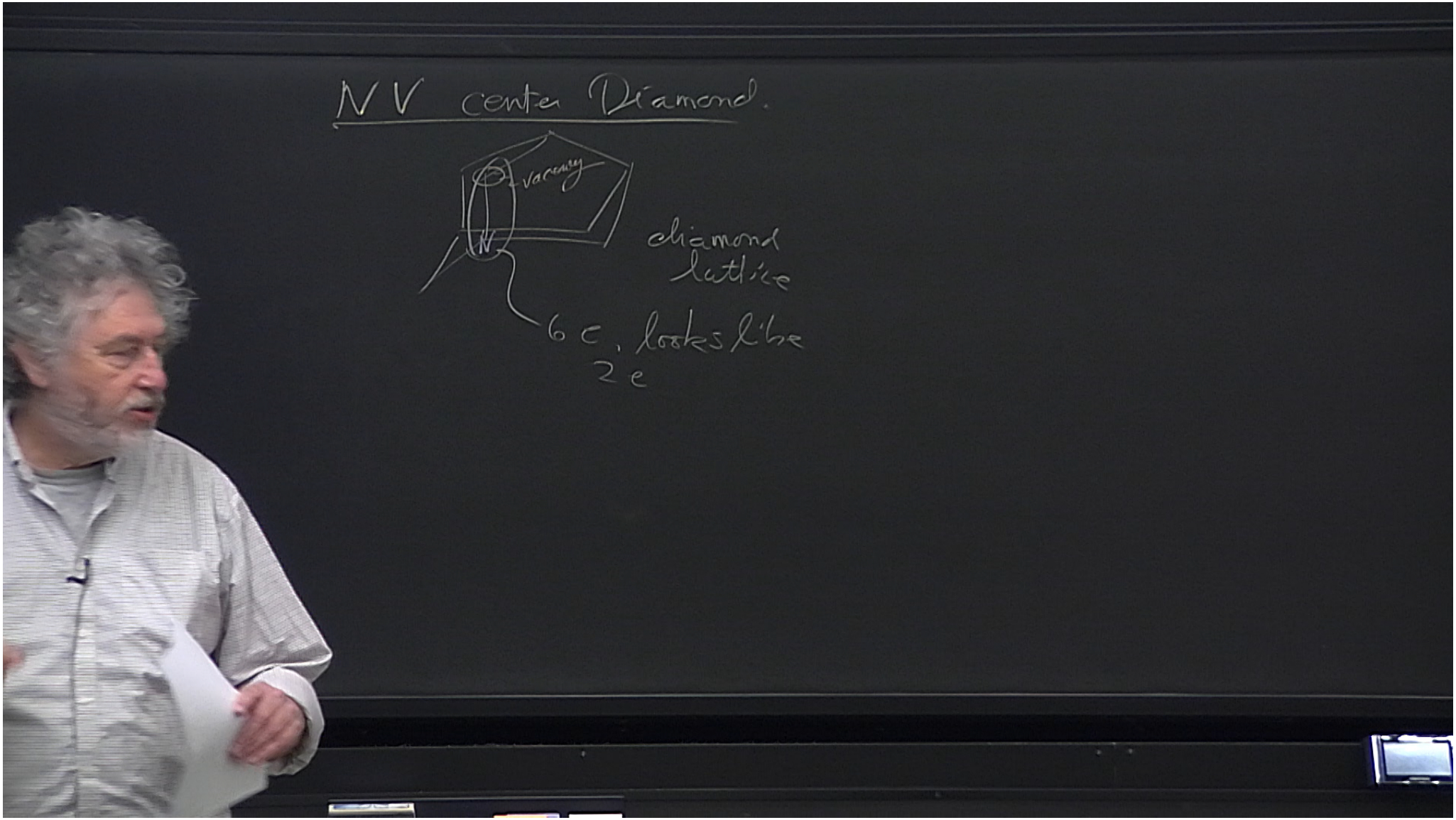
Title: PSI 2016/2017 Explorations in Quantum Information - Lecture 10

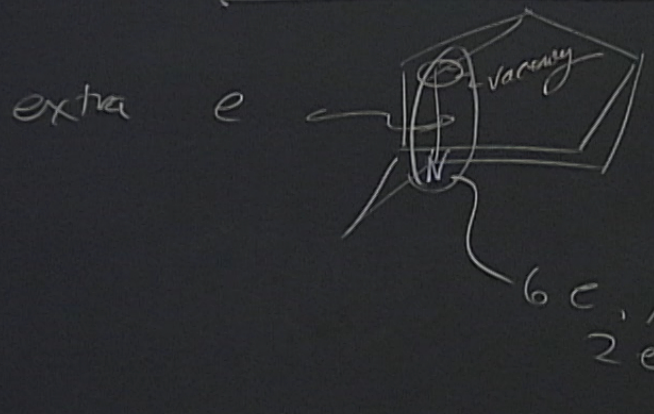
Date: Mar 31, 2017 09:00 AM

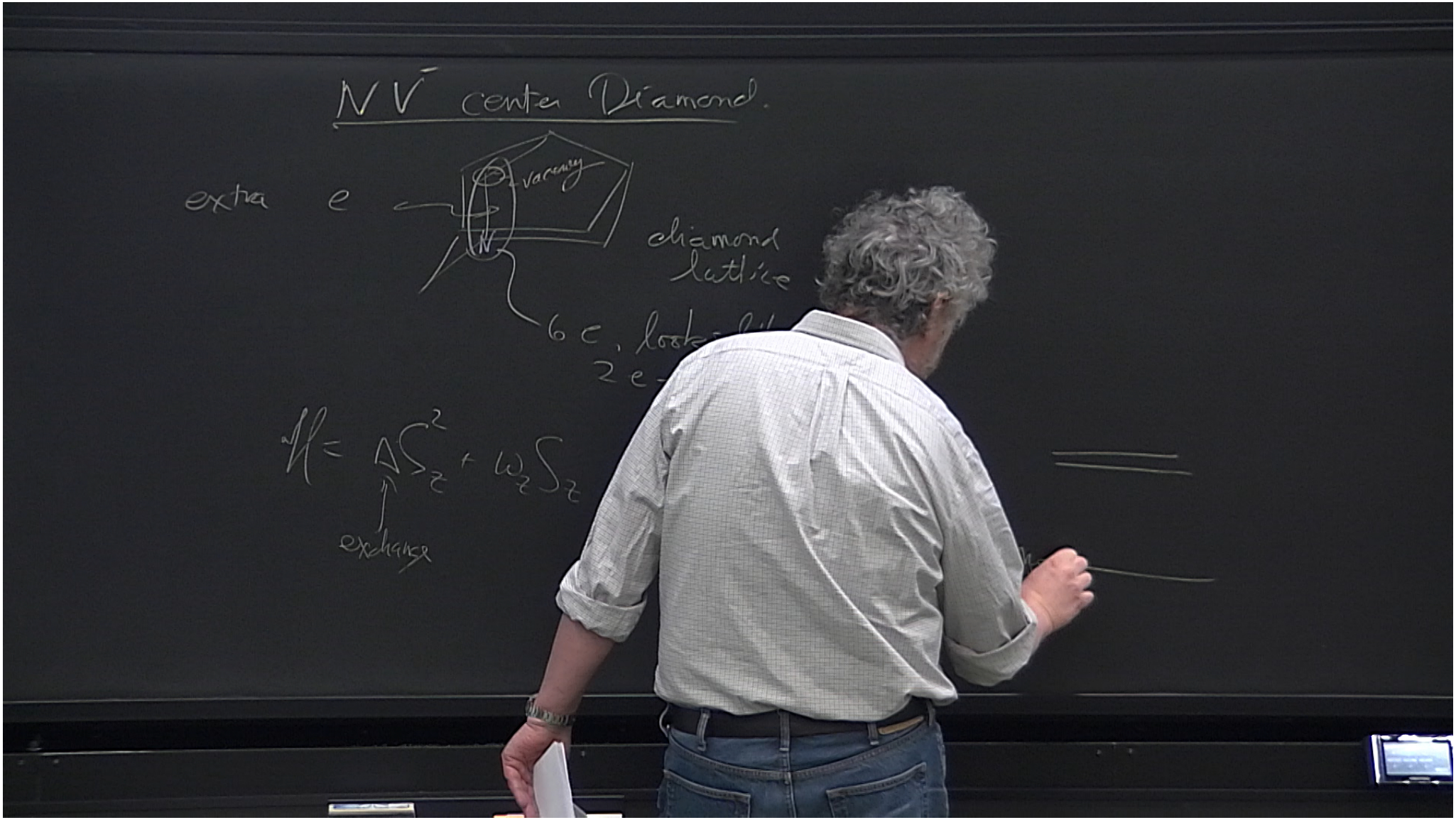
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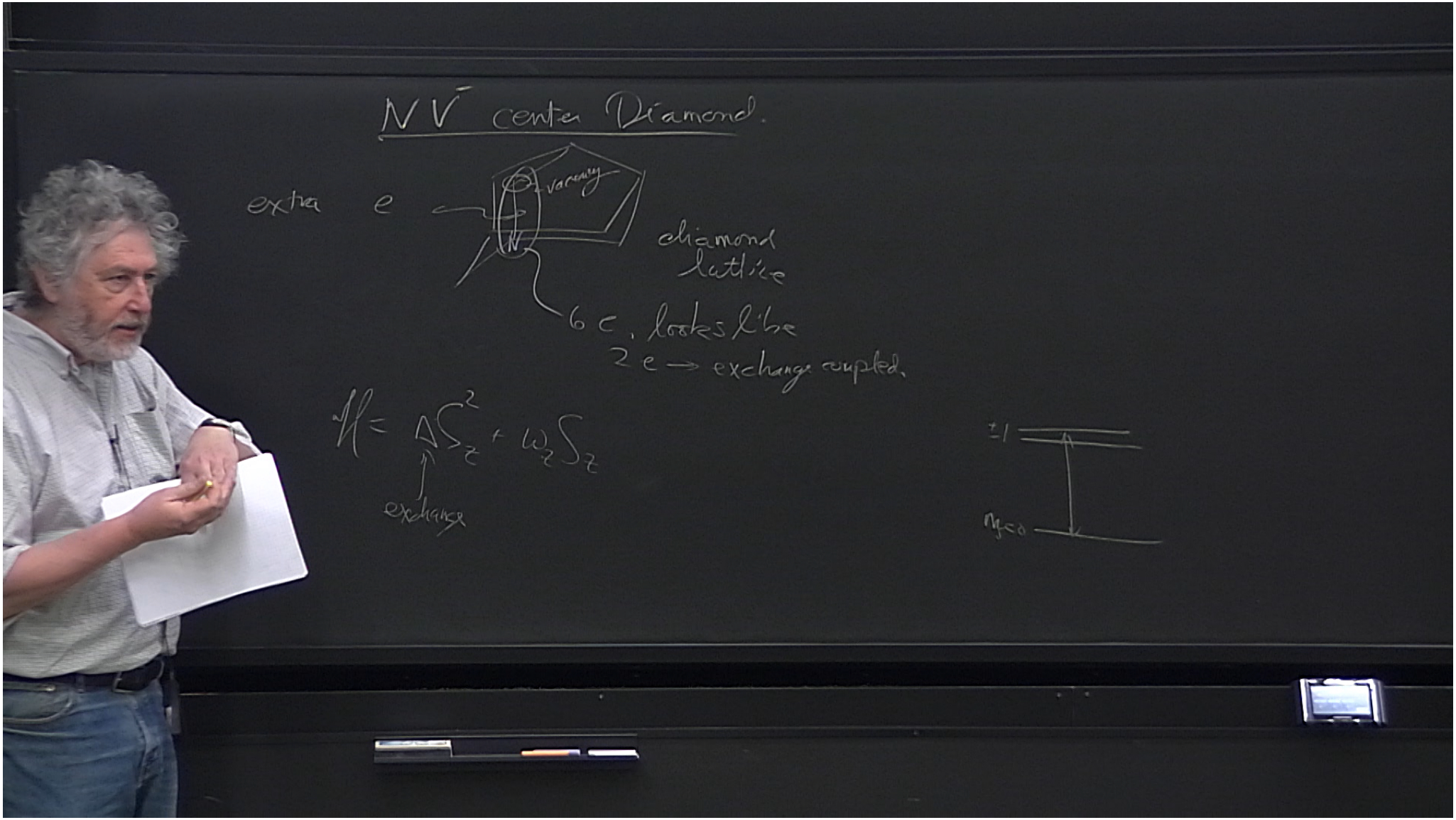
Abstract:

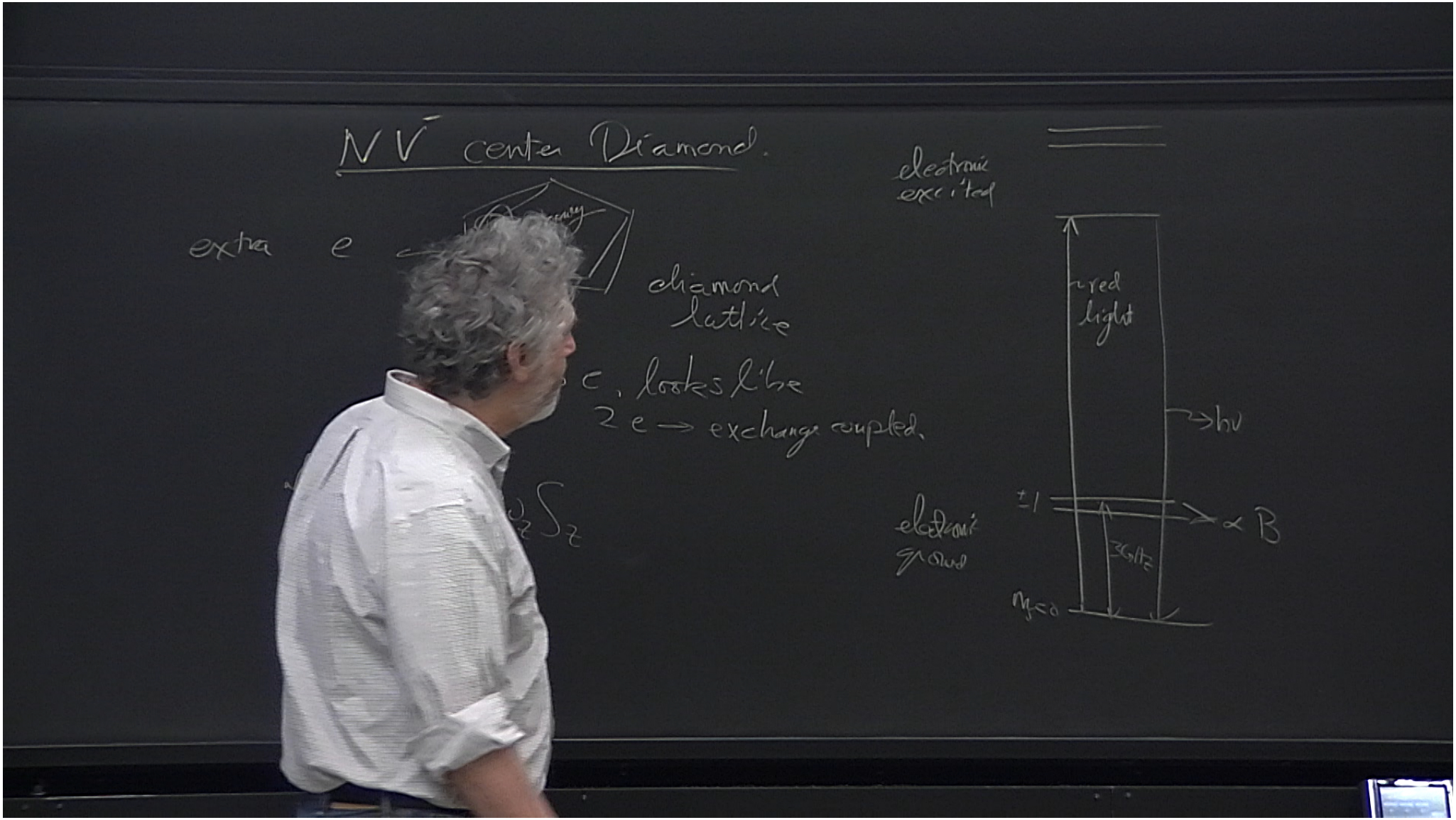

NV center Diamond.
vacancy
N
diamond
lattice
6 C, looks like
2 e

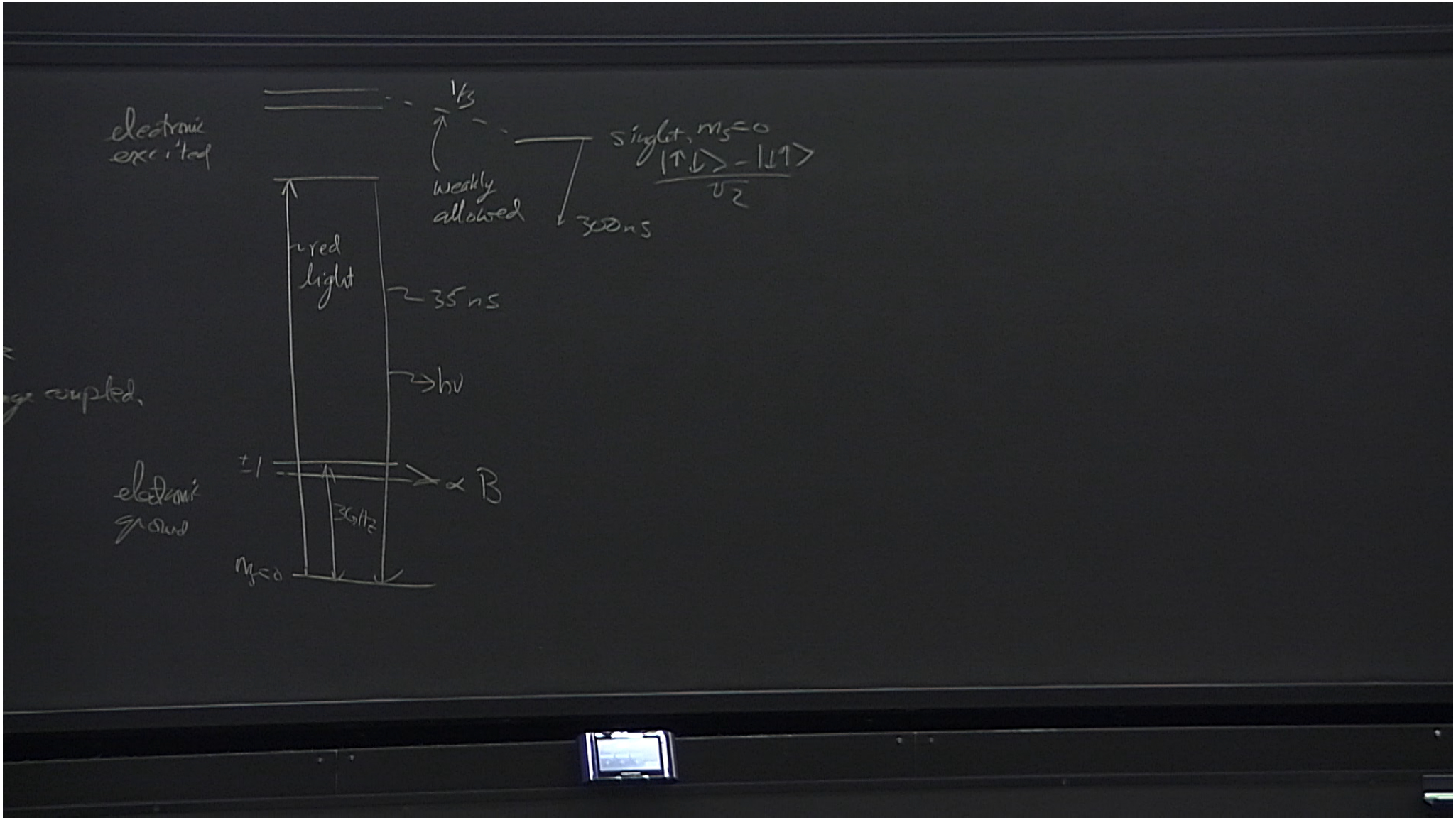
NV center Diamond.

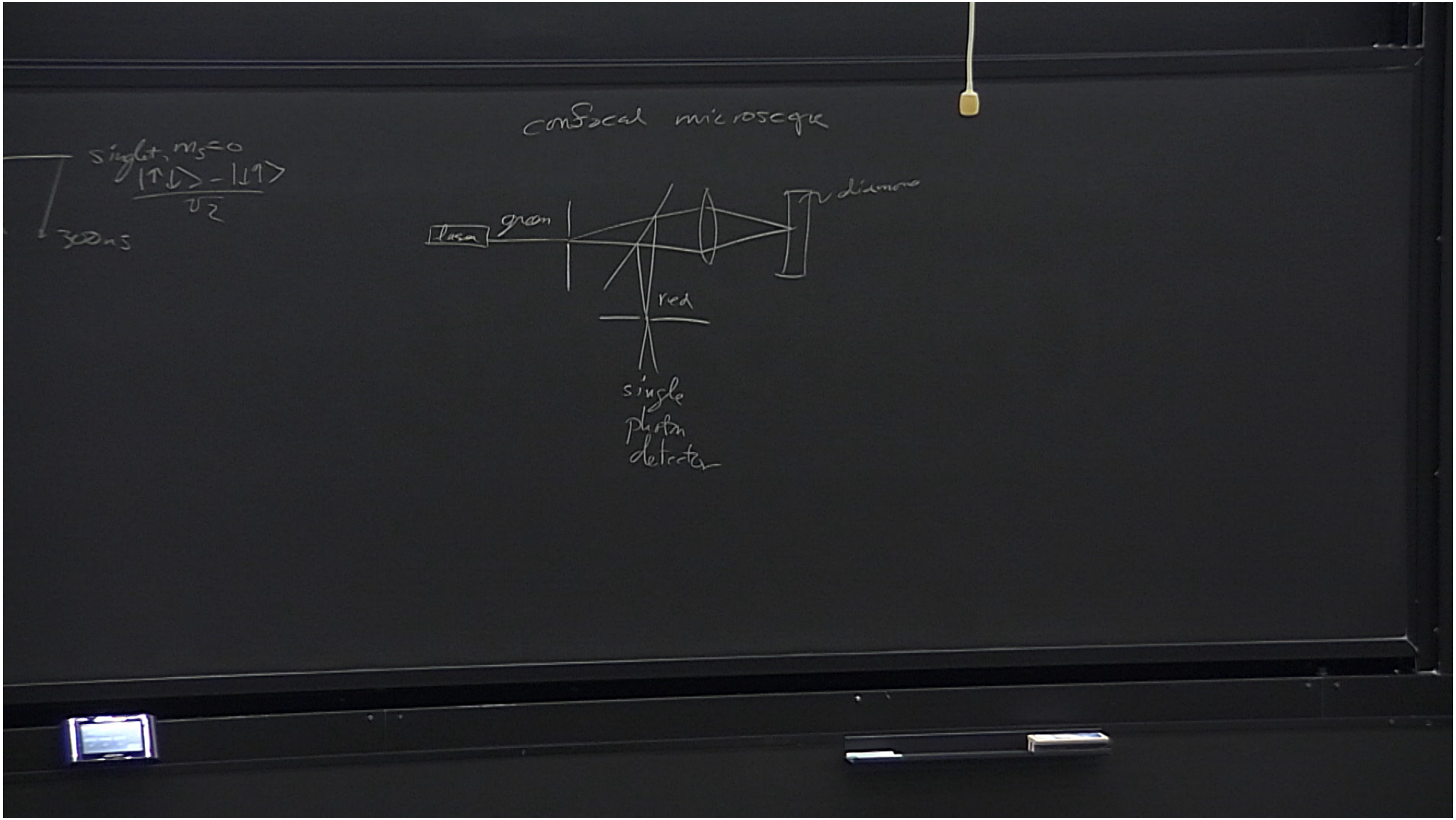



NV center Diamond.
extra e
vacancy
N
diamond lattice
6 e, look
2 e
exchange

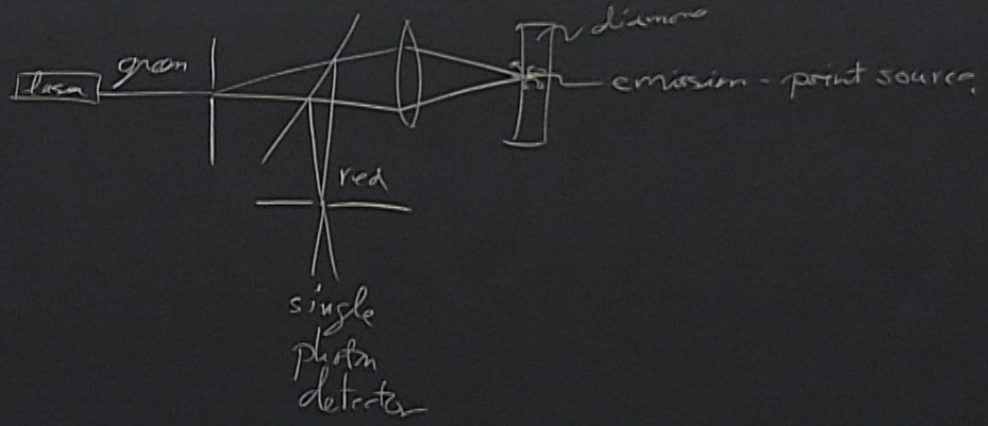

NV center Diamond.
extra e
vacancy
diamond lattice
6 C, looks like
2 e → exchange coupled.
$\mathcal{H} = \Delta S_z^2 + \omega_z S_z$
exchange
±1
$m_s=0$


NV center Diamond.
extra e
diamond lattice
c. looks like
2 e → exchange coupled.
electronic excited
red light
→ hν
±1
∝ B
electronic ground
3 GHz
mS=0


electronic excited
1/3
weakly allowed
singlet, $m_s=0$
$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$
300 ns
red light
~35 ns
hν
±1
∝ B
electronic ground
3GHz
$m_s=0$


confocal microscope
singlet, $m_S=0$
$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$
300 ns
laser
green
diamond
red
single photon detector

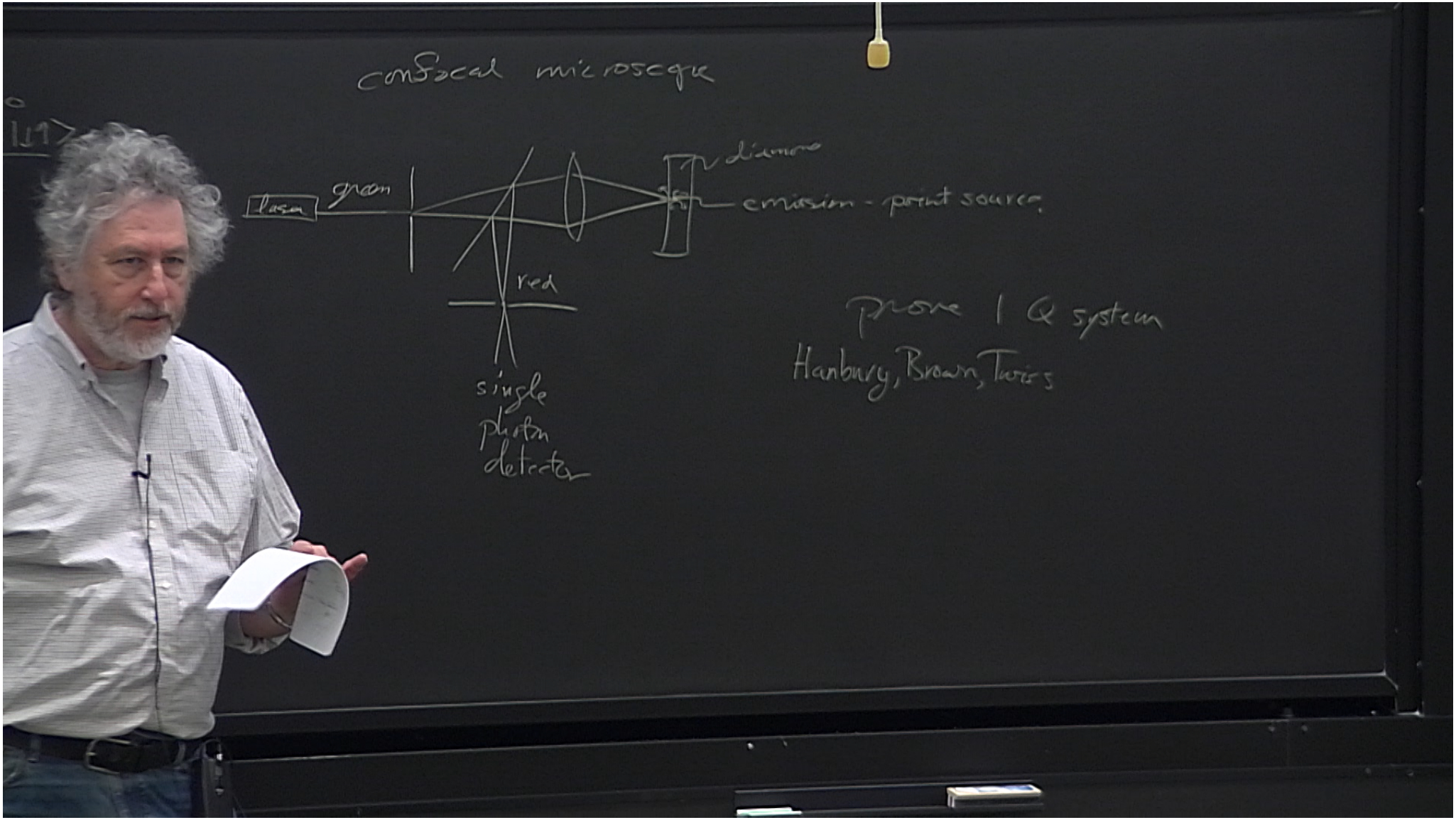
confocal microscope

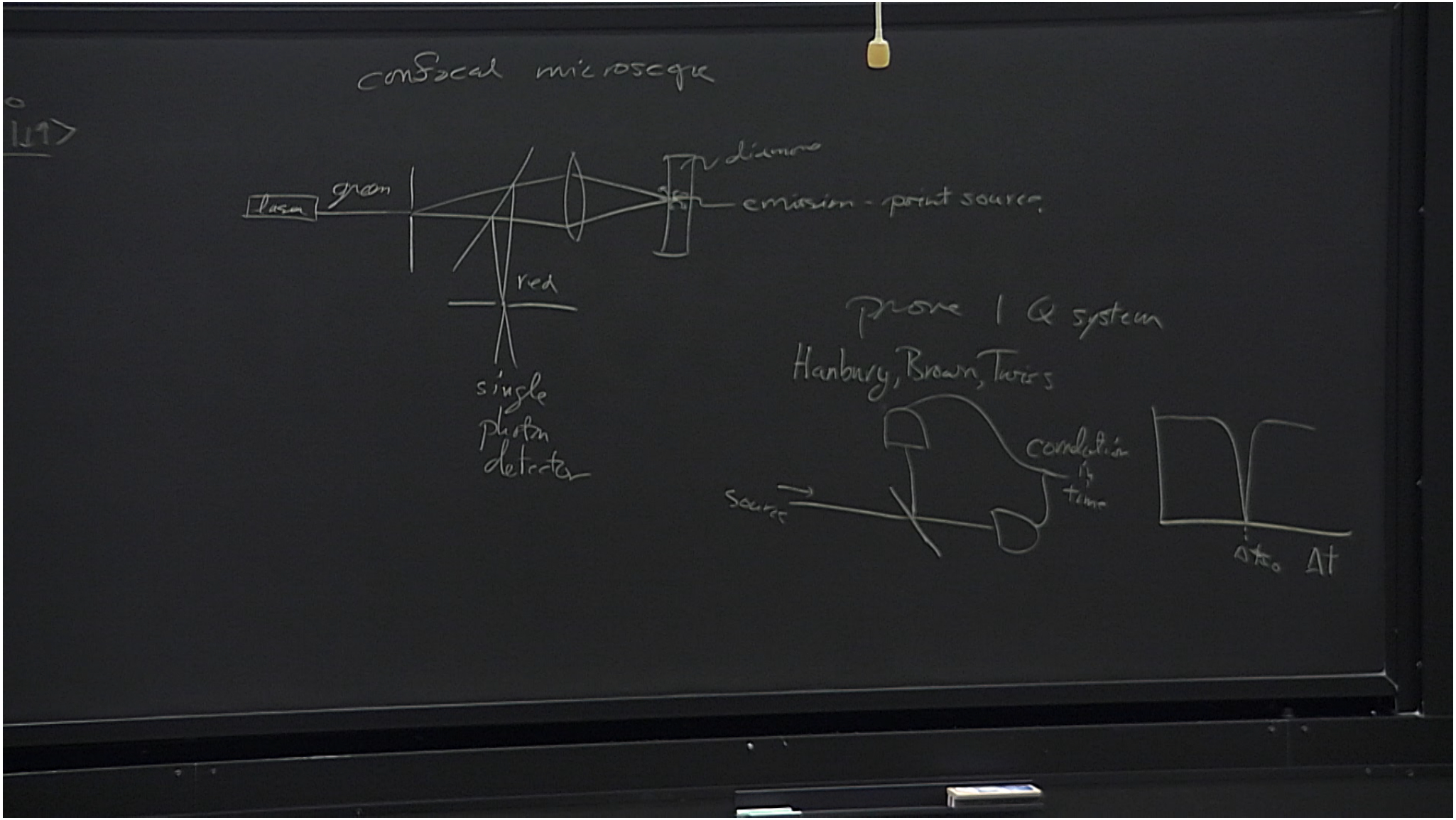


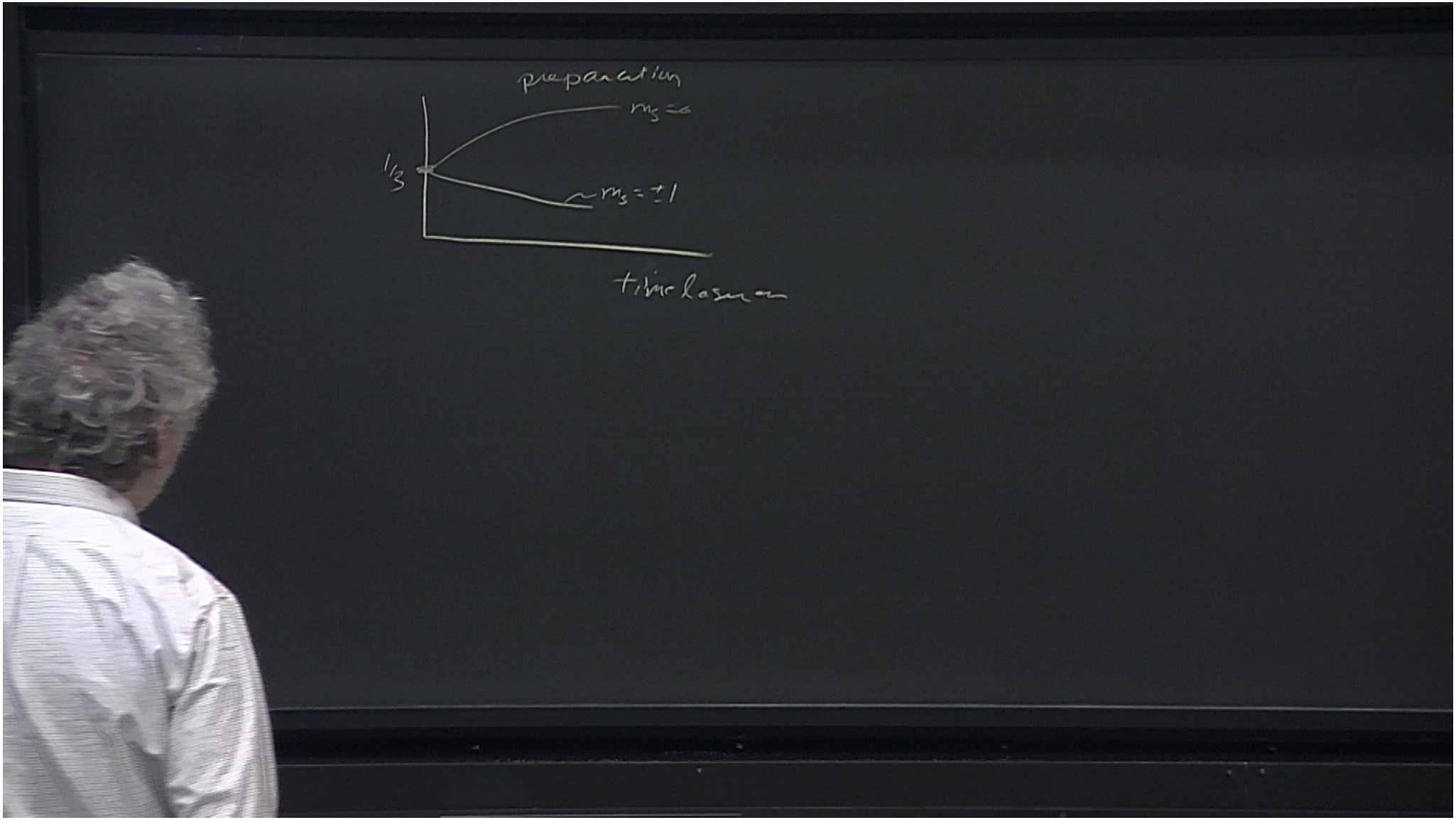
singlet, $m_s=0$

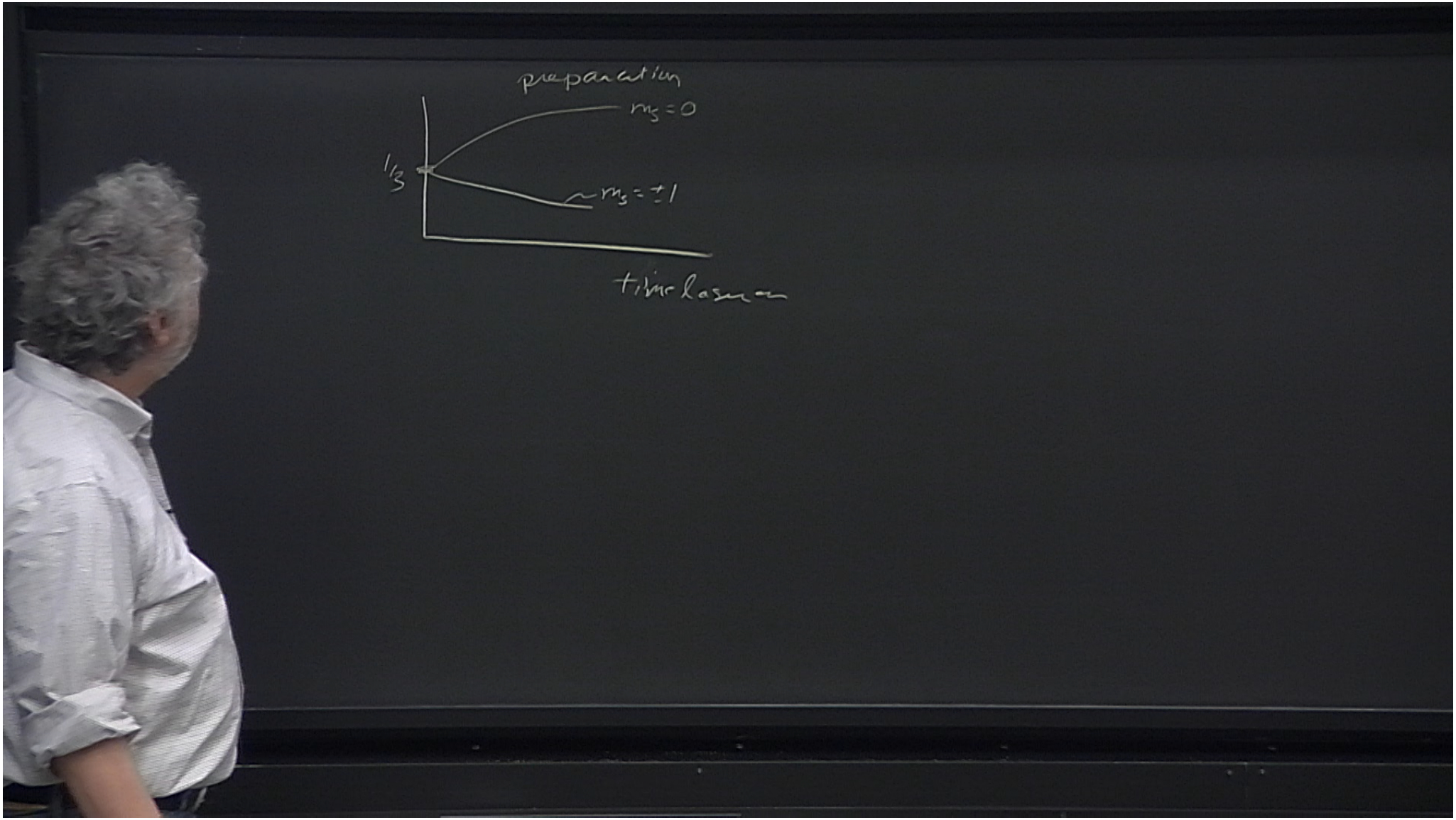
$\frac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$

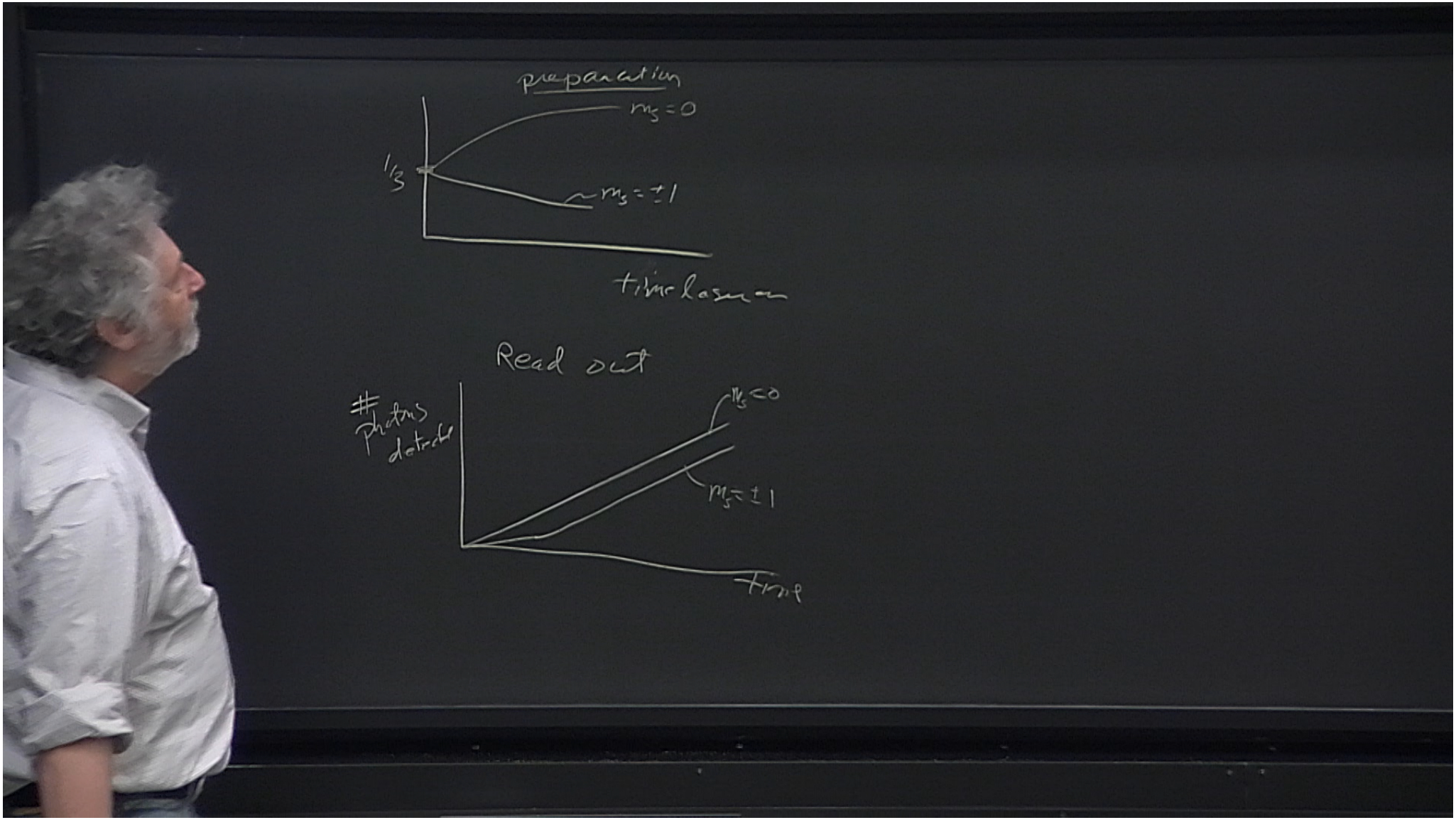
300 ns

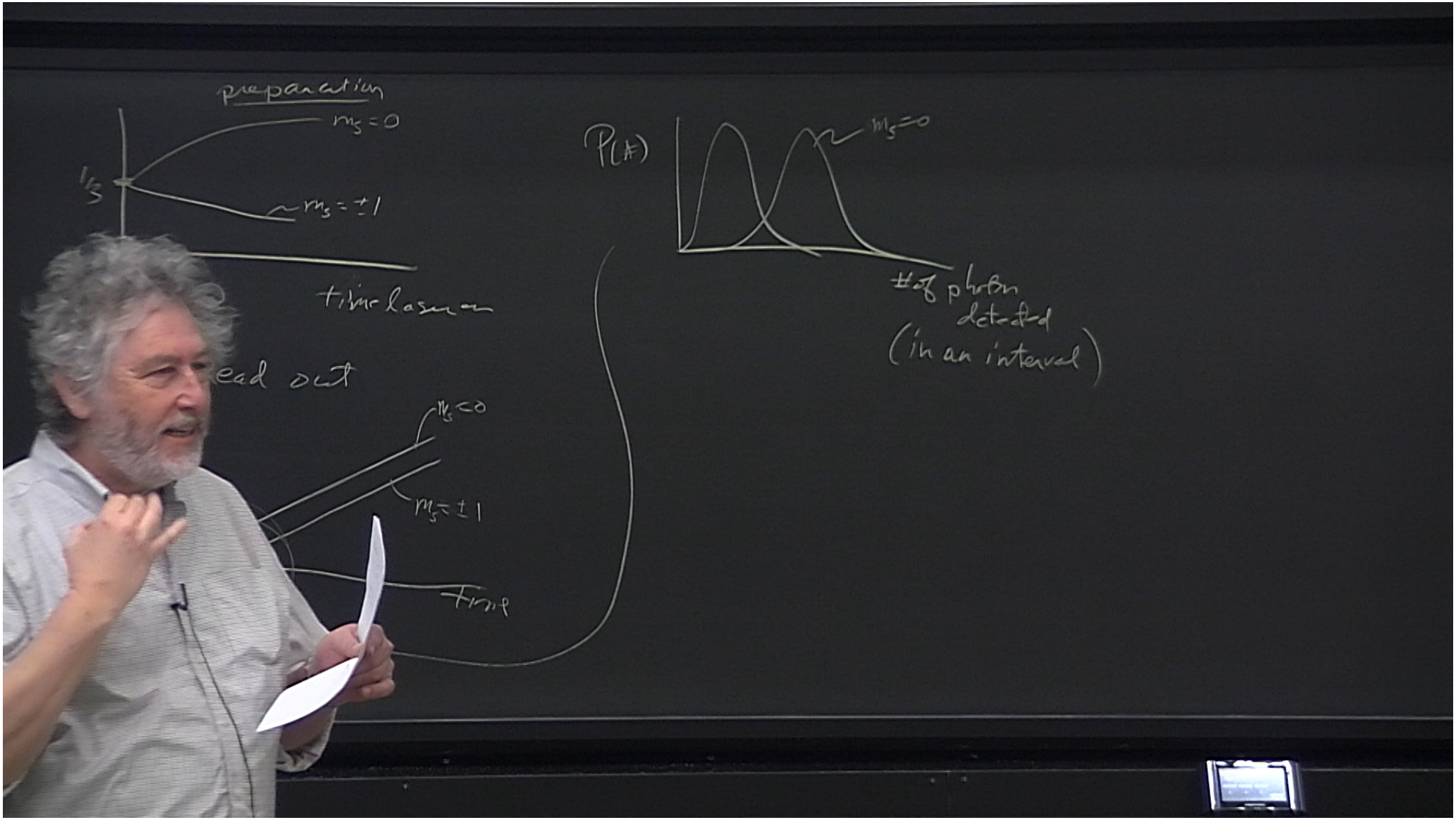

confocal microscope
laser
green
diamond
emission - point source
red
single photon detector
prove 1 & system
Hanbury, Brown, Twiss

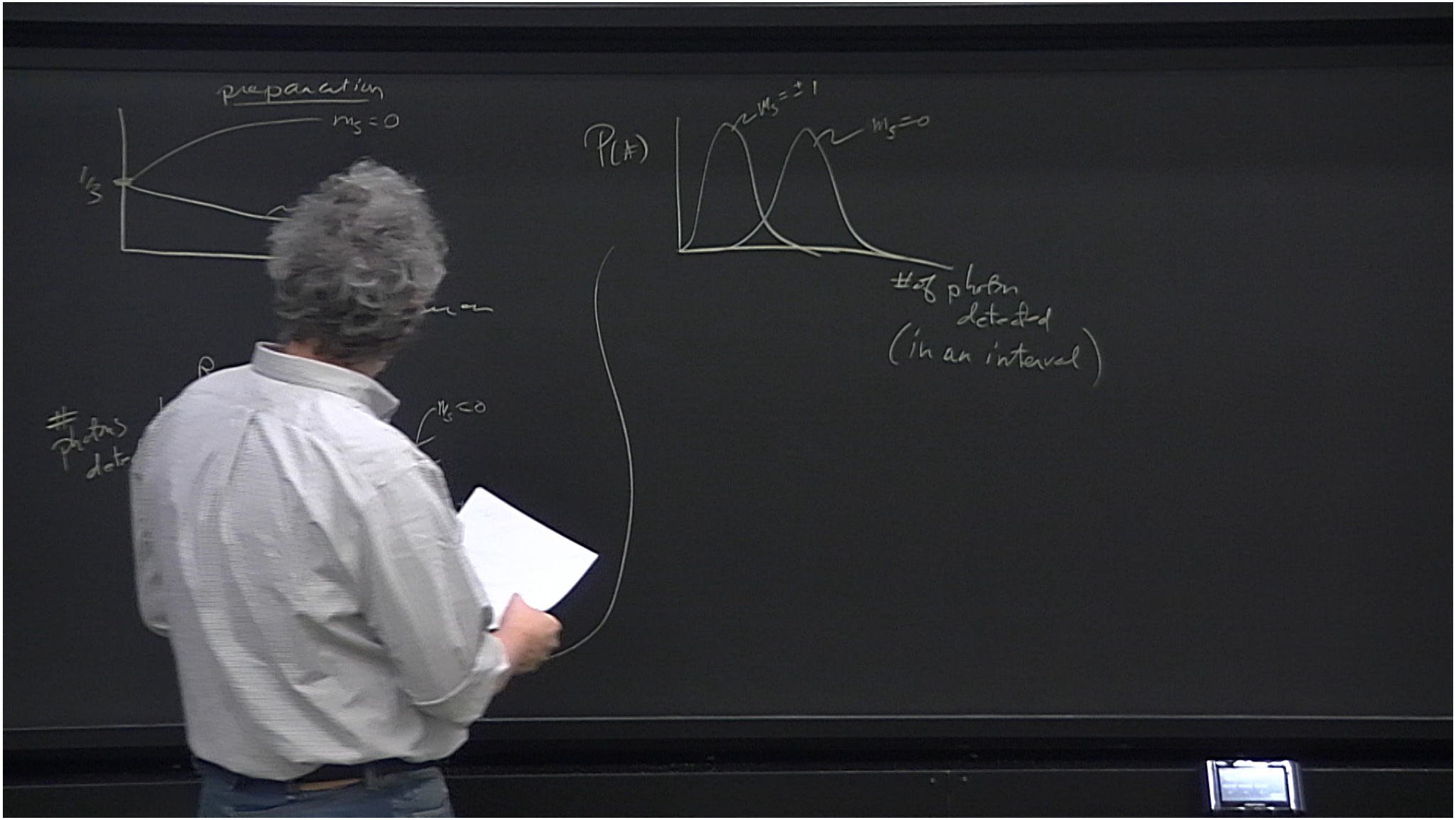

confocal microscope
|1>
green
laser
diamond
emission - point source
red
single photon detector
prove 1 & system
Hanbury, Brown, Twiss
correlation in time
source
Δt=0
Δt

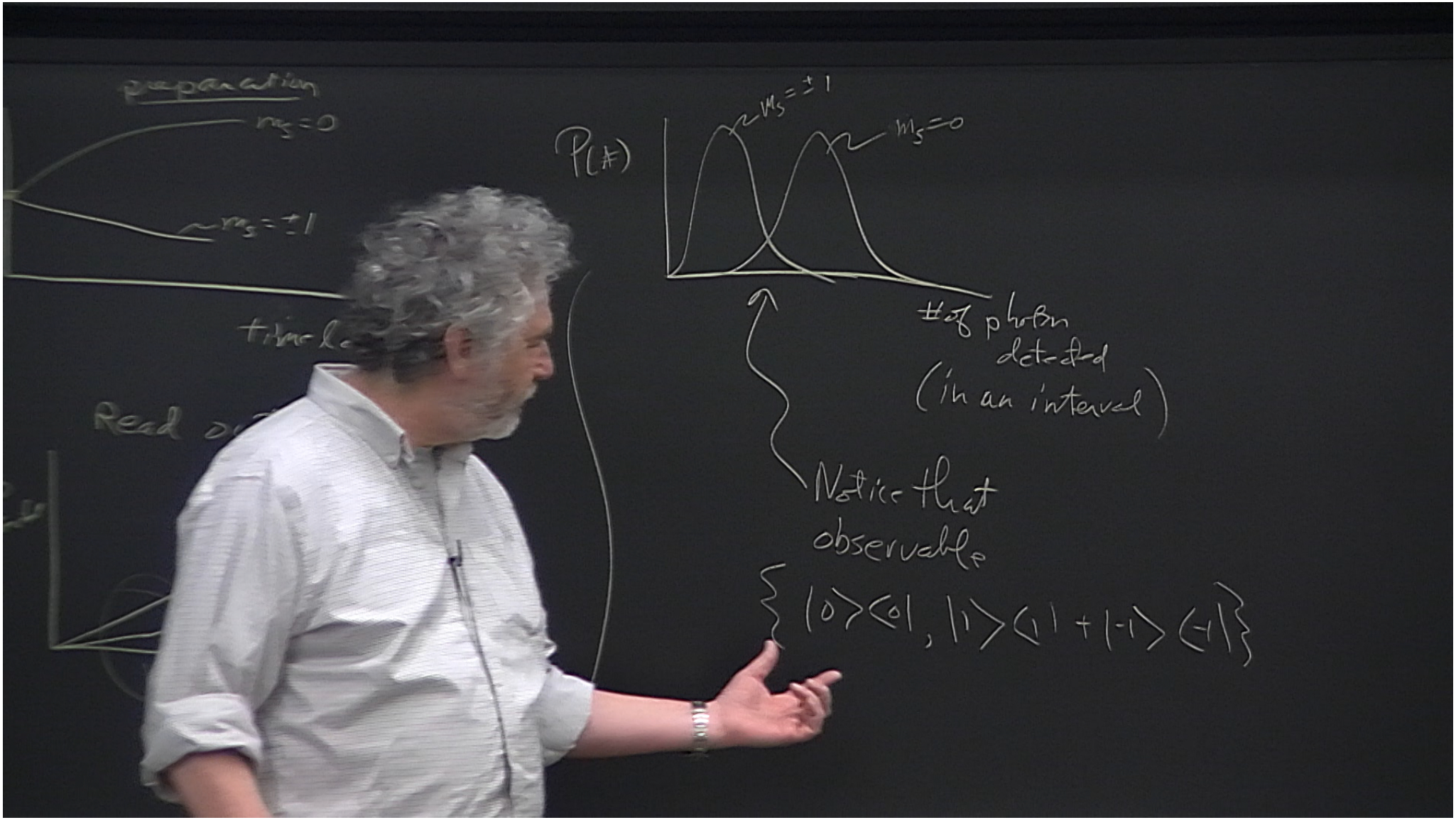

preparation
$m_s = 0$
1/3
$m_s = \pm 1$
time lasers

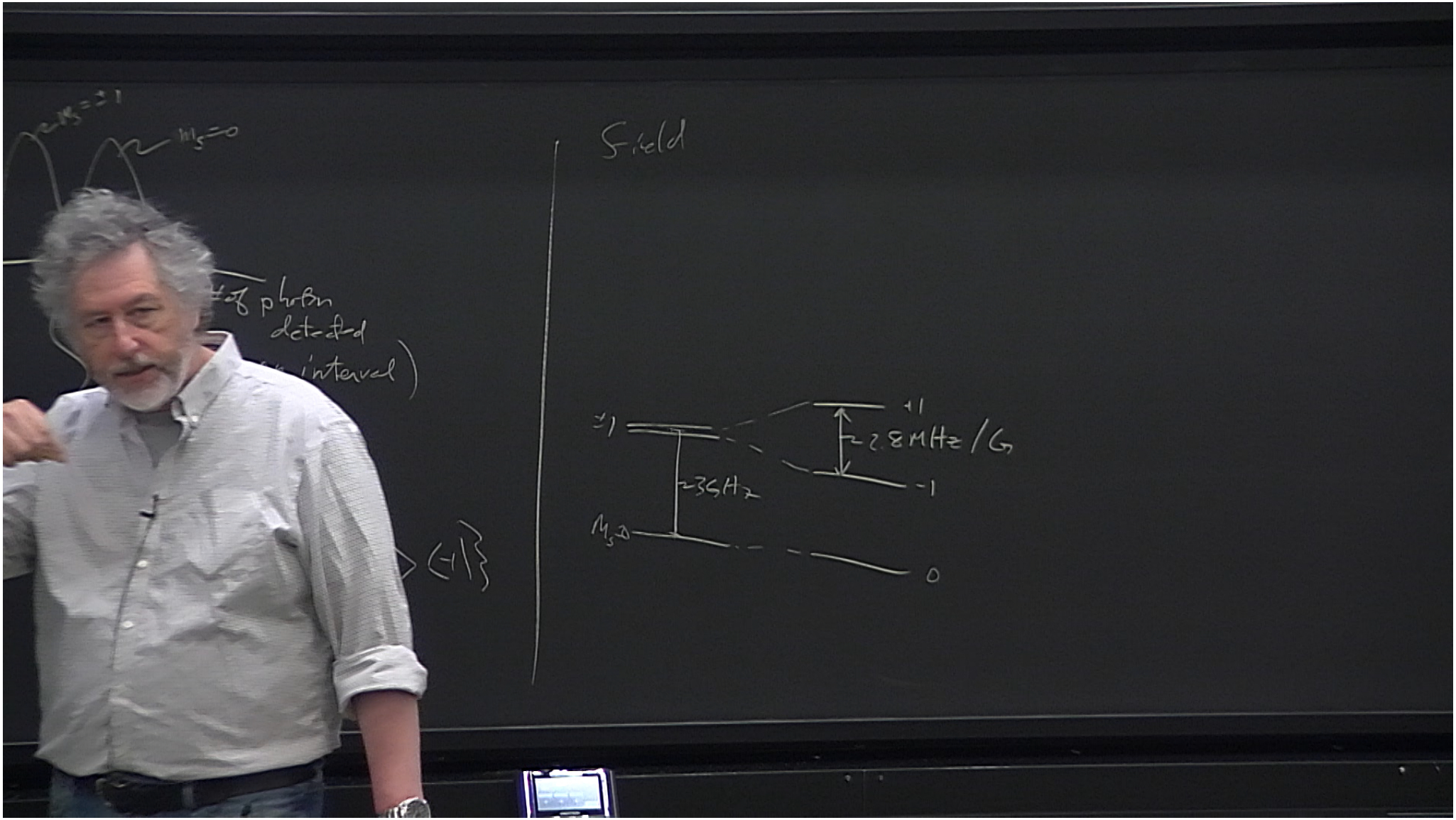

preparation
$m_s = 0$
1/3
$m_s = \pm 1$
time

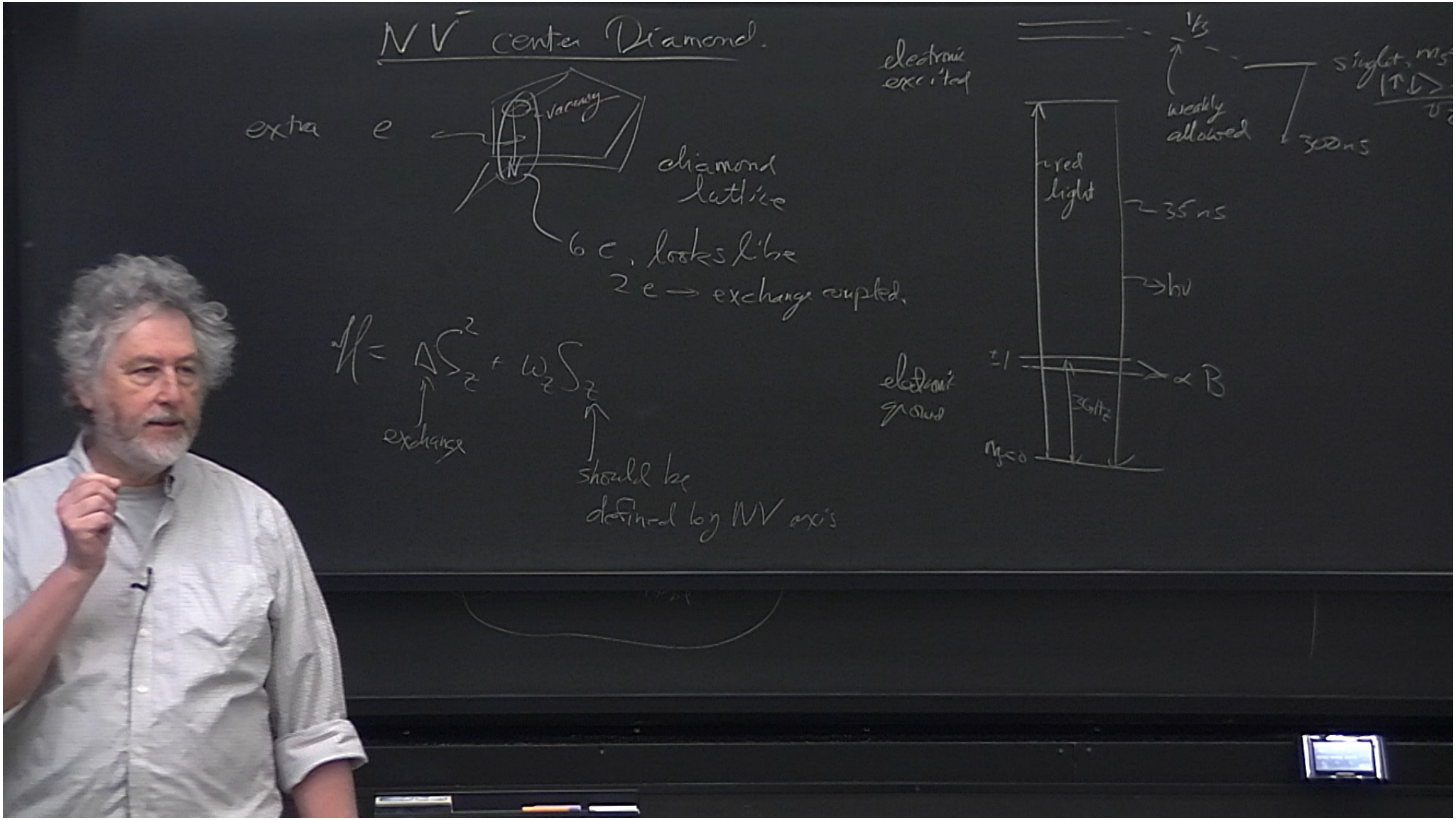

preparation
$m_s = 0$
1/3
$m_s = \pm 1$
time laser
Read out
photons detected
$m_s = 0$
$m_s = \pm 1$
Time

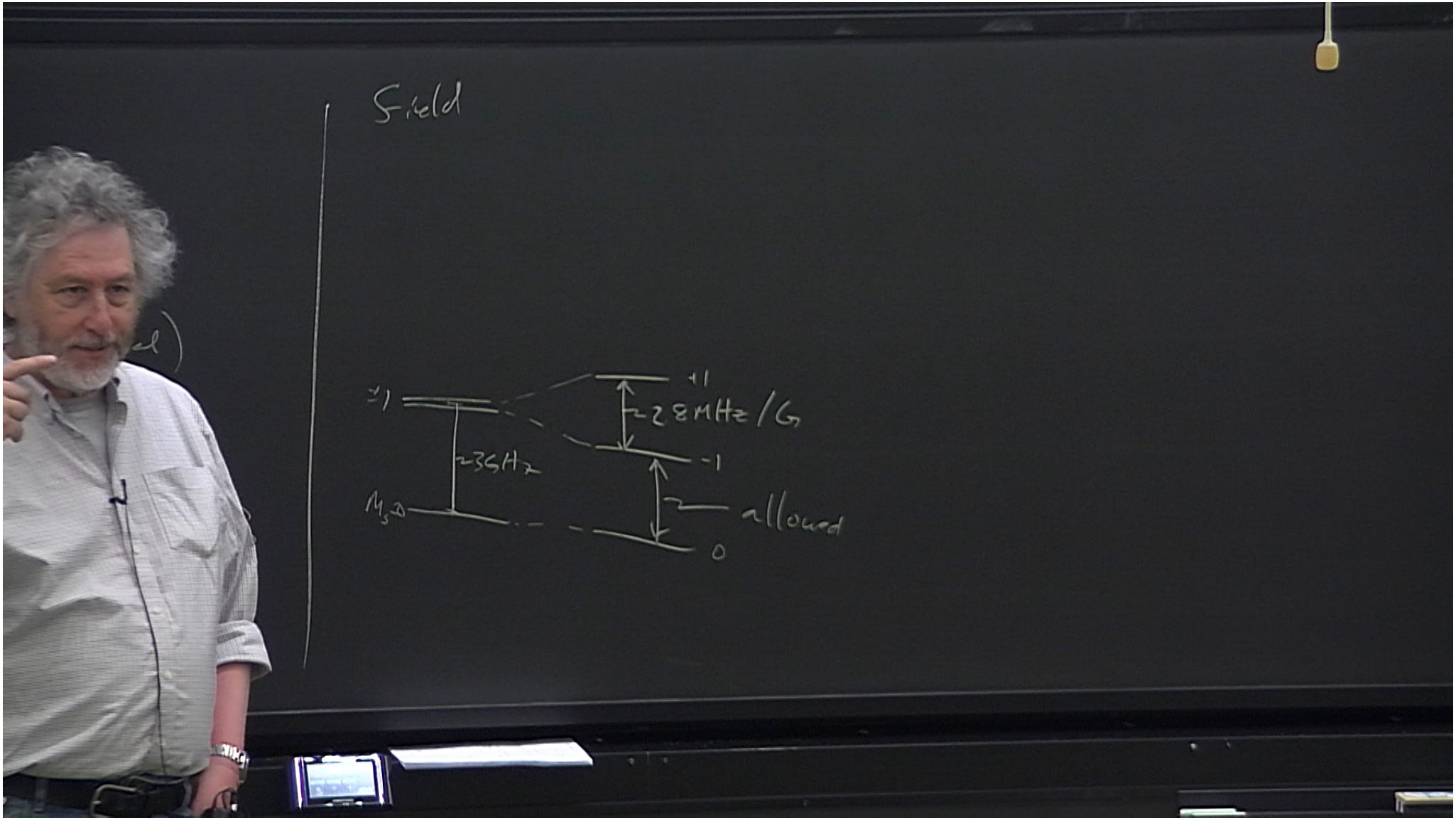

preparation
$m_s = 0$
$m_s = \pm 1$
laser
read out
$m_s = 0$
$m_s = \pm 1$
time
P(#)
$m_s = 0$
# of photon detected
(in an interval)

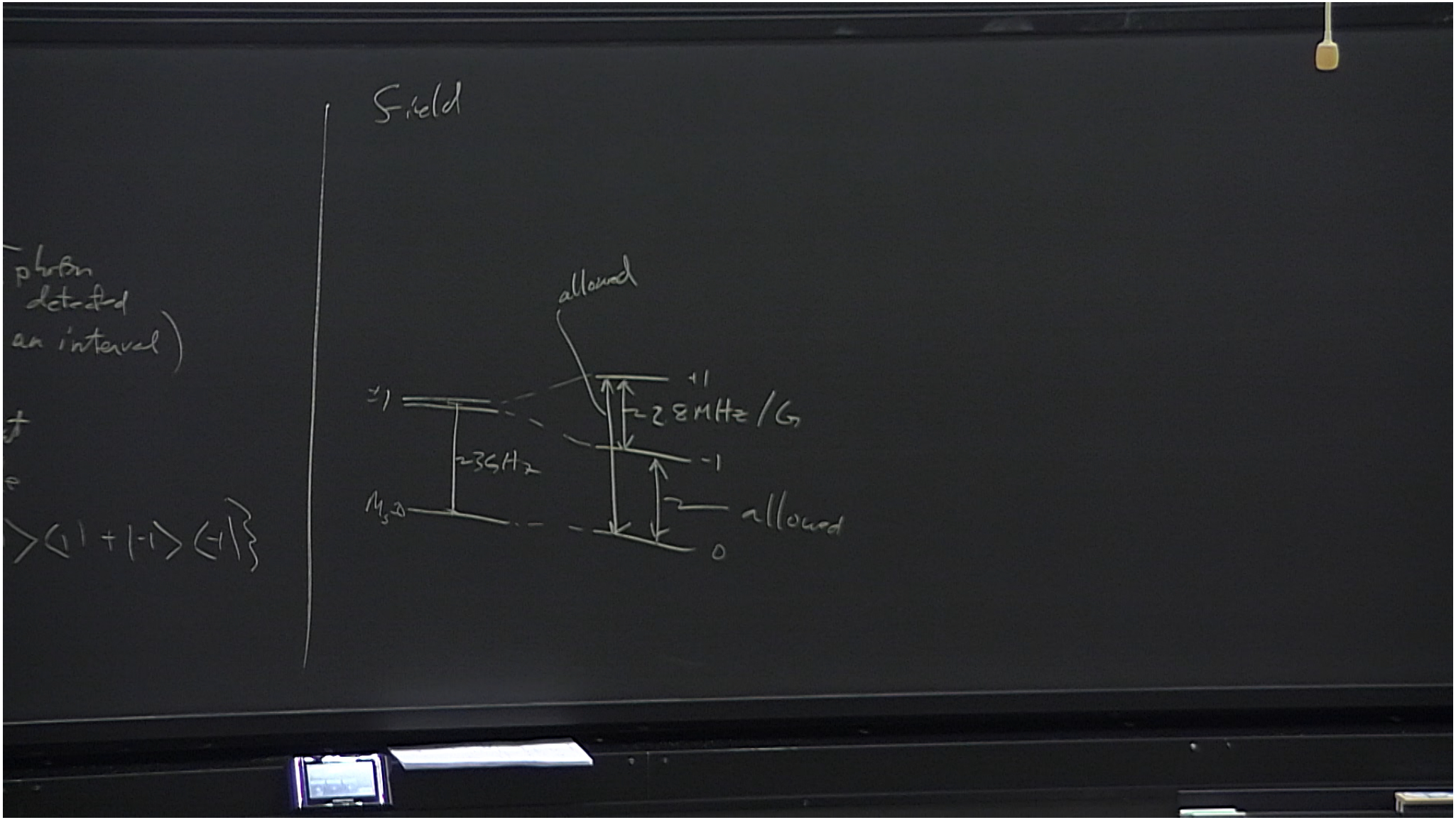

preparation
$m_s = 0$
1/3
P(#)
$m_s = \pm 1$
$m_s = 0$
# of photon detected
(in an interval)
photons
$m_s < 0$

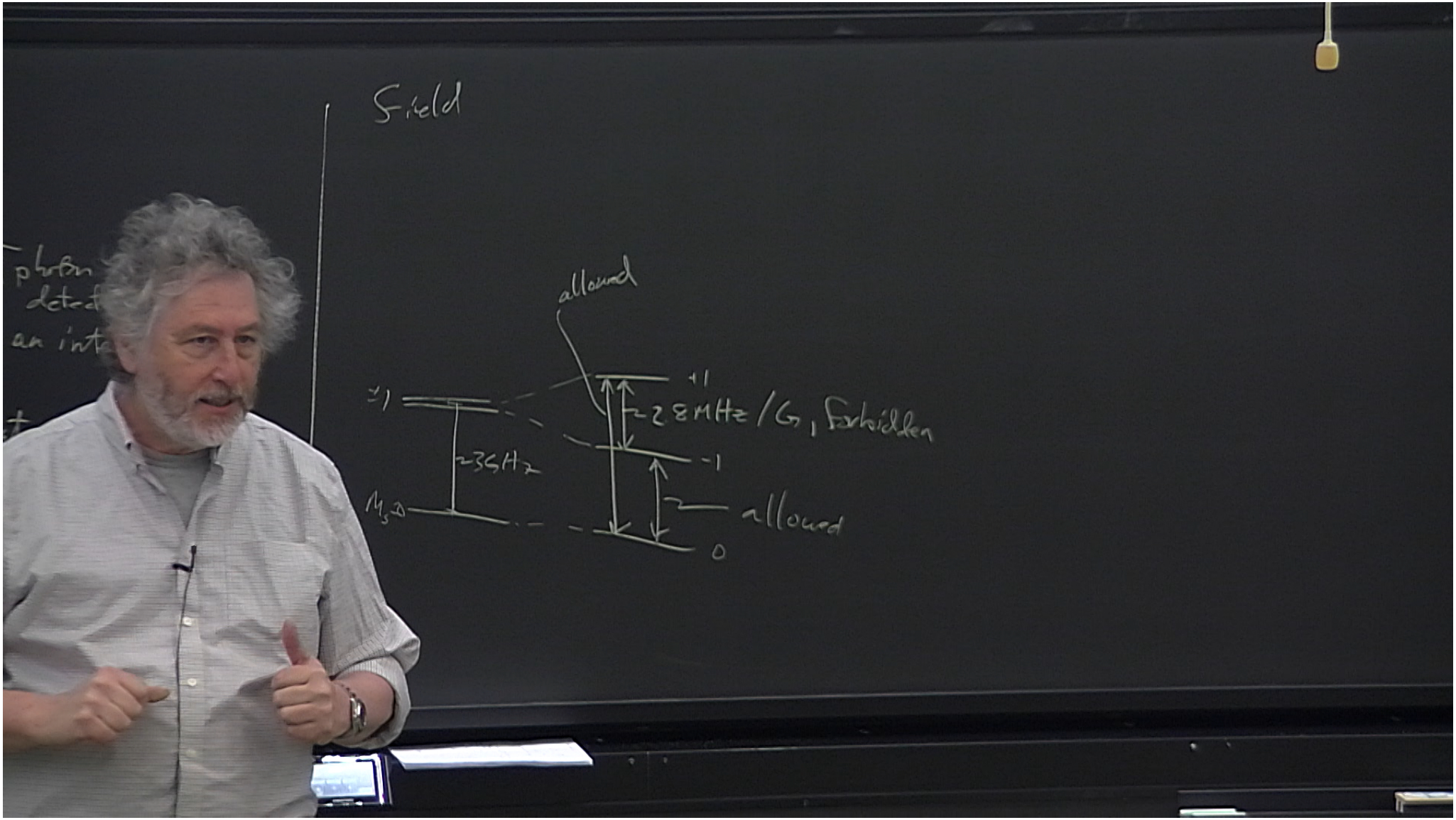

preparation
$m_s = 0$
$m_s = \pm 1$
time
Read o
P(#)
$m_s = \pm 1$
$m_s = 0$
# of photons detected (in an interval)
Notice that observable
$\{|0\rangle\langle 0|, |1\rangle\langle 1| + |-1\rangle\langle -1|\}$

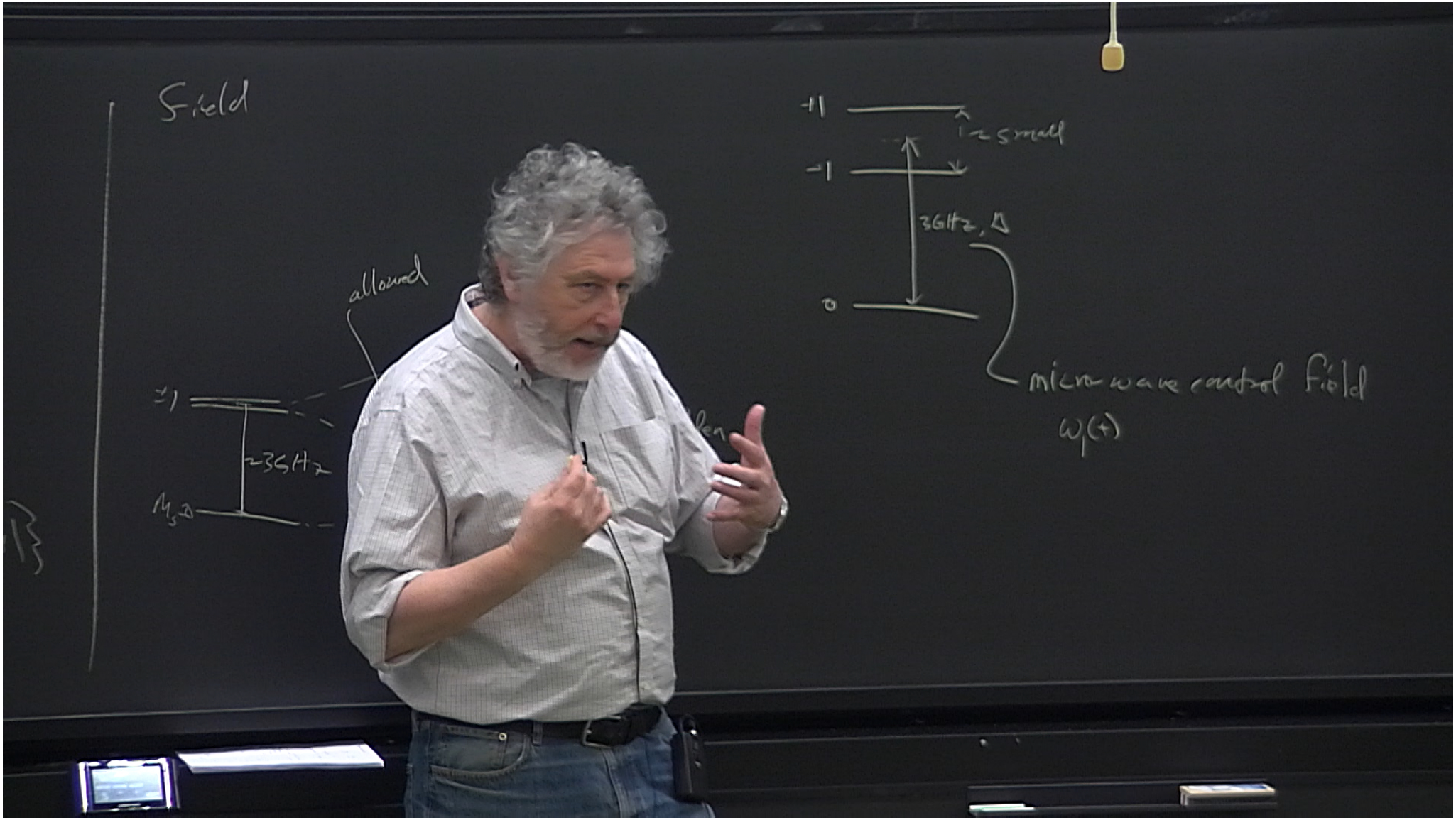

Field
+1
2.8MHz/G
-1
35Hz
0

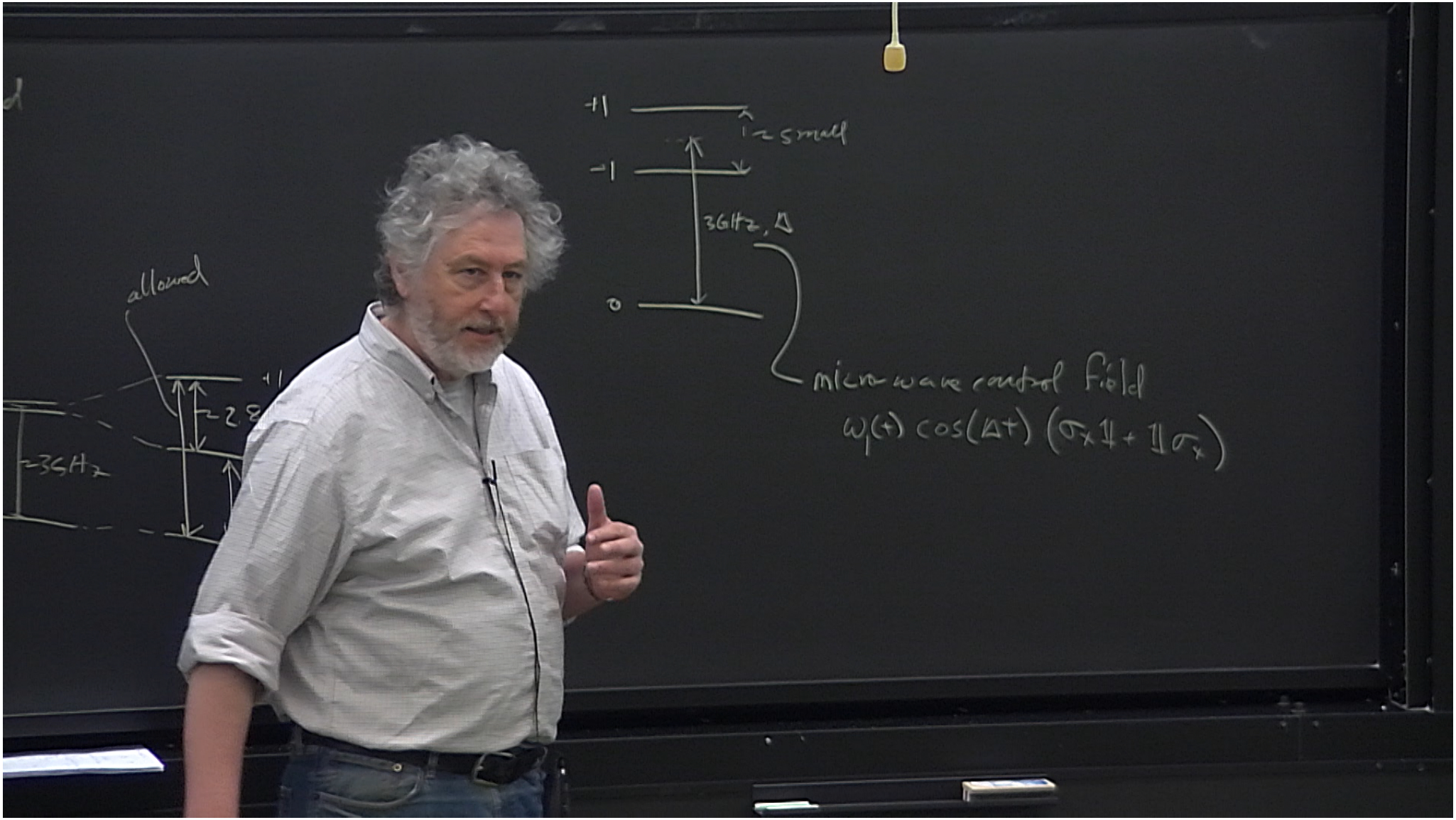

NV center Diamond.
extra e
vacancy
N
diamond lattice
6 C, looks like
2 e → exchange coupled.
exchange
should be defined by NV axis
electronic excited
weakly allowed
1/3
singlet, ms
|T L>
300 ns
red light
~35 ns
hν
±1
∝ B
2GHz
ms=0
electronic ground

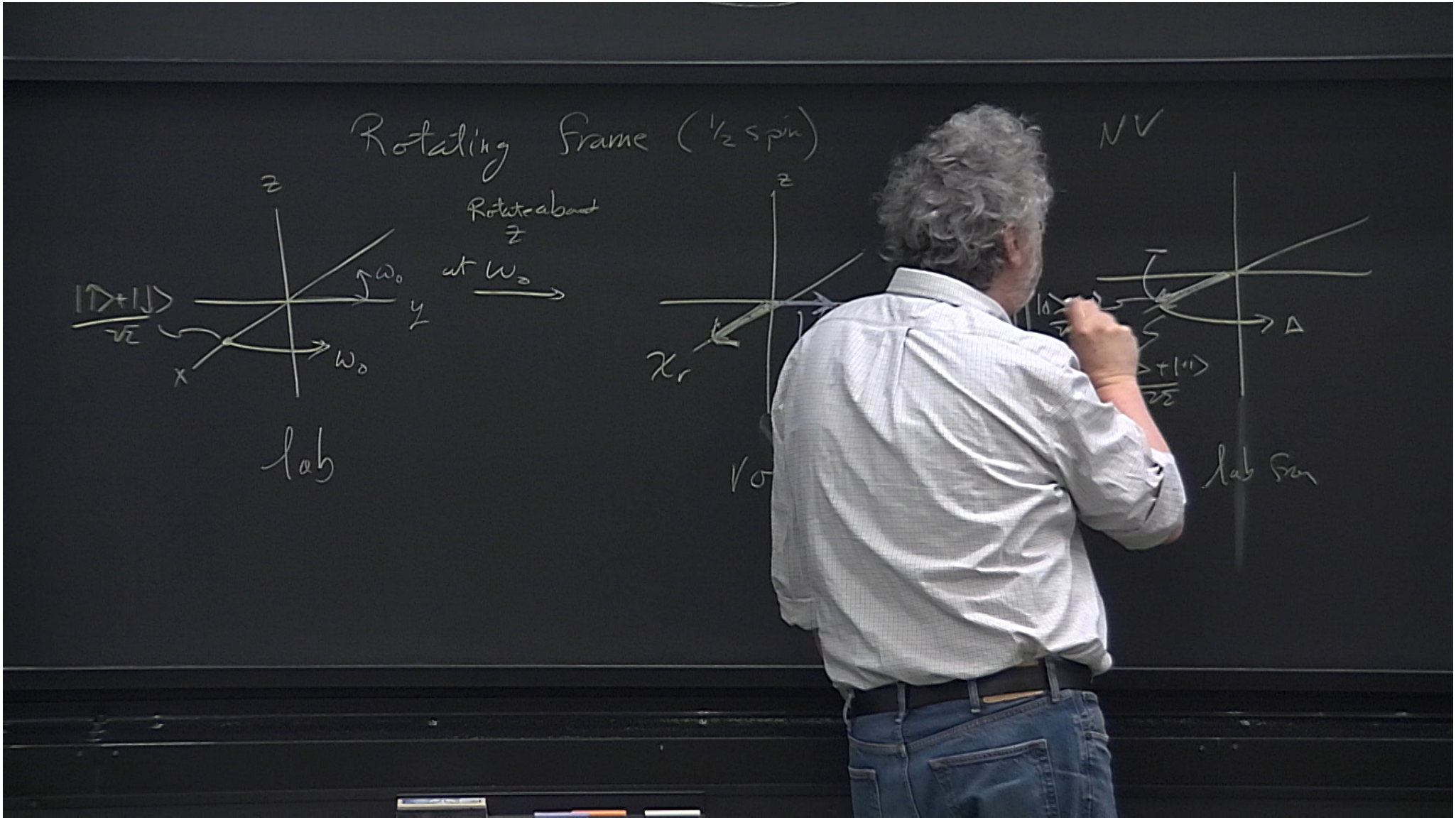

Field
+1
2.8 MHz/G
-1
allowed
0

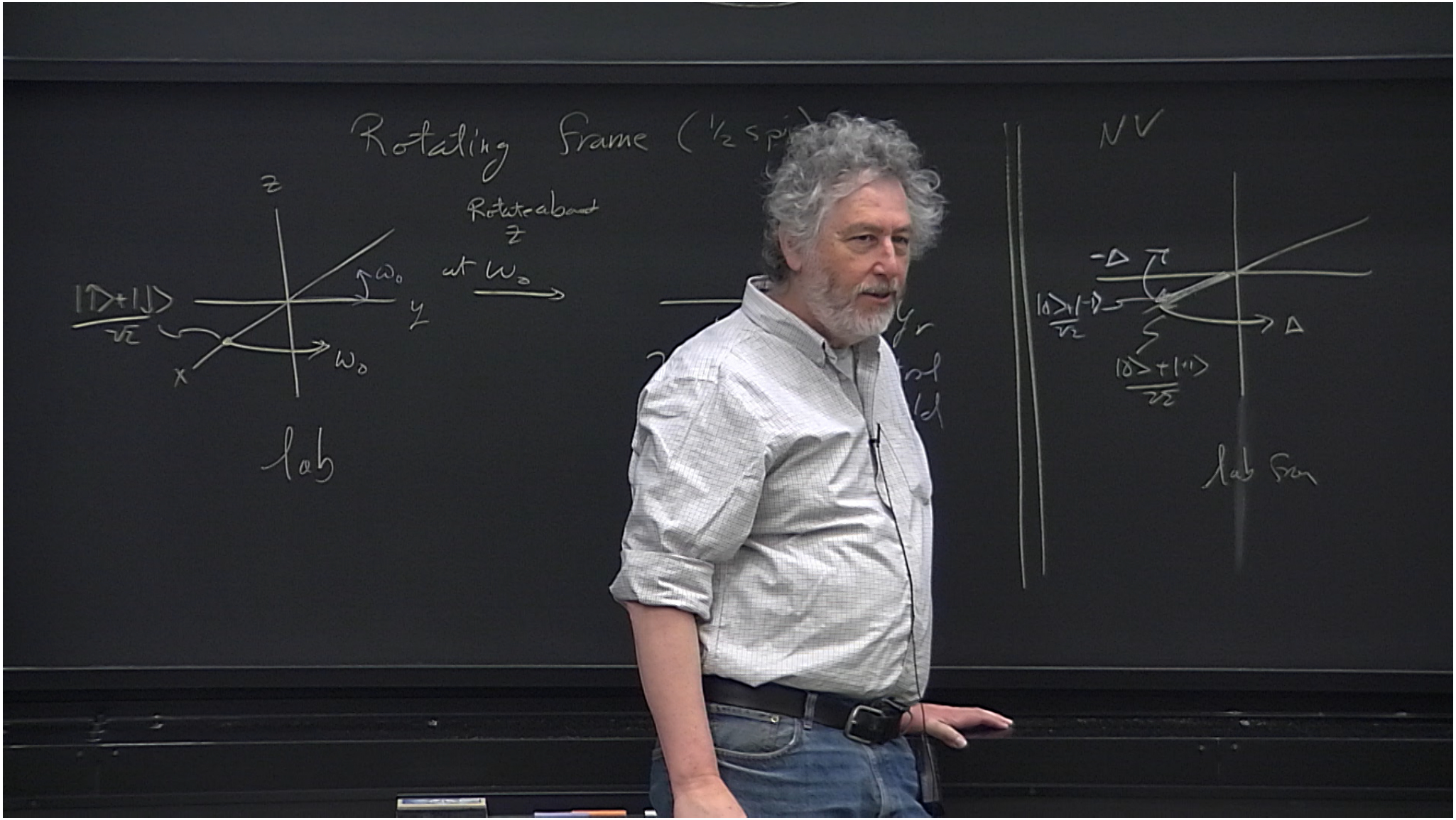

Field
allowed
+1
≈28 MHz/G
-1
≈35 Hz
allowed
0

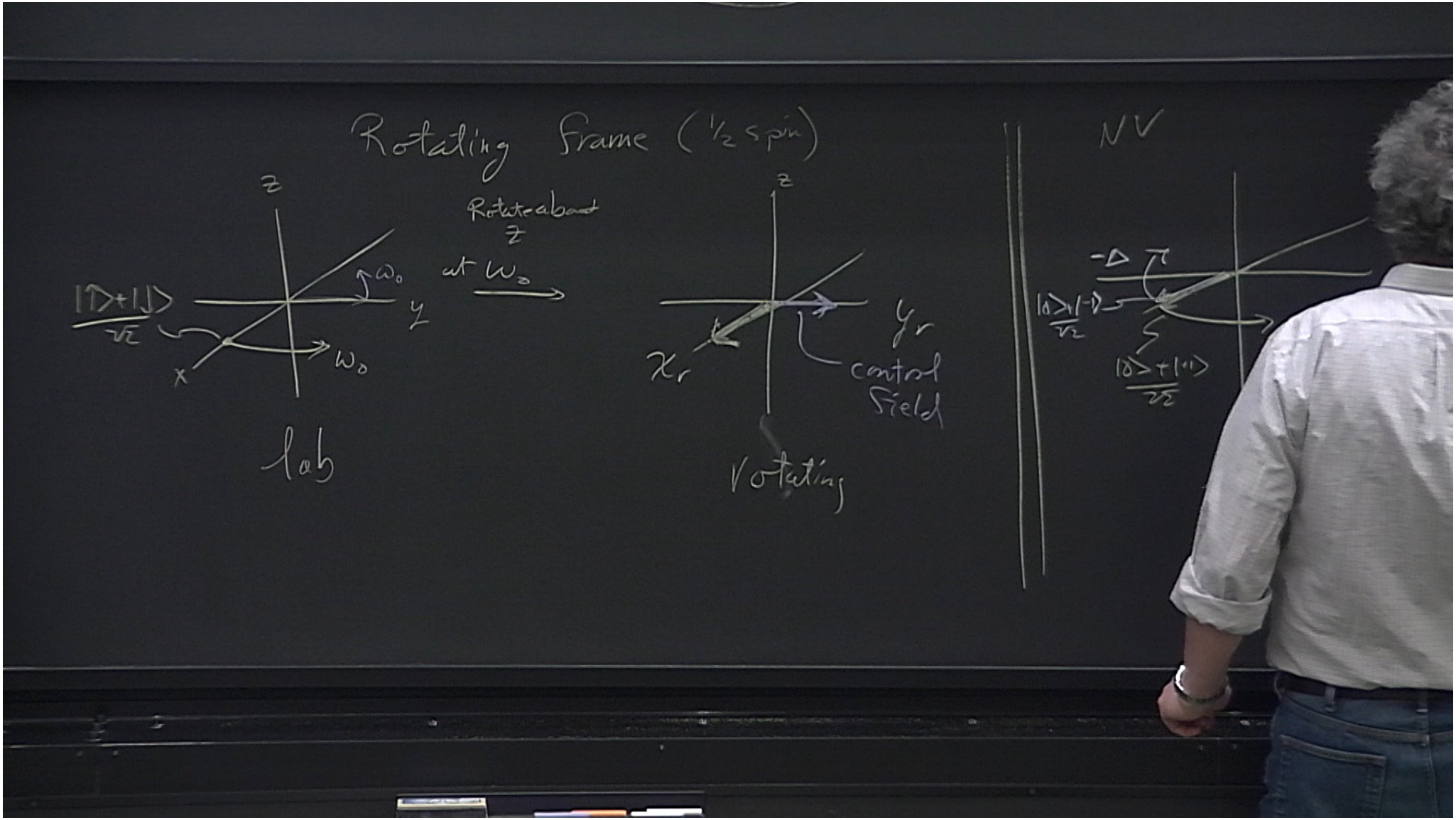

Field
allowed
+1
2.8 MHz/G, forbidden
-1
allowed
0

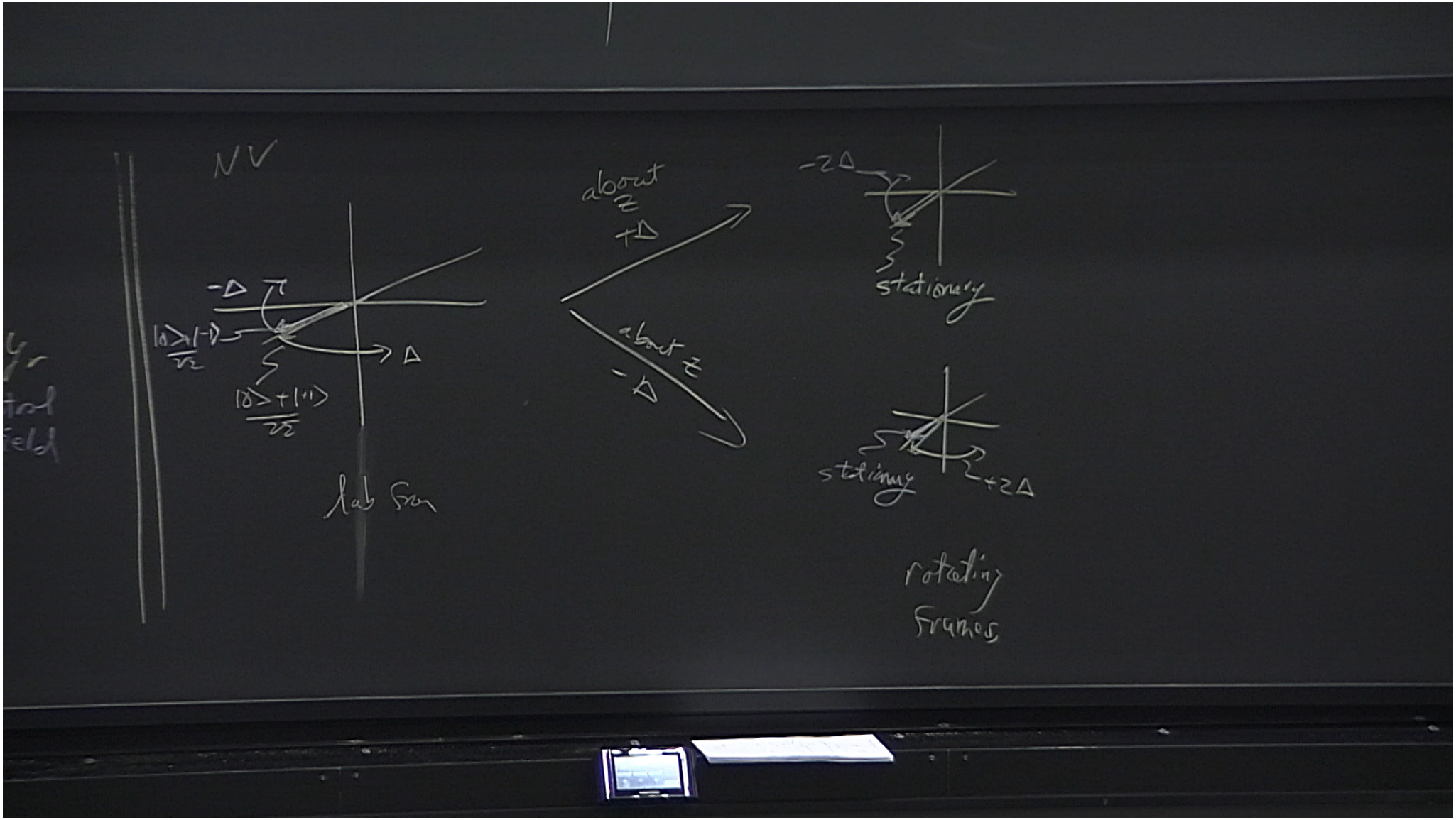

Field
allowed
+1
-1
0
3GHz, Δ
small
microwave control field
$\omega_1(t)$
+1
-1
3GHz
M_s 0

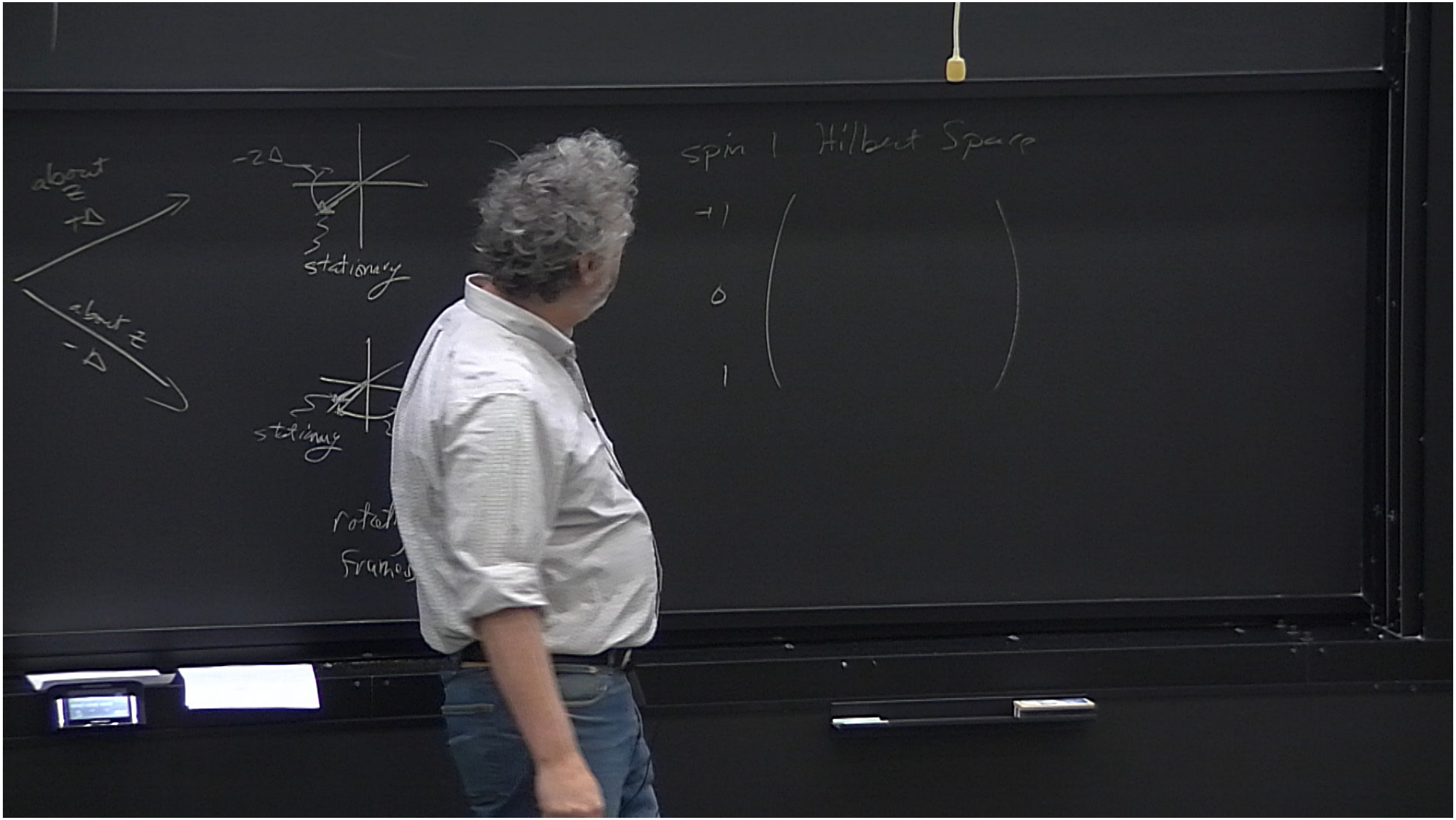

+1
-1
0
3GHz, Δ
allowed
microwave control field
$\omega_1(t)\cos(\Delta t)(\sigma_x \mathbb{1} + \mathbb{1}\sigma_x)$

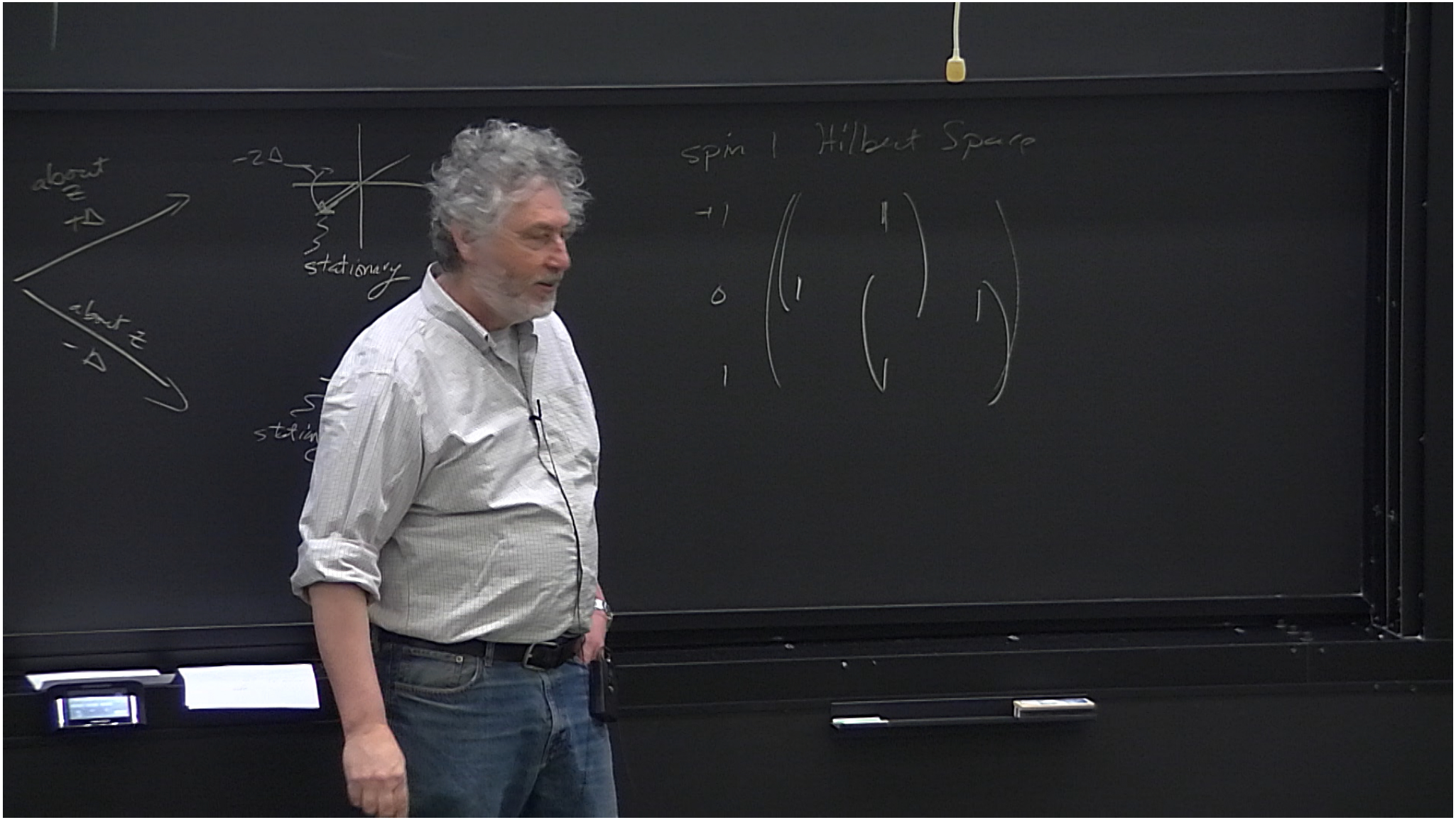

Rotating frame (½ spin)
NV
Rotate about z
at ω₀
lab
lab frame

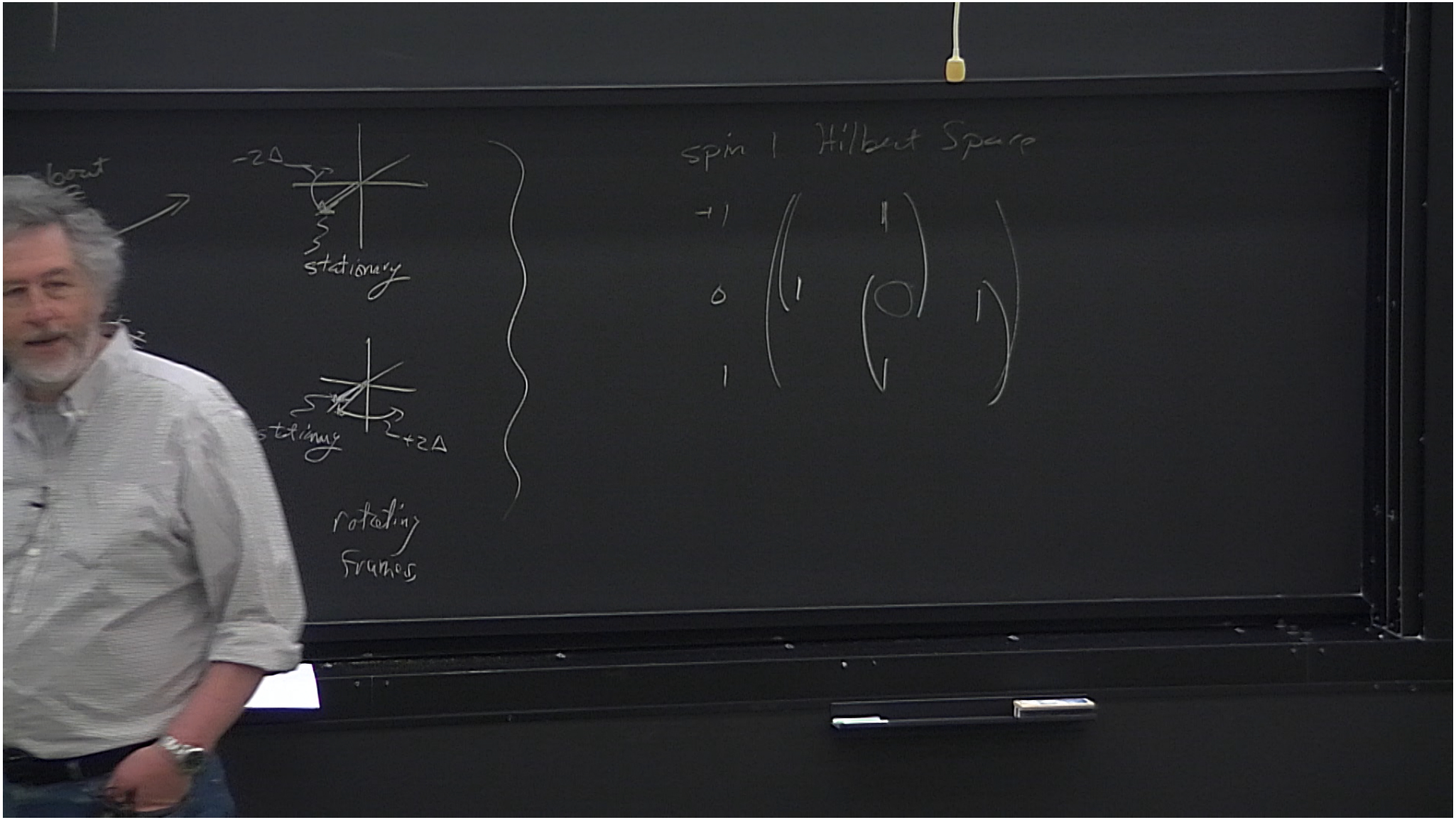

Rotating frame (½ spi
Rotate about z at ω₀
z
y
x
ω₀
ω₀
|1⟩+|-1⟩/√2
lab
NV
-Δ
Δ
|0⟩|-1⟩/√2
|0⟩+|+1⟩/√2
lab fra

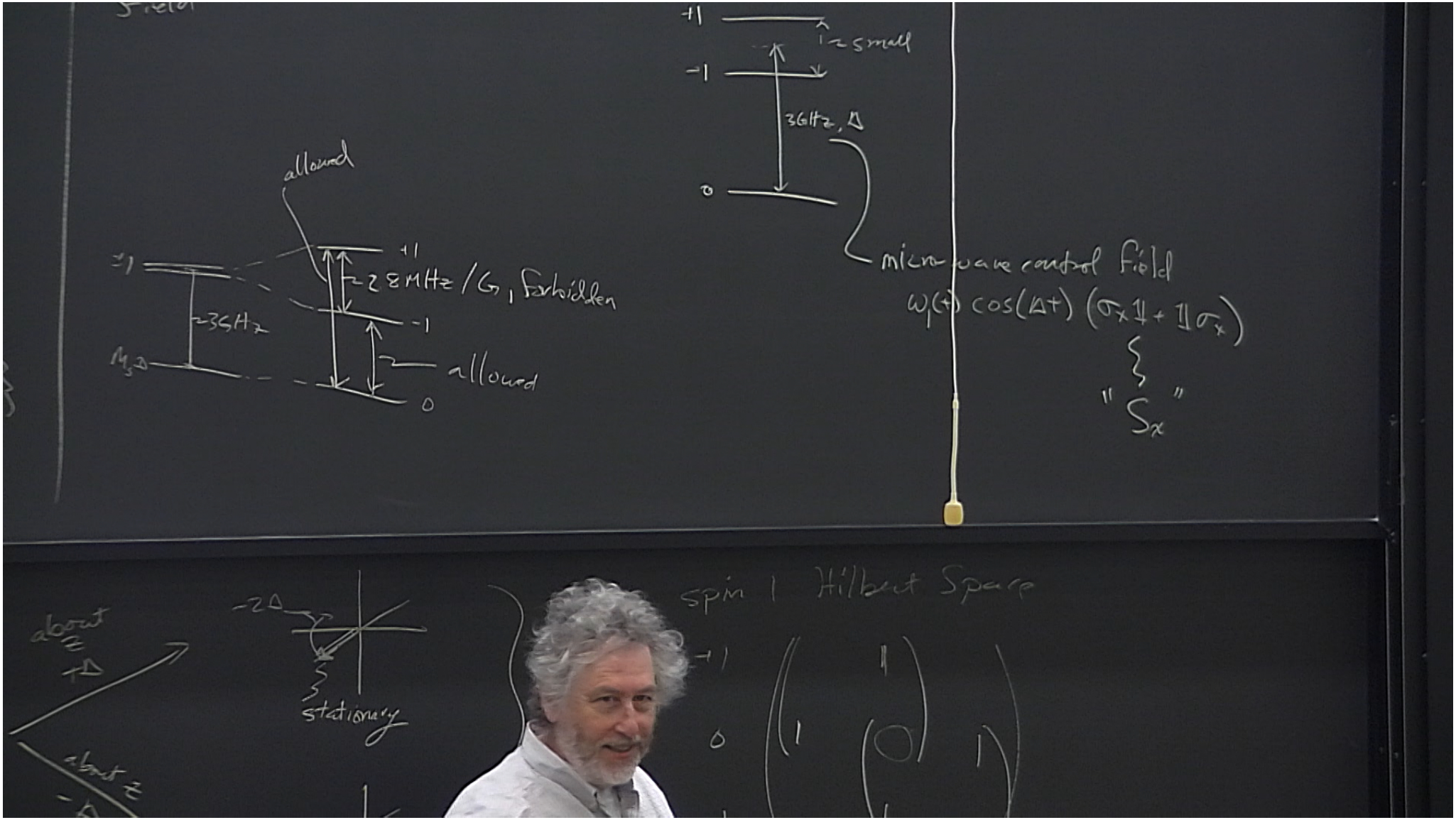

Rotating frame (½ spin)
z
Rotate about z at ω₀
ω₀
y
x
ω₀
lab
z
y_r
x_r
control field
Rotating
NV
-Δ
π
|0⟩|-1⟩/√2
|0⟩+|-1⟩/√2

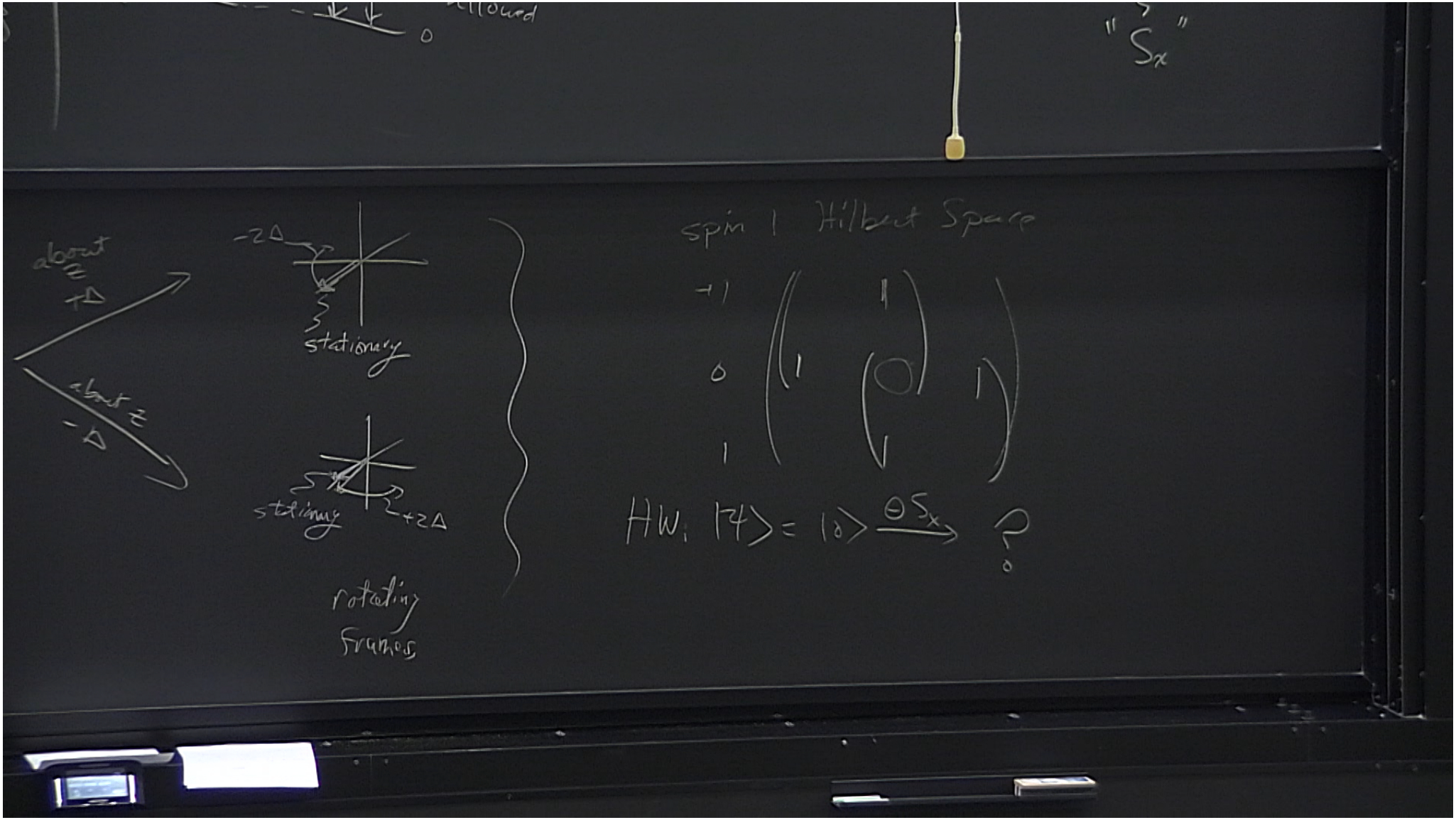

NV
-Δ
|0⟩-|-1⟩
√2
|0⟩+|+1⟩
√2
Δ
lab frame
about z
+Δ
about z
-Δ
-2Δ
stationary
stationary
+2Δ
rotating frames

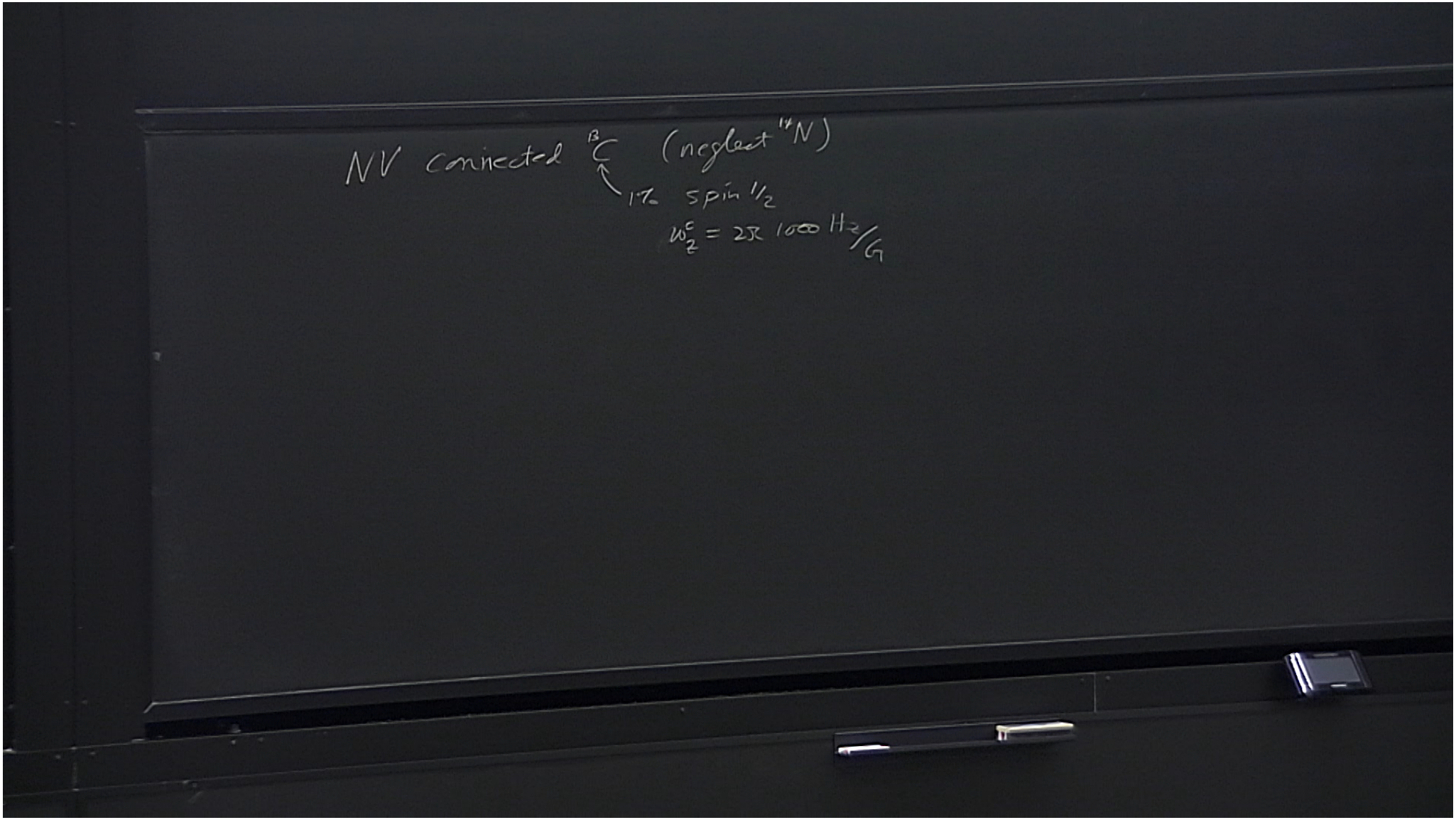

about z
+Δ
about z
-Δ
-2Δ
stationary
stationary
spin 1 Hilbert Space
+1
0
-1

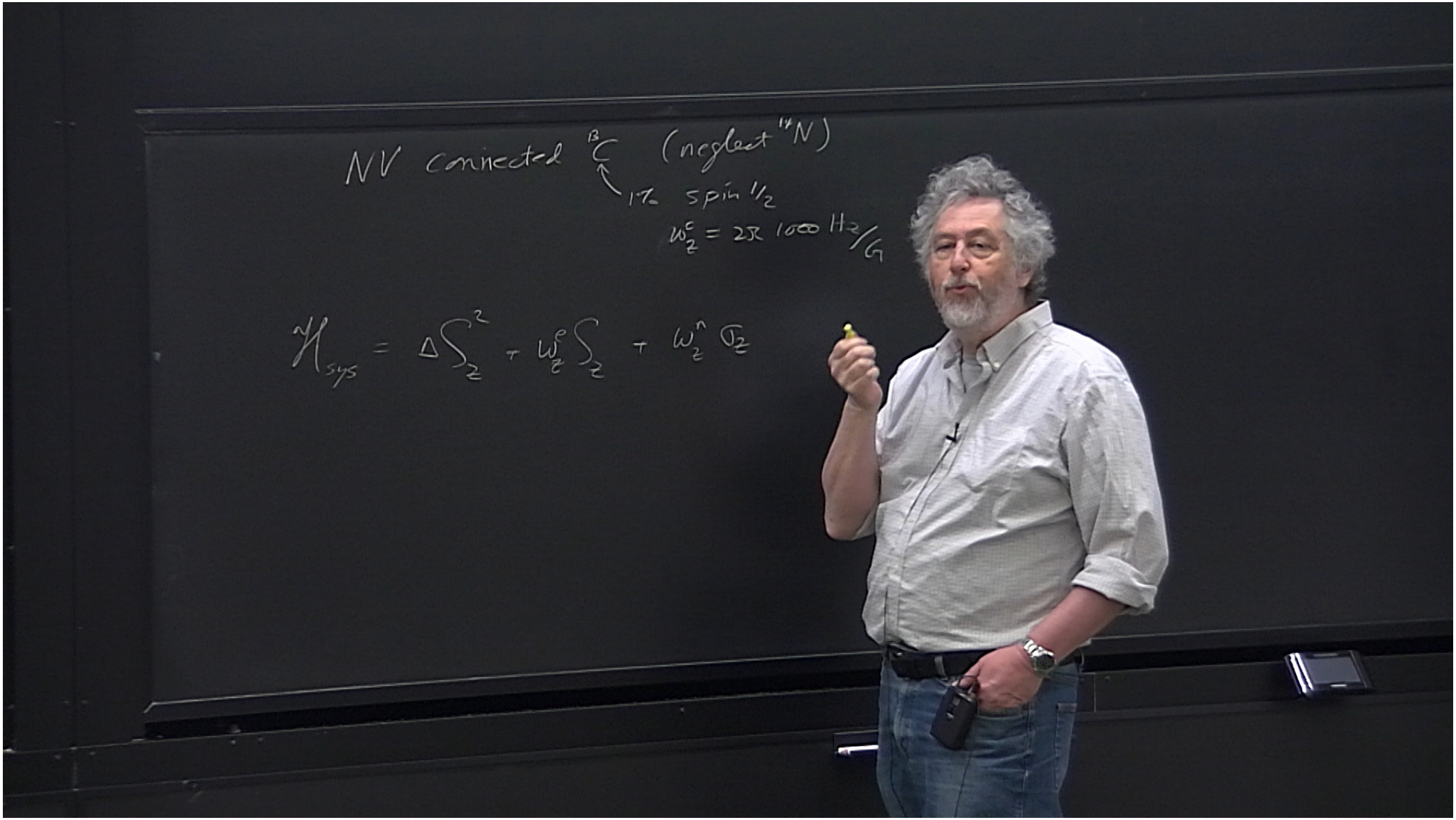

about z
+Δ
about z
-Δ
-2Δ
stationary
spin 1 Hilbert Space
+1
0
-1

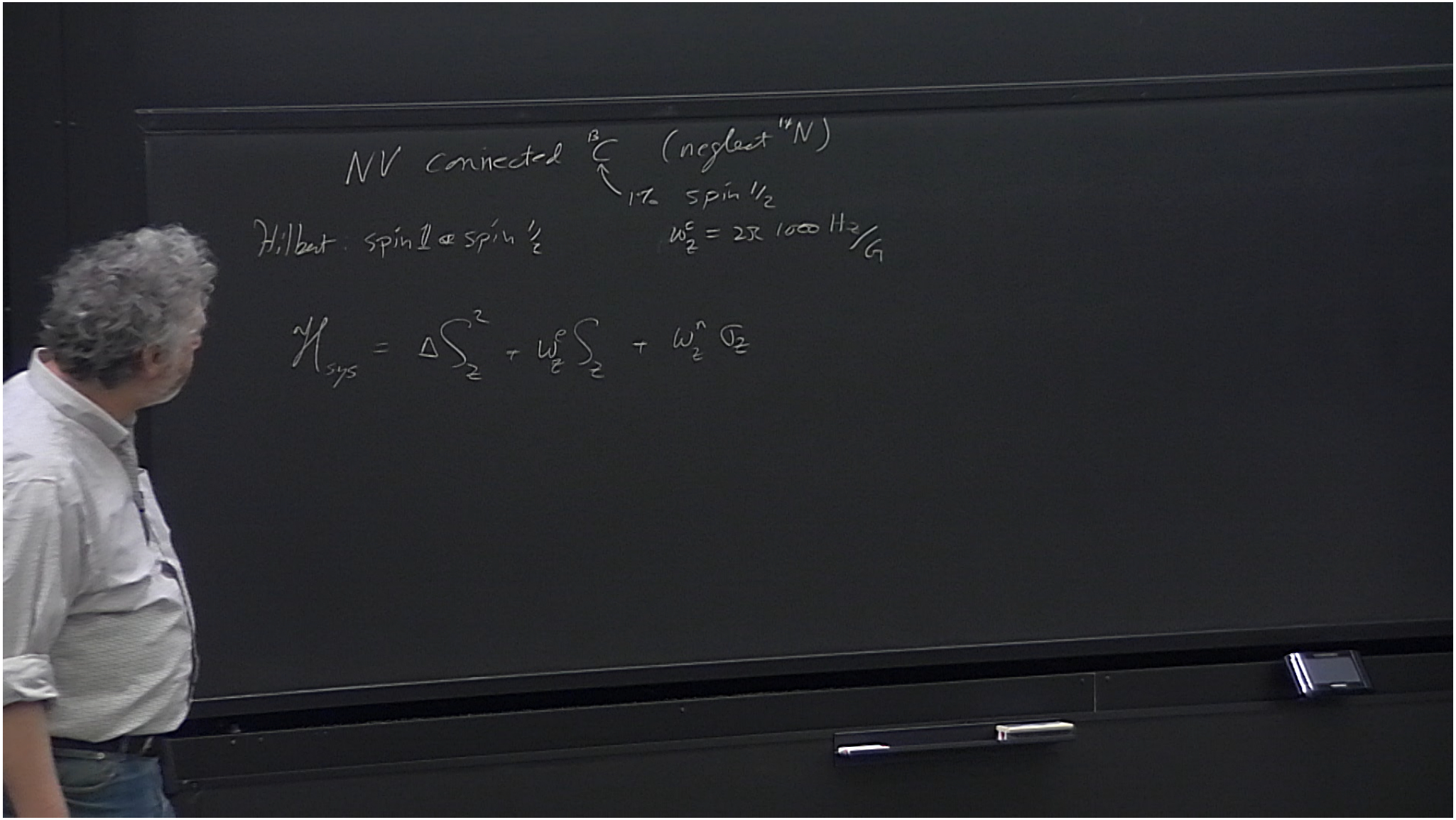

-2Δ
stationary
+2Δ
rotating
frames
spin 1 Hilbert Space
+1
0
-1


+1
-1
small
3GHz, Δ
0
microwave control field
$\omega_1(t)\cos(\Delta t)\,(\sigma_x \mathbb{1} + \mathbb{1}\sigma_x)$
"S_x"
allowed
+1
-1
0
2.8MHz/G, forbidden
3GHz
allowed
spin 1 Hilbert Space
+1
0
-1
$\begin{pmatrix} 1 & & \\ & 0 & \\ & & 1 \end{pmatrix}$
about z
+Δ
-Δ
-2Δ
stationary


about z
+Δ
about z
-Δ
-2Δ
stationary
stationary
+2Δ
rotating frames
spin 1 Hilbert Space
+1
0
-1
HW: |↑⟩ = |0⟩ →θSx ?
"Sx"


NV connected ^{13}C (neglect ^{14}N)
1% spin 1/2
$\omega_z^C = 2\pi \times 1000\ Hz/G$


NV connected ^{13}C (neglect ^{14}N)
1% spin 1/2
$\omega_z^c = 2\pi\ 1000\ Hz/G$
$\mathcal{H}_{sys} = \Delta S_z^2 + \omega_z^e S_z + \omega_z^n \sigma_z$


NV connected ^{13}C (neglect ^{14}N)
1% spin 1/2
Hilbert: spin 1 ⊗ spin 1/2
$\omega_z^c = 2\pi \cdot 1000\ \mathrm{Hz/G}$
$\mathcal{H}_{sys} = \Delta S_z^2 + \omega_z^e S_z + \omega_z^n \sigma_z$

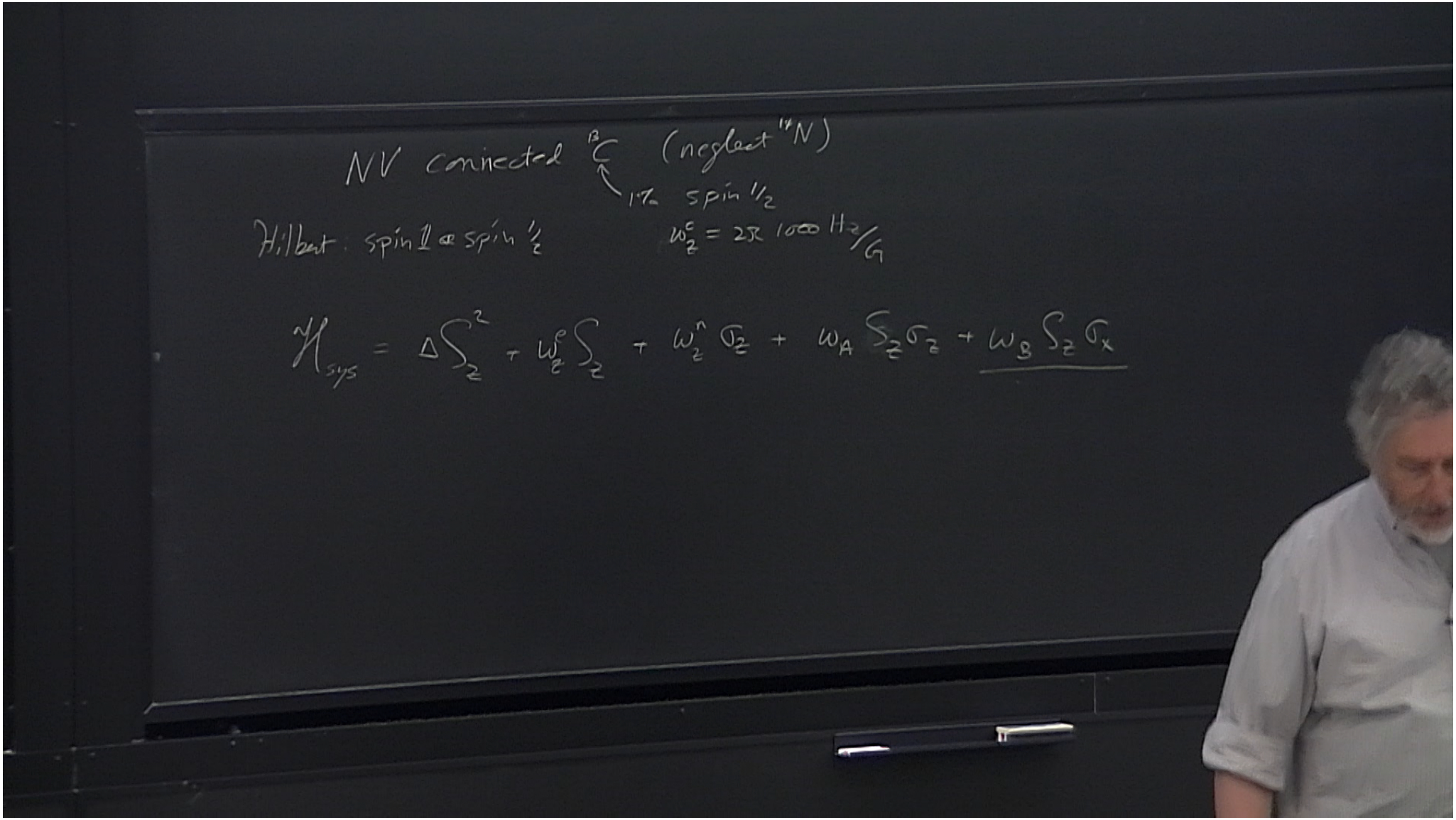
NV connected ^{13}C (neglect ^{14}N)

1% spin 1/2

Hilbert. spin 1 ⊗ spin 1/2

$\omega_z^c = 2\pi \times 1000\ \mathrm{Hz/G}$

$$\mathcal{H}_{sys} = \Delta S_z^2 + \omega_z^e S_z + \omega_z^n \sigma_z + \omega_A S_z \sigma_z + \omega_B S_z \sigma_x$$


NV connected ^{13}C (neglect ^{14}N)
1% spin 1/2
Hilbert: spin 1 ⊗ spin 1/2
$\omega_z^c = 2\pi \times 1000$ Hz/G
$\mathcal{H}_{sys} = \Delta S_z^2 + \omega_z^e S_z + \omega_z^n \sigma_z + \omega_A S_z \sigma_z + \omega_B S_z \sigma_x$

Spin 1/2 e

Spin 1/2 n

$$\mathcal{H} = \omega_z^e \sigma_z^e + \omega_z^n \sigma_z^n + \omega_A \sigma_z^e \sigma_z^n + \omega_B \sigma_z^e \sigma_x^n$$

effective Hamiltonian on n, condition on the e spin state $\begin{cases} +1/2 \\ -1/2 \end{cases}$

of

Spin 1/2 e

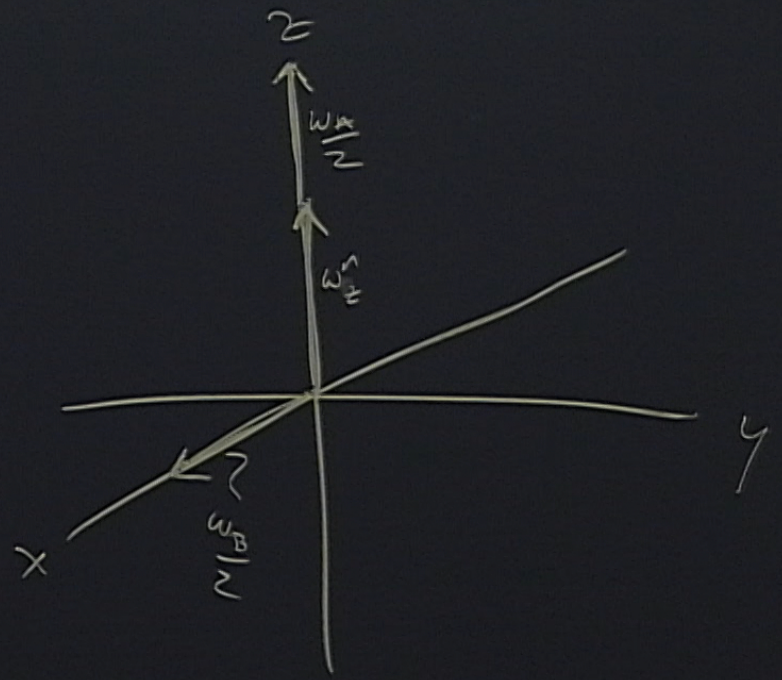
Spin 1/2 n

$$\mathcal{H} = \omega_z^e \sigma_z^e + \omega_z^n \sigma_z^n + \omega_A \sigma_z^e \sigma_z^n + \omega_B \sigma_z^e \sigma_x^n$$

effective Hamiltonian on n, condition on the e spin state $\begin{cases} +1/2 \\ -1/2 \end{cases}$

$$\mathcal{H}_\uparrow = \omega_z^n \sigma_z^n + \frac{\omega_A}{2} \sigma_z^n + \frac{\omega_B}{2} \sigma_x^n$$

$$\mathcal{H}_\downarrow = \omega_z^n \sigma_z^n - \frac{\omega_A}{2} \sigma_z^n - \frac{\omega_B}{2} \sigma_x^n$$



Spin ½ e

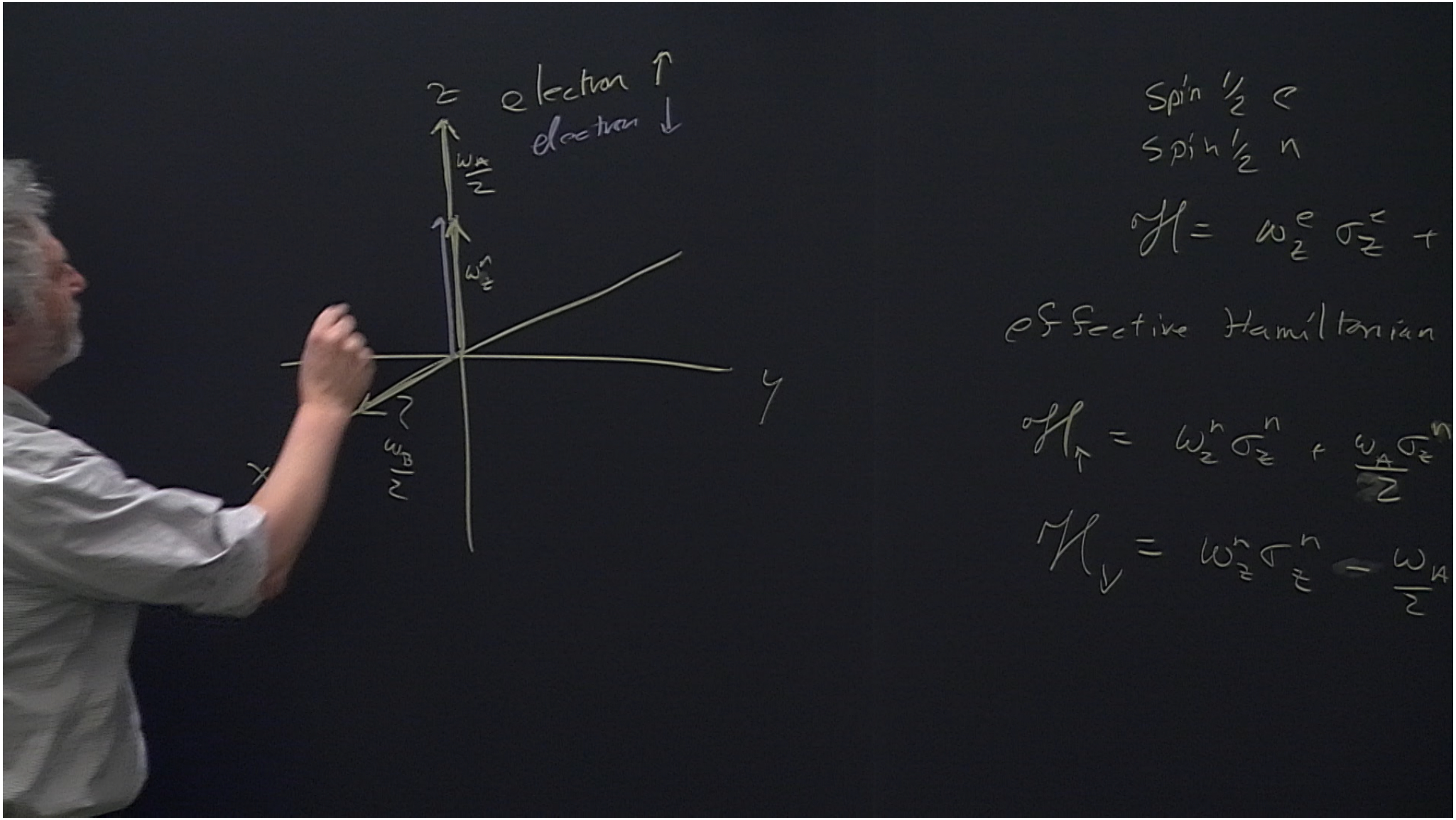
Spin ½ n

$\mathcal{H} = \omega_z^e \sigma_z^e +$

effective Hamiltonian

$\mathcal{H}_\uparrow = \omega_z^n \sigma_z^n + \frac{\omega_A}{2} \sigma_z^n$

$\mathcal{H}_\downarrow = \omega_z^n \sigma_z^n - \frac{\omega_A}{2}$



Spin ½ e

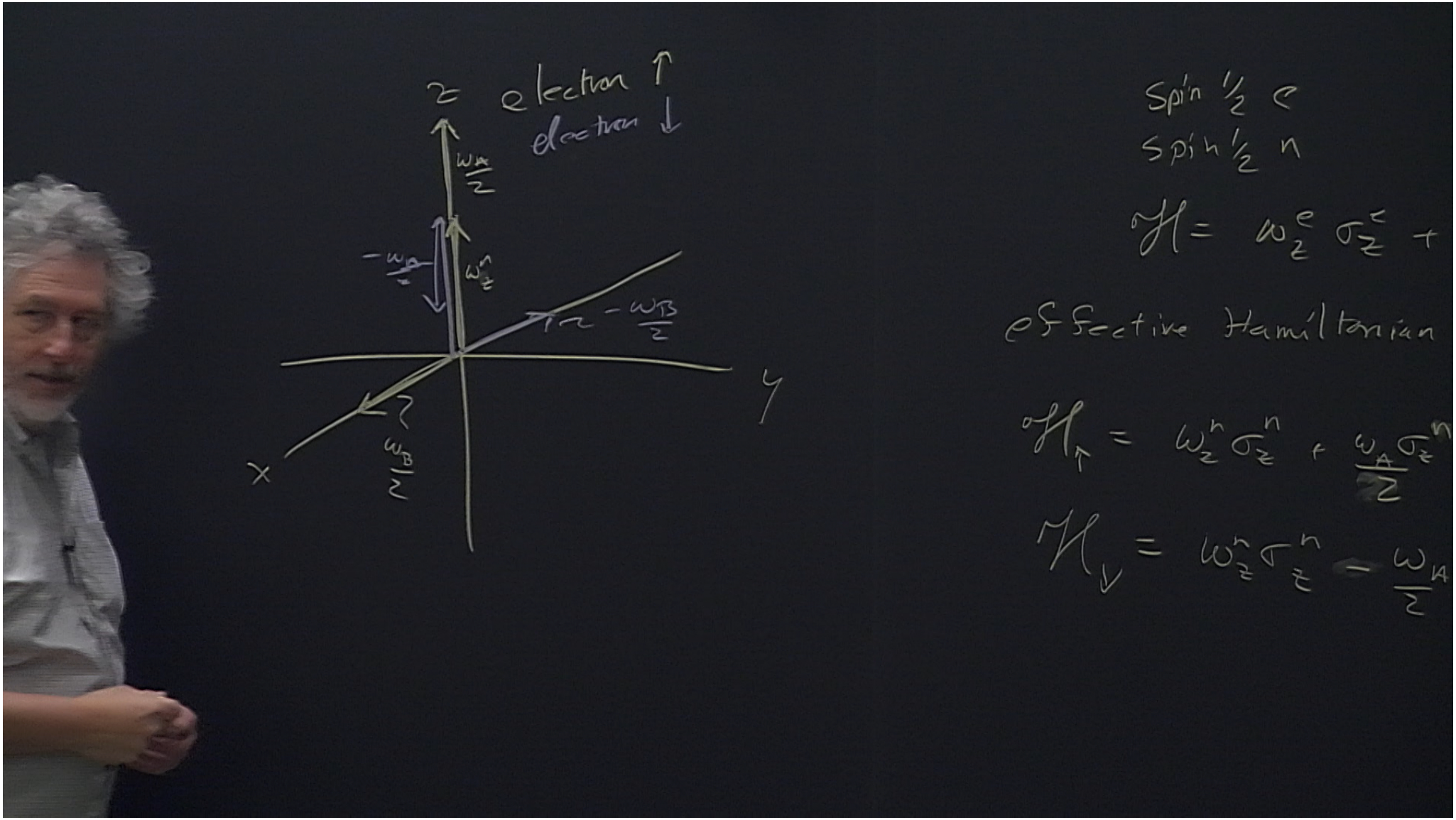
Spin ½ n

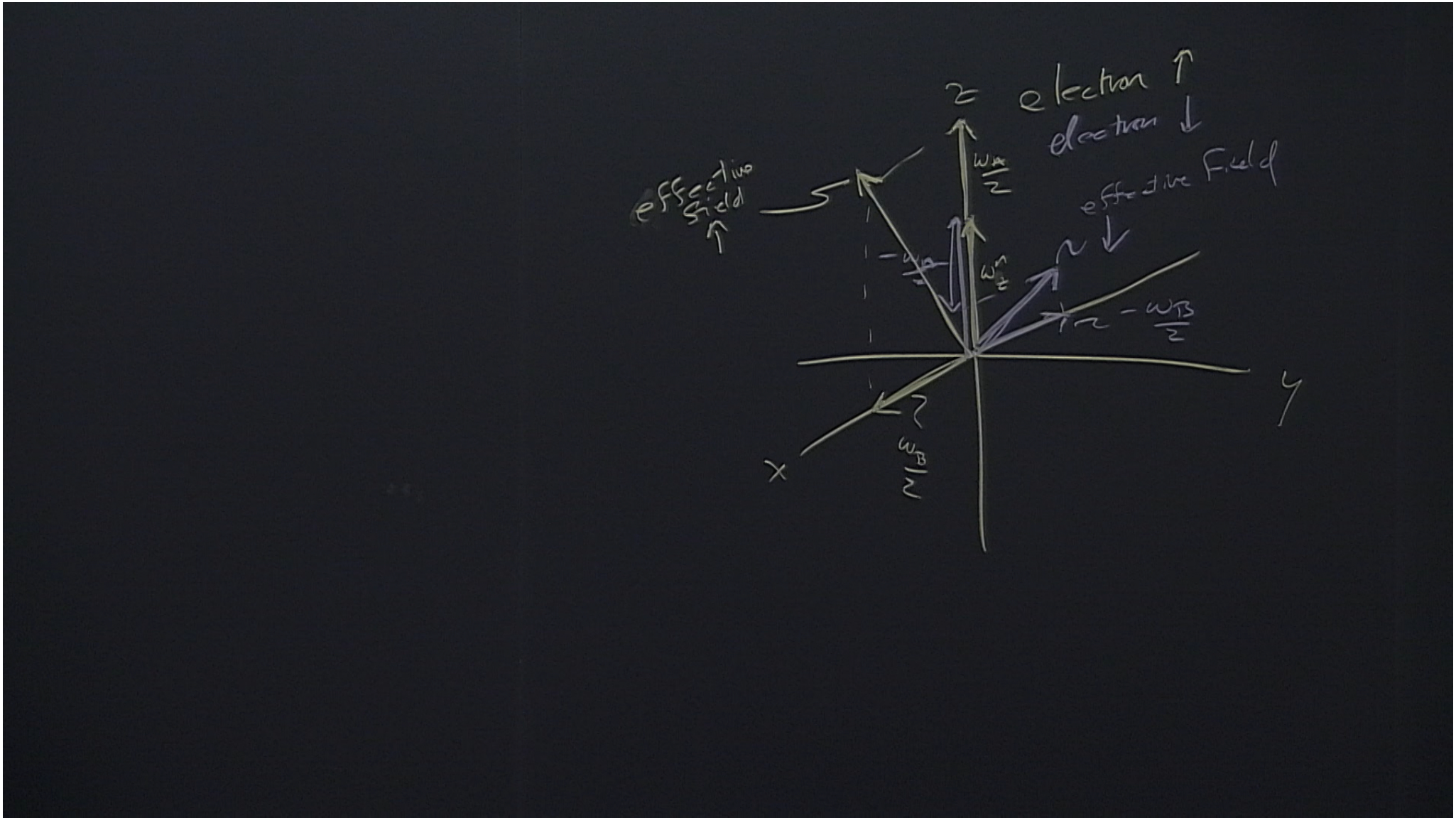
$\mathcal{H} = \omega_z^e \sigma_z^e +$

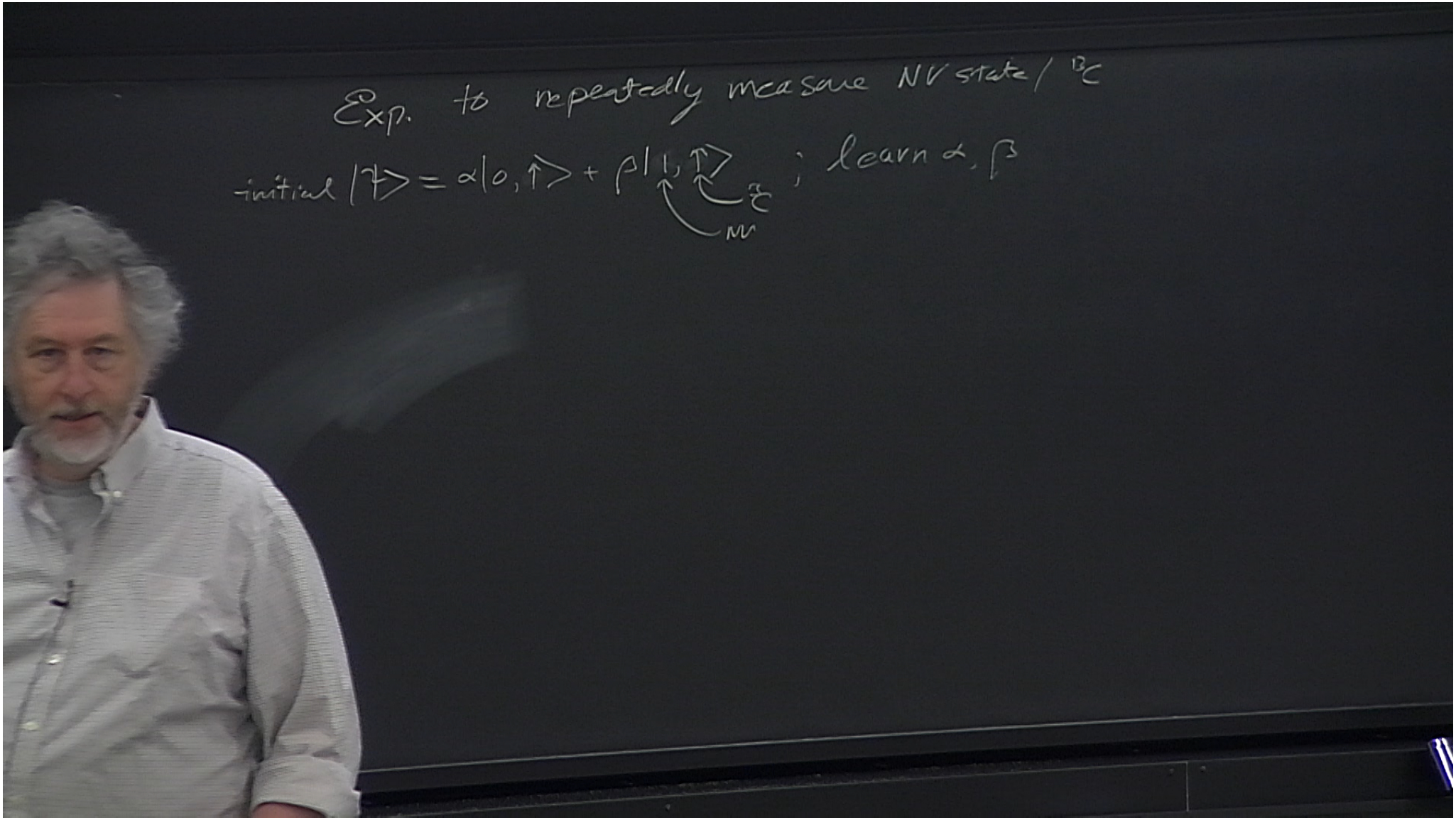
effective Hamiltonian

$\mathcal{H}_\uparrow = \omega_z^n \sigma_z^n + \frac{\omega_A}{2} \sigma_z^n$

$\mathcal{H}_\downarrow = \omega_z^n \sigma_z^n - \frac{\omega_A}{2}$

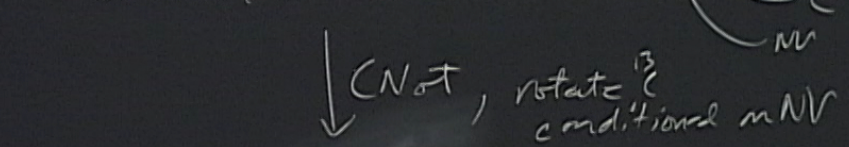

z
electron ↑
electron ↓
$\frac{\omega_A^e}{2}$
$-\frac{\omega_B^e}{2}$
ω_z^n
$\frac{\omega_B}{2}$
$-\frac{\omega_B}{2}$
y
x
Spin ½ e
Spin ½ n
$\mathcal{H} = \omega_z^e \sigma_z^e +$
effective Hamiltonian
$\mathcal{H}_\uparrow = \omega_z^n \sigma_z^n + \frac{\omega_A}{2} \sigma_z^n$
$\mathcal{H}_\downarrow = \omega_z^n \sigma_z^n - \frac{\omega_A}{2}$


z
electron
electron
effective Field
effective Field
$\frac{\omega_{IA}}{2}$
$-\frac{\omega_{IA}}{2}$
$\frac{\omega_{IA}}{2}$
$+\frac{\omega_{IB}}{2}$
$-\frac{\omega_{IB}}{2}$
ω_{RF}/N
x
y


Exp. to repeatedly measure NV state / ^{13}C
initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$
ξ
N
; learn α, β

Exp. to repeatedly measure NV state / ^{13}C

initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β



↓ CNot, rotate ^{13}C conditioned on NV

$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$

Exp. to repeatedly measure NV state / ^{13}C

initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β

$\downarrow$ CNot, rotate ^{13}C conditioned on NV

$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$

$\downarrow$ measure

Exp. to repeatedly measure NV state / ^{13}C

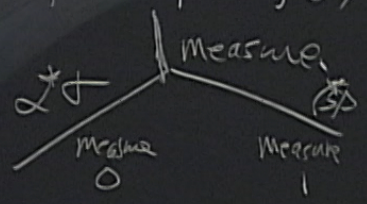
initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β

^{13}C

NV

↓ CNot, rotate ^{13}C conditioned on NV

$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$



Exp. to repeatedly measure NV state / ^{13}C

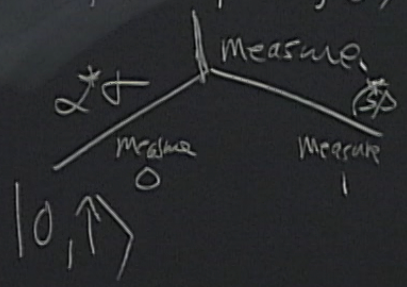
initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β

^{13}C

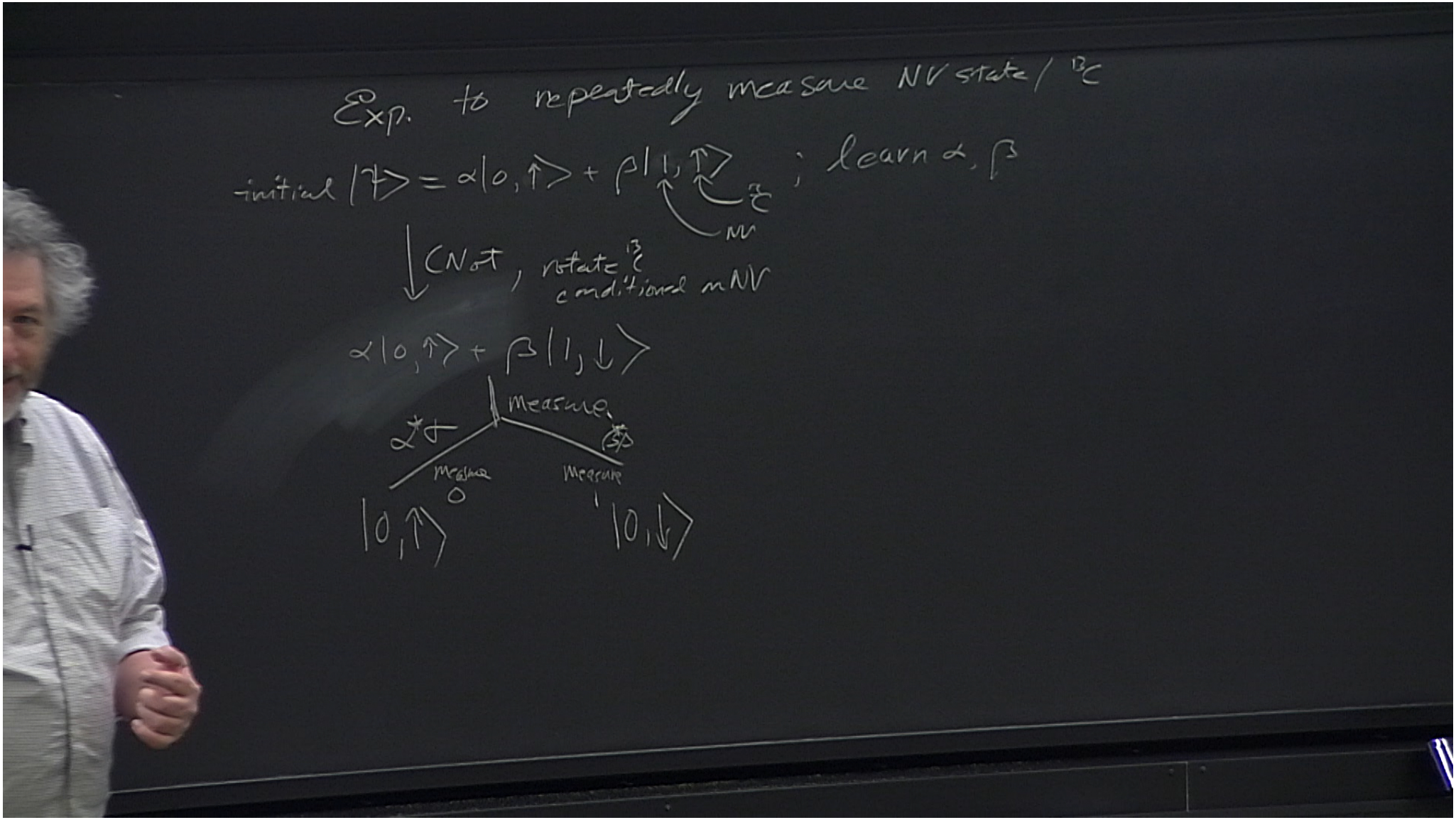
NV

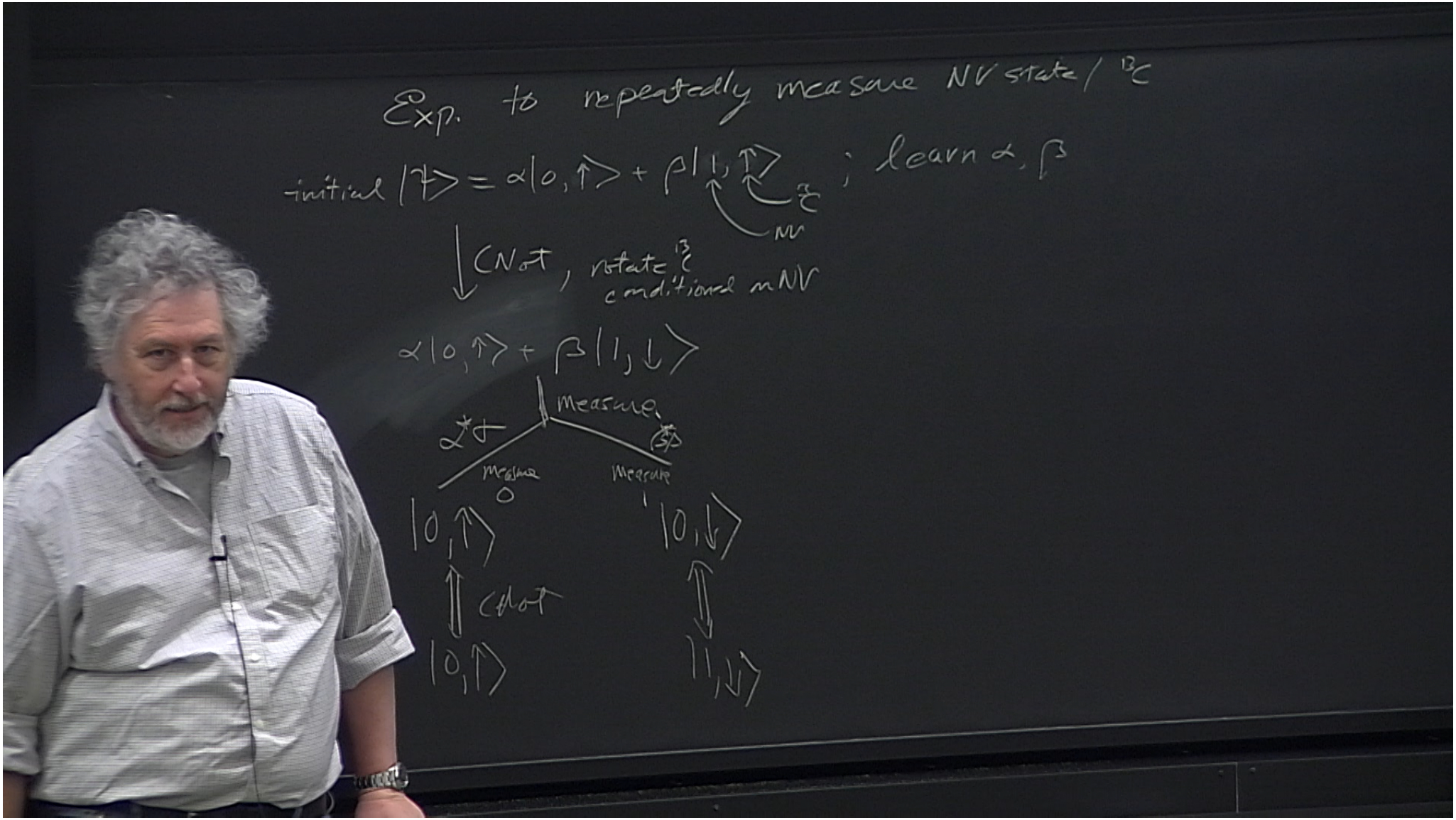
↓ CNot, rotate ^{13}C conditioned on NV

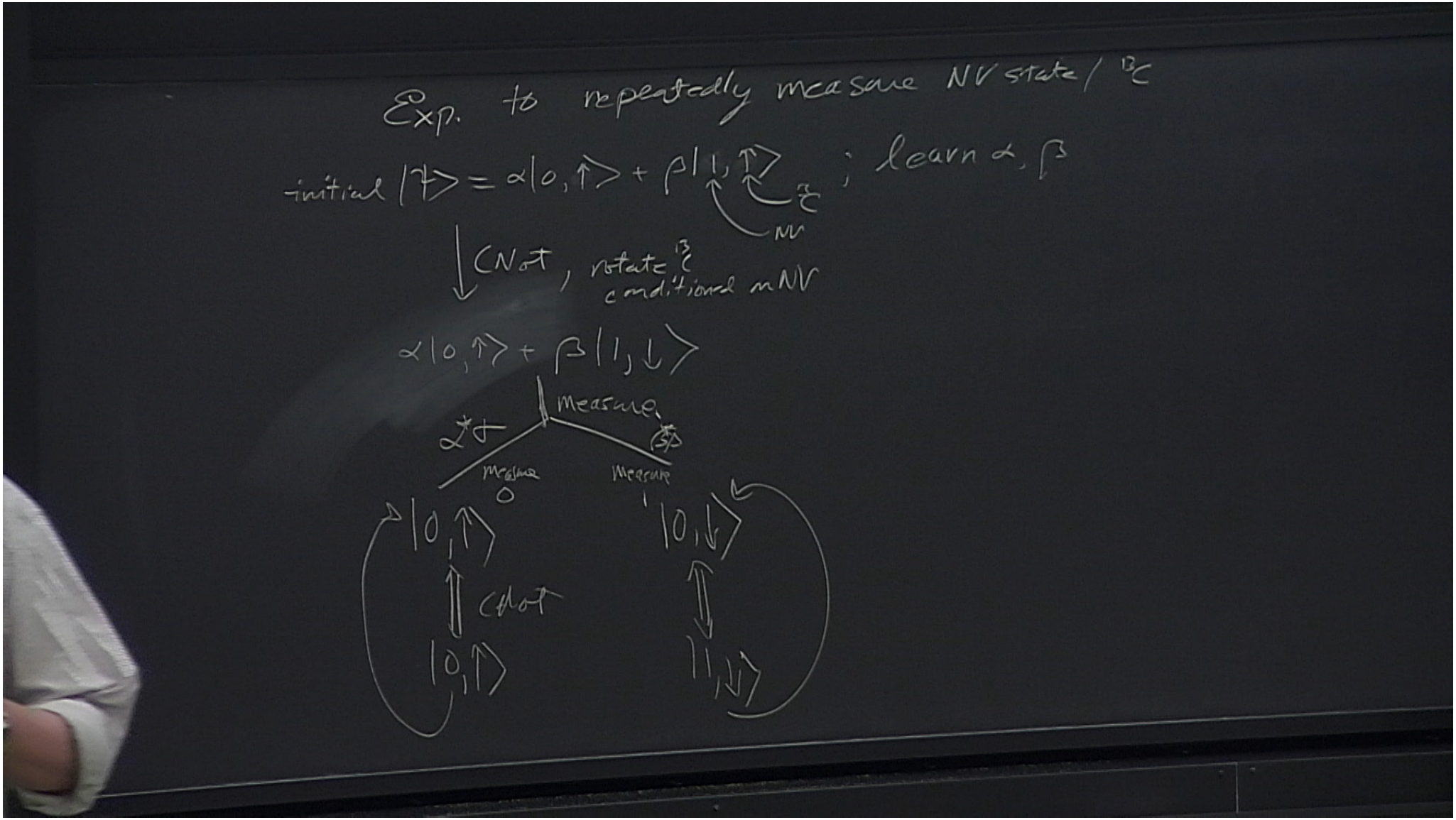
$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$



$|0,\uparrow\rangle$


Exp. to repeatedly measure NV state / ^{13}C
initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β
^{13}C
NV
CNot, rotate ^{13}C conditioned on NV
$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$
measure
$\alpha^*\alpha$
$\beta^*\beta$
measure 0
measure 1
$|0,\uparrow\rangle$
$|0,\downarrow\rangle$


Exp. to repeatedly measure NV state / ^{13}C
initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β
NV
CNot, rotate ^{13}C conditioned on NV
$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$
measure
$\alpha^*\alpha$
$\beta^*\beta$
measure 0
measure 1
$|0,\uparrow\rangle$
$|0,\downarrow\rangle$
CNot
$|0,\uparrow\rangle$
$|1,\downarrow\rangle$


Exp. to repeatedly measure NV state / ^{13}C
initial $|\psi\rangle = \alpha|0,\uparrow\rangle + \beta|1,\uparrow\rangle$; learn α, β
^{13}C
NV
CNot, rotate ^{13}C conditioned on NV
$\alpha|0,\uparrow\rangle + \beta|1,\downarrow\rangle$
measure
$\alpha^*\downarrow$
$\beta^*\uparrow$
Measure 0
Measure 1
$|0,\uparrow\rangle$
$|0,\downarrow\rangle$
CNot
$|0,\uparrow\rangle$
$|1,\downarrow\rangle$