Title: Challenges for a quantum theory of the universe

Date: Jul 18, 2009 02:30 PM

URL: http://pirsa.org/09070034

Abstract: I review three challenges faced by attempts to develop a quantum theory of the universe and examine possible relationships between them. 1) The clock ambiguity: The choice of time parameter leads to profound ambiguities. 2) The choice of state: I contrast the de Sitter equilibrium picture with eternal inflation. 3) The Born rule crisis: The born rule is insufficient to construct probabilities in a large multiverse without additional rules or assumptions (as discussed by Don Page).

1) Clock Ambiguity AA, AA Iglesias

2) Born Rule Crisis (Page)

$$H|\psi\rangle_S = 0$$

$$S = C \otimes R$$

$$|\psi\rangle_S = \sum_{ij} \alpha_{ij} |t_i\rangle_C |j\rangle_R$$

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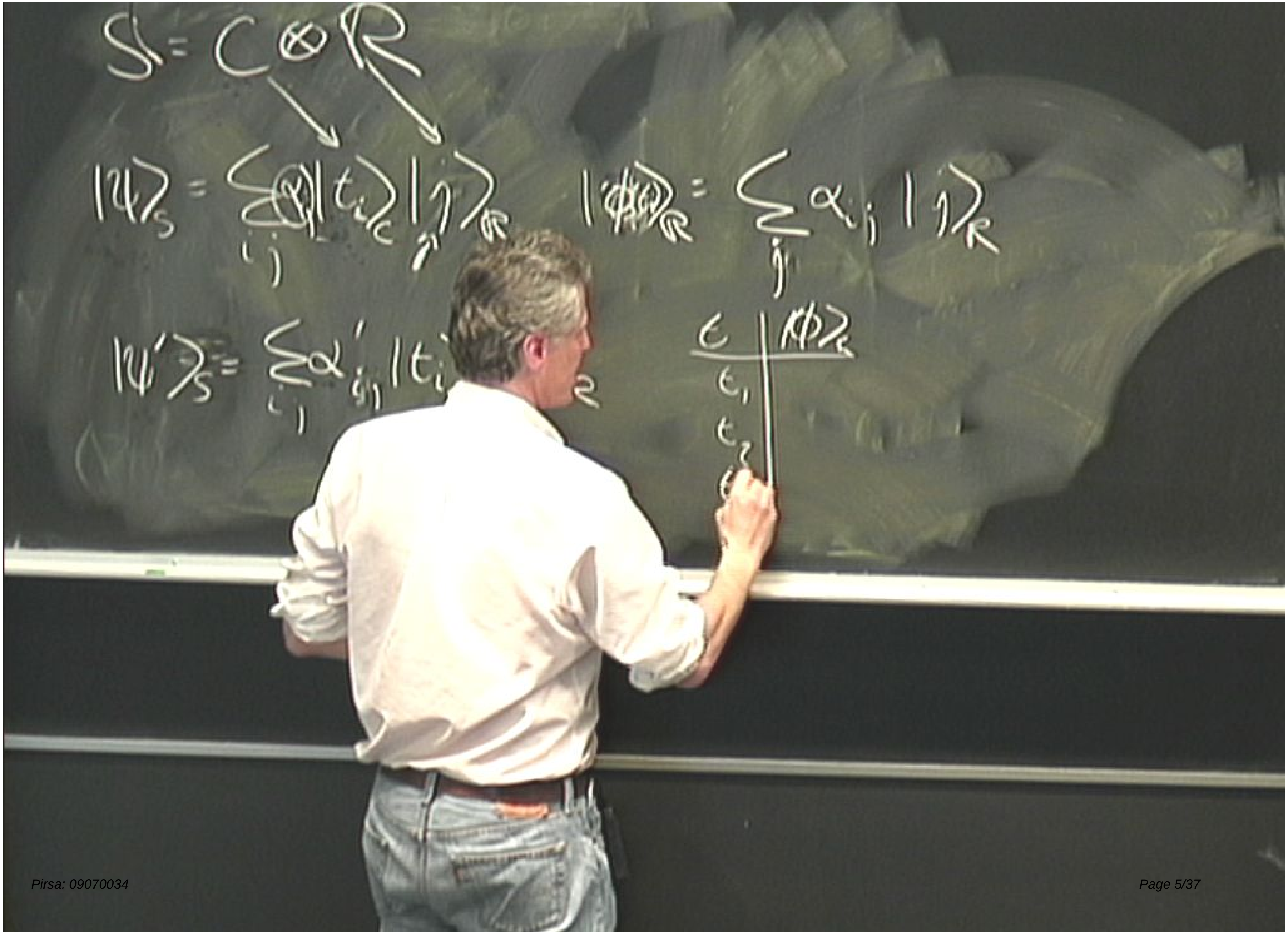
S = C ⊗ R
|φ⟩_R = Σ_j α_ij |j⟩_R
C | |φ⟩_R
t_1
t_2

$$S = C \otimes R$$

$$|\psi\rangle_S = \sum_{i,j} \alpha_{i,j} |t_i\rangle_C |j\rangle_R \qquad |\phi_{t_i}\rangle_R = \sum_j \alpha_{i,j} |j\rangle_R$$

$$|\psi'\rangle_S = \sum_{i,j} \alpha'_{i,j} |t_i\rangle_C |j\rangle_R$$

t	$\vert\phi\rangle_R$
t_1	$\phi(t_1)$
t_2	$\vdots$
t_3	$\vdots$

$$M|\psi'\rangle_s = |\psi\rangle_s$$

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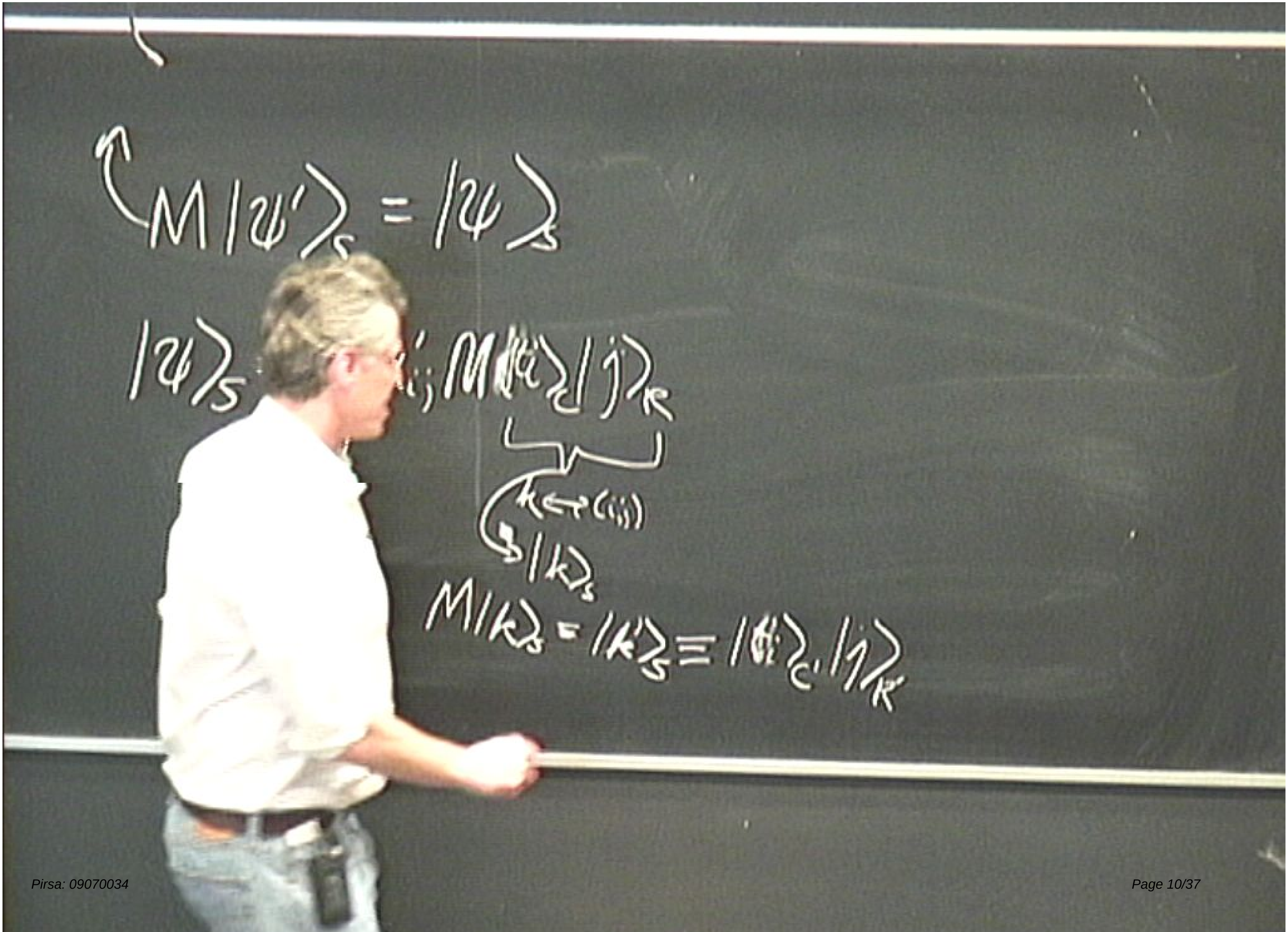
$$|\psi\rangle_S = \sum_{ij} \alpha'_{ij} M |i\rangle_S |j\rangle_R$$

$$M|\psi'\rangle_S = |\psi\rangle_S$$

$$|\psi\rangle_S = \sum_{i,j} \alpha'_{ij} M \underbrace{|i\rangle_S |j\rangle_R}_{k \leftrightarrow (i,j)}$$

$$|k\rangle_S$$

$$M|k\rangle_S = |k'\rangle_S$$


$M|\psi'\rangle_S = |\psi\rangle_S$
$|\psi\rangle_S$ ... $M|i\rangle_C|j\rangle_R$
$k \leftrightarrow (i,j)$
$\sum|k\rangle_S$
$M|k\rangle_S = |k'\rangle_S \equiv |i\rangle_C|j\rangle_R$

$$M|\psi'\rangle_S = |\psi\rangle_S$$

$$|\psi\rangle_S = \sum_{i,j} \alpha'_{ij} M \underbrace{|t_i\rangle_{c'} |j\rangle_{R}}_{\substack{k \leftrightarrow (i,j) \\ |k\rangle_S}} = \sum_{i,j} \alpha'_{ij} |t_i\rangle_{c'} |j\rangle_{R'}$$

defines $S = C' \otimes R'$

$$M|k\rangle_S = |k'\rangle_S \equiv |t_i\rangle_{c'} |j\rangle_{R'}$$

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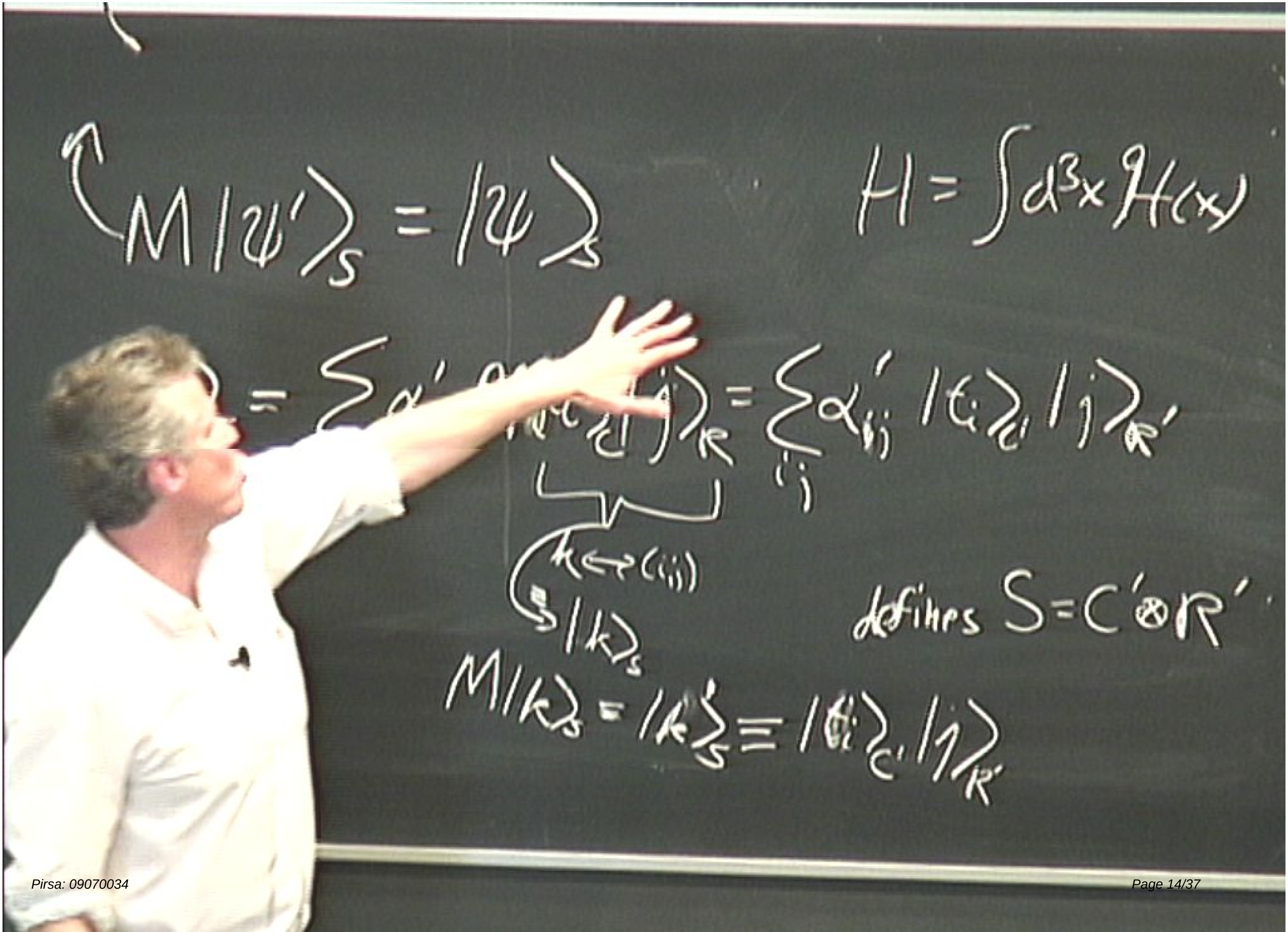
$M|\psi'\rangle_S = |\psi\rangle_S$
$H = \int d^3x\, \mathcal{H}(x)$
$= \sum_{ij} \alpha'_{ij}\, |t_i\rangle_{C'}\, |j\rangle_{R'}$
$k \leftrightarrow (i,j)$
$|k\rangle_S$
defines $S = C' \otimes R'$
$M|k\rangle_S = |k'\rangle_S \equiv |t_i\rangle_{C'}\, |j\rangle_{R'}$

$$M|\psi'\rangle_S = |\psi\rangle_S$$

$$H = \int d^3x\, \mathcal{H}(x)$$

$$|\psi\rangle_S = \sum_{ij} \alpha'_{ij}\, \underbrace{M|t_i\rangle_C |j\rangle_R}_{k \leftrightarrow (i,j)} = \sum_{ij} \alpha'_{ij}\, |t_i\rangle_{C'} |j\rangle_{R'}$$

$$|k\rangle_S$$

defines $S = C' \otimes R'$

$$M|k\rangle_S = |k'\rangle_S \equiv |t_i\rangle_{C'} |j\rangle_{R'}$$

$$M|\psi'\rangle_S = |\psi\rangle_S$$

$$H = \int d^3x\, \mathcal{H}(x)$$

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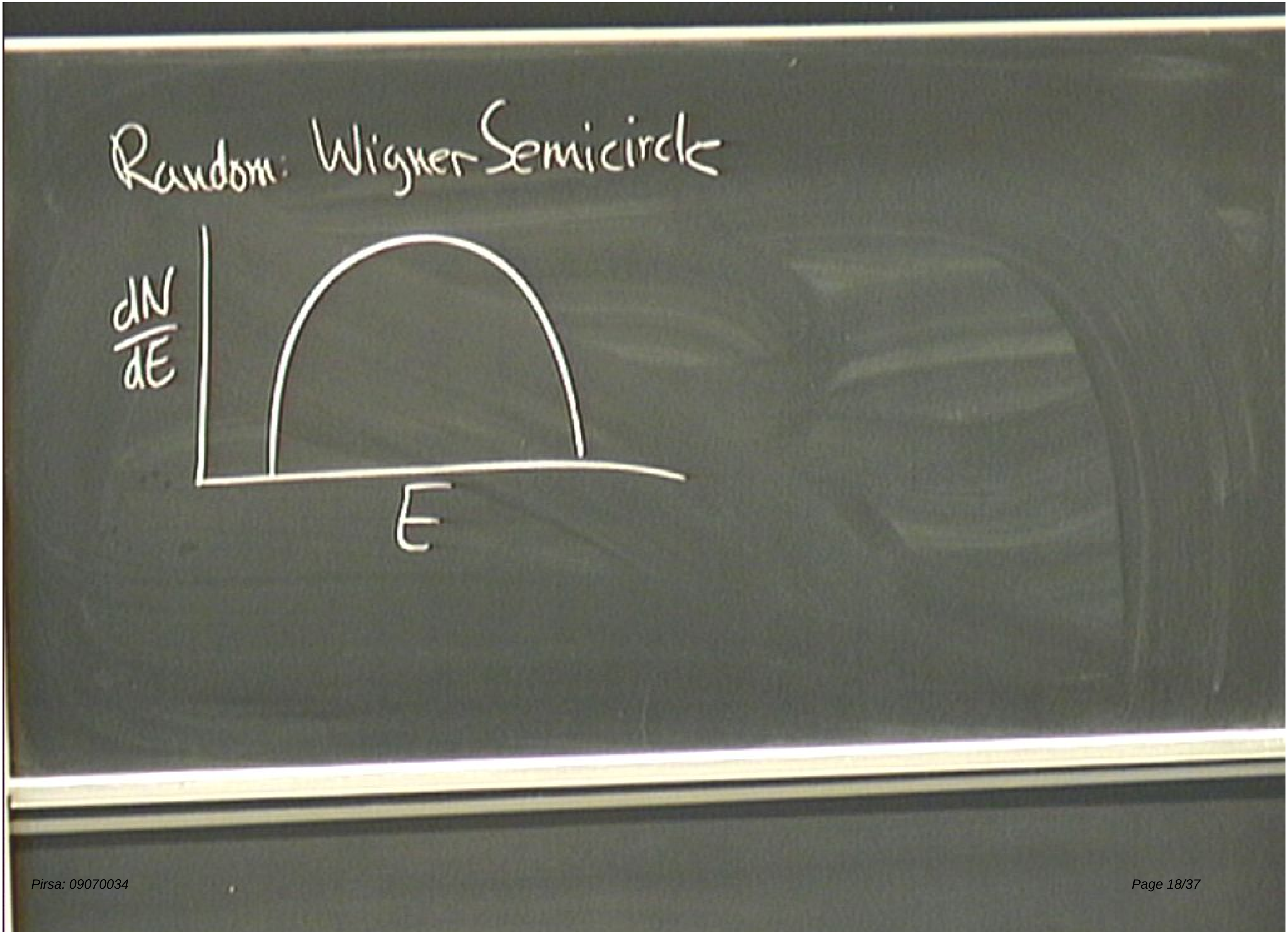
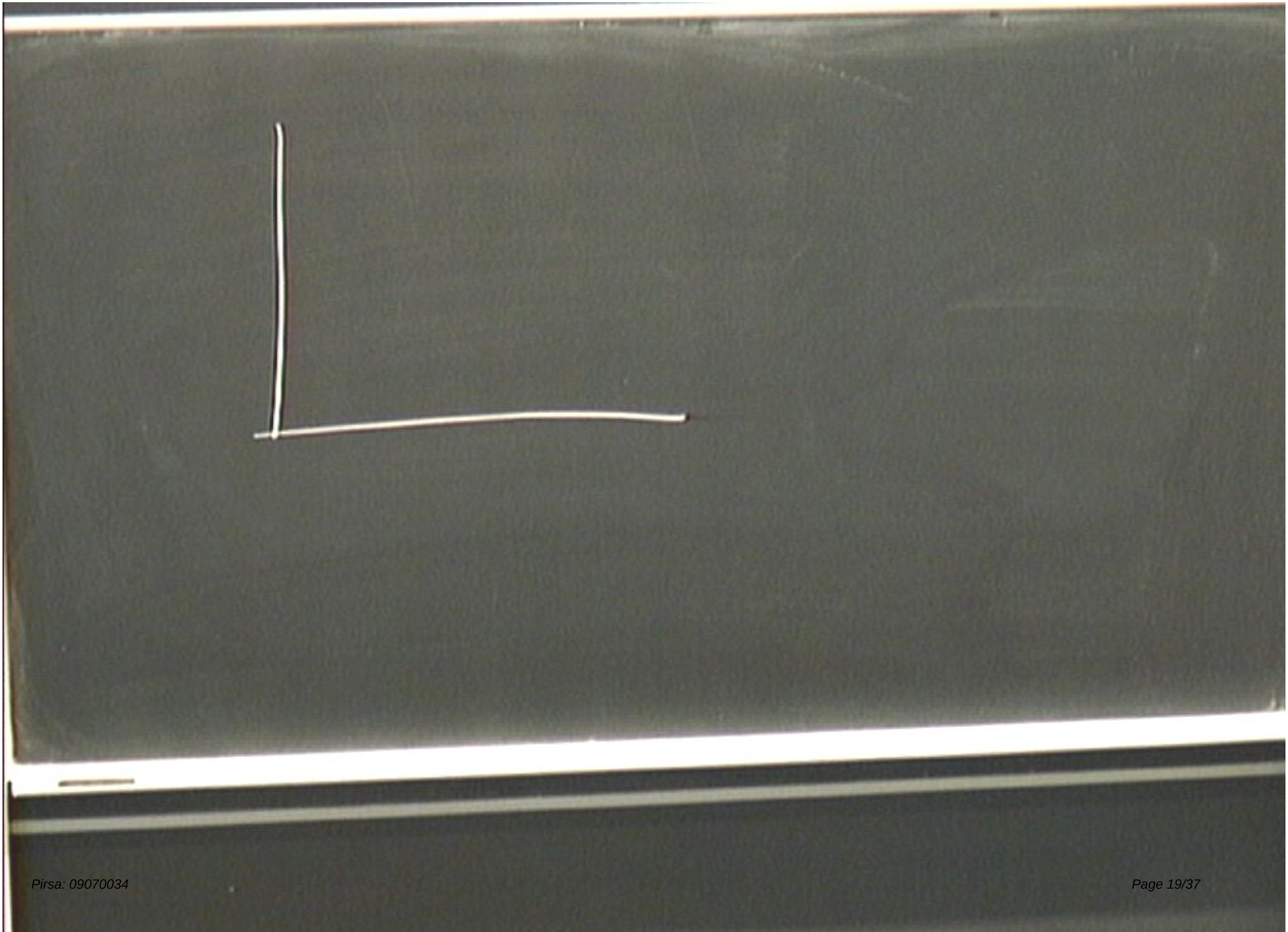
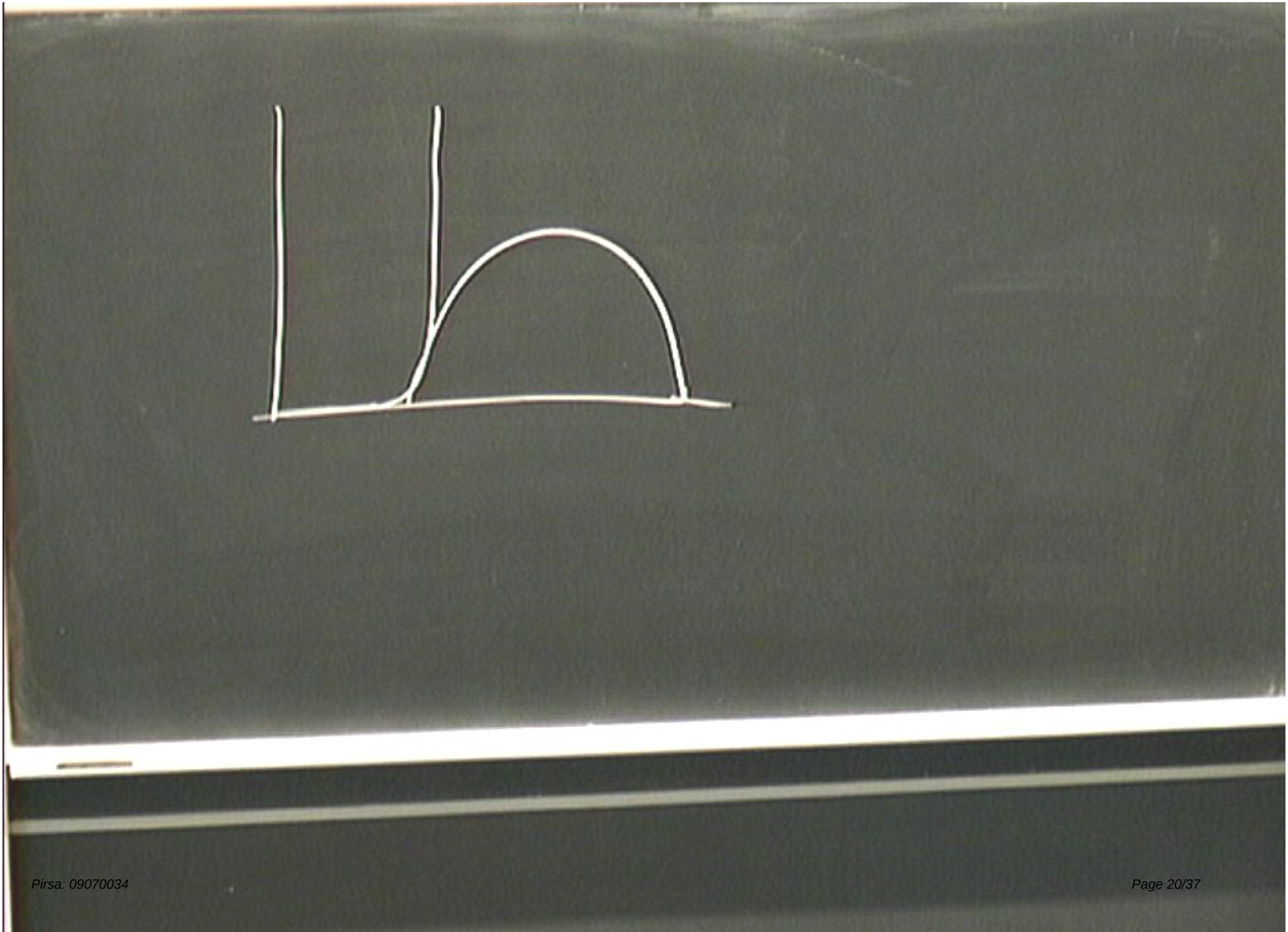
defines $S = C' \otimes R'$

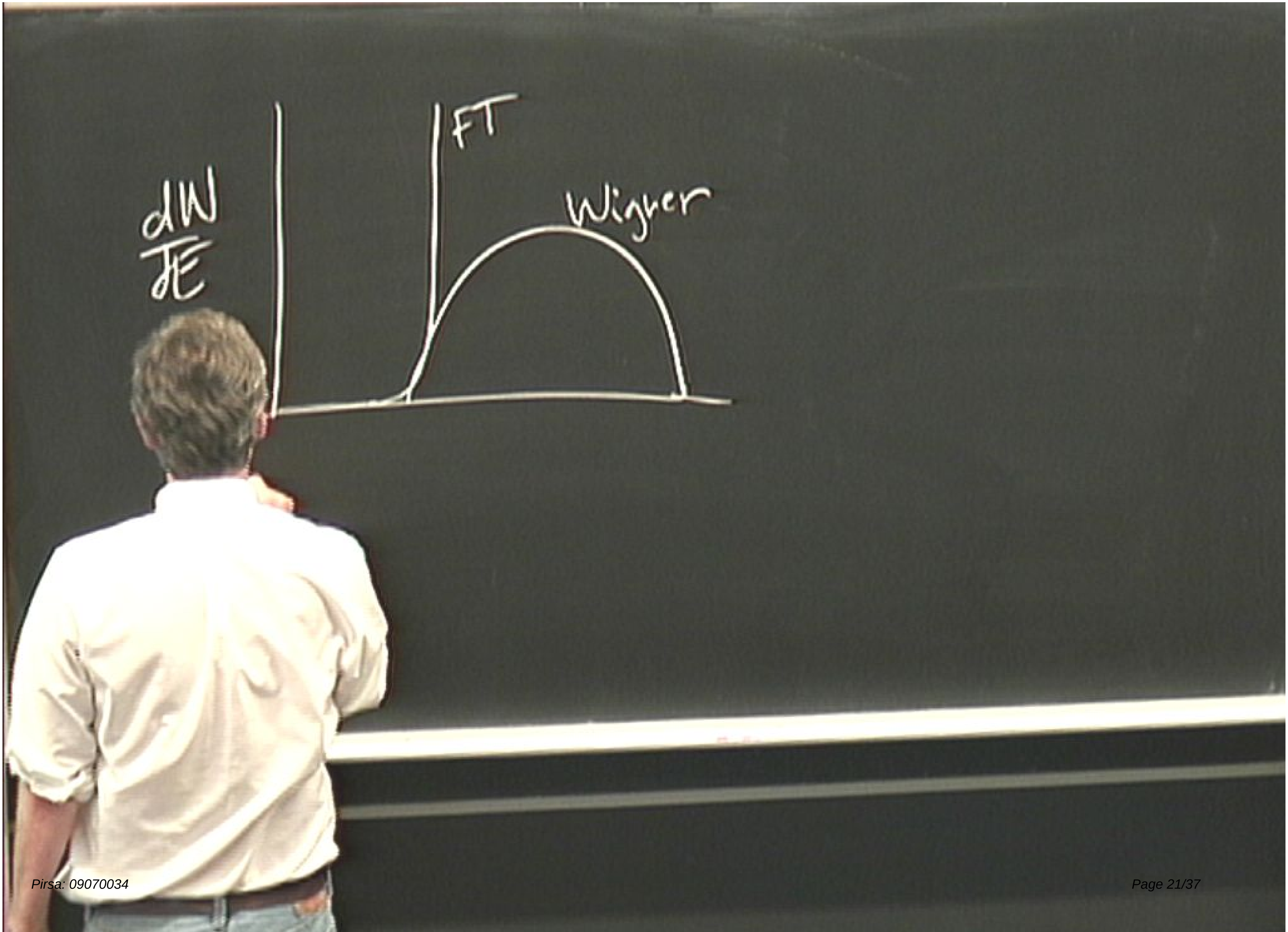
$$M|k\rangle_S = |k'\rangle_S \equiv |i\rangle_{C'} |j\rangle_{R'}$$

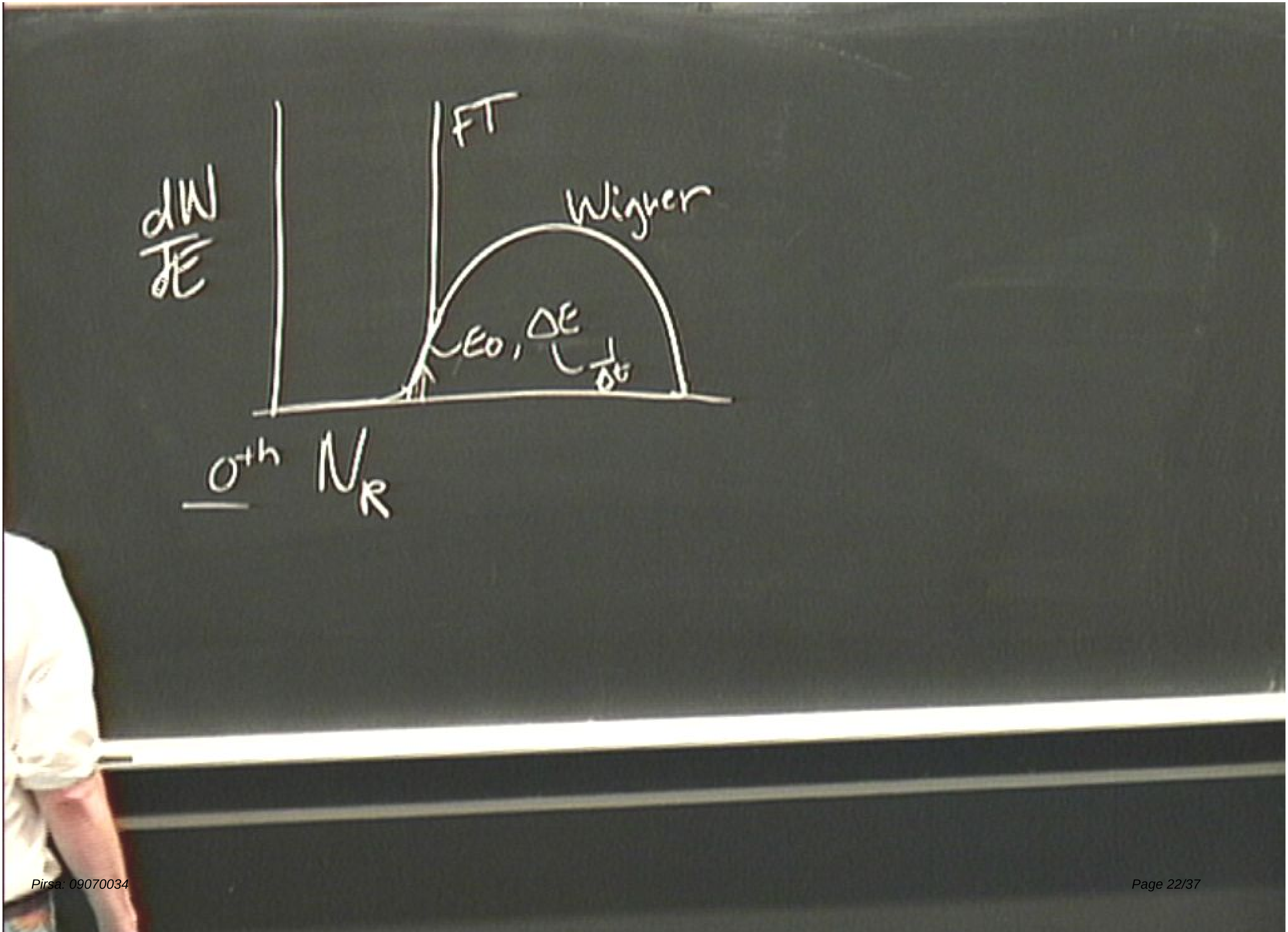
Random:


Random: Wigner Semicircle
dN/dE
E

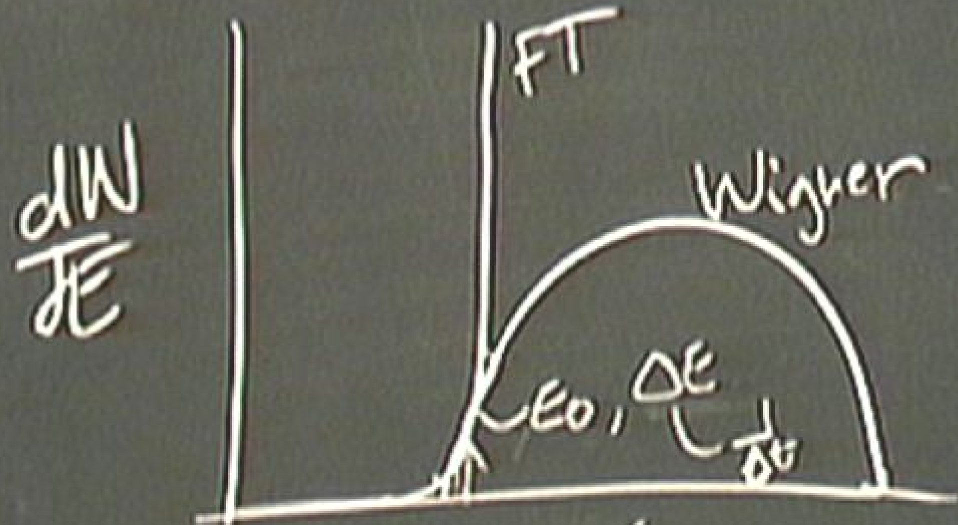





dW
dE
FT
Wigner



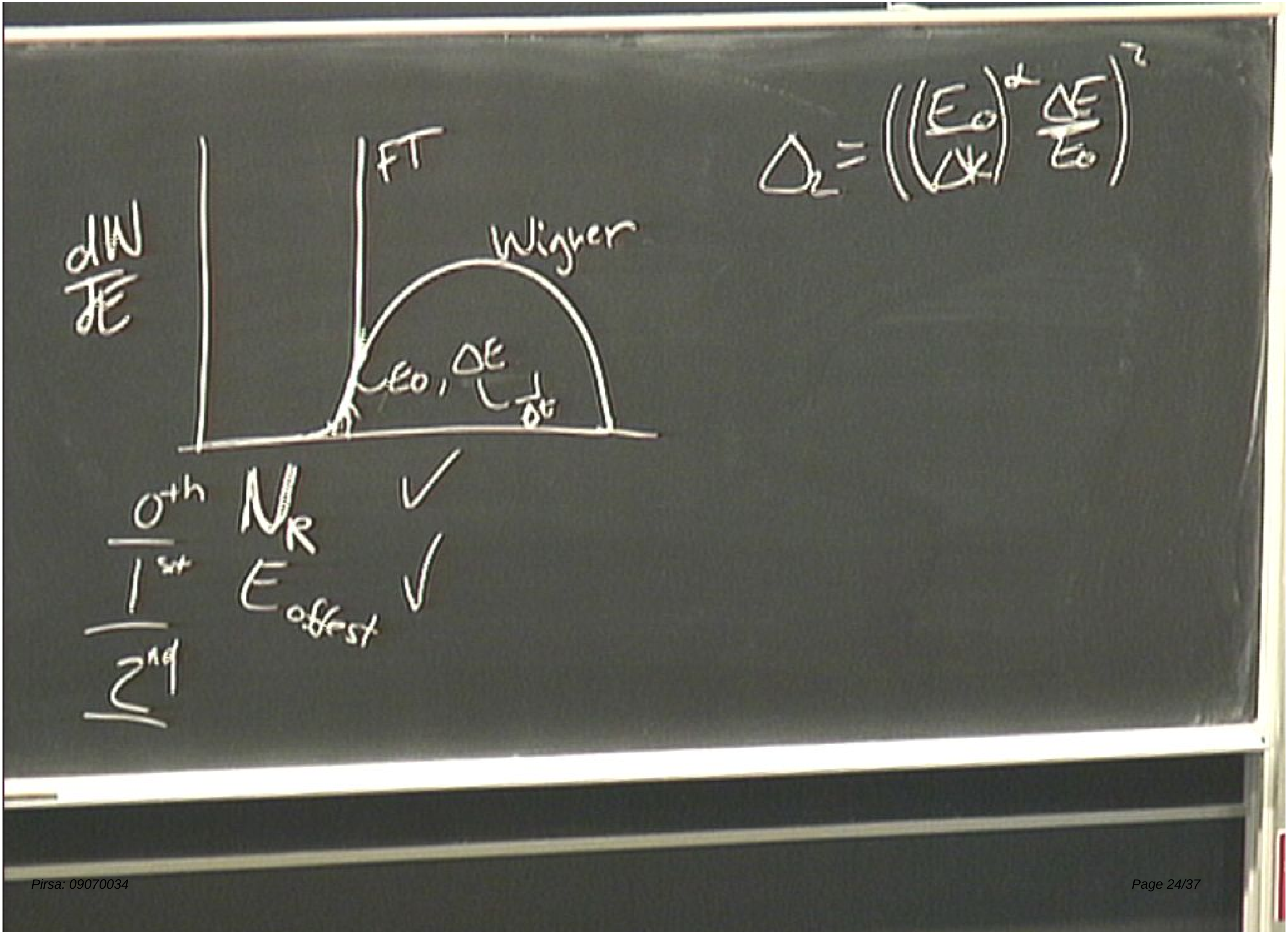
dW/dE
FT
Wigner
E0, ΔE
1/δt
0th
N_R

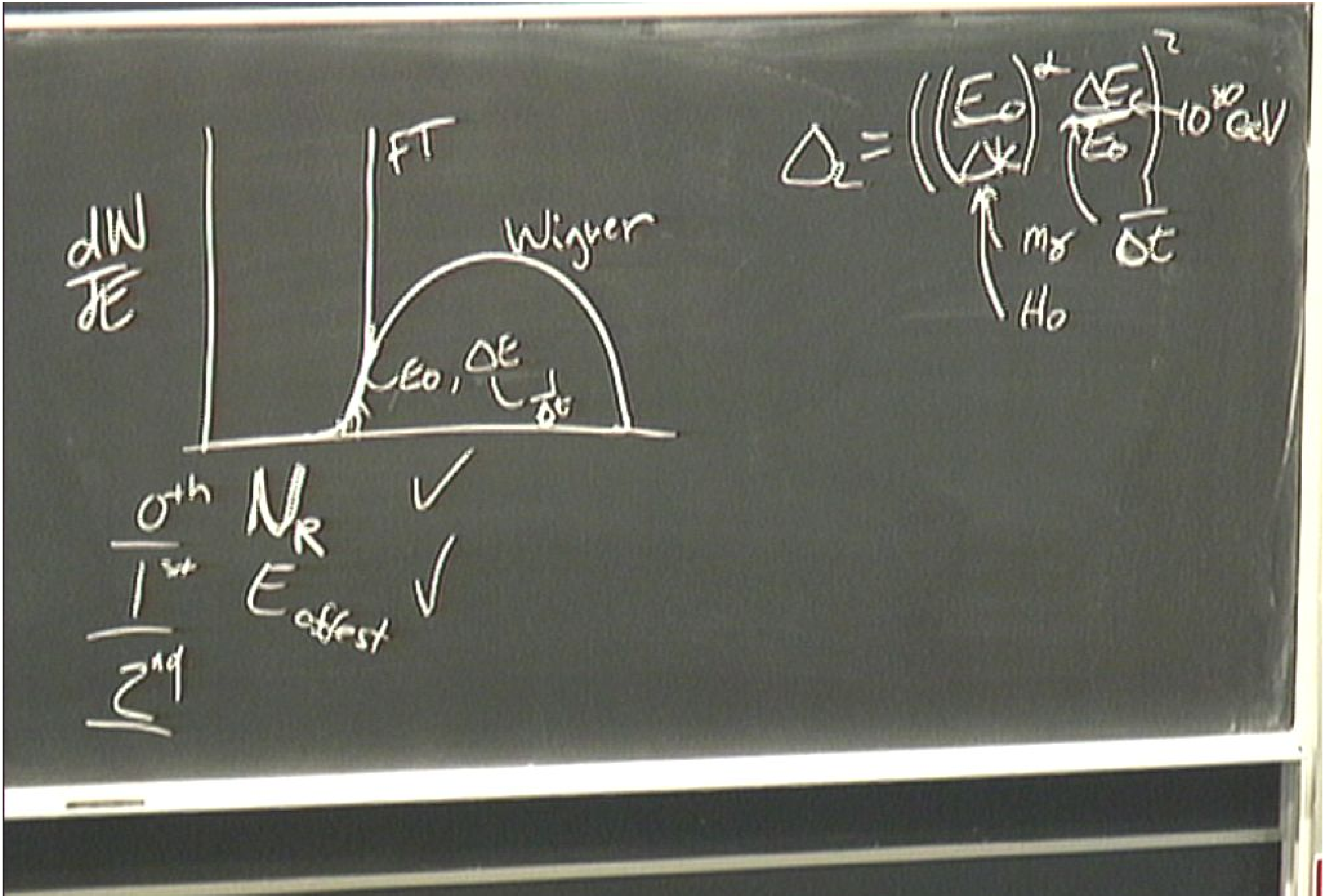


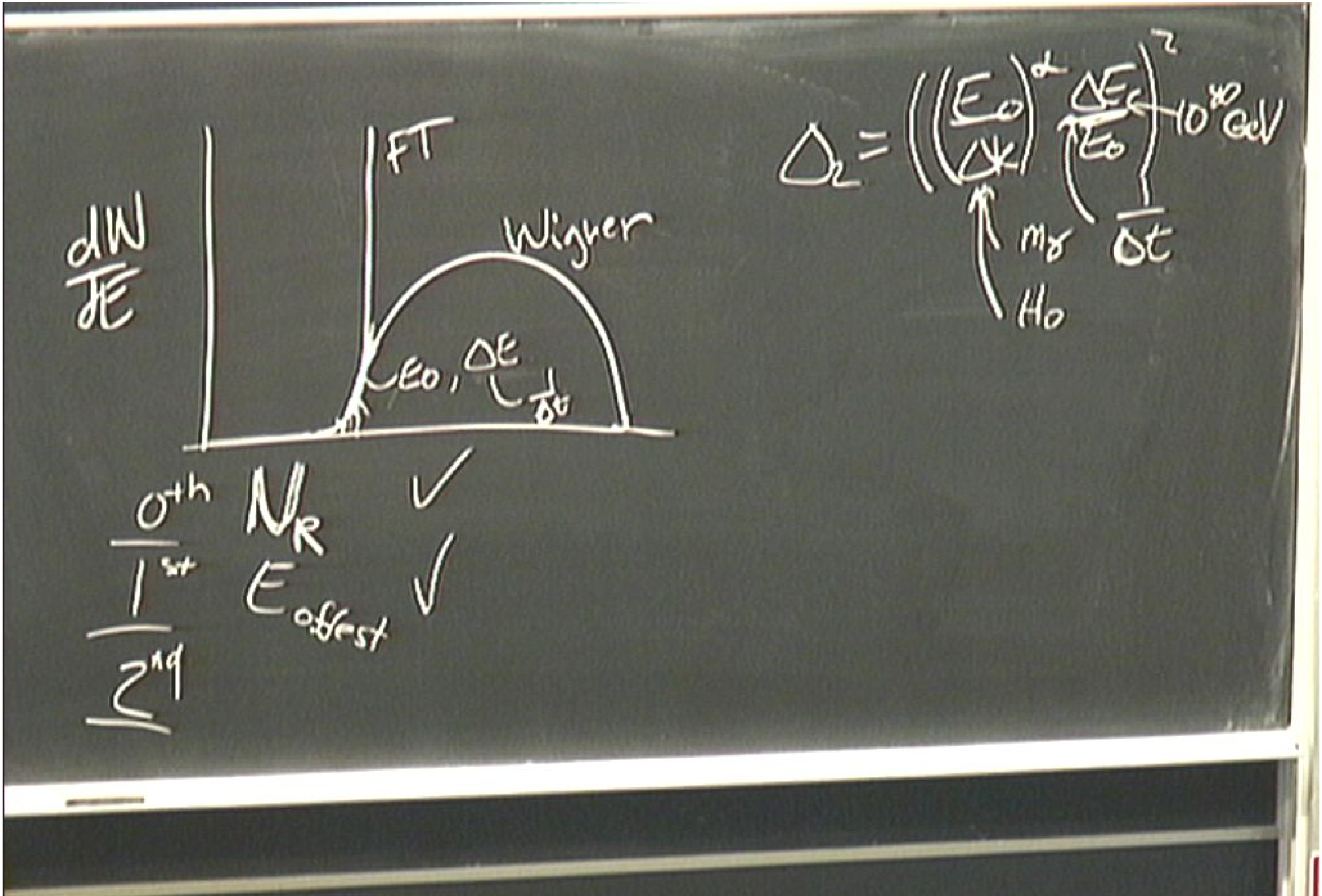
0th N_R ✓

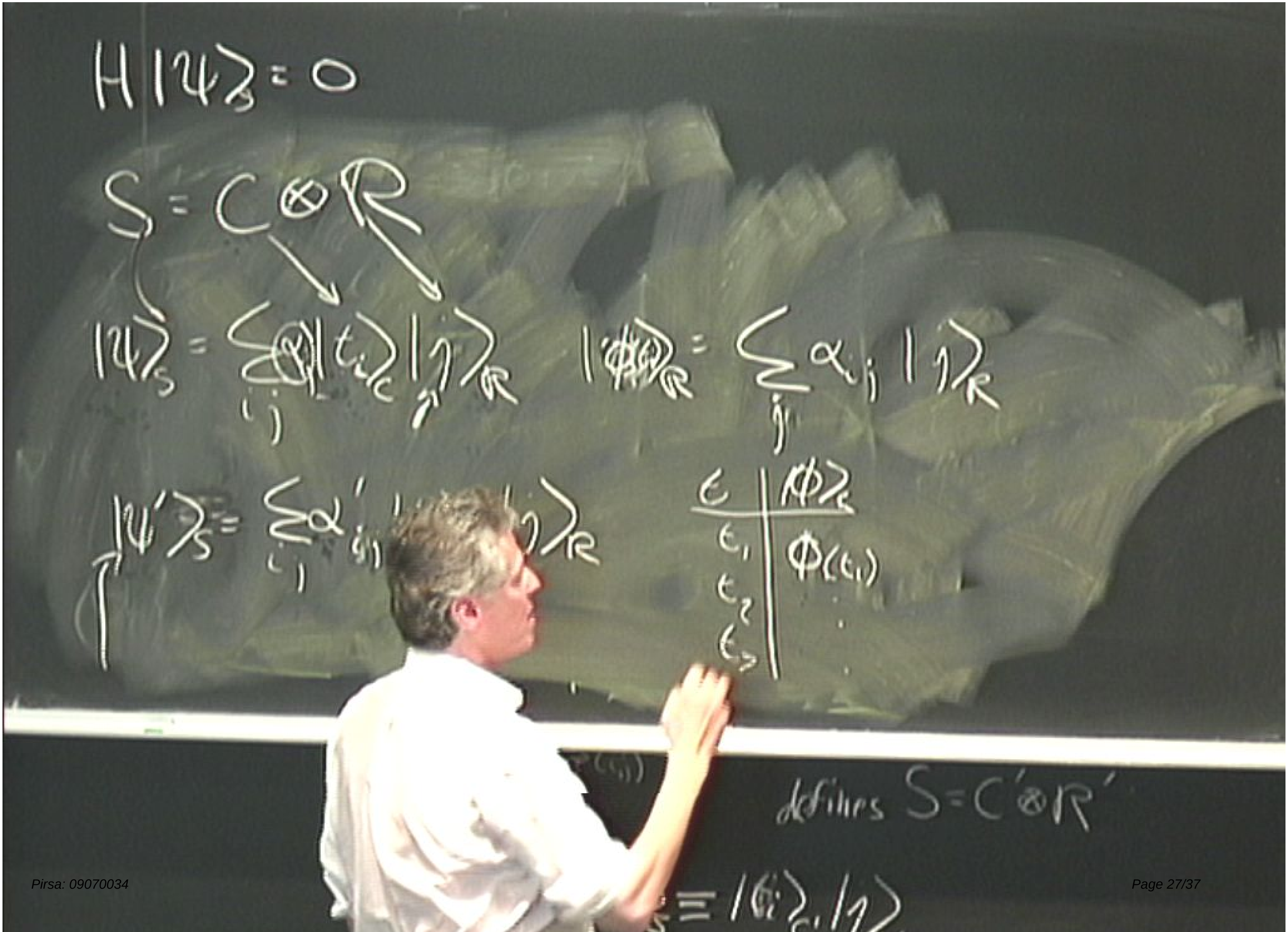
1st E_{offest} ✓

2nd


$\frac{dW}{dE}$
FT
Wigner
$E_0, \Delta E$
$\frac{1}{\Delta t}$
0^{th} N_R ✓
1^{st} E_{offset} ✓
2^{nd}
$\Delta_2 = \left(\left(\frac{E_0}{\Delta k} \right)^{\alpha} \frac{\Delta E}{E_0} \right)^2$


dW/dE
FT
Wigner
E0, ΔE
1/δt
0th N_R ✓
1st E_offset ✓
2nd
Δ2 = ((E0/Λ*)^α ΔE0/E0)^2 10^10 GeV
mγ
δt
H0


dW
dE
FT
Wigner
E0, ΔE
1/Δt
0th N_R ✓
1st E_0,best ✓
2nd
Δ2 = ((E0/Δk)^α ΔE0/E0)^2
10^40 GeV
mγ
H0
Δt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S = C⊗R
defines S = C'⊗R'

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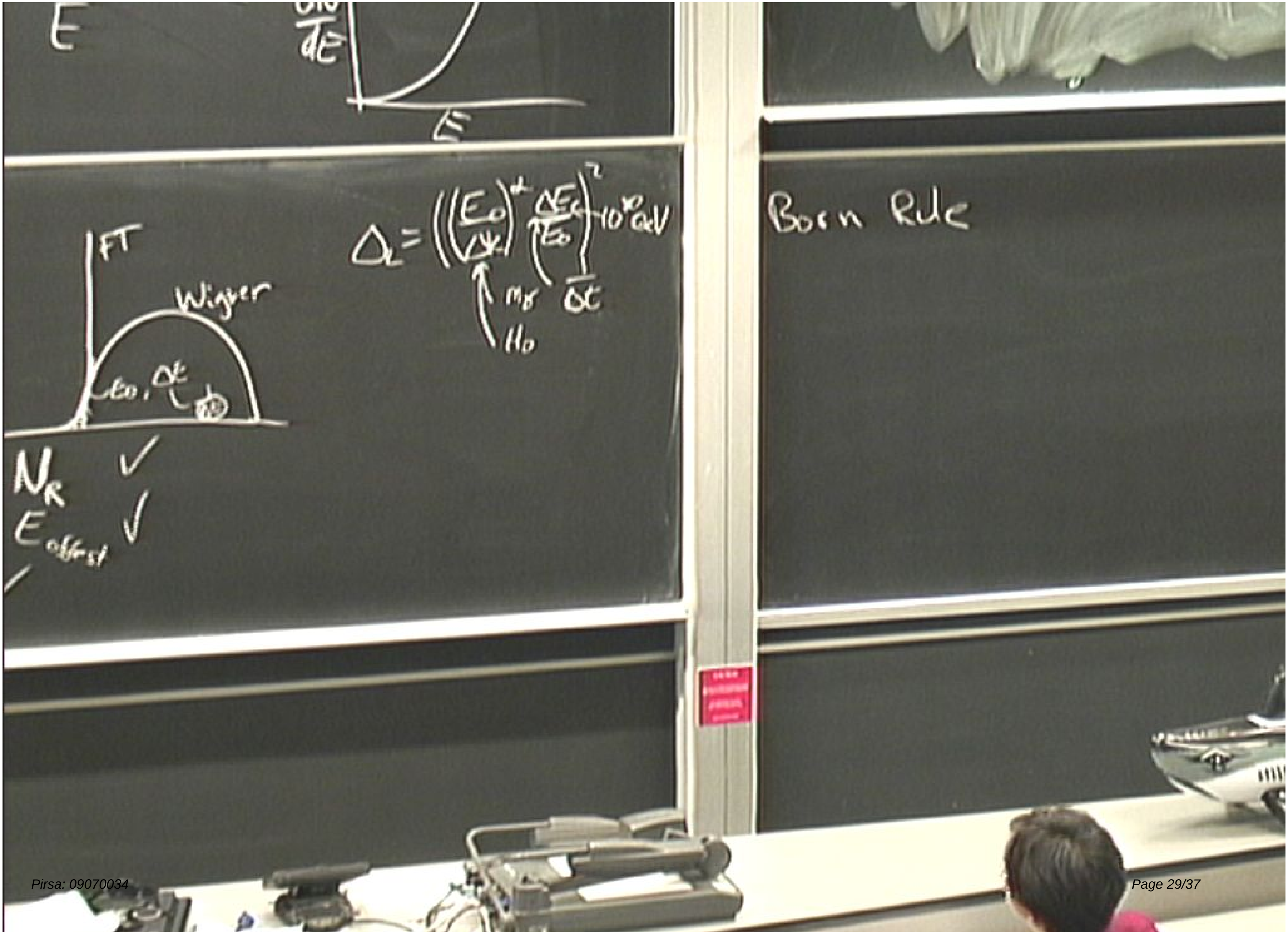
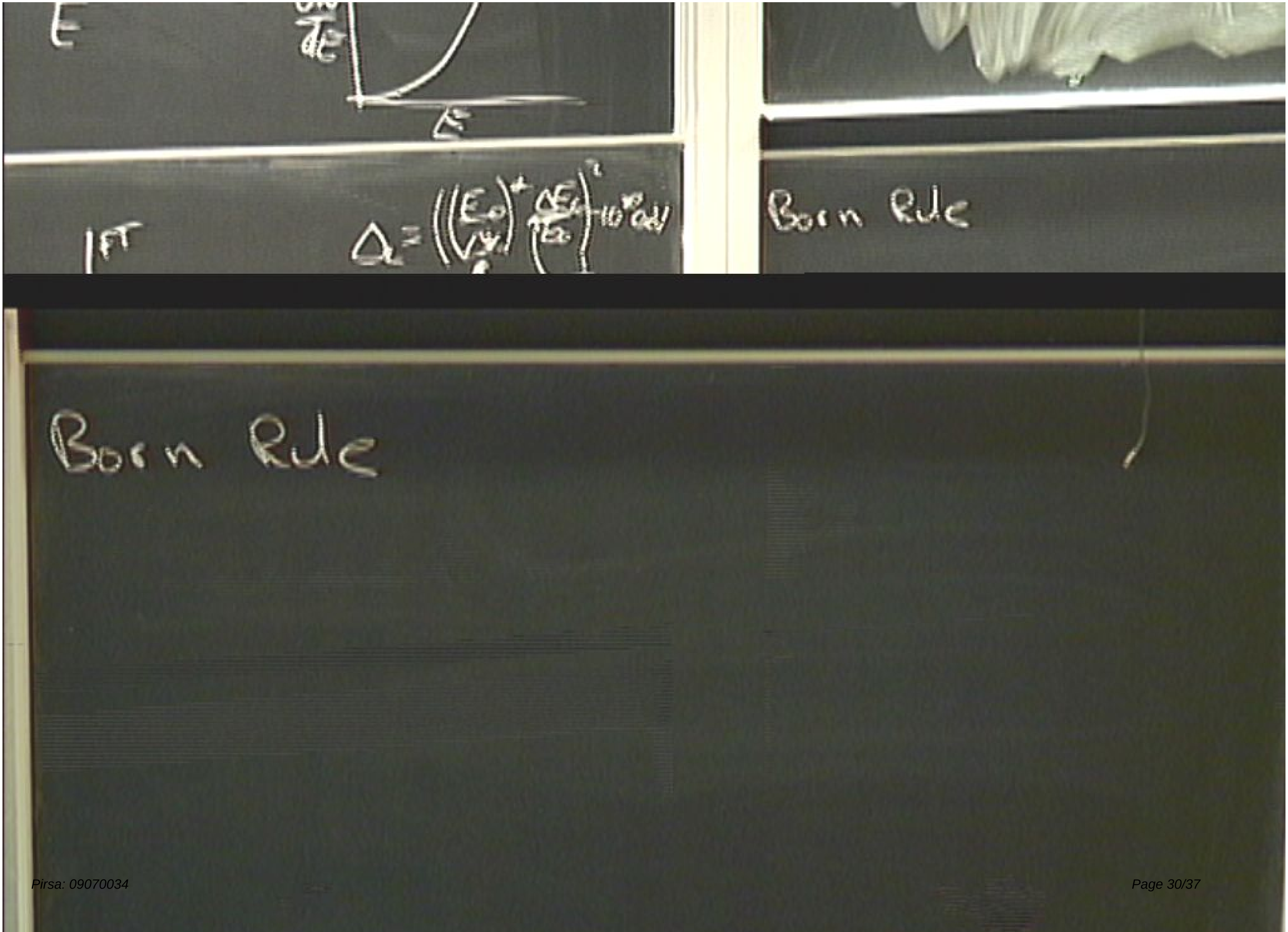
$$|\psi'\rangle_S = \sum_{i,j} \alpha'_{ij} |t_i\rangle_C |j\rangle_R$$

t	$\lvert\phi\rangle_R$
t_1	$\phi(t_1)$
t_2	$\vdots$
t_3	$\vdots$

$\langle s|k\rangle_S$ defines $S = C' \otimes R'$

$$M|k\rangle_S = |k\rangle_S \equiv |t_i\rangle_C |j\rangle$$

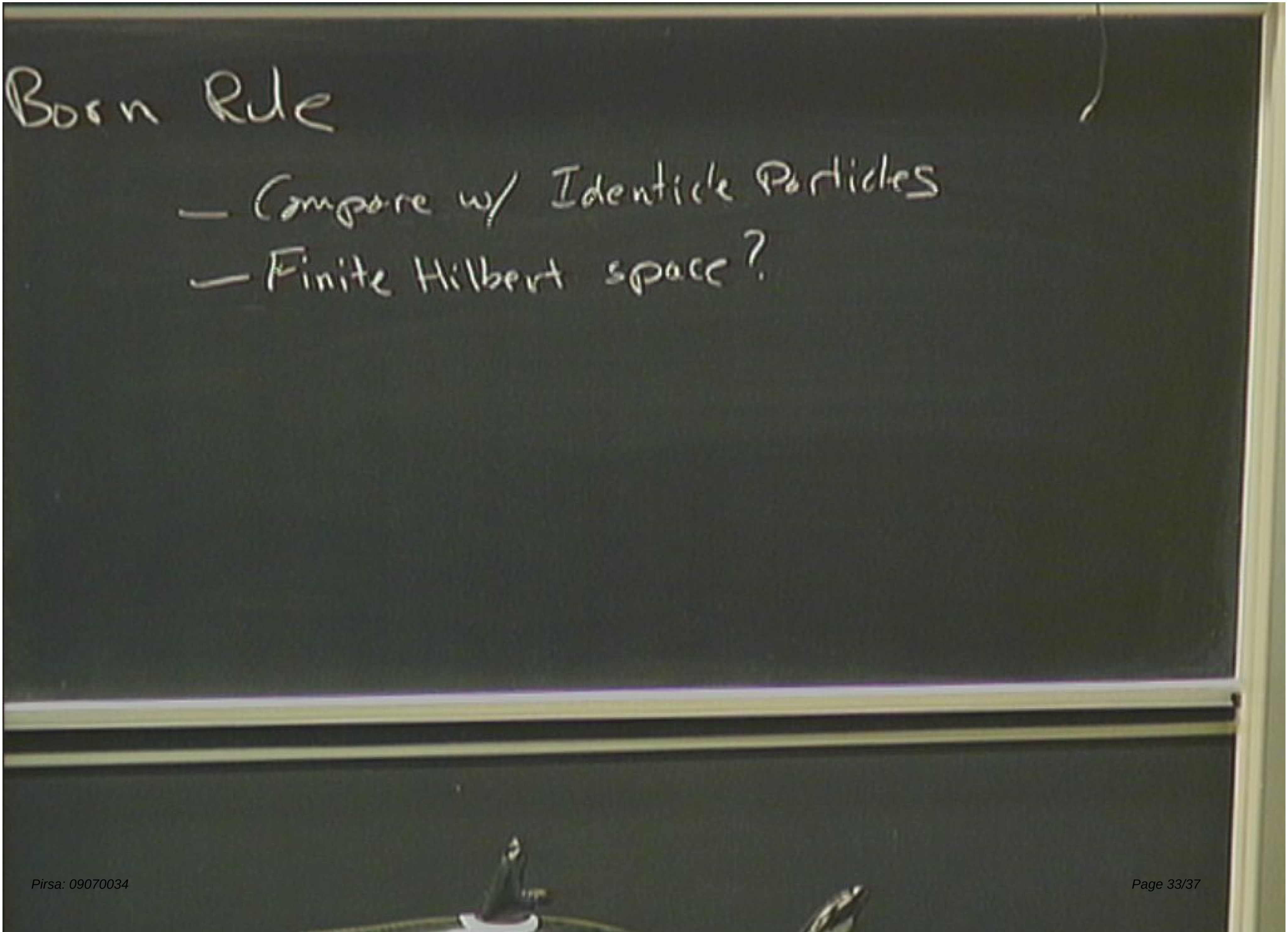

FT
Wigner
Born Rule

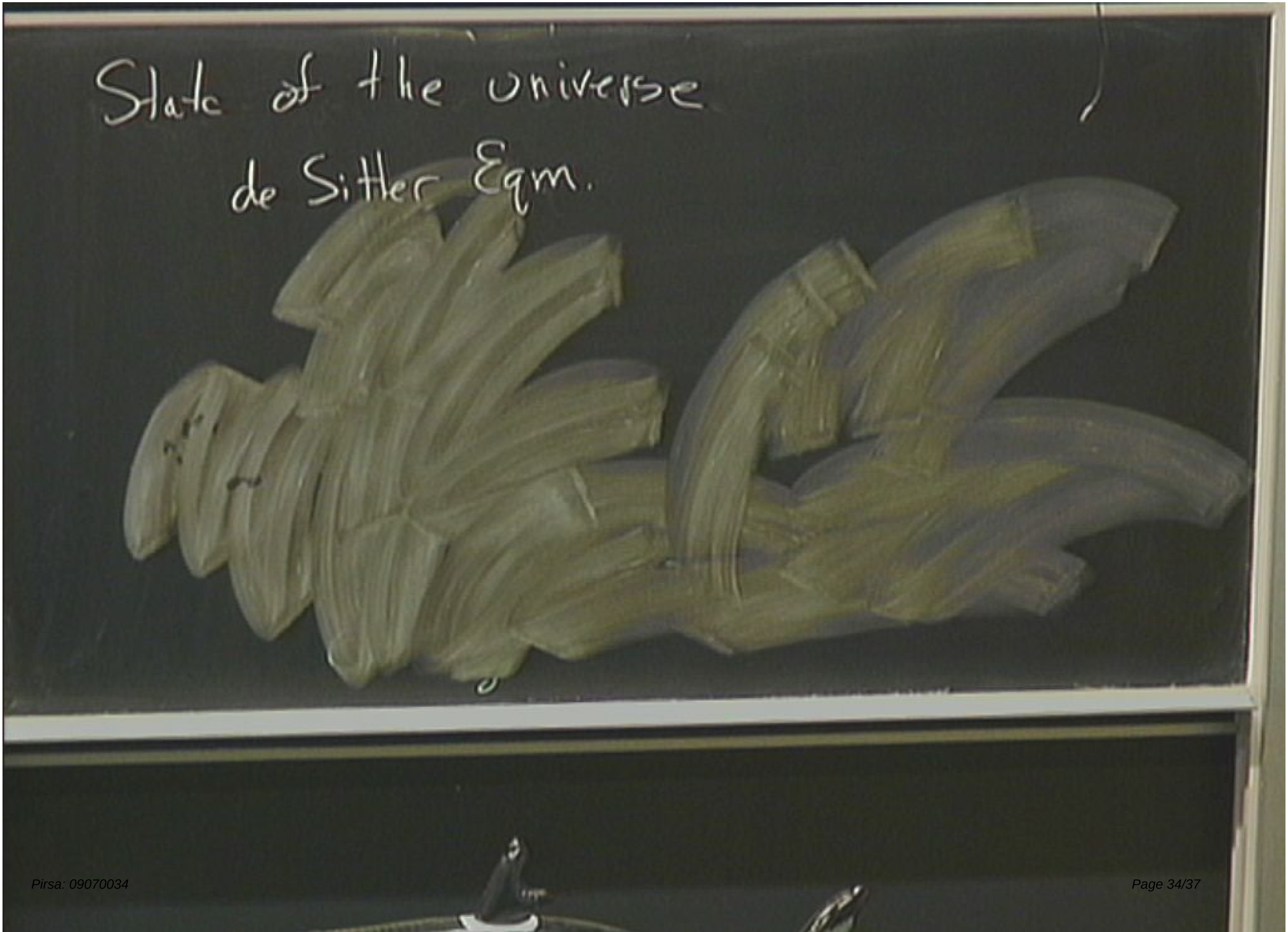

Born Rule
Born Rule

Born Rule

Born Rule

- Compare w/ Identicle Particles
-


Born Rule
— Compare w/ Identicle Particles
— Finite Hilbert space?


State of the universe
de Sitter Eqm.

State of the universe

de Sitter Eqm. $N \equiv e^{S_\Lambda} = e^{10^{120}}$,

State of the universe

– de Sitter Eqm. $N = e^{S_\Lambda} = e^{10^{120}}$

– no initial state

– prob given H

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$$P_{fluct} = e^{+(S_{fluct} - S_\Lambda)}$$