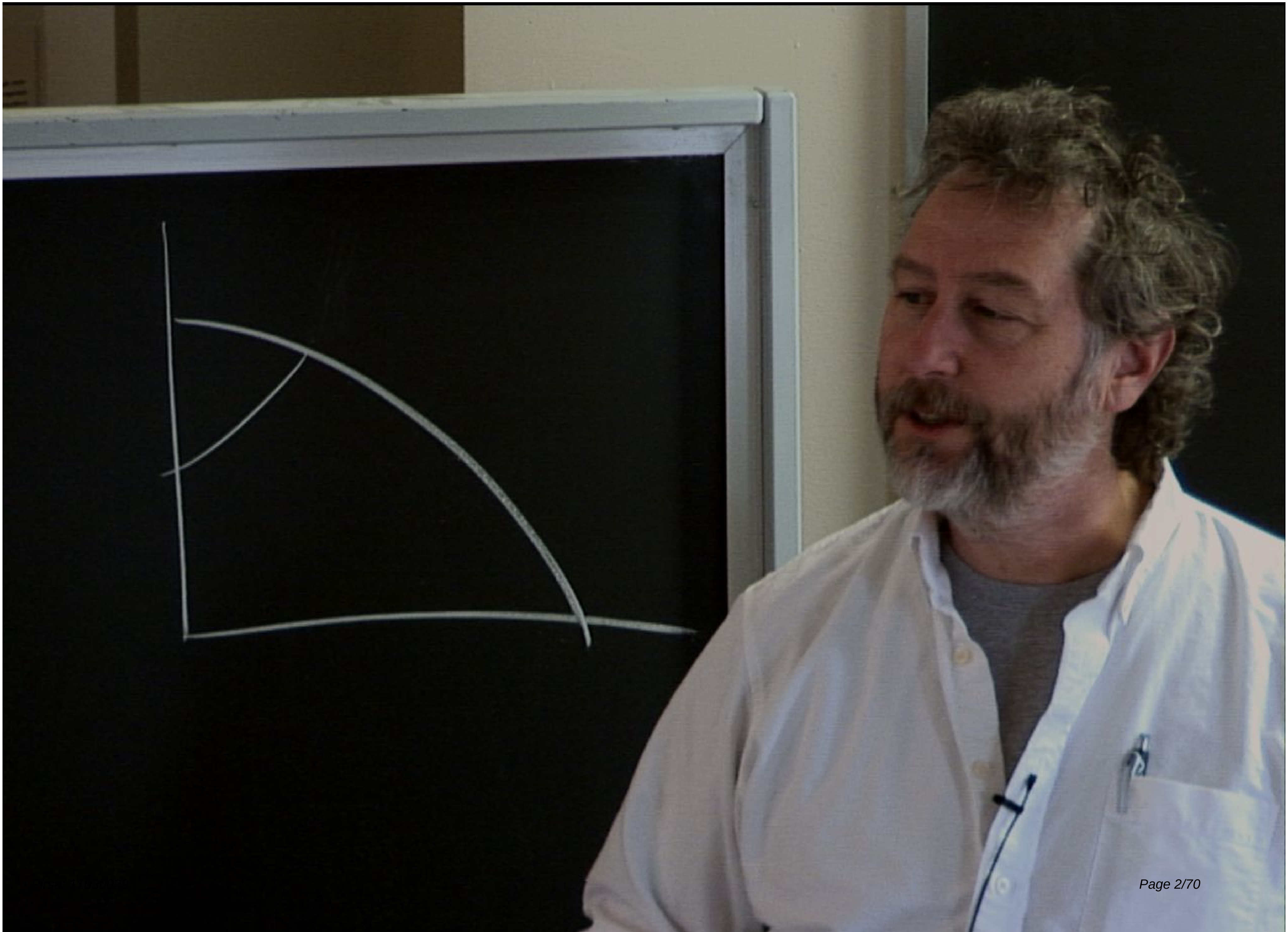
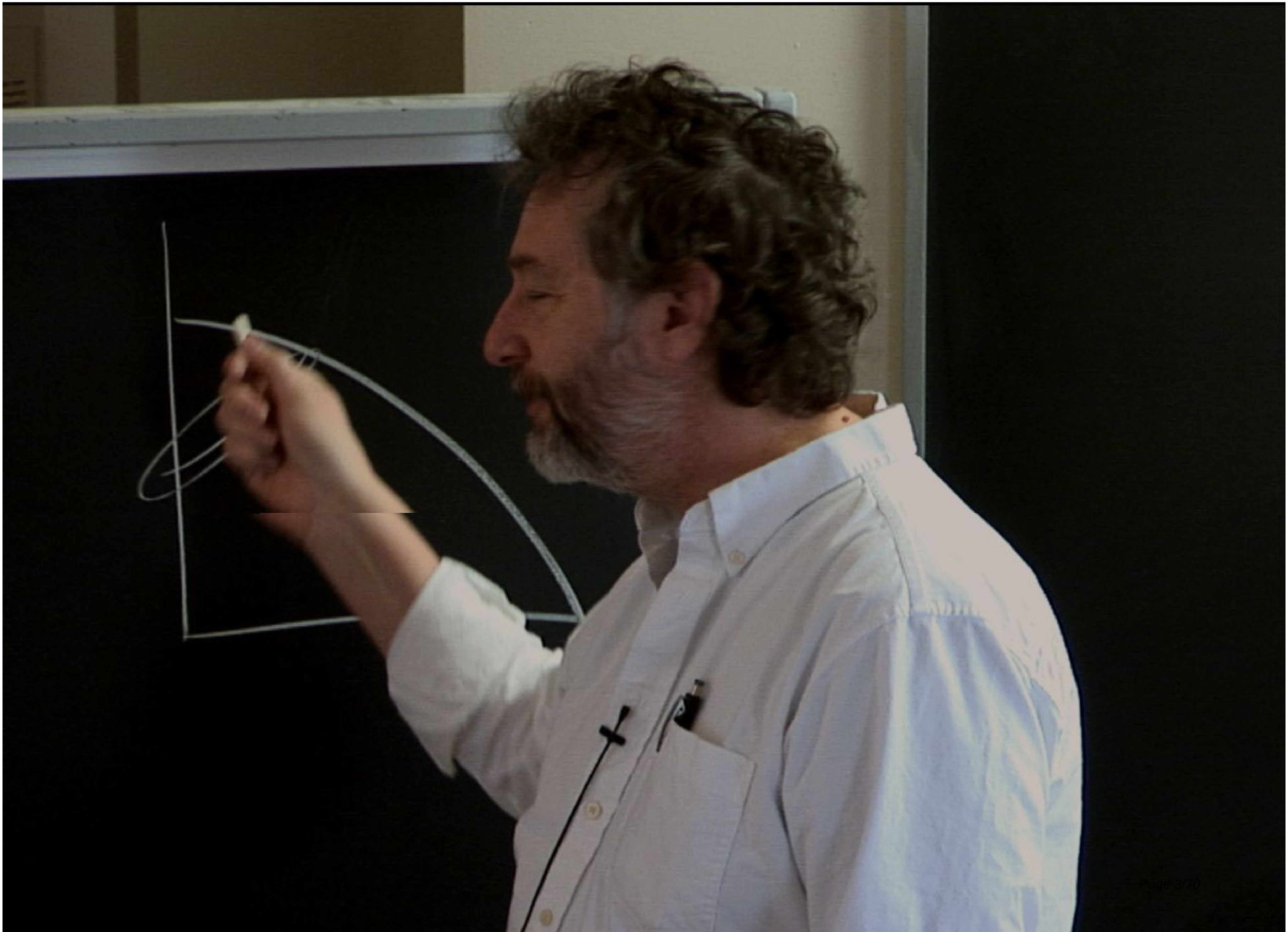
Title: Explorations in Quantum Information - Lecture 14

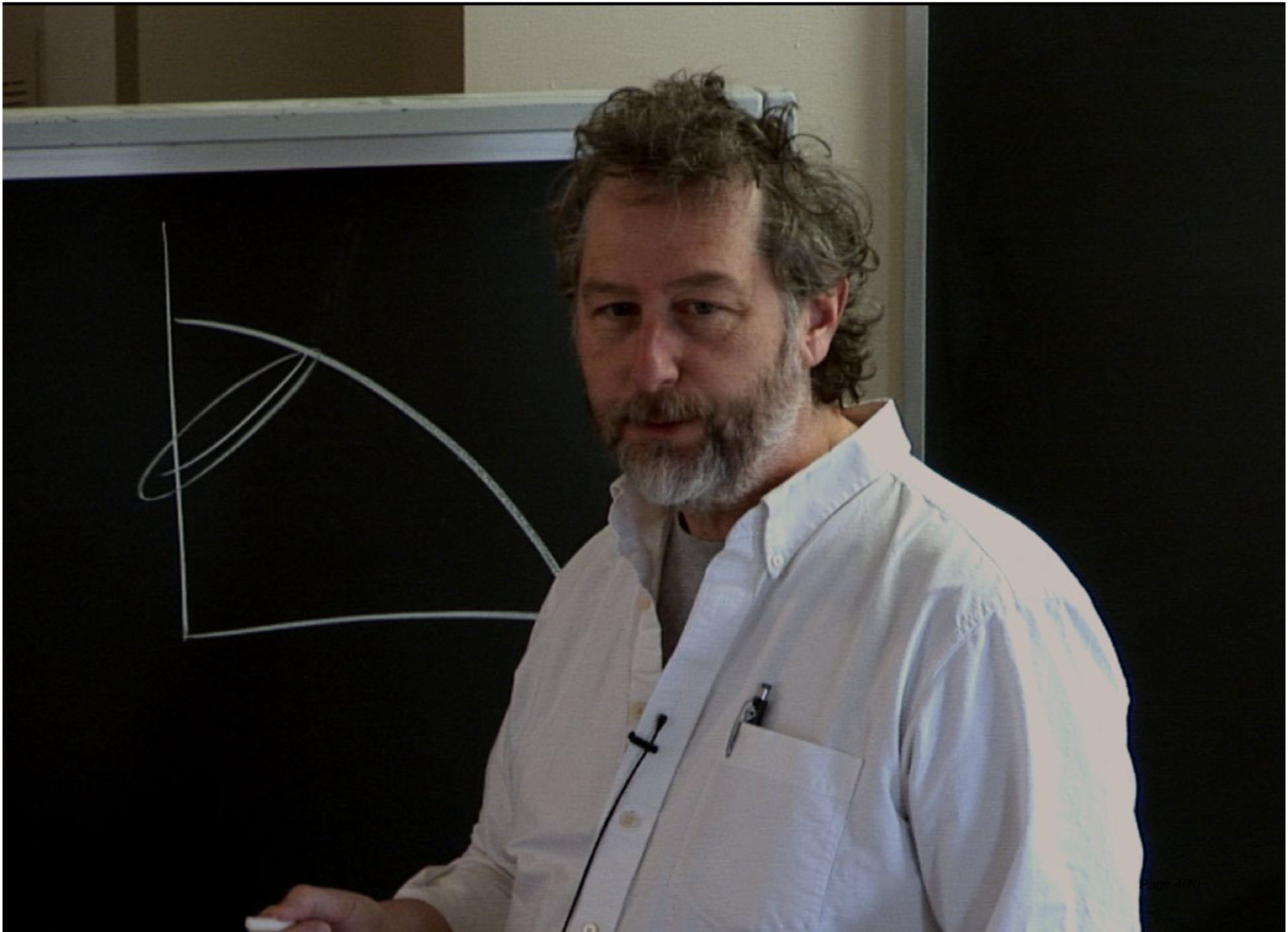
Date: Apr 01, 2011 09:00 AM

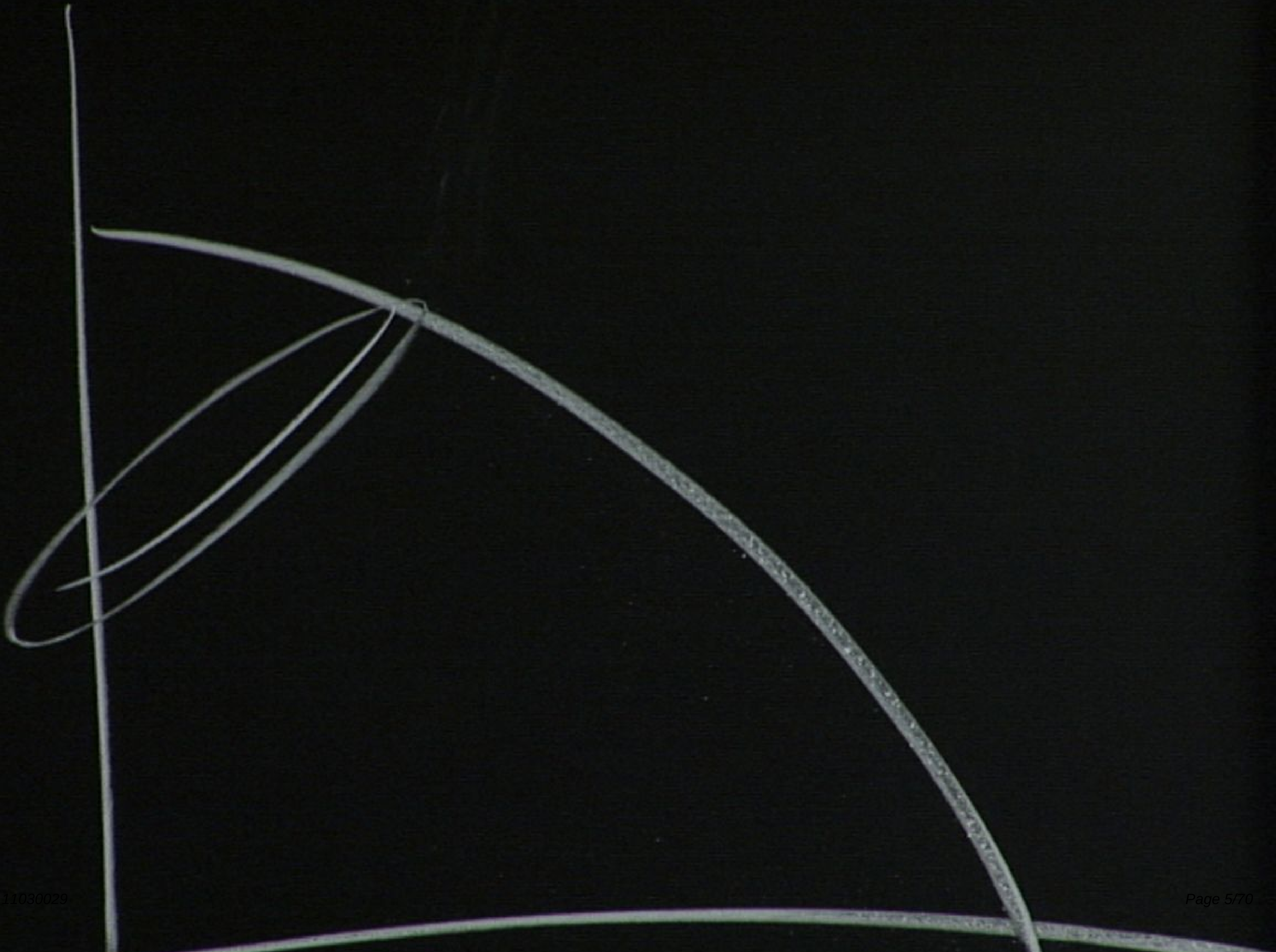
URL: http://pirsa.org/11030029

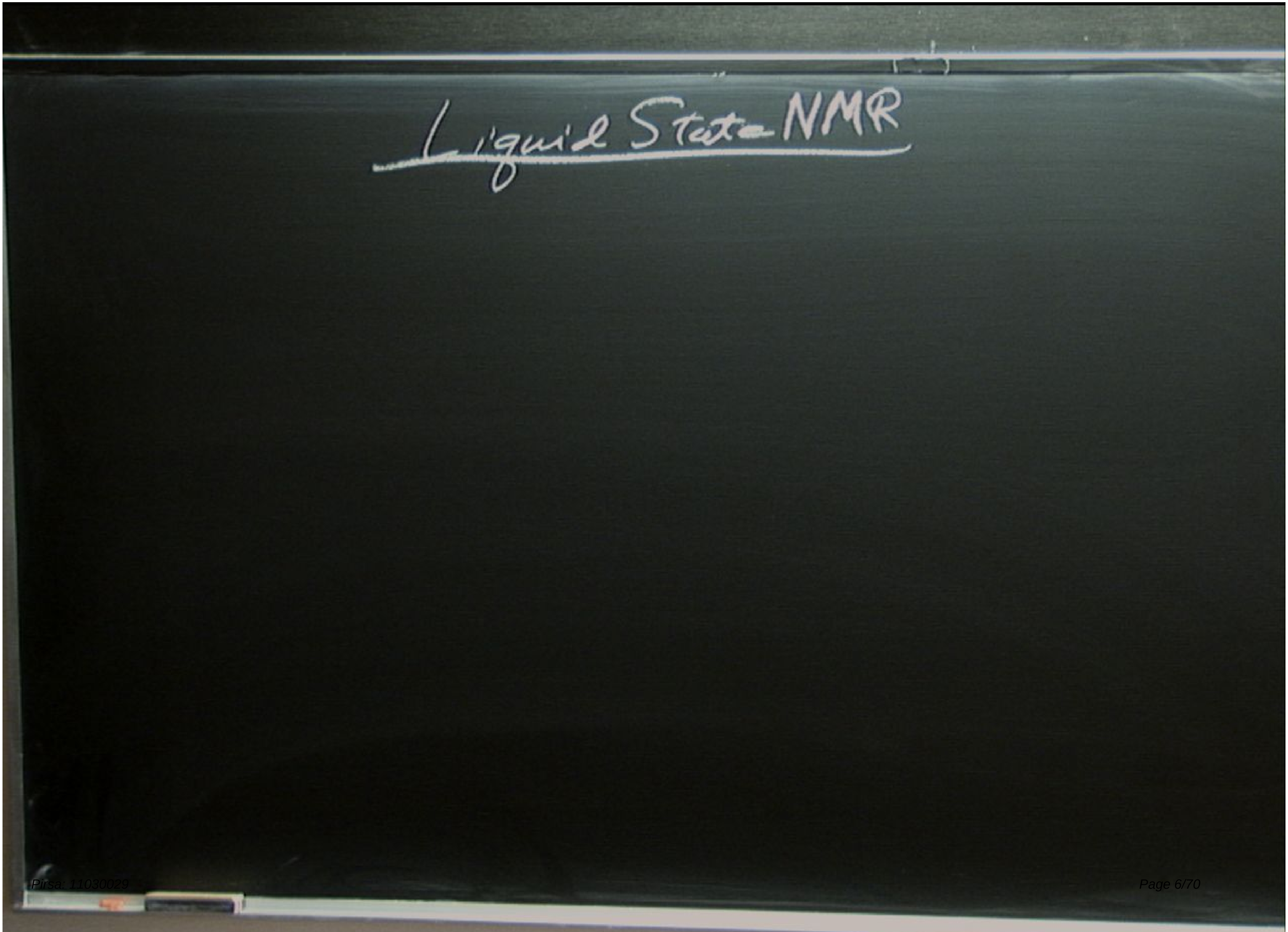
Abstract:



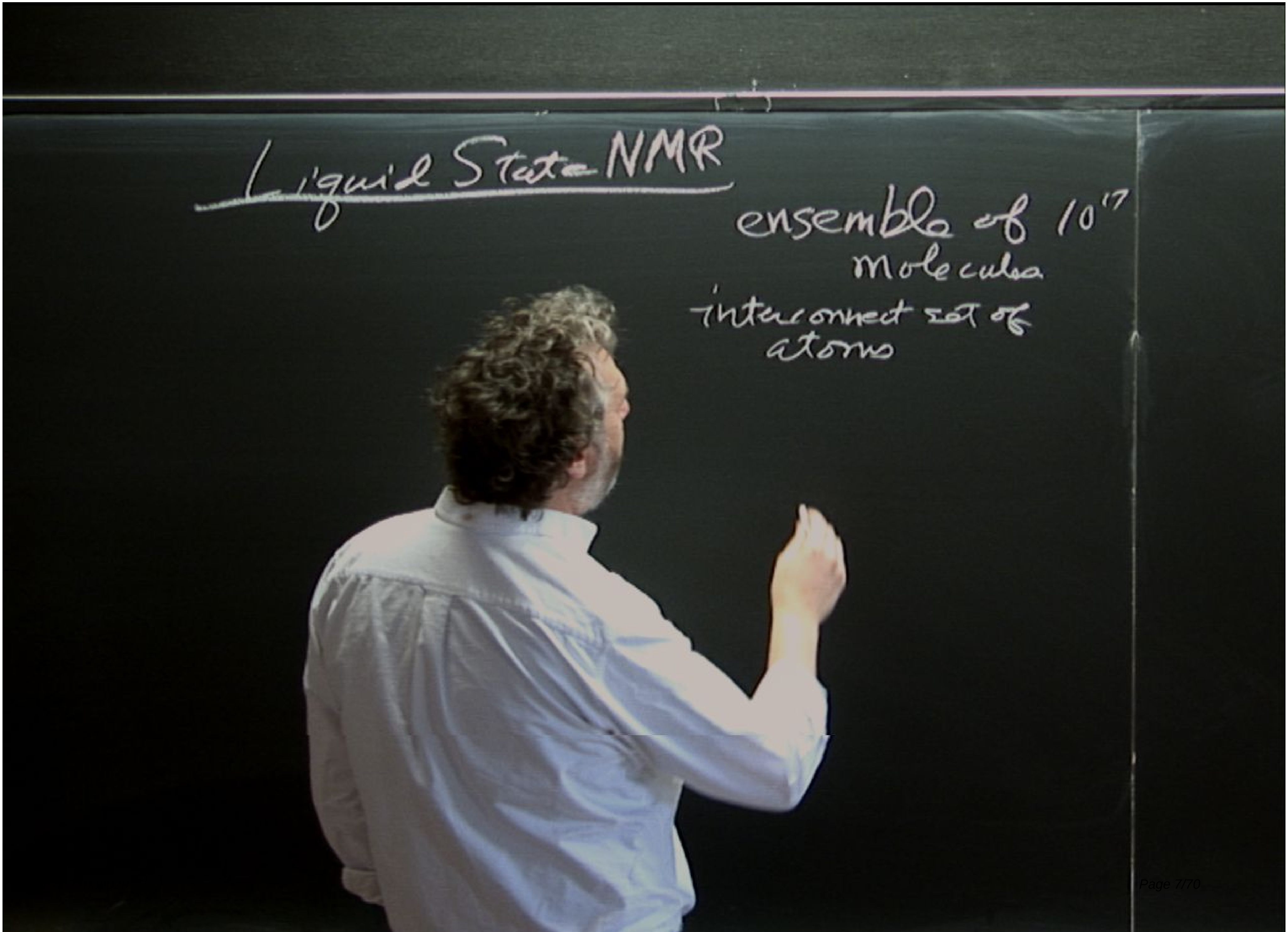








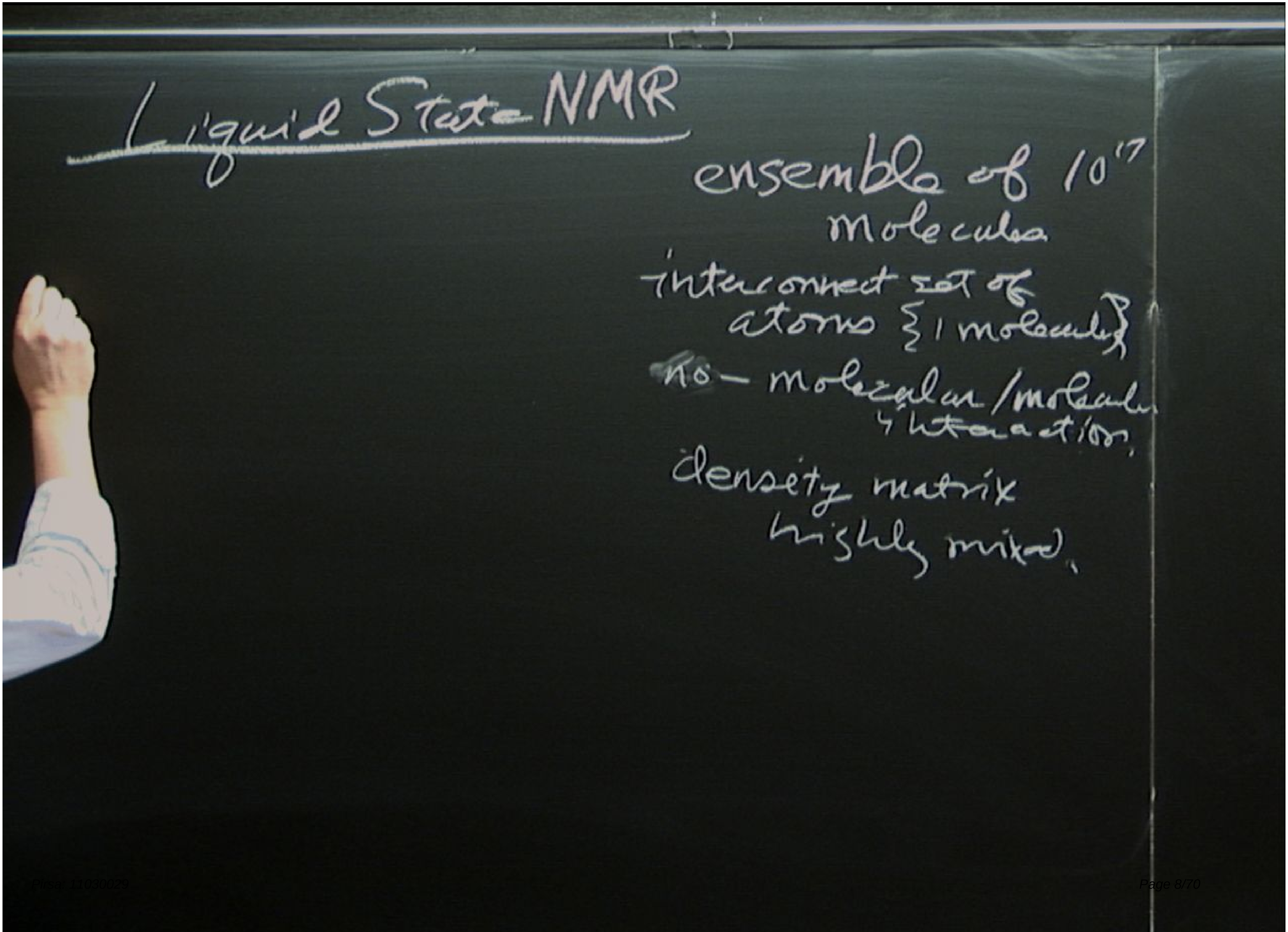
Liquid State NMR



Liquid State NMR

ensemble of 10^{17} molecules

interconnect set of atoms



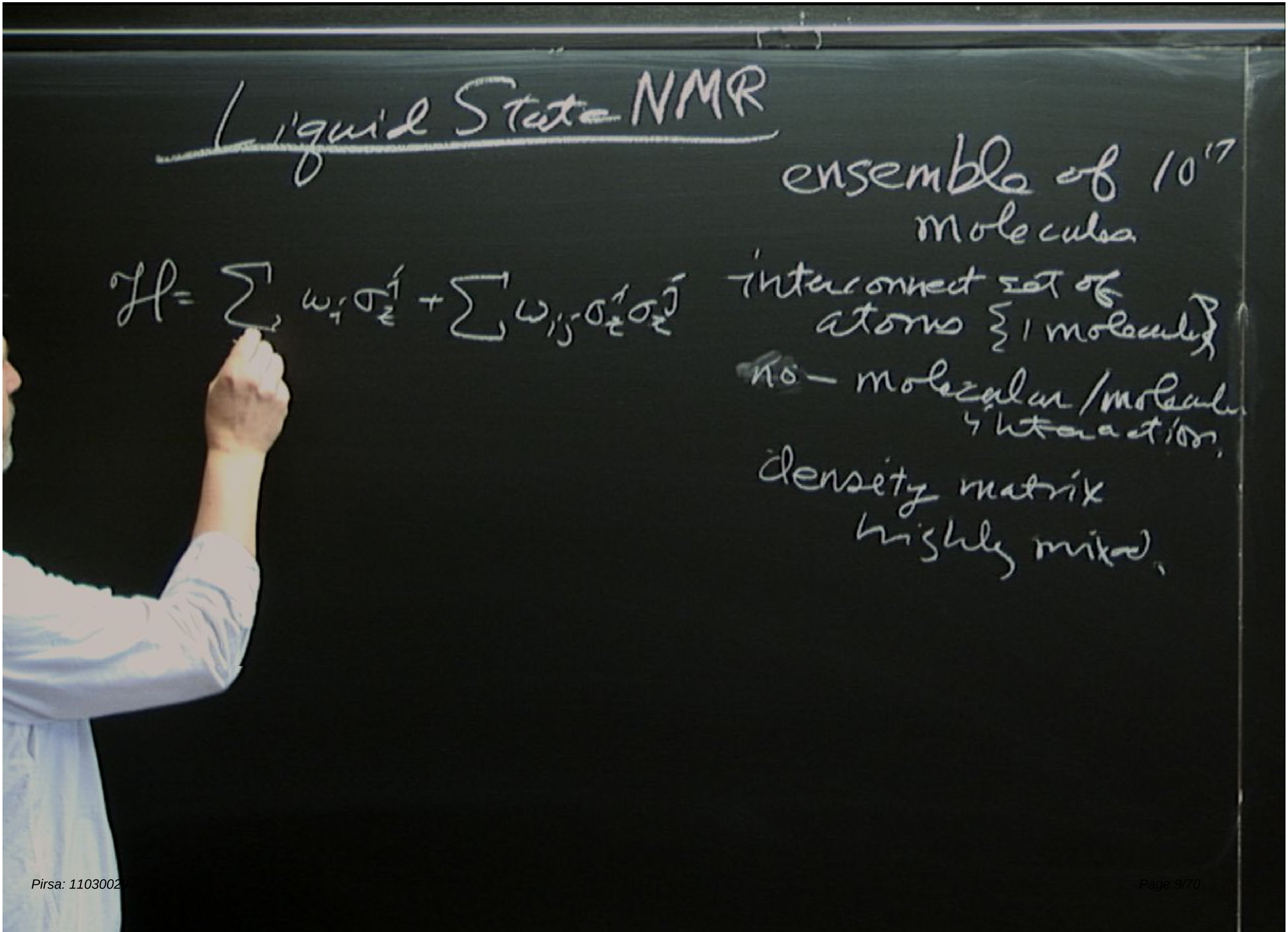
Liquid State NMR

ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

no - molecular/molecule interaction.

density matrix highly mixed.



Liquid State NMR

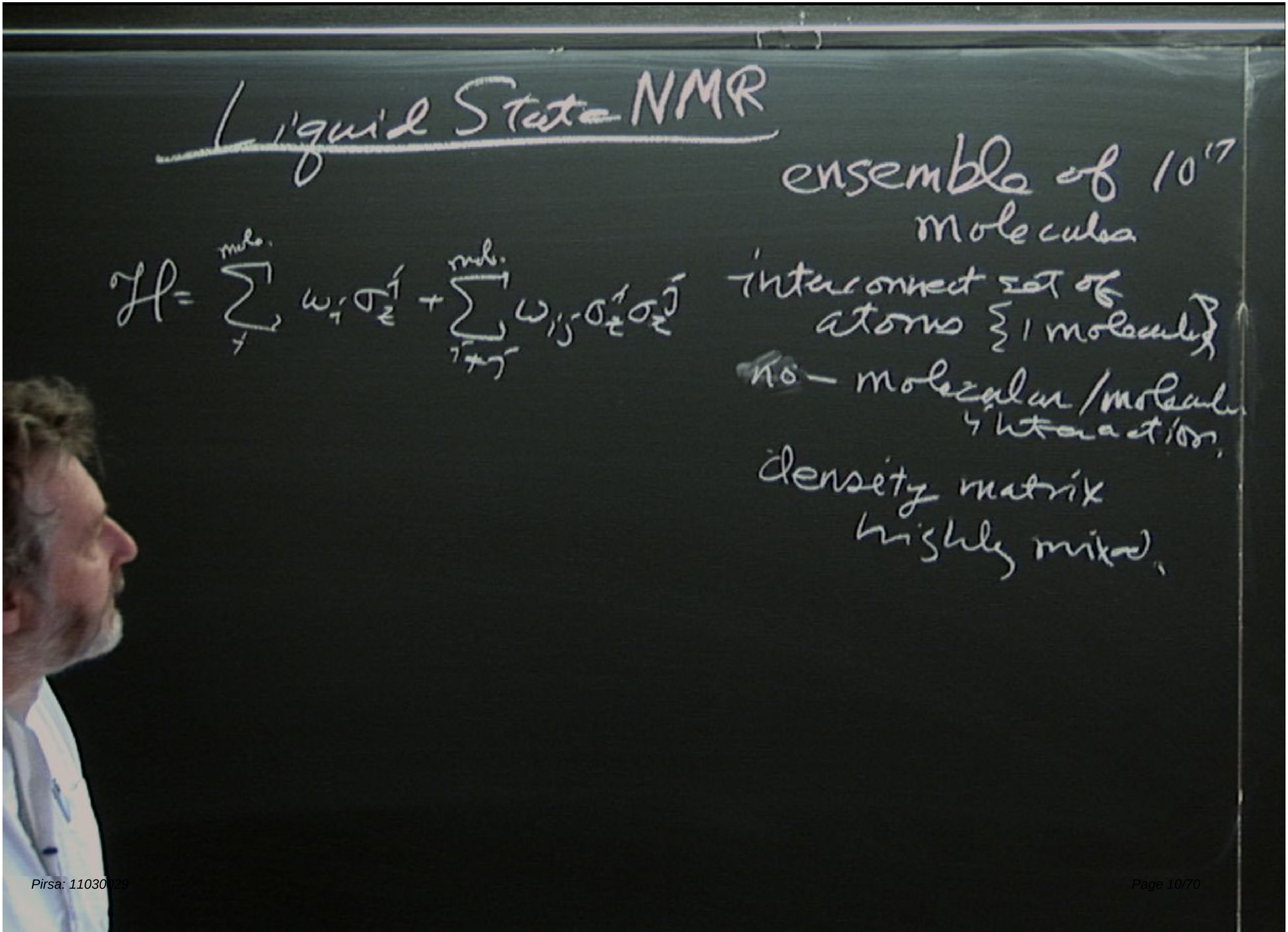
$$\mathcal{H} = \sum_i \omega_i \sigma_z^i + \sum \omega_{ij} \sigma_z^i \sigma_z^j$$

ensemble of 10^{17}
molecules

interconnect set of
atoms {1 molecule}

no - molecular/molecule
interaction.

density matrix
highly mixed.



Liquid State NMR

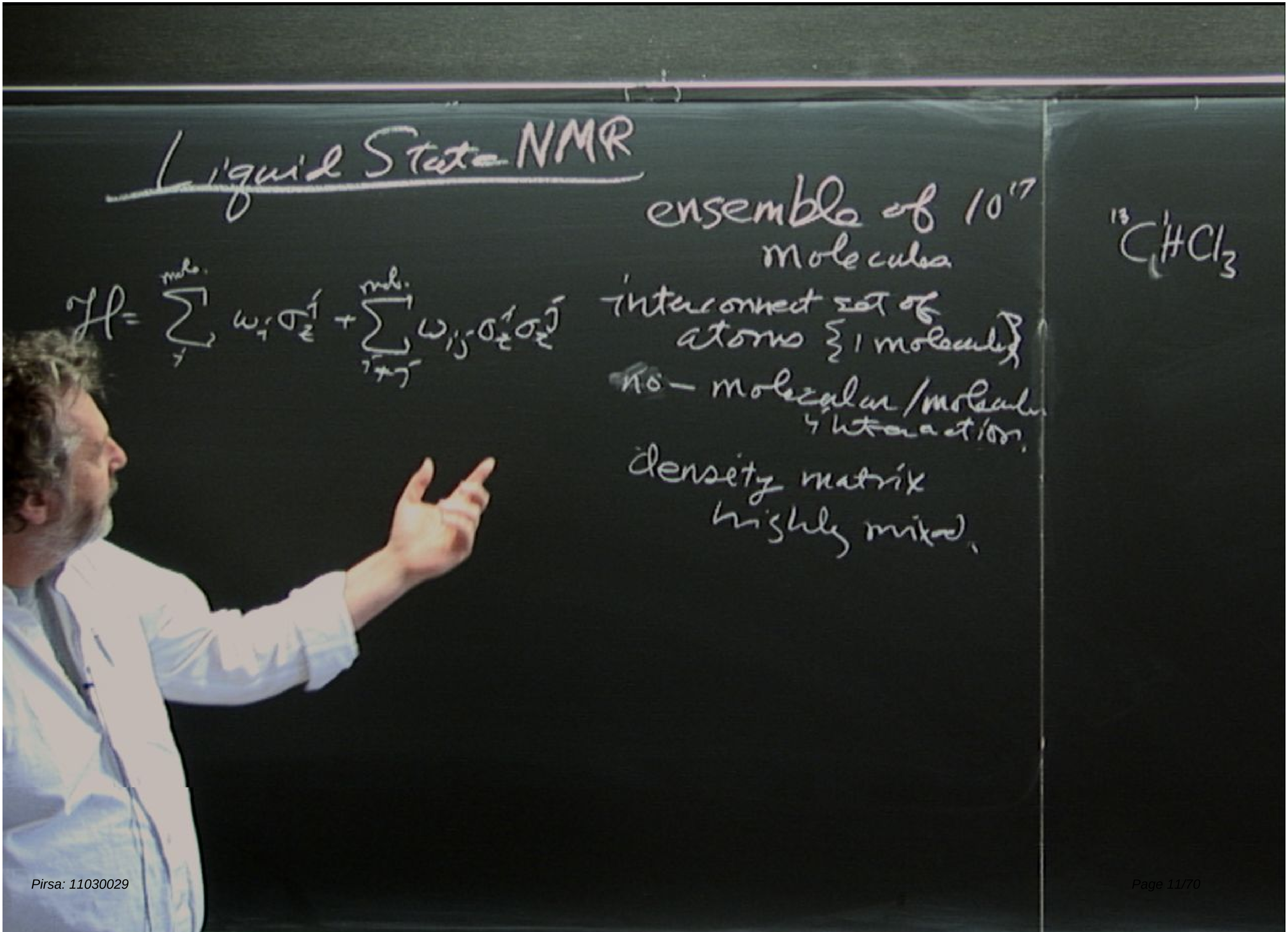
$$\mathcal{H} = \sum_{i}^{\text{mols.}} \omega_i \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \omega_{ij} \sigma_z^i \sigma_z^j$$

ensemble of 10^{17}
molecules

interconnect set of
atoms {1 molecule}

no - molecular/molecule
interaction.

density matrix
highly mixed.



Liquid State NMR

$$\mathcal{H} = \sum_{i}^{mols.} \omega_i \sigma_z^i + \sum_{i \neq j}^{mols.} \omega_{ij} \sigma_z^i \sigma_z^j$$

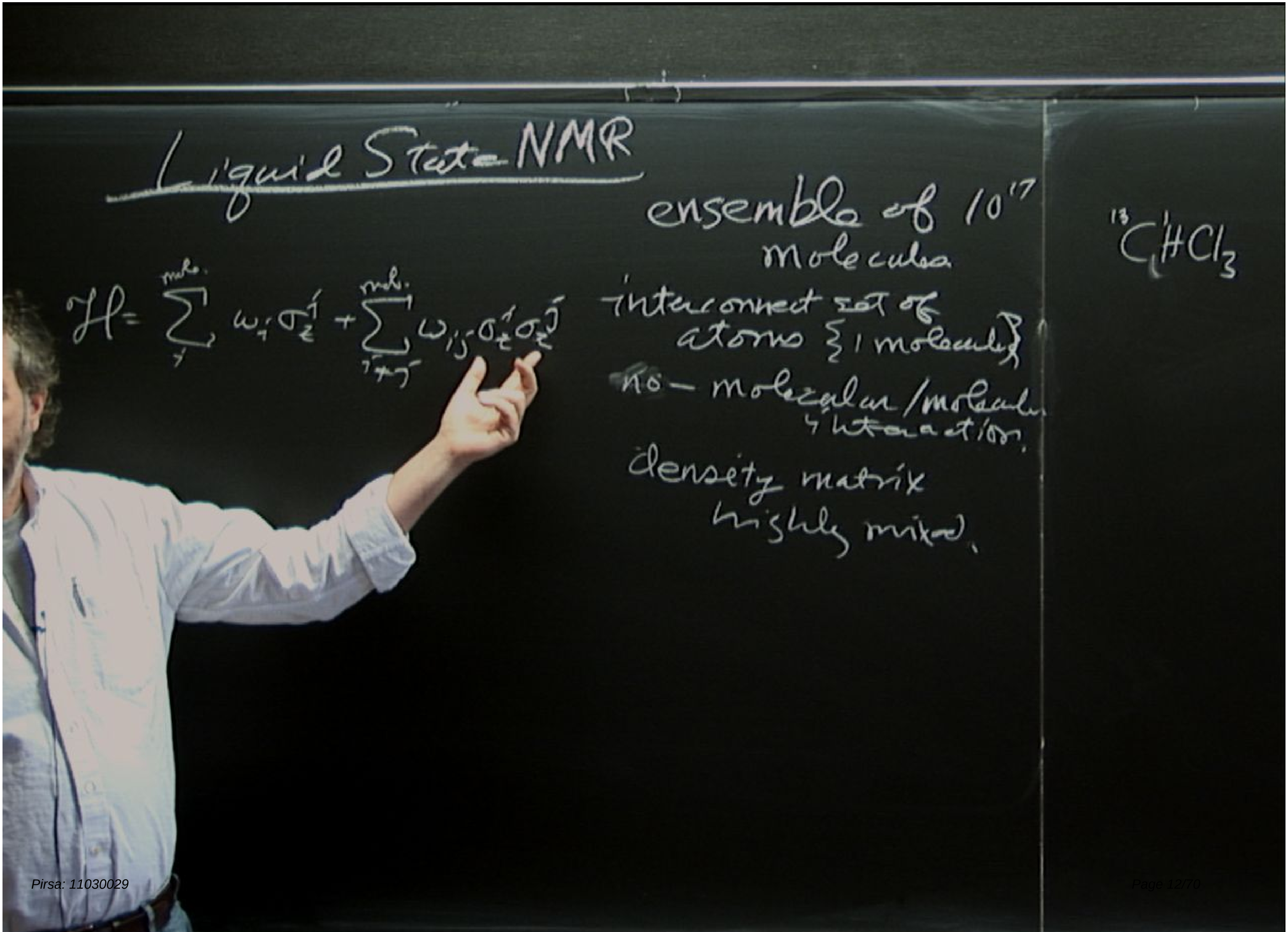
ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

no - molecular/molecular interaction.

density matrix highly mixed.

$^{13}C\,^{1}HCl_3$



Liquid State NMR

$$\mathcal{H} = \sum_{i}^{\text{mols.}} \omega_i \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \omega_{ij} \sigma_z^i \sigma_z^j$$

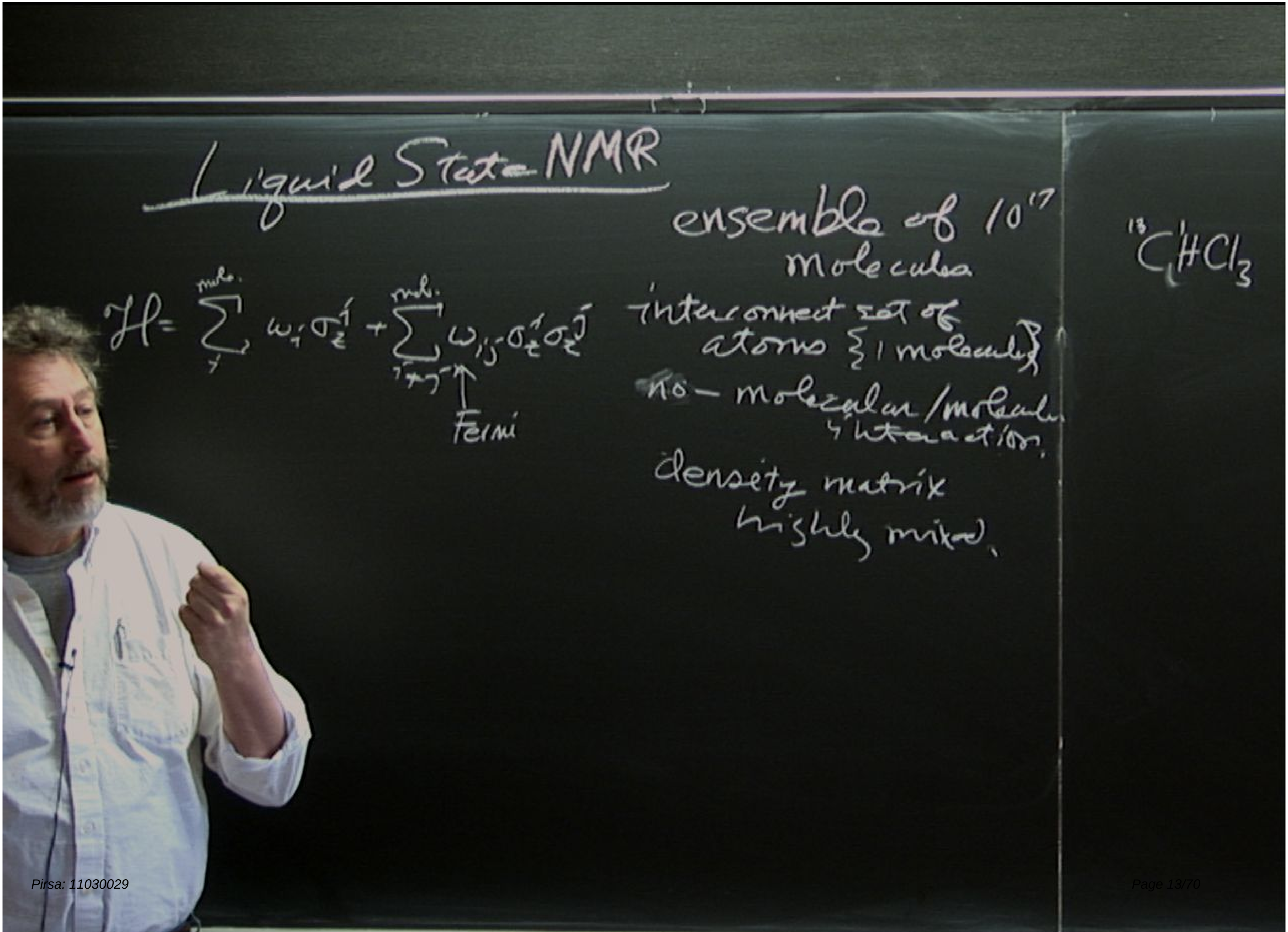
ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

no - molecular/molecular interaction.

density matrix highly mixed.

$^{13}C\,^{1}H\,Cl_3$



Liquid State NMR

$$\mathcal{H} = \sum_{i}^{\text{mol.}} \omega_i \sigma_z^i + \underbrace{\sum_{i \neq j}^{\text{mol.}}}_{} \omega_{ij} \sigma_z^i \sigma_z^j$$

↑ Fermi

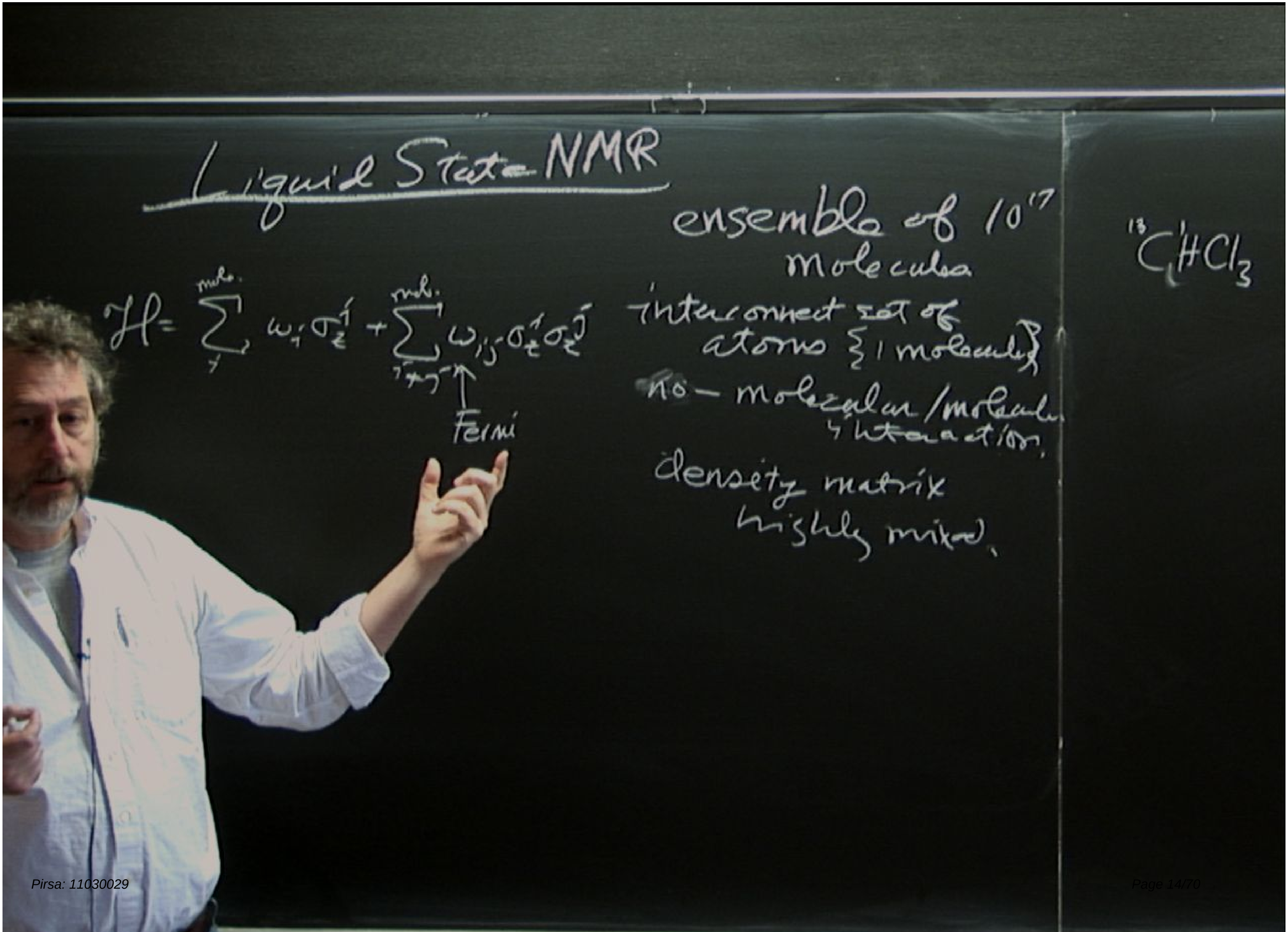
ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

no – molecular/molecule interaction.

density matrix highly mixed.

$^{13}C\,^{1}HCl_3$



Liquid State NMR

$$\mathcal{H} = \sum_{i}^{\text{mols.}} \omega_i \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \omega_{ij} \sigma_z^i \sigma_z^j$$

↑ Fermi

ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

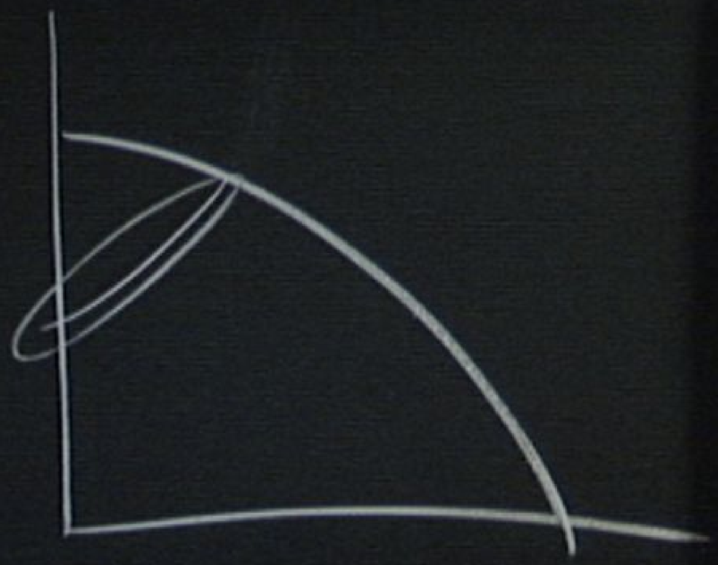
no - molecular/molecule interaction.

density matrix highly mixed.

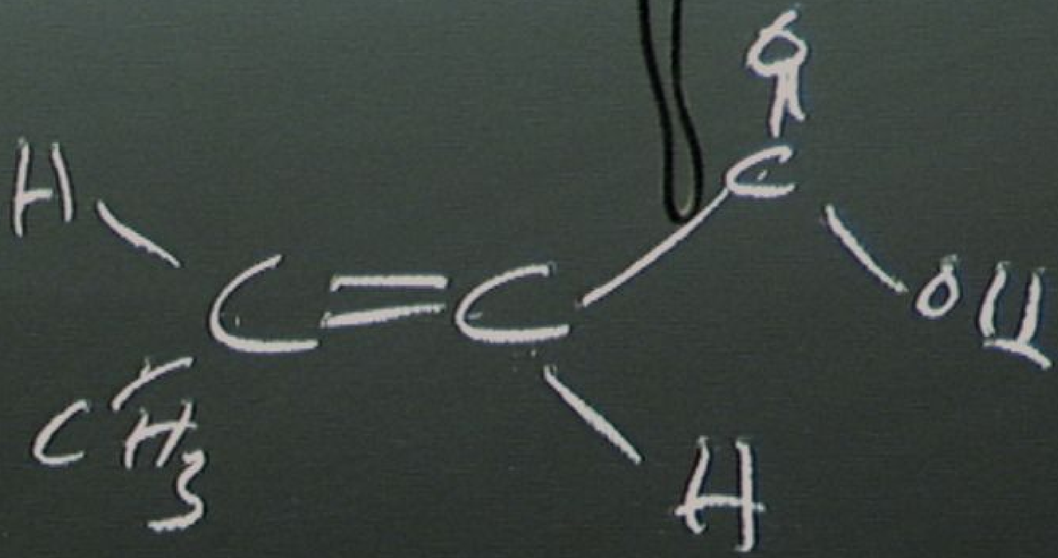
$^{13}C\,^{1}HCl_3$

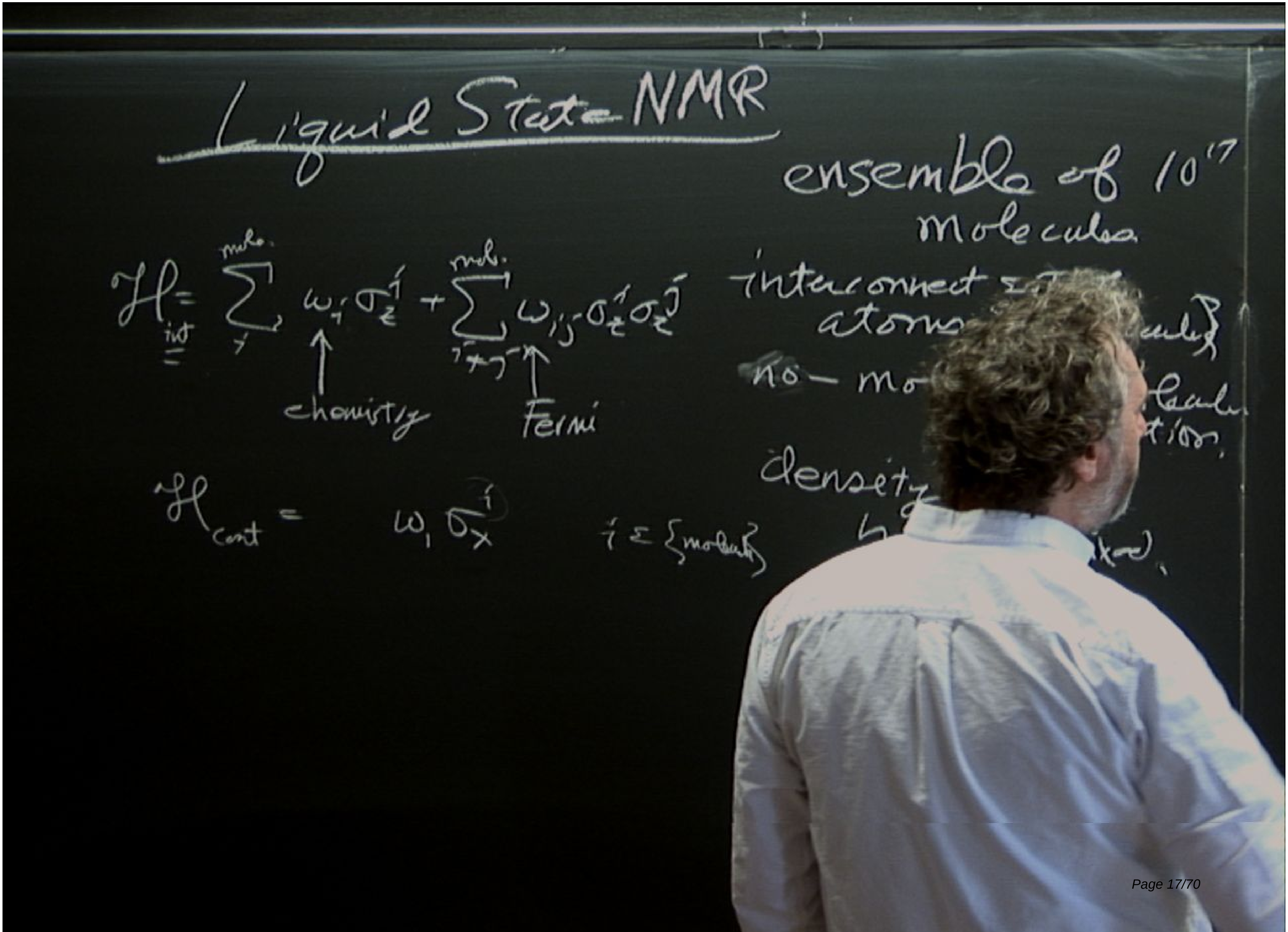
$$\Delta\omega(\sigma_z^1 - \sigma_z^2) + \omega_{ij}\sigma^1 \cdot \sigma^2$$

$$\sigma_+\sigma_- + \sigma_-\sigma_+ + \sigma_z\sigma_z$$



$^{13}CHCl_3$





Liquid State NMR

$$\mathcal{H}_{\underline{\underline{int}}} = \sum_{i}^{\text{mols.}} \underset{\overset{\uparrow}{\text{chemistry}}}{\omega_i \sigma_z^i} + \sum_{i \neq j}^{\text{mols.}} \underset{\overset{\uparrow}{\text{Fermi}}}{\omega_{ij}} \sigma_z^i \sigma_z^j$$

$$\mathcal{H}_{cont} = \omega_1 \sigma_x^i \qquad i \in \{\text{molecules}\}$$

ensemble of 10^{17} molecules

interconnect ... atoms ... cules}

no – mo... ...lecule ...tion;

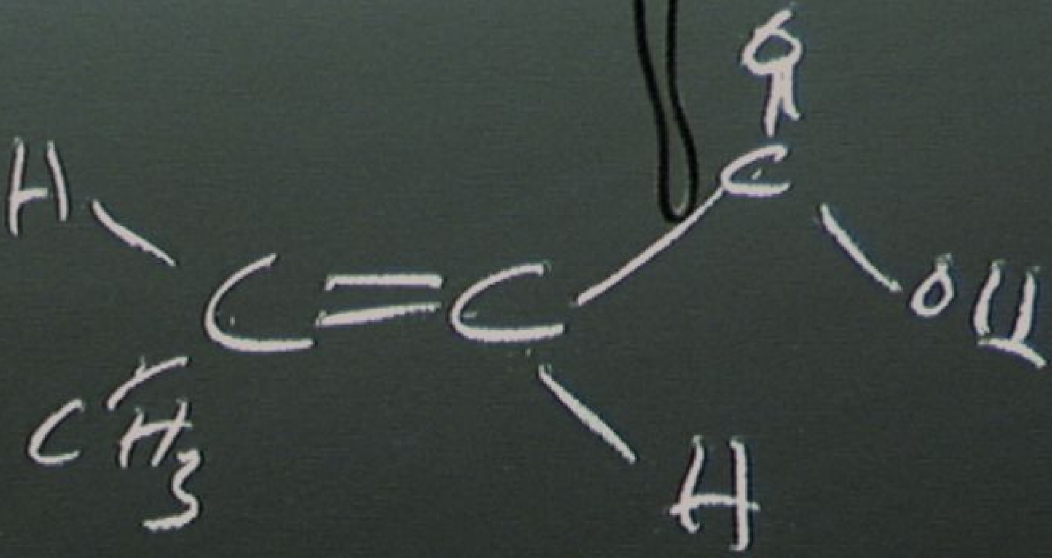
density ... b... ...ixed.

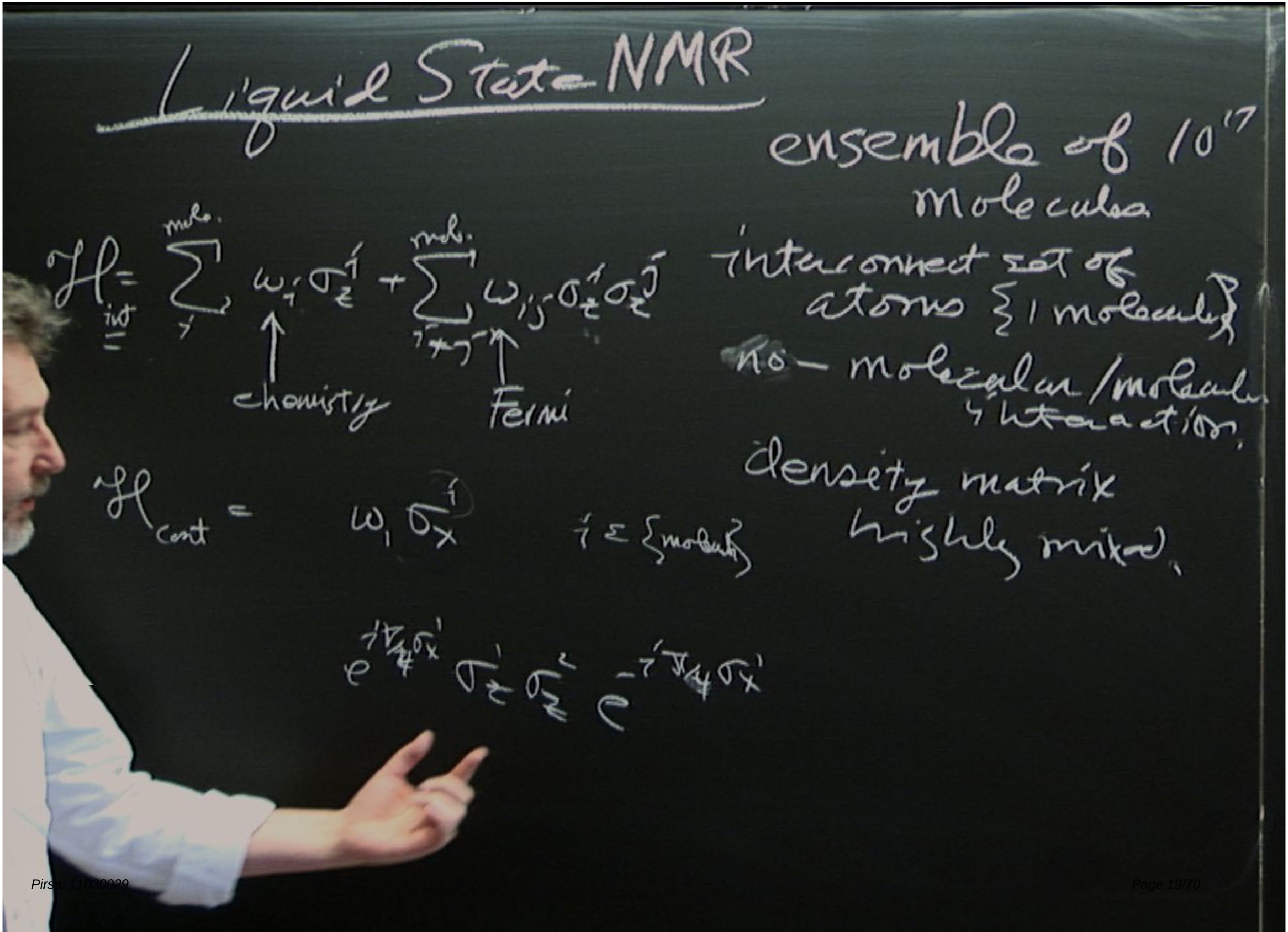
$^{13}CHCl_3$

$\sigma^{C}_{xyz} \otimes \underline{1\!\!1}^{H}$

$\sigma^{H}_{xyz} \otimes 1\!\!1^{C}$

$\sigma^{C}_{xyz} \otimes \sigma^{H}_{xyz}$





Liquid State NMR

ensemble of 10^{17} molecules

$$\mathcal{H}_{\underline{\underline{int}}} = \sum_{i}^{mols.} \omega_i \sigma_z^i + \sum_{i \neq j}^{mols.} \omega_{ij} \sigma_z^i \sigma_z^j$$

chemistry Fermi

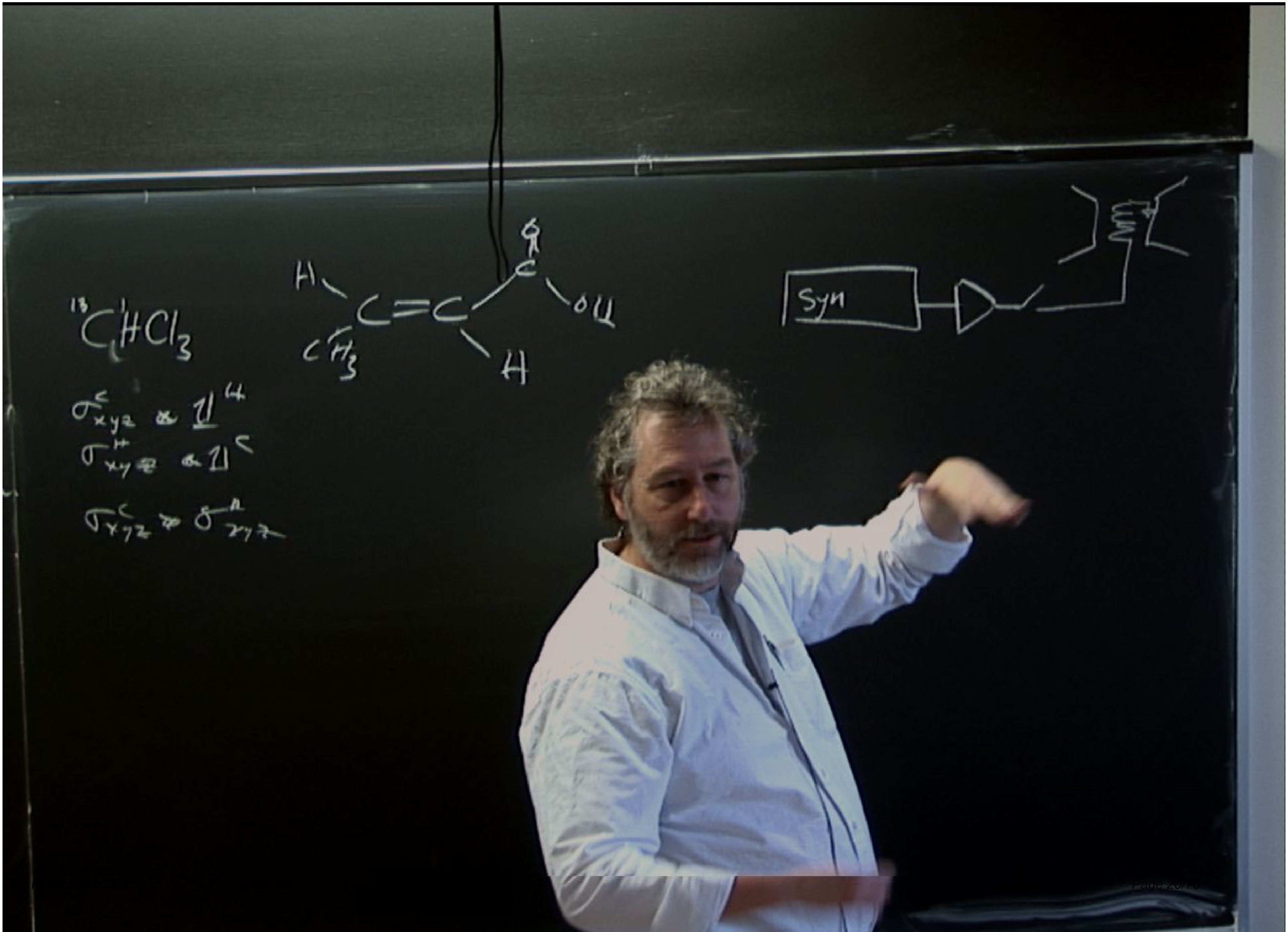
interconnect set of atoms {1 molecule}

no – molecular/molecule interaction.

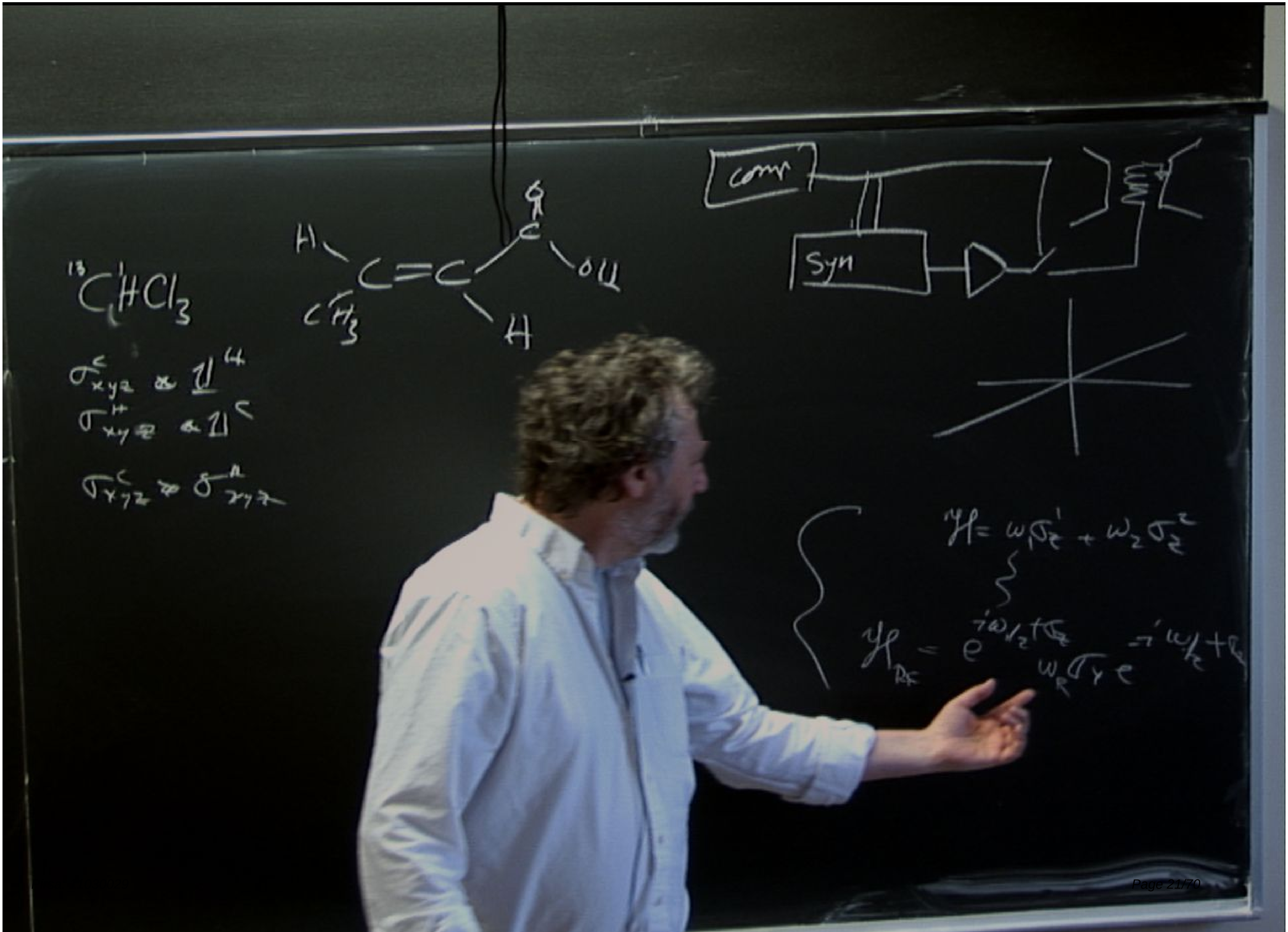
density matrix highly mixed.

$$\mathcal{H}_{cont} = \omega_1 \sigma_x^i \qquad i \in \{\text{molecule}\}$$

$$e^{i\pi/4\,\sigma_x^1}\,\sigma_z^1 \sigma_z^2\, e^{-i\pi/4\,\sigma_x^1}$$



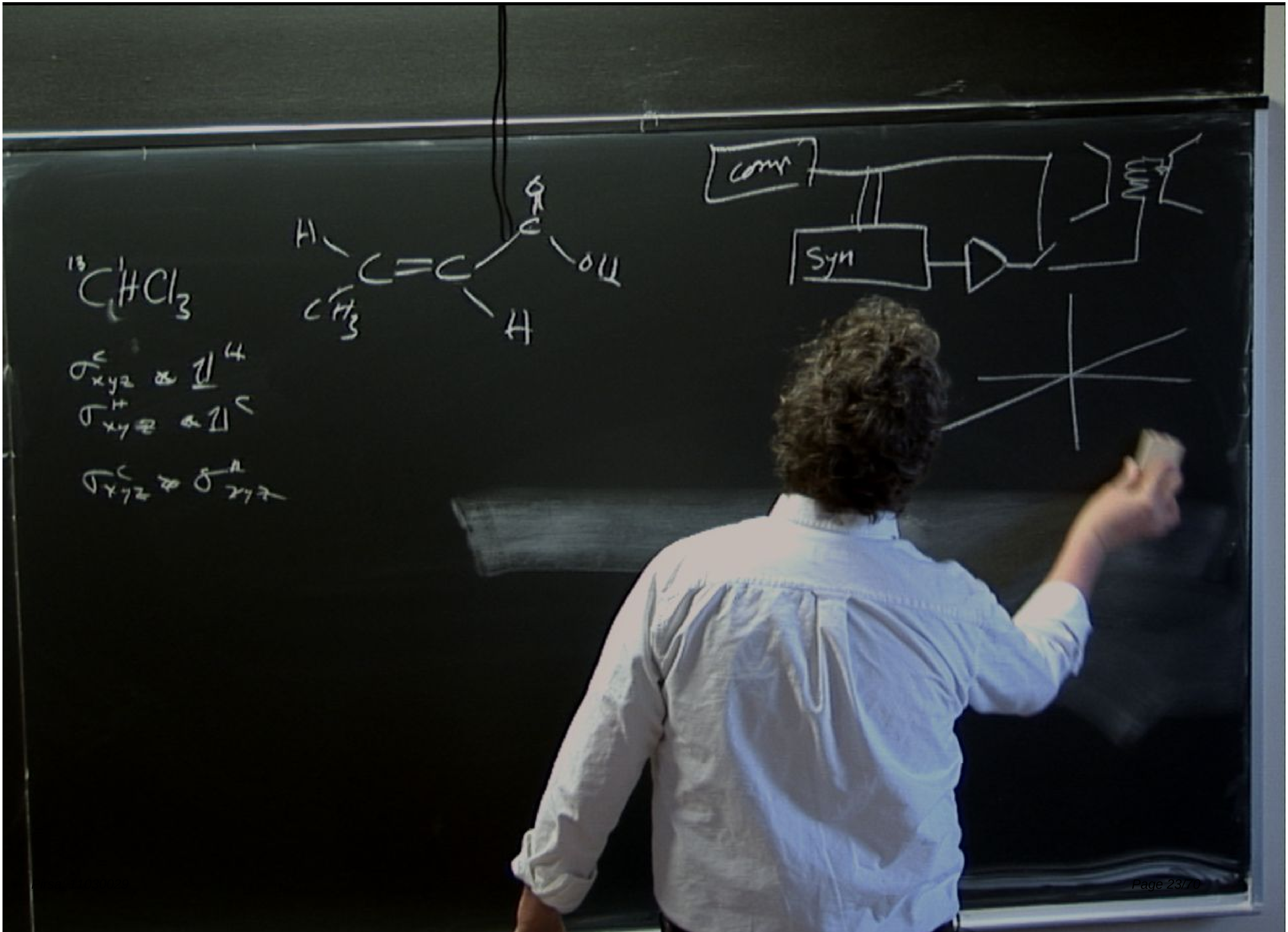
$^{13}C^{1}HCl_3$
$\sigma^{C}_{xyz} \propto \gamma^{H}$
$\sigma^{H}_{xyz} \propto \gamma^{C}$
$\sigma^{C}_{xyz} \gg \sigma^{H}_{xyz}$
H
C=C
CH3
H
O
C
OH
Syn

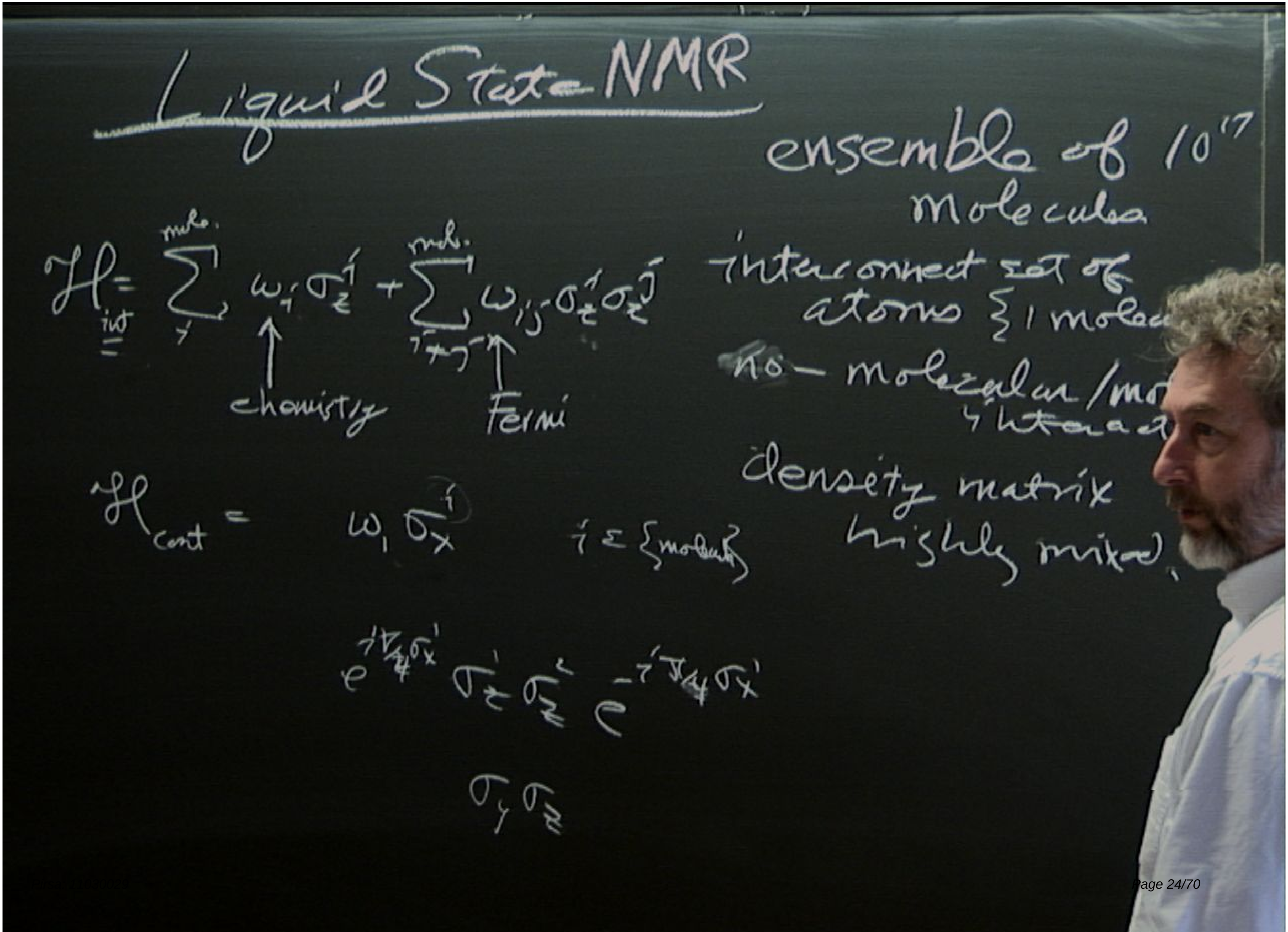

$^{13}C\,^{1}HCl_3$
$\sigma^{C}_{xyz} \propto \mathcal{U}^{H}$
$\sigma^{H}_{xyz} \propto \mathcal{U}^{C}$
$\sigma^{C}_{xyz} \not\propto \sigma^{H}_{xyz}$
H
C=C
CH3
O
C
OH
H
comp
Syn
$\mathcal{H} = \omega_1 \sigma^1_z + \omega_2 \sigma^2_z$
$\mathcal{H}_{RF} = e^{i\omega_1/2 t\sigma_z} \omega_R \sigma_x e^{-i\omega_1/2 t\sigma_z}$

$$\mathcal{H} = \omega_1 \sigma_z^1 + \omega_2 \sigma_z^2$$

$$\Bigg\{ \quad \big\downarrow \quad$$

$$\mathcal{H}_{RF} = e^{i\omega_{1/2} t \sigma_z} \, \omega_R \sigma_x \, e^{-i\omega_{1/2} t \sigma_z}$$


$^{13}C\,^{1}HCl_3$
$\sigma^{C}_{xyz} \propto \mathcal{U}^{H}$
$\sigma^{H}_{xyz} \propto \mathcal{U}^{C}$
$\sigma^{C}_{xyz} \propto \sigma^{H}_{xyz}$
H
C=C
CH3
O
C
OH
H
comp
Syn



Liquid State NMR

ensemble of 10^{17} molecules

interconnect set of atoms $\in$ 1 molec

no - molecular / mo
interact

density matrix
highly mixed.

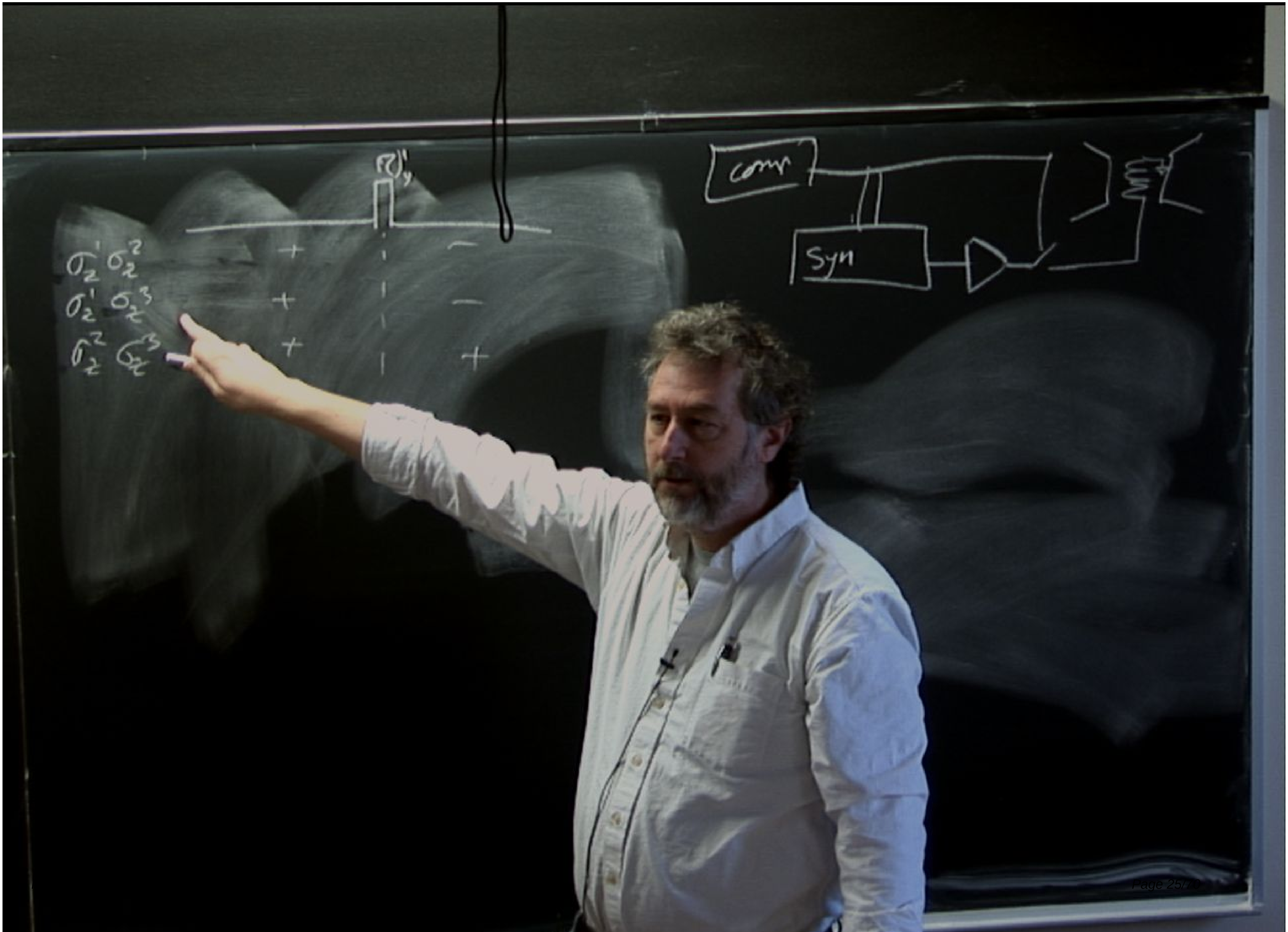
$$\mathcal{H}_{\underline{\underline{int}}} = \sum_{i}^{\text{mols.}} \omega_i \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \omega_{ij} \sigma_z^i \sigma_z^j$$

$\uparrow$ chemistry $\qquad$ $\uparrow$ Fermi

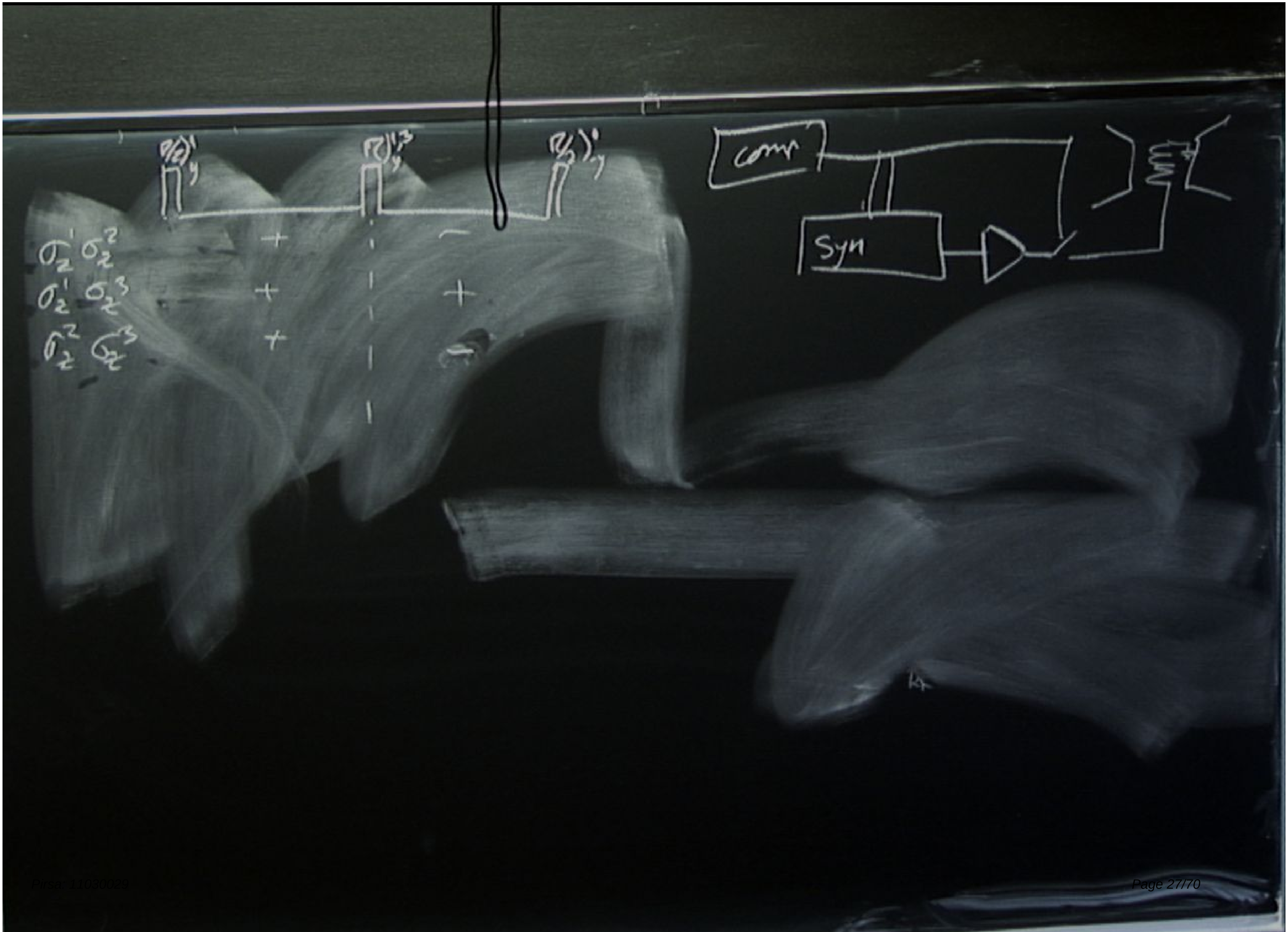
$$\mathcal{H}_{cont} = \omega_1 \sigma_x^i \qquad i \in \{\text{molecules}\}$$

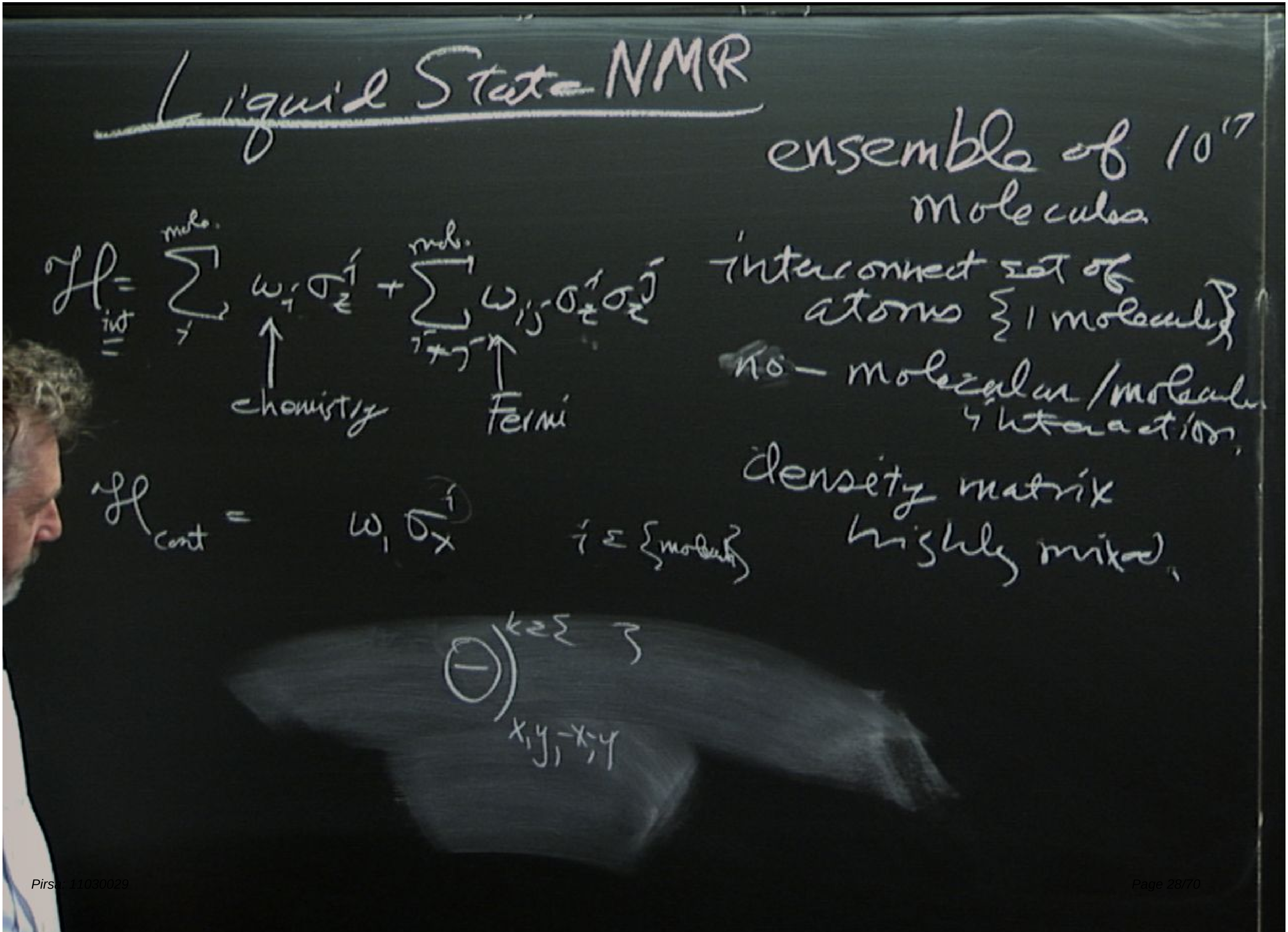
$$e^{i\pi/4\,\sigma_x^1} \sigma_z^1 \sigma_z^2 \, e^{-i\pi/4\,\sigma_x^1}$$

$$\sigma_y \sigma_z$$


comp
Syn
$\sigma_z^1 \sigma_z^2$
$\sigma_z^1 \sigma_z^3$
$\sigma_z^2 \sigma_z^3$
+
+
+
−
−
+


$\sigma_z^1 \sigma_z^2$ + −
$\sigma_z^1 \sigma_z^3$ + +
$\sigma_z^2 \sigma_z^3$ + +
comp
Syn


$(\pi/2)^1_y$
$(\pi/2)^{1,3}_y$
$(\pi/2)^1_y$
$\sigma_z^1\sigma_z^2$ + −
$\sigma_z^1\sigma_z^3$ + +
$\sigma_z^2\sigma_z^3$ + −
comp
Syn



Liquid State NMR

ensemble of 10^{17}
molecules

interconnect set of
atoms {1 molecule}

no - molecular/molecule
interaction

density matrix
highly mixed.

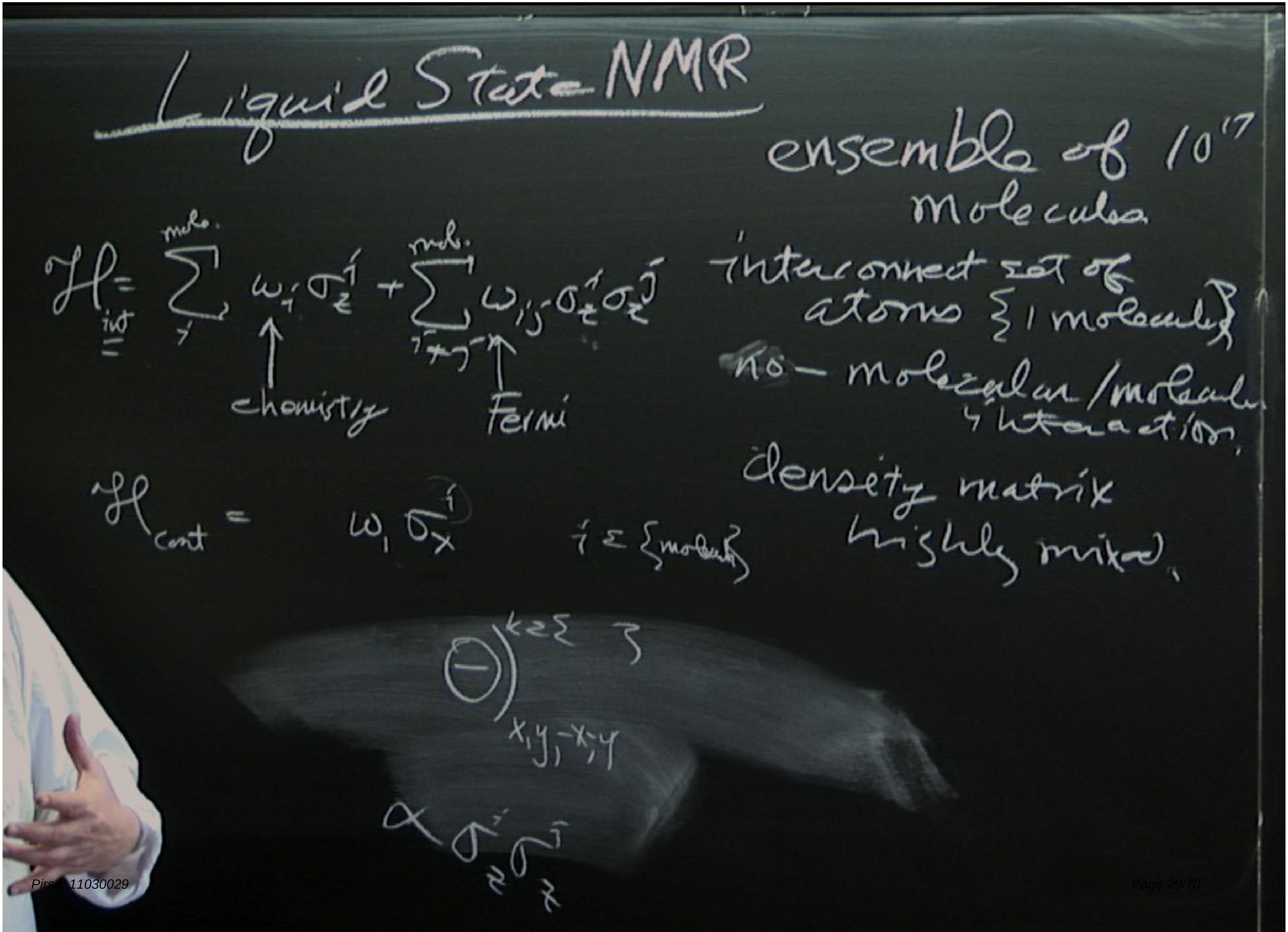
$$\underline{\underline{\mathcal{H}_{int}}} = \sum_{i}^{\text{mols.}} \omega_i \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \omega_{ij} \sigma_z^i \sigma_z^j$$

$\uparrow$ chemistry

$\uparrow$ Fermi

$$\mathcal{H}_{cont} = \omega_1 \sigma_x^i \qquad i \in \{\text{molecule}\}$$

$$\Theta \Big)^{k \in \{\ \}}_{x, y, -x, -y}$$



Liquid State NMR

$$\mathcal{H}_{\underline{\underline{int}}} = \sum_{i}^{\text{mols.}} \underset{\substack{\uparrow \\ \text{chemistry}}}{\omega_i} \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \underset{\substack{\uparrow \\ \text{Fermi}}}{\omega_{ij}} \sigma_z^i \sigma_z^j$$

$$\mathcal{H}_{cont} = \omega_1 \sigma_x^i \qquad i \in \{\text{molecule}\}$$

ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

no – molecular/molecular interaction.

density matrix highly mixed.

$$\ominus \Big)^{k \in \{\quad\}}_{x, y, -x, -y}$$

$$\propto \sigma_z^i \sigma_z^j$$

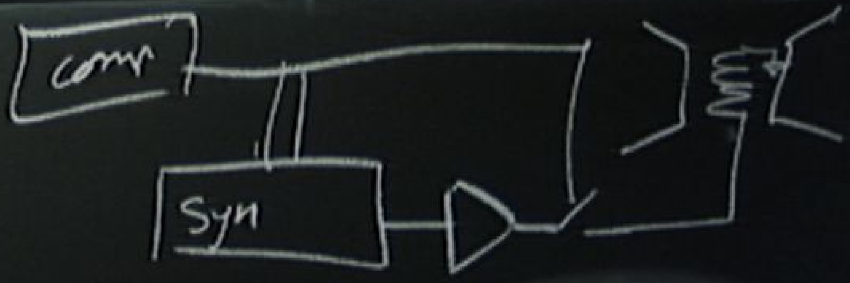
$$\mathcal{U} = \sigma_x E_- + \mathbb{1} E_+$$

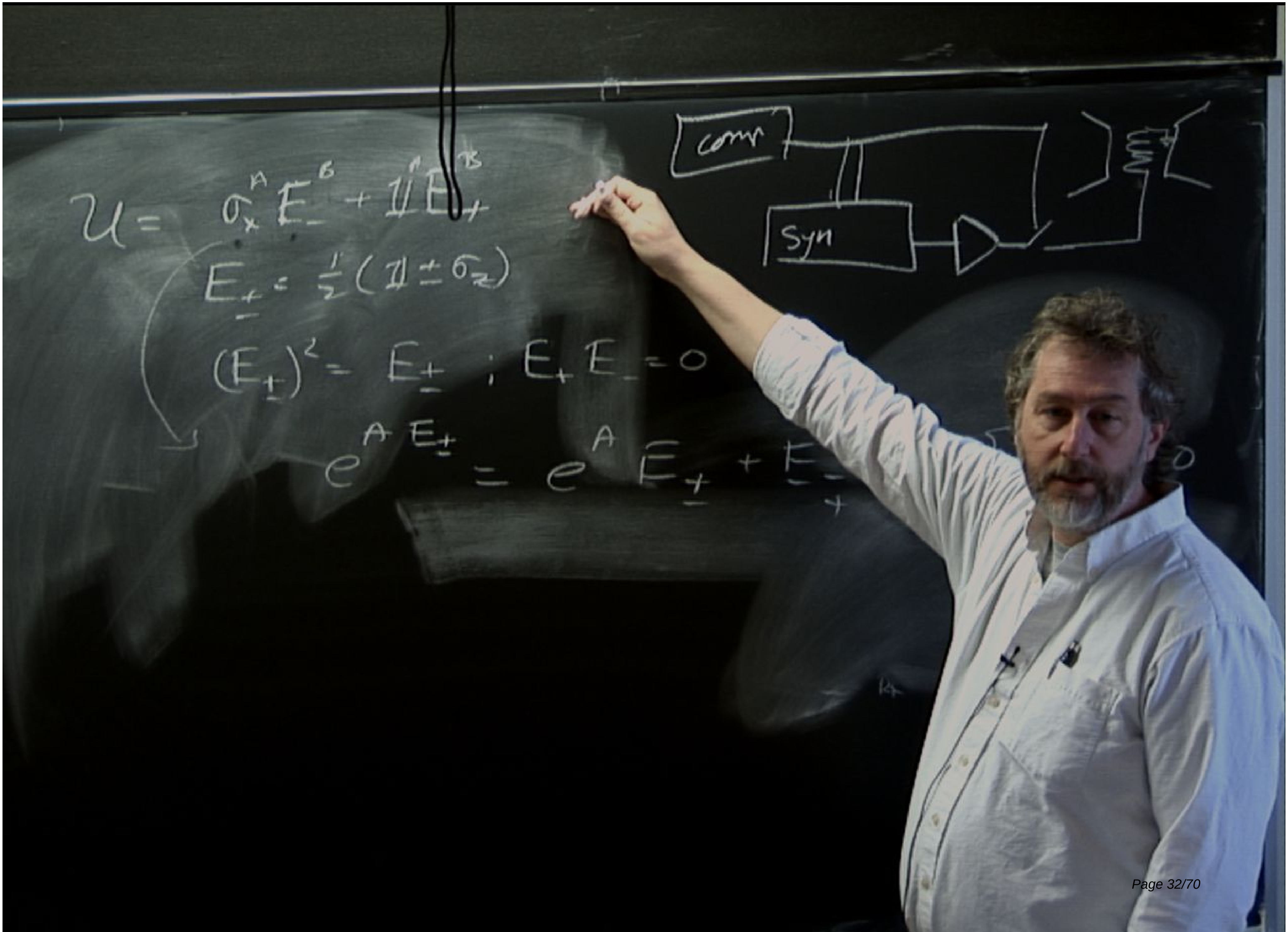
$$E_\pm = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

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

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$



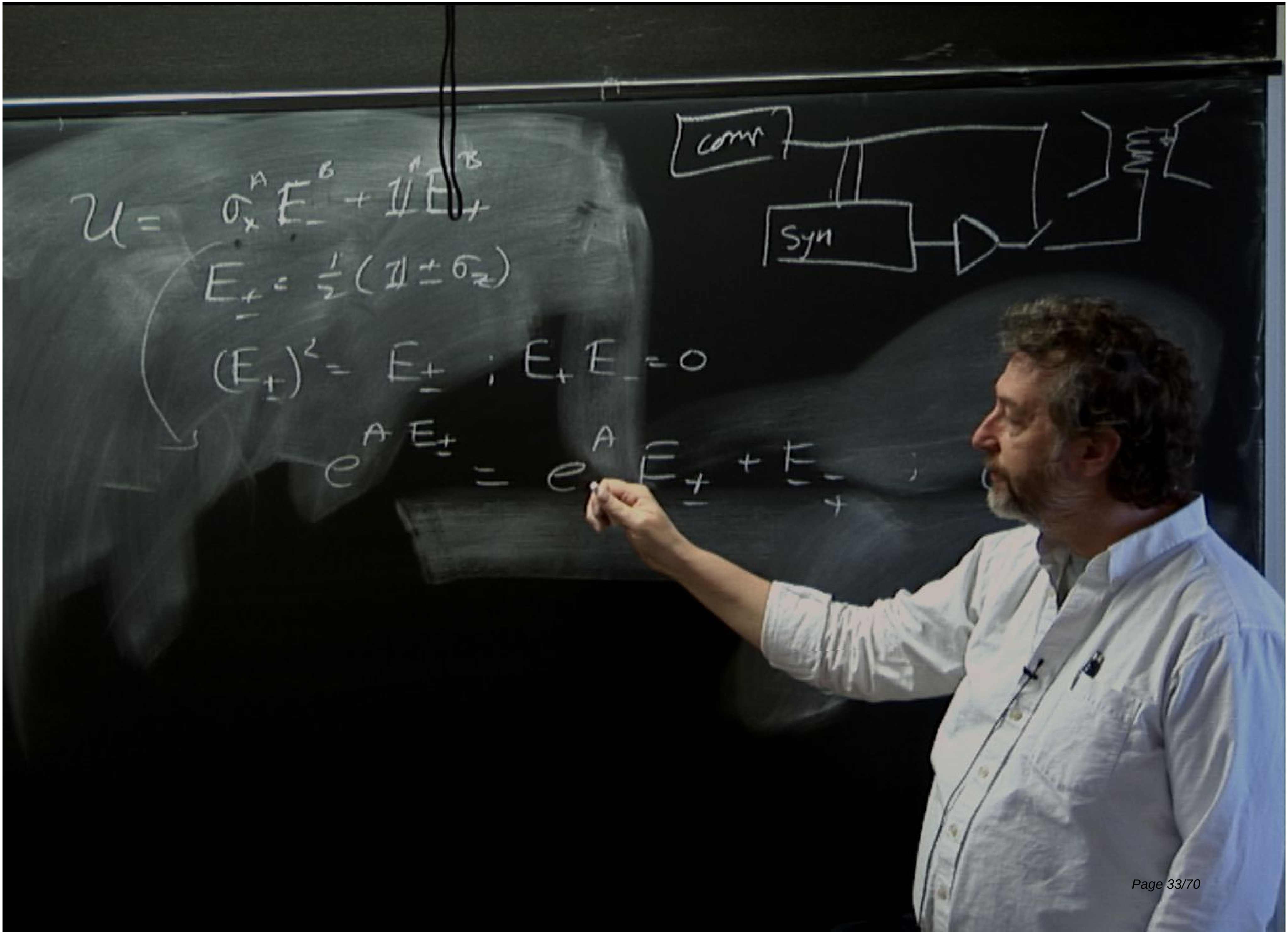


$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

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

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$

$$e^{A E_\pm} = e^A E_\pm + E_\mp$$

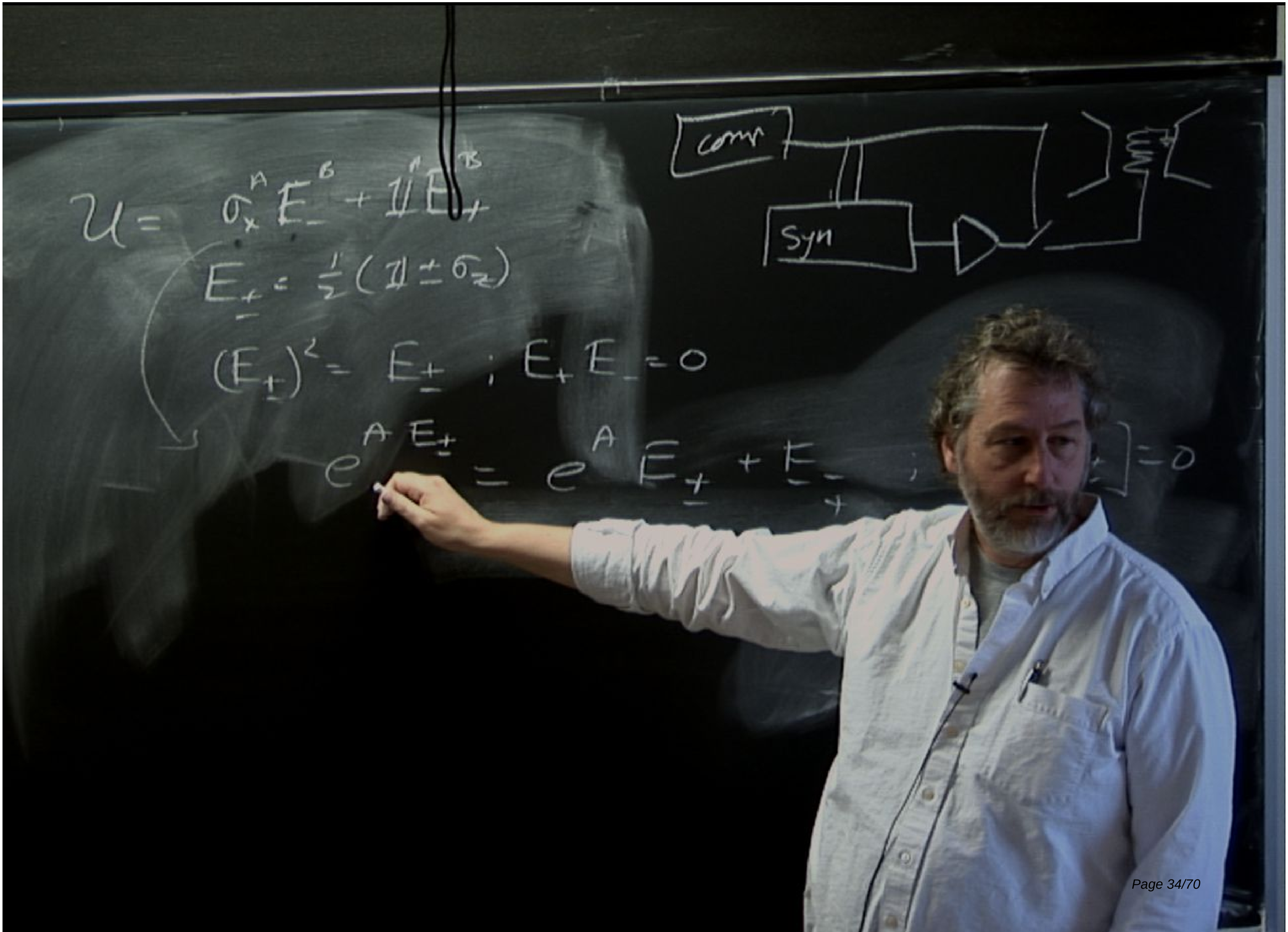


$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

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

$$(E_{\pm})^2 = E_{\pm} \; ; \; E_+ E_- = 0$$

$$e^{A E_{\pm}} = e^A E_{\pm} + E_{\mp} \; ;$$



$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

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

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$

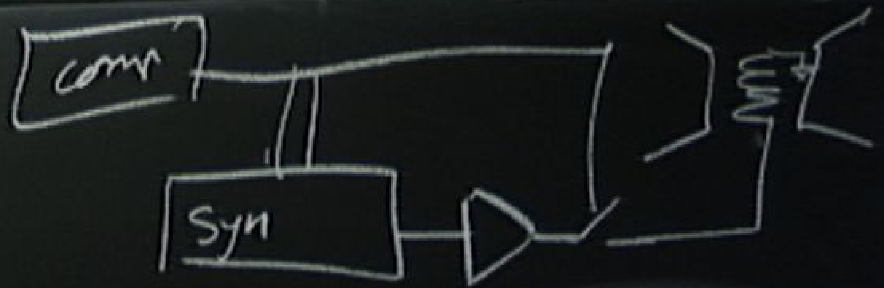
$$e^{A E_\pm} = e^A E_\pm + E_\mp \; ; \quad \pm] = 0$$

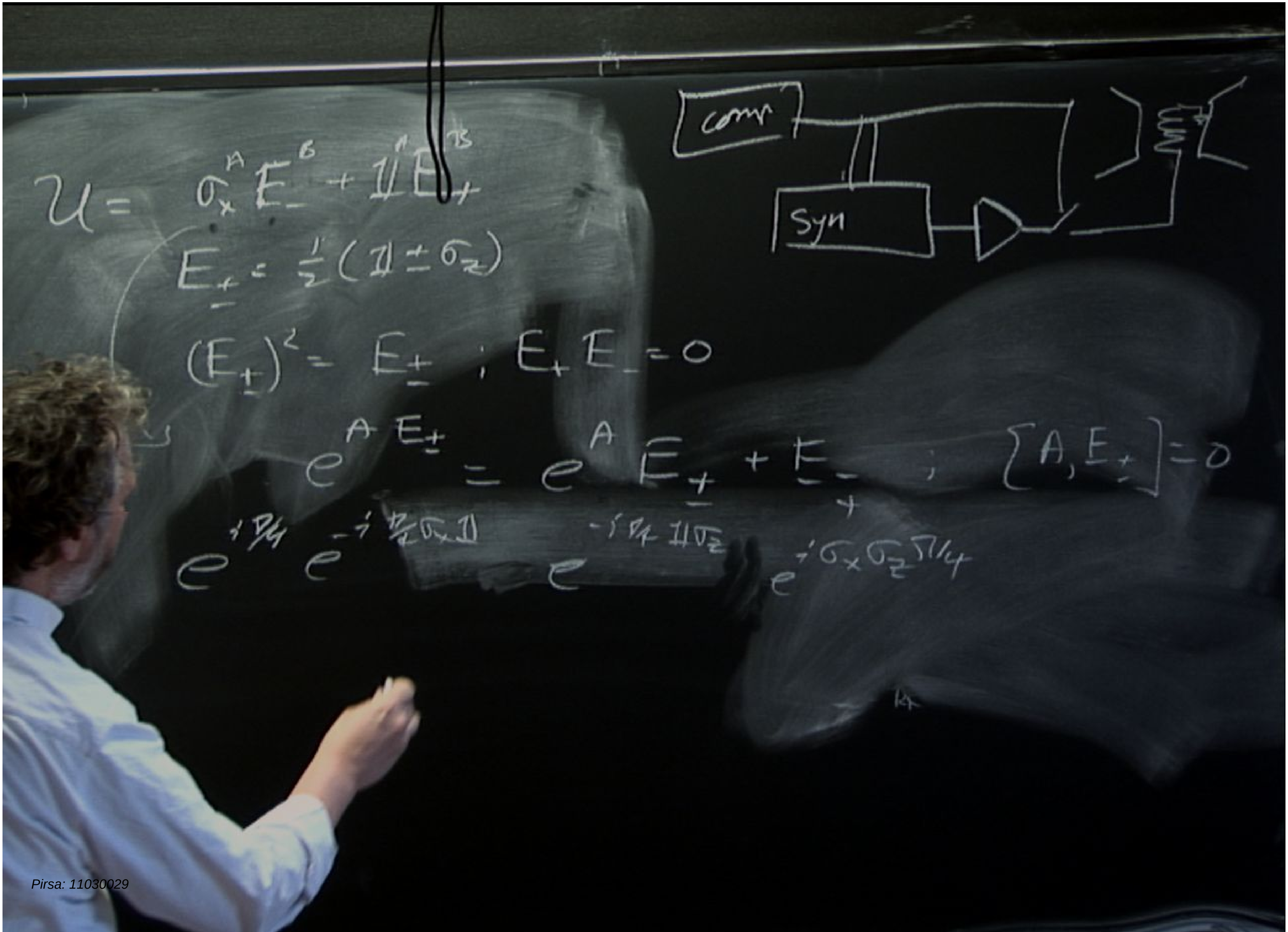
$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

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

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$

$$e^{A E_\pm} = e^A E_\pm + E_\mp \; ; \; [A, E_\pm] = 0$$





$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

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

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$

$$e^{A E_\pm} = e^A E_\pm + E_\mp \; ; \; [A, E_\pm] = 0$$

$$e^{i\pi/4} \, e^{-i\frac{\pi}{4}\sigma_x \mathbb{1}} \, e^{-i\pi/4 \, \mathbb{1}\sigma_z} \, e^{-i\sigma_x\sigma_z \pi/4}$$

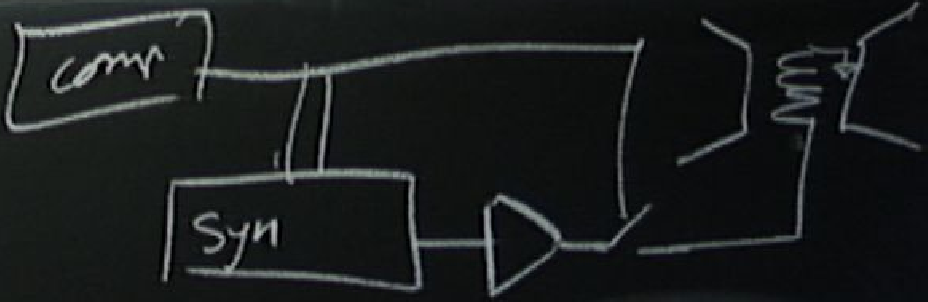
$$U = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

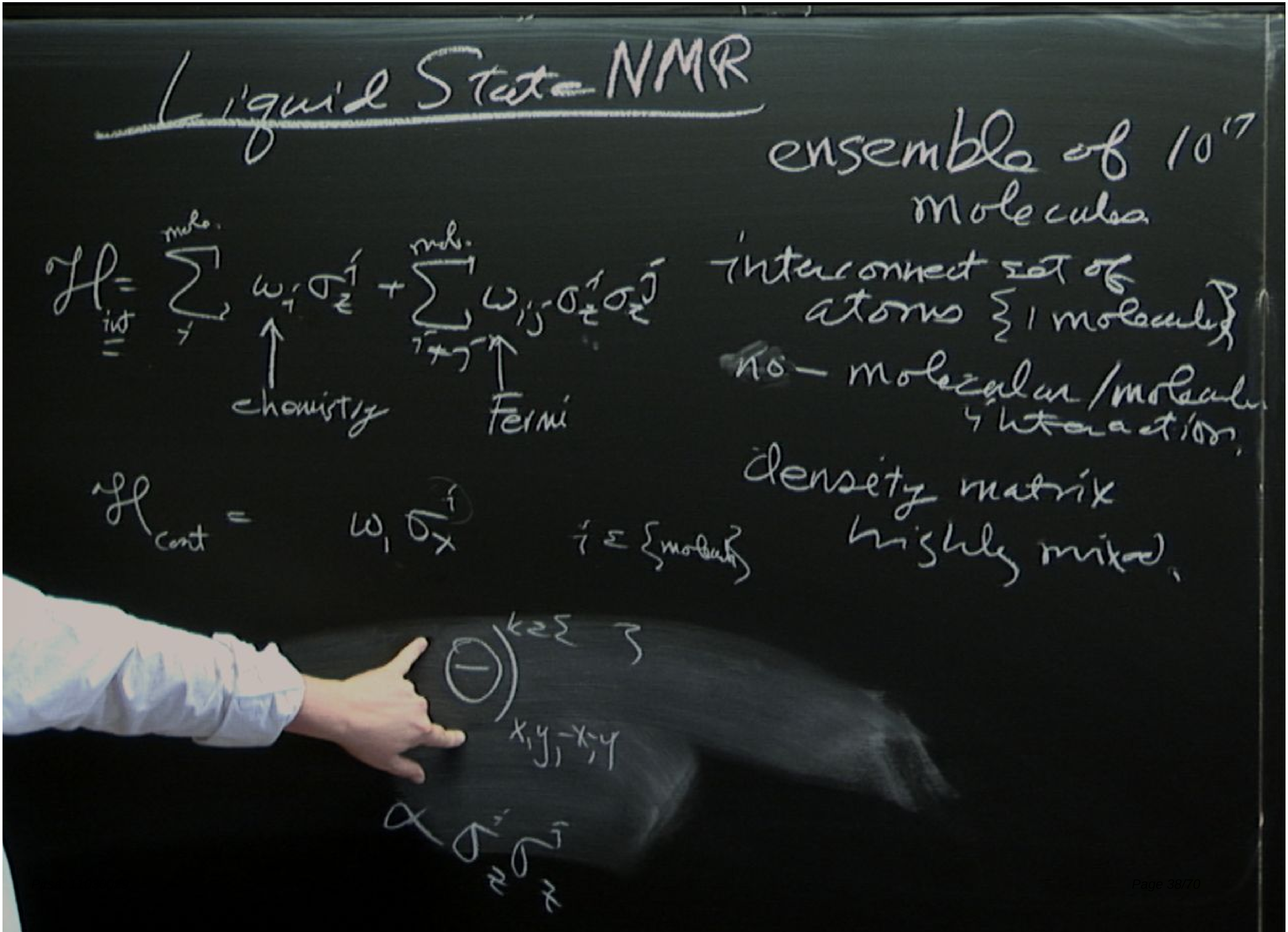
$$E_{\pm} = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

$$(E_{\pm})^2 = E_{\pm} \; ; \; E_+ E_- = 0$$

$$e^{A E_{\pm}} = e^{A} E_{\pm} + E_{\mp} \; ; \; [A, E_{\pm}] = 0$$

$$U = e^{i\pi/4} e^{-i\frac{\pi}{2}\sigma_x \mathbb{1}} e^{-i\pi/4\, \mathbb{1}\sigma_z} e^{i\sigma_x\sigma_z\pi/4}$$





Liquid State NMR

ensemble of 10^{17} molecules

interconnect set of atoms {1 molecule}

no — molecular/molecule interaction

density matrix highly mixed.

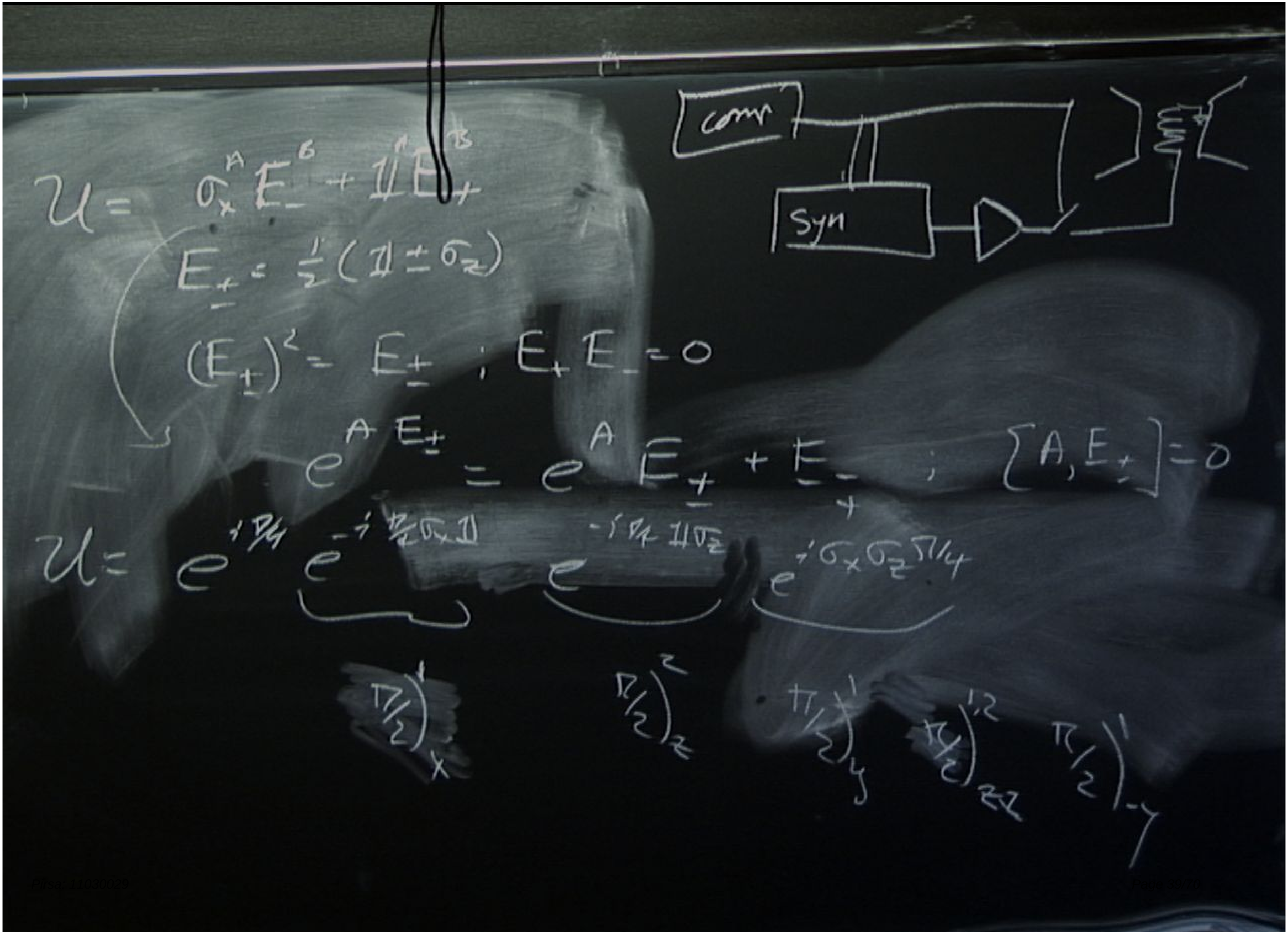
$$\mathcal{H}_{\underline{\underline{int}}} = \sum_{i}^{\text{mols.}} \underset{\overset{\uparrow}{\text{chemistry}}}{\omega_i \sigma_z^i} + \sum_{i \neq j}^{\text{mols.}} \underset{\overset{\uparrow}{\text{Fermi}}}{\omega_{ij} \sigma_z^i \sigma_z^j}$$

$$\mathcal{H}_{cont} = \omega_1 \sigma_x^{i} \qquad i \in \{\text{molecule}\}$$

$$\left(\ominus\right)^{k \in \{\ \}}$$

$x, y, -x, -y$

$$\propto \sigma_z^i \sigma_z^j$$



$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

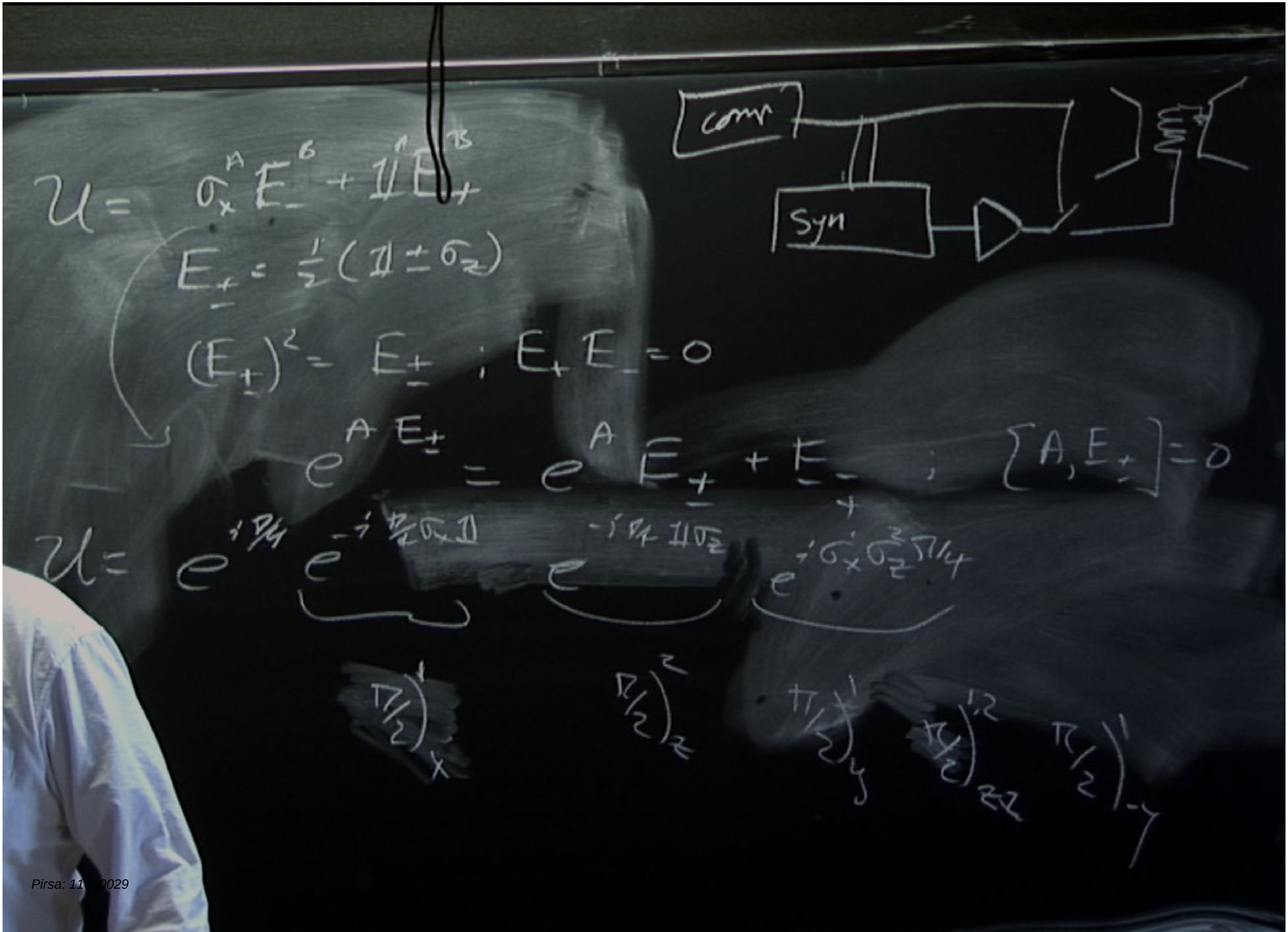
$$E_\pm = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$

$$e^{A E_\pm} = e^A E_\pm + E_\mp \; ; \; [A, E_\pm] = 0$$

$$\mathcal{U} = e^{i\pi/4} \underbrace{e^{-i\frac{\pi}{4}\sigma_x \mathbb{1}}}_{(\pi/2)_x^1} \underbrace{e^{-i\pi/4\, \mathbb{1}\sigma_z}}_{(\pi/2)_z^2} \underbrace{e^{i\sigma_x\sigma_z \pi/4}}$$

$$(\pi/2)_y^1 \quad (\pi/2)_{zz}^{1,2} \quad (\pi/2)_{-y}^1$$



$$\mathcal{U} = \sigma_x^A E_-^B + \mathbb{1}^A E_+^B$$

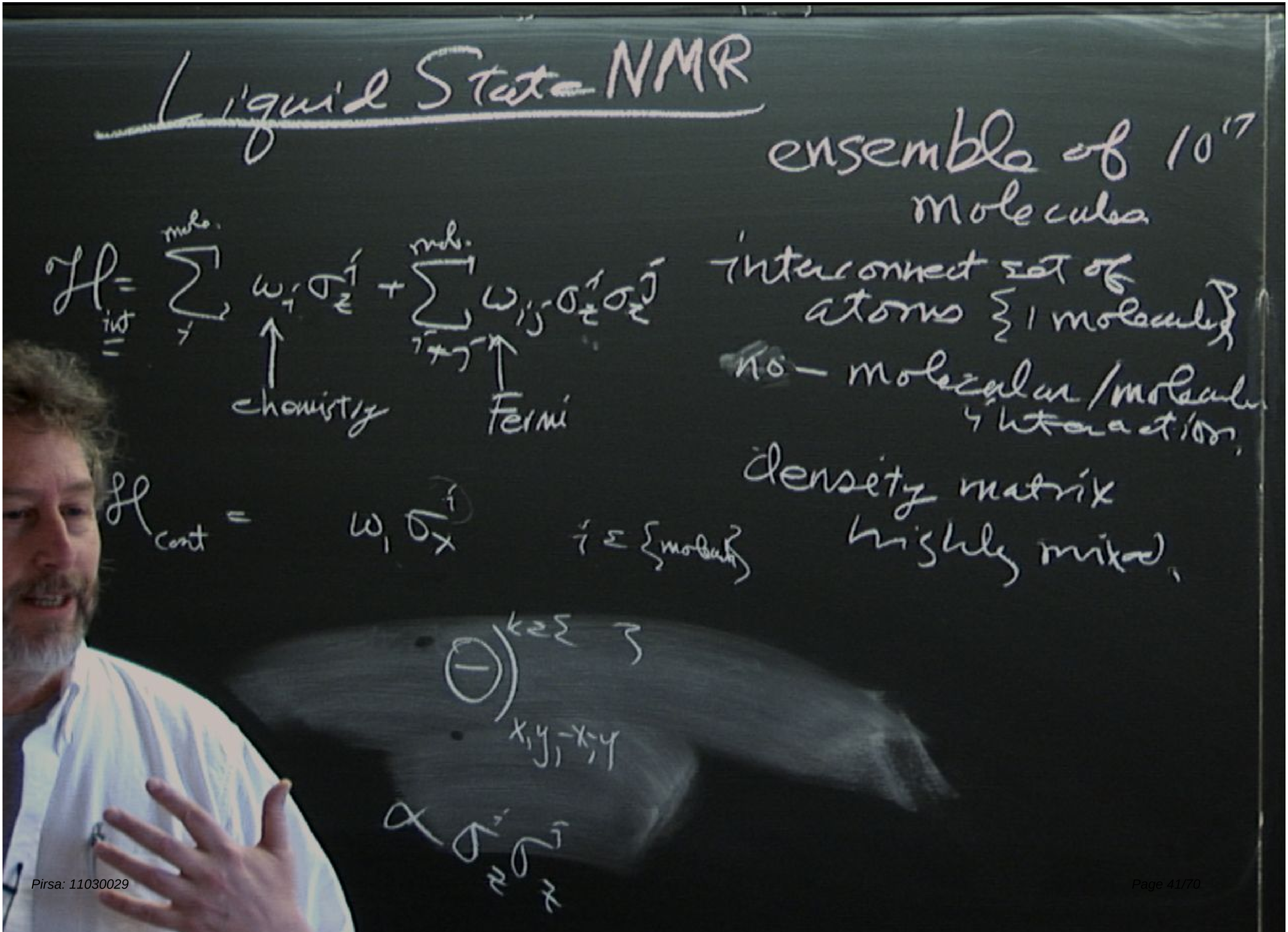
$$E_\pm = \frac{1}{2}(\mathbb{1} \pm \sigma_z)$$

$$(E_\pm)^2 = E_\pm \; ; \; E_+ E_- = 0$$

$$e^{A E_\pm} = e^A E_\pm + E_\mp \; ; \; [A, E_\pm] = 0$$

$$\mathcal{U} = e^{i\pi/4} \underbrace{e^{-i\frac{\pi}{4}\sigma_x \mathbb{1}}} \underbrace{e^{-i\pi/4\, \mathbb{1}\sigma_z}} \underbrace{e^{i\sigma_x^1\sigma_z^2 \pi/4}}$$

$$\frac{\pi}{2}\Big)_x^1 \qquad \frac{\pi}{2}\Big)_z^2 \qquad \frac{\pi}{2}\Big)_y^1 \qquad \frac{\pi}{2}\Big)_{zz}^{12} \qquad \frac{\pi}{2}\Big)_{-y}^1$$



Liquid State NMR

$$\underset{=}{\mathcal{H}_{int}} = \sum_{i}^{\text{mols.}} \omega_i \sigma_z^i + \sum_{i \neq j}^{\text{mols.}} \omega_{ij} \sigma_z^i \sigma_z^j$$

chemistry

Fermi

$$\mathcal{H}_{cont} = \omega_1 \sigma_x^i \qquad i \in \{\text{molecule}\}$$

$$\left(\ominus\right)^{k \in \{\ \}}_{x, y, -x, -y}$$

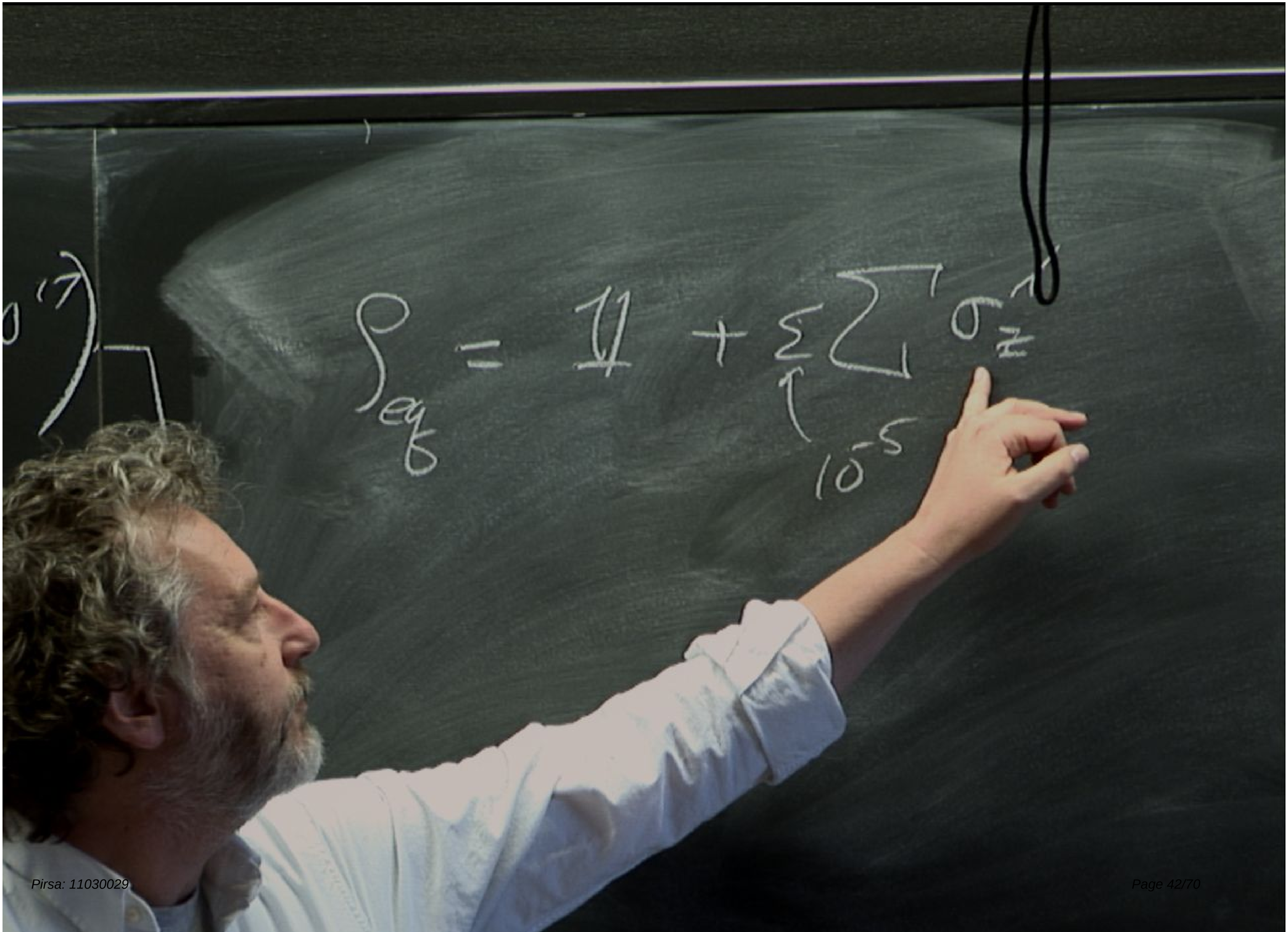
$$\propto \sigma_z^i \sigma_z^j$$

ensemble of 10^{17} molecules

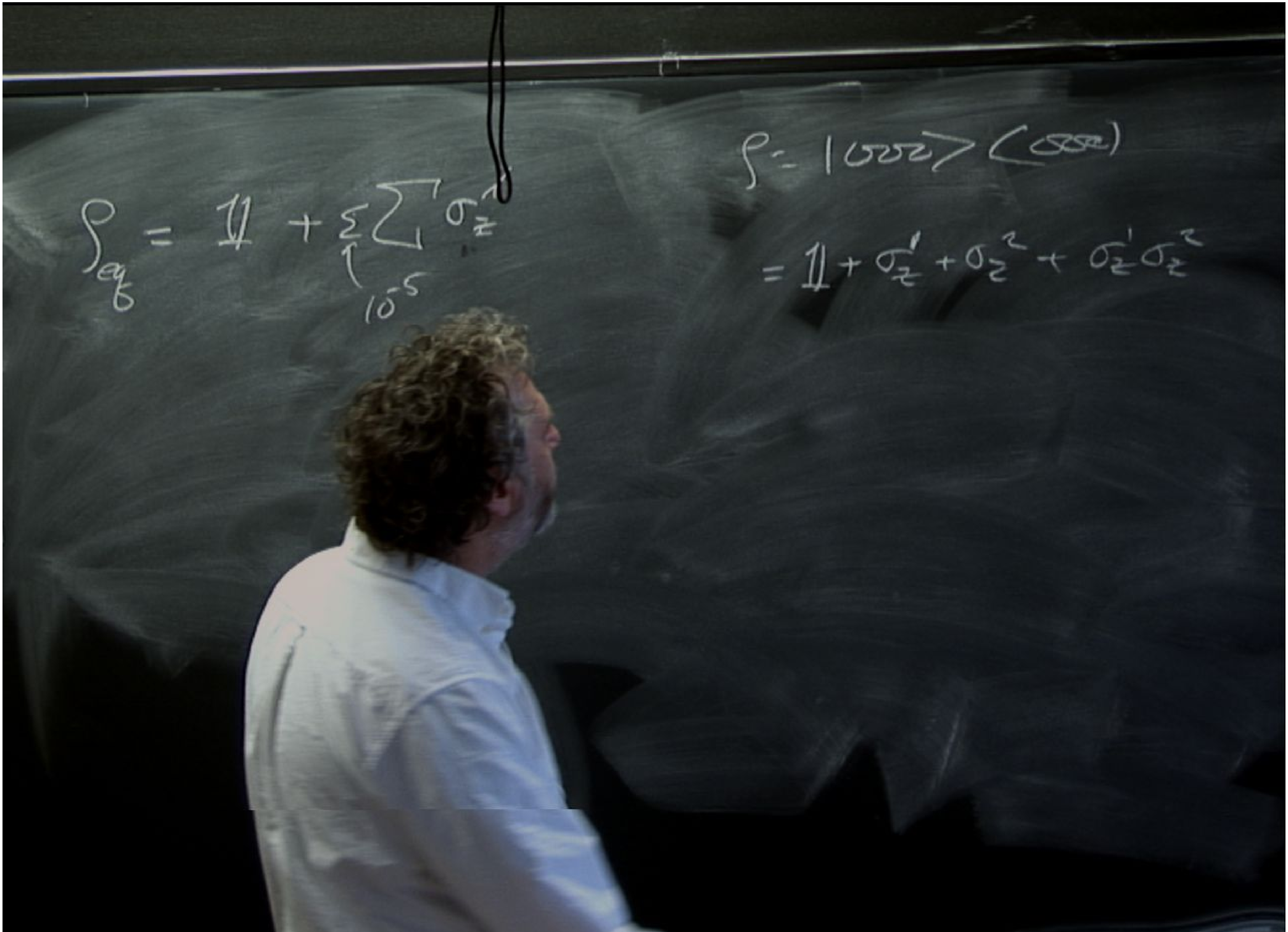
interconnect set of atoms {1 molecule}

no – molecular/molecule interaction,

density matrix highly mixed.



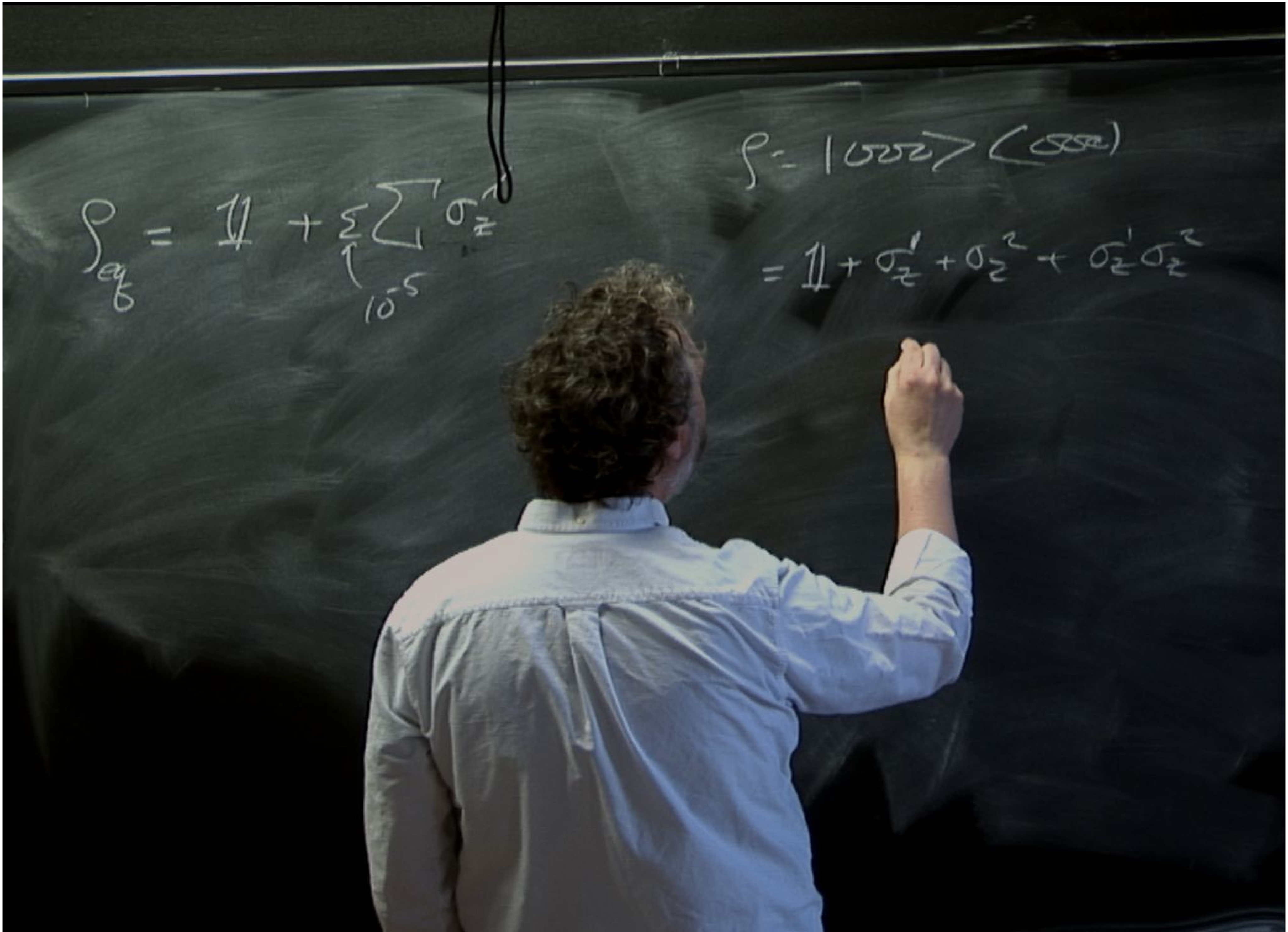
$$\rho_{eq} = \mathbb{1} + \underset{\underset{10^{-5}}{\uparrow}}{\varepsilon} \sum{}' \sigma_z^{i}$$

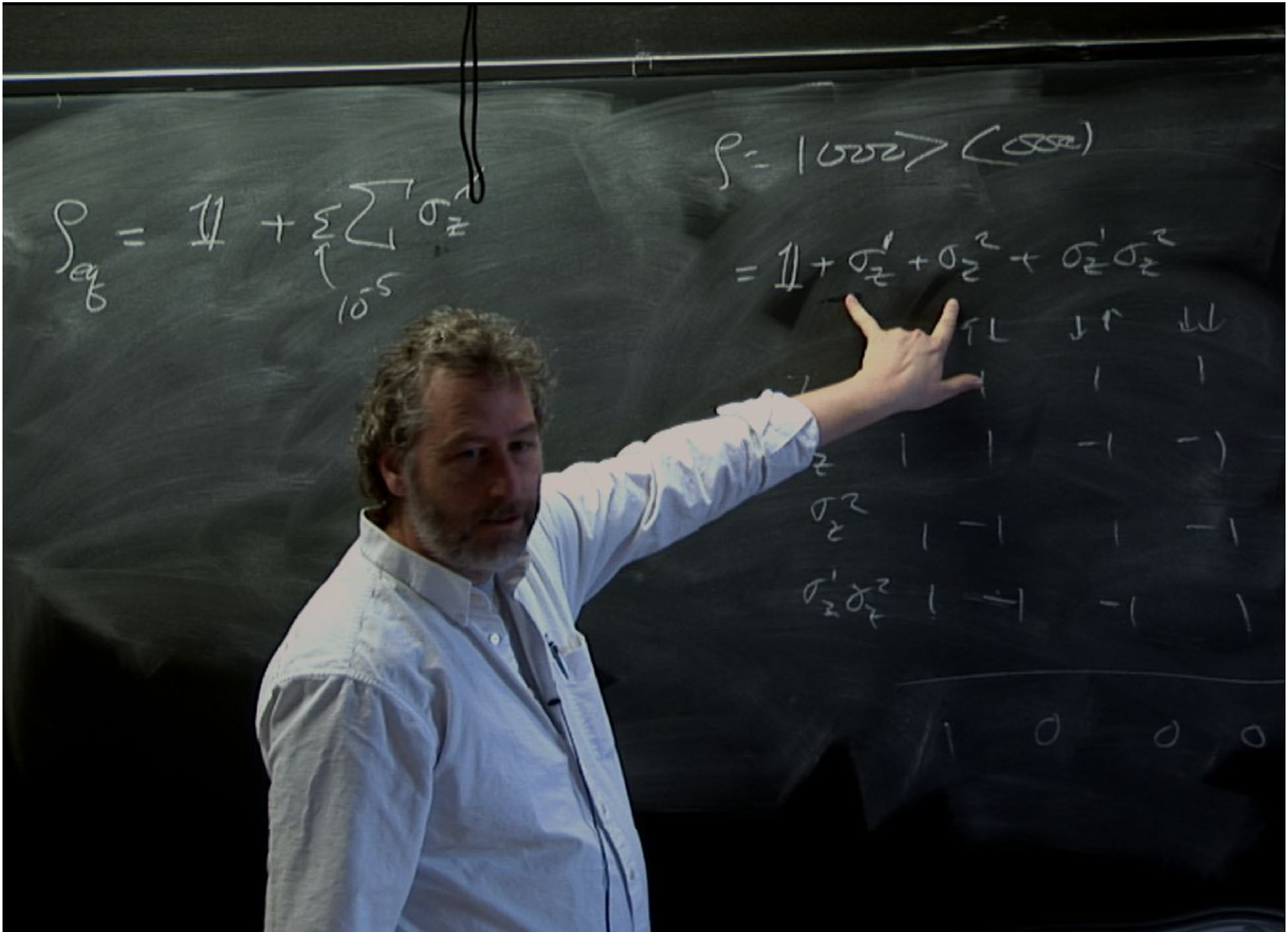


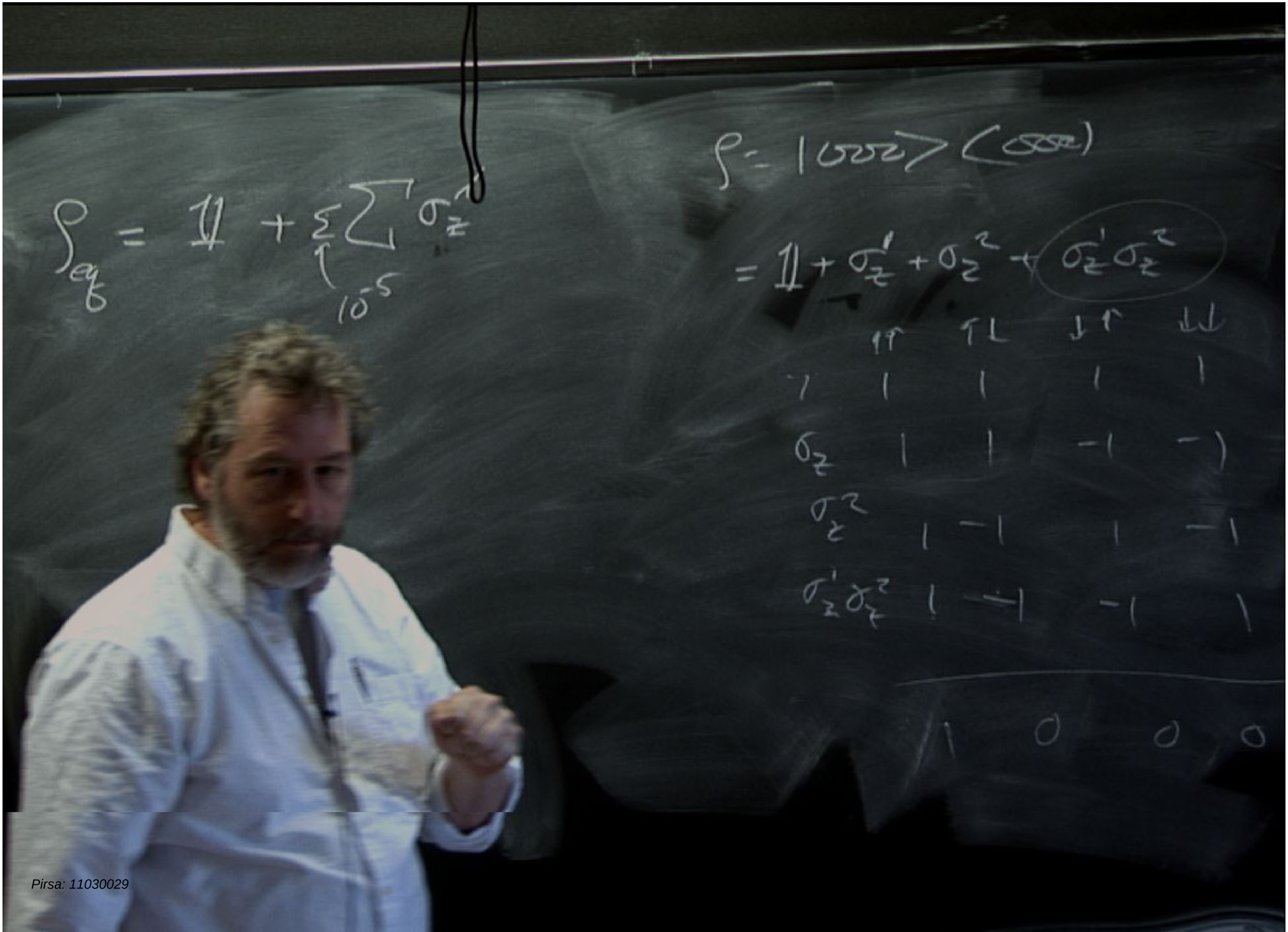
$$\rho_{eq} = \mathbb{1} + \underset{\overset{\uparrow}{10^{-5}}}{\varepsilon} \sum_i \sigma_z^i$$

$$\rho = |000\rangle\langle 000|$$

$$= \mathbb{1} + \sigma_z^1 + \sigma_z^2 + \sigma_z^1 \sigma_z^2$$


$\rho_{eq} = \mathbb{1} + \varepsilon \sum \sigma_z$
10^{-5}
$\rho = |\sigma\sigma\sigma\rangle\langle\sigma\sigma\sigma|$
$= \mathbb{1} + \sigma_z^1 + \sigma_z^2 + \sigma_z^1\sigma_z^2$


ρ = |00⟩⟨00|
ρ_eq = 1 + ε Σ σ_z^i
10^-5
= 1 + σ_z^1 + σ_z^2 + σ_z^1 σ_z^2
↑↓ ↓↑ ↓↓
1 1 1
1 1 -1 -1
σ_z^2 1 -1 1 -1
σ_z^1 σ_z^2 1 -1 -1 1
1 0 0 0

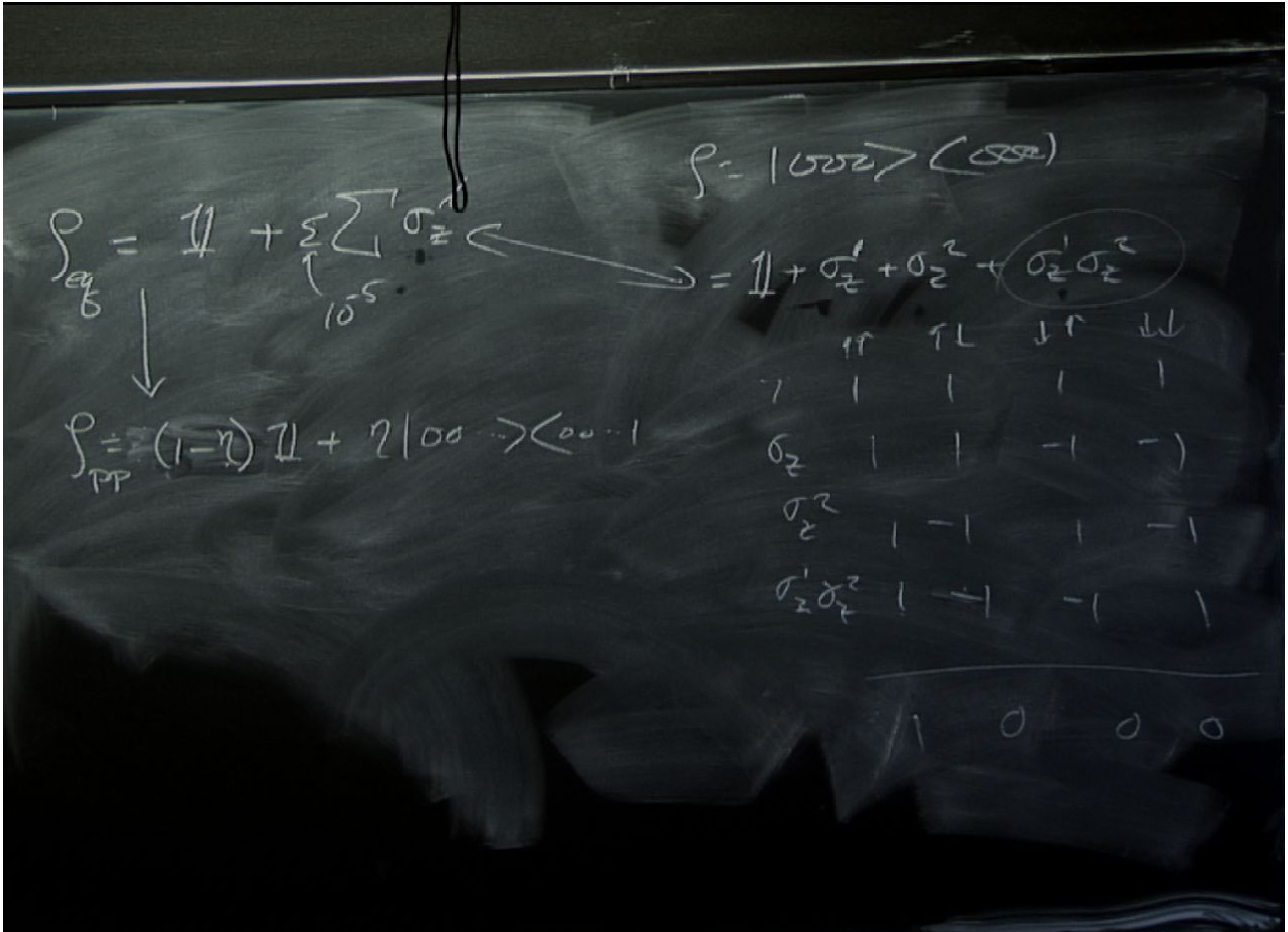


$$\rho_{eq} = \mathbb{1} + \underset{10^{-5}}{\epsilon} \sum \sigma_z^i$$

$$\rho = |000\rangle\langle 000|$$

$$= \mathbb{1} + \sigma_z^1 + \sigma_z^2 + \boxed{\sigma_z^1 \sigma_z^2}$$

	↑↑	↑↓	↓↑	↓↓
$\mathbb{1}$	1	1	1	1
σ_z	1	1	−1	−1
σ_z^2	1	−1	1	−1
$\sigma_z^1\sigma_z^2$	1	−1	−1	1
	1	0	0	0



$$\rho = |0000\rangle\langle 0000|$$

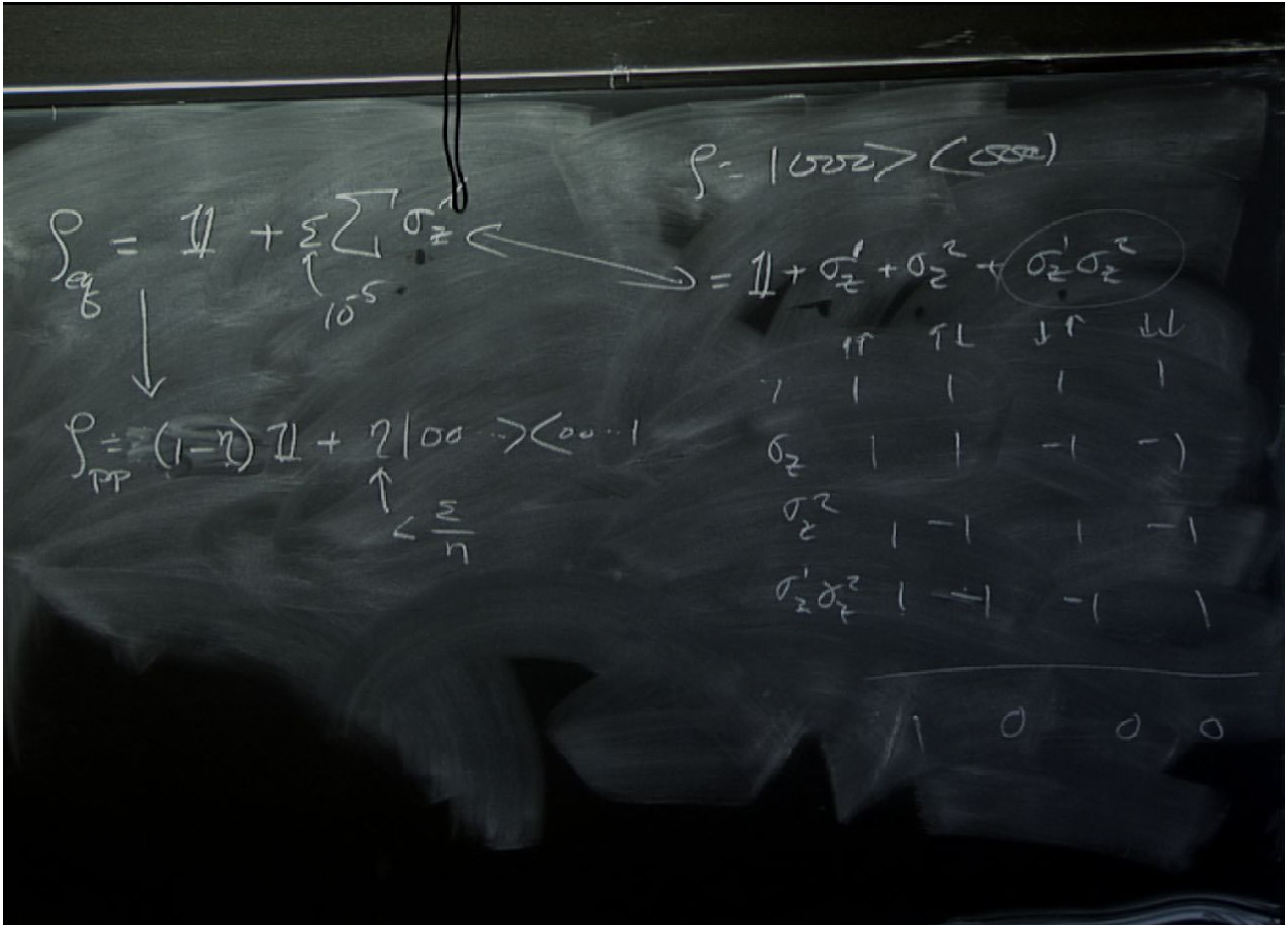
$$\rho_{eq} = \mathbb{1} + \underset{\overset{\uparrow}{10^{-5}}}{\varepsilon} \sum_i \sigma_z^i$$

$$\downarrow$$

$$\rho_{pp} \doteq (1-\eta)\,\mathbb{1} + \eta\,|00\cdots\rangle\langle 00\cdots|$$

$$= \mathbb{1} + \sigma_z^1 + \sigma_z^2 + \boxed{\sigma_z^1\sigma_z^2}$$

	$\uparrow\uparrow$	$\uparrow\downarrow$	$\downarrow\uparrow$	$\downarrow\downarrow$
$\mathbb{1}$	1	1	1	1
σ_z	1	1	−1	−1
σ_z^2	1	−1	1	−1
$\sigma_z^1\sigma_z^2$	1	−1	−1	1
	1	0	0	0



$$\rho = |0000\rangle\langle 0000|$$

$$\rho_{eq} = \mathbb{1} + \underset{\substack{\uparrow\\10^{-5}}}{\varepsilon}\sum_i \sigma_z^i \longleftrightarrow = \mathbb{1} + \sigma_z^1 + \sigma_z^2 + \boxed{\sigma_z^1\sigma_z^2}$$

$$\downarrow$$

$$\rho_{PP} \doteq (1-\eta)\mathbb{1} + \underset{\substack{\uparrow\\< \frac{\varepsilon}{n}}}{\eta}|00\cdots\rangle\langle 00\cdots|$$

	↑↑	↑↓	↓↑	↓↓
1	1	1	1	1
σ_z	1	1	-1	-1
σ_z^2	1	-1	1	-1
$\sigma_z^1\sigma_z^2$	1	-1	-1	1
	1	0	0	0

$$\rho = |0000\rangle\langle 0000|$$

$$\rho_{eq} = \mathbb{1} + \underset{\substack{\uparrow \\ 10^{-5}}}{\varepsilon} \sum_i \sigma_z^i \longleftrightarrow = \mathbb{1} + \sigma_z^1 + \sigma_z^2 + \sigma_z^1 \sigma_z^2$$

$$\Big\downarrow \text{non-Unitary}$$

$$\rho_{PP} \doteq (1-\eta)\,\mathbb{1} + \boxed{\underset{\substack{\uparrow \\ < \frac{\varepsilon}{\eta}}}{\eta}\,|00\cdots\rangle\langle 00\cdots|}$$

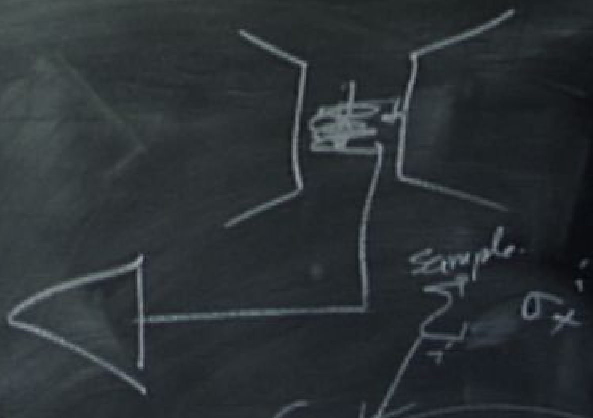
	↑↑	↑↓	↓↑	↓↓
$\mathbb{1}$	1	1	1	1
σ_z	1	1	-1	-1
σ_z^2	1	-1	1	-1
$\sigma_z^1\sigma_z^2$	1	-1	-1	1
	1	0	0	0

Sample

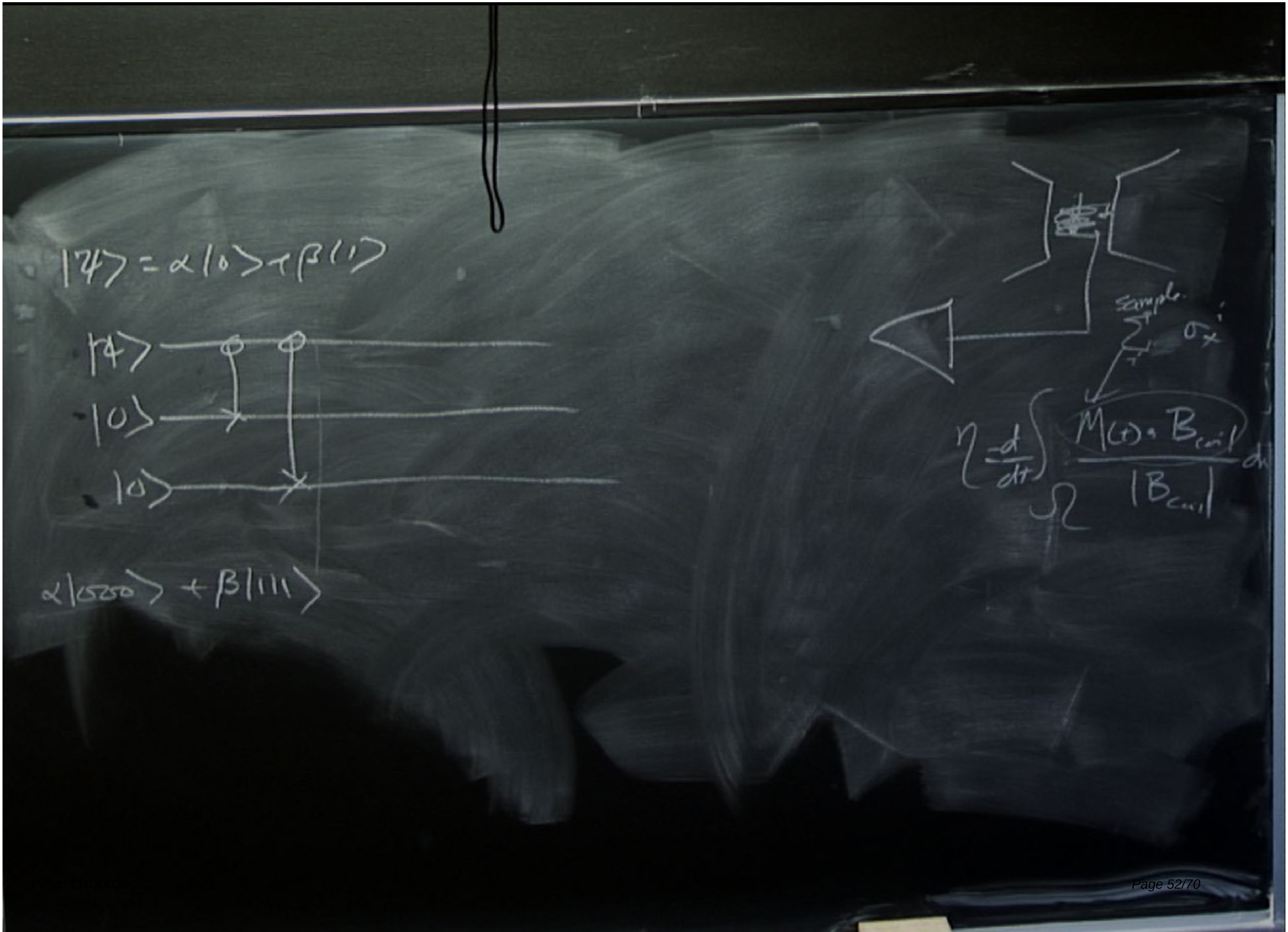
$\sum_i \sigma_x^i$

$$\eta \frac{d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\, dr$$

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



$$\eta = \frac{d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\, d$$

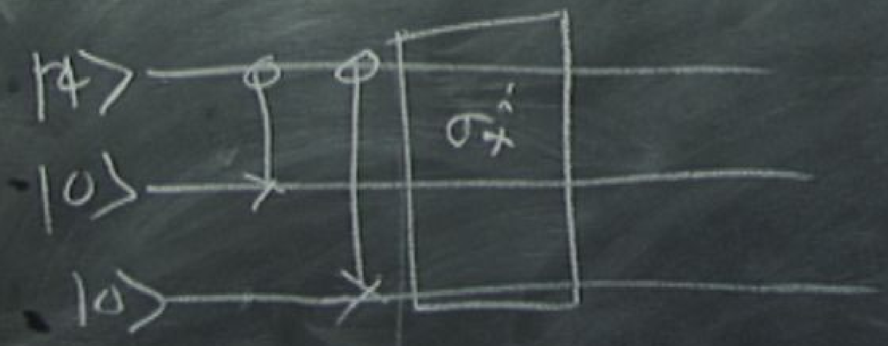


$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$\alpha|000\rangle + \beta|111\rangle$

$$\eta \frac{-d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\, d$$

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

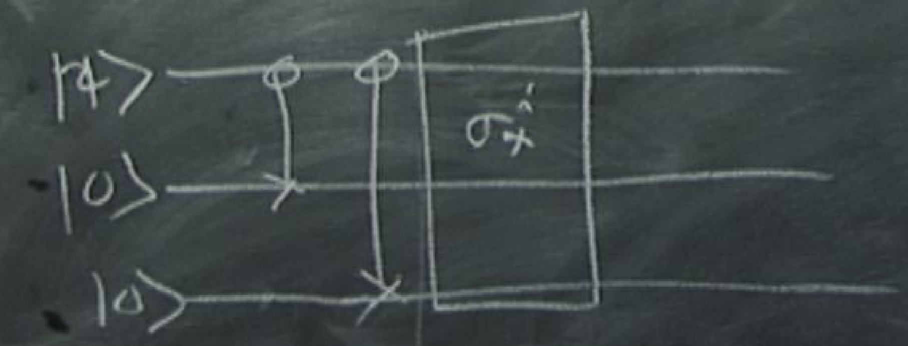


$\alpha|000\rangle + \beta|111\rangle$

Sample $\sum_i \sigma_x^i$

$$\eta \frac{-d}{dt} \int_{\Omega} \frac{M(t) \cdot B_{coil}}{|B_{coil}|} d$$

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



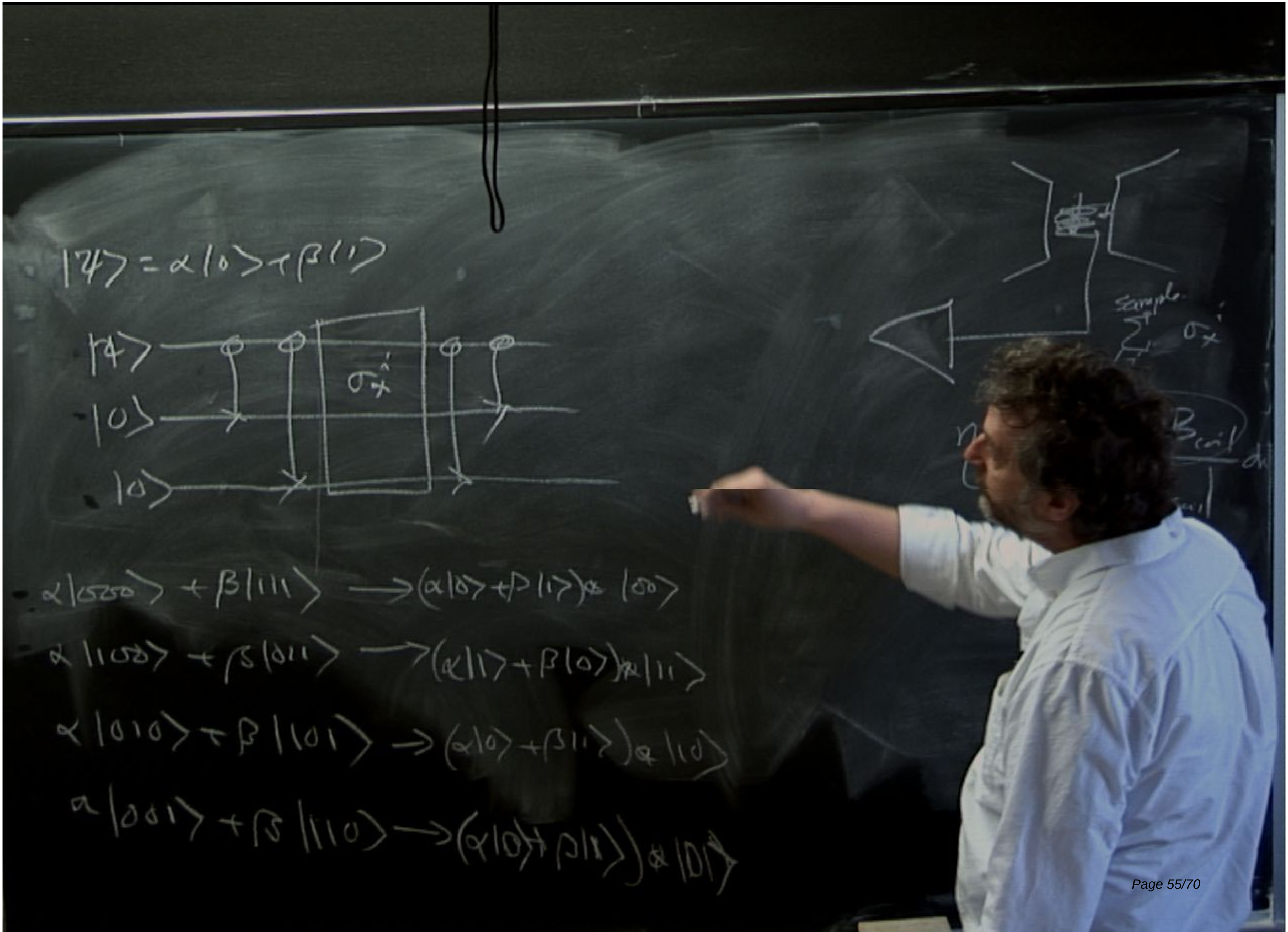
$$\eta = \frac{-d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\, dV$$

$\alpha|000\rangle + \beta|111\rangle$

$\alpha|100\rangle + \beta|011\rangle$

$\alpha|010\rangle + \beta|101\rangle$

$\alpha|001\rangle + \beta|110\rangle$



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

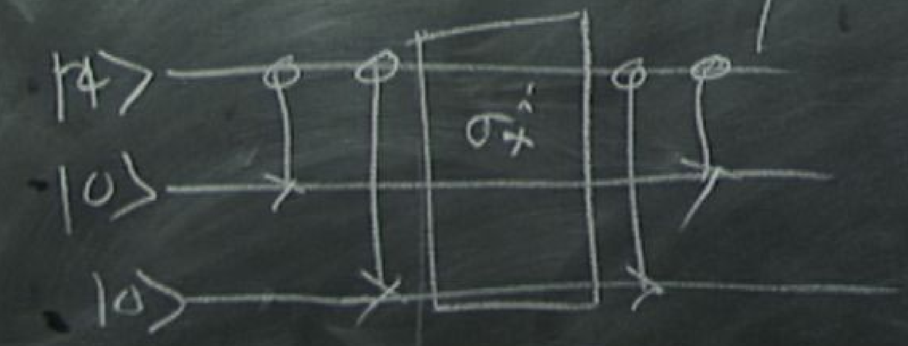
$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle) \otimes |00\rangle$

$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle) \otimes |11\rangle$

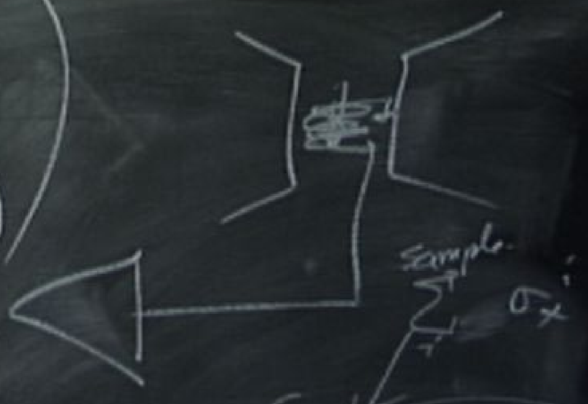
$\alpha|010\rangle + \beta|101\rangle \rightarrow (\alpha|0\rangle + \beta|1\rangle) \otimes |10\rangle$

$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle) \otimes |01\rangle$

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



$$\begin{pmatrix} |\psi\rangle & & & \\ & |\psi\rangle & & \\ & & |\psi\rangle & \\ & & & \sigma_x|\psi\rangle \end{pmatrix}$$



$$\eta = \frac{-d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\,dv$$

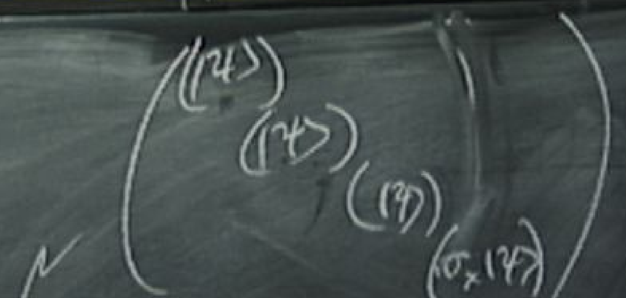
$$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$$

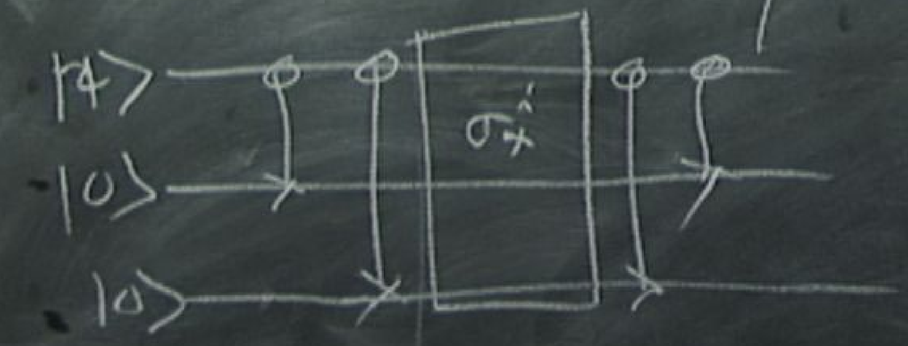
$$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$$

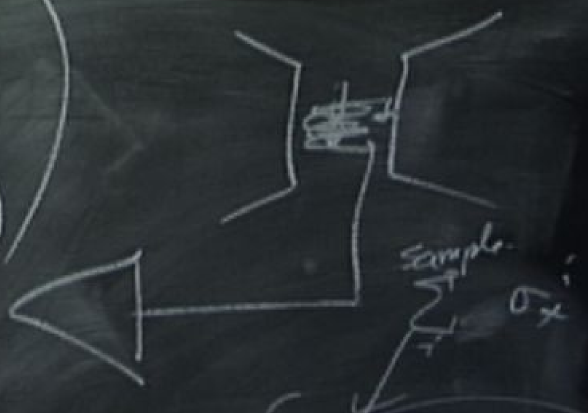
$$\alpha|010\rangle + \beta|101\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$$

$$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|01\rangle$$

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







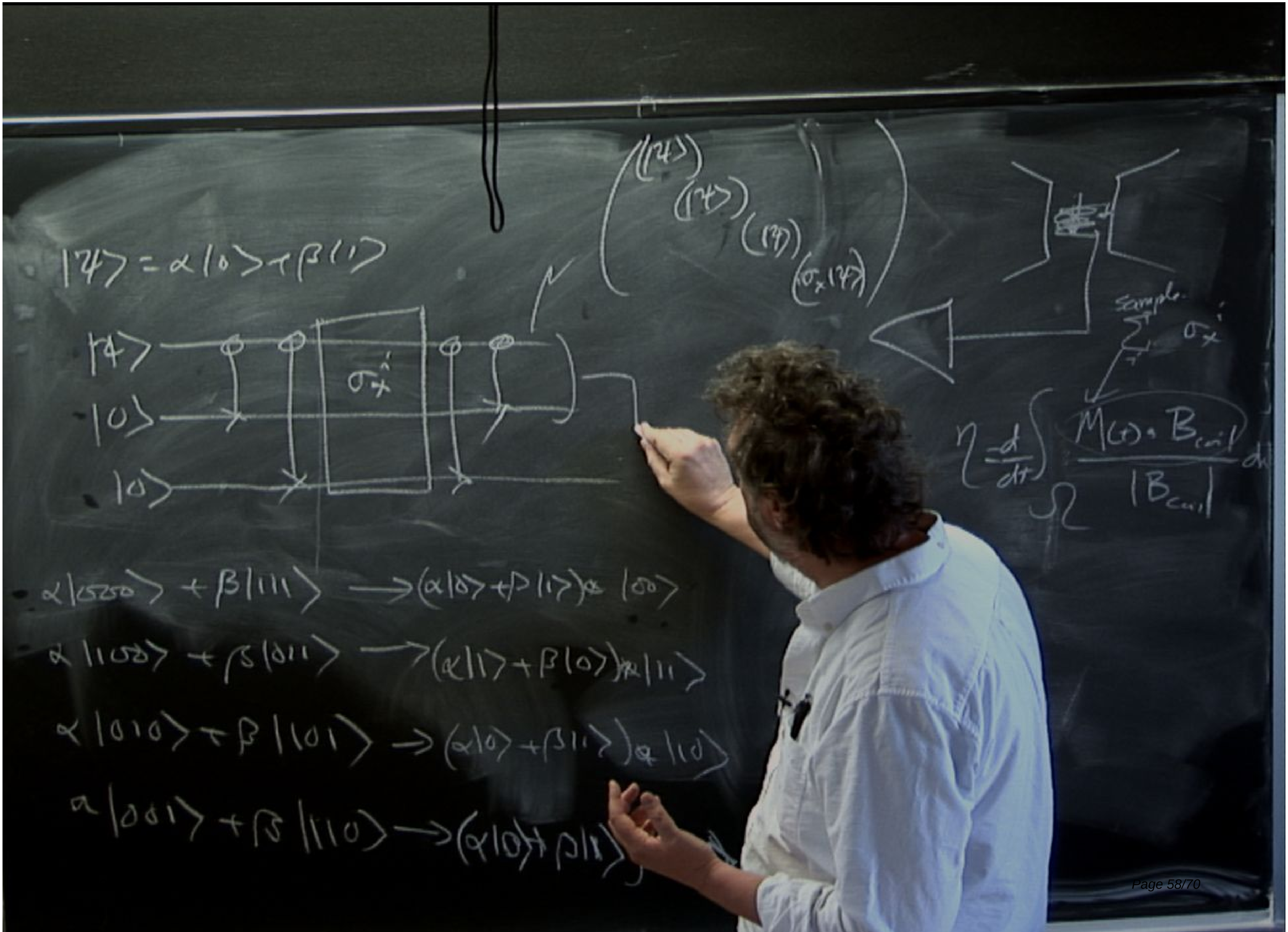
$$\eta = -\frac{d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\, dV$$

$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$

$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$

$\alpha|010\rangle + \beta|101\rangle \rightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$

$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|01\rangle$



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

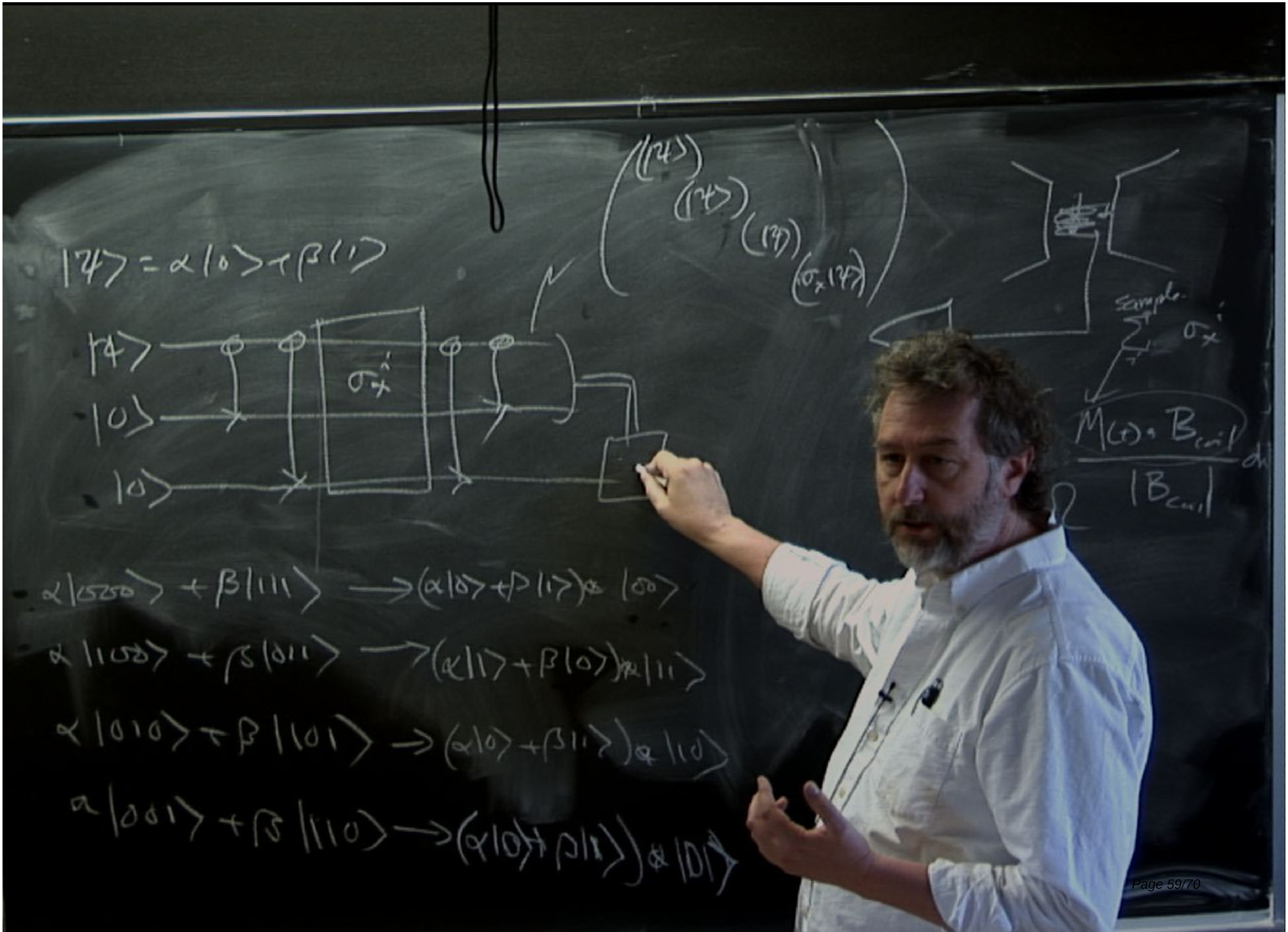
$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$

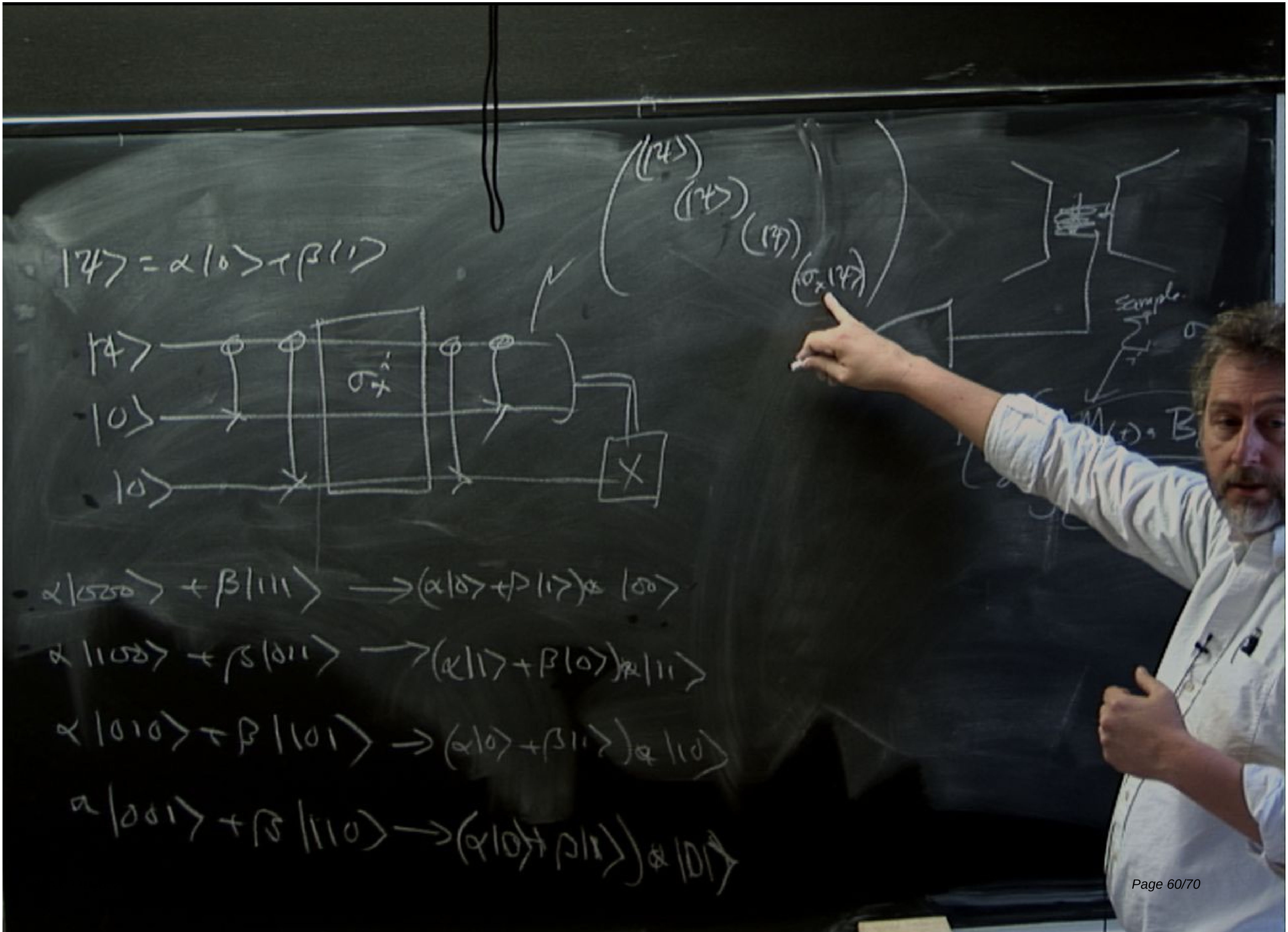
$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$

$\alpha|010\rangle + \beta|101\rangle \rightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$

$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)$

$$\eta = \frac{-d}{dt}\int_{\Omega} \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\, d\Omega$$


$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
$|\psi\rangle$
$|0\rangle$
$|0\rangle$
σ_x^i
$|\psi\rangle$
$|\psi\rangle$
$|\psi\rangle$
$\sigma_x|\psi\rangle$
Sample
σ_x^i
$\frac{M(t) \cdot B_{coil}}{|B_{coil}|} dt$
$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle) \otimes |00\rangle$
$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle) \otimes |11\rangle$
$\alpha|010\rangle + \beta|101\rangle \rightarrow (\alpha|0\rangle + \beta|1\rangle) \otimes |10\rangle$
$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle) \otimes |01\rangle$



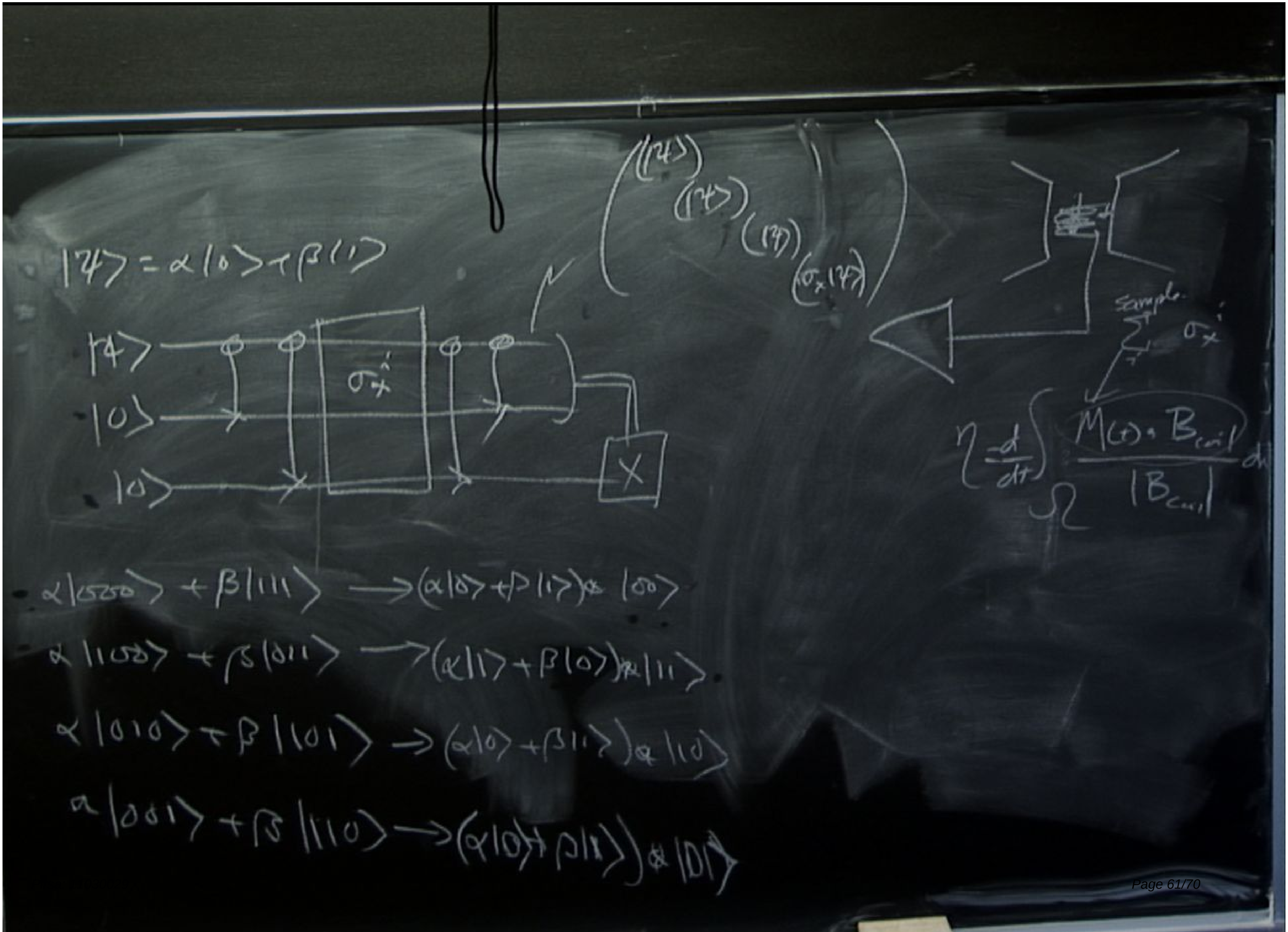
$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$

$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$

$\alpha|010\rangle + \beta|101\rangle \rightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$

$a|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|01\rangle$



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

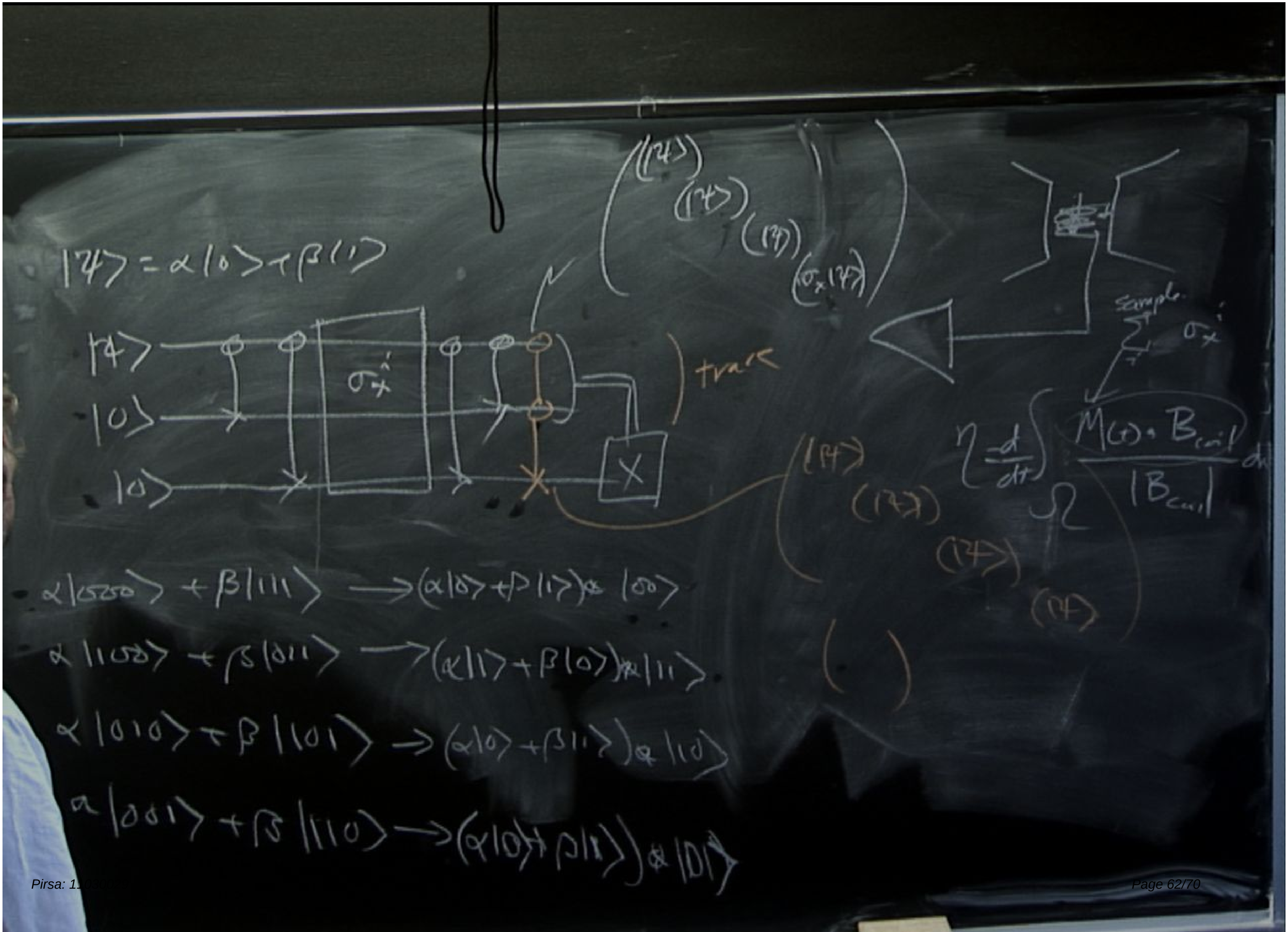
$$\eta = \frac{d}{dt}\int_\Omega \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\,dv$$

$$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$$

$$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$$

$$\alpha|010\rangle + \beta|101\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$$

$$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|01\rangle$$



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

$$\mathcal{E} = \frac{-d}{dt}\int \frac{M(t)\cdot B_{coil}}{|B_{coil}|}\,dv$$

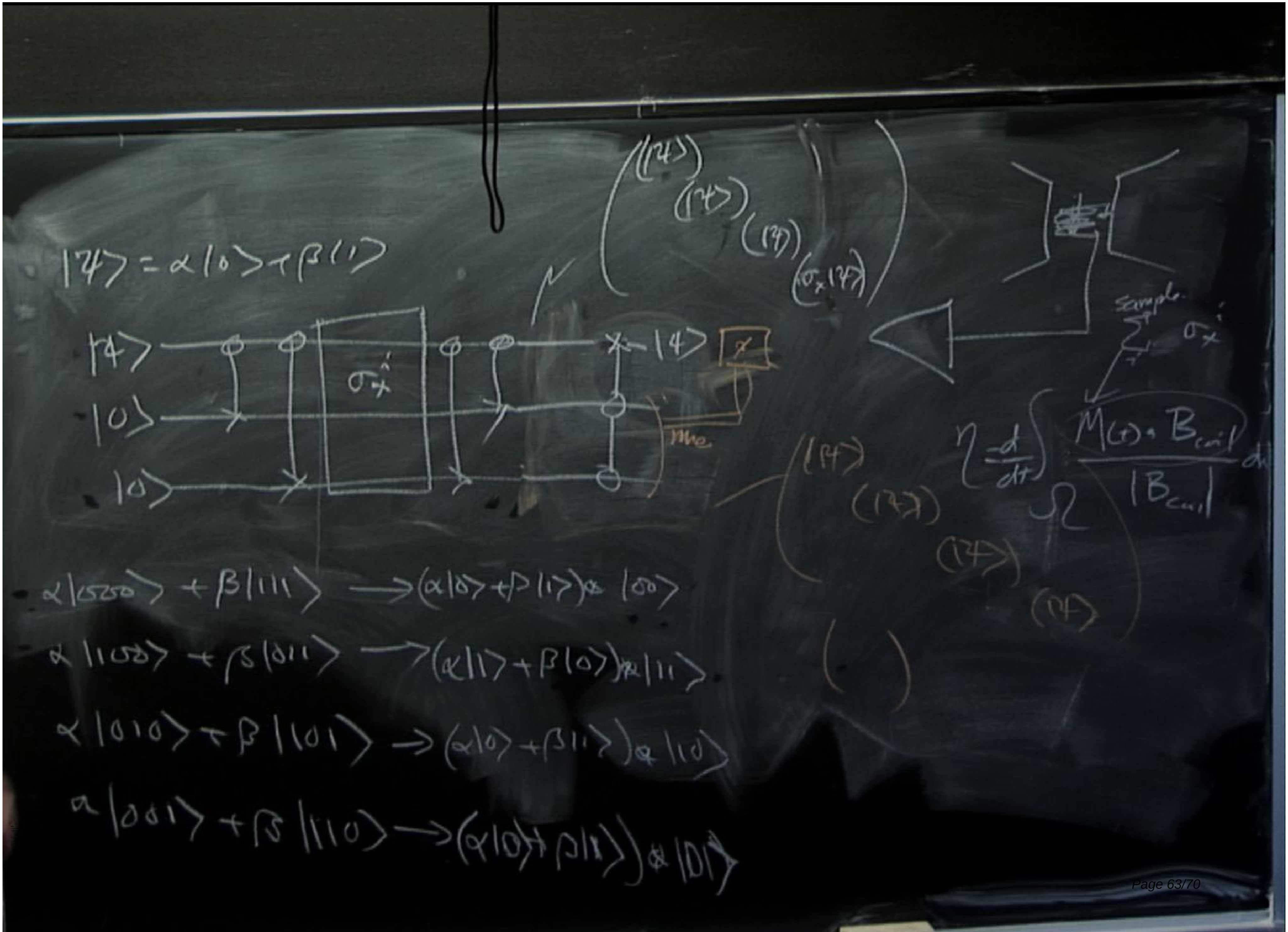
Ω

$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$

$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$

$\alpha|010\rangle + \beta|101\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$

$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|01\rangle$



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

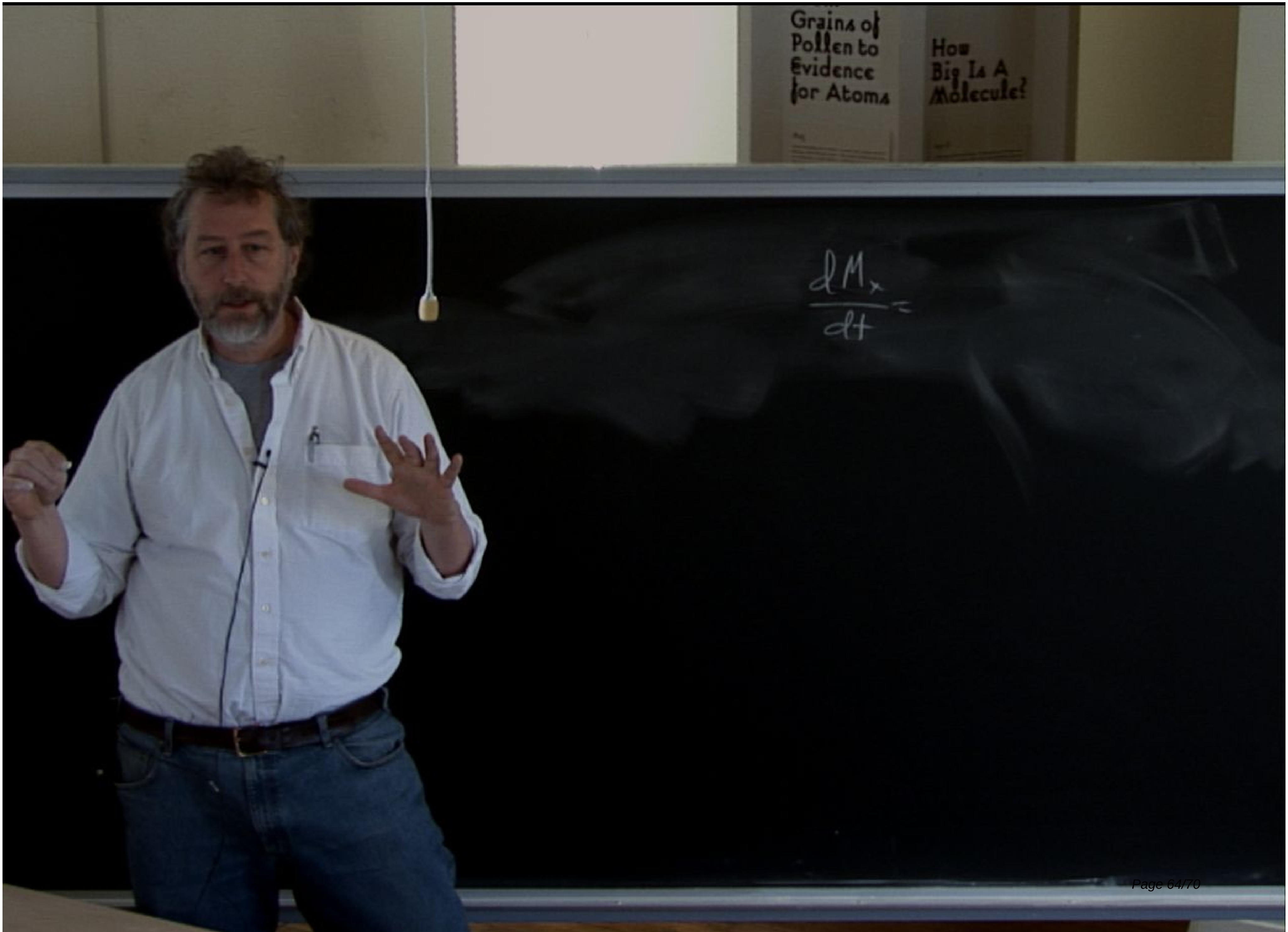
$\eta \frac{-d}{dt}\int \frac{M(t)\cdot B_{coil}}{|B_{coil}|} dr$

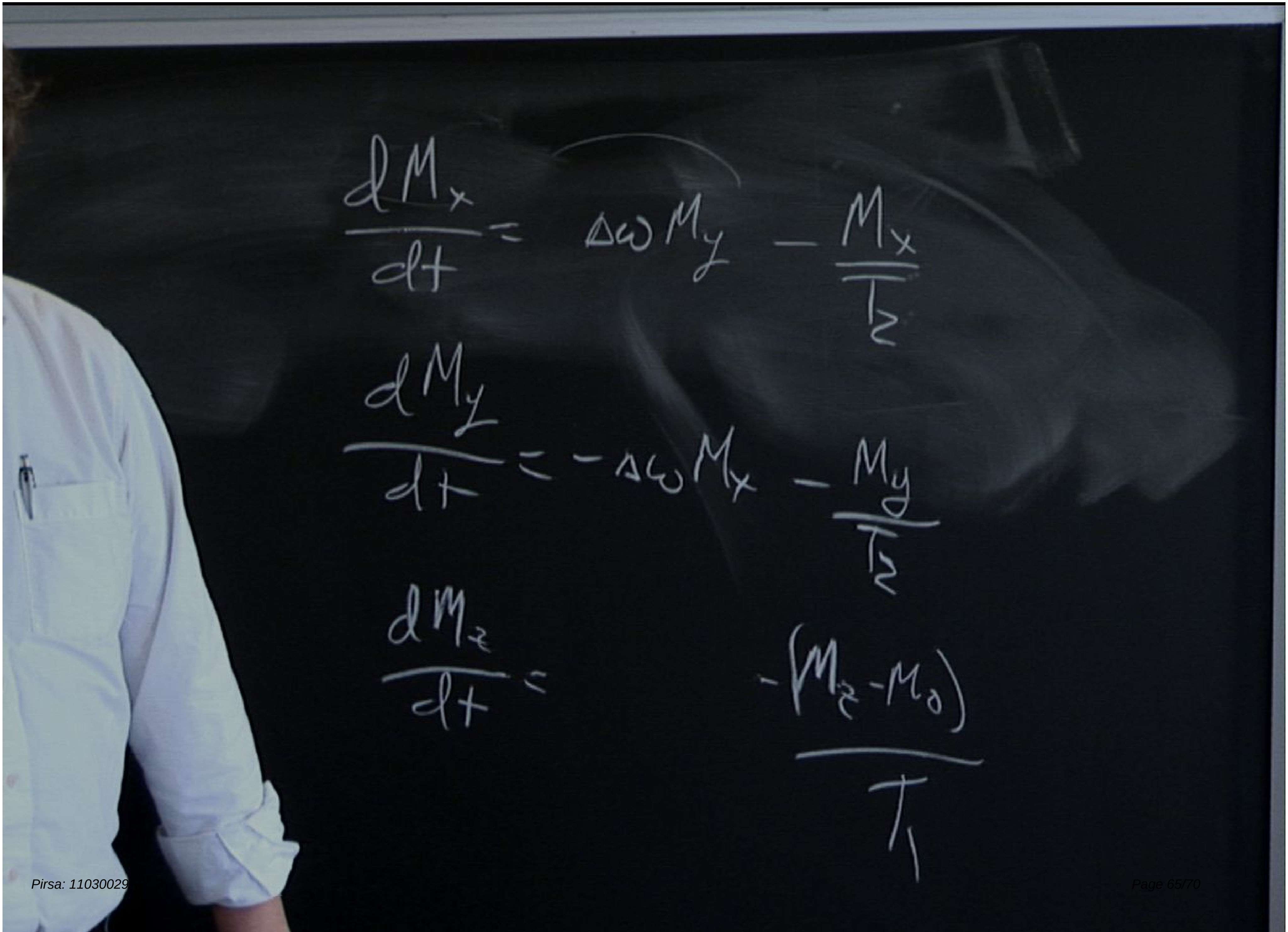
$\alpha|000\rangle + \beta|111\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|00\rangle$

$\alpha|100\rangle + \beta|011\rangle \longrightarrow (\alpha|1\rangle + \beta|0\rangle)\otimes|11\rangle$

$\alpha|010\rangle + \beta|101\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|10\rangle$

$\alpha|001\rangle + \beta|110\rangle \longrightarrow (\alpha|0\rangle + \beta|1\rangle)\otimes|01\rangle$

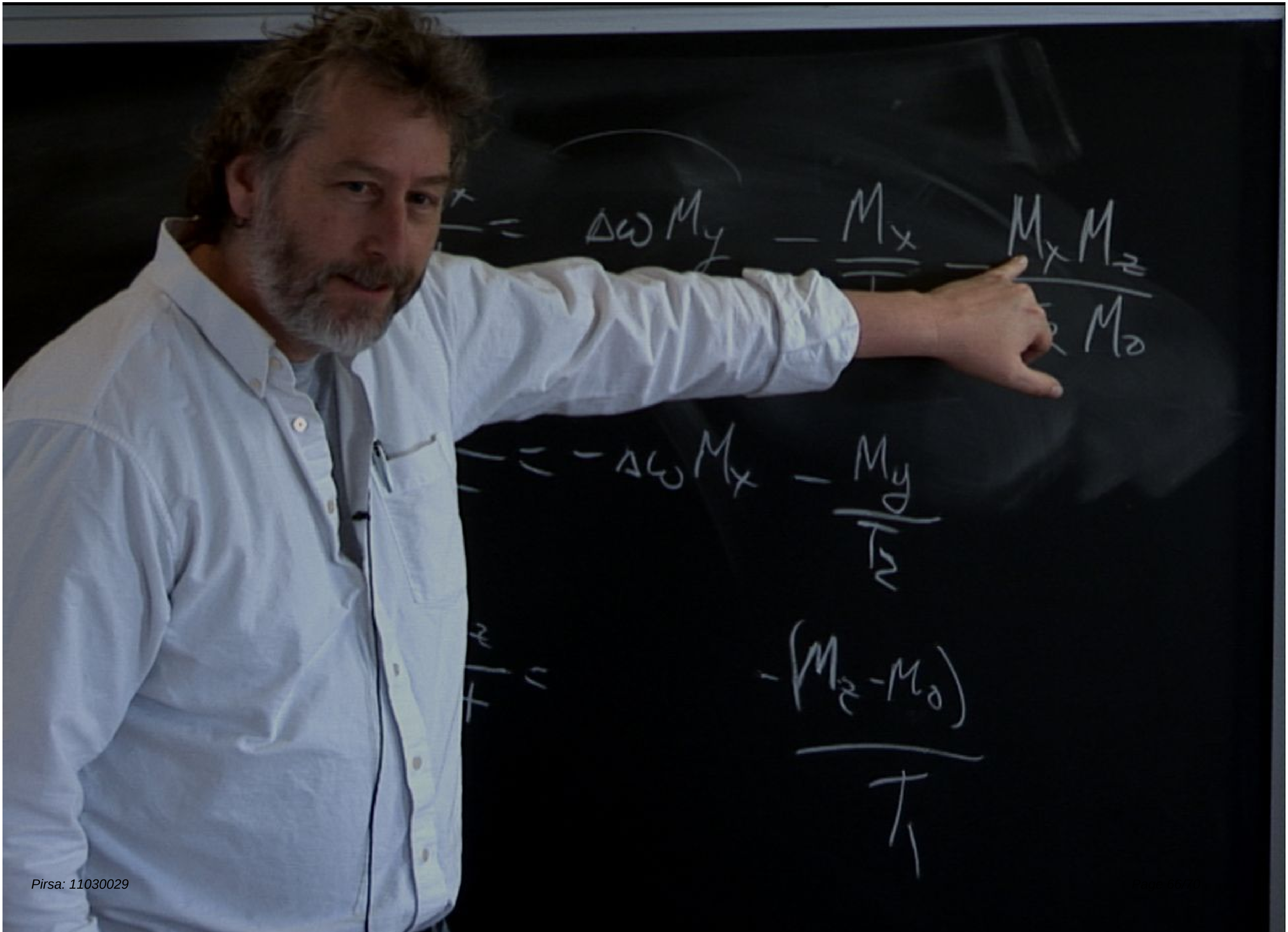

Grains of Pollen to Evidence for Atoms
How Big Is A Molecule?
$\frac{dM_x}{dt} =$

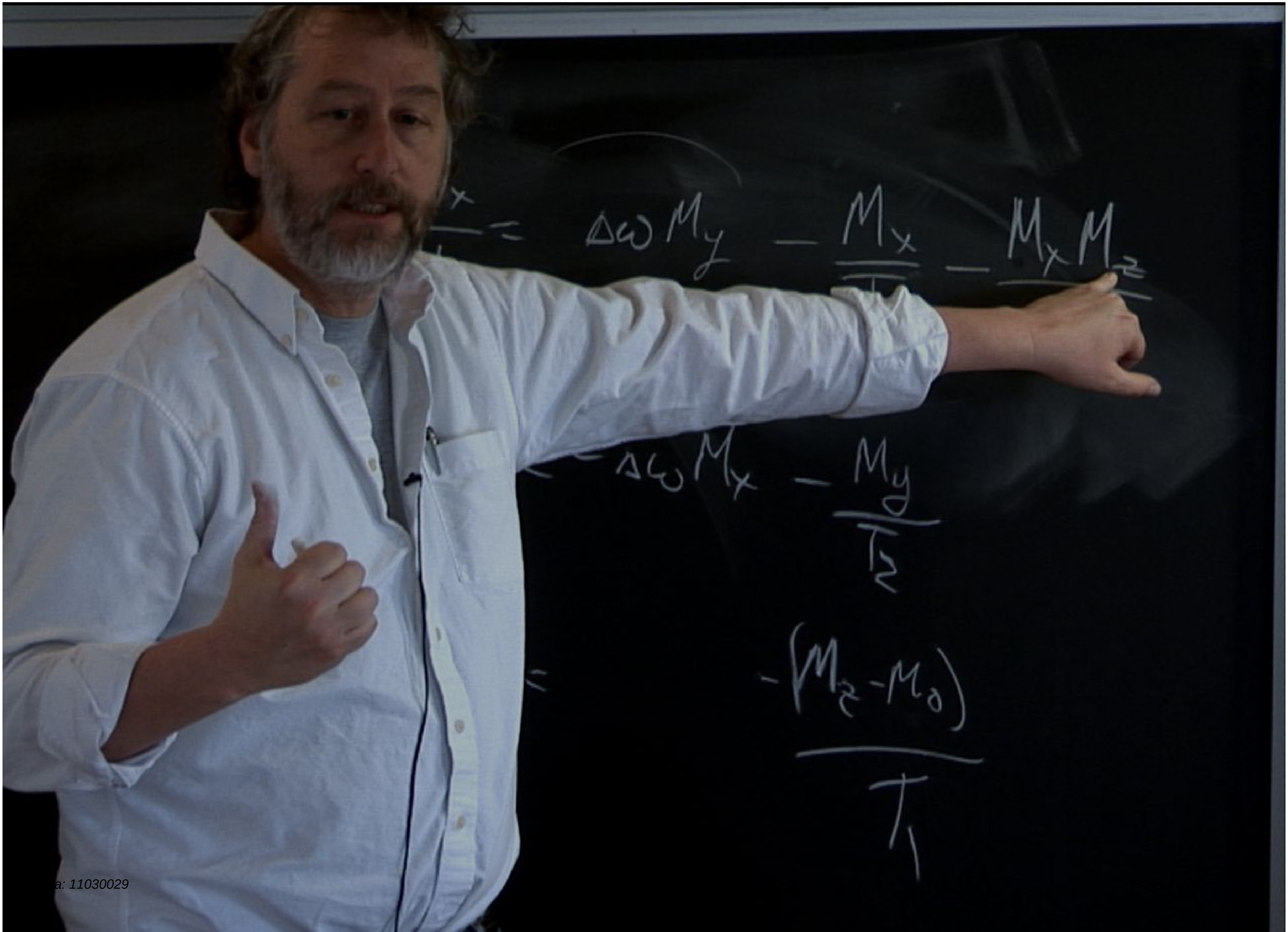


$$\frac{dM_x}{dt} = \Delta\omega M_y - \frac{M_x}{T_2}$$

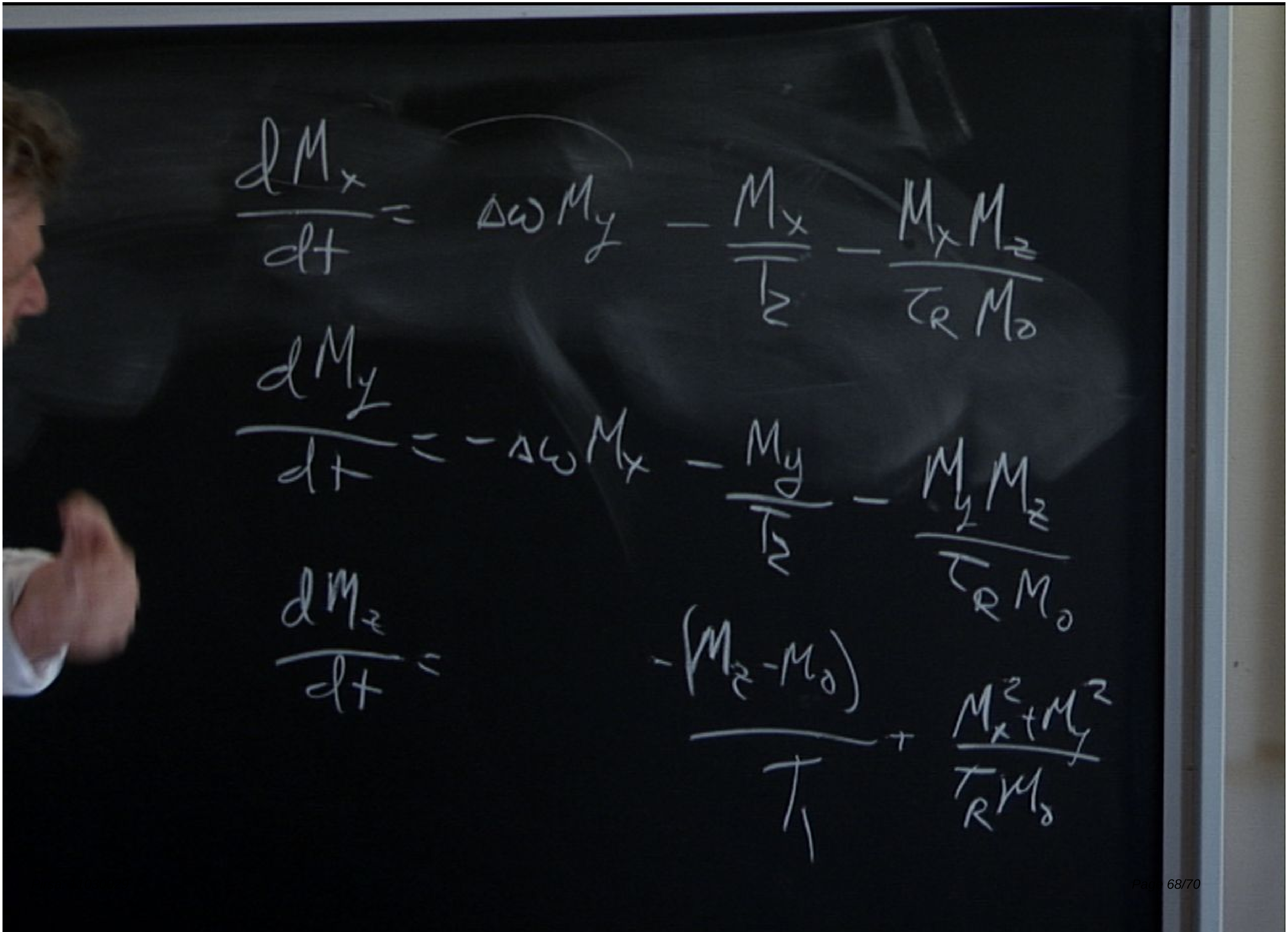
$$\frac{dM_y}{dt} = -\Delta\omega M_x - \frac{M_y}{T_2}$$

$$\frac{dM_z}{dt} = \frac{-(M_z - M_0)}{T_1}$$


$= \Delta\omega M_y - \frac{M_x}{T} - \frac{M_x M_z}{M_0}$
$= -\Delta\omega M_x - \frac{M_y}{T_2}$
$= \frac{-(M_z - M_0)}{T_1}$



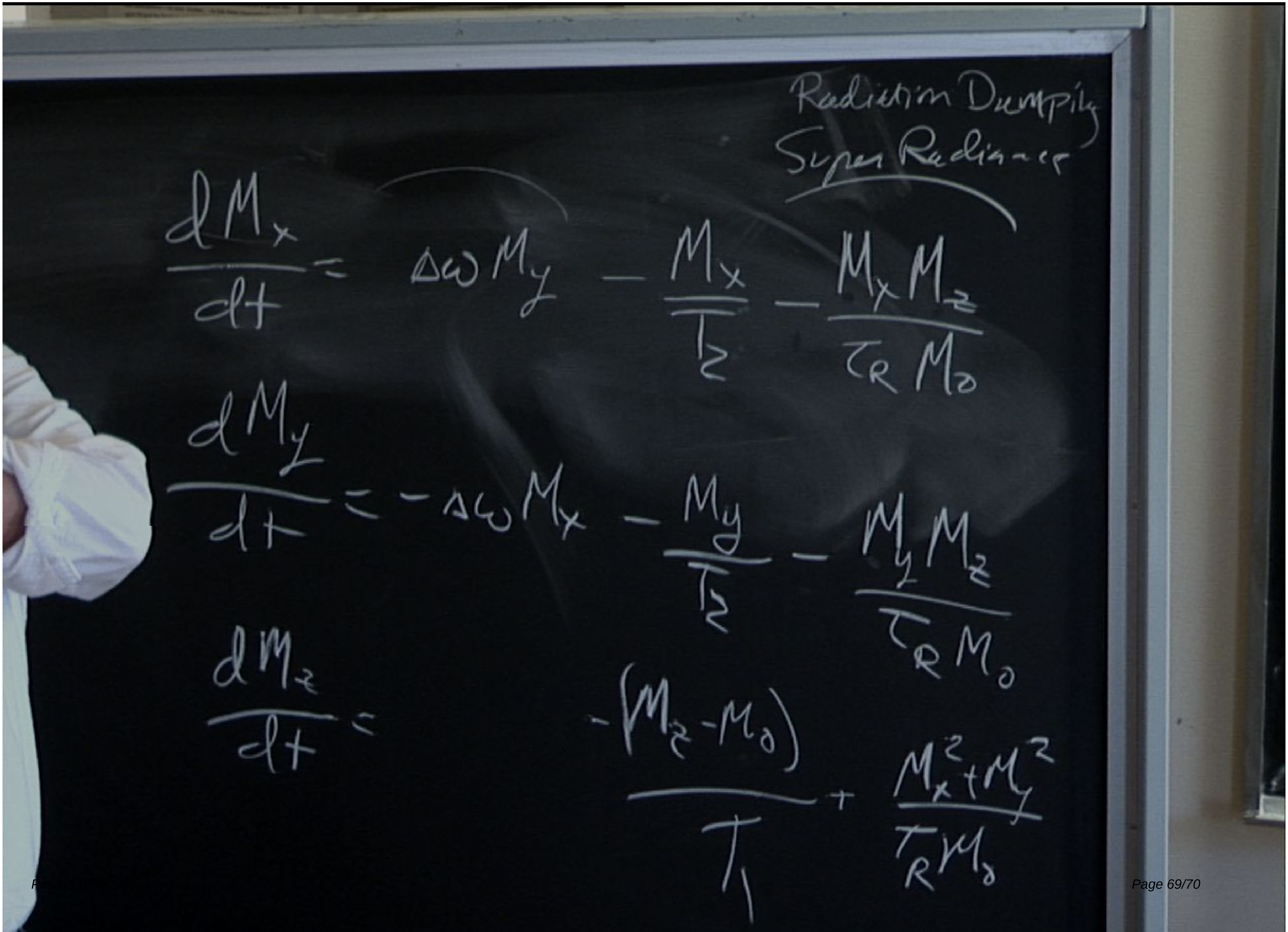
a: 11030029



$$\frac{dM_x}{dt} = \Delta\omega M_y - \frac{M_x}{T_2} - \frac{M_x M_z}{\tau_R M_0}$$

$$\frac{dM_y}{dt} = -\Delta\omega M_x - \frac{M_y}{T_2} - \frac{M_y M_z}{\tau_R M_0}$$

$$\frac{dM_z}{dt} = \frac{-(M_z - M_0)}{T_1} + \frac{M_x^2 + M_y^2}{\tau_R M_0}$$



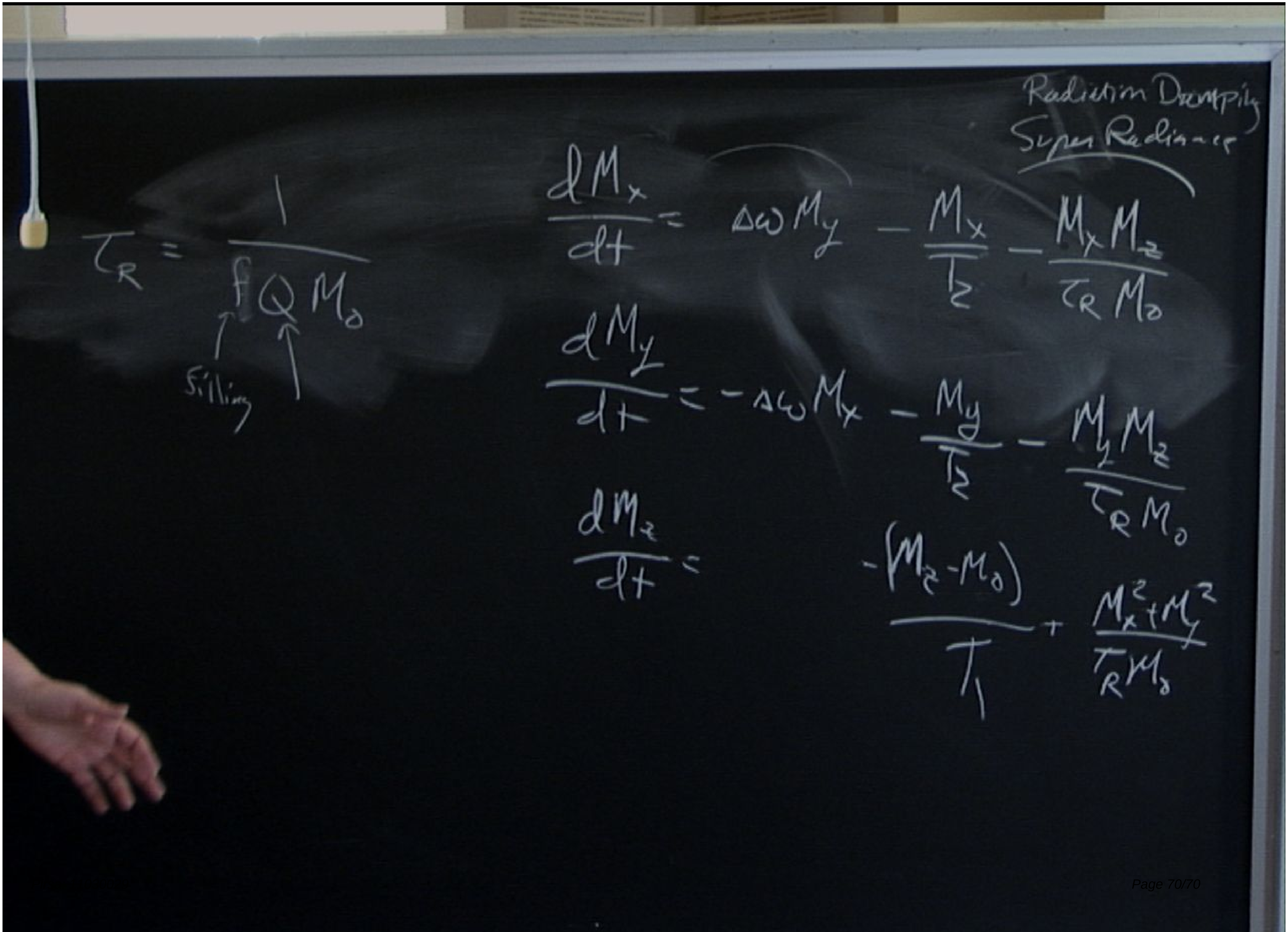
Radiation Damping

Super Radiance

$$\frac{dM_x}{dt} = \Delta\omega M_y - \frac{M_x}{T_2} - \frac{M_x M_z}{\tau_R M_0}$$

$$\frac{dM_y}{dt} = -\Delta\omega M_x - \frac{M_y}{T_2} - \frac{M_y M_z}{\tau_R M_0}$$

$$\frac{dM_z}{dt} = \frac{-(M_z - M_0)}{T_1} + \frac{M_x^2 + M_y^2}{\tau_R M_0}$$



Radiation Damping

Super Radiance

$$\tau_R = \frac{1}{\underset{\uparrow\ \text{filling}}{f}\,\underset{\uparrow}{Q}\,M_0}$$

$$\frac{dM_x}{dt} = \Delta\omega M_y - \frac{M_x}{T_2} - \frac{M_x M_z}{\tau_R M_0}$$

$$\frac{dM_y}{dt} = -\Delta\omega M_x - \frac{M_y}{T_2} - \frac{M_y M_z}{\tau_R M_0}$$

$$\frac{dM_z}{dt} = \frac{-(M_z - M_0)}{T_1} + \frac{M_x^2 + M_y^2}{\tau_R M_0}$$