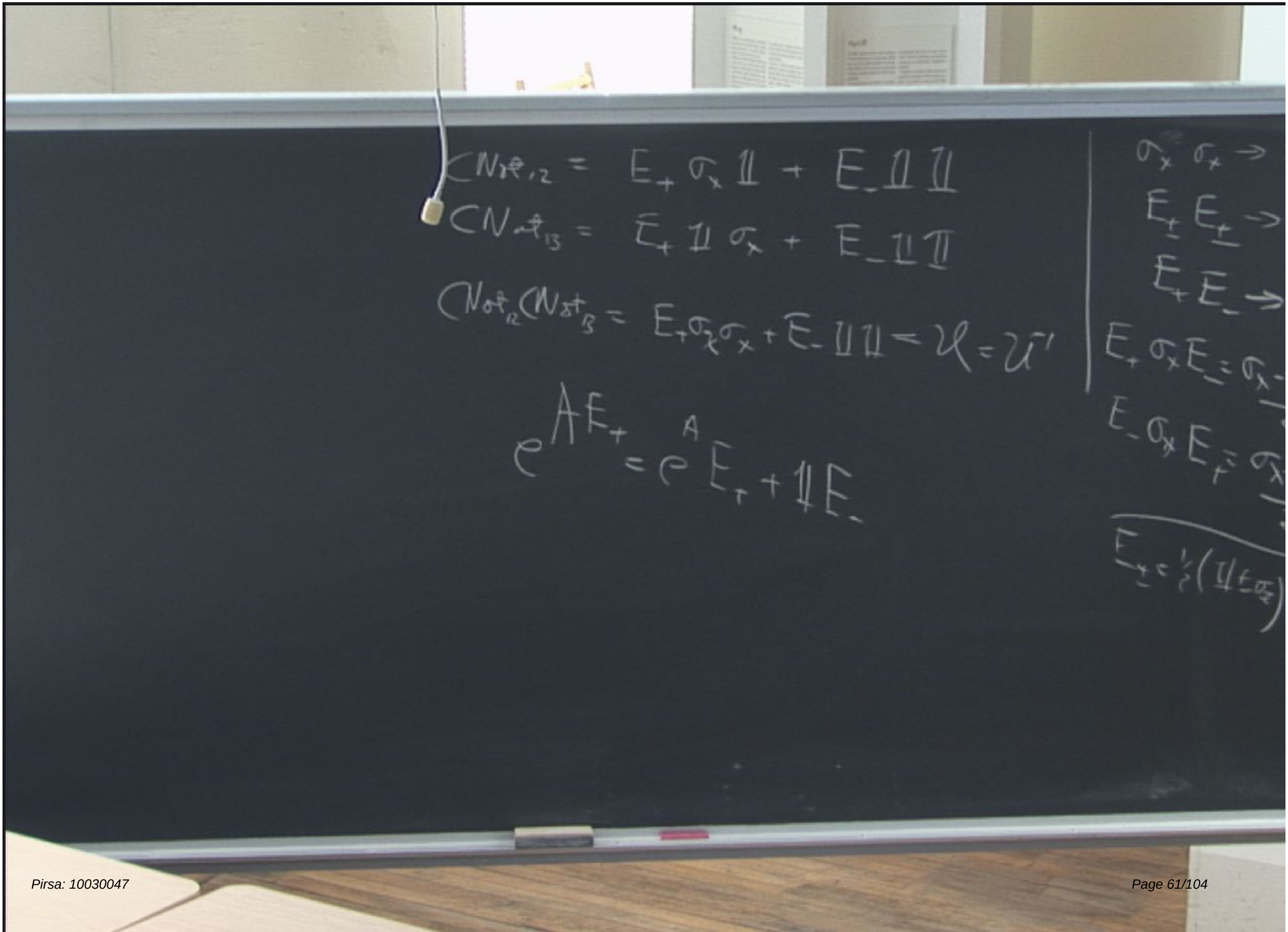


+ 𝟙 E+ E- + 𝟙 E- E+
S(t) = 1/2 (3e^{-t/T1} - e^{-3t/T1})
α|0> + β|1>
= √P1 σx 𝟙 𝟙
= √P2 𝟙 σx 𝟙
= √P3 𝟙 𝟙 σx
K2 = σx σx σx → 𝟙 σx σx
𝟙 σx 𝟙
𝟙 𝟙 σx




= σx E+ E+ + 𝟙 E- E-
+ 𝟙 E+ E- + 𝟙 E- E+
α|0> + β|1>
H = Dω(σz1 - σz2) + ΩJ σz1 σz2


CNot12 = E+ σx 𝟙 + E- 𝟙 𝟙
CNot13 = E+ 𝟙 σx + E- 𝟙 𝟙
CNot12 CNot13 = E+ σx σx + E- 𝟙 𝟙 = U = U^-1
E± = ½(𝟙 ± σz)


CNot12 = E+ σx 𝟙 + E- 𝟙 𝟙
CNot13 = E+ 𝟙 σx + E- 𝟙 𝟙
CNot12 CNot13 = E+ σx σx + E- 𝟙 𝟙 = U = U^-1
e^{A E+} = e^A E+ + 𝟙 E-
σx σx →
E± E± →
E+ E- →
E+ σx E- = σx
E- σx E+ = σx
E± = ½ (𝟙 ± σz)

$$E_+ E_+ + \mathbb{1}\, E_- E_-$$

$$E_- + \mathbb{1}\, E_- E_+$$

$$\mathcal{H} = D\omega(\sigma_z^1 - \sigma_z^2) + \Omega J \sigma_z^1 \sigma_z^2$$

CNOT

$$\text{CNOT} = E_+ \mathbb{1} + E_- \sigma_x$$

$E_+ E_+ + \mathbb{1} E_- E_-$

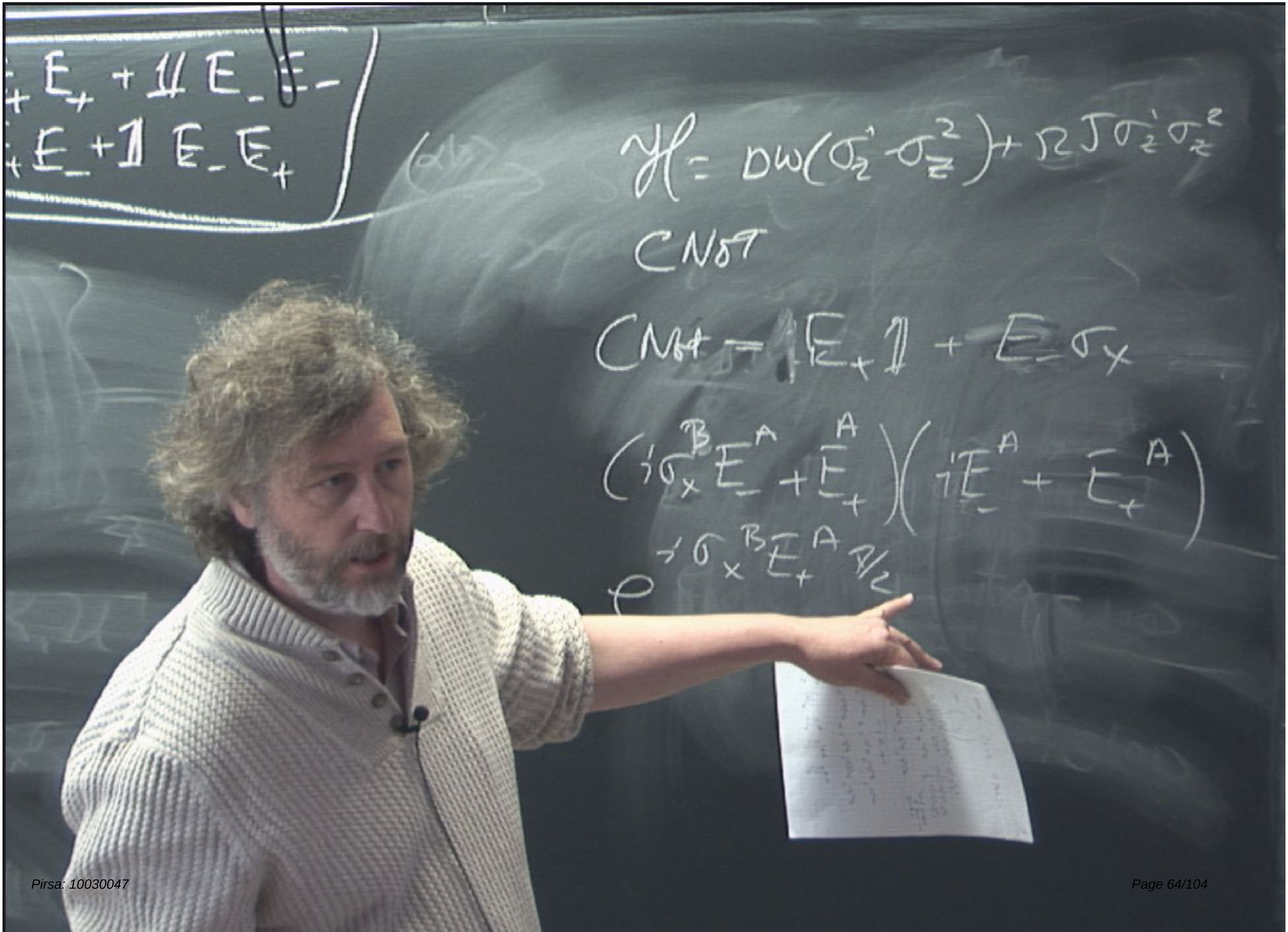
$E_+ E_- + \mathbb{1} E_- E_+$

$\mathcal{H} = \hbar\omega(\sigma_z^1 - \sigma_z^2) + \hbar J \sigma_z^1 \sigma_z^2$

CNOT

$CNOT = E_+ \mathbb{1} + E_- \sigma_x$

$(\sigma_x^B E_-^A + E_+^A)(E_-^A + E_+^A)$



E_+ E_+ + 1 E_- E_-
E_+ E_- + 1 E_- E_+
H = DW(σ_z^1 − σ_z^2) + ΩJ σ_z^1 σ_z^2
CNOT
CNOT = E_+ 1 + E_- σ_x
(iσ_x^B E_-^A + E_+^A)(iE_-^A + E_+^A)
e^{iσ_x^B E_+^A π/2}

$E_+ E_+ + \mathbb{1}\, E_- E_-$

$E_+ E_- + \mathbb{1}\, E_- E_+$

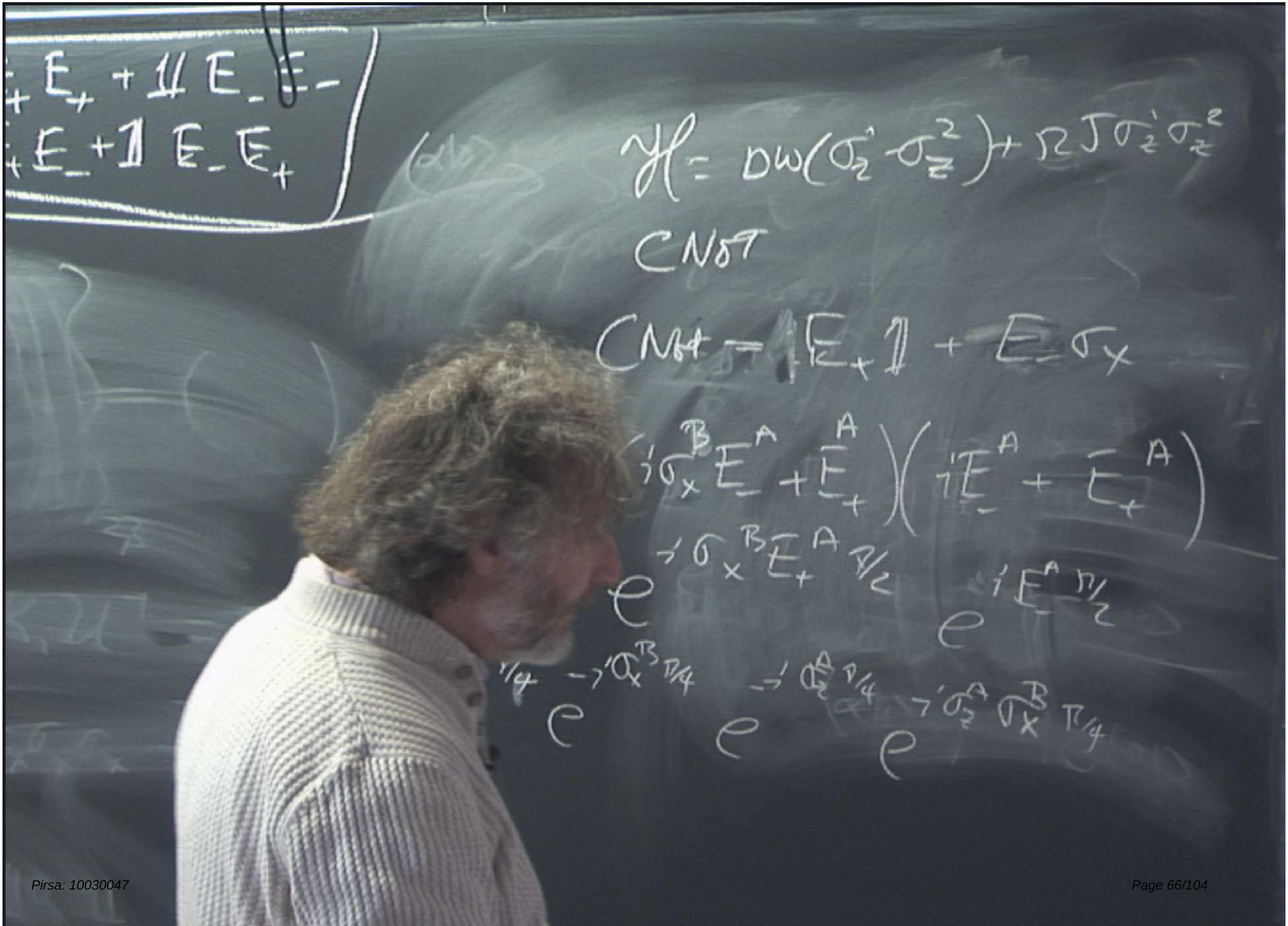
$\mathcal{H} = D\omega(\sigma_z^1 - \sigma_z^2) + \Omega J \sigma_z^1 \sigma_z^2$

CNOT

$CNOT = E_+ \mathbb{1} + E_- \sigma_x$

$(i\sigma_x^B E_-^A + E_+^A)(iE_-^A + E_+^A)$

$e^{i\sigma_x^B E_+^A \pi/2} \quad e^{iE_-^A \pi/2}$



$$E_+ E_+ + \mathbb{1} E_- E_-$$

$$E_+ E_- + \mathbb{1} E_- E_+$$

$$\mathcal{H} = \Delta\omega(\sigma_z^1 - \sigma_z^2) + \Omega J \sigma_z^1 \sigma_z^2$$

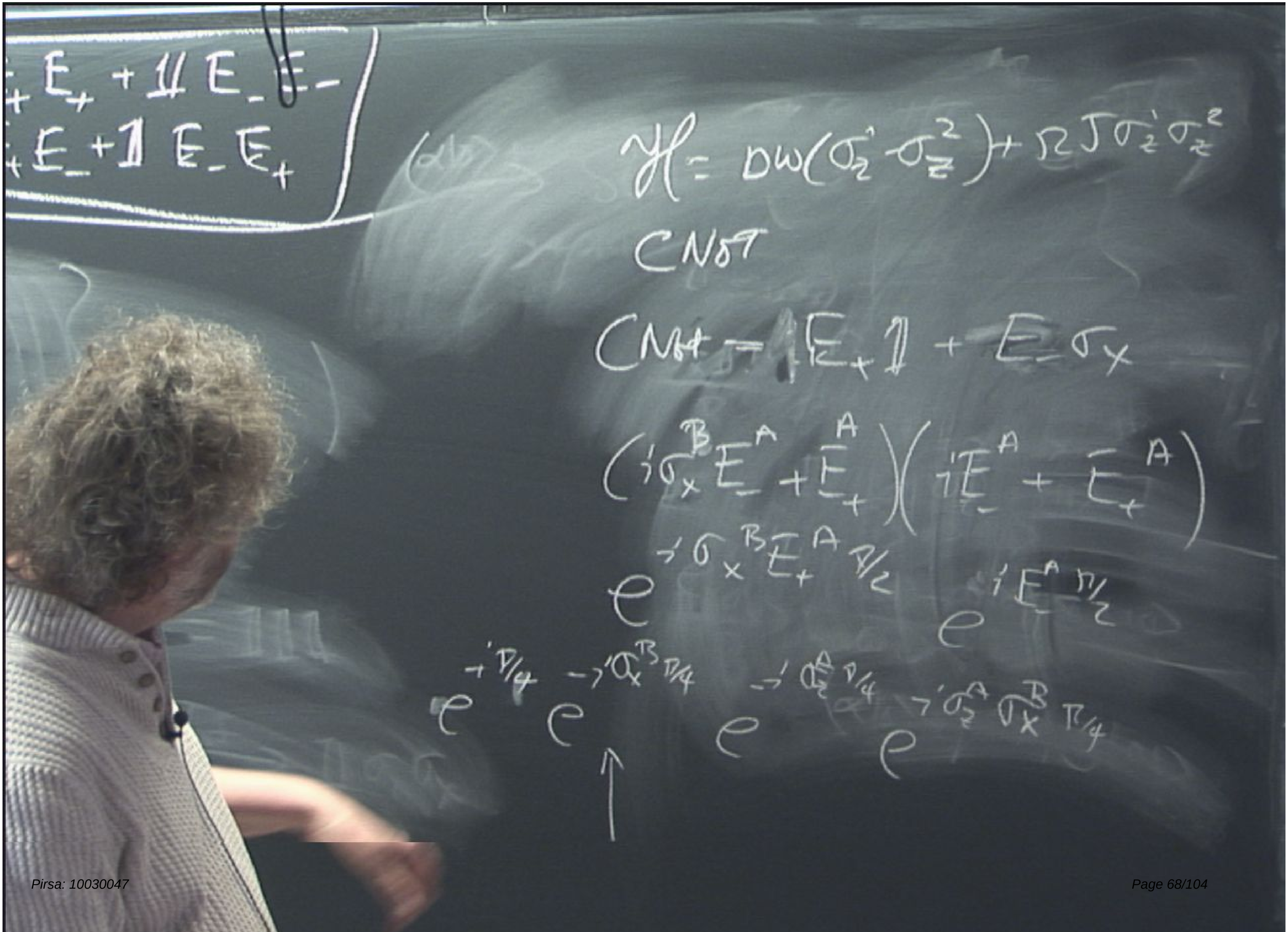
CNOT

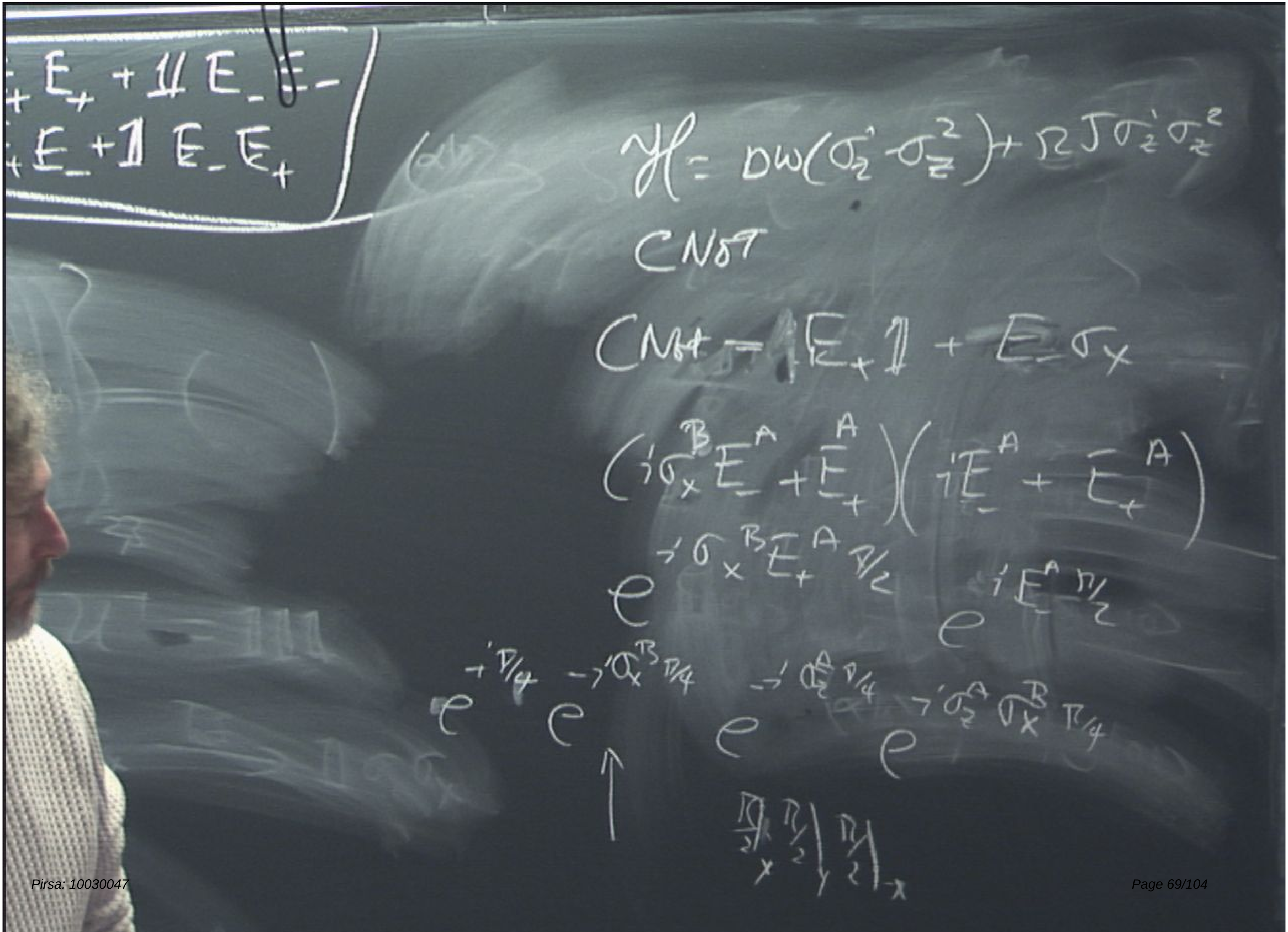
$$\text{CNOT} = E_+ \mathbb{1} + E_- \sigma_x$$

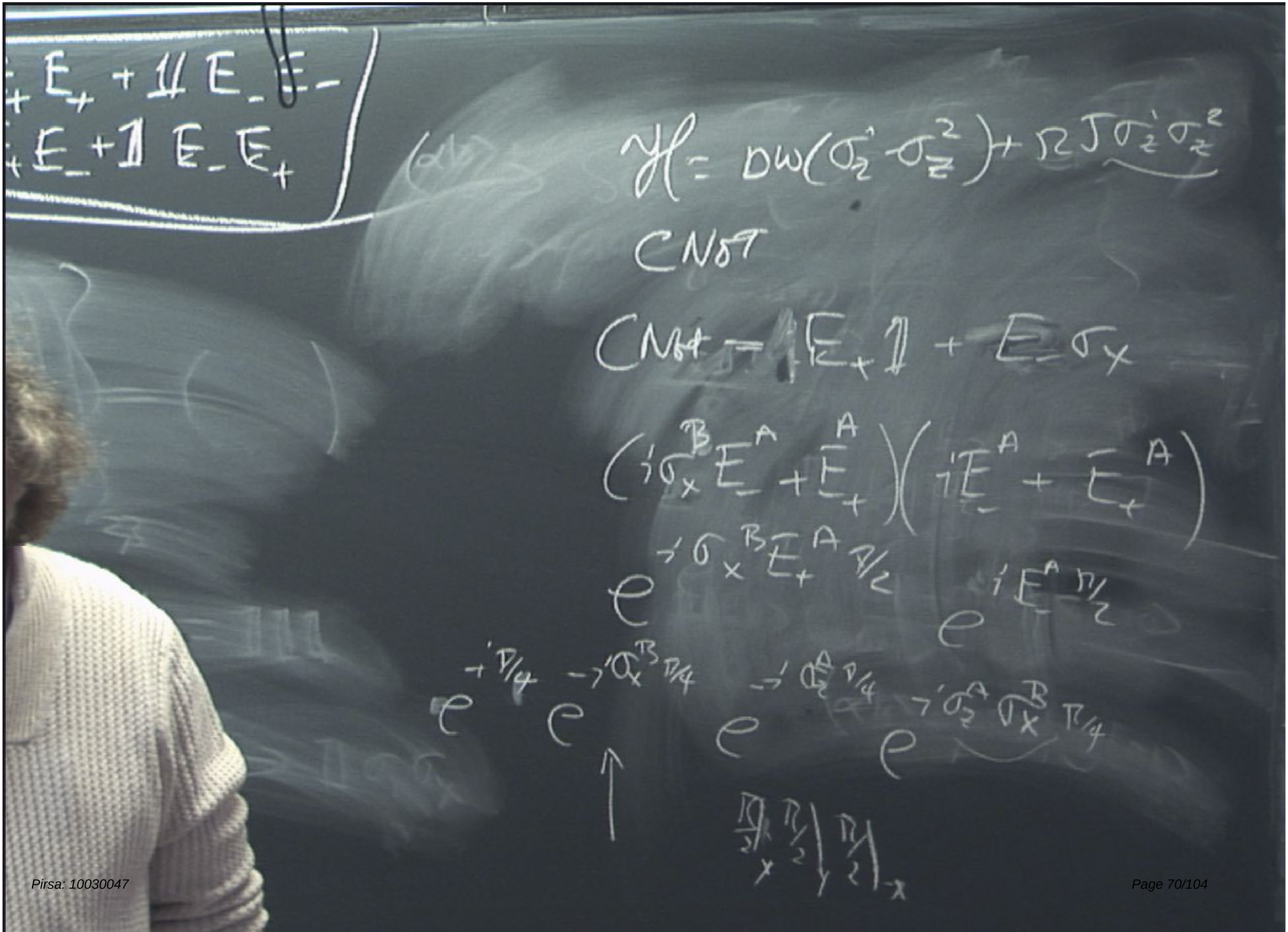
$$(i\sigma_x^B E_-^A + E_+^A)(iE_-^A + E_+^A)$$

$$e^{-i\sigma_x^B E_+^A \pi/2} \quad e^{iE_-^A \pi/2}$$

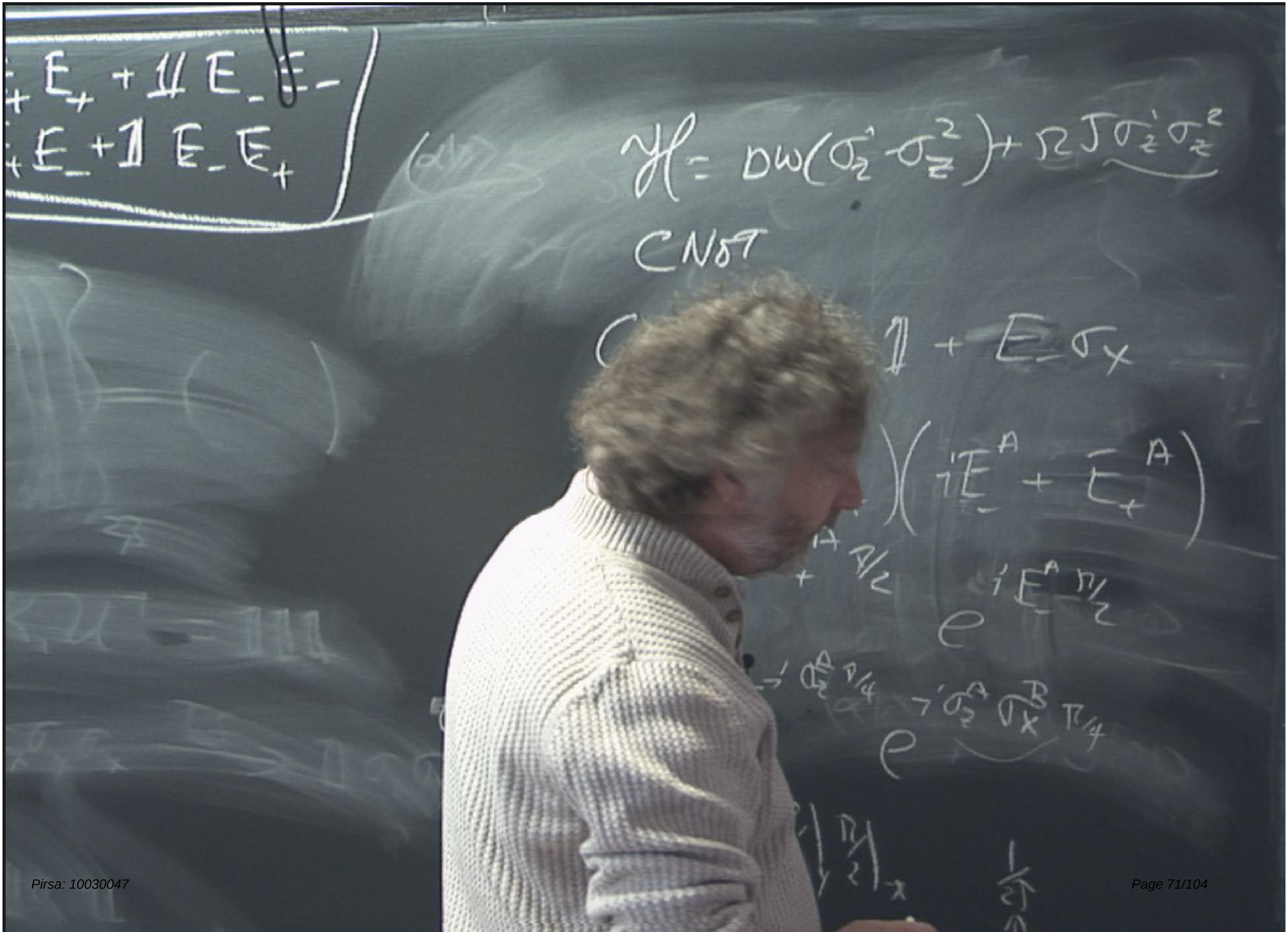
$$e^{-i\pi/4} \; e^{-i\sigma_x^B \pi/4} \; e^{-i\sigma_z^A \pi/4} \; e^{-i\sigma_z^A \sigma_x^B \pi/4}$$

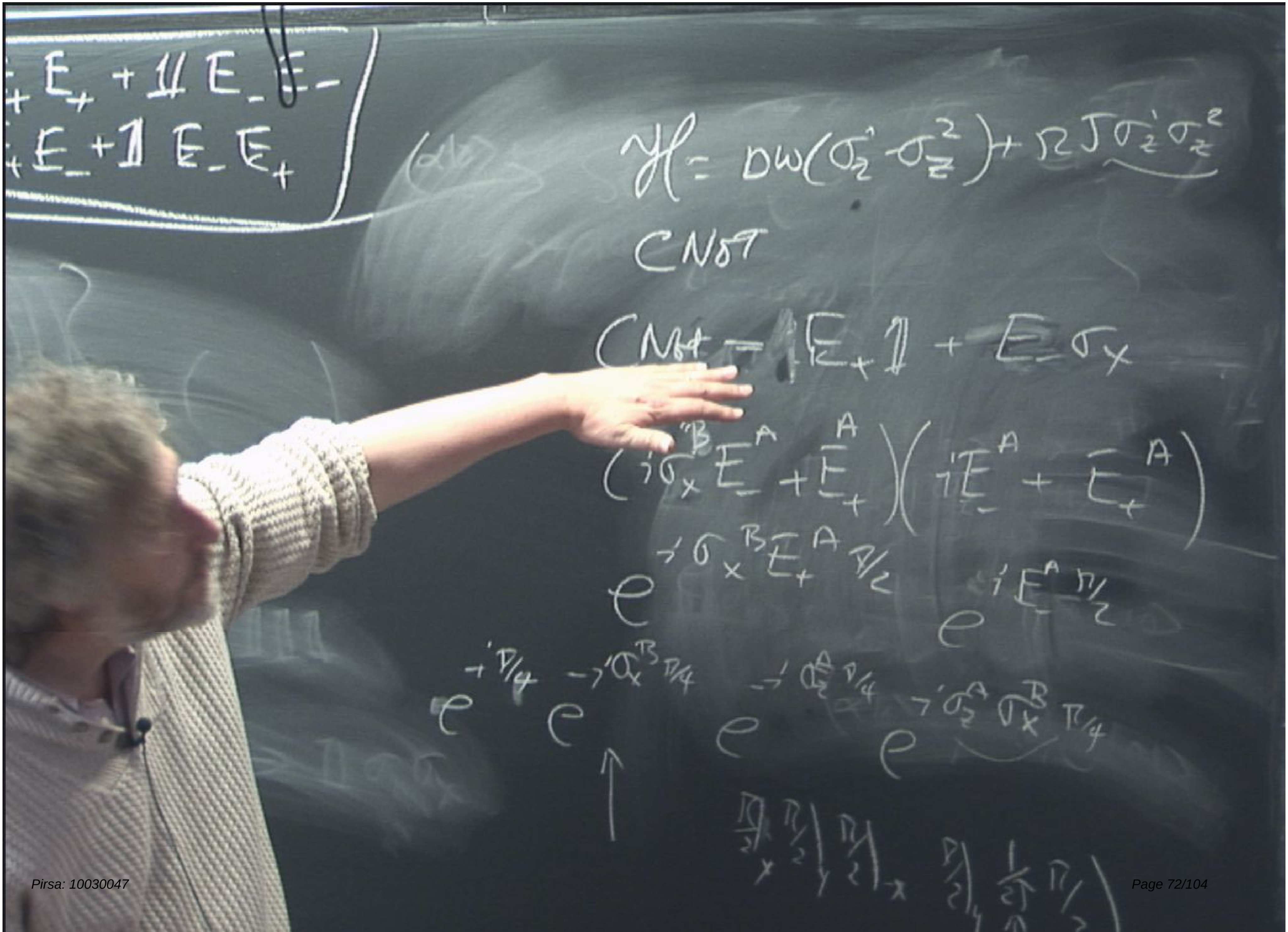

H = DW(σz1 − σz2) + ΩJ σz1 σz2
CNOT
CNOT = E+ 1 + E− σx

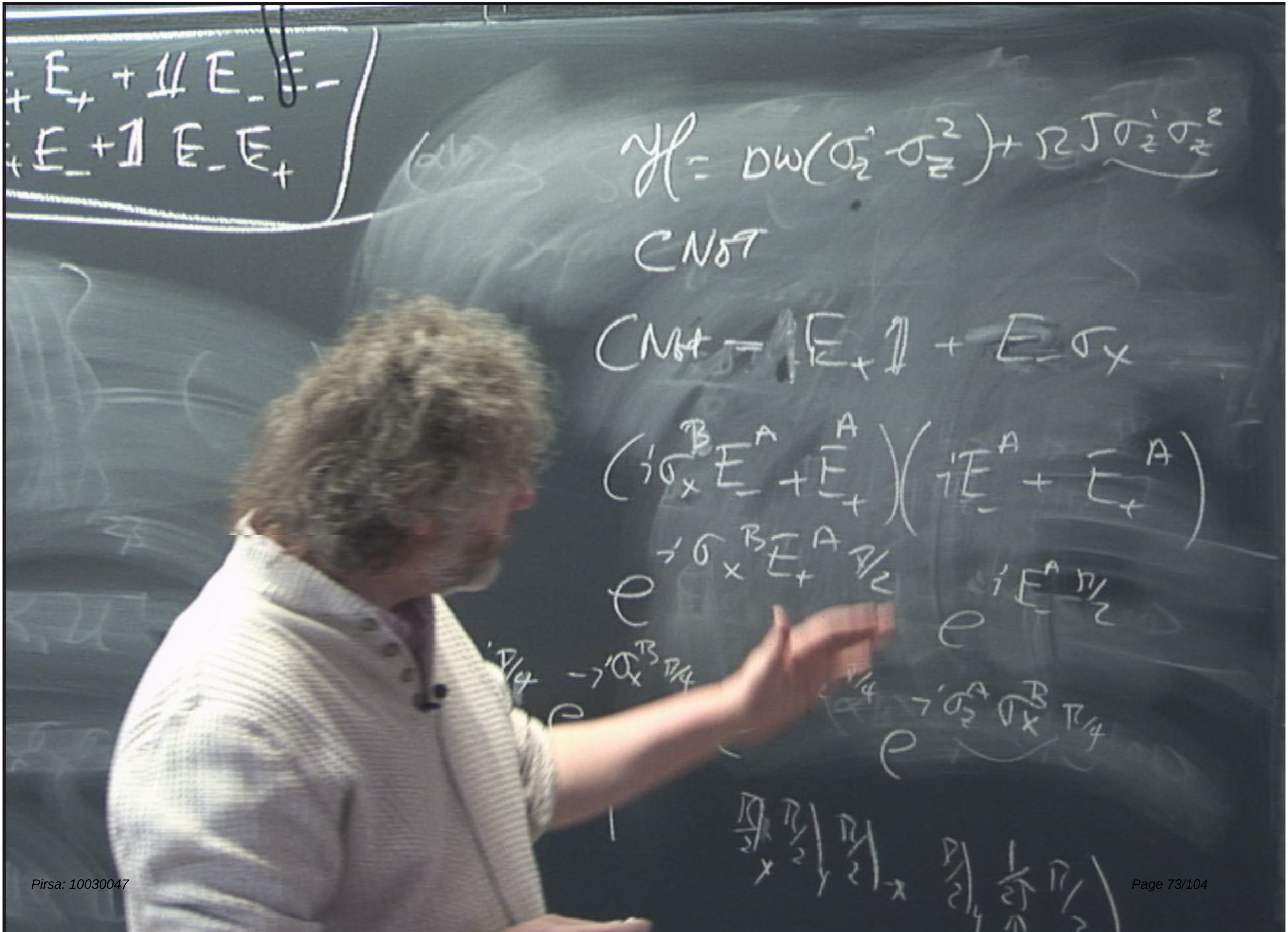

E₊ + 𝟙 E₋ E₋
E₋ + 𝟙 E₋ E₊
H = Dω(σ_z¹ − σ_z²) + ΩJ σ_z¹ σ_z²
CNOT
CNOT = E₊ 𝟙 + E₋ σ_x
(iσ_x^B E₋^A + E₊^A)(iE₋^A + E₊^A)
e^{−iσ_x^B E₊^A π/2} e^{iE₋^A π/2}
e^{−iπ/4} e^{−iσ_x^B π/4} e^{−iσ_z^A π/4} e^{−iσ_z^A σ_x^B π/4}

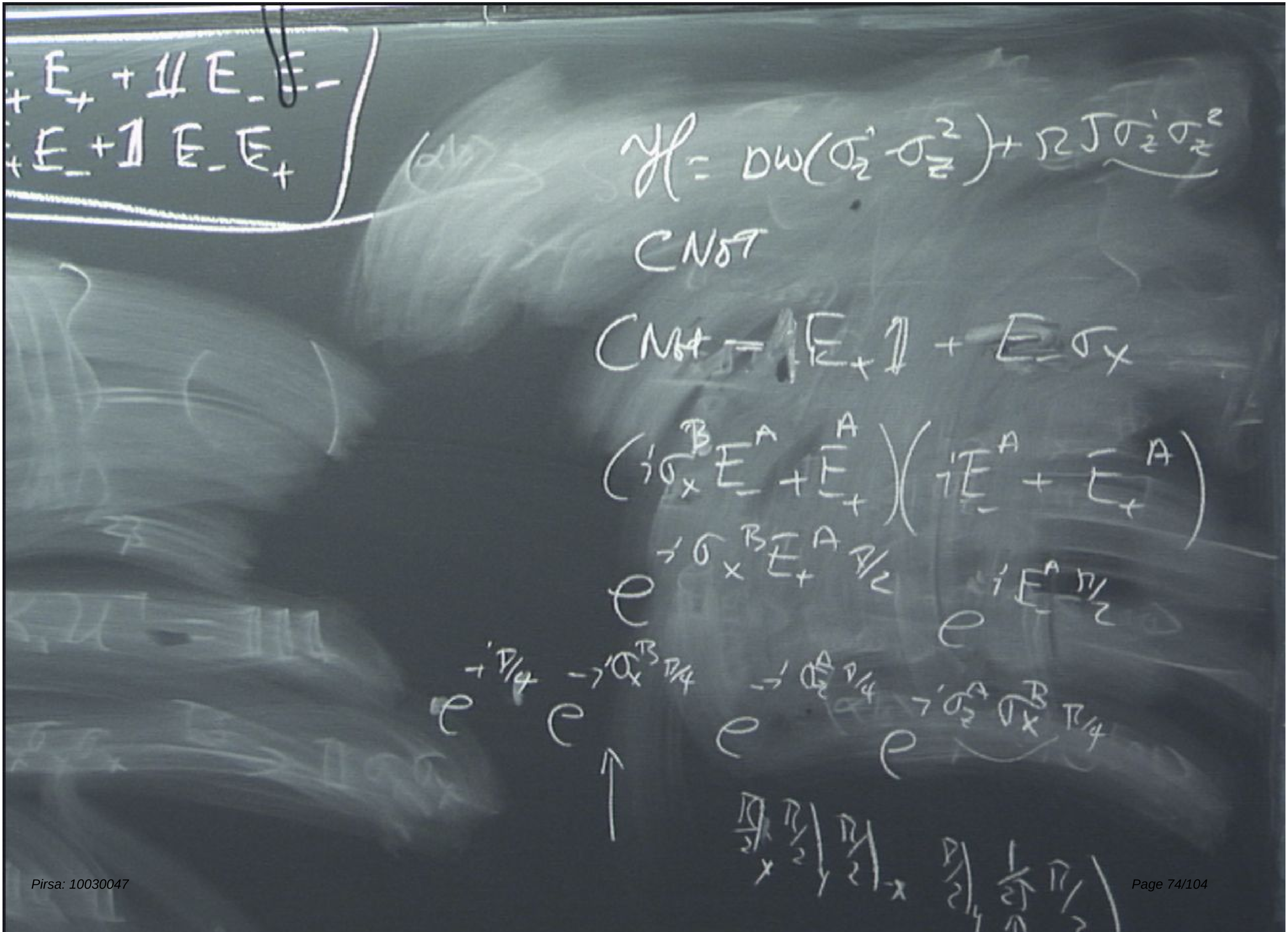


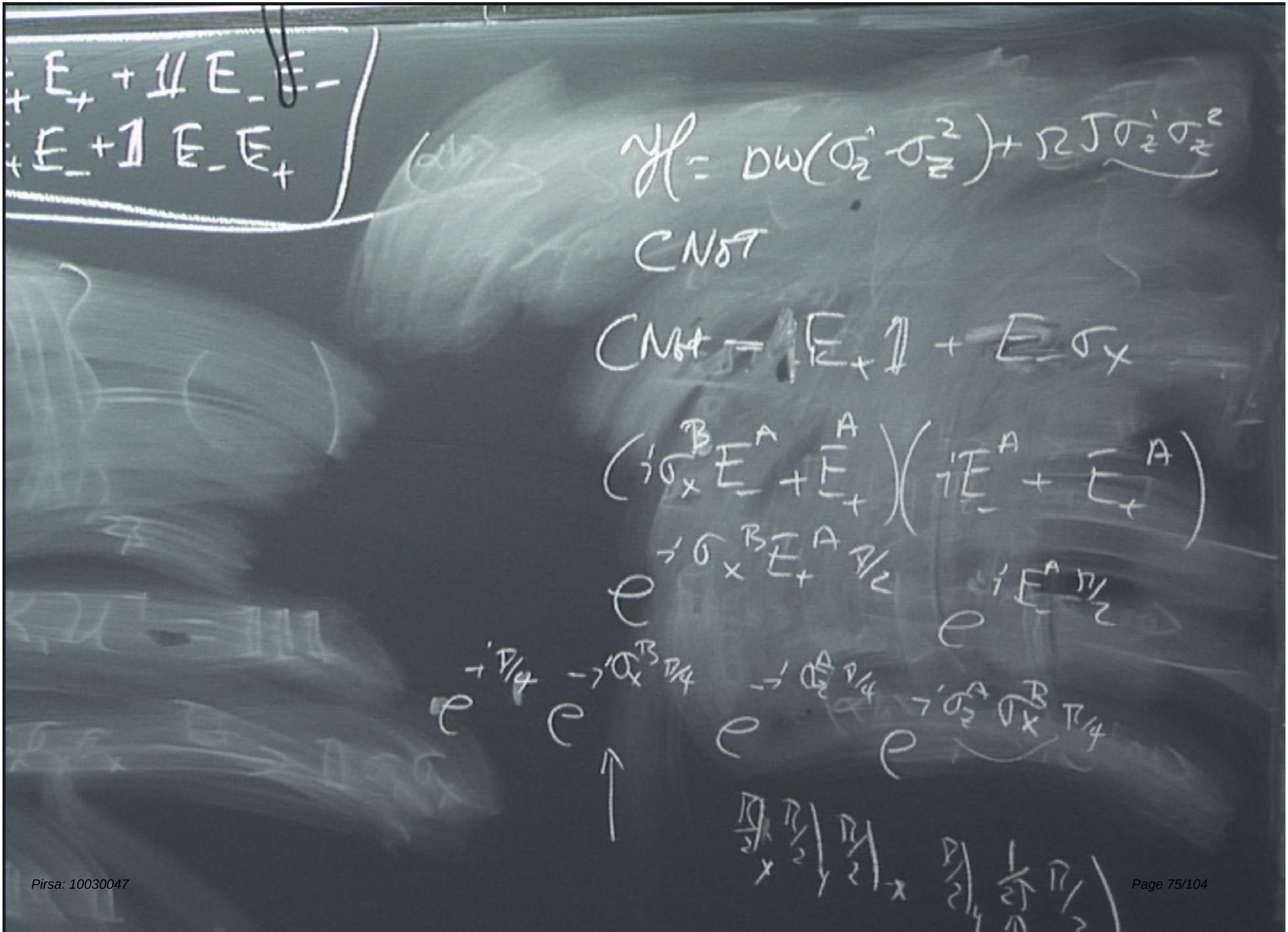
E_+ E_+ + 1 E_- E_-
E_+ E_- + 1 E_- E_+
H = Dω(σ_z^1 − σ_z^2) + ΩJ σ_z^1 σ_z^2
CNOT
CNOT = E_+ 1 + E_- σ_x
(iσ_x^B E_-^A + E_+^A)(iE_-^A + E_+^A)
e^{-iσ_x^B E_+^A π/2}
e^{iE_-^A π/2}
e^{-iπ/4} e^{-iσ_x^B π/4} e^{-iσ_z^A π/4} e^{-iσ_z^A σ_x^B π/4}


CNOT


CNOT




E₊E₊ + 𝟙 E₋E₋
E₊E₋ + 𝟙 E₋E₊
H = DW(σz¹ − σz²) + ΩJ σz¹ σz²
CNOT
CNOT = E₊ 𝟙 + E₋ σx
(iσx^B E₋^A + E₊^A)(iE₋^A + E₊^A)
e^{-iσx^B E₊^A π/2} e^{iE₋^A π/2}
e^{-iπ/4} e^{-iσx^B π/4} e^{-iσz^A π/4} e^{-iσz^A σx^B π/4}


CNOT

$$E_+ E_+ + \mathbb{1} E_- E_-$$

$$E_+ E_- + \mathbb{1} E_- E_+$$

$$\mathcal{H} = DW(\sigma_z^1 - \sigma_z^2) + \Omega J \sigma_z^1 \sigma_z^2$$

CNOT

$$CNOT = E_+ \mathbb{1} + E_- \sigma_x$$

$$(i\sigma_x^B E_-^A + E_+^A)(iE_-^A + E_+^A)$$

$$e^{-i\sigma_x^B E_+^A \pi/2} \quad e^{iE_-^A \pi/2}$$

$$e^{-i\pi/4} \, e^{-i\sigma_x^B \pi/4} \, e^{-i\sigma_z^A \pi/4} \, e^{-i\sigma_z^A \sigma_x^B \pi/4}$$

$$\uparrow$$

$$\frac{\pi}{2}\Big|_x \frac{\pi}{2}\Big|_y \frac{\pi}{2}\Big|_{-x} \frac{\pi}{2}\Big|_y \ \frac{1}{2J}\frac{\pi}{2}\Big)$$

$$\text{Toffoli} = \sigma_x E_+ E_+ + \mathbb{1} E_- E_- + \mathbb{1} E_+ E_- + \mathbb{1} E_- E_+$$

$\alpha|0\rangle + \beta|1\rangle$

$\mathcal{H} = DW(\sigma_z - \sigma$

CNOT

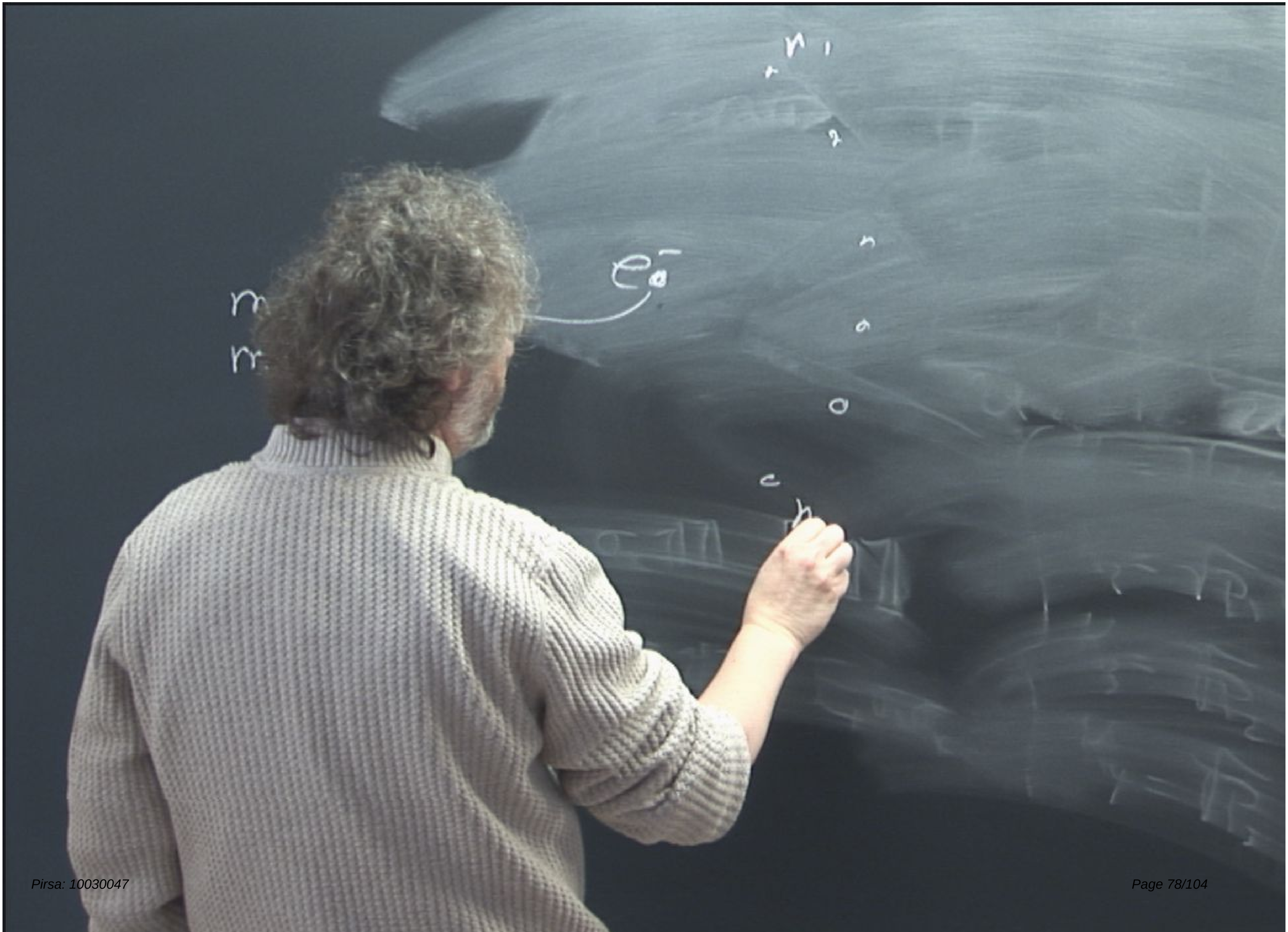
$\text{CNOT} = E_+ \mathbb{1}$

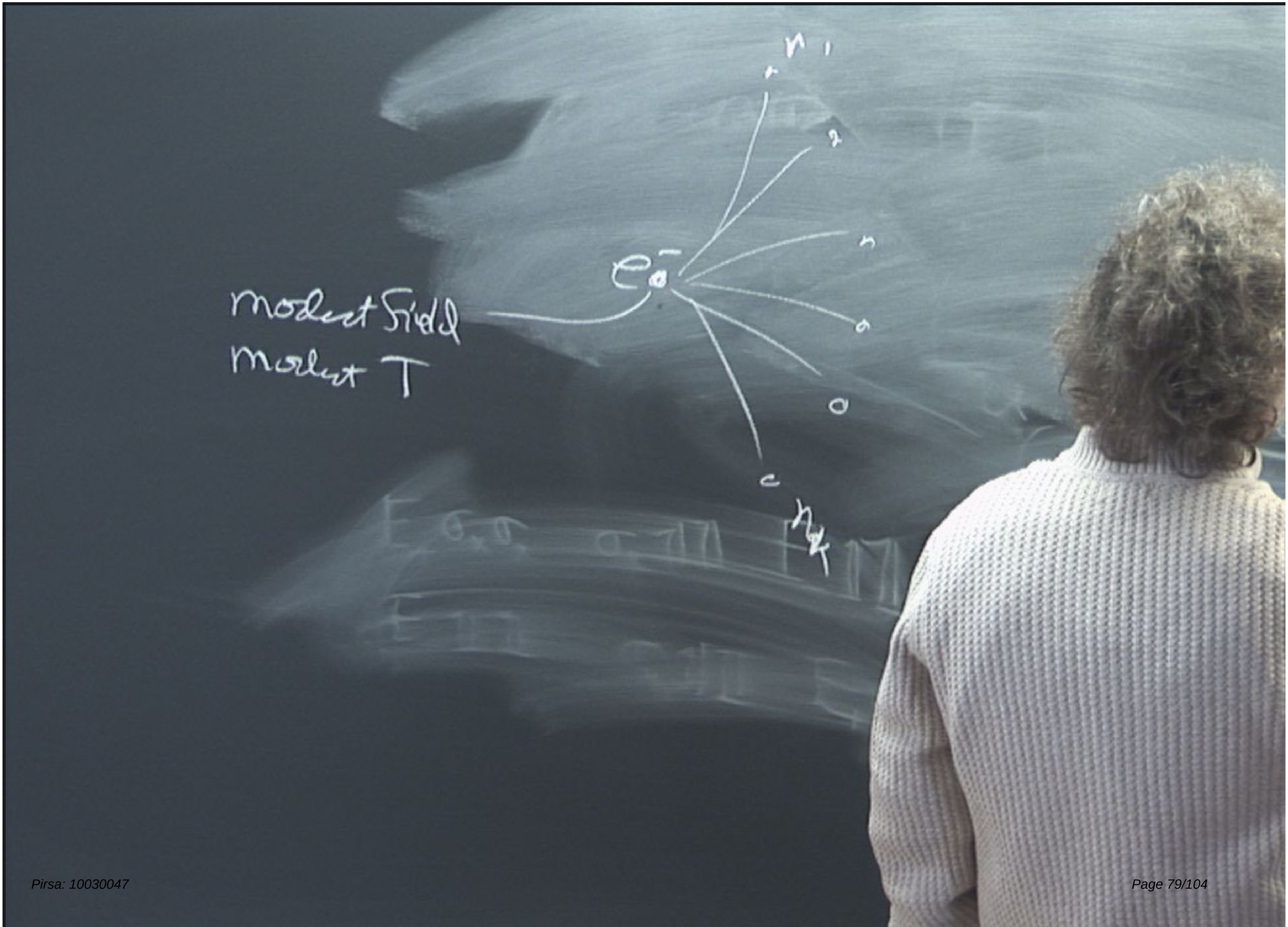
$(i\sigma_x^B E_-^A + E_+^A)($

$e^{-i\sigma_x^B E_+^A \pi/2}$

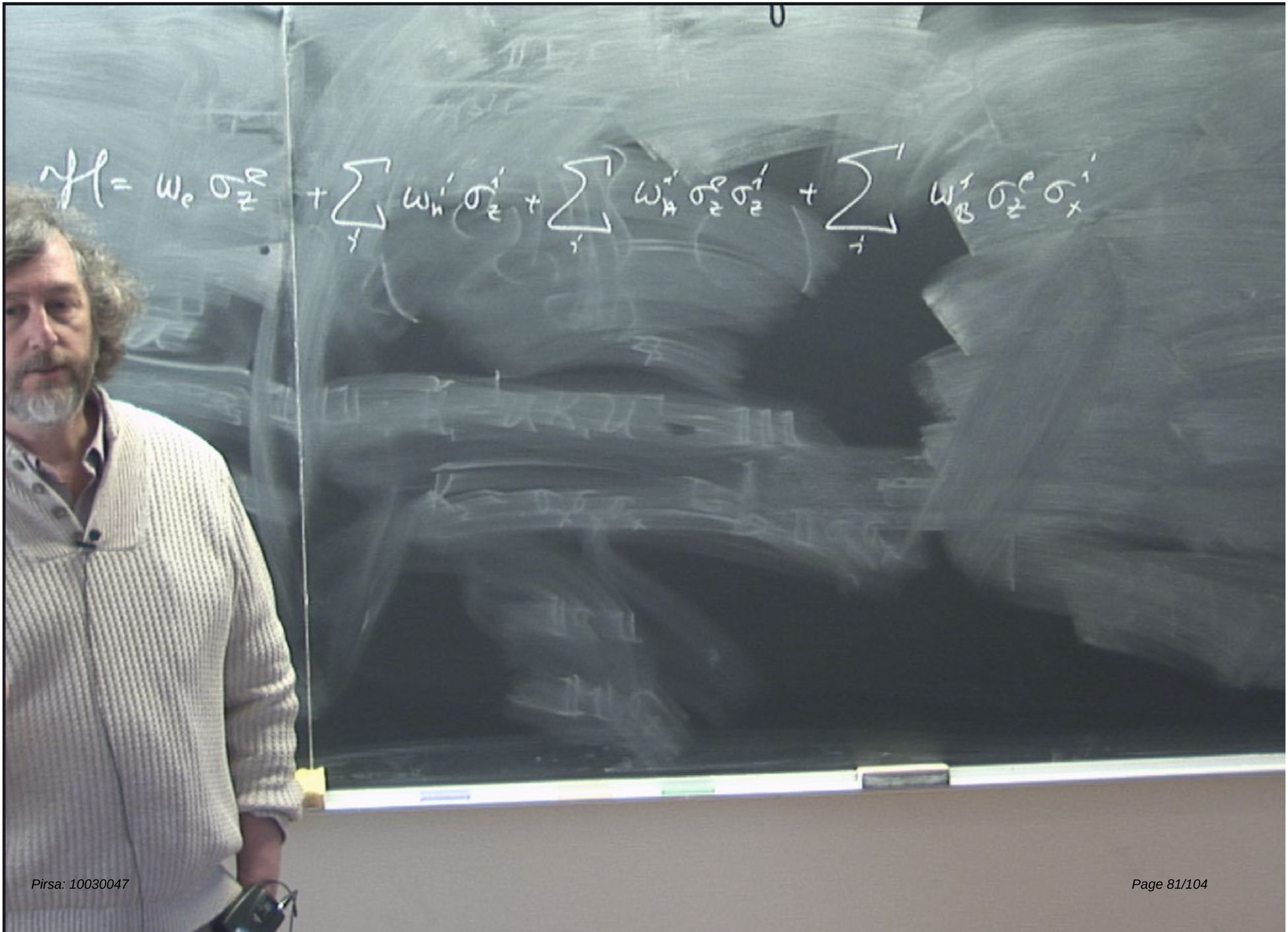
$e^{-i\pi/4} \; e^{-i\sigma_x^B \pi/4} \; e^{-i\sigma_z^A \pi/4} \; e$

$\frac{\pi}{2}_x \; \frac{\pi}{2} \Big| \frac{\pi}{2} \Big|_{-x}$




modest field
modest T

$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i$$



$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$

$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

$\omega_e \sigma_z^e$: ~10 GHz

ω_n^i: 10 MHz

ω_A^i, ω_B^i: 30 MHz

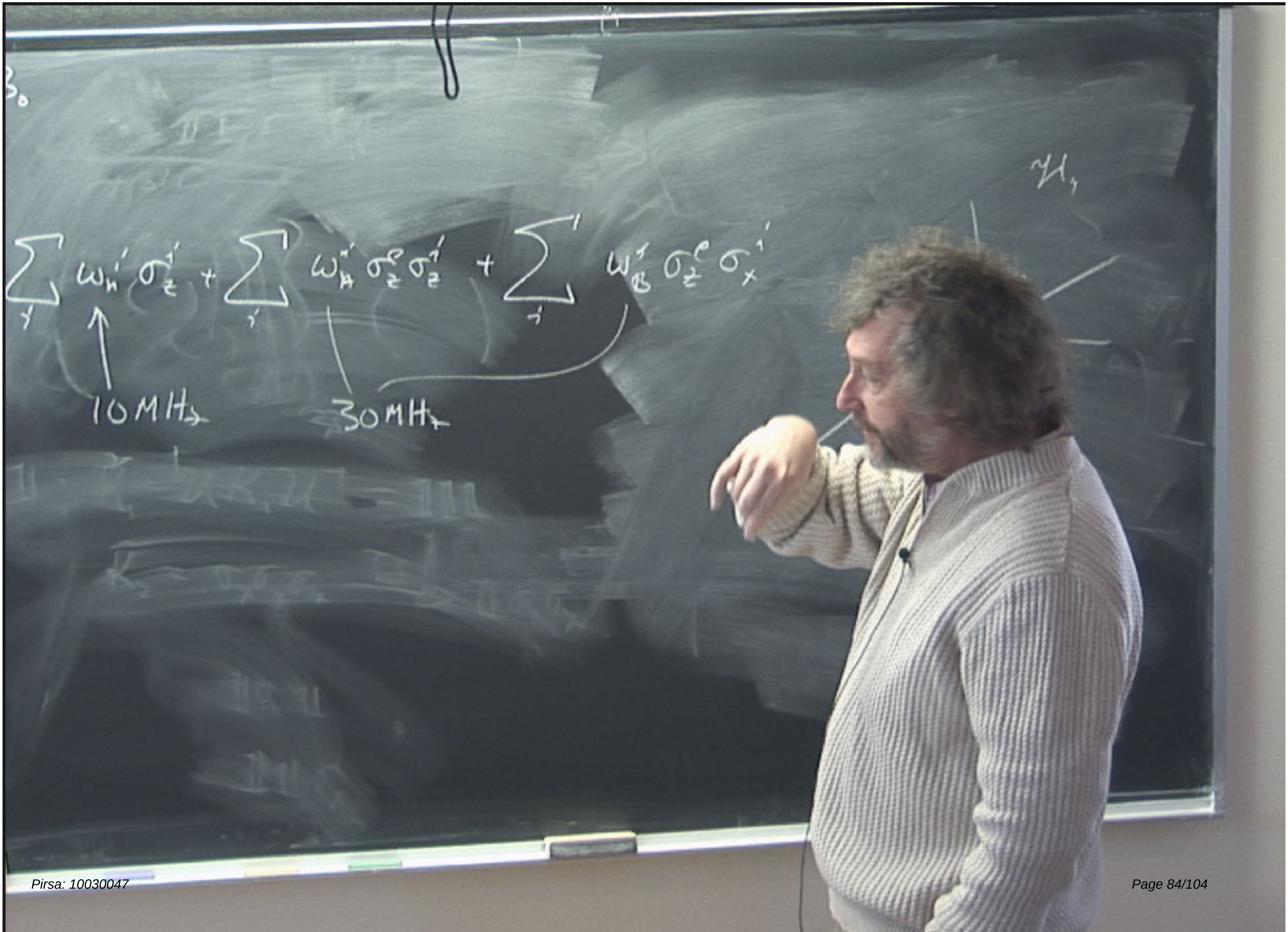
$\omega_e = \gamma_e B_0$

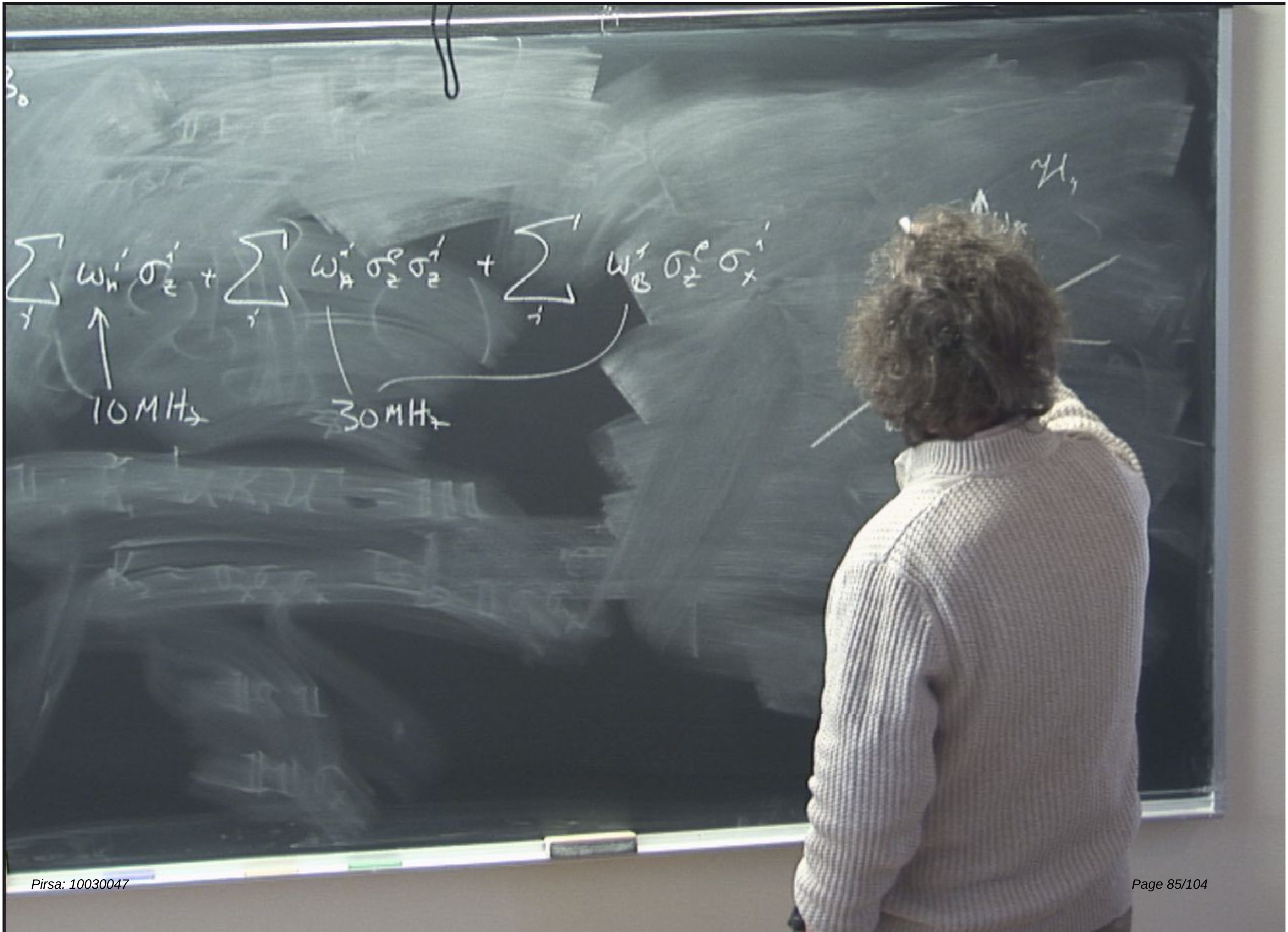
$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

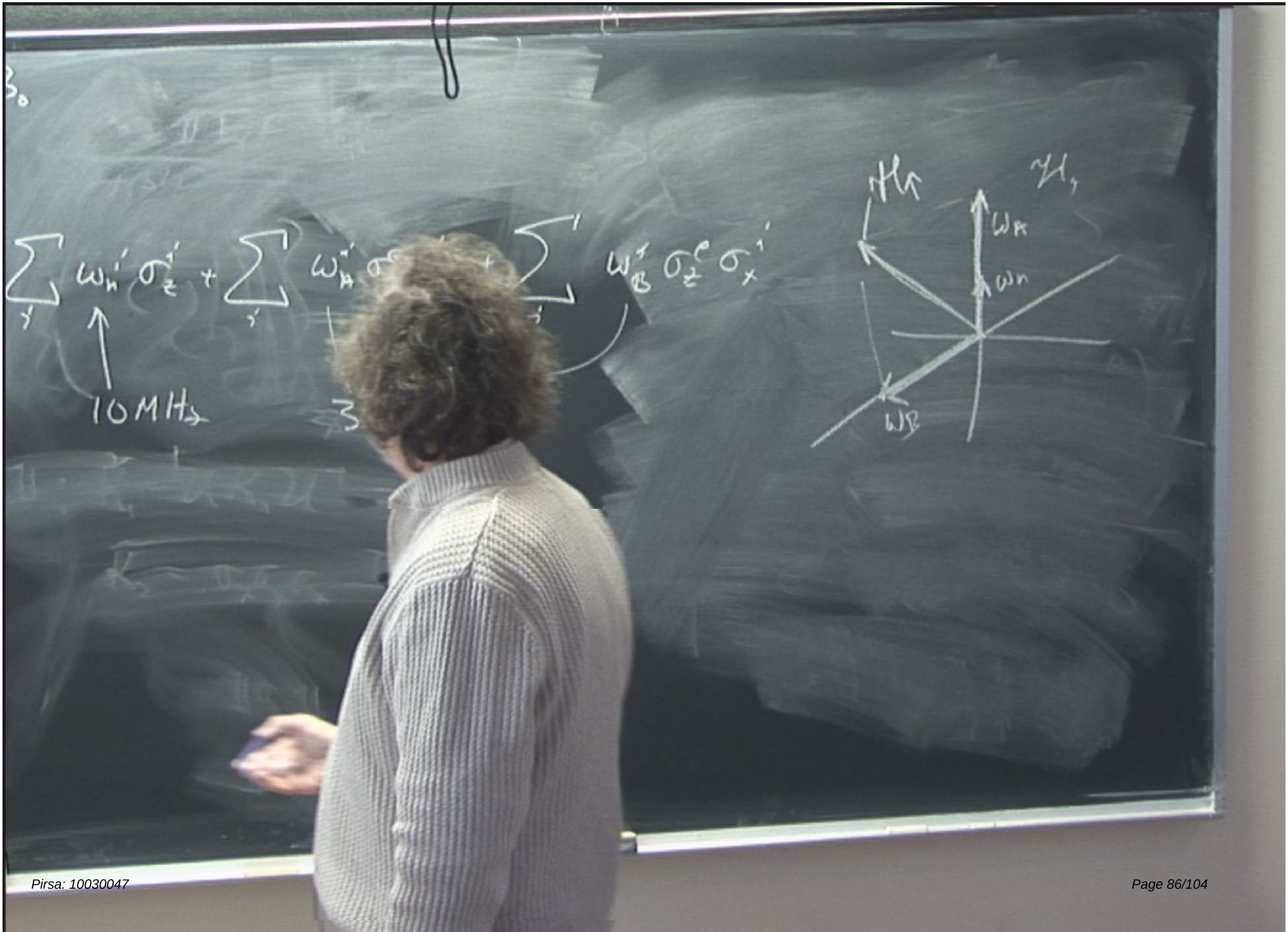
$\sim 10\,\text{GHz}$

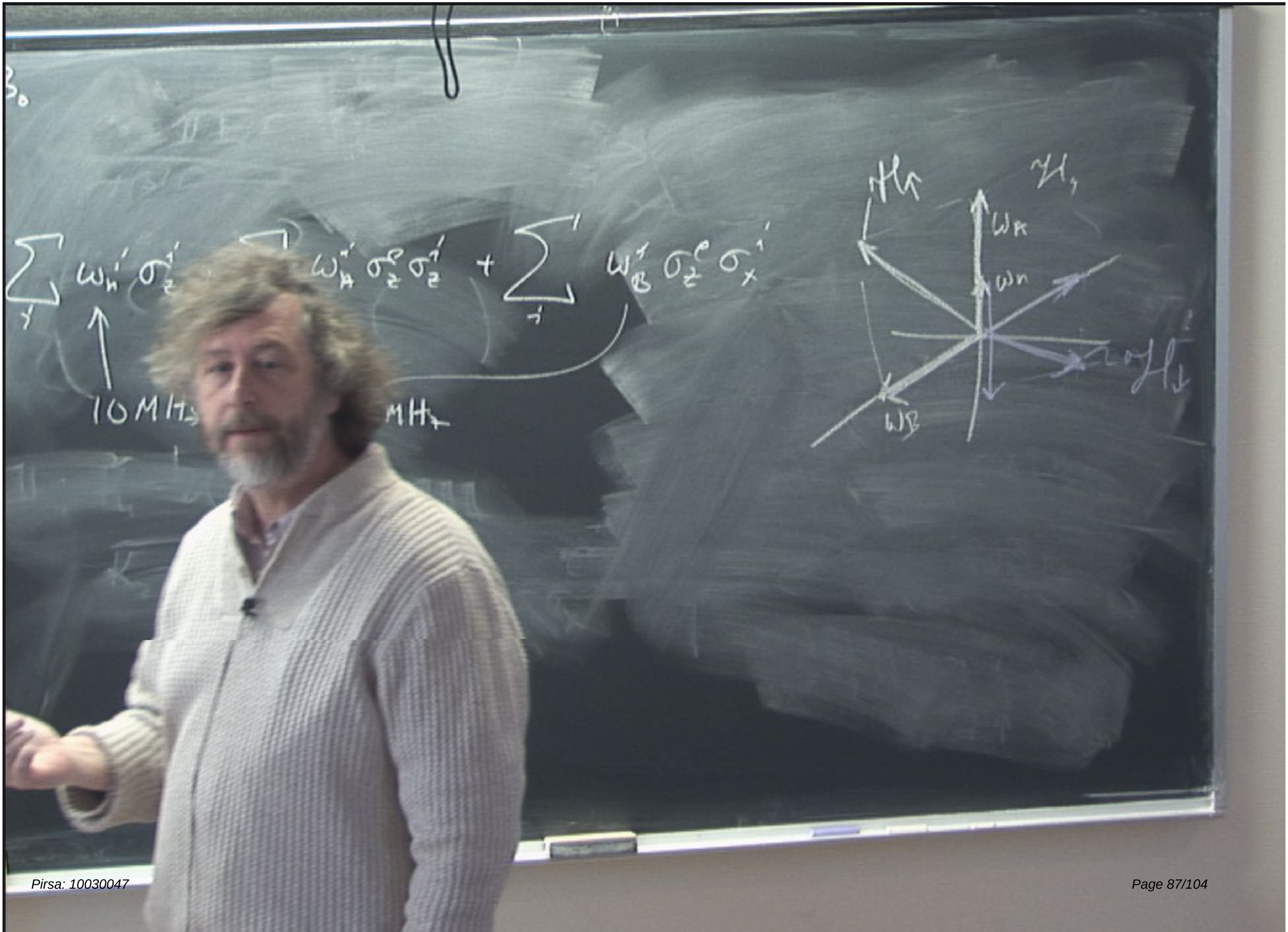
$10\,\text{MHz}$

$30\,\text{MHz}$


10MHz
30MHz


$\sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$
10 MHz
30 MHz


10 MHz

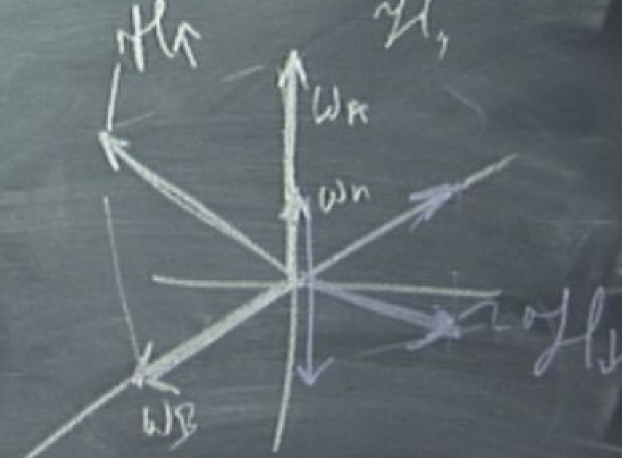


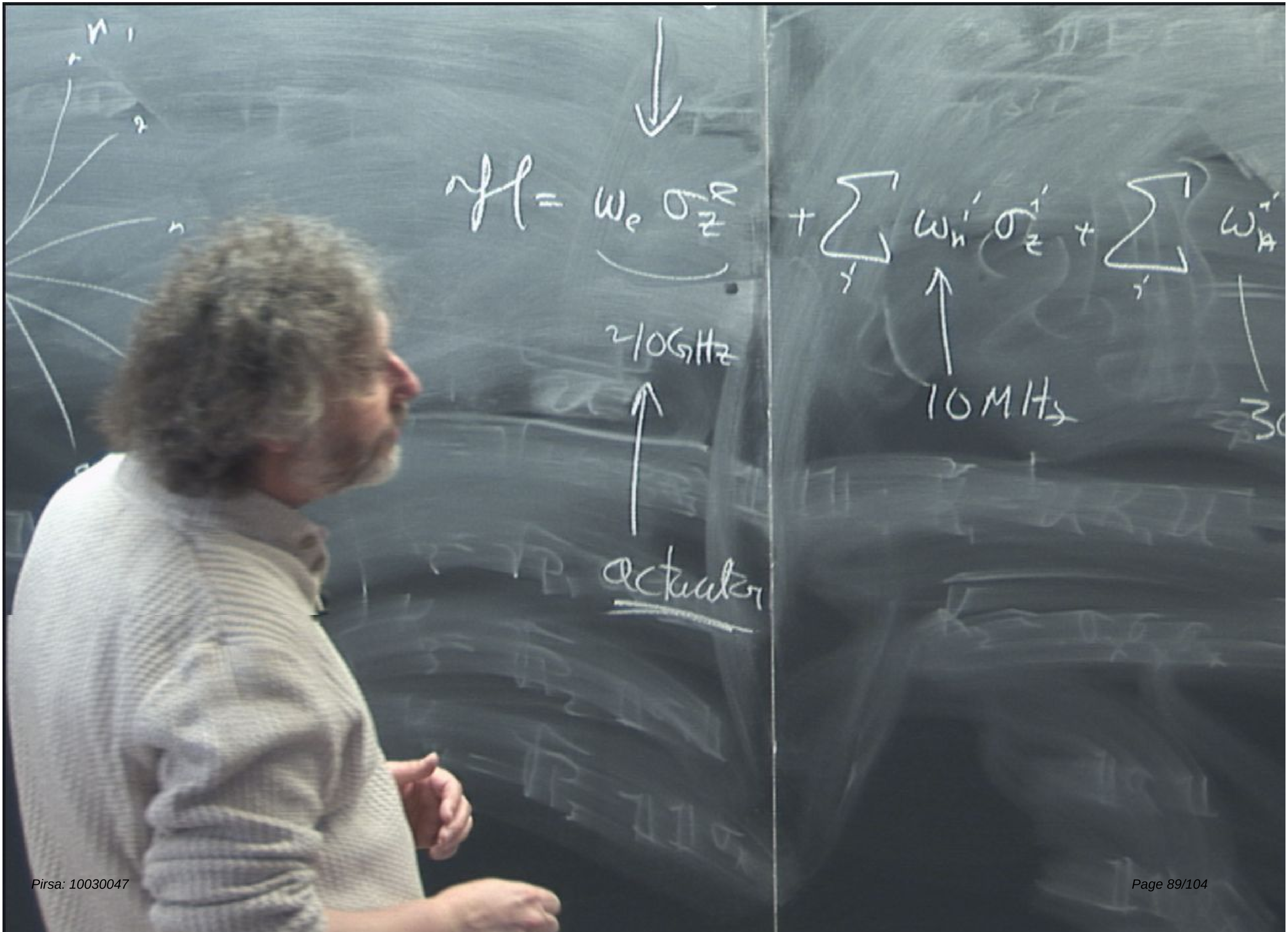
B_0

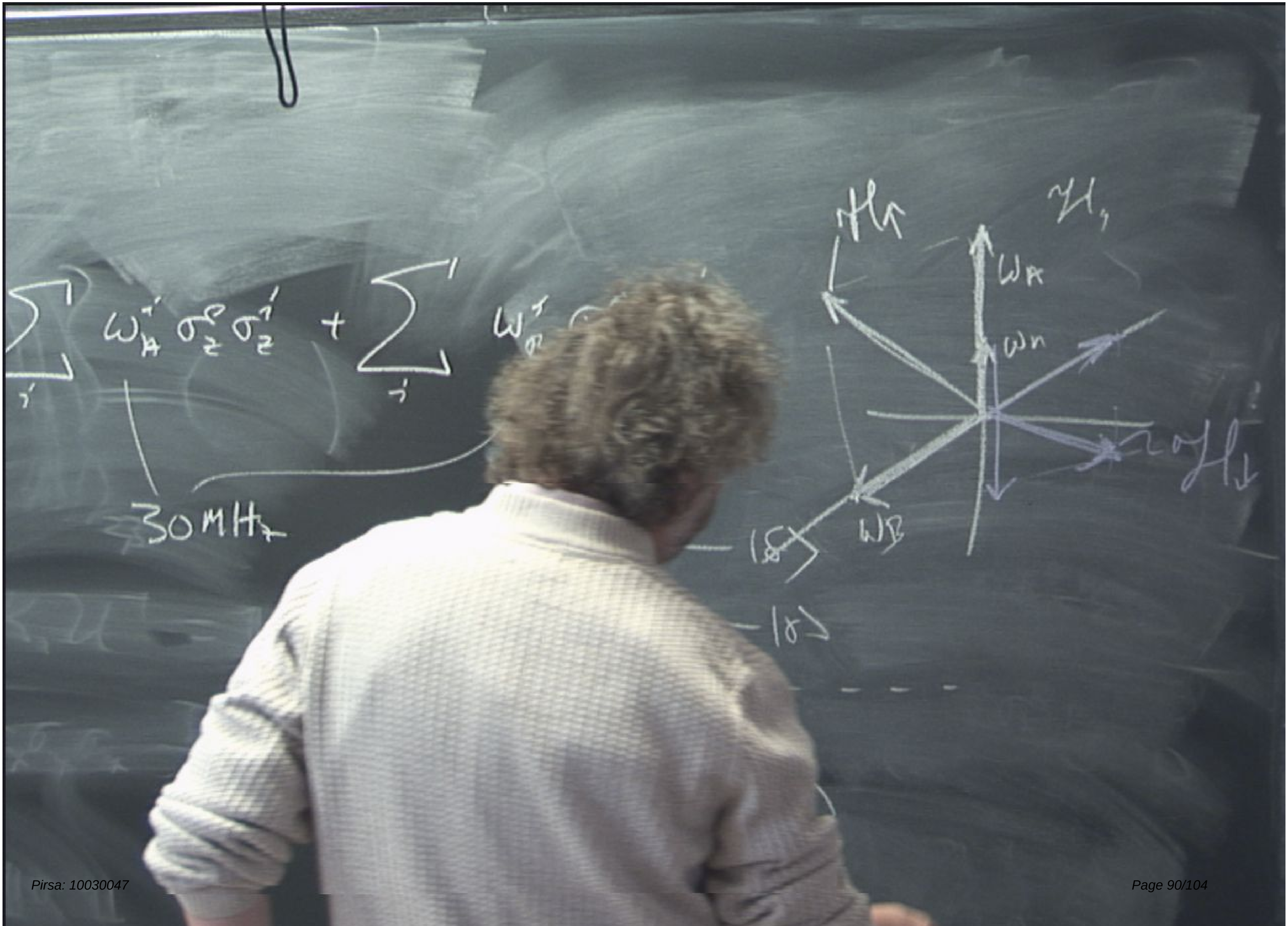
$$\sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

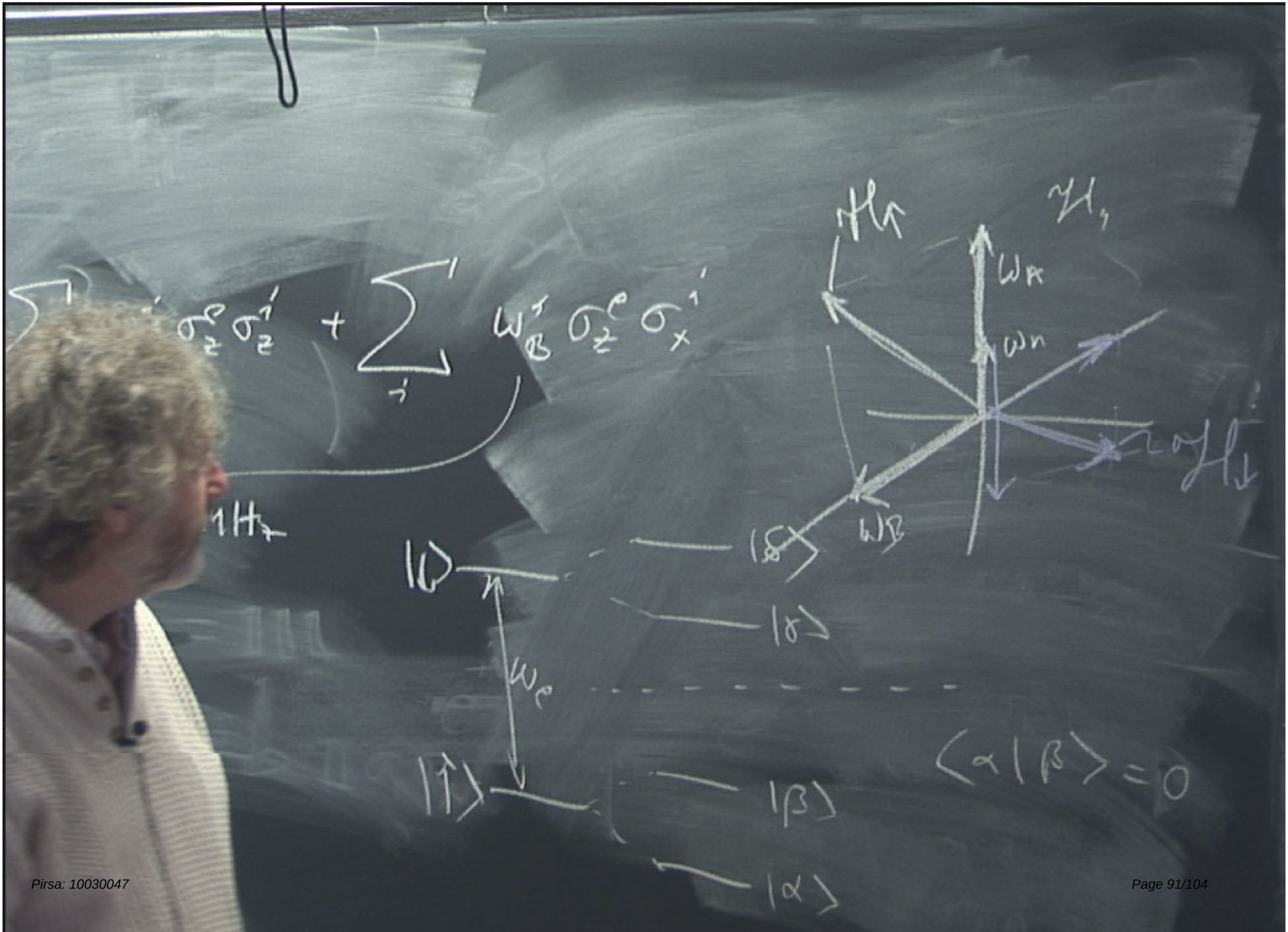
10 MHz

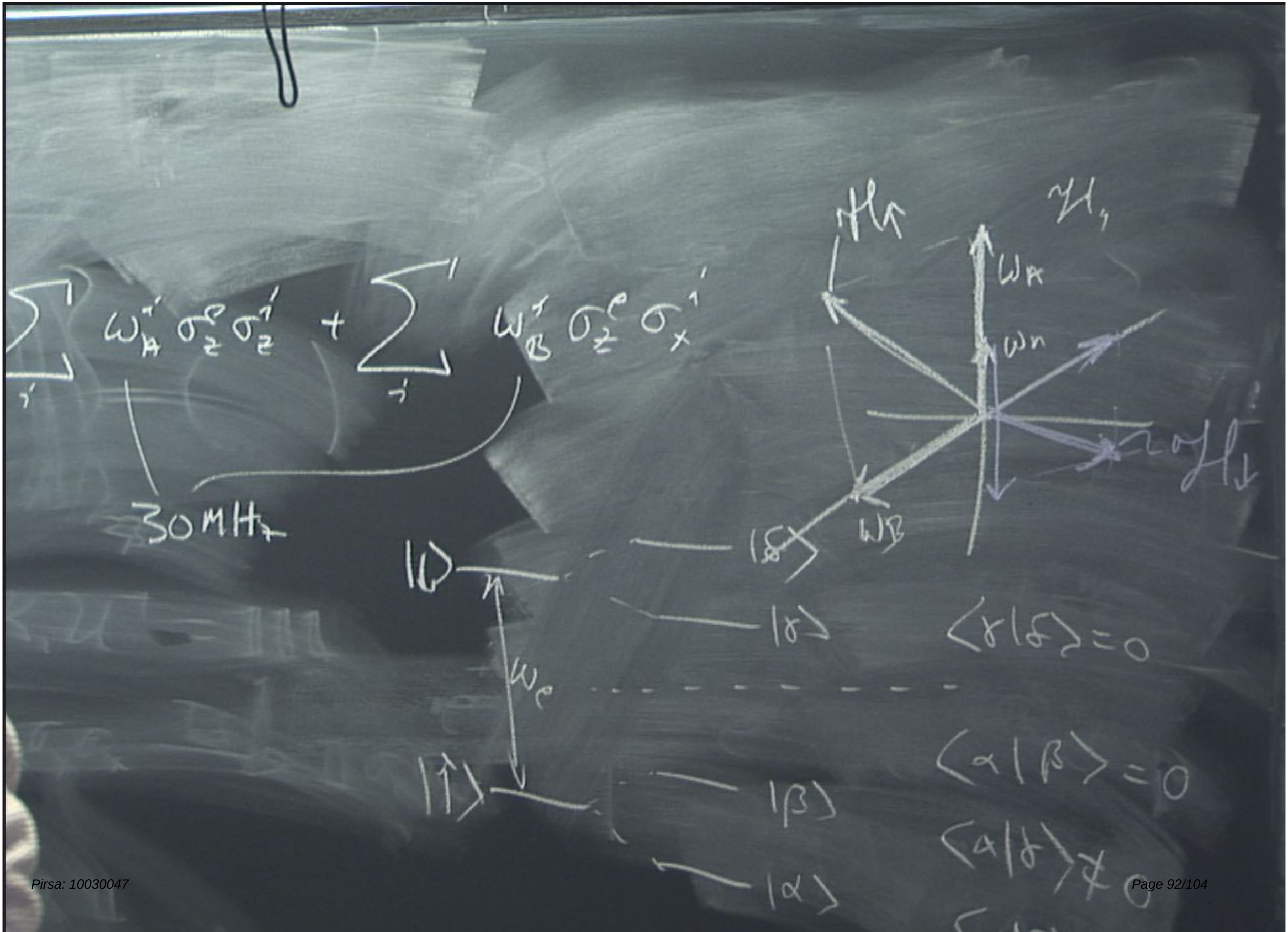
30 MHz



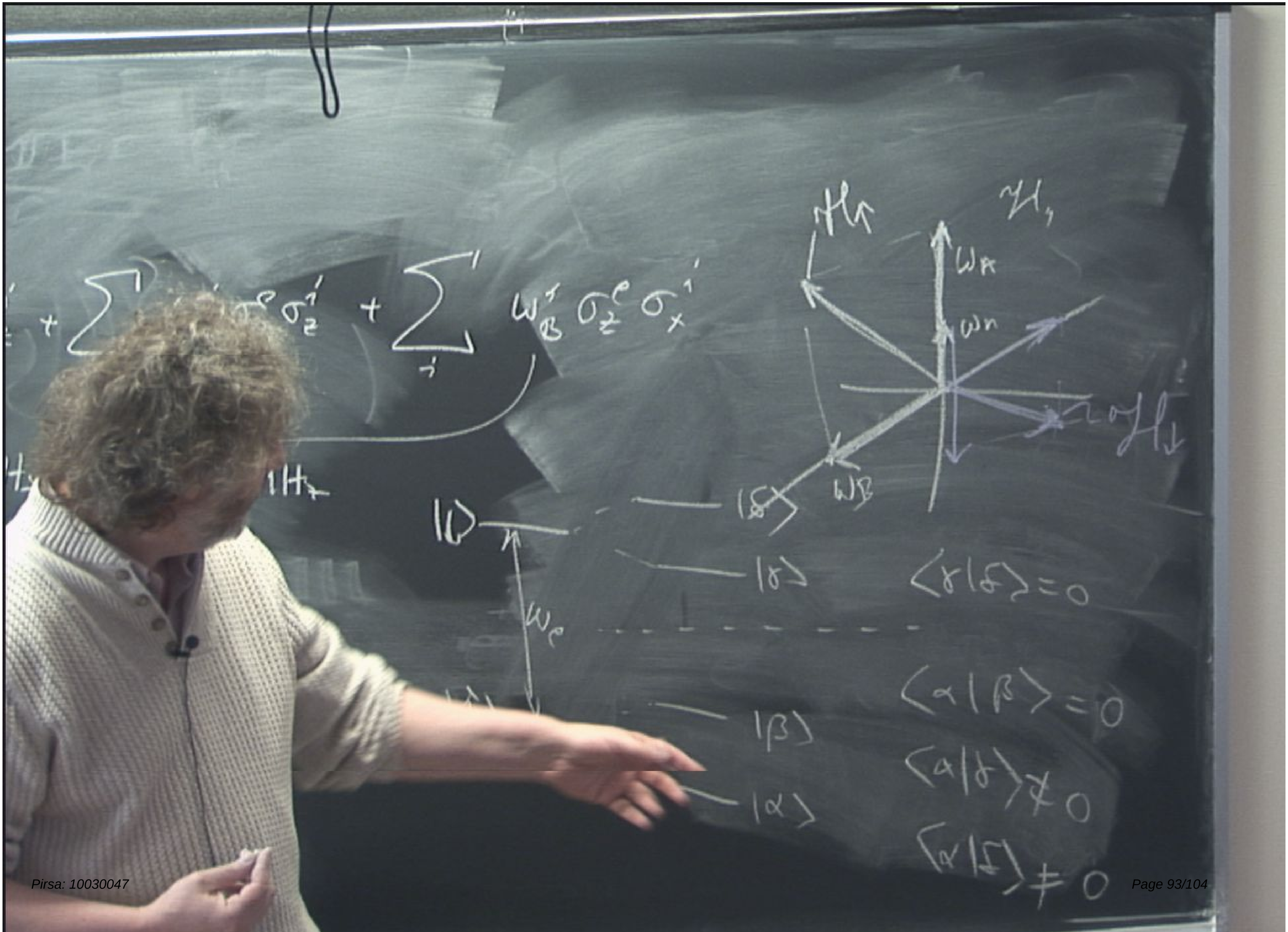

$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_H^i$
~10GHz
10 MHz
actuator

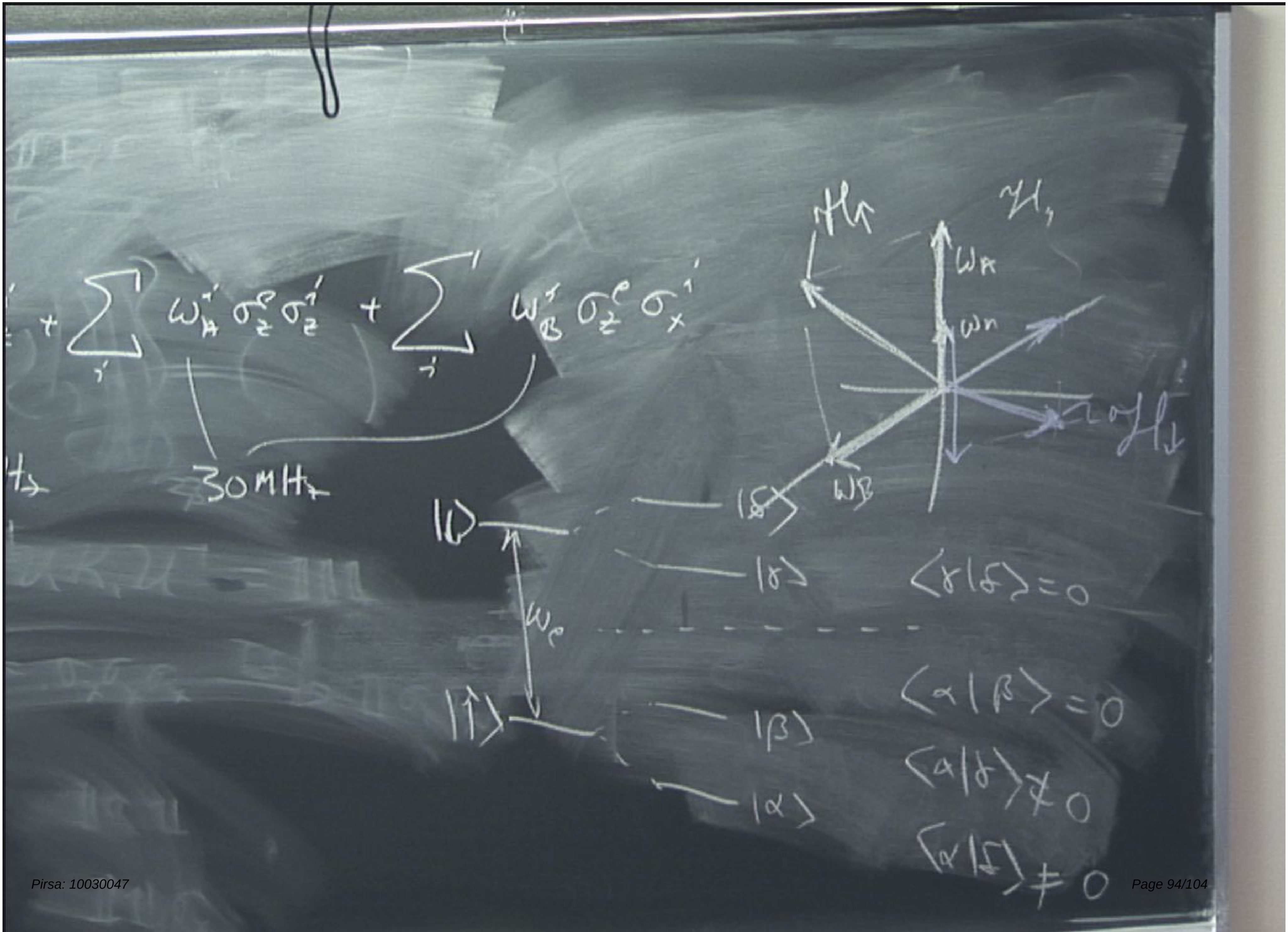

30MHz

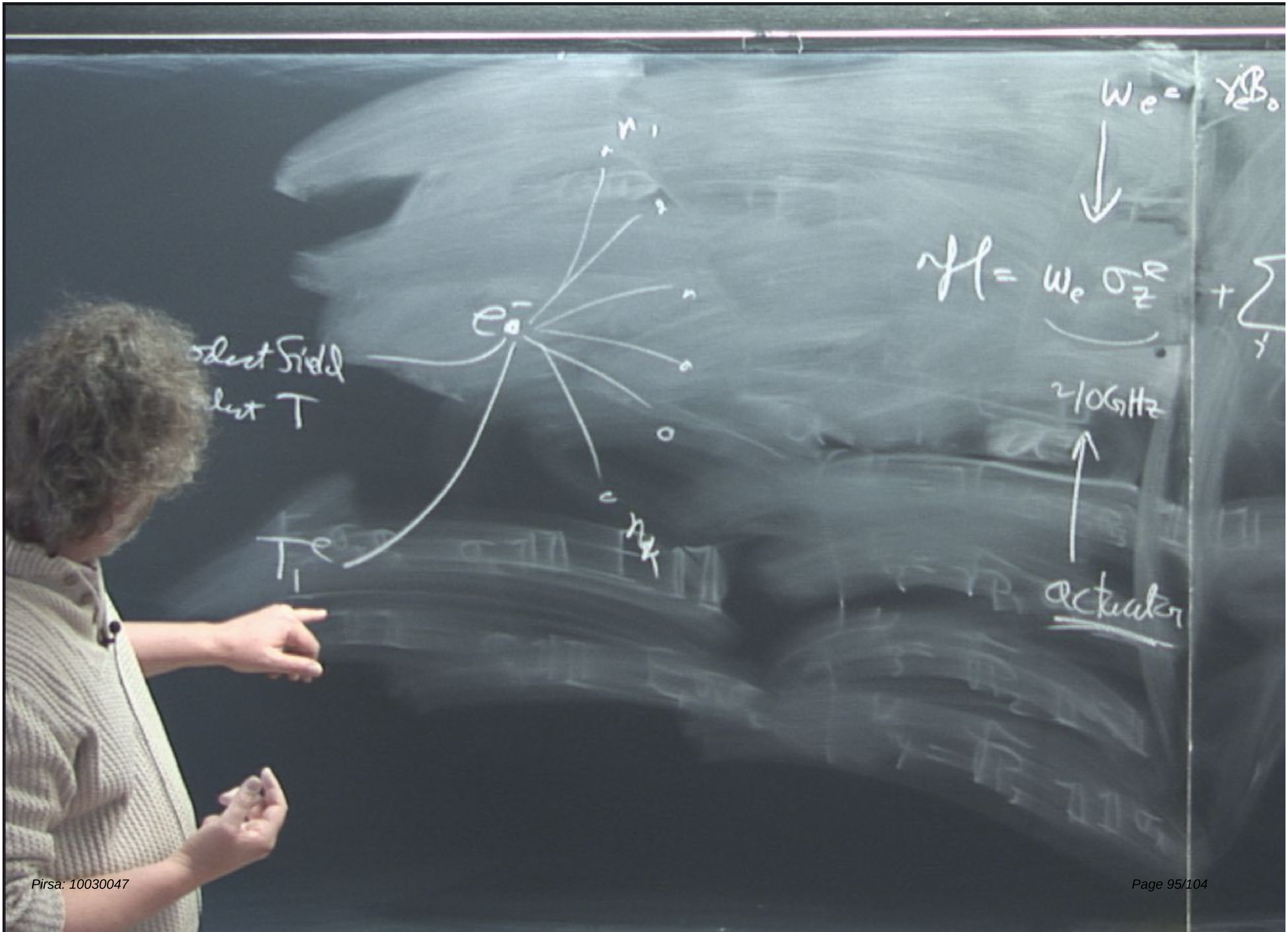

|β⟩
|γ⟩
|↑⟩
|β⟩
|α⟩
⟨α|β⟩=0



30 MHz
|↓⟩
|↑⟩
ω_e
|δ⟩
|γ⟩
|β⟩
|α⟩
⟨γ|δ⟩=0
⟨α|β⟩=0
⟨α|γ⟩≠0
ω_A
ω_n
ω_B


|δ⟩
|γ⟩
⟨γ|δ⟩=0
⟨α|β⟩=0
|β⟩
⟨α|γ⟩≠0
|α⟩
⟨α|δ⟩≠0


$+ \sum_j \omega_A^j \sigma_z^e \sigma_z^j + \sum_j \omega_B^j \sigma_z^e \sigma_x^j$
30 MHz
$\mathcal{H}_\uparrow$
ω_A
ω_n
ω_B
$\mathcal{H}_\downarrow$
$|\downarrow\rangle$
ω_e
$|\uparrow\rangle$
$|\delta\rangle$
$|\gamma\rangle$
$|\beta\rangle$
$|\alpha\rangle$
$\langle\gamma|\delta\rangle = 0$
$\langle\alpha|\beta\rangle = 0$
$\langle\alpha|\gamma\rangle \neq 0$
$\langle\alpha|\delta\rangle \neq 0$



$\omega_e = \gamma_e B_0$
$\mathcal{H} = \omega_e \sigma_z^e + \sum_j$
~10GHz
actuator
e^-
T_1

$\omega_e = \gamma_e B_0$

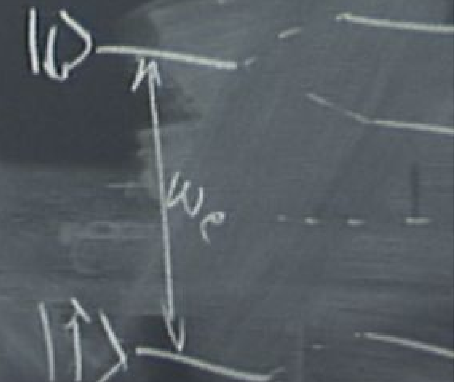
Y_2

$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

$\sim 10\,\mathrm{GHz}$ (actuator)

$10\,\mathrm{MHz}$

$30\,\mathrm{MHz}$



$$\omega_e = \gamma_e B_0$$

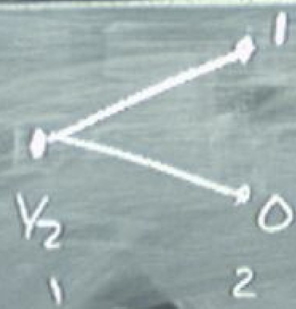
$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

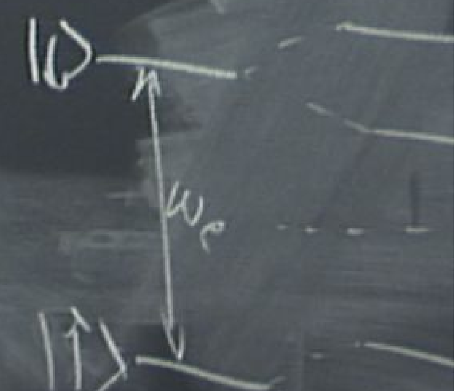
~10 GHz

actuator

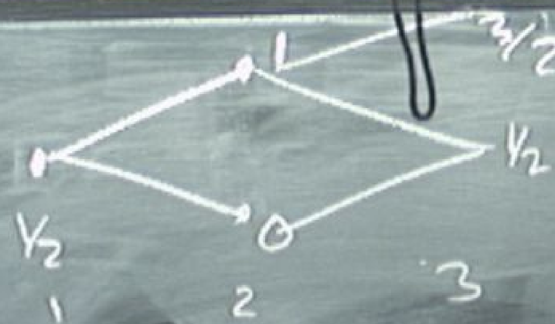
10 MHz

30 MHz





$\omega_e = \gamma_e B_0$



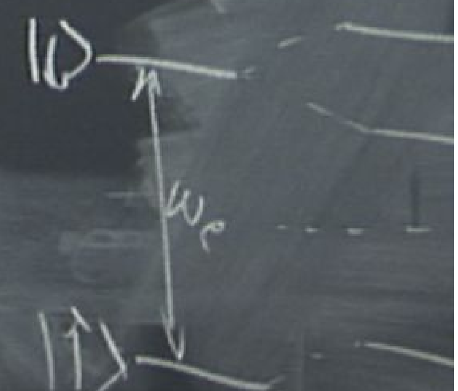
$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

~10 GHz

10 MHz

30 MHz

actuator



$\omega_e = \gamma_e B_0$

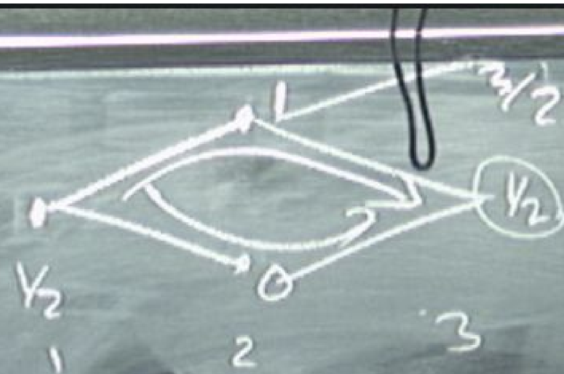
$$\mathcal{H} = \omega_e \sigma_z^e + \sum_i \omega_n^i \sigma_z^i + \sum_i \omega_A^i \sigma_z^e \sigma_z^i + \sum_i \omega_B^i \sigma_z^e \sigma_x^i$$

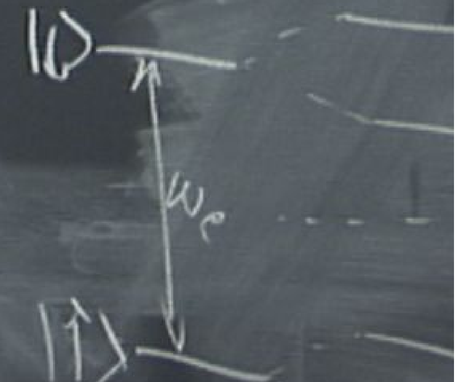
~10 GHz

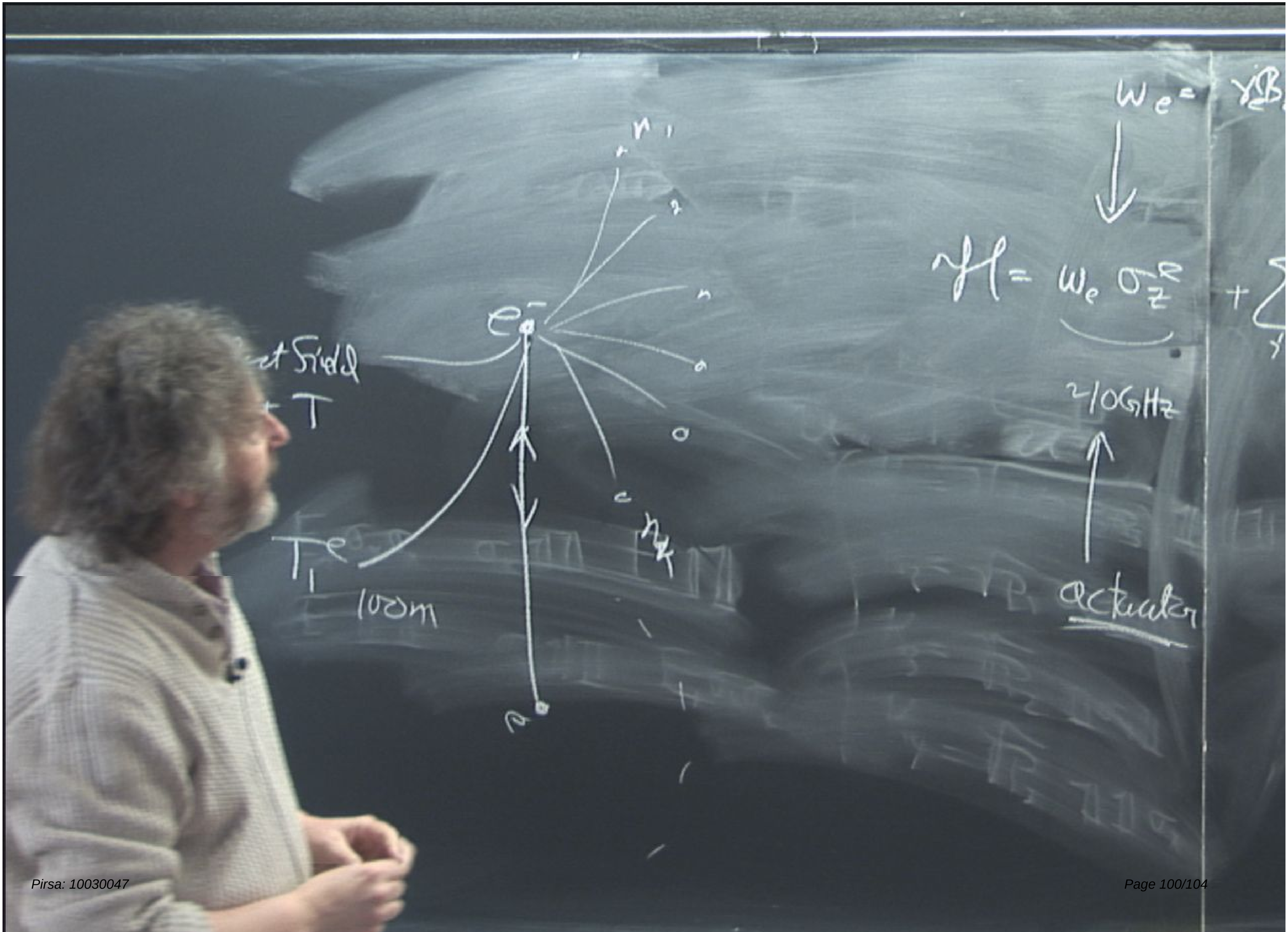
actuator

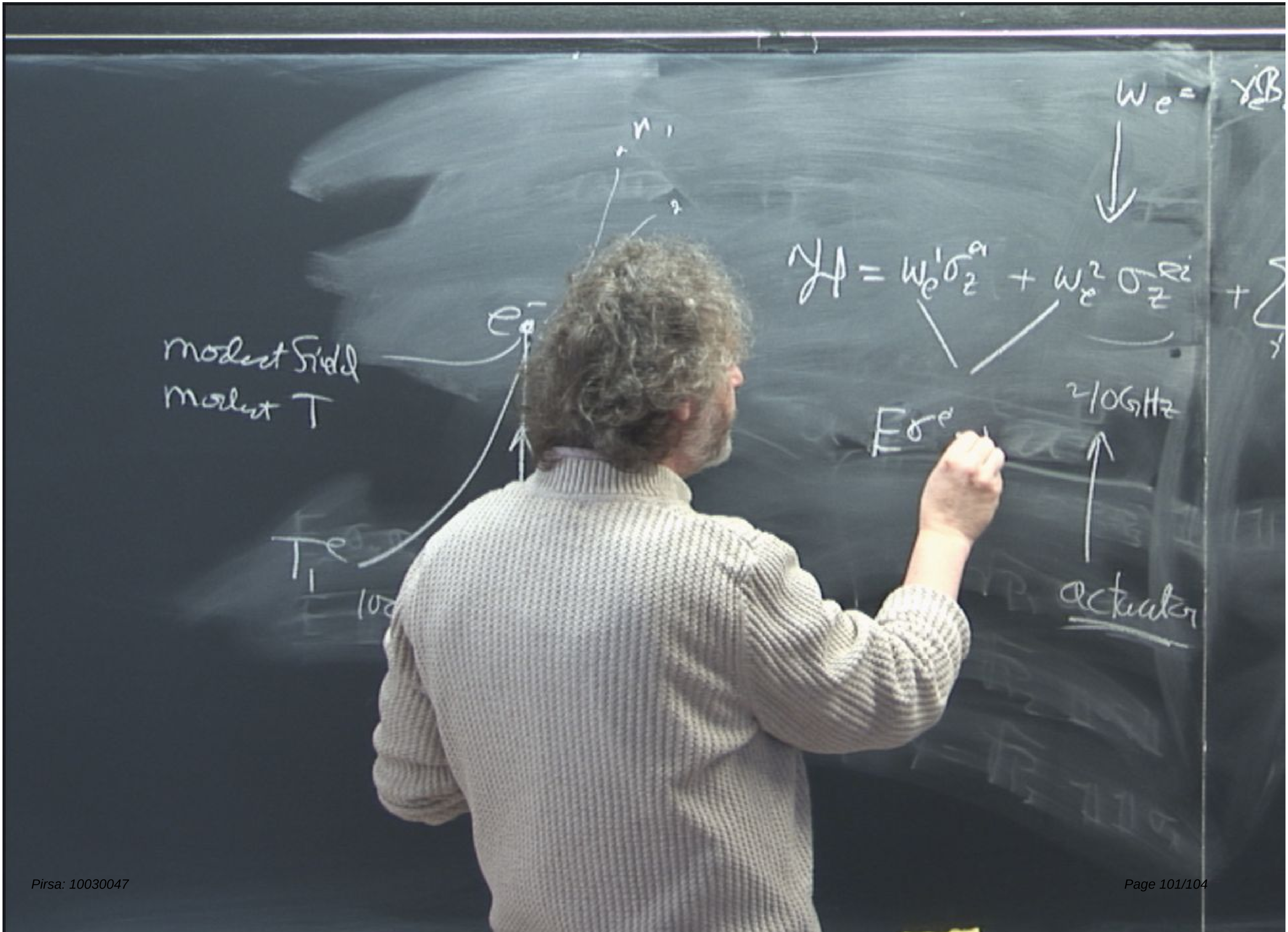
10 MHz

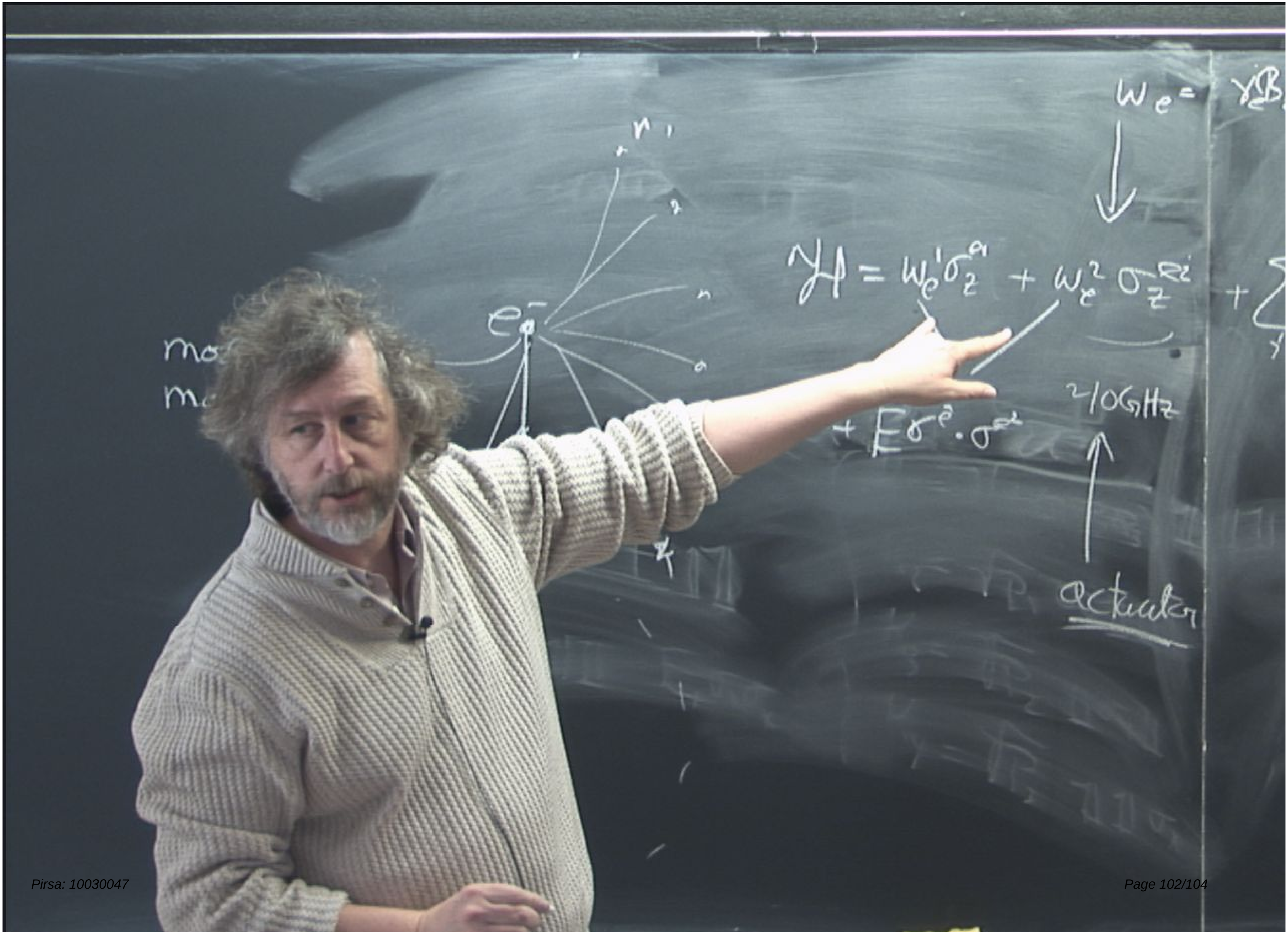
30 MHz

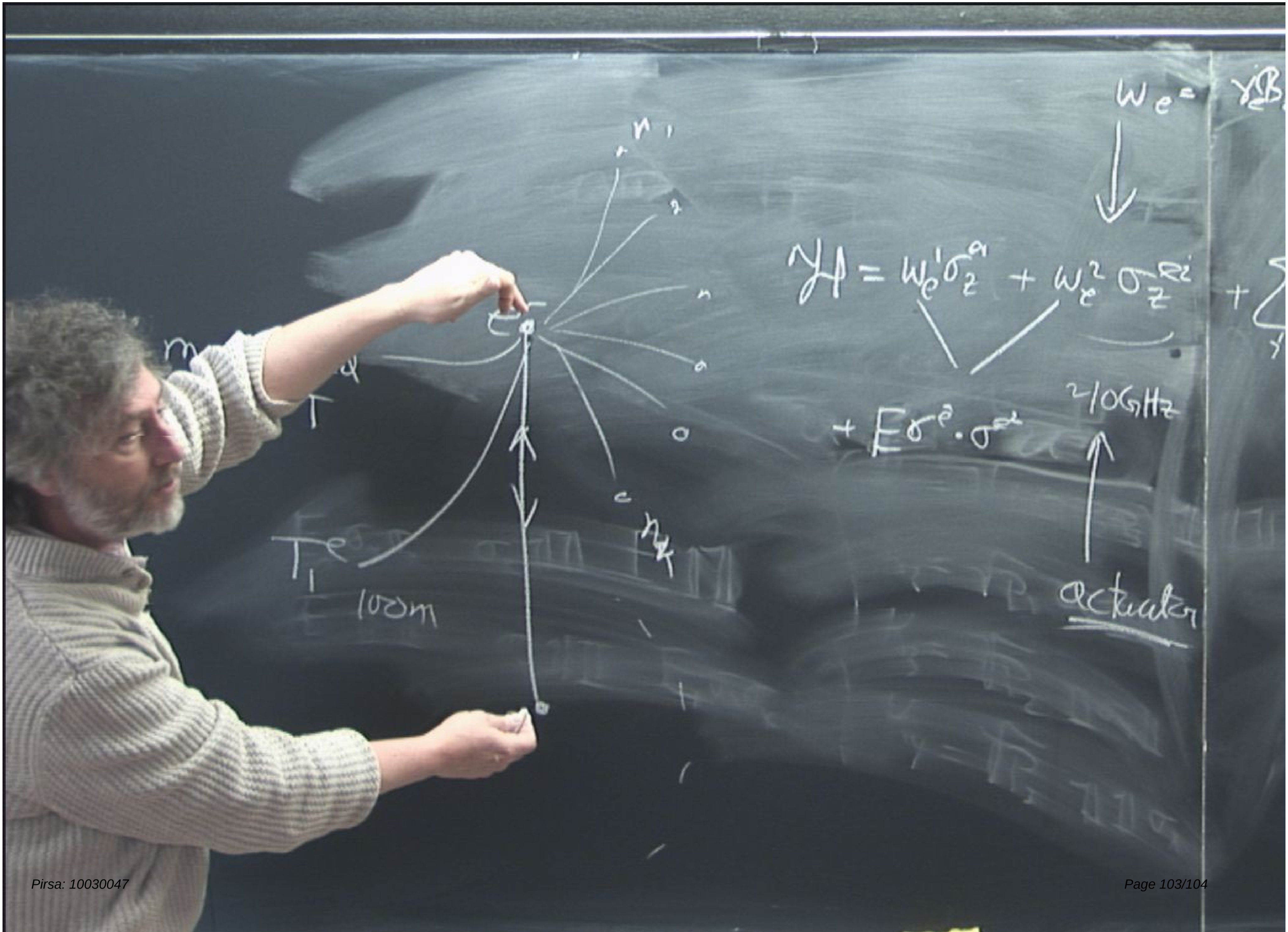


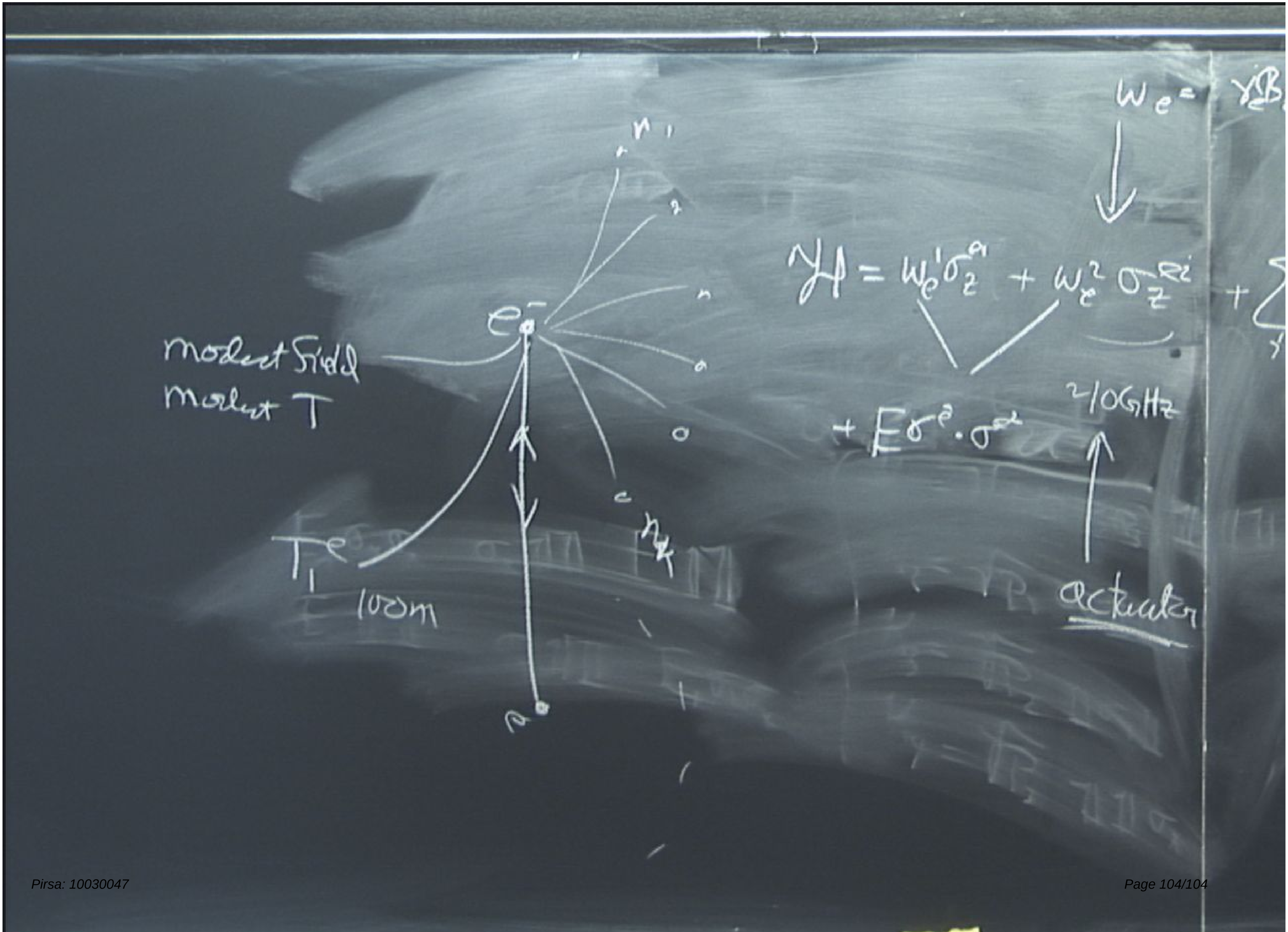



e⁻
T₁
100m
~10GHz
actuator


modest field
modest T
e^-
T_1^e
$\omega_e = \gamma_e B$
$\mathcal{H} = \omega_e^1 \sigma_z^{a} + \omega_e^2 \sigma_z^{e2} + \Sigma$
~10 GHz
actuator







modest field
modest T
T1
100m
e-
ωe = γeB
~10GHz
actuator